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INTERACTION OF INORGANIC LEACHATE WITH COMPACTED POZZOLANIC FLY ASH

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ABSTRACT: This paper presents results of a study on the feasibility of using pozzolanic western coal fly ash, either by itself or mixed with sand, as a construction material for waste-containment liners and impermeable covers. Liners can be constructed from pozzolanic fly ash or fly ash-sand mixtures to meet the usual requirement for the permeability to be 10^{-7} cm/s or less. This paper reports an investigation of the effects of long-term permeation of inorganic leachate solutions on such liner materials. The effluent leachate was tested to determine changes in chemical composition (in particular pH, boron, and heavy metals) due to leaching from the liner. The inorganic solution had no detrimental effect on liner permeability; in fact, the permeability decreased over time. The main chemical change in the permeate solution is an increase in pH, because the fly ash is highly alkaline. This had the beneficial effect of precipitating the heavy metals within the liner, so heavy metals in the effluent were minimal. Overall, the use of compacted pozzolanic fly ash as a liner material appears to be feasible in terms of its physical properties and chemical attributes.

INTRODUCTION

Fly ash is generated in vast quantities (more than 70,000,000 metric tons per year) as a by-product of burning coal at electric power plants (Vesperman 1990). The fly ash is removed from flue gas by electrostatic precipitators or filter bag houses. Some fly ashes, such as those from subbituminous and lignite coals, are pozzolanic; that is, when mixed with water they are self-hardening and set to create a high-strength, lightweight, low-permeability material. These properties make fly ash useful as a concrete additive, a subgrade stabilizer, a fill or embankment stabilizer, and as a soil amendment to promote plant growth. Only about 20% of fly ash is used for these or other purposes; the rest is disposed of by burial in landfills or storage in lagoons (Bowders 1988).

Storage and solid-waste-containment facilities must be lined to restrict the escape of leachate from the site. Pozzolanic fly ash is attractive as an alternative to clay as an impermeable-liner construction material for landfills and storage lagoons (Vesperman et al. 1985; Sachdev and Amdurer 1985; Bowders et al. 1987).

The suitability of a material for construction of a liner depends on the following factors.

- Permeability, or hydraulic conductivity, is a measure of the mate-

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rial's ability to provide containment of leachate. A low permeability, generally less than 10^{-7} cm/s or less, is required for a liner to be acceptable under most state codes.

- Durability and resistance to weathering is the quality of bonding in the material, which should be strong enough to withstand the destructive forces of alternating wet/dry and freeze/thaw cycles.
- Constructability, which means the material should be reasonably workable in terms of placement and compaction under field construction conditions.
- Compatibility with leachate, which means the liner material must maintain its strength and low permeability after prolonged contact with the leachate solution, should not release harmful chemicals from its matrix to the leachate solution, and should have an adsorptive or attenuative capacity for critical pollutants, such as heavy metals.

In previous studies (Edil et al. 1987; Edil and Berthouex 1987; Burkhalter 1987), it was found that the class C pozzolanic fly ash used in this study met several of the foregoing criteria when used alone, mixed with sand, and mixed with bentonite. The average permeability of laboratory specimens compacted at optimum water content was low enough to meet the usual landfill liner permeability requirement of 10^{-7} cm/s or less. Physically, fly ash particles are silt-sized. This particle size is generally associated with frost susceptibility and low plasticity, raising the question of whether the material would deteriorate in freeze/thaw conditions and doubts about its rigidity. It was found that wet/dry and freeze/thaw cycles typical of the climate in the northern United States did not significantly affect the permeability, static modulus of elasticity, or tensile strength of the compacted fly ash liner specimens. One concern with class C fly ash is the fast speed of the pozzolanic reactions, which could cause the material to set before it could be placed and compacted under field conditions. It was shown that careful control of the construction variables (water content, compactive effort, and time elapsed after adding water) and the addition of set retarders (such as lignin solutions) does make construction practical. Short-term permeation tests (three to five pore volumes) using simulated coal-pile runoff as a leachate indicated that: (1) A wide range of influent pH (pH 4 to 10) and salt content did not cause undesirable changes in the permeability of the liner specimens; (2) heavy metals in the fly ash (in low concentration) and influent were not released into the effluent; and (3) that boron in the influent was attenuated.

Based on these favorable results, fly ash appeared to have potential utility as a liner construction material, and the performance of long-term permeation tests was considered worthwhile to check the conclusions about chemical stability and leachate effluent quality for fly ash and fly ash/sand mixtures. A major concern associated with using fly ash as a landfill liner is that undesirable elements, such as heavy metals, may leach into solution and be transported through the liner by the leachate. This was investigated in this study. These permeation tests were done on samples having different permeabilities, and hence different leachate-retention times, to determine whether permeability would affect the effluent quality of a fly ash/sand liner. Some clay liner specimens were also tested in long-term permeation in order to compare the effluents from clay and fly ash liners.

Two objectives of this study were to determine the effect of long-term permeation (20 + pore volumes) of an inorganic permeant on the perme-

ability and the effluent characteristics of a compacted liner made of fly ash and sand.

EXPERIMENTAL PROGRAM

Compacted specimens of a fly ash and sand mixture and a liner clay were prepared to have different permeabilities. These were used in long-term permeation tests. The permeability of a specimen is inversely proportional to the permeant solution retention time and, consequently, to the time available for the leachate to be affected by chemical reactions as it passes through the liner specimen. The objective was to investigate whether low-permeability specimens were affected more than high-permeability specimens with respect to changes in permeability and leachate-effluent quality. It was also of interest to learn whether using high-permeability specimens could be used in testing for chemical breakthrough of liners. If possible, this would provide results much faster than using test specimens having the typical statutory permeability of 10^{-7} cm/s in all tests. Clay and fly ash/sand specimens having similar initial permeabilities were compared in terms of leachate-effluent quality and changes in permeability.

Soil Materials

The ASTM class C pozzolanic fly ash used was from the Wisconsin Power and Light Columbia Unit II power plant, which burns coal from ARCO's Black Thunder mine, in Wyoming. Class C pozzolans are produced by burning lignite and subbituminous coals. The physical and chemical properties of the fly ash are given in Table 1. The sand that was mixed with fly ash was coarse Portage sand, mined near Portage, Wisc., which is referred to as #4060 sand. The clay used in these tests was being considered for use as a liner construction material for a proposed landfill in Wisconsin. The deposit from which the clay was taken is characterized by an average liquid limit of 43%, plasticity index of 19%, clay content of 26%, optimum moisture content of 17.5%, and maximum dry unit weight of 16.8 kN/m³.

Preparation of Test Specimens

The fly ash/sand samples consisted of 50% fly ash and 50% sand, by dry weight. The following procedure was used for the samples that contained fly ash: (1) Dry mix the fly ash and sand to produce a uniform mixture; and (2) add the required amount of tap water (established from prior testing to be 7%) and mix until a uniform consistency is achieved. The procedure for clay specimens was to: (1) Air dry the clay and break up clumps; (2) add the required water (18–20%) and mix; (3) place the clay in a pan and cover with damp paper towels; and (4) wrap in the pan with plastic and hold for 24 hr so the moisture content reaches equilibrium. The compaction procedure for fly ash and clay samples in preparing test specimens involved the following steps: (1) Hand tamp three equal layers of moist fly ash or clay into the Proctor mold (102 mm diameter, 114 mm high); (2) apply a pre-determined static pressure (known from previous testing for a specific permeability) with a hydraulic compression machine for 30 sec; and (3) trim the specimen, extrude it from the mold using a hydraulic jack, and weigh it.

Different compaction pressures were used to prepare specimens with different densities and, consequently, permeabilities. The fly ash specimens that were to have a "low" permeability were compacted using a force of

TABLE 1. Chemical and Physical Properties of Fly Ash

Mineral (1)	Property (2)	Black Thunder % (3)	Black Thunder (4)
SiO ₂		36.9	
Al ₂ O ₃		18.8	
TiO ₂		1.4	
Fe ₂ O ₃		6.2	
CaO		25.4	
MgO		4.9	
K ₂ O		0.3	
Na ₂ O		1.4	
SO ₃		2.5	
P ₂ O ₅		1.2	
SrO		0.3	
BaO		0.5	
Mn ₂ O ₄		0.1	
	Silica value		50.3
	Base: acid ratio		0.67
	Specific gravity		2.60
	Sand fraction ^a		25–45%
	Silt fraction ^b		55–75%
	Uniformity		6–9

^aPercent retained on #200 sieve; maximum grain size 0.3 mm.

^b0.002–0.075 mm.

44,480 N for 30 sec resulting in a dry unit weight of 19.6 kN/m³; the "high" permeability specimens were compacted at 8,896 N for 30 sec resulting in a dry unit weight of 18.7 kN/m³ (all specimens had the same area of 8,107 mm²). The clay specimens were also compacted statically to 90–95% of the maximum standard Proctor dry density at water contents just wet of optimum. The resulting unit weights of the low- and high-permeability clay specimens were 16.2 kN/m³ and 15.4 kN/m³, respectively. All the fly ash specimens were cured for seven days according to ASTM Standard Procedure D1632-63 (that is, protected from free moisture in a 100% relative humidity room at 21°C).

Permeameter Design and Operation

The permeability tests were conducted using a variation of the flexible-wall permeameter described by House (1985) (shown in Fig. 1). The flexible-wall permeameters were designed to hold 102 mm diameter specimens made in a Proctor mold. Marriotte bottles were used as inflow and outflow reservoirs to maintain a constant-pressure closed system and to provide a continuous source of feed solution. These bottles were closed to the atmosphere, but open to an air-intake tube, which pressurized the bottles. The Marriotte bottles were specially blown from borosilicate glass to withstand working pressures of 620 kPa and to hold about 380 cm³ of fluid. Graduated Plexiglas burettes, connected in parallel with the Marriotte bottles and accurate to 0.05 cm³, were used to measure the flow rates from which the permeability was calculated. All permeant lines were of 4.7 mm outside diameter nylon tubing. Brass ball valves and fittings were used on

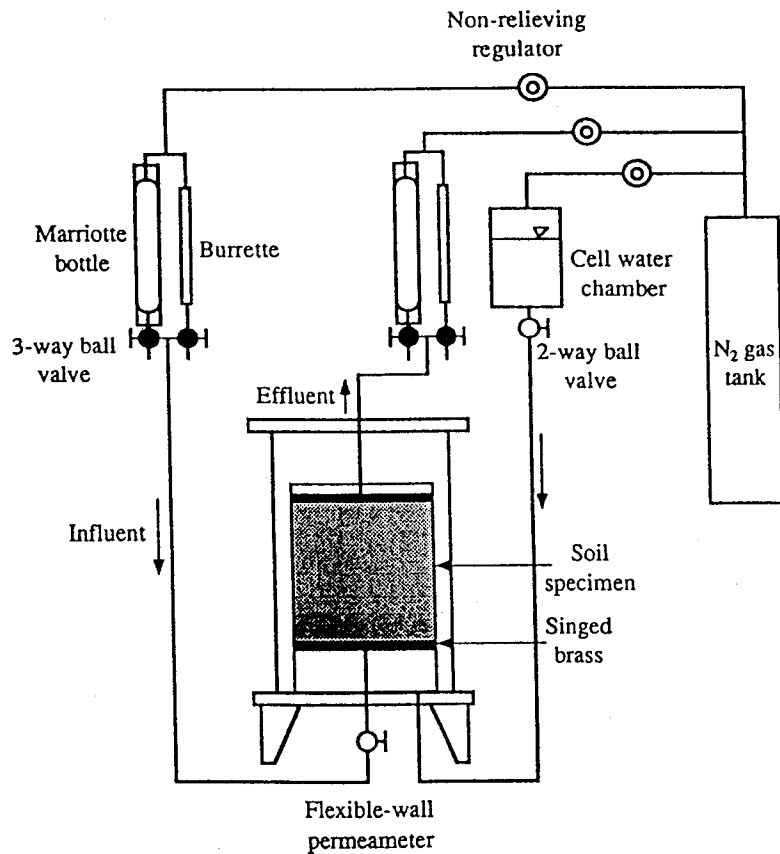


FIG. 1. Flexible-Wall Permeameter Setup

all fluid (air and liquid) lines. Air pressure was controlled by relieving regulators and measured with a pressure transducer that was accurate to 0.7 kPa.

The coefficient of permeability (hydraulic conductivity) was calculated assuming flow under a constant head. This assumption gives a coefficient valve that is within 1% of that estimated by the falling-head equation that would be more strictly correct for these tests. House (1985) determined the sensitivity of the coefficient of permeability to be acceptable with respect to the precision of the measured and controlled test variables of the experiment.

Leachate Feed Solution

The permeant solutions were either Madison tap water or a solution of inorganic salts in deionized water. The composition of these solutions is given in Table 2. The sodium, chloride, sulfur, boron, and cadmium concentrations of the salt solution were selected to be similar to the leachate from a fly ash storage facility since this was a potential use of a fly ash liner in Wisconsin. Of course, there are many other industrial solid wastes that

TABLE 2. Inorganic Permeant Concentrations

Element (1)	Inorganic Permeant Solution		Madison tap water (4)
	Design (2)	Measured (3)	
B	15 mg/L	15 mg/L	0.1 mg/L
Ca	50 mg/L	45 mg/L	63 mg/L
Cd	15 mg/L	14 mg/L	<0.012 mg/L
Na	1,384 mg/L	1,315 mg/L	3 mg/L
Zn	3 mg/L	2.6 mg/L	4 mg/L
Cl	1,633 mg/L	1,680 mg/L	---
SO ₄ (as S)	267 mg/L	250 mg/L	4 mg/L
[pH]	7-8	7-8	7.5
[Conductivity]	—	4,000 micromhos/cm	70 micromhos/cm

would contain high levels of these elements. Aside from this, these chemicals are interesting to evaluate because: (1) Boron is generally considered to be mobile, and it is phytotoxic; (2) cadmium is a toxic heavy metal for which strict ground-water and surface-water standards exist; and (3) high sodium levels can affect the physiochemical properties of clays.

The clay samples were initially permeated with tap water until approximately one pore volume of effluent had been collected and then the permeation with inorganic salt solution was started. All the fly ash specimens were permeated with the inorganic salt solution from the start of the experiment.

Leachate Effluent Analyses

All effluent samples were collected in 250 ml polyethylene bottles that had been cleaned in an acid bath. From this sample, a 20 ml aliquot was taken to be used for metal analyses. This was placed in a 25 ml polyethylene bottle, to which 5 ml of 1:1 nitric acid was added as a preservative.

Immediately after sample collection, the pH of the nonacidified sample was measured using an Orion research Model 901 ion analyzer and a Corning pH electrode. The effluent from fly ash specimens was highly alkaline, so the pH meter was calibrated at two levels, pH 7.0 and pH 12.0 (or 12.5). For clay specimens the effluent was near neutral pH and calibration was done at pH 7.0. The pH-values were recorded to the nearest 0.01 unit. Alkalinity and conductivity were also measured very soon after the sample was collected. Alkalinity was measured according to *Standard Methods* (1985); and conductivity measurements were made with a Kernco Instruments Co. Type 60 conductivity meter.

Silica, chloride, total dissolved solids, and total solids were measured according to *Standard Methods* (1985). The acidified samples were analyzed for cadmium, strontium, selenium, arsenic, chromium, calcium, sodium, sulfate (sulfur), zinc, aluminum, and boron by the Soil and Plant Analysis Laboratory, University of Wisconsin-Madison, using inductively coupled plasma emission. The samples were stored at 4°C until the analyses were done.

RESULTS AND COMMENT

The observed effluent patterns for permeability and for each chemical species were plotted as a function of pore volumes of effluent discharged.

The time required for one pore volume to pass through the low-permeability test specimens was much longer than the throughput time for the high-permeability specimens, being approximately seven days and two days, respectively, for the fly ash/sand specimens. This is why fewer pore volumes of leachate were collected from the low-permeability specimens even though all tests were carried through the same length of time.

Permeability of Fly Ash/Sand Specimens

Permeability gradually decreased over time in most specimens, as shown in Fig. 2(a). In no case did the permeability increase over time, and there is

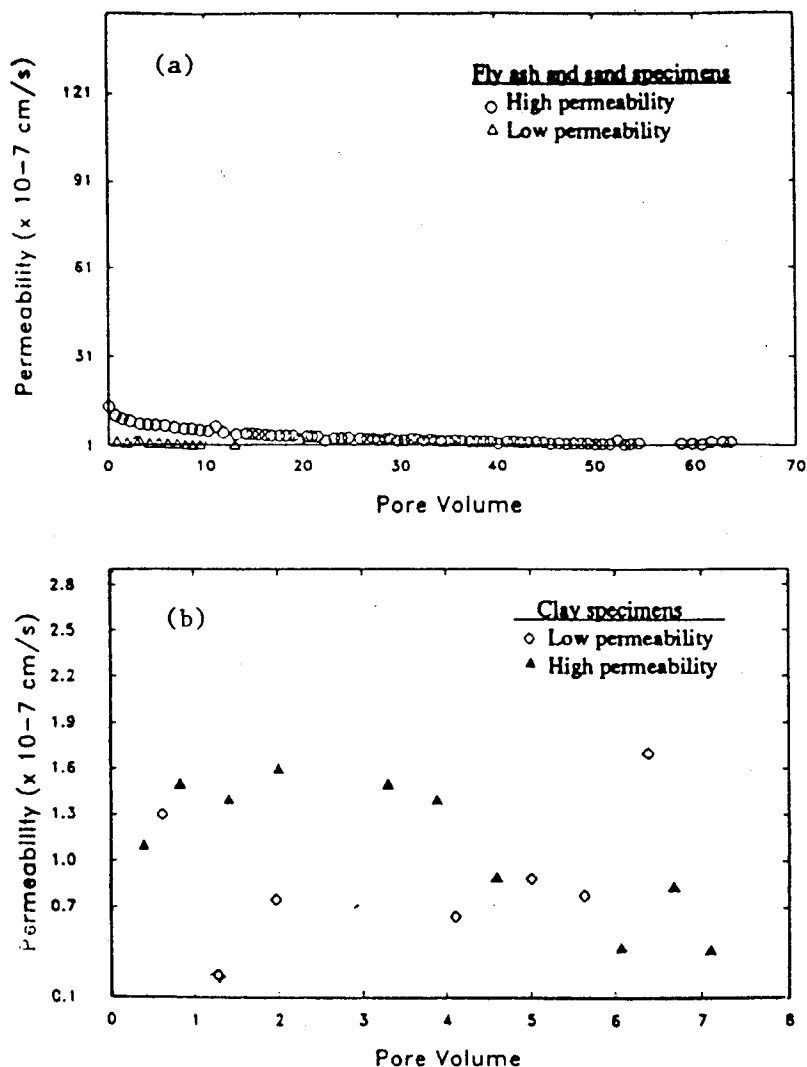


FIG. 2. Coefficient of Permeability versus Pore Volume of Flow

no indication that the inorganic leachate solution had any adverse effect on the permeabilities of the fly ash/sand specimens. This observation was consistent with the water-permeation test results of House (1985) and Burkhalter (1987) and with the inorganic solution tests of Edil and Berthouex (1987). This trend is attributed to the relatively slow hydration (cementation) reactions continuing throughout the experiment (Edil and Berthouex 1987).

To assess the effects of long-term permeation on the effluent characteristics, the fly ash/sand effluent characteristics were compared with the short-term test (three pore volumes) results reported by Edil and Berthouex (1987). These tests had used the same inorganic permeant and the same materials and procedures to make the specimens. In the short-term tests, boron and cadmium levels did not vary with permeability. The long-term permeation tests showed a higher concentration of cadmium at the low-permeability condition. The boron concentrations after about 10 pore volumes were higher for the high-permeability condition in the longer tests. The short-term tests indicated that the zinc concentrations were significantly higher for the low-permeability than for the high, whereas the long-term tests showed very little difference.

One conclusion is that long-term permeation tests should be used because the critical conditions may occur initially or after many pore volumes have been processed. Understanding of the process at this time is incomplete, and the rates and patterns of the transient behavior cannot be predicted with confidence.

With respect to trying to shorten the duration of the long-term tests by using a more permeable specimen, it is concluded that this would be acceptable only if the initial behavior is not of critical interest. The high- and low-permeability specimens tended to reach the same levels after 10–20 pore volumes of leachate had passed through, but large differences could be observed during the first part of the tests.

Effluent Chemical Quality for Fly Ash/Sand Specimens

The leachate quality was measured in terms of the chemical species that were in the feed solution (boron, calcium, cadmium, sodium, zinc, chloride, and sulfate) and for elements of special interest that were expected in the fly ash (aluminum, arsenic, chromium, selenium, silica, and strontium). None of the latter were present in the feed solution.

At this time no model has been developed to predict the complex simultaneous chemical reactions that occur. This means that these results should not be extrapolated to other soil mixtures or feed solutions. Future work should be directed toward this goal. A starting point for this model would be to assume that the system is always in equilibrium with respect to pH and alkalinity. The main difficulties are associated with the many possible chemical forms in which the most important elements may exist.

Figs. 3(a) and 4(a) show pH and alkalinity. For the fly ash/sand specimens, the initial pH was 12.0–12.5, decreasing to an apparent steady-state level slightly above pH 11.5. The clay specimens had nearly neutral pH throughout the test.

At the high pH levels observed for fly ash specimens, the alkalinity would be in the form of hydroxide, which would be created by the dissolution of oxides in the fly ash. Alkalinity and the pH decrease as oxides are removed from the fly ash. The alkalinity patterns for the fly ash samples, therefore, matched the pH patterns, generally starting from a high level and decreasing over time.

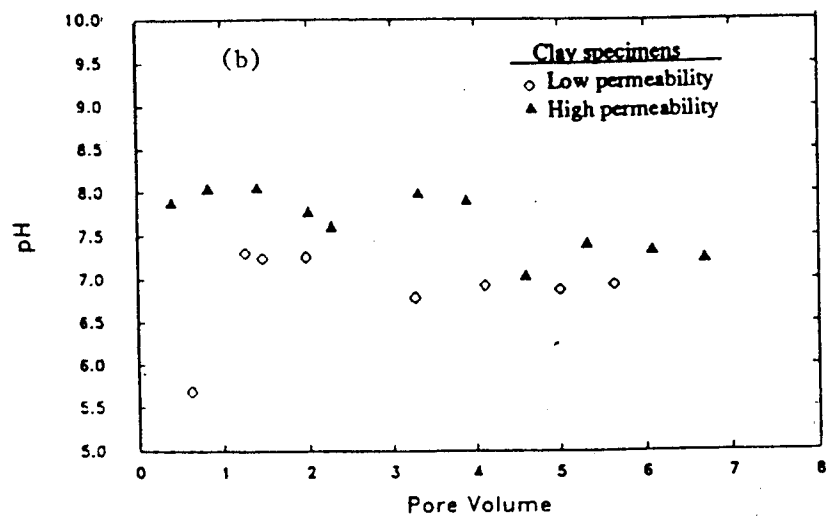
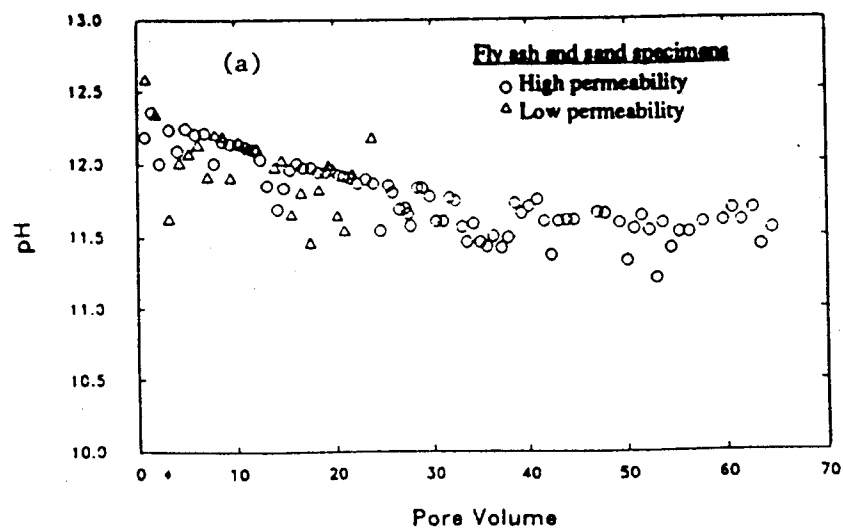


FIG. 3. pH of Effluents

The changes in pH affected the desorption/adsorption or dissolution/precipitation of some of the metals. Corresponding to the high initial pH of the high-permeability fly ash/sand specimen were high concentrations of aluminum, zinc, and arsenic; the initial boron and strontium concentrations were low. As the pH of these specimens decreased, the high- and low-permeability fly ash specimens became similar with respect to pH and other measures of effluent quality. For the low-permeability specimen, the pH was decreasing and there was an increase in boron and a decrease in the aluminum, zinc, and arsenic concentrations. Cadmium and zinc were insoluble at high pH and were effectively removed, and with their concen-

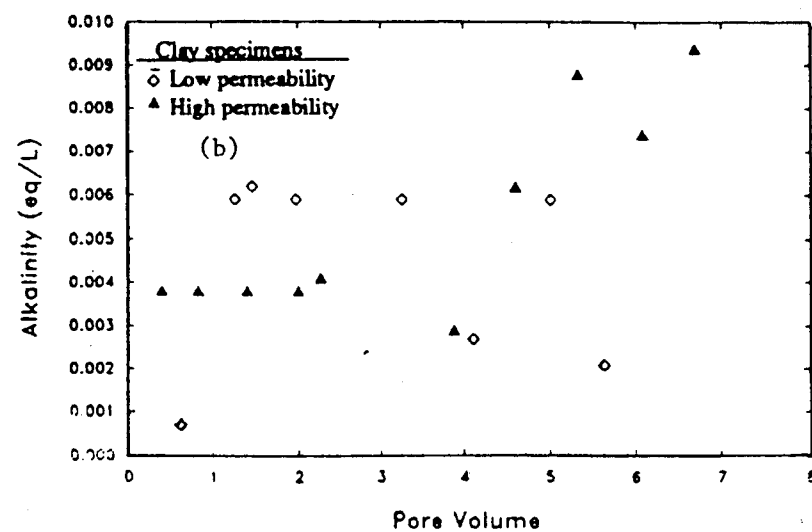
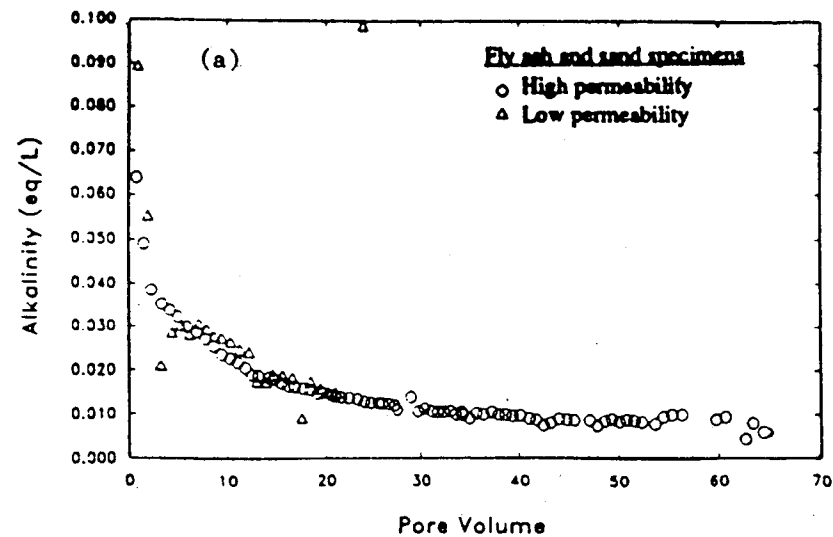


FIG. 4. Alkalinity of Effluents

trations often dropping below the analytical limit of detection. Chromium was released from the fly ash. Strontium increased for about five to 10 pore volumes and then decreased.

The release patterns can be classified into a few basic shapes. Fig. 5 shows two general types of response that were observed for species that were released from the fly ash/soil matrix (i.e., that were not present in the feed solution). These responses are called the first-flush response and the lagged-flush response. The first-flush response occurs when a chemical species is soluble under the initial permeation conditions (high pH, high soil matrix

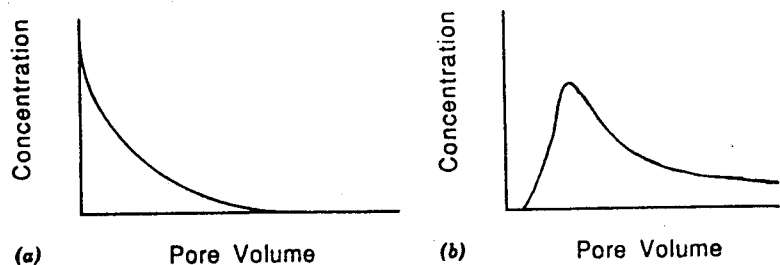


FIG. 5. Typical Effluent Response Curves of Elements Released from Fly Ash: (a) First Flush; (b) Lagged Response

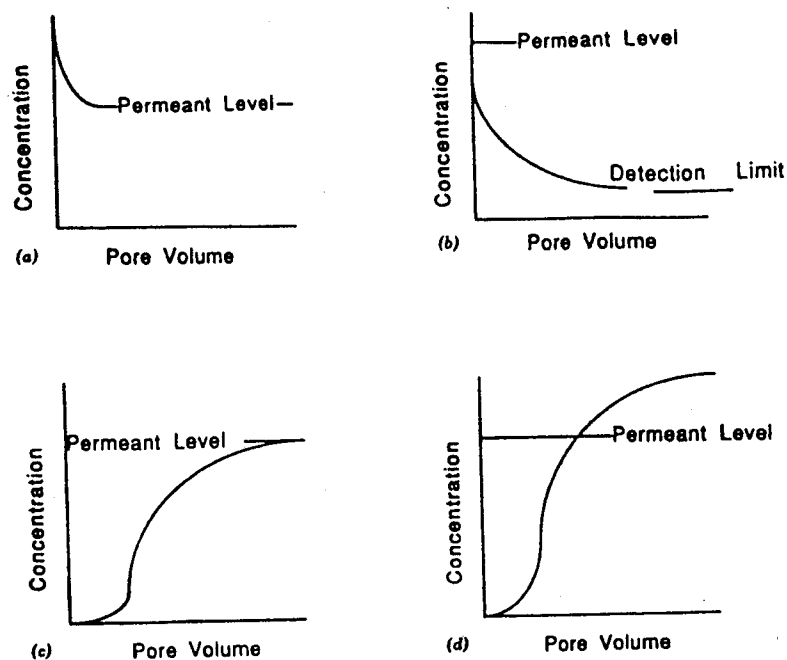


FIG. 6. Typical Effluent Response Curves of Elements in Inorganic Permeant: (a) Type 1; (b) Type 2; (c) Type 3; (d) Type 4

concentration, or low solution concentration). The decrease in concentration with time could be due to a drop in solubility as the pH and alkalinity decrease (e.g., aluminum) or a drop in the species concentration in the soil matrix. The lagged-flush response represents the opposite initial response of the first flush. Initial conditions foster retention of species that become more soluble as the pH and alkalinity decrease (e.g., some metals, strontium).

Four basic release patterns, shown in Fig. 6, were observed for the species that were in the feed solution. The first few pore volumes represent a transition between the tap water initialization and discharge of the chemical leachate.

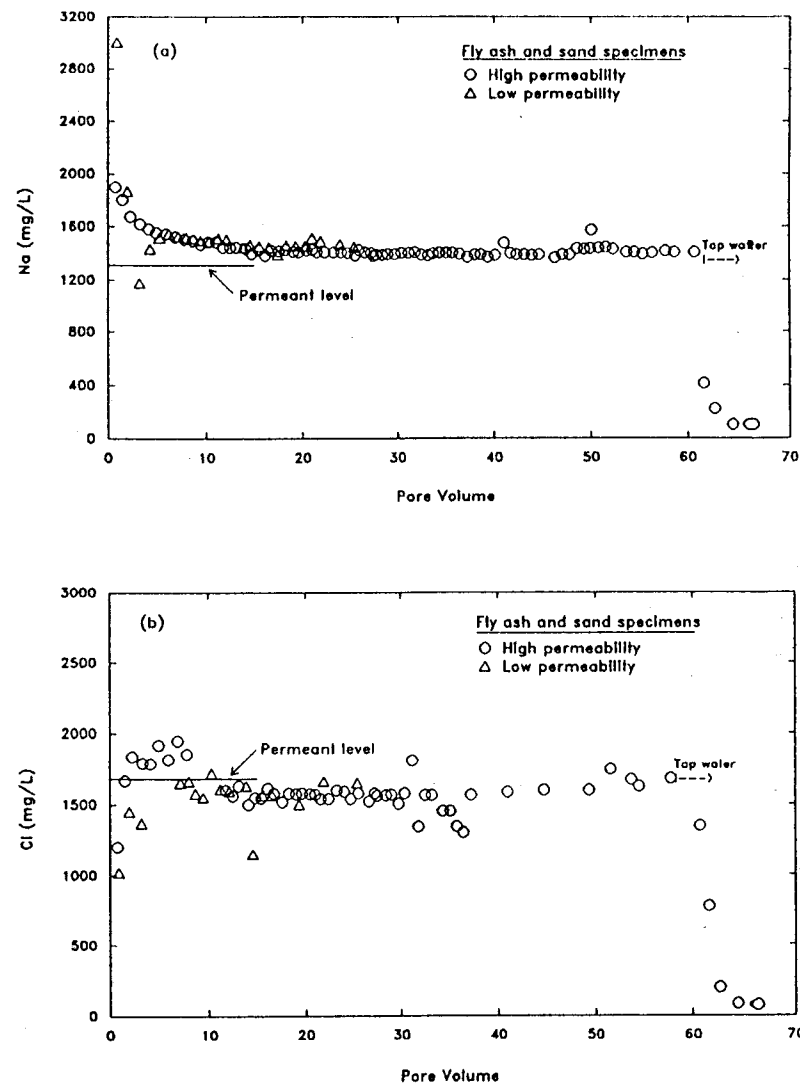


FIG. 7. (a) Sodium and (b) Chloride Effluent Concentrations

- Type 1—effluent concentration decreased to equilibrium at the permeant concentration. This occurred for the highly soluble simple species, specifically sodium and chloride.
- Type 2—effluent concentration decreased to equilibrium below the permeant concentration (and perhaps also below the detection limit). Cadmium and zinc showed this response.
- Type 3—a breakthrough curve that reached equilibrium at approximately the feed concentration. On a finer time scale (say one to three pore volumes) any soluble species would show a typical break-

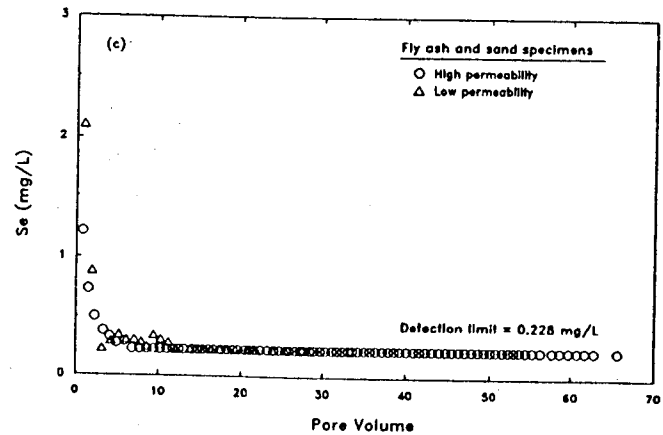
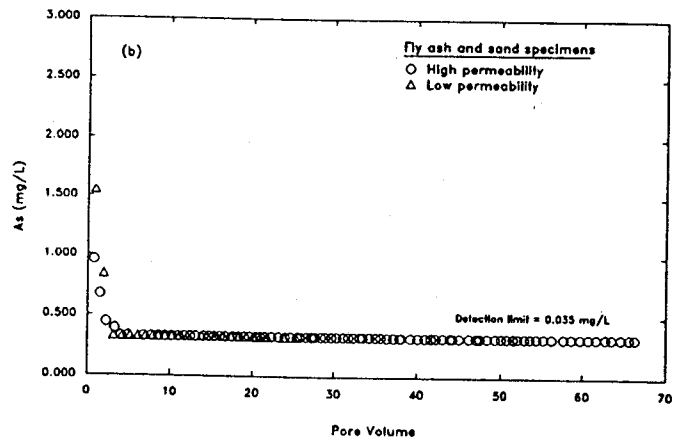
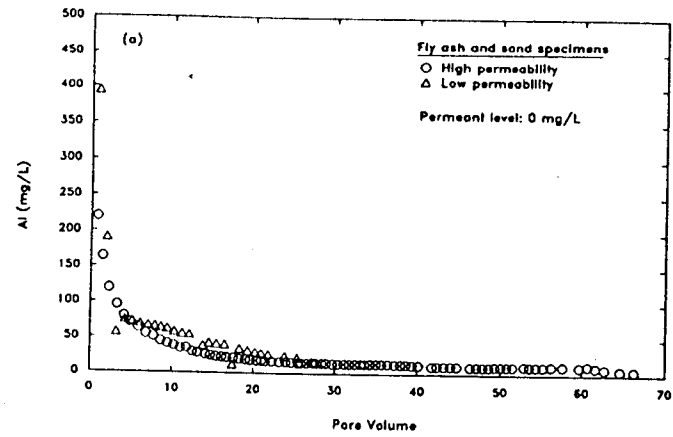


FIG. 8. (a) Aluminum; (b) Arsenic Effluent Concentrations; and (c) Selenium Effluent Concentration

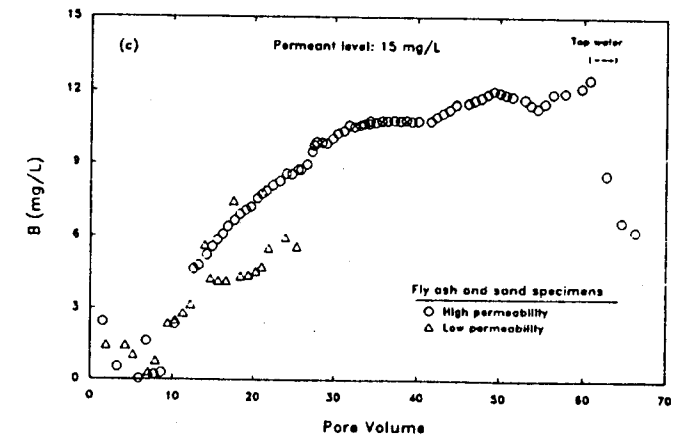
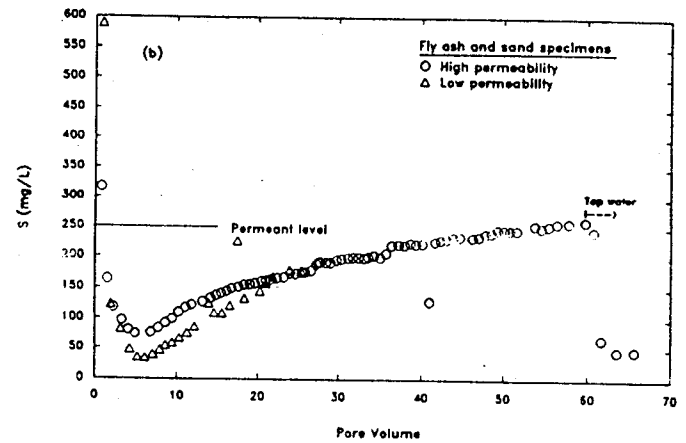
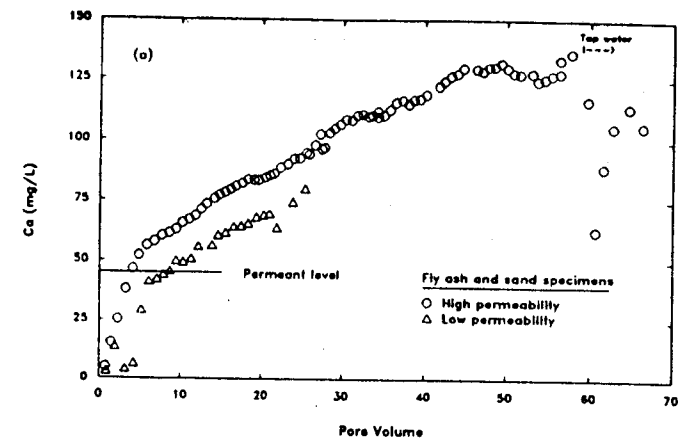


FIG. 9. (a) Calcium; (b) Sulfur Effluent Concentrations; and (c) Boron Effluent Concentration

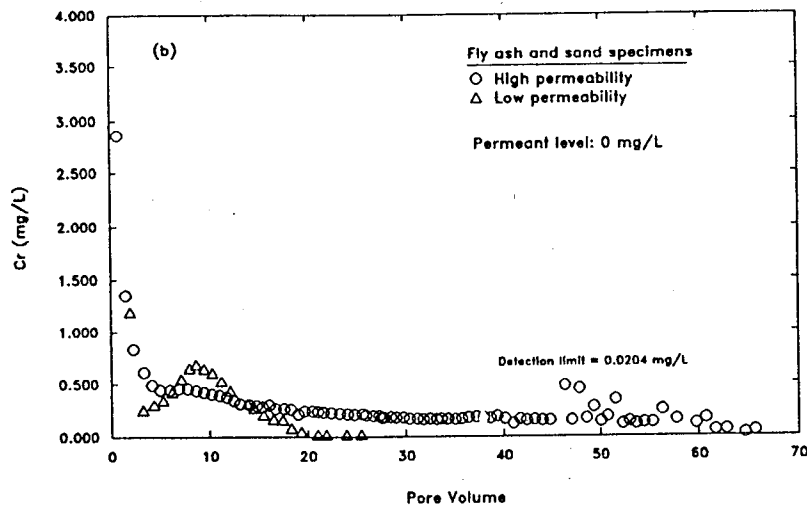
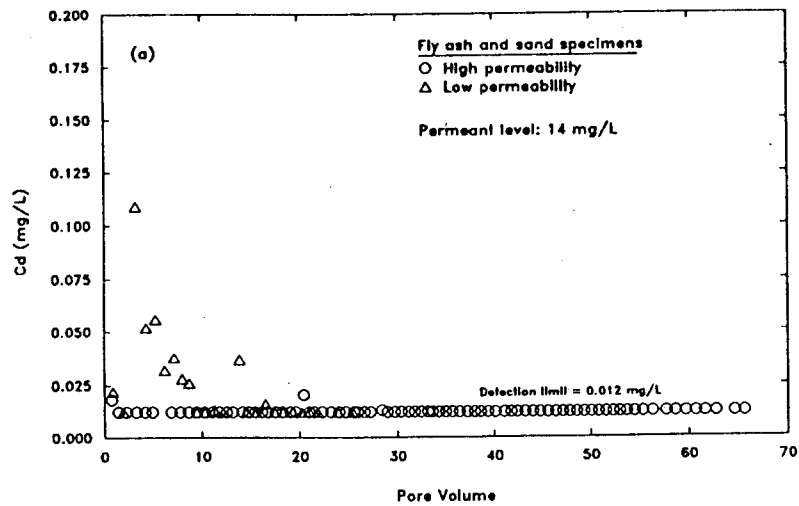


FIG. 10. (a) Cadmium and (b) Chromium Effluent Concentrations

through curve. The breakthrough curve for boron has the type 3 shape but it results because the chemistry of boron is complex at high pH and not simply because of physical dispersion in the sample (Rai and Zachara 1984). At pH 12.5 boron forms hydroxide complexes that are immobile; these are destroyed as the pH drops and boron is transformed into mobile species. Sulfur (sulfate) was also type 3, being removed initially, probably as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), and then being released as the pH decreases.

- Type 4—a breakthrough curve that increased to a concentration

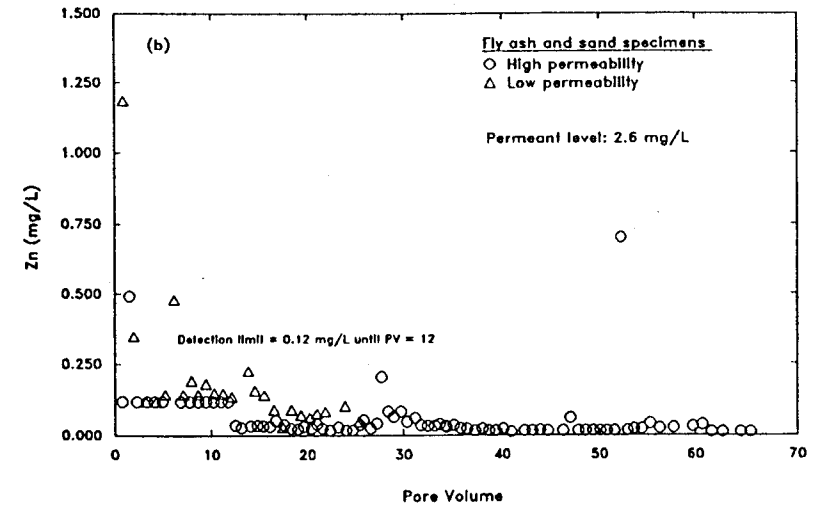
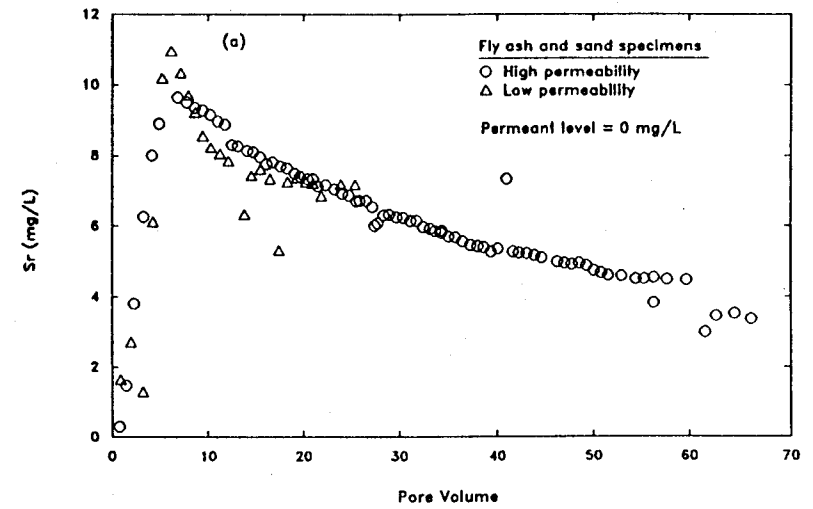


FIG. 11. (a) Strontium and (b) Zinc Effluent Concentrations

greater than that of the feed solution. Calcium showed this behavior when the inorganic salt influent was used. There is little carbonate in the system to precipitate the calcium, but at the high pH-level calcium may precipitate as $\text{Ca}(\text{OH})_2$ or as gypsum. Calcium would also enter the hydration reactions of the pozzolanic material. As the pH decreases gypsum precipitation will decrease, and gypsum may actually dissolve, thus increasing the concentration of both calcium and sulfur (sulfate) in the effluent. When the feed solution was switched to tap water the Ca concentration decreased. This was

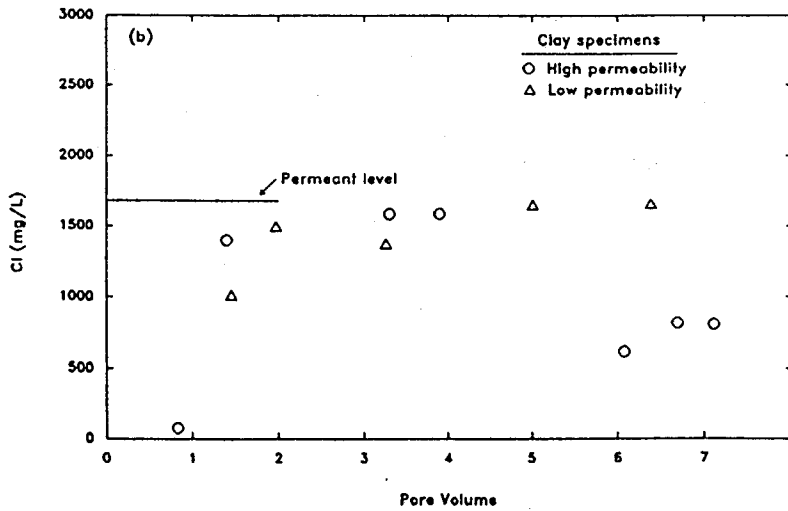
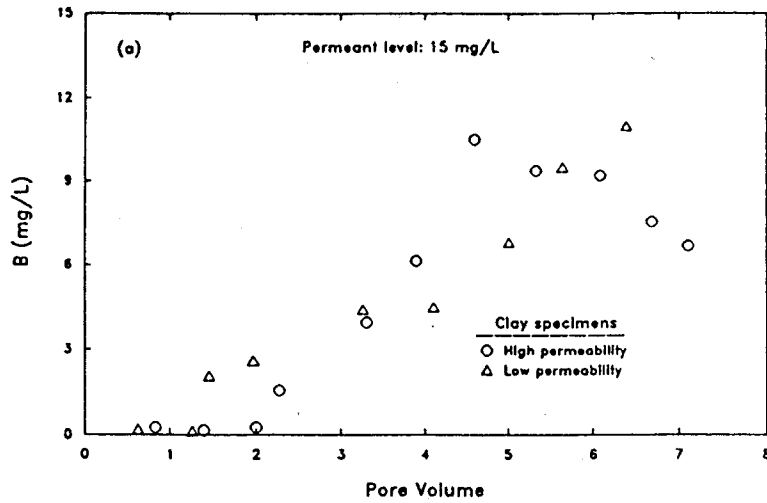


FIG. 12. (a) Boron and (b) Chloride Effluent Concentrations in Clay Specimens

because Madison tap water is high in carbonate alkalinity, which precipitates calcium at high pH conditions.

These patterns could be generalized further by saying that some tests reached equilibrium at the feed permeant concentration and the rest found another equilibrium level. In the first case the chemical species has a simple chemistry (it is highly soluble and mobile). The latter cases indicates a more complex dependence of species on each other, on pH, and perhaps on the physical properties (e.g., permeability and pore structure) of the liner specimen.

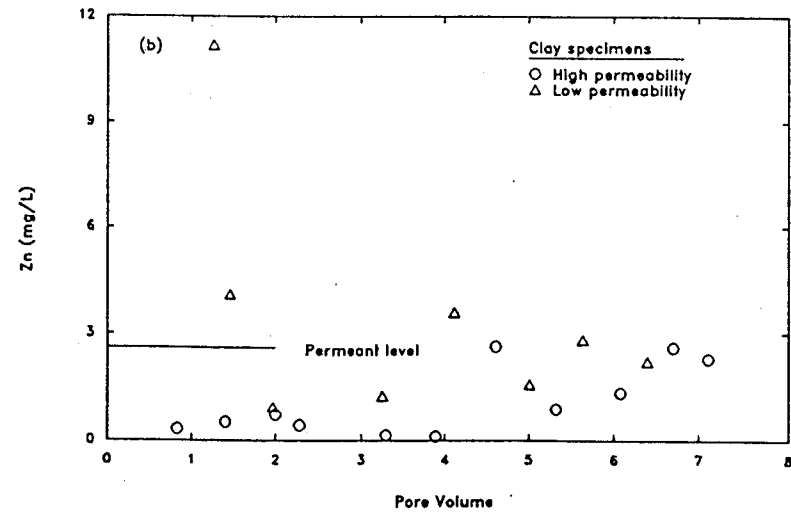
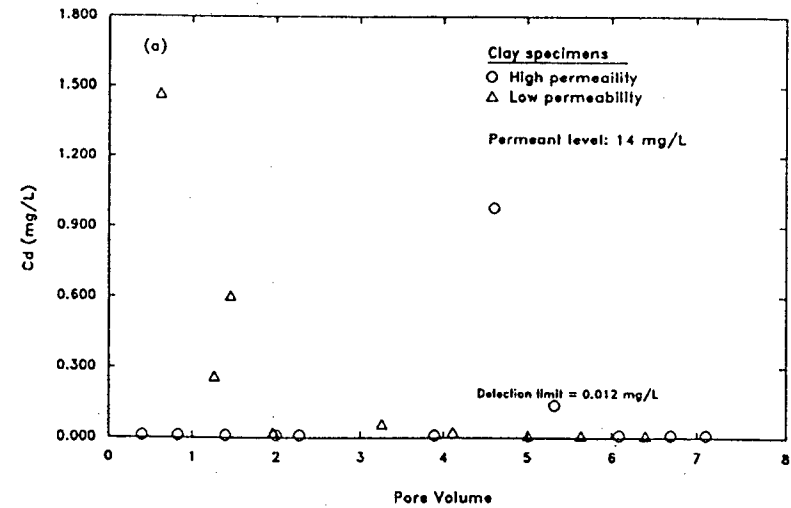


FIG. 13. (a) Cadmium and (b) Zinc Effluent Concentrations in Clay Specimens

For the fly ash/sand specimens, the effluent-concentration patterns are shown in Figs. 7-11. Sodium, chloride, aluminum, and arsenic were the same for the high- and low-permeability specimens (Figs. 7 and 8). This was also true for total dissolved solids (not shown), pH, and alkalinity (Figs. 3 and 4). Calcium, sulfur, and boron concentrations were lower when the permeability was lower but the general shape of the concentration-versus-pore volume curves did not depend on permeability (Fig. 9). Cadmium, chromium, and zinc concentrations were slightly higher when the permeabilities were lower (opposite of calcium, sulfur, and boron) (Figs. 10 and

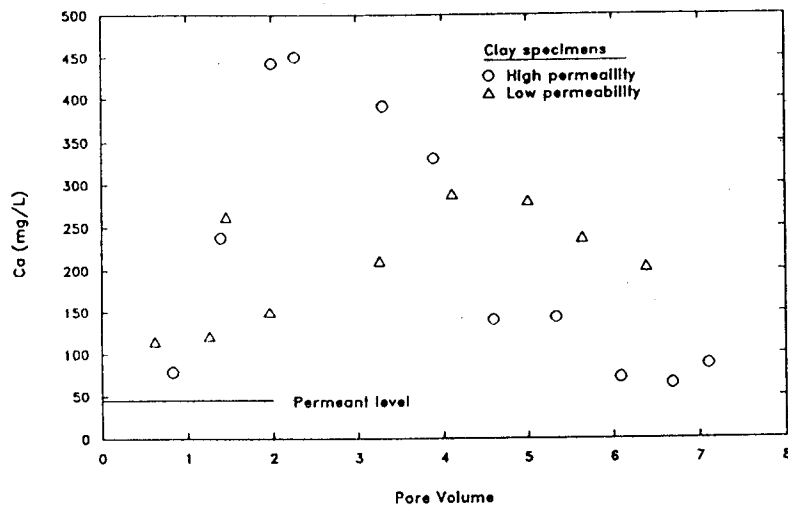


FIG. 14. Calcium Effluent Concentration in Clay Specimens

11). Strontium was released initially, with the concentration reaching a peak at about eight to 10 pore volumes, after which the concentration showed a steady exponential decrease (Fig. 11).

After 60 pore volumes of inorganic solution had been permeated through the high-permeability sample, the feed solution was switched to be Madison tap water. This caused the concentrations of sodium, chloride, calcium, boron, sulfur, total solids, and total dissolved solids to drop rapidly to the feed concentration (see Figs. 7 and 9 for some of these elements).

Leachate Quality for the Clay Liner

The permeability of the clay samples remained fairly constant at a level of about 10^{-7} cm/s through the tests [Fig. 2(b)]. The high-permeability sample had a slightly higher pH than the low-permeability sample [see Fig. 4(b)], but both samples were at near neutral pH with a slight decrease over time. Typical breakthrough responses were observed for boron, chloride, sodium, and sulfur (see Fig. 12 for boron and chloride). There was good removal (adsorption/precipitation) of cadmium, but little removal of zinc (Fig. 13). Calcium demonstrated a lagged response, reaching a maximum concentration above the feed concentration but then dropping to the influent concentration. The low-permeability sample appeared to be showing the same pattern but had not reached equilibrium when the test was terminated (Fig. 14).

SUMMARY AND CONCLUSIONS

The research reported herein forms a part of a study investigating the feasibility of using compacted pozzolanic, western coal fly ashes, either by themselves or mixed with sand, as potential landfill liner materials. Previous studies (Edil and Berthouex 1987) indicated the following.

It is possible to achieve permeabilities less than 1×10^{-7} cm/s. The major variables, besides the compaction effort and moisture content, affecting the permeability is the type and percentage of fly ash used.

Fly ash and fly ash/sand specimens have displayed a tensile strength of slightly lower than the common tensile strength of concrete while being 1/10 as rigid as concrete.

Climatic conditions typical of the northern United States should not significantly affect the permeability or the physical properties of the ashes, as shown in the modified exposure tests performed by House (1985) and Burkhalter (1987).

Adding 10% bentonite improves the workability of the fly ash mixtures but not their permeability.

Comparisons of leachate from specimens with two different permeabilities showed the following: (1) The calcium and sulfur concentrations were lower when the permeability was lower. However, the shape of the concentration-versus-pore volume curve was approximately the same. (2) sodium, chloride, boron, cadmium, and pH data showed no significant changes. And (3) zinc concentrations were higher with lower permeabilities.

The following are the conclusions of this phase of the study. Until some equilibrium/geochemical modeling can be performed to evaluate precipitation and adsorption processes, these are basically qualitative interpretations.

A synthetic inorganic solution simulating a fly ash landfill leachate did not have an adverse effect on the permeability of the compacted fly ash.

The permeability affects the concentrations of certain elements leaching or desorbing out of, or adsorbing into, the fly ash. Calcium, sulfur, and boron concentrations are lower in the low-permeability specimens. Cadmium and zinc concentrations are higher in the low-permeability specimens.

The high pH of the fly ash leachate helped keep the cadmium, zinc, and boron in the fly ash matrix. Chromium, however, was released at a low level (<1 mg/L) for most of the test periods.

Many of the constituents found in fly ash had a slight first-flush phenomenon. This may not be a problem, however, since this occurs for such a short period of time (about five pore volumes) and at such low concentrations that dilution effects may eliminate any problems.

The clay specimens did not demonstrate any adverse effects in permeability. The differences in the effluent characteristics for clay in comparison to the fly ash/sand specimens were: (1) Boron, chloride, sodium, and sulfur demonstrated typical breakthrough curves; (2) almost complete adsorption/precipitation of cadmium and zinc; and (3) calcium demonstrated lagged response, which released calcium such that the maximum concentration was higher than that of the permeant.

The duration of permeation tests is important in delineating the impact of different permeabilities, i.e., reaction times on the effluent characteristics.

Long-term permeation tests should be used because the critical conditions may occur initially or after many pore volumes have been processed. Understanding of the process at this time is incomplete, and the rates and patterns of the transient behavior cannot be predicted with confidence.

With respect to trying to shorten the duration of the long-term tests by using a more permeable specimen, it is concluded that this would be acceptable only if the initial behavior is not of critical interest. The high- and low-permeability specimens tended to reach the same levels after 10–20 pore volumes of leachate had passed through, but large differences could be observed during the first part of the test.

Although there are enforcement standards that apply to ground water,

they are not directly applicable to this study. The degree of dilution and attenuation of the leachate between the landfill and the monitoring wells, and also the point of compliance of the waste management unit, are very site-specific. The results of this study indicate that fly-ash-stabilized soils present a significant alternative as a resistant and cost-effective barrier material.

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