

Leachate Generation from Raw and Cement Stabilized Phosphogypsum

MARTY E. TITTLEBAUM, HARISH THIMMEGOWDA, ROGER K. SEALS, AND SARAH COOLEY JONES

The results of a study to determine the leaching characteristics of portland cement stabilized phosphogypsum mixtures developed for base course applications are presented. The study used the Environmental Protection Agency Toxicity Characteristics Leaching Procedure to investigate leaching of mixtures prepared using two cement contents, four cement types, and two levels of relative compaction. The stabilized mixtures were cured 28 days before testing. The results generally indicated higher levels of leaching for the stabilized mixtures for the metals investigated compared with the raw phosphogypsum. Increased relative compaction tended to reduce leached amounts. Type I portland cement usually resulted in increased leaching compared with Types II, III, and V.

A research study was conducted to determine the leaching characteristics of portland cement stabilized phosphogypsum (PG) mixtures developed for highway base course applications. PG is a member of the family of by-product gypsum materials produced by the minerals, agricultural chemicals, and power-generating industries. Specifically, PG is a residual from the production of phosphoric acid from phosphate rock using the so-called wet process (1). On the average, approximately 5 tons of PG are produced for each ton of phosphoric acid. Thus, large quantities of PG have been produced and are being produced annually. This research study is part of a larger research program of the Institute for Recyclable Materials, Louisiana State University, to develop and evaluate high-volume uses for PG. It represents only one of several environmentally related projects associated with the use of PG in various forms and applications.

The specific objective of this study was to determine the leaching characteristic of portland cement stabilized PG for a range of cement contents, cement types, and compaction states. The leaching characteristics of the mixtures were determined using the Environmental Protection Agency (EPA) Toxicity Characteristics Leaching Procedure (TCLP) test (2). The mixtures were prepared using two cement contents, four cement types, and two levels of relative compaction. Specimens of the stabilized mixtures were cured 28 days before conducting the leaching tests.

BACKGROUND

As a by-product of wet process phosphoric acid production, PG forms as calcium sulphate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). PG is the by-product of the acidulation process where sulfuric acid is reacted with phosphate rock. The reaction products—phosphoric acid and

PG—are then separated by a filtration process. PG is then slurried with water and pumped to the disposal stack where it is deposited in temporarily diked areas on top of the stack.

The major elements of PG are calcium, sulphur, and silica. Other elements present in quantities exceeding 0.1 percent by weight include fluoride, iron, phosphorus, and aluminum. In addition, traces of arsenic, barium, calcium, chromium, lead, mercury, selenium, silver, and other elements are found in PG. As a carryover from the phosphate rock, PG contains radium 226 and uranium 238. These are normally occurring radioactive materials present in the phosphate rock. However, approximately 86 percent of the uranium 238 is retained in the phosphoric acid stream, whereas about 80 percent of the radium 226 follows the PG. Principally because of the radon 222 decay product of the radium 226 present in PG, EPA has regulated use of PG (3). Effectively, the regulations limit the distribution of PG for commercial purposes by requiring PG to be disposed in stacks or abandoned phosphate rock mines. Permits for using PG for any purpose will be approved if it can be demonstrated that the proposed use will be at least as safe to human health and the environment as the previously indicated disposal methods.

Although the concentrations of trace elements present in PG are comparatively low, the leaching potential of these elements must be assessed for stabilized and unstabilized applications to assess potential environmental impacts. The former application is the subject of this paper.

SUMMARY OF PREVIOUS RESEARCH

Several heavy metals in PG are included on the EPA list of potentially toxic elements. The main concern about contamination is that the heavy metals released or leached from the PG stacks may affect the environment and human health. The potential for significant contamination includes contamination of groundwater by the leaching of water vertically and laterally into the aquifer as well as the contamination of surface water.

Many studies have been conducted to determine whether PG contains toxic materials and whether leaching of these toxic materials from PG occurs at levels of concern (4). Samples of PG taken from existing stockpiles were evaluated using the EPA extraction procedure (EP), atomic absorption spectrophotometry, and physical and chemical tests. The results demonstrated that PG is not hazardous as defined by EPA criteria. Trace elements are not present in large quantities and are not leached in substantial amounts.

May and Sweeney (5) conducted an investigation of nine PG stacks in Florida to study the various physical and chemical characteristics of PG. Samples were collected from top to bottom and

across all nine stacks at 10-ft intervals for the entire thickness of the stacks. Analytical tests were conducted to characterize PG to assess its potential environmental impact. The total concentrations of trace elements in PG were considered instead of only the toxicity due to leachable elements (5). Emission spectrographic analyses of the PG solids were used to find trace elements. The results of these analyses were correlated with the EPA leaching test criteria that are based on an extraction procedure to identify toxic elements likely to leach into the groundwater. The results of these analyses showed that (a) trace elements were distributed uniformly within the PG stacks and (b) the eight metals listed by EPA as toxic elements were detected at concentrations far less than the EPA limits. In addition to the spectrophotometric analysis of total metals content in phosphogypsum, the EPA EP was used to find the leachable inorganic contaminants in PG. The results presented in Table 1 indicate that all the EPA priority metals were found to be present in the extract at concentrations lower than EPA maximum contaminant level (MCL). This further confirms that the leaching of trace elements from PG stockpiles is not significant in introducing toxic materials into the environment.

A study by Naff (6) investigated the environmental aspects of PG produced at Mobil Mining and Minerals Co., La Porte, Texas, by conducting EPA EP tests. EP tests were conducted on three types of PG from the Mobil stacks: fresh, aged, and stabilized. Fresh and aged PG was found to meet leachate and drinking water standards for the eight specified heavy metals listed by EPA as toxic elements. Sulfates and fluoride levels exceeded drinking water levels primarily because of the solubility of PG. The stabilized PG investigated was stabilized using cement and fly ash. The results showed that the stabilized PG forms a monolithic slab containing insoluble compounds, which help bind the metals within the block. Thus, the impact of stabilized PG on ground- and drinking water was judged to be lower than the raw PG.

More recently, data from groundwater monitoring at four active phosphogypsum stacks were evaluated for possible leachate effects on groundwater as judged by the EPA Primary Drinking Water Standards (7). These studies investigated the mobility of trace metals within the surficial aquifers (surficial aquifers are the primary groundwater systems potentially contaminated by leachate from PG stacks). Influence contours were developed for the model site using exceedance distances tabulated for the seven Primary Drinking

Water Standards and are presented in Figure 1. For the four PG stacks selected, down gradient concentrations of selenium, silver, and fluoride decreased very quickly and were less than the EPA MCLs within about 30 m (100 ft) from the source. Concentrations of other metals, including lead and arsenic, met the standards within 91.4 and 243.8 m (300 and 800 ft), respectively. Finally, chromium and cadmium exhibited the greatest mobility within the surficial aquifer, requiring distances up to approximately 365 (1,200 ft) before falling below drinking water standards.

EXPERIMENTAL PROGRAM

Overview

The testing program for this study consisted principally of conducting TCLP tests on compacted specimens of portland cement stabilized PG after a 28-day curing period. In addition to these tests, the program encompassed elemental analyses of PG and the four cement types, a TCLP test of the raw PG, and TCLP tests of the various cements used in the study.

Materials

The PG used in this study was obtained from the Uncle Sam Plant of the Agrico Chemical Company near Donaldsonville, Louisiana. Although this material was produced in Louisiana, the feedstock phosphate rock was mined in central Florida. Representative samples of major and trace element composition of PG are provided in Tables 2 and 3, respectively. Types I, II, III, and V portland cement from three different sources were used. The chemical composition of these cements, as provided by the respective suppliers, is given in Table 4. Deionized water was used to mold the specimens.

Specimen Preparation

For each mixture combination, duplicate statically compacted specimens were fabricated in a 5.1 cm (2-in.) diameter by 10.2 cm (4-in.) high mold at a relative compaction of 85 or 110 percent and

TABLE 1 Concentrations of Toxic Elements in Extract from EPA EP (2)

| Sample | Toxic element, mg/L | | | | | | | |
|----------|---------------------|-----|------|------|------|-------|-------|------|
| | As | Ba | Cd | Cr | Pb | Hg | Se | Ag |
| AL..... | 0.020 | 0.2 | 0.01 | 0.04 | 0.01 | 0.000 | 0.002 | 0.08 |
| A2..... | .019 | .2 | .01 | .05 | .03 | .000 | .003 | .07 |
| A3..... | .029 | .0 | .02 | .06 | .00 | .000 | .005 | .10 |
| B1..... | .014 | .0 | .01 | .07 | .01 | .000 | .004 | .01 |
| B2..... | .011 | .2 | .01 | .01 | .00 | .001 | .003 | .04 |
| C1..... | .016 | .2 | .02 | .02 | .00 | .001 | .005 | .04 |
| C2..... | .007 | .4 | .03 | .05 | .00 | .001 | .003 | .10 |
| D..... | .009 | .0 | .01 | .11 | .01 | .001 | .003 | .09 |
| E..... | .005 | .2 | .03 | .03 | .03 | .001 | .004 | .06 |
| F..... | .002 | .1 | .01 | .01 | .04 | .001 | .002 | .05 |
| G..... | .005 | .3 | .01 | .01 | .01 | .001 | .002 | .08 |
| H..... | .018 | .3 | .01 | .05 | .00 | .001 | .003 | .04 |
| I..... | .019 | .2 | .01 | .02 | .01 | .004 | .002 | .07 |
| Ave..... | .013 | .2 | .01 | .04 | .01 | .001 | .003 | .06 |

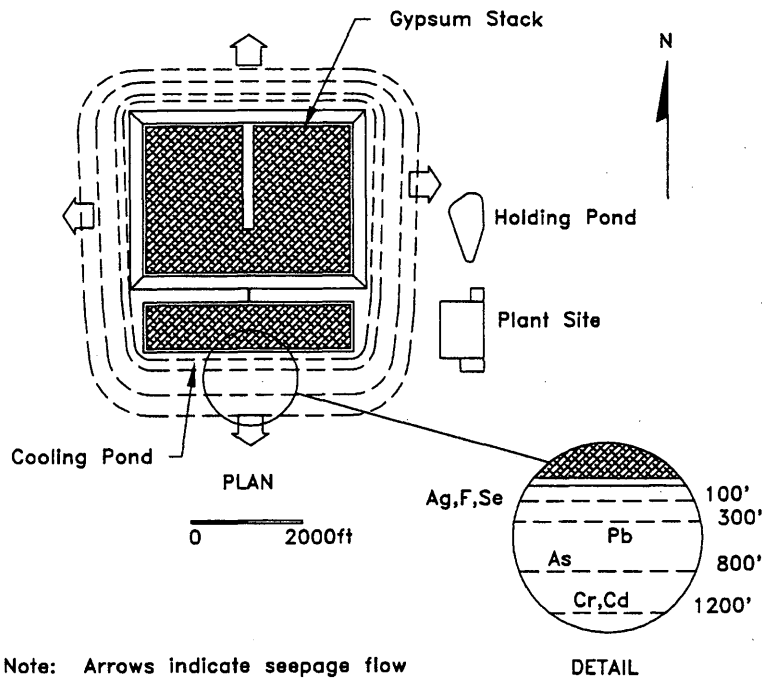


FIGURE 1 Plume migration model Primary Drinking Water Standards (7).

optimum moisture content (both based on standard Proctor compaction). The optimum moisture content varied slightly with type of cement but was approximately 20 percent, based on the combined dry weight of cement and PG, for the various combinations of cement type and content. Sixteen different combinations of cement type, cement content, and relative compaction were evaluated.

Elemental and Leachate Testing and Analysis

Determination of metal concentrations (bulk analysis) for cadmium (Cd), chromium (Cr), barium (Ba), lead (Pb), and silver (Ag) in the PG and four types of portland cement was accomplished using the EPA Method 3050 digestion procedure (2) followed by an inductively coupled argon plasma (ICAP) analysis. The EPA Method 7471 digestion procedure (2) was used for mercury followed by an

atomic absorption spectrophotometer analysis. Each elemental determination was conducted on triplicate analytes from duplicate samples.

Leachate tests were conducted in accordance with the standards for the EPA Toxicity Characteristics Leaching Procedure test (Method 1311) (2). The generated leachate was digested using EPA Method 3010 (2) to determine the metals using ICAP, and EPA Method 7470 (2) was followed to analyze mercury. Leachate was generated using duplicate samples of the cement stabilized PG mixtures. The analysis of each leachate sample was triplicated.

Quality Control

The following quality control samples were included in each batch of digestion where a batch varied from five to eight extractions:

TABLE 2 Results of Chemical Analysis of PG (8)

| Constituent | Content (%) |
|--------------------------------|-------------|
| CaO | 29 - 31 |
| SO ₄ | 50 - 53 |
| SiO ₂ | 5 - 10 |
| F | 0.3 - 1.0 |
| P ₂ O ₅ | 0.7 - 1.3 |
| Fe ₂ O ₃ | 0.1 - 0.2 |
| Al ₂ O ₃ | 0.1 - 0.3 |
| pH* | 2.8 - 5.0 |

*pH: not measured as a percent.

TABLE 3 Trace Element Concentration in PG (8)

| Element | Concentration (ppm) |
|-------------------------------|---------------------|
| As | 1.0 - 5.0 |
| Ba | 50.0 |
| Cd | 0.3 - 0.4 |
| Cr | 2.0 - 5.0 |
| Pb | 2.0 - 10.0 |
| Hg | 0.02 - 0.05 |
| Se | 1.0 |
| Ag | 0.1 - 0.2 |
| U ₃ O ₈ | 5.0 - 10.0 |

- Reagent blank—digested distilled water,
- Reagent blank spike—the distilled deionized water was spiked with analytes of interest and digested, and
- Sample spike—the representative leachate sample was spiked with analytes of interest and digested.

The spiked solutions were added before the leachate samples were digested, and the final concentrations in the digested quality control samples were maintained below the highest concentration of the calibration curve and within the range of interest. The purpose of the spike addition was to monitor the performance of the analytical methods used and to determine whether matrix interference exists (Method 1311) (2).

RESULTS AND DISCUSSION

Individual Materials

The results of the bulk analysis for raw PG and the four types of portland cement are given in Table 5. These results indicate that, with the exception of mercury, the concentration of metals present in the four types of portland cement significantly exceed

those present in PG. However, the amount of portland cement present in the PG mixtures was equal to or less than 12 percent of the dry weight of the PG. Thus, in the mixture, the PG component generally contained the larger portion of each metal present.

The TCLP test results for raw phosphogypsum and the four types of portland cement are given in Table 6. By using the results of the bulk analysis for each material, the theoretical leachate concentration for 100 percent extraction of a given metal was calculated using the following equation:

$$TLC_i = kC_i$$

where

TLC_i = theoretical 100 percent leachate concentration of metal (mg/L),

$k = 0.05$ = factor to convert concentration based on mass to concentration based on volume (mass = 0.1 kg and volume = 2 L), and

C_i = concentration of metal i from bulk analysis (mg/kg).

TABLE 4 Chemical Composition of Cement Used for Stabilization Study of PG (9)

| Element | Type I | Type II | Type III | Type V |
|------------------------------------|--------|---------|----------|--------|
| SiO ₂ (%) | 20.78 | 20.26 | 20.62 | 20.42 |
| Al ₂ O ₃ (%) | 5.72 | 4.53 | 5.25 | 4.42 |
| Fe ₂ O ₃ (%) | 2.82 | 3.84 | 3.71 | 5.30 |
| CaO (%) | NA | 64.61 | Nil | 64.87 |
| MgO (%) | 0.99 | 0.86 | 0.97 | 0.84 |
| SO ₃ (%) | 3.01 | 2.97 | 2.84 | 2.00 |
| C ₃ S (%) | 58.10 | 62.89 | 61.50 | 62.89 |
| C ₂ S (%) | 15.80 | 11.10 | 12.70 | 11.10 |
| C ₃ A (%) | 10.40 | 6.67 | 7.70 | 3.97 |
| C ₄ AF (%) | Nil | 11.69 | Nil | 16.13 |
| CaSO ₄ (%) | Nil | 5.05 | Nil | 3.4 |

TABLE 5 Total Metals Present in PG and Cement (7)

| Material | Cd (ppm) | Pb (ppm) | Cr (ppm) | Ba (ppm) | Ag (ppm) | Hg (ppb) |
|----------|----------|----------|----------|----------|----------|----------|
| PG | 0.02 | 15.70 | 1.60 | 31.50 | 16.20 | 194.00 |
| Type I | 2.20 | 30.50 | 36.20 | 84.10 | 51.00 | 96.50 |
| Type II | 2.30 | 29.90 | 37.30 | 85.17 | 51.30 | 75.00 |
| Type III | 2.80 | 56.00 | 100.00 | 152.00 | 54.90 | 91.50 |
| Type V | 2.80 | 36.30 | 25.30 | 114.90 | 49.60 | 75.00 |

When the concentration of each metal leached from raw PG was compared with the theoretical 100 percent leachate concentration of each metal determined from the equation, the leached amount did not exceed 26.8 percent. In the case of portland cements, with the exception of barium, the percentage of each metal leached for any given metal was less than 9.6 percent. Barium leached in an amount ranging from 49.4 to 63.9 percent of the theoretical 100 percent extraction value for the individual cements. Thus, if portland cement leached at the same level when contained in a mixture containing PG and 12 percent cement (by dry weight of PG), the concentration of a given metal contributed by the cement to the leachate could range from 0.07 percent (Cr for Type III cement) to 7.7 percent (Ba for type V cement) of the corresponding amount of that metal present in the cement alone. However, because of morphological changes, chemical reactions, and the change in the chemical environment that takes place during the cement stabilization process, the mixtures will not behave as simple physical mixtures.

Cement Stabilized Mixtures

The average results of the TCLP tests performed on the various mixtures are given in Table 7. An individual result represents the average of results of triplicated tests on leachate from duplicate molded specimens. Of the six metals considered, the concentrations of all the metals (excluding cadmium) in the leachate exceeded EPA drinking water standards. None of the metal concentration values exceeded EPA leachate standards. Cadmium was not detected at levels above the detection limit of 0.02 ppm.

The primary objective of the test program was to examine the effects of cement type and content and relative compaction on the leachate behavior of stabilized mixtures of PG. Because of the comparatively small amount of data as well as the variability of the data, a qualitative assessment method was used to investigate the effects of a given factor on the results. Thus, to assess the effect of cement content on the concentrations of metals in the leachate,

TABLE 6 Results of TCLP Average Leaching from PG and Cement: (top) Cd, Pb, and Cr; (bottom) Ba, Ag, and Hg (10)

| Item | Amount of Cd Leached (ppm) | Standard Deviation (ppm) | Amount of Pb Leached (ppm) | Standard Deviation (ppm) | Amount of Cr Leached (ppm) | Standard Deviation (ppm) |
|-----------------|----------------------------|--------------------------|----------------------------|--------------------------|----------------------------|--------------------------|
| Raw Pg | ND | - | 0.210 | 0.087 | 0.009 | 0.000 |
| Type I Cement | ND | - | 0.092 | 0.044 | 0.018 | 0.001 |
| Type II Cement | ND | - | 0.143 | 0.004 | 0.012 | 0.001 |
| Type III Cement | ND | - | 0.134 | 0.024 | 0.030 | 0.001 |
| Type V Cement | ND | - | 0.137 | 0.003 | 0.024 | 0.001 |

| Item | Amount of Ba Leached (ppm) | Standard Deviation (ppm) | Amount of Ag Leached (ppm) | Standard Deviation (ppm) | Amount of Hg Leached (ppb) | Standard Deviation (ppb) |
|-----------------|----------------------------|--------------------------|----------------------------|--------------------------|----------------------------|--------------------------|
| Raw Pg | 0.175 | 0.015 | 0.209 | 0.068 | 0.206 | 0.128 |
| Type I Cement | 2.076 | 0.054 | 0.182 | 0.127 | 0.230 | 0.000 |
| Type II Cement | 2.165 | 0.047 | 0.147 | 0.032 | 0.267 | 0.063 |
| Type III Cement | 4.133 | 0.740 | 0.144 | 0.006 | 0.110 | 0.000 |
| Type V Cement | 3.671 | 0.010 | 0.134 | 0.002 | 0.150 | 0.06 |

TABLE 7 Concentration of Leached Metals from Cement-Stabilized PG Mixtures (10)

| % C | R.C. | Cement Type | Metals Concentration (ppm) | | | | | |
|-----|------|-------------|----------------------------|------|------|------|------|------|
| | | | Cd | Pb | Cr | Ba | Ag | Hg* |
| 4 | 85 | I | ND | .186 | .074 | .329 | .330 | .225 |
| | | II | | .198 | .055 | .273 | .464 | .020 |
| | | III | | .194 | .103 | .265 | .213 | ND |
| | | IV | | .157 | 0.51 | .262 | .182 | .110 |
| | 110 | I | ND | .161 | .065 | .249 | .462 | .220 |
| | | II | | .238 | .048 | .219 | .203 | .093 |
| | | III | | .217 | .090 | .205 | .248 | .096 |
| | | IV | | .164 | .103 | .275 | .184 | .206 |
| 12 | 85 | I | ND | .226 | .152 | .446 | .544 | .250 |
| | | II | | .204 | .115 | .542 | .326 | ND |
| | | III | | .101 | .191 | .309 | .402 | .168 |
| | | IV | | .252 | .050 | .360 | .203 | .305 |
| | 110 | I | ND | .205 | .133 | .623 | .255 | .170 |
| | | II | | .157 | .092 | .518 | .147 | .285 |
| | | III | | .101 | .204 | .412 | .125 | .265 |
| | | IV | | 0.96 | .090 | .271 | .147 | .260 |

*ppb

the results for a given metal for all cement types and each relative compaction were examined (see Table 7) to determine whether the larger cement content resulted in higher metal concentrations. Of the 40 data sets, 29 exhibited higher metal concentration values for the higher cement content. The most pronounced effect occurred at the lower relative compaction value where 17 out of 20 results exhibited increases. Only 60 percent of the results for the higher relative compaction value exhibited increases. Thus, it appears that increased dry density contributes to physical and chemical changes that somewhat inhibit leaching.

The data sets were examined to determine the qualitative response (increase or decrease) corresponding to the higher value of relative compaction for a given percentage of cement. Because the weight of the sample used for leaching was 100 gm, independent of the relative compaction value, the leachate concentrations should be unaffected by the value of relative compaction. This is borne out by an examination of the data that revealed that only 17 out of the 40 data sets exhibited increases. Of the two sets of relative compaction data, the set corresponding to the lower cement content value was more likely to exhibit an increase (11 out of 20 compared with 6 out of 20 for the higher cement content). When data is evaluated on this basis, it again appears that increased relative compaction (or increased dry density) contributes to the development of more physically and chemically stable mixture products.

To examine the possible contribution of cement type and content to leachate concentrations, a simple physical mixture model was developed to compare actual and theoretical leachate concentrations. To predict the theoretical leachate concentrations, the following process was followed:

1. A hypothetical composite mixture of phosphogypsum, portland cement, and water having a total mass of 100 g was assumed.

2. By using a moisture content of 20 percent, the dry weights of PG and portland cement were calculated for the 4 and 12 percent cement treatments.

3. For both treatments, the mass of each metal present in the PG and portland cement components of the mixture was determined by multiplying the concentrations of each metal based on the bulk analysis by the respective mass of the component.

4. The calculated mass of each metal present in the PG and portland cement component was then multiplied by the respective leach ratios, considering type of material and metal.

5. The sum of the two values calculated in Step 4 for each component for a given metal was then added to yield the predicted leached mass from a mixture. This value was divided by two liters to derive an equivalent theoretical leachate concentration.

Once the theoretical leachate concentration values were predicted, they were used to calculate the ratio of actual to theoretical leachate concentration values. The actual concentration value represented the average of the values for the two relative compaction levels. These data are summarized in Table 8.

Overall, the results presented in Table 8 indicate no specific trend with respect to cement content. That is, a cured mixture can exhibit either higher or lower leachate concentrations than those predicted by a simple physical model. However, with the exception of chromium, the actual to theoretical leach concentrations for the metals ranged from 72 to 159 percent for both cement contents, giving an overall average of 120 percent. As noted in Table 8, the actual to predicted leachate concentrations (for all cement contents and types and the two relative compaction levels) for the metals are as follows:

TABLE 8 Actual and Theoretical Leachate Concentrations for Variable Cement Content and Type

| % C | Cement Type | Actual/Theoretical Leachate Concentration (%) | | | | |
|-----------------|-------------|---|------|-----|-----|-----|
| | | Pb | Cr | Ba | Ag | Hg |
| 4 | I | 103 | 868 | 141 | 232 | 130 |
| | II | 127 | 644 | 118 | 196 | 33 |
| | III | 120 | 1206 | 87 | 136 | 29 |
| | V | 94 | 962 | 105 | 71 | 94 |
| | All | 111 | 920 | 113 | 159 | 72 |
| 12 | I | 131 | 1781 | 170 | 225 | 121 |
| | II | 107 | 1294 | 165 | 141 | 81 |
| | III | 60 | 2194 | 72 | 157 | 134 |
| | V | 104 | 778 | 69 | 105 | 170 |
| | All | 101 | 1512 | 119 | 157 | 127 |
| Overall Average | | 106 | 1216 | 116 | 158 | 99 |

| Metal | Actual to Predicted Leachate Concentration (%) |
|-------|--|
| Pb | 106 |
| Cr | 1216 |
| Ba | 116 |
| Ag | 158 |
| Hg | 99 |

Thus, the addition of portland cement for physical stabilization of PG appears to selectively improve or degrade the leaching characteristics for specific metals in the mixture. The average actual to predicted leachate concentration of all metals combined for 4 percent cement (excluding chromium) is 114 percent, and the corresponding value for 12 percent cement (excluding chromium) is 132 percent.

Relative to the effect of cement type on leachate concentrations, it is difficult to define any specific trends. At the higher cement contents, 23 out of 30 data sets for the combined Type II, III, and V data exhibited lower leachate concentrations than the values corresponding to Type I cement. At the lower cement content, the corresponding comparison yielded 19 out of 30 data sets showing decreases. The observed differences by metal are given in Table 9. (The relative compaction data are combined so that "inc" represents an increased concentration for both relative compaction levels "dec" represents a decrease in values of concentration for both lev-

els of relative compaction, and "o" represents a data set with both a smaller and a larger value of concentration.) It is apparent that the Type II, III, and V cements generally produce decreased values of leachate concentrations relative to Type I cement when used to stabilize PG.

SUMMARY AND CONCLUSIONS

The results of this study have demonstrated that a simple physical mixture model is inadequate to describe the leaching behavior of cement-stabilized PG. For the metals considered, some leached in less-than-predicted amounts, but generally most leached in greater-than-predicted amounts. The data clearly indicate that (Cr) was leached in far greater proportions than would be predicted. However, the leachate concentrations of all the metals from the cement-stabilized PG mixtures were still well within EPA leachate standards. In general, increased dry density appears to have an overall beneficial effect relative to the leaching behavior of cement-stabilized PG. Cement type also affects the leaching behavior of cement-stabilized PG, with Type I portland cement generally producing higher concentrations of leached metals. Because of the physical degradation requirements of the TCLP test, the possible influence of the improved physical stability of cement-stabilized PG at the higher cement content was probably minimized. Thus, a more

TABLE 9 Leaching Behavior Using Various Types of Cement Compared With Type I Cement

| Leachate | | Concentration Compared to Type I | | | | |
|----------|-------------|----------------------------------|-----|-----|-----|-----|
| % C | Cement Type | Pb | Cr | Ba | Ag | Hg |
| 4 | II | inc | dec | dec | o | dec |
| | III | inc | inc | dec | dec | dec |
| | V | o | o | o | dec | o |
| 12 | II | dec | dec | o | dec | o |
| | III | dec | inc | dec | dec | o |
| | V | o | dec | dec | dec | inc |

realistic test methodology will have to be developed and used to predict possible environmental impacts resulting from the use of cement-stabilized PG and, perhaps, other cement-stabilized industrial residuals used for base course applications.

ACKNOWLEDGMENT

The authors acknowledge Freeport-McMoRan, Inc., of New Orleans, Louisiana, for providing funds to the Institute for Recyclable Materials, Louisiana State University, to support this study.

REFERENCES

1. Borris, D., and Boody, P. Phosphogypsum. *Proc., International Symposium on Phosphogypsum*, Florida Institute for Phosphate Research, Bartow, Nov. 1980.
2. Test Methods for Evaluating Solid Waste. *Laboratory Manual*, SW-846, Vol. 1, 3rd ed., Environmental Protection Agency, 1986.
3. *Final Regulatory Determination for Special Wastes from Mineral Processing (Mining Waste Exclusion)*. Environmental Protection Agency, 40 C.F.R., Part 261, *Federal Register*, Vol. 56, No. 114, June 13, 1991.
4. May, A., and J. W. Sweeney. Assessment of Environmental Impacts Associated with Phosphogypsum in Florida. Bureau of Mines *Report of Investigation 8639*, 1982.
5. May, A., and J. W. Sweeney. Evaluation of Radium and Toxic Element Leaching Characteristics of Florida Phosphogypsum Stockpiles. Bureau of Mines *Report of Investigation 8776*, 1983.
6. Naff, D. B. The Classification of Phosphogypsum for the Environmental Purposes. *Proc., Fertilizer Institute's Environmental Symposium*, The Fertilizer Institute, Kissimmee, Fla., 1984.
7. Bromwell, L., and R. Carrier. Phosphate Chemical Processing Facilities—Ground Water Chapters. *Project*, No. 7130, 1987.
8. Taha, R., and R. K. Seals. Preliminary Review of Phosphogypsum Laboratory Stabilization Study Conducted by Pittsburgh Testing Laboratory for Freeport-McMoRan, Inc. Report No. 1-90-1. Feb. 1990.
9. Ong, S. *Unconfined Compressive Strength of Cement Stabilized Phosphogypsum*. M.S. thesis. Louisiana State University, Baton Rouge, 1993.
10. Thimmegowda, H. *Generation and Evaluation of Raw and Cement Stabilized Phosphogypsum Leachates*. Master's thesis. Department of Civil Engineering, Louisiana State University, Baton Rouge, 1993.

Publication of this paper sponsored by Committee on Cementitious Stabilization.