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미국 인디아나주 남서부의 Friar Tuck 폐탄광에 대한 환경평가 및 최종 복구설계

Environmental Evaluation and Final Reclamation Design for the Friar Tuck Abandonded Coal Mine Site, Southwestern Indiana, U.S.A.

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요약/Abstract

Friar Tuck, an Abandoned Mine Lands (AML) site, is located on the Greene-Sullivan county line in southwest Indiana. Prior to the on-going reclamation, Friar Tuck was one of the Indiana's largest and most environmentally adverse abandoned mine lands. The direct vegetation method was used to reclaim tailing ponds. Grading, capping, and revegetaion using agricultural limestone, fertilizer, mulch and seed were applied to the gob piles to abate acid mine drainage (AMD) and off-side sedimentaion. Erosion control structures such as terrace, diversion ditch, and gabion structures were also constructed to minimize erosion at slopes. A new method for treatment of AMD using apatite was tested in the laboratory and field. Apatite effectively removed iron, aluminum and sulfate while maintaining an almost constant pH. Apparently, this method can be applied to control AMD from mining refuse materials, even those containing high concentrations of iron and aluminum ions.

Friar Tuck 폐광산은 미국 인디아나주 남서부 Greene-Sullivan 군 경계에 위치하여 있다. 현재 진행중인 복구작업이 시행되기 전, Friar Tuck 광산은 인디아나주 내에서 가장 규모가 크고 환경오염상태가 심각한 폐탄광중의 하나였다. 직접 식물재배법이 tailing pond에 적용되었다. 버럭더미는 산성수의 오염을 막고 토양이 외부로 흘러 나가는 것을 방지하기 위해 표면을 고른 후 토양오염이 비교적 덜 된 흙으로 덮고 농업용 석회석, 화학비료 및 퇴비를 뿌려 풀 종자를 심었다. 사면의 침식방지를 최소화 하기 위하여 terrace, diversion ditich 및 gabion structure가 설치되었다. 산성수 처리를 위하여 실내 및 광산현장에서 인회석을 이용한 새로운 방법이 실험되었다. 인회석은 산성수 본래의 pH를 유지하면서 철 및 알루미늄을 효과적으로 제거하였다. 광산 폐기물에서 파생되는 산성수 내의 철 및 알루미늄의 농도가 높은 경우에도 이 방법을 사용할 수 있을 것으로 사료된다.

INTRODUCTION

The Friar Tuck Abandoned Mine Lands site is located on the Greene-Sullivan county line one mile north of Dugger in southwestern Indiana. The site was the location for intermittent strip mining, underground mining and coal processing, from 1929 to 1965.

The Friar Tuck Mine reclamation project is a multi-disciplinary endeavor that involved studies by several investigators. The project included working in geology, engineering geology, hydrology, hydrogeology, and soil sciences. The primary objective of this research was to characterize the general site conditions before and during the project reclamation. Refuse from the old coal-fired power plant and the coal processing plants was scattered indiscriminately across an area over two square miles at the Friar Tuck site. Six major gob piles, hundreds acres of spoil ridges, and slurry ponds of various dimensions were formed. Gob is coarse-sized refuse composed of shale, pyrite, coal, and associated clays and rock fragments which were separated from usable coal. Rubble removed from underground mines was dumped into piles of gob. Spoil is derived from surface mining operation and consists of the soil and rock overburden that is stripped off to expose the coal seam. Spoil of the Friar Tuck site is composed of sandstone, limestone, and coal fragments along with clay. Tailings, which are generated during the coal process, consist of coal fines, shale fragment and pyrite which were pumped as a sediment-water mixture into settling ponds. At the Friar Tuck site, drainage valleys and depressions were ideal sites for slurry pond construction.

A primary environmental concern at the Friar Tuck site is Acid Mine Drainage (AMD) resulting from oxidation of framboidal pyrite in the refuse piles. Pyrite oxidation occurs in the presence of water and oxygen, producing ferrous iron and sulfuric acid. The AMD problems are not unique to the United States. They are also known in Australia, Japan, Korea, Russia, and South Africa (Powell, 1988). Mud Creek and its tributary, which flow directly through the Friar Tuck site, have been polluted by acidic surface water or by acidic groundwater seepage from the site. Five kilo metetrs downstream from the Friar Tuck site, Mud Creek flows into Big Branch resulting in depressed water quality in Big Branch.

Strip mining activities also accelerated post-mining erosion and sedimentation. With removal of ground cover, water moved across the denude areas, picking up soil particles and leaving erosional gullies. All the gob piles, spoil ridges, and haulage roads were subjected to a high rate of erosion. Stream beds become heavily sedimented with the fine refuse from the site.

GEOLOGIC SETTING

The Friar Tuck site is located on the eastern flank of the Illinoian Basin. The site lies within the Wabash Lowland, which is the largest of the southern Indiana physiographic units.

The Wabash Lowland is a low lying area with wide, flat plains forming the most common feature. Most of the bedrock is composed of soft shales and siltstones of Pennsylvanian age, covered by glacial deposits of Illinoian age. Most major stream valleys were once narrow bedrock valleys, but these have been filled with glacial and lake deposits of the Pleistocene Epoch. The upland areas are broad, rolling plaines with slight slopes. The Wabash Lowland has an average elevation of 150m above sea level (Schneider, 1966). Lying above Illinoian till at the site is a loess cover as much as 3.6m thick (Shurig, 1967). Texturally, the soils at the Friar Tuck are silt loams and silty loams (Dombrouski, 1985).

Bedrock underlying the study area consists of the Pennsylvanian Petersburg, Dugger, and Shelburn formations. These rocks are nearly about 5.6m per km toward the flat-lying, dipping to the southwest at Illinoian Basin (Gray, 1979). At the site, the Danville (Ⅶ) and Hymera (Ⅵ) coals were surface-mined, whereas the Survant (Ⅳ), Springfield (V) and Hymera coals were underground-mined (See Figure 1).

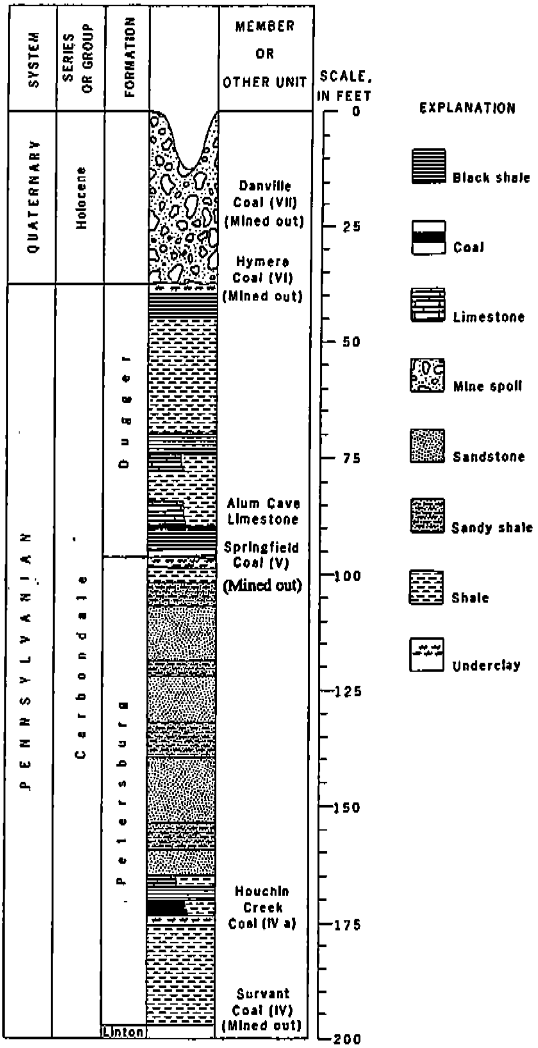

Figure 1. Geologic column for the site showing generalized stratigraphy.

SUBSURFACE INVESTIGATION AND MONITORING PROGRAMS

Since 1984, the Friar Tuck Mine site has been the focus of surface and subsurface investigations by engineering geology students at Purdue University. An initial investigation of the site began in 1984 when Richard Dombrouski (1985) conducted surface geology mapping and drilled ten soil borings using truck-mounted, single flight auger with a maximum depth capacity of 7.5m.

The main drilling program began at the site in July, 1987. A local company was subcontracted to drill 26 borings, providing a total length of 305m. A truck mounted rig with eight-inch hollow stem augers was used to drill the unconsolidated materials. At 1.5m intervals, split-spoon sampling was performed as part of the Standard Penetration Test (SPT). Atterberg limits, specific gravity, moisture content, and size gradation were ultimately determined from the disturbed samples (Petersen, 1989). Thin wall tube (Shelby tube) sampling also was used to obtain relatively undisturbed samples. A Shelby tube was forced into soil, using the static force from the weight of the drilling rig. At seven locations, shallow borings were made adjacent to deeper ones and monitoring wells were placed in the two aquifers to provide a well cluster. Two borings were cored through rock (with a coal exploration rig) to establish wells in the underground workings of Coal V and Ⅵ.

The second phase of boring, drilled by the Indiana Geological Survey, began in October, 1987. Several borings were made in tailigs using vibracoring to take shallow samples. Senventy eight meters of drilling were accomplished in this phase.

In May, 1988, the local drilling company was mobilized again to perform the third phase of drilling. By the end of phase Ⅲ, total 35 monitoring wells had been installed. This high well density allows accurate determination of the seasonal water table fluctuation across the site. Detailed chemical analysis also was facilitated by the large number of wells.

Wells were installed immediately upon boring completion, and were constructed as follows (See Figure 2) : Two inch PVC pipe was installed as casing, generally having five- or ten-feet of screened casing at the bottom. Except for wells into the underground mines, Ottawa sand was used as a pack around the well screen. This sand pack was extended to a level about five feet above the top of the screen. The remainder of the annulus (between casing and boring wall) was backfilled with cuttings, and sealed with bentonite. After allowing bentonite to saturate, a concrete pad (Sakrets) was built at the surface around the casing. The casing was cut off about two feet above ground surface, and equipped with a screw-on cap. A metal well protector and locking cap were placed over the PVC pipe and anchored into the Sakrete before it hardened.

Suction lysimeters were used to obtain water for chemical analysis from the unsaturated zone. Lysimeters are porous ceramic tips, connected at depth by polyethylene tubing to valves at the surface. When a vacuum is applied. the tip draws water from the surrounding vadose zone. Lysimeters were placed at two or three depths at a location. Also placed were neutron probe access tubes cased in aluminum, and used to measure the soil moisture profile. More than 15 lysimeters were located in the different materials. Eight water-level monitoring stake were placed in the lakes and ponds. All also serve as collection points for water chemistry analysis. Some hand-auger samples were obtained at a depth of 15cm to 90cm, and tested for grain-size, plasticity characteristics and/or compaction testing.

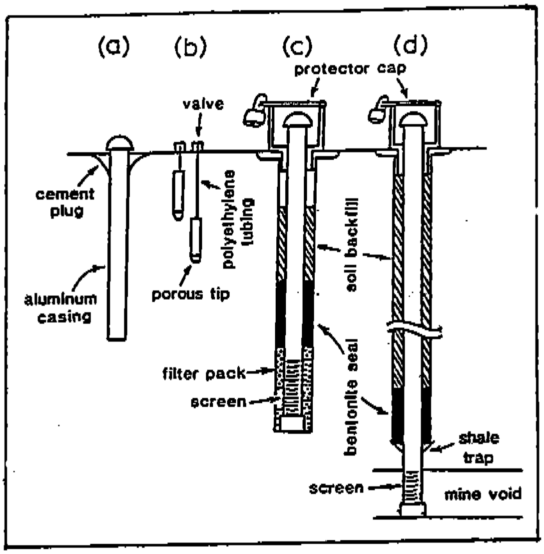

Figure 2. Cross-section of subsurface monitoring devices : (a) neutron probe, (b) suction lysimeter, (c) well into unconsolidated deposits and (d) well into mine.

LABORATORY TESTING

Soil samples were analyzed for engineering soil properties as part of the site investigation prior to reclamation design. Characterization of the surface deposits provides important information to evaluate reclamation techniques and identify sources of borrow material.

Engineering soil properties determined were : natural moisture content, grain size analysis, Atterberg limits, density, hydraulic conductivity. Unconfined compression test, compaction tests, CBR tests, and in-situ tests were also performed to analyze other soil properties.

Moisture content (ω_n) was determined for 185 samples in accordance with ASTM D2216. The range in ω_n provides an indication of the extent of moisture variation in subsurface materials. Grain size analyses were performed on 126 samples in accordance with ASTM D422. Sieve analyses were used to determine the coarse-grained fraction of each sample, whereas hydrometer tests were used on the fine-grained fraction. Percentages of clay, silt, and sand/gravel in each sample were determined from each distribution curve, and were used to classify the soil by the procedure described in ASTM D2847.

Shape parameters, including the coefficient of uniformity, Cu, and the coefficient of curvature, Cc, were determined from the distribution curves. In general, a soil with Cu greater than 6 is well-graded, whereas a soil with less than 6 is poorly graded. A soil sample with well-graded distribution generally has a Cc value between 1 and 3. A soil sample with poorly-graded distribution generally has a Cc value either less than 1 or greater than 3.

Atterberg limits are the moisture contents which mark the boundaries between zones of mechanical behavior of a soil. The liquid limit marks the transition from plastic to liquid behavior, and the plastic limit defines the lower limit of the plastic range. The Atterberg limits of each sample were determined from air-dried soil passing the ♯40 sieve according to ASTM D421. Liquid and plastic limits tests were accomplished in accordance with ASTM D4318. When liquid and plastic limits for a given sample have been determined, the other two important parameters can be calculated. These are plasticity index, PI, and liquidity index, LI. The PI measures the range in moisture content over which the soil behaves plastically. The LI indicates how the natural moisture content compares with the liquid or plastic limit. If moisture content is within the plastic range, the LI ranges between 0 and 1. A negative value indicates the soil is drier than its plastic limit and is relatively stiff and brittle. Likewise, a value greater than unity indicates the soil is in a liquified state and is quite compressive.

Bulk density, ρ, and dry bulk density, ρ_d, were determined from selected Shelby tube samples, using the drive-cylinder method described in ASTM D2937. Hydraulic conductivity (or permeability) of some soils taken from Shelby tubes was determined on 16 samples, using the falling head permeameter method. Disc-shaped specimens about one inch long and 1.75 inches in diameter were placed in the permeameter chamber and capped with screen and porous stone. After mounting the chamber, the vertical tygon tube was filled with water to apply and elevation had of about 88 inches. At a completion of the test, the final head and elapsed time were recorded (Petersen, 1989).

To determine unconfined compression strength, five Shelby tube samples of clayey silt were tested from the embankment surrounding the 42 ha tailing pond. The purpose of this test was to provide strength data for evaluating embankment stability. The test was performed according to ASTM D2166. Hogentogler, unconfined compression testing machine, was used to fail the specimens.

Compaction tests were performed to characterize the potential borrow material available at the Friar Tuck site. The purpose of compaction testing is to determine the maximum dry density of a soil sample through mechanical compaction, and the moisture content at which this maximum dry density can be achieved. A total of nine samples was tested in accordance with ASTM D698 (Kuo, 1990). Compaction and permeability are important parameters regarding the borrow material selection. Permeability is dependent on the soils state of compaction. Typically, the permeability is about two orders of magnitude (100 times) less at the optimum content than it is for soil a few percentage points dry of optimum.

The in-situ densities were determined according to ASTM D1556. This procedure, also as known as the sand cone method, involves excavating a small hole (approximately 2,700 to 5,400cm^3) in the material. The mass of dry and uniform sand required to fill the hole is measured and converted to volume through a calibration procedure. By using the dry weight of material removed, a dry density can be calculated.

The in-situ tests to determine the undrained shear strength, were performed with a penetrometer and torvane in four test pits which were dug into the side of the embankment. The penetrometer is held perpendicular to the surface of the soil and pushed until it penetrates to the red line on the shaft (6.35mm), giving a value of compressive strength in kg/cm^2. The torvane, on the other hand, fails the soil in shear, also giving values in tsf. A circular, toothed vane is attached to the rotating handle and then pushed into a flat soil surface until the teeth are completely embedded in the soil. The handle twisted until the soil fails, recording the maximum rotating on the dial.

The California Bearing Ratio (CBR) test was developed by the California Division of Highways in 1929 as a means to empirically relate the observed performance of a subgrade material to the results of a laboratory test. The CBR test is a penetration test in which the penetration resistance of a given material is related to that of a standard value for crushed stone. The standard unit load for crushed rock at 0.1 inch penetration is 100 psi and 0.2 inch penetration is 1500 psi. The CBR, then, is measure of the quality of a given material in terms of an excellent base course material which, by definition, has a CBR of 100 percent (O'Hara, 1992).

ENGINEERING PROPERTIES OF SOIL

Unconsolidated materials at the site were evaluated to determine their potential as borrow sources for reclamation construction. These include spoil, loess, alluvium, and till (See Figure 3). The properties of the two mine wastes, gob and tailings, were also compiled.

Spoil is derived from the stripped overburden of coal-measure rocks of variable composition formed by cyclic deposition. The spoil ridges left by area mining cover large area at the Friar Tuck site. These spoil ridges are composed of combination of loess, till, limestone, shale, coal, sandstone, and pyrite. Most of the spoil at the site has been present for more than forty years (up to sixty years), and for this reason, the rock fragments have decomposed to a large extent into sand, silt and clay-sized particle. Preliminary field investigations and laboratory tests show that spoil is the recommended for borrow material. This spoil is classified as a gravelly clay. The gravel and binding clay of the spoil are resistant to scouring and water erosion. Table 1 is a summary of the engineering properties of the spoil.

Loess distributed at the site is weathered and contains much more clay than is generally expected for windblown silt. Unweathered loess displays poor cohesion and has a high porosity and permeability (vertical>horizontal), whereas weathered loess is slightly plastic and less permeable. At natural moisture contents, loess has a relatively high strength, as well as low compressibility, due to partial cementation. However, when wetted, the cementing agent softens and the loose structure can collapse, particularly when the soil is stressed by foundation loads. Loess can experience a high capillary rise which results in a heaving of foundations and pavements during freezing. Dry loess naturally stands on a vertical slope, therefore, cut slopes are commonly more stable when made vertical. Cut slopes other than vertical should be stabilized by vegetation, with a drainage ditch placed along the top of the slope to prevent wetting (Johnson, 1989).

Table 1. Spoil properties.

Average moisture content, ω_n : 14.03

Average plasticity index, PI : 13.6

Average liquidity index, LI : -0.497

Average maximum dry density, ρd_{max} : 109.1 pcf

Average optimum moisture content, ω_{opt} : 16.6

Permeability when compacted : highly impervious (10^{-6} cm/sec)

Erodibility : high (fine constituent when uncompacted)

Shear strength : 0.5-1.0 tsf (compacted)

Shrink-swell potential : low to moderate

Resistance to cracking : low to moderate

Frost action : medium to high

Homogeneity : very consistent on large scale

Quantity : almost unlimited at abandoned strip mine

Acessibility : trees pose problem, no resultant depressions

ASTM classification : GC/SC (fines are CL and CL-ML)

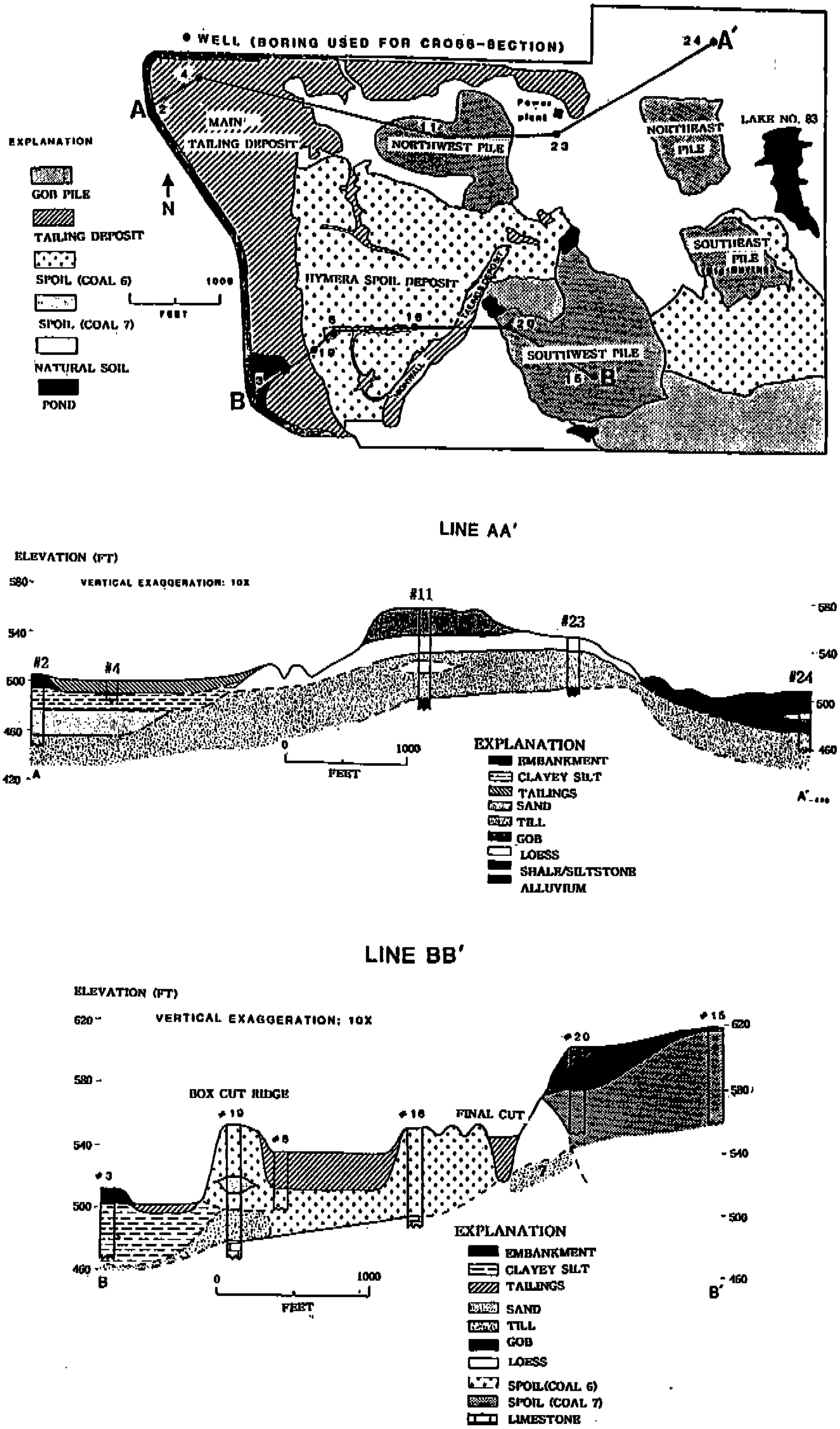

Figure 3. Surface soil map displaying orientation of cross section AA' and BB'.

The extensive soil layer of loess at the site was not considered as a proper source for borrow material because of the high erodibility of fine silt material. Table 2 shows a summary of the engineering properties of loess.

Table 2. Loess properties.

Average moisture content, ω_n : 15.68

Average plasticity index, PI : 17.256

Average liquidity index, LI : 0.033

Average maximum dry density, ρd_{max} : 109.2 pcf

Average optimum moisture content, ω_{opt} : 16.9

Permeability when compacted : highly impervious (10^{-6} cm/sec)

Erodibility : extremly high

Shear strength : 0.8-1.0 tsf (compacted)

Shrink-swell potential : low to moderate (susceptible to increase with reorientation of montmorillonite)

Resistance to cracking : low to moderate (better wet of optimum)

Frost action : medium to high

Homogeneity : extremely consistent in properties, appearance

Quantity : Large quantities available on the site

Acessibility : in most locations, vegetation would require removal and depressions would result from excavation

ASTM classification : CL

Unweathered till is gray to greenish calcareous mixture of reworked soil particles and rock fragments densely compacted by glacial action. Lenses of clay, silt, sand, and gravel are common with peat and marl occurring less frequently. Large cobbles and boulders are infrequent but present. unweathered till (CL to ML) is moderately plastic (PI 10-20) with liquid limits varying between 25 and 40. Weathered till (CL to CH) is more plastic (PI 20-40) with liquid limits ranging from 35 to 55. These materials are densely compacted, though uncemented, due to consolidation from their glacial deposition. This type of lodgement deposition results in a high density and low void ratio. Till tends to be very impervious in the vertical direction and occasionally pervious via sand and gravel lenses (Johnson, 1989). However; the till distributed at the site is a homogeneous and continuous deposit, occurring in large quantities underlying the entire area except where strip-mined (Petersen, 1989). The till has accessibility problems as it is mantled by as much as 12 feet of loess, and locally is covered by gob. The till is a very stiff in a dry and overconsolidated state. Water would have to be added during compaction to bring this soil to optimum moisture. These conditions could be overcome during construction but because of the poor accessibility it is not recommended as borrow material. The Mudcreek alluvial deposits along the northern boundary of the site are situated on the Mud Creek flood plain. These deposits are designated as ML soils, silt of low plasticity. The groundwater table is seasonably high in this area and flooding is common. The hydraulic properties of this material are generally poor. Permeability varies considerably from one location to another. This predominantly fine material is also subject to high capillarity, high frost-heave, and high liquefaction susceptibility (Johnson, 1989). In conclusion, alluvial materials along Mud Creek are heterogeneous, silty soils with poor engineering characteristics and poor accessibility. therefore they are not recommended as borrow materials.

Tailings are fine-grained coal waste, consisting predominantly of coal, pyrite, and shale. At some tipple sites, the coal was washed after it had been separated from the coarse refuse (gob). The derived slurry of water and fine-grained refuse (finer than 1/8 inch) flowed from the tipple into a low-lying area for settling, known as a tailing pond (Allen, 1978). Average moisture content of tailing is 62.62% and average natural density is 64.3 pcf. Permeability ranges from 10^{-2} to 10^{-4}cm/sec and decreases with depth. Stability analysis of the embankment surrounding the 90-acre tailings pond was performed using the slope stability computer program STABL. These results are shown in Table 3. Based on these results, it was concluded that the creation of a wetland would not be safe for logical reclamation alternative. An additional discouraging factor this alternative is the abundant vegetation on the embankment. Root holes from large trees are conduits for large-scale piping leading to ultimate breaching of the embankment.

Table 3. Factors of safety against embankment failure for various water levels in the western tailing pond.

Water level (elevation in feet)	Factors of safety
Northern section	
502	1.093
504	0.835
506	0.745
Southern section	
506.6	0.965
507.5	0.926
508.7	0.874

Gob is coarse-sized refuse composed of shale, coal, pyrite, and associated clays and rock fragments which were separated from usable coal. Rubble removed from underground mines was dumped into piles as gob. The rubble contains significant amount of coal which could not be economically separated from the waste. Other gob piles accumulated at tipple sites where coal and rubble were separated in mounds. At the older, insufficient tipples, the gob contains 20 to 40 percent coal (Allen, 1978). The average moisture content of gob on the site is 12.37% and the average natural dry density is 69.6 pcf. Permeability is very high in upper horizons, but may be as low as 10^{-6}cm/sec in lower horizons where clay has accumulated. Gob was used in the embankment for the old rail road and the main haul road surface as well as for slopes. The gob material ranges in thickness from 1 to 8 feet.

CHEMISTRY OF SOIL

Gob and tailings samples from different locations at different depths were collected for chemical analysis. All samples were obtained using a soil auger. Most samples were collected from depths of 0 to 6 inches but some samples were obtained from depths of 30 to 36 inches. Samples were analyzed by A & L Agricultural laboratory, Memphis, Tennessee. These sample were analyzed for pyritic sulfur, sulfate sulfur, pH, and following metals : Fe, Ca, Mg, K, Na, Zn, Cu, Mn, B, and Al. Values of pyritic sulfur were used to determine the amount of agricultural limestone necessary for direct vegetation. According to the results, the gob is heterogeneous in character and most of the chemical species evaluated show an irregular distribution. The average pyritic sulfur values for surface gob range from 0.04 percent to 0.88 percent whereas the average pyritic sulfur values for the subsurface samples taken at the depth of 30 to 36 inches, range from 0.22 percent to 3.47 percent. This means that the acidity potential of the gob has gradually decreased because of weathering and oxidation over the past several decades. Therefore bacterial acid production should be minimal in the weathered zone. These results coincide with research results by Belly and Brock (1974). They took gob samples (0 to 4cm) from the Friar Tuck site and incubated the samples with gaseous $^{14}CO_2$ at 30° C. They observed low microbial $^{14}CO_2$ uptake in Friar Tuck gob piles and suggest that bacterial acid production is minimal in these piles. The Northwest Gob Pile has the highest pyritic sulfur content in-surface gob, whereas the Northeast Gob Pile has the lowest pyritic sulfur content in surface gob. This high pyritic sulfur content at the surface may be attributed to grading of the Northwest Gob Pile in the early 1970s. Grading removed the weathered surface layer and exposed fresher, less weathered pyrite.

The average pyritic sulfur values of surface tailings ranged from 2.7 percent to 3.0 percent whereas the average pyritic sulfur values of subsurface samples from a depth of 30 to 36 inches ranged 1.79 to 2.78 percent. In case of the Main Tailings Deposits, several decades of aging and weathering have extensively oxidized the unsaturated surface zone. Although oxidation of pyritic sulfur generated harsh immediate acidity values (pH=3), potential acidity of surface zones has been greatly reduced (<10 tons $CaCO_3$ eq/1,000 tons) (Nawrot, 1988).

HYDROLOGY AND WATER CHEMISTRY

Water pollution problems created by coal refuse are very serious. Acid Mine Drainage (AMD) usually contains elevated concentrations of metals such as iron, aluminum and manganese, and are quite corrosive. When AMD enters a stream, aquatic environments are greatly altered and desirable organisms are usually reduced or eliminated. When AMD infiltrated into the groundwater, aquifers can become polluted and drinking water obtained from these sources can cause health problems. Among a variety of water quality problems caused by AMD, water quality degradation is one of the most common types of pollution.

The most direct field method for estimating obtain hydraulic conductivity is the single well (or piezometer) water-level monitoring. Data were analyzed using the time lag method of Hvorslev. Kuo (1991) performed slug test in some monitoring wells at the Friar Tuck site. The slug test conducted, the falling head test, begin with lowering of a 5-foot solid pipe into the 2-inch diameter monitoring well to displace the water column from the initial steady water level. The displaced water rises 3.82 feet in the annular space between the pipe and the casing of the monitoring well. A transducer connected to a data logger was installed at the lower end of the pipe to measure the pressure change due to the falling of water level in the monitoring well. The data logger was connected to a portable computer to record the water level changes. The transducer is measuring water-level changes in increments of 0.01 feet, from 0 to 50 feet. Table 4 shows the hydraulic conductivity for each well analyzed from slug test data performed by Kuo (1991).

Table 4. Hydraulic conductivity analyzed from slug test.

Well	Screened material	Confined or unconfined	Hydraulic conductivity (cm/sec)
1	alluvium	C	3×10^{-4}
2	alluvium	C	7×10^{-4}
3A	alluvium	C	3×10^{-4}
4	tailings	U	1×10^{-5}
8A	spoil	U	3×10^{-4}
10A	tailings	U	1×10^{-4}
11A	gob	U	1×10^{-4}
13A	till	C	1×10^{-4}
13B	till	C	4×10^{-5}
14	gob	C	1×10^{-5}
16A	spoil	C	9×10^{-5}
17B	coal	C	1×10^{-4}
20A	spoil	C	1×10^{-4}
23	till	C	1×10^{-6}
24	till	C	9×10^{-6}

The shallow aquifer for Friar Tuck is composed of castover spoil, gob, tailings, and unmined, unconsolidated material. The unconsolidated overburden, prior to strip mining, was composed of loess, Illinoian glacial till, and alluvial deposits above the Pennsylvanian bedrock. The aquifer is unconfined, and is underlain by shale and by underclays lying below the coal seams. These shales and underclays prevent interconnection between the shallow aquifer and deeper groundwater system in bedrock. However, interconnection between the shallow aquifer and the deeper bedrock aquifers may occur at several places where old mine shafts or springs are located.

Water samples were collected during a period of five years (from September, 1987 through December, 1992). Groundwater samples were obtained from monitoring wells that were first bailed out and allowed to recharge before obtaining a representative sample. The exception to this procedure was the monitoring wells installed in flooded mine voids, where complete purging by bailing was impractical. For these sites, three well volumes were bailed out prior to collecting a sample. Water for the unsaturated zone was collected using vacuum lysimeters. A vacuum was applied to the lysimeters 24 to 48 hours before sampling.

The major inorganic constituents in most natural waters occur mainly in ionic form, and are commonly referred to as major ions. These are sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and sulfate (SO_4^{2-}). The major cations in groundwater samples are calcium and magnesium. These cations probably originated from dissolution of carbonate minerals in limestone or dolomite. The dominant cations in natural, fresh water in order of their abundance are calcium > magnesium > sodium > potassium. The dominant cations in most groundwater samples at the Friar Tuck Mine showed the same pattern.

Table 5 shows a summary of selected chemical analyses of water samples for tailings, spoil and gob. The spoil deposits are a relatively minor source of contamination. It is apparent that the spoil contains carbonate minerals. These carbonates (calcite and dolomite) are moderately soluble in acidic waters. In this process, hydrogen ions combine with the carbonate (CO_3^{2-}), thereby raising the alkalinity of the water. The bicarbonate, calcium and magnesium ions resulting from dissolution of calcite and dolomite raise the total dissolved solids in the water.

Acidity is greatest in the shallow unsaturated zone of the Northwest Gob Pile and decreases with depth, whereas shallow waters are least acidic in the Southeast Gob Pile and acidity increases with depth. However, the acidity of saturated-zone waters in both piles are similar. These differences are consequence of the different stories for the piles. The Southeast Gob Pile has remained undisturbed since its construction in the 1940s, promoting development of a deep zone of weathering (pyrite depleted in upper 3 feet). In contrast, the failed reclamation attempt that was made on the Northwest Gob Pile in the early 1970s resulted in the exposure of fresh pyrite to the surface when the weathered layer was removed.

EVALUATION OF RECLAMATION DESIGN

Gob piles are very susceptible to erosion because of steep slopes, loosely compacted material and lack of vegetative growth. The majority of gob piles are too acidic (unless oxidized) to support plant life. As a result, most piles are barren and exposed to the elements. Without vegetative cover, the pile surface is exposed to direct rain drop impact. Runoff forms gullies and carries sediment particles into streams.

Sedimentation of stream beds can have a disastrous effect on a stream. Sediment fills the creek bed destroying fish habitat and creating flooding conditions. Silt attaches to fish eggs preventing sufficient exchange of oxygen and carbon dioxide between the eggs and the overlying water. Suspended solids cloud water, interfering with photosynthesis by reducing light penetration and they increase treatment costs for industrial and municipal water supply.

Several alternatives for erosion control on the refuse piles were evaluated based on condition, characteristics, topography, and quantity. They are as follows :

(1) Grading, soil cover, and revegetation.
(2) Burial of gob between the spoil ridges, soil cover and revegetation.
(3) Direct vegetation on acid refuse without soil cover.

Table 5. Summary of selected chemical analysis of water samples.

UNSATURATED ZONE				
	Main Tailing	Hymera Spoil	Northwast Gob	Southwest Gob
n	48	18	183	249
pH				
Average	3.2	6.2	2.2	2.0
Range	1.6-6.7	5.5-7.1	0.7-4.2	1.3-3.2
ACIDITY (mg/l, CaCO3 equivalent)				
Average	4,100	41	41,000	7,300
Range	0-58,000	0-350	9,000-16,000	1,400-13,000
SULFATE (mg/l)				
Average	5,100	3,600	43,000	7,900
Range	200-58,000	180-7,100	8900-160,000	2,600-25,000
TOTAL IRON (mg/l)				
Average	1,100	5	15,000	840
Range	1-18,000	0-29	2,000-55,000	49-7,100
TOTAL DISSOLVED SOLIDS (mg/l)				
Average	7,400	5,400	60,000	9,900
Range	310-79,000	610-9,800	12,000-220,000	3,600-33,000

SATURATED ZONE				
	Main tailing	Hymera Spoil	Northwast Gob	Southwest Gob
n	62	15	15	32
pH				
Average	5.0	5.9	4.0	1.8
Range	2.7-6.7	4.6-6.7	1.8-5.9	1.4-2.5
ACIDITY (mg/l, CaCO3 equivalent)				
Average	1,000	730	24,000	22,000
Range	0-4,400	60-1,800	1,200-110,000	13,000-35,000
SULFATE (mg/l)				
Average	1,800	3,400	23,000	23,000
Range	430-4,900	180-7,100	5,600-40,000	13,000-31,000
TOTAL IRON (mg/l)				
Average	330	890	9,400	3,800
Range	5-1,800	81-10,000	500-19,000	2,200-7,000
TOTAL DISSOLVED SOLIDS (mg/l)				
Average	2,800	5,000	35,000	9,900
Range	640-7,500	4,200-6,700	7,800-60,000	18,000-43,000

SHALLOW SAMPLES (uppermost 6 inches)

	Main Tailings	*North Tailings*	*Northwest Gob*	*Southwest Gob*	*Northeast Gob*	*Southeast Gob*
n	35	28	27	19	12	45
SOIL pH						
average	3.0	2.7	1.8	2.2	2.4	2.6
range	2.3 - 5.8	2.1 - 3.5	1.1 - 2.2	1.5 - 2.7	2.1 - 2.7	1.7 - 3.8
PYRITIC SULFUR (percent)						
average	0.31	0.1	0.88	0.24	0.04	0.14
range	0.01 - 2.01	0 - 0.8	0 - 4.17	0 - 1.93	0 - 0.14	0 - 0.84
SULFATE SULFUR (ppm)						
average	1,300	470	6,200	6,200	7,900	8,800
range	170 - 3,700	100 - 1,100	1,200 - 12,000	1,100 - 14,000	2,400 - 13,000	1,000 - 14,000
IRON (ppm)						
average	200	270	2,600	940	790	690
range	96 - 360	33 - 790	930 - 6,800	230 - 3,600	370 - 1,600	150 - 3,500
SOLUBLE SALTS (mmhos cm^{-1})						
average	3.5	3.7	14.3	8.2	5.6	6.9
range	0.2 - 8.9	0.2 - 10.1	7.4 - 24.5	3.9 - 21.4	4.2 - 7.4	3.0 - 25.8

DEEP SAMPLES (30 to 36 inches)

	Main Tailings	*North Tailings*	*Northwest Gob*	*Southwest Gob*	*Northeast Gob*	*Southeast Gob*
n	7	5	3	3	1	3
PYRITIC SULFUR (percent)						
average	1.79	2.18	3.47	1.23	0.22	0.31
range	0.12 - 3.66	1.3 - 4.5	2.17 - 4.42	0.47 - 2.19		0.01 - 0.53
SULFATE SULFUR (ppm)						
average	1,200	490	5,400	5,600	530	7,000
range	200 - 2,000	220 - 740	4,100 - 6,100	4,900 - 6,800		5,700 - 9,400
IRON (ppm)						
average	180	260	2,200	1,000	920	1,300
range	46 - 250	220 - 500	1,900 - 2,600	460 - 1,600		490 - 2,900
SOLUBLE SALTS (mmhos cm$_{,1}$)						
average	2.9	3.3	7.9	10.1	5.7	8.7
range	0.5 - 4.6	1.1 - 7.3	7.1 - 8.3	4.7 - 19.6		4.9 - 15.8

Alternative (1) is the traditional method of coal refuse piles requiring 60cm thick soil cover. The surface of refuse pile can be graded and shaped to reduce and detain runoff. This includes topsoiling, mulching, liming and revegetation.

Alternative (2) is feasible for the small gob piles which have been able Table 5. Summary of selected chemical analysis of water samples disposed of on the highwall or along the highwall. These piles should be moved to an inland basin between spoil ridges, covered with borrow material, and revegetated.

Alternative (3) may not be appropriate for all sites owing to topographic or hydrologic constraints. However, when feasible, building and developing refuse into a cover soil through alkaline and organic matter enhancement (limestone amendment and cover crop/green manuring) represents a practical approach to obtaining long-term chemical and vegetative stability of the reclaimed area (Nawrot, 1988). Direct vegetation using agricultural limestone, mulch, fertilizer, and seed was applied to tailings in order to neutralize the acidity generated from the surface layer of the tailings and to establish vegetation.

In case of two major gob piles, The Northwest Gob Pile and Southwest Gob Pile, the gullies were filled with borrow spoil, and agricultural limestone was incorporated into the gobs. Spoil was borrowed from near by ridges and terraces were constructed on the gobs with minimal grading, and diversion ditches were emplaced. In general, the whole diversion system consisted of parallel terraces with trapezoidal ditches and several downdrains, which receive the discharge from the different terraces. An erosion control blanket was used in this diversion system to prevent excess erosion. Downdrains were protected by rock riprap. The rock riprap serves as the energy dissipator for the drains. An 18-inch layer of riprap of 6-inch size rock was designed for the lining of the downdrains to reduce the erosive force of the running water. The recommended upper limit of the slope gradient for downdrains is approximately 15 percent. A design storm 25-years frequency was used in the terrace system design. The rational method was used to determine peak flow rates.of runoff from the small area drained by each terrace. The maximum allowable gradient of the terrace was 0.5 percent. A gabion structure was designed and located between the downdrains and drainage channel to protect erosion.

EVALUATION OF ACID MINE DRAINAGE CONTROL

Today, the reclaimed areas including the Main Tailings Deposits, the Northwest Gob Pile, the Southwest Gob pile, are covered with dense vegetation including volunteer plants (See Figure 4). However, acid seepage is still coming from the slopes of gob piles and there is not much change in groundwater quality at reclaimed gob piles and tailings deposits, according to the chemical analyses of groundwater samples.

Staged, aerobic constructed wetlands offer a potential low-cost, natural, low-maintenance, and long-term alternative to conventional treatment of acid mine drainage. The TVA has a 75% success rate of aerobic wetlands consistently meeting compliance without chemical treatment. However, due to adverse water quality, it is unlikely that this constructed wetland design for AMD treatment is workable for seepages coming from gob piles at the Friar Tuck Mine site.

The apatite drain system developed by author is a new method for AMD treatment. A naturally occurred material was sought which will remove metals from AMD, produce insoluble and powdery precipitates, have buffering capacity or at the least maintain the pH after reaction, and dissolve slowly so that it lasts several years or several decades. Apatite from Florida satisfied these conditions. Laboratory tests and the field experiment showed that this technique is quite effective for the removal of high concentrations of iron and aluminum in the AMD with pH less than 4.0 (Choi and West, 1995 a and b). In addition, this system removes

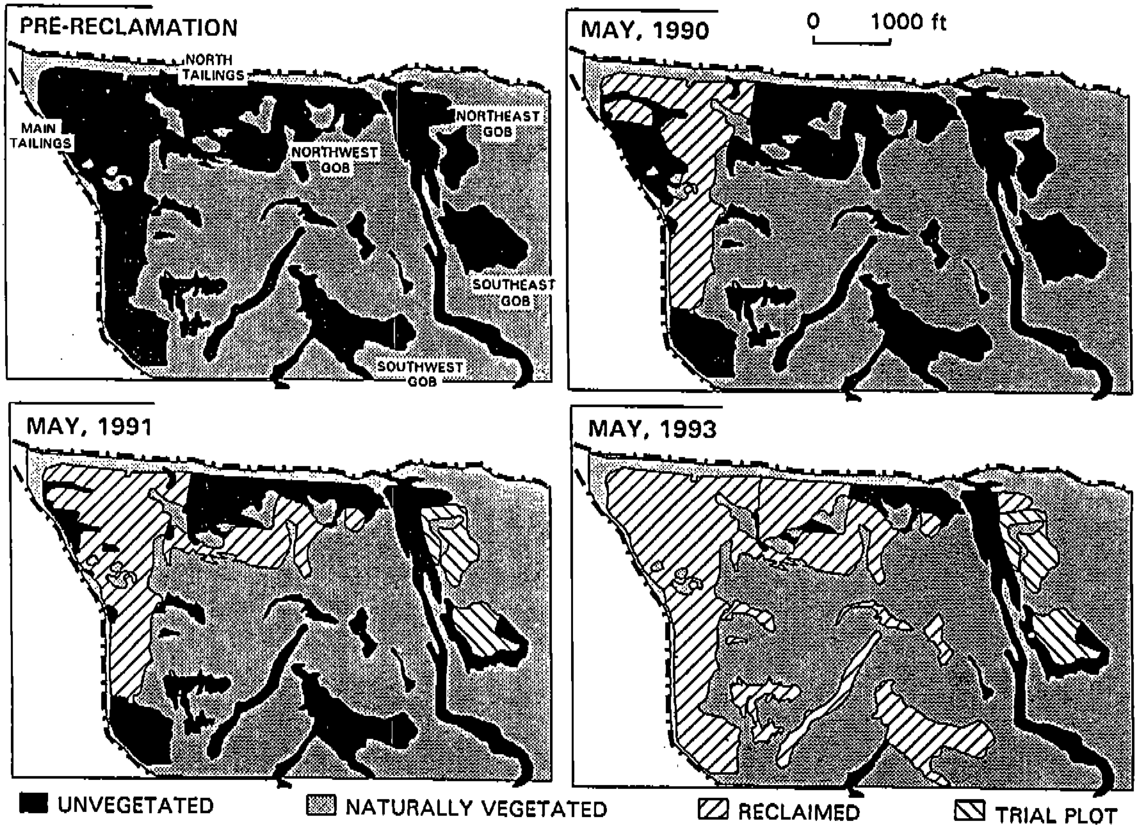

Figure 4. Map showing the progress of vegetation at the friar tuck site.

both ferric iron and ferrous iron whereas constructed wetlands systems remove only ferric iron when it is converted from ferrous iron in the wetlands. Until now, chemical treatment using lime, limestone, and sodium hydroxide is employed for high concentrations of iron and aluminum in the AMD with low pH. However, the cost is high and maintenance must be done continuously. Low cost, easy installation, and long working life providing an alternative to chemical treatment are the advantages of the apatite drain system. However, further research on the apatite drain system is recommended because the removal mechanism for iron and aluminum using apatite is not fully defined.

CONCLUSIONS

The site had six major unreclaimed gob piles, several tailings deposits, and hundreds of acres of spoil resulting from coal mining. This study included a feasibility evaluation of several techniques used to control acid formation in coal refuse. The effectiveness and cost of these methods varies over a wide range. Any methods proposed for acid formation control at the Friar Tuck site involve consideration of economic factors due to the extensive size of the site and the major amount of on-site refuse.

According to the results, surface layers of the gob piles and the tailings ponds are a consequence of weathering over several decades and therefore they are less toxic than the interior of the deposits. Acid mine drainage is in a post-peak stage and acid formation potential is probably situated in the unsaturated zone of the refuse.

The direct vegetation method was used to reclaim tailings ponds. The application and incorporation of limestone, fertilizer, and mulch was quickly followed by the establishment of shallowly rooted vegetation across all of the treated areas. Grading, capping, and revegetation using agricultural limestone, fertilizer, mulch and seed was applied to the Northwest Gob Pile and the Southwest Gob Pile to abate acid mine drainage and off-site sedimentation. Erosion control structures such as terrace, diversion ditch, and gabion structures were also constructed to minimize erosion at slopes.

A new method for treatment of AMD using apatite was tested in the laboratory and field. Apatite effectively removed iron, aluminum and sulfate while maintaining an almost constant pH. Apparently, this method can be applied to control AMD from mining refuse materials, even those containing high concentrations of iron and aluminum ions. Future research on the reaction between AMD and apatite is recommended to define the mechanism of precipitation and constituents of the precipitates in order to optimize the design of the AMD treatment system.

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