ENGINEERING EVALUATION OF AMENDED FLY ASH FOR HYDRAULIC BARRIERS[1]

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Abstract: A laboratory investigation was conducted to determine the potential for producing low-hydraulic conductivity ($k<10^{-7}$ cm/s), amended fly ash barriers. The objective is to control sources of water which now leach and transport products of oxidization from mine spoil and overburden materials -- the result of which is acidic drainage. The surface barrier evaluation program consisted of blending a Class F fly ash, clay and sand at varying dry weight percentages and water contents and analyzing the resulting mixtures' physical and engineering properties. Optimum water content for the mixes ranged from 16.7% for 10% clay to 13.8% for 30% clay. Specimens were prepared at water contents from approximately -4% to +4% of optimum for each mix ratio. Over this range, the hydraulic conductivity typically varied by one order of magnitude. The lowest hydraulic conductivity achieved during the project was 1.5×10^{-7} cm/s for a mix containing 40% fly ash, 30% clay, and 30% sand.

Additional Key Words: acid mine drainage, hydraulic conductivity, permeability, fly ash, reclamation

Introduction

Numerous abandoned and reclaimed surface mines continue to discharge acidic drainage. New technologic and economic methods to prevent or reduce the acidic drainage are required in order to improve and safeguard surface and groundwater. In many instances, reclamation budgets have long been exhausted. Continued control and treatment attempts by the owner or agency push budgets further into deficit. Thus, it is important to find effective, economic means for controlling and reducing acidic drainage from these sites.

Seepage cutoff systems using traditional materials, whether they are applied at the surface (infiltration barriers) or subsurface (grout curtains), have been effective when applied in well characterized materials (Bowman 1968, Powell and Morganstern 1985); however, this project involves developing nontraditional materials (fly ash, AMD sludge) to be placed in uncharacterized, highly heterogeneous material (surface mine backfill) for the purpose of controlling and reducing AMD. The abundance of fly ash leads to excessive disposal costs, and its proximity to existing acid drainage sites makes it an attractive material for hydraulic barriers, provided the ash can be engineered to have the necessary behavioral properties. This must be accomplished in an economic manner to allow the technique to be used throughout the mining and reclamation industry.

The work reported herein is the laboratory phase of a larger project whose objective is to demonstrate at-source control or reduction of AMD from surface mined sites through the utilization of combustion waste materials in subsurface grouts and surface barriers. The objectives of the laboratory phase include refining the surface barrier mixtures to optimize engineering and economic properties, including: minimizing hydraulic conductivity through constituent

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proportioning, characterizing elemental constituents that leach from the mixtures, and determining the nature (pH, acidity, alkalinity) of any resulting flows from the mixtures.

Hart et al. (1992) showed that diffusion of oxygen to unreacted pyrite controls the rate of formation of oxidation products. When water is kept from the reacted material, a buildup of oxidation products occurs. These deposits not only slow diffusion of oxygen to the unreacted pyrite but also increase the resistance of subsequent leaching due to reduced pore size and tortuosity of the remaining flow paths. Results using a simulation model by Hart (1992) showed that system porosity was the second most important parameter controlling the generation of acid mine drainage. Acid transport rate is inversely proportional to the amount and size of the pores in the formation. These findings indicate two potential modes for controlling acidic drainage from exisiting sites: (1) cut off or reduce the supply of oxygen to the reaction system or (2) cut off or reduce the supply of water to the leaching system. A third potential control mode is to precipitate the Fe^{2+} during the final stage of the reaction. While this is done during treatment processes, it is the least efficient mode to implement in situ at existing sites.

Controlling the flow of water to the leaching process is the easiest mode to implement in situ. Two techniques for water control are possible: elimination and rate reduction. The first technique, elimination, reduces the quantity of water entering the volume of oxidized material, thereby reducing the volume of acidic drainage emanating from the oxidized volume. This reduction is obtained by placing a seepage cutoff barrier around the oxidized material. Barriers can be in the form of surface barriers or subsurface grout curtains. The second technique is to actually grout the matrix containing the pyritic material. This technique reduces the porosity of the matrix, thus slowing the rate of both the oxygen reaching the unreacted pyrite and the leaching and subsequent transport of the oxidation products.

For either water control technique to be effective requires that a low-hydraulic-conductivity material be available in significant quantities. Although clays or clay-rich soils can be ideal candidates, their lack of availability in mining areas is a limiting factor. Additionally, significant deposits of clay may be developed for more economical applications. Thus, an alternate source of material is required, and for many AMD sites in the Appalachian region, fly ash from the coal combustion process provides an attractive alternative (American Coal Ash Association 1991). However, the ash must first be amended with other agents to provide the needed engineering properties - low hydraulic conductivity and constituent retention during permeation. In this article we report on our laboratory efforts to characterize and optimize the physical properties through the addition of various amendments.

Program of Investigation

The primary parameter for the success of a surface barrier is that it possess and maintain a low hydraulic conductivity. In solid waste disposal applications this means maintaining a hydraulic conductivity at or below 10^{-7} cm/s. While this hydraulic conductivity does not exclude all flow, it can reduce the volume of flow passing through the barrier by up to 80% of the impinging water provided adequate drainage is supplied (Bowders and Chiado 1990). In the reclamation industry, a barrier possessing a higher hydraulic conductivity could be implemented while still reducing the volume of water entering a pyritic zone.

It was the intent of this investigation to minimize the hydraulic conductivity of the fly ash by adding clay and/or sand while maintaining the ash as the principal constituent. Several factors were analyzed to determine their effect on producing low-hydraulic-conductivity material: molding water content, percentages of sand and clay, clay type, hydraulic gradient during test, and grain-size distribution of mixtures.

Index properties of the materials used in the investigation are shown in table 1. Twelve test mixes were prepared with varying percentages of fly ash, clay, and sand. Mix ratios are provided in table 2. Both the clay and sand were air-dried prior to mixing with the fly ash, which was at a nominal moisture content of 10%. Distilled de-ionized water was added during mixing to bring the mixtures to the desired moisture contents. Use of the fly ash and sand in conjunction with the low-plasticity clay were believed to produce a mixture that was not particularly sensitive to permeant liquid chemistry; thus, the distilled de-ionied water was used. Mixtures were placed in sealed plastic bags, and moisture equilibration was permitted for 24 h after which specimens were compacted using ASTM D698, standard Proctor compaction procedures (ASTM 1993a).

Hydraulic conductivities of the compacted specimens were measured in double-ring, rigid-wall permeameters (fig. 1). Hydraulic conductivities were calculated using the constant-head analysis (ASTM 1993b). Calculations of hydraulic conductivity were made for inflow volume and for outflow volumes for both the inner and outer rings. Termination of tests was based on the following: minimum of 3 pore volumes of flow and inflow hydraulic conductivity falling within 25% of the average hydraulic conductivity measured after 2 pore volumes (Peirce and Witter 1986).

Table 1. Index properties of materials.

Material	Specific Gravity	Max Dry Density Mg/m^3	Optimum Water Content %	Atterberg Limits LL	PI	Grain Size Parameters, Cu	Clay Fraction %	Unified Soil Classification
BBL	2.71	1.71	18.0	46	23	XXX	79.0	CL
LMS	2.73	1.68	17.3	40	19	XXX	67.8	CL
OR	2.69	1.78	XXX	NP		3.15	0	SP
AFA	2.29	1.45	20.4	NP		4.10	14.2	ML

BBL = Big Bear Lake Clay
LMS = Lake Monongahela Sediment
OR Sand = Ohio River Sand
AFA = Albright Fly Ash

LL = Liquid Limit
PI = Plasticity Index
Cu = Coefficient of Uniformity
NP = Non Plastic

Upon completion of the permeability tests, each test specimen was sectioned, water content was measured, and degree of saturation was calculated. In addition, grain-size distribution was measured to assess the effect of constituent material proportioning on the gradation of the test mixes.

Results and Discussion

Sixty-one specimens were prepared, and their hydraulic conductivities were measured at two hydraulic gradients. For each mix ratio shown in table 2, five specimens were compacted ranging from approximately 4% dry of optimum moisture content to 4% wet of optimum. After the specimens were compacted into the rigid-wall molds, end platens were added and permeation was initiated at a hydraulic gradient of 59. After steady flow and hydraulic conductivity was achieved, the gradient was increased to 118. A response, typical of that shown in figure 2, for hydraulic conductivity at the various molding water contents was exhibited for all mixes tested. As molding water content increased, the hydraulic conductivity decreased, reaching a minimum value for specimens prepared 2% to 4% wet of optimum. The hydraulic conductivity measured at the higher gradient (i=118) typically exceeded that at the lower gradient (i=59) when the specimens were compacted dry of optimum. When samples were compacted wet of optimum, the permeabilities measured at the higher gradient were lower than those at the lower gradient. The measured permeabilities typically differed by a factor between 0.5 and 1.75 (table 2, col. 8).

A summary of the compaction and hydraulic conductivity results is given in table 2. The minimum hydraulic conductivities for each mix design at both hydraulic gradients are presented. Examination of the data indicates that an increase in sand percentage produced a subsequent reduction in mixture hydraulic conductivity for all clay contents tested. However, the effectiveness of the increased sand percentage diminished as the clay contents increased, as shown in figure 3.

Table 2. Compaction and hydraulic conductivity results for compacted fly ash, clay and sand mixtures.

Mix	γ_{dry}, Mg/m^3		w, %		Kmin$_{i1}$, cm/s x10^{-7}	Kmin$_{i2}$, cm/s x10^{-7}	Kmin$_{i1}$/ Kmin$_{i2}$	Kmin$_{avg}$, cm/s x10^{-7}
AS/CL/SA (1)	Max (2)	Mix (3)	Opt (4)	Mix (5)	(6)	(7)	(8)	(9)
100/0/0	1.45	1.42	20.4	23.0	150.0	200.0	1.33	180.0
80/10/10	1.60	1.59	16.7	18.0	17.0	21.0	1.24	19.0
75/15/10	1.63	1.60	16.0	17.8	7.0	6.5	0.93	6.8
70/20/10	1.64	1.59	16.0	19.0	5.5	2.4	0.44	4.0
60/30/10	1.64	1.58	15.3	20.0	2.5	2.0	0.80	2.3
70/10/20	1.64	1.62	15.2	17.2	9.0	8.0	0.89	8.5
60/20/20	1.67	1.66	14.8	17.0	2.8	2.6	0.93	2.7
50/30/20	1.68	1.64	14.6	17.0	1.8	1.6	0.89	1.7
60/10/30	1.74	1.67	13.8	17.0	5.0	5.0	1.00	5.0
50/20/30	1.77	1.66	14.1	18.0	1.9	1.8	0.95	1.9
40/30/30	1.77	1.68	14.2	17.5	1.5	1.4	0.93	1.5
80/L10/10	98.4	97.7	16.2	18.5	40.0	70.0	1.75	55.0
70/L20/10	98.9	97.0	16.9	19.5	20.0	30.0	1.50	25.0

(1) Fly Ash/Clay/Sand proportion by dry weight.
(2) Maximum dry unit weight for the mixture.
(3) Dry unit weight of specimen for reported hydraulic conductivity.
(4) Optimum water content (gravimetric) at max unit weight.
(5) Water content of specimen for reported hydraulic conductivity.
(6) Minimum hydraulic conductivity at i1= 29.5 for tests 1-3 and i1= 58.9 for tests 4-13.
(7) Minimum hydraulic conductivity at i2= 58.9 for tests 1-3 and i2= 117.8 for tests 4-13.
(8) Ratio between K measured at different hydraulic gradients.
(9) Average minimum hydraulic conductivity for the two testing gradients.

This is also illustrated in the hydraulic conductivity ratios given in table 3. The values in table 3 indicate the factors by which the hydraulic conductivity decreased as the sand percentage was increased above 10% for a constant clay content. At the low clay content (10%) the reduction due to the addition of 30% sand is nearing an order of magnitude. At the 30% clay content, the reduction in hydraulic conductivity due to the addition of 30% sand is about one-half order of magnitude.

Traditional thinking supposes that hydraulic conductivity decreases as the percentage of fines increase in a soil mass; however, the results of this investigation show this is not necessarily true when the primary constituent is fine, noncohesive particles, i.e., fly ash. The postpermeation grain-size distribution curves for fly ash-10% Big Bear Lake Clay-sand are shown in figure

4. The decrease (from 80% to 60%) in the percentage of fines (sizes less than 0.074 mm) is readily evident as the percentage of sand was increased from 10% to 30%. The corresponding coefficients of uniformity (Cu), a measure of the gradation of the mixture, are given in table 3. For the mixtures shown in figure 4, the Cu values increase from 8.0 for the mixture with 10% sand to 30 for the mixture with 30% sand. An increase in Cu indicates that the mixture is trending toward a more well-graded mixture, i.e., one containing a wide range of particle sizes.

Table 3. Hydraulic conductivity ratios, dry unit weights and coefficients of uniformity as a function of sand percentage for constant clay contents.

	10% Clay	20% Clay	30% Clay
10% Sand			
Kratio	1	1	1
γ_{dry}, Mg/m^3	1.58	1.58	1.58
Cu	8.0	11.0	17.3
20% Sand			
Kratio	0.45	0.68	0.74
γ_{dry}, Mg/m^3	1.62	1.66	1.64
Cu	18.3	24.2	41.7
30% Sand			
Kratio	0.26	0.48	0.65
γ_{dry}, Mg/m^3	1.67	1.66	1.68
Cu	29.8	32.0	51.9

Kratio = K @ X% sand/K @ 10% sand. Cu = coefficient of uniformity.
γ_{dry} = dry unit weight of specimen.

From compaction theory, we know that maximum densities are achieved when the material being compacted has a blend of particle sizes rather than having particles of a uniform size. Such a blend promotes dense packing, with the smaller particles filling in the interstices of the matrix of larger particles. This is also borne out by the data shown in table 3. The dry unit weights increase as the percentage of sand increases for a constant clay content. For example, at a clay content of 10%, the dry unit weight increases from 99 to 104 lb/ft^3 for a 20% increase in the sand content. From this increase in density, we can infer a decrease in the hydraulic conductivity of the compacted mixture. Indeed, this has been shown in tables 2 and 3. Thus, the addition of sand to the fly ash resulted in significant decreases in the hydraulic conductivity of the fly ash mixtures by permitting the mixtures to be compacted to greater densities than possible with mixtures of fly ash and clay alone.

Conclusions

The work reported herein was aimed at optimizing engineering properties of fly ash mixtures for surface hydraulic barrier applications. For the surface barrier mixture, the minimum hydraulic conductivity (1.5x10^{-7} cm/s) was obtained for a compacted mixture containing 40% ash, 30% clay and 30% sand. The addition of sand to the ash-clay mixtures resulted in a decreased hydraulic conductivity-about an order of magnitude for ash with 10% clay and one-half order for ash with 30% clay. The addition of sand widened the grain-size distribution of the mixtures, thereby allowing the mixtures to be compacted to greater densities, resulting in decreased hydraulic conductivities. A surface barrier at 10^{-7} cm/s, with adequate drainage for the repelled water, can exclude up to 80% of the potential infiltrating water. Hydraulic conductivities of the surface barrier mixtures are in the range that makes it a candidate for hydraulic barriers at acid mine drainage sites.

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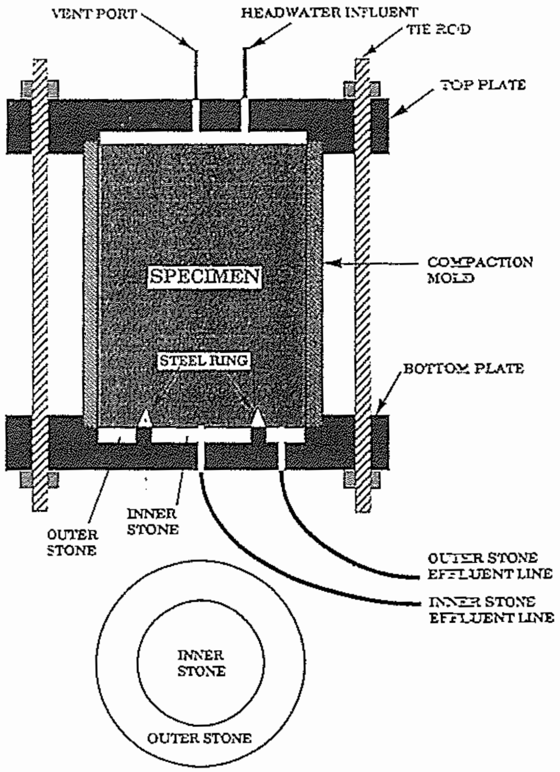

Figure 1. Double-ring, rigid-wall permeameter.

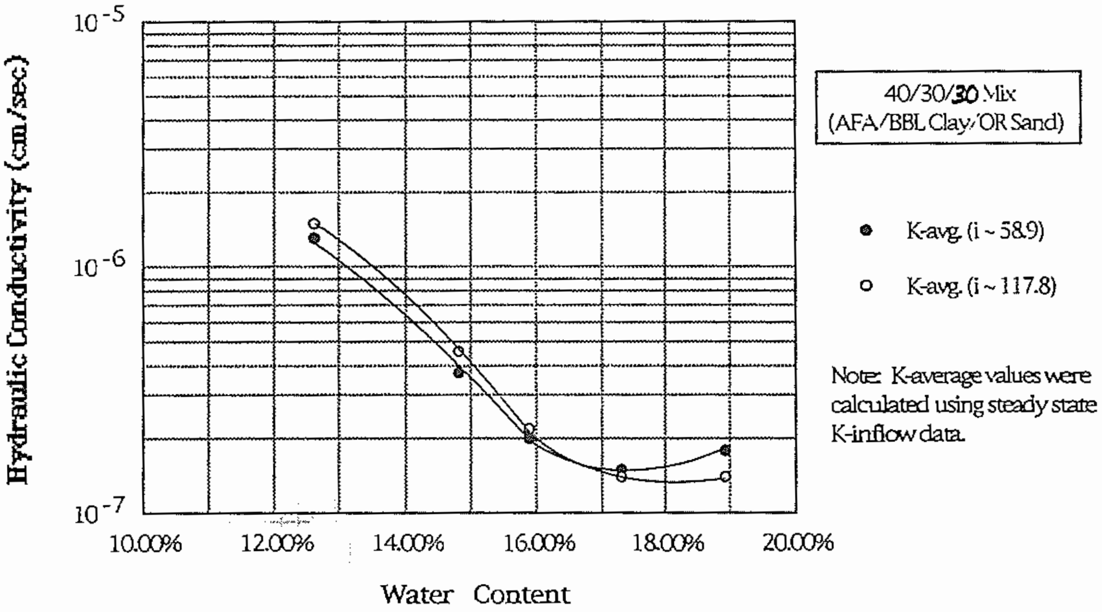

Figure 2. Typical hydraulic conductivity vs. molding water content for compacted fly ash-clay-sand mixtures (40%Ash/30%BBL-Clay/30%Sand).

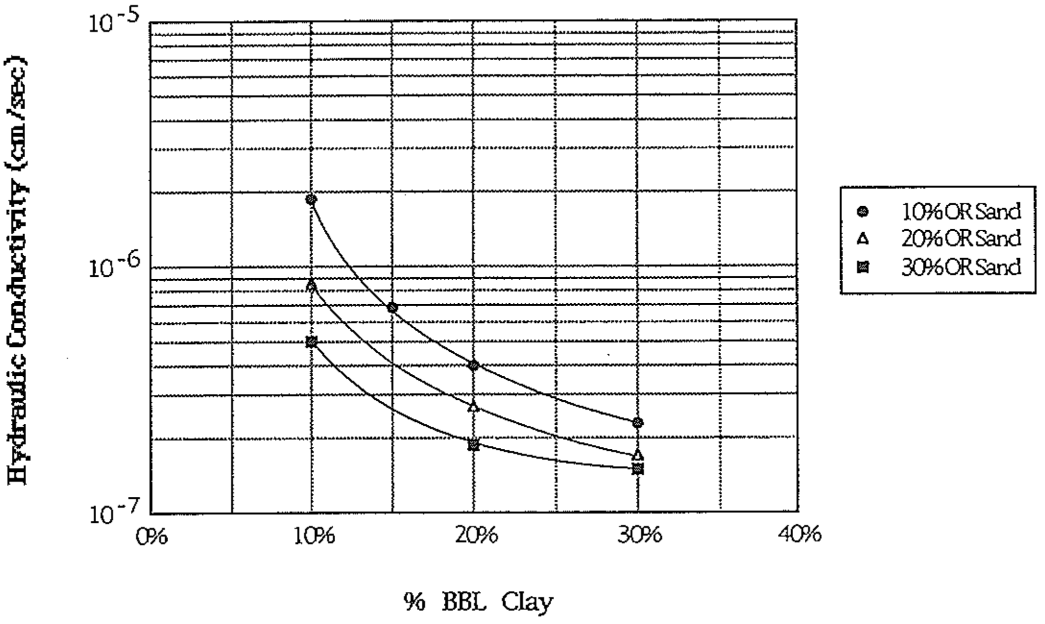

Figure 3. Hydraulic conductivity vs. percent BBL-clay and percent sand for all mixtures.

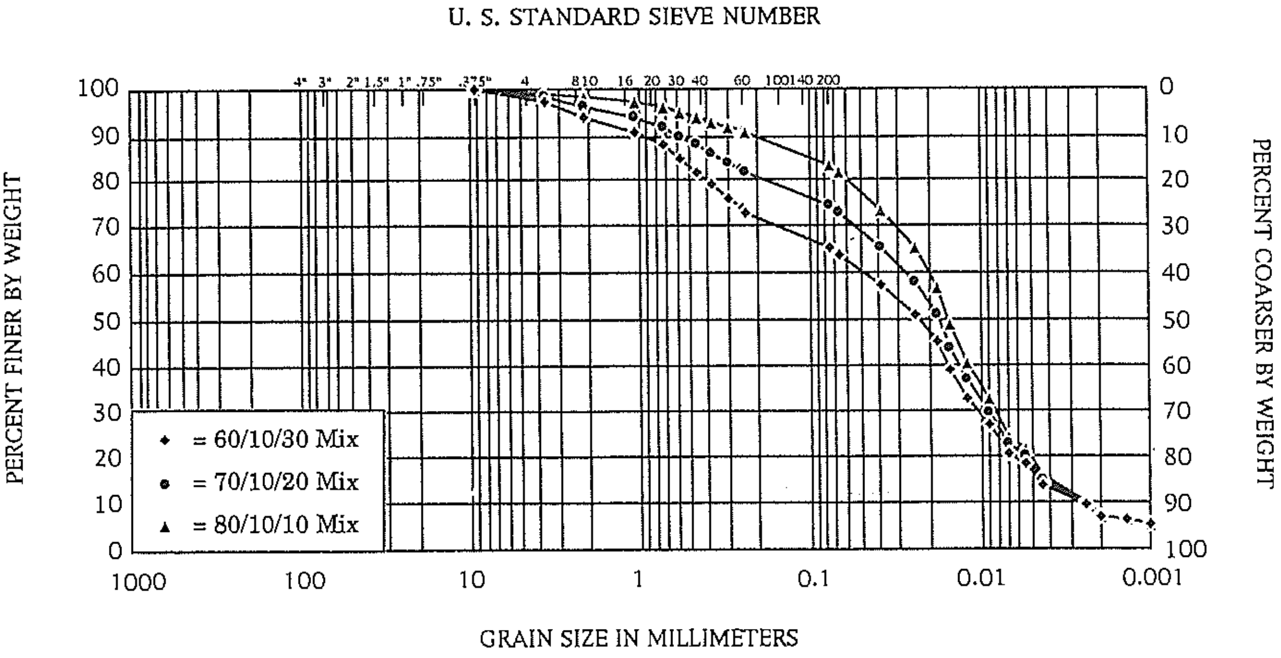

Figure 4. Postpermeation grain-size distribution curves for 10 percent BBL clay specimens.