Relevance of Durability Testing of Shales to Field Behavior

JAMES L. WITHIAM AND DAVID E. ANDREWS

Geologic materials exhibit a wide range of behavioral responses following excavation and replacement in a new environment. This is a result of various mechanisms induced by variations in moisture and stress regimes or other environmental aspects of the materials. The physical disintegration of such geologic materials caused by fundamental changes in stress conditions or strength characteristics is referred to as slaking. The most distinctive aspect of the slaking process is a relatively rapid decrease in fragment size of the material. To develop an understanding of the slaking process, a comprehensive evaluation of existing data was undertaken that included a detailed literature review of geotechnical, agronomical, and geochemical test procedures used to identify potentially problematic slakable materials. The findings from this review are incorporated into a comprehensive laboratory testing program that forms the basis for a proposed classification system and spoil management program. It is concluded that a relatively simple series of tests can be used to assess the probable impact of slaking of fine-grained materials on stability, settlement, and erosion potential. Comparisons are made between laboratory and field observations to support this conclusion.

To develop an understanding of the slaking process as it relates to mine spoils, a comprehensive evaluation of existing laboratory techniques was undertaken. The principal objectives of previous laboratory durability testing programs have centered around (a) assessing the applicability of accelerated rock weathering tests to help predict long-term performance, (b) quantifying the effects of time-dependent rock degradation caused by various slaking mechanisms, and (c) finding additional tests that can quickly identify problem materials.

A summary of previous research efforts and general survey studies associated with durability testing programs is presented in Figure 1 [full citations for the studies included are presented in the report by Andrews and others (1)]. Tests are classified according to their nature and applicability as identification (physicochemical and mineralogical), durability, and strength tests. Many of these consist of standard and modified geotechnical, agronomical, and geochemical tests. Most programs include both identification tests, such as grain size and mineralogy, and behavioral tests, such as rate of slaking. Ideally, the simplest and most reliable indicators are sought for a given purpose, although more sophisticated tests often serve a useful purpose.

Physicochemical tests have been incorporated into several durability-related testing programs because much useful data can be collected quickly, at low cost, by using relatively standard equipment and test procedures (2). As Figure 1 indicates, those tests that show the greatest success in correlations with observed durability behavior are water content and, to lesser degrees, grain size and Atterberg limits. The successful performance of these tests is principally related to the fact that most low-durability geologic materials are fine-grained and often active clay mineralogies that absorb water following stress relief. Because durability is fundamentally related to mineralogical composition, applications of mineralogical tests also have formed the basis for several slake durability studies. Of those techniques identified in Figure 1, X-ray diffraction has been applied most successfully, although its high cost makes other less quantitative procedures, such as the methlyene blue absorption (MBA) test, attractive substitutes.

Figure 1. Summary of laboratory tests associated with slaking.

	Identification Tests										Durability Tests										Strength Tests			
	Physico-Chemical							Mineral-ogical																
Studies(3)	Water Content	Grain Size	Atterberg Limits	Unit Weight	Specific Gravity	pH	Chemical Analysis	Petrographic Examination	X-Ray Diffraction	Methylene Blue Absorption	Jar Slake(1)	Cyclic Wet-Dry(2)	Rate of Absorption	Rate of Slaking	Slake Durability	Washington Degradation	Ultrasonic Degradation	L. A. Abrasion	Freeze-Thaw	Swelling Tests	Unconfined and Triaxial Compression	Point Load	Schmidt Hammer	Shore Hardness
Gamble	●	○	○	●					○		○	○			●					○				
Heley and MacIver	○	○	○	○					○		○	○								○				
Deo		○	○	○					○			●	○		●			○						
Eigenbrod	●	○	●						○			○		●							○			
Laguros		●	○		○	○		○	●		●						○			●				
Aufmuth															●							○	●	
Goodman, Heuze, Thorpe, and Chatoian	○			○											●							○		
Nettleton			○							●					●									
Reidenouer, Geiger, and Howe		○	○	○				○	●		●	○	○			●	●	●	○					
Chapman	●		●						○		●	●		●	●	○	○	○					○	
Augenbaugh and Bruzewski	●		○										●		○					○	○			○
Bailey	○	●									○											○		○
Rodrigues											○				○									
Lutton	○					○			○		●				●									○
Noble							○		●		●	●			○									
Strohm	○	○	○									○			○							○		
Strohm, Bragg, and Ziegler			○			○					○	○		○	●							○		
Hudec	●			○								●	●	○	●					○				

(1) Water, ethylene glycol, hydrogen peroxide, or sulfuric acid used as slaking fluids.
(2) Water and sodium sulfate solutions used for slaking wet-dry cycles.
(3) Study citations are omitted for brevity.

LEGEND:
○ - Test conducted.
● - Fair to good correlation with durability.

Several types of tests have been developed or modified to provide qualitative and/or quantitative assessments of the slake potential of geologic materials. As illustrated in Figure 1, several of these have shown moderate to very good success. Others, because of severe test conditions, show little apparent value. In general, those durability tests that show the better correlation with field response also represent the more realistic models of slaking processes. By most accounts, slaking of geologic media results from physical breakdown by wetting and drying, chemical action by leaching, and other processes following stress relief. Based on these criteria, the first five durability tests identified in Figure 1 represent the most realistic models of field behavior. They have also shown the greatest success during previous investigations.

The jar slake test is the simplest of all durability tests and consists of placing a rock fragment or gradation of rock fragments into a beaker containing water or some chemical solution. After immersion, sample breakdown is observed for some period of time ranging from hours to days. Cyclic wet-dry durability tests subject rock fragments to conditions more consistent with observed field response. These tests impose several cycles of alternating wetting and drying by soaking samples in water or chemical solutions (e.g., sodium sulfate) and air or oven drying over a range of temperatures. These test conditions are consistent with the cyclic wet-dry, rate of absorption, and rate of slaking durability tests. Finally, the slake durability test (3) uses the additional feature of mechanical agitation to accelerate slaking under laboratory conditions. To date, the slake durability test is the only procedure acknowledged as part of an accepted industry standard (3). Most of the other reported durability test procedures represent unusually severe conditions that frequently result in rapid and complete sample deterioration. Such complete sample breakdown provides neither a reasonable physical model nor a reliable model of field behavior. This is especially true for geologic media of an intermediate durability range.

The principal purpose in relating strength to durability has been for various classification schemes, although strength tests have also been used to directly identify rock durability or to infer future settlement or stability behavior. Several attempts have been made to relate the strength tests identified in Figure 1 to durability. These efforts have generally failed because of a lack of sensitivity in distinguishing ranges of slaking response, bias imposed by a need to test specimens prepared to certain tolerances, and a need to perform large numbers of tests to provide a statistical basis for test conclusions.

FIELD PROGRAM

To examine the nature and impact of slaking at coal surface mine sites in the eastern and central United States, detailed field and laboratory programs were designed and implemented. The field program was developed to document the nature, occurrence, distribution, and effects of slaking at sites in this region. A detailed account of the field program followed at four sites is provided in the paper by Perry and Andrews elsewhere in this Record.

Of particular importance to the laboratory program were highwall and mine spoil exploration programs, for these would yield undisturbed highwall and bulk spoil samples for laboratory evaluation. Highwall exploration was accomplished by drilling near the active highwall and using standard wireline techniques that provided NQ-sized core (1.875 in in diameter). The rock core was then placed in specially designed boxes that used weather stripping and heavy sheet plastic to minimize change in moisture content. In addition, bag samples of each major lithotype were collected from the fresh spoil area at every site to supplement the rock core samples obtained for the laboratory program.

To evaluate the mode, degree, and extent of slaking in mine spoils and the associated environmental effects, a thorough test-pit exploration and visual reconnaissance program was conducted by examining spoil recently placed as well as 2-, 5-, and 10-year-old spoils. After the completion of test-pit logging, bulk samples weighing approximately 100 lb were taken from a selected subsurface layer for subsequent determination of bulk grain-size distribution.

LABORATORY PROGRAM

As discussed previously, several slake testing procedures are available and these provided the framework for the laboratory program implemented for this study. In addition, several supportive analytic procedures were used for classification or identification purposes. The laboratory program was designed to be efficient and provide information needed to evaluate various parameters that affect the degradation of geologic materials. Incorporated into the design were those procedures and techniques that would allow anticipated key relations to be addressed.

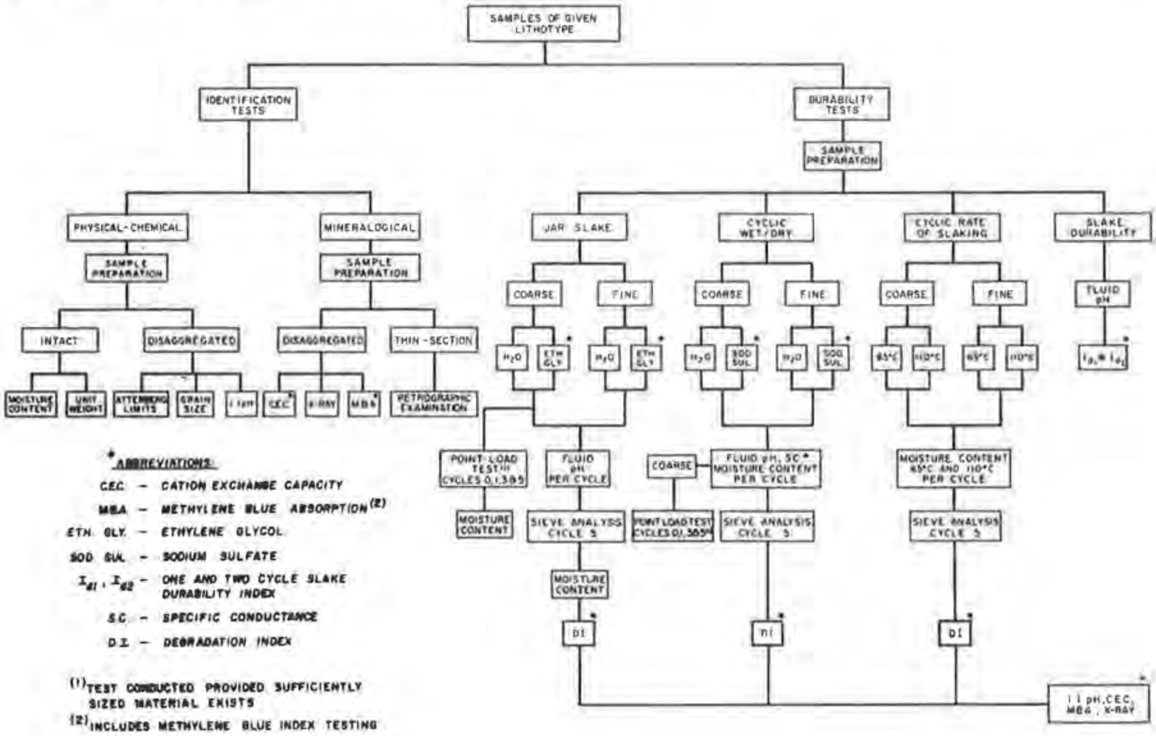
The selected laboratory tests were grouped in three categories: durability, identification, and ancillary testing. These categories were found useful for quantifying, classifying, and predicting the long-term durability characteristics of geologic materials. A flow diagram of the laboratory testing program is shown in Figure 2. Because space does not permit a detailed description of the test procedures used, the interested reader is referred to the completed report (1).

The lithotypes that represented major portions of the overburden or exhibited unusual field behavior were used for the testing program. Whenever possible, geologic materials obtained from test borings were selected because they were collected and preserved as closely as possible to the in situ conditions. Because siltstone, mudstone, and shale generally make up a high percentage of overburden and typically exhibit more severe slaking characteristics, the majority of samples for this study were fine-grained. Limestones were only tested with the slake durability apparatus because limestone seldom exhibits large amounts of physical deterioration. When an insufficient quantity of rock core was available, given lithotypes were supplemented with recently spoiled material. Occasionally, due to fragment size or material availability, insufficient quantities of a given lithotype were collected for the completion of the full series of tests.

The major portion of each sampled lithotype was used for the durability testing program. To determine the effects of fragment size on slaking, both coarse and fine components were selected for the jar slake, cyclic wet-dry, and cyclic rate of slaking durability tests. The coarse component consisted of 1.5- to 2-in fragments; the fine component ranged in size from 0.25 to 0.75 in in diameter. Samples prepared for the physicochemical testing were generally crushed at the natural water content to the required grain size (approximately No. 60 mesh size). Samples prepared for mineralogical analysis (X-ray diffraction) were dried and crushed to less than a No. 200 mesh size.

Durability tests used to measure the slaking po-

Figure 2. Generalized flow diagram for laboratory testing.



tential of the various highwall lithologies were the slake durability, jar slake, cyclic wet-dry, and rate of slaking tests. These tests were selected because they represent a wide range of conditions (e.g., sample fragment size, wetting and drying cycles, temperature, and slaking fluids) and had some degree of proven success.

Nine identification tests were used in the laboratory program. Moisture content, disaggregated grain size, Atterberg limits, and unit weight tests were performed in general accordance with standard testing procedures. Petrographic examination of thin sections of rock fragments was performed on coarse-grained sedimentary materials. The principal purpose for using this tool was to examine in detail the composition of matrix cements and rock fabric as they relate to the observed durability behavior. The remaining identification tests [1:1 pH, cation exchange capacity (CEC), MBA, methlyene blue index (MBI), and X-ray diffraction] were included to identify the chemical or mineralogical composition of the sampled lithotypes. X-ray diffraction and CEC were intended to provide an understanding of the mineralogical composition of the samples that could be used as a reference for comparing the results of other less costly and time-consuming test procedures (e.g., CEC versus MBA or MBI).

Additional tests that were expected to give insight into the durability characteristics of the sampled lithotypes included point load tests, analyses of the slaking fluid (pH and specific conductance), and fragment moisture contents. Point load strength tests were used to monitor the degree of strength reduction during the "slaking" tests and were performed as part of the coarse-fragment portion of jar slaking and cyclic wet-dry tests. Fragments were periodically selected for testing to determine incremental strength deterioration. Fluid pH, specific conductance, and fragment moisture contents were determined at key stages in the program.

The durability tests selected for study consisted of the jar slake, cyclic wet-dry, cyclic rate of slaking, and slake durability tests. These tests were selected because the influence of a wide range of parametric effects could be closely examined by using procedures that had previously proved successful. The parametric factors that could be considered from this series of tests include (a) lithotype; (b) sample size; (c) slaking fluid (i.e., distilled water and solutions of ethylene glycol and sodium sulfate); (d) temperature (i.e., 65° and 110° C for cyclic rate of slaking test); and (e) energy input. Because each of these may control, to some degree, the slaking response of geologic materials, the testing program represents a comprehensive attempt to identify the key factors that affect this behavior.

To quantify the deterioration of samples subjected to the jar slake, cyclic wet-dry, and cyclic rate of slake durability tests, a degradation index (DI) was used in accordance with a procedure suggested by Bailey (4). The DI is defined by using mean equivalent mesh sizes from sieving operations before and after slake testing as weighing factors to produce an index that is a measure of the amount of sample breakdown. The limits for this index range from zero (no breakdown) to 100 percent (complete breakdown). The slake durability index (I_d) was used to define the slake durability test results (3). Numerical subscripts to I_d (e.g., I_{d2}) are presented to indicate the number of testing cycles used to determine the index value. For purposes of comparison with the other durability test results, however, the term ($1 - I_{d2}$) is used to define a DI for the slake durability tests.

LABORATORY TEST RESULTS

Durability Tests

As shown in Figure 3, 128 individual durability tests were conducted by using 14 lithologic units

Figure 3. Summary of durability test results.

SITE	LITHOTYPE	DURABILITY TEST[1]															
		JAR SLAKE[2]				CYCLIC WET/DRY[2]				CYCLIC RATE OF SLAKE[2]				SLAKE DURABILITY	
		COARSE		FINE		COARSE		FINE		COARSE		FINE			
		WATER	ETHYLENE GLYCOL	WATER	ETHYLENE GLYCOL	WATER	SODIUM SULFATE	WATER	SODIUM SULFATE	65°C	110°C	65°C	110°C	I_{d_2}[3]	$1-I_{d_2}$
A	Brown Sandstone	0	2.7	0.5	0.5	2.0	4.9	0.8	0.3	0	0	0.8	0.3	99.0	1.0
	Gray Shale	11.7	14.8	0.4	0.3	31.6	34.2	0.7	0.7	40.9	52.5	1.2	1.8	87.6	12.4
	Green Mudstone	●	●	47.5	51.9	76.6	■	56.6	30.7	●	●	48.7	58.6	87.1	12.9
	Black Carbonaceous Shale	21.8	26.2	0.5	0.2	42.1	52.1	2.1	0.8	■	35.2	1.9	1.2	97.6	2.4
	Gray Limestone	●	●	●	●	●	●	●	●	●	●	●	●	99.3	0.7
B	Gray Siltstone	3.7	0	1.6	0	75.2	72.2	26.5	16.4	0	76.2	12.1	24.3	98.5	1.5
C	Yellow Sandstone	0	0.3	●	●	0	0	●	●	0	0	●	●	97.1	2.9
	White Sandstone	0	0	0.3	0.3	0	0	0.6	0.7	0	0	1.2	0.5	97.7	2.3
	Gray Siltstone	31.4	25.4	●	●	24.4	25.7	7.5	3.0	26.8	31.6	●	●	94.3	5.7
D	Brown Sandstone	5.4	3.4	●	●	0	18.1	●	●	10.4	7.5	●	●	99.5	0.5
	Gray Shale	38.3	52.6	13.5	16.9	41.9	64.4	42.0	32.6	80.5	87.5	45.7	57.6	98.3	1.7
	Green Mudstone	13.3	9.7	19.3	10.9	20.6	21.8	27.4	15.3	2.3	24.2	21.2	22.6	75.7	24.3
	Red/Green Mudstone	85.6	●	●	●	92.7	●	●	●	●	●	●	●	63.4	36.6
	Gray Limestone	●	●	●	●	●	●	●	●	●	●	●	●	99.7	0.3

[1] All numbers expressed as percent.
[2] Numbers in columns represent Degradation Index (DI) values.
[3] 2-cycle slake durability index.

LEGEND
● - No test performed.
■ - Test performed; sample crushed for X-ray prior to sieving.

collected from four different active surface mining sites. These lithologic units included four sandstones, two limestones, two siltstones, three mudstones, and three shales.

The size of sample fragments is important for almost all cases studied. In general, the coarse samples developed greater breakdown for all fluids and drying temperatures. This was most noticeable for thinly bedded, anisotropic sediments, such as siltstones and shales. Consequently, for complete slake potential identification, samples of sufficient size must be tested. The results of these tests suggest that a minimum fragment size of 1 in be used.

For the samples tested, the application of solutions of sodium sulfate and ethylene glycol led to slight differences in breakdown compared with the use of distilled water. Because the distinctions are small, the use of chemical slake fluids probably can be ignored.

With the exception of the slake durability test, cyclic wetting and drying provided the greatest assurance of breakdown. Of the cyclic tests, the cyclic rate of slaking procedure at 110° C is the most severe, which indicates that short soaking periods that cause only partial saturation are more effective for the tested samples. An advantage of this method is the shorter soaking observation period, which reduces the overall time required for testing. The range of DI values obtained for the jar slake test was narrower than for the cyclic tests, which makes the analysis more difficult and subjective. Therefore, cyclic testing is preferred to the static jar slake test.

The results of the cyclic rate of slaking test provided an opportunity to study the relation between drying temperatures and slake durability behavior. These tests indicate that a reduction in durability occurs with increasing drying temperatures. This pattern is stronger for the coarse size fraction, which also demonstrates the effect of particle size on the durability of the tested samples.

With the possible exception of the slake durability tests, greater degrees of breakdown were realized with test procedures that involved the greatest energy effort. This effort was developed by several means, including fluid infiltration, oven drying, chemical attack, and mechanical agitation. Of the durability tests considered for study, both the cyclic wet-dry and cyclic rate of slaking tests at 110° C provided the broadest range of breakdown (DI values ranging from 0 to 93 percent) and sufficient sensitivity to characterize relations within these boundaries.

Identification Tests

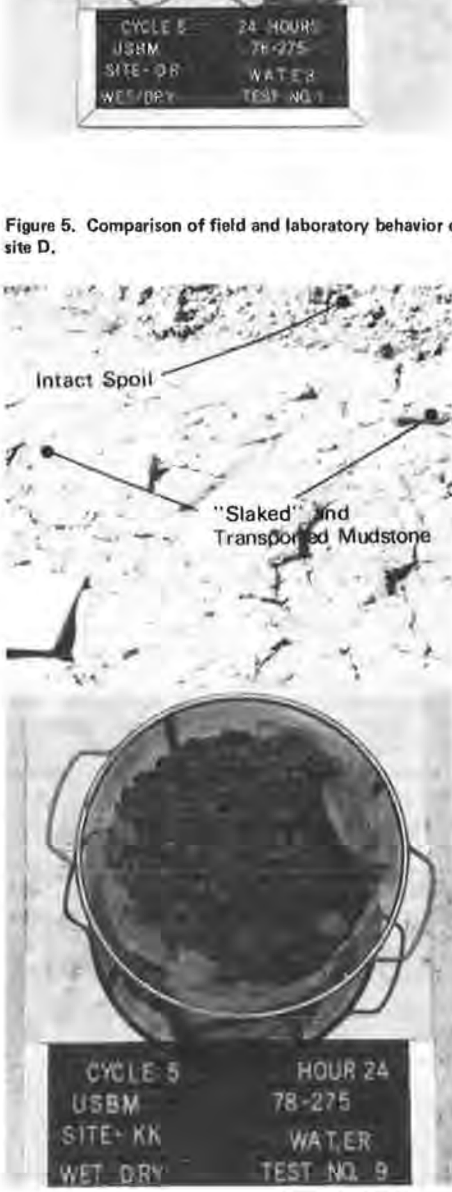
Knowledge of the physical, chemical, and mineralogical composition of geologic materials can provide corroborative information regarding their slake durability behavior. The major goal of these tests, therefore, was to identify procedures that can be confidently used as part of an overall slake durability predictive model.

Except for moisture content determinations taken at the end of test cycles, none of the geotechnical index tests provided any reliable basis for predicting durability behavior. Grain-size analyses and Atterberg limits tests of disaggregated samples revealed a small range of values that bore little relation to the observed durability behavior. These results were generally confirmed through X-ray diffraction analysis, which indicated relatively inactive clay mineralogies. A similar small range of initial moisture content values was measured for undisturbed highwall samples collected from all sites. The range of in situ moisture contents was generally unrelated to durability behavior, and no correlations could be made between unit weight and durability.

Variations in moisture content with increasing cycles of durability testing generally follow two trends. For sandstones and more durable siltstones and shales, the moisture content increased to an equilibrium value within one or two cycles. All other fine-grained sediments exhibited an increasing moisture content with increasing numbers of cycles. Accordingly, these patterns can be correlated with

Figure 4. Comparison of field and laboratory behavior of gray siltstone from site B.

Figure 5. Comparison of field and laboratory behavior of mudstones from site D.



durability. In a similar fashion, moisture contents for samples consisting of the fine fragment size always exceeded the coarse-fraction moisture content for corresponding samples and solutions. The smallest increases were realized for sandstones and the largest for mudstones. The principal factor controlling the moisture-content behavior of coarse and fine fragments is the relation between surface area and volume.

Of all other identification tests, only 1:1 (soil) pH and CEC showed any relation to durability test results. Application of this observation is described subsequently.

Ancillary Tests

Additional testing was performed concurrently with the durability testing program. This included point load tests and analyses of pH and specific conductance of the slake fluid. These various techniques were relatively simple to perform and were thought to possibly provide additional data for understanding the slaking phenomenon.

Although much effort was spent to test the suitability of the point load test as a predictor of durability, only limited trends could be discerned. The point load strength index (I_s) generally increased with increasing durability, but the results are biased toward the more durable rock fragments that remained at the end of various test cycles. For lithotypes with very low durability (e.g., mudstone), the lack of samples of sufficient size precluded the possibility of testing. Measurements of slake fluid pH and specific conductance provided no recognizable trends.

COMPARISON OF FIELD AND LABORATORY PROGRAMS

Some previous studies of slaking have failed to correlate laboratory test results with observed field behavior. This has often led to incomplete recognition of several of the prime factors that control the breakdown of geologic materials. Furthermore, because of the similitude and time-effect problems associated with laboratory programs, the implications of several factors (e.g., sample size and accelerated weathering) in relation to field behavior are not completely understood. Accordingly, field observations of durability and modes of slaking were generally substantiated by, and in agreement with, the laboratory program. Two examples at different sites are summarized to show the similarity of field and laboratory response.

At site B, the gray siltstone is initially massive with high rock quality designation (RQD) values and no apparent bedding. When subjected to slaking stresses, however, this siltstone undergoes chip slaking, which was seen in both the field and the laboratory (see Figure 4). This behavior is strongly controlled by structure (thin bedding planes) that originates during deposition of the sediments. The coarse fractions subjected to laboratory testing showed high DI values, whereas the fine fractions were more durable and had DI values equal to approximately one-third those of the coarse samples. This is generally consistent with the observed field behavior in that the fine chips appeared to resist further degradation.

At site D, although the lithology of the red-green mudstone and green mudstone is similar, the rate of deterioration was far more rapid for the red-green mudstone, as evidenced by the general lack of this material in even recent spoil piles. This was supported by the very rapid disintegration that developed in the laboratory following immersion. However, the impact of this lithotype within the

spoils is negligible because it represents less than 5 percent of the highwall materials. The RQDs for the red-green mudstone were extremely high. This suggests that RQD and similar classification systems do not accurately reflect slaking potential. Similar results were obtained for other lithotypes throughout the study.

The observed pattern for both mudstones at site D, however, is similar because neither appears to be affected by fragment size or structural control. Even though the green mudstone initially undergoes chip slaking in the field, it slakes with time to its constituent particle size. Figure 5 shows examples of the pattern of slaking for these mudstones in the field and the laboratory.

PROPOSED CLASSIFICATION SYSTEM

The proposed classification system is based on a series of field and laboratory decision filters. Each portion of the system provides the necessary ingredients to identify potentially problematic geologic materials. In addition, the final mixture of slakable and nonslakable units in spoil piles is considered, based on information obtained during the field program. It should be noted, however, that because this system is based on limited information obtained from only seven sites (four of which were studied in detail), the proposed scheme is tentative and additional input is warranted.

The proposed system is presented in Figure 6 and includes those techniques that were found to reliably predict the slaking potential and behavior of geologic materials. It is divided into field and laboratory phases and uses relatively simple inspection and routine test procedures that are often a part of surface mine permitting programs. The classification system is divided into four categories: preliminary field reconnaissance, exploration program, preliminary laboratory program, and durability testing program.

The preliminary field reconnaissance takes advantage of the useful information that can be gathered by examining bedrock outcrops in the vicinity of the proposed site. Of particular importance are the type and quantity of fine-grained sediments because these factors bear a direct relation to the nature of problems that may be encountered following spoiling operations.

Drilling programs represent the second tier of the proposed classification system. At this level, the behavior of fresh rock samples can be compared with the behavior in bedrock exposures. In addition, simple testing with dilute HCl can be used to ascertain the need for proceeding with a laboratory testing program. The specific decisions in this phase of the program are illustrated in Figure 6.

The laboratory testing program is designed as a two-phase filtering system. The principal purpose is to separate durable and nondurable geologic materials based on two tests by using crushed, powdered rock samples (1:1 pH and CEC). A relation exists between CEC and 1:1 pH that can be extended to include rock durability based on a five-cycle DI. Figure 7 demonstrates that the DI increases with increasing 1:1 pH and CEC, which is related to the influence of carbonates and various clay mineral phases. To incorporate this behavior into the proposed classification scheme, a DI value of 50 percent (representing the delineation between moderate and high degradation levels) was selected as a threshold. This value, in conjunction with the chemical performance of the suite of materials tested, suggested that maximum limits of 7.8 (1:1 pH) and 15 meq/100 g (CEC) be used, as indicated in Figure 7, as criteria to assess the need for durability testing. If, for a particular sample, the preliminary test results fall below these boundaries (crosshatched zone in Figure 7), no further testing is necessary nor are special design measures beyond normal practical requirements expected. If either of these bounds is exceeded, then further testing is required.

The final stage in the classification system uses

Figure 6. Proposed classification system.

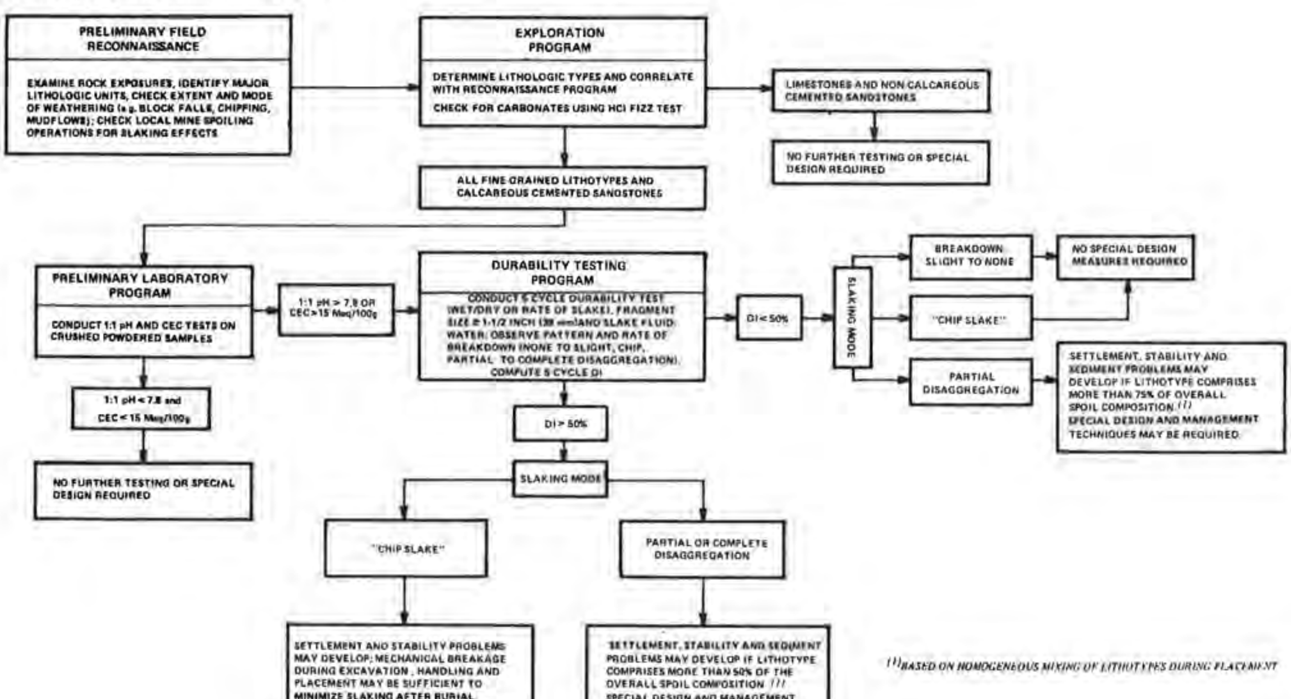
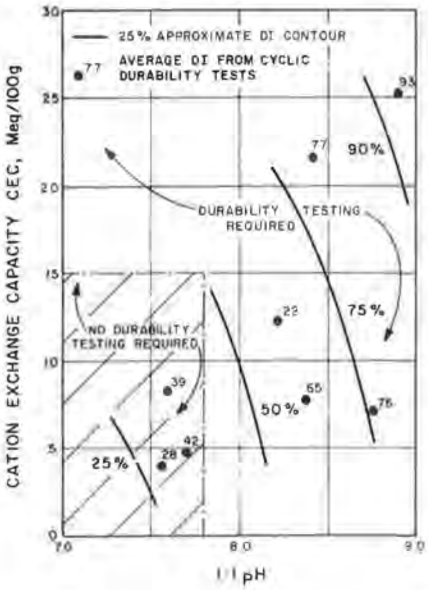


Figure 7. Proposed laboratory classification filter.



durability testing. This may be readily and simply accomplished by subjecting the remaining samples to either of the cyclic durability test procedures described previously. Based on results from the laboratory program, it is recommended that these tests be conducted by using coarse fragments 1.5 in or larger and water as the slaking medium. Intensity and mode of breakdown then can be identified and compared with the results of the field reconnaissance, and appropriate design considerations can be implemented to minimize potential environmental impacts of spoiling these materials.

The assessment of spoil management control measures for the above categories was developed from the field program. At each site, the reclamation procedures that are practiced follow relatively routine patterns that seem to provide sufficient amounts of breakdown and densification to minimize slaking effects. These result in relatively minor problems (mostly surficial) despite the fact that some lithotypes developed DI values that were higher than expected (e.g., gray siltstone at site B) or were present in sampled spoils in relatively high amounts (e.g., 60-70 percent mudstone at site D). This suggests that the effort expended during excavation, handling, and placement and the intermixing of durable and nondurable sediments can control, to a large degree, the ultimate behavior of geologic materials. Therefore, present spoiling and reclamation practices may overcome the majority of problems that could be associated with low-durability materials.

SUMMARY

Based on evidence provided from a detailed field and laboratory testing program, laboratory durability testing appears to provide a rational basis for predicting field behavior. Several types of durability tests and various procedures were evaluated along with a variety of supplemental tests to provide index, mineralogical, and chemical data. Of these, cyclic wet-dry durability testing using coarse site fragments soaked in water along with other simple chemical tests (i.e., soil pH and CEC) appears to offer a reasonable basis for a predictive model. Finally, a classification system is outlined that uses observed field spoil response as a basis for development. Although the proposed model is preliminary due to its limited data base, the classification system nonetheless represents a reasonable first-step approach to the assessment of mine spoil durability.

ACKNOWLEDGMENT

The findings described in this paper are part of a project sponsored by the Bureau of Mines, U.S. Department of the Interior (1). The views and conclusions presented are ours and should not be interpreted as necessarily representing the official policies or recommendations of the U.S. Department of the Interior or the Bureau of Mines. Finally, we appreciate the support of D'Appolonia Consulting Engineers, Inc., in the preparation of this paper.

REFERENCES

1. D.E. Andrews, J.L. Withiam, E.F. Perry, and H.L. Crouse. Environmental Effects of Slaking of Surface Mine Spoils: Eastern and Central United States. Bureau of Mines, U.S. Department of the Interior, Denver, CO, Final Rept., 1980, 247 pp.
2. 1979 Annual Book of ASTM Standards: Part 19--Natural Building Stones; Soil and Rock; Peats, Mosses and Humus. ASTM, Philadelphia, 1979.
3. E.T. Brown, ed. Rock Characterization, Testing, and Monitoring: ISRM Suggested Methods. Pergamon Press, Oxford, England, 1981, pp. 92-94.
4. M.J. Bailey. Degradation and Other Parameters Related to the Use of Shale in Compacted Embankments. Indiana State Highway Commission, Indianapolis, and Engineering Experiment Station, Purdue Univ., West Lafayette, IN, Joint Highway Research Project JHRP-76-23, 1976, 230 pp.

Publication of this paper sponsored by Committee on Engineering Geology.