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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

Mines to document the nature, occurrence, distribution, and effects of slaking in surface mine spoils. The results of the laboratory portion of this study are presented in the paper by Withiam and Andrews in this Record. The field program consisted of five phases:

1. Preliminary site selection,
2. Site reconnaissance and final site selection,
3. Highwall exploration,
4. Mine spoil exploration, and
5. Interviews with mine and regulatory personnel.

Preliminary site selection was based on consideration of mining technology, duration of operations, and overburden lithologies of candidate sites. Further screening was provided by consideration of mining and reclamation techniques, geographic location, production characteristics, and minable extent of seams mined at each site as well as uniformity of overburden materials on a site-specific and regional basis.

Following the preliminary site-selection process, a one-day field reconnaissance was performed at seven potential sites. Site-specific information was obtained to assess the compatibility of each site with study objectives and to collect additional data on mining and reclamation methods, overburden composition, and slaking characteristics. Based on the reconnaissance results, four sites that provided an optimum mixture of mining methods and geologic materials as well as good spatial distribution within the study area were selected for detailed field studies (see Figure 1).

A boring was drilled near the active highwall to evaluate in situ overburden characteristics at each site. Rock coring was conducted through the full section of overburden (stratigraphy overlying the coal) to the lowest mined coal seam by using truck-mounted drill rigs and clear water as the drilling fluid. Rock core was described and visually classified by using a standard format that included color, lithology, relative hardness, depths and thickness of rock units, recovery and rock quality designation, and other significant features. The logs were correlated with the exposed highwall, and any additional pertinent highwall observations were incorporated.

A test-pit exploration program was conducted to evaluate slaking and associated effects in spoil 0 (recent), 2, 5, and 10 years old at each site. The investigation included

1. Identification of lithologies undergoing slaking,
2. Identification of inherent lithologic properties influencing slaking,
3. Evaluation of time effects on slaking, and
4. Evaluation of mining and reclamation techniques on slaking.

Four test pits on spoil of each age, a total of 16 per site, were excavated to a depth of approximately 2 m after a detailed inspection of surficial characteristics. Preliminary logs were prepared, and two representative test pits were selected and logged in detail. Geologic and agronomic descriptions used for characterization are given in Table 1. Bulk density and water content determinations were made at the surface and within two selected subsurface layers in one detailed test pit. A bulk sample was collected from one subsurface layer, and bag samples of major lithologies were collected from fresh spoil for laboratory testing.

Informal interviews were conducted with mining and regulatory personnel to supplement information collected during other portions of the program. Data on the following subjects were collected:

1. Rates, modes, and degrees of slaking of spoil materials;
2. Environmental effects of slaking;
3. Control measures to alleviate adverse environmental effects of slaking;
4. Mining techniques;
5. Geologic features; and
6. Final reclamation practices, including water and erosion control, fertilization, seeding, and plant methods.

FIELD OBSERVATIONS

Slaking Modes

Slaking in mine spoils is a function of several variables, including material properties, mining techniques, and reclamation procedures. Three modes of slaking were observed to occur in mine spoils: slaking to inherent grain size, chip slaking, and slab or block slaking. Slaking to inherent grain size results in the destruction of original rock structure and production of a sediment mass consisting of fine-grained particles. Disintegration of rocks by this slaking mode can occur in a time period that ranges from a few days to several years or longer.

Chip slaking results in the production of flat fragments that range in thickness from 0.6 to 2.0 cm and in length and width from 2.5 to 15.0 cm. Usually, the chips are relatively stable and resist further degradation. Initial breakdown occurs along subparallel planes of weakness that may not be apparent during visual inspection of fresh rock core. However, the existence of thin interbeds of contrasting mineralogy or chemical composition was found to be a reliable indicator of incipient chip slaking.

Slab or block slaking results in the production of thick slabs or approximately equidimensional blocks that range in size from about 7.5 cm to 1.8 m or more. Breakdown commonly occurs along natural or blasting-induced fractures. Once broken into blocks or slabs, the fragments are generally resistant to further breakdown or deteriorate slowly over time.

Inherent rock properties are a major factor in determining mode, rate, and degree of slaking. Lithology, bedding, and mineralogy were observed to influence the slaking characteristics of mine spoils. Mudstones, siltstones, and shales were found generally to be the most slakeprone lithologies. Slaking of sandstone and limestone was variable but generally minor in occurrence. Bedding characteristics primarily influence the mode of slaking; i.e., rocks that exhibited thin bedding were found to undergo chip slaking, whereas massive rock units were prone to slab or block slaking or slaked to their constituent grain size.

The percentage content of 2- to 20-mm-sized coarse fragments, which shows little variation with depth at all sites, seems to suggest that slaking of large coarse fragments can take place rapidly but that the rate of degradation may decrease substantially with smaller particle size. Hence, an equilibrium point may exist for many geologic materials when the 2- to 20-mm-sized fraction is reached. Slaking of large coarse fragments was observed to occur principally along natural zones of weakness such as bedding planes, fractures, and weakly cemented grains. It is believed that few zones of structural weakness exist in smaller fragments, which substantially reduces the rate of slaking.

Readily identifiable minerals also correlated with various slaking characteristics. For example, carbonate cemented clastic rocks often disintegrate rapidly when placed in spoils. Lithologies with interbeds of contrasting mineralogy, such as concentrations of iron oxides or coarse mica flakes, provide zones of weakness that augment the slaking process.

General relations between slaking modes and inherent rock properties are summarized in Table 2.

Physical Characteristics of Spoils

To understand the various parameters associated with deterioration of spoil materials, the field program examined variations in density and grain size among spoils of various ages. Bulk density of spoils is a function of placement methods, slaking characteristics, lithologic content, and age of spoils. Typical in situ bulk density and moisture content data are shown in Figure 2. Bulk density generally de-

Figure 1. Appalachian and Illinois Basins and approximate location of study sites.

Table 1. Descriptors used in characterization of mine spoil.

Location	Variable	Descriptor[a]
Recent and 2-, 5-, 10-year aged spoil areas	Spoil geomorphology	Outslope, bench, backfilled highwall, valley fill, rolling upland, other[b]
	Slope	Length, gradient, configuration, uniformity
	Slope stability	Surface creep, bulges, scars, failures
	Surface hydrology	Type (e.g., seeps, springs, ponded water), areal extent, flow, pH, depth
	Hydrologic structures	Type (e.g., sediment pond, diversion ditch), dimensions, drainage basin, topographic position, rock riprap
	Erosion	Type (e.g., sheet action, rills, gullies), rock pavement
	Surface condition	Disc marks, bulldozer or rubber tire tracks, other[b]
Test pit		
Surficial features	Vegetation	Species, cover, distribution, litter
	Surface condition	Rock mulch, desiccation cracks, crusting, heaving
	Surface materials	Lithotype, hardness, structure, color, mode of slaking
Subsurface features		
A	Stratification	Depth, thickness, coarse fragment content (percent), lithotypes (percent of each), texture (grain size), special features
B[c]	Stratification[d]	Pores and voids, roots, moist color (Munsell designations for matrix and mottles), structure, moist consistency, boundary, special features, bulk density, water content[e]

[a] Unless noted, any descriptor that required quantification (i.e., gradient) was estimated by visual observation. Soil descriptors were characterized according to standard U.S. Department of Agriculture methodology.
[b] When the descriptor did not fall within the preselected terminology, further definition was required.
[c] In one pit of each age spoil, samples were taken for point load testing, water contents, and bulk grain sizes.
[d] Compiled for two pits in each age spoil.
[e] Measured in one pit in each age spoil.

creases with depth in the fresh and 2-year-old spoils and increases with depth in the 5- and 10-year-old spoils. The higher surface densities in the younger spoils, particularly in the 2-year-old spoils, are a result of more intensive materials-handling activities that have crusted and compacted the surface layer, whereas the lower surface densities in the older spoils are believed to be a result of less machinery traffic. Ten-year-old spoils received minimal grading compared with younger spoils. Increasing density with depth may also indicate that settlement of the spoil materials has taken place.

Spoils exhibit a broad range of grain sizes, from boulders to clay. Because slaking, by definition, involves the physical degradation of rocks, a net decrease in grain size occurs. However, since slaking rates vary greatly, even spoils that have undergone extreme slaking of a particular lithology usually retain some coarse fragments of slake-resistant lithologies. A typical grain-size analysis is shown in Figure 3. Material properties apparently control grain-size distribution in these spoils. Generally, the proportion of fine-grained material increases with increasing spoil age. Younger spoils contain fewer coarse fragments due to increased handling, which, in turn, relates to the increased grading associated with restoration to approximate original contour. Older spoils generally required less grading.

Slaking was observed to occur as a function of depth in spoils of all ages, and, generally, evidence for the occurrence of slaking was negligible below 5 ft. Total coarse-fragment content generally increases with depth as does the proportion of larger fragments. The proportion of smaller coarse fragments typically decreases with depth whereas the distribution of intermediate-sized fractions is more variable.

Table 2. Relation of slaking modes to rock properties.

Slaking Mode	Associated Rock Properties
Slaking to grain size	Generally occurs in mudstones and occasionally in sandstones; rocks are usually massive and may be carbonate cemented
Chip slaking	Generally occurs in shales and siltstones, occasionally in thin bedded sandstones; bedding may be indistinct to well expressed and often micaceous
Slab or block slaking	Generally occurs in sandstones and limestones; rocks are usually massive and may be micaceous

Excavation and Placement Techniques

Mining techniques were observed to affect slaking characteristics in two ways. First, the type of mining used (e.g, area mining versus haulback) influences slaking. Second, the increase in equipment size, machinery traffic, and spoil handling associated with all mining methods has produced an attendant increased impact on slaking. These impacts include greater crushing and abrasion of spoil fragments as a result of increased material handling, more controlled placement, and more extensive final grading.

Blasting methods depend on both the mining method and the number of seams mined. Blasting directly affects slaking in at least three ways: total disintegration of the rock into its constituent particles, partial breakdown of the rock into smaller

Figure 2. Dry bulk density and water content versus depth for spoils of different ages.

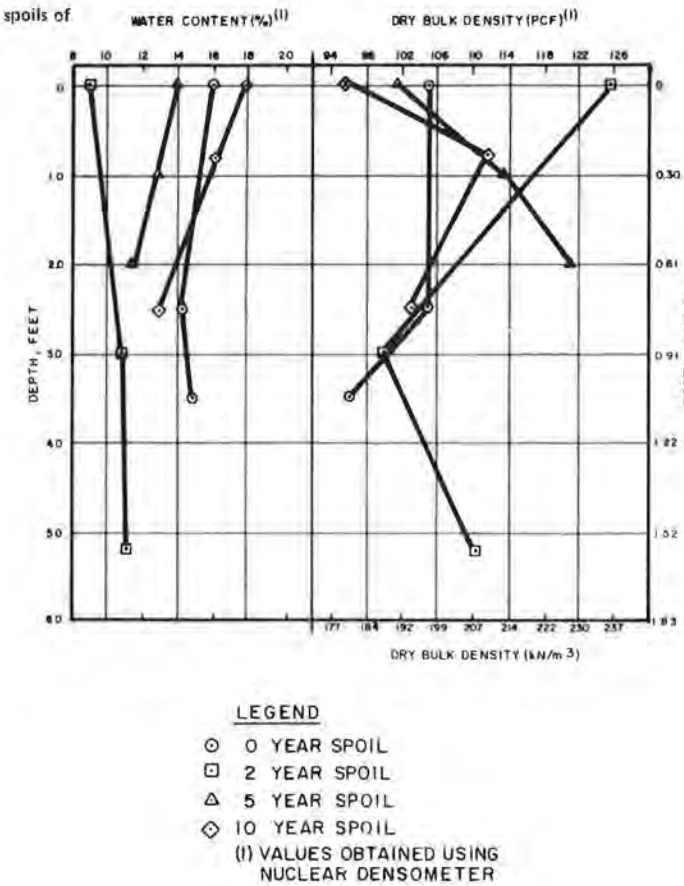
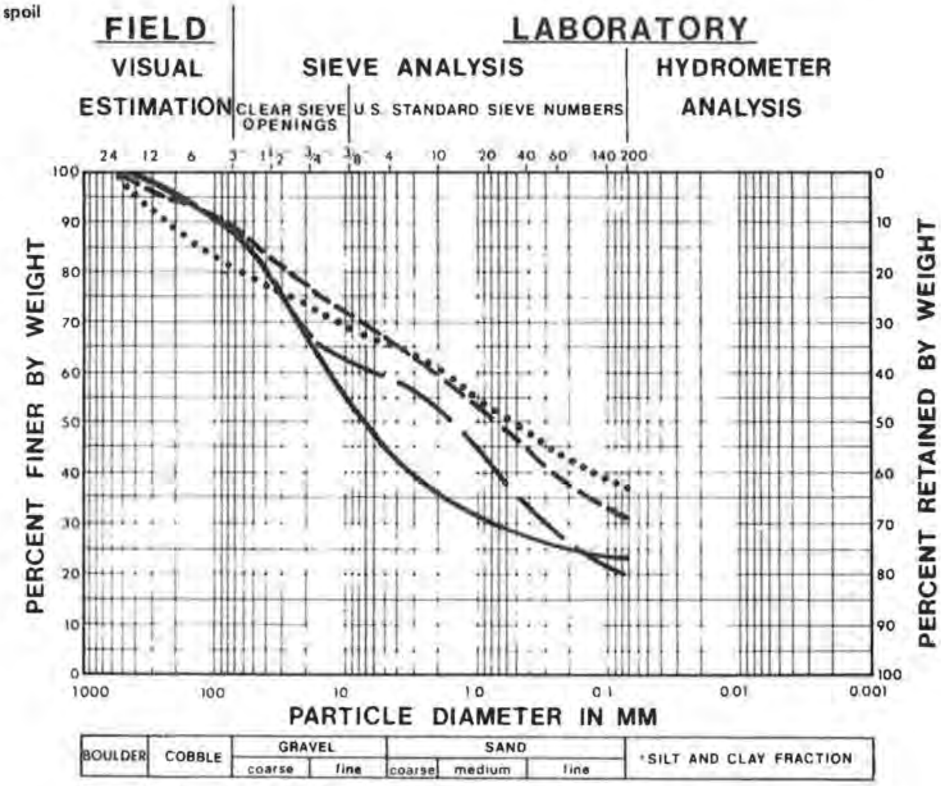


Figure 3. Grain-size distribution in a spoil pile.



SYMBOL	SPOIL AGE YEARS	DEPTH IN	DEPTH CM	COMPOSITION
——	0	36	91	15 % SANDSTONE ; 25 % SHALE ; 60 % MUDSTONE
— —	2	60	152	20% LIMESTONE ; 30% SHALE ; 60% MUDSTONE
----	5	36	91	10 % BLACK SHALE ; 30 % SHALE ; 60 % MUDSTONE
······	10	48	122	10 % SANDSTONE ; 20% SHALE ; 70 % MUDSTONE

NOTE: COMPOSITION IS BASED ON PARTICLE DIAMETERS > 5/64 INCH (2mm)

fragments, and disruption and weakening of bonds within the rock without a decrease in fragment size. The first mechanism is responsible for the production of dust, whereas the remaining two mechanisms provide suitable conditions for slaking to proceed during excavation, placement, and reclamation activities.

Excavation and placement techniques also affect the slaking process. Spoil placement in dragline operations consists of dumping in parallel ridges with successive lifts compacted only by the weight of the overlying spoil. The porous character of the spoil ridges tends to be open, accessible to air and water; therefore, slaking can be initiated after placement.

Spoil placement in haulback and mountaintop removal is usually accomplished by using large trucks. Spoil loading, transport, and dumping can cause crushing and abrasion of materials. In addition, placed spoils located in access areas sustain heavy truck traffic, which results in further crushing, grinding, and compaction. Therefore, the spoils that result from this type of placement are often denser and less susceptible to atmospheric agents below the surface.

Final grading to approximate the original contour often involves considerable reworking of the spoil and may have the greatest impact on slaking of the entire mining and reclamation program. This conclusion is based on inspection of graded and ungraded fresh spoil and comments from mining personnel. Ungraded fresh spoil appeared to have a coarser particle-size distribution than graded materials. In addition, rocks were observed to be broken, cracked, or crushed during actual grading. Finally, when topsoiling is conducted, machinery passes further accelerate material breakdown.

Effects of Slaking

Slaking of mine spoils produces a variety of associated effects. Some, such as accelerated erosion, may adversely affect local environmental quality. Slaking-related environmental effects observed in the field program included the following: pebble pavement formation on the spoil surface; development of a surface crust; variations in sheet, rill, and gully erosion; vegetation impacts; variations in slope stability; and changes in spoil hydrology.

The presence of a pebble pavement on the spoil surface was characteristic of all sites studied. The size of fragments ranged from about 0.5 to 50 cm but was commonly 1-8 cm. The pebble pavement usually consisted of fragments of slake-resistant lithologies such as limestone or strongly cemented sandstone. Pebble-pavement cover ranged from as little as 30 to virtually 100 percent areal cover. Total or near-total pebble cover appeared to assist erosion control, moisture conservation, and seed germination.

Spoils that had not been topsoiled commonly exhibited a crusted layer immediately beneath the pebble pavement. Crusts usually consisted of materials that had slaked to their inherent grain size and

were from 1 to 13 cm thick. The thickness and compaction of the crust are a function of the proportion of materials present that slake to constituent grain size, machinery traffic, and moisture content. Development of a surface crust appeared most pronounced where mudstone materials composed a large amount of the surface spoil. The presence of durable fragments appeared to partly offset compaction and crust formation, as did the establishment and continued growth of vegetation with vigorous root systems.

Sheet, rill, and gully erosion were observed to occur to varying degrees on all spoils. Spoils containing a high proportion of materials that slake to their inherent grain size exhibited the most severe erosion. Conversely, spoils with a high percentage of slake-resistant rocks were least affected by erosion. The presence of a durable pebble pavement was observed to be effective in controlling sheet erosion. Concentrated surface flow created numerous rills and occasional deep gullies, particularly on spoils that slake to their inherent grain size. Riprap that is composed of stable materials prevents down-cutting, whereas slakable riprap typically yields V-shaped ditches with active down-cutting. Off-site damage can occur as a result of slaking in the form of increased sediment loads and stream siltation, particularly when materials slake to their inherent grain size.

Slaking may produce both adverse and beneficial effects on vegetation. Adverse effects include dense crusting of the surface, which impedes seed germination, root proliferation, and moisture infiltration. Beneficial effects include the production of fine particles, which results in a suitable blend of coarse and fine materials to provide physical support to plants, allow easy root proliferation, and store sufficient amounts of plant-available water. It is also probable that slaking increases the levels of plant-available nutrients. Slaking involves a decrease in fragment size, which increases the surface area so that more material is exposed to chemical weathering and subsequent mobilization of plant nutrients.

Slaking can affect embankment stability. Major causes of embankment instability include excessive lift thickness, which results in high void ratios that can enhance the amount of future settlement; inadequate compaction; physical and chemical deterioration (primarily of argillaceous materials); expansive characteristics related to the mineralogy of the fill materials; inadequate drainage; and excessive side slopes near the angle of repose (5). In our study, slope stability was also found to be related to the mode of slaking. Little or no stability problem was found where slab or block slaking dominated. Where chip slaking was dominant, the mass appeared to be relatively stable. The chips form an interlocking matrix that is resistant to bulk movement. When slaking to inherent grain size was found to be the primary mode, stability problems were observed, as evidenced by slips, slides, and similar features. Degradation processes that control settlement and stability behavior may also be influenced by excavation and placement techniques. In general, methods that involve some mechanical crushing and compacting will most likely result in less deterioration following placement than those that involve disposal by simple dumping. Increased crushing and compaction increase bulk density, thereby reducing contact of the geologic materials with air and water. In conjunction with compaction, reclamation procedures that involve proper drainage and revegetation will minimize the influence of slaking on stability and settlement.

Spoil hydrology and its interaction with slaking were observed to be a complex process. Contrary to the belief that spoils are highly permeable and free draining and retain little water, spoils were found to be effective reservoirs. Perched water tables were found in several test pits within 1.5 m of the surface. Within spoil profiles, water moves by three means: capillary action, gravitational drainage, and vapor transport. Vapor transport could not be directly observed in the field, but evidence of capillary and gravitational movements was seen. The presence of a wetting front was noted in several test pits excavated immediately after a rain shower. Gravitational drainage was observed in large pores and voids in numerous profiles.

Precipitation in the Appalachian Basin is fairly well distributed throughout the year. Consequently, cyclic wetting and drying appear to be confined to approximately the upper 1.5 m of the spoil profile, and extreme desiccation is limited to the top 0.5 m. Below this zone, the moisture regime in mine spoils appears to be relatively stable. The depth of cyclic wetting and drying appears to coincide with the depth of observed slaking in many spoil profiles.

SUMMARY AND CONCLUSIONS

Slaking is a short-term, physical disintegration process that may occur in some geologic materials following excavation. The rate and degree of disintegration are directly related to material characteristics and local environmental conditions. Argillaceous materials with closely spaced bedding planes, principally shales and siltstones, may deteriorate rapidly to small chips when exposed. Soft, weakly consolidated argillaceous materials, principally mudstone, may experience almost complete disintegration to constituent particles shortly after exposure. Many sandstones are strongly cemented and composed of relatively inert particles that weather slowly in relation to slaking processes. Sandstone disintegration is therefore typically not a significant factor in slaking and is generally limited to the production of slabs or blocks. Argillaceous limestones with a significant number of planes of weakness may also be susceptible to disintegration through chip, slab, or block slaking, but solution-weathering phenomena that are predominant in more massive crystalline limestone are relatively slow and are not considered to be a part of the slaking process.

Although slaking is caused by many complex and interrelated variables, certain factors are important in determining the slaking potential of geologic materials; these factors include inherent particle size, mineralogy, rock fabric, spoil fragment size, and local hydrologic conditions. Inherently fine-grained sediments appear to be more susceptible to breakdown and at higher rates than coarse-grained sediments. In conjunction with particle-size effects, the mineralogical composition of argillaceous sediments affects the nature, degree, and rate of slaking. Small amounts of active clay minerals can influence material behavior because of interlayer water absorption and the type of ions adsorbed on exchange sites. Environmental effects associated with slaking include embankment instability, erosion and sedimentation, vegetation, and hydrologic impacts. However, these impacts can be alleviated through application of appropriate control measures that minimize the adverse effects of slaking.

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Statistical Analysis of Shale Durability Factors

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The results of a study performed to develop durability tests for shales for use in embankments and swamp fills are presented. Forty-three shale samples, representing all exposed shale units in Ontario, were collected. The samples were subjected to a variety of tests, some standard soundness tests, some recently developed shale durability tests, and some special tests devised by the author. The tests included freeze-thaw durability, Franklin slake test, wet-dry deterioration, modified "rate of slaking", water adsorption at controlled humidities, water absorption, abrasion, and dry bulk density. The results of the tests were statistically analyzed. The principal analytic method was multivariate stepwise regression analysis, but other statistics were also obtained. The stepwise regression analysis picks the testing procedures that have the greatest influence on the desired property and produces a multitest equation that can be used to determine that property. A series of seemingly unrelated tests can thus be used to determine the durability of shales. For instance, wet-dry deterioration is related to and can be calculated from water absorption, freeze-thaw, and abrasion results. The results obtained apply to the variety of shales found in southwestern Ontario. A larger data base may be necessary to extend the conclusions to all shales as a group.

Shale as a construction material has always been shunned. Its tendency to "slake", or turn to mud, is too well known in the construction industry. However, not all shale slakes equally, and some shale is rocklike--i.e., very little affected by weathering. Shale exists in many different forms, ranging from soft mudstone to indurated hard slate. The behavior of shale cannot be predicted from its composition, since the main constituent of any shale is clay. The amount of clay, the degree of natural compaction, cementation, and organic content all have a bearing on the physical properties of shale.

The purpose of the research described in this paper, supported by the Ontario Ministry of Transportation and Communications, was to develop durability tests for shale material and to classify Ontario shales as to their durability. Ontario shales are no less varied than shales found elsewhere. Some are highly susceptible to weathering, whereas others are rocklike in all aspects. All varieties of exposed shale across the province were collected--some from brick quarries, some from fresh road cuts, some from weathered road cuts. Although shales from weathered road cuts are not as desirable, they were included because no other examples of shales in that locality were available. The 43 different samples obtained represented all formational shale units found in the province. The formational units sampled and the number of samples representing the unit are given below. The total number of samples permits statistical treatment of data, which is the main purpose of this paper.

Shale Unit	No. of Samples
Upper Devonian, Kettle Point (black shale)	1
Middle Devonian, Hamilton Group (grey shale)	4
Mid-Low Silurian	
Clinton-Cataract Group	7
Decew dolomite	
Cabbot Head shale	
Rochester shale	
Billings shale	
Upper Ordovician	
Queenston formation (red shale)	10
Georgian Bay formation	11
Dundas shale	
Blue Mountain shale	
Meaford shale	
Whitby formation	3
Precambrian (shale and slate)	7
Rowe formation	
Gunflint formation	
Sibley shale	

CAUSES OF SHALE DETERIORATION

Shale and water interaction, with or without attendant freezing, can be considered as the main cause of shale deterioration. The actual processes involved in the breakdown are still not fully understood; however, it is known that shale-water interaction causes expansion of the shale. This expansion may be due to a number of factors: (a) "structuring" of water on clay surfaces, (b) osmotic pressure, and (c) frost action.

The structuring of water in clay-water mixtures causes the well-known thixotropic effect, in which the viscosity of the water increases as the water