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Interim Report

SHALE CLASSIFICATION TESTS AND
SYSTEMS: A COMPARATIVE STUDY

David R. Chapman

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

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16. Abstract The abundance of shale rock necessitates its economical and efficient use in compacted embankments. Differing shale durabilities require a variety of design parameters and construction techniques. Classification systems for shales are available, and are helpful, but most have not been definitively correlated with field performance of compacted shales. Simple laboratory tests were selected from several existing classification systems, and performed on six Indiana shales. Tests included: Slake Durability, slaking tests with different slaking fluids, Atterberg limits, Los Angeles Abrasion, Schmidt Hammer hardness, and the Washington Degradation test. Also included was a study of sample preparation effects on Atterberg limits results. The shales were then classified by each system, and the descriptive categories for the various systems were compared. Regression analysis was used to examine statistical relationships among results from different tests. X-ray diffraction patterns and some soil chemistry procedures were used to identify constituent minerals and their relative percentages. Tests expected to be particularly useful in shale classification include Slake Durability and two simple slaking procedures. Tests designed to evaluate mineral aggregates for pavements were generally too severe for the softer shales which are most prevalent in Indiana.			
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HIGHLIGHT SUMMARY

Shale is one of the most common naturally occurring geologic materials in the earth's crust. Its abundance necessitates its economical and efficient use in compacted embankments for highways. Attaining this objective is complicated by the range of durabilities encountered with shale materials. Thus, a variety of design and construction guidelines are required. Classification systems have been proposed to this end, but until now, no study has been made to compare the results of these systems on the same shales.

For this investigation, tests were selected from several existing classification systems, and performed on six Indiana shales. The shales were classified by each system, and the descriptive categories for the various systems were compared for identification of any significant trends in relationships between the systems. As expected, it was found that some of the systems gave similar information.

Tests expected to be particularly useful in shale classification include slake-durability and two simple slaking procedures. Some of the other tests evaluated were deemed too severe for use with the average shale encountered in Indiana.

The major deficiency in the present State-of-the-Art seems to be the lack of correlation of classification efforts with field performance. Recommendations are made to hopefully correct this deficiency. A program of classification testing combined with instrumentation of shale embankments for performance information would be involved.

Interim Report
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A COMPARATIVE STUDY

by

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LIST OF SYMBOLS

- C_{uo} = original compressive strength
 C_u = compressive strength of identical specimen after soaking
 D_n = Washington Degradation Factor (presently in use by Washington Department of Highways)
 D_o = Washington Degradation Factor (formerly used by Washington, presently used by Pennsylvania Department of Transportation)
 H = height of sediment in cylinder (Washington Degradation test)
 I_d = slake durability index, in general, for oven-dry samples
 $(I_d)_d$ = slake durability index, for oven-dry samples
 $(I_d)_{d,200}$ = slake durability index, for oven-dry samples, tested for 200 revolutions of drum
 $(I_d)_{d,500}$ = slake durability index, for oven-dry samples, 500 revolutions
 $(I_d)_{d,200,2nd\ cycle}$ = slake durability index, for oven-dry samples, 2 cycles of 200 revolutions each
 $(I_d)_s$ = slake durability index, for oven dry samples soaked 6 hours prior to testing
 $(I_d)_{s,200}$ = slake durability index, for soaked samples, 200 revolutions
 $(I_d)_{s,500}$ = slake durability index, for soaked samples, 500 revolutions
 I_L = liquidity index
 I_{Lf} = liquidity index at end of rate of slaking test
 I_{Lo} = liquidity index before rate of slaking test

I_p = plasticity index

I_s = modified soundness index

L10 = weight loss through #10 sieve

L200 = weight loss through #200 sieve

w = natural moisture content

w_L = liquid limit

w_p = plastic limit

w_s = maximum moisture content reached during slaking

ΔI_L = change in liquidity index during rate of slaking test

Δw = change in moisture content during rate of slaking test

ABSTRACT

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Shale Classification Tests and Systems: A Comparative Study.
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The abundance of shale rock necessitates its economical and efficient use in compacted embankments. Differing shale durabilities require a variety of design parameters and construction techniques. Classification systems for shales are available, and are helpful, but most have not been definitively correlated with field performance of compacted shales.

Simple laboratory tests were selected from several existing classification systems, and performed on six Indiana shales. Tests included: Slake Durability, slaking tests with different slaking fluids, Atterberg limits, Los Angeles Abrasion, Schmidt Hammer hardness, and the Washington Degradation test. Also included was a study of sample preparation effects on Atterberg limits results. The shales were then classified by each system, and the descriptive categories for the various systems were compared. Regression analysis was used to examine statistical relationships among results from different tests. X-ray diffraction patterns and some soil chemistry procedures were used to identify constituent minerals and their relative percentages.

Tests expected to be particularly useful in shale classification include Slake Durability and two simple slaking procedures. Tests designed to evaluate mineral aggregates for pavements were generally too severe for the softer shales which are most prevalent in Indiana.

The major deficiency in the present State-of-the-Art seems to be the lack of correlation of classification indices with field performance. Recommendations are made for instrumentation of shale embankments to provide the information necessary to correct this deficiency.

I. INTRODUCTION

Shale

Shale is one of the most commonly occurring soil or rock materials on the earth's surface. The term "shale" has been applied to many classes of materials, which can be generally described as fine-grained, clastic sedimentary rocks.

A geologic dictionary, compiled by the American Geological Institute, defines shale as follows: "Shale includes the indurated, laminated, or fissile claystones and siltstones. The cleavage is that of bedding and such other secondary cleavage or fissility that is approximately parallel to bedding. The secondary cleavage has been produced by the pressure of overlying sediments and plastic flow" (2).¹ The definition preferred by the writer, close to the one given above, is "an argillaceous rock possessing lamination or fissility." The non-fissile equivalents are then termed mudstone, siltstone, or claystone, depending on their composition. This definition follows Underwood (40).

Shales are problem materials in several phases of geotechnical engineering because of their composition and durability. Shale is the boundary material between "soil" and "rock," and for some applications, it needs different treatment from either soil or rock. This study was conducted as part of a research project dealing with the use of shales for embankment materials.

Shale properties pertinent to embankment construction include its degradation and slaking behavior. Degradation is defined as reduction in aggregation size due to construction operations, and slaking as decomposition due to subsequent weathering within the embankment. Because shales are widely variable due to differences in composition and cementation, their durabilities and degradation characteristics are thus variable also.

¹ Items in parentheses refer to entries in the Bibliography, page 83.

Shale Classification

Variations in shale properties give rise to a need for guidelines for safe, economical use of shales as construction materials. The guidelines must be formulated upon the basis of a sound, concise classification system which groups shales by expected construction and long-term behavior. Because of these factors, a number of classification systems for argillaceous rocks have been developed.

These systems fall into 3 basic categories:

1. General systems developed for use by geologists, consisting primarily of genetic, qualitative information.
2. General systems developed for use by engineers, emphasizing quantitative information obtained from tests performed to evaluate properties of the shales.
3. Systems developed by a given agency for its own purposes and use. These can fall into either of the other two categories, or contain elements of both. This type of system may work well for a given locality and be virtually inapplicable elsewhere.

This study dealt primarily with the engineer's type of classification system, because quantification of the classification categories was felt to be essential. This approach involves the use of existing tests and classification procedures, or the development of new ones.

At this time, there are several existing systems, including one developed at Purdue (12). It was decided to study the interrelationships of these systems as they are used to classify a given group of shales. From such a comparative assessment, it may be found that there is little if any difference between results predicted by various tests and systems. If this is the case, a simpler, more rational, and more universal system may be identified and recommended for use.

II. RESEARCH PROBLEM AND APPROACH

General Problems with Shales

As stated before, shale is the most common sedimentary rock, and is often encountered in construction. It is thus desirable to use shale as much as is practical, e.g., shale excavated from cut sections should be used in adjacent fill sections, rather than borrowing non-shale material.

Shale is typically described as a "problem" embankment material, and traditionally considered by many to be comparatively useless (10). The fine-grained structure of shale has made it intrinsically more difficult to study and analyze than other rocks. Concurrently, the fact that many shales are too "hard" to test conventionally as soils and too "soft" to test conventionally as rocks restricts their rational use.

Because of the prevalence of shales, a whole spectrum of varying properties can be expected. There is a great range in the composition of shales, both in primary constitutive material, and in secondary materials such as agents of cementation (40). These variations can be seen through adjectives such as calcareous, carbonaceous, ferruginous, and siliceous, which are commonly used to describe shales. The variation in constitutive material can be with respect to clay minerals, or even include large amounts of non-clay material. The shales in Indiana are predominantly silty, exhibit low plasticity indices, and often contain more silt size than clay size (12, 21).

Stress history, as well as compositional variation, are important in the behavior of a shale. Some shales are little more than highly overconsolidated clays, and in fact would be so called in some countries of the world. Others have been cemented with various materials, or subjected to enough heat and pressure to have attained a substantial durability and strength. The slaking behavior of these two classes of

materials can be expected to be greatly different. The non-cemented or "compaction" shales, as they have been termed by Mead (30), are much more susceptible to disintegration in water.

Shales as Embankment Materials

In Indiana, shales are often encountered in building highways, especially in the southern part of the state. For this reason, research is being directed toward formulating design and construction guidelines for shale embankments in order to promote efficient and economical use of any shale encountered. These guidelines should permit the engineer to predict the in-service behavior of a shale from the results of relatively simple laboratory tests.

Varying shale properties, and their effect on embankment performance, make it desirable to first classify shales by means of their differing expected behaviors. Some shales degrade readily in the process of excavation, hauling, and placement. Others seem more durable, as they remain in large chunks during construction, but may cause settlement due to slaking later if placed so that there are relatively large voids present. A third class of shales has seemed to perform satisfactorily as rockfill. It is obvious that failure to correctly predict these differences can be unsafe on one hand, and overly conservative on the other. It is necessary to have some means of accurately predicting shale behavior so the proper decisions can be made at the time of construction.

Shale is intermediate between soil and rock. However, shales in general vary enough so that in many cases, "soil" and "rock" classification systems are inadequate. It is not simple to measure elastic modulus and compressive strength, yet the material can be hard enough to prevent adequate breakdown to prepare for Atterberg limits determination. These discrepancies have led to the development of several classification systems for shales or argillaceous rocks. These are discussed in Chapter III.

Implementation of Shale Classification

A problem that besets the designer of any classification system is validating the system once it is formulated. Much testing is carried out in the laboratory for classification purposes, and systems are formulated with little if any opportunity to observe the field behavior of the classified material. Franklin (15) suggests that a great deal of the present day confusion concerning classification systems can be attributed to the belief that special structures, e.g., embankments, require a special classification system. At any rate, more activity is needed in the area of observation of field performance, in conjunction with the classification process.

Research Approach

The number of existing classification systems, and the fact that in few if any cases have the same shales been tested and classified in more than one system, led to the decision to make a comparison between classification systems. The real objective of the testing program was to identify simple, economical tests to be used in classifying shale, and to verify, modify, and/or supplement the classification system proposed by Deo (12) and by the Indiana State Highway Commission (26).

Tests from several classification systems were chosen to accomplish this objective. These tests were selected primarily on the basis of simplicity since this is one of the requirements for a good classification test.

The systems chosen for investigation were Deo's "Classification for Shales for Embankment Construction" (12); "Durability-Plasticity Classification of Shales and Other Argillaceous Rocks," by Gamble (17); a procedure from Pennsylvania Department of Transportation, "Shale Suitability - Phase II" (36); a portion of "Classification of Argillaceous Soils and Rocks," by Morgenstern and Eigenbrod (31); and a portion of a study by Saltzman which quantifies rock properties for riprap (37).

Conclusions will be drawn with respect to the degree of overlap of the various systems, and the ability of certain tests to predict the

results of others. If possible, a combination of the most successful tests will be selected and proposed for use. It is hoped that agencies currently using some of the proposed classification tests will be motivated to try others for correlation purposes. Through this process, statistical refinements in the ranges of variables can be made, improving the validity of the system.

Eventually, it is hoped that results from one or two simple tests can be used at the time of the subsurface investigation, to reasonably predict the properties of each shale stratum encountered. When this approach is perfected, it will be a vast improvement over the present techniques in Indiana, where shale is identified from borings, but most of the design parameters and construction decisions are not determined until the shale is encountered in excavation.

III. LITERATURE REVIEW

Shale

"Shale" is a rather loosely used term, applied to fine-grained clastic sedimentary rocks. The nature of this class of rocks is such that they are extremely variable; ranging from hard clay to moderately hard rock; and from massive to fissile in structure. The deterioration characteristics of the rock when submerged and the compressive strength are important properties which vary greatly. Other properties of varying engineering significance include grain size, breaking characteristics, lamination or bedding, mineral composition, hardness, plasticity, compressibility, swell potential, and color (17).

Philosophy of Classifying Engineering Materials

The variability, and the wide occurrence of a material such as shale, make classification and evaluation of its probable behavior an important stage in the design and construction process. A number of classification systems have been developed to deal with the problems caused by the character of shale.

Classification, if well done, in a rational manner, can improve the likelihood that an expedient design will be made. This presupposes, of course, that an adequate classification system is already at the disposal of someone qualified to use it. The very number of classification systems in existence give evidence that there is no one system which is widely accepted as satisfactory.

To be useful, a classification system must tell the engineer something which helps him in design or construction. Since rock materials are conventionally identified by a geologist, and the information is principally used by an engineer, the importance of clear communication should be emphasized (5). Franklin, in discussing

the philosophy of rock classification, states "An optimum classification for rock engineering is likely to employ both observations and tests" (15).

The characteristics of individual tests used have great bearing on the effectiveness of a system. Some practical items that should be included in test selection include (5, 15):

1. Tests should be quick and inexpensive, with few observations required.
2. Simple techniques should be employed.
3. Results should be reproducible between locations, when standardized procedures and equipment are used.
4. The apparatus must be strong, portable, and not prohibitively expensive.

Other items, required for adequate characterization of a rock for classification are:

5. Relevance of the test results to in-situ rock properties.
6. Applicability of the result obtained to engineering problems.
7. The capacity of the test to differentiate correctly between samples.

Classification Systems

To meet the needs described previously, classification systems have been proposed by several investigators (5, 8, 11, 12, 17, 28, 31, 35, 40). Because the various researchers had differing objectives, there is considerable variation in the types of tests investigated, and also in the types and ages of geologic materials which were tested.

Underwood (40) discussed many pertinent properties of shales, and recommended an engineering evaluation, with respect to pore pressures, bearing capacity, tendency to rebound, behavior in cut slopes, slaking behavior, erosion potential, and tunnel support problems. It was recommended that basic engineering properties conventionally determined in the laboratory for major engineering projects be used to make this assessment. His analysis is depicted in Table 1.

Table I. An Engineering Evaluation of Shales (40).

PHYSICAL PROPERTIES			PROBABLE IN-SITU BEHAVIOR						
LABORATORY TESTS AND IN-SITU OBSERVATIONS	AVERAGE RANGE OF VALUES		High Pore Pressure	Low Bearing Capacity	Tendency to Rebound	Slope Stability Problems	Rapid Slaking	Rapid Erosion	Tunnel Support Problems
	UNFAVORABLE	FAVORABLE							
Compressive Strength	50 - 300 psi	300 - 5000 psi	✓	✓					
Modulus of Elasticity	20,000 - 200,000 psi	200,000 - 2×10^6 psi		✓					✓
Cohesive Strength	5 - 100 psi	100 psi to >1500 psi			✓	✓			
Angle of Internal Friction	10 - 20°	20 - 65°			✓				
Dry Density	70 - 110 pcf	110 - 160 pcf	✓					✓	
Potential Swell	3 - 15 %	1 - 3 %			✓	✓		✓	✓
Natural Moisture Content	20 - 35 %	5 - 15 %	✓			✓			
Coefficient of Permeability	10^{-3} - 10^{-10} cm/sec	> 10^{-8} cm/sec	✓			✓	✓		
Predominant Clay Minerals	Montmorillonite, Illite	Kaolinite, Chlorite	✓			✓			
Activity Ratio = $\frac{PI}{\% \text{ Clay}}$	0.75 to > 2.0	0.35 to 0.75				✓			
Wetting and Drying Cycles	Reduces to grain sizes	Reduces to flakes					✓	✓	
Spacing of Rock Defects	Closely Spaced	Widely Spaced		✓		✓		✓	✓
Orientation of Rock Defects	Adversely Oriented	Favorably Oriented		✓		✓			✓
State of Stress	> Existing Overburden Load	≅ Overburden Load			✓	✓			✓

Gamble (17) tested 120 shales from many areas of the United States. He discussed the shortcomings of geological classification systems for shales, and proposed the classification system and standardized nomenclature shown in Table 2. Grain size and breaking characteristics are the primary considerations. It is suggested that "... slaking characteristics for mudrocks or shales be determined from a slake durability test and modifiers to describe the relative durability be used with the suggested terms, e.g., low durability claystone, or high durability silty shale" (17).

Based on extensive laboratory testing, which included determination of the slake durability after 2 cycles of testing, and the Atterberg limits, Gamble also proposed the engineering classification for shales and other argillaceous rocks shown in Figure 1. It is necessary to compare the slake durability test results with performance of cut slopes and other excavations to give real meaning to the slake durability values.

In a study by Laguros (28), index property tests and strength-related property tests were performed. These results were supplemented by X-ray diffraction analyses of the mineralogy of the samples tested. This study was an attempt to identify a process which would allow preparation of material similar to the expected product of in-service weathering, and to study its properties, thereby improving design of pavements and highway side slopes.

Shales were disaggregated for Atterberg limits and grain-size distribution using ultrasonic equipment. This treatment effected changes in grain-size distribution, plasticity characteristics, X-ray diffraction patterns, and in shale fabric. The recommended treatment time was 1 hour.

Percentage of 2-micron clay was determined to be important in appraisal of the engineering performance of shales. Based on percentages of silt and clay present, a shale is classed as a "problem" or "no problem" shale. Problem shales, by definition, have more than 40% of combined silt and clay^{silt & clay}. Index properties for problem shales are determined using ultrasonically disaggregated material. Additional

Table 2. Classification for Argillaceous Rocks (I7).

Unindurated	Indurated Group		After Incipient Metamorphism	Metamorphic Equivalents
	Mudrocks (Shales or Mudstones)			
	Breaking Characteristics			
	Massive	Fissile or Shaly		
Silt →	Siltstone	Silty Shale	<div> <div>Argillite →</div> </div>	Slate, Phyllite, or Schist
Mud (mixture of underdetermined amounts of silt and clay, with minor amount of sand)	Mudstone	Shale		
Clay →	Claystone	Clayey Shale

Figure 1. Gambles' Durability-Plasticity Classification for Shales and Other Argillaceous Rocks (17).

correlation of laboratory test results with field performance will be necessary in order to establish the validity of Laguros' system (28).

The geological conditions in the State of Pennsylvania are such that there is a shortage of high quality aggregates. This situation led to a comprehensive study of the suitability of the abundant shale deposits in Pennsylvania for use as aggregate (36). After testing 124 samples using various durability tests, index property tests, and geologic, petrographic, and mineralogical examination, an evaluation method was proposed.

The shale in question is subjected to a visual examination, which may reject the shale. If not rejected, it is subjected to soaking in ethylene glycol. If the results are satisfactory, the Washington Degradation Test is performed. The Washington Degradation Factor is then used to determine the applications for which the shale is suitable, ranging from rolled embankment material to base course aggregate.

An additional classification scheme, directed specifically toward argillaceous materials, was recently reported by Morgenstern and Eigenbrod (31). The primary objective of the study was to facilitate determination of variations in strength and water deterioration characteristics of shales as a basis for their classification. The method developed is based on the principle that a soil will disintegrate when exposed to water in an unconfined manner, and a rock will not (31).

Tests developed include the Standard Compression Softening test, which measures the time-dependent strength loss; the Quantitative Slaking test, which measures the increase of water content with the number of drying and wetting cycles; and the Rate of Slaking test, which measures the change of water content after 2 hours of immersion.

Various classification categories are defined with respect to amount of strength loss, time for 50% strength loss to occur, and change in water content during slaking. It is recommended that the Standard Compression Softening test be used to differentiate between clays and mudstones, as shown in Figure 2. The liquid limit of the materials can be used to predict the maximum water content reached during slaking, and also in conjunction with the results from the Rate of Slaking test, to describe slaking behavior, as shown in Figure 3.

Figure 2 Engineering Classification of Argillaceous Materials

Rate of Slaking: * $\Delta I_L = I_{L_f} - I_{L_0}$	Amount of Slaking $w_S = w_L$				
	very low	low	medium	high	very high
	VL $w_L < 20$	L $20 < w_L < 50$	M $50 < w_L < 90$	H $90 < w_L < 140$	VH $w_L > 140$
slow S , $\Delta I_L < 0.75$	VL S	L S	M S	H S	VH S
fast F $0.75 < I_L < 1.25$	VL F	L F	M F	H F	VH F
very fast VF $\Delta I_L > 1.25$	VL VF	L VF	M VF	H VF	VH VF

* 2 hours of water immersion

Figure 3 Classification in terms of Slaking Characteristics

A recent paper by Aufmuth (5), expresses the need for index property tests in rock mechanics similar to those used in soil mechanics. To be useful, such a test must:

1. measure a property of the material which is applicable to the solution of engineering design problems.
2. be inexpensive, simple, and easy to perform.
3. yield results which are reproducible between operators and localities using standardized equipment and procedures (5).

Recommended tests include the Schmidt Rebound Hammer, Slake Durability, and Field Direct Shear Strength tests. Over 800 cores from 168 formations, representing 25 lithologic types were tested, and extensive statistical analysis was carried out using regression analysis to develop correlative equations. Equations with 80% confidence limits were given for compressive strength vs. Schmidt value, modulus of elasticity vs. Schmidt value, modulus of elasticity vs. Slake Durability; and a zoned plot of Slake Durability vs. Schmidt value was also shown. The suggestion was made that additional tests be performed and analyzed for refinement of the regression coefficients. Also stressed was the importance of including with the system a lithologic description of the rock mass.

Saltzman (37) developed a general approach to the quantification of rock properties, directed toward selection of stone for rip-rap and other similar uses. The study included an examination of the mechanisms of rock weathering, and the significance of rock structure and textural features in relation to weathering. The degree to which the common engineering tests are representative of weathering processes and agents was also investigated.

Tests evaluated included: specific gravity, absorption, Schmidt Rebound Hammer, pulse velocity and dynamic modulus of elasticity, unconfined compression, Brazilian tensile test, modified Los Angeles Abrasion, freeze-thaw test, ethylene glycol soaking test, and ultrasonic cavitation.

Four tests were selected as acceptable for quantification of rock properties: Schmidt Rebound Hammer, L. A. Abrasion, freeze-thaw, and

ultrasonic cavitation. The defined ranges for acceptable rock are given in Table 3. As with most systems discussed, more data are needed to develop the necessary confidence in the given ranges of values, or to refine the limits.

Deo (12), in the Purdue study which preceded the current research, developed a rating system for shales to be used as embankment materials. It is based on 4 simple tests, and divided shales into "soil-like" shales, "rock-like" shales, and "intermediate 1 or 2." The tests used are a 5-cycle simple slaking test, 500 revolution slake durability tests on dry and soaked samples, and a sodium sulfate soundness test, modified by using 50% solution rather than a saturated one.

This system, currently being tested for applicability by the Indiana State Highway Commission, is shown in Figure 4. There has been no formal monitoring of performance of embankments constructed from any given shale category for which results are available, but Deo gave hypothetical guidelines for each. Soil-like shales are susceptible to weathering, and thus should be broken down and compacted in thin lifts. Rock-like shales can probably be placed as rockfill. Intermediate shales should be treated like soils, but larger chunks can be tolerated than with soil-like shales. It is still important to insure that large voids do not remain in the embankment after compaction (12).

Rock materials in nature constantly undergo degradation due to weathering, some of which takes place over long periods of time, and some which takes place at a sufficiently rapid rate to be of significance within the life of the structure (8). Chandra (8) sought to develop a test which could predict the expected degree of "short-term" weathering. He defined "slake durability" as the "... capacity of the rock to resist changes, wear, or breakdown with time when subjected to the slaking action of water, as exhibited by breaking or disintegrating into smaller pieces. It is essentially a physical process, and broken particles do not lose their identity, but still resemble the parent rock material" (8). He developed the Slake durability test, which gives a numerical result I_d , and which can be used to describe durability as shown in Table 4.

Table 3 Criteria for Selection of Rock Blocks (37)

Test	Excellent	Acceptable	Not Acceptable	Units
Ultrasonic Cavitation	0-20	20-90	> 90	total wt. loss in mg.
Schmidt Value	> 40	35-40	< 35	
L. A. Abrasion (modified)	< 20	20-40	> 40	% wt. loss
Freeze-Thaw Test	< 20	20-30	> 30	% wt. loss

Figure 4. Deo's Classification for Shales for Embankment Construction (I2).

Table 4 Chandra's Classification System (8).

I_d	Descriptor of Durability
0-25	very low
25-50	low
50-75	medium
75-90	high
90-95	very high
95-100	extremely high

An application of the test, because it is simple, and the apparatus portable, is in core logging, where I_d can be plotted vs. depth, with other properties (8).

In New South Wales, Australia, a shortage of high quality aggregates necessitated the investigation of shales for pavement construction (11). Shales were sampled from quarries and from existing roads, and subjected to mineralogical analysis, Atterberg limits determinations, various accelerated weathering tests, and several "strength" tests.

Physical and chemical weathering effects were evaluated. Chemical weathering, though definitely significant, could not be meaningfully correlated with observed performance, and thus was not further studied. Several physical weathering tests were evaluated, and the one selected for use was a 10-cycle slaking test in which the slaking cycle included tumbling in a jar.

The mechanical stability of the shales was also investigated, through tests such as aggregate impact, aggregate crushing, L. A. Abrasion, and a ball-mill test. It was found that the resistance of the shales to breakdown was dependent upon the clay mineral content and type. The ball-mill test was selected because of its simplicity. This test, performed on soaked samples, was particularly effective for revealing the unsuitability of non-indurated and micaceous shales (11). The final recommendations included a dye absorption technique, for rapid, simple assessment of the mineralogical composition.

Classification Tests

Slaking Tests

The classic distinction between soil and rock is linked to a property known as "slaking." Slaking is defined thus: "Loosely, the crumbling and disintegration of earth materials when exposed to air or moisture. More specifically, the breaking up of dried clay when saturated with water, due either to compression of entrapped air by inwardly migrating capillary water, or to the progressive swelling and sloughing off of the outer layers" (2). Terzaghi used the following criterion to arbitrarily separate soil from rock for engineering purposes. "Soil is a natural aggregate of mineral grains that can be separated by such gentle mechanical means as agitation in water. Rock, on the other hand, is a natural aggregate of mineral grains connected by strong and permanent cohesive forces" (38).

This criterion is virtually applicable when working with shale, since some shales slake rapidly, and others remain unaffected. A 5-cycle slaking test was recommended by Philbrick (35), and used by Deo in his study. According to Philbrick, shales which are reduced to aggregates of very small size are "compaction" shales. Those unaffected, or reduced only to flakes are "cemented" shales. One drawback to this test is its qualitative nature, since it relies on subjective descriptions of changes in the condition of the shale. Following up Deo's work (12), the Indiana State Highway Commission has developed a quantification for the slaking test as follows. After each soaking cycle, the material is washed over a #10 sieve, and retained material is subjected to additional cycles. The Slake Index of a shale is defined (24), after 5 cycles as:

$$SI = \frac{\text{Total wt. of shale lost through \#10 sieve}}{\text{Total original wt. of shale}}$$

The #10 sieve is selected to permit a comparison between this test and the Slake Durability Test, which employs a drum constructed from #10 mesh.

Other tests have been developed which measure the slaking tendencies of shales. In their classification, Morgenstern and Eigenbrod developed tests referred to as the Rate of Slaking test, and the Quantitative Slaking test. The Rate of Slaking test was developed because of the impractical, excessive amount of time required by the Quantitative Slaking test. It was found that most shales reach a constant water content within about 2 hours when immersed and the Rate of Slaking test measures the water content change during a 2 hour immersion period (31).

The Quantitative Slaking test was designed to measure the change in water content of shale during wetting. A brass mesh container was used to contain the shale, which was alternately air dried and wetted by placing it on wet filter paper. The test is very time consuming, and thus impractical for general classification work. However, it was found that the maximum slaking water content, reached after varying numbers of cycles for different materials, was nearly equal to the liquid limit, and thus the liquid limit can be used to predict the results of the test (31).

Soaking tests using ethylene glycol as the fluid have been used in various forms by Saltzman (37) and the Pennsylvania Department of Transportation (36). Reidenour et al. (36) found ethylene glycol to be useful in immediately failing an unsatisfactory sample of shale. In the present study the test was performed according to designation CRD-C 148-69 from the "Handbook of Concrete and Cement," entitled "Method of Testing Stone for Expansive Breakdown in Ethylene Glycol" (20).

According to the procedure, ethylene glycol reacts with swelling clays of the montmorillonite group to form a product occupying a greater volume than the reactants. Thus a rock containing such clay is expected to undergo expansive breakdown when soaked in ethylene glycol if the state of expansion is such that glycol can be imbibed. Rocks affected by this test can be expected to break down when exposed to wet-dry and freeze-thaw environmental fluctuations in service (20).

Tests Combining Slaking and Agitation

The slake durability test was developed at Imperial College in London (8, 15). The intent of the test is "... to provide a simple, relatively rapid method of distinguishing between shales by their slaking characteristics."

In such a test, it is necessary to cause disruption of the rock, and to estimate its extent. The best way of accomplishing the latter seemed to be sieving. The slake durability test was developed, using a rotating drum made of 2 mm mesh. The sample is approximately 500 grams of shale, in 10 lumps. It is oven dried at 105°C. before the test, and the drum is rotated through water as the slaking fluid. The shale durability index, I_d , is the percent by weight retained in the drum after 10 minutes at 20 rpm. It was tentatively suggested that an I_d of 90 be the cutoff between soil and rock. The proposed classification, which utilizes I_d , is shown in Table 4.

The Slake Durability test has been used by Gamble (17), Deo (12), and Aufmuth (5). Gamble modified the test by performing a second cycle of slaking on the material retained in the drum. The purpose of the extra cycle was to add greater resolution for the more durable shales (17). The modification is now recommended as standard by the original developers of the test (5, 15, 16). Both methods were evaluated in this research.

The Washington Degradation test was developed because conventional aggregate quality tests failed in many instances to distinguish between satisfactory and unsatisfactory aggregates for pavements. The premature failures were determined to be caused by plastic fines that developed as a result of particles abrading against each other in the presence of water (29). The Washington Degradation test accelerates and duplicates the degradation process, providing an index value of the aggregate's durability (29).

The Washington Degradation Factor can range from 0 to 100, with high values indicative of superior aggregates.

The test was designed with aggregate suitability in mind, but it may be desirable to apply it to shale classification, in its present

or modified form. In the Pennsylvania Department of Transportation report (36), the test was adopted (in a slightly modified form) for use in rating shales. The recommended specifications are shown in Table 5.

Table 5 Pennsylvania Department of Transportation Shale Specifications Based on Washington Degradation Factor (36):

Washington Degradation Factor, D_o	Recommended Use of Shale Material
< 10	Unsuitable for any construction requiring durable granular material.
$10 < D < 20$	The shale has sufficient durability for use in embankments, and as granular material up to the subgrade.
$20 < D < 45$	The shale is durable enough for use as subbase, as stone backfill, and in stone slope walls.
$D \geq 45$	The shale has sufficient durability for use in base courses.

Miscellaneous Tests

The Atterberg limits have been employed in several classification systems (14, 17, 28, 31), and in conjunction with others (12, 36). The reasons for this are apparent; shales are fine-grained engineering materials, many of which exhibit plasticity, and the tests simple and commonly performed.

The conclusions as to the applicability of the Atterberg limits in shale classification are varied. Gamble (17) found them directly applicable in his system, as did Laguros (28) and Eigenbrod (14). The Pennsylvania study (36) and Deo (12) concluded that they were of marginal value in predicting the durability of a shale.

The nature of shale materials presents somewhat of a problem in preparation of the samples for the Atterberg limits tests. Although

shales may be non-durable materials for construction, some of them seem extremely durable when being prepared for index testing, due to the presence of interparticle bonds (39). To determine an accurate index of plasticity, it is important that shales be intensively disaggregated.

A variety of disaggregation methods have been recommended (28, 39) which are expected to be more effective than ASTM D421-58, the standard preparation method for soil. Ultrasonic disaggregation is suggested by Laguros (28) for preparation of "problem" shales as he defined them. The ultrasonic cleaner employed has a 200 watt generator, and the recommended treatment time is 1 hour.

Townsend and Banks (39) presented a review of methods used by the Corps of Engineers and others in disaggregation of shales. The techniques employed were cyclic drying and slaking, and/or mechanical manipulation such as blender action or grinding to effect the aggregation size reduction.

The ultrasonic cavitation test was developed in the form discussed here, by Saltzman (37). The test was designed to evaluate the textural and mineralogical weaknesses of a rock through measurement of damage incurred by the rock when subjected to cavitation of water by ultrasound. A 9/16 inch diameter rock core about 1 inch long was placed in a device which gripped the sample firmly. It was then submerged in warm water and subjected to high-energy bubbles, which were generated in the water by an ultrasonic probe. The bubbles impinged upon the rock surface, causing particles to be loosened and detached. The weight loss of the specimen was then determined. Information concerning input energy, and capabilities of the test apparatus, are discussed thoroughly by Saltzman (37). The original study included a thin section petrographic analysis before and after the test to determine the type and degree of damage to the rock, and which minerals were affected.

Slaking Mechanisms and Weathering Processes

In the research reported in this thesis, very little attention was paid to study of slaking processes and mechanisms by laboratory testing, because the objective was to identify simple, practical tests. However,

the subject is covered to some degree in the literature, and was reviewed to aid in development of a better understanding of shale behavior.

Terzaghi explained slaking in terms of a phenomenon that has been referred to as "air breakage." His logic is as follows: When a dried specimen of shale is immersed, the outer portion of the specimen is saturated, trapping air in the inner voids. The presence in the air produces tension in the solid skeleton, causing some zones to fail in tension, and resulting in breakdown of the specimen (38 - p. 146).

This explanation has been somewhat substantiated for some materials (33), and found not to be accurate for others (7). Nakano (33), in a study of Tertiary, landslide-susceptible mudstone in Japan, found a somewhat different explanation. To test the "air breakage" theory, slaking tests were run under atmospheric pressure, and in a vacuum. If the "air-breakage" explanation is correct, then the amount of slaking in a vacuum should be less than that occurring at atmospheric pressure. However for the materials tested, this was found not to be the case. In tests using water and other slaking fluids, it was found that dried mudstone slaked rapidly, while that at natural moisture content disintegrated very little, even when immersed for long periods of time. The hypothesis is that the chemical potential of adsorbed water is considerably lower than that of free water, and that when dried, the zone of inactivity is affected by the drying. When the zone is disturbed, hydrogen bonds are formed between adsorbed and free water molecules, resulting in slaking (33).

Chenevert (9) worked with a hypothesis that expansion of clays and montmorillonitic rocks is caused by water or ion adsorption onto the electrically charged surfaces of clays. It was found that illitic and chloritic shales as well as montmorillonitic shales showed significant alteration of properties as a result of water adsorption (9).

Grice (18) studied disintegration characteristics of nonexpandable shales, specifically some Ordovician Utica shales from the Montreal area, which are classified "non-problem" shales by the Underwood criteria (40). His objectives were: (1) to establish that a given shale would be unaffected by weather if it was exposed to a certain

temperature-humidity range for a specified period of time, and (2) to quantify breakdown. The test involved partial saturation from adsorption of water vapor and shorter cycles than most other methods. This gives the advantage of less testing time, and the partial saturation more accurately models field conditions. Sieving is not used, as the mechanical disturbance could alter the particle interaction and shielding effects. The results varied from breakdown in one cycle to 9 months of cyclic wetting and drying with little evidence of alteration (18).

Badger et al. (7), conducting research on breakdown characteristics of shales clogging screens in coal separation processes, developed a test similar to the Washington Degradation test, and investigated slaking mechanisms. Slaking is attributed to 2 basic processes, which can act separately, or concurrently. The softening and dispersion of colloidal binding material, which is dependent upon exchangeable ions and slaking fluid properties is common to all shales. Also a factor in some shales is the "air-breakage" mechanism. A theoretical explanation, involving a logarithmic relation for quantity, time, and disintegration constant is also reported (7).

Other mechanisms which can contribute to deterioration are mentioned by Aughenbaugh (6). These include freezing and thawing and expansion-causing growth of secondary minerals due to chemical reactions. Relative humidity exposure tests similar to those of Grice (18) were also performed.

Moriwaki (32) studied slaking mechanisms, and factors affecting slaking, which he defined as "... any engineering-wise significant deterioration due to immersion in or exposure to some liquid or gas, usually water or water vapor. Therefore, slaking may include dispersion or swelling." Through an extensive literature review, he found that there were 3 generally accepted slaking mechanisms. The first is the "air-breakage" phenomenon, reported to be significant for non-swelling materials which have been dried prior to slaking. The second, differential swelling due to hydration or osmotic swelling, is reported to effect mainly expansive materials. The third mechanism, important for shales, siltstones, and mudstones which are cemented by diagenetic bonds, is the dissolution of cementing agents, as reported by Badger et al. (7).

Summary

From the references cited, it can be seen that the problems associated with shale classification and utilization are many and varied. Classification systems already in use are numerous, and diverse in their scope and application. The systems discussed here are basically only the ones applying to the present research objectives. It is probable that existing systems can be modified and combined to identify a more applicable combination of tests and classification criteria. The actual mechanisms which govern disintegration of shales are complicated and hard to identify, especially when there are interaction effects between mechanisms.

IV. LABORATORY TESTING PROGRAM

The objectives of the testing program were to evaluate and compare the selected classification systems. Although all the systems involve shale classification, no attempt has been made to date to perform the tests from several systems on the same group of shales. Hence, it was not known how the different systems and methods would classify the same shales. Through this comparative study, it should be possible to gain insight into the differences and similarities of the previously developed systems, and possibly to form a more comprehensive, or equally comprehensive and simpler, scheme for classifying a broad spectrum of shales.

The basis for selecting the tests and systems was in most cases the simplicity of the procedures. The reason for this is that any such system is more readily accepted by practicing agencies if the tests are familiar ones, and if not familiar, simple, and utilizing already available equipment. Another element of practicality is added if the test can be performed by personnel with limited expertise.

Another objective proposed was to formulate a new system using the same tests to cover the whole range of shale properties. It is particularly inconvenient to require changes of equipment and procedure to classify certain ranges of materials (15). In all cases, tests were chosen in which the results were reported quantitatively.

Classification Systems

The systems selected for study have been reviewed in Chapter III, and the reader is referred there for more detailed descriptions of the selected tests. The chosen methods are as follows:

1. Deo's "Classification of Shales for Embankment Construction" (12). The method employs a simple 5-cycle slaking test, hereafter referred to as the Slake Index test; Slake

Durability tests on dry and soaked samples; and a Modified Soundness test.

2. J. C. Gamble's "Durability-Plasticity Classification of Shales and Other Argillaceous Rocks" (17). Atterberg limits tests and a 2-cycle Slake Durability test on dry samples form the basis for this method.
3. Morgenstern and Eigenbrod's "Classification of Argillaceous Soils and Rocks" (31). Only a portion of the system was selected, because it was felt that the remaining tests were too time-consuming for the intended purpose of this study. The selected portion includes Atterberg limits tests and a simple Rate of Slaking test.
4. Pennsylvania Department of Highways "Shale Suitability-Phase II, Final Report" (36). A simple visual field examination, and the Washington Degradation test were selected from this method for correlation with other systems.
5. Saltzman's "Rock Quality Determination for Large-Size Stone Used in Protective Blankets" (37). This classification method, recently developed at Purdue University, was included in order to provide more information about the properties of the rocks used in the research. Tests included the Schmidt Rebound Hammer hardness, Los Angeles Abrasion, and Ultrasonic Cavitation (described in Chapter III).

Also included in the testing program was another soaking test, using ethylene glycol as the slaking fluid. X-ray diffraction was performed for mineralogical information. Data from extensive tests on the subject shales were available from the Division of Materials and Tests of the Indiana State Highway Commission, who made samples available in large quantities for testing.

Tests: Description, Procedure, and Apparatus

Slaking Tests

The numerous varieties of slaking tests which are currently in use have been described in Chapter III. The four tests selected for

further study include tests that measure amount of degradation, amount of water absorbed, and include 3 different slaking fluids.

Slake Index

For this test, 6 chunks of shale weighing approximately 150 grams each were selected and dried to constant weight at about 105°C. Each chunk was then soaked in a beaker of water, such that the chunk was covered by at least $\frac{1}{2}$ inch of water, for 16 hours. The sample was then drained, and washed over a #10 sieve, and the retained material oven dried to constant weight. After 5 cycles, the Slake Index was calculated as the average of the results for the 6 chunks (24).

Rate of Slaking

Irregular lumps of shale less than 1 inch in size were selected and dried to constant weight at 105°C. The dry weight of the material was around 20 grams. The material was immersed as shown in Figure 5. After 2 hours, the excess water was allowed to drip off, and the final water content was determined (14).

From this, the change in Liquidity Index is calculated from the following relationships:

$$I_L = \frac{w - w_p}{w_L - w_p} = \frac{w - w_p}{I_p}$$

and

$$\Delta I_L = I_{L_f} - I_{L_o}$$

where w = natural moisture content

w_p = plastic limit

w_L = liquid limit

I_p = plasticity index

I_{L_o} = liquidity index (original)

I_{L_f} = liquidity index (final)

Based on the value of I_L , the shale is classified as slow, fast, or very fast slaking (see Chapter III).

Figure 5. Set-up for Rate of Slaking Test (14).

For each shale, six tests were run, and the results reported are the average values.

Modified Soundness Test

This test is a modification of ASTM designation C88-73, "Soundness of Aggregates by use of Sodium Sulfate or Magnesium Sulfate" (3). The purpose of the test is to give some indication of structural weaknesses present in the aggregate, and its potential resistance to weathering, and to provide results in substantially less time than required by the freeze-thaw test. The sodium sulfate test was modified by Deo (12), to reduce its severity for use with shales. The modifications included dilution of the solution from saturation to 50% of saturation, and a revision of the gradation such that 670 grams of $\frac{3}{4}$ to $\frac{1}{2}$ in. material and 330 grams of $\frac{1}{2}$ to $\frac{3}{8}$ in. material were used. Three tests were performed on each shale, and average results were reported.

Ethylene Glycol Soaking Test

For this study, the test was performed according to Designation CRD-C 148-69 from the Handbook of Concrete and Cement, entitled "Method of Testing Stone for Expansive Breakdown in Ethylene Glycol" (20). Reagent grade glycol was used as specified, and the amount of sample was reduced from 10 pounds to 5 pounds, to conserve material for future phases of the research. The sample was also separated into fractions of size 3 in. to $2\frac{1}{2}$ in., $2\frac{1}{2}$ in. to 2 in., 2 in. to $1\frac{1}{2}$ in., $1\frac{1}{2}$ in. to 1 in., and 1 in. to $\frac{3}{4}$ in. Weight losses due to slaking were calculated for each fraction, as suggested in the procedure.

Tests Combining Slaking and Agitation

Many tests have been devised to accelerate slaking, or increase the severity of a slaking test by adding mechanical agitation. Some of these have been described in Chapter III. Two of these tests were selected for this research, as the methods of agitation were quite different.

Slake Durability Test

The sample used was ten pieces of shale, selected to be equidimensional if possible, each weighing between 40 and 60 grams. The sample was oven dried to constant weight at 105°C. and placed in the drum of the apparatus shown in Figure 6. The drum was half immersed in water and rotated at 20 revolutions per minute. Tests were run at 200 and 500 revolutions on dry and soaked material. Following the test, the material in the drum was oven dried and weighed, allowing calculation of the Slake Durability Index,

$$(I_d)_{a,b} = \frac{\text{Oven dry sample wt. before test}}{\text{Oven dry wt. of retained material}}$$

where a = d for dry, or s for soaked

b = the number of revolutions.

$(I_d)_{d,200}$ was determined, and the retained material was subjected to another cycle as per Gamble (17). At least 3 repetitions were made for each category of slake durability index, and average values are reported.

Washington Degradation Test

The test was conducted according to the standard test procedure as developed by the Washington Department of Highways. The procedure is given below (29).

1. Crush the material to be tested to pass the $\frac{1}{2}$ in. sieve, wash over a #10 sieve, and dry to constant weight.
2. Grade a sample in the following proportions:

$\frac{1}{2}$ to $\frac{1}{4}$ in.	500 grams
$\frac{1}{4}$ in. to #10 sieve	500 grams
3. Place the sample in a plastic cannister ($7\frac{1}{2}$ in. diam., 6 in. high), add 200 cc. water and cover tightly.
4. Place in sieve shaker with $1\frac{1}{4}$ in. throw on cam at 300 ± 5 oscillations/minute and agitate for 20 minutes.
5. Empty into nested #10 and #200 sieves placed in a funnel, over a 500 ml. graduate to catch all the water.
6. Wash out the cannister and continue to wash the sample until the graduate is filled to the 500 ml. mark.

Figure 6. Slake Durability Apparatus.

7. Pour 7 ml. of sand equivalent stock solution into a sand equivalent cylinder (1).
8. Agitate the material in the graduate.
9. Pour into the cylinder to the 15 in. mark.
10. Stopper the cylinder and agitate thoroughly by tipping from end to end.
11. Place cylinder on table, remove stopper. After 20 minutes, record the height of the sediment column, H, to the nearest 0.1 inch.
12. Calculate D_n

$$D_n = \frac{15 - H}{(15 + 1.75H)} \times 100$$

Also calculated was D_o , the original Washington Degradation Factor, since superseded in Washington practice by D_n . D_o is the value used by Pennsylvania Department of Transportation, and is given by the equation:

$$D_o = \left[0.3 \left(1.00 - \frac{L200}{L10} \right) + 0.7 \left(\frac{6 - 0.4H}{6 + 0.6H} \right) \right] \times 100$$

where L200 = wt. of material finer than #200 sieve, in grams

L10 = wt. of material finer than #10 sieve, in grams

The criteria developed in Pennsylvania, given in Table 5, are based on values of D_o .

It was stated in the Pennsylvania report that any shale which disintegrated in the simple slaking test was not subjected to the Washington Degradation Test because it was obvious that it would fail (36). For this research, the recommended 5 tests were performed on the "non-slaking" shales, with average values reported for D_o and D_n .

Miscellaneous Tests

The remainder of tests performed include Atterberg limits, tests recommended by Saltzman (37), and X-ray diffraction procedures for identification of minerals.

Atterberg Limits

For this research, ASTM D421-58 (4) was used as the preparation method to obtain limits for use in Gamble's and Morgenstern and

Eigenbrod's classification systems (17, 31). Also used were procedures given by Townsend and Banks (39). Their research was directed primarily toward "clay shales"; thus the effects of the various proposed methods on Indiana shales was not known. The shales in Indiana are predominantly silty, and tend to exhibit less plasticity than the clay shales of the Great Plains. Therefore, the methods proposed by Townsend and Banks were selected for comparison to ASTM D421-58. The procedures, listed below, are hereafter referred to as "air dried" and "blenderized" (39).

"Air Dried" Procedure

1. Shave or shred material using a knife or salad grater.
2. Dry to a constant weight (for at least 48 hours) at less than 50°C. and less than 30% relative humidity.
3. Soak 48 hours in distilled water.
4. Decant excess water and grind wet material with mortar and rubber-tipped pestle, and wash through #40 sieve.
5. Remove excess water. Work material at a water content above the liquid limit in a thin layer on a glass plate with a steel spatula until no further reduction in the size of lumps can be achieved.

"Blenderized" Procedure

Steps 1-3 same as for "air dried" procedure.

4. Take about 500 ml. of the slurry and place in the blender cup at a water content of at least 300% or twice the liquid limit, whichever is greater. The dry weight of the material should not exceed 150 grams. Blenderize for 10 minutes, and wash through the #40 sieve.

Step 5 same as for "air-dried" procedure.

Three repetitions of limits for each method were made initially to check the consistency of the results. It was found to be satisfactory, and thereafter, one test was made using each of the 3 methods.

Ultrasonic Cavitation

It was hoped that this test would provide values that would correlate with results from other tests. Since it was designed for testing

rock, it is more applicable to defining the properties of the harder shales. The values from the test can be compared with values obtained by Saltzman for other rock types, and also checked with Saltzman's values for the Schmidt Hammer Hardness and the Los Angeles Abrasion.

The test procedure was as follows (37).

1. Sample cores were drilled from blocks of rock in directions perpendicular and parallel to the bedding planes using a diamond core bit 9/16 inches I.D. mounted in a small drill press.
2. Each sample was trimmed as close as possible to a right angle with the longitudinal axis of the sample, using a thin-section saw, and subsequently surface ground and lapped.
3. Samples were dried at 105°C for 48 hours and then cooled in a dessicator for 2 hours before weighing.
4. The samples were weighed on a Mettler analytical balance, Type H, with a maximum capacity of 128 grams and a precision of 0.0001 grams.
5. Water to be used in the test was heated to about 50°C. (120°F.).
6. The cavitation was carried out for 10 minutes on each sample.
7. The weight was recorded before and after testing and the weight loss was calculated.

Six tests were performed on each of the 2 "non-slaking" shales, and average values were reported.

Schmidt Hammer

The Schmidt hammer is an accepted non-destructive test for concrete and rock cores, and was used to evaluate the hardness of the shales in the study. The test is very simple, requiring a specimen with a smooth surface, such as a block sample or rock core; a steel block upon which to anchor the sample and standardize the rebound characteristics; and the hammer itself. A small plunger is placed against the rock surface and the hammer depressed until a mass impacts against the plunger. This causes a rebound, which is measured by a scale and pointer on the side of the hammer. Hardness can be rapidly evaluated, and empirical correlations are available to predict uniaxial compressive strength and elastic modulus.

Two blocks approximately 6 in. by 3 in. by 2 in. were tested for each shale, and at least 15 readings were taken on each block. The blocks were prepared by carefully sawing and sanding pieces of shale to produce a smooth surface for testing. Mean values were reported.

Los Angeles Abrasion

The Los Angeles Abrasion test was developed as a means of supplementing visual and other evaluations for determination of aggregate quality. The test was conducted according to ASTM C535-69, "Resistance to Abrasion of Large Size Coarse Aggregate by Use of the Los Angeles Machine" (3). This procedure was selected because it was desired to compare values with Saltzman's results (37), especially as they correlate with the ultrasonic cavitation test. In addition, it was desired to test the largest pieces possible, since large fragments are prevalent in shale placed as embankment materials. Only one test was carried out on each shale type, due to the large amount of shale required, and the excellent agreement obtained when three tests were run on the first shale tested.

Mineralogical Analysis

Analysis of mineralogy was carried out on the 6 shales, for both qualitative and quantitative results. The minerals present were identified from X-ray diffraction patterns. Approximate percentages of the constitutive materials were determined using soil chemistry procedures recommended by Jackson (27) and Grim (19), and described in Appendix A.

V. EXPERIMENTAL MATERIALS

The geology of shales in Indiana has been reviewed by Deo (12) and presented in the geological literature of Indiana. The shales of Indiana are all Paleozoic, ranging from Ordovician up through Pennsylvanian. Their composition is somewhat silty, with significant percentages of quartz and somewhat lesser percentages of the clay minerals kaolinite and illite (21).

Six shales were sampled for this research. Since the current phase of work will be followed by additional phases seeking to measure properties of the same materials, large amounts of shale were needed. In addition, it was desired to store the shale at a moisture content as close as possible to the in-situ value since the effects of drying on test results are not known in all instances.

Garbage cans, lined with 2 or 3 plastic liners, were used to store the necessary quantities of shale. Due to space limitations, they could not be placed in a humid room, but the plastic liners were sealed as carefully as possible after each opening of the containers. Some migration of moisture occurred as expected; however, the magnitude was not great, and identical tests conducted early and late in the research yielded virtually identical results.

Sampling was generally accomplished with the assistance of the Indiana State Highway Commission, and most often took place on highway contracts currently under construction.

Shale #1, sampled from a cut on an Interstate 64 project at Sulphur, Indiana, was identified as the Lower Hardinsburg Formation of the Mississippian Chester Series. The shale was dark gray in color, quite dense, soft, and quite wet. It was also weak and could be easily crumbled by pressure of the fingers. It had been excavated by ripping.

Shale #2, the New Albany Shale, was sampled at the base of a cut for I-265 near New Albany, Indiana, where it had been excavated by

blasting. The shale, which was black in color, was very hard and durable and contained almost no moisture. Some oil and some pyrite seams and nodules were found throughout the shale. The New Albany Shale forms a transition between Devonian and Mississippian rocks in Indiana, with this particular portion being part of the Mississippian Kinderhookian Series.

Shales #3 and #4 were sampled near St. Croix, Indiana, on an I-64 contract, where they were excavated by ripping. Shale #3 was found above the Mississippian-Pennsylvanian contact, and belongs to the Mansfield Formation of the Pennsylvanian Pottsville Series. It was medium gray, silty, and medium hard, with a fairly low moisture content. Shale #4 was identified as shale facies of the Palestine Formation in the Chesterian Series of Mississippian rocks. It too was gray, silty, and medium hard, but broke easily along fossilized plant fragments and minute coal seams.

Shale #5, part of the Kope Formation in the Ordovician Cincinnati Series, is soft, although somewhat durable until immersed in water, and gray-green in color. It was sampled along I-74 in Dearborn County, Indiana, near the Ohio state line, where it was excavated for use in a landslide correction keyway.

Shale #6 was sampled from an abandoned quarry near Klondike, Indiana. The bedrock here is very high, coming to the surface of the ground, whereas it is overlain by many feet of glacial till throughout most of the surrounding area. The shale is one of the Borden Group, a Mississippian shale of the Osage Series. It was very hard and quite durable, gray to light tan in color, and was found in laminae of varying thicknesses.

Sampling locations are shown on a geologic map of Indiana in Figure 7. Data from classification, compaction, and California Bearing Ratio tests by the Indiana State Highway Commission (23) are given in Appendix B.

Figure 7. Bedrock Geology of Indiana, and Shale Sampling Locations (21).

VI. PRESENTATION AND DISCUSSION OF RESULTS

In this chapter, the results of the laboratory study will be presented according to groupings by the various classification systems employed in the research. The shales will then be classified by each system for which results have been obtained. The results will be discussed with respect to selection of tests suitable for classifying shale for embankment use.

Deo's Classification System

The tests included in this system are slake index; slake durability, 200 and 500 revolutions, on dry and soaked samples; and the modified soundness test. The classification flow chart for the system is given as Figure 4.

Slake Index Test

This test, time consuming and tedious, gave results ranging approximately from zero to nearly one hundred, as may be seen in Table 6. Low values indicate the more competent materials. Photographs showing the manner of breakdown and size of fragments obtained from slaking shale #3 are shown in Figure 8. The test results are of only qualitative value at this time, because no known relationship exists between slake index and field performance.

Slake Durability Test

The slake durability test, combining slaking with mechanical agitation for a quickly obtainable index, shows favorable materials by high values of the index. Results for the test, ranging from 7.7 to 99.7 are shown in Table 6. The results of the "soaked" tests are generally lower than for the "dry" tests at both 200 and 500 revolution effort

Table 6 Results for Tests from Deo's Classification System (12)

Shale	Shake Index S. I.	Modified Soundness Index I_s	Slake Durability Index						Material Type
			200 Revolutions			500 Revolutions			
			$(I_d)_d$	$(I_d)^*_d$	$(I_d)_s$	$(I_d)_d$	$(I_d)_s$		
1	99.1	0 (2 cycles)	28.6	9.8	19.2	23.3	21.0	3	
2	0.14	99.6	99.6	99.3	99.6	99.7	99.2	1	
3	28.2	0 (5 cycles)	90.1	72.2	74.8	79.8	56.8	2	
4	42.3	0 (3 cycles)	79.7	53.5	56.6	58.4	40.3	2	
5	97.8	0 (2 cycles)	80.1	48.6	16.6	28.4	7.7	3	
6	0.08	99.7	98.8	98.3	98.2	97.8	97.6	1	

* Values for 2nd cycle of 200 revolutions.

Figure 8. Retained Material from Slake Index Test.

levels. The 2-cycle, 200 revolution dry test result is sometimes higher and sometimes lower than the 200 revolution soaked test result. This is thought to be due to geologic variability within each shale, because at times, greatly differing results were obtained. Shale #4, for example, contained plant fragments and some concretions in different portions of the sample, the fragments giving rise to low values, and the concretions to abnormally high values. Photographs of various samples are shown in Figures 9A, B, and C. Condition of all shales prior to testing can be seen approximately in Figure 9C.

In addition to the numerical result for the slake durability test, a post-test material description may be helpful in relating test results to field behavior for any given shale. Samples could be photographed, and a copy of the photo filed with the laboratory report, or standard verbal descriptions could be noted on a data sheet. A possible means of implementing the latter is given below.

Since some shales break into small fragments readily, and yet give high slake durability index values, the material should be described by one of the following categories:

Type I - pieces remain virtually unchanged.

Type II - retained material consists of large and small fragments.

Type III - retained material is exclusively small fragments.

Photos representing the 3 types are shown in Figure 10. Types are numbered in general order of decreasing index values, although Type III could conceivably have a higher index value than Type II, depending on the material.

Modified Soundness Test

This test, which is a modification of the conventional Sodium Sulfate Soundness Test, was found to be quite severe for softer shales, and to have little effect on the very hard ones. Four of the six shales gave values of zero, and the other two gave values greater than 99, as shown in Table 6. This evident lack of resolution is a disadvantage of the test, rendering it nearly inapplicable in general classification of shales. The Indiana State Highway Commission is

Figure 9A. Retained Material from Slake Durability Tests.

Figure 9B. Retained Material from Slake Durability Tests.

Figure 9C. Retained Material from Slake Durability Test.

Figure 10A. Material Type Classification for Slake Durability Test.

Figure 10B. Material Type Classification for Slake Durability Test.

currently using the Deo group of tests for shale classification, with the modified soundness test supposedly the most severe. In some instances, the modified soundness test indicates that a shale is an "intermediate - 1" whereas the supposedly less severe tests rank the same material "soil-like" (23).

Classification

Table 7 depicts the six shales used in the study when they are classified according to Deo's system (Figure 4). Of the 4 "soil-like" shales, shales #1 and #5 would definitely be weak construction materials, and would probably compact readily. Shale #4, where the plant fragments are absent is somewhat hard, as is shale #3. However, the deleterious effects of water on these shales, as reflected by all test results, indicates that they should be thoroughly degraded and compacted to insure that large voids are not left in the embankment, which would allow slaking and probably excessive settlement. The "rock-like" shales, although hard and durable when fresh, may or may not be expected to slake with resulting problems during the life of an embankment. It is not possible to speculate further at this time, since field performance of such shales has not been observed. A rock-fill embankment has been constructed from shale #2, and should provide a means of answering the question left unanswered here, as the embankment is observed over a period of years.

Figure 11 shows a plot of 200 revolution, 2nd cycle, "dry" slake durability index, $(I_d)_{d,200,2nd\ cycle}$ vs. slake index. The trend is roughly linear, with high values of slake durability index corresponding to lower values of slake index.

Gamble's Classification System

The tests involved in this system are both fairly simple and quick to perform. They are Atterberg limits and the slake durability test in which $(I_d)_{d,200,2nd\ cycle}$ is determined.

Table 7 Shales Classified by Deo (12), Gamble (17), and Morgenstern and Eigenbrod (31) Methods.

Shale	C L A S S I F I C A T I O N S Y S T E M				
	Deo	Gamble		Morgenstern and Eigenbrod	
		Durability	Plasticity	Rate of Slaking	Amount of Slaking
1	Soil-like	Very Low	Medium	Very Fast	Low
2	Rock-like	Very High	Low	Slow	Low
3	Soil-like	Medium	Medium	Slow	Low
4	Soil-like	Low	Medium	Slow	Low
5	Soil-like	Low	Medium	Fast	Low
6	Rock-like	Very High	Low	Fast	Low

Figure 11. 200 Revolution, 2nd Cycle Slake Durability Index vs. Slake Index

Slake Durability Test

The results for this test were expedient to obtain, requiring only subsection of material retained in the drum from a 200 revolution, "dry" test to a second cycle of slaking in the machine. As expected, the results are lower than those obtained for the first cycle although not greatly so for the "rock-like" shales. The results are presented in Table 8. A problem noted by Gamble (17), not encountered in this research, was the formation of "mudballs" with montmorillonite materials, giving apparently high results for I_d . This phenomenon should be carefully noted if it occurs in the use of this test, as it causes errors on the unconservative side.

Atterberg Limits

The results of the Atterberg limits tests are given in Table 8, and are plotted on Casagrande's chart in Figure 12. The Atterberg limits for Gamble's classification were obtained using ASTM D421-58. The silty nature of the shales can be recognized from the low plasticity indices.

The limits for shale #2 are not representative, as the material was prepared differently. Because of its high durability and difficulty in preparation of samples, the shale was subjected to a high temperature (800°F) to burn off organic material (25). This certainly resulted in damage to the clay minerals, and altered the plasticity.

Classification

To classify a material by Gamble's system, the slake durability index and plasticity index are plotted on Figure 13. (See also Figure 1). For example, shale #5 is a low durability-medium plasticity mudstone, since it is somewhat non-fissile. Classifications for all six shales are given in Table 7. Classified by Gamble's system, the "rock-like" shales from Deo's classification both have "very high" durability and "low" plasticity. The "soil-like" shales all exhibit "medium" plasticity, with durabilities ranging from "very low" to "medium." It is likely that most or all shales in Indiana will exhibit plasticity

Table 8 Results for Tests from Gamble's Classification System (17)

Shale	Slake Durability Test (I_d) _{d,200,2nd cycle}	Atterberg Limits*			Unified Soil Classification
		w_L	w_p	I_p	
1	9.8	42.3	27.3	15.0	ML or OL
2	99.3	34.0	28.4	5.6	ML or OL**
3	72.2	36.9	21.2	15.7	CL
4	53.5	40.6	19.4	21.2	CL
5	48.6	40.6	22.2	18.4	CL
6	98.3	26.5	21.0	5.5	CL - ML

* Determined by ASTM D423-66 and D424-59 (4).

** See Chapter IV for information on preparation method.

Figure 12. Atterberg Limits Results plotted on Casagrande's Plasticity Chart

Figure 13. Plasticity Index vs. 200 Revolution, 2nd Cycle Slake Durability Index

indices in the low to medium range, because of the silty nature of the shale materials in general.

No recommendations are made by Gamble as to which classifications should be treated as soil fill, rockfill, etc. Again, no definitive recommendation can be made because correlation to monitored field performance is not available. However, based on Deo's guidelines and the data available from the Indiana State Highway Commission, the author would recommend careful degradation and compaction of any shale with $(I_d)_{s,200,2nd}$ cycle values less than 70. The number might be higher, depending on what is shown by embankments built of shale, but it is not expected to be lower.

Morgenstern and Eigenbrod's Classification System

This classification scheme involved standard compression testing and a tedious slaking procedure, the "Quantitative Slaking Test," as well as "Rate of Slaking" and Atterberg limits. However, due to the objective of this research to obtain simple, economical tests for classification, only the Rate of Slaking and the Atterberg limits were used. Morgenstern and Eigenbrod found that the maximum water content reached by the shale during the Quantitative Slaking Test could be predicted from the liquid limit of the material.

Rate of Slaking Test

The Rate of Slaking test is very simple to perform, and requires only a beaker, a funnel, and filter paper. Due to the simplicity of the test and the seeming uncertainty of letting all excess water drip from the shale so that an accurate final moisture content could be obtained, difficulty in obtaining respectable results was anticipated. This was not found to be the case, and the results of test repetitions were quite uniform. Results shown in Table 9 are averages of six trials.

Photos are shown in Figure 14, illustrating the test set-up, and the behavior of 2 shales, one of which breaks down in water and one which does not. The only result which does not properly describe behavior is that for shale #6, which though "rock-like" according to

Table 9 Results for Tests from Morgenstern and Eigenbrod's Classification System (31)

Shale	w	w _L	w _p	I _p	I _L	Δw	ΔI _L
1	12.68	42.3	27.3	15.0	-0.99	37.11	2.47
2	0.90	34.0	28.4	5.6*	-4.94	0.24	0.04
3	6.30	36.9	21.2	15.7	-0.97	6.25	0.40
4	5.30	40.6	19.4	21.2	-0.65	10.50	0.51
5	10.70	40.6	22.2	18.4	-0.71	19.03	1.03
6	6.80	26.5	21.0	5.5	-3.18	4.85	0.91

* See Chapter IV for explanation of material preparation method.

Figure 14. Shale Appearance for Rate of Slaking Test for a.) Soil-like Shale, b.) Rock-like Shale.

Deo, and of "very high" durability according to Gamble, had a comparatively high in-situ moisture content and high values of ΔI_L and Δw , changes in liquidity index and water content during the test, respectively. Otherwise, the shales showed increasing values of ΔI_L , from strongest to weakest shale as ranked by other tests. High values of Δw and ΔI_L indicate materials which have greater susceptibility to water, and therefore can be expected to slake.

Atterberg Limits

The Atterberg limits for this classification were obtained using ASTM D421-58, and are the same as the results used in Gamble's classification. The results are repeated for convenience in Table 9.

Classification

To classify materials by this method, the assumption that the liquid limit predicts maximum slaking water content is used, in conjunction with values of Δw and ΔI_L from the Rate of Slaking Test. Thus, all materials tested are ranked as "low" slaking by amount, as shown in Table 7. Classification criteria showed materials ranging from "slow" to "very fast" in rate of slaking. As mentioned before, the result for Shale #6 is not indicative of present behavior and durability. However, the absorptive tendency of this material may indicate that weathering could occur rapidly with moisture changes. Due to this uncertainty, this material should not be employed as rockfill in any important embankment until more was known about its potential in-service behavior.

Saltzman's Criteria for Selection of Rock Blocks

The tests in this section, though originally designed to evaluate riprap material, were used in this study in an attempt to understand the behavior of the more durable shales. Thus, the tests were somewhat severe, and it was impossible to obtain values for the softer shales.

Los Angeles Abrasion

The values for this test, intended for use with rock materials, ranged from 27.5 to 72.8 percent, and are given in Table 10. A common specification for acceptability in aggregate testing allows a maximum value of 35 percent. By this criterion, shale #2 is acceptable, shale #6 is marginal, and all other shales fail the test. In examining the material after the test, it seemed that for the shales which failed the test, the powder formed by abrasion had shielded some of the larger particles from further breakdown, thus decreasing the index obtained. The mode of breakdown varied with the shale type, as shown in Figure 15A, B, and C. The photos show the amount and size of material retained on the #12 sieve at the end of the test. The value of 50.2 percent for shale #1 seems especially low because almost all the material retained was finer than $\frac{1}{2}$ inch, indicating that the material is less durable than the test result reflects.

Ultrasonic Cavitation

Due to the nature of the shales tested in the research, the cavitation test could be performed on only the 2 "rock-like" shales: shale #1 and #6. The weight losses due to cavitation were quite small for all samples tested, except one, where a fragment of shale chipped off along an existing joint. Values given in Table 10 are averages of 6 tests, except that for shale #6, the sample which chipped was not averaged.

Schmidt Rebound Hammer

The Schmidt Hammer proved to be too severe for all but 2 of the shales tested. In some cases, the samples cracked as a result of the impact of the device, and 4 of the 6 shales did not give even the minimum reading of 10. Values are shown in Table 10. The values reported for shales #2 and #6 are average values, although in neither case was the scatter excessive.

Table 10 Values from Tests Recommended by Saltzman (37)

Shale	L. A. Abrasion* (% wt. loss)	Ultrasonic Cavitation (wt. loss in mg.)	Schmidt Hammer (rebound reading)
1	50.2	**	<10***
2	27.5	3.6	35
3	44.7	**	<10
4	47.7	**	<10
5	72.8	**	<10
6	35.4	9.1	21

* ASTM C535-69.

** Cavitation test cannot be performed on shales which slake in water.

*** 10 is the minimum reading that can be measured by the device.

Figure 15A. Appearance of Material from L. A. Abrasion Test.

Figure 15B. Appearance of Material from L. A. Abrasion Test.

Figure 15C. Appearance of Material from L. A. Abrasion Test.

Classification

The criteria for acceptability are given for Saltzman's system in Table 3. The 4 "soil-like" shales are classified as "not acceptable" by all tests; shale #2 is "excellent" by cavitation and "acceptable" by Schmidt value and L. A. Abrasion; and shale #6 is "excellent" in cavitation, "acceptable" by L. A. Abrasion, and "not acceptable" according to the Schmidt value. Of the shales tested, only shale #2 meets the given criteria. However, the shale tested was in an unweathered condition, and when weathered, the performance could be substantially different. Again, it will be necessary to turn to the field performance of embankments constructed from this shale to decide if the shale is adequate for rockfill.

Washington Degradation Test

As with most of the more severe tests used, the Washington Degradation test could not be performed on the softer shales. Thus, the numerical values given in Table 11 were obtained only for shales #2 and #6, although a material description is given for each shale. At least one test was attempted on each shale type, although it was soon apparent that the test was not suitable for shales which readily slake in water. The material could have been washed over the sieves as recommended, but great quantities of water would have been required, due to the extreme stickiness of the material after the test.

Other Tests

Tests here described as "other tests" were not drawn directly from any particular classification system.

Ethylene Glycol Soaking Test

This test was performed on the 2 "rock-like" shales and the most competent "soil-like" shale, i.e., shale #3. Results shown in Table 12 indicate that the breakdown caused by ethylene glycol is much less severe than that caused by water. The "rock-like" shales were not

Table 11 Results for Washington Degradation Test

Shale Number	Washington Degradation Factor		Material Description
	D _o	D _n	
1	-- *	-- *	Material aggregated into large cohesive lumps. Water was cloudy, and small fragments had broken off. A sticky, cohesive mass was formed, in which some pieces were still identifiable. Same as for Shale 3. A very sticky, cohesive mass was formed. Same as for Shale 2.
2	68.0	96.4	
3	-- *	-- *	
4	-- *	-- *	
5	-- *	-- *	
6	69.4	95.6	

* See Chapter IV for discussion of performing this test on soft shales.

Table 12 Results for Ethylene Glycol Soaking Test.

Shale Number	Percentage by Weight Before and After Test					
	2		3		6	
Size	Before	After	Before	After	Before	After
3"-2½"	46.7	46.7	17.0	0	18.4	18.4
2½"-2"	12.5	12.5	32.2	6.6	38.9	38.9
2"-1½"	23.0	23.0	24.0	28.1	24.4	24.4
1½"-1"	15.3	15.3	21.5	33.3	13.3	13.3
1"-¾"	2.5	2.5	5.3	15.8	5.0	5.0
Minus ¾"	--	--	--	16.2	--	--

affected to any appreciable degree, and even for shale #3, it seemed that there was as much breakdown due to handling of the wet shale as there was from soaking. In comparing the results to the hypothetical action of ethylene glycol (see Chapter III), it would seem that the small amount of breakdown relates to the absence of clay minerals of the montmorillonite group in the shales tested. As with the other tests, the ethylene glycol soaking response affords the engineer some intuition concerning relevant characteristics of shales, but cannot be used to directly predict performance. The cost¹ of the reagent grade glycol needed for the test may limit its use.

Atterberg Limits Preparation Effects Study

Two alternates to the conventional method of material preparation, given in ASTM D421-58, were used to evaluate preparation effects on the Atterberg limits test results. These were described, and their procedures given in Chapter IV. The methods are referred to as "air-dried" and "blenderized," and are expected to yield higher indices of plasticity than ASTM D421-58 because of the greater energy devoted to disaggregation of the shale.

It was not feasible to include shales #2 and #6 in the preparation effects study because of their hardness. Limits for these materials were obtained from the Indiana State Highway Commission. Their procedure for disaggregating shale #6 was cyclic air-drying and slaking, in conjunction with crushing in a soil pulverizer. This was continued until the material seemed to be well broken down. Material thus prepared was used for Atterberg limits, grain size analysis, and specific gravity determination (25).

Shale #2 presented an additional problem in disaggregation because of organic cementation (22, 25). Thus a procedure known as "low temperature burnoff" was used. The shale was burned at 800°F. for 24 hours, causing formation of a crust on the surface of the sample. The crust was then removed in a soil pulverizer, and the procedure repeated until

¹ Reagent grade glycol costs several dollars per gallon, and about two gallons would be needed per test.

the whole sample was reduced to powder (25). According to personal communication with personnel at the Indiana Geological Survey, the plasticity index so determined would be too low, due to reduced activity of the clay minerals (22).

The results of the Atterberg limits for the 4 shales which could be subjected to the recommended treatments are given in Table 13.

It can be seen that generally, the "air dried" and "blenderized" techniques produce greater indices of plasticity than the ASTM D421-58 method, although there are some slight deviations from this trend. The increase in plastic limit is generally 1 to 2 percent, and that in the liquid limit on the order of several percent. Although the magnitudes of the differences are not as dramatic as those reported by Townsend and Banks for "clay shales" (39), a significant trend can be seen. In almost all cases, samples that were prepared using a food blender gave higher values of plasticity. The differences can be great enough to change the AASHTO classification of the material from A-6 to A-7-6.

Mineralogy

The mineralogical analysis showed the 6 shales to be of quite similar composition. The primary clay constituents are illite, with smaller amounts of kaolinite and chlorite, and the non-clay components are mostly quartz, with minor percentages of feldspars. Organic materials are also present in most samples, and calcite is present in shale #5.

The minerals and their percentages are shown in Table 14. The absence of montmorillonite substantiated the hypothesis that ethylene glycol reacts only with montmorillonitic materials.

Statistical Analysis

Because of the many tests used and the fact that the variables investigated had different units, it was impractical to attempt to design the experiments such that there would be a certainty of statistical validity. Thus, for each test, as many repetitions were made as practicality and amount of material permitted, and mean values were

Table 13 Results for Comparison of Preparation Effects on Atterberg Limits of Shale.

Shale	ASTM D421-58			Air dried			Blenderized		
	w _L	w _p	I _p	w _L	w _p	I _p	w _L	w _p	I _p
1	42.3	27.3	15.0	44.2	28.8	15.4	49.7	28.2	21.5
3	36.9	21.2	15.7	38.3	21.6	16.7	38.6	23.4	15.2
4	40.6	19.4	21.2	38.0	19.8	18.2	53.3	25.0	28.3
5	40.6	22.2	18.4	33.7	21.2	12.5	44.8	23.8	21.0

Table 14 Mineralogical Data.*

Shale	Mineral Percentages		
	Kaolinite	Illite	Quartz and Feldspar
1	1.1	28.0	19.9
2	1.0	23.0	30.4
3	1.4	25.5	31.4
4	0.6	17.5	38.8
5	0.9	43.0	28.9
6	0	19.0	52.2

* X-ray diffraction was used to identify the minerals present in each shale. The procedures described in Appendix A were used to determine the given percentages of illite, kaolinite, and combined quartz and feldspar. Feldspar was expected to be present only in trace amounts.

reported. It was hoped that trends in the data would be visible, thus allowing a regression analysis to be carried out, resulting in equations to predict certain variables. The logical approach here is to obtain regression equations with the desired confidence limits, from which results to the more tedious, time-consuming tests can be predicted from simple tests. This technique must be grounded upon a considerable amount of data in order to give the statistical predictions the desired reliability.

Pearson correlations (34) were run for all data to check correlation coefficients for possible combinations of variables. From this information, groupings of variables with substantial correlation coefficients were selected. A computer program performing simple regression analysis (34) was then used to further narrow down the number of variable combinations thought to be useful, and of significance. Finally, multiple regression analysis was used on the groupings of variables which appeared to give the best correlation. This procedure gave R^2 values to measure the goodness of fit of the regression lines, as well as coefficients for terms in the equation of the lines.

The combinations of variables which appeared to exhibit significant tendencies are given below, with comments on their validity and applicability.

The slake index appeared to correlate well with $(I_d)_{s,500}$ for the 6 shales in this study, with an R^2 value of 0.92. The correlation, if determined to be significant, would permit prediction of slake index from $(I_d)_{s,500}$. However, when data for 30 additional shales tested by the Indiana State Highway Commission were included in the analysis, R^2 dropped to 0.62. A plot of the data and the regression lines are shown in Figure 16, where the equations of the line are also given.

The Los Angeles Abrasion test is another tedious test, for which it would be desirable to predict results from a more simple test. For the six shales tested, an R^2 value of 0.81 resulted when Los Angeles Abrasion was correlated with the ratio of $(I_d)_{d,200}$ to $(I_d)_{s,200}$. However, in examining of data from the Indiana State Highway Commission, where the ratio of $(I_d)_{d,200}$ to $(I_d)_{s,200}$ varied from 0.6 to 13, no usable correlation could be conceived. In addition, the Los Angeles Abrasion test does not seem applicable to the usual Indiana shales.

Figure 16. Slake Index vs 500 Revolution
"Dry" Slake Durability

Change in water content during the Rate of Slaking test, Δw , showed a linear correlation with 200 revolution, 2nd cycle slake durability index $(I_d)_{d,200,2nd\ cycle}$. The R^2 value was 0.90 for the data plotted in Figure 17, where the regression equation is given. Each variable was used as the dependent variable and both regression lines are shown. The data available are not sufficient to formulate a definite prediction, but a definite trend is present. The tests are both simple to perform, and both should be used in practice to obtain data to make a more significant correlation.

Several other variables were investigated as the dependent variable, but all are the results of simple tests, and correlation coefficients were marginal. Thus it would be more advantageous to run the tests than to attempt to predict the results.

General Discussion

In rating the applicability of the tests evaluated in this research for shale classification evaluated in this research, it is well to recall the characterization of adequate tests given by Franklin (15) and Aufmuth (5), and presented in Chapter III. These include: standardization, reproducibility, simplicity, reasonable spread of values among shales, and applicability of results to engineering design.

Of the tests attempted, the ones which gave a reasonable spread of values included the: slake index test, slake durability test, rate of slaking test, and Los Angeles Abrasion test. Those giving a very poor spread of results were the: Washington Degradation test, ultrasonic cavitation test, Schmidt hammer test, ethylene glycol test, modified soundness tests and Atterberg limits tests.

One reason for the poor differentiation among materials by some tests is the fact that these tests were intended for rock or pavement aggregate materials, and are too severe for all but the hardest shales. The Atterberg limits showed fairly constant results because of similar mineralogy and textural characteristics for all shales.

Figure 17. 200 Revolution, 2nd Cycle Slake Durability vs Δw from Rate of Slaking Test

Since the shales in Indiana are predominantly of the softer type, tests which provide a spread of values for such materials should be identified for further investigation. Tests in this category include slake index, slake durability, and rate of slaking. The slake index test is probably less accurate than the others in predicting probable behavior of shales, but can be very useful in quickly identifying a very poor material, i.e., any material which slakes significantly on the first cycle will obviously be severely affected by the other tests.

The classification systems applicable to shale classification are compared for the six shales tested in Table 7. Shales classified soil-like by Deo (12), rank low in durability and medium in plasticity on Gamble's scale (17). Rock-like shales are very high in durability and low in plasticity. Soil-like shales range from slow to very fast in the Rate of Slaking test, and rock-like shales from slow to fast. All rank low in amount of slaking, as predicted by the liquid limit (see Chapter III).

There should be a careful program of observation of performance of shales placed as embankment material in conjunction with the application of any classification system. At this point in time, the major deficiency with all of the classification systems is the lack of correlation between classification test values and design and construction standards and specifications.

VII. SUMMARY AND CONCLUSIONS

The statements made in this section apply specifically to the use of shales in compacted embankments, and are based upon the testing of only six shales, all from Indiana.

1. Tests which show little promise in adequately characterizing shale variabilities are the: Washington Degradation, Ultrasonic Cavitation, Schmidt Hammer, Ethylene Glycol, Modified Soundness, and Los Angeles Abrasion.

2. Tests which are particularly useful in classifying shales are the: Slake Index, Slake Durability, and Rate of Slaking.

3. Valuable additional information can be obtained from the Slake Durability test by a second cycle of slaking and agitation, as recommended by Gamble (17), and endorsed by Franklin and Chandra (16).

4. It is advisable to continue performing index tests such as grain size distribution, specific gravity, and Atterberg limits, even though they have proven to be of limited direct use in engineering classification of shales because of their usefulness in general shale description.

5. The Atterberg limits are a function of the energy input during preparation. For most shales it is advisable to use a preparation procedure which involves more energy input than does the conventional ASTM D421-58. Possibilities for such a procedure include the "air dried" and "blenderized" procedures recommended by Townsend and Banks (39), or other combinations of cyclic air drying and slaking in conjunction with mechanical grinding or pulverization. It is not recommended that great effort be devoted to disaggregating "rock-like" shales for index testing, especially when the necessary techniques are sufficiently severe to impair the activity of clay minerals.

6. Deo's system, in its original form (12), seems to have some limitations. No "intermediate - 1 or 2" shales have been identified, either by this study, or by extensive testing by the Indiana State

Highway Commission (23). Deo could not store samples at the natural moisture content and they were air dried prior to testing (12). Chandra (8) found that such air drying caused the slake durability index values to be higher by about 15 percent. This phenomenon could be an explanation for some of Deo's high I_d values, and his subsequent definition of the "intermediate" categories.

7. Information gained from this study does not warrant proposing a new shale classification system. However, general testing guidelines can be proposed as follows. The Slake Index test should be run first, and immediate response in this test is sufficient to classify the shale as definitely "soil-like." If little or no slaking occurs, the shale should be subjected to Slake Durability and Rate of Slaking tests. Low values of Slake Durability Index and high values of change in water content during the Rate of Slaking test indicate poorer materials which should be treated like soils. Field performance of shales must be compared with these test results before quantitative design and construction guidelines can be formulated.

8. Predictions of how thoroughly to degrade and compact shales can be accomplished from classification test values, but only after considerable monitoring of actual embankment performance.

VIII. RECOMMENDATIONS FOR FURTHER RESEARCH

1. Data on more shales are needed before definitive statements can be made concerning a classification system. Therefore, it is recommended that Slake Index, Slake Durability, and Rate of Slaking test values be accumulated for all embankment shales, and correlated among themselves and with classification indices, compaction, and California Bearing Ratio data.

2. Extensive study of the behavior of shales placed in instrumented embankments is needed. Excessive settlement is a primary indicator of inadequate shale placement, and can be monitored with settlement plates. Full profile settlement gages as described by Dunnycliff (13) could also be used to advantage in assessing the distribution of settlements within the embankments. Slope indicators and piezometers should also be installed for additional warning of high shear stresses and any trending toward a slope failure.

3. To determine if harder "soil-like" shales, e.g., shale #3, actually have to be placed in thin lifts, a test embankment is proposed. Lifts of fifteen or eighteen inches in thickness should then be placed and well compacted. Settlement plates, full profile settlement gages, slope indicators, and piezometers should be installed. If movements exceeded predetermined tolerable limits, berms could be quickly placed to increase stability.

4. Information obtained from all monitored embankments should be compared to results from recommended laboratory tests. Ultimately, design and construction guidelines can be predicted on the numerical values of simple classification tests.

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APPENDIX A

Mineralogical Analysis of Shale

Minerals present in the six shales used in the research were identified from their X-ray diffraction patterns. Major minerals identified were quartz, kaolinite, and illite. Small amounts of feldspars, chlorite, or calcite were also present in some samples.

A combination of procedures was used to determine mineral percentages, excepting chlorite and calcite, which were not determined. Calcite was present in only one sample. Chlorite was not expected in large amounts, and the procedure for determination of chlorite quantities is very difficult and involved.

Percentages of quartz and feldspar were determined by a procedure recommended by Jackson (27). Sodium pyrosulfate fusion of shale samples, and subsequent dissolution of the samples in hydrochloric acid, leave a residue containing only quartz and feldspar. Feldspar was assumed to be present in very small amounts, as indicated by its peak heights on the X-ray diffraction patterns. No further determination was made to differentiate quartz from feldspar, because the expected accuracy of the procedure ($\pm 5\%$) does not warrant such discrimination.

Illite (mica) percentages were obtained by a dissolution process using hydrofluoric acid. The objective was to determine the percentage of K_2O present in the sample and thereby calculate the percentage of illite. This can be done because illite contains approximately 10 percent K_2O , and a simple multiplication yields the percent illite in the total sample (27).

Thermal analysis was used to determine percentages of kaolinite present. Kaolinite contains about 14 percent hydroxyl water by weight, as calculated from its chemical formula. Heating kaolinite from 400°C .

to 550°C. will drive off all but 2 to 3 percent of this hydroxy-
water (19). Multiplication of weight loss due to heating through this
temperature by about 12 percent yields the approximate percentage of
kaolinite in the total sample.

APPENDIX B

Additional Data for the Shales Tested, as Determined
by the Indiana State Highway Commission (23)

Shale Number Characteristic	1	2	3	4	5	6
Natural Wet Density, pcf.	139.5	141.1	151.5	153.6	145.5	137.3
Natural Dry Density, pcf.	123.5	139.8	141.6	145.9	131.4	128.5
Water content	12.7	0.9	6.3	5.3	10.7	6.8
Specific Gravity	2.73	2.76	2.75	2.68	2.78	2.70
AASHTO Group Classification	A-7-6	A-4	A-6	A-6	A-6	A-4
% Sand	3.2	2.0	2.0	3.0	2.0	53.0
% Silt Size	36.5	54.0	52.0	52.0	43.0	21.0
% Clay Size	36.8	27.0	28.0	27.0	28.0	11.0
% Colloids	23.5	17.0	18.0	18.0	27.0	15.0
Std. AASHTO Compacted Wet Density	128.5	97.5	135.6	129.7	133.9	128.4
Std. AASHTO Compacted Dry Density	106.0	90.1	119.8	115.1	116.6	109.6
Optimum Moisture Content	16.8	8.3	12.4	12.3	14.7	17.3
As Compacted CBR	--	13.8	8.1	7.5	9.2	--
Soaked CBR	--	14.4	1.6	1.8	2.1	--
% Swell	--	0.1	2.0	2.0	0.5	--