ENGINEERING EVALUATION OF WASTE PHOSPHATIC PLAY FOR PRODUCING LOW PERMEABILITY BARRIERS [1]

by

John J. Bowders, Jr.

and

Eric D. Chiado [2]

Abstract. The findings of a laboratory study in which the feasibility of using waste phosphatic clay as a low permeability barrier was evaluated are reported herein. The ability of the waste phosphatic clay to chemically ameliorate any AMD produced was also assessed and the engineering parameters most important to achieving a successful barrier were determined. Two mine spoils, one cover soil and one phosphatic clay sample were used to construct the test specimens used in this study. Experiments consisted of performing permeability tests on different configurations of these soils, using rigid-wall, double-ring permeameters. Analyses of effluents for various water quality parameters (typical of mining requirements) were also performed. Three different methods of employing the phosphatic clay were evaluated including; placing the clay into a slurry and then applying it over top of the spoil, mixing dry phosphatic clay with the cover soil and then applying it over top of the spoil , and mixing dry clay directly with the spoil. Results indicated that the optimum method for reducing permeability and improving effluent quality was to mix the phosphatic clay directly with the spoil. Using this configuration, average coefficients of permeability were 50 to 5,400 times lower than the average coefficient of permeability of the spoil alone. Improvements in water quality were also substantial, with reductions in heavy metals and acidity averaging approximately 95 percent, relative to effluents from spoil alone. Compaction of individual layers had a dominating effect on permeability. The lowest coefficients of permeability were demonstrated in specimens in which all layers were compacted. Compaction also appeared to enhance the ameliorative characteristics of the clay by allowing increased residence times for the drainage to react with the phosphate in the spoil. Finally, 10 percent replacement by weight of the phosphatic clay in either the cover soil or the spoil layer produced the best results, relative to other replacement percentages.

Additional Key Words: Hydraulic Conductivity, Permeability, Acid Mine Drainage, Effluent Analyses, Water Quality, Slurry, Phosphatic Clay, Waste Materials

[1] Paper presented at the 1990 Mining and Reclamation Conference and Exhibition, Charleston, West Virginia, April 23-26, 1990.

[2] John J. Bowders, Jr. is an Assistant Professor, Department of civil Engineering, West Virginia University, Morgantown, WV, 26506. Eric d. Chiado is A Geotechnical Engineer, Almes and Associates, Trafford, PA 15085.

Introduction

In northern West Virginia and Southwestern Pennsylvania, mining bituminous coal provides much of the economic base. Any threat to this industry poses a similar and severe threat to the economic lifeline of these areas. With the ever-increasing trend of environmental awareness, one outcome of the mining in these areas looms as a potential for limiting coal production. This outcome, acid mine drainage (AMD), is especially acute in these areas. As the environmental focus on water quality increases, mining companies will be increasingly regulated to reduce the amount of AMD which exits from their operations.

Although there are numerous techniques that are used to control the formation or treatment of AMD, the effectiveness and cost of these methods vary over a wide range. Thus, there remains a need for the development

and implementation of methods which would maximize the effectiveness and minimize the cost. In the case of surface mines, active or abandoned, one such technique which shows significant promise is that of waste phosphatic clay barriers.

Waste phosphatic clay is produced during the preparation of fertilizer from phosphate ore. The disposal of this waste clay presents a significant problem to the phosphate producers located in the southeastern United States. It is estimated that by the year 2000, there will be over 1 billion tons of this waste. Areas used to contain the waste clay are rendered unusable until such time as the clays stabilize. This can be as long as 20 to 30 years.

To significantly reduce the environmental impact of these waste clays requires that any beneficial use must result in the utilization of a large volume of the clays. Such a use might be achieved by constructing hydraulic barriers from the waste clay, which could be applied at surface mine sites where AMD is present.

Past researchers (Renton and Stiller 1989) found that phosphatic clay has the potential to chemically ameliorate AMD. A secondary finding was that the clay reduced the volume of flow through the acidic material when they were mixed together. Thus, phosphatic clay may offer a "two-pronged" remedy to the AMD problem by physically limiting the quantity produced, and chemically ameliorating any AMD that is produced.

The objectives of the engineering evaluation reported herein were to: (1) determine the feasibility of using the waste phosphatic clay as a low permeability hydraulic barrier and (2) determine those engineering parameters most important to achieving this goal. The ability of the waste phosphatic clay to chemically ameliorate any AMD produced was also characterized. In addition, a computer model was used to simulate various arrangements of waste phosphatic clay barriers using the properties determined in the first two objectives. The results of the computer simulation are discussed in detail elsewhere (Bowders 1989).

Experimental Program

Two acidic spoils, one cover soil, and one phosphatic clay were used in the testing program. Rigid-wall, double-ring permeameters were used to measure the permeability of the phosphatic clay barrier configurations. Effluent collected from the permeability tests was analyzed for constituents common to AMD.

Four factors were investigated to determine their effect on producing a low permeability, chemically enhanced system. These factors included: methods of employing the phosphatic clay (dry or slurry), location of phosphatic clay in the system by itself, mixed with the spoil, or the cover) and percentage by weight of phosphatic clay included in the system.

Soil and Waste Materials. The spoil materials used in this study were obtained from a surface mine and a coal refuse disposal facility in central and northern West Virginia, respectively. No testing was performed to exclusively determine the mineralogical composition of the spoils; however, the analysis of effluent from each spoil showed both to have high acid producing potential . The cover soil was also obtained from the surface mine. Test results indicated that the cover would not contribute to the chemical amelioration of AMD, The phosphatic clay was obtained from Mulberry, Florida. It is Predominantly smectitic clay with calcium being the only detectable metal in effluents from the clay alone. The index properties of the spoils, cover soil and clay are presented in Table 1.

Specimen Preparation. Three different configurations were used to evaluate the phosphatic clay barriers (Fig. 1). Each configuration produced a layered system which represented the hydraulic barrier similar to what would exist at a reclaimed surface mine site. The four soils were used to construct five distinct layers: Phosphatic clay placed in slurry form (Chiado, Bowders and Sencindiver 1988), cover soil mixed with phosphatic clay, cover soil alone, spoil mixed with phosphatic clay, and spoil alone.

The spoil and cover layers were either uncompacted or compacted to standard Proctor energy (12,375 ft-lb/ft^3). For spoil or cover soil which contained dry phosphatic clay, the clay was added at either 5, 10, or 20 percent by weight. Placement gravimetric water contents of the slurries ranged from 150 to 375 percent. The configurations of all the tests are given in Table 2.

Permeability Testing. The major objective of this work was to determine if a suitable low permeability barrier could be developed using the phosphatic clay. Thus, permeability testing was a major emphasis of the work. Rigid-wall, double-ring permeameters (Fig. 2) were used to measure the permeability. Using these permeameters

permitted the detection of any "side-wall" leakage, a sometimes common problem with rigid-wall permeameters (Daniel, Anderson and Boynton 1985).

All of the specimens were permeated with distilled water. Hydraulic gradients of 10 to 200 were used throughout the testing. The selection of a gradient was based on the need to expedite the testing process.

The permeability was calculated using Darcy's law (Eq. 1). The volume of flow into the specimen over a known period of time was used to compute permeability.

$$K = Q/(t\ i\ A) \qquad (1)$$

Where:
K = coefficient of permeability (L^3/T)
Q = quantity of inflow (L^3)
t = time for flow Q to occur (T)
i = hydraulic gradient (dimensionless)
A = cross-sectional area of flow (L^2)

Constant-head permeability tests were used throughout the program. Tests were ended after two pore volumes of flow had passed through the specimen and the coefficient of permeability had achieved equilibrium. Effluent from each permeability test was collected. periodically, samples of the effluent were analyzed to determine the concentration of iron, manganese, magnesium, aluminum, calcium, and sulfate. The acidity, pH and electrical conductivity of each effluent sample were also measured. For the permeability tests in which the phosphatic clay layer was present from the beginning of the test, effluent samples were taken from near the initial and final pore volumes of flow in order to ascertain the effect of time on the chemistry of the system.

Results and Discussion

Results of thirty-four permeability tests are reported in this article. The tests are grouped according to the phosphatic clay placement scheme. The results and ensuing discussion are in the following order: test using phosphatic clay slurry, phosphatic clay mixed with cover soil, and phosphatic clay mixed with spoil material. Permeability results are considered first followed by the effluent chemical analysis results.

Permeability Results. The results of the permeability tests in which the phosphatic clay was placed in the form of a slurry are shown in Table 3. With the exception of tests 5(l), 5(2), and 7(2), the *addition of* phosphatic clay slurry *decreased the* permeability of the layered system. The magnitude of these decreases was not consistent. The slurry appreciably decreased the permeability of the systems containing the uncompacted spoil, but were relatively ineffective when applied to compacted spoil. However, the lowest permeabilities were demonstrated in systems where the spoil was compacted. This result was attributed to the compaction and not the presence of the slurry. When applied to uncompacted samples, the low water content slurries *produced the* largest change in system permeability. The thickness of the slurry *did* not appear to be an important variable in producing low permeability systems. However, hairline cracking was found in several specimens. Thicker slurry layers may reduce the event of crack propagation through the entire slurry layer.

Results from the tests in which dry phosphatic clay was mixed with the cover soil and applied overtop of the spoil are presented in Tables 4 and 5. The spoil layer was compacted in all of these tests. The results in Table 4 are for incremental tests, i.e., the permeability of the spoil was measured, then the cover/clay mixture was added and the permeability of the system was measured. The addition of the uncompacted clay/cover material to Spoil 1 resulted in a reduction of the permeability on average by a factor of three. This was only slightly more effective than the *addition of* the slurry to the acidic systems. The *addition of* uncompacted clay/cover to Spoil 2 resulted in an increase in the permeability of the system. No explanation exists for this behavior. Thus, the addition of uncompacted clay/cover to the acidic system is deemed ineffective.

The results presented in Table 5 show the effect of *adding compacted* clay/cover above the spoil layer. Permeabilities of the system were reduced by more than two orders-of-magnitude when compared to the uncompacted clay/cover system. Perhaps more important is the fact that when compared to the average permeability of the compacted spoil alone, the results of the compacted clay/cover represented a 30-fold decrease. Thus, even for a compacted spoil, the *addition of* the compacted clay/cover substantially reduced the system permeability.

Within the scope of clay/cover mixtures, the percentage of clay was varied from 5 to 20 percent by weight. Permeability results indicated that the 10 percent replacement resulted in the lowest permeabilities.

The final configuration of the barrier system included mixing dry phosphatic clay directly with the acidic spoil and compacting it. The results of the permeability tests are listed in Table 6. Addition of the dry phosphatic clay to the spoil material produced the lowest permeabilities of any of the systems investigated in this project. The average permeability of Spoil 1 was found to be 3.3 X 10 cm/sec. It appeared that this method of using the clay provided the best means of reducing the permeability of an acidic system.

Effluent Analyses. Only effluents from two of the eleven permeability tests which included slurry were analyzed for quality. The results are shown in Table 7. The addition of the phosphatic clay slurry to the acidic system significantly improved the effluent water quality. All of the metal s present in the pre-slurry effluent analysis showed drastic reductions in concentration after the slurry was added to the system. The only increase in concentration was for the case of calcium which was expected since the other metals replace the calciums on the phosphate radical. The pH of the effluents were not significantly altered by the presence of the clay slurry. Even though the slurry was placed in an individual layer, it was still able to exert a positive influence on the chemistry of the system.

Results of the effluent analyses from the tests with the clay mixed with the cover soil are shown in Tables 8 and 9. The incremental tests (Table 8) indicated large decreases in the iron and manganese effluent concentrations. The calcium concentrations increased while the pH again remained unchanged; however, the acidity levels were sharply reduced. This indicates that the effluent could be buffered to a neutral pH without much difficulty relative to that for an effluent from a system without phosphatic clay.

In the one-step tests (Table 9), the phosphatic clay was present from the beginning of permeation. The concentrations of the metals in the effluent were reduced to levels more near to those of the slurry arrangement. Thus, it appears beneficial to include the phosphatic clay from the onset of permeation. The passage of large pore volumes of water through the specimens did not appear to exhaust the capacity of the phosphatic clay to contain the metals from the effluent. Even after 18 pore volumes of flow the metals concentrations were low as illustrated by test number 11(2) in Table 9.

Results of the analyses of the effluents from the permeability tests on phosphatic clay mixed with the acidic spoil material are listed in Table 10. This system appeared to optimize the ameliorative capacity of the phosphate as evidenced by the reduced concentration of metals, sulfates, and acidity relative to tests in which the clay was used in other manners. Compaction of the layer did not reduce the capacity of the clay to improve the effluent quality. As the quantity of clay was increased, the quality of the effluent continued to improve; however, the amount of improvement decreased for increasing quantities of clay. The optimum clay addition was about 10 percent by weight.

Conclusions

The findings of this research program have shown that waste phosphatic clay can be effective in reducing the permeability and improving the quality of the effluent water of an acidic system. The following conclusions are based on these findings:

1. Reduction in permeability varied depending on the method of application and location of the clay in the system.

2. Slurries of phosphatic clay were ineffective in significantly reducing the permeability of acidic systems.
3. The addition of dry phosphatic clay to either the cover soil or the spoil material produced systems with exceptionally low permeabilities.

4. Compaction appeared to be the most dominant engineering parameter for reducing permeability in these systems.

5. The inclusion of phosphatic clay provided further reductions in the coefficient of permeability even in those systems that were compacted.

6. A 10 percent by weight replacement of phosphatic clay in either the cover soil or spoil provided the

optimum configuration for reducing the permeability.

In regard to the quality of the effluent water, the following conclusions are advanced:

1. All methods of phosphatic clay application produced significant reductions in metal, sulfate, and acidity concentrations.
2. Mass transfer of phosphate did not appear to be inhibited when dry phosphatic clay was used.
3. Compaction of the layers enhanced the clay's ameliorative capacity by creating longer residence times through reduced permeability.
4. Although the effective chemical life of the phosphatic clay was not determined, the movement of water through the different systems did not reduce the effectiveness of the clay over time, in any test.
5. The incorporation of larger percentages of clay in the system resulted in better water quality.

The most efficient use of the physical and chemical properties of the phosphatic clay occurred in systems containing a compacted layer of dry clay mixed directly with the spoil material. This configuration produced systems with average permeabilities 5,400 times lower than the **average** coefficient of permeability for uncompacted spoil alone and 50 to 300 times lower than the average permeability for compacted spoil alone. These exceptionally low permeabilities were matched by substantial improvements in effluent quality. Generally, metal concentrations were as low or lower than those produced by other system configurations, and acidity concentration was greatly reduced relative to other systems.

Finally, it must be noted that these results were obtained from controlled laboratory tests. As such, the coefficients of permeability and chemical characteristics may not be exactly duplicated in a field setting. Attention to engineering detail during the construction of a barrier employing phosphatic clay could help to achieve similar results. Careful control of compactive effort, adequate mixing of the clay and spoil, obtaining the proper barrier water content and thickness, and limiting desiccation, will be required to produce a phosphatic clay barrier which satisfies its intended function; namely substantially reducing the volume of flow through the backfill spoil, and improving the quality of the seepage that is generated.

Acknowledgements

The authors are extremely indebted to their co-investigator Professor John C. Sencindiver of the Plant and Soil Sciences Div. at West Virginia University. His help and encouragement are gratefully appreciated. The work was accomplished through funds provided by the West Virginia Water Research Institute and the National Mine Land Reclamation Center. Continued interest in this work by Dr. Robert Jenkins and Dr. Paul Ziemkiewicz of those organizations, respectively, is sincerely appreciated.

References

Bowders, J.J. 1989 Computer Simulation of Phosphatic Clay Barriers for Control of AMD. Article under preparation for publication. Dept. of Civil Engineering, West Virginia University, Morgantown, WV.

Chiado, E.D. , J.J. Bowders and J.C. Sencindiver 1988 Phosphatic Clay Slurries for Reducing AMD from Reclaimed Mine Sites. Proc., Mine Drainage and Surface Mine Reclamation, Vol I, Conf. Pittsburgh, PA, April 19-21 pp. 44-51.

Daniel, D.E., D.C. Anderson and S.S. Boynton 1985 p. 44-51. Fixed-Wall Versus Flexible-Wall Permeameter. Hydraulic Barriers in Soil and Rock, ASTM STP 874, p 107-126.

Renton, J.J. and A.H. Stiller 1989 The Use of Phosphatic Materials as Ameliorants for Acid Mine Drainage, Vol. I. The Use of Rock Phosphate (apatite) for the Amelioration of Acid Mine Drainage from the Mining of Coal. Publication No. 02-050-072, Florida Institute of Phosphate Research, Bartow, FL, February, 1989.

Table 1 Index Properties of Soils Used in Research

SOIL	Gs	NAT w (%)	OPT w (%)	MAX DRY UNIT WGHT (pcf)	ATTERBERG LIMITS LL	PL	PI	GRAIN SIZE PARAMETERS Cu	Cz	CLAY SIZE FRACTION (%)	UNIFIED SOIL CLASS
PHOS CLAY	2.80	31	10	75	137	47	90	8.6	1.0	95	CH
SPOIL 1	2.62	4	*	107	29	19	10	20.8	1.2	0	GC
SPOIL 2	2.32	18	*	97	36	26	10	7.6	0.9	3	GC
COVER	2.79	13	18	105	34	22	12	14.3	1.8	5	SC

* Optimum water content was not determined for either spoil 1 or 2 because the addition of water to these soils could have resulted in the formation of AMD

Table 2 Arrangement and nature of each test specimen

TEST	LAYER ONE	LAYER TWO	LAYER THREE	COMMENTS
1(1)	UNCOMPACTED SPOIL 1			
1(2)	UNCOMPACTED SPOIL 1			
2(1)	PHOS CLAY SLURRY			WATER CONTENT = 179% THICKNESS = 5.5 cm
2(2)	PHOS CLAY SLURRY			WATER CONTENT = 194% THICKNESS = 7.2 cm
2(3)	PHOS CLAY SLURRY			WATER CONTENT = 329% THICKNESS = 2.6 cm
2(4)	PHOS CLAY SLURRY			WATER CONTENT = 386% THICKNESS = 4.3 cm
3(1)	COMPACTED SPOIL 1	PHOS CLAY SLURRY		WATER CONTENT = 274% THICKNESS = 3.1 cm
3(2)	COMPACTED SPOIL 1	PHOS CLAY SLURRY		WATER CONTENT = 353% THICKNESS = 3.7 cm
4(1)	UNCOMPACTED SPOIL 1	PHOS CLAY SLURRY		WATER CONTENT = 172% THICKNESS = 3.4 cm
4(2)	UNCOMPACTED SPOIL 1	PHOS CLAY SLURRY		WATER CONTENT = 256% THICKNESS = 3.9 cm
5(1)	COMPACTED SPOIL 1	PHOS CLAY SLURRY		WATER CONTENT = 187% THICKNESS = 1.77 cm
5(2)	COMPACTED SPOIL 1	PHOS CLAY SLURRY		WATER CONTENT = 290% THICKNESS = 2.54 cm
6(1)	UNCOMPACTED SPOIL 1	PHOS CLAY SLURRY		WATER CONTENT = 187% THICKNESS = 1.27 cm
6(2)	UNCOMPACTED SPOIL 1	PHOS CLAY SLURRY		WATER CONTENT = 290% THICKNESS = 2.1 cm
7(1)	COMPACTED SPOIL 1	PHOS CLAY SLURRY	LOOSE COVER SOIL	WATER CONTENT = 166% THICKNESS = 3.3 cm
7(2)	COMPACTED SPOIL 1	PHOS CLAY SLURRY	LOOSE COVER SOIL	WATER CONTENT = 278% THICKNESS = 3.8 cm
7(3)	UNCOMPACTED SPOIL 1	PHOS CLAY SLURRY	LOOSE COVER SOIL	WATER CONTENT = 272% THICKNESS = 3.4 cm
9(1)	COMPACTED SPOIL 1	UNCOMP CLAY/COVER		5% CLAY
9(2)	COMPACTED SPOIL 1	UNCOMP CLAY/COVER		10% CLAY
9(3)	COMPACTED SPOIL 1	UNCOMP CLAY/COVER		20% CLAY
10(1)	COMPACTED SPOIL 2	UNCOMP CLAY/COVER		5% CLAY
10(2)	COMPACTED SPOIL 2	UNCOMP CLAY/COVER		10% CLAY
10(3)	COMPACTED SPOIL 2	UNCOMP CLAY/COVER		20% CLAY
11(1)	DESTROYED			
11(2)	COMPACTED SPOIL 1	COMP CLAY/COVER		10% CLAY
11(3)	COMPACTED SPOIL 1	COMP CLAY/COVER		20% CLAY
12(1)	COMPACTED SPOIL 2	COMP CLAY/COVER		5% CLAY
12(2)	COMPACTED SPOIL 2	COMP CLAY/COVER		10% CLAY
12(3)	COMPACTED SPOIL 2	COMP CLAY/COVER		20% CLAY
13(1)	COMP CLAY/SPOIL 1	COMP COVER SOIL		5% CLAY
13(2)	COMP CLAY/SPOIL 1	COMP COVER SOIL		10% CLAY
13(3)	COMP CLAY/SPOIL 1	COMP COVER SOIL		20% CLAY
14(1)	COMP CLAY/SPOIL 2	COMP COVER SOIL		5% CLAY
14(2)	COMP CLAY/SPOIL 2	COMP COVER SOIL		10% CLAY
14(3)	COMP CLAY/SPOIL 2	COMP COVER SOIL		20% CLAY

Table 3 Summary of Permeability Tests With Phosphatic Clay Slurry.

TEST (1)	SOIL LAYERS (2)	COEFFICIENT OF PERMEABILITY k_{sp} (cm/s) (3)	k_{sp-pcs} (cm/s) (4)	$k_{sp-pcs-cs}$ (cm/s) (5)	k(3)/k(4) (6)	k(3)/k(5) (7)
1(1)	USP	1.7E-4	na	na	na	na
1(2)	USP	1.1E-4	na	na	na	na
2(1)	PCS	1.5E-6	na	na	na	na
2(2)	PCS	1.8E-6	na	na	na	na
2(3)	PCS	3.7E-6	na	na	na	na
2(4)	PCS	5.2E-6	na	na	na	na
3(1)	CSP-PCS	2.1E-5	5.8E-6	na	3.6	na
3(2)	CSP-PCS	2.2E-5	5.5E-6	na	4.0	na
4(1)	USP-PCS	2.4E-4	1.6E-5	na	15.0	na
4(2)	USP-PCS	1.4E-4	5.2E-5	na	2.7	na
5(1)	CSP-PCS	3.2E-6	4.8E-6	na	0.7	na
5(2)	CSP-PCS	3.6E-6	4.3E-6	na	0.8	na
6(1)	USP-PCS	2.4E-4	7.9E-6	na	30.1	na
6(2)	USP-PCS	1.4E-4	3.2E-5	na	4.2	na
7(1)	CSP-PCS-UCS	7.9E-6	4.4E-6	1.5E-6	1.7	5.4
7(2)	CSP-PCS-UCS	7.3E-6	7.6E-6	4.4E-7	0.9	16.6
7(3)	USP-PCS-UCS	1.8E-4	3.7E-5	6.6E-7	4.8	274.4

Key to Soil Layers
USP: Uncompacted Spoil
CSP: Compacted Spoil
PCS: Phosphatic Clay Slurry
UCS: Uncompacted Cover Soil

Table 4 Summary of Incremental Permeability Tests With Phosphatic Clay/Cover Soil Mix.

TEST (1)	SOIL LAYERS (2)	COEFFICIENT OF PERMEABILITY k_{spoil} (cm/s) (3)	$k_{spoil/phos\ clay-cover}$ (cm/s) (4)	k(3)/k(4) (5)
9(1)	CSP1-UPCC	1.2E-5	8.1E-6	1.5
9(2)	CSP1-UPCC	1.2E-5	2.4E-6	4.8
9(3)	CSP1-UPCC	9.2E-6	1.3E-6	2.2
10(1)	CSP2-UPCC	4.3E-6	1.1E-5	0.4
10(2)	CSP2-UPCC	2.7E-6	3.8E-5	0.1
10(3)	CSP2-UPCC	1.6E-6	1.5E-5	0.1

Key to Soil Layers
CSP1: Compacted Spoil 1
CSP2: Compacted Spoil 2
UPCC: Uncompacted Phosphatic Clay/Cover Soil Mix

Table 5 Summary of One-Step Permeability Tests With Phosphatic Clay/Cover Soil Mix

TEST (1)	SOIL LAYERS (2)	COEFFICIENT OF PERMEABILITY $k_{spoil/phos\ clay-cover\ mix}$ (cm/s) (3)	$\frac{k_{USP}}{k(3)}$ (4)	$\frac{k_{CSP}}{k(3)}$ (5)
11(1)	DESTROYED	-	-	-
11(2)	CSP1-CPCC	7.3E-7	245	15
11(3)	CSP1-CPCC	3.4E-8	5,220	323
12(1)	CSP2-CPCC	3.4E-8	na	84
12(2)	CSP2-CPCC	3.2E-8	na	90
12(3)	CSP2-CPCC	2.2E-7	na	13

Key to Soil Layers
CSP1: Compacted Spoil 1
CSP2: Compacted Spoil 2
CPCC: Compacted Phosphatic Clay/Cover Soil Mix

Average Coefficients of Permeability Used to Obtain Ratios in Columns 4 and 5:
Uncompacted Spoil 1 = 1.8E-4 cm/sec
Compacted Spoil 1 = 1.1E-5 cm/sec
Compacted Spoil 2 = 2.9E-6 cm/sec

Note: No coefficient available for uncompacted spoil 2 because it was not tested in this state.

Table 6 Summary of One-Step Permeability Tests With Phosphatic Clay/Spoil Mix.

TEST (1)	SOIL LAYERS (2)	COEFFICIENT OF PERMEABILITY $k_{phos\ clay-spoil\ mix/cover}$ (cm/s) (3)	$\frac{k_{USP}}{k(3)}$ (4)	$\frac{k_{CSP}}{k(3)}$ (5)
13(1)	CSP1PC-CCS	4.2E-8	4,238	262
13(2)	CPS1PC-CCS	9.3E-9	19,160	1,188
13(3)	CSP1PC-CCS	4.9E-8	3,670	227
14(1)	CSP2PC-CCS	8.0E-8	na	36
14(2)	CSP2PC-CCS	4.6E-8	na	62
14(3)	CSP2PC-CCS	3.8E-8	na	76

Key to Soil Layers
CSP1PC: Compacted Spoil 1/Phosphatic Clay Mix
CSP2PC: Compacted Spoil 2/Phosphatic Clay Mix
CCS: Compacted Cover Soil

Average Coefficients of Permeability Used to Obtain Ratios in Columns 4 and 5:
Uncompacted Spoil 1 = 1.8E-4 cm/sec
Compacted Spoil 1 = 1.1E-5 cm/sec
Compacted Spoil 2 = 2.9E-6 cm/sec

Note: No coefficient available for uncompacted spoil 2 because it was not tested in this state.

Table 7 Summary of Effluent Analyses for Permeability Tests with Phosphatic Clay Slurry

TEST		pH	CONCENTRATIONS (mg/l) Fe	Mn	Mg	Al	Ca	SO_4^{-2}
3(1)	Before	3.89	82	248	557	623	249	9,320
	After	5.73	6	17	80	6	658	2,145
	% Change		(93)	(86)	(86)	(99)	(164)	(77)
3(2)	Before	4.14	186	271	586	344	299	8,580
	After	4.32	13	80	50	10	467	1,833
	% Change		(93)	(70)	(91)	(97)	(156)	(79)

Note: "Before" refers to values obtained prior to the addition of phosphatic clay slurry, while "after" refers to values obtained after the addition of phosphatic clay slurry

Table 8 Summary of Effluent Analyses for Incremental Permeability Tests With Phosphatic Clay/Cover Soil Mix

TEST		pH	METAL CONCENTRATIONS (mg/l) Fe	Mn	Ca	SO_4^{-2}	ACIDITY (mg $CaCO_3$/l) pH7	pH8.3	ELEC COND
9(1)	B	3.60	540	406	430	15,537	7,587	8,625	10.0
	A	-	-	-	-	-	-	-	-
	%	-	-	-	-	-	-	-	-
9(3)	B	3.70	580	370	420	14,106	7,162	8,212	9.6
	A	3.58	320	51	1430	4,100	620	700	3.2
	%		(45)	(86)	(340)	(71)	(91)	(91)	(67)
10(2)	B	2.83	9940	42	550	16,290	16,837	17,138	13.6
	A	3.06	860	11	1340	4,250	820	860	3.7
	%		(91)	(73)	(244)	(74)	(95)	(95)	(73)
10(3)	B	2.35	9730	43	490	13,027	18,825	19,488	16.4
	A	3.21	1010	10	1330	5,300	890	950	4.5
	%		(90)	(80)	(271)	(59)	(95)	(95)	(73)

B: Before addition of phosphatic clay/cover layer
A: After addition of phosphatic clay/cover layer
%: Percent change in concentration with addition of layer

Electrical Conductivity units are mmhos/cm

Tests 9(1) and 9(2) contained spoil 1
Tests 10(2) and 10(3) contained spoil 2

Table 9 Summary of Effluent Analyses for One-Step Permeability Tests With Phosphatic Clay/Cover Soil Mix

TEST		pH	METAL CONCENTRATIONS Fe	Mn	Ca	SO_4^{-2}	ACIDITY pH7	pH8.3	ELEC COND
			(mg/l)				(mg $CaCO_3$/l)		
11(2)	E	3.82	224	37	-	-	4,000	4,400	-
	L	3.12	20	6	545	830	1,750	1,950	1.5
	%		(91)	(83)	-	-	(56)	(56)	-
11(3)	E	3.79	414	410	-	-	30,400	34,700	-
	L	2.98	160	13	548	4,250	6,300	6,900	3.1
	%		(61)	(97)	-	-	(79)	(80)	-
12(1)	E	2.89	2245	43	-	-	25,600	27,400	-
	L	2.56	200	22	511	5,750	1,670	1,760	4.3
	%		(91)	(49)	-	-	(93)	(94)	-
12(2)	E	2.75	7719	90	-	-	73,000	76,500	-
	L	2.45	60	3	660	6,325	1,920	2,025	4.6
	%		(99)	(97)	-	-	(97)	(97)	-
12(3)	E	2.86	4583	134	-	-	34,700	40,700	-
	L	2.98	20	27	322	4,100	2,425	2,840	3.4
	%		(99)	(80)	-	-	(93)	(93)	-

E: Early in test
L: Late in test
%: Percent change in concentration over time

Electrical Conductivity units are mmhos/cm

Tests 11(2) and 11(3) contained spoil 1
Tests 12(1), 12(2), and 12(3) contained spoil 2

Table 10 Summary of Effluent Analyses for One-Step Permeability Tests With Phosphatic Clay/Spoil Mix

TEST		pH	METAL CONCENTRATIONS Fe	Mn	Ca	SO_4^{-2}	ACIDITY pH7	pH8.3	ELEC COND
			(mg/l)				(mg $CaCO_3$/l)		
13(1)	E	3.23	80	173	354	7,575	5,100	8,200	7.6
	L	-	-	-	-	-	-	-	-
	%		-	-	-	-	-	-	-
13(2)	E	3.91	-	-	-	10,000	-	-	8.9
	L	-	-	-	-	-	-	-	-
	%		-	-	-	-	-	-	-
13(3)	E	7.23	-	-	820	4,900	0	20	5.6
	L	6.10	210	37	1050	3,400	0	20	3.5
	%		-	-	(128)	(31)	NONE	NONE	(39)
14(1)	E	3.97	980	57	490	14,100	1,885	2,040	10.0
	L	2.20	320	23	1140	2,920	145	163	3.4
	%		(67)	(59)	(233)	(79)	(92)	(92)	(66)
14(2)	E	3.19	330	36	540	8,850	935	1,030	7.5
	L	3.10	20	18	1050	2,920	170	185	3.1
	%		(94)	(50)	(194)	(67)	(82)	(82)	(59)
14(3)	E	5.12	-	13	810	5,750	25	25	4.9
	L	3.10	23	11	1020	2,660	15	15	2.9
	%		-	(12)	(126)	(54)	(40)	(40)	(42)

E: Early in test
L: Late in test
%: Percent change in concentration over time

Electrical Conductivity units are mmhos/cm

Tests 13(1) through 13(3) contained spoil 1
Tests 14(1) through 14(3) contained spoil 2

Figure 1 Physical arrangement of samples used in study

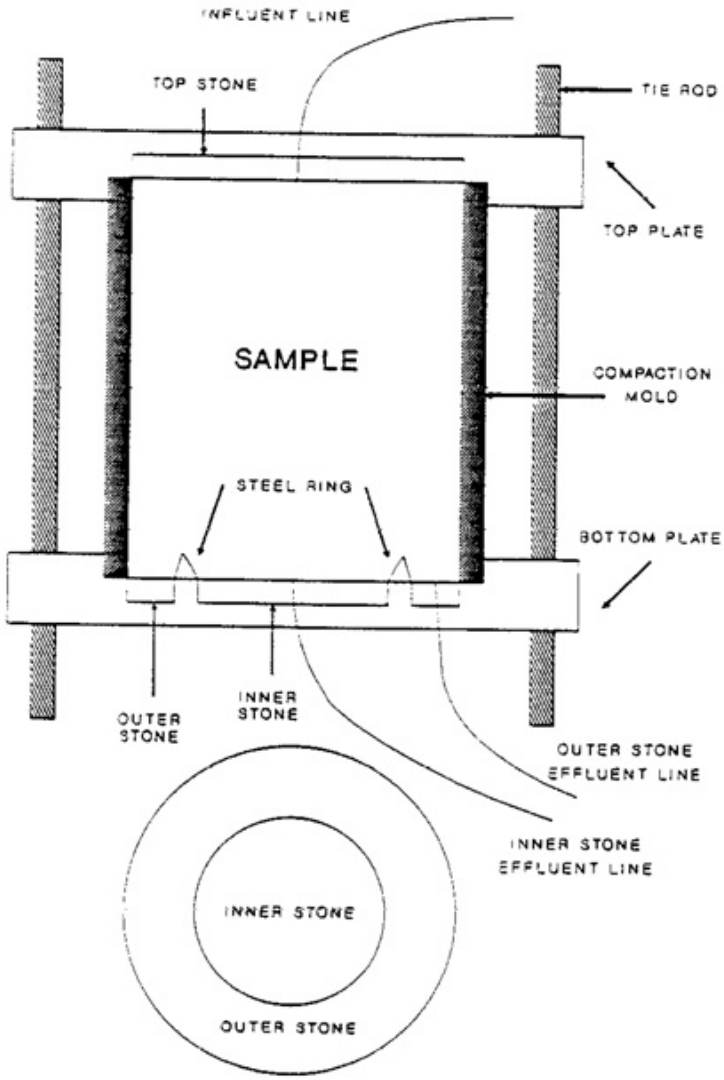

Figure 2 Schematic diagram of fixed-wall double-ring permeameter