Laboratory Studies of the Stabilization of Nondurable Shales

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Research performed to identify suitable chemical additives that could either (a) help break down shales during placement or (b) reduce the deterioration caused by slaking during the service life of a compacted shale embankment is described. Many combinations of durability and strength can be expected when dealing with shales to be used in compacted highway embankments. Hard and durable shales can be placed as a rock fill, whereas soft and nondurable shales must be thoroughly degraded and placed in thin lifts as a soil fill. The hard and nondurable shales are difficult to stabilize by mechanical means, such as increased compactive effort. However, because of their nondurable nature, they often develop excessive settlements during the service life of the embankment and even cause slope failures. The slake-durability test was used to evaluate the change in durability effected by various chemical additives in the slaking fluid as well as lime in the compaction water. The shales were Indiana shales of both the hard and nondurable and soft and nondurable types. Since the primary slaking mechanism varies among midwestern U.S. shales, the salts that improve durability also varied with the material. At concentration levels of 0.1 N, sodium chloride, calcium sulfate, or ferrous sulfate produced favorable results. The effects of lime on durability also varied by type of shale, percentage admixture, and curing time, but very substantial improvements were effected by adding lime.

Shale is the most commonly occurring sedimentary rock and is often exposed on the surface. Construction of highway embankments requires economical use of material from adjacent cuts or nearby borrow sources. Shale formations crop out in most parts of southern Indiana, and they frequently occur in highway cuts. Use of excavated shale from cuts and borrow areas as a rock fill in compacted embankments [in lift thicknesses of about 1 m (3 ft)] has led to various problems, such as excessive settlement and slope failures. These problems led to a research program at Purdue University, through the Joint Highway Research Project, to study the use of Indiana shale in compacted highway embankments.

Deo (1) investigated different Indiana shales and proposed a classification system (based on laboratory tests used to predict field behavior) that is currently being used by the Indiana State Highway Commission (ISHC). Chapman (2) investigated several laboratory tests to evaluate the shale behavior to be used during classification. Bailey (3) investigated the factors that relate to the degradation of shales during the compaction process. A statistical analysis of the data provided by ISHC for shales tested in the ISHC laboratory was prepared by van Zyl (4). Abeyesekera (5) investigated the stress-deformation and strength characteristics of compacted New Providence shale. Witsman (6) investigated the effect of compacted prestress on the compressibility of compacted New Providence shale. Hale (7) investigated different compaction methods to develop a standard for evaluating the degradation of shales during the compaction process.

Table 1 lists the shales and shale properties investigated by these researchers.

The behavior of a shale during construction and its performance in an embankment depend on its degradation and slaking properties. The classification systems used to categorize shales as durable and nondurable are based on the slaking properties of the shales evaluated in the laboratory and correlated with field behavior. These systems do not consider the hardness, degradability, or physicochemical properties of the shales. The hard and durable shales can be placed as a rock fill and the soft and nondurable shales as a soil fill. The hard and nondurable shales pose particular problems in embankments. They often develop excessive settlement and even slope failures and are difficult to stabilize by mechanical means, such as increased compactive effort.

The objectives of this research were (a) to study the type of (chemical) additives that could possibly be used during the excavation and placement stages of construction and thereby reduce the slaking of shales during service and (b) to study the control of lime used as an additive with different types of compacted shales.

The shales used in this research are given below:

No.	Type of Shale
1	New Providence
2	Mansfield
3	New Albany
4	Osgood
5	Attica
6	Palestine
7	Hardinsburg
8	Klondike

The properties studied and the tests performed for these shales were as follows:

1. Slaking characteristics with different salt solutions (shales 1-3),
2. Lime as an additive in the compacted state (shales 1 and 4),

Table 1. Summary of shale properties investigated.

Researcher	Shales Studied	Properties Studied and Tests Performed
Deo (1)	Klondike; Attica; Paoli X, Y, 3, 5; Scottsburg; Lynnville; Cannelton; I-65; I-75; IN-37 A, B; IN-67 A, B	Slaking in water (slake-durability index); soundness; abrasion characteristics; X-ray diffraction; activity, Atterberg limits; compaction and California bearing ratio; absorption; bulk unit weight; breaking characteristics
Chapman (2)	Hardinsburg, New Albany, Mansfield, Palestine, Kope, Klondike	Slaking, soundness, Atterberg limits, rate of slaking, Los Angeles abrasion test, ultrasonic cavitation, Schmidt hardness test, Washington degradation test, ethylene glycol soaking test, mineralogy
Bailey (3)	Big Clifty, Borden, Clore, Haney, Hardinsburg, Kope, New Albany, New Providence, Mansfield, Palestine, Waltersburg, Dillsboro	Scleroscope hardness, point load strength, degradation due to long-term soaking, absorption due to long-term soaking, degradation and compacted density from static, dynamic, kneading, and gyratory types of compaction
Abeyesekera (5)	New Providence	Strength characteristics of compacted shales
Witsman (6)	New Providence	Effects of prestressing in compaction, effective embankment loadings with surcharges
Hale (7)	Osgood, New Providence, Palestine	Point load strength, degradation due to static and dynamic compaction

3. X-ray diffraction for estimation of clay minerals (shales 1-3),
4. Point-load strength (shales 1-3 and 5-7), and
5. Pore-size distribution (all shales).

LITERATURE REVIEW

Slaking Tests

Slaking is defined in the dictionary of Geological Terms of the American Geological Institute (8) as "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." Slaking is measured in the laboratory by the percentage of weight retained or lost through a given sieve as a result of soaking in water. A number of tests based on this concept have been developed by various investigators.

Slaking of soil aggregates is studied by placing a sample on a screen and subjecting it to slaking by the impact of a water drop (9). Slaking is evaluated in the classification test proposed by Deo (1) by means of the five-cycle slaking test, the 500-revolution slake-durability test on dried samples, and the modified sodium sulfate soundness test. The five-cycle slaking test involves repeated wetting and drying of shale material retained on a 2-mm (no. 10) sieve. The percentage dry weight of material lost at the end of the fifth cycle gives the slaking index. The slake-durability test developed by Franklin (10) uses a rotating drum made of 2-mm (0.078-in) mesh, and the percentage by weight of material retained at the end of a number of revolutions in water gives the slake-durability index. The modified sulfate soundness test involves soaking the shale specimen for five cycles in a solution of 50 percent sodium sulfate for 16-18 h, followed by oven drying. The percentage weight of material retained on the 12.5- and 8-mm (0.5- and 0.312-in) sieves gives the sodium soundness index [details of this test are given by Deo (1)].

Chapman (2) reviewed several tests (the rate-of-slaking test by Morgenstern and Eigenbrod, the ethylene glycol test used by the Pennsylvania Department of Transportation, the Washington degradation test, ultrasonic cavitation, and the Los Angeles abrasion test) and reported that the slake index and the slake-durability and rate-of-slaking tests were most practical in identifying "problem shales" for embankment construction.

Noble (11) used a 25 percent solution of sulfuric acid as the slaking fluid and identified shales from Virginia that were nondurable. Both the slaking test and the slake-durability test were unable to identify these shales as nondurable. In Noble's tests, the sulfides in the shale reacted with water to produce sulfuric acid, which deteriorated the shales further by solution action and the hydrolysis of the weathering process. Therefore, this test simulates the field weathering process for shales that are rich in sulfides.

Slaking Mechanisms

Terzaghi and Peck (12, p. 146) attributed the slaking phenomenon to the compression of entrapped air in the pores of the material as water enters the pores. This entrapped air in the pores exerts tension on the solid skeleton, causing the material to fail in tension. This behavior can be recognized in soil aggregates and poorly cemented (i.e., compacted) shales and mudstones. Moriwaki (13) found that slaking of compacted kaolinite can be attributed to this mechanism. However, there have been cases (14,15) in which this mechanism did not satisfactorily explain the behavior observed.

Clay surface hydration by ion adsorption has been suggested as a second mechanism that causes slaking through the swelling of illite, chlorite, and montmorillonitic clays (16). Differential swelling caused by hydration or osmotic swelling is reported to be the main cause of slaking in expansive materials (13). Tschebotarioff (17, p. 102) defines slaking as a surface phenomenon in the following way: "[If] the clay layer at the exposed surface swells first and therefore expands more than the adjoining inner layers, the induced relative displacements are liable to detach the surface layer and cause it to distintegrate and slough away. The process can then be repeated and gradually progress from the surface inward."

The removal of cementing agents in the case of shales, siltstones, and mudstones by the dissolving action of the moving groundwater is considered to be a third mechanism that causes slaking (13,14). The pH of the percolating groundwater and the presence of oxygen, carbon dioxide, and various minerals in the shales control the slaking caused by this mechanism. Simple stress relief may also be adequate to open shale fissures and initiate slaking.

No single mechanism can be considered the dominant cause of the slaking of shales. A combination of the mechanisms mentioned above--either by one triggering the other or by each occurring independently--is the most likely. The composition and the environment in which the shale is placed determine the principal mechanism causing the failure.

Additives Used in Stabilization

Various additives have been used to improve soil properties. Additives have been used to improve strength, reduce permeability, control settlement, prevent erosion, and in some cases hasten a chemical reaction. The additives that are discussed in this section are inorganic salts and lime.

Inorganic Salts

Many salts ($NaCl$, $CaCl_2$, $NaNO_3$, $NaHCO_3$, NaH_2PO_4, $BaCl_2$, $MgCl_2$, KCl, $KMnO_4$, and Na_2SiO_3) have been studied in the laboratory as potential stabilizers, but economics have restricted use in the field to only a few of these. NaCl and $CaCl_2$ are the salts commonly cited in the literature as stabilizing agents (18). The salt solution increases the concentration of electrolyte in the pore water and substitutes higher-valence ions for those of lower valence. The increase in the electrolyte concentration causes the double layer to depress and the repulsive forces to decrease. The effect of NaCl on plastic and liquid limits has been found to depend on the soil type (18). An increase in strength has been observed in soils stabilized with NaCl. It has also been observed that NaCl reduces or eliminates frost heave by lowering the freezing point of water and decreasing permeability. No cementation is said to occur between the NaCl and the soil; however, an increase in compressive strength suggests the possibility of cementation between particles as a result of the addition of salt. To react most efficiently, NaCl requires fine-grained material and freedom from organic matter.

$CaCl_2$ has also been used successfully in stabilization (18). Addition of $CaCl_2$ in excess of 1 percent has been shown to decrease density: The calcium ions increase the repulsive forces by changing the charge on the particle from negative to positive. $CaCl_2$ has been used for frost-heave protection.

Inorganic salts have been used as trace amounts in lime, lime/fly-ash, and cement stabilization. The postulated mechanisms involved are (a) acceleration of the pozzolanic reaction, (b) production of secondary cementitious products, and (c) combination with the primary, or pozzolanic, cementitious products (19).

The type of soil is an important factor in salt stabilization: For example, sodium salts seem effective with calcareous soils.

Lime

The purposes of lime stabilization include hastening construction operations, modifying the subgrade, and improving the strength and durability (resistance to freeze-thaw action) of fine-grained soils. The most common types of lime used in stabilization are hydrated high-calcium lime [$Ca(OH)_2$], monohydrated dolomitic lime [$Ca(OH)_2 \cdot MgO$], calcitic quicklime (CaO), and dolomitic quicklime ($CaO \cdot MgO$). Hydrated lime is used more frequently than quicklime.

The reactions that take place in soils treated with lime are complex. However, several explanations have been presented in the literature. Cation exchange and flocculation agglomeration are said to occur rapidly and to result in immediate changes in soil plasticity, workability, and immediate uncured strength. Depending on the soil type and temperature, pozzolanic reaction will occur; this forms various cementing agents and results in increased strength and durability of the soil-lime mixture. Since pozzolanic reactions are time dependent, there are increases in strength with time.

Flocculation and agglomeration produce an apparent change in texture--i.e., the clay particles "clump" together into larger-sized "aggregates" (20). The mechanism of flocculation and agglomeration is explained by Herzog and Mitchell (21) as an ion exchange phenomenon in which the electrolyte concentration of the pore fluid is increased by the exchange of calcium ions. Diamond and Kinter (22) suggest that the rapid formation of cementing material of calcium aluminate hydrate develops flocculation and agglomeration tendencies in soil-lime mixtures.

Soil-lime pozzolanic reaction occurs between lime, water, and sources of soil silica and alumina. The sources of silica and alumina in soil are quartz, feldspars, micas, and other alumino-silicate minerals.

Eades and Grim (23) suggested that elevation of the pH level of the soil-lime mixture causes the silica in the clay minerals to be dissolved out of the structure and to combine with the calcium to form calcium silicate. This process continues as long as $Ca(OH)_2$ and silica are available to react to the soil-lime mixture. Diamond and others (24) concluded that, in a highly alkaline soil-lime system, the reaction involves a dissolution at the edges of the silicate particles followed by the precipitation of the reaction products. It is also suggested, by Diamond and Kinter (22) and Ormsby and Bolz (25), that surface chemical reactions can occur and new phases may be formed on the surface of clay particles.

The degree to which the soil-lime pozzolanic reaction can take place depends on the natural soil properties. Thompson (26) has termed those soils that react with lime to produce a substantial strength increase [greater than 344.75 kPa (50 lbf/in²) after 28-day curing at 22.8°C] as reactive and those that display limited pozzolanic reactivity (a strength increase less than 344.75 kPa) as nonreactive. Some of the major soil properties and characteristics that affect the lime reactivity of a soil are soil pH, organic carbon content, natural drainage, the presence of excessive quantities of exchangeable sodium, clay mineralogy, degree of weathering, presence of carbonates, extractable iron, silica-sesquioxide ratio, and silica-alumina ratio (20).

Lime has been used successfully by mixing it with pulverized shale and compacting to form an erosion-resistant lining for the "Black Thunder Slot" storage in Wyoming (27).

MATERIALS AND LABORATORY TESTING

Shales Sampled

The principal shales used in this study were New Providence, Mansfield, New Albany, and Osgood. The New Providence shale lies at the base of the Borden group, which crops out in a narrow band about 19-24 km (12-15 miles) wide in Indiana. Mansfield shale belongs to the Mansfield formation of the Pennsylvanian Pottsville series and was found above the Mississippian-Pennsylvanian contact. The New Albany shale forms a transition between Devonian and Mississippian rocks in Indiana; some portions are part of the Mississippian Kinderhookian series. The Osgood shale, a blue-gray, hard, and flaggy shale, is a member of the Salominie Dolomite and lies at the base of the Niagaran series in the Silurian system. Table 2 gives a brief description of the nature of these four principal shales and the investigations in which they were sampled. ISHC soil index data for these shales are given in Table 3, and further data are given by Surendra (28).

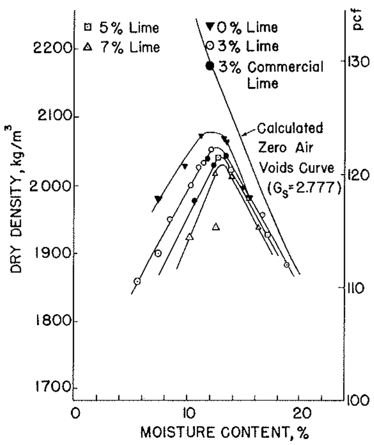
Table 2. Description of principal shales studied.

Shale	Deo's Classification (1)	Physical Nature	Sampled by
New Providence	Soillike	Hard and nondurable	Abeyesekera (5), Hale (7)
Mansfield	Soillike	Soft and nondurable	Chapman (2)
New Albany	Rocklike	Hard and durable	Chapman (2)
Osgood	Soillike	Hard and nondurable	Hale (7)

Table 3. Soil index values from ISHC laboratory test results.

Shale	Atterberg Limits w_L	w_P	I_P	Unified Soil Classification	AASHTO Classification	Textural Classification
New Providence	34	23	11	CL	A-4(10)	Silty clay (shale)
Mansfield	32	22	10	CL	A-6(17)	Silty clay (shale)
New Albany	34	28	6	ML, OL	A-4(7)	Silty clay (shale)
Osgood	26	18	8	CL	A-4(4)	Silty loam (siltstone)

Figure 1. Moisture-density results from standard Proctor compaction tests on New Providence shale with various percentages of lime.



Slaking-Index Test

The slaking index was determined according to the ISHC test procedure described by Surendra (28). In this test, six pieces of shale weighing approximately 150 g were selected and oven-dried to constant weight at about 105°C. Each piece was soaked for 24 h in a 600-mL beaker that contained the slaking fluid (usually distilled water). The water level was at least 13.0 mm (0.5 in) higher than the shale sample. Water was then drained from the shale sample and washed over a 2.0-mm (no. 10) sieve, and the retained material was oven-dried at 105 ± 5°C to constant weight (for approximately 24 h). After five cycles of this procedure, the slaking index (expressed as a percentage) was calculated as follows: Slaking index = (oven-dry weight of material lost at end of five cycles ÷ oven-dry weight of sample before test) x 100. When this generally accepted definition is used, durability decreases with increasing slaking-index values.

Five tests were performed on each shale, and the average was reported. The slaking indices for the shales studied are given below (water was the slaking fluid):

Shale	Slaking Index	Shale	Slaking Index
New Providence	50.81	New Albany	0.14
Mansfield	40.78	Osgood	52.70

The index for the Osgood shale is taken from ISHC test results.

Slake-Durability Test

The slake-durability index was determined according to the procedure of the International Society for Rock Mechanics (ISRM) (29). The slake-durability apparatus [developed from Franklin (10)] consists of a drum with a screen opening of 2 mm (no. 10). The drum is rotated by an electric motor in a bath of slaking fluid (usually water) at a constant rate (20 rpm). The slaking sample consists of 10 equidimensional pieces of shale, each weighing between 40 and 60 g. The pieces are oven-dried to constant weight at 110 ± 5°C, cooled to room temperature, and placed in the drum of the apparatus. The drum is immersed in the tub that contains the slaking fluid and is rotated for 200 revolutions. At the end of the test, the material retained in the drum was oven-dried and weighed. The retained material was subjected to another cycle of slaking in the rotating drum. The slake-durability index (I_{d_2}) was calculated at the end of the second cycle as follows: I_{d_2} = (oven-dry weight of material retained at end of second cycle ÷ oven-dry weight of sample before test) x 100.

When this generally accepted definition is used, durability increases with increasing values of I_{d_2}. The slake-durability indices presented below are an average of six tests (the index for the Osgood shale is taken from ISHC test results):

Shale	I_{d_2}	Shale	I_{d_2}
New Providence	58	New Albany	99.1
Mansfield	66	Osgood	67.3

Compaction

Shales from the New Providence and Osgood formations were used for the study of stabilization with lime in the compacted state. Both of these shales belong to the same category--hard and nondurable--and they have been used for other studies at Purdue University (3,5-7). The shale samples were broken into pieces about 100 mm (4 in) in diameter, which were passed through a jaw crusher that was set to yield pieces of less than 12.5 mm (0.5 in), the largest practical size for laboratory study. The crushed shale was sieved and separated by using a nest of sieves [12.5, 9.5, 4.75, 2.36, and 1.00 mm and 75 μm (0.5 in, 0.3875 in, no. 4, no. 8, no. 16, and no. 200) in a Gilson sieve shaker. The gradation used for compaction matches closely the exponential gradation of n = 1 in the Talbot and Richart equation (30):

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

where

P = percentage by weight finer than size d,
d = any diameter,
D = maximum grain diameter, and
n = an abstract number.

This gradation was selected by Witsman (6) when a batch of crushed New Providence shale gave a gradation that closely matched the gradation of n = 1. This gradation also falls within the range of gradation investigated by Abeyesekera (5) and makes the shale efficient for use in compaction.

After the addition of water, the samples were cured in plastic bags for 12-24 h and then compacted. Even with the limited curing time, the shale samples did slake to a limited extent. However, well-defined compaction curves were obtained. The test results agreed closely with those of Witsman (6) for the New Providence shale. Figure 1 shows the moisture-density curves for the New Providence shale with various percentages of lime for the standard Proctor compactive effort.

When lime was added in the form of a slurry, there was a very uniform distribution of lime and reproducible densities. Different percentages of lime were used (3, 5, and 7 percent by weight of soil solids), and the moisture-density curves were obtained for each percentage in the standard Proctor compaction test, as shown in Figure 1.

It can be seen from Figure 1 that the optimum moisture content for the different percentages of lime did not vary much. The maximum dry density of the New Providence shale was reduced from 2070.25 to 2040.75 kg/m³ (123.8-121 lb/ft³), a reduction of 2.3 percent, and that of the Osgood shale was reduced from 2261.54 to 2186.36 kg/m³ (134.5-130 lb/ft³), a reduction of 3.5 percent (28).

The samples for evaluation of the effect of lime on slaking were compacted at a moisture content of about 2 percent wet of optimum (i.e., at 14 percent for the New Providence shale and at 12-13 percent for the Osgood shale) to ensure that there would be enough water available for the curing of lime. The lime used subsequently in this study was from a single batch [23-kg (50-lb) bags] of commercial slaked lime [$Ca(OH)_2$]. The moisture-density curve obtained by using the commercial lime was essentially the same as the one obtained by using the laboratory reagent lime (Figure 1).

RESULTS AND DISCUSSION

Slaking of Shales in Different Slaking Fluids

The slaking fluid used in the slake-durability and slaking tests was changed by adding different inorganic salts to the water, and the effects were studied (28,31).

Slaking of shales was studied in a simplified (one-cycle) slaking test and in the regular (two-cycle) slake-durability test. The slaking fluid used in these tests consisted of salt solutions at one level of concentration. The concentration of the slaking fluid was kept constant at one relatively low level: 0.1 N solution. The salts used were those commonly used in civil engineering practice either as chemical additives or as catalysts with lime stabilization. Sodium chloride, calcium chloride, ferric chloride, calcium sulfate, aluminum sulfate, and ferrous sulfate were selected. The results obtained when these solutions were used as the slaking fluid are given in Tables 4 and 5. By examining the coefficient of variation, it can be seen that the inherent variation in the result of a treatment can be very appreciable. To facilitate the comparisons of the different treatments with water, a t distribution was used in the statistical hypothesis testing. The null hypothesis was that there is no difference between the mean value of the index obtained for any one treatment and the control slaking (i.e., when water was used as a slaking fluid).

The treatments were compared at 95 and 98 percent levels of confidence, as shown in Figure 2. The slaking test was not very good in discriminating between the treatments, since values of the t statistics were very high.

In the slake-durability test, sodium chloride and calcium chloride have no effect at the 98 percent level of confidence. Sodium chloride does have an effect at the 95 percent confidence level. Ferric chloride increases the slaking of Mansfield shale but not of New Providence shale at a 98 percent level. Calcium sulfate and ferrous sulfate reduce slaking at a 98 percent level of both shales. The slaking of Mansfield shale with the addition of aluminum sulfate is different from that of New Providence shale. Aluminum sulfate produced increased durability, as measured by both slake

Table 4. Results of slake-durability tests.

Shale	Slaking Fluid[a]	Mean	Δ Mean	Percentage Δ Mean	SD	t	Coefficient of Variation
New Providence	Water	58			5.85		3.86
	NaCl	69	+11	19	8.12	3.32	11.77
	$CaCl_2$	60.5	+2.5	4.3	8.15	0.751	13.47
	$FeCl_3$	57.4	-0.6	-1	1.04	-1.41	1.81
	$CaSO_4$	69.3	+11.3	19.5	3.52	7.86	5.08
	$Al_2(SO_4)_3$	34.5	-23.5	-40.5	7.06	-8.15	20.46
	$FeSO_4$	71.3	+13.3	22.9	3.95	8.27	5.54
Mansfield	Water	66			2.55		3.86
	NaCl	64.8	-1.2	-1.8	0.79	-3.40	1.22
	$CaCl_2$	66.2	+0.2	0.3	0.66	0.75	1.00
	$FeCl_3$	56.1	-9.9	-15	0.58	-41.7	1.03
	$CaSO_4$	77.2[b]	+11.2	17	3.52	6.36	4.56
	$Al_2(SO_4)_3$	88.5[b]	+16.5	25	1.22	27.05	1.48
	$FeSO_4$	78.6	+12.6	19.1	2.96	9.52	3.77

Note: All indices are the mean of six tests except where noted; "+" sign indicates increased slaking-durability index.

[a] All salt solutions at level of 0.1 N. [b] Mean of four tests.

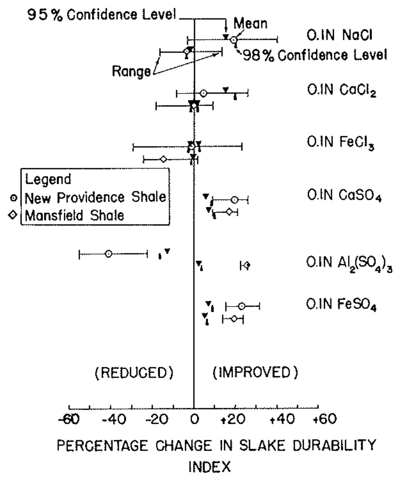
Table 5. Results of one-cycle slaking tests.

Shale	Slaking Fluid[a]	Mean	Δ Mean	Percentage Δ Mean	SD	t	Coefficient of Variation
New Providence	Water	3.16[b]			1.48		46.84
	NaCl	0.84	+2.32	73.42	0.19	17.18	22.74
	$CaCl_2$	0.47	+2.69	85.13	0.064	59.44	13.62
	$FeCl_3$	1.06	+2.10	66.46	0.11	27.94	10.03
	$CaSO_4$	0.79	+2.37	75	0.099	33.86	12.53
	$Al_2(SO_4)_3$	1.52	+1.64	51.9	0.92	2.52	60.47
	$FeSO_4$	0.65	+2.51	79.43	0.36	9.84	55.49
Mansfield	Water	5.41[b]			1.23		23.97
	NaCl	3.32	+2.09	38.63	0.4596	6.43	13.84
	$CaCl_2$	5.75	-0.34	-6.28	3.2881	-0.15	57.18
	$FeCl_3$	5.72	-0.31	-5.73	5.332	-0.08	93.22
	$CaSO_4$	2.64	+2.77	51.2	2.375	1.65	89.96
	$Al_2(SO_4)_3$	1.24	+4.17	77.08	0.24	24.57	19.35
	$FeSO_4$	2.20	+3.21	59.33	0.48	9.46	21.82

Note: All indices are the mean of two tests except where noted; "+" sign indicates increased slaking.

[a] All salt solutions at level of 0.1 N. [b] Mean of five tests.

Figure 2. Percentage change in slake-durability index of shale with different slaking fluids.



durability and one-cycle slaking tests, at a 98 percent level of confidence for Mansfield shale, which is rich in kaolinite content compared with the New Providence shale. Sodium chloride and calcium sulfate increased the durability in both slake-durability and one-cycle slaking tests for New Providence shale, which has a high percentage of sodium in the saturation extract.

New Albany shale, a durable shale, was unaffected by different slaking fluids. This shale is well cemented and has a high percentage (about 5 percent) of organic matter compared with the other shales.

These results are sufficiently positive to indicate that the slaking properties of shales can be altered by altering the slaking fluid for a particular type of shale. Such chemicals can be incorporated in an embankment during placement by adding water prior to the compaction process. Water is essential to the chemical reaction.

The long-term alteration of durability has not been investigated and will require both laboratory testing and field verification. Other chemicals not investigated in this study may be more effective for shales of different composition.

Slaking of Compacted Shales with Additives

Slaking of Compacted Shales

The slaking behavior of a shale is evaluated in the laboratory by using slaking and slake-durability tests on discrete shale aggregates. The values that are obtained from these tests are used as a guide to the behavior of the compacted shale in the field. The mode of breakdown in this test depends on the type of shale (i.e., composition, formation, age, etc.). Some shales tend to break down completely, and the end product is a claylike material; others do not break down at all. There is an intermediate state of breakdown in which the shale piece may decrease in size as a result of the breakdown of the edges and, in some cases, separation of the fissures. The behavior of compacted shales that have an intermediate type of breakdown is most difficult to predict. If the discrete piece of shale is loaded perpendicular to its fissures in the compacted state, it will break down less than it will if it is loaded parallel to its fissures. Hence, the breakdown of a shale that results from water under load depends in part on how well cemented the shale is along its fissures. The slaked portion of a shale remains intact with its parent material unless it is displaced by an external force. This external force can be gravity (as in the case of a slaking test), induced mechanical energy (as in the tumbling action in the slake-durability test), compactive forces (during compaction and under pavement loadings), and percolating water in or under an embankment.

The durability of compacted shale specimens with lime added was evaluated in the laboratory by using the slake-durability test on a sample of compacted shale instead of discrete shale pieces. Because the compacted sample used in the slake-durability test was much larger than the ones used in a standard slake-durability test, no attempt was made to correlate the indices obtained from these tests. As the sample size increases, the slake-durability index decreases and vice versa (32). When the compacted sample disaggregates into discrete pieces, these discrete pieces are much smaller than the sample in the standard test, and a lower value of the slake-durability index results.

In addition to obtaining the slake-durability index, the type of breakdown of the sample was visually observed. Compacted specimens subjected to a slake-durability test can undergo three types of fragmentation, shown schematically in Figure 3. Type 1 is a complete disaggregation of the individual aggregates that constituted the compacted specimen at the beginning of the test. Type 2 is a type of breakdown in which the compacted specimen is reduced to less than half its initial volume and the remainder is disaggregated. In this case, the aggregates start to disaggregate at the boundary and progress inward. In the last type of breakdown, type 3, the sample is little affected by the slaking process and more or less retains its initial shape and volume.

The breakdown of shales in the compacted state can occur at two levels. The first level of slaking is disaggregation, which is exemplified by the type 1 fragment. The second level is a further breakdown of the aggregations once they have separated from the compacted state. There may be an intermediate state in which the aggregates tend to break down while they are still in the compacted mass, but this can occur only on the edge or face of the compacted specimen. This intermediate state of breakdown is represented by type 2 fragments. The intermediate state may ultimately result in a breakdown to type 1 fragments. The reduction of type 2 into type 1 fragments depends on the type of shale and on gradation, molding water content, and the compactive effort used during the process of compaction.

An additive used during compaction can limit the slaking of shales in two ways: The additive can (a) react with the discrete pieces of shale in reducing the amount of breakdown or (b) act as a cementing agent in binding the aggregates of the compacted mass to maintain its compacted state. If the

Figure 3. Types of fragmentation during slake-durability test of compacted shale.

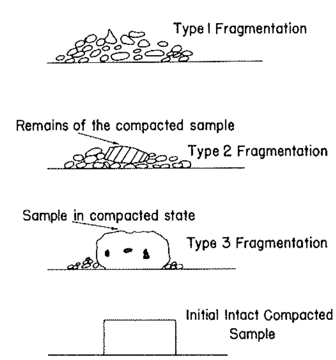


Figure 4. Slake-durability index of compacted New Providence shale versus curing period.

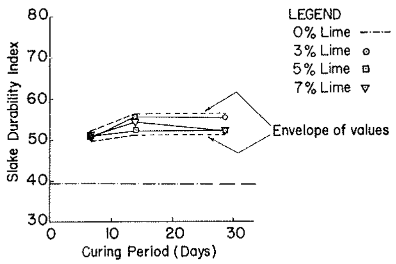
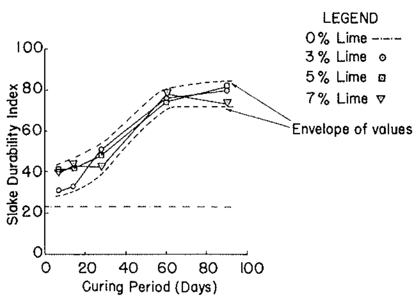


Figure 5. Slake-durability index of compacted Osgood shale versus curing period.



compacted sample is disaggregated, then the slaking properties of the individual shale particles control further slaking of the shale.

Lime Stabilization

Compacted samples were prepared as described earlier with various percentages of lime: 3, 5, and 7 percent. The shale samples were compacted with lime at about 2 percent wet of optimum to ensure the availability of water for the reaction with lime during the curing period. At the end of the curing period, the compacted samples were cut in half to give two samples about 101.6 mm (4 in) in diameter and 55.9 mm (2.2 in) in height. These samples were tested for durability in a slake-durability apparatus. The slaking fluid was deionized water.

The results of slake-durability testing of compacted samples with lime added are shown in Figures 4 and 5 for Osgood and New Providence shales, respectively. Figure 5 shows that the durability of compacted New Providence shale does not improve until it reaches 28 days of curing. The durability of the shale increases rapidly up to 60 days of curing, after which further increases in the curing period (i.e., 90 days) produce very little improvement. The samples cured for 7 and 14 days had type 1 fragments at the end of the test. Samples cured for 28 days had type 2 fragments, and a chunk of compacted sample about 50 x 30 mm in size was left at the end of the test. The rest of the sample was disaggregated. The samples tested at the end of 60- and 90-day curing periods had type 3 fragments and very little disaggregation. Osgood shale had type 1 fragments at the end of all the tests that were performed for all curing periods and all percentages of lime.

It can be seen from the results in Figure 4 that lime was of little help in improving the slake durability of Osgood shale for a 28-day curing period. Exchangeable sodium percentage (ESP) gives an indication of lime reactivity with soil (20). In the shales studied, the New Providence shale had a much higher ESP (18.2 percent) than the Osgood shale (0.34 percent).

The type of breakdown, indicated by the mode of fragmentation, demonstrates the extent to which lime is effective. As mentioned earlier, type 2 fragmentation is an intermediate stage of disaggregation and may result in type 1 fragmentation upon subsequent slaking. Hence, in investigating the slaking characteristics of compacted shales, changes in the type of fragmentation should be examined as well as changes in slake-durability indices.

As in the case of chemical additives, the results of lime stabilization reported here are preliminary in nature. Longer curing times must be studied as well as the practical field problems of (a) mixing the lime and shale and (b) retention of the stabilization over the service life of the embankment.

CONCLUSIONS

The conclusions presented here are based on the results of the laboratory investigations conducted during this research on Indiana shales. Laboratory tests were performed on shale samples taken from a particular location in a shale formation. Since the properties of these shales often vary laterally and with depth within the same formation, a variation in the results is expected for samples from different locations of the same formation.

The conclusions of this research can be stated as follows:

1. The slaking properties of shales can be changed (i.e., either increased or decreased, as shown in Figure 2) by altering the slaking fluid. The type and concentration of slaking fluid that will effectively alter the slaking property of a shale depends on the geologic formation, age, and chemical composition of the shale and the clay minerals present.

The slake-durability index of discrete pieces of New Providence (a hard and nondurable) shale was increased by adding sodium chloride, calcium sulfate, and ferrous sulfate to the slaking fluid at a concentration level of 0.1 N. Aluminum sulfate reduced the slake-durability index when used in the slaking fluid at the same concentration (Figure 2). The slake durability of discrete pieces of Mansfield (a soft and nondurable) shale was increased when 0.1 N concentration of calcium sulfate, aluminum sulfate, and ferrous sulfate was used in the slaking fluid. Ferric chloride at the same concentration level in the slaking fluid decreased the slake durability of Mansfield shale (Figure 2).

Shales that have origins and chemical compositions similar to the ones tested can be expected to display similar changes in durability characteristics. Other chemicals may be more effective in changing the durability of shales of different composition.

2. Lime mixed with the compaction water increased the slake-durability characteristics of the compacted New Providence shale. The durability increased with increasing curing period. There was a gradual increase in durability up to 28 days of curing and a sudden increase in durability up to 60 days of curing. Further lengthening of the curing period resulted in very little increase in durability (Figure 5). Three percent lime was found to be a sufficient percentage for improving the durability.

3. Lime was of limited effectiveness in increasing the durability of compacted Osgood shale (Figure 4).

4. ESP appears to be an indicator of the reactiveness of a shale with lime. Lime was effective in increasing the durability of compacted New Providence shale, which had an ESP of 18.2; Osgood shale, which had an ESP of 0.3 percent, did not show any appreciable increase in durability with the addition of lime.

5. The slake-durability test can be used to compare the effects of lime on the durability of compacted shales in the laboratory.

6. The mode of fragmentation during slaking of a lime-treated, compacted shale is instructive. Type 3 fragmentation indicates that lime is effective in improving the durability as it binds the aggregates and retains the compacted state. Type 2 fragmentation may lead to type 1 fragmentation upon further slaking, which would indicate that lime may not be effective.

Showing that additives work under laboratory conditions is an important first step, but field experimentation is also required before the findings are put to practical use. Since the alternative to stabilizing certain shales in this manner is to waste them, there is significant economic justification for such studies.

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Swelling Shale and Collapsing Soil

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Geotechnical engineering parameters of both rock and soil can be significantly influenced by regional environmental factors. Climatic factors such as rainfall and temperature, coupled with geologic and geomorphic factors such as bedrock type and landform configuration, combine to present very different kinds of problems for highway pavements in the several physiographic provinces of the world. Two causes for pavement deformation that are physiographically bounded are swelling shale and collapsing soil. Swelling soil is not a significant problem for highway builders in the semiarid climates of the western United States. Swelling bedded shale, however, can completely disrupt the traveled way. Soil surveys, laboratory testing, and corrective and/or preventive measures designed for swelling soils are frequently not appropriate for effectively dealing with swelling shales. Low-level blasting is presented as one method of preventing or correcting swelling-shale problems under roadway pavements. This technique cost-effectively approximates subexcavation. Proper selection and placement of the explosive are important to the success of the technique. Soils that have a measurable swell potential can collapse on wetting in a semiarid climate because of a combination of environmental factors. Pavement distortions over collapsible soils are often misidentified as resulting only from swelling soil or internal fill deterioration. Prewetting of collapse-susceptible soils alleviates long-term settlement problems.

Two major causes of distortion in highway pavements have been identified in Colorado: swelling shale and collapsing soil. Both are products of local geologic, geomorphic, and climatic factors. Neither swelling nor collapse is significant in many parts of the United States. But in physiographic regions where either of these problems exists, substantial disruption of the traveled way can occur.

Problems with swelling soil and/or shale have been recognized and treated in Colorado for several years. Collapsing soils have only recently been identified as a cause for gradual deterioration in rideability on roadways over outwash-mudflow soil sequences. Previously, undulating pavement surfaces over collapsible soils were attributed to swell, especially in areas where swelling shales were used in fill construction. Although either phenomenon can occur independently, this paper reports on both because of their interrelationship with environmental factors and their similar effect on the riding surface.

Literature searches have failed to turn up definitive mapping for areas where either problem may exist. Independently variable environmental factors, including climate, rainfall, slope, bedrock, exposure, and vegetative cover, must be collated onto a single map in order to delineate physiographic regions that may be susceptible to either phenomenon. This, to our knowledge, has yet to be accomplished.

SWELLING SHALE

Swelling bedded shale is a common cause of pavement distortion in arid and semiarid climates. Swelling soils are much less likely to cause significant deformation of the riding surface in these climates. This is an important distinction for both the design and the maintenance of roadways in areas where swelling is known to occur.

Swell Potential

Snethen and others at the U.S. Army Engineer Waterways Experiment Station (WES) at Vicksburg, Mississippi, have performed extensive compilations of the existing literature as well as independent research on the swelling phenomenon under a Federal Highway Administration (FHWA) research grant. The several reports that have resulted from these studies represent the most comprehensive literature available on swelling soils.

Very briefly, significant swell potential in shale is attributable to the presence of montmorillinitic clay minerals (1,2). Most clay minerals will expand on wetting, but significant volume changes are related to montmorillonite clay content and distribution.

Occurrence

Shales in the United States that exhibit significant swell potential are typically Mesozoic and Tertiary in age and are abundant in the semiarid climates of the West.

Sampling and Testing

Sampling and testing requirements for determining the presence of swelling clay minerals in bedded shale for highway-design purposes are much less stringent than, for example, those for building-construction purposes. In fact, no testing is required where a knowledge of local geology and performance of existing pavements can provide qualitative data.

Where sampling and testing programs are contemplated, it is important to obtain samples from bedded materials rather than from alluvial and residual soils. Tests performed on samples from unbedded soil deposits are not reliable indicators of the swelling problems that may be experienced over bedded shales after the roadway is completed.

The shales can be sampled in test pits or by using coring equipment. Testing has traditionally been performed on material crushed to soil gradations (3).

Correction and Prevention

Subexcavation and recompaction of bedded shale below the profile grade line to a depth of 2-3 m (6-10 ft) have consistently proved to be the most cost-effective solution to swelling-shale problems in semiarid climates; however, the costs of this procedure are relatively high in comparison with