CHAPTER

# 6

# Mine Waste: A Brief Overview of Origins, Quantities, and Methods of Storage☆

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OUTLINE



## 1 ORIGINS AND QUANTITIES OF MINE WASTE

With an expanding world market for mineral commodities such as chrome, coal, copper, diamonds, fluorspar, gold, iron, manganese, and zinc, so necessary for the functioning of the modern world, mining companies are exploiting ever low-grade ore bodies on an ever-increasing scale. Mining on a vast scale is usually necessary for profitability of a lower-grade mine, and volumes of waste are commensurately large.

The actual volume of mine waste in need of disposal in dumps and tailings storage facilities, worldwide, is difficult to assess. In 1996 the International Commission on Large Dams (ICOLD) [1] estimated that this "almost

☆ The first edition of this chapter was written by Professor Geoff Blight. Professor Blight passed away on November 7, 2013. Dr. Vallero has only slightly modified the text from the first edition. In addition, two boxes have been added to address recent mine waste issues.

*Waste*
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certainly" exceeds $5 \times 10^9$ t year$^{-1}$ (5 billion tonnes per year). Considering that some valuable commodities occur in their ores in concentrations of grams or carats per tonne (1 carat = 0.2 g, 1 t = 1000 kg), and that many individual mines extract ore in excess of $5 \times 10^7$ t year$^{-1}$ (even the estimate of ICOLD is probably too low). For example, a single platinum tailings storage at Rustenburg, South Africa has a storage capacity of almost $1 \times 10^9$ t over a life of 50 years [2]. The mine currently sends $0.5 \times 10^6$ t of tailings to storage every month and plans to increase this to $2 \times 10^6$ t every month.

More recent estimated quantities of mine waste are as follows:

- The world's iron, copper, gold, lead, and bauxite (aluminum) mines together generated $35 \times 10^9$ t of waste in 1995 alone [3].
- The South African gold mining industry produced $7.4 \times 10^5$ t of gold tailings in the decade from 1997 to 2006, that is, $7.4 \times 10^4$ t year$^{-1}$ [4].
- All gold mining waste produced in the past century in South Africa amounts to $6 \times 10^9$ t, which covers a total area of 400–500 km$^2$, and contains $4.30 \times 10^5$ t of uranium and $3.0 \times 10^4$ t of sulfur, both of which, and especially the sulfur, have a high pollution potential [5].

The term "mine waste storage" is preferred to the more common "mine waste disposal," because advances in extractive metallurgy, along with increased demand and price for a commodity periodically coincide to allow a particular mine waste deposit to be reworked and further resources to be extracted from it at a profit. As examples, some gold mine waste storages in South Africa have been remined and reprocessed three times in the past 100 years. Some of these deposits started out as waste rock which was unprofitable to process at the time, but was necessary to remove to access richer ores. Some platinum mines are now considering reprocessing their older tailings storages for platinum and other minerals, and coal mines are reprocessing their old coal discard storages. Thus there is a realization that mine waste deposits are really storages of low-grade ore. They do not consist of the waste they were formerly considered to be. Even if the grade of mineral they contain remains too low for economical extraction, there may be a present or future economic value for other minerals in what is presently waste, or as a construction material.

It is for this reason that there is a great reluctance in the mining industry to "dispose" of waste by placing it in locations that render the waste inaccessible for future reprocessing, for example, in "worked out" parts of a mine, except where it can be used for strata support. In time to come, not only may the waste become profitable to reprocess but the stopes themselves may also be worth remining to remove seams or reefs of ore previously regarded as uneconomical to mine.

Ore bodies usually contain more than one type of mineralization. As examples, ore mined primarily for its platinum content, usually also contains chrome, used in stainless steel manufacture, and apatite from which phosphate fertilizers can be produced. At least one platinum mine in South Africa also extracts chrome as a by-product and supports a phosphoric acid plant for fertilizer manufacture. Another example relating to by-products is the South African gold mining industry which produced uranium as a by-product, much of which contributed to the Hiroshima and Nagasaki bombs during World War II. This activity stopped in the mid-1960s when the price of uranium fell, but it is now starting up again as it is being realized that nuclear power will have to be used in the future to replace dwindling coal and oil supplies. Fig. 6.1 shows a dump of waste sand, from early mining operations (1885–1905), in the process of being removed for reprocessing to extract gold and uranium left in the sand after the initial extraction process, 100 years ago.

Some mine waste can be recycled for other purposes. For example, waste rock can be used as a fill material in civil engineering works, or

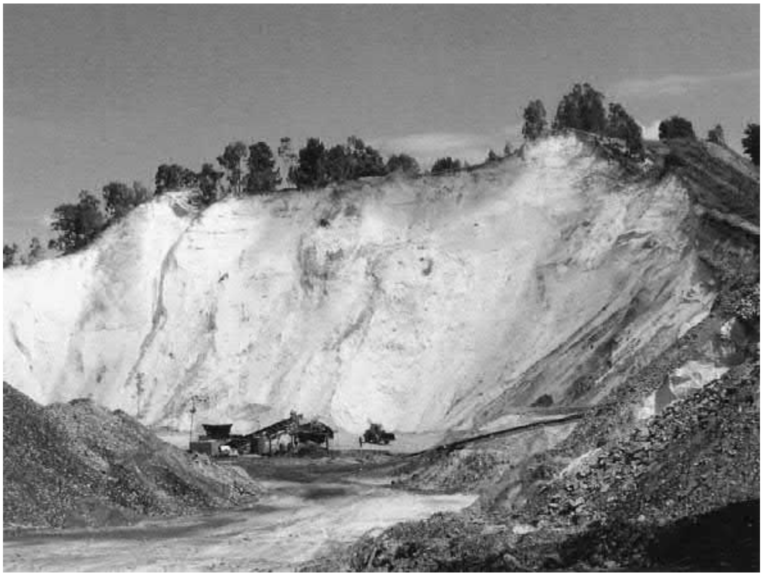

FIG. 6.1 A 100-year-old dump of gold tailings sand being remined for processing to extract the uranium and residual gold content.

if the rock is sound, durable, and unweathered and has a satisfactory mineralogy, as aggregate for concrete and in asphalt and road layer works. Gypsum, a by-product of fertilizer manufacture from apatite rock, can be used to make building boards or can be reprocessed to produce sulfuric acid and building cement.

## 2 WASTE CHARACTERISTICS

Mine waste may arise in a number of forms: as stripped soil and coarse, broken, partly weathered rock overburden in open cast or strip-mining operations; as unweathered development waste rock in underground mining; and as fine-grained tailings, the residuum of the process of comminution and mineral extraction from ores. The various wastes are usually stored separately. The top soil is stock piled for eventual use in environmentally rehabilitating the dumps of coarse wastes or the surfaces of backfilled surface-mining voids. The coarse broken rock is usually stored in dumps, either with or without compaction, or is used to progressively backfill opencast or strip-mining voids.

Fig. 6.2 shows typical particle size analyses for a range of tailings from various sources. In the diagram, the horizontal axis represents the particle size in millimeters and the vertical axis represents the proportion of material finer than a specific size. For example, for the vanadium tailings, 63% is finer than 0.06 mm, that is, the tailings contain 63% of silt and clay-sized particles.

In addition to its physical characteristics, mine waste and especially tailings may have characteristics or contain substances that may be prejudicial to the health of those living near the waste storage or the local natural environment. Examples of these are:

- combustible substances, usually carbon;
- free asbestos fiber (See Discussion Box 6.1);
- metallic sulfides, sulfuric acid, and metal sulfates;
- radon gas; and
- soluble salts of heavy metals, for example arsenic, cadmium, copper, lead, or nickel.

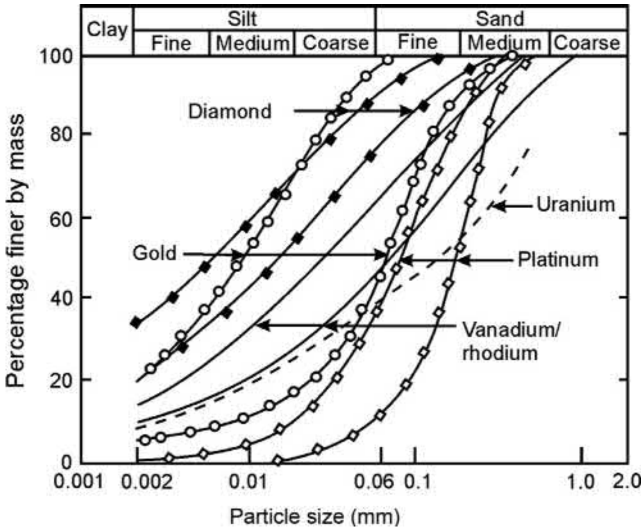


FIG. 6.2 Particle size analyses for typical tailings from mineral extraction of various ores (e.g., Vanadium tailings contain 63% of particles finer than 0.06 mm).

## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS

Mining rock for ore and manufacturing of mined products from the ore emit considerable amounts of particulate matter at every stage of the operation. These particulates may include fine mineral dusts of a size to cause damage to the lungs. Depending on the type of rock, mineral fibers can also be released, notably asbestos. The threshold values for such dusts have been set quite low to prevent disabling diseases for the worker, including lung cancer, mesothelioma, pleural diseases, asbestosis, and silicosis.

After extraction, depending on the rock and the ore, downstream life cycle stages may involve crushing and grinding, pelletizing, and separating by magnets or sieving. Such postextraction processes can be enclosed and controlled to prevent the emission of particles. In many cases, the recovered particles can be returned to the process, that is, reused in an earlier stage in the product life cycle [6].

To make the math easier, such as when calculating aerodynamic diameter or Stokes diameter, airborne particles are often considered to be spheres, which may be true, for example, those found in metal refining emissions [6–8]. In the real world, particles come in myriad shapes, including angular, for example, soil particles. One of the most troublesome morphologies is elongated particles, which are differentiated from other particulates as “fibers.” Such elongation is expressed as a particle’s aspect ratio, that is, the ratio of the length to width. Fibers generally have aspect ratios >3:1; often much greater. For example, the lungs of mice exposed to a complex mixture of fiber sizes and nonfibrous material known as the “Libby 6 mix” from the Montana vermiculate mining area had a mean aspect ratio of 16 [9].

Recently, the scientific community has differentiated elongate mineral particles (EMPs) as an important pollutant class. Asbestos is a naturally occurring EMP, which has been mined and used for many industrial purposes.

The term, asbestos, is a regulatory term. In the United States, for example, regulators limit asbestos to six fibrous hydrated silicate minerals [10] (See Table 6.1), even though about 400 minerals have fibrous morphologies [11] Exposure to

## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (*cont'd*)

**TABLE 6.1** Asbestos Minerals in the United States

| Name Used by Federal Regulatory Agencies | Mineral Name | Mineral Group | Chemical Formula |
|---|---|---|---|
| Chrysotile | Chrysotile | Serpentine | $Mg_3Si_2O_5(OH)_4$ |
| Tremolite asbestos | Tremolite | Amphibole | $Ca_2Mg_5Si_8O_{22}(OH)_2$ |
| Actinolite asbestos | Actinolite | Amphibole | $Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$ |
| Anthophyllite asbestos | Anthophyllite | Amphibole | $Mg_7Si_8O_{22}(OH)_2$ |
| Crocidolite | Riebeckite | Amphibole | $Na_2Fe_3{}^{2+}, Fe_2{}^{3+}Si_8O_{22}(OH)_2$ |
| Amosite | Cummingtonite-Grunerite | Amphibole | $(Mg,Fe^{2+})_7Si_8O_{22}(OH)_2$ |

airborne asbestos fibers is known to producedebilitating health effects in humans. "Total EMP" includes any mineral particle with a minimum aspect ratio of at least 3:1, but which is also small enough to penetrate the airway, that is, inhalable, thoracic, or respirable size [12]. An amphibole EMP is a subset comprised of double chain silicate minerals, that is, crocidolite, amosite, anthophyllite, tremolite, and actinolite, which can be asbestiform or nonasbestiform [13]. An asbestiform EMP is usually narrower, longer, and more flexible than a nonasbestiform EMP [14].

As indicated in Table 6.2 the chemical composition of particulate matter emitted by mining activities varies by the mineralogy of rock strata in an area, but also by distance from the mining site. In this case, samples taken in and near a taconite mine show that, not surprisingly, the ore contains the highest amount of iron, which drops with distance from the mine. The clay content shows the opposite trend, as soil mixes with the particulates from the ore and tailing piles. What the table does not show is the number and types of EMPs.

Mining and ore processing activities produce asbestos, a group of highly fibrous minerals with separable, long, and thin fibers. Cases of mesothelioma have also been seen in individuals withoutoccupational asbestos exposure who live close to asbestos mines [15]. Human exposure to concentrations much higher than $10^{-4}$ fibers $mL^{-1}$ is suspected of causing health effects. Asbestos fibers are very persistent and resist chemical degradation (i.e., they are inert under most environmental conditions) so their vapor pressure is nearly zero meaning they do not evaporate, not do they dissolve in water. However, the most commonly encountered asbestos, chrysotile, may degrade slowly in acidic environments. In addition, previously mined areas can be problematic since segments of fibers of even for the more resistant forms will enter the air and water as asbestos-containing rocks and minerals weather naturally or are physically altered during mining operations [16].

Waste managers should also be aware that products containing asbestos enter the waste stream as solid wastes, from construction, renovation, and repair. Indeed, among the most important exposures is when manufactured products, like pipe wrapping and fire-resistant materials, wear down. Small diameter asbestos

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## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (*cont'd*)

**TABLE 6.2** Bulk Sample Microscopic Analysis of Particulate Matter Near a Taconite Ore Processing Facility in Minnesota

| Component | Ore Percent Volume | Tailings Basin | Roadside in Nearby Neighborhood | Window Seal in Nearby Neighborhood |
|---|---|---|---|---|
| Mineral—total | 100 | 100 | 100 | 97 |
| Quartz—feldspar | 30 | 57 | 52 | 48 |
| Limestone | <1 | <1 | <1 | <1 |
| Clay—humus | 2 | 8 | 10 | 15 |
| Magnetic iron | <1 | 2 | 2 | 2 |
| Iron oxide | 43 | 12 | 16 | 15 |
| Other | 25 | 21 | 20 | 17 |
| Biological—total | 0 | 0 | 0 | 0 |
| Insect parts | <1 | <1 | <1 | <1 |
| Plant material | <1 | <1 | <1 | <1 |
| Pollen—spores | <1 | <1 | <1 | <1 |
| Starch grains | <1 | <1 | <1 | <1 |
| Other | | | | |
| Combustion—total | 1 | 1 | 0 | 1 |
| Ash—cinder | 1 | 1 | <1 | 1 |
| Coal—coke—oil | <1 | <1 | <1 | <1 |
| Cenospheres | <1 | <1 | <1 | <1 |
| Fine carbonaceous | <1 | <1 | <1 | <1 |
| Other | | | | |
| Miscellaneous—total | 0 | 2 | 0 | 2 |
| Tire fragments | <1 | <1 | <1 | <1 |
| Wood fibers | <1 | <1 | <1 | <1 |
| Paper fibers | <1 | <1 | <1 | <1 |
| Concrete | <1 | <1 | <1 | <1 |
| Asphalt | <1 | <1 | <1 | <1 |
| Metal fume | <1 | <1 | <1 | <1 |
| Paint | <1 | 2 | <1 | 2 |
| Other | <1 | <1 | <1 | <1 |

*Data from Minnesota Pollution Control Agency, 2012.*

## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (*cont'd*)

fibers may remain suspended in the air for a long time and be transported advectively by wind or water before sedimentation. Like particles, heavier fibers settle more quickly. Asbestos fibers-may break into shorter strands and, therefore, increased number of fibers, by mechanical processes, for example, grinding and pulverization.

### Analytical Techniques

Because of its toxicity, effective monitoring techniques and analytical methods are needed to detect, quantify, and control asbestos in the environment. Whereas chemical composition is often the critical feature of particulate matter's health effects, the shape of EMPs is usually even more important. Therefore both morphological and chemical analysis of EMPs is need. These methods have been developed for a variety of purposes including support health risk assessments and controls.

Like all particulate matter, ELP's diameter determines the type and severity of disease that results from exposure. For example, asbestos exposure has been directly associated with three different diseases, mesothelioma, lung cancer, and asbestos, but these differ by the length and diameter of the fiber (See Fig. 6.3). The major concern with asbestos is when it is breathed in as a fiber. The size and shape of any aerosol, including a fiber, largely determines its toxicity. Fine particles (diameter $<2.5\,\mu m$) can infiltrate the lungs more deeply and deposit with greater efficiency than larger particles. Particulate matter (PM) is measured using instruments that draw air through filters that collect particles using size selection components to separate out the mass of each size fraction. These "dichotomous" samplers allow for separation of fine particles with aerodynamic diameters $<2.5\,\mu m$ ($PM_{2.5}$) from coarse particles with aerodynamic diameters $>2.5\,\mu m$, but $<10\,\mu m$ ($PM_{10}$) [16].

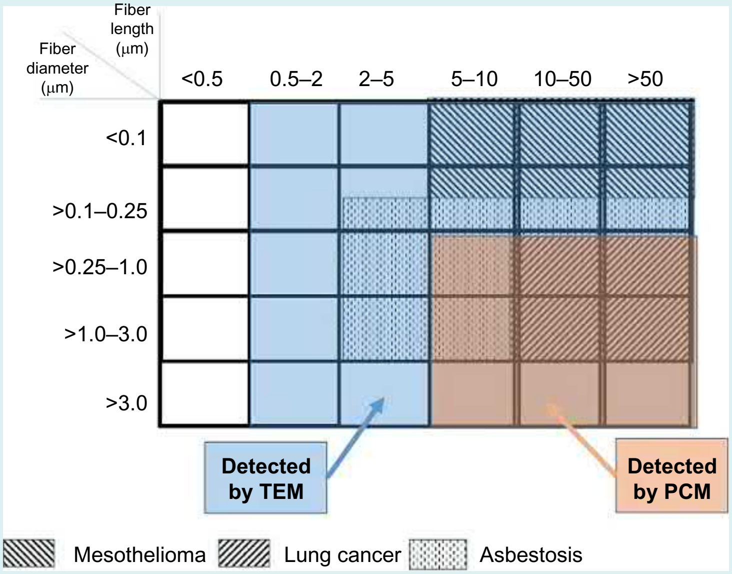


FIG. 6.3 Length and diameter ranges of asbestos fibers and associated diseases, along with the comparative detection ranges for transmission electron microscopy (TEM) and phase contrast microscopy (PCM). *Drawing by D.A. Vallero; modified from P. Baron, Measurement of fibers, NIOSH Manual of Analytical Methods, 2003, pp. 143–166; adapted from K. Ashley, NIOSH manual of analytical methods 5th edition and harmonization of occupational exposure monitoring, Gefahrst. Reinhalt. Luft. 2015(1–2) (2015) 7.*

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## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (*cont'd*)

In addition to size and counts of fibers, optical and electronic microscopy can help to characterize morphological features of ELPs. These techniques include phase contrast microscopy (PCM), polarized light microscopy (PLM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The chemical constituents of ELPs can also be analyzed, forexample, by X-ray diffraction spectrometry (XRD). Following are brief descriptions of these processes [17, 18].

### Phase Contrast Microscopy

Airborne levels of asbestos in the workplace can be monitored using PCM. Air samples are collected on a 0.45–1.2 μm cellulose ester membrane filter. A portion of the filter is mounted on a microscope slide, cleared using an organic solvent and fibers are observed in a bright field at a magnification of 100 to 400×. PCM is reported to detect fibers as thin as 0.25 μm in thickness. PCM can detect fibrous materials but cannot directly distinguish asbestos fibers from other fibrous materials. PCM is typically used in workplace environments where the fiber type is known. Quantitatively, PCM methods report fibers per cubic centimeter of air sampled (f $cm^{-3}$). Normally fibers longer than 5 μm in length and having an aspect ratio (length to width) of 3:1 or greater are counted. Some protocols use an aspect ratio of 5:1 and count fibers with diameters <3 μm. It should be noted that current risk models are based on fibers with a 3:1 aspect ratio and data from methods employing a 5:1 aspect ratio cannot be used by such models.

### Polarized Light Microscopy

Asbestos and other fibers, and minerals in bulk samples can be measured using PLM, in which the bulk material is examined by stereomicroscopy at a magnification between 10 and 60× and subsamples of the various phases in the material are taken and mounted on a microscope slide in various refractive index liquids. Fibers are examined by PLM at magnifications between 100 and 500× and identified by their optical properties including morphology (characteristic shape), color, refractive indices, birefringence, extinction angle, and sign of elongation. Characteristic dispersion staining colors are also commonly used to identify mineral type.

PLM methods typically report fibers by percent area or percent weight. The percentage may be estimated by visual estimation, comparison with charts showing various area percentages or with gravimetrically prepared standards, or by a point counting procedure. Although point counting is a systematic means of determining the relative amounts of materials in a mixture, it is not a reliable means of determining mass since one point may represent a single thin fiber or a large mineral "boulder." Quantitative PLM results using these techniques are usually referred to as "semiquantitative" because they do not measure quantity directly. Some PLM procedures call for calculating the volume of each fiber, summing these volumes, and multiplying by the density of the fiber detected to calculate a total mass. If a sample has been processed to eliminate the matrix, the quantity of asbestos may be estimated by the loss in weight. It is difficult for the analyst to effectively convert the number of fibers observed by microscopy into a mass percent result.

### X-Ray Diffraction Spectrometry

XRD is used to identify and to quantify mineral phases of EMPs, including asbestos. The method directs an X-ray beam to the sample, producing a diffraction pattern characteristic of the mineral phase. The observed pattern is then compared to standard patterns produced by known minerals by means of reference files or through

## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (*cont'd*)

computer analysis. XRD cannot distinguish between asbestiform and nonasbestiform materials of the same mineral phase. All identification of possible asbestos minerals by XRD must be confirmed by observing the fibers either by PLM, SEM, or TEM.

### Scanning Electron Microscopy

Typically, samples are collected on either cellulose ester or polycarbonate membrane filters and prepared for analysis. Filters or bulk materials are carbon coated or gold coated and mounted on a sample "stub." An electron beam is directed at the sample and emissions are measured by a detector at an angle to the electron beam. An image of the surface features on the filter is generated and fibers may be observed and counted (See Fig. 6.4). SEM magnifications may range from 2000 to 20,000 × and higher. SEM is more focused, so it can detect fibers that are much thinner than those detected by optical microscopy. Newer SEM devices can detect fibers narrower than the 0.25 μm limit for the PCM method. An energy dispersive spectrometer (EDS) unit used in conjunction with the SEM may also detect the chemical composition of the fiber observed allowing distinction between fibers showing a chemistry consistent with asbestos and other minerals. Fibers measured by SEM are typically reported in fibers per cubic centimeter. Fibers in bulk materials measured by SEM are typically reported as a percentage of the total sample with the percentage determination being made by visual estimation, comparison with standards of known composition, or gravimetry.

### Transmission Electron Microscopy

Samples collected on membrane filters or bulk samples transferred to membrane filters are carbon coated and a thin carbon layer including the fibers is transferred to a grid for TEM analysis. An electron beam is transmitted through the sample and an image of the material on the grid is projected onto a screen. TEMs provided magnifications from about 5000 to 20,000 × or more and fibers with diameters of about 0.01 μm can be detected. Like the SEM, an EDS unit can provide the chemical composition of the fiber. Selected area electron diffraction (SAED) directs an electron beam to the fiber to generate an electron diffraction pattern that indicates the crystal structure of the material. Regulatory agencies usually consider the TEM to be the most definitive technique for detecting and identifying asbestos materials.

TEM typically reports in fibers per cubic centimeter. Fibers in bulk materials measured by TEM are typically reported as a percentage of the total sample with the percentage determination being made by visual estimation, comparison with standards of known composition, or gravimetry. Some methods size each fiber, calculate the volume, and use the density of the fiber to determine a mass. Masses for all fibers are then summed and used to determine mass or percent mass. Counting protocols for fibers by TEM are similar to those by SEM [18].

The optical microscopy techniques typically use magnifications of about 400–500 × while the electron microscopy may use magnifications of 2000–20,000 ×. The higher magnification of the electron microscopy techniques allows for the detection of thinner fibers than those detected by the optical techniques [14, 15, 17, 18]. However, since the amount of sample observed at higher magnification is usually much less than the amount observed at lower magnification, quantitative analysis by electron microscopy may be impractical for some applications due to the small amount of sample analyzed.

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## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (*cont'd*)

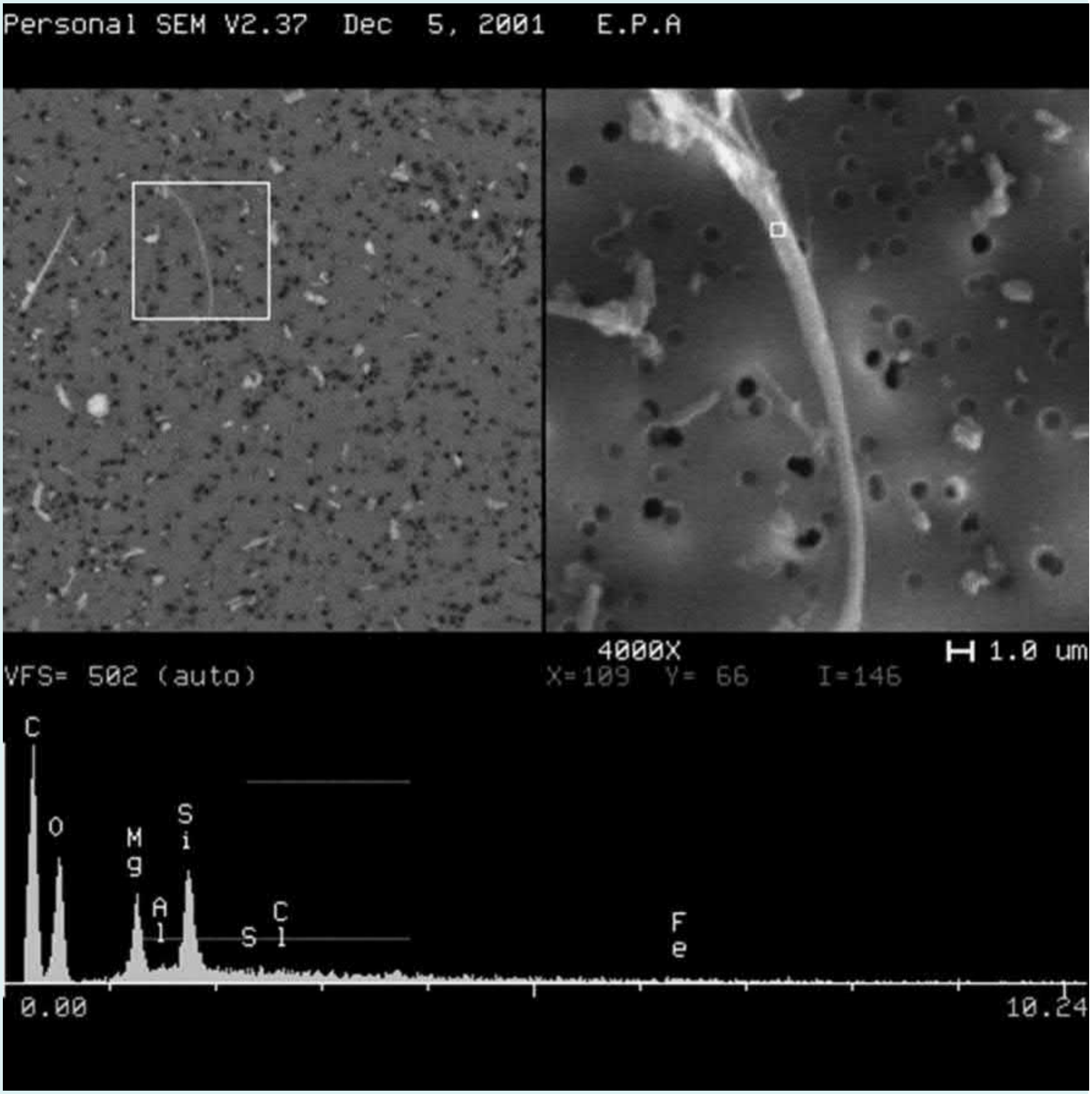


FIG. 6.4 Scanning electron micrograph of fibers in dust collected near the World Trade Center, Manhattan, NY in September 2001. Acquired using an Aspex Instruments, Ltd. Scanning electron microscope. The bottom of the micrograph represents the elemental composition of the highlighted 15 μm long fiber by energy dispersive spectroscopy (EDS). This composition (i.e., O, Si, Al, and Mg) and the morphology of the fibers indicate they are probably asbestos. The EDS carbon peak results from the dust being scanned on a polycarbonate filter. *Courtesy of U.S. Environmental Protection Agency, 2004. Photo courtesy of T. Conner, used with permission.*

## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (*cont'd*)

### Exposure

Exposure to EMPs, like other particulate matter can be occupational or environmental. Occupational exposures during mining differ from those during ore processing, handling tailings, and other postmining activities. For example, surface mining can cover many hectares, whereas processing often takes place in much smaller, confined areas. Thus miner exposure may be similar in type to environmental exposures, that is, from air transport, but at much higher concentrations. However, since occupational regulations require personal protective equipment, the exposures may be lower than those from environmental exposures in nearby communities (See Fig. 6.5). Environmental exposures often result from EMPs that are blown off or ore and tailing piles, fugitive emissions from not only disturbance of rock formations, for example, blasting, but also from unpaved roads from the mine to processing facilities, and outdoor storage piles.

### Naturally Occurring Asbestos

Mining, whether for asbestos or for other materials found in asbestos-laden strata is not

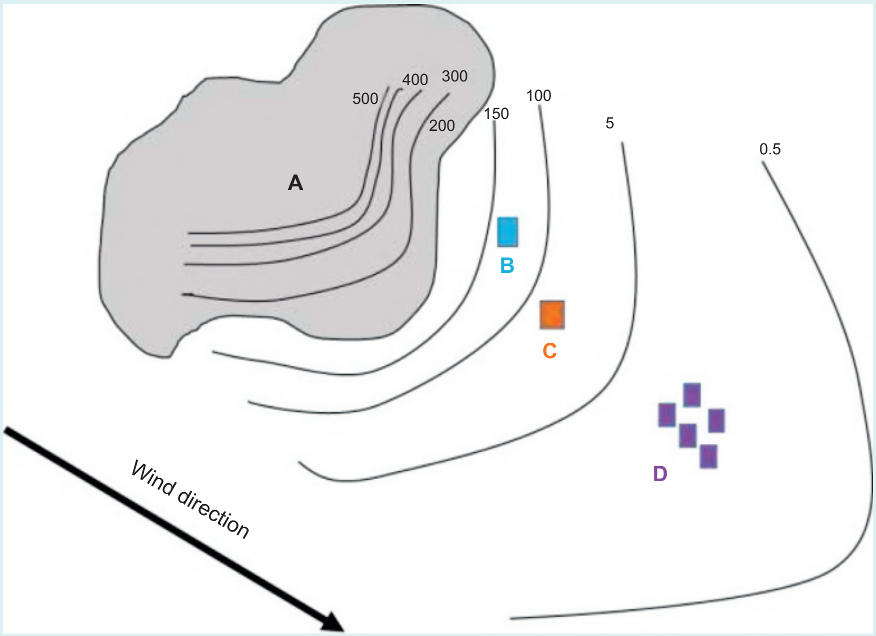


FIG. 6.5 Occupational versus environmental exposure (isopleths in $mg\,L^{-1}$). In this hypothetical illustration, the miner (A) working in the mine (gray area) with about $500\,mg\,L^{-1}$ is using personal protective equipment, so that even though the particulate matter (PM) concentration is $500\,mg\,L^{-1}$, the personal exposure of the miner is only $150\,\mu g\,L^{-1}$ using a 99.97% efficient respirator. A person living near the mine may be breathing a thousand times higher concentrations of PM in his yard. Even with distance, the environmental exposures are higher than those of the protected worker, with (C and D) being exposed to >5 and $0.5\,mg\,L^{-1}$, respectively. *Drawing by D.A. Vallero.*

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## DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (*cont'd*)

only problematic in active mines, but in the uses of the land that follows. Time series and other epidemiological studies have shown that new cases of asbestos-related diseases can arise after mining has ceased [19].

Naturally occurring asbestos (NOA) is comprised of asbestos and asbestiform minerals that are found in place in their natural state, such as in bedrock or soils [19]. The main concern arises when human activities lead to increased exposure to NOA, such as when construction or natural erosion disturbs the rock and soil. In mined areas, the disturbance has already occurred, so simply using the road, path, school yard, and so on, may lead to exposures to ELPs.

Areas of NOA can be relatively confined to several km$^2$. Thus NOA is indeed a concern for any waste manager for several reasons. Siting any waste facility, such as a landfill or combustor, should determine the presence of NOA and, if present, what actions to take and to avoid. A municipality may receive wastes from areas with disturbed or underlying NOA, so these materials may find their way to waste handlers and disposal sites. In addition, waste managers and engineers may be consulted or be members of advisory groups on plans for areas of NOA. As such, the advice and consultation must hold paramount the safety, health, and welfare of the public [20–22].

FIG. 6.6 A burning dump of coal waste.

The first and third examples are particular problems with coal wastes, which often catch fire as a result of spontaneous heating caused by oxidation of metallic sulfides contained in the coal. Oxidation of sulfides also results in the production of seepage containing sulfuric acid and soluble metal salts such as iron and magnesium sulfates. Fig. 6.6 shows a burning dump of coal waste. Once on fire, a large dump like this, often containing several million tons of combustible material, is a major source of air pollution and very difficult, dangerous, and costly to extinguish.

## 3 STORAGE OF FINE-GRAINED WASTES

Fine-grained wastes (tailings) containing a high proportion of silt-sized particles are the most difficult wastes to store. Some fine-grained wastes can be "dry-dumped" or "stacked" either by truck or belt conveyor, although they must always contain some water to prevent dust pollution arising during transport and deposition. However, economics dictate that most of the tailings be transported hydraulically either as a slurry or as a "thickened tailings" or "paste" and be deposited or "beached" into hydraulic fill tailings storages where the tailings flow under their own weight, settle, and consolidate to form fine-grained silty deposits. Alternative methods of deposition are to discharge a thickened tailings slurry from a single, or a series of, point discharges around each of which the tailings form a flat-sloping conical deposit; or to transport a tailings paste by conveyor belt and discharge it from a preconstructed earthen ramp to form a wedge-shaped deposit by viscous flow.

Fig. 6.7 shows a hydraulic fill storage of fine tailings formed by "beaching," that is, by depositing a slurry of tailings around the outer perimeter of the tailings storage and allowing it to run down a "beach" toward the pool of water formed in the arms of the Y-shaped causeway or pool training wall. The darker (wet) surfaces show where slurry has recently been deposited. Water that collects in the pool is decanted through a vertical decant shaft that is visible at the center of the Y. The decant shaft leads to a subhorizontal outfall pipe or conduit that leads the decanted water to a return water reservoir, before being returned to the mineral extraction plant.

## 4 WATER BALANCES FOR MINE WASTE STORAGES

A water balance is a statement that sets out how much water enters, leaves, and is stored in tailings storage. Water enters as a component of the waste slurry and as rain, and it can be

FIG. 6.7 A typical hydraulic fill tailings storage constructed by "beaching" toward a decant shaft.

recovered as water decanted from the pool and collected from the drains around the storage. A large proportion of the water remains in the void spaces between the solid waste particles and cannot be recovered, and a proportion is lost by evaporation from the outer surface of the storage and by seepage into the ground strata under the storage. Water balances are used to estimate and control the quantities of water involved in the waste storage process and for environmental control by checking on the quantities of water lost in seepage to the natural ground water.

Every hydraulic fill waste storage has a water or seepage surface in it, called the phreatic surface, where the pressure of the water is the same as the atmospheric pressure. Below the phreatic surface, the water pressure is greater than atmospheric pressure and acts to destabilize the outer containing slopes of the storage. Above the phreatic surface, the pressure of the water is less than atmospheric pressure and helps to stabilize the slopes.

Fig. 6.8 shows the components of the water balance for a hydraulic fill tailings storage, including the phreatic surface and the drains designed to release water from the tailings and enable it to be returned to the mineral extraction plant, via the return water reservoir.

When a mine waste storage ceases operation, the pool is drained and thereafter remains dry except for rainfall that runs off from the surface. The phreatic surface slowly subsides once the supply of slurry water ceases and the outer slopes of the storage become more stable. At this stage, the surface of the waste storage needs to be "rehabilitated" which means that the waste surface is protected from erosion by water and wind and is usually planted with indigenous vegetation to enable it to blend, as much as possible, into the natural landscape.

## 5 SAFETY OF MINE WASTE STORAGE STRUCTURES DURING THEIR OPERATIONAL LIFETIME

Mine waste storages are very large structures, easily visible from space, that have very long operating lives (often >50 years) and often were not properly planned in the first place or carefully operated. They are under construction for the whole of their operating lives and are

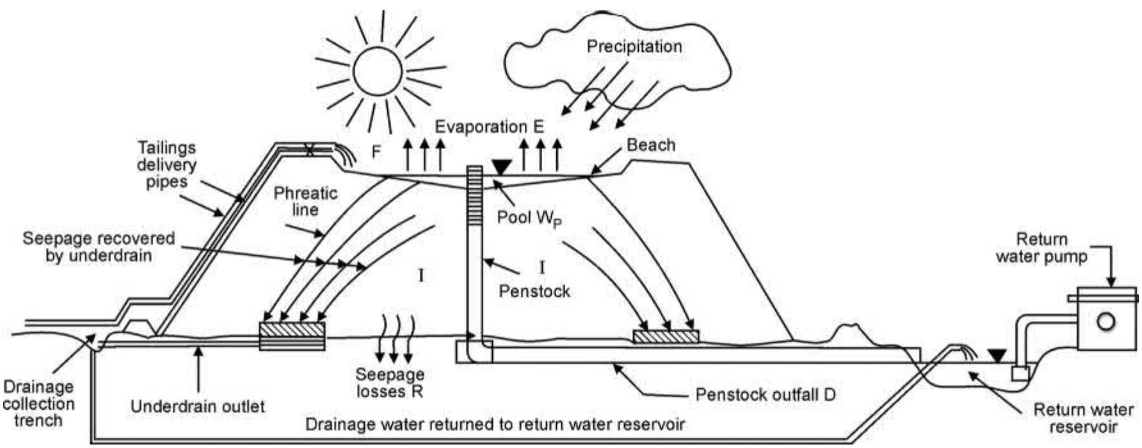


FIG. 6.8 Diagrammatic representation of components of a water balance for a beached unthickened tailings storage.

operated by a succession of people, not all of whom are dedicated to carrying out their assigned tasks to the best of their abilities, not all of whom are properly trained, and not all of whom understand why they must undertake certain tasks and what the consequences of negligence may be. Not all of the workers can recognize that a dangerous situation may be developing, and not all of them know the correct course of action to be taken in an emergency. The foregoing statement is not flattering, but it is a reality. Adding to the unknown dangers are natural hazards; severe rain storms; earthquakes; undetected adverse geological or ground water conditions; human errors such as well-intentioned, but faulty design, theft, or lack of maintenance of vital components; warning systems that fail at the crucial time; and finally, so-called Acts of God.

Failures of tailings and coarse waste storages can take many forms, the most dangerous and destructive of which are those in which the waste loses strength, becomes mobile, and flows as a viscous liquid in which the supporting fluid can either be air in deposits of dry waste, but more commonly, water. Nineteen major flow failures of tailings storages occurred between 1928 and 2000, which together caused at least 1080 deaths of which 1065 occurred between 1965 and 1996, an average of >34 deaths per year. Deaths from failures of other forms of waste storage do not lag behind. Deaths caused by only three failures of municipal solid waste dumps between 1993 and 2005 alone, totaled 464, an average of >38 deaths per year [23]. However, to keep these numbers in perspective, it must be remembered that they are miniscule in comparison with the yearly death toll on the roads of the world and with other preventable causes of death, such as HIV-AIDS.

It is also interesting to note that many of the 19 failures occurred in small waste storages at operations that were being run on a "shoe-string," or at mines threatened by closure. The failures at Stava, in 1985, which killed 268 people and Star Diamonds (see Fig. 6.9) were of this type. Also, by no means all mine waste

FIG. 6.9 Aftermath of the collapse of a tailings storage at a diamond mine into shallow underground workings. The level of the tailings before the collapse can be seen as a level surface in the background. The small pump barge is located over the site of the collapse.

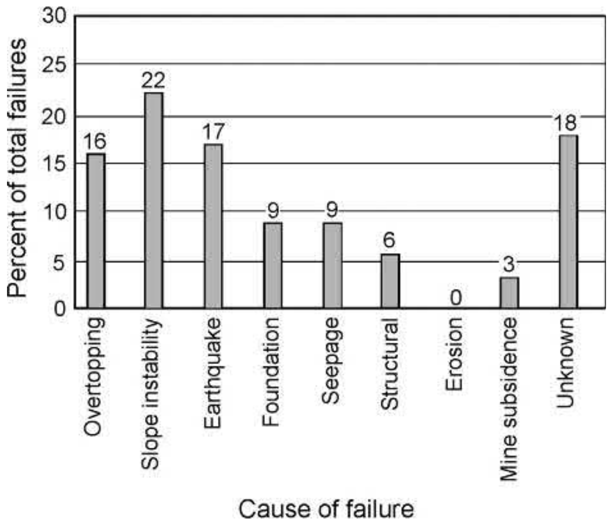


FIG. 6.10 Analysis of causes of 185 tailings dam failures.

"incidents or accidents" are reported in the widely read or viewed news media nor do all lead to disasters.

Fig. 6.10 summarizes the causes of 185 failures of hydraulic fill tailings storages, collected by the United States Commission on Large Dams [24]. Explanations of the listed causes of failure are given as follows.

## 5.1 Overtopping

Overtopping occurs when the pool of water around the decant shaft (see Fig. 6.7) either grows so large that it reaches and overtops the impoundment wall, or the pool moves away from the decant shaft due to uneven distribution of the tailings around the pool. If this happens, the water cannot be decanted and if the problem is not noticed and corrected, the pool may overtop the outer wall. The usual cause of overtopping is holding too much water on the top of the storage, resulting in an insufficient height margin or freeboard to contain water suddenly deposited by a large rain storm. Overtopping usually results in the eroding of a breach in the storage outer wall, possibly causing the contents of the storage to liquefy and flow out of the breach. (It is not quite correct to rule out erosion as a cause of failure, as in Fig. 6.10. Erosion may not be a primary cause of failure, but it often forms part of the process of failure.)

## 5.2 Slope Instability

Slope instability occurs when the strength of the material forming the outer wall of the storage is insufficient to carry the weight of the wall, with the result that a segment of the wall slides out on a failure surface that is often cylindrical in shape. Fig. 6.11 shows a typical slope instability failure or slide in the outer wall of a tailings storage. (The moment of the weight *W* about the center of rotation *O* became too large for the moment of the shear forces *S* about *O* to resist.) In this real example, the rotational movement on the failure surface was relatively small and the freeboard of the storage surface was reduced by height $AA^I$ of just >2 m. However, because tailings storages are sometimes operated with freeboards as low as 1.0 m, even a loss of freeboard of 2 m could have resulted in overtopping, followed by erosion and a flood of escaping liquefied tailings.

## 5.3 Earthquakes

Earthquakes can cause failure of structures, including slopes by imposing alternating vertical and horizontal accelerations (and therefore forces) that may be appreciable fractions (e.g., 0.2–0.3) of normal gravitational acceleration. Referring to Fig. 6.11, vertically downward accelerations would effectively increase the disturbing force of the weight *W* and horizontal accelerations would impose a lateral force *E*, both of which would tend to destabilize the mass of tailings above the potential failure surface. Because earthquake forces are cyclical and periodically reverse, usually with a frequency of 1–2 applications and reversals per second, water in the pool of the tailings storage may begin to slop backward and forward with a magnitude that increases with every cycle until the pool overtops the outer wall, with all the consequences of an overtopping.

## 5.4 Foundation Failures

Foundation failures occur when the strength of the foundation strata of the tailings storage becomes inadequate, as the storage increases in height. This usually results in instability of the entire outer wall along a failure surface, such as the failure surface shown in Fig. 6.11 but which cuts into the weak foundation stratum.

## 5.5 Seepage

Seepage from the pond of a storage through the outer wall can cause slope instability because it weakens the tailings by increasing water pressures in the slope (i.e., by a rise in the phreatic surface). The same effect can occur if the storage is built too rapidly, so that the "rate of rise" in meters per year is too quick for the tailings to settle, consolidate, and gain strength to the extent assumed in the design. Fig. 6.12 is an aerial photograph of a 28-m high tailings storage that was built at an excessive rate of rise and as a consequence suffered three rotational failures in the course of 3 days. The first failure took place on a Friday night; the second, next to the first, on Saturday night; and the third on Sunday night. The safe rate of rise had been determined as 1.5 m $year^{-1}$, but because of an increase in production at the mine, this had been increased to 2.57 m $year^{-1}$, and in the month prior to the failure, it increased to 2.83 m $year^{-1}$. Fortunately,

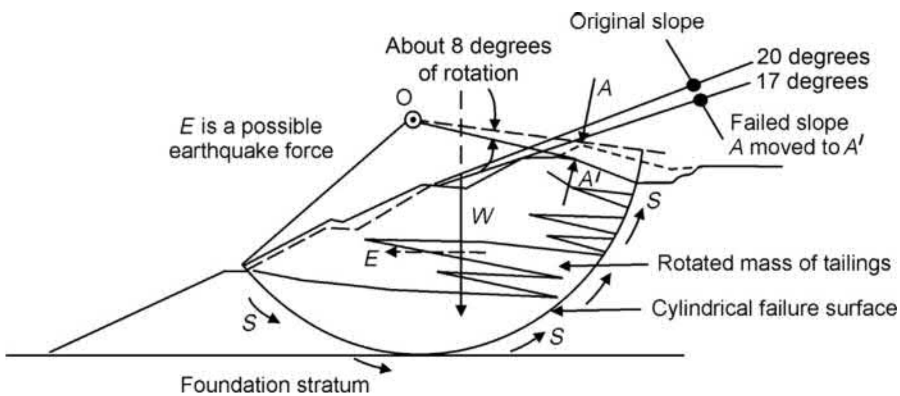


FIG. 6.11 Postfailure profile of outer slope of a tailings storage. Failure was caused by insufficient strength of the tailings forming the wall.

FIG. 6.12 Failures of a gold tailings storage at Saaiplaas mine that was being built at an excessive rate of rise. (Two failures are visible, side by side in the center of the photograph, and one in the center-right.)

nobody was injured and damage was confined to the mine property.

### 5.6 Structural Failure

Structural failure is a poorly defined term, but might include the result of damage from burst tailings delivery pipes, resulting in the cutting of an erosion gully, or the collapse of the decant control structure, either the outlet shaft or the outlet pipe, also resulting in erosion damage.

### 5.7 Mine Subsidence

Failure caused by mine subsidence usually occurs when tailings are stored on surface over shallow mine workings, and the strata between the underground workings and the ground surface collapse, allowing tailings to flood into the underground workings. Fig. 6.9 shows the result of one such occurrence in which four miners were drowned underground. In a similar accident in Zambia in 1970, 89 miners were drowned underground.

## 6 DECOMMISSIONING, CLOSING AND REHABILITATING TAILINGS, AND OTHER MINE WASTE STORAGES

The decommissioning and closure processes consist of removing all the installations associated with operating the storage, such as tailings delivery pipes, conveyors, and so on. A permanent surface drainage system is installed, sealing the decant system and replacing it with a permanent spillway, and the surface of the storage is reshaped so that surplus surface water can enter the surface drainage system and either be held on the top surface of the deposit, to evaporate, or be conducted to natural ground level without causing any erosion or flooding. At natural ground level, the surplus surface drainage should be purified, if necessary, and channeled into a natural water course.

The biggest problem in rehabilitating the surface of a closed waste storage is to permanently protect the surface from water and wind erosion, thus maintaining a stable surface in which vegetation can be established. Cleaning up any waste site, especially the large ones associated with mining, involves risk trade-offs, for example, whether the remediation itself will increase the amount of waste constituents like heavy metals temporarily in order to lower future risks. These releases will be worsened if engineering and other mistakes are made (See Discussion Box 6.2).

It is becoming more and more common for regulatory agencies to require that the rehabilitation of a tailings dam or other waste deposit be designed to be maintenance free for 500–1000 years. This seems quite unrealistic when one thinks of the changes only 100 years can cause to a landscape (e.g., the areas now occupied by the cities, freeways, and waste deposits of many cities in the "new world" were untouched countryside just over a century ago). However, very ancient man-made earth mounds exist in many parts of the world with slopes that have been subject to 1000 or more years of erosion and still exist in good condition. Fig. 6.14 shows the profiles of several ancient man-made monumental mounds in China [28]. All these are accurately dated and are from 700 to >2000 years old. The mounds around Xi'an are all constructed of fine sandy silts from

## DISCUSSION BOX 6.2 GOLD KING MINE

Some 23,000 abandoned mines exit in Colorado. Recently, one of these, the Gold King Mine near Silverton, Colorado became notorious as a source of heavy metals and other contaminants. The mine exists in the Upper Animas Watershed in the southwestern part of the state. Mining altered the hydrology and hydrogeology, which changed the speed and amount of water reaching streams.

The Rocky Mountains contain pyrite (iron sulfide) that reacts with oxygen to form sulfuric acid, which increases the rate and amount of metals that can be dissolved in water. Mines in this area exacerbate these physical and chemical processes, allowed the acidic, metal-laden surface water and groundwater to enter the mine's horizontal access and drainage conveyances known as adits and vertical shafts (See Fig. 6.13). Mining ended at Gold1991 and the mining company plugged, that is, bulkheaded, the mine and to remediate other nearby mines nearby, and to decrease the amount of metal-laden waters transported away from the mine. Given the extent and intensity of the disturbance, however, the leaching and transport of contaminants continue after mining ends [25].

The U.S. Environmental Protection Agency (EPA) conducts environmental investigations as part of its regulatory authority. On August 5, 2015, EPA was conducting an investigation of the Gold King Mine to assess the ongoing water releases from the mine, to treat mine water, and to assess the feasibility of further mine remediation [26]. While excavating atop an abandoned adit, pressurized water started to leak above the mine tunnel, over a nine-hour period, releasing over 11 million liters of water that had been stored behind the collapsed material.

The contaminated water reached Cement Creek, a tributary of the Animas River and San Juan River, reaching Lake Powell. The water contains the metalloid, arsenic, and the metals aluminum, cadmium, copper, iron, lead, manganese, mercury, and zinc [27].

EPA has taken responsibility for the release and has been working with local communities, states, and tribes to address the harm.

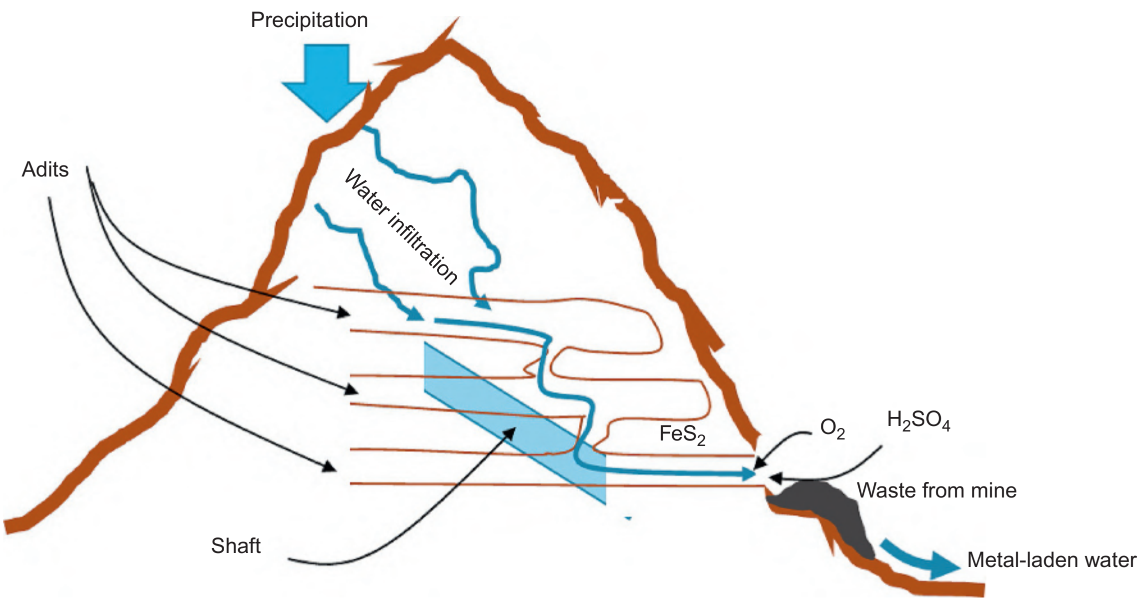


FIG. 6.13 Side view of mine workings into which water infiltrates, dissolves iron sulfide (pyrite) in the rock, and then reacts with atmospheric oxygen to form sulfuric acid. The lower pH increases the rate of metal dissolution, so that the acidic, metal-laden mine drainage that contaminates surface water and groundwater. *Drawing by D.A. Vallero; modified from J.P. Thompson, An Acid Mine Drainage Explainer, and a Curious Account of the Gold King Circa 1901, 2015. Available from: http://jonathanpthompson.blogspot.com/2015/08/an-acid-mine-drainage-explainer-and.html (Accessed 20 March 2018).*

river alluvium and loess, which are intrinsically fairly erodible. The climate has distinct wet and dry seasons, rainfall is between 500 and 1000 mm year$^{-1}$, and there is an annual water deficit, that is, potential evaporation from the soil exceeds rainfall. The mound near Yinchuan is also of loess, but the area has a desert climate. It might have been expected that over a period of 1000 years, the slopes would all have eroded to similar and very flat slope angles. But this has not occurred. As shown in Fig. 6.14, the slopes vary from 16 to 28 degrees. Hence, one cannot conclude that if a slope has less than a certain limiting angle, it will not erode. The contrast between the mounds near Xi'an and those near Yinchuan shows, however, that climate plays a role in determining an erosion-resistant slope. Observations and measurements of the erosion of the slopes of gold tailings dams in South Africa [29] have shown that an "erosion rate surface" exists in a (slope angle-slope length-erosion loss) space. This surface, illustrated in Fig. 6.15, shows that erosion rates increase with slope length but are low both at very flat and very steep slope angles. The "belly" of the erosion rate "sail" at intermediate slope angles represents the range of slope angles often used for tailings dams (25–35 degrees), which thus usually have the worst possible slope angles for erosion losses.

The larger the surface strength of a slope, the lower is the rate of erosion. Hence, the effect of a varying surface strength would be like the wind on a spinnaker sail; it would move the erosion rate surface inward (as the shear strength increases) or outward (as the shear strength reduces) relative to that of the erosion loss axis (or "mast"). Protecting the surface of a slope, by armoring it or covering it with vegetation, has a similar effect to increasing the surface

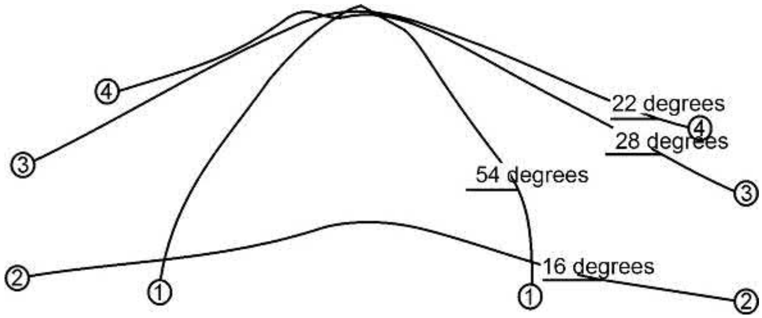


FIG. 6.14 Profiles of ancient earth mounds in China.

shear strength, and therefore moves the "sail" in, that is, back toward the "mast."

Fig. 6.15 illustrates the following very important principles:

- *Slope angles* should be made as flat as possible. Around 10–15 degrees is practical and approaches the ideal angle.
- *Slope lengths* should likewise be limited. The maximum length should not exceed 25–30 m.

To achieve these two requirements, long slopes should be interrupted at height intervals of about 7–8 m by horizontal berms or steps

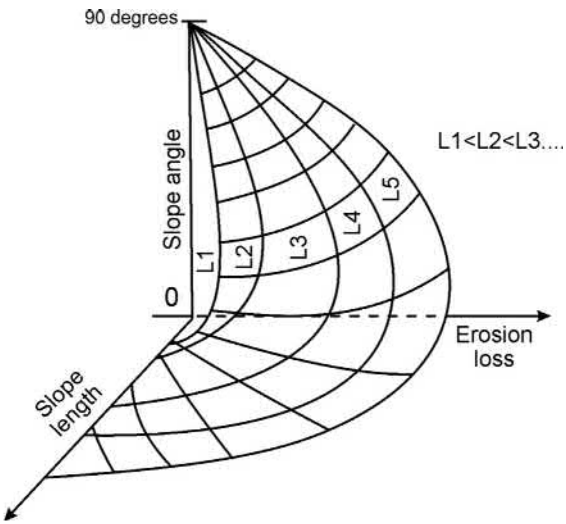


FIG. 6.15 Erosion rate surface.

equipped with lined, erosion-proof surface drains designed to conduct the surface runoff from the slope above to ground level, without causing any erosion of the lower slope surfaces.

- *Very flat slopes and horizontal surfaces* (e.g., the flat top surface of a tailings storage) do not erode to any significant extent and hence do not require protection against erosion.

So far, the term "erosion" has not differentiated between wind erosion and water erosion. Both can be very significant. In wetter climates, water erosion predominates, and in drier climates, there is more wind erosion. In South Africa, for example, wind erosion accounts for two-thirds of total erosion and (perhaps surprisingly) in Iceland, wind erosion also predominates over water erosion.

Concerning *rates of erosion*, unprotected tailings slopes may erode at rates of up to 1000 t $ha^{-1}$ $year^{-1}$, whereas natural slopes usually erode at 50–100 t $ha^{-1}$ $year^{-1}$ or less. The aim of protecting tailings slopes should be such that their rate of erosion is reduced to $<$100 t $ha^{-1}$ $year^{-1}$.

There is a controversy [30] as to whether the Qin mound (No. 2) was ever actually 116 m high, or whether this was the planned height, but the mound was only built to 52 m, its present height. If one calculates back 2200 years from the present height and plan dimensions of 330 m $\times$ 330 m, assuming a rate of erosion of 100 t $ha^{-1}$ $year^{-1}$

(appropriate for the soil from which it is built) and maintaining the present average slope of 16 degrees, the calculated original height works out as 115 m. Hence, 115 m is a very likely original height. Because it was a memorial mound to the first emperor of a united China, it is likely that the mound has been maintained over the 2000 years since it was built. Nevertheless, its height has halved in that time. This illustrates the futility of legislating for a design period of even 100 years as a maintenance-free life. Closed tailings storages, like the Chinese mounds, cannot be made erosion free.

## 7 SUMMARY

Mining activities produce larger quantities of waste and have more adverse environmental impacts than waste from any other human activity. It is difficult to do more than briefly outline the subject of mine waste storage in a single chapter, and the reader is referred to a full-length book on the subject [23] for further details.

Mine waste can be divided into coarse-grained wastes that are usually stored in surface dumps, and fine-grained wastes, usually stored in hydraulic-fill structures. Both coarse and fine mine wastes could contain toxic substances, emit radioactive radon gas, or be combustible. Therefore mine waste storages need to be constructed and protected in such a way that their adverse effects on human health and the natural environment are minimized on a long-term, continuing basis. Fortunately, controls and statutory regulations for the storage of mine waste are being tightened in most countries, and at the same time, the engineering skills needed to construct and maintain storages safely and for long periods of time are also improving.

It is very important to realize that once a mine waste storage has been created, it constitutes a hazard that requires ongoing maintenance and care for millennia to come.

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