Standardized Tests for Compacted Shale Highway Embankments

MICHAEL W. OAKLAND AND C. W. LOVELL

Economic considerations often dictate the use of shales in embankments. However, due to the nature of some shales, the embankment may deteriorate with time. Research that defined a series of laboratory tests and a numerical classification system (after Franklin) to be used to predict the performance of shales as embankment materials is described. The criteria for the tests are simplicity, economic and rapid evaluation, use of existing standard testing equipment, clear distinction between suitable and nonsuitable shales, and sufficient range to test most shales. Many tests, therefore, are simply standard tests modified for soft rock. The tests selected are Atterberg limits, five-cycle slake resistance, slake durability, point load strength, impact compaction-degradation, compaction moisture density, one-dimensional consolidation, and triaxial shear. Summarized procedures and discussions of each of these tests are presented.

During the building of the modern Interstate system, many embankments were constructed of shale. This was unavoidable because of the common occurrence of shale near the earth's surface. Where the shale was found to be hard, it was often used as a rock fill. This means that large fragments of rock were placed in thick lifts by being dumped from a truck and compacted minimally. A problem developed in that these shales were sometimes nondurable. Many cases can be cited in the literature of excessive settlements and sometimes failures of shale embankments due to slaking of the shale over time. Basically, the problem is one of the large fragments breaking apart and falling into the large voids that exist in a rock fill.

Because of these failures, several agencies sponsored studies to develop design and construction criteria for shale embankments. One of the largest of these was conducted at Purdue University, funded by the Joint Highway Research Project with the Indiana Department of Highways. The reports that were a result of this study are identified in Table 1.

The initial step involved in the design of any embankment is the sampling and classification of any shales that may be used as fill material. The sampling may be difficult due to the nature of the shale, and typical methods may not be useful. The classification should be based on the time-dependent characteristics of the shale. If the shale is classified as not being suitable material for a rock fill, then four additional characteristics must be ascertained: moisture density, compaction-degradation, compressibility, and shear strength.

EXPLORATION

The basic objective in sampling shale for embankment material is not only to define the complete shale section but also to obtain the quantity and quality of shale sample to run the classification and property tests. Table 2 lists the tests generally required as well as the quantity and the minimum chunk size of the sampled material. Core boring alone may be adequate to classify the material as to hardness and durability, but the layer would have to be both thick and generously sampled to get enough material. The rounded sides of a cored sample may also reduce the abrasion in the slake durability test and give misleading and unsafe results. In addition, it is often very difficult to obtain much intact material when coring in shale. Bailey (3) cites a case in which only 6 m (20 ft) of material was recovered from 15 m (50 ft) of boring, and of that there was only one piece more than 8 cm (3 in)

Table 1. Summary of Purdue University research on shale.

Report	Description
Deo (1)	Useful tests and classification system for determining shale behavior as an embankment material
Chapman (2)	Comparative study of certain test and classification systems by Deo, Gamble, Morgenstern, Eigenbrod, and Saltzman for determining shale behavior
Bailey (3)	Study of field and laboratory shale degradation due to compaction and its relation to point load strength
van Zyl (4)	Statistical analysis of existing shale data and storage and retrieval system for these data
Abeyesekera (5)	Study of stress-deformation and strength characteristics of a compacted shale by use of triaxial testing
Witsman (6)	Determination of effect of compacted prestress on compacted shale compressibility
Hale (7)	Development and application of a standard compaction-degradation test for shales
Surendra (8)	Study of additives that can be used to control slaking in compacted shale embankments
Oakland (9)	Battery of tests and a shale classification system useful in the design and construction of compacted shale embankments

Table 2. Tests and sampling requirements.

Test	Purpose	Quantity	Maximum Aggregate Size	Sampling Method
Atterberg limits	Classification	500 g	None	Auger
Five-cycle slaking	Classification	100-150 g	Intact	Test pit, possibly coring
Slake durability	Classification	450-550 g	10 pieces, 40-60 g each	Test pit
Point load strength	Classification	20 aggregates	25-mm diameter	Test pit, possibly coring
Compaction-degradation	Compaction control	9 kg	38.1 mm	Test pit
Moisture density	Compaction control	45 kg	38.1 mm	Test pit
1-D consolidation[a]	Settlement analysis	32 kg	19.0 mm	Test pit
Triaxial	Slope stability analysis	32 kg	19.0 mm	Test pit

Note: 1 kg = 2.2 lb; 1 mm = 0.039 in.
[a]One-dimensional.

long. Core borings can be used to define the soil and weathered shale depths, the thickness and inclination of the shale strata, and the layers draining into the shale embankment near the cut-fill transition (10). However, for classification purposes a test pit will very often be required. It is also helpful if the stratum can be traced to a nearby existing outcrop where unweathered material can be sampled in quantity.

CLASSIFICATION AND BEHAVIOR CHARACTERIZATION

As a result of the work done at Purdue University, a battery of tests has been developed that is useful in the design and construction of shale embankments for highways. These tests are Atterberg limits, five-cycle slaking, slake durability, point load strength, impact compaction-degradation, moisture-density relations, compressibility, and shear strength. Basically, these tests can be divided into two categories: those that classify the shale by its hardness and durability and those that give actual design parameters. The Atterberg limits, five-cycle slaking, slake durability, and point load strength tests are of the former type and the other tests make up the latter. It is not possible to completely describe these tests in a paper. However, this is done elsewhere (9).

The hardness and durability of a shale determine whether it should be placed as a rock or soil fill. If the shale is classified as being both hard and durable, it can be placed in thick lifts with relatively little compaction control. If it is not both hard and durable, then it must usually be thoroughly degraded and placed as a soil in thin lifts with strict compaction control.

Atterberg Limits

Although there is limited logic in applying a soil plasticity test to shale, Atterberg limits are used in several classification systems (11,12). Deo (1) describes the limitations of these tests for shales, and Abeyesekera (13) recommends that they be used only for classifying relatively soft shales that are to be degraded and placed as a soil fill. Franklin (11) reinforces this idea by developing a classification system that uses the Atterberg limits only for shales that have a slake durability of less than 80. Such shales are usually relatively soft, and standard testing procedures (ASTM D424-59) are suitable.

For any hard shale, degradation of the shale to perform the Atterberg limits tests becomes a tedious, time-consuming process. It is recommended that this effort be avoided. When for some reason this is not possible, ultrasonic devices can be used to facilitate degradation (14). However, such procedures are not suitable for routine use.

Five-Cycle Slaking Test

The five-cycle slaking test is an outgrowth of a slaking test that involves just one cycle of drying and wetting. The one-cycle test was found not to be severe enough to distinguish among the durabilities of various shales (1). The five-cycle test is useful in separating the "compacted" from the "cemented" shales (15) and can determine the shales that are obviously not durable when subjected to water. Cemented bonds will usually make the shales more durable (13).

The test, as originally described by Philbrick (15) and used by Deo (1), consisted of five cycles of drying a 50- to 60-g shale aggregate for 8 h and then submerging the aggregate in water (or another slaking fluid) for 16 h. As Philbrick describes the test, it is qualitative. The end condition of the shale is noted as being "fully slaked", "partially slaked", or "not affected". A description of the shape and size of the remaining shale fragments may also be given.

Surendra (8) and Chapman (2) later used a modified version of the test in which the soaking period was 24 h and the drying time at least 16 h. The degree of slaking was also measured quantitatively as the percentage of material able to pass a 2-mm (No. 10) sieve after each cycle. They also recommended that the appearance of the nonslaked fragments be described. However, the procedure used by Surendra and Chapman is too lengthy to be practical. The original periods of 8 h of drying and 16 h of soaking are recommended. It is also recommended that the slaking index be defined as the percentage of material retained on a 2-mm sieve in order to parallel the index of the slake durability test, which will be described later. Therefore, a shale that is not affected by water would be given a rating of 100 percent and a shale that totally slaked would be rated at 0.0 percent. The condition of the fragments retained should be recorded, since their shape and size can be a help with the durability prediction (13).

An important aspect of the test is the size and shape of the initial shale aggregate (13). In order to keep the tests as uniform as possible, the specific surface (surface area divided by the volume) of the shale aggregates should be as similar as practicable. Therefore, the weight of the essentially one-sized aggregates should be 50-60 g and the shape roughly equidimensional with no protruding corners.

The advantage of the test is its simplicity. It directly evaluates susceptibility to slaking, which is the prime evidence of nondurability. The disadvantages are that it is lengthy, involving a minimum of six days; it may not distinguish among the harder shales; and it does not model the stresses on a shale fragment confined in an embankment.

Slake Durability Test

To resolve the problems of the five-cycle slaking test--i.e., the length of time needed to run the test and the lack of ability to distinguish among the harder shales--an energy input is needed. One solution is the slake durability test developed by Franklin (11). The test adds a tumbling and abrasion action to the normal slaking process. Thus, the slake durability test requires only about two days, and it is more severe in evaluating durability. The disadvantages are that it requires a special piece of equipment and it does not model embankment confinement.

In this test, 10 fragments of shale are tumbled inside a rotating mesh drum that is partially submerged. The drum is made of 2-mm (No. 10) wire screen and rotates at 20 revolutions/min. As with the five-cycle tests, the charge should be closely controlled. The specific surface of the shale fragment is controlled by using shale fragments that weigh 40-60 g each and are roughly equidimensional with no protruding corners.

Another restriction to keep the samples similar is that the entire sample shall weigh 450-550 g.

The selection of the number of revolutions to be used for testing comes from research by Deo (1). He found that the greater the number of revolutions the greater was the contrast among durable and nondurable shales. However, beyond 200 revolutions values were not repeatable. A total of 200 revolutions is therefore recommended. The slake durability index is defined as the percentage of material remaining in the drum after it is rotated in the slaking fluid. Deo (1) also found that samples allowed to soak in water for 6 h before testing degraded more than samples that were tested immediately after being oven dried. In general, the soaked sample testing is too severe to be recommended. However, for the harder shales, specifically those that have an index greater than 85 percent, the soaked test may be used for further durability differentiation (1).

Deo (1) and Franklin (11) concluded that the slake durability index determined from the first cycle of the test gave inconsistent and nonrepresentative values. This may be due to loose material initially adhering to the specimen or easily broken protruding corners. It is therefore recommended that the slake durability index be determined from a second cycle of drying and 200-revolution testing.

Point Load Strength

The point load strength test normally produces a splitting or tensile failure that can be correlated with the rock hardness and compressive strength. Evaluating the shale in this manner is useful since the failure is like that which may occur under rolling or embankment weight. Again, confinement effects are not simulated.

The point load strength test is primarily advantageous for shales because preparation of cylindrical samples for uniaxial compression testing can be avoided. The cost is not the only prohibitive factor with shales. The normal preparation techniques of diamond bit coring and grinding require water as a coolant. This may cause slaking of the shale and may change the natural water content, which is an important factor. A review of test history and use is given by Hale (7).

Basically, the procedure is to place a shale aggregate between two axial contact points and load it to failure. The point load index (I_s) is defined as the load at failure divided by the square of the initial distance (d) between the platens. The value of I_s has the units of stress and is simply related to the stress on the plane of failure at failure.

The disadvantages of this test are that (a) there is considerable scatter in the results, (b) the index varies with the size of the specimen and so a correction factor must be used, and (c) the index varies with the shape of the specimen (7). The advantages include test speed, which allows the difficulty of variation in the results to be overcome by running many tests. In addition, the test device is portable so it can be conveniently used in the field. A third advantage accrues from the first two--i.e., the test can be conducted with very little change in the natural moisture content.

To account for the dependency of the point load index on the size of the specimen, a correction chart has been developed to adjust the index to that of a standard-sized specimen. Usually, the standard diameter is 50 mm; however, Hardy (16) quotes Bieniawski as suggesting that it be 54 mm, which is the diameter of an NX core (16). We favor the 50-mm standard size because of its common acceptance (11,17). Correction charts have been developed primarily from tests on sandstone, quartzite, and limestone (16). Abeyesekera (13) has found that these charts are not generally applicable to Indiana shales. The correction factor depends not only on the shale type but also on the sample shape and the orientation of the bedding planes of the specimen.

With sufficient testing, a unique size correction factor can be derived for each major shale member. Test samples should be bulky in shape and larger than a minimum dimension. Bieniawski recommends that the minimum dimension be 30 mm (16). Hale shows a disproportionately large increase in the point load index as the dimension goes below about 22 mm. This inconsistency may be explained by a certain amount of crushing at the contact platens, which spreads the load over a finite area. It is believed that the error is a function of the ratio of the finite area of contact and the volume of the specimen. This ratio would be small for larger samples but increases rapidly in smaller samples. It is therefore recommended that the samples tested be as large as possible, at least 25 mm.

Investigations of sample shape (18) have led to the prescription that the diameter of an irregular lump (direction in the axial direction of the platen) be 1.0-1.4 times the average width. This is an extremely difficult criterion due to the fissility of shale and especially because the shale is usually loaded perpendicular to the bedding planes. That is, in most cases the smallest dimension for a shale fragment is perpendicular to the bedding planes, yet the recommendation calls for it to be the largest. All shale fragments should be as close to equidimensional as possible.

Since point load strength depends on the direction of loading with respect to the bedding planes (13), more accurate and consistent results can be achieved if the samples are always loaded in the same direction with respect to the bedding planes. The shale aggregates will usually be loaded normal to the bedding planes in the fill. Accordingly, this direction of loading is selected for the point load test.

The water content of the shale at which the point load test is conducted critically influences the index. Bailey (3) considered the effect of three reference water contents on the point load strengths of Indiana shales: 100 percent saturation, 0 percent saturation, and the natural water content. He found it impractical to use 100 percent saturation since wetting the shales caused excessive slaking. At zero percent water content, there was considerable data scatter. Close inspection of the dried shale revealed that many small cracks developed during drying. On the other hand, Bailey was able to produce reasonable and reliable values at the natural water contents. Accordingly, it is recommended that the point load strength test be conducted at the natural water contents of shales.

CLASSIFICATION SYSTEMS

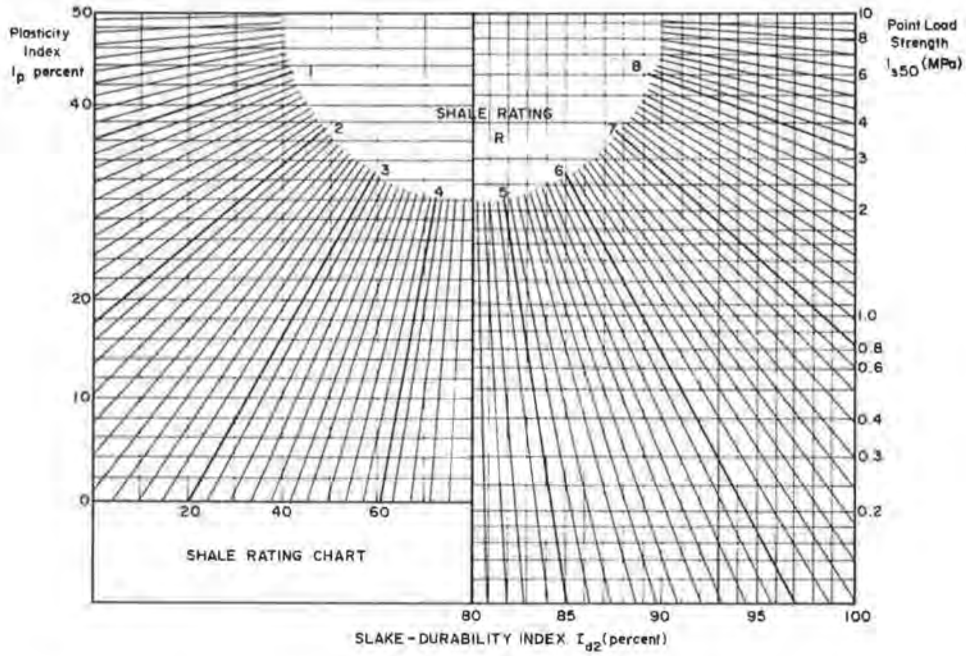
The first generation of shale classification systems was generally based on visual properties. These were classifications used by geologists to describe the shales and were only incidentally related to engineering behavior. Fissility is an obvious characteristic of most shales, and Alling (19), Ingram (20), and McKee and Weir (21) established scales of fissility.

Other classifications used variations in color, texture, and composition in the alternating laminae. Still another common system classified argillaceous rock by the sedimentary particle size (22). Certain adjectives have long been used to describe shales (15,23,24)--e.g., bituminous, oil, arkosic, micaceous, chloritic, and immature. Such classifications are of little help in predicting the behavior of compacted shale embankments.

A second wave of classification systems uses slaking behavior as the primary criterion. Such classifications are more suitable to engineering applications than those previously described.

Mead (25) separated shales into "cemented" and

Figure 1. Shale rating chart.



"compacted" categories. Compacted shales lack a significant amount of cementing agent such as calcite. The cemented shales are considered "rocklike", whereas the compacted shales are considered "soillike". A simple slaking test is used to make the distinction. Systems proposed by Deo (1), Chandra (26), and Hudec (27) extended this concept. Chandra and Hudec used slake durability test values to define the various levels of durability. Deo used multiple slaking tests and a soundness test to classify shales. Others have combined a slaking test with some other index. Gamble (12) and Morgenstern and Eigenbrod (28) use a slaking test and the plasticity index. Gamble used the slake durability test whereas Morgenstern and Eigenbrod developed a rate of slaking test. The system is best suited to softer shales that are easily degraded for the Atterberg limits tests (1).

Saltzman (29) geared his classification system toward the harder shales in using the Los Angeles abrasion test in combination with the Schmidt hammer. Both tests are too severe for Indiana shales.

The most modern systems are by Franklin (11) and Strohm, Bragg, and Ziegler (10). Franklin uses the slake durability test, the plasticity index, and the point load strength test. The point load index is applied to classify the more durable shales, and the plasticity index is used to rate the others.

In choosing a classification system, four criteria must be met:

1. The tests must be relatively simple, using only readily available and, if possible, easily portable equipment.
2. The test should be relatively rapid to permit classification soon after the shales have been excavated.
3. The system must be able to distinguish clearly among shales in the geologic population.
4. It is essential that the classification values be quantitative and numerical.

The Franklin system seems to meet all of the above criteria and should be used to classify embankment shales. Most laboratories already have the apparatus to conduct the Atterberg limits and point load strength tests, and the equipment for the slake durability test is relatively inexpensive. As was emphasized earlier, the tests are rapid, especially if a microwave oven is used for drying. The classification scale (R-value) is broad enough to cover all but the most exceptionally hard argillites. It ranges from zero to nine and thus affords a continuous numerical rating. The chart used to classify shales by this method is shown in Figure 1 (11): If the slake durability index is less than 80, it is used in conjunction with the Atterberg plasticity index; otherwise, the slake durability index and point load strength are used.

COMPACTION OR DEGRADATION TESTS

Since embankments of nondurable shales must be thoroughly degraded and tightly compacted in thin lifts, standard tests that rate the degradability and define the compaction relations are required.

Compaction-Degradation Test

Degradation of the shale will occur in all handling processes from excavation through final compaction. Correlations among rock classifications and methods of excavation are available (30). Predictions of degradability under field rolling are needed as well, and the laboratory compaction-degradation test is a first step in meeting this need.

The test is basically one in which the change of gradation produced by a standard compaction process is measured. Bailey (3) summarizes the various ways that gradation and change in gradation may be represented. In an extension of Bailey's research, Hale (7) selected the "index of crushing" as the standard measure of degradation. This index is the percentage change in mean shale aggregate size due to compaction. The compaction-degradation test is commonly needed only for harder shales. Indeed, it may be difficult to run for softer shales that tend to be cohesive and have the fragments bonded together when compacted. Fortunately, degradation measures are not needed for such shales.

The initial gradation--that is, the gradation before compaction--is one of the variables of the test. Ideally, the gradation should parallel that of the field gradation before compaction, but this is an unknown and varies widely with the project. A convenient gradation is afforded by the following expression:

$$P = 100(d/D)^n \tag{1}$$

where

- P = percentage by weight finer than size d,
- d = sieve size,
- D = maximum aggregate diameter, and
- n = 1.

This is a good approximation of the gradation of the material after crushing in a reciprocating jaw crusher, and wasted material is minimized. In cases where the field gradation is known to be significantly different from this relation, the gradation for the laboratory test can be modified accordingly.

To produce the proper gradation, the crushed material is separated in a nest of sieves and recombined by size fractions to fit the gradation. The sieved product exists in a discrete function and will imperfectly fit the continuous function of the gradation equation. The error is reduced by using more sieves, but this requires additional time to prepare the gradation. Since the test should be conducted at the natural moisture content, significant drying of the material may occur if the sieving process is too long.

In earlier work by Aughenbaugh (31) and Bailey (3), 10 sieve groups were used. Hale (7) enlarged the average range of each sieve group by increasing the maximum size aggregate but reduced the number of groups to 9. It is believed that the test can be further simplified by combining the smaller aggregate sizes into one sieve group. It can be shown that relatively large errors in the percentage of these fine materials will result in negligible changes in the gradation (28).

The maximum aggregate size also has a major effect on degradation. Hale (7) found that the larger the maximum size, the larger is the index. This is logical since the coarser gradation should have fewer aggregate contact points and hence higher contact stresses. The higher values of the index tend to make it easier to distinguish among different shales. It is therefore recommended that the maximum aggregate size be as large as is practical. Since a 15.2-cm (6.0-in) mold will be used, the maximum size that works well is 3.8 cm (1.5 in).

The type and effort of compaction are other important factors. Bailey (3) studied four types of compaction: kneading, gyratory, static, and impact. He favored the static and impact compaction methods. The static method has the advantages of being consistent and simple and uses a known compactive force. The impact method displayed almost as much consistency and had the advantage of being a widely accepted compaction mode. Hale (7) made a further study of the two methods and recommended the impact method for the reason of common acceptance.

Hale (7) also investigated various levels of nominal compaction effort. Based on many trials, a nominal effort of 790 kJ/m^3 (16 500 $lbf{\cdot}ft/ft^3$) was selected. This is obtained by compacting 0.002 m^3 (0.075 ft^3) in three layers with 25 blows/layer by using a 4.5-kg (10-lb) modified Proctor hammer with 43.5 cm (18 in) of free fall.

Compaction Control Test

Whenever possible, the compaction control should be generated in a test pad. It may be stated in terms of an end result, procedure, or combination thereof. The techniques that follow apply to the definition of a laboratory moisture-density curve that can be used in an end-result specification.

If the shale is soft and has good absorption characteristics, water content may be used as a variable in the usual way. Raising the water content weakens the shale and increases its degradability (7). Just as with soils, however, there is a point at which additional water hampers the compaction process and lowers the compacted dry density. Thus, an optimum water content and maximum density can be defined for a given shale and compactive effort.

The test is not well suited to hard shales because, in general, added water is not absorbed. Such materials must ordinarily be compacted at or near their natural water content. Density values for specification are defined by varying the compactive effort at constant water content either in the laboratory or in the field.

To achieve consistent and reproducible results, the moisture content throughout the sample should be as uniform as possible. Two techniques are recommended: (a) adding water in a spray and mixing thoroughly and (b) allowing the material to cure for two days. Bailey (3) found little or no benefit from curing more than two days.

Because the same basic procedures are used for defining a single point in compaction control and in the compaction-degradation test, the latter test may be used to produce a single point for the moisture-density curve.

Compressibility Test and Settlement

A compressibility test is needed whenever it is necessary to predict embankment settlement. The ordinary one-dimensional consolidation test apparatus can be used for the measurements. Example measurements by Witsman (6) are shown in Figure 2. As-compacted compressibility is shown by the initial curve. This curve will change in shape at the compaction prestress. After the shale has compressed under a pressure that approximates an embankment confinement, the sample is saturated and either settles or heaves. The saturation simulates the effect of the environment on the embankment in service and is represented by the vertical portion of the curve in Figure 2. Further loading would produce settlement according to the compressibility of the shale in a saturated condition.

Such laboratory data can be scaled upward from laboratory model to embankment prototype and used to predict the embankment settlement. Other data by Witsman (6) show that the as-compacted compression (under self weight) will occur as rapidly as the embankment is constructed.

To make the compression tests as consistent as possible with the other shale tests, the sample preparation is much the same as for the moisture-density test. It is recommended that the same gradation function used in the compaction-degradation test be used in this test. The mold for this test is only 10.2 cm (4.0 in) in diameter, and therefore the maximum particle size is reduced to 1.9 cm (0.75 in).

The water content selected for the test should be that predicted for the field application. This might be the natural water content or the optimum water content defined in a laboratory moisture-density test. Again, to achieve the most consistent results, the water content must be uniform throughout the sample. It is therefore recommended that the water be added as a spray and the sample be allowed to cure for at least one day. The curing

Figure 2. Collapse-consolidation test on New Providence shale.

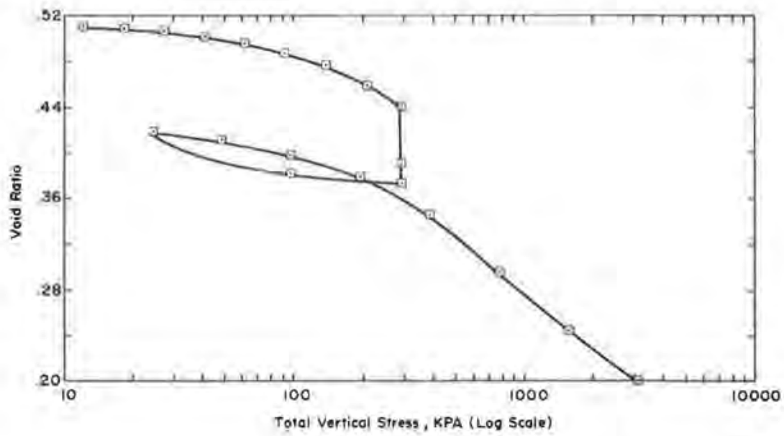
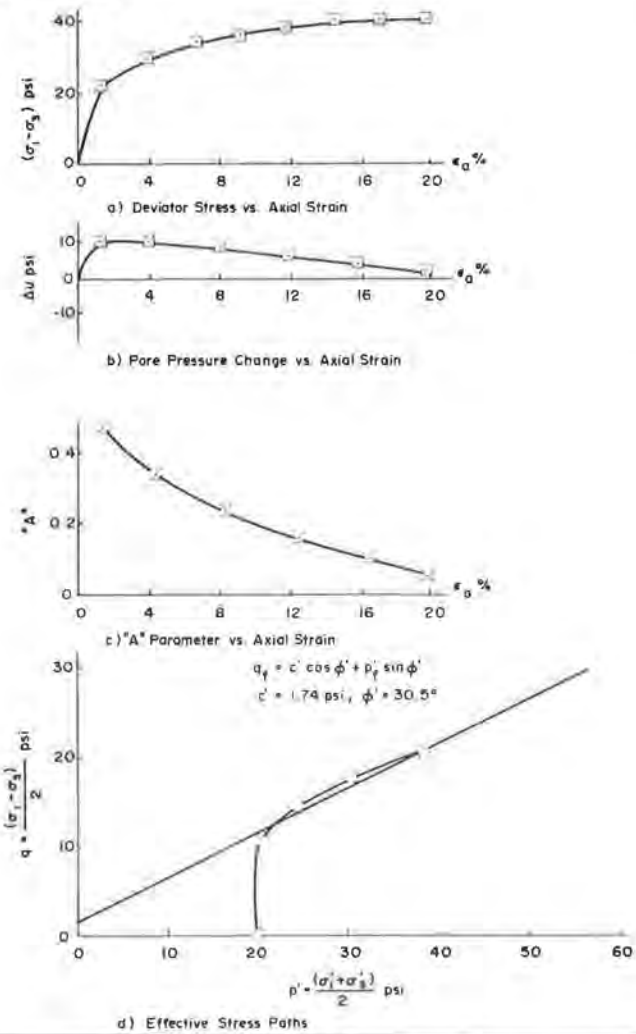


Figure 3. Isotropically consolidated undrained triaxial shear test on New Providence shale.



time for these samples is less than that for the compaction samples because both the maximum aggregate size and the sample size are smaller.

To approximate the field compaction, the laboratory kneading compaction is recommended. In this technique, kneading foot pressures are adjusted to match the density of the laboratory control curve at the desired water content. It is further recommended that these samples be compacted in five equal layers to achieve better sample homogeneity.

The test procedure will start by loading the partially saturated compacted sample in small load-increment ratios until the prestress point is defined. The second stage is to saturate the shale while monitoring the volume change. The confining load should correspond to a depth in the embankment prototype. It is necessary to conduct several tests to establish the settlement for the entire vertical profile of the embankment. Finally, the sample should be unloaded and reloaded to establish the rebound and loading relations of the saturated shale.

Abeyesekera's collapse test (5) gives an indication of what may happen if the shale is not well degraded and thoroughly compacted.

Shear Strength Test and Slope Stability

Strength tests are needed to estimate the likelihood of a slope failure. The preferred procedure is to extract intact cylindrical samples from a compacted test pad. Such samples can be confined to approximate various embankment positions. If these are sheared undrained, the as-compacted strength is defined and slope stability analysis can be undertaken by using a suitable computer program such as STABL2 (32).

If the samples are produced in the laboratory, the sample gradation and preparation are the same as for the compressibility test, except that the sample height is 21.6 cm (8.5 in) with a diameter of 10.2 cm (4.0 in). In order to keep the thickness of each layer of compaction the same as was used in the consolidation test, nine layers are needed. The calibration relating kneading foot pressure to density at a given water content may also be used in this test.

To determine the embankment stability in the long term, samples are consolidated to a range of values approximating the range of embankment heights and are back pressure saturated. It is possible to measure the volume change that takes place by monitoring the flow of water into and out of the sample during saturation. If an estimation of settlement or heave at isotropic stress is needed, it can be made from this stage of the test. The samples are then sheared undrained, preferably with pore pressure measurements.

Typical stress-strain, pore pressure-strain, A-factor-strain, and stress-path relations for the New Providence shale tested by Abeyesekera (5) are shown in Figure 3. These relations depend greatly on the confining pressure and its ratio with the compaction prestress. Strength is interpreted in terms of either total or effective normal stress (Mohr-Coulomb), and the long-term stability is assessed.

Values of the effective stress intercept (c') for all saturated samples at reasonable conditions of compaction are expected to be small, and the effective stress-strength angle (ϕ') is insensitive to compaction variables. Abeyesekera (5) found a ϕ' for Indiana New Providence shale of 28°-30°. In contrast, if the same shale was loosely placed, ϕ' decreased to 25°. Excess pore pressures at failure did vary considerably with the details of compaction and the confinement. Accordingly, the factor of safety against an undrained failure could vary significantly with the above compaction factors.

SUMMARY

Economic design and construction of shale highway embankment require three activities: exploration and sampling, classification, and testing for design parameters. Exploration determines the depth and lateral extent of the shale layers. Proper sampling produces the required quantity and maximum aggregate size of shale at the natural water content. Classification determines whether the fill is to be constructed as rock fill or a soil fill. The tests used for classification are the slake durability test (or the five-cycle slaking test if the former test equipment is not available) and either the Atterberg limits or the point load strength test. The Franklin system (11) is used to classify the shales. Finally, a design parameter suite of four tests is performed. A compaction-degradation test shows the degradability at natural water content, and the moisture-density test is the same type used for soils. Compressibility is evaluated for loading in an as-compacted condition, heave or settlement on confined saturation, and loading in a saturated condition in a one-dimensional (oedometer) test. Strength is evaluated with triaxial samples for both as-compacted and saturated samples. The tests are undrained and for the long-term case should include pore pressure measurements.

The tests have been selected after extensive review of the state of knowledge of compacted shale embankments and after 10 years of concentrated research in this area at Purdue University.

ACKNOWLEDGMENT

We are grateful to the Indiana State Department of Highways and the Federal Highway Administration for their support of this study. The research was administered through the Joint Highway Research Project, Purdue University.

REFERENCES

1. P. Deo. Shales as Embankment Materials. Purdue Univ., West Lafayette, IN, Ph.D. thesis, and Joint Highway Research Project Rept. 45, Dec. 1972, 202 pp.
2. D.R. Chapman. Shale Classification Tests and Systems: A Comparative Study. Purdue Univ., West Lafayette, IN, M.S.C.E. thesis and Joint Highway Research Project Rept. 75-11, May 1975, 90 pp.
3. M.J. Bailey. Degradation and Other Parameters Related to the Use of Shale in Compacted Embankments. Purdue Univ., West Lafayette, IN, M.S.C.E. thesis and Joint Highway Research Project Rept. 76-23, Aug. 1976, 209 pp.
4. D.J.A. van Zyl. Storage, Retrieval and Statistical Analysis of Indiana Shale Data. Purdue Univ., West Lafayette, IN, Joint Highway Research Project Rept. 77-11, July 1977, 98 pp.
5. R.A. Abeyesekera. Stress-Deformation and Strength Characteristics of a Compacted Shale. Purdue Univ., West Lafayette, IN, Ph.D. thesis and Joint Highway Research Project Rept. 77-24, Dec. 1977, 420 pp.
6. G.R. Witsman and C.W. Lovell. The Effect of Compacted Prestress on Compacted Shale Compressibility. Purdue Univ., West Lafayette, IN, M.S.C.E. thesis and Joint Highway Research Project Rept. 79-16, Sept. 1979, 181 pp.
7. B.C. Hale. The Development and Application of a Standard Compaction-Degradation Test for Shales. Purdue Univ., West Lafayette, IN, M.S.C.E. thesis and Joint Highway Research Project Rept. 79-21, Oct. 1979, 180 pp.
8. M. Surendra. Additives to Control Slaking in Compacted Shales. Purdue Univ., West Lafayette, IN, Ph.D. thesis and Joint Highway Research Project Rept. 80-6, May 1980, 304 pp.
9. M.W. Oakland. Classification and Testing of Shale to Be Used in Compacted Shale Embankments. Purdue Univ., West Lafayette, IN, M.S.C.E. thesis and Joint Highway Research Project Rept., Dec. 1981.
10. W.E. Strohm, Jr., G.H. Bragg, Jr., and T.W. Ziegler. Design and Construction of Compacted Shale Embankments: Volume 5--Technical Guidelines. Offices of Research and Development, FHWA, Dec. 1978.
11. J.A. Franklin. A Shale Rating System and Tentative Applications to Shale Performance. TRB, Transportation Research Record 790, 1981, pp. 2-12.
12. J.C. Gamble. Durability-Plasticity Classification of Shales and Other Argillaceous Rocks. Univ. of Illinois, Urbana-Champaign, Ph.D. thesis, 1971.
13. R.A. Abeyesekera and C.W. Lovell. Characterization of Shales by Plasticity Limits, Point Load Strength, and Slake Durability. Proc., 31st Annual Highway Geology Symposium, Austin, TX, Aug. 1980.
14. J.G. Laguros. Suggested Test Procedure for Ultrasonic Disaggregation of Clay Forming Materials. Univ. of Oklahoma Research Institute, Norman, Aug. 1972.
15. S.S. Philbrick. Foundation Problems of Sedimentary Rocks. In Applied Sedimentation (P.D. Trask, ed.), Wiley, New York, 1950.
16. H.R. Hardy. A Laboratory Manual for Rock Mechanics, rev. ed. College of Earth and Mineral Sciences, Pennsylvania State Univ., University Park, 1982.
17. Suggested Method for Determining the Point Load Strength Index. Commission on Standardization of Laboratory and Field Tests, International Society of Rock Mechanics, Lisbon, Portugal, Document 1, Part 2, Oct. 1972.
18. E. Broch and J.A. Franklin. The Point Load Strength Test. International Journal of Rock Mechanics and Mining Sciences, Vol. 9, No. 6, Nov. 1972.
19. H.L. Alling. Use of Microlithologies as Illustrated by Some New York Sedimentary Rocks. Bull., Geological Society of America, Vol. 56, 1945.
20. R.L. Ingram. Fissility of Mudrocks. Bull., Geological Society of America, Vol. 64, Aug. 1953.
21. E.D. McKee and G.W. Weir. Terminology for Stratification and Cross-Stratification in Sedimentary Rocks. Bull., Geological Society of America, Vol. 64, 1953.
22. P.E. Potter, J.B. Maynard, and W.A. Pryor. Sedimentology of Shales. Springer-Verlag, New York, 1980.
23. W.T. Huang. Petrology. McGraw-Hill, New York, 1962.

24. L.B. Underwood. Classification and Identification of Shales. Journal of Soil Mechanics and Foundations Division, ASCE, Vol. 95, No. SM5, 1969.
25. W.J. Mead. Redistribution of Elements in the Formation of Sedimentary Rocks. Journal of Geology, Vol. 15, 1907.
26. R. Chandra. Slake Durability Test for Rocks. Imperial College of Science and Technology, Univ. of London, London, England, M.S. thesis, Rock Mechanics Res. Rept., 1970.
27. P.P. Hudec. Development of Durability Tests for Shales in Embankments and Swamp Fills. Research and Development Division, Ontario Ministry of Transportation and Communications, Downsview, Res. Rept. 216, April 1978.
28. N.R. Morgenstern and K.D. Eigenbrod. Classification of Argillaceous Soils and Rocks. Journal of Geotechnical Engineering Division, ASCE, Vol. 100, No. GT10, Oct. 1974.
29. U. Saltzman. Rock Quality Determination for Large-Size Stone Used in Protective Blankets. Purdue Univ., West Lafayette, IN, Ph.D. thesis, May 1975.
30. H.R. Thomas, J.H. Willenbrock, and J.L. Burati, Jr. CE 431 Supplementary Class Notes. Department of Civil Engineering, Pennsylvania State Univ., University Park, July 1979.
31. N.B. Aughenbaugh, R.B. Johnson, and E.J. Yoder. Degradation of Base Course Aggregates During Compaction. School of Civil Engineering, Purdue Univ., West Lafayette, IN, May 1963.
32. E. Boutrup. Computerized Slope Stability Analysis for Indiana Highways: Volumes I and II. Purdue Univ., West Lafayette, IN, M.S.C.E. thesis and Joint Highway Research Project Repts. 77-25 and 77-26, 1977, 512 pp.

Publication of this paper sponsored by Committee on Engineering Geology.

Slaking Modes of Geologic Materials and Their Impact on Embankment Stabilization

ERIC F. PERRY AND DAVID E. ANDREWS

The results of a study of the impacts of slaking on surface mine spoils in the Appalachian Basin are discussed. Representative samples were collected for laboratory analyses from core borings near the active highwall and from test pits excavated in fresh and 2-, 5-, and 10-year-old spoils from four selected mine sites. Extensive qualitative and semiquantitative data were collected on the behavior, causes, and effect of slaking materials. Three slaking modes were identified in the field: (a) slaking to constituent grain size; (b) chip slaking to thin, platy fragments; and (c) slab or block slaking to large, approximately equidimensional fragments. These modes are dependent on inherent material properties such as bedding, cementation, and grain size and may affect overall spoil pile or embankment stability. Slaking to inherent grain size promoted surface crusting, reducing infiltration and accelerating sheet erosion. Stability problems in embankments and spoil piles can be anticipated by observing the rate, degree, and modes of slaking.

The problem of understanding the impact of the slaking process is underscored by the fact that there is no universally accepted definition of the term "slaking". It has been defined as "the crumbling and disintegration of earth materials when exposed to air or moisture" (1), the "disintegration of rocks by water immersion" (2), or the "disintegration of mudstones upon alternate drying and wetting" (3). These definitions fail to consider the element of rate of breakdown and changing stress or strength conditions within the material.

An alternative definition of slaking has been proposed that focuses on short-term dynamic stress and strength conditions and the fundamental mechanisms involved (4).

The proposed definition is as follows: Slaking is the short-term physical disintegration of a geologic material following removal of confining stresses. Breakage may result either from the establishment or the occurrence of sufficient stresses within the material or from the decrease in structural strength. The significance of the disintegration rate depends on the specific engineering consideration; for definition, "short-term" may be taken to mean less than several years.

Since slaking by definition involves the degradation of geologic materials, it follows that the properties of these materials play an integral part in the slaking phenomenon. These properties can be broadly characterized as stratigraphic or structural.

Two stratigraphic components related to durability of a given material are lithology and mineralogy. Lithology, such as sandstone or shale, considered in conjunction with bedding characteristics, can generally be related to durability; e.g., argillaceous materials have a higher slake potential than arenaceous materials. Mineralogy also affects durability by defining the composition and stability of individual grains and cementing agents.

Clay minerals, because of their water absorption and ion adsorption properties, can exert physicochemical stresses within rock materials, a process that can lead to slaking. In addition, mineralogic properties of cementing agents, including bond strength and chemical activity, may influence slakability.

Megascopic and microscopic structures, as they relate to planes of weakness, influence durability by controlling the entry and mobility of pore fluids, residual stresses, and fragment size. Megascopic geologic structures, especially faults and joints, relate to zones of weakness created during earth movements. Microscopic structures (rock fabric) describe spatial relations between individual grains and among grains. Fabric can directly affect rock integrity by influencing interactions between grains and their reaction to imposed stress. This is especially prominent where a strongly anisotropic fabric is present.

STUDY METHODOLOGY

A detailed field program was implemented as part of a research program sponsored by the U.S. Bureau of