

CHAPTER 11. INTERPRETATION, APPLICATIONS AND CONCLUSIONS

**Barry E. Scheetz, Caroline M. Loop, William B. White,
Michael J. Menghini, Roger J. Hornberger, William F. Pounds, Tim Kania**

11.1 PURPOSE FOR EVALUATING COAL ASH BENEFICIAL USE IN MINE RECLAMATION

In recent years the beneficial use of coal ash on mine sites has become a controversial topic on a national level. As a result, the U. S. EPA has been tasked to review the adequacy of coal ash beneficial use programs nationwide, to determine if federal regulation, guidelines or other requirements are needed to help insure that the beneficial use of ash on mine sites does not cause groundwater contamination. Recently, the commissioning of a National Academy of Sciences study to evaluate the results of coal ash beneficial use was announced.

Some of the sites identified as “damage cases” by critics of coal ash beneficial use are Pennsylvania sites. In reviewing the concerns over the Pennsylvania sites, it becomes apparent that many of them were generated by misinterpretation of data and a lack of in-depth analysis of the sites. For example, coal ash has been cited as a source of contamination where background sampling shows that the contamination predated coal ash use. In other cases alkaline coal ash has been identified as the cause of acid mine drainage contamination, when the technical data demonstrate that rock strata native to the sites caused the contamination, and that the alkaline coal ash was not chemically capable of generating acid mine drainage. Cause-effect relationships have been assumed without consideration of critical factors such as the timing of events, site hydrogeology, site background conditions, and site history. Individuals and organizations with interests only tangentially related to the beneficial use of coal ash and groundwater protection have weighed in on the debate, further complicating the issue.

The U.S. EPA’s review of this issue has not documented any damage cases related to the use of coal ash at coal mine sites. However, EPA has documented at least five coal ash damage cases related to utilization of coal ash at sand and gravel mine sites. These sites are noted by some critics as coal ash damage cases, but in reality, there were other waste materials deposited at each site with the coal ash, and therefore, a clear cause of any “damage” is not easily defined. The actual history of these sites is also vague or not available, which further complicates the determination of the actual cause of any “damage”.

Against this background, PA DEP and the Penn State Materials Research Institute decided to develop this book, to take an in-depth look at Pennsylvania’s coal ash beneficial use program. The goal was not to examine every site; such broad-based evaluations tend toward the superficial. Rather this effort was designed to evaluate in detail sites representative of various beneficial use practices. Some of the sites selected are ones that have been identified by other investigators as coal ash “damage” cases. In addition, another central goal of this effort was to investigate in detail the demonstration sites Pennsylvania has permitted in recent years to advance the science of the beneficial use of coal ash.

The following sections of this chapter summarize the information and findings of this endeavor. Section 11.2 presents a synopsis of the key findings from the previous ten chapters. Sections 11.3 and 11.4 present some of the more important scientific findings concerning ash fill integrity and chemical effects from the three Anthracite Region demonstration projects discussed in chapters 7 through 9. The remaining sections provide some thoughts for consideration by those involved in the beneficial use of coal ash in mine site reclamation.

11.2 KEY FINDINGS AND PRINCIPLES FROM PREVIOUS CHAPTERS

Approximately 52% of the electrical power produced in Pennsylvania is from coal burning power plants, and these plants produce about 10 million tons of coal ash annually. During the past five years, an average of 6.3 million tons of coal ash per year has been beneficially used at mine sites. Fifteen fluidized bed combustor (FBC) power plants operating in Pennsylvania have reclaimed more than 3,400 acres of abandoned mine lands within the past 15 years. These 15 FBC plants have consumed 88,551,078 tons of coal refuse and produced 58,188,180 tons of alkaline coal ash from 1988 to 2002.

There are 21 pulverized coal (PC) power plants operated by major utilities in Pennsylvania. These PC power plants burn about 45 million tons of coal and produce about 5 million tons of ash annually. The FBC plants produce more ash per ton of fuel burned than PC plants because the coal refuse contains more inorganic mineral matter than the coal. About 80% of the coal ash beneficially used for mine reclamation in Pennsylvania is from the FBC power plants.

The geologic setting of the Anthracite and Bituminous Coal Fields of Pennsylvania provides a foundation for much of the subject matter in this book. Pennsylvania was blessed with abundant coal reserves. Along with this blessing of abundant coal reserves, Pennsylvania was also bestowed with somewhat of a curse of abundant abandoned mine land problems--- including greater than 189,000 acres of abandoned, unreclaimed surface mines, more than 3,100 miles of stream polluted by acid mine drainage, and thousands of mine subsidence features, mine fires and other mine hazards. The physiography, geologic structure, stratigraphy and hydrogeology of the anthracite and bituminous coal regions are significantly different, but there are substantial similarities in the beneficial use of coal ash in these regions to reclaim abandoned mine lands and remediate acid mine drainage problems. The anthracite coal fields have the most significant abandoned mine land reclamation problems due to the complexity of the geologic structure, the thickness of these coals, and the hydrology of the minepool systems. The bituminous coal fields have the greatest number of acid mine drainage discharge problems and the most severe concentrations of acidity, iron and other parameters of the acidic drainage, due to the stratigraphy and depositional environments (i.e. greater sulfur contents) of these coals and overburden strata.

The physical properties of the coal ash make it an ideal material for backfilling abandoned mines, and its chemical characteristics promote further usefulness of coal ash as a stabilized product and component in cementitious grouts for abatement of mine subsidence features and other mine hazards. Coal ash generally contains approximately 60 to 70% silt-size particles, and 30 to 40% sand-size particles, which classifies it as a silt loam in a soils

engineering context. Standard laboratory and field tests used in soils engineering practices are specified in DEP regulations and permit conditions to determine the strength or bearing capacity of the coal ash. There are established interrelationships among the laboratory Proctor Density Test, the theoretical Maximum Dry Density and the Optimum Moisture Content (Fig. 3.2), which are evaluated to ensure that field compaction results achieve 90% of the standard laboratory maximum density. Monitoring data from more than 10 years of test data in DEP files for four FBC ash sites showed that maximum dry densities varied from approximately 70 to 105 lbs/cu.ft. (mean = 85 pcf), the optimum moisture content varied from 16 to 38% (mean = 25%), and field compaction tests were almost always 90% or higher. The engineering and monitoring data on the physical properties of the coal ash placement at mine sites document that the compacted ash backfills have sufficient bearing capacity to support a variety of structures and other post mining land uses.

A very significant amount of abandoned mine reclamation in the four anthracite coal fields has been completed through the beneficial use of coal ash on remining sites, such as the 209 acres reclaimed at the Mt. Carmel cogeneration plant site and the 113 acres reclaimed at the Wheelabrator site. The evaluation of more than 15 years worth of groundwater monitoring data for the case study sites presented in Chapter 4, and other permitted sites throughout the anthracite region, has not resulted in any significant findings of environmentally damaging groundwater pollution cases, as measured at key downgradient minepool monitoring points. For example, the placement of more than 15 million tons of coal ash from the Gilberton Power and Schuylkill Energy Resources FBC plants in the Mahanoy Creek watershed did not result in significant median aluminum increases in any of the downgradient monitoring wells, and the median aluminum concentration of the Gilberton shaft and Packer V minepool discharges have been relatively constant at less than 1.0 mg/L from 1986 to 2003, despite the relatively high aluminum (and iron) concentrations in the ash. At least two sites discussed in Chapter 4 produced a significant increase in alkalinity concentrations, or reduction in acidity or other analytes that is attributable to the beneficial use of coal ash on these sites.

The development of realistic groundwater monitoring plans for anthracite coal ash sites should include some combination of monitoring wells and shafts or minepool overflow discharges, because each of these groundwater monitoring tools was shown to have advantages and disadvantages, and there is no guarantee that any of these tools alone, is sufficient. The groundwater monitoring data for some of the case study sites and the hydrologic budget discussion in Chapter 4 demonstrate that the “high and dry” concept of placing relatively dry (optimum moisture content) ash into a relatively dry mine environment is working well.

The beneficial use of coal ash in mine reclamation and mine drainage remediation in the Bituminous Coal Region of western Pennsylvania includes: a) remining of large coal refuse piles, b) the use of coal ash as an alkaline addition material, and c) use as a pit floor and/or final backfill capping material as shown in Chapter 5.

The use of FBC ash in the remining and reclamation of two large refuse piles at Revloc, PA has resulted in a large reduction in pollution load from site discharges and in a substantial improvement in downstream quality on the South Branch Blacklick Creek. Both flows and concentrations of pollutants have declined at the largest discharge points. A downgradient

monitoring well (MW-1) that was severely degraded by AMD, showed a steady trend of declining concentrations of acidity, iron, manganese and sulfate throughout the remining and reclamation period (1988 to 2004). In addition, pollution loads and flows have decreased at the four largest seeps from the Revloc site. The major mechanism for the decrease of mine drainage pollution at the Revloc site appears to be the removal of the marketable coal refuse and encapsulation of the remaining reject in the compacted FBC ash rather than the neutralization of mine drainage by alkaline leachate from the ash.

Remining and partial reclamation of the McDermott active surface mining permit area caused an increase in AMD degradation. Overburden analysis data in the permit application identified strata with the potential for AMD production and the applicant formulated an alkaline addition plan, using FBC ash, to address this deficiency in neutralizing material in the overburden. Water quality data indicate that the large quantity of coal ash placed in the backfill may be neutralizing some AMD, but has not prevented the formation of AMD, and has not generated net-alkaline water. Water quality data at the McDermott site show that, while the ash did not prevent AMD formation, it also did not cause pollution in terms of increased non-AMD toxic metals in downgradient monitoring points.

The Abel-Dreshman site is an abandoned bond forfeiture surface mine site in Clarion County, Pennsylvania, where the use of FBC ash in the reclamation of the site resulted in an improvement in downgradient water quality. Overburden analysis data for this site show that the site overburden had significant potential to generate AMD. The use of ash on the site, including the addition of a layer of compacted ash on the surface of the backfill, appears to be generating alkalinity, whereas the overburden on site did not have the capability to do so.

Coal ash has been used in mine subsidence control and mine fire control in Pennsylvania since at least 1965, when the Bureau of Mines of the U.S. Dept. of the Interior and the PA Dept. of Mines and Mineral Industries cooperated in a project to build subsurface barriers with coal ash to control the Centralia Mine Fire. These state and federal agencies developed specifications for various mixtures of coal ash, Portland cement, sand, and other materials for use in mine subsidence “flushing” projects and mine fire control projects. The Office of Surface Mining Reclamation and Enforcement (OSMRE) of the U.S. Department of the Interior and the DEP Bureau of Abandoned Mine Reclamation (BAMR) are continuing to use similar ash cement grout mixtures in specifications for mine subsidence control and mine fire control projects in the anthracite and bituminous regions of Pennsylvania.

The cropfall type of mine subsidence features, that are prevalent in the Southern Anthracite Field, present a significant challenge in abandoned mine reclamation efforts because of the general lack of adjacent backfill materials. Conventional backfill materials, or concrete, have resubsided shortly after completion of previous reclamation projects. The Sharp Mountain cropfall project described in Chapter 6 is an innovative approach to abating the mine subsidence problems, utilizing FBC ash in formulating ash cement grout mixtures, and using PC ash as a bulk fill material. Various mixtures of FBC ash and Portland cement or cement kiln dust (CKD) were evaluated to determine their relative strengths, bearing capacities, and cost-effectiveness.

Coal ash cement grout mixtures have also been effectively used in acid mine drainage remediation projects in the Bituminous Coal Region of Pennsylvania. At the Fran site in Clinton County, a FBC ash grout was pressure injected in boreholes drilled on a backfilled surface mine directly into buried pods of acid-producing materials to fill void spaces and encapsulate the pyritic materials with the cementitious mixture. An overall improvement in water quality of the post-mining discharges occurred at the Fran site, and the mean concentrations of AMD parameters decreased by 30 to 40% in some of the discharges. FBC coal ash was also used to form an impermeable cap at the reclaimed McCloskey surface mine site in Clearfield County, in order to promote a reduction in the flow of post-mining AMD discharges from the site. The coal ash cap at the McCloskey site has not generated any secondary pollution problems in the receiving stream, and has allowed the stream to support a population of fish, which would not previously survive there.

The Ellengowan and Shen Penn demonstration projects described in Chapter 7 are related to the first of three one-of-a-kind Waste Demonstration Permits issued to evaluate alternative ash placement methodology in the anthracite region (i.e. alternatives to the conventional coal ash beneficial use requirements of placing relatively dry (optimum moisture content) ash in a relatively dry mine environment, at least 8 ft. above groundwater levels). The Ellengowan demonstration project was a necessary precursor to the three Waste Demonstration Permits in order to develop tangible data on a small scale before embarking on the full-scale demonstration projects. The Ellengowan silt dam was within the approved ash disposal area on the Reading Anthracite surface mining permit, and it contained about 9 ft. of water wherein two ash placement techniques were evaluated: direct dry-to-wet end dumping of ash into the water, and slurry delivered, wet-to-wet placement. Both placement techniques were successful in the shallow water impoundment. Slurry placement of the ash was found to be an adequate approach if the slurry is allowed to flow into shallow standing water in a slow delta-like spreading flow of material. Unfortunately, the Shen Penn Waste Demonstration Permit was never activated after issuance, due to the ash tax imposed on the project. The water-filled mine hazard remains unchanged.

The Knickerbocker demonstration project described in Chapter 8 is the second Waste Demonstration Permit issued to evaluate the alternative ash placement technology of using an ash slurry pipeline to fill a dry abandoned surface mine pit (i.e. wet-to-dry placement). A water/ash slurry consisting of a mixture of 60% (by volume) minepool water pumped from the Maple Hill shaft and 40% coal ash from the SER cogeneration plant was delivered to the Knickerbocker pit in a 10 inch diameter high-density polyethylene pipe, extending for a distance of about 1 km from the power plant. Discharge of the slurry into the abandoned surface mine pit was controlled so that laminar flow conditions were maintained, because turbulent mixing of the slurry would result in excessive turbidity in the transporting water or the water infiltrating back into the minepool. When placed in a manner that allowed the transport water to flow in a slow and laminar fashion, the ash dropped out of suspension rapidly and resulted in a dense, strong compacted fill onto which mining equipment could immediately drive (compaction of the ash was routinely above 90%). The use of cement kiln dust (CKD) as a material to augment the properties of the slurry appears to make a beneficial contribution to material strength, but it is believed that this is partly due to enhancement of the packing efficiencies of the slurry material.

The Big Gorilla demonstration project described in Chapter 9 is the third Waste Demonstration Permit issued to evaluate alternative ash placement technology of placing relatively dry (optimum moisture content) ash into a water-filled abandoned surface mine pit (i.e. dry-to-wet placement). Early in the process of filling the pit with FBC ash from the NEPCO power plant, two significant findings were recognized: a) the pH of the 80 ft. deep mine water impoundment had changed from a background water quality of pH 3.6 to a pH of approximately 11, homogeneously throughout the impoundment, due to the unreacted calcium hydroxide in the FBC ash, and b) the physical properties of the completed ash terrace, resulting from the placement technique of end-dumping the ash into the standing water, had adequate stability and bearing capacity to support heavy equipment, meet the DEP compaction requirements, and allow an orderly advancement of the dumping face from east to west, without causing turbidity in the western portion of the impoundment. Detailed scientific research produced three additional significant conclusions: c) the pore water chemistry within the completed coal ash fill closely resembles the chemistry of pore water solutions in conventional Portland cement and concrete products, d) the mineral ettringite has formed and is abundant in the completed ash fill, which is an important component in the cement formulation process, and e) the relatively high sulfate concentrations of the mine pool chemistry were necessary to promote the formation of the ettringite, and then the ettringite provides an additional environmental benefit by sequestering heavy metals.

Some physical and chemical characteristics of coal ash make it useful in mine land reclamation for ameliorating the adverse conditions associated with many coal mine soils. The major benefits are improved physical properties and neutralization of acidity. Most PC ashes and FBC ashes will increase water holding capacity of coarse-textured, high-rock-fragment soils and reduce compaction in heavier textured soils. The use of coal ash as a soil additive or soil amendment reduces mine soil acidity and provides plant nutrients. Seventeen elements have been demonstrated to be essential for plant growth, of which the macronutrients include nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur; while the micronutrients include iron, manganese, boron, molybdenum, copper, zinc, chlorine, and cobalt. Boron and molybdenum are examples of constituents in coal ash that are essential plant nutrients. Amendment of mine soils and spoils with coal ash requires managing application rates, and selection of plant species to maximize positive effects, minimize negative effects and insure that the overall result is an increase in the ability and capacity of the mine soil or spoil to support a sustained vegetative community.

11.3 ASH FILL INTEGRITY AND STABILITY

11.3.1 Mechanical Properties

The mechanical properties of structural fills for restoration of minelands can be reduced to three categories:

- density
- bearing capacity
- permeability

All of these mechanical properties relate to potential end uses of the restored minelands such that industrial development could occur on the land. Compaction is related to end use through the optimum moisture content of fly ashes, usually between 8 and 20% (Fig. 11.1), and in turn relates through Proctor density measurements to a requirement of 90% or greater as determined with a Troxler nuclear density moisture gauge.

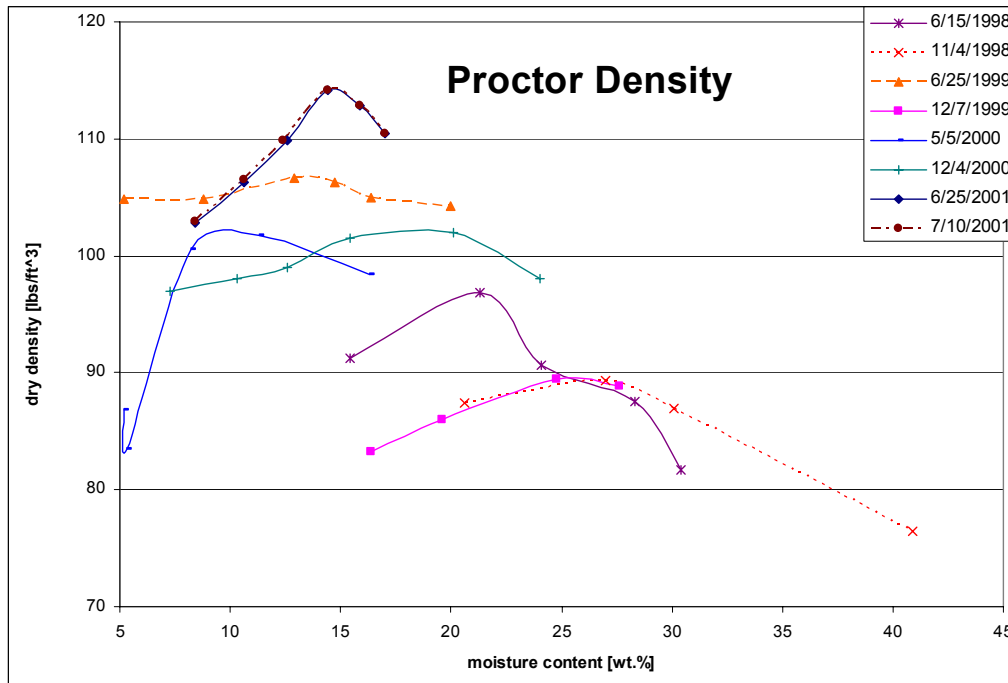


Figure 11.1 Range in proctor density measurements for a single FBC facility.

At these densities, bearing capacities are typically in excess of 4000 pounds per square foot. Split spoon sampling following ASTM D 1586 is used to provide additional indication of the structural stability of the fill. For most mineland projects, 50 blow counts per foot with a standard pound is considered the point of rejection and further attempts to penetration stopped. Structural fills meeting these minimum geotechnical requirements are more than adequate for the construction of foundation walls for industrial construction. A hydraulic conductivity between 10^{-5} to 10^{-6} cm/sec, comparable to requirements for closures of hazardous landfills, limits ingress of fluids, which under heavy traffic load or earthquake could become unstable and fluidize. Since the vast majority of reclamation projects represent a fill scenario, no requirements for the angle of repose are presented.

The primary reason for attempting a wet-to-dry ash remediation project is the elimination of dangerous conditions that have been recognized as threats to public health and safety. The technical and economic issues addressed by this approach of reclamation are: 1) materials handling, 2) reliability of delivery, 3) disposition of delivery water, 4) mechanical stability of the placed ash, and 5) economics of the methodology.

Delivery in the form of a dense slurry to the deposition area eliminates all issues of dusting from the ash handling and truck traffic on the access roads; it further eliminates the need for watering trucks and the associated atmospheric emission from delivery and water vehicles. The experience gained from this demonstration support the conclusions that down time from failure of the delivery piping and clogging of delivery piping was minimal. It was necessary to pump the slurry and not rely upon gravity feed. The water used to carry the ash through the delivery piping was re-circulated back to the combustion facility and reused. Monitoring of the waters in the flooded deep mines beneath the demonstration site did not detect any influence from the surface activities. The practice of recycling the delivery water was discontinued later in the demonstration and the water allowed to re-enter the deep mine from which it was drawn, with no observed impact. The placed ash was shown to possess a bearing capacity sufficient for trucks to drive on the surfaces immediately adjacent to the incoming ash. A sub-study conducted to evaluate the impact of CKD additions to the ash slurry suggested that a recognizable benefit from enhanced particle packing could be gained by its use and the researchers speculated that enhanced cementitious behavior would also occur if 1) the CKD was adequately mixed during placement and 2) of sufficient quality to improve the alkalinity of the pore fluids in the placed ash. Finally, an economic evaluation by the company comparing the delivery of ash for placement by truck, to belt delivery, and to a dense slurry demonstrated a remarkable 97% reduction in cost by using the dense slurry compared to the truck delivery approach. This approach has the potential to significantly extend the amount of mine lands that could be recovered per unit cost.

The structural and chemical stability of wet or dry ash placement into standing water, in our opinion, is not limited in any scientific way to the size of the reclamation project, nor to the geometry of the pit. However, consideration should be given to the size as it relates to the projected scope in terms of the available ash. A project should not be started that cannot be completed in a reasonable time frame or that cannot be completed with the projected volume of ash generated by the permit holder of the project.

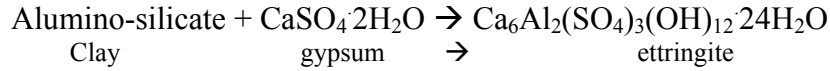
11.3.2 Chemical Integrity

The following sections will examine the anticipated changes in the ash fill as it undergoes chemical reaction resulting in the hydration of the mineralogical constituents of the ash and will attempt to provide bounding calculations on the anticipated durability of the ash fill based upon the most soluble component of the phase assemblage. The sections will also provide some insight into mechanisms for the sequestration of metals associated with the mix.

11.3.2.1 Paragenesis of mineralogical assemblage in the ash

The mineralogy of the NEPCO ash was quantified and reported in table 9.6. Some of the mineralogical constituents of the ash remain inert with respect to the chemical reactions that take place within the ash fill. Quartz, mullite, and hematite from the NEPCO ash fall into this category. The pore fluids were sampled and determined to have a pH of 12. Loop et al. (2003) demonstrated that this pH was in part a result of the fluids striving to reach a pH of 12.45, the equilibrium value for portlandite, and the reactions with atmospheric carbon dioxide in an open system precipitating calcite. The high pH and the presence of both gypsum and sulfates in the

mine water are responsible for the reaction of the thermally altered clays to form ettringite and possibly gysmondine.



Ettringite is an important component of the alteration of the ash since it has been demonstrated thermodynamically that it is not only responsible for limiting control of the solubility of aluminum in the mine-pit lake waters at high pH (Fig 11.2), but it is also an important component in the cementitious reactions that are taking place within the ash fill and an important control for arsenic sequestration. Scanning electron microscopic (SEM) characterization of placed ash has visually confirmed the development of ettringite (Fig. 11.3).

The high alkalinity also results in a large amount of meta-clay undergoing pozzolanic reactions with the formation of hydrous calcium silicate phases. Thermodynamic modeling has confirmed the existence of 14Å tobermorite. This phase is the crystalline equivalent of C-S-H, the glue in Portland cement. Although the thermodynamic calculations have been conducted for a phase that contains no aluminum, C-S-H that forms under real world cement hydration conditions always contains a finite amount of aluminum substitution that is at the maximum solubility limits (Barnes and Scheetz, 1989).

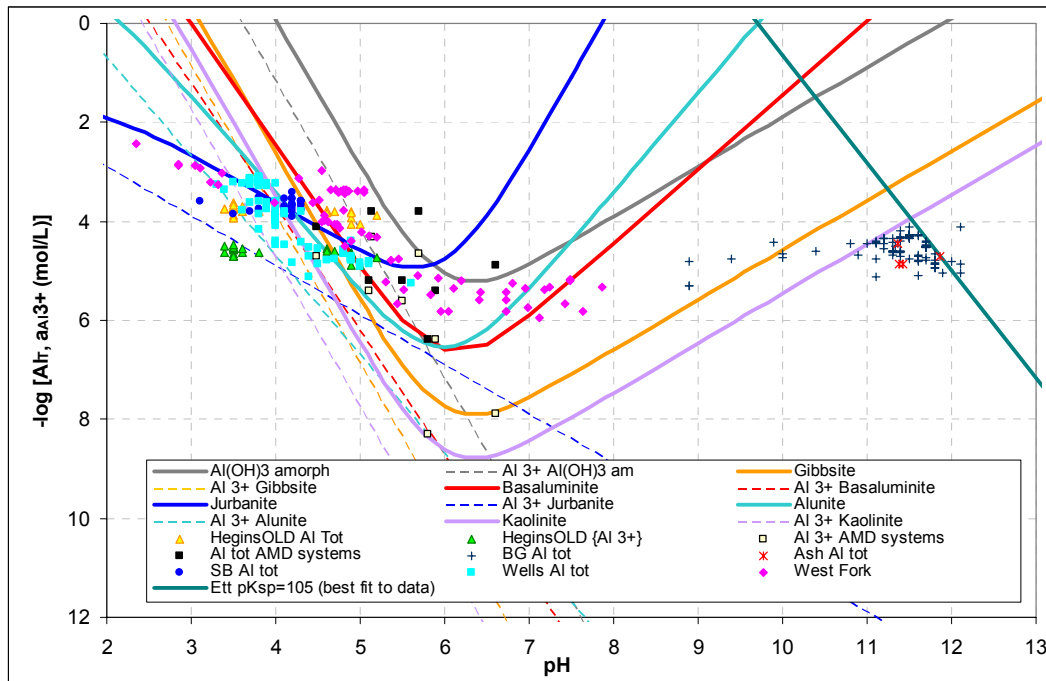


Figure 11.2. Thermodynamic control over the solubility of aluminum in AMD and the Gorilla mine-pit lake waters. Plot constructed by Dr. Charles Cravotta of the U.S. Geological Survey, with an ettringite solubility line altered by the authors to best fit the Big Gorilla data.

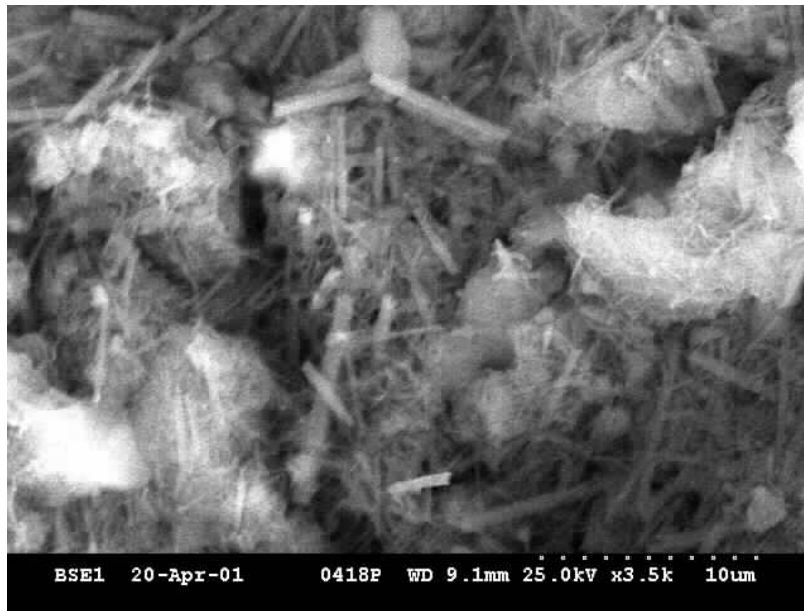


Figure 11.3. Scanning electron micrograph of ettringite growth in FBC ash.

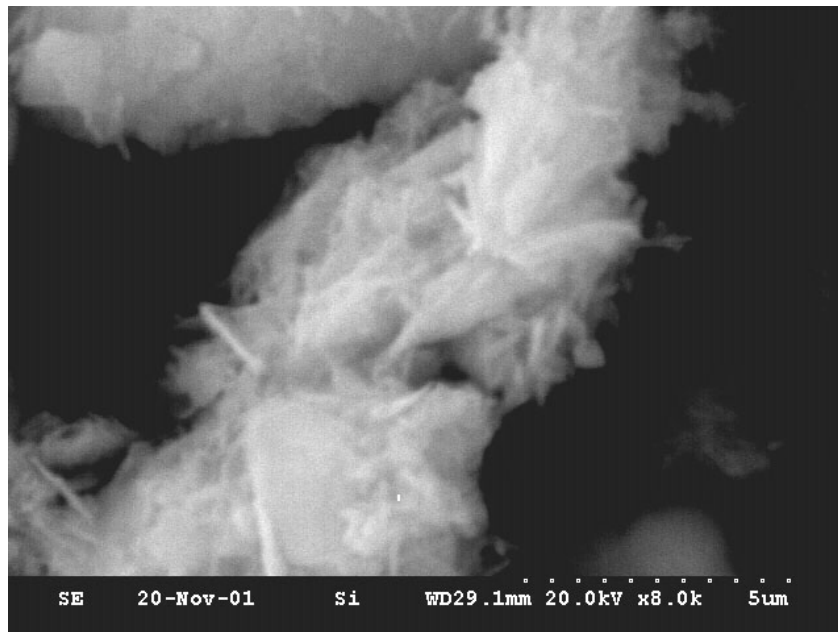


Figure 11.4. Development of C-S-H in ash.

Thermodynamic calculations also suggest the formation of gysmondine, a calcium zeolite in the assemblage of reaction products in the ash. Although this particular zeolite has not been identified in the ash via SEM characterization, the presence of zeolites in hydrating cementitious systems is well documented (Grutzeck et al., 1997, 1999, 2003). Finally, the thermodynamic calculations also suggest that in the presence of atmospheric carbon dioxide, common carbonate

minerals of the alkaline earth elements are forming, including calcite and to a lesser extent, whiterite.

Although these FBC ashes are not strongly pozzolanic, the presence of large amounts of thermally altered clays in the presence of an alkalinity source that will raise the pH in excess of 9.5 results in hydration products forming that are not unlike those which are formed in the Portland cement system. The similarities offer us an unprecedented opportunity to model the behavior of these structural ash fills

11.3.2.2 Longevity of the ash fill

The primary question that is most commonly asked of a structural fill like the Big Gorilla project is “How long will it be stable?” This is a fair question that can be addressed in several ways. Subsequent calculations will attempt to provide bounding calculations that will bracket anticipated longevity questions based upon several different approaches describing the ash fill.

During the course of the ash placement, both compaction measurements on the ash fill and hydraulic conductivity measurements were made. It was determined that the hydraulic conductivity of the ash was 1×10^{-6} cm/sec, a value not atypical of others reported for ash monofills (Ghosh and Subbarao, 1998). The structural fill can be represented as a homogeneous body in which water movement will remain in a laminar flow condition. With these assumptions, Darcy’s law can be used to describe the time it would take for a given volume of water to flow through the mass.

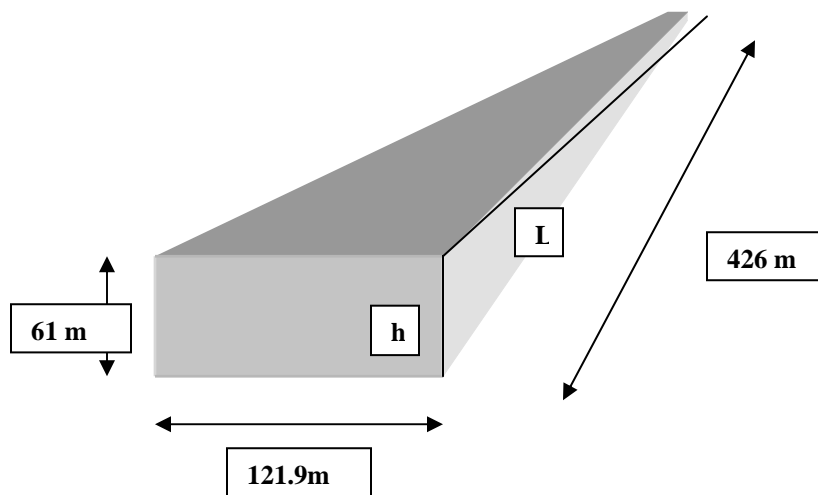


Figure 11.5. Model for calculation of hydraulic conductivity.

$$Q = KIA$$

Where:

Q = flow rate (vol/time)

K = hydraulic conductivity (1×10^{-6} cm/sec)

I = hydraulic head (h/L)

A = cross sectional area of the pile (cm)

The compacted mass of ash in the Gorilla represents approximately 60 million cubic feet of ash. If the porosity is approximately twenty percent, the volume of ash contains about 12 million cubic feet or about 51 million gallons of pore water. Using Darcy's Law, one can determine the time required for a single gallon of this 51 million gallons of pore water to flow through this modeled system based on the conservative assumptions that the hydraulic head is the complete thickness of the fill. Using the stated assumptions and the dimensions of the Big Gorilla pit and assuming a rectangular parallelepiped as shown in Figure 11.5, an estimated 3,000,000 years is calculated for that one gallon of pore water to move through the entire ash body. It must also be recognized that as this water moves through the fill, it will become alkaline with the fill acting as a large alkaline reservoir.

The initial calculations were conservative, based on a hydraulic head of ~15% compared to the more commonly encountered 1% head. The corresponding time interval for the smaller gradient is well in excess of 10,000,000 years.

The paragenesis of hydrated phases in the ash structure has the potential to form large quantities of C-S-H from the 63 wt% thermally altered clays. Using the model for the ash structure based upon a Portland cement model suggested by thermodynamic calculations of the pore fluids, a portrait of the long-term behavior of the ash structure can be constructed. Figure 11.6 is a schematic representation of the resulting phase assemblage and pH.

Stage I, [T₀ – T₁] represents a period when the pH of the ash structure is controlled by the buffer established by portlandite and C-S-H. The leachates will remain at a value of 12.45 until such time as all of the portlandite has been removed. Table 8.1 details the reported solubility product constants for the phase assemblage in the ash structure; as can be readily seen, portlandite is the most soluble component of the system.

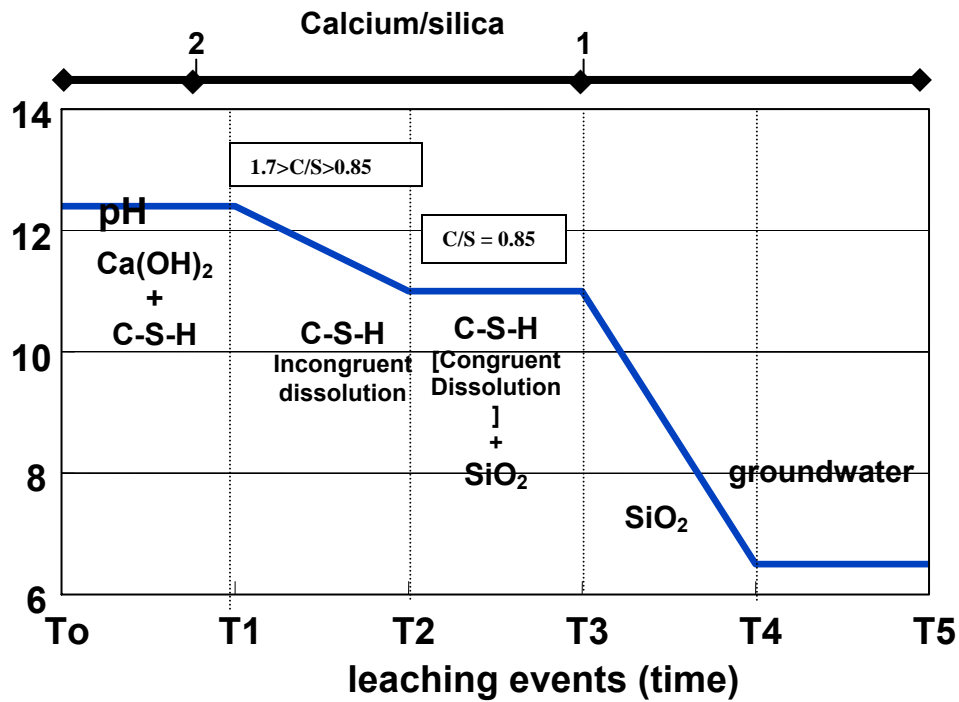


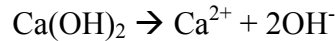
Figure 11.6 Effects of leaching on pH of C-S-H-portlandite-silica system as a function continued leaching. (after Atkinson, 1985)

Table 11.1. Summary of the solubility products of phases in the ash structure.

<i>Name</i>	<i>Formula</i>	<i>log K_{sp}</i>	<i>reference</i>
Portlandite	Ca(OH) ₂	-5.31	Allison et al. (1992)
14Å tobermorite	Ca ₅ Si ₆ O ₁₆ (OH) ₂ ·4H ₂ O	-14.6	Geelhoed et al. (2002)
Ettringite	Ca ₆ Al ₂ (SO ₄) ₃ (OH) ₁₂ ·26H ₂ O	-111.6	Myneni et al. (1998)
Brucite	Mg(OH) ₂	-16.79	Geelhoed et al (2002)
Calcite	CaCO ₃	-8.48	Geelhoed et al (2002)
Gypsum	CaSO ₄	-5.2	Rothstein et al. (2002)

Bounding calculations can be conducted for the leach interval To-T1 based upon a) ash structure control of the leaching and b) the contacting geologic control of the leaching.

The shrinking core model is based on the dissolution of portlandite in the cement:



The flux is calculated from:

$$\text{Flux} = -D_i [(C_l - C_{gw})/X]$$

$$dX/dt = [D_i/X][C_l - C_{gw}/C_s]$$

Walton et al. (1990) have developed an approach for the depth of leaching of portlandite from a cementitious body that takes the form:

$$x = (2D_i [C_p - C_{gw}] / C_s t)^{0.5}$$

Where:

X	distance	Cm
D _i	intrinsic diffusivity	cm ² /sec
C _p	concrete pore	Moles/cm ³
C _{gw}	groundwater	Moles/cm ³
C _s	solids	Moles/cm ³
T	time	Sec

The shrinking core model assumes that the removal of calcium from the exterior surface of the concrete is rapid relative to the movement through the concrete. This relationship takes the inventory of Ca-ions in the pore fluids of the ash structure minus the leaching water concentration and ratios it to the total available in the solids. By multiplying against the intrinsic diffusivity for calcium in the ash as a function of the square root of time (diffusion controls the leaching), a depth of penetration into the structure can be calculated. Because concrete is less permeable than the surrounding geology, the dominant flow direction will rarely be normal to the concrete (structural fill) surface.

Based on 61 m, the smallest dimension of the filled Gorilla pit and assuming diffusion through both sides toward the middle of the structure, a time (t) can be calculated when both diffusion surfaces meet. The results of this calculation, based on a conservative intrinsic diffusivity of 3×10^{-6} cm²/sec, yielded a time frame for To-T1 on the order of 10,000,000 years (Fig. 11.7).

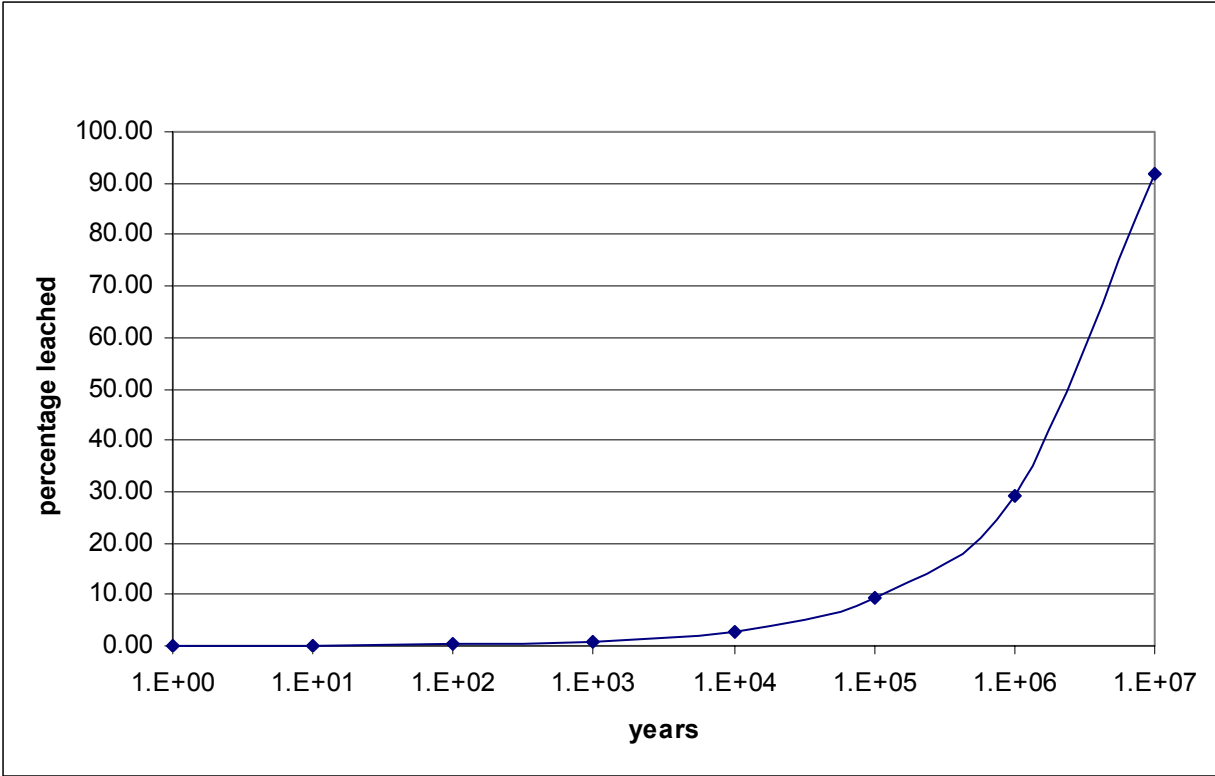


Figure 11.7 Percentage leached of the smallest dimension of the Gorilla ash fill as a function of time based on an ash structure-controlled leaching model.

The alternative approach suggested by Walton et al. (1990) (after Atkinson and Hearne, 1984) was to allow the surrounding geology to control the diffusion of calcium from portlandite in the ash fill to diffuse into the surrounding geology. In this approach, the concentrations are described by an error function:

$$[C - C_{gw} / C_l - C_{gw}] = \operatorname{erfc}[X / (4D_e t / R_d)^{1/2}]$$

The total material leached in a given time period is obtained by integrating with respect to time:

$$M_t = \Phi C_l - C_{gw} (4R_d D_e t / \pi)^{1/2}$$

The total amount of calcium hydroxide removed can be related to the inventory in the fill as:

$$M_t = X C_{\text{bulk}}$$

Following a similar approach, Walton presented the following equation in which he calculated the depth of leaching in the ash fill:

$$x=2\Phi[C_p-C_{gw}/C_s](R_d D_e T/\pi)^{0.5}$$

where:

X	distance	cm
π	pi	
C_p	concrete pore	moles/cm ³
C_{gw}	ground water	moles/cm ³
C_s	solids	moles/cm ³
R_d	retardation	
D_e	effective diffusivity	cm ² /sec
Φ	porosity	
T	time	sec

In this analysis he also utilizes the percentage of the total inventory of calcium in the ash released but controlled by the effective diffusivity of the geologic media as well as the retardation of the geologic media. Assuming conservative values for R_d and D_e , the estimated time that the leaching process took to diffuse through parallel sides of the ash structure 61 m thick was on the order of 255,000 years (Fig. 11.8).

Although the spread of time to accomplish the total removal of portlandite from the ash structure in the Gorilla ranges over two-orders of magnitude, the bounding calculations suggest that for the leaching interval T_0 - T_1 , times in excess of a quarter of a million years will transpire. It is noteworthy to point out that during this time interval a slow release of alkalinity in the form of calcium hydroxide will be taking place. Only after the total removal will the pH begin to drop.

Stage II [T_1 - T_2] is represented by the stability of a single phase and described by the incongruent dissolution of C-S-H from a calcium to silica ratio of 1.7 to a value of 0.85 and will proceed until pH 10.7 is reached. All of the excess calcium in the structure is removed and C-S-H begins to undergo congruent dissolution. Estimates of the length of time involved in this stage of leaching of the fill are difficult to make since they depend on the amount of C-S-H formed during the hydration of the ash components. In Portland cement concrete as a point of reference, this stage typically is calculated to require approximately 1,000,000 years to reach the onset of congruent dissolution of the C-S-H (Atkinson, 1985).

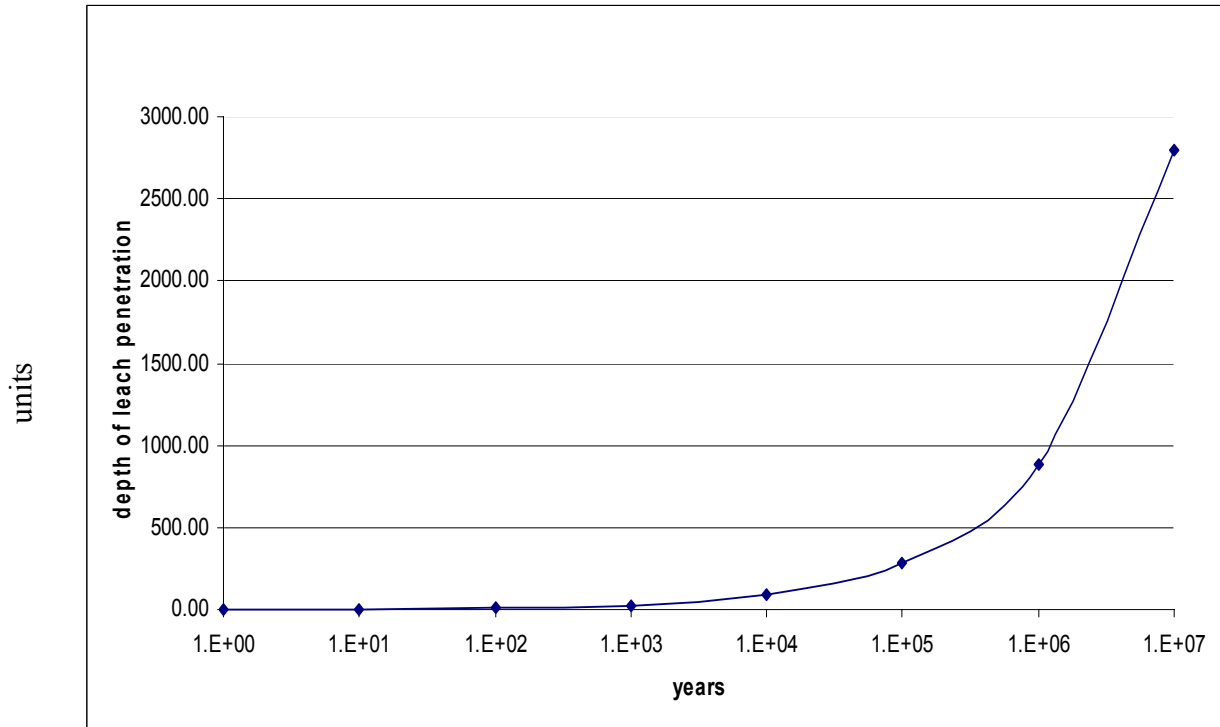


Figure 11.8 Percentage leached of the smallest dimension of the Gorilla ash fill as a function of time based on a geology-controlled leaching model.

The transition marks the onset of Stage III [T2-T3] in which the phase rule dictates the coexistence of two phases, C-S-H and SiO₂. Dissolution follows at a constant pH until all of the C-S-H is removed. Following a similar argument direct estimates of the durability are not possible to make but by analogy with concrete Atkinson (1985) calculates about 500,000 years to achieve complete dissolution of the C-S-H. Stage IV represents the stability of only a single phase, SiO₂, thus allowing by the Gibbs Phase Rule, the pH to drop to the controlling groundwater pH, Stage V.

The above exercises were conducted in order to provide some sense of the long-term stability that may be anticipated from the structural fill in the Big Gorilla Pit. The calculations were conducted based upon our recognition that the changing mineralogy of the fill materials could be modeled using Portland cement as an analog. Furthermore, the calculations were conducted with conservative input data to the model, that is to say that reasonable but aggressive parameters were chosen that would hasten the leaching of the fill and in this manner provide a more conservative interpretation of the data.

These results suggest that the structural fill will be stable for a period of time most probably in excess of 100,000 years and likely well in excess of 1,000,000 years. During the period of time in which it is altering, the pH of the leachates released from the fill will be above a value of 10.7 for the vast majority of that time. In an environment where the ground waters are impacted by acid mine drainage, the fill will act as a local reserve of alkalinity that will slowly be released over its service life.

11.3.3 Mechanisms of Controlling Heavy Metals

Sequestration of heavy metals in the hydration products in the ash fill takes on several forms. The metals can be precipitated as a result of the elevated pH levels in the pore fluids of this ash, they can be crystal chemically incorporated into the developing hydration products, they can form surface compounds on the grains of the ash, they can be chemisorbed onto ash grains and/or they can become incorporated as inclusions in the matrix of the hydrated compounds in the ash fill. Figure 11.9 from Gougar et al. (1996) graphically summarizes these options.

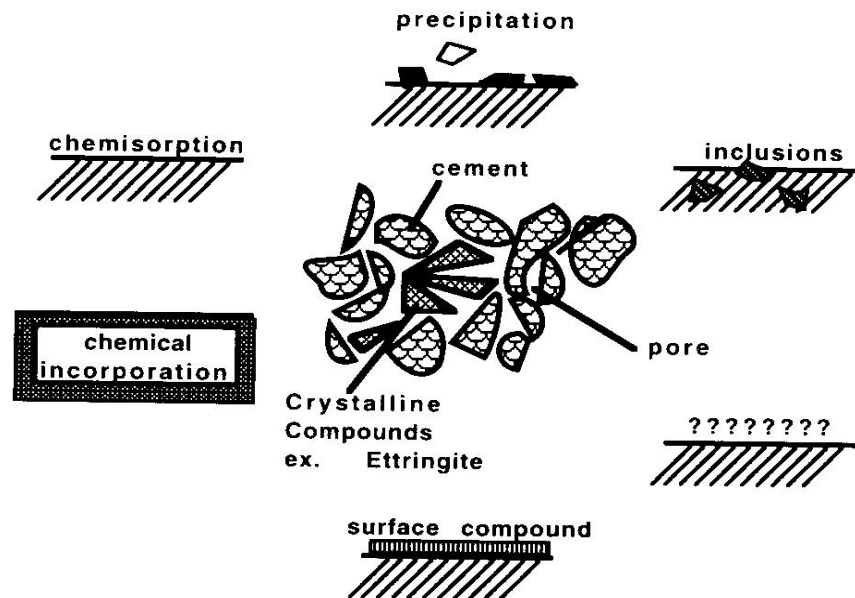


Figure 11.9 Various possibilities for the interaction of heavy metals in a cementitious matrix (after Gougar et al., 1996).

11.3.3.1 $\text{Ca}(\text{OH})_2$

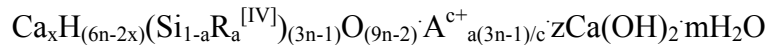
All of our experiences suggest that the presence of free lime ($\text{Ca}(\text{OH})_2$) is necessary for placement of ash in standing mine water. Lime serves to immobilize labile heavy metals but more importantly, it is the activator that initiates chemical reactions among the fly ash phases. These hydration reactions not only contribute to the immobilization of metals but also to the development of cementitious chemical reactions that will influence the development of favorable mechanical and physical properties of the ash. As the hydration reactions mature with time, the resulting microstructure of the mass will continue to develop leading to a decrease in permeability to external fluids. Lime from the ash in contact with the pit waters will result in an elevated pH, the driving factor in the chemical reactions. The aluminosilicate structures of the glass or meta-clay phases are activated by elevated pH values to initiate the hydration reactions which begin to dissolve their structures. The presence of aluminum and silica in solution in the

presence of calcium results in the precipitation of tobermorite (a fibrous mineral that acts like the glue in Portland cement and the glue in the ash hydration). The formation of tobermorite has been predicted by thermodynamic calculations demonstrating the stability of this phase.

The exact amount of excess lime necessary to accomplish these favorable chemical reactions is dependent upon the mineralogy of the ash to be placed. Any ash that contains either a glassy phase or a dehydroxylated ‘meta’-clay as the dominant phase will respond to the lime additions. Our best estimate at this point is that a minimum of 3 to 5% by mass of the ash should consist of lime. If the ash is predominantly crystalline quartz, it is likely that even the presence of large amounts of excess free lime will have little influence on the hydration reactions. Under these unique circumstances, the ash placement would be similar to the placement of sand as a structural fill material.

11.3.3.2 Calcium-silicate-hydrate

In Portland cement, calcium-silicate-hydrate (C-S-H) forms as an amorphous hydration product of both di- and tri-calcium silicate. It is the morphology of this phase that imparts the mechanical properties that are attributed to concrete. C-S-H is the ‘glue’ in Portland cement. In the ash fill, clays in the culm and coal are thermally altered to the point where the clays give off their water and dehydroxylate. It is the reaction of these meta-clays with Ca at elevated pH that forms C-S-H. C-S-H does not possess long-range crystalline structure. A general formula for it has been proposed in the form of the Richardson-Groves model:



Where:

$$\begin{aligned} x &= 0.5(6n-w) \\ z &= 0.5[w+n(y-2)] \\ \text{and for } 0 < y < 2 &\rightarrow n(2-y) < w < 2n \\ 2 < y < 4 &\rightarrow 0 < w < 2n \\ 4 < y < 6 &\rightarrow 0 < w < n(6-y) \end{aligned}$$

and $0 < a < n-1/3n-1$

R is a trivalent cation in tetrahedral coordination

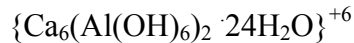
A is an interlayer ion

C-S-H has been identified with scanning electron microscopic studies and in thermodynamic calculations in the hydration products of ash.

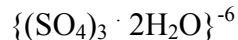
Gougar et al. (1996) have reported in a review of relevant literature that the sequestration mechanism for mercury oxide and cadmium hydroxide is encapsulated within the matrix of hydrating C-S-H. Nickel, lead and uranium are immobilized by chemisorption on the hydrating C-S-H particles.

11.3.3.3 Ettringite

Ettringite is essential in the hydration of Portland cement for controlling the setting time of the hydration reaction. It also occurs as a predominant reaction product in FBC ashes derived from bituminous mining waste. Ettringite is a crystalline material composed of columnar units of:



with large channels containing:



Extensive crystal chemical substitution has been reported in the ettringite structure. Table 11.2 summarizes the extent of this substitution. Of particular importance in this list of immobilized elements are arsenic and selenium, and to a lesser extent hexa-valent chromium, which substitute for sulfate in the structure.

The results of our studies have pointed out the importance of the formation of the mineral phase ettringite in the hydrating ash body and in the mine pit water in contact with the ash. At the elevated pH ranges established by the lime, the glass or meta-clays will release aluminum to the pit waters in excess of that amount precipitated into the hydrous calcium aluminosilicate phase. The solubility levels of aluminum at the pH 12 range is in excess of 6 orders of magnitude higher than that encountered at pH 6.5 and as such could represent the formation of a potential environmental threat. The observation that ettringite formation limited the solubility of aluminum in the pit waters suggests that the sulfate content of the pit water/ash mass is also an important controlling component.

In the case of the Gorilla demonstration, sufficient sulfate from both the mine pit water and the gypsum formed in the ash were present to limit the solubilization of aluminum. The total sulfur content of the ash was 5000 ppm and the water concentration ~500 ppm. It is apparent that concerns of aluminum solubilization would only be an issue in non-FBC ashes without the addition of a sulfate source. For example, a lime stabilized PC ash would require the admixture of a calcium sulfate from FGD or another gypsum source.

The thermodynamic analysis of the Al-pH system also indicates that ettringite is not stable below a pH value of 10.5. This study of the Gorilla waters contains several data points for the pit water while it has been in transition from a dormant condition where ash was not actively being placed with a mildly alkaline condition (pH 8), to active ash placement with a pH values approaching 12. The aluminum solubility for these few points also remained low. We have not at this point identified the mineral phase that is responsible for the control of aluminum in the pit water but literature references also suggest the presence of a yet to be identified hydrous aluminosulfate compound. The reason for the scarcity of data is the unusual confluence of the chemical conditions that are represented and hence a lack of detailed study in the area.

Table 11.2. Reported substitutions in the ettringite structure

$(Ca^{2+})^{VIII}$	$(Al^{3+})^{VI}$	(SO_4^{2-})	(OH^{-})
Sr	Cr	B(OH) ₄	O
Ba	Si	CO ₃	
Pb	Fe	Cl	
Cd	Mn	CrO₄	
Co	Ni	AsO₄	
Ni	Co	SeO₄	
Zn	Ti	VO ₄	
		BrO ₃	
		NO ₃	
		MoO ₄	
		ClO ₃	
		SO ₃	
		IO ₃	

Elements designated in bold type are of concern in AMD waters.

11.3.3.4 Metal hydroxides

Most metals exhibit a change in solubility as a function of pH that is marked by increased solubility at both acid and basic conditions with minimum solubility at varying pH values characteristic to the individual metal. Figure 11.10 is an example of several metals over a pH range extending to 14. As can be seen in this figure, the majority of metals exhibit a solubility minimum in the range of 9 to 12. Chemically, hydroxides are controlling the solubility behavior at pH values above 7.

Since no one pH value is ideal for ‘all’ elements, the immobilization is based solely on the idea that metal hydroxide precipitation is a trade off that nonetheless is an effective means of lowering metal concentrations.

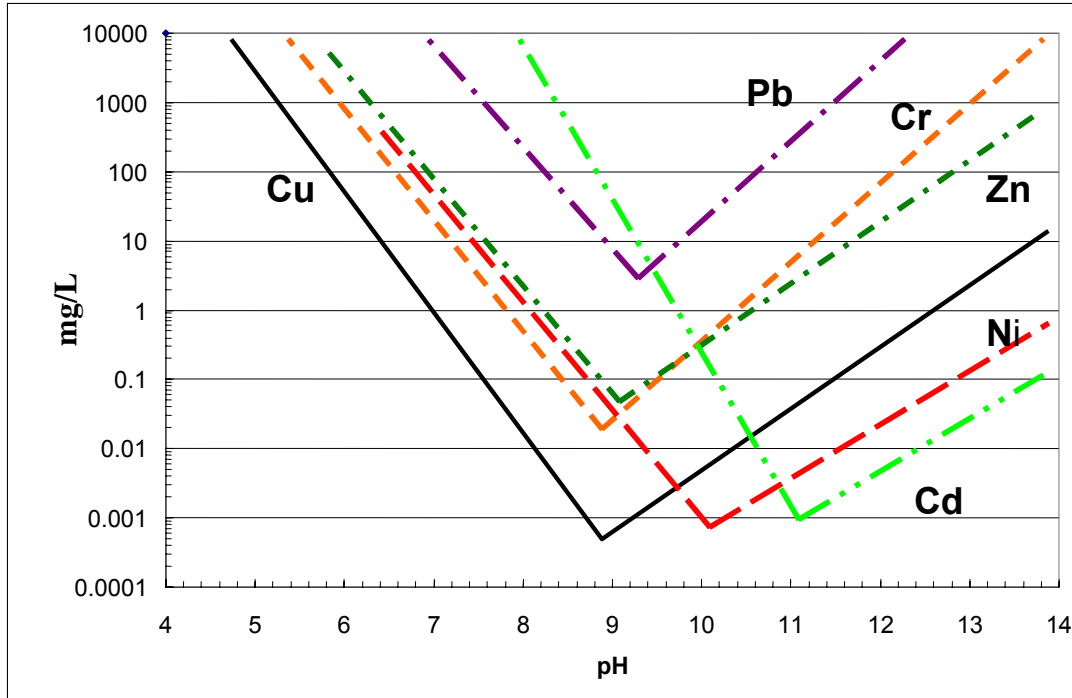


Figure 11.10 Solubility (mg/L) vs. pH plots for selected metallic elements in the system M-O-H showing minimum solubilities.

11.4 IMPACTS OF ASH PLACEMENT ON WATERS

11.4.1 Selected Properties

Modification of existing pit lakes by ash addition is expected to have both immediate and long term effects on the chemical quality of water. It is, of course, the water in the pit lake that will be dramatically modified in the short term but by the end of the project, the lake will no longer exist. The remnant of the pit water exists in the pore spaces of the ash pile, which now acts as a low permeability aquifer. In the case of the Big Gorilla demonstration site, the Silverbrook outfall serves as an overflow point for the entire basin and forms a tributary of the Little Schuylkill River. In a deep-mined synclinal valley such as the Silverbrook Basin, ground water is hard to define. The present state of the interconnecting tunnels of the deep mining operation is largely unknown. Some are definitely open; some may be clogged with silt. The locations of the outfalls from all of the demonstration sites are known, but the details of the flow paths are at best conjectural. There must be some exchange of ground water between the flooded mines and the permeable rock units. Ground water can be sampled from monitoring wells but the relationship between waters from monitoring wells and other ground waters is not always apparent.

With these limitations in mind, some interesting conclusions can be drawn from the water quality data collected during the closure of the Big Gorilla pit lake. The details from which these conclusions are drawn are found in Chapter 9.

11.4.1.1 Acidity

The initial pH of the Big Gorilla pit lake was in the range of 3.4 before ash addition commenced. With the first ash addition, the pH rose rapidly to values in the range of 11. The ash slid into the lake and along the bottom as a density current, causing rapid mixing of the lake water and destruction of the stratification that had been observed earlier. Ash addition was discontinued in the winter season and in the first year the pH of the undisturbed lake water dropped to the range of 6 but not back to the pre-addition acidity levels. When ash addition was resumed the following summer, pH rose quickly to 11.4 and afterwards only rarely dropped below 11.

The strongly alkaline water in the diminishing pit lake was due to the presence of CaO in the ash. CaO hydrates rapidly to Ca(OH)_2 which ionizes with the release of OH^- ions. The upper pH limit for water saturated with Ca(OH)_2 would be 12.45. These high pH waters are unstable. Over long time periods of time, the excess OH^- ions in the water will react with carbon dioxide from the atmosphere and result in the formation of bicarbonate ions precipitating CaCO_3 . The pH value will eventually decrease to somewhere in the range of 8–9 depending on the effective CO_2 pressure in the ash pile. Some evidence for this mechanism is provided by the white band of calcite-containing deposit that formed around the water-line of the lake.

11.4.1.2 Iron

The concentration of iron in the pit lake was in the range of 1 mg/L before ash addition. As would be expected, the concentration fell even lower in the alkaline water created by the ash. Because the pit lake is exposed to atmospheric oxygen, iron is expected to be in the Fe^{3+} valence state. When the pH climbs into the neutral and alkaline regime, Fe^{3+} , which is soluble in acid solution, precipitates as the highly insoluble Fe(OH)_3 . This material would be adsorbed on the ash particles and be incorporated as part of the ash pile.

11.4.1.3 Aluminum and sulfate

The behavior of aluminum is very interesting because it is the element for which the high pH of the pit lake could be expected to cause problems. Aluminum is amphoteric, meaning that its solubility increases at both low and high pH. Aluminum is extracted from rocks by acid mine waters to give a mean concentration in the pit lake of 1.2 mg/L (Table 9.7). One would expect high concentrations of aluminum in the alkaline lake water because of the dissolution of modified clays in the ash by the strongly alkaline water. This was not observed. The sulfate concentrations in the pit lake had typical values greater than 400 mg/L and these rose to near 1000 mg/L with ash emplacement. Leaching of gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, from the ash is an additional source of sulfate. At these concentrations, aluminum becomes immobilized as insoluble alumino-sulfate compounds and the expected increase in aluminum in the strongly alkaline pit lake water did not take place. Etringite, $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$, is the likely immobilization phase. Mobilization of aluminum was seen as one of the largest risks to water quality from placing ash in an acid pit lake. If the sulfate concentrations are high, in excess of 400 mg/L, mobilization of aluminum is unlikely to take place.

11.4.1.4 Toxic metals

The water in the Big Gorilla pit lake contains quantities in the range of a few parts per billion to several hundred parts per billion of an array of toxic elements (Table 9.7). These include As, Cd, Cr, Cu, Pb, Hg, Ni, Se, and Ba. The question is what happens to these elements when the background chemistry of the lake water is changed by the addition of ash?

Arsenic and selenium both occur in the oxidized form as the AsO_4^{3-} and SeO_4^{2-} ions. Both ions readily substitute for sulfate, SO_4^{2-} and should be immobilized in any sulfate minerals that may form. During the period of ash addition, the maximum concentration observed in the pit lake was 101 ppb for Se and 22 ppb for As. There was no apparent trend in concentration of either element with respect to ash input.

The highest concentrations of Cd, Hg, and Ni in the pit lake were 18 ppb, 3 ppb, and 284 ppb respectively. The value for nickel seems anomalously high. The values measured during ash addition were comparable to those measured before ash placement was undertaken.

Barium is likely to track with calcium and to coprecipitate in calcite in the reactions of the alkaline lake with atmospheric CO_2 . There was no barium detected in the pre-ash placement pit lake. After ash placement began, barium concentrations were in the range of 10 to 40 ppb. The concentrations appear to respond to ash input, increasing when ash loads are increased.

Chromium concentrations before ash placement were never higher than 50 ppb. The concentrations increased after ash placement began but never exceeded 260 ppb. The concentrations appeared to increase with ash input and decrease when ash placement was halted.

Lead is a very minor element in both pre- and post-placement lake water. The highest pre-placement concentration was 2 ppb. The highest post-placement concentration was 27 ppb. Only 3 samples in the post-placement period exceeded the drinking water standard for lead. The concentrations were so low that relationships between lead concentration and ash placement were difficult to distinguish.

Copper is present in the pit lake with a maximum concentration of 132 ppb. The measured concentrations varied erratically with no obvious relation to ash placement.

11.4.2 Zone of Influence

In spite of the dramatic increase of pH in the pit lake, the pH of the Silverbrook outfall had not changed as of the writing of this book. Water discharging from the Silverbrook remains near 4.0. Before any ash addition, the acidity of the Silverbrook was in the range of 75 mg/L compared with 40 mg/L in the Big Gorilla pit lake. There was an upward spike to about 175 mg/L acidity in the time period of 1995 – 1998, after which the acidity at the Silverbrook has dropped back to values in the range of 50 – 100 mg/L. The behavior of acidity and pH at the Silverbrook outfall suggests that it is mainly discharging water from the flooded deep mines and that the hydraulic connections between the pit lake and the outfall, if any, are very inefficient.

The Silverbrook outfall contains substantially more iron than does the pit lake (Fig. 9.19). Data collected before the beginning of ash placement show considerable scatter, but iron concentrations range from 5–15 mg/L. After 1997, the start of the project, the iron content of the Silverbrook water increased to the range of 15 – 25 mg/L.

Calcium, iron, and sulfate concentrations increased in the water flowing from the Silverbrook discharge. These data were first collected at the beginning of active remediation within the Silverbrook outfall, approximately eight years before ash was first placed in the Big Gorilla. A pattern of gradual increase in calcium, starting shortly after surface remediation began on the eastern flank of the Silverbrook basin, has been attributed to the early land remediation using CaO-rich ash. Surface reclamation of the exposed and mined Buck and Mammoth veins took place. These areas connect to deeper underground workings, and hence, directly to the Silverbrook discharge.

Concurrent with initial ash placement at the Big Gorilla, the operation activities at the power facility intensified, and a fuel (culm) storage area was activated and enlarged. Surface runoff from the access road to the facility and associated parking areas all drain through this freshly disturbed site and ultimately leave the basin at the Silverbrook discharge. Iron and sulfate concentrations in the Silverbrook discharge increased due to the newly exposed pyrite surfaces within the culm piles. Although the disturbance, transportation, and storage of waste coal piles is an unavoidable step in permanently removing them, in some cases future operations may need to consider interim measures to limit any temporary impacts that may occur from affecting long-dormant piles.

Finally, winter-time use of de-icing salt on the access road to the facility has been observed to correlate with a cyclical sodium and chloride signature in the Silverbrook outfall. Enhanced activity at the fuel storage area represented a significant increase in the amount of fuel that was being trucked to the site from locations outside the Silverbrook basin. Thus, there was an increased need to keep truck access open during inclement weather conditions.

11.4.3 Water Monitoring

The need to monitor the effluent from a demonstration site is predominantly regulatory, however, if sufficient additional control can be added, the long-term observations of the site chemistry can add valuable scientific data. Demonstration projects carry the burden to provide scientific data necessary to evaluate the effectiveness and value of the practice being demonstrated; the monitoring plans for those projects must take this extra burden into consideration. For non-demonstration mine reclamation projects, the monitoring plan must be adequate to meet the regulatory requirements that are in place to protect public health and safety. Good monitoring also provides the necessary data to evaluate damage claims and helps to build a track record of results, which can be helpful in public acceptance of future projects. In all cases monitoring plans must be adapted to project-specific considerations such as: duration of the project, scale of the project, hydrogeologic setting, intent of the project, surrounding resources, materials being used, and risk assessment.

It is recommended that the six-month pre-placement monitoring be maintained to establish a baseline information set. Beyond that the frequency should be adapted to the project. Projects that involve the use of large amounts of ash over relatively short periods, such as intensive backfilling or slurring of ash into large pits may need to be monitored as frequently as monthly, while lesser frequencies would probably suffice in most active mining situations where the addition of ash is incidental to mining activity. Tiered monitoring plans are also an option to consider; under such plans the monitoring frequency could be increased if data showed results that warranted closer evaluation for a period of time and then could be scaled back again if the results that caused the concern proved to be temporary or anomalous. On most projects monitoring should be continued for a minimum of 5 years. On smaller projects where the monitoring data set has been stable, monitoring may not have to continue for the entire five years. On the other hand, in cases where evaluation of the data shows a changing condition or other reason for concern the monitoring may need to be extended beyond five years.

The current DEP requirement for both downgradient and upgradient wells should be maintained. (It is recognized that in some upland settings, establishment of a functional upgradient well may not be achievable.) In some cases, especially on larger projects or demonstration projects, at least one well in the interior of the ash fill may be required (more may be required if the geometry warrants) in order to track changes in the ash chemistry with time. Where downgradient ground water discharge points, clearly hydrologically connected to the ash placement area, are available these can be used to supplement or replace monitoring well data. The number of monitoring points should be commensurate with the size and complexity of the site. Large long-duration sites may require numerous monitoring points, while smaller, shorter-duration sites, such as small refuse-reclamation sites lasting only a few weeks, may require few monitoring points.

In addition to acidity, alkalinity, field and laboratory pH, iron, aluminum and sulfate taken on filtered and unfiltered samples the complete suite of rock forming elements should also be included in the routine analyses. These should include Si and K as well as the RCRA trace elements. The rationale for this recommendation is the need to obtain an electrical balance in the water chemistry. This is required for speciation and reactions path computer models that will make geochemical predictions.

11.5 IMPACTS AND BENEFITS OF THE CLOSURE PROJECTS

11.5.1 The Big Gorilla Demonstration

The ultimate benefit for the Gorilla has not yet been realized because the Silverbook reclamation project is still ongoing and is likely to take 5 to 10 years to totally reclaim the basin. The dry-to-wet demonstration represented only a Phase I of the overall Gorilla project, with Phase II consisting of conventional dry ash placement to bring the pit back to approximate original contour.

The Gorilla Demonstration Project succeeded in removing approximately 135,000,000 gallons of acid mine drainage impacted water from the 465,000,000 gallons in the Silverbrook inventory, about 30%. This observation means that all of the acid loading, the sulfate loading,

and metal loadings that were associated with the Gorilla waters are no longer available to the complex aquifer system of the Silverbrook Basin. From a human health and safety standpoint, the hazard of the water-filled pit and associated highwall from the strip mining has been eliminated for the small community of people living immediately adjacent to the mine property.

In total, for both phases of the project, approximately 7 million tons of fill will have been consumed to restore just the Gorilla site. The Bureau of Abandoned Mineland Reclamation of the Commonwealth's Department of Environmental Protection has saved approximately \$4.5 million in deferred costs to the DEP through this cooperative partnership with NEPCO. Economically, the McAdoo community has also benefited, both directly through the continued employment of local people, and indirectly through the purchasing of products and services from the local community, the payment of local taxes by the utility and its employees. The intangible benefit to the community and the Commonwealth can be ascribed to the visual change that will occur at the completion of the project, transforming the site from a blighted wasteland to a restored meadow that will provide wildlife habitat.

11.5.2 The Knickerbocker Demonstration

The Knickerbocker coal ash slurry site demonstrated that an abandoned surface mine pit could be effectively reclaimed using an ash slurry from the SER cogeneration plant. The FBC ash from that plant was mixed with minewater pumped from the Maple Hill shaft and transported by the ash slurry pipeline to the Knickerbocker pit. The ash slurry technology has been successfully used at pulverized coal (PC) power plant sites for many years, but the mine site characteristics and the minewater/coal ash interactions in this demonstration project are different from the conventional ash slurry impoundment sites.

The Knickerbocker demonstration site proved at least two significant aspects of this type of slurry project: 1) the water to solids ratio in the slurry was not a big issue in the ash placement procedures on the site, as the excess water from the slurry rapidly infiltrated into the underlying minepool and was recycled back to the Maple Hill shaft pumping location, and 2) the dewatered ash slurry material in the Knickerbocker pit solidified into a deposit that had sufficient bearing capacity to support large rubber-tired equipment, almost immediately after placement. The success of this demonstration permit project is indicative of the results that could be achieved at the Shen Penn site.

11.5.3 The Shen Penn Demonstration

The Shen Penn demonstration project showed significant potential to abate and reclaim a significant mine hazard (i.e.\$20 to 28 million) at no cost to the taxpayers. The success of the Knickerbocker demonstration project in refining the ash slurry technology, as adapted to the surface mine environment , provides a measure of confidence that the technology proposed will work at the Shen Penn site. The coal ash/minewaeer interactions described in Chapter 9 and this chapter, show that the minepool chemistry, helps rather than impedes the process of getting a stable surface. Therefore, the unknowns of the Shen Penn project have been substantially reduced by the success of the other two demonstration projects, and the most significant remaining unknown is the interactions of the deep minepool chemistry and the coal ash slurry.

However, the greater sulfate concentrations of the minepool at 230 foot depth should improve ash solidification.

11.6 MINE SITE EVALUATION CRITERIA FOR COAL ASH PLACEMENT

The first step associated with any coal ash placement scenario should be the testing of the proposed coal ash to be utilized at the site. If the coal ash does not meet the regulatory guidelines or limits, the project cannot proceed. Should the coal ash meet the regulatory guidelines or limits, the next step is to review the proposed site information. The site information reviewed should include, but is not limited to the following: depth to groundwater, geologic/hydrologic site characterization, site volume calculations, proposed site reclamation plan, water uses in and around the proposed site (both surface and groundwater), location of any adjacent public or private buildings, any suitable or unsuitable site characteristics related to the proposed placement, and the potential to mitigate any safety or pollution issues once the site is reclaimed. Some of these items may limit the type of coal ash that should be proposed for utilization at the site. This item was discussed earlier in the book, and one must not forget that not all types of coal ash are suitable for all proposed placement scenarios.

If the coal ash and the proposed site appear to meet the regulatory requirements and/or guidelines, the project design phase should begin. The project design or operational plans should include a number of basic requirements or specifications related to fugitive dust control, coal ash placement criteria, final grading, erosion and sedimentation controls, and final cover and revegetation. The proposed site monitoring plan should also be included in these plans, and a thorough review of the adequacy of the plan should be conducted. Once the coal ash and site design or operational plan are reviewed and deemed adequate, the overall site and risk assessment of the proposed coal ash placement can be conducted. This assessment considers all the pertinent site factors and the characteristics or properties of the coal ash itself. The assessment is also based on known historical or scientific information, or data related to the coal ash and sites with similar geologic and hydrologic site characteristics, and other pertinent site information.

Some basic site evaluation factors that have been established by the approximately 20 years of coal ash placement and site monitoring, as well as scientific research and modeling are:

- A. Is the tested and approved ash being placed in or above groundwater?
- B. Is the tested and approved ash going to be conditioned to the optimum moisture content and compacted to 90% Modified Proctor Density if the use requires such compaction?
- C. Is the groundwater degraded or impacted by acid mine drainage?
- D. Is the final cover or capping designed to promote positive drainage and the development of vegetation?
- E. What type of coal ash is planned to be utilized: FBC or PC?
- F. What are the chemical and physical characteristics of the coal ash to be utilized?
- G. Are the site's operational and monitoring plans adequate and practical?
- H. What resources exist in or around the site that could possibly be impacted if something unplanned occurs?

- I. What is the nature and the scale of the abandoned mine features to be reclaimed, and what is the value of that reclamation in terms of dollars and public safety.

These are only a few of the questions that are entertained in a site risk assessment or selection, but they represent the core of what a decision to approve or deny an application is usually based on by a reviewer for the following reasons:

- A. If the proposed coal ash placement is above groundwater, and if the coal ash meets all regulatory beneficial use requirements, and the ash is going to be placed in accordance with generally accepted practices, the likelihood of any adverse impact from the ash placement is very low.
- B. If the coal ash is FBC ash or alkaline PC ash, the likelihood of degradation from any coal ash leachate should be minimal; as the metals within the ash are less likely to be leached by any water that may come in contact with the coal ash.

These conclusions or generalizations are based on data, testing, and scientific information that has been developed over the past 20 years from actual coal ash placement sites, coal ash demonstration projects, scientific testing and a host of other measures. However, each proposed coal ash placement site or project must be reviewed individually, and if necessary, additional testing or permit required actions should be implemented for any potential issues that may arise from the proposed coal ash placement. In fact, we have determined that there are specific coal ash types and mine site scenarios that should not be approved for various chemical, geological or other scientific reasons, even though the sites may represent significant abandoned mine land hazards. The risk of the potential solution creating a bigger problem should never be dismissed. For example, in the Bituminous Region, where coal ash has been used as an alkaline addition agent on surface mine sites to offset large deficiencies in overburden quality, the results have generally not been favorable and additional AMD was produced. The coal ash itself caused no damage, but it did not prevent AMD, just as limestone addition has often failed to prevent AMD on sites with clearly bad overburden. Based on these results, using alkaline ash to offset large deficiencies in site overburden is in most cases not an advisable practice.

11.7 CLOSING THOUGHTS

This book has presented descriptions of a variety of permit and project sites in Pennsylvania where coal ash has been beneficially used in mine reclamation and mine drainage remediation. Most of these sites have been clear success stories: abandoned mine lands and their associated safety and environmental hazards have been reclaimed at no cost to the taxpayer; water quality has been improved; a waste material has been recycled to a useful end rather than being landfilled. None of these sites represent environmental damage groundwater pollution cases attributable to the coal ash quality. However, a few of the mine sites cannot be counted as successes, because existing mine drainage worsened as a result of the re-mining of the sites. The production of AMD on these sites occurred because the ability of the alkaline ash to remediate and prevent the AMD was overestimated; on at least one site, poor mining and reclamation techniques were also a factor.

Are the sites where AMD worsened “coal ash damage cases?” Some investigators, particularly those associated with various advocacy groups, have argued “yes,” but the correct answer to this important question is clearly “no.” To be meaningful and useful the term “coal ash damage case” must be reserved for sites where the application of coal ash has caused some deleterious effect. The cause-effect relationship is critical to the integrity of the term. Where other site activities, such as additional mining has caused problems, it is important those problems be identified and understood so that the conditions that led to them are not repeated. However, incorrectly labeling such sites as “coal ash damage cases,” serves to obscure the causes and potential remedies for the production of AMD on those sites, and only muddies the discussion over when and how coal ash may be beneficially used at mine sites. The determination of whether a site represents a damage case should be based on science, not semantics.

Much attention has been given to the potential effects of coal ash placement on groundwater quality in this book and in the many criticisms of coal ash use on mine sites. That attention is well founded, because land reclamation benefits should not be achieved at the cost of water quality degradation. That principle has been a centerpiece of Pennsylvania’s coal ash beneficial use program from the beginning and will continue to be so.

In addition to the general lack of water quality impacts and the contrasting demonstrations of water quality improvements in the chapters of this book, the favorable physical characteristics of compacted coal ash have been described in an engineering context chapters of this book. The reams of monitoring data on these physical properties of coal ash often go unnoticed by the public in DEP file searches, so they were explained in an easy to read format in the book. The natural pozzolonic properties of some coal ash types were featured in several chapters of the book, and the use of ash grout cements in abating mine hazards was described.

Finally, this book contains some significant new information on the interactions between coal ash and minewater that has not been previously published. These findings were set forth in the chapters on the waste demonstration sites, where the coal ash was placed directly into the minewater, or mixed with the minewater in the ash slurry application (and are further described in the preceding sections of this chapter). The presence of significant sulfate concentrations in the minewater, which is characteristically the dominant anion in acid mine drainage and neutralized AMD, fortuitously promotes the formation of ettringite and other similar mineral phases. These minerals enhance the cementitious behavior of the coal ash and also sequester arsenic and other constituents of concern found in the ash and in coal refuse. These findings suggest that, while the traditional practice of maintaining a separation distance between the coal ash and the groundwater table was a prudent practice, there may be applications beyond these waste demonstration permit sites where some types of coal ash should be permitted to be in contact with minewaters, in order to reclaim abandoned pits, abate mine hazards or remediate mine drainage problems. This is not to suggest the wholesale application of the techniques employed at the waste demonstration sites, but rather to provide alternatives for consideration by those engaged in defining the range of acceptable practices in the beneficial use of coal ash.