

# Survey of Techniques Used for Predicting Leachate Quality

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Prediction of waste or fill leachate quality is often an important consideration, as it can be used in determining material placement, drainage designs, leachate containment (clay liner), or surrounding material interaction evaluations and identifying potential impacts to hydrologic regimes, ecological systems, or treatment requirements. In addition, leachate characteristics are often used to classify materials (e.g., hazardous wastes or acid-producing overburden or fill). There are several leachate evaluation test methods, which range from predicting the potential presence of selected characteristics within possible leachates to actual leachate quality determinations of representative materials by using representative leachate fluids. Because cost and time requirements vary with each leachate prediction test, the test method chosen to evaluate a material's potential leachate quality should be based on information requirements of the investigation. Several nonleaching, batch, and column leaching tests were examined as to information that can be obtained from these leachate prediction techniques. Several of these leachate quality prediction techniques, which included reaction pH, total sulfur, acid-base accounting, American Society of Testing and Materials 1:4 shake extraction of solid waste with water, U.S. Environmental Protection Agency extraction procedure toxicity test, and periodic column leaching tests, were then applied to several waste materials. The resulting test data were then compared. The application and usefulness of the various testing procedures in predicting leachate quality of inorganic parameters are discussed.

This paper examines the most commonly used techniques for predicting the potential leachate quality of wastes and other materials. In addition, the techniques are assessed as to information that can be obtained and to their most appropriate application.

The potential presence of selected characteristics in a leachate from a waste can be assessed by employing several nonleaching methods, such as those given in Table 1. These methods have been widely used to predict the potential environmental impact from geologic and waste materials (e.g., acid mine drainage) (1). Nonleaching test methods can be used to predict leachate characteristics because poor-quality leachates are most often associated with materials that are acidic or significantly soluble in water. Even though nonleaching methods have been used with considerable success, they are only qualitative and do not provide any quantitative information about specific pollutants that may contaminate the environment.

The representative leaching fluids from a waste or fill material have traditionally been obtained by using some form of laboratory leach test. Existing leach test methods fall into two broad categories: batch (shake) and column tests. In batch tests, the material to be leached is placed in a container with a known volume of eluant and agitated for desired parameters. Several batch tests have been proposed, and the basic differences among them lie in the nature of eluant used, solid-to-liquid ratio, material particle size, elution time, number of elutions, and type of agitation. Examples of the most commonly used batch tests include American Society of Testing and Materials (ASTM) shake extraction and U.S. Environmental Protection Agency (EPA) extraction procedure (EP) toxicity tests, among many others.

There are several advantages and disadvantages in using batch tests. These are noted below:

1. Advantages: (a) experimental variables can be more easily controlled, (b) several environmental factors that affect leaching potential of material

Table 1. Summary of nonleaching test methods for predicting potential leachate quality.

Test	Measurement and Test Use
Reaction pH	Equilibrium pH at 25°C of a distilled water and test material mixture that is used to assess acid or alkaline reaction of material
Buffer pH and exchangeable acidity	Equilibrium pH at 25°C of a test material, distilled water, and buffer mixture used to assess exchangeable acidity (acidity that will be immediately available to be leached by percolating waters) or lime requirement of material
Total sulfur	Total level of all sulfur forms present; includes sulfates, sulfides, and organic sulfur; used to determine maximum potential acidity
Pyritic sulfur	Total level of all metal sulfides present; may be used to calculate potential acidity
Maximum potential acidity and potential acidity	Indicates "latent" acidity of a material; this type of activity usually results from oxidation (of sulfide minerals for most geological materials) and may be released over a long period (months or years); maximum potential acidity is calculated from total sulfur content; may be determined by oxidation and base titration or calculated from pyritic sulfur for geologic materials
Neutralization potential	Characterizes total capability of a material to neutralize acidity
Acid-base accounting	Accounting of overall acid-producing or neutralizing potential of a material that is used to assess its long-term potential to produce acid or alkaline leachates; difference between potential acidity and neutralization potential
Specific conductance and filterable residue	Measure of level of immediately soluble constituents of a material, usually in a 1:1 or saturated paste mixture

can be simulated, (c) most reproducible, and (d) simple, quick, and inexpensive.

2. Disadvantages: (a) equilibrium conditions are hard to achieve; (b) data concerning long-term reaction kinetics are difficult to obtain; (c) conditions chosen may be difficult to relate to actual in situ conditions; (d) test results are dependent on duration of test, solid-to-liquid ratio, particle size of waste, and eluant; and (f) often much more aggressive than natural leaching environment.

Although the batch tests have several disadvantages, the ease of operation of batch tests and, more importantly, the long time requirements and high cost of column tests have convinced researchers to accept batch tests as the only feasible alternative for generating leachate from a waste or fill material on a routine basis.

Column tests are usually performed by placing the materials to be leached in a glass or plastic column of known dimension and then allowing a desired eluant to flow through the materials in the column. The primary advantages of column tests are that the time variability in potential leachate quality can be evaluated and in situ conditions can be more accurately simulated, including sample permeability and solid-to-liquid ratio. Eluant is added to the column either continuously (continuous column leaching test) or periodically (periodic column flushing test) at set intervals, usually with oxygenation between leachings by the passing of water-saturated

air through the sample. The column test effluent is monitored for desired parameters. The rate of flow through the sample is proportional to the gradient across the column sample and the permeability of the material. The primary advantages and disadvantages of column tests are noted below:

1. Advantages: (a) can more accurately simulate in situ environmental conditions, (b) better simulation of material and liquid contact under in situ conditions, (c) can determine potential time variability in leachate quality, (d) more accurate simulation of kinetic factors that affect environmental systems, (e) can provide accelerated natural oxidation of tested materials (periodic leaching test), and (f) can provide data on permeability and long-term changes in permeability of tested materials by using representative (natural) eluants as a permeant (continuous column test).

2. Disadvantages: (a) difficulty in obtaining reproducible results, (b) problems arising from channeling and nonuniform packing, (c) potential unnatural clogging, (d) possible unnatural biological effects, (e) edge effects, (f) long-term and often difficult test, and (g) expensive.

#### PREVIOUS BATCH LEACHING RESEARCH

An extensive background study was conducted by Ham and others (2) on existing leach test methods to formulate a single leach test method that could be used to generate leachates from various waste or fill materials. They concluded that column tests are too time consuming and difficult to perform for a routine leaching test and recommended shake or batch tests for determining the leaching potential of fill materials. They also proposed a leach test called the standard leaching test (SLT) for generating leachates from waste or fill materials on a routine basis. In this test, the waste is shaken (slow tumbling) with either synthetic leachate (composed mainly of acetic acid and sodium acetate and adjusted to pH 4.5) or distilled water in 1:10 or varied solid-to-solution ratios for 24 h at room temperature. The procedure is repeated three or more times, and the resulting composite leachate is analyzed for desired parameters.

Löwenbach (3) compared and evaluated the SLT (also called the Wisconsin test) with more than 30 other widely used batch or shake tests for their ability to generate data in a reproducible manner, ability to provide rapid assessment of the generation of aqueous toxic contaminants from the disposal of solid wastes in a landfill, ability to model natural leachate generation, their consideration of environmental factors that control leaching in actual landfills, and their ability to serve the legislative and regulatory needs of EPA. After an in-depth study, three tests were recommended for further evaluation: the SLT, the Minnesota test, and the IU Conversion Systems test (IUCS). The Minnesota test consists of shaking the waste material for 24 h either with an acetate buffer (pH 4.5) or with distilled water in a 1:40 solid-to-solution ratio at room temperature (4). In the IUCS tests (5), the waste is agitated with distilled water in a 1:4 solid-to-solution ratio for 48 h at room temperature. The procedure is repeated four times and the combined extract is analyzed for desired parameters. These three leach test methods were compared and evaluated (6) by extracting 14 different industrial wastes supplied by EPA. This study revealed that the SLT was the only test able to representatively leach each of the 14 different industrial wastes and was also the procedure with the most aggressive conditions.

In 1977, ASTM recognized the need for a method to assess the leaching potential of solid materials and proposed two shake extraction methods: ASTM distilled water and ASTM acid methods. The distilled water extraction method consists of shaking (slow tumbling preferred) the test material and distilled water at a 1:4 ratio for 48 h, filtering through a 0.45  $\mu\text{m}$  filter, and analyzing the filtrate for desired parameters (similar to the IUCS test). The acid extraction method is similar to the ASTM distilled waste method except an acetic acid buffer solution (pH 4.5) is used as the eluant instead of distilled water. In 1980, ASTM decided to drop the acid extraction method and proposed only the distilled water extraction method as a standard leachate characterization method (7).

EPA (8) adopted a standard leaching procedure called the EP toxicity test to determine the hazardous nature of waste materials. In this procedure, which is similar to the SLT procedure, the material sample to be tested is mixed with distilled water at a ratio of 1:20 (total), the pH of the mixture adjusted to pH 5.0 with acetic acid (if the mixture pH was initially above 5.0), and the mixture agitated for 24 h; the pH is then monitored and adjusted for the first 6 h of agitation. The resulting extract is filtrated, and the filtrate is analyzed for the EPA National Interim Primary Drinking Water Standards for metals and organics. If the concentration of any of these parameters exceeds the drinking water standards by 100 times or more, then the waste is considered hazardous.

The validity of EPA's EP toxicity test procedure, however, has been questioned by several industrialists and researchers. Some of the major objections to the EP procedure include the following:

1. Too strict and costly,
2. Uses one set of conditions for all situations (9),
3. Does not take into account site-specific conditions (i.e., properties of disposal site, solid-contaminant interactions, etc.) (9),
4. Concentration limits are unreasonable (9),
5. Often poor reproducibility (10,11), and
6. Acidic, aqueous eluant does not satisfactorily extract nonpolar organic compounds in the waste (12).

The ASTM distilled water test has also been criticized for its inadequacy and drawbacks. Lee and Jones (9) contend that this procedure has essentially the same fundamental deficiencies as the EPA EP toxicity test procedure and that the method cannot yield results that can be related to in situ conditions.

Several comparative studies have been conducted to assess the efficacy and reproducibility of the ASTM distilled water and the EPA EP leachate techniques by extracting the same type of waste by these two techniques. Boegly (13) extracted waste ash from the coal gasification process with these two techniques and also with the ASTM acetic acid technique, 0.1 N  $\text{HNO}_3$ , and 0.1 N  $\text{NH}_4\text{OH}$  and found that the concentrations of Resource Conservation and Recovery Act (RCRA) parameters [arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), selenium (Se), silver (Ag), and zinc (Zn)] in the leachates from the ASTM distilled water and EPA EP toxicity tests were almost identical. The ASTM acetic acid technique, however, extracted slightly more Ba, Cr, Ni, and Zn. The 0.1 N  $\text{HNO}_3$  extracted the highest amounts of trace metals from the waste. They also compared the EPA EP toxicity test with a column leaching technique and found that the concentrations

of sulfates and other secondary drinking water standard parameters in the leachates from the column technique far exceeded the amounts found in the leachates from the EPA EP toxicity test.

Another study (14) compared the reproducibility of three procedures--ASTM distilled water, ASTM acetic acid, and EPA EP toxicity test--by extracting reference fly ash with these techniques. This study found that the concentrations of heavy metals leached under the three extraction procedures could not, in general, be shown as statistically different. The study also found no consistent difference in precision between the three extraction procedures.

Another investigation (10) into the reproducibility and source of variation in ASTM distilled water and EPA EP leaching techniques was conducted by statistically analyzing the leachate quality results of reference fly ash from 13 different laboratories. This study found that, when the sample heterogeneity was controlled, the principal source of variation in these two methods was the variability in the leaching process. The study also found that the EPA EP method has slightly better precision than the ASTM method, but the differences between the two methods are not significant at the 5 percent probability level. The EPA EP method yielded better precision on pH (as it was buffered) and marginally better precision on trace metals than the ASTM distilled water method.

#### EXPERIMENTS

Three coal-related waste types were used to demonstrate some of the variances in different leachate prediction methods. These included a slag material and a power station bottom ash and fly ash. Nonleaching potential leachate quality predictive methods (1) included reaction pH, total sulfur, and acid-base accounting. Leachates were generated by using two batch techniques: ASTM 1:4 shake extraction of solid wastes with distilled water (7) and the EPA EP toxicity test (8). Leachate from the slag material was also generated by using a periodic column leaching method modified after Caruccio and others (15). This method, which is similar to the recently proposed ASTM method (16) for column leaching, consisted of placing the slag in a glass column and flushing it continuously with water-saturated air to simulate natural but accelerated oxidation of the slag. The slag was then periodically (approximately biweekly) leached with known volumes of distilled water by allowing the eluant to remain in contact with the slag for 1-h periods. Leachates were chemically monitored for selected parameters and composited for later analysis. The test was concluded at four weeks, after both acidity and specific conductance of the leachates had reached peak values. All leachates were filtered through a 0.45- $\mu$ m filter and analyzed in accordance with EPA procedures (17).

#### RESULTS AND DISCUSSION

The nonleaching characteristics of the waste materials selected for study are given in Table 2. The reaction pH of waste materials indicates that the slag and fly ash are moderately acidic in nature, whereas the bottom ash is near neutral in nature. However, none of the tested materials showed any exchangeable or immediately available acidity. The total sulfur content points out that the slag material, which contains almost 0.8 percent sulfur, has a higher potential to be acid producing than the two ash materials. This is substantiated by the acid-base accounting values. The slag material has an

Table 2. Nonleaching characteristics of test materials.

Parameter	Unit	Waste Type		
		Slag	Bottom Ash	Fly Ash
Reaction pH	pH	5.50	7.10	4.95
Buffer pH	pH	7.60	ND <sup>a</sup>	7.00
Exchangeable acidity	meq H <sup>+</sup> /100 g	0	0	0
Total sulfur	Percentage of S	0.78	0.14	0.19
Potential acidity	Percentage of CaCO <sub>3</sub> equivalent	1.6	0.4	0.6
Neutralization potential	Percentage of CaCO <sub>3</sub> equivalent	1.4	1.2	1.1
Acid-base accounting	Percentage of CaCO <sub>3</sub> equivalent	-0.2	+0.8	+0.5

<sup>a</sup>ND = not determined, or irrelevant, if reaction pH is 7.0 or above.

acid-base accounting of -2 t of CaCO<sub>3</sub> equivalent per 1000 t, which indicates that this material has a slight potential to produce acidic (and therefore toxic) leachates if exposed to an oxidizing environment in the presence of water. The two ash samples have an acid-base accounting of +8 and +5 t of CaCO<sub>3</sub> equivalent per 1000 t of material, which indicates that potential leachates from these two materials would probably not be acidic or, hence, toxic in nature.

The nonleaching characteristics of these materials point out that only the slag has a potential to produce acidic leachates and, hence, should be treated (neutralized) or disposed of with proper precaution. These characteristics, however, provide only a qualitative indication, but no quantitative information, about the magnitude of pollutant concentrations that may be released from the materials. This information is often necessary to assess the extent of possible contamination or to design necessary leachate treatment facilities.

The characteristics of leachates from all three materials that were generated by using the ASTM 1:4 and the EPA EP extraction methods are given in Table 3. Also included in this table are the characteristics of the leachate from the slag generated by using a periodic column leaching technique. The column leachate values represent solute concentrations in composited effluents from eight different leachings.

The ASTM 1:4 leachates given in Table 3 generally are of poorer quality than those leachates generated by the EPA EP toxicity test method for all three waste materials. Typically, higher filterable residues, anions, and metal levels are observable in the ASTM leachates. In contrast, the ASTM leachates for the two ash materials also had pH's that were higher than those of the EPA EP method. This would appear to be a contradiction, as one would expect these wastes to be more soluble in leachates with lower pH's (most metals are mobilized in acidic environments). However, closer examination of the leaching techniques shows that the waste materials were more soluble in the lower pH 5.0 EPA EP leachates. The ASTM method uses a 1:4 extraction ratio while the EPA EP toxicity test uses a 1:16 extraction ratio (1:20 final dilution). Therefore, on a mass soluble per unit mass of waste material, the EPA EP method was the most aggressive leaching technique for all three waste materials. [To convert the EPA EP leachate analyses values from mass per volume of leachate (mg/L) to mass soluble per unit mass of waste material or micrograms soluble per gram of waste ( $\mu$ g/g), multiply the reported mg/L value in Table 3 by 20. The same conversion for the ASTM

Table 3. Leachate characteristics of test materials.

Parameter	Unit	Slag			Bottom Ash		Fly Ash	
		Periodic Column Test	ASTM 1:4 Extraction	EPA EP Toxicity Test	ASTM 1:4 Extraction	EPA EP Toxicity Test	ASTM 1:4 Extraction	EPA EP Toxicity Test
pH	pH	5.00	4.45	4.90	8.15	5.45	7.40	5.30
Acidity	mg/L CaCO <sub>3</sub>	378	98	ND <sup>a</sup>	<2	ND <sup>a</sup>	<2	ND <sup>a</sup>
Alkalinity	mg/L CaCO <sub>3</sub>	10	0	ND <sup>a</sup>	64	ND <sup>a</sup>	38	ND <sup>a</sup>
Filterable residue	mg/L	595	278	156	250	501	2320	659
Chloride	mg/L	52	22	11	9	2.4	20	2.4
Sulfate	mg/L	380	180	88	83	4	1200	204
Dissolved metals								
Aluminum	mg/L	14	2.5	2.6	<0.1	0.2	0.1	2.4
Arsenic	mg/L	0.015	0.006	0.005	0.005	<0.001	0.015	0.008
Barium	mg/L	<0.1	<0.1	<0.1	0.13	0.76	0.18	0.11
Cadmium	mg/L	0.08	0.03	<0.01	<0.001	<0.001	0.01	<0.001
Calcium	mg/L	88	45	12	65	74	420	80
Chromium	mg/L	0.13	0.03	0.08	0.008	<0.001	<0.01	0.017
Copper	mg/L	0.05	0.03	0.02	<0.01	<0.01	0.2	0.21
Iron	mg/L	7.5	1.6	51	<0.01	5.5	9.5	<0.1
Lead	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Magnesium	mg/L	14	7.0	2.0	3.8	3.0	39	8.0
Manganese	mg/L	1.2	0.6	0.6	<0.01	0.61	0.50	0.41
Mercury	mg/L	<0.0005	<0.0005	<0.0005	0.001	<0.0005	<0.0005	<0.0005
Potassium	mg/L	20	10	3.9	11	1.5	160	25
Selenium	mg/L	0.043	0.029	0.0034	1.15	0.23	0.0025	<0.001
Silver	mg/L	<0.01	<0.01	<0.01	<0.001	<0.001	<0.0025	<0.001
Sodium	mg/L	17	8.5	2.8	7.3	3.0	81	11
Zinc	mg/L	9.9	3.9	0.8	0.02	0.02	1.2	0.22

<sup>a</sup>ND = not determined due to addition of acetic acid to leachates.

method is performed by using a multiplier of 4.] However, due to the solid-to-liquid ratios of the two methods, the EPA EP method allows greater dilution in the final leachate that, for these waste materials, resulted in better-quality leachates than those generated by the ASTM method. Note that, in some instances, higher metal levels, especially for iron, were found in the final leachates of the EPA EP method but that these leachates have an overall lower solute concentration than those of the ASTM method.

The leachate quality results of the ASTM and EPA batch leaching techniques showed variations in the materials tested but could have easily shown more significant differences if the wastes were more alkaline or acidic. This is because there is no pH adjustment in the ASTM method and the leachates of the EPA EP method are buffered at pH 5.0 or lower and diluted five times more than the ASTM method. The more alkaline a material, the more aggressive the EPA EP toxicity test should be as metals generally are more soluble in acidic environments. (The EPA EP toxicity test does limit the amount of acetic acid that can be added to a sample such that extremely alkaline materials should remain alkaline.) Conversely, for slightly to very acidic wastes, the EPA and ASTM methods should yield about similar leachate qualities or the EPA EP toxicity test may even show a slightly better quality due to its dilution ratio, as shown for the tested materials in Table 3.

Comparison of the leachate quality obtained with the periodic column test to those of the two batch techniques (Table 3) shows the column test leachate to be of generally poorer quality than those of either batch protocol. This is attributed to two factors:

1. The pH values of the leachates from the three leaching techniques were approximately the same at pH 5.0, and
2. Enhanced natural oxidation of the slag material occurred in the column test, which caused the slag to continually produce more acid and hence be more soluble.

Therefore, for the tested slag material, simulation of natural oxidation and percolating water through the slag resulted in a poorer-quality leachate than those yielded by the ASTM or EPA batch methods. (This column leaching method did not, nor was it intended to, simulate an in situ solid-to-liquid ratio or compacted slag permeability.)

The results of the nonleaching test (Table 2) indicated that the slag showed the largest potential to produce acidic and high solute concentration leachates. The leaching tests performed confirmed the predictions of the nonleaching tests, although the metal levels of the ash materials were only slightly lower than those of the slag. If the acid-base accounting of the slag had been lower than 0.2 percent CaCO<sub>3</sub> equivalent (which is only slightly negative or acidic), more substantial differences in the leachate qualities of the slag and ash materials should have been observable.

#### SUMMARY

A summary of the most commonly used techniques available for predicting leachate quality is given in Table 4. Reaction pH, buffer pH, total sulfur, and acid-base potential are qualitative techniques and provide minimal quantitative information that can be used to gauge the extent of contamination. They are useful indicators of suitability of a material for vegetative growth or of the potential for generation of acidic leachates from a material.

The leaching test methods, on the other hand, are quantitative in nature and provide information as to the nature, type, and amount of contaminants in any waste material. The batch tests (ASTM and EPA methods) are rapid and useful for assessing the leachate quality of wastes on a routine basis. The column tests are time consuming but provide information on the long-term or time-variable quality of waste leachates and can be designed to better simulate in situ conditions. The periodic column tests are useful to study the quality of leachate from a material under a natural but accelerated oxidizing environment. The continuous column method provides time-

Table 4. Application of most commonly used leachate quality prediction techniques.

Method	Application	Test Material	Leachate Predictive Information	Approximate Test Duration	Approximate Cost <sup>a</sup> (\$)
Reaction pH	Index test to determine acid or alkaline reaction	All types	Qualitative: assesses acidic or basic nature of material	0.5 h	5-7
Buffer pH	Index test to determine presence of exchangeable acidity	All types	Qualitative: assesses immediate lime requirement to neutralize exchangeable acidity	0.5 h	5-8
Total sulfur or other sulfur forms	Index test to determine presence of latent acidity that results from oxidation	Geologic materials, especially coal related	Qualitative: assesses potential for acidity release on oxidation	0.5 h to 1 day	7-30
Acid-base accounting	Index test to determine differential between potential to produce or neutralize acid	All types	Qualitative: assesses long-term potential to produce acidic leachates	1 day	25-30
ASTM 1:4 shake extraction of solid waste with water	To predict potential leachate quality	All types	Quantitative: yields leachate quality under conditions of the test, simulates natural pH	3 days	30+
EPA EP toxicity test	To predict potential leachate quality and assess possible hazardous nature of materials	All types, especially potentially hazardous wastes that may be regulated by EPA	Quantitative: yields leachate quality under conditions of test, simulates acidic environment	2 days	75+
Periodic column leaching test	To predict potential leachate quality, or time-variable leachate quality under natural oxidizing conditions by using synthetic or representative leaching fluid	All types, especially geologic materials that produce acid on oxidation	Quantitative: yields leachate quality, especially its variability with time and in oxidizing conditions	4-8 weeks	200+
Continuous column leaching test	To predict potential leachate quality, or time-variable leachate quality and permeability of a material by using synthetic or representative leaching fluid	All types, especially those materials where emplaced permeability is important and in situ leaching fluid is very aggressive	Quantitative: yields leachate quality, especially its variability with time	6-12 weeks	350+

<sup>a</sup> Approximate cost per test, excluding leachate analyses.

variable information on the quality of waste leachate and, if properly compacted, permeability of an emplaced material.

Because cost and time requirements vary with each leachate prediction technique, the test method chosen to evaluate a material's potential leachate quality should be based on information requirements, time constraints, and the ultimate goal of each specific investigation. Often, a combination of less-expensive nonleaching tests as indexers can be used with a limited number of leaching tests to provide a maximum of information on material variability and potential leachate characteristics at reasonable costs. However, a material's actual leachate quality will be environment dependent; therefore, the best predicting technique of leachate quality will be the test method that best simulates the field conditions of each material under study.

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# Identification of Source Materials for Acid Leachates in Maryland Coastal Plain

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Acid leachates are produced in the oxidation of naturally occurring, sulfide-bearing sediments distributed throughout much of the Maryland Coastal Plain. Geologic ages for the sediments span from Lower Cretaceous through Tertiary. When these sediments are exposed to the atmosphere, sulfuric acid is produced in quantities sufficient to prohibit plant growth, dissolve concrete, and corrode metal. Initial pH values of near neutral or above may drop to as low as 2 after the sulfidic sediments undergo oxidation. In addition to pH, characteristics useful in identifying sulfide-bearing Coastal Plain sediments include sulfur content, sediment morphology, presence of sulfide or sulfate minerals, and morphology of surface soils formed from the sediments. Unoxidized sulfidic sediments are mostly dark colored. Typical colors include black (5Y 2.5/1), gray (10YR 5/1), or dark gray (5Y 4/1). Pyrite has been identified as the principal sulfide mineral present in the sediments. Pyrite morphology ranges from large megascopic crystals associated with Lower Cretaceous lignitic deposits to microscopic framboids common in Upper Cretaceous and Tertiary formations. Sulfate minerals formed from pyrite oxidation are useful field indicators of acid-generating sediments. Sulfate minerals that have been identified in acidic sediments include rozenite, szomolnokite, ferroxahydrate, copiapite, gypsum, and jarosite. Jarosite is a highly persistent mineral and has often been observed in naturally weathered soil profiles formed from sulfide-bearing sediments. The identification of jarosite in near-surface soil horizons thus may serve as an indication of underlying sediments with acid-generating potential.

The generation of excessive amounts of sulfuric acid often becomes a severe problem when excavation activities cause the exposure of sulfide-bearing rocks and sediments to the oxidizing environment of the earth's surface. One of the most common examples of this phenomenon is the well-known problem of acid mine drainage associated with coal mining excavations. Interception of sulfide-bearing strata by earth-moving operations is, however, not a hazard unique only to coal or other mining activities. Numerous reports (1-8) have described the occurrences of sulfidic strata across a wide spectrum of geologic settings.

Soil materials that have undergone sulfide oxidation and have excessively low pH values are commonly referred to as acid sulfate soils or cat clays. In the past, these terms have been used principally for identifying acid-generating soils in tidal areas of the world. Recently, investigators have also found it appropriate to apply these terms to upland Coastal Plain soils that display features derived from sulfide oxidation processes. With studies of acid sulfate features in upland Coastal Plain soils (9-11) has come the recognition of the widespread nature of sulfides in many subsurface Coastal Plain strata. Because of the hazards these sediments pose to building materials and ecosystems when exposed to the atmosphere by excavation, identification of sulfidic strata is an important first step in the

course of construction activities to avoid or control acid sulfate problems.

## MATERIALS AND METHODS

Study sites were selected on the basis of morphological properties observed in the field. Sites were located by reconnaissance of areas where outcropping geologic formations were suspected of containing sulfides. Soil and sediment samples were retrieved from road cuts, hand-dug pits, and hand borings.

Samples were air-dried and passed through a 10-mesh (2-mm) sieve. Soil pH was measured by using a 1:1 ratio of soil to water. Identification of sulfur minerals was accomplished by either scanning electron microscopy with energy-dispersive X-ray microanalysis or X-ray diffraction. X-ray diffraction analyses were performed by using a Phillips diffractometer with a 2-theta compensating slit and graphite crystal monochromator. Concentrations of sulfur and free iron were determined by the X-ray spectroscopic procedures of Snow (12) and Fanning and others (13), respectively.

## RESULTS AND DISCUSSION

### Properties of Sulfidic Strata

At least seven geologic formations in the Maryland Coastal Plain were found to contain subsurface sulfide-bearing strata that, when exposed to the atmosphere, were capable of producing high amounts of sulfuric acid. These sediments were found throughout much of the western and central portions of the Maryland Coastal Plain. The general properties of the sulfidic strata are given in Table 1.

As is apparent from Table 1, a common property shared by each of the sediment types was dark coloration. Dark colors for these materials probably result from the presence of organic compounds associated with reduced sulfidic strata as well as darkness of metallic sulfides (mostly pyrite) themselves. In applying Munsell soil color notation for describing chroma and value, sulfide-rich materials generally have chromas of 1 or less and values of 4 or less.

Beyond color, however, few other similarities existed for the sulfide-rich strata. Textures ranged from loamy sand to clay, and geologic ages for the materials span from Lower Cretaceous through Miocene. In addition, it must be emphasized that the formations listed in Table 1 are generally not