

Permeability and Leachate Characteristics of Stabilized Class F Fly Ash

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A 2-year laboratory investigation of the permeability and leachate characteristics of stabilized fly ash has been completed at West Virginia University. Two class F fly ashes from coal-fired power plants in West Virginia were amended with either lime, cement, or bentonite. Stabilized specimens were permeated in either rigid- or flexible-wall permeameters. Permeant liquids included distilled water, highly concentrated organic solutions, and acidic solutions. Effluents from the permeability tests were collected periodically during the tests and analyzed for toxic elements. Results from the study indicate, for the ashes tested, permeabilities near $1.0\text{E-}06$ cm/s can readily be obtained when 15 percent (by weight) of lime or cement is added to the fly ash. Much lower permeabilities ($1.0\text{E-}08$ cm/sec) can be obtained by substituting bentonite in place of the lime or cement. Addition of lime or cement appears to stabilize the fly ash with respect to toxic elements being leached from the ash. Bentonite may not be as successful at fixing the elements onto the fly ash. In conclusion, difficulty in using fly ash as a liner material probably does not lie in the ability to obtain low permeability nor in fixing the toxic elements from leaching but rather in combining those two properties into one material. Permeability can be decreased to acceptable values through the addition of bentonite, but some ability to fix elements from leaching may be lost. In addition, ashes from different plants and from different operating periods, as found in this study, can have markedly different properties. To use a particular ash in a liner application, ash must be tested for its behavior to ensure that the correct properties are used in design of the particular liner.

Use of coal as a fuel for the production of power has increased owing to improved technology for burning coal cleanly, the increased cost of oil and gas, and the mounting problems in the nuclear industry. This increased burning of coal has resulted in the production of vast quantities of fly ash, which is the finely divided residue that results from the burning of coal and is composed of noncombustible mineral matter in the coal and any carbon remaining owing to incomplete combustion.

Disposal of fly ash on-site or in landfills can be a major concern for power plant owners. The principal environmental concern is the possibility of leaching heavy metals from the fly ash into the underlying groundwater. A method of stabilizing the fly ash and, if possible, incorporating it into a useful material will be of major benefit to the electric utility industry, the coal industry, and the supporting industries, including those that transport coal or fly ash.

Stabilization can result in reducing the permeability of the ash in addition to fixing the elements from being leached from the fly ash. The use for such a material in vast quantities

already exists and is demonstrated in the waste disposal industry as liners for landfills (1,2). Current regulations require liner systems for waste impoundment facilities to be composed of one or more synthetic liners backed up, or underlain, by an earth material liner or a demonstrated substitute (3). Stabilized fly ash may provide an attractive alternative in areas where natural soils are insufficient or their supply inadequate. Indeed, stabilized fly ash may even provide a method of lining areas to contain the quantities of fly ash that must be disposed.

Findings of a comprehensive study involving the stabilization of fly ash are reported in this paper. Two class F fly ashes from West Virginia power plants were acquired and evaluated for permeability and leaching characteristics both in the stabilized and unstabilized form. Compaction, strength, and durability characteristics also were evaluated (4,5). Initially, stabilization was performed by adding lime or cement. Later, bentonite was added as an alternative admixture for some specimens. The admixture and stabilizer materials were acquired commercially. The hydrated lime and Type I portland cement were produced locally (West Virginia), and the bentonite was obtained from Black Hills, Wyoming.

MATERIAL PROPERTIES

The composition of fly ash can vary considerably depending on the nature of the coal burned and power plant operational characteristics. Two somewhat different ashes were selected for this study. However, both are typical of ashes produced in the eastern United States by electric utilities that burn bituminous coal.

The first ash, known as Harrison, was obtained from the Harrison Power Plant in West Virginia. The second ash, Amos, was acquired from the Amos Power Plant, also located in West Virginia. Both ashes were obtained from the hopper at a moisture content of 0.1 percent and were tested to determine their relevant material properties. Harrison ash was found to have a higher iron (Fe_2O_3) content and thus a higher specific gravity (2.81) when compared with Amos (2.25). Harrison, showing only 4.4 percent retained on the No. 200 sieve and 14.4 percent retained on the No. 325 sieve, was somewhat finer than the Amos, with 8.9 percent and 22.4 percent retained on the respective sieves. The Amos ash had a higher pozzolanic activity index with lime and a higher lime-pozzolan strength development than the Harrison ash and is likely owing to the Amos ash's higher total of glassy components.

Both ashes were mixed with 3 to 15 percent by weight of either lime or portland cement and compacted by using Standard Proctor procedures. Maximum dry densities (MDD)

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decreased with increasing lime content and remained about the same regardless of the cement content. Harrison ash unit weights ranged from 15.7 to 17.0 kN/m³ (100 to 108 pcf) for lime and 17.3 to 17.6 kN/m³ (110 to 112 pcf) for cement addition. Amos ash unit weights ranged from 13.3 to 13.8 kN/m³ (85 to 88 pcf) for lime addition and from 14.1 to 14.3 kN/m³ (90 to 91 pcf) for cement addition. Optimum moisture contents (OMC) for Harrison ash ranged from 16 percent to 20 percent for a 3 percent lime addition to 15 percent lime addition. The cement addition resulted in OMCs from 18 to 19 percent. OMCs ranged from 20 to 22 percent for 3 to 15 percent lime for the Amos ash, and from 18 to 19 percent for 3 to 15 percent cement. Because Harrison had a higher specific gravity than does Amos, the resulting MDDs were higher than for the Amos ash. Adequate strength and durability could be obtained on the fly ashes by adding sufficient quantities of lime or cement and by curing for a sufficient period. A detailed discussion of the material properties can be found elsewhere (4, Usmen and Bowders, this Record).

EXPERIMENTAL PROGRAM

The principal experiment was permeability testing of stabilized fly ash specimens. Effluent was collected during the permeability tests and analyzed for elements that might have leached from the ash. The majority of the permeability tests were performed in rigid-wall, double-ring compaction mold permeameters. However, a series of flexible-wall permeability tests was performed on specimens that had been allowed an extended curing period. Hydraulic gradients of 100 were used in the compaction mold permeability tests. The gradients varied in the flexible-wall tests but were generally higher than 100 to reduce the testing time for the specimens with the lowest permeabilities. Specimens were permeated until the permeability stabilized and until two pore volumes of flow had taken place.

Fly ashes were mixed with lime or cement, compacted by using standard Proctor compaction procedures, and allowed to moist cure for 7 or 28 days. One series of specimens was permitted longer curing times. The Amos ash was eliminated from further testing when the permeability to water results indicated that the ash would not meet typical landfill liner requirements.

Three different permeant liquids were used in the study: distilled-deionized water, a solution of 5 percent methanol in water, and a 3.2 percent solution of acetic acid. Water was used to obtain baseline permeabilities and was considered a nonreactive liquid. The methanol solution contained a high level of organic carbon (18,750 mg/l), representing the possible organic carbon content in a landfill leachate. The 3.2 percent acetic acid solution had a pH of 2.5, typical of some landfill leachates especially in the early years of leachate generation.

Permeabilities were calculated on the basis of the quantity of liquid that flowed into the specimens. A constant-head test was performed, and the hydraulic conductivities were calculated based on Darcy's law:

$$K = (Q/t)/(iA) \quad (1)$$

where Q is the quantity of inflow, t is the time during which the inflow was measured, A is the cross-sectional area of the specimen perpendicular to the flow, i is the hydraulic gradient (change in head divided by the length of flow through the specimen), and K is the permeability of the specimen.

Note that throughout the remainder of this paper, the term "permeability" will be used to refer to values of K , the hydraulic conductivity (or coefficient of permeability). This usage is traditional among highway engineers. The values given should not be confused with the intrinsic permeability k given by

$$k = (u/\rho) K, \quad (2)$$

where u is the dynamic viscosity and ρ the density of the permeant liquid.

Three samples of the effluent were collected during each permeability test. The first sample of each test was collected at the beginning of the test, the second at about one pore volume of flow, and the third at about two pore volumes of flow. Effluents were analyzed by using atomic absorption spectroscopy for cadmium, chromium, copper, lead, and mercury.

The fly ash itself was also chemically analyzed for major and trace constituents. The major constituents determined were aluminum, potassium, calcium, and iron, assumed to be present as oxides. The trace constituents determined were cadmium, copper, lead, mercury, manganese, and zinc. Ash samples were prepared for atomic absorption analysis by fusion at 1000°C with lithium metaborate as a flux and followed by dissolution in a nitric acid solution (ASTM D4503-86) (5).

PERMEABILITY TEST RESULTS

The permeability of the fly ash in liner applications is the property of principal concern. Assuming low hydraulic gradients, the permeability controls the flow volumes passing through the liner. If low permeabilities are maintained, then the total mass flux of the leachate constituents remains small and the liner will have been successful. Permeability tests on various configurations of stabilized fly ash were performed to ascertain the effectiveness of the stabilizers. Four different series of tests were performed on the specimens. The first three series were based on the type of permeating liquid, deionized-distilled water, methanol, and acetic acid. The fourth series of tests was based on the length and conditions of the curing period. The results of each series of tests are presented next.

Distilled-Deionized Water Series

The permeability results for the specimens permeated with distilled-deionized (DD) water are presented in Table 1. The reported values are generally the average of two tests. Three or four tests were conducted in a few cases for that particular mix design. Time constraints did not allow for a statistically valid number of tests for each mix design. As such, the conclusions drawn have not been statistically verified. The permeability of unstabilized Harrison, compacted at optimum moisture content, was 7.2E-06 cm/sec and for Amos was 1.9E-05 cm/sec. Both ashes showed a trend of decreasing permeability

TABLE 1 PERMEABILITIES OF FLY ASH SPECIMENS STABILIZED WITH LIME, CEMENT, OR BENTONITE AND PERMEATED WITH DISTILLED-DEIONIZED WATER (cm/sec)

| Stabilizer (%) | Harrison | | | | Amos | | | |
|-------------------|----------|-----------|---------|-----------|---------|-----------|---------|-----------|
| | 7-Day | | 28-Day | | 7-Day | | 28-Day | |
| | K_f | K_f/K_o | K_f | K_f/K_o | K_f | K_f/K_o | K_f | K_f/K_o |
| Lime | | | | | | | | |
| 0 | 7.2E-06 | 1.0 | --- | ---- | 1.9E-05 | 1.0 | --- | ---- |
| 3 | 2.8E-06 | 0.39 | 2.2E-06 | 0.31 | 8.1E-06 | 0.43 | 6.4E-06 | 0.34 |
| 9 | 2.2E-06 | 0.31 | 1.8E-06 | 0.25 | 3.7E-06 | 0.19 | 4.6E-06 | 0.24 |
| 15 | 1.6E-06 | 0.22 | 1.2E-06 | 0.17 | 4.4E-06 | 0.23 | 3.7E-06 | 0.19 |
| Cement | | | | | | | | |
| 3 | 6.6E-06 | 0.92 | 5.6E-06 | 0.78 | 6.2E-06 | 0.33 | 1.1E-05 | 0.58 |
| 9 | 1.6E-06 | 0.31 | 1.4E-06 | 0.19 | 3.1E-06 | 0.16 | 3.7E-06 | 0.19 |
| 15 | 7.5E-07 | 0.10 | 1.1E-06 | 0.15 | 3.0E-06 | 0.16 | 2.1E-06 | 0.11 |
| Bentonite | | | | | | | | |
| 0.5 | 3.5E-06 | 0.49 | ----- | | 1.5E-05 | 0.08 | ----- | |
| 2 | 1.7E-06 | 0.24 | ----- | | 8.6E-06 | 0.45 | ----- | |
| 5 | 2.2E-07 | 0.03 | ----- | | 7.2E-07 | 0.04 | ----- | |
| 10 | 5.0E-08 | 0.01 | ----- | | 1.5E-07 | 0.01 | ----- | |

K_o : Permeability of the unstabilized ash to water

K_f : Final permeability for the specimen.

K_f/K_o : Final permeability of the specimen divided by the permeability of the unstabilized ash.

$K_f/K_o < 1.0$ indicates that the stabilizer reduced the permeability of the ash.

7-Day: Seven day moist curing time.

28-Day: Twenty-eight day moist curing time.

-----: No tests under these conditions

as the percentage of stabilizer increased. At 15 percent lime or cement (by dry weight), the decrease in permeability was slightly less than 1 order of magnitude. The increased curing times, from 7 to 28 days, resulted in a slight but insignificant decrease in the permeability. Lowest permeabilities were recorded for the specimens with the maximum stabilizer content. At the 7-day curing times and 15 percent stabilizer addition, Harrison had permeabilities of 1.6E-06 for lime and 7.5E-07 for cement additions. Amos showed permeabilities of 4.4E-06 cm/sec for lime and 3.0E-06 for cement at 15 percent replacement.

At this juncture it became obvious that to reduce the permeability of those fly ashes to meet landfill regulations for the soil component (3), an alternative additive would be necessary. To this end bentonite was added to the two fly ashes in an attempt to reach the 1.0E-07 cm/sec permeability typically required. Those results are also presented in Table 1. Harrison required 5 percent bentonite to produce a permeability near 1.0E-07 cm/sec, and Amos required 10 percent replacement to meet the same mark. This behavior might be expected because Amos had an unstabilized permeability about three times greater than did the Harrison ash.

In addition, bentonite was added to lime or cement stabilized fly ashes to see what effect it would have on the stabilized materials. Of special concern were the possible effects on the leaching characteristics (which are presented in a later section). Regarding permeability, results presented in Table 2 indicate that adding bentonite to either lime or cement stabilized fly ash does not result in as large a reduction in the permeability as when bentonite is the sole admixture. Reduction was generally less than a factor of one-half when com-

pared with one or two orders-of-magnitude for the bentonite alone. The final permeability was actually greater than that for the ash stabilized with cement when 10 percent bentonite was added to fly ash containing nine percent cement. It is believed that the free calcium associated with either the lime or cement replaces some of the sodium cations in the bentonite, thus reducing its ability to swell and reduce the permeability of the fly ash.

Methanol Series

The results of the permeability tests where a 5 percent solution of methanol was used as the permeant liquid are presented in Table 3. The ratio of the permeability of the methanol compared with that of the same mixture to water is reported in the fifth column of the table. Values less than 1.0 indicate that the permeability of the ash decreased for the methanol relative to that for water.

As is indicated in Table 3, the permeabilities to methanol were highly varied. Specimens in which lime was used for stabilization showed decreases in the permeability to methanol. Cement-stabilized specimens indicated an increase in the permeability to methanol. The specimens in which bentonite was used as the sole additive indicated mixed permeability results. It might be suspected that the methanol reacted with the ash of stabilizer and resulted in the varied response seen in the permeabilities. However, similar work with soils (6,7) indicated that dilute organic liquids do not readily affect the permeability of the soil. This conclusion is considered to be applicable to the fly ash work, and the variances in the

TABLE 2 PERMEABILITIES OF HARRISON SPECIMENS STABILIZED WITH LIME OR CEMENT MIXED WITH BENTONITE AND PERMEATED WITH DISTILLED-DEIONIZED WATER (cm/sec)

| Bentonite (%) | 3% Cement | | 3% Lime | |
|------------------|-----------|-----------|---------|-----------|
| | K_f | K_f/K_0 | K_f | K_f/K_0 |
| 0 | 6.6E-06 | 1.0 | 2.8E-06 | 1.0 |
| 2.5 | 2.7E-06 | 0.41 | 1.2E-06 | 0.43 |
| 5 | 1.4E-06 | 0.21 | 2.6E-06 | 0.93 |
| 10 | 1.4E-06 | 0.21 | 2.6E-06 | 0.93 |

| | 9% Cement | | 9% Lime | |
|-----|-----------|-----------|---------|-----------|
| | K_f | K_f/K_0 | K_f | K_f/K_0 |
| 0 | 1.6E-06 | 1.0 | 2.2E-06 | 1.0 |
| 2.5 | 1.6E-06 | 1.0 | 1.6E-06 | 0.73 |
| 5 | 6.2E-07 | 0.39 | 2.1E-06 | 0.95 |
| 10 | 2.4E-06 | 1.50 | 1.8E-06 | 0.82 |

K_0 : Permeability of the Harrison ash with the noted lime or cement content, no bentonite (values from Table 1).

K_f : Permeability of the Harrison ash with the noted lime or cement, and bentonite contents.

K_f/K_0 : Indicates the permeability of the stabilized specimen with a particular percentage of bentonite divided by the permeability of the stabilized ash without the bentonite addition.

TABLE 3 PERMEABILITY OF STABILIZED HARRISON SPECIMENS PERMEATED WITH A PERCENT SOLUTION OF METHANOL (cm/sec)

| Material Composition | Specimen No. | K_f | K_w | K_f/K_w |
|-----------------------|--------------|---------|---------|-----------|
| 15% Cement | 1 | 1.2E-06 | 7.5E-07 | 1.60 |
| | 2 | 8.7E-06 | | 11.6 |
| 15% Lime | 1 | 2.2E-08 | 1.6E-06 | 0.01 |
| | 2 | 4.9E-07 | | 0.31 |
| 5% Bentonite | 1 | 5.2E-07 | 2.2E-07 | 2.36 |
| | | 8.6E-09 | | 0.04 |
| 10% Bentonite | 1 | 1.9E-06 | 5.0E-08 | 38.0 |
| | 2 | 1.3E-08 | | 0.26 |
| 5% Bent/ 9% Cement | 1 | 1.9E-06 | 6.2E-07 | 3.1 |
| | 2 | 3.8E-06 | | 6.2 |
| 5% Bent/ 9% Lime | 1 | 4.0E-07 | 2.1E-07 | 0.19 |
| | 2 | 8.2E-08 | | 0.04 |

K_w : Permeability of the mixture to distilled water (Tables 1 or 2).

K_f : Permeability of the mixture to methanol.

K_f/K_w : Final permeability using methanol divided by the permeability of the same material composition to water.

permeabilities are reasoned to be attributable to specimen variability than to complex chemical alteration. Indeed, this is an area that deserves considerably more attention.

Acetic Acid Series

The permeabilities of lime-, cement-, and bentonite-stabilized fly ash specimens permeated with a 3.2 percent solution of

acetic acid are presented in Table 4. The acid solution had a pH of 2.5. An examination of the final permeabilities of the specimens indicates that permeation with the acid solution lowered the permeabilities when compared with values for permeation with water or the methanol solution and indicates that the acid might be responsible for increasing the degree to which a stabilized specimen cures while also increasing the rate of the curing process. Observations of the specimens after testing showed small crystal particles throughout the speci-

TABLE 4 PERMEABILITY OF STABILIZED HARRISON SPECIMENS PERMEATED WITH A SOLUTION OF ACETIC ACID (cm/sec)

| Material Composition | Specimen No. | K_f | K_w | K_f/K_w |
|-----------------------|--------------|---------|---------|-----------|
| 15% Cement | 1 | 1.2E-08 | 7.5E-07 | 0.02 |
| | 2 | 4.3E-08 | | 0.06 |
| 15% Lime | 1 | 1.8E-08 | 1.6E-06 | 0.01 |
| | 2 | ----- | | ----- |
| 5% Bentonite | 1 | 8.1E-08 | 2.2E-07 | 0.37 |
| | 2 | 4.3E-08 | | 0.20 |
| 10% Bentonite | 1 | 8.2E-07 | 5.0E-08 | 16.1 |
| | 2 | 3.9E-07 | | 7.8 |
| 5% Bent/ 9% Cement | 1 | 1.9E-08 | 6.2E-08 | 0.03 |
| | 2 | 1.4E-08 | | 0.02 |
| 10% Bent/ 9% Lime | 1 | 8.2E-08 | 2.1E-06 | 0.04 |
| | 2 | 3.9E-08 | | 0.02 |

K_w : Permeability of the mixture to distilled water (Tables 1 or 2).

K_f : Permeability of the mixture to acetic acid.

K_f/K_w : Final permeability using acetic acid divided by the permeability of the same material composition to water.

TABLE 5 EFFECT OF CURING CONDITIONS ON THE PERMEABILITY OF STABILIZED HARRISON PERMEATED WITH DISTILLED-DEIONIZED WATER (cm/sec)

| No. of Days of Curing | 9% Lime | | 9% Cement | |
|--------------------------|---------|-----------|-----------|-----------|
| | K_f | K_f/K_7 | K_f | K_f/K_7 |
| 7 | 1.7E-05 | 1.0 | 6.5E-06 | 1.0 |
| 28 | 1.5E-06 | 0.09 | 3.7E-06 | 0.57 |
| 56 | 8.1E-07 | 0.05 | 8.0E-06 | 1.23 |
| 128 | 3.2E-07 | 0.02 | 3.4E-06 | 0.52 |
| 256 | 2.7E-08 | 0.002 | 3.2E-07 | 0.05 |

All specimens were cured in a 100% humidity, 22C environment.

K_7 : Permeability of the specimen cured for seven days.

K_f : Permeability of the specimen at the specified number of days.

K_f/K_7 : Final permeability divided by the permeability of the specimen which was cured for seven days.

mens. No direct investigation was made. However, it is believed that those particles resulted from the interaction of the acid with the admixtures or the fly ash or both.

Specimens stabilized with bentonite alone exhibited permeabilities greater than when permeated with water. Specimens that included either lime or cement alone or with 5 percent bentonite exhibited the lowest values of permeability.

Findings indicate that the acid possibly has a beneficial effect on the lime- and cement-stabilized specimens and causes a decrease in the permeability as permeation proceeds. This is a positive note in light of the fact that many municipal waste landfill leachates are acidic in nature.

Curing Conditions Series

A set of specimens was prepared with 9 percent cement or lime and allowed to cure for up to 256 days in a constant

temperature (21°C) and humidity (100 percent) environment to examine the effect of curing conditions on the permeability of the stabilized fly ash. Permeabilities of the specimens were measured at various times during the curing process. Results of the tests are presented in Table 5. Lime-stabilized specimens showed marked decreases in permeability as the curing times increased. The 256-day specimen exhibited a three order-of-magnitude decrease in permeability when compared with that of the 7-day specimen.

Cement-stabilized specimens showed little variation in permeability at extended curing times, except the 256-day specimen, which underwent about a two order-of-magnitude decrease in permeability.

Some shrinkage of the stabilized fly ash was expected during the curing process. In some instances, especially under dry curing, this shrinkage process has been considered as a contributing cause to cracking and increased permeability of the stabilized material. Thus, the effect of extended periods of

dry curing was also evaluated in a second set of specimens. A group of 11 specimens stabilized with 9 to 15 percent lime or cement was first moist cured for a period of 7 or 28 days. Specimens were then placed in a room environment where the temperature remained about 21°C. Humidity was low but varied slightly. The specimens remained in this environment until they were set up in permeameters and tested. This period ranged from 180 to 270 days.

Mean permeability of the specimens was 2.6E-05 cm/sec. The lowest permeability was 4.2E-06 cm/sec, and the highest was 8.6E-05 cm/sec. Those values are slightly greater than the values for specimens tested immediately following moist curing (Table 1). However, no evidence of significant shrinkage cracking appeared, as would be indicated by large increases in the permeability of the dry cured specimens. Visual inspection of the specimens before and after permeation did not detect any macro-cracks.

EFFLUENT ANALYSIS RESULTS

Not only does the stabilized fly ash have to contain the waste of the facility it is used to line but it must contain any toxic elements inherent within its own matrix. The chief concern here is the chance of certain constituents leaching into the groundwater at concentrations determined to be hazardous to health. Those constituents include metals such as cadmium, chromium, copper, lead, and mercury. In a study by Malik

et al. (8), a class F fly ash was subjected to leaching experiments. The U.S. EPA's procedure for determining if a waste is to be considered hazardous was used. The researchers also devised a flow-through leaching system, in which simulated rain was used in a setting that much more closely approximated the actual leaching process. Both raw ash and ash stabilized with 7 percent Type I portland cement were subjected to leaching. It was concluded that the cement stabilization lowered the solubilities of most elements relative to the raw ash. Only sodium, released from the cement, exceeded the elements released from the raw ash. The stabilized ash was determined not to be a hazardous material.

In this project samples of fly ash were analyzed for their chemical composition to be characterized for comparison with other fly ashes and to assess the potential for their leaching of toxic elements. Concentrations of the major constituents in the fly ashes used in this study are presented in Table 6. Concentrations of selected trace elements in the fly ashes, stabilizers, and bentonite are presented in Table 7. Note that the trace element concentrations in the fly ashes are significantly greater than in the stabilizers or bentonite.

The Harrison ash has undergone the most extensive testing of the two ashes. Therefore, the discussion of the results of the effluent analyses will be limited to this ash. Effluent analyses were performed for copper, cadmium, chromium, and lead. Results from eight of the mixes are presented in Table 8. In general, the percentage of copper, cadmium, and lead leached from the fly ash mixtures within this study was less than 0.041 percent. The percentage of chromium leached was up to 0.427 percent. Of special note, as indicated in Table 8, is that the rate of leaching is much higher within the initial flows and subsequently decreases after one or two pore volumes of flow. The percent concentrations of those four metals is a function of the type and percent of stabilizer added. In general, the leachability of cadmium and lead decreased as the length of the curing period increased. The cadmium and chromium concentrations were reduced with the addition of cement or lime. Addition of bentonite to the cement-stabilized ash resulted in an increase in the copper and chromium concentrations in the effluent. Bentonite may inhibit the fixation of those elements by the cement.

TABLE 6 SELECTED MAJOR ELEMENTS IN THE FLY ASH COMPOSITION

| Constituent | Concentrations (% as oxide) | |
|--------------------------------|-----------------------------|--------|
| | Harrison | Amos |
| Al ₂ O ₃ | 18.9 | 30.0 |
| K ₂ O | 1.76 | 2.91 |
| CaO | 6.76 | 1.41 |
| Fe ₂ O ₃ | 25.4 | (9.98) |

Parentheses indicate less reliable values.

TABLE 7 CONCENTRATION OF SELECTED TRACE ELEMENTS IN FLY ASH, STABILIZERS, AND BENTONITE

| Element | Concentrations (mg/kg) | | | | |
|-----------|------------------------|------|-------|-------------|-----------|
| | Harrison | Amos | Lime | Port Cement | Bentonite |
| Cadmium | 25.3 | 24.7 | 18.3 | 20.8 | 230.8 |
| Chromium | 358 | 293 | 47.5 | 100.8 | 66.7 |
| Copper | 336 | 441 | 259.2 | 279.2 | 288.3 |
| Lead | 250 | 169 | 429.2 | 503.3 | 583.3 |
| Manganese | 409 | 340 | -- | -- | -- |
| Mercury | 89 | (13) | -- | -- | -- |
| Zinc | 93 | 103 | -- | -- | -- |

Parentheses indicate less reliable values.

TABLE 8 SELECTED EFFLUENT ANALYSES INDICATING THE EFFECT OF STABILIZATION ON HARRISON ASH

| | Effluent Concentrations* (mg/l) | | | | | | | | | | | |
|----------------|---------------------------------|-------|-------|---------|-------|-------|----------|-------|-------|-------|-------|-------|
| | Copper | | | Cadmium | | | Chromium | | | Lead | | |
| Mixture | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| H-0-0 | 0.079 | 0.088 | 0.026 | 0.024 | 0.012 | 0.009 | 3.229 | 1.700 | 0.719 | 0.867 | 0.867 | 0.733 |
| H-7-15C | 1.131 | 0.270 | 0.190 | 0.016 | 0.006 | 0.005 | 1.381 | 0.500 | 0.090 | 2.067 | 0.733 | 0.867 |
| H-28-15C | 0.478 | 0.192 | 0.062 | 0.013 | 0.007 | 0.005 | 0.423 | 0.176 | 0.039 | 1.367 | 0.300 | 0.014 |
| H-7-3L | 0.943 | 0.178 | 0.706 | 0.026 | 0.014 | 0.009 | 1.116 | 0.988 | 0.176 | 0.867 | 0.467 | 0.733 |
| H-28-3L | 1.327 | 0.316 | 0.135 | 0.014 | 0.006 | 0.004 | 1.463 | 0.142 | 0.042 | 0.400 | 0.333 | 0.200 |
| H-7-9L | 0.713 | 0.496 | 0.414 | 0.014 | 0.012 | 0.012 | 1.762 | 0.765 | 0.158 | 0.555 | 0.400 | 0.289 |
| H-7-9C +5B | 0.333 | 0.212 | 0.128 | 0.013 | 0.011 | 0.008 | 7.859 | 4.995 | 3.303 | 0.200 | 0.078 | 0.100 |
| H-7-9C +10B | 0.303 | 0.166 | 0.116 | 0.010 | 0.007 | 0.006 | 7.076 | 2.331 | 1.189 | 0.200 | 0.200 | 0.200 |

H-0-0: Harrison Ash-Uncured-No Stabilizer

H-7-15C: Harrison Ash-7 Days Curing-15% Cement

H-28-15C: Harrison Ash-28 Days Curing-15% Cement

H-7-3L: Harrison Ash-7 Days Curing-3% Lime

H-28-3L: Harrison Ash-28 Days Curing-3% Lime

H-7-9L: Harrison Ash-7 Days Curing-9% Lime

H-7-9C+5B: Harrison Ash-7 Days Curing-9% Cement + 5% Bentonite

H-7-9C+10B: Harrison Ash-7 Days Curing-9% Cement + 10% Bentonite

*1: Initial Effluent Collection Period

2: Effluent Collected At About One Pore Volume of Flow

3: Effluent Collected At About Two Pore Volumes of Flow

CONCLUSIONS

Two fly ashes from West Virginia have been stabilized with lime and cement by using stabilizer contents ranging from 3 to 15 percent. The stabilized, compacted specimens have been tested for permeability and leaching characteristics by using different permeant liquids.

Permeability results indicate that cement- and lime-stabilization can reduce the permeabilities of the ashes to about $1.0\text{E-}06$ cm/sec when either stabilizer (15 percent by dry weight) is added. Adding bentonite to the stabilized fly ash further reduces the permeability. However, when water is the permeating liquid, the lowest permeabilities are obtained for fly ash mixed solely with bentonite. The lime and cement impede the effectiveness of the bentonite in reducing the permeability when they are incorporated together.

Results of the permeability tests where a solution of methanol was used indicated there was no significant change in the permeability of the stabilized ash specimens. The high concentration of organic carbon in the solution, similar to what might exist in a landfill leachate, does not appear to cause the deterioration of the stabilized ash.

The acid-permeated specimens displayed a marked decrease in permeability, especially in the lime-stabilized specimens. The cement specimens underwent a small decrease in permeability, and the bentonite specimens exhibited an even smaller

and almost negligible decrease in permeability. The effect of the acid may be one of enhancing the degree of curing and of speeding up the process in the lime- and cement-stabilized specimens.

Extended periods of curing had negligible effect on the permeability of dry-cured specimens. No evidence of significant shrinkage cracking was found, as demonstrated by consistently low permeabilities. Increased moist curing of lime-stabilized specimens resulted in up to a three order-of-magnitude decrease in the permeability for curing times of 256 days. Permeabilities of the moist-cured cement specimens were unaltered except for the 256-day specimen and is believed to be partially due to cement's initially rapid curing rate and subsequent decreased rate of curing at long periods.

Leaching tests indicate that much of the concentration of toxic elements is loosely bound on the surface of the ash. This concentration is washed from the ash during the initial flow of liquid. Subsequent flow indicates a marked decrease in the concentration of toxic elements. Addition of lime or cement appears to stabilize the fly ash with respect to some of the toxic elements being leached from it. However, ash stabilized with bentonite alone may not be as successful at immobilizing the elements monitored in this study.

The difficulty in using fly ash as a liner material probably does not lie in the ability to obtain a low permeability or in immobilizing the toxic elements from leaching but rather in

the variability in the ash itself. Ashes from different plants and from the same plants at different operating periods, as found in this investigation, can have dramatically different properties. Thus, to use a particular ash in a liner application, test that particular ash to determine its properties. Of course, the testing must continue long enough to determine the variability of the ash with time. A final note concerns the fact that the permeabilities reported here were measured in the laboratory. A trial fly ash liner in the field, constructed with the equipment designated for the actual liner, is recommended to determine field permeabilities.

In summary, given the need for a sufficient supply of adequate materials for use as liners for landfills, waste impoundments, and other disposal facilities coupled with the increasing supply of fly ash from electric power-generating facilities, a stabilized fly ash liner represents an attractive development. This high volume use of fly ash in an environmentally beneficial role can lead to enhanced economic returns for the electric power industry, the coal industry, and the transportation network serving both entities.

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