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ENVIRONMENTAL EFFECTS OF SLAKING OF SURFACE MINE SPOILS EASTERN & CENTRAL UNITED STATES

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16. Abstracts The objective of this study was to investigate the environmental effects of slaking of surface mine spoils. To accomplish this, both field and laboratory programs were undertaken, supplemented by a thorough literature search. The field program consisted of drilling the highwall as well as test pitting in recent, two-, five-, and ten-year-old spoil piles at four active mining sites in the eastern bituminous coal fields. Pertinent observations were made and samples collected for laboratory analyses which consisted of several standard geotechnical, agronomic, and geochemical tests. Durability tests utilized included jar slake, cyclic wet-dry, rate of slake, and slake durability tests. Correlation between field and laboratory portions was made and results presented. The report is concluded with a discussion of the slaking process and associated environmental impacts, proposal of a preliminary classification system for use in premine planning, and presentation of management techniques to optimize the slaking process.		14.	
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FOREWORD

This report was prepared by D'Appolonia Consulting Engineers, Inc., under USBM Contract No. J0285024. The contract was initiated under the Mining Environmental Research Program and completed under the Minerals Environmental Technology Program. It was administered under the technical direction of Bureau of Mines with Mr. Michael J. Bailey acting as Technical Project Officer. Mr. William R. Case was the Contract Administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period October 1978 to November 1979. This report was submitted by the authors on September 30, 1980.

We wish to acknowledge the participation of the many D'Appolonia employees who aided with the various phases and tasks of the study. Special recognition is given to Mr. Kevin Roberts who provided the majority of literature review during the initial stages of the project.

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1.0 INTRODUCTION

Geologic materials may exhibit a wide range of behavioral responses following excavation and replacement in a new environment. Surface mine spoils, comprised of overburden and interburden materials moved during the mining of coal, may experience changes in physical integrity. This is a result of various mechanisms induced by variations in moisture and stress regimes or other environmental aspects of the materials. The physical disintegration of such geologic materials caused by fundamental changes in stress conditions or strength characteristics is referred to as slaking. The most distinctive aspect of the slaking process is a relatively rapid decrease in grain size or fragment size of the material.

A decrease in grain size caused by slaking may have a wide range of effects on the behavior of the bulk material, in this case the spoil pile. These effects will depend on the gross characteristics of the spoil pile (such as topography and degree of compaction), the durability of the materials, the proportion of slakable materials, and the dynamic changes in the surficial or internal moisture regimes.

Possible adverse effects of spoil slaking include decreases in slope stability, increases in settlement and surface erosion, and alterations of hydrologic regimes and vegetation. Because of these potential impacts upon reclaimed spoil piles, the Bureau of Mines contracted D'Appolonia Consulting Engineers, Inc. (D'Appolonia) to conduct a study on the environmental effects of the slaking phenomenon. The purpose of this investigation was to provide a "first look" at this phenomenon which may cause environmental problems associated with surface mine spoils. Because of its limited scope, it was not meant to be an exhaustive study considering all categories of mining activities or all geologic provinces. The intent was to assemble and evaluate sufficient data to determine if more extensive studies of slaking phenomena are warranted relative to their environmental effects on surface mine spoils. The major observations or conclusions from this study include the following:

- The rate and degree of disintegration of spoil material are directly related to material characteristics and local environmental conditions.
- The most active zone of slaking of spoil materials generally occurs within approximately one meter of ground surface.
- The major observed effect of slaking of spoil material is related to a decrease in particle size and resulting change in the hydrologic regime of the spoil pile.

- The significance of slaking in surface mine spoils appeared to be minimized by the mixing of slakable and nonslakable materials that usually occurs during typical spoiling operations.
- No gross environmental damages were observed to be related to slaking of surface mine spoils.

This report is based on an intensive field and laboratory program to define the slaking process, supplemented by review of geologic, engineering, environmental, and soil genesis literature. Chapter 2.0 of the report discusses the nature of various mechanisms believed to be responsible for the slaking process. Chapters 3.0 and 4.0 contain a summary of the distribution and characteristics of geologic materials and mining techniques associated with surface mining in the Appalachian and Illinois coal basins. Chapter 5.0 outlines the selection process used to delineate study sites, while Chapter 6.0 summarizes the various site conditions. Chapter 7.0 presents a summary of the published slaking classification systems and testing procedures and forms the foundation for the current laboratory program as outlined in Chapter 8.0. Chapter 9.0 details the results of this investigation. These results are presented in such a manner as to provide insight into the independence as well as compatibility of the field and laboratory programs. Chapter 10.0 presents the conclusions and recommendations of the study. They are presented as a summary of the slaking phenomenon, known or expected environmental effects of slaking, a premining classification system for assessing slake potential, and suggestions for managerial techniques to optimize the slaking impact.

2.0 SLAKING MECHANISMS

The problem of understanding the slaking process is underscored by the fact that there is no universally accepted definition of the term "slaking." The term has been vaguely defined as "the crumbling and disintegration of earth materials when exposed to air or moisture" (American Geological Institute, 1962) or as the "disintegration of rocks by water immersion" (Nettleton, 1974). Other more mechanistic definitions indicate that slaking is "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" (American Geological Institute, 1962), or that slaking is "the disintegration of mudstones upon alternate drying and wetting" (Morgenstern and Eigenbrod, 1974). A range of other generally similar definitions has been proposed in the technical literature.

There are two fundamental problems with the preceding definitions of slaking. The first is that the element of time or rate has not been considered. The second problem occurs because slaking is primarily a physical breakdown of materials. It should, therefore, be defined with respect to changing stress or strength conditions existing within the material rather than loosely described external environmental parameters. The proposed definition, based on short-term dynamic stress and strength conditions, is environmentally more comprehensive and yet more rate restrictive than the previously cited definitions. It also focuses attention on fundamental mechanisms involved in these short-term stress or strength changes. The proposed definition follows:

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

A rational approach for evaluating the impact of the slaking process on mine spoils requires consideration of the following factors:

- Mechanisms: The fundamental mechanisms responsible for material disintegration and their relationship to changes in the physical, chemical, or biological environment of the material.
- Materials: Intrinsic material properties which increase the potential for disintegration following a change in the material's environment.

- Time: The rates of material disintegration as related to material properties, specific mechanisms causing disintegration, and changes in the material's environment.

The mechanisms related to the slaking process (short-term disintegration) can be classified in terms of the type of stress and/or strength changes involved. These changes, caused by various physical, chemical, or biological conditions, are hereafter referred to as "slaking mechanisms" and are as follow:

- Confining stress relief
- Hydration force increase
- Double layer repulsion force increase
- Pore air compression
- Negative pore pressure increase
- Crystal growth force increase
- Bond or particle deterioration
- Surface energy reduction

Tables 2.1 and 2.2 summarize the relationship of each mechanism to various material and environmental parameters.

The various types of stress or strength changes that may occur can be related to physical or chemical mechanisms, to a combination of these, or to direct or indirect biological influences on these mechanisms. The technical literature on rock weathering processes has traditionally considered physical, chemical, and biological weathering processes independently (Ollier, 1969; Birkeland, 1974; Keller, 1957), but this categorization has caused some confusion leading some authors to favor the term "physico-chemical" (e.g., Gamble, 1971). The hydration mechanism may serve as an example; it may be considered a chemical mechanism related to combination with water, a physical mechanism due to the importance of the forces involved in water migration and development of layers of ordered water, and, in some cases, it may even be influenced by biological factors related to water migration such as plant transpiration.

2.1 CONFINING STRESS RELIEF

The physical basis for slaking due to stress relief is the development of elastic strains, unlike the other slaking mechanisms which can be related to the activity of water or the ions contained in solution, and is dependent on the following three major factors:

- Overconsolidation: Higher stresses, often related to burial under great depths of overburden or to tectonic forces, caused compression of the material and subsequent storage of recoverable strain energy (Franklin and Chandra, 1972; Krinitzsky and Kolb, 1969).

TABLE 2.1
SUMMARY OF SLAKING MECHANISMS: MATERIAL RELATIONSHIPS

SLAKING MECHANISM	BRIEF DESCRIPTION OF MECHANISM	GENERAL MATERIAL CHARACTERISTICS RELATED TO MECHANISM			REFERENCES
		STRUCTURE AND GRAIN SIZE	MINERALOGY	OTHER	
Confining Stress Relief	Release of recoverable strain energy upon unloading may lead to disruption of weak intergranular bonds or relaxation and opening of planes of weakness, allowing other mechanisms to become more active.	Argillaceous materials with dispersed structure(1) most susceptible; nonargillaceous materials generally not susceptible.	Clay mineralogy may be relatively unimportant; montmorillonite possibly more susceptible.(2)	High overconsolidation ratio favors mechanism; weak cementation or high fissility favor mechanism.	Franklin, 1970; Franklin and Chandra, 1972; Mitchell, 1976; Shamburger, et al., 1975
Hydration Force Increase	Development of ordered water layers around clay platelets and/or hydration of interlayer clay mineral positions upon wetting or wetting and drying exerts expansive forces which may disrupt structural integrity of material.	Argillaceous materials with flocculated structure most susceptible; nonargillaceous materials not susceptible except if clayey separations occur.	Important in montmorillonite; intermediate importance in illite; relatively unimportant in kaolinite.	Initially low water content and/or void ratio favor mechanism.	Chenevert, 1970b; Chorley, 1969; Moriwaki, 1974; Ollier, 1969; Shamburger, et al., 1975.
Double Layer Repulsion Force Increase	Repulsive forces between clay platelets related to ionic charge distributions close to surface and in pore fluid may disrupt structure.	Argillaceous materials with dispersed structure most susceptible; nonargillaceous materials not susceptible.	Montmorillonite most susceptible; illite is intermediate; kaolinite relatively unsusceptible.	Percentage of exchangeable sodium (ESP) on clays and pore fluid chemistry are of outstanding importance; ESP >15 to 30 very susceptible.	Franklin and Chandra, 1972; Moriwaki, 1974; Shamburger, et al., 1975; Taylor, 1974; Taylor and Spears, 1970.
Pore Air Compression	Pore air compression during rapid rewetting following significant desiccation may disrupt structure.	Argillaceous materials with flocculated structure most susceptible; nonargillaceous materials relatively unsusceptible.	Kaolinitic and nonswelling clay minerals most susceptible; montmorillonite relatively unsusceptible; illite is intermediate.	High degree of desiccation necessary, high proportion of micropores and strong surface adsorption favor mechanism.	Badger, et al., 1956; Moriwaki, 1974; Taylor and Spears, 1970.
Negative Pore Pressure Increase	Development of negative pore pressures (suction stresses) upon desiccation may cause tensile failure of structure.	Only argillaceous materials are susceptible; flocculated structures may be more susceptible than dispersed structures.(2)	Montmorillonite may be most susceptible.(2)	Fissile materials may be more susceptible than massive materials.(2)	Chenevert, 1970a; Kennard, et al., 1967
Crystal Growth Force Increase (Mineral Alteration and/or Ice Formation)	Increased volume resulting from crystal growth exerts expansive forces and may disrupt structure.	Not directly related although silty and very fine-grained sandstone sediments may be more susceptible due to porosity and permeability characteristics.	Pyrite-bearing sediments and some calcium carbonate-bearing sediments may be most susceptible to mineral alteration; feldspars also susceptible to gradual alteration.	High content of very fine micropores in argillaceous materials decreases ice formation; fissile materials may crack along planes of weakness.	Dunn and Hudec, 1965, 1972; Hudec and Dunn, 1967; Ollier, 1969; Penner, et al., 1970; Quigley, et al., 1973; Shamburger, et al., 1975
Bond or Particle Deterioration	Cement or particle deterioration, chiefly by dissolution, may weaken structural strength until existing stresses cause failure.	Generally not directly related, although porosity and permeability characteristics of sandstones may favor cement dissolution.	Chlorite, calcium carbonate, pyrite, and dolomite are most susceptible to deterioration; gypsum and siderite have variable susceptibility; other minerals and cements generally stable or are altered slowly.	Low permeability may decrease deterioration.	Noble, 1977; Shamburger, et al., 1975; Taylor, 1973

See footnotes at end of table.

TABLE 2.1
(Continued)

SLAKING MECHANISM	BRIEF DESCRIPTION OF MECHANISM	GENERAL MATERIAL CHARACTERISTICS RELATED TO MECHANISM			REFERENCES
		STRUCTURE AND GRAIN SIZE	MINERALOGY	OTHER	
Surface Energy Reduction	Strength reduction results from wetting of dry or partly dry surfaces; may soften material sufficiently to increase probability of disintegration caused by other types of stress.	Not directly related, although argillaceous materials possibly more susceptible.	No direct relationship evident, although larger surface area of montmorillonite may make it more susceptible.(2)	Low initial water content favors surface energy reduction.	Franklin, 1970; Parate, 1973; Van Eeckhout, 1976

(1) The term "structure" represents internal structural fabric of the material, not large-scale geologic structures.

(2) Relationship not substantiated in technical literature on slaking.

TABLE 2.2
SUMMARY OF SLAKING MECHANISMS:
ENVIRONMENTAL AND RATE RELATIONSHIPS (1)

SLAKING MECHANISM	GENERAL ENVIRONMENTAL CHARACTERISTICS RELATED TO MECHANISM			RELATIVE RATE OF SLAKING (2)
	WETTING AND/OR DRYING CYCLE	PORE FLUID CHEMISTRY	OTHER	
Confining Stress Relief	Generally unimportant.	Generally unimportant, though may be related to structure (dispersed versus flocculated).	NA (3)	Rapid; slaking generally incomplete due to stress relief alone.
Hydration Force Increase	Wetting of initially dry material or alternating drying and rewetting favor mechanism.	Decreased electrolyte concentration may favor mechanism; low valence ions (sodium) may favor mechanism.	NA	Moderate to rapid for materials with low void ratio and water content; repeated drying and wetting may result in moderate rates.
Double Layer Repulsion Force Increase	Alternating wetting and drying relatively unimportant unless pore fluid chemistry changes.	Very low electrolyte concentration and/or high proportion of dissolved sodium favor mechanism.	NA	Very rapid for low water content montmorillonite with dispersive structure (high ESP); rate dependent on ESP, mineralogy and pore fluid chemistry.
Pore Air Compression	High degree of desiccation followed by rapid rewetting necessary; relatively stable moisture regime likely at depth decreases susceptibility.	Relatively unimportant for most natural waters.	Surface exposure and slope aspect influence desiccation; south- and west-facing slopes more susceptible in United States.	Rapid to very rapid for extremely desiccated materials following rewetting.
Negative Pore Pressure Increase	Relatively rapid or long-term desiccation necessary; stable moisture regime decreases susceptibility.	Probably not important for most natural waters.	Surface exposure and slope aspect influence desiccation; south- and west-facing slopes more susceptible in United States.	Probably moderate, continuing through drying cycles.
Crystal Growth Force Increase (Mineral Alteration and/or Ice Formation)	Mineral alteration favored by ion transport in pore fluids; precipitation favored by desiccation.	Oxygenated water or acidic water necessary for alteration of pyrite or calcite, respectively; decreased solute content increases frost formation.	Frequency of freezing-thawing cycles increased on south- and west-facing slopes in United States; pyrite alteration favored by presence of autotrophic bacteria.	Mineral alteration typically slow; ice formation cracking typically rapid but does not cause complete disintegration.
Bond or Particle Deterioration	Continuous leaching favors deterioration.	Oxygenated, acidic waters favor most types of deterioration.	Deterioration may be insignificant in unsaturated zone with little water movement.	Typically slow to very slow, except if strongly acidic waters leaching calcium carbonate cemented sandstones.
Surface Energy Reduction	Wetting of initially dry materials reduces surface energy; drying increases surface energy.	Probably not important for most natural waters.	NA	Moderate to rapid strength reduction upon wetting of initially dry materials may not be sufficient to cause slaking in most cases.

(1) References related to each mechanism are cited in Table 2.1.

(2) Relative rates assuming material and environmental conditions are generally favorable.

(3) NA - Data indicating other important relationships not available in technical literature on slaking.

- Clay content and structural fabric of the material: Argillaceous materials can store considerably more recoverable strain energy than other types of sedimentary rock due to their more compressible nature. The storage of this energy is not only a function of the mineralogy but also the direction of stress.
- Nature of interparticle bonds or planes of weakness: For disintegration to occur, the recoverable strain energy must be sufficient to break interparticle bonds or break the material along preexisting planes of weakness. Compaction shales with minimal bond strength are the most likely to fail. Well-cemented materials may not fail unless additional forces (slaking mechanisms) become active or there is a deterioration of the cement (Shamburger, et al., 1975).

Therefore, slaking due to the release of confining stresses is likely to be important only in uncemented or very weakly cemented compaction shales. Disintegration is likely to be rapid, being initiated within minutes after stress relief. Stress relief, however, may not act as a totally independent slaking mechanism. Other slaking mechanisms can be more significant and stress relief may only be a contributing force leading to slaking (Kennard, et al., 1967; Franklin and Chandra, 1972).

2.2 HYDRATION FORCE INCREASE

An increase in forces due to hydration in geologic materials results from either wetting or alternating wetting and drying cycles. This slaking mechanism may occur in conjunction with other slaking mechanisms related to wetting and drying.

The relationship between hydration and material disintegration may be related to the development of internal expansive forces (Ollier, 1969), reduction of van der Waals attractive forces (Shamburger, et al., 1975), or excess free energy evolved when hydrogen bonds are formed between originally adsorbed water molecules and newly adsorbed ones around clay particles (Nakano, 1967). An additional hypothesis regarding the relationship between hydration and slaking has been proposed by Murayama and Yagi (1966); they indicated that structural failure of rock materials may be caused by localized unequal expansion of minerals or by non-uniform distribution of adsorbed water. Other investigators including Chenevert (1970a and b), Gamble (1971), and Balasubramonian (1972), have indicated the importance of hydration forces in slaking processes or geologic material alteration.

The relationship between hydration forces and intrinsic material properties is summarized as follows:

- Hydration is least significant in kaolinite where the crystal lattice is closely bonded and allows little further reaction to take place. It is relatively insignificant in illitic minerals, although hydration does occur to some extent. Hydration is most significant in the third common clay mineral, montmorillonite, where the crystal lattice is relatively open allowing the entry of water and great expansion of the lattice (Chorley, 1969). The conclusions of Reidenouer, Geiger, and Howe (1974, 1976) suggest that large percentages of illite may have approximately the same effect as relatively small percentages of montmorillonite.
- Hydration is more significant for materials with an initially low water content and/or low void ratio (Moriwaki, 1974).
- Hydration is more significant for materials with a flocculated structure than for materials with a dispersed structure (Moriwaki, 1974), but overall expansion of the latter may be more significant due to the operation of additional slaking mechanisms (Taylor and Spears, 1970; Taylor, 1974). The tendency for hydration expansion may be greater if the pore fluid has a very low electrolyte concentration (Mitchell, 1976) or a greater relative concentration of low valence ions, such as sodium (Olson and Mesri, 1970).
- Hydration of argillaceous layers along bedding planes in some sandstones may lead to rapid disintegration of these materials (Heald, et al., 1974); otherwise, hydration is not likely to cause slaking of nonargillaceous materials.
- The rate of hydration force increase cannot be identified for a general case; it is primarily dependent on the permeability and porosity of the material, and on environmental moisture conditions, since these control the entry, retention, and mobility of pore fluids in the material (Franklin and Chandra, 1972).

Increases in hydration forces are likely to be initiated very shortly after wetting and the mechanism is likely to be operative throughout the disintegration process or until the layers of ordered water exceed a thickness of 20 angstroms (Moriwaki, 1974). Hydration forces are not likely to be solely responsible for rapid slaking following stress relief and a change in environmental conditions. An

exception may be in argillaceous materials with low water contents, low void ratios, a significant content of montmorillonite, or sufficient fissility and planes of weakness to permit entry of water. Other slaking mechanisms closely related to wetting and drying may be favored by similar material characteristics and, therefore, may act in conjunction with increases in hydration forces or in alternating cycles.

2.3 DOUBLE LAYER REPULSION FORCE INCREASE

Double layer repulsion forces in a clay-water system result from the relationship between exchangeable ions close to a clay particle, considered to be the first layer, and the outer solution of free electrolyte ions which comprise the second layer. This mechanism has also been referred to as the dispersion or ion exchange mechanism. According to the Gouy-Chapman theory (Mitchell, 1976), these layers are diffuse and the repulsive forces between clay particles are related to the following properties of the double layer:

- Ionic concentrations in the double layer (lower concentrations cause increased repulsive forces).
- Valence of the ions (lower valence causes increased repulsive forces).
- Other factors, such as dielectric constant of the liquid and system temperature, probably have little significant effect in natural systems.

The importance of the double layer repulsion force mechanism, or dispersion, may be significant depending on the mineralogy and the double layer properties cited above. Franklin and Chandra (1972) considered this mechanism as a possible dominant cause of slaking. The importance of this mechanism has also been emphasized in rock disintegration and slaking studies by Badger, Cummings, and Whitmore (1956); Berkovitch, Manackerman, and Potter (1959); Taylor and Spears (1970); and Taylor (1974, 1975).

The relationship between double layer repulsion forces and mineralogical properties is analogous to that for hydration forces. The clay mineral most susceptible to increased repulsion forces is montmorillonite. Illite and kaolinite are significantly less susceptible (Shamburger, et al., 1975).

Increases in double layer repulsion forces are likely to be a significant slaking mechanism in argillaceous materials with high percentages of exchangeable sodium when they are leached with waters with moderately low electrolyte concentrations (typical in most natural waters). Weakly cemented montmorillonitic materials are the most susceptible.

This slaking mechanism may operate very rapidly; a dried mudstone from England with 70 percent montmorillonite literally exploded upon

wetting (Taylor, 1974). If intergranular cements are very strong and material permeabilities are very low, repulsion forces may be most significant along planes of weakness and cause only partial disintegration. Materials with calcium and/or magnesium as the predominant exchangeable cations are unlikely to be susceptible to slaking by this mechanism.

2.4 PORE AIR COMPRESSION

The slaking of geologic materials by pore air compression has been described by Taylor and Spears (1970) as follows:

- During a drying cycle, the bulk of the voids in a material may become filled with air, particularly if desiccation is extreme.
- Upon rapid wetting, the pore air may become pressurized by the capillary pressures developed in the outer pores.
- These internal stresses may cause failure (slaking) of the material along the weakest planes. The increased surface area is then exposed to a further sequence of events.

Although Franklin (1970), Taylor and Spears (1970), and Taylor (1974) referred to this mechanism as "air breakage," this term should be avoided so as not to confuse this mechanism with the "air slaking" or confining stress relief mechanisms referred to by Moriwaki (1974).

The importance of the pore air compression mechanism was recognized in early research on shale disintegration by Badger, Cummings, and Whitmore (1956). In a follow-up study, Berkovitch, Manackerman, and Potter (1959) indicated that pore air compression is likely to be a significant slaking mechanism only in "mechanically weak" materials.

Moriwaki (1974) conducted one of the most exhaustive studies of the relationship between the pore air compression mechanism and material properties. His materials consisted of prepared mixtures of clay and nonclay minerals with controlled exchangeable cation distributions. The following conclusions, which may have significance in natural systems, were reached:

- Pore air compression can be a significant slaking mechanism for materials composed primarily of "nonswelling" clay minerals, principally kaolinite, and, to a lesser degree, illite. Montmorillonitic materials are least susceptible to pore air compression slaking. Montmorillonite and, to a lesser degree, illite may resist disintegration by pore air compression because they can accommodate a significantly greater portion of the generated stresses by bending, swelling, and particle

rearrangement processes which are not very significant for comparatively inert kaolinite.

- Pore air compression is most significant for flocculated structures and it may not be significant at all for dispersed structures, even if the primary clay mineral is kaolinite. This may be related to the faster rate of pore fluid absorption in flocculated materials and the consequent increase in air pressurization. Also, rearrangement of clay particles is significantly easier in dispersed structures, preventing an excessive build-up in pore pressures.
- Pore air compression is favored by small pore radii. This is why many sandstones, with significantly greater percentages of macropores than argillaceous rocks, are unlikely to slake by this mechanism. The much smaller pore radii in argillaceous materials also mean that the total surface area of the pore walls will be much greater, assuming roughly equal total porosity, and the surface absorption of pore fluids causing entrapped air compression will be much stronger.
- The absorption of pore fluids should be relatively rapid to effect significant pore air compression. This factor tends to be counteracted by the importance of small pore radii cited above. Therefore, to achieve rapid absorption in argillaceous materials, it is necessary to have a low degree of saturation. Materials must be significantly desiccated for pore air compression to be important. This mechanism, therefore, may be somewhat more significant for materials on south- and west-facing slopes than for those on north- and east-facing slopes, due to the greater absorption of solar energy and resultant evaporative drying effects.

Slaking caused by the pore air compression mechanism is rapid because the pore air pressures may dissipate if the material does not fail rapidly. The process is unlikely to be active below the ground surface because extreme desiccation and rapid fluctuations in moisture conditions are unlikely to occur. It has been reported that approximately 80 to 90 percent of the total disintegration of a shale susceptible to pore air compression occurs within five minutes of rewetting (Badger, et al., 1956).

2.5 NEGATIVE PORE PRESSURE INCREASE

The disintegration of geologic materials due to an increase in negative pore pressure is unlike the three previously discussed slaking mechanisms (Sections 2.2 to 2.4) in that it occurs during a drying cycle rather than a wetting cycle. Negative pore pressures exist where the free energy of pore water is less than that of water under atmospheric pressure (Mitchell, 1976); that is, when the pore pressure in a material is less than atmospheric pressure, it is considered to be negative. The adsorbed or ordered water close to clay mineral surfaces has less free energy than free water and, thus, exerts negative pore pressures, sometimes referred to as "adsorptive" pore pressures (Chenevert, 1970a). Water exerting negative pore pressures exists in a state of tension and exerts stresses on the material's structure. Highly argillaceous, compacted materials with a large proportion of very fine micropores may contain a significant percentage of their pore water in an adsorbed, ordered state and, therefore, may exhibit significant negative pore pressures. The loss of free water during desiccation of such materials causes an increase in the negative pore pressures (internal suction stresses) and may lead to a tensile failure, or slaking of the materials (Kennard, et al., 1967). The wetting and drying cycles occurring at the ground surface can be considered to be "pressure cycles" due to the negative pore pressures generated by desiccation (Grice, 1968).

Kennard, et al. (1967) concluded that negative pore pressures are unlikely to cause disintegration into particles smaller than fine gravel or coarse sand. However, these fragments are then more susceptible to attack by other mechanisms due to increased surface area.

The relationships between certain material properties and negative pore pressure development have not been investigated, but it is believed that the following are probable:

- Negative pore pressures are very unlikely to be significant in nonargillaceous materials.
- Montmorillonitic materials, because of their significantly greater surface area and proportionally greater percentages of adsorbed water, are likely to develop greater negative pore pressures than illitic or kaolinitic materials upon desiccation. The tensile stress caused by negative pore pressures may also be increased in these materials by internal structural stress resulting from shrinkage upon water loss.
- The increase in negative pore pressures may be more significant for flocculated structures than for dispersed structures because they are typically more permeable (permitting more rapid desiccation).

- Fissile materials are more likely to disintegrate as a result of negative pore pressure development than massive materials, due to more rapid desiccation.

As described above, slaking in certain materials due to negative pore pressure development is likely to continue throughout the drying cycle. In the eastern and central United States, the negative pore pressure mechanism is expected to be insignificant below the surface of the spoil pile due to relatively stable moisture conditions.

2.6 CRYSTAL GROWTH FORCE INCREASE

Stresses may be developed within geologic materials as a result of volume changes due to crystal growth. Ollier (1969) reviewed three general types of crystal growth that may lead to physical disintegration of materials including:

- Crystal growth from solution, also referred to as salt weathering.
- Chemical alteration of preexisting minerals to new minerals with increased volume. The preexisting minerals may occur within the cement matrix as discrete particles or in seams.
- Formation of ice in voids or in open cracks.

Long-term migration of pore fluids to the surface followed by evaporation may lead to significant crystallization stresses (salt weathering), but this process is only significant in arid or arctic areas (Chorley, 1969; Ollier, 1969). Aside from the lack of adequate environmental conditions in the eastern and central United States, there are not likely to be sufficient concentrations of salts in the pore fluids of spoil materials for crystal growth from solution to be a significant cause of slaking.

The chemical alteration of preexisting minerals leading to a net crystal growth may be more significant in certain cases. The growth of crystals generally results from hydration and oxidation of minerals which were stable in their previous in situ condition. The most important types of mineral alteration, excluding clay mineral hydration (discussed in Section 2.2), generally involve the oxidation and hydration of pyrite or the conversion of calcite to gypsum. A number of researchers have emphasized the importance of these processes in causing expansion and potential failure of geologic materials (e.g., Gamble, 1971; Penner, et al., 1970; Quigley, et al., 1973; and Shamburger, et al., 1975). Residual weathering of certain constituent minerals (for example, feldspars) is comparatively slow and, thus, cannot be considered important in slaking.

Several important chemical alterations and their associated volume increases include the following:

- Pyrite (FeS_2) to melanterite ($2\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$); 536 percent increase in volume (Shamburger, et al., 1975).
- Pyrite to jarosite ($\text{KFe}_3[\text{SO}_4]_2[\text{OH}]_6$); 115 percent increase in volume (Penner, et al., 1970).
- Calcite (CaCO_3) to gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$); 60 percent increase in volume (Shamburger, et al., 1975).

It is obvious from a consideration of the mineral alterations cited above that very specific material properties are responsible. Pyrite must be present in the material for either of the first two types of alterations to occur and calcite must be present for the third type to occur. The conversion of calcite to gypsum requires a source of sulfate; this is typically derived from the oxidation of a sulfide mineral, most often pyrite. Materials not containing pyrite or other sulfide minerals are, therefore, unlikely to slake by these types of crystallization stresses. Taylor and Spears (1970) hypothesized that because the unstable minerals normally constitute only a small fraction of the total mineralogy, the average rate of chemical change is slow. Therefore, the rate of slaking from this process is considerably slower than for some of the other mechanisms discussed.

The third general type of crystal growth, ice formation, has not been universally accepted as belonging to the set of slaking mechanisms and processes. The confusion may be a direct result of the problem with the definition of slaking. Those who consider slaking to be a process resulting from water immersion might not accept ice formation as a possible slaking mechanism, a concept continued by Morgenstern and Eigenbrod (1974). Those who adhere to a definition proposing disintegration due to stress development or strength deterioration following environmental change would accept ice formation as a potential slaking mechanism (e.g., Franklin, 1970).

The increase in volume of water upon freezing is approximately nine percent, but the nature of the stresses generated is not only a result of the net volume increase but also the rate of volume increase. While certain other mineral alterations are often slow processes, water may be super-cooled to as low as -5 degrees Celsius before freezing occurs very rapidly. The outer surface may suddenly freeze, thus closing the system, even in cracks and pores; the resulting pressures may be as high as 30,000 pounds per square inch (4,350 kN/square meter) at -22 degrees Celsius (Ollier, 1969).

Dunn and Hudec (1965, 1972) found that the adsorbed, ordered water associated with clay mineral surfaces, micropores, and capillarity is essentially nonfreezable, and, therefore, cannot exert stresses directly

related to crystal growth. Thus, ice formation is probably more operative in the larger pores that occur in silty or fine sandy materials than it is in the very small micropores of shales. It may be a significant slaking mechanism along preexisting planes of weakness which had been slightly opened by stress relief or other mechanisms. Ice formation is probably responsible only for disintegration of materials into relatively coarse fragments which are then susceptible to attack by other slaking mechanisms.

2.7 BOND OR PARTICLE DETERIORATION

The slaking of geologic materials by bond or particle deterioration is unlike other mechanisms previously discussed in that changes in stress conditions are not required for disintegration to occur. The physical and chemical changes in sedimentary materials following deposition, which lead to consolidation and increased strength, are generally referred to as diagenesis, and the resulting bonds are sometimes referred to as diagenetic bonds (Bjerrum, 1967). The deterioration of these bonds or of the particles comprising the material may weaken the internal structure until the existing stresses are sufficient to cause disintegration.

The diagenetic processes involved in consolidation typically include compaction, recrystallization, and cementation. Compaction processes are most characteristic of argillaceous materials, and the resulting materials are generally considered to be uncemented or unbonded (Underwood, 1967). These materials may experience deterioration of component particles, but they are most likely to disintegrate by other mechanisms, such as hydration or double layer repulsion. Recrystallization processes in argillaceous materials generally involve what is referred to by Underwood (1967) as "clay bonding." In other sedimentary rocks, recrystallization generally involves dissolution of original minerals and precipitation of other minerals as cements or discrete particles. The deterioration of "clay bonding" is unlikely to result from clay mineral dissolution; therefore, slaking will more typically be caused by other mechanisms.

The most important influences on cement deterioration are the type of cement, the degree of cementation, and the stability of the cement in the new environment of the material following stress relief. The major mineral phases which act as cements in sedimentary materials include quartz, silica (amorphous), calcium carbonate, iron oxides and hydroxides, siderite, dolomite, gypsum, pyrite, and organic compounds (Blatt, et al., 1972; Shamburger, et al., 1975). Various clay minerals, including illite and sericite, may also act as cements. The degree of cementation is related primarily to the permeability and porosity of the original sediments, to the duration of the cementation process, and the existence of overburden pressures favoring increased diagenesis. The permeability and porosity characteristics of sandstones facilitate the transport of ions in solution and the precipitation of cements to a significantly greater degree than in associated argillaceous materials.

A change in the stability of a particular cement following stress relief can usually be attributed to a change in the oxidation potential (related to the presence of oxygen) and/or the acidity or alkalinity of the material's environment. Following stress relief, a material is typically in an oxidizing environment. Reducing environments may occur deep in a spoil pile if the materials become saturated with groundwater lacking oxygen. In eastern and central United States, most materials will be subjected to a slightly acidic environment following stress relief. Neutral and alkaline materials near the surface gradually become more acidic due to leaching by rainfall and the action of organic acids from vegetation. Strongly acidic conditions may be generated locally due to the oxidation of certain sulfide minerals, if present.

Silica, iron oxide and hydroxide, illite, sericite, and to a lesser extent carbonaceous cements are stable in typical spoil pile environments. Clastic particles comprising the materials are also typically stable or are chemically altered to new minerals so slowly compared with other slaking mechanisms that this type of deterioration is not considered to be a cause of slaking. Chlorite, although very susceptible to acid attack, is rarely a predominant clay mineral in argillaceous materials. Bond or particle deterioration, therefore, is not often the cause of slaking. The slaking of calcareous sandstones by bond dissolution is likely to be a gradual process compared with the disintegration of certain argillaceous materials caused by other mechanisms.

2.8 SURFACE ENERGY REDUCTION

The reduction of surface energy upon wetting is a fundamental physical process which directly decreases the strength of a material. The absorption of gases or vapor on the internal surfaces of geologic materials diminishes the surface energy (Parate, 1973), and decreases the tensile stresses necessary to cause cracking (Van Eeckhout, 1976).

Franklin (1970) stated that the strength reduction on wetting alone is rarely sufficient to cause complete disruption of nonargillaceous materials. He also indicated that the reduction in strength from a completely dry to a completely saturated condition is commonly as great as 50 percent and that the extent of weakening is a function of the initial and final moisture contents of the material. Precise relationships between strength loss in natural materials and change in moisture content may be very complex due to the potential importance of ions in the pore fluids (Franklin, 1970). A second strength reduction process upon wetting, although it may not be directly related to surface energy reduction, is the relief of capillary tension at grain contacts and at tips of cracks as saturation increases (Franklin, 1970; Van Eeckhout and Peng, 1975).

The strength reduction upon wetting is likely to be at least partially responsible for the softening of certain argillaceous materials. Since many argillaceous materials are saturated or at least partially saturated in their in situ condition, these types of strength reduction

are probably not solely responsible for slaking in most cases. Strength reduction of argillaceous materials upon saturation will increase the likelihood of disintegration.

3.0 GEOLOGY OF COAL-BEARING UNITS OF APPALACHIAN AND ILLINOIS BASINS

By definition, slaking is a process during which geologic materials disintegrate. It follows, therefore, that the various properties of these materials play an integral part in the slaking phenomenon. These properties can be broadly categorized as either stratigraphic or structural. Stratigraphy includes the composition, genesis, sequence, and correlation of various rock strata, whereas structure is related to megascopic and microscopic features usually associated with diagenetic processes.

Two component parts of stratigraphy which can be directly correlated to the durability of a given material are lithology and mineralogy. Correlation of these parameters may allow the development of a regional zonation of slaking potential. Lithology is the physical character or type of rock, such as shale, siltstone, and sandstone. This, along with the thickness and character of bedding, can generally be related to durability; i.e., argillaceous materials have a higher slake potential than arenaceous materials.

Mineralogy also plays an important part in an assessment of durability. It relates not only to the composition of individual grains, but also to types of cementing agents. The composition and amount of clay minerals present (e.g., kaolinite, montmorillonite, illite, and chlorite) are related to length of transport, source material, and degree of alteration undergone during and subsequent to deposition. As discussed in Chapter 2.0, mineralogy can have a direct impact upon the degree to which various slaking mechanisms affect the durability of geologic materials. Of primary importance are various clay minerals because of their interlayer water-absorption characteristics and the type of ions adsorbed on exchange sites. Also, mineralogical properties of interparticle cementing agents, including bond strength and chemical activity, may influence slakeability.

Both megascopic and microscopic structural characteristics can affect the slakeability of overburden materials. They relate to various planes of weakness which influence durability by controlling the entry and mobility of pore fluids, residual stresses, and fragment size during excavation.

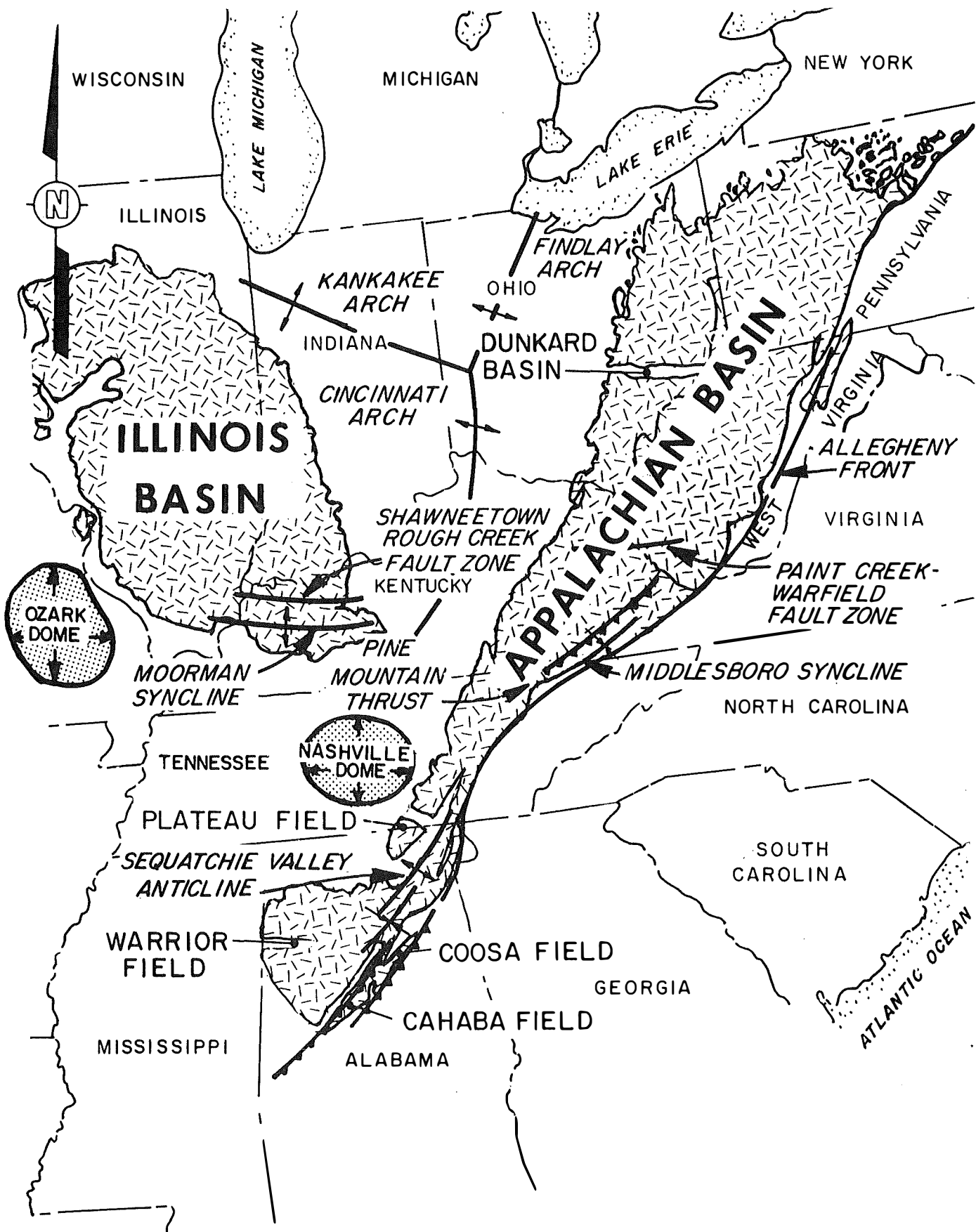
Megascopic geologic structures, especially faults and joints, relate to zones of weakness created during earth movements in the geologic past. Also, the presence of anticlinal and synclinal structures can provide insight into stress regimes which may influence rock properties during and subsequent to excavation. Microscopic structures (rock fabric) describe spatial relationships of individual grains and among grains, and are mainly a function of the depositional environment, mineralogy, and diagenetic stress conditions. Fabric can directly affect the integrity of the rock by influencing the physical interaction between individual grains and their reaction to stresses imposed during

the slaking process. This is especially true where a strongly anisotropic fabric is present, such as in sediments with dispersed clays.

3.1 GEOLOGY OF THE APPALACHIAN AND ILLINOIS BASINS

The Appalachian and Illinois basins are the two major coal-producing areas in the eastern and central United States (Figure 3-1). Although geological parameters vary within these regions, the following generalizations can be observed:

- All coal-bearing strata that are presently economically viable are Paleozoic in age and were deposited during the Pennsylvanian and Permian periods.
- Conditions within these basins varied widely in both time and space (McKee and Crosby, 1975a and b). These variations in sediment type were correlated to episodic activity in mountain building and major fluctuations in sea level. This type of depositional mode was cyclic and the resulting vertical repetition of lithological sequences is commonly referred to as cyclothems (Wanless, 1975a and b). The initiation cycle was associated with an influx of detrital sediments from adjacent elevated areas, producing typical deltaic, stream channel, and floodplain deposits. With a decrease in material, sedimentation slowed and marshy or swampy conditions prevailed. The organic matter within these zones, later to be converted to coal, was covered by marine sediments deposited in a transgressing sea. During the subsequent marine regression, intercalated muds and sands were deposited. Although this cyclic depositional history describes a "typical" cyclothem, certain portions may be absent in some areas.
- Argillaceous materials generally become more frequent as sediments decrease in age and increase in distance from the sediment source (McKee and Crosby, 1975a and b).
- The clay mineralogy in the argillaceous units remains fairly constant (Lessing and Thompson, 1973; O'Neil, et al., 1965; Harrison and Murray, 1964). This is believed to be true because of the similarity in regional depositional environments and source materials, as well as length of time available for diagenetic alteration of various clays to illite. The reported analyses of



APPALACHIAN AND ILLINOIS BASINS WITH ASSOCIATED MAJOR STRUCTURAL FEATURES

clays associated with coal-bearing strata demonstrate a general predominance of illite with minor amounts of chlorite, montmorillonite, and kaolinite.

A general lack of information related to regional variations in other geological parameters, such as adsorbed ions, rock fabric, and cementing agents, requires that these parameters be evaluated on a site-specific basis.

3.1.1 Appalachian Basin

The Appalachian Basin occupies an extensive area, ranging from western Pennsylvania to northern Alabama, and encompasses sections of Ohio, West Virginia, eastern Kentucky, Tennessee, Maryland, and Virginia. The latter three states are not incorporated in this study due to the relatively small geographic areas in which strippable coal occurs.

The entire Appalachian Basin lies within the boundaries of the Appalachian Plateaus physiographic province as described by Fenneman (1938). This plateau is highly dissected and exhibits moderate to strong relief throughout most of its area. This geomorphology has contributed to the fact that the prevalent mining method has been conventional contour mining. This method has been modified, due to legal and environmental pressures, to include haulback or partial haulback methods. With the exception of Pennsylvania, which contains 20 surface minable seams, states within the Appalachian Basin have between 40 and 46 (USDI-BM, 1971).

Structurally, the Appalachian Basin is a north-northeasterly trending depression which is located west of the Allegheny Front and the folded portion of the Appalachian Mountains. The Nashville Dome, and Cincinnati and Findlay arches form the western and northwestern boundaries, respectively (Figure 3-1).

The basin itself is generally characterized by gently dipping beds. Generally, those beds in the western portion of the basin dip to the east and those in the east dip to the west. Localized dips up to 90 degrees occur near the adjacent Appalachian Mountains and in other isolated zones where intense deformation has occurred. Examples of these other localized tectonic features are the Paint Creek - Warfield Fault Zone (Huddle, et al., 1963) located in eastern Kentucky and the Pine Mountain Thrust - Middleboro Syncline, located along the southeastern border of Kentucky and Virginia. In Alabama, the Coosa and Cahaba coal fields are long narrow troughs which have been dissected by thrust faults (Adams, et al., 1926). Two other coal fields in Alabama, the Warrior and Plateau, are found farther to the west within shallower synclines.

The coal-bearing stratigraphy ranges from Lower Pennsylvanian to Lower Permian in age with the younger materials being encountered in the

northern portions of the Appalachian Basin. The sediments become older to the south because of the thickening of the basal Pottsville Formation, decrease in deformation which occurred concurrent with deposition, and subsequent erosion. The basin during Pennsylvanian time probably existed as a transitional zone between shallow seas to the west and highlands to the east. The basin has undergone slow subsidence as it filled with sediments eroded from adjacent highlands. Although cyclic sedimentation (cyclothems) can be observed, the presence of marine deposits is minimal.

The Dunkard Basin in southwestern Pennsylvania and western West Virginia contains almost the entire sequence of coal measure strata in this area. The southern tip of the Appalachian Basin is subdivided into several smaller basins, including the Warrior, Cahaba, and Coosa. Each contains only the Pottsville and Parkwood formations which, in places, have been structurally thickened to more than 10,000 feet (3,050 meters) (McKee and Crosby, 1975a, b, and c). Detailed summaries of the coal-bearing units by state and field (if delineated) are presented in Tables 3.1 through 3.8.

Within the southern portions of the Appalachian Basin, the A, C, and D intervals in Alabama and the Breathitt Formation in eastern Kentucky contain the highest proportion of shale compared to other formations in this area. In the northern portions of the basin, the Allegheny, Monongahela, Conemaugh, and Dunkard formations generally have higher shale contents. It may be assumed that the units containing higher proportions of shale will possess a greater potential for slaking. This is especially true of the "red beds" within the Conemaugh Formation.

3.1.2 Illinois Basin

The Illinois Basin is a north-northwesterly trending depression which covers the southern two-thirds of Illinois, the southwestern portion of Indiana, and extends into western Kentucky (Figure 3-1). It lies within two physiographic provinces as defined by Fenneman (1938). The Central Lowland province is located in Illinois and western portions of Indiana. This province is covered with a blanket of glacial drift (Treworgy, et al., 1978) and exhibits low relief. The remainder of the basin lies within the Interior Lowland plateau province and has low to moderate relief. Because of this geomorphology, area mining is the most prevalent mining method in the Illinois Basin. The number of surface minable seams ranges from seven in western Kentucky to 15 and 16 in Illinois and Indiana, respectively (USDI-BM, 1971).

Tectonically, the Illinois Basin is bounded on the west by the Mississippi Arch, on the south by the Ozark Dome, and on the east and northeast by the Cincinnati and Kankakee arches, respectively (Figure 3-1). Strata in the majority of the basin dip gently, usually less than 50 feet per mile (nine meters per kilometer). The Fairfield Basin, which is located in the southeastern corner of the Illinois Basin, has

TABLE 3.1
SUMMARY OF COAL-BEARING UNITS IN ALABAMA-CAHABA FIELD

SYSTEM	FORMATION	INTERVAL ⁽¹⁾ (thickness)	DESCRIPTION ⁽¹⁾	STRIPPABLE COAL SEAMS ⁽²⁾	SANDSTONE-SHALE RATIO ⁽¹⁾
PENNSYLVANIAN	Pottsville	B (~2,000 ft) (~600 m)	Predominantly sandstone with thin layers of shale near top and middle formation.	Montevallo ⁽³⁾ Yeshic	<1
		A ₂ (~2,300 ft) (~700 m)	Upper 2/3 of the formation consists of sandstone and shale in near equal amounts. Lower portion is predominantly shale.	Helena Thompson Clark Youngblood Buck Pump Big Bone Wadsworth Harkness	-1
		A ₁ (~5,500 ft) (~1,680 m)	Portion above Nunnally coal is predominantly shale. The unit grades to predominantly sandstone at the bottom.	Nunnally Gould	-1

(1) McKee and Crosby, 1975c.

(2) USDI-BM, 1971.

(3) Coal seams listed at approximate position in stratigraphic section.

TABLE 3.2
SUMMARY OF COAL-BEARING UNITS IN ALABAMA-COOSA FIELD

SYSTEM	GROUP	INTERVAL ⁽¹⁾ (thickness)	DESCRIPTION ⁽²⁾	STRIPPABLE COAL SEAMS ⁽³⁾	SANDSTONE- SHALE RATIO ^(1,4)
PENNSYLVANIAN	Pottsville	Coal-Bearing Interval (1,980 ft) (600 m)	Lenticular carbonaceous brown weathering claystone, sandstone, and siltstone. Numerous coal beds. Shale is evenly interspersed throughout.	Hammond ⁽⁵⁾ Coal City Broken Arrow Marion Gann Fairview Upper Chapman	~1

(1) Rothrock, 1949.

(2) Daniel and Fies, 1970.

(3) USDI-BM, 1971.

(4) McKee and Crosby, 1975c.

(5) Coal seams listed at approximate position in stratigraphic section.

TABLE 3.3
SUMMARY OF COAL-BEARING UNITS IN ALABAMA-PLATEAU FIELD

SYSTEM	GROUP	INTERVAL	DESCRIPTION ^(1,2)	STRIPPABLE COAL SEAMS ⁽³⁾	SANDSTONE-SHALE RATIO ⁽⁴⁾
PENNSYLVANIAN	Pottsville	Not Delineated	Interbedded sandstone and shale with sandstone predominating. Thin coal beds also present with a conglomerate at the base of the Underwood seam.	Underwood ⁽⁵⁾	>1

(1) Rothrock, 1949.

(2) Daniel and Fies, 1970.

(3) USDI-BM, 1971.

(4) McKee and Crosby, 1975c.

(5) Coal seam listed at approximate position in stratigraphic section.

TABLE 3.4
SUMMARY OF COAL-BEARING UNITS IN ALABAMA-WARRIOR FIELD

SYSTEM	FORMATION	INTERVAL ⁽¹⁾ (thickness) Stage	DESCRIPTION ⁽¹⁾	STRIPPABLE COAL SEAMS ⁽²⁾	SANDSTONE-SHALE RATIO ^(1,3)
PENNSYLVANIAN	Pottsville	F (~250 ft) (~75 m) New River	Layers of sandstone, shale, and conglomerate with some thin coal beds. Middle portion of section more shaly.	Johnson ⁽⁴⁾ Clements Utley	~1
		E (~225 ft) (~70 m) New River	Contains massive sandstones (some as thick as 60 ft/18 m) and thick shale units.	Gwin Thompson Mill Upper Cobb Lower Cobb	~1
		D (~250 ft) (~75 m) New River	Consists mainly of shale with some layers of sandstone near middle and top. Includes thin seams of coal and conglomerate.	Pratt	<1
		C (~310 ft) (~95 m) New River	Lower portion is predominantly shale with thin beds of limestone and coal. Upper half of the interval contains a massive sandstone (~50 ft/15 m) sandy shale, and thin beds of coal.	American Curry Gillespy New Castle Mary Lee	<1
		B (~300 ft) (~90 m) New River	Predominantly massive sandstones and sandy shales with subordinate amounts of shale and thin beds of coal interspersed throughout.	Blue Creek Jagger Jefferson Black Creek	>1
		A (~970 ft) (~295 m) Pocahontas	Lower 200 feet (60 m) largely composed of shale and sandy shale with some layers of sandstone. Overall sandstone predominates with shale units constituting less than half of formation.	Rosa Bear Creek	<0.75

(1) Metzger, 1965.

(2) USDI-BM, 1971.

(3) McKee and Crosby, 1975c.

(4) Coal seams listed at approximate position in stratigraphic section.

TABLE 3.5
SUMMARY OF COAL-BEARING UNITS IN EASTERN KENTUCKY

SYSTEM	GROUP (thickness)	FORMATION	DESCRIPTION ⁽¹⁾	STRIPPABLE COAL SEAMS ⁽²⁾	SANDSTONE-SHALE RATIO ⁽³⁾
PENNSYLVANIAN	Conemaugh (max 500 ft) (max 150 m)	None Delineated	Mainly shale (red, green, purple) with lesser amounts of siltstone and sandstone. Unit also contains small amounts of limestone which appear as thin semicontinuous beds.	Princess No. 9 ⁽⁴⁾	<1
	Breathitt (~2,300 ft) (~700 m)	None Delineated	Alternating beds of sandstone, shale and siltstone with thin beds of limestone interspersed throughout. Unit contains much of the minable reserve in eastern Kentucky. Thickens drastically from extreme northeast Kentucky to southwest. Highly lenticular nature and rapid thickening of units make correlation and general description of stratigraphy on a regional basis extremely difficult.	Princess No. 8 Princess No. 7 Princess No. 6 Princess No. 5A Princess No. 5 Hindman Princess No. 4 Hazard No. 7 Hazard No. 5A Haddix Copland Upper Hamlin Lower Hamlin Stray Gin Creek Fire Clay Rider Fire Clay Upper Whitesburg Lower Whitesburg Gun Creek D Upper Elkhorn No. 3 Elkhorn Leader Elkhorn No. 2 Rich Mountain Upper Elkhorn No. 1 Bingham Eagle Millaro Hagy Auxier Zahariah Upper Banner Elswick	~1
	Lee (350-800 ft) (105-245 m)	None Delineated	Contains conglomerate, sandstone, siltstone, shale underclay. Conglomerates can be massive cliff formers in some areas.	Barren Fork Beattyville Hudson	>1

(1) Huddle, et al., 1963.

(2) USDI-BM, 1971.

(3) McKee and Crosby, 1975c.

(4) Coal seams listed at approximate position in stratigraphic section.

TABLE 3.6
SUMMARY OF COAL-BEARING UNITS IN OHIO

SYSTEM	GROUP (thickness)	FORMATION	DESCRIPTION ^(1,2)	STRIPPABLE COAL SEAMS ⁽³⁾	SANDSTONE- SHALES RATIO ⁽⁴⁾
PERMIAN	Dunkard (~625 ft) (~190 m)	Washington	Predominantly shale and sandstone with small amounts of limestone throughout. Sandstone becomes more massive near bottom of unit. Major coal seam is the Washington, considered of little or no value.	None Delineated	~1
PENNSYLVANIAN	Monongahela (~250 ft) (~75 m)	None Delineated	Predominantly limestone, calcareous shale, and sandstone with minor amounts of noncalcareous shale and clay. Unit becomes sandier in southern portion of state.	Meigs Creek ⁽⁵⁾ Redstone Pittsburgh	~1
	Conemaugh (~400 ft) (~120 m)	None Delineated	Composed mainly of shale and clay with consistent limestones throughout formation. Massive sandstones are interspersed throughout and can comprise 25-40 percent of unit. Relatively thin coal seams in this unit are not considered minable.	None Delineated	~0.5
	Allegheny (~210 ft) (~65 m)	None Delineated	Rich coal-producing unit. Consists mainly of interbedded sandstone and shale/clay with minor amounts of limestone. Sandstone predominates in upper portion of unit.	Upper Freeport Lower Freeport Middle Kittanning Lower Kittanning Clarion Brookville	~0.5
	Pottsville (~250 ft) (~75 m)	None Delineated	Dominated by shale/clay and sandstone with subordinate amounts of marine limestone. Contains several minable seams not considered strippable.	None Delineated	>1

(1) Brant, 1964.

(2) Stout, 1947.

(3) USDI-BM, 1971.

(4) McKee and Crosby, 1975c.

(5) Coal seams listed at approximate position in stratigraphic section.

TABLE 3.7
SUMMARY OF COAL-BEARING UNITS IN WESTERN PENNSYLVANIA

SYSTEM	GROUP (thickness)	FORMATION	DESCRIPTION ⁽¹⁾	STRIPPABLE COAL SEAMS ^(2,3)	SANDSTONE- SHALES RATIO ^(1,4)
PERMIAN	Dunkard (<1,200 ft) (<365 m)	Washington	Alternating fine grained shale and sandstone. Some discontinuous thin-bedded limestone. Coals generally thin but locally minable.	Washington ⁽⁵⁾	~1
		Waynesburg		Waynesburg	
PENNSYLVANIAN	Monongahela (~350 ft) (~105 m)	None Delineated	Known as "upper production" coal measure. Massive limestone with variable shales, discontinuous sandstone and coals. The section becomes sandier to south and contains some red shales. Pittsburgh coal located at the base of the formation, considered the greatest single mineral resource in state.	Uniontown Sewickley Redstone Pittsburgh	<1
	Conemaugh (~600 ft) (~180 m)	Casselman	Upper portion of the unit contains green and gray shales with several thin, discontinuous sandstones and limestones. The lower portion of the unit contains predominantly locally massive sandstones enclosed in thin beds of shale and limestone. The unit shows high horizontal variability in stratigraphy with units lensing in and out very quickly.	Brush Creek Mahoning	<1
		Glenshaw		None Delineated	>1
	Allegheny (~300 ft) (~90 m)	None Delineated	The unit consists of shales, thin sandstones, and limestones. Several very persistent coals and some prominent underclays. Shales are olive green - drab in upper portion of the section and brown in the lower portion due to iron oxide. In some areas sandstone is nearly absent from the section.	Upper Freeport "E" Lower Freeport "D" Upper Kittanning "C prime" Middle Kittanning "C" Lower Kittanning "B" Upper Clarion Lower Clarion Brookville "A"	~0.5
	Pottsville (~200 ft) (~60 m)	None Delineated	The Pottsville Group consists largely of sandstone with subordinate amounts of shale and some thin locally minable coal beds.	Upper Mercer	>1
Lower Mercer Quakertown Sharon					

(1) Piper, 1933.

(2) Sisler, 1961.

(3) USDI-BM, 1971.

(4) McKee and Crosby, 1975c.

(5) Coal seams listed at approximate position in stratigraphic section.

TABLE 3.8
SUMMARY OF COAL-BEARING UNITS IN WEST VIRGINIA

SYSTEM	GROUP ⁽¹⁾ (thickness)	FORMATION (thickness)	DESCRIPTION ^(1,2)	STRIPPABLE COAL SEAMS ⁽³⁾	SANDSTONE- SHALES RATIO ⁽⁴⁾
PERMIAN	Dunkard (max 1,200 ft) (max 365 m)	None Delineated	Primarily red shale with subordinate amounts of sandstone, limestone, coal and clay. Section thins to the north.	Washington ⁽⁵⁾	<1
				Waynesburg	
PENNSYLVANIAN	Monongahela (200-400 ft) (60-120 m)	None Delineated	Red and gray shale, sandstone, non-marine limestone, and smaller amounts of coal and clay.	Sewickley	<1
				Redstone	
	Conemaugh (450-600 ft) (135-185 m)	None Delineated	Red and gray shale sandstone, non-marine limestone, and lesser amounts of marine shale, coal and clay.	Upper Bakerstown	<1
				Bakerstown	
	Allegheny (200-300 ft) (60-90 m)	None Delineated	Primarily sandstone and gray shale with minor amounts of clay, coal, and limestone.	Brush Creek	~1
				Mahoning	
	Kanawha (600-2,000 ft) (185-610 m)	None Delineated	In the south, primarily sandstone, gray shale with abundant thin coal seams and small amounts of clay, and limestone. To the north, the Pottsville thins rapidly, loses its commercial seams, and is not differentiated.	Upper Freeport	>1
Lower Freeport					
Pottsville	New River (400-1,000 ft) (120-305 m)	Mainly clean sandstone, lesser amounts of shale and coal, and thin beds of clay and limestone.	Upper Kittanning	>>1	
			Middle Kittanning		
			Lower Kittanning		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Clarion	>>1	
			Mercer		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Stockton	>>1	
			Coalburg		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Buffalo Creek	>>1	
			Winifrede		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Chilton	>>1	
			Hernshaw		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Williamsou	>>1	
			Cedar Grove		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Lower Cedar Grove	>>1	
			Alma		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Campbell Creek	>>1	
			Powellton		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Eagle	>>1	
			Little Eagle		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Lower War Eagle	>>1	
			Gilbert		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Iager	>>1	
			Sewell		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Welch	>>1	
			Little Raleigh		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	Beckley	>>1	
			Fire Creek		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	No. 9 Pocahontas	>>1	
			No. 8 Pocahontas		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	No. 7 Pocahontas	>>1	
			No. 6 Pocahontas		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	No. 5 Pocahontas	>>1	
			No. 4 Pocahontas		
Pocahontas (200-700 ft) (60-215 m)	None Delineated	Sandstone predominant with subordinate amounts of shale and coal. Also contains thin beds of clay.	No. 3 Pocahontas	>>1	
			No. 2 Pocahontas		

(1) Keystone Coal Industry Manual, 1978.

(2) Wilmoth and Ward, 1968.

(3) USDI-BM, 1971.

(4) McKee and Crosby, 1975c.

(5) Coal seams listed at approximate position in stratigraphic section.

the greatest accumulation of sediments and is associated with several small anticlines. These flexures, along with a number of other northerly trending folds, are found throughout the Illinois Basin. The majority of these are of low amplitude and have little structural significance. In the southeastern corner, a major structural feature including the Shawneetown - Rough Creek Fault Zone and Moorman Syncline occurs.

All productive coal seams are Pennsylvanian in age (Wanless, 1975b). The lithologic sequences are similar to those described in the Appalachian Basin; however, because the depositional environment was more strongly influenced by marine sedimentation, higher percentages of shale and limestones are encountered (Wier and Gray, 1961). The sediment sources were primarily the Canadian Shield and ancestral Appalachian Mountains. Detailed summaries of coal-bearing units in the Illinois Basin, by state, are presented in Tables 3.9 through 3.11.

Those formations, which exhibit a higher content of shale or argillaceous materials, are the Carbondale, Bond, and Lisman formations. Units above the Danville (No. 7) coal seam in Indiana exhibit a high content of chlorite (Harrison and Murray, 1964); this mineral is relatively unstable and may influence the slakability of these overburden materials.

TABLE 3.9
SUMMARY OF COAL-BEARING UNITS IN ILLINOIS

SYSTEM	GROUP	FORMATION (thickness)	DESCRIPTION ⁽¹⁾	STRIPPABLE COAL SEAMS ⁽²⁾	SANDSTONE- SHALES RATIO ^(1,3)
PENNSYLVANIAN	McCleansboro	Mattoon (0-700+ ft) (0-215+ m)	Cyclic deposits of shale, sandstone, coal, and limestone.	Trowbridge ⁽⁴⁾ Shelbyville Opdyke Friendsville	-1
		Bond (100-350 ft) (30-105 m)	Predominantly limestone with equal subordinate amounts of sandstone and shale. Trace amounts of coal and clay.	Unnamed Seam	-1
	Kewanee	Carbondale (200-400 ft) (60-120 m)	Cyclic deposits of shale, limestone, sandstone, coal and clay. Contains several important coal seams.	Danville (No. 7) Herrin (No. 6) Springfield (No. 5) Harrisburg Sumnum (No. 4) Colchester (No. 2)	<1
		Spoon (0-350 ft) (0-105 m)	As above. Contains more sandstone in south.	DeKoven Davis Murphysboro Rock Island	-1
	McCormick	Abbott (0-550 ft) (0-170 m)	Very thin in north. Thickens to south, predominantly sandstone with lesser amounts of shale, coal, and clay.	Willis Reynoldsburg	-1
		Caseyville (0-600 ft) (0-185 m)	Largely sandstone with trace clay and shale. Section thickens to the south.	Gentry	>>1

(1) Willman, et al., 1967.

(2) Treworgy, et al., 1978.

(3) McKee and Crosby, 1975c.

(4) Coal seams listed at approximate position in stratigraphic section.

TABLE 3.10
SUMMARY OF COAL-BEARING UNITS IN INDIANA

SYSTEM	GROUP	FORMATION ⁽¹⁾ (thickness)	DESCRIPTION ^(1,2,3)	STRIPPABLE COAL SEAMS ⁽⁴⁾	SANDSTONE-SHALE RATIO ^(2,3,5)
PENNSYLVANIAN	McCleensboro	Mattoon (<150 ft) (<45 m)	Contains sandstone and lesser thicknesses of shale, coal, limestone, clay. Coals are not of economic importance.	None Delineated	>1
		Bond (max 150 ft) (max 45 m)	Predominantly shale and sandstone with thin beds of limestone and small amounts of clay and coal.	None Delineated	<1
		Patoka (100-350 ft) (30-105 m)	Largely composed of sandstone and shale with thin beds of shale and coal of little economic importance.	None Delineated	~1
		Shelburn (50-250 ft) (15-75m)	As above.	None Delineated	~1 ⁽⁶⁾
	Carbondale	Dugger (33-185 ft) (10-55 m)	Consists of shale, lesser amounts of sandstone, and thin deposits of limestone and coal. Basal unit is a black shale associated with an underlying pyritic limestone.	Danville (VII) ⁽⁷⁾ Hymera (VI) Coal (Vb)	<1
		Petersburg (70-193 ft) (21-59 m)	Contains shale and sandstone with thin beds of limestone and several thin coal beds along with the important Springfield seam.	Springfield (V)	<1
		Linton (43-162 ft) (13-50 m)	Shale and sandstone with subordinate amounts of limestone and coal.	Survant (IV) Colchester (IIIA)	<1
	Raccoon Creek	Staunton (75-125 ft) (23-38 m)	Shale is predominant with sandstone and trace of limestone appearing as thin beds.	Seelyville (III)	0.5±
		Brazil (40-90 ft) (12-27 m)	Predominantly shale with minor amounts of sandstone and coal.	Minshall Unnamed Seam Upper Block Lower Block	0.5±
		Mansfield (50-300 ft) (15-90 m)	Sandstone predominates with lesser amounts of shale and minor amounts of coal, limestone, and clay. Lithologies are arranged in a crude cyclic pattern.	Mariah Hill Blue Creek Unnamed Seam	>>1

(1) Shaver, et al., 1970.

(2) Wier and Gray, 1961.

(3) Gray, et al., 1970.

(4) USDI-BM, 1971.

(5) McKee and Crosby, 1975c.

(6) The shale unit on top of the Danville No. 7 coal contains anomalously more chlorite than any other shale in the section.

(7) Coal seams listed at approximate position in stratigraphic section.

TABLE 3.11
SUMMARY OF COAL-BEARING UNITS IN WESTERN KENTUCKY⁽¹⁾

SYSTEM	GROUP	FORMATION (thickness)	DESCRIPTION ⁽¹⁾	STRIPPABLE COAL SEAMS ^(2,3)	SANDSTONE- SHALE RATIO ⁽²⁾
PENNSYLVANIAN	None Delineated	Lisman (~800 ft) (~245 m)	Consists mainly of shale units with limestone near the base of formation and small sandstone zones throughout.	No. 14 ^(4,5) No. 13 ⁽⁴⁾ No. 12 ⁽⁴⁾	<0.75
		Carbondale (~250 ft) (~75 m)	Predominantly shale with some discontinuous sandstone lenses.	No. 11 ⁽⁴⁾ No. 10 ⁽⁶⁾ No. 9 ⁽⁴⁾ Schultztown ⁽⁶⁾ DeKoven ⁽⁶⁾ Davis (No. 6) ⁽⁶⁾	<1
		Tradewater (350 ft) (105 m)	Near equal distribution of sandstone and shale. Shalier units predominate in the upper half and sandstone in the lower half.	Mining City (No. 4) ⁽⁴⁾ Bell ⁽⁶⁾	~1
		Caseyville (~310 ft) (~95 m)	Composed of alternating beds of sandstone, siltstone, and shale.	Main Nolin ⁽⁶⁾	~1

(1) McKee and Crosby, 1975c.

(2) Keystone Coal Industry Manual, 1978.

(3) USDI-BM, 1971.

(4) Main producing seam.

(5) Coal seams listed at approximate position in stratigraphic section.

(6) Minor producing seam.

4.0 MINING AND RECLAMATION TECHNIQUES

In addition to inherent properties of geologic materials, mining and reclamation techniques influence the mode, rate, and degree of slaking encountered in mine spoils in the eastern and central United States.

4.1 EXCAVATION AND PLACEMENT TECHNIQUES

Four general methods of surface coal mining (area, mountaintop removal, partial or complete haulback, and conventional contour mining) are prevalent in the eastern and central portions of the United States. Although methodology is primarily topography dependent, other site characteristics provide input into the selection process.

Spoil placement techniques within the study area consisted of two basic methods:

- Spoils are placed at the angle of repose by pushing over the outslope as in contour mining or piling from above as in area mining.
- Spoils are placed in controlled lifts. Lift thickness and degree of compaction are variable depending on equipment and number of machine passes. This type of placement typically occurs in haulback mining, and in head of hollow and valley fill construction.

Area mining operations are found in the gently rolling topography of the Illinois Basin and in the low sloping hills around the margins of the Appalachian Basin. Operations range in size from several hundred to several thousand acres and mine life is typically 5 to 30 or more years in duration. Overburden removal is accomplished by either continuous bucket-wheel excavators, walking draglines, or stripping shovels. Where unconsolidated materials such as glacial till or loess comprise a significant portion of the overburden, primarily limited to areas of central Illinois, bucket-wheel excavators are employed. More commonly, overburden removal in area mining is accomplished by walking draglines or stripping shovels. Bucket capacities of these machines range from approximately 20 to as much as 200 cubic yards (15 to 150 cubic meters). The larger-capacity draglines and shovels are generally found in Illinois and Indiana, while the smaller machines are utilized in the eastern states.

Spoil placement is accomplished by dropping materials, forming a ridge of spoil piles parallel to the active pit; each new cut results in a new ridge. In the past, ridges were often left as deposited or had

the tops "leveled" with a single pass of a bulldozer resulting in a ridge and trough type of topography. This practice has been discontinued with the advent of new state and federal regulatory programs. Current area mining operations return the spoil to approximate original contour, which is usually accomplished by grading the spoil ridges with bulldozers and less frequently by placement with scrapers. The net effect has been to increase spoil handling and machinery traffic on newer spoil areas.

Mountaintop removal mining, usually performed in conjunction with valley or head-of-hollow fills, is a technique which has only recently come into widespread use. Mountaintop removal in conjunction with haulback mining is rapidly replacing conventional contour mining in the steep slope areas of the eastern coal fields.

Advances in mining technology and particularly improved efficiency in overburden excavation have made mountaintop removal an economically viable method for surface mining of coal. Operations are commonly several hundred acres in size and mine life ranges from two to ten years. Coal removal is generally conducted on several seams with total overburden-interburden thickness as much as 500 feet (150 meters) or more. Spoil removal is accomplished with small electric shovels of 10- to 25-cubic-yard (7.6 to 19 cubic meters) capacity or endloaders. It is transported by trucks ranging in capacity from 30 to 80 tons to fill areas and dumped in controlled lifts. The lifts are then graded and compacted with bulldozers. At the termination of coal removal operations, the mountaintop area is graded to a gently rolling plateau.

Haulback mining, as mountaintop removal, has evolved within the past 10 to 15 years and is conducted primarily in the mountainous regions of the eastern states. Operations range from as small as 20 to several hundred acres in size with mine life from six months to approximately ten years in duration. Although overburden is usually loaded by endloaders, small electric shovels are occasionally utilized. Spoil is hauled back to a previously mined area by truck, dumped, and then graded by bulldozers. Older haulback areas were "partially" backfilled against the highwall and excess spoil disposed of by extending the width of the bench area. Current haulback operations, in attempting to comply with state and federal "original-contour" requirements, eliminate much of the highwall. This extra grading, required to return the materials to their approximate original contour, has resulted in more spoil handling and increased machinery traffic.

Conventional contour mining was once the principal surface coal mining method used in the mountainous areas of the eastern states. As previously noted, it is rapidly being replaced by haulback and mountaintop removal methods, and presently accounts for a small percentage of current surface mine operations. Contour operations range in size from 20 to several hundred acres and mine life is from six months to several years. Conventional contour mining involves minimal spoil handling

with materials placed on or pushed over the outslope with little or no compaction and minimal placement control. Most state regulations now prohibit spoil placement on the outslope and this mining method is expected to become even less common in the future.

Many changes have occurred in mining techniques within the past 15 years. Area mining continues to be a major method of coal production in the central states while haulback and mountaintop removal are rapidly replacing conventional contour mining in the eastern states.

Changing laws and regulations, technological advances, and economic and environmental considerations have combined to alter the impact of mining methods on the slaking phenomenon. In particular, these changes have manifested themselves in the form of heavier and more powerful stripping equipment, increased spoil handling, and more controlled spoil placement. The results of the field program (Section 9.1) suggest that current mining methods have an increased effect on slaking.

Minimizing spoil handling is a key aspect of surface mining operations. Older operations typically handled spoil by draglines, shovels, or end loaders only once with minimal grading after placement. Current operations still utilize single handling when possible; however, greater emphasis on spoil handling sometimes requires additional handling. Regrading, often with multiple passes, has become much more extensive.

The increased spoil handling and manipulation, and the use of larger and more powerful equipment is believed to impact the rate and degree of slaking primarily through a more rapid breakdown of materials by means of crushing, abrasion, and weakening of bonds in rock fragments.

4.2 RECLAMATION TECHNIQUES

Reclamation techniques for surface mine spoils have evolved in the past ten years even more rapidly than mining procedures. Reclamation, which in older operations was generally considered a minor activity, is now an integral part of mine planning.

Reclamation activities on older operations vary from state to state and even from mine to mine, ranging from minimal to intensive levels of effort. Increased state and federal regulations as well as increased awareness of the benefits of proper reclamation by the mining industry have brought about many changes in techniques and procedure.

Currently, toxic or potentially toxic materials are segregated and safely disposed of, usually by deep burial. In contrast, most older operations made no attempt to segregate any spoil materials. Topsoiling which was practiced only in isolated instances in past operations is now conducted on all current mining operations. Most mining operations now mulch, lime, and fertilize topsoil or spoil materials as needed in

contrast to older operations where this was an infrequent practice. Seedbed preparation by disking, dragging, or other means has also become a widespread practice with grass-legume mixtures, shrubs, and trees seeded or planted at recommended rates to establish a dense stand of vegetation promoting erosion and stability control. Furthermore, diversion ditches, terraces, and sediment ponds are being incorporated into reclamation planning to control runoff, erosion, and stability problems. The marked increase in reclamation activities in recent years has caused an increase in machinery traffic and manipulation of spoils and refined final placement methods.

As with mining operations, current reclamation activities affect slaking of mine spoils. Additionally, spoil manipulation due to re-grading and shaping further stresses the spoil materials and reduces strength characteristics of rock fragments. Final grading often results in long smooth slopes which are prone to accelerated erosion and surficial slaking. Seedbed preparation by mechanical tillage may also impact the slakability of near-surface spoil fragments.

The effects of topsoiling on slaking depend on several variables. Thickness and permeability of the topsoil layer and the nature of the topsoil-spoil interface are the principal controlling factors. Topsoiling generally reduces slaking since it impedes direct access of atmospheric agents to the underlying spoil.

5.0 FIELD PROGRAM

A detailed field program was implemented to document the nature, occurrence, distribution, and effects of slaking in surface mine spoils. It consisted of the following five phases:

- Preliminary Site Selection
- Site Reconnaissance and Final Selection
- Highwall Exploration
- Mine Spoil Exploration
- Interviews with Mine and Regulatory Personnel

The field program was designed to obtain information which is representative of various mining and reclamation techniques and properties of geologic materials for a given region, as well as optimize collection of necessary data from external sources.

5.1 PRELIMINARY SITE SELECTION

Initial site selection was based on an intensive telephone campaign in which support of various mining companies was solicited. Nearly 50 companies and/or mines were contacted; a verbal explanation of the project was provided to each organization. Those organizations that were receptive to the study were asked to provide site-specific information relating to mining technology, age of mining, and overburden characteristics. A final screening was performed giving consideration to mining and reclamation techniques. Area mining by draglines, mountaintop removal by truck and shovel methods, and haulback techniques were all included. Conventional contour mining, which is rapidly disappearing in current operations, was not included; however, several sites had older spoils mined by this technique. Recognizing that inherent properties of the geologic materials exert a major influence on the degree, rate, and mode of slaking encountered in mine spoils, an assumption was made that those sites with higher percentages of argillaceous lithologies would provide more occurrences of slaking than those with sandstones as a major component of the overburden. Therefore, overburden composition was considered as a prime factor during the preliminary site selection process. Other factors evaluated included the following:

- Geographic location.
- Production characteristics and minable extent of the coal seams mined at each site.
- Availability and access of the various age spoils and drilling locations at each site.
- Uniformity of overburden materials on a site-specific and regional basis.

- The level of cooperation and interest exhibited by mining company personnel.
- Unique characteristics.

5.2 SITE RECONNAISSANCE AND FINAL SELECTION

Following the preliminary site selection process, a one-day field reconnaissance at each of seven potential study sites was conducted (Figure 5-1). Site-specific information was obtained to assess the compatibility of each site with the objectives of the study and to aid in properly designing and implementing the remainder of the field program. This information included the following:

- Better definition of mining and reclamation history.
- Better definition of the thickness and composition of overburden materials.
- Occurrence of slaking and associated environmental effects.
- Location and accessibility of spoils and drill sites.
- Information from regulatory and environmental groups.

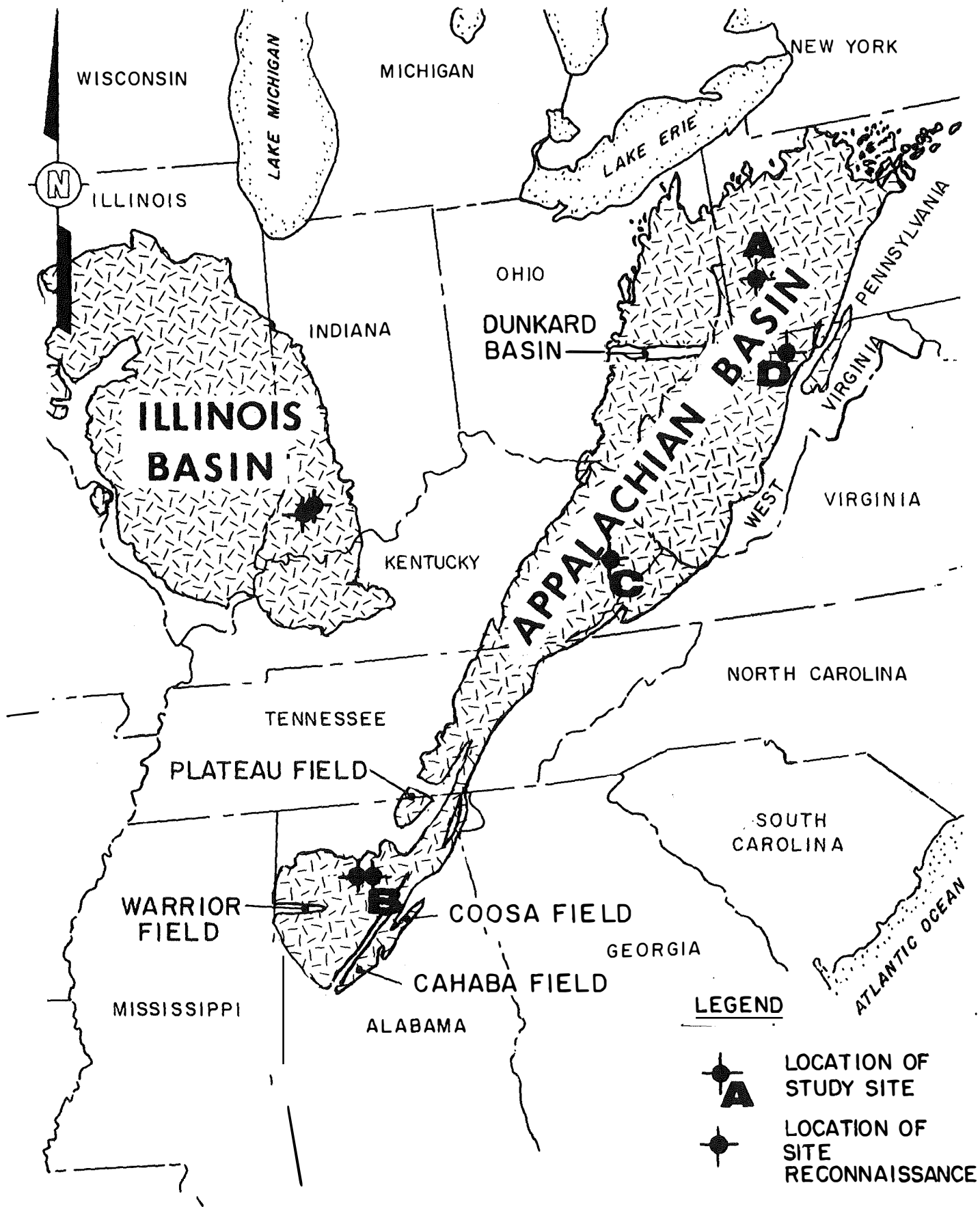
Each mine site was evaluated by interviewing mine personnel as well as field checking the active mining and reclamation operations and reclaimed spoil areas.

Based on the results of this reconnaissance, five sites providing an optimum mixture of mining techniques and geologic materials as well as good spatial distribution within the study area were chosen for the detailed field program. However, during the latter stages of this program, one mining company withdrew from the program with the resulting four sites located entirely within the Appalachian Basin (Figure 5-1).

A systematic field investigation, which consisted of examining both highwall and spoil materials at each site, commenced in late April and was concluded in early June 1979. The same investigative techniques at the same level of intensity by the same personnel were employed at all study sites to facilitate comparison and extrapolation of results and conclusions.

5.3 HIGHWALL EXPLORATION

A boring was drilled to evaluate the in situ or premining condition of the overburden at each site. The hole was located near the active



APPALACHIAN AND ILLINOIS BASINS WITH APPROXIMATE LOCATION OF STUDY SITES

FIGURE 5-1

highwall to provide visual correlation with the observed lithologic units. The hole was placed so as to core the full section of overburden, and interburden if present, to the lowest mined coal. Drilling was conducted with truck-mounted drill rigs using water as drilling fluid. The soil was not sampled and coring commenced when durable rock was encountered. Core runs were generally ten feet in length and were retrieved by standard wire-line techniques, providing NQ-sized core (1-7/8 inches, 48 millimeters) for visual identification.

The visual descriptions were logged using a standard format and included the following:

- Color.
- Lithology.
- Relative hardness.
- Special features such as natural fractures, slickensides, fossils, and identifiable minerals such as carbonates, mica, pyrite, or others.
- Spatial distribution of discontinuities.
- Depth and thickness of each lithologic unit.
- Percent recovery and rock quality designation (RQD).
- Depth of groundwater (if encountered).

The rock core was placed in specially designed boxes which utilized weather stripping and heavy sheet plastic to minimize fluctuations in moisture content. Each box was accurately labeled to assure proper sample selection during the subsequent laboratory program.

The logs were correlated with highwall observations and any lithologic variations or discontinuities noted. Other pertinent geologic parameters which were observed in the exposed highwall were also incorporated. An attempt was made to correlate the lithotypes observed in the core and highwall with test pit observations to identify and characterize the location and extent of slakeable lithologies.

5.4 MINE SPOIL EXPLORATION

To evaluate the mode, degree, and extent of slaking in mine spoils and the associated environmental effects, a thorough test pit exploration and visual reconnaissance program was conducted at each site. Specific variables and/or relationships which were investigated follow:

- Identification of which lithotypes undergo slaking in mine spoils.

- Identification of inherent lithologic properties which influence slaking.
- Evaluation of the effects of time on slaking.
- Evaluation of the effects of mining and reclamation techniques, including depth of placement and packing density on slaking.

To fulfill the objectives of the field program, both surficial and subsurface characteristics of recently placed, as well as two-, five-, and ten-year-old spoils were observed, described, and evaluated. The location and limits of each area were defined by mine personnel and mining records, if available. Each area was traversed on foot and surficial features characterized, as shown in Table 5.1. Based on observations of surficial features, the locations of four test pits per age spoil (16 per mine site) were flagged. Test pits six to eight feet (1.8 to 2.4 meters) deep, six feet (1.8 meters) wide, and 10 to 15 feet (3.1 to 4.6 meters) long were excavated using a backhoe. This method of subsurface exploration was chosen because of its speed, mobility, and magnitude of observational area achieved. Occasionally, pits were excavated to a depth of approximately 10 feet (3 meters) so that slaking could be observed at its maximum; however, this was only necessary in a few instances.

Surficial features as well as a preliminary log of subsurface features at each test pit were compiled, as indicated in Table 5.1. Based on this information, two representative test pits in each age spoil were logged in detail (Table 5.1). One of these detailed pits was then selected as typifying the spoil area and prepared for sampling and in situ testing.

Bulk density and moisture content determinations were conducted at the surface and within two selected subsurface layers using a nuclear density gage. Tests were conducted using standard recommended procedures with three replications in each layer. A bag sample, weighing approximately two pounds (1 kilogram), was taken at each test location for gravimetric water content determinations for calibration purposes. Subsurface tests were prepared by carefully benching off one side of the test pit with the backhoe to the desired depth. A bulk sample, weighing approximately 100 pounds (45 kilograms), was taken from a selected subsurface layer for subsequent determination of bulk grain size distribution. All test pits were backfilled at the conclusion of the exploration program. Bag samples of each major lithotype, weighing approximately 125 pounds (55 kilograms), were collected from the fresh spoil area at every site to supplement the rock core samples and provide an auxiliary supply of testing materials for the laboratory program.

TABLE 5.1
 OUTLINE OF DESCRIPTORS USED FOR
 MINE SPOIL CHARACTERIZATION

LOCATION	VARIABLE	DESCRIPTOR ⁽¹⁾
Recent, 2-, 5-, 10-Year Aged Spoil Areas	Spoil Geomorphology	Outslope, Bench, Backfilled Highwall, Valley Fill, Rolling Upland, Other ⁽²⁾
	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, Gulleys), Rock Pavement
	Surface Condition	Disk Marks, Bulldozer, or Rubber Tire Tracks, Other ⁽²⁾
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
Test Pit (Subsurface Features)	Stratification	Depth, Thickness, Coarse Fragment Content (%), Lithotypes, and % of Each, Texture (Grain Size), Special Features

See footnotes at end of table.

TABLE 5.1
(Continued)

LOCATION	VARIABLE	DESCRIPTOR ⁽¹⁾
Test Pit (Subsurface Features) ⁽³⁾	Stratification ⁽⁴⁾	Pores and Voids, Roots, Moist Color (Munsell Designations for Matrix and Mottles), Structure, Moist Consistence, Boundary, Special Features, Bulk Density and Water Content ⁽⁵⁾

- (1) Unless noted, any descriptor which required quantification (i.e., gradient) was estimated by visual observation. Soil descriptors were characterized according to standard USDA methodology.
- (2) When descriptor did not fall within the preselected terminology, further definition was required.
- (3) In one pit of each age spoil, samples were taken for point load testing, water contents, and bulk grain sizes.
- (4) Compiled for two pits in each age spoil.
- (5) Measured in one pit in each age spoil.

5.5 INTERVIEWS WITH MINE AND REGULATORY PERSONNEL

Informal interviews were conducted with mining, regulatory, and other pertinent government agency personnel to supplement information collected during other portions of the field program. Information regarding slaking and associated effects, mining and reclamation techniques, and related subjects was collected and summarized as described in the following paragraphs. Individuals were also asked to identify local environmental groups or persons familiar with mining in the study area. None of the mining, regulatory, or government personnel were aware of any such groups or individuals.

Preliminary information collected during the site reconnaissance was supplemented by further consultations with mining personnel during the exploration program and included specific data on the following subjects:

- Rates, modes, and degrees of slaking of spoil materials encountered at the mine site. At Site A, the green mudstone was identified as the major slakable lithotype, disintegrating to its constituent grain size in less than five years. Mining personnel at Sites B and C indicated that the massive siltstones broke into small chips within about five years. Localized slaking of weathered sandstone to constituent grain size was reported to occur within ten years at Site C.

Personnel at Site D indicated that gray mudstone was the prevalent slakable lithotype, disintegrating to its constituent particle size within two to three years. The red-green mudstone was also reported to disintegrate within six months.

- Environmental effects of slaking. Mining personnel at all study sites identified surficial erosion and sedimentation as the most common environmental effects of slaking. Personnel at Sites A and D also included shallow slips and small slides.
- Control measures utilized to alleviate adverse effects of slaking. At all sites, sediment-control structures and quick establishment of vegetation were considered the most effective measures for controlling slaking. Personnel at Site D also felt that diversion ditches with rock riprap contributed to sediment control. None of the sites visited segregated overburden materials solely for the purpose of isolating slakable materials.

Several people expressed concern that implementation of approximate original contour requirements could cause accelerated erosion and spoil stability problems in much of the Appalachian coal fields.

- Mining techniques including equipment, blasting and spoil handling procedures, and timing and sequence of operations (Chapter 6.0).
- Geologic features including lithologic characteristics, faults or joints, groundwater information, highwall stability problems, and other related features (Chapter 6.0).
- Final reclamation practices including soil and fertilizer amendments, erosion and stability control measures, water control and treatment techniques, and seeding and planting methods (Chapter 6.0).

Telephone interviews were conducted with local regulatory personnel and other government agency personnel familiar with each study site and mining characteristics of the area. Information collected from these sources included:

- Similarities and differences of the study site compared to other mines in the area. Regulatory and government personnel generally indicated that the study sites were typical of other mines in the area with respect to mining techniques and geologic characteristics. Site C was described as being larger in areal extent, duration of operations, and coal production than most mines in the area. Nearly all regulatory and government personnel suggested that the mining company at the study site in question performed above average, and in some cases, excellent reclamation work.
- The existence and significance of slaking and associated environmental effects on the mine site and in the study area. Slaking was described as an existent problem on the study sites and other mines in the surrounding areas. However, they felt that it did not cause major adverse effects. Other parameters such as proper disposal of acid spoil were regarded as a more critical priority.

- Suggestions for improved control of undesirable effects of slaking. Regulatory and government personnel consistently identified improved sediment and erosion control as the best means of controlling slaking effects. Contemporaneous reclamation was cited by one individual to reduce exposure time, and one individual suggested that fines or cessation of operation orders would provide greater incentive to control adverse effects.

The information supplied through these interviews was used to supplement on-site observations, formulate conclusions and recommendations, and extrapolate the results of the field and laboratory programs to a regional analysis.

6.0 SITE CONDITIONS

As discussed earlier, material properties in conjunction with mining and reclamation techniques tend to control the rate and magnitude of slaking. However, to accurately assess these phenomena, the geologic and mining variables must be supplemented with other parameters. Physiography, climate, and previous mining history are such parameters.

While physiography is a prime factor in determining mining methods and can influence the selection of reclamation procedures, climatic conditions, particularly temperature and precipitation, provide the various environmental stresses that impact slaking rates. Previous mining history can require modified mining and reclamation methods with attendant effects on slaking.

Although the conditions outlined below are generally site-specific, an attempt was made during the site visits to regionalize the various parameters. As mentioned in Chapter 5.0, sites were selected to gain representative and spatially distributed locations so that data extrapolation throughout the eastern and central coal basins might be possible.

6.1 SITE A

Site A is located in southwestern Pennsylvania in the physiographic province known as the Appalachian Plateaus. It is characterized by low rolling hills with elevations of approximately 1,000 to 1,200 feet (300 to 365 meters). Slopes on undisturbed areas average approximately 20 percent, and range in length from 200 to 600 feet (60 to 180 meters). Colluvial deposits are common on foot slopes and in drainageways, indicative of weathering and slaking processes in unmined areas. Spoils mined under the Office of Surface Mining and Reclamation (OSM) regulations are reclaimed to approximate the premining topography.

The study area has a typical continental climate with cold winters and warm humid summers. Yearly precipitation averages 35 inches (89 centimeters) (U.S. Department of Commerce, NOAA, 1961-1974) and is well distributed throughout the year. Occasionally, high intensity rains occur in the summer while spring and fall are characterized by gentle, low intensity rains and most winter precipitation occurs as snow. The average temperature is approximately 13 degrees Celsius with extremes ranging from approximately -25 to 40 degrees Celsius.

The study area has a long history of coal production, having been both underground and surface mined. Underground mining by the room-and-pillar method with approximately 50 percent recovery was conducted on the site during a period between 1920 to 1935. Crop coal was surface mined on the site from about 1925 to 1945 with no attempts made to reclaim mined areas. The site was then abandoned until 1969 when the present company began operations. Current operations have eliminated many

point sources of acid mine drainage emanating from the abandoned underground workings, reclaimed previously disturbed surface areas, and maximized coal recovery at this site.

6.1.1 Geologic Conditions

The Pittsburgh coal, which is the target seam at Site A, is the basal member of the Monongahela Group of the upper Pennsylvanian System (Table 3.7). The associated overburden lithologies are among the younger rocks of the eastern coal measures and contain a high percentage of argillaceous materials.

Typical overburden thickness at this site is approximately 100 feet (30 meters), but, depending upon variations in original sedimentation and subsequent erosion, may be as thin as 70 feet (20 meters) or as great as 160 feet (50 meters). Five major lithologies were recognized and their properties are summarized in Table 6.1. A generalized stratigraphic column for the site is shown in Figure 6-1. Lithologies and unit thicknesses were observed in the rock core and exposed highwalls to be laterally consistent over the mine site, and the entire section dips two to three degrees to the northwest. Although no major folds, faults, or fractures were observed, localized fractures and faults were common in some lithologies; mudstones recovered in the core drilling program were badly fractured due to low strength characteristics. Throughout the argillaceous units, slickensides were present, which is indicative of past movement. The limestone unit was also fractured and, in some instances, fracture faces were coated with iron oxides. Most observed fractures in the rock core and highwall appeared to be of recent origin and were likely induced by blasting in the immediate vicinity.

Water was not encountered during the core drilling program; however, water was observed seeping from the Pittsburgh coal seam into the working pit.

6.1.2 Mining Technology and Spoil Handling

Site A is a single seam, area mining operation covering a total of 700 acres. Current surface mining operations began in 1969 with approximately 70 acres mined each year. The size of this site and duration of mining are typical of area mining operations in this region of the eastern coal fields.

The entire overburden above the Pittsburgh coal is drilled and shot in one lift and the spoil is moved by a Page 7-40 dragline with a 27 cubic yard (21 cubic meter) capacity bucket. Spoil is deposited in ridges parallel to the active pit with the piles approximately 120 feet (35 meters) high and several hundred feet wide at the base. Due to the presence of two working pits, irregular permit boundaries and unreclaimed spoil from previous mining, some spoil is double- or triple-handled by the dragline. This extra handling may significantly increase material breakdown at the site and is rather atypical of most area mining operations, where single handling by the dragline usually occurs.

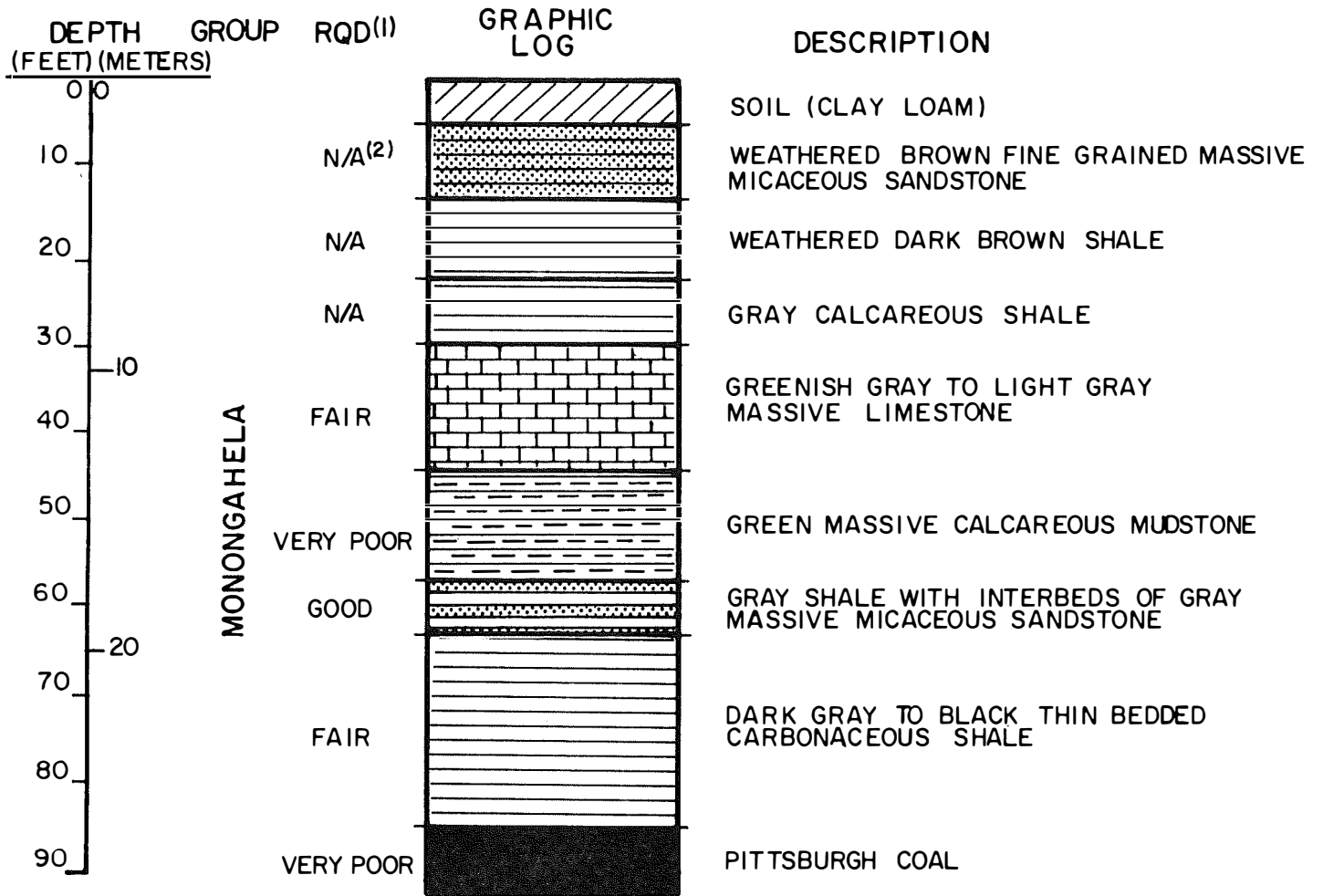
TABLE 6.1
SITE A: SUMMARY OF LITHOLOGIC PROPERTIES

LITHOTYPE	MODE OF SLAKING ⁽¹⁾	PERCENT OF OVERBURDEN ⁽²⁾	BEDDING	RQD ⁽³⁾	ADDITIONAL FEATURES
Green mudstone	Chip, slake to constituent grain size	40	Massive	Very poor	Calcareous
Gray shale	Chip	30	Indistinct, parallel planes, spaced approximately 0.5 inch (1.3 centimeters)	Fair	None
Gray limestone	Slab	10	Massive	Good	None
Black shale	Chip	10	Indistinct, parallel planes, spaced approximately 0.5 inch (1.3 centimeters)	Fair	Carbonaceous
Brown sandstone	Slab	10	Massive, occasional indistinct, parallel planes, spaced approximately 3 inches (8 centimeters)	Fair	Fine grained, micaceous

(1) Modes of slaking are defined in Section 9.1.1.

(2) Percent composition based on visual estimates of highwall and rock core.

(3) RQD = Rock Quality Designation (Section 7.1.2).



- (1) AVERAGE VALUE PER LITHOLOGIC UNIT.
- (2) VALUES NOT TABULATED BECAUSE INTERVAL WAS NOT CORED.

GENERALIZED STRATIGRAPHIC COLUMN

SITE A

Spoil ridges are graded to wide flat ridgetops and long side slopes using D-9 bulldozers with blades 18 to 21 feet (5.5 to 6.4 meters) wide. Graded ridgetops are from 200 to 500 feet (60 to 150 meters) wide and as much as one mile (1.6 kilometers) long with final slopes less than five percent. Graded side slopes are approximately 500 feet (150 meters) long with gradients of five to 25 percent. Grading steep spoil ridges to wide ridgetops and gentle side slopes requires extensive spoil manipulation by bulldozers; consequently, some spoil areas are subjected to impact by heavy equipment several times.

6.1.3 Reclamation Techniques

Reclamation techniques employed at Site A have changed during the past ten years due to changing laws and regulations and improved reclamation technology. These changes have resulted in increased grading, surface treatments, and manipulation of younger spoils. The implementation of OSM regulations has resulted in the practice of topsoil application on the most recent spoils.

Ten-year spoil received limited grading with little or no segregation of materials. No disking, dragging, or similar seedbed preparation was performed prior to planting of a grass-legume mixture. A sediment pond was constructed on this spoil and is still functioning as designed. Erosion and sediment production are not excessive and slope stability or other adverse environmental problems were not apparent.

Five-year spoil was graded to a smooth level topography and covered with 6 to 12 inches (15 to 30 centimeters) of topsoil material derived from the native soil. The spoil was mulched, fertilized, and seeded with a grass-legume mixture. Sediment control structures are not present in this area and some erosion of the topsoil has taken place. Gulleys, which had eroded through the topsoil, are U-shaped indicating that the underlying spoil is relatively more resistant to erosion. Slope stability or other adverse environmental problems were not observed in this area.

Two-year and fresh spoil are graded to a smooth level topography. Spoils subject to OSM regulations are covered with approximately one-foot-thick (30 centimeters) lifts of topsoil applied with Caterpillar 637 scrapers. Steeper areas are dragged with chains and mulched with hay to prepare the seedbed and control erosion. Fertilizer is applied as needed and the spoils are hydroseeded with a grass-legume mixture. A water treatment facility in the fresh spoil area was constructed to control acid mine drainage emanating from the abandoned underground workings. Fragments of blasted limestone are segregated during spoil excavation and used to treat the drainage before it is released into natural streams off site. Occasional small surficial slumps of fresh ungraded spoil were observed, but no evidence of massive spoil movement or other adverse environmental effects of slaking were encountered.

6.2 SITE B

Site B is located in north central Alabama and lies in the extreme southern portion of the Appalachian Plateaus. The site is characterized by low rolling hills at elevations of approximately 300 to 500 feet (90 to 150 meters). Slopes on undisturbed areas average 25 percent, and range from 100 to 400 feet (30 to 120 meters) in length. Spoils mined under OSM regulations are reclaimed to approximate the premining topography.

The study area has a warm climate with mild wet winters and hot humid summers. Precipitation averages approximately 50 inches (130 centimeters) annually (U.S. Department of Commerce, NOAA) and is well distributed throughout the year. High intensity rainstorms are common in the summer and occasionally occur in the spring and fall also. Winter precipitation occurs as rain or snow. The average temperature is approximately 18 degrees Celsius with extremes ranging from -20 to in excess of 40 degrees Celsius.

Coal has been surface mined on the site since the early 1960's by area mining techniques. Early production was restricted to locations where the overburden was relatively thin, while more recent mining has taken place in areas of thicker overburden. Reclamation on spoils older than five years was variable in terms of level of effort, treatment techniques, and the time period from initial excavation to final reclamation. The company currently on the site took over mining and reclamation operations in 1974.

6.2.1 Geologic Conditions

The Mary Lee and Newcastle coals, which are the target seams at this site, are members of the New River Stage, C Interval of the Pottsville Formation in the lower Pennsylvanian System of the eastern coal measures (Table 3.4). The associated overburden and interburden consist almost entirely of massive siltstone and are approximately 100 feet (30 meters) thick. This value, however, varies from as little as 30 to as much as 150 feet (10 to 45 meters). The properties of the principal lithology are summarized in Table 6.2 with the associated stratigraphic column shown in Figure 6-2. Lithologic composition was found to be laterally consistent based on rock core and highwall observations over the mine site, with the entire section dipping three to four degrees to the east. No major faults, folds, or fractures were observed; however, blasting-induced fractures were present in the exposed highwall.

Water was not encountered during core drilling operations, but water was observed to be seeping into the pit from the Mary Lee coal seam.

6.2.2 Mining Technology and Spoil Handling

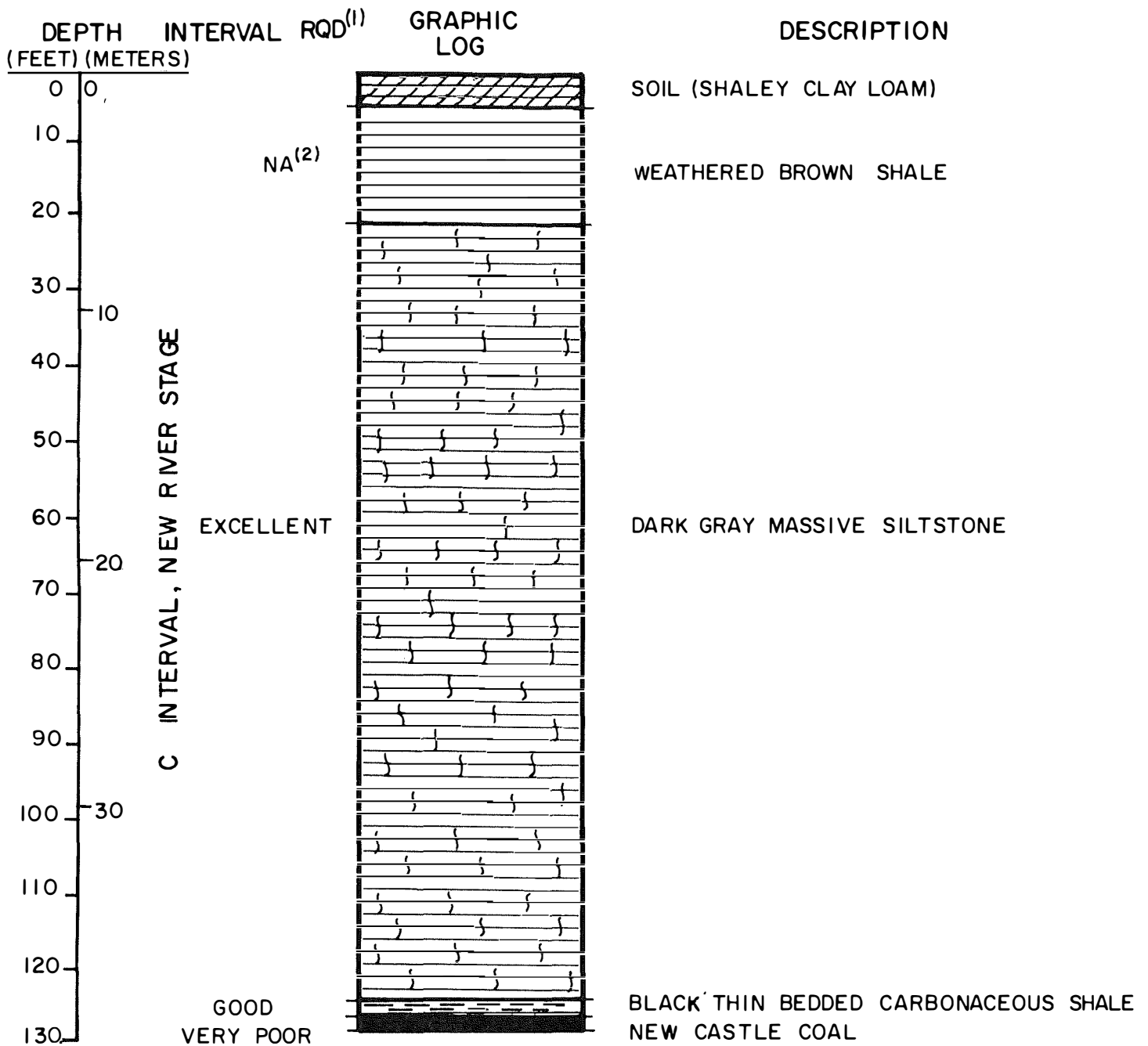
Site B is a two seam, area mining operation covering approximately 600 total acres with 50 acres mined annually. The size of this site and

TABLE 6.2
SITE B: SUMMARY OF LITHOLOGIC PROPERTIES

LITHOTYPE	MODE OF SLAKING ⁽¹⁾	PERCENT OF OVERBURDEN ⁽²⁾	BEDDING	RQD ⁽³⁾	ADDITIONAL FEATURES
Gray siltstone	Chip	≈100	Massive	Excellent	Micaceous

65

- (1) Modes of slaking are defined in Section 9.1.1.
- (2) Percent composition based on visual estimates of highwall and rock core.
- (3) RQD = Rock Quality Designation (Section 7.1.2).



(1) AVERAGE VALUE PER LITHOLOGIC UNIT.
(2) VALUES NOT TABULATED BECAUSE INTERVAL WAS NOT CORED.

GENERALIZED STRATIGRAPHIC COLUMN

SITE B

duration of operations, which began in the early 1960's, are typical of area mining operations in this region of the eastern coal fields.

The entire overburden above the Newcastle coal is drilled and shot in one lift and blasting patterns are designed to blow as much spoil as possible into the active pit with the remaining spoil being pushed into the pit by endloaders and bulldozers. The spoil is moved by a Page 7-32 dragline with a 21 cubic yard (16 cubic meters) capacity bucket and placed in ridges parallel to the active pit. Spoil piles are approximately 80 feet (25 meters) high and several hundred feet wide at the base with very steep side slopes. After the Newcastle coal has been removed by endloaders and trucks, the remaining interburden to the Mary Lee coal is drilled and shot in one lift and the spoil removed by the dragline. Spoil is handled only once by the dragline as is typical of most area mining operations.

Spoil ridges are graded to a low rolling topography with a maximum relief of about 40 feet (12 meters) using D-9 bulldozers. Slopes are generally less than 150 feet (45 meters) in length with gradients of zero to 20 percent. Spoils under current OSM regulations are graded to slightly steeper relief to approximate premining topography.

6.2.3 Reclamation Techniques

Reclamation techniques at Site B have become more intensive during the past ten years due to changing laws and technology, and increased interest in postmining land use. Ten-year spoil, located in the valley bottom, was graded to a smooth, level topography. The natural stream drainage was rerouted and now flows through the final cut which was left open. The graded spoil was seeded with a grass-legume mixture and is currently used for hay, pastureland, and wildlife cover. This agricultural land use, however, is not typical of most ten-year-old spoils in the area. Reclamation activities at that time generally consisted of little or no grading, leaving spoils with steep side slopes. The usual vegetation technique consisted of planting locally adapted conifers, usually loblolly pine. At Site B no erosion or slope stability problems were apparent on the ten-year spoil. The rerouted stream effectively controls water runoff and the water which has a near neutral pH is clear indicating low sediment loads.

The area containing five-year spoil was graded to a rolling topography with short slopes. It exhibited a pebble pavement cover of nearly 100 percent, which is effective in controlling runoff and erosion. The spoil was originally disked to a depth of approximately six inches with the disk marks following the contour. Fertilizer was then applied as needed and the area seeded with a mixture of grasses and legumes.

The two-year-old spoil was similarly graded with the pebble pavement covering approximately 80 percent of the surface. It also effectively controls erosion. The spoil was fertilized as needed and seeded

with a grass-legume mixture and a grain cover crop. In neither spoil area were slope stability problems, excessive erosion, or other adverse environmental effects of slaking observed.

The fresh spoil is graded to a rolling topography and covered with approximately two feet (0.6 meter) of topsoil derived from the native soil. Topsoil is dumped from 35-ton-capacity trucks and spread with bulldozers. The topsoiled spoil is then fertilized, mulched with hay, and seeded with a mixture of grasses and legumes. The topsoil, even though protected by mulch, appeared to be more erosive than the spoil materials. Other than topsoil erosion, however, adverse effects were not observed.

Reclamation activities on spoils older than five years were often not completed for a period of two years or longer following initial excavation. Reclamation of fresh spoils, however, is kept concurrent with mining with only one ridge of spoil present immediately adjacent to the active pit at any time. On these fresh spoil areas final reclamation is usually complete within six months of initial excavation.

6.3 SITE C

Site C is located in southeast Kentucky on the western edge of the Appalachian Plateaus. The site is characterized by very steep hills at elevations of approximately 1,000 to 1,400 feet (300 to 425 meters). Slopes on undisturbed areas are often in excess of 50 percent and are 500 to 1,000 feet (150 to 300 meters) in length.

The study area has a humid continental climate with cold winters and warm summers. Yearly precipitation averages 45 inches (114 centimeters) and is well distributed throughout the year (U.S. Department of Commerce, NOAA, 1940-1978). Occasionally high intensity rainstorms occur in the summer while spring and fall are characterized by gentle rains. Most winter precipitation occurs as snow. The average annual temperature is approximately 15 degrees Celsius.

The study region has historically been a major coal producer. Mining began on the site in 1969. Older spoils were mined by modified haulback methods with spoil placed in small head-of-hollow fills or stacked on the outslope. More recent spoils have been mined by mountaintop removal methods in conjunction with valley and head-of-hollow fills.

6.3.1 Geologic Conditions

A number of coal seams and associated riders are mined at the site. The Princess Sub 5 to Princess 8 coals are in the uppermost portions of the Breathitt Group while the Princess 9 coal is the basal member of the Conemaugh Group (Table 3.5). The associated overburden and interburden consist primarily of sandstone and siltstone, with the former predominating.

Total thickness of overburden and interburden at this site is approximately 220 feet (65 meters). The Princess Sub 5, 5A, 7, and 9 coals are mined at this site as well as various rider coals where they thicken locally. The characteristics of the principal lithologies present in the spoil, overburden, and interburden are summarized in Table 6.3. Spoils derived from the intercalated sandstone/siltstone units associated primarily with the Princess 5A and Princess Sub 5 interburden were deeply buried and not accessible for observations. A generalized stratigraphic column is presented in Figure 6-3. Major lithologic units were observed to be laterally consistent based on rock core and highwall observations with the section dipping gently to the east. No major folds, faults, or fractures were observed; however, blasting-induced fractures were present in the siltstone units and small fractures were present in the weathered sandstone units.

Water was not encountered in the core drilling operation, nor was any water observed in the working pits. However, mining personnel did report that water frequently seeps into the working pit from the Princess 5A coal.

6.3.2 Mining Technology and Spoil Handling

Site C is a multiple seam, mountaintop removal mining operation covering approximately 300 acres. Mining began in 1969 and about 150 acres are currently being mined or have valley or head-of-hollow fills under construction. The size of the site and duration of operations are typical of mountaintop removal operations in this region. Each interval over or between coal seams is drilled and shot as a separate lift. Spoil is loaded either by a Bucyrus Erie B-280 shovel or by endloaders into trucks of 50- to 80-ton capacity. Spoil is transported distances of one quarter to one mile (0.4 to 1.6 kilometers) and dumped in four-foot (1.2-meter) lifts. Dumped spoil is partially compacted and graded to a smooth, nearly level slope by D-9 bulldozers. Complete construction and reclamation of valley or head-of-hollow fills requires from two to five years depending on the size of the fill area.

6.3.3 Reclamation Techniques

Reclamation procedures at Site C have evolved concurrent with changes in mining methods and laws and regulations. Ten- and five-year-old spoils consist of small head-of-hollow fills and wide flat benches. They are usually on slopes of less than ten percent and are 200 to 500 feet (60 to 150 meters) wide. Out slopes are very steep, generally in excess of 50 percent, and are from 100 to 400 feet (30 to 120 meters) in length. When final grading by bulldozers was completed, the spoils were seeded with a mixture of grasses and legumes. A pebble pavement covers approximately 70 percent of the surface on the five- and ten-year spoils and, in conjunction with a dense stand of vegetation, appeared to be effective in controlling erosion. Slope stability problems or other adverse environmental effects were not observed on these spoils.

TABLE 6.3
SITE C: SUMMARY OF LITHOLOGIC PROPERTIES

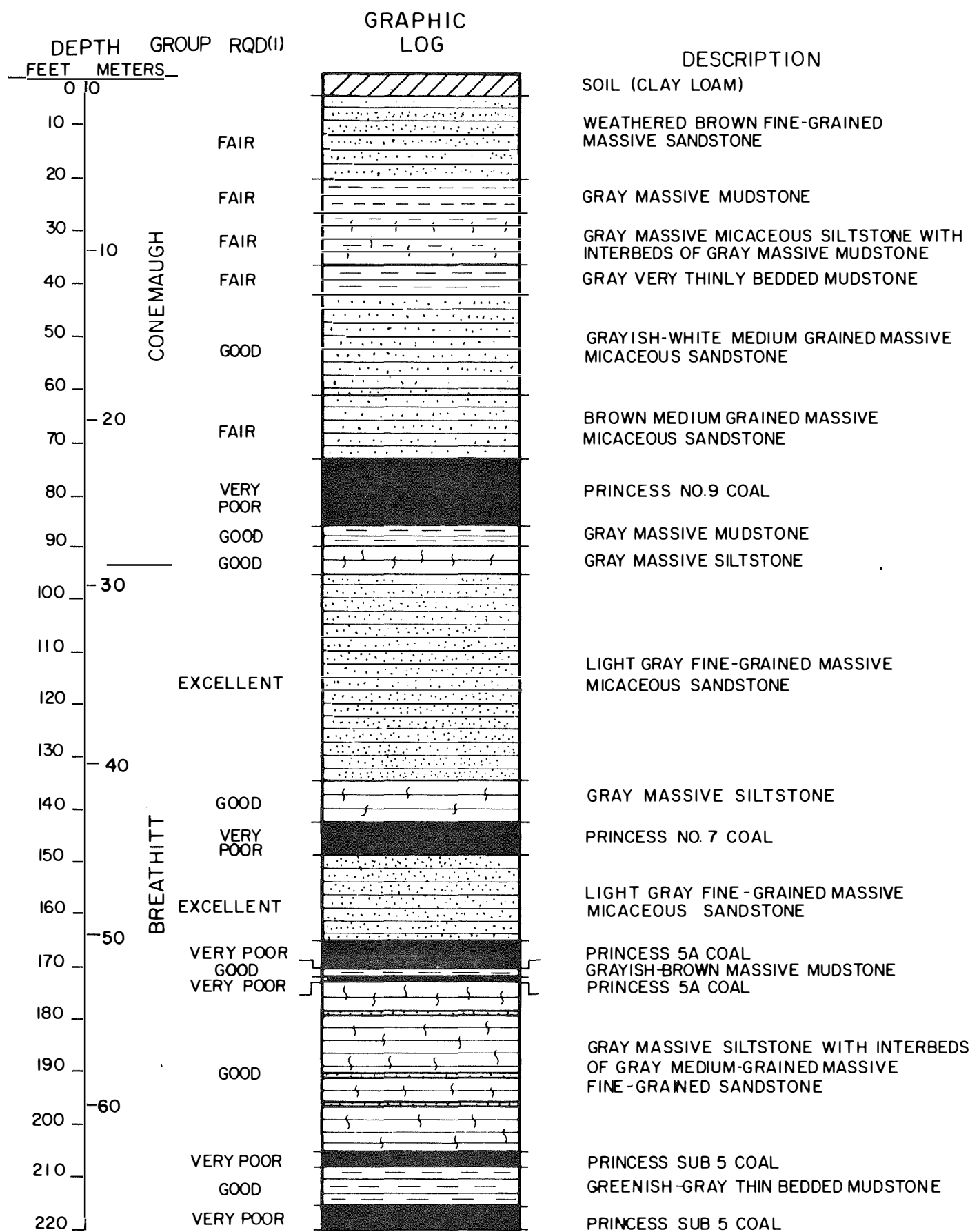
LITHOTYPE	MODE OF SLAKING ⁽¹⁾	PERCENT OF OVERBURDEN ⁽²⁾	BEDDING	RQD ⁽³⁾	ADDITIONAL FEATURES
Brown sandstone	Slab or block	10	Massive	Fair	
White to light gray sandstone	Slab or block	50	Massive	Good to excellent	Micaceous, occasional carbonaceous interbeds
Siltstone	Chip	20	Massive	Good	Occasional interbeds of carbonaceous materials
Intercalated sandstone/siltstone	N.O. ⁽⁴⁾	20	Parallel beds, spaced 0.5 - 5.0 inches (1.3 - 12.7 centimeters)	Fair to good	Micaceous, occasional interbeds of carbonaceous materials

(1) Modes of slaking are defined in Section 9.1.1.

(2) Percent composition based on visual estimates of highwall and rock core.

(3) RQD = Rock Quality Designation (Section 7.1.2).

(4) This lithotype not observed in spoils.



(I) AVERAGE VALUE PER LITHOLOGIC UNIT.

GENERALIZED STRATIGRAPHIC COLUMN SITE C

FIGURE 6-3

Two-year spoil comprises a flat fill area with the last cut of spoil left in a ridge about 30 feet (9 meters) high and 150 feet (45 meters) wide parallel to the highwall. Spoil was fertilized as needed and seeded with a mixture of grasses and legumes. A pebble pavement is present and covers 90 to 100 percent of the surface of this spoil.

Fresh spoil is located in head-of-hollow fills which are currently under construction. The dumped lifts are compacted and graded to slopes of less than five percent, with very steep fill outslopes. When construction is complete, these fill areas will be topsoiled with material derived from the native soil and seeded with a mixture of grasses and legumes. The mountaintop removal area, when completed, will be graded to a rolling plateau, topsoiled, and also seeded with a mixture of grasses and legumes. No major erosion or slope stability problems, nor adverse environmental effects of slaking, were observed at any of the spoil areas.

6.4 SITE D

Site D is located in north central West Virginia on the Appalachian Plateaus. It is characterized by steep hills at elevations of approximately 1,100 to 1,500 feet (335 to 450 meters). Slopes on undisturbed areas average 30 percent and are 200 to 500 feet (60 to 150 meters) in length. Colluvial deposits, springs, slips, and small landslides are common on undisturbed terrain indicative of weathering and natural slaking processes in this area. Spoils mined under OSM regulations are reclaimed to approximate the premining topography.

The study area has a typical continental climate with cold winters and warm humid summers. Yearly precipitation averages approximately 42 inches (107 centimeters) (U.S. Department of Commerce, NOAA, 1977-1978) and is well distributed throughout the year. Occasionally heavy rains occur in the summer while spring and fall are characterized by gentle, low-intensity rains. Most winter precipitation occurs as snow. The average temperature is 10 degrees Celsius with extremes ranging from approximately -30 to 40 degrees Celsius.

The study area has been underground mined; however, precise records of previous mining were not available. Current surface mining operations began about 1969. Initially partial or modified haulback methods were utilized while newer spoils have been placed by complete haulback techniques. Augering has been instituted in some areas to increase coal recovery. Ongoing surface mining operations have alleviated several point sources of acid mine drainage emanating from the abandoned underground workings.

6.4.1 Geologic Conditions

The Pittsburgh coal, which is the target seam at this site, is the basal member of the Monongahela Group of the upper Pennsylvanian System (Table 3.8). The associated overburden lithologies are among the

younger rocks of the eastern coal measures and contain a high percentage of argillaceous materials.

Typical overburden thickness at this site is 150 feet (45 meters) but ranges from 120 to 200 feet (35 to 60 meters). Three major lithologies are present in the overburden; their properties are summarized in Table 6.4. A generalized stratigraphic column is shown in Figure 6-4. Lithologies and unit thicknesses are laterally consistent throughout the site based on rock core and highwall observations with the exception of the limestone which is locally replaced by mudstone. Localized, massive, channel sandstones were also observed. The entire section dips two to three degrees to the northwest. No major faults, folds, or fractures were observed; however, blasting-induced fractures are present in limestone and mudstone units. Slickensides are present in the mudstone units, indicative of past movement in this lithotype. Water was encountered during the drilling program at a depth of approximately 150 feet (45 meters) and appeared to be associated with the limestone unit between the Redstone and Pittsburgh coals. Some seepage associated with the Pittsburgh coal also was observed.

6.4.2 Mining Technology and Spoil Handling

Site D is a two seam, haulback operation covering approximately seven to eight linear miles (11 to 13 kilometers) since the inception of mining. Active operations cover approximately 70 to 80 acres. The size of this site and duration of mining are somewhat greater than typical haulback operations in this region.

The Redstone overburden is drilled and shot in three lifts while the Redstone-Pittsburgh interburden is drilled and shot in two lifts. Spoil is loaded into 50-ton-capacity trucks by end loaders, hauled back to a previously mined area, and end dumped into the fill area. Spoil located in access areas is subjected to constant heavy truck traffic which significantly influences the slaking process. Surficial spoil located in access areas appeared to be compacted to a depth of about six inches (15 centimeters). Sandstone and limestone fragments had apparently been crushed by truck traffic into particles typically smaller than about one inch (2.5 centimeters). Less traveled spoil areas contained sandstone and limestone fragments three to six inches (7.5 to 15 centimeters) in size. The spoil surface appeared to be less compacted in these areas also. Surficial spoil in heavy traffic areas contained few recognizable mudstone fragments; these materials had apparently been crushed to their constituent particle size. The resulting materials consisted of a fine powder when dry and a liquefied mud when wet. Heavy truck traffic evidently accelerates slaking by crushing, shearing, and mechanical abrasion of rock fragments.

The dumped spoil is graded by D-9 bulldozers to smooth slopes, 200 to 500 feet (60 to 150 meters) long. The gradients range from 20 to 35 percent and the highwall is completely covered. Two- and five-year

TABLE 6.4
SITE D: SUMMARY OF LITHOLOGIC PROPERTIES

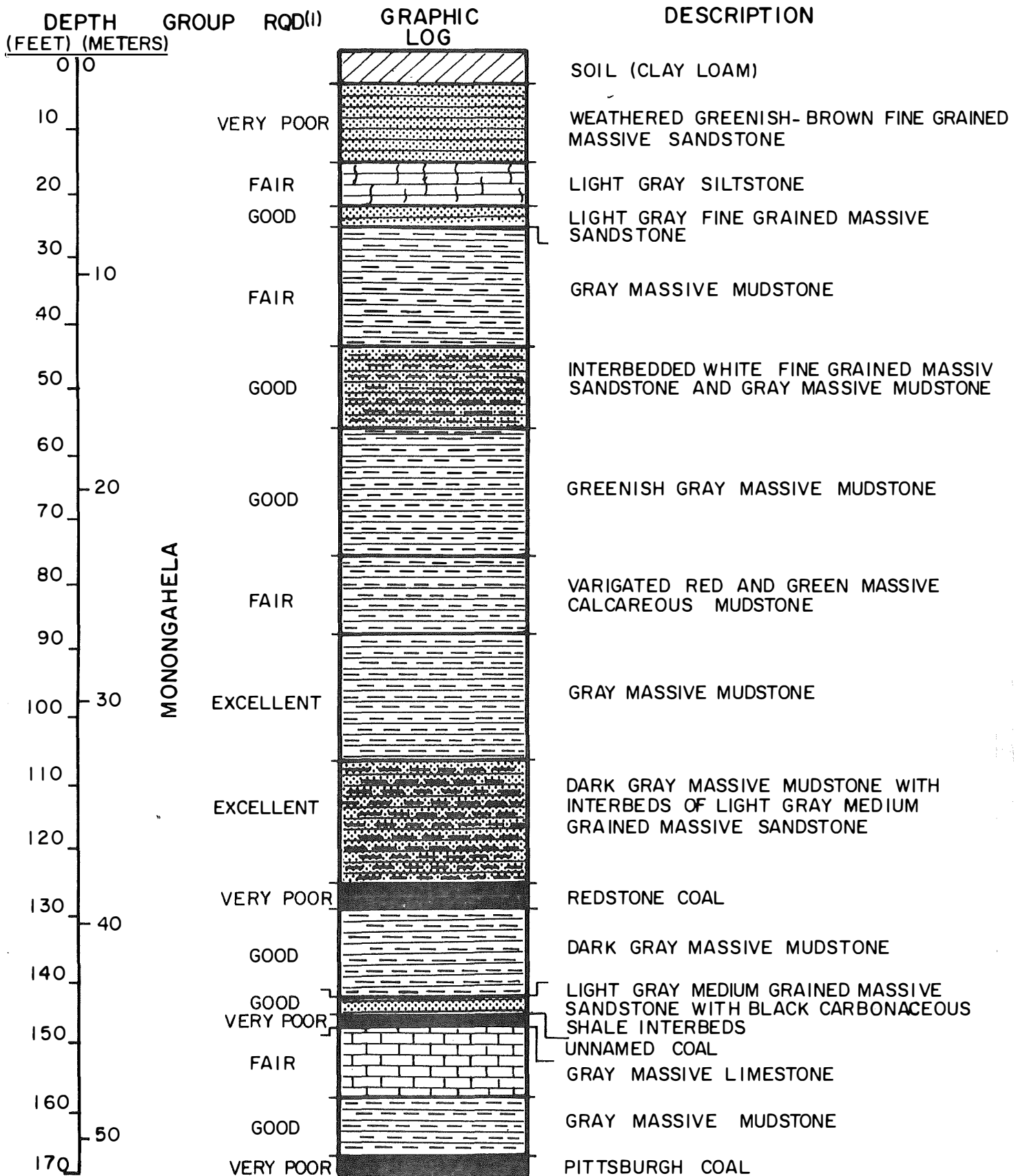
LITHOTYPE	MODE OF SLAKING ⁽¹⁾	PERCENT OF OVERBURDEN INTERBURDEN ⁽²⁾	BEDDING	RQD ⁽³⁾	ADDITIONAL FEATURES
Red-green mudstone	Chip, slake to constituent grain size	10	Massive	Very poor to poor	Calcareous
Gray limestone	Slab	10	Massive	Good	None
Gray to green mudstone	Chip, slake to constituent grain size	65	Massive	Fair to good	Occasionally calcareous
White to light gray sandstone	Slab or block	15	Massive	Good	None

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(1) Modes of slaking are defined in Section 9.1.1.

(2) Percent composition based on visual estimates of highwall and rock core. Remaining 10 percent of overburden consists of carbonaceous shale, sandstone, and soil.

(3) RQD = Rock Quality Designation (Section 7.1.2).



(I) AVERAGE VALUE PER LITHOLOGIC UNIT.

GENERALIZED STRATIGRAPHIC COLUMN

SITE D

FIGURE 6-4

spoils were graded to a nearly level, wide bench with the uppermost 30 feet (9 meters) of the highwall left exposed. Benches are 100 to 500 feet (30 to 150 meters) wide with slopes of five percent or less, and the partially backfilled highwall area consists of slopes 100 to 200 feet (30 to 60 meters) long and gradients of approximately 40 percent. Ten-year-old spoil was graded to a flat bench with excess spoil placed on the outslope and spoil from the last cut left in a low ridge parallel to the highwall.

6.4.3 Reclamation Techniques

Reclamation techniques used at Site D have become more intensive during the past ten years due to changing laws and technological improvements. Ten-year-old spoil received minimal grading after placement and was seeded with a mixture of grasses, legumes, and shrubs. Naturally invading woody species are also abundant on this age spoil. The spoil ridge parallel to the highwall appears to be effective in controlling erosion and mass wasting of the highwall. Stability problems in the form of shallow slips and failures were evident on the bench and outslope areas. These slope movements are initiated or accelerated by several natural springs which occur in the area.

Several sediment ponds located in the valley appear to be effective in preventing excessive sediment loads from entering the natural drainageway. A dense stand of vegetation in conjunction with a surface pebble pavement of limestone fragments helps control surficial erosion.

Five-year spoil was graded to partially eliminate the highwall, leaving the upper 30 feet of highwall exposed. Excess spoil was disposed of by extending the bench area. Bench width ranges from 100 to 300 feet and the outslope was graded to blend with the existing natural slopes. The area was seeded with a mixture of grasses and legumes and some areas are used for hay production or pastureland. Small shallow slope failures are present on backfilled highwall areas and outslopes. Diversion ditches, approximately one foot (30 centimeters) deep and cut on the contour, are present on the outslope and are used to channel runoff into sediment ponds. The sides of several ditches had failed or were eroding due to a relative lack of slake-resistant riprap in the ditches. Several natural seeps or springs are present and, where not controlled by drain pipes, were causing slips and gully erosion. Sediment ponds appeared to effectively alleviate sedimentation of natural drainageways. A pebble pavement, consisting of sandstone and limestone fragments in conjunction with a dense stand of vegetation appears to control sheet erosion.

Two-year spoil was graded to eliminate the highwall and approximate the original contour. The backfill is as much as 750 feet wide and steep (approximately 50 percent slopes) near the final cut. The remainder of the backfill was graded to gentle slopes (approximately 15 percent) similar to the natural bench which existed prior to mining.

The area was mulched with hay and seeded with a mixture of grasses and legumes. Slope stability problems were not apparent on this spoil which may be due to a spoil base of massive sandstone. Surficial erosion is controlled by a dense stand of vegetation and a pebble pavement consisting primarily of limestone and some sandstone fragments.

Fresh spoil is regraded to completely cover the highwall and approximate the premining topographic conditions. Consequently, this spoil receives more extensive grading, thus altering the slaking process of this spoil. Final reclamation was not complete at the time of sampling and observations; however, plans call for the spoil to be covered with approximately one foot of topsoil derived from the native soil by dumping from trucks and grading with bulldozers. The area will then be mulched with hay and seeded with a mixture of grasses and legumes. Due to the presence of three working pits and seasonal factors, final reclamation activities are completed six months to two years after initial excavation.

7.0 PREVIOUSLY DEVELOPED SLAKING-RELATED CLASSIFICATIONS AND LABORATORY TECHNIQUES

To develop an understanding of the slaking process as it relates to mine spoils, a comprehensive evaluation of existing data was undertaken. Because much of the previous work pertained to disciplines unrelated to mine spoil studies, the data were collectively examined so that relatable aspects of each could be included. For example, many previous investigations into the deterioration of geologic materials have been associated with highway embankments (e.g., Deo, 1972; Laguros, 1972; Chapman, 1975; Strohm, 1978) with much emphasis having been placed upon simulating various compaction procedures. Because surface mining spoils are usually reclaimed with a minimum of compaction, this aspect had to be removed prior to the incorporation of these studies. A brief summary of the various classification and laboratory tests that have been specifically related to slaking processes and the major conclusions of these studies are discussed in the following sections.

7.1 CLASSIFICATION

A wide range of classification systems has been utilized to describe geologic materials with particular reference to slaking. These may be broadly categorized as either taxonomic or engineering (technical) systems. Taxonomic systems are designed to bring out inherent relationships between material properties while technical classification systems are generally designed to serve some practical or applied purpose such as behavioral prediction. Accordingly, technical or engineering classification systems represent the majority and have provided the more useful approaches for describing the slaking of geologic materials.

7.1.1 Taxonomic Classification Systems

The materials of interest in surface mining in the eastern and central United States and the most susceptible to slaking are predominantly sedimentary rocks. Because of the polygenetic nature of sedimentary materials, however, no universally acceptable classification has yet been established. Several examples of this type include the generalized classification of sedimentary rocks (Deo, 1972), compositional and textural systems (Krumbein and Sloss, 1963), and systems developed to isolate a particular class or type of material such as the classification of argillaceous materials developed by Gamble (1971). Although each of these systems has been used with some success, the major thrust of each has been to develop a verbal description of genesis and rock type, independent of potential behavior.

To alleviate this type of problem, nomenclature systems have been proposed in conjunction with various taxonomic systems to identify particular structural or behavioral characteristics. Such modifying terms as compaction or cemented, fissile or shaly, and massive, flaggy, or flaky are commonly used in the discussion of argillaceous materials.

7.1.2 Engineering (Technical) Classification Systems

Engineering classifications of geologic materials generally take the form of either a quality grouping or a specific set of index test results which are empirically correlated with material behavior. Quality groupings are often subjective and closely associated with a specific type of engineering problem; for example, a material considered to be durable for one purpose may be considered weak for another. Index test classifications are generally the most objective and are usually relatively independent of specific design objectives. In many cases, quality groupings are based on the results of index tests interpreted for specific types of engineering problems.

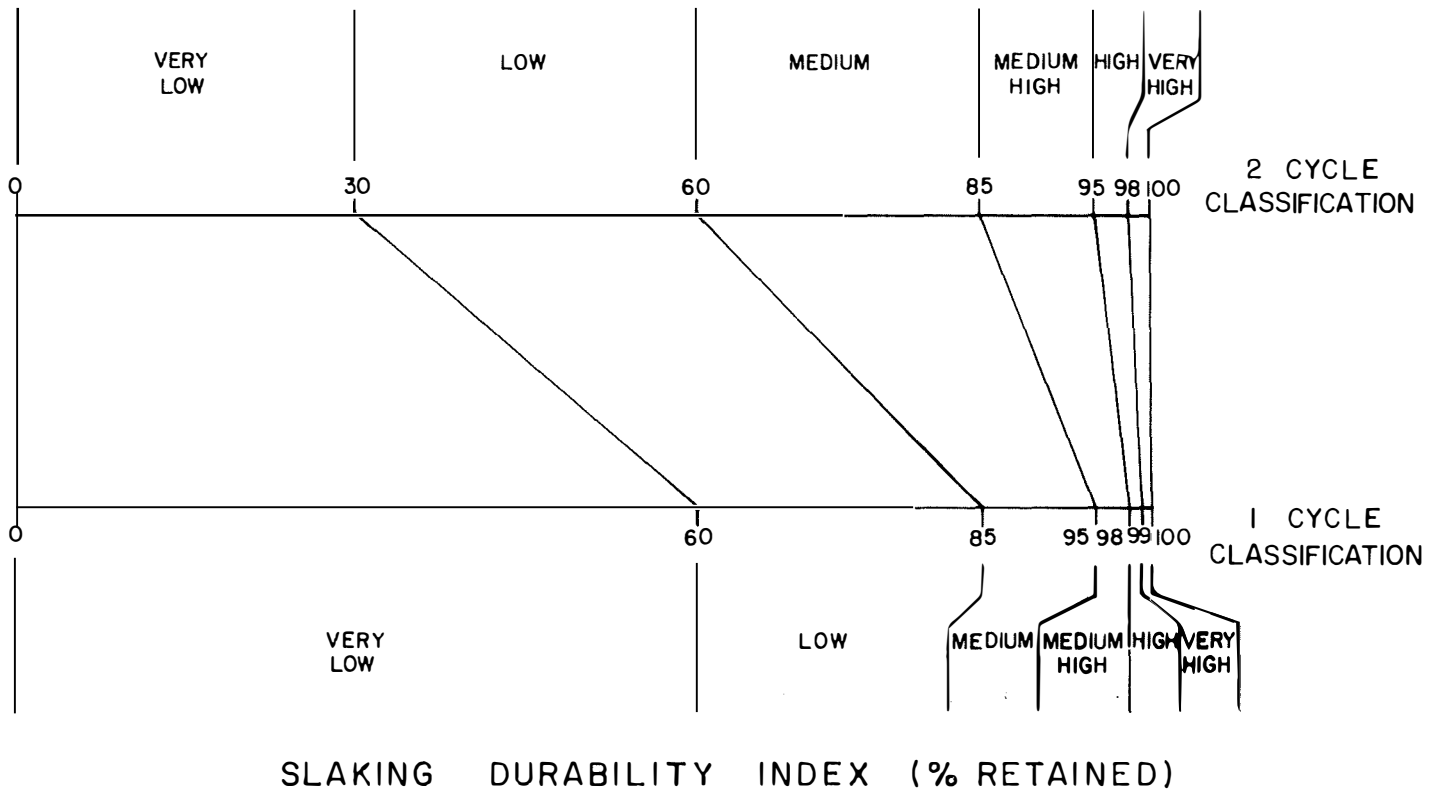
The engineering classification schemes that have been proposed are of two types: those based on a single parameter and those based on multiple indices. The first type is, of course, the simplest. It is a subjective quality grouping based on a single index test parameter, such as the slake durability index, I_d (e.g., Chandra, 1970; Gamble, 1971). The second type may take several forms; it may be a matrix-type classification based on two index test parameters (e.g., Eigenbrod, 1972; Gamble, 1971), a multiple factor ranking system (e.g., Reidenouer, et al., 1974, 1976), or a flow chart-type system involving one or more tests (e.g., Deo, 1972; Eigenbrod, 1972; Strohm, et al., 1978).

Single Index Classifications

Chandra (1970) proposed a tentative slake durability classification based on a ranking of the single-cycle slake durability index (I_d , defined in Section 9.2.1). Subsequently, Gamble (1971) proposed a somewhat different classification based on a two-cycle slake durability index. The classification boundaries defined in Figure 7-1, were designed to extend the classification, particularly in the low durability ranges. After reviewing Gamble's work, Franklin and Chandra (1972) favored his system over their own and presently the two-cycle classification model is widely accepted (International Society of Rock Mechanics, 1979).

As one component of a more comprehensive classification system, Deo (1972) proposed an alternate grouping based on a modified sodium sulfate soundness index (I_s). This classification follows:

- Soil-like shales: $I_s = 0$ to 70 percent
- Intermediate-2 shales: $I_s = 70$ to 90 percent
- Intermediate-1 shales: $I_s = 90$ to 98 percent
- Rock-like shales: $I_s = 98$ to 100 percent



REFERENCE

GAMBLE, J. C., 1971, "DURABILITY-PLASTICITY CLASSIFICATION OF SHALES AND OTHER ARGILLACEOUS ROCKS," PH.D. DISSERTATION, UNIVERSITY OF ILLINOIS, URBANA, ILLINOIS, 161 pp.

**SLAKE DURABILITY INDEX CLASSIFICATION
SUGGESTED BY GAMBLE**

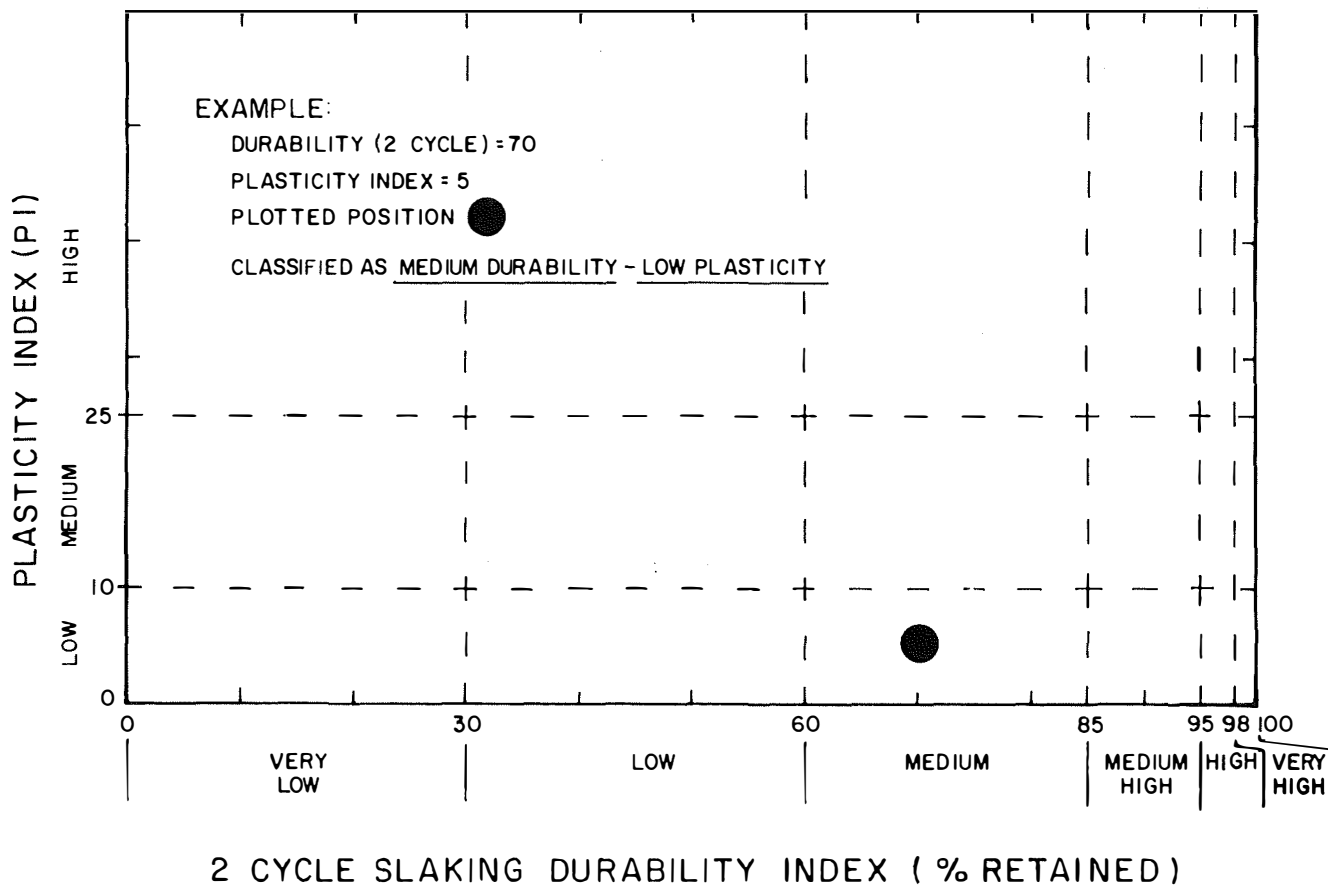
Noble (1977) proposed a similar system based upon the same index. Both of these classifications were designed to assist in material evaluation for embankment construction.

Multiple Index Classifications

Gamble (1971) recognized that plasticity has perhaps equal importance to slake durability properties in determining engineering behavior of geologic materials. He noted evidence of correlation between liquid limit or plasticity index and residual shear strength and swelling potential. The latter two properties may have great significance, particularly following disintegration of rock materials. Therefore, Gamble (1971) proposed a matrix classification system based on a two-cycle slaking durability and plasticity index, as illustrated in Figure 7-2. This type of classification may be useful because it is possible that medium durability-high plasticity materials can pose greater engineering problems than low durability-low plasticity materials. He suggested use of his classification terms as modifiers along with the geologic classification of the material (e.g., medium durability-low plasticity silty shale).

Eigenbrod (1972) developed another matrix classification which was subsequently modified by Morgenstern and Eigenbrod (1974) and is presented in Figure 7-3. This scheme is based on index parameters different from those used by Gamble (1971), i.e., the liquid limit (w_L) and the rate of change of liquidity index following immersion of an oven-dried sample. Eigenbrod (1972) observed a high correlation between the amount of slaking experienced by a material during cyclic wetting and drying and its liquid limit as follows:

- Very low slaking: w_L less than 20 percent; only slight disintegration and opening of fissures can be observed.
- Low slaking: w_L ranges from 20 percent to 50 percent; the materials generally disintegrate into a granular discontinuous mass.
- Medium slaking: w_L ranges from 50 percent to 90 percent; the materials disintegrate into a medium soft clay but often do not lose a granular structure.
- High slaking: w_L ranges from 90 percent to 140 percent; the materials disintegrate into a soft clay of homogeneous materials.
- Very high slaking: w_L greater than 140 percent; materials may quickly lose their original structure.



REFERENCE

GAMBLE, J. C., 1971, "DURABILITY-PLASTICITY CLASSIFICATION OF SHALES AND OTHER ARGILLACEOUS ROCKS," PH.D. DISSERTATION, UNIVERSITY OF ILLINOIS, URBANA, ILLINOIS, 161 pp.

DURABILITY - PLASTICITY CLASSIFICATION FOR SHALES AND OTHER ARGILLACEOUS ROCKS SUGGESTED BY GAMBLE

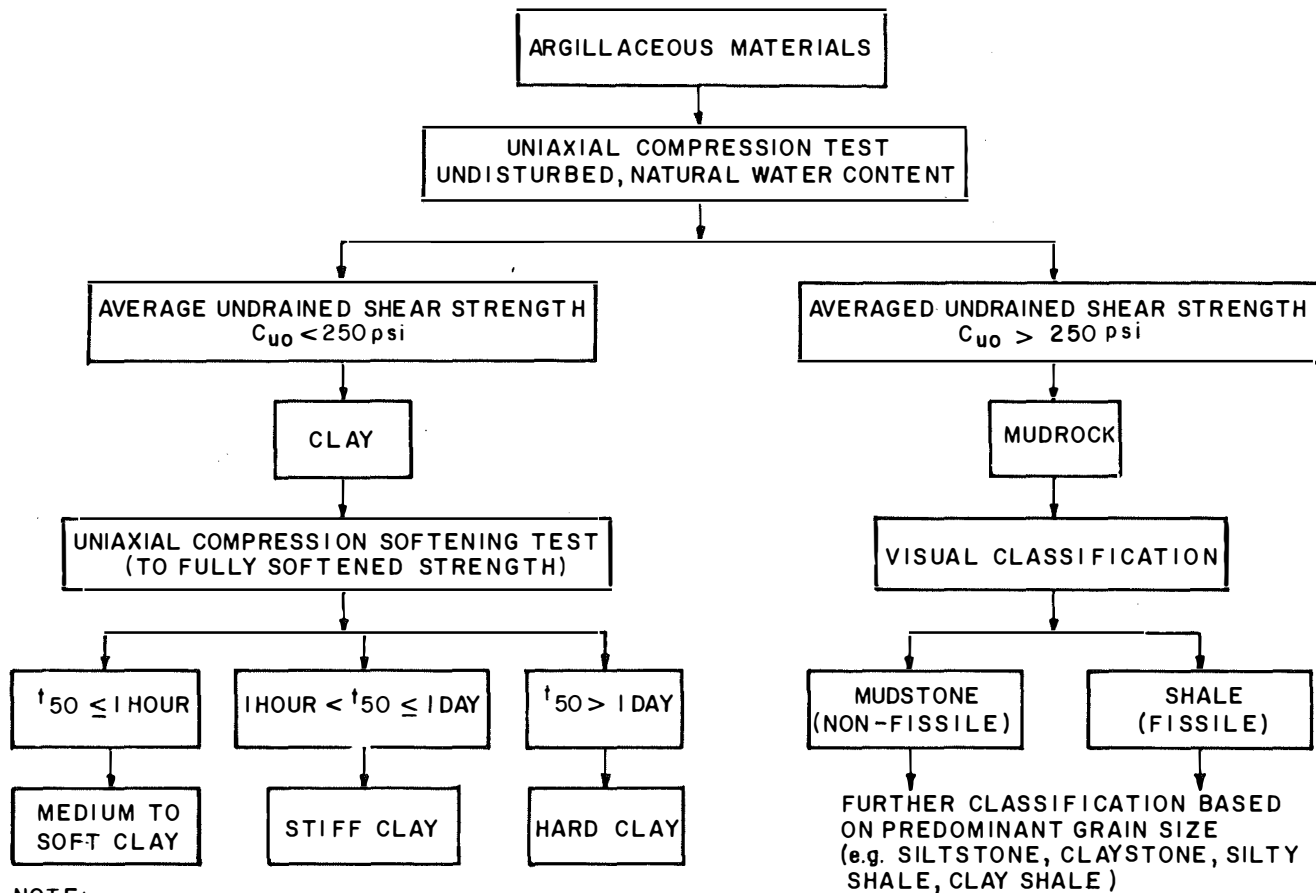
Although these correlations are tentative, being based exclusively on Eigenbrod's (1972) tested materials, there is logic to the above correlation; liquid limits are strongly influenced by clay mineralogy (Seed, et al., 1964) with high values generally being indicative of significant contents of highly active clay minerals. Chapter 2.0 suggested that these clay minerals (e.g., montmorillonite) may have a strong influence on several important mechanisms. One source of potential problems with this approach is that sample preparation techniques, such as drying and disaggregation methods, may have a strong influence on liquid limit values obtained. To overcome this limitation, Hudec (1978) suggested that the rate of water content change used to indicate the degree of breakdown be based on a more readily determined parameter using several wetting and drying cycles and various drying temperatures.

Multiple factor ranking classifications have been developed to identify slaking potential (Reidenouer, et al., 1974, 1976; Cottiss, et al., 1971a, 1971b) using diverse groupings of field and laboratory test indicators. These systems are based on weighting factors with test results providing an index or score that can be related to slaking. The major disadvantages of these models, however, are the need to perform several time consuming and often costly tests to develop a score or index value, and the difficulty associated with correlating index values from site to site.

To eliminate the need to potentially run a single material through several series of tests, several flow path or flow chart classification schemes have been devised (Morgenstern and Eigenbrod, 1974; Deo, 1972; Strohm, et al., 1978). Morgenstern and Eigenbrod (1974) proposed a classification system for argillaceous materials based on undrained shear strength (c_u) and rate of strength loss during saturation and softening (Figure 7-3). A series of standard compression tests and water content determinations were performed prior to, and at various time intervals during sample immersion until a fully softened strength was obtained.

Deo (1972) proposed a flow chart classification system, illustrated in Figure 7-4, which provides several alternatives for testing and classification system design. The system has the advantage of showing relationships among the various tests while providing classification boundaries for each test type.

Strohm, et al. (1978) modified Deo's (1972) flow chart concept, incorporating certain aspects of both Gamble's (1971) and Morgenstern and Eigenbrod's (1974) classification systems, and adding the concept of visual description. Their classification system, illustrated in Figure 7-5, added an apparently new concept to the two-cycle slake durability test recommended by Gamble (1971) and Franklin and Chandra (1972); that is, visual and "hand-durability" descriptions of the material retained in the slaking chamber.



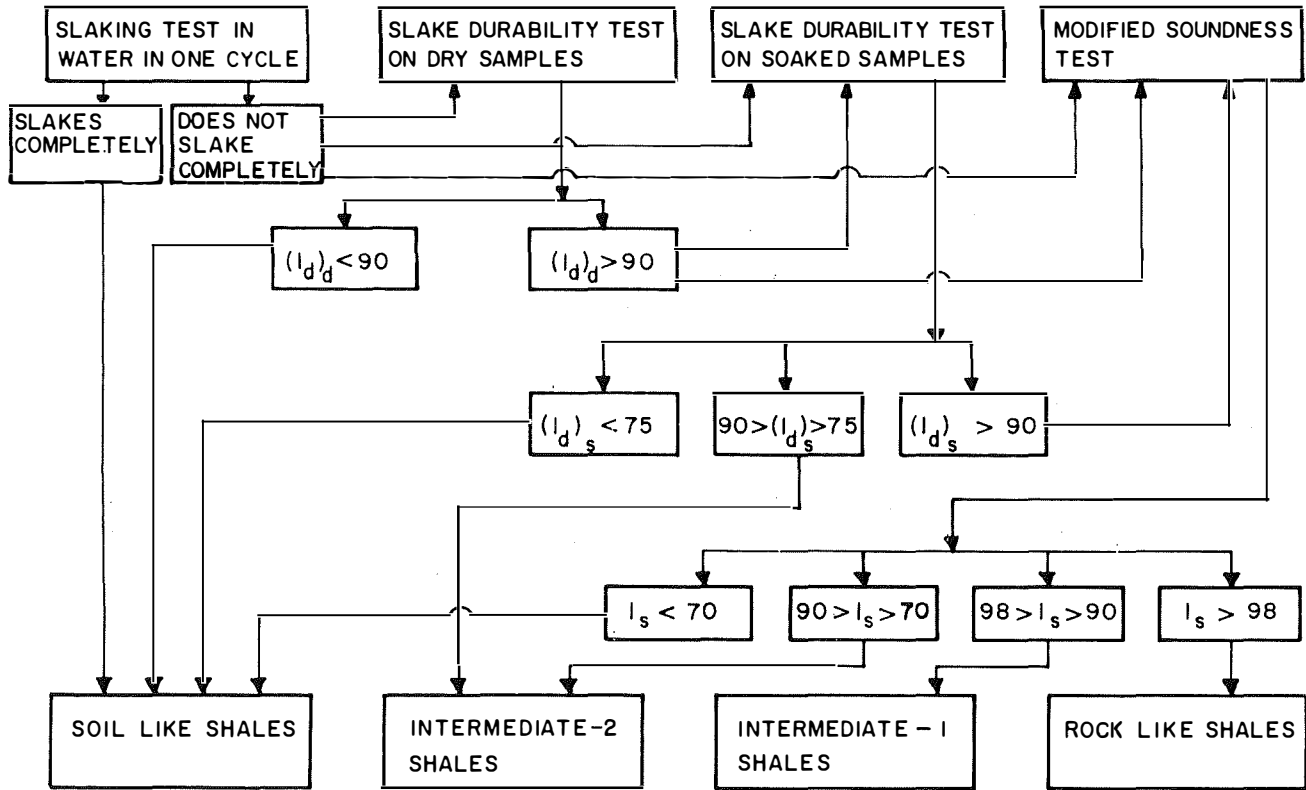
NOTE:

t₅₀ IS TIME OF SOFTENING FOR
LOSS OF 50 PERCENT OF C_{uo}.

REFERENCE

MORGENSTERN, N. R. AND K. D. EIGENBROD, 1974,
"CLASSIFICATION OF ARGILLACEOUS SOILS AND ROCK,"
JOURNAL OF THE GEOTECHNICAL ENGINEERING DIVISION,
ASCE, VOL. 100, NO. GT10, PP. 1137-1156.

ENGINEERING CLASSIFICATION OF
ARGILLACEOUS MATERIALS



REFERENCE

DEO, P., 1972, "SHALES AS EMBANKMENT MATERIALS, FINAL REPORT," JHRP-72-45, INDIANA STATE HIGHWAY COMMISSION AND PURDUE UNIVERSITY, ENGINEERING EXPERIMENT STATION, JOINT HIGHWAY RESEARCH PROJECT, WEST LAFAYETTE, INDIANA, 202 PP.

DURABILITY CLASSIFICATION SYSTEM FOR SHALE EMBANKMENTS SUGGESTED BY DEO

In Situ Classification of Geologic Materials

Classification of the in situ condition and quality of geologic materials may include aspects of both taxonomic and engineering classification systems. Several investigators have proposed in situ classification systems, most notably Deere, et al. (1969), Aufmuth (1974a), and the Imperial College group in London, England (Franklin, 1970; Fookes, et al., 1971; Saunders and Fookes, 1970; Cottiss, et al., 1971a and b). Despite this work, no single system has yet become widely accepted and applied. Certain aspects of in situ classification may have relevance to field assessment of slaking potential, selection of samples for further slake durability testing, or the description of the state of deterioration within surface mine spoil piles. These in situ classifications consider discontinuity spacing, weathering, and rock strength.

Discontinuities include fractures, fissures, joints, cleavages, bedding planes, and fault planes. Very closely spaced discontinuities, particularly in argillaceous materials, increase the potential rates of water penetration or drying and, thus, the potential rate of slaking. A wide range of different classifications has been proposed for discontinuities, mostly based on thickness or spacing. The most widely used discontinuity classification system was developed by Deere, et al. (1969) for use specifically with NX (2-1/8 inch, 54 millimeters) size rock core. This system, referred to as Rock Quality Designation (RQD), requires the measurement of all naturally occurring fragments longer than four inches (approximately ten centimeters). The RQD is determined by expressing the sum of these lengths as a percentage of the total length of the particular core run. The RQD numbers are then classified according to the following categories:

- Very poor: RQD = 0 to 25 percent
- Poor: RQD = 25 to 50 percent
- Fair: RQD = 50 to 75 percent
- Good: RQD = 75 to 90 percent
- Excellent: RQD = 90 to 100 percent

The relationship between RQD and the proportion of materials susceptible to slaking has received little attention. Further investigation into this potential relationship may be valuable.

A number of weathering grade classifications have been proposed but are mostly concerned with geotechnical design problems. Because these have been developed for particular sites, the validity of a particular model outside the area may be low (Fookes, et al., 1971). Therefore, the development of a generalized model to describe the slaking of surface mine spoil may not be possible.

The estimation of in situ strength properties of geologic materials has great significance to many engineering applications and is also relevant to prediction of slaking behavior to some degree, as suggested by Morgenstern and Eigenbrod's (1974) flow chart classification. A major

factor in developing in situ strength classification systems is the selection of a test that can be carried out easily in the field and preferably one which requires no sample preparation. In situ tests are generally considered to be preferable to laboratory tests due to the lack of sample disturbance, moisture loss, and other problems.

Several portable testing devices have been utilized for field strength classification, including the Schmidt Rebound Hammer (Aufmuth, 1974a), the Point Load Device (Fookes, et al., 1971; Franklin, 1970; and others), and the Field Shear Test (Aufmuth, 1974a). Of these tests, the point load test has gained the widest acceptance. The Schmidt Rebound Hammer has been found to provide generally unreliable values for softer shales because this device was originally designed for use with much harder materials (Chapman, 1975).

7.2 MATERIAL TESTING

The principal objectives of laboratory testing programs relating to the slake durability of geologic materials have been as follows:

- To assess the applicability of accelerated rock weathering tests that can be used to help predict long-term performance.
- To find additional tests that can quickly identify problem materials.
- To quantify, to some degree, the effects of time-dependent rock degradation caused by various slaking mechanisms.

This has led to the development of diverse programs which consist of many standard and modified geotechnical tests. Since much of the work has involved highway-related problem areas, laboratory tests germane to that field of study have been used either directly (e.g., sand equivalent and Los Angeles abrasion tests) or in somewhat altered formats (e.g., modified sodium sulfate test) to evaluate the susceptibility of geologic materials to slake. Frequently, new test procedures have been developed specifically to study slaking (e.g., the slake durability test [Franklin and Chandra, 1972]). A summary of research efforts and general survey studies associated with durability testing programs is presented in Table 7.1. In this summary, tests have been classified according to their nature and applicability into identification (physicochemical and mineralogical), durability, and strength tests.

A limited number of index tests are usually selected for a given engineering problem to serve as a basis for classification, behavioral prediction, and planning for design or materials management. These tests generally include both identification tests, such as grain size and mineralogy, and behavioral tests, such as rate of slaking. Ideally, the simplest and most reliable indicators are sought for a given purpose.

TABLE 7.1
SUMMARY OF LABORATORY TESTS ASSOCIATED WITH SLAKING

REFERENCE	IDENTIFICATION TESTS							DURABILITY TESTS							STRENGTH TESTS									
	PHYSICO-CHEMICAL					MINERAL-OGICAL																		
	WATER CONTENT	GRAIN SIZE	ATTERBERG LIMITS	UNIT WEIGHT	SPECIFIC GRAVITY	pH	CHEMICAL ANALYSIS	PETROGRAPHIC EXAMINATION	X-RAY DIFFRACTION	METHYLENE BLUE ABSORPTION	JAR SLAKE (1)	CYCLIC WET-DRY(2)	RATE OF ABSORPTION	RATE OF SLAKING	SLAKE DURABILITY	WASHINGTON DEGRADATION	ULTRASONIC DEGRADATION	L. A. ABRASION	FREEZE-THAW	SWELLING TESTS	UNCONFINED AND TRIAXIAL COMPRESSION	POINT LOAD	SCHMIDT HAMMER	SHORE HARDNESS
Gamble (1971)	●	○	○	●					○		○	○			●					○				
Heley and MacIver (1971)	○	○	○	○					○		○	○								○				
Deo (1972)		○	○	○					○		●	○			●			○						
Eigenbrod (1972)	●	○	●						○		○		●								○			
Laguros (1972)		●			○	○		○	●		●						○			●				
Aufmuth (1974a. b)															●						○		●	
Goodman, Heuzé, Thorpe, and Chatoian (1974)	○			○											●						○		●	
Nettleton (1974)			○						●						●									
Reidenouer, Geiger, and Howe (1974)		○	○	○				○	●		●	○	○		●	●	●	○						
Chapman (1975)	●		●						○		●	●	●	●	●	○	○	○					○	
Augenbaugh and Bruzewski (1976)	●		○									●			○					○	○			○
Bailey (1976)	○	●									○											○		○
Rodrigues (1976)															○									○
Lutton (1977)	○					○			○		●				●									○
Noble (1977)						○			●		●	●			○									○
Strohm (1978)	○	○	○								○	○			○							○		
Strohm, Bragg, and Ziegler (1978)			○		○						○	○	○		●						○			
Hudec (1978)	●			○							●	●	○		●					○				

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

LEGEND:

- - Test conducted.
 ● - Fair to good correlation with durability.

For research investigations, correlation of simple indicator tests (such as grain size or Atterberg limits) with more sophisticated tests (such as mineralogical analyses by X-ray diffraction) can serve a useful purpose. The following sections examine the details and suitability of particular tests to the study of surface mine spoils.

7.2.1 Identification Tests

As shown in Table 7.1, the identification tests (physico-chemical and mineralogical) that have been utilized in the past as part of several comprehensive laboratory programs have consisted of the following:

- Physico-Chemical
 - Natural Water Content
 - Grain Size Distribution
 - Atterberg Limits
 - Unit Weight
 - Specific Gravity
 - pH
 - Chemical Analysis

- Mineralogical
 - Petrographic Examination
 - X-Ray Diffraction
 - Methylene Blue Absorption

A brief discussion of the purpose and success in characterizing or identifying slaking is discussed below in the presented order.

Natural Water Content

The natural water content has been shown to be a generally good indicator of the durability and quality of geologic materials. This conclusion is supported from the results of several studies related to mineralogy and state of weathering (Gamble, 1971), the rate of slaking for overconsolidated clays and mudstones (Eigenbrod, 1972), shale embankments (Chapman, 1975), and the stability of coal mine roofs (Augenbaugh and Bruzewski, 1976). Based upon these observations, the natural moisture content of intact highwall materials and surface mine spoils may control, to a large degree, the degradation and resulting stability and settlement performance of spoil piles. Similar observations have been reported for spoil heaps in Great Britain (National Coal Board, 1972).

Grain Size Distribution

Grain size distribution forms the basis for many soil and rock classification systems. Accordingly, several slaking studies have included particle size determinations within their scope of testing to examine the influence of grain size distribution on the deterioration of materials. The most conclusive evidence of particle size effects has

been reported by Laguros (1972). He found, in a study of Oklahoma shales, that combined amounts of silt and clay size particles greater than 40 percent result in durability problems in the field. Since durability is often controlled by factors other than grain size (e.g., clay mineralogy), most studies have included particle size distributions as additional supportive evidence in classifications of field behavior (Gamble, 1971; Reidenouer, et al., 1974).

Because of the problems associated with the various disaggregation methods, an accurate and reproducible determination of the particle size distribution for fine-grained rocks is often not possible (Heley and MacIver, 1971; Deo, 1972; Laguros, 1972; Reidenouer, et al., 1974). This is probably the reason for the lack of definite correlations between grain size distribution and slaking characteristics.

Atterberg Limits

The Atterberg limit values have found wide acceptance as valuable indicators of potential behavior and as reference points for several classification systems. With regard to identifying the slake potential of geologic materials, correlations have ranged from low (Reidenouer, et al., 1974) to high (Eigenbrod, 1972; Chapman, 1975). The high correlation between liquid limit and clay mineralogy reported by Seed, Woodward, and Lundgren (1964) suggests that Atterberg limits may serve as an indirect indicator of slaking potential.

It has been shown that many of the problems associated with disaggregation for grain size analyses also influence the determinations of Atterberg limits (Heley and MacIver, 1971; Laguros, 1972; Townsend and Banks, 1974). Because of the influence of clay mineralogy on the limits, sample preparation is an important factor and the results therefore can be significantly altered. This is particularly true for liquid limit values (Sangrey, et al., 1976). Comparison of reported test results is very difficult because of the number of different procedures that are available (e.g., Townsend and Banks, 1974). Because many laboratories are not equipped with specialized slake durability or ultrasonic equipment, the most acceptable procedure that can be used routinely should consist of soaking and grinding operations using geologic materials that have been preserved at the in situ moisture conditions.

Unit Weight

The unit weight of geologic materials may readily be determined using standard testing procedures (International Society for Rock Mechanics, 1979) which are routinely utilized in most geotechnical laboratories. Comparison of unit weights for siltstones and shales by Gamble (1971) generally indicated that the denser samples showed higher slake durability. The lowest unit weights and durability values are typically for montmorillonitic clay shales or mudstones and tuffaceous siltstones or shales. Weathered clay shales were also found to have low durability and unit weight values while carbonaceous shales exhibited the higher

durability and unit weights (Gamble, 1971). Based on these types of observations, particularly for materials from diverse geologic environments, unit weight may provide useful correlations with rock durability.

Specific Gravity

Although the specific gravity of solids in soils is routinely determined as a part of many geotechnical investigations, only one instance of its use was found during this review (Laguros, 1972). For that study, values of specific gravity (G_s) ranged from 2.36 to 2.80; but, since most values were between 2.72 and 2.80, no specific correlations could be made either with mineralogy or rock durability. Also, because specific gravity tests require disaggregation of the sample, the difficulties discussed previously for grain size analyses and determination of Atterberg limits are associated with this test. Therefore, unless very diverse mineralogies are expected, the value of specific gravity tests for prediction of slaking is limited.

pH Tests

Several investigators have utilized pH tests to determine if there is any correlation with durability behavior (Laguros, 1972; Lutton, 1977; Strohm, et al., 1978). No direct correlations were observed between pH measurements and material durability. The measurement of pH may, however, help identify potential acid-producing materials that might cause some further degradation if certain cements (e.g., carbonates) or component minerals (e.g., chlorite) are present in significant amounts.

Chemical Analysis

Only limited and slightly successful use of various chemical analysis in reference to slaking investigations has been reported (Noble, 1977). One possible type of test, exchangeable ion content, may provide relevant information although similar predictive information may be gained more readily by simpler, less expensive slake index tests (e.g., jar slake or slake durability tests). Exchangeable sodium percentage (ESP), which can be determined by routine soil chemical analysis techniques following disaggregation, may provide useful information as part of a research program. The routine use of ESP as a general indicator of low durability is questionable.

Petrographic Examination

The use of thin-section petrographic techniques has been reported by Reidenouer (1970) and Reidenouer, et al. (1974) in an investigation of shale durability. The identification of the coarse grained constituents did not show a significant correlation with material durability. However, identification of matrix composition did demonstrate some correlation with siliceous cements relating to enhanced durability. Another type of petrographic examination, electron microscopy techniques used

to describe the structural fabric of fine grained materials, has found only limited application as part of durability studies (Laguros, 1972). The relative complexity and time-consuming nature of these test procedures make it too costly to incorporate such tests as part of a routine durability testing program, particularly with the observed lack of a close correlation between many of the tests results and durability.

X-Ray Diffraction

The identification of clay minerals may provide useful information regarding material durability (Laguros, 1972; Reidenouer, et al., 1974; Noble, 1977). A quantitative or semiquantitative analysis of the clay mineralogical composition of a material is typically achieved by X-ray diffraction techniques or by a combination of X-ray diffraction and other techniques (Black, 1965). However, these methods are fairly expensive and time consuming. The durability behavior problems that may be influenced by mineralogical composition would be more readily detected on a routine basis by durability index tests such as those described in subsequent sections. In addition, it should be noted that although the identification of clay minerals is most likely to be suitable for elucidation of possible slaking mechanisms, it is not always a reliable indicator of low-durability materials.

Methylene Blue Absorption (MBA) Test

The previously discussed chemical and mineralogical tests are time consuming, costly, and require highly trained personnel. Because of these factors, Nettleton (1974) proposed a relatively simple test procedure which involves titrating a methylene blue trihydrate dye solution ($C_{16}H_{18}N_3SCl \cdot 3H_2O$) into an acidified soil-water solution. A related procedure referred to as Methylene Blue Index (MBI) is outlined in ASTM C 837-76 (ASTM, Part 17, 1977).

Studies of the MBA test have been used to assess the quality of argillaceous rock and have found that a significant relationship exists between the MBA and swell potential, and the Los Angeles abrasion test. These relationships suggest that the MBA technique may serve as a gross indicator of the sample's clay mineralogy. It may be particularly useful for detection of moderate to significant contents of montmorillonite. Preliminary comparisons with other durability tests (specifically the Franklin and Chandra [1972] device) have also shown good correlations. Although the MBA method has not been widely used as part of durability studies, it may potentially serve as an inexpensive substitute for more detailed analytical techniques. Its successful use in the study of the weatherability of argillaceous materials suggests that the procedure should be considered for analyses of slaking in surface mine spoil piles.

7.2.2 Durability Tests

Several types of tests have been developed or modified to provide qualitative and/or quantitative assessments of the slake potential of geologic materials. As briefly discussed in subsequent sections and

summarized in Table 7.1, several test procedures have shown moderate to very good success; others, because of severe test conditions show little apparent value. The durability tests that have been suggested consist of the following:

- Jar Slake
- Cyclic Wet-Dry
- Rate of Absorption
- Rate of Slaking
- Slake Durability
- Washington Degradation
- Ultrasonic Degradation
- L. A. Abrasion
- Freeze-Thaw
- Swelling Tests

Jar Slake Tests

Several types of jar slake test procedures have been designed to provide a simple technique for evaluating the slaking potential of geologic materials. The testing procedure consists of placing a rock fragment or prepared gradation of rock fragments into a beaker containing a solution. The slaking solution has typically been water, although hydrogen peroxide (Laguros, 1972), ethylene glycol (Reidenouer, et al., 1974), and sulfuric acid (Noble, 1977) have been successfully used for special cases. Most test procedures require rock fragments at or near the natural moisture conditions while a few suggest air or oven drying prior to immersion. Following immersion, the breakdown of the sample is observed for a period of time ranging from a few hours to several days. Description of the sample behavior is usually qualitative based on visual observations and a description such as the one discussed by Heley and MacIver (1971). By using many of these techniques, the jar slake test has been found to be a useful and simple tool for assessing the durability of geologic materials.

Cyclic Wet-Dry Tests

A more severe variation of the jar slake test is the cyclic wet-dry test that subjects immersed rock fragments to several alternating cycles of soaking followed by air drying in a desiccation chamber or in an oven. Several different variations of the basic concept have been developed and a few investigators have shown successful applications of this method (Deo, 1972; Chapman, 1975; Noble, 1977).

The most general procedure was that of Philbrick (1950) who subjected broken shale pieces to five cycles of wetting and drying and visually described the remaining fragments at the end of the last cycle. The sodium sulfate test for evaluating the soundness of aggregates for construction (ASTM C 88-73 [ASTM, 1978a]) is identical to the previous procedure except that a saturated sodium or magnesium sulfate solution is substituted as the slaking fluid. Several studies have since shown

that this test is too severe for most slakable geologic materials (Gamble, 1971; Reidenouer, et al., 1974). However, finer degrees of slaking resistance have been identified by simply reducing the solution concentration by 50 percent (Chapman, 1975; Noble, 1977). For particularly tough (durable) shales in western Virginia, Noble (1977) found that a 25 percent sulfuric acid solution provided good correlations with observed field behavior. Often, the cyclic increase in water content following each soaking sample can provide a good indication of the slaking characteristics of geologic materials (Eigenbrod, 1972).

Rate of Absorption Test

Several test procedures have been devised to monitor the rate of moisture absorption as part of other slake durability tests (Deo, 1972; Eigenbrod, 1972) or under well controlled environmental conditions (Reidenouer, et al., 1974; Augenbaugh and Bruzewski, 1976). Results of these studies have shown a general trend of increased absorption rate with decreasing durability. Although temperature and pressure conditions show little direct relationship with shale durability (Augenbaugh and Bruzewski, 1976), the inclusion of absorption data as part of other durability tests may be worthwhile.

Rate of Slaking Test

In an attempt to reduce the amount of time required to conduct cyclic wet-dry tests, Eigenbrod (1972) developed a procedure to measure the rate of slaking that was reached after two hours of soaking. A two-hour limit was established as the amount of time that was required for most of the tested materials to reach a constant water content.

The rate of slaking test has been found to be a relatively quick and reliable procedure for evaluating durability characteristics (Eigenbrod, 1972; Chapman, 1975). A possible negative aspect of Eigenbrod's method is a dependency on the Atterberg limits. The potential problems with "limits" were discussed in the previous section (7.2.1) regarding the disaggregation of geologic materials. To overcome this problem, Hudec (1978) has suggested that the rate of slake test be conducted in several cycles using various drying temperatures. The cyclic rate of water absorption can then be used as a quantitative indicator of durability.

Slake Durability Test

Chandra (1970) and Franklin and Chandra (1972) developed a test apparatus to help quantify durability and evaluate the weathering resistance of shales, mudstones, siltstone, and other clay-bearing rocks. This apparatus combines the effects of soaking and abrasion to accelerate the rate of weathering that can be obtained by water immersion alone, while maintaining a "realistic" model of field slaking processes. The original test procedure has been modified and is presently an accepted standard test procedure of the International Society for Rock Mechanics (1979).

Many investigators have successfully applied the slake durability test to a range of studies involving the weatherability of geologic materials. Investigative studies have ranged from assessments of compacted shale embankments (Deo, 1972; Chapman, 1975; Lutton, 1977) to weathering of highway cuts in shale (Goodman, et al., 1974) to classification (Nettleton, 1974).

The slake durability test has found a high degree of acceptance for a wide range of problems associated with weathering of geologic materials. This method, however, has not been used to examine problems with slaking of surface mine spoils.

Washington Degradation Test

The Washington Degradation Test, like the slake durability test, combines the effects of soaking and sample agitation to accelerate slaking processes. Although this method was primarily designed to assess the suitability of aggregates for pavements, occasionally it has been used to identify degradable materials (Reidenouer, et al., 1974; Chapman, 1975). Although the method as developed by Reidenouer, et al. (1974) has shown reasonably good correlation with field durability observations, the suitability of this test method to evaluate surface mine spoils is limited by the large quantities of raw samples and the amount of sample preparation that are required. The large number of determinations that must be made also negates the use of this method.

Ultrasonic Degradation

An ultrasonic device was first used as a method for the disaggregation of shales for particle size analyses by Gipson (1963). Laguros (1972) and his colleagues at Oklahoma State University (Annamalai, 1974) first applied this approach to artificially weathered geologic materials. Despite the successes they observed in using this procedure, the cost and care which must be exercised to conduct ultrasonic tests limit its applicability for general use. As such, use of this method should probably only be considered if several other durability tests provide conflicting results.

Los Angeles Abrasion Test

The Los Angeles Abrasion Test (ASTM C 131-69 [ASTM, 1978a]) was devised to test the suitability of coarse aggregate for use in concrete. Most studies that have used this procedure (or a slightly modified version) to study shale durability have found this method to be too severe a procedure for estimating the durability of soft geologic materials (Deo, 1972; Chapman, 1975).

Freeze-Thaw Tests

Freeze-thaw tests have found only moderate success as indicators of rock durability (Reidenouer, et al., 1974; Hudec, 1978). Hudec (1978)

observed a correlation of results from freeze-thaw tests and simple "wet-dry deterioration" tests (e.g., jar slake test), and slake durability tests (e.g., the Franklin test). However, he concluded that the latter two types of tests were excellent for slaking classification, whereas the freeze-thaw test only provided a "good" slaking classification. Considering the shorter total time requirements for the slaking tests and the special requirements for ventilated freezers in the freeze-thaw tests, it is not recommended that these tests be incorporated into routine testing programs.

Swelling Tests

Several studies to assess the durability of geologic materials have attempted to use the swelling behavior of intact cored samples as a measure of rock durability (Gamble, 1971; Heley and MacIver, 1971; Augenbaugh and Bruzewski, 1976). The testing procedures have consisted of free swell and restrained swell tests in which swelling strains or swelling pressures were measured. The premise for using these tests has been the belief that low durability materials are likely to possess high swelling potential. Contrary to this, no reasonably useful correlation has been found between rock durability and swelling behavior. Gamble (1971) suggested that swelling probably commences during the sampling and specimen trimming operations and may noticeably reduce the swell behavior observed from these tests.

7.2.3 Strength Tests

The principal purpose in relating strength to durability has been for various classification schemes, although strength tests have been employed to directly identify rock durability or to infer future settlement or stability behavior. The strength tests that have been used for these objectives, as presented in Table 7.1, include the following:

- Unconfined and Triaxial Compression
- Point Load
- Schmidt Hammer
- Shore Hardness

The use and success of these tests related to slake durability are summarized in the paragraphs below.

Unconfined and Triaxial Compression

Although unconfined and triaxial compression tests are routinely performed for many geotechnical projects, only two instances have been found relating these tests to studies of rock durability (Eigenbrod, 1972; Augenbaugh and Bruzewski, 1976). Eigenbrod (1972) investigated the change in strength of samples immersed in water and found that compressive strength reduction correlated quite well with increased water content and decreased durability. These correlations were substantiated by work done by Augenbaugh and Bruzewski (1976).

The time requirements to prepare, soak, and test samples in compression as suggested by Eigenbrod (1972) are quite long (possibly a month or more). In addition, strength changes may occur between field sampling and laboratory testing. Compression tests, therefore, should be limited to use as reference tests.

Point Load Test

Franklin (1970) was the first to recommend the point load test as part of an overall system for rock classification which also included durability and average fracture spacing as quantitative indicators. The testing procedures and equipment were later refined (Franklin, et al., 1971; Brook, 1977) to provide a portable field method for assessing the strength of freshly cored rock or rock fragments. Accordingly, the point load test has shown generally good acceptance for a wide range of conditions and as part of several studies to assess the durability of sedimentary rock (Goodman, et al., 1974; Bailey, 1976; Strohm, 1978; Strohm, et al., 1978). A summary of the point load test procedure is presented in Appendix A (A.7.0).

The primary advantages of this test procedure are portability, speed, adaptability to sample shape, and cost. Furthermore, because many tests can be run quickly, a statistical evaluation of strength values is possible that could not otherwise be done from the results of far fewer unconfined compression tests. Lastly, because tests can be conducted in the field, freshly sampled materials may be used, reducing the quantity of samples that must be returned to the laboratory and minimizing sample preservation and storage problems.

Schmidt Hammer

The Schmidt rebound hammer was originally developed as a nondestructive test to evaluate the compressive strength of concrete, although recently this device has been used for testing rock (Cottiss, et al., 1971a and b; Aufmuth, 1974a and b; Chapman, 1975). Studies employing this device for measuring the unconfined compressive strength (particularly for soft and highly fractured rock) have found the test too severe because the rock tends to fail under impact (Aufmuth, 1974a and b; Chapman, 1975).

Shore Hardness Test

The Shore hardness or Scleroscope hardness test is somewhat similar to the Rockwell hardness test for metals and utilizes a nondestructive impact device. Application of this test procedure to measure rock hardness has typically used rock-cored specimens with cut and polished surfaces (Bailey, 1976; Lutton, 1977). Accordingly, much time is often required to prepare rock specimens for testing. For cases in which slakeable materials have been tested, sample preparation becomes more difficult and time consuming to prevent or minimize deterioration of the test specimen. The weaker materials often break down, so that tests

cannot be performed. The hardness values are, therefore, skewed toward the side of the more durable rock types (Bailey, 1976). Although valid correlations have been obtained using this method (e.g., with moisture content), no direct correlations have been made with durability.

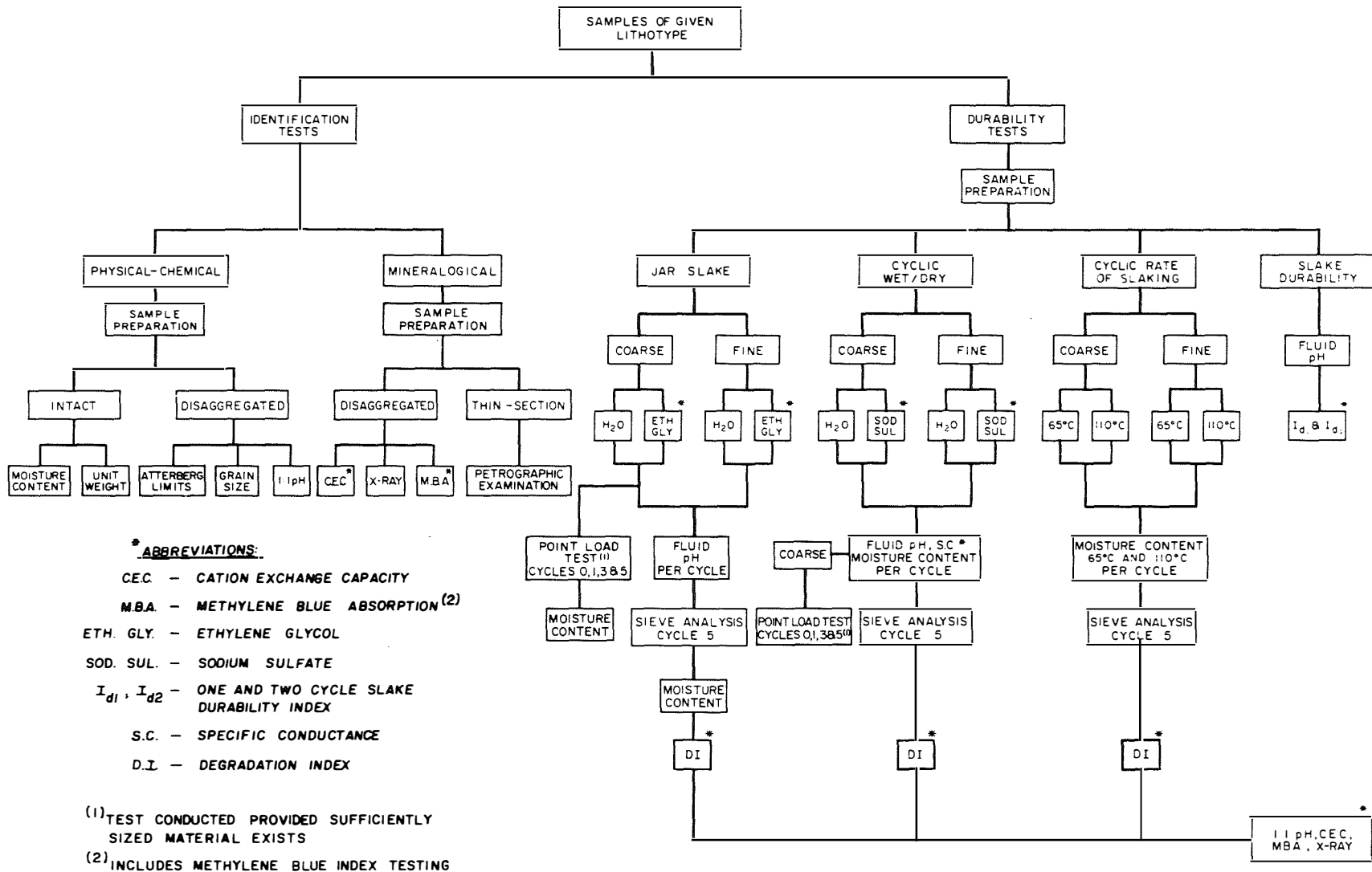
8.0 LABORATORY PROGRAM

The major objectives of the laboratory testing program were to assess the slaking potential of overburden materials sampled during the field portion of the study and provide an understanding of the slaking process. As discussed previously, many documented testing procedures are available and these provided the foundation for the laboratory program implemented for this study. In addition, several supportive analytical procedures were employed for classification or identification purposes. The laboratory program was designed to be efficient and provide information needed to evaluate various parameters that impact the degradation of geologic materials. Incorporated into the design were those procedures and techniques that would allow key relationships to be addressed including:

- Specific accelerated laboratory tests compared to long-term field behavior and quantification of such results.
- Simple index or sophisticated quantitative techniques as correlated to laboratory durability behavior.

The selected laboratory tests can be grouped under the category headings of "durability," "identification," and "ancillary" testing. These categories are useful for quantifying, classifying, and predicting the long-term durability characteristics of geologic materials. Durability tests provide direct evaluation of slaking characteristics of field-sampled materials. Jar slake, cyclic wet/dry, slake durability, and rate of slaking tests offer relatively simple and reliable methods for predicting the degradation of overburden sediments. Other durability tests (outlined in Section 7.2.2) were not included because they generally require large sample amounts, specialized equipment, or long testing times and often do not provide a realistic indication of slaking potential. Identification tests are separated into the broad areas of physical-chemical and mineralogical tests. These were used as a basis for establishing a fundamental description of material characteristics and to provide indirect measurements of durability. The "ancillary" tests serve a purpose similar to identification tests and were run concurrently with the durability testing portion of the program. They included point load tests, analysis of the slaking fluid (i.e., pH and specific conductance), and moisture contents of the durability test samples.

A flow diagram of the laboratory testing program is presented in Figure 8-1. Specific testing details are discussed in the sections which follow or in Appendix A. Details presented in Appendix A are specialized test procedures not readily available in the literature, some of which have been designed especially for this study.



GENERALIZED FLOW DIAGRAM FOR LABORATORY TESTING

8.1 SAMPLE SELECTION AND PREPARATION

Upon completion of the field reconnaissance and exploration program (Chapter 5.0) at each site, geologic features and other pertinent data that might influence the sample selection or laboratory testing program were analyzed. This analysis included a review of a geologic log of the highwall materials and descriptions of test pits excavated in various spoil piles. The desired goal was to identify spoil materials in test pits with reference to rock units observed in the highwall cores. Slaking characteristics of fresh overburden (rock core) or recently spoiled material could then be correlated to degradation observed in test pits of variously aged spoils.

To optimize sampling for laboratory testing, rock strata in each highwall were categorized according to major lithotype. The lithotypes which represented major portions of the overburden or exhibited unusual behavior were then used as a basis for sample selection. Whenever possible, geologic materials obtained from test borings were selected for laboratory testing because they were collected and preserved as closely as possible to the in situ conditions. When a sufficient quantity of rock core was unavailable, the samples of a given lithotype were supplemented with recent spoils. Assuming a complete series of tests would be conducted, approximately 70 pounds (32 kilograms) of each sampled lithotype was required. Occasionally, due to fragment size, durability, or material availability, insufficient quantities of a given rock type were collected for the completion of the full suite of tests.

The major portion of each sampled lithotype was used for the durability testing program. To determine the effects of fragment size on slaking, both coarse and fine components were selected for the jar slake, cyclic wet/dry, and cyclic rate of slaking durability tests. The coarse component consisted of 1-1/2- to 2-inch (38- to 51-millimeters) sized fragments; the fine component ranged in size from 1/4 to 3/4 inch (6 to 19 millimeters) in diameter. The coarse sized components were trimmed to the nominal dimensions using a diamond edged saw with the final sample shapes being roughly cylindrical if rock core was used or cubical if fresh spoil samples were utilized. The fine component was prepared by breaking coarser portions with a small hammer with the final sample prepared by lightly sieving the broken angularly shaped particles. Samples for the slake durability test were prepared by a trimming and grinding process to provide sample fragments weighing between 1.5 and 2 ounces (40 to 60 grams). Throughout the study, test specimens were placed within sealed containers to minimize the reduction of moisture content of the samples. Samples were tested either at the natural water content or subsequent to oven drying at 110 degrees Celsius +3 degrees.

Sample preparation for the physical-chemical tests was conducted in accordance with the guidelines presented in Appendix A (A.5.0). Because the results of Atterberg limits can be affected by the method of sample preparation (Section 7.2.1), care was taken to minimize the amount of sample drying that occurred. Samples used for these determinations,

as well as grain size analyses, were crushed (at natural water content) to the required grain size using a Bico Rock Pulverizer. Samples prepared for mineralogical analysis (X-ray diffraction) were dried and crushed to less than a 200 mesh size (74 microns).

8.2 DURABILITY TESTS

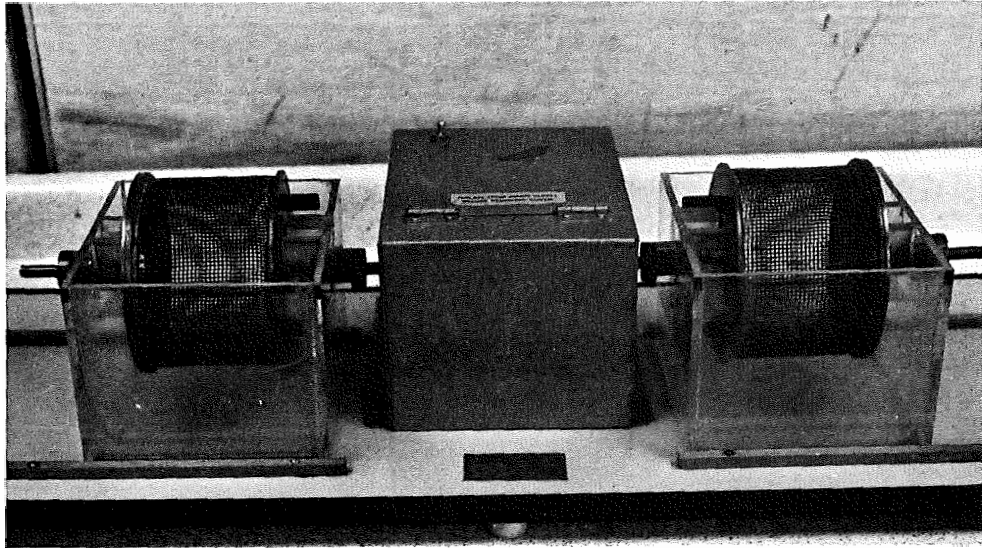
Durability tests used to measure the slaking potential of the various highwall lithologies were the slake durability, jar slake, cyclic wet/dry, and rate of slaking tests. The slake durability test, which required special equipment (Figure 8-2) to provide continual agitation to the sample, was performed in accordance with standard procedures (International Society of Rock Mechanics, 1979). The equipment requirements and test procedures for the remaining durability tests are presented in Appendix A (A.1.0, A.2.0, A.3.0). These various tests were selected because they represent a wide range of conditions (e.g., sample fragment size, wetting and drying cycles, temperature, slaking fluids, and degree of agitation) and have had some degree of proven success.

As mentioned previously, the selection of a particular lithotype for durability testing was based on two criteria; namely, its observed field behavior and volumetric proportion of the overburden material. Because siltstone, mudstone, and shale generally comprise a high percentage of overburden and typically exhibit more severe slaking characteristics, the majority of samples for this study were fine grained. Limestones were only tested with the slake durability apparatus because this material seldom exhibits large amounts of physical deterioration. If insufficient highwall and spoil samples for a particular lithotype were available for a complete suite of durability tests, emphasis was placed on the coarse fragment size tests using jar slake and cyclic wet/dry test procedures in water. In these cases, the selection of coarse fragment size was based on an anticipated greater degradation than with the finer fragments. The testing procedures were selected to provide as much variation in testing conditions as possible while minimizing the use of special equipment (slake durability apparatus) and fluids (sodium sulfate or ethylene glycol).

The principal objectives of the durability testing were directed towards quantifying the test results, correlating the laboratory behavior with the observed performance of spoil materials in the field, and finally identifying the particular test or tests that provide the most reliable results. Based on the latter consideration, the greatest emphasis was placed on the test procedures requiring the least amount of time and/or sophisticated testing equipment.

8.3 IDENTIFICATION TESTS

The durability or slaking resistance of geologic materials is partially a function of their inherent characteristics (i.e., mineralogy and fabric). As discussed in Chapter 2.0, the probability of slaking in argillaceous (clayey) sediments is significantly higher than in other common sedimentary materials.



SLAKE DURABILITY TESTING APPARATUS

Nine identification tests were utilized in the laboratory program. The testing schedule with reference to lithotype and type of test is presented in Table 8.1. The first four test types (i.e., moisture content, disaggregated grain size, Atterberg limits, and unit weight) were performed in general accordance with standard testing procedures and form the basis for material identification and classification for many geotechnical testing programs. Preparation procedures for grain size analysis and Atterberg limits for disaggregated samples, as modified for this study, are discussed in Appendix A (A.5.0). Several previous studies of slaking have identified these tests as modest to strong indicators of rock durability and, therefore, these tests have been included in the testing schedule.

Petrographic examination of thin sections of rock fragments was performed on coarse-grained sedimentary materials using generally accepted procedures. The principal purpose for use of this tool was to examine, in detail, the composition of matrix cements and rock fabric as they relate to the observed durability behavior.

The remaining tests (i.e., 1:1 pH, CEC, MBA, MBI X-ray diffraction) were included to identify the chemical or mineralogical composition of the sampled lithotypes. Methylene Blue tests and pH are relatively simple procedures that provide reference information for other detailed analyses or general indications of slake durability. The procedure used for the MBA test method, as suggested by Nettleton (1974), is presented in Appendix A (A.6.0) while the procedure for MBI is set forth in ASTM C 837-76 (ASTM, Part 17, 1977).

X-ray diffraction and CEC were intended to provide an understanding of the mineralogical composition of the samples which could be used as a reference for comparing the results of other less costly and time consuming test procedures (e.g., CEC versus MBA/MBI). X-ray diffraction and CEC analyses were conducted in accordance with standard procedures (Carroll, 1970; Black, 1965).

8.4 ANCILLARY TESTS

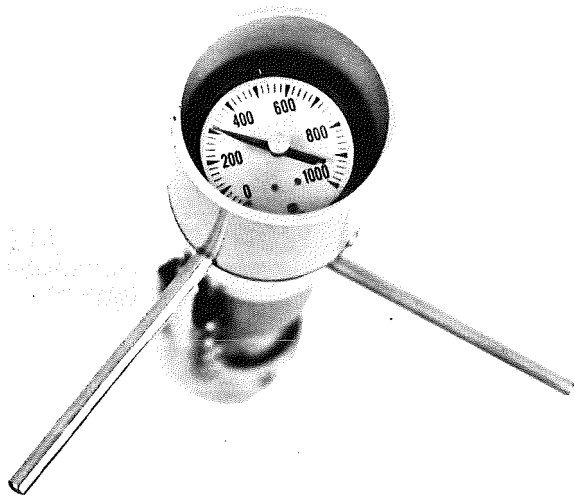
Additional tests, which were anticipated to give insight into durability characteristics of the sampled lithotypes, were incorporated into the durability testing program. These included point load tests, analysis of the slaking fluid (pH and specific conductance), and fragment moisture contents.

The point load strength test was used to monitor the degree of strength reduction during the "slaking" tests. It was selected because previous studies suggested that it provides the most direct correlation between rock strength and durability. The tests were performed as part of the coarse fragment portion of jar slaking and cyclic wet/dry tests. Fragments were periodically selected for testing to determine the incremental strength deterioration. The point load apparatus, which is capable of determining strength loss even when irregularly shaped fragments are used, is shown in Figure 8-3 and the procedures which were followed are presented in Appendix A (A.7.0).

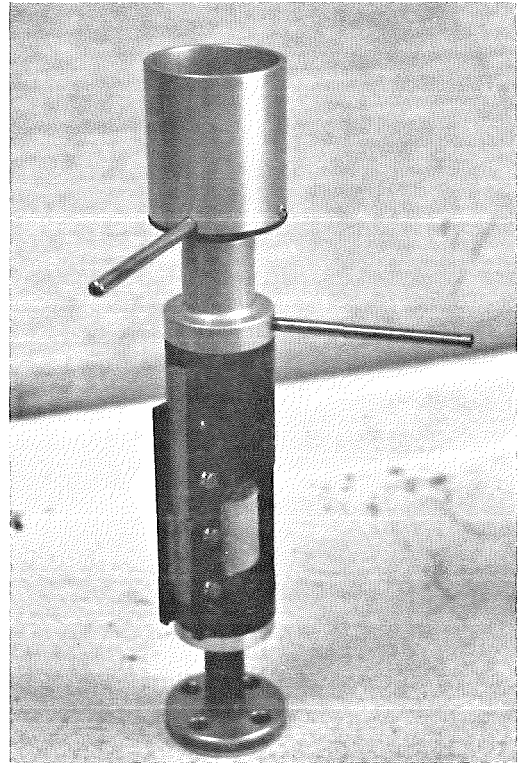
TABLE 8.1
SCHEDULE FOR IDENTIFICATION TESTS

IDENTIFICATION TEST	LITHOTYPE ⁽¹⁾				
	SANDSTONE	LIMESTONE	SILTSTONE	MUDSTONE	SHALE
Moisture Content	●	●	●	●	●
Grain Size	○	○	●	●	●
Atterberg Limits	○	○	●	●	●
Unit Weight	●	●	●	●	●
Petrographic Examination ⁽²⁾	●	●	○	○	○
1:1 pH ⁽³⁾	○	○	●	●	●
CEC ⁽³⁾	○	○	●	●	●
MBA ⁽³⁾	○	○	●	●	●
X-ray Diffraction ⁽³⁾	●	●	●	●	●

- (1) ● Indicates that test was performed.
 ○ Indicates that test was not performed.
- (2) Performed with thin sections parallel and perpendicular to bedding.
- (3) Performed before and after durability testing.



TOP VIEW



SIDE VIEW

POINT LOAD TESTING APPARATUS

The remaining tests (fluid pH, specific conductance, and fragment moisture contents) were determined at key stages in the program. Moisture contents, as discussed previously, were determined using commonly referenced geotechnical procedures. Specific conductance and pH were periodically monitored following standard procedures outlined by EPA (1979).

9.0 RESULTS OF FIELD AND LABORATORY PROGRAMS

Although the primary purpose of this study was to relate experimental results obtained in the laboratory to observations made in the field, valuable information was independently derived from each program. This chapter presents results obtained in both programs which can be considered separately, as well as information which resulted from correlating the two study portions.

9.1 FIELD PROGRAM

Slaking in mine spoils is a function of several variables, including material properties, mining techniques, and reclamation procedures. The associated environmental effects depend on the mode, degree, and rate of slaking. This section considers observations made or results obtained during the field program.

9.1.1 Modes of Slaking

Three modes of slaking were observed to occur in mine spoils. These include:

- Slaking to inherent grain size
- Chip slaking
- Slab or block slaking

Slaking to inherent grain size results in the destruction of the original rock structure and the production of a sediment mass consisting of fine-grained particles. Disintegration of rocks by this mode of slaking can occur in a period of time ranging from a few days to several years.

Chip slaking results in the production of flat fragments ranging in thickness from approximately 1/4 to 3/4 inch (0.6 to two centimeters) and in length and width from one to six inches (2.5 to 15 centimeters). Usually, the chips are relatively stable and resist further degradation. Initial breakdown occurs along subparallel planes of weakness which may not be apparent during visual inspection of fresh rock core. However, the existence of thin interbeds of contrasting mineralogy or chemical composition, such as concentrations of mica flakes or organic materials, was found to be a reliable indicator of incipient chip slaking.

Slab or block slaking results in the production of thick slabs or equidimensional blocks ranging in size from approximately three inches (7.5 centimeters) to six feet (1.8 meters) 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 a period of time.

Occasionally, rocks may undergo more than one mode of slaking. When this occurs, it is usually a progression from chip slaking to inherent grain size. The time required for this change of state to occur is expected to be less than six months. This time frame may be considerably less, and in some lithologies, nearly instantaneous.

9.1.2 Impact of Material Properties on Slaking

Inherent rock properties are a major factor in determining the mode, rate, and degree of slaking in mine spoils. The following geologic features were observed to influence slaking characteristics of mine spoils:

- Lithology
- Bedding
- Mineralogy

Mudstones, siltstones, and shales were found, in general, to be the most slake-prone lithologies. Slaking of sandstone and limestone was variable, but generally minor in occurrence. Bedding characteristics primarily influence the mode of slaking; i.e., rocks which exhibited thin bedding were found to undergo chip slaking, whereas massive rock units were prone to block or slab slaking or slaked to their constituent grain size.

Readily identifiable minerals also correlate 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 which augment the slaking process.

General relationships between modes of slaking and inherent rock properties are summarized in Table 9.1. Further discussion relating lithology, grain size, and depth is presented in Section 9.1.4.

9.1.3 Impact of Mining Techniques on Slaking

Mining techniques were observed to affect slaking characteristics of mine spoils in two ways. First, the type of mining method utilized (e.g., area mining versus haulback) influences slaking. Second, the increase in equipment size and machinery traffic within the last 10 to 15 years associated with all mining methods has produced an attendant increased impact on slaking. These impacts include greater crushing, abrasion, and shearing of spoil fragments as a result of increased material handling, more controlled placement, and more extensive final grading.

Blasting methods depend both on the mining method and number of coal seams mined. Most area and mountaintop removal mining operations blast the overburden in large lifts, while haulback operations generally

TABLE 9.1
RELATIONSHIP OF SLAKING MODES TO ROCK PROPERTIES

<u>SLAKING MODE</u>	<u>ASSOCIATED ROCK PROPERTIES</u>
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.

shoot smaller lifts. Where multiple seam mining occurs, one or more lifts are shot in each interburden interval. Blasting directly affects slaking of rocks in at least three ways including:

- Total disintegration of the rock into its constituent particles.
- Partial breakdown of the rock into smaller fragments.
- Disruption and weakening of bonds within the rock without a decrease in fragment size.

The first mechanism is responsible for the production of dust where the rock is completely broken down to its constituent grain size. The remaining two mechanisms provide suitable conditions for slaking to proceed during excavation, placement, and reclamation activities.

Excavation and placement techniques also impact the slaking process. Dragline excavation, as in area mining operations, consists of pulling or dragging the bucket across the materials. Disintegration occurs by abrasion and grinding of spoil against the bucket and within the spoil itself. Spoil excavation by shovels creates a similar effect. Excavation by endloaders, as in haulback mining, results in the crushing and fracturing of spoil materials by the weight of the equipment moving across the spoil surface.

Initial spoil placement in area mining consists of dumping the spoil in ridges with successive lifts compacted only by the weight of the overlying spoil. Relatively little crushing and abrasion of contact points occur in this method of placement. The spoil ridges tend to have an open, porous character, readily accessible to air and water; and, therefore, slaking can easily be initiated after placement.

Spoil placement in haulback mining and mountaintop removal is usually accomplished by large trucks. Spoil is loaded, transported to a previously mined or designated fill area, and end dumped. Loading and transport cause additional crushing and abrasion of rock materials. In addition, previously placed spoils located on access areas sustain repeated heavy truck traffic resulting in further crushing, grinding, and compaction. Therefore, spoils resulting from this type of placement are generally denser in nature and less susceptible to atmospheric agents below the surface.

Placed spoils are graded, generally with large bulldozers, to a topography approximating the original contour. In area mining and mountaintop removal operations, the spoil is usually graded to a gentle slope, while in haulback mining, the final slopes are much steeper. In either case, considerable reworking of the spoil is required. Final grading operations apparently have the greatest impact on slaking of the

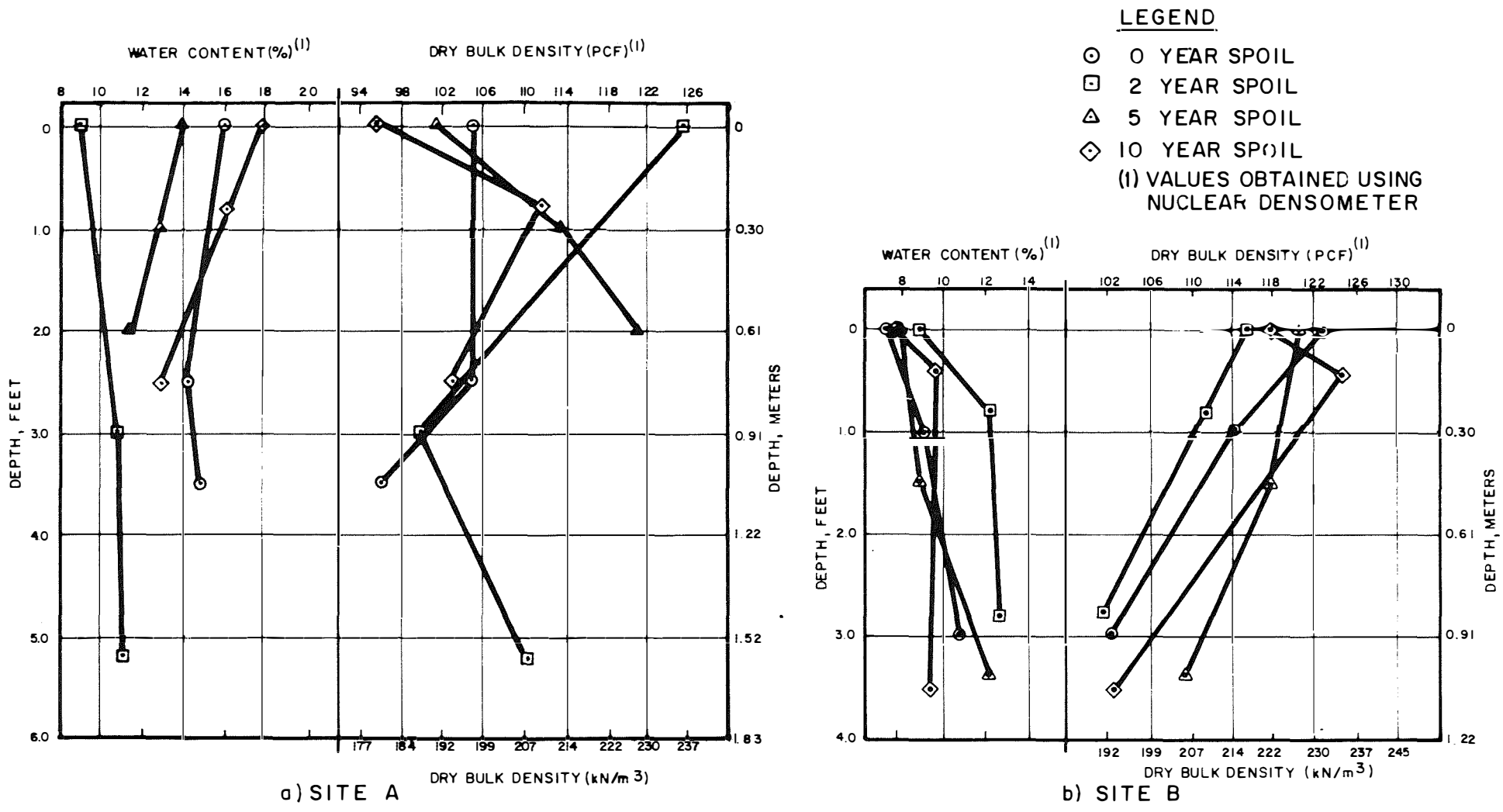
entire mining and reclamation program. This conclusion is based on inspection of graded and ungraded fresh spoil and comments from mining personnel. Ungraded fresh spoil at all sites appeared to have a coarser particle size distribution than graded materials. In addition, rocks were observed to be broken, cracked, or crushed during actual grading, and broken or crushed rock materials were noted in bulldozer tracks in recently graded areas. Discussions with several mining company personnel also supported these observations. Spoil materials which have been crushed, abraded, and weakened by prior activities are subjected to intensive manipulation by repeated passes of bulldozers. Additionally, when topsoil is placed on the final spoil surface, machinery passes by scrapers, trucks, and bulldozers further accelerate material breakdown. The effects of these activities are generally restricted to the near-surface spoil material due to the limited number of machinery passes and relatively small size of equipment involved.

9.1.4 Physical Characteristics of Spoil Piles as Related to Slaking

To understand the various parameters associated with deterioration of spoil materials, the field program was designed to examine variations in density and grain size among spoils of various ages at each site. Replicate density measurements and water contents were taken at various depths using a nuclear densometer (Section 5.4). To establish grain size relationships, bulk samples were taken for sieving. The results were combined with visual estimates of coarse fractions (greater than three inches or 7.5 centimeters) to obtain overall grain size distributions. Because only one grain size analysis was conducted for each spoil area, sample depth was kept as constant as possible for each site. The relationships which follow were derived through an analysis of these data supplemented by information obtained through interviews with mining personnel.

Bulk density of mine spoils is a function of placement methods, slaking characteristics, lithologic content, and age of spoils. Results of the in situ bulk density tests and moisture content determinations are presented in Figures 9-1 and 9-2. Each data point represents the average of four replications. Bulk density and water content values increase or decrease with depth depending on the site conditions as outlined in Chapter 6.0, and are a function of the duration, frequency, and magnitude of the wetting and drying cycles. Generally, an inverse relationship was developed between bulk density and water content. The correlation between these two parameters aided in the verification of the density measurements and their associated variations.

At Site A, bulk density generally decreases with depth in the fresh and two-year spoils and increases with depth in the five- and ten-year spoils. The higher surface densities in the younger spoils, particularly in the two-year spoil which was located in an equipment access area, are a result of more intensive materials handling activities which 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

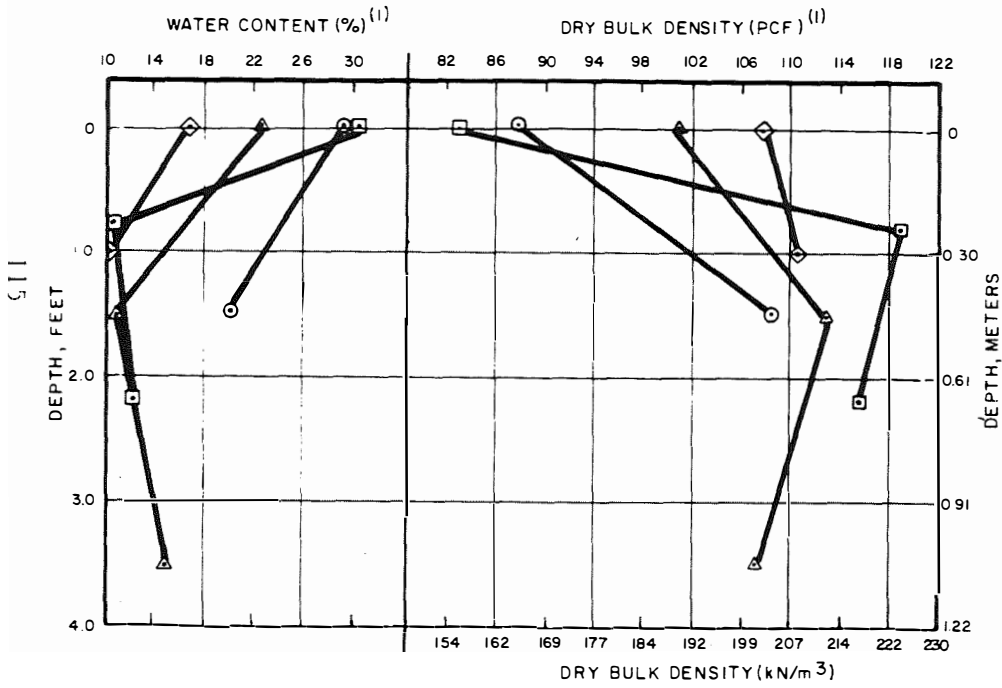


DRY BULK DENSITY and WATER CONTENT vs DEPTH
SITES A and B

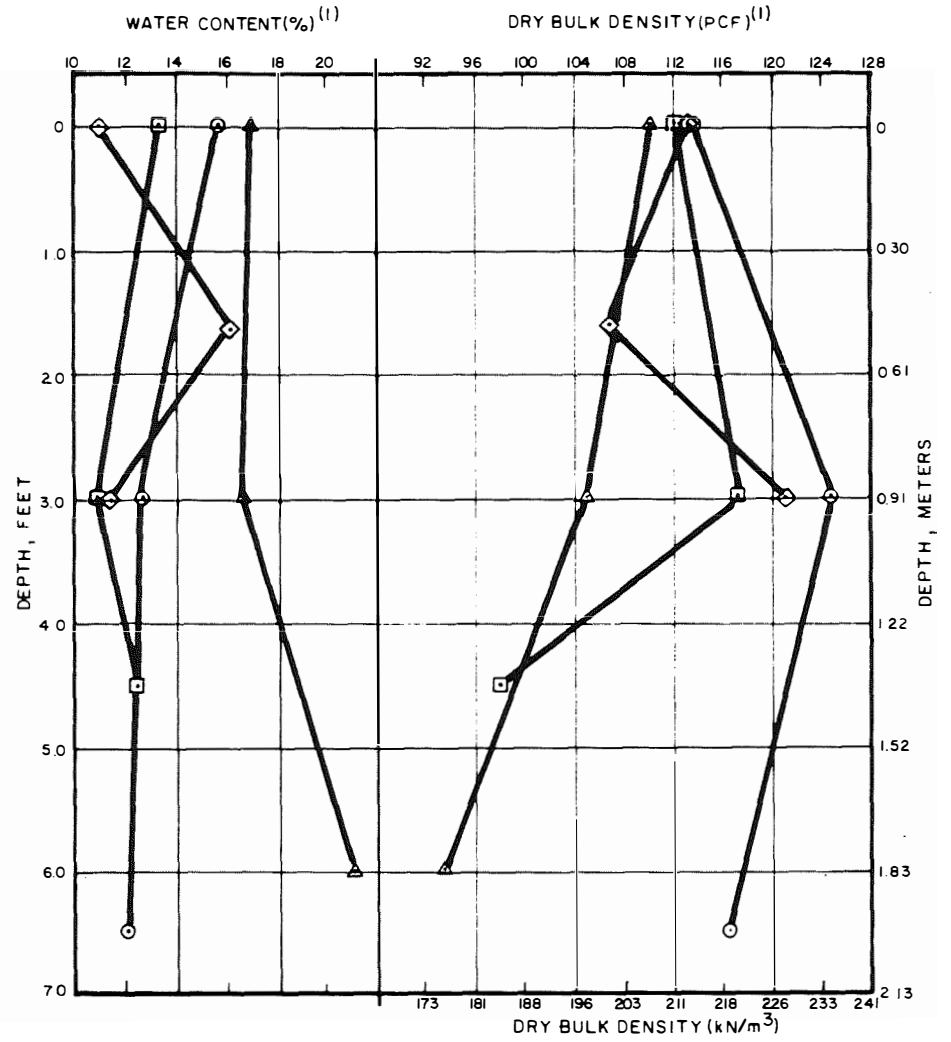
LEGEND

- ⊙ 0 YEAR SPOIL
- 2 YEAR SPOIL
- △ 5 YEAR SPOIL
- ◇ 10 YEAR SPOIL

(1) VALUES OBTAINED USING NUCLEAR DENSOMETER



a) SITE C



b) SITE D

DRY BULK DENSITY AND WATER CONTENT vs DEPTH
SITES C and D

FIGURE 9-2

traffic. Ten-year spoils received minimal grading compared to younger spoils. Increasing density with depth may also indicate that settlement of the spoil materials has taken place.

At Site B, bulk density generally decreases with depth in all age spoils. This is due to the initial placement of spoils by dumping from the dragline bucket on all age spoils and the character of the spoil itself. The spoils consist primarily of relatively hard siltstone chips and slabs which, when placed, form a stable, porous matrix which resists compaction. The higher surface density appears to be a result of machinery traffic during final grading with slaked materials filling large voids in this layer. Mechanical tillage for seedbed preparation on two- and five-year spoils did not appear to appreciably affect surface density when compared to the fresh spoil which had not been tilled.

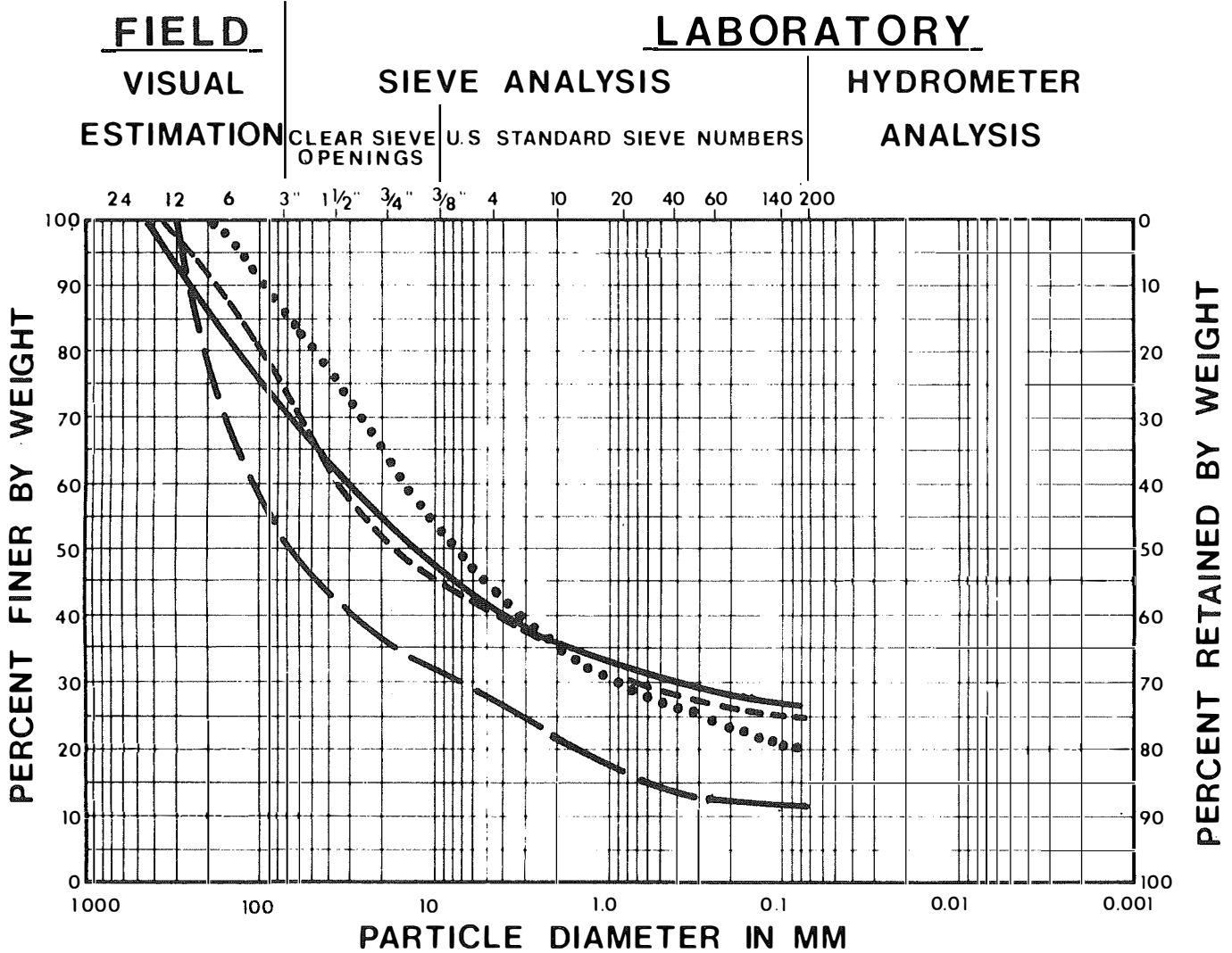
At Site C, bulk density increases with depth in fresh, two- and five-year spoils and shows a slight increase in the ten-year spoils. The fresh spoil is located in a valley fill area in which each lift is graded and compacted; consequently, the sublayers are quite dense.

At Site D, bulk density decreases with depth on five-year spoils and is variable on fresh, two-, and ten-year spoils. The variable densities with depth on most spoils are a function of moisture content, lift thickness, and number of machine passes during placement and final grading. Fresh spoil, which has the highest density values overall, has been regraded to approximate original contour. Five- and ten-year spoils, which exhibit lower overall densities, were partially backfilled against the highwall with less extensive grading.

Spoils exhibit a broad spectrum of grain sizes ranging 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 which have undergone extreme slaking of a particular lithology usually retain some coarse fragments of slake-resistant lithologies. Even at Site D, which exhibited extreme slaking to constituent grain size by mudstone materials, some coarse fragments were observed in all spoils.

The results of the grain size analyses are shown in Figures 9-3 through 9-6. The data indicate that lithologic composition generally has a greater influence on grain size distribution than does time. Sites where lithologic composition is generally uniform throughout the various age spoils, as at Site B, have similar grain size curves for all age spoils, while sites with more variable lithologic composition among the various age spoils have more diverse grain size curves.

At Site A, material properties apparently control grain size distribution. Recent and five-year spoils have very similar grain size curves and similar composition, with mudstone, slaking to constituent grain size, being the dominant lithology. Two-year spoil contains no mudstone and consequently has the coarsest grain size distribution.

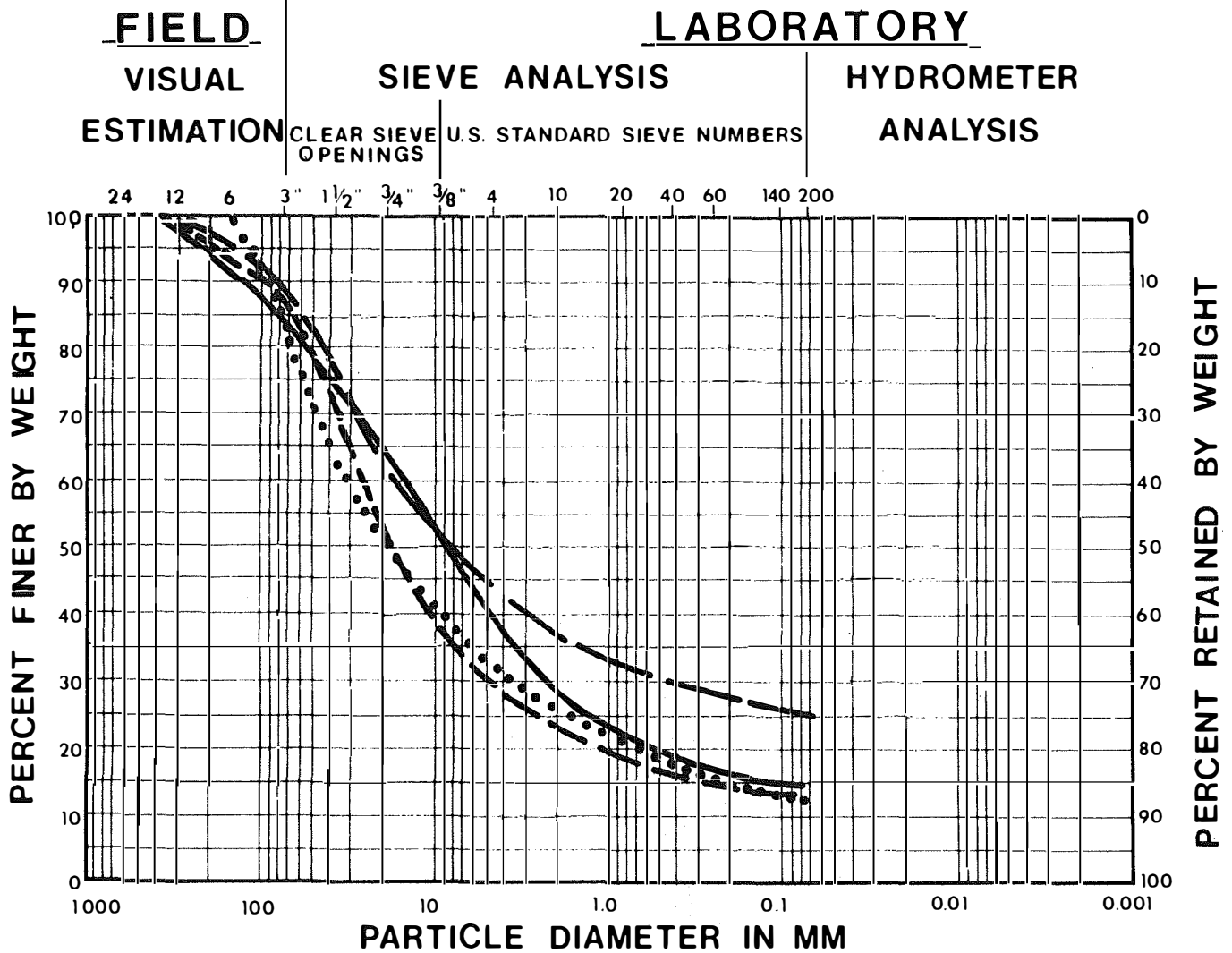


BOULDER	COBBLE	GRAVEL		SAND			SILT AND CLAY FRACTION
		coarse	fine	coarse	medium	fine	

SYMBOL	SPOIL AGE YEARS	DEPTH		COMPOSITION
		IN	CM	
—	0	46	117	20% SHALE; 80% MUDSTONE
- - -	2	36	91	20% BLACK SHALE; 80% SHALE
- - - -	5	30	76	10% SANDSTONE; 20% BLACK SHALE; 70% MUDSTONE
.....	10	30	76	30% MUDSTONE; 30% BLACK SHALE; 40% SHALE

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

**SPOIL PILE GRAIN SIZE DISTRIBUTION
SITE A**



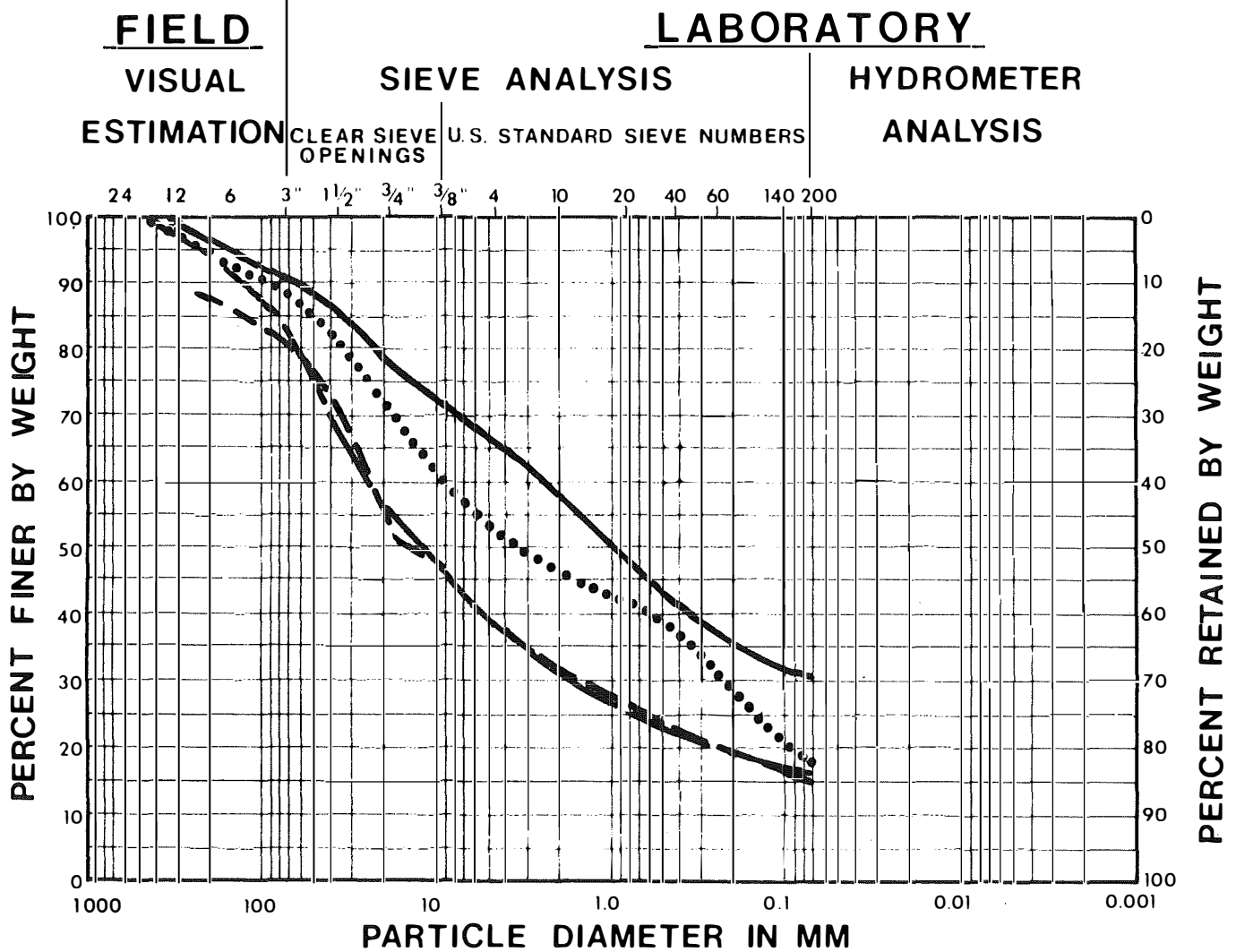
BOULDER	COBBLE	GRAVEL		SAND			SILT AND CLAY FRACTION
		coarse	fine	coarse	medium	fine	

SYMBOL	SPOIL AGE YEARS	DEPTH		COMPOSITION
		IN	CM	
—	0	40	102	30% SHALE ; 70% SILTSTONE
- -	2	34	86	20% SHALE ; 80% SILTSTONE
· · · · ·	5	46	117	30% SHALE ; 70% SILTSTONE
· · · · ·	10	48	122	10 % MUDSTONE ; 30 % SHALE ; 60% SILTSTONE

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

SPOIL PILE GRAIN SIZE DISTRIBUTION

SITE B



BOULDER	COBBLE	GRAVEL		SAND			SILT AND CLAY FRACTION
		coarse	fine	coarse	medium	fine	

SYMBOL	SPOIL AGE YEARS	DEPTH		COMPOSITION
		IN	CM	
————	0	24	61	20% BLACK SHALE; 30% SILTSTONE; 50% MUDSTONE
-----	2	32	81	10% BLACK SHALE; 20% SANDSTONE; 70% SILTSTONE
.....	5	42	107	10% BLACK SHALE; 40% SILTSTONE; 50% SANDSTONE
.....	10	24	61	40% SILTSTONE; 60% SANDSTONE

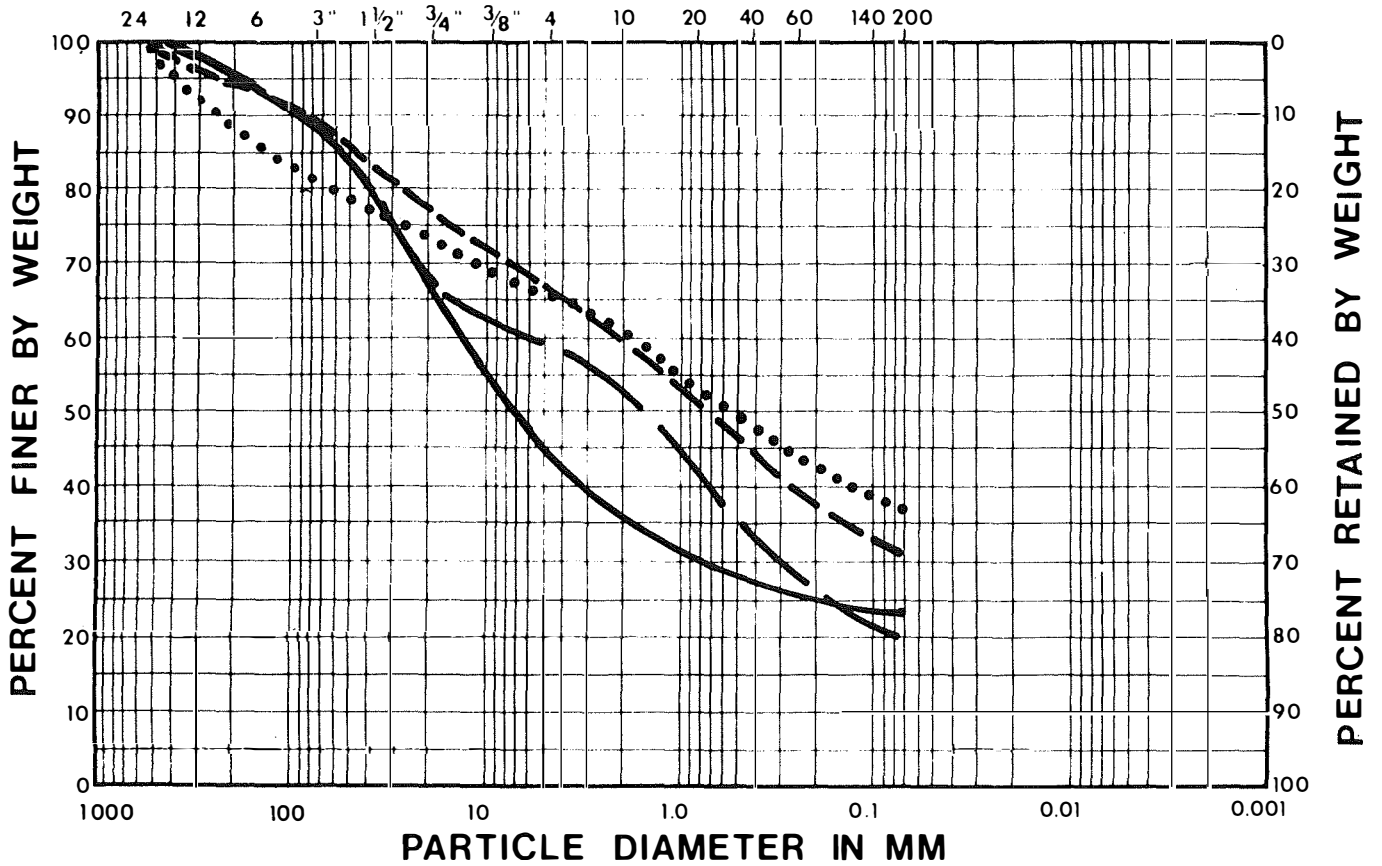
NOTE: COMPOSITION IS BASED ON PARTICLE DIAMETERS > 5/64 INCH (2mm)

SPOIL PILE GRAIN SIZE DISTRIBUTION SITE C

FIELD
VISUAL
ESTIMATION

LABORATORY
SIEVE ANALYSIS
 CLEAR SIEVE OPENINGS | U.S. STANDARD SIEVE NUMBERS

HYDROMETER
ANALYSIS



BOULDER	COBBLE	GRAVEL		SAND			SILT AND CLAY FRACTION
		coarse	fine	coarse	medium	fine	

SYMBOL	SPOIL AGE YEARS	DEPTH		COMPOSITION
		IN	CM	
—	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)

SPOIL PILE GRAIN SIZE DISTRIBUTION
SITE D

This is reflective of the chip slaking which the shales have undergone, producing fragments generally larger than about two inches (five centimeters) in size. These chips appear to be relatively stable and further degradation is expected to take place slowly. The ten-year spoil contains an intermediate amount of mudstone, but displays a grain size curve similar to the fresh and five-year spoil. Slaking, over a longer time, may be responsible for the production of a grain size distribution similar to younger spoils.

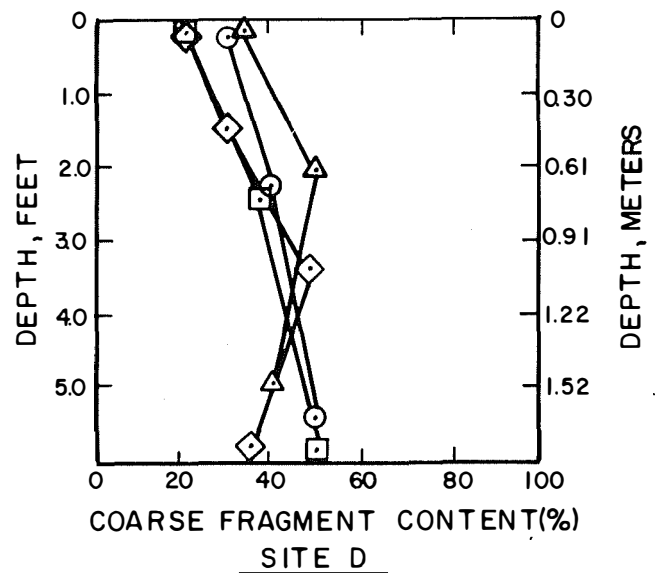
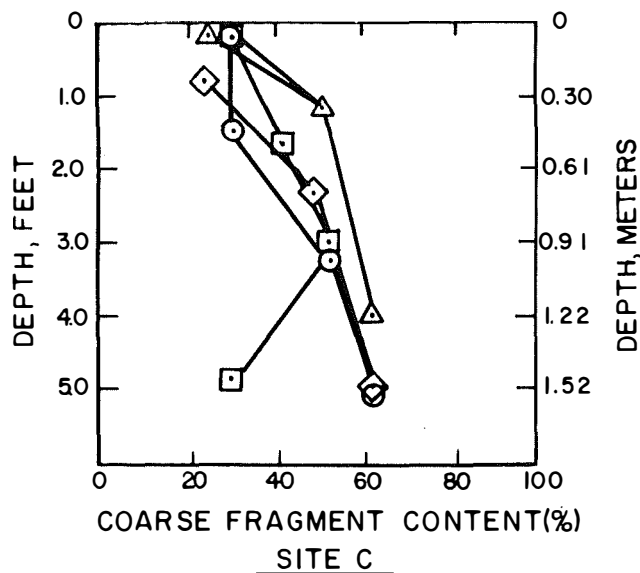
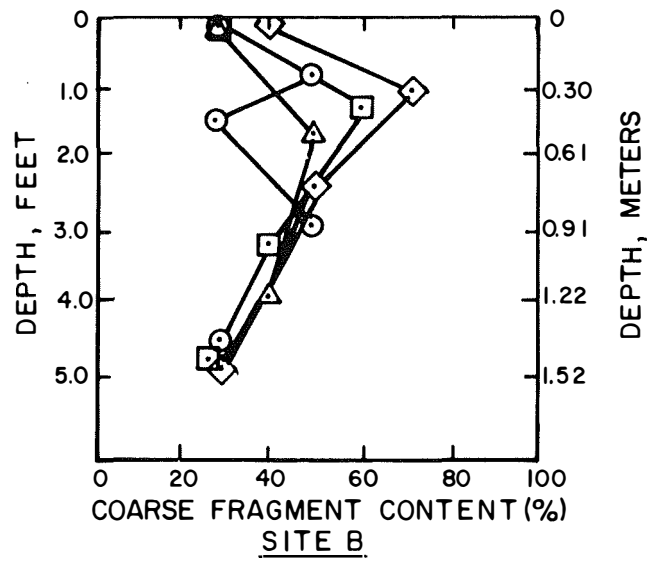
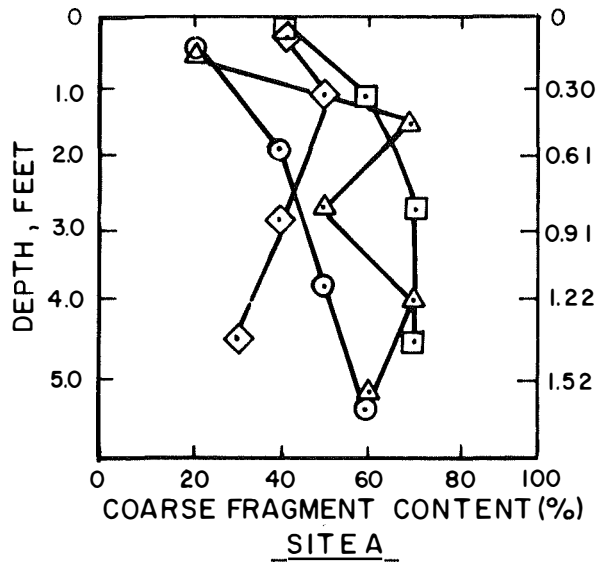
At Site B, the fresh, five- and ten-year spoils have similar grain size curves, while the two-year spoil contains slightly more fine material. The relatively uniform lithologic composition in all spoils apparently indicates that time is not a significant factor influencing slaking at this site.

At Site C, the grain size curves for the two- and five-year spoils are similar, while the fresh and ten-year spoils contain more fine materials. The finer materials in the fresh spoil are a result of more intensive materials handling and compaction associated with valley-fill construction and higher proportion of materials prone to extreme slaking. The finer materials in the ten-year spoil are believed to be the product of slaking over time.

At Site D, where all spoil ages contain a relatively high proportion of slake-prone materials, the effects of time on slaking are more apparent. Generally, the proportion of fine material increases with increasing spoil age, with the exception of the larger size fractions. Younger spoils contain fewer coarse fragments due to increased materials handling relating to more grading associated with restoration of approximate original contour. Older spoils at this site, as mentioned previously, were partially backfilled with less grading.

Slaking was observed to occur as a function of depth in all age spoils and generally, evidence for the occurrence of slaking was negligible below five feet. Total coarse fragment content generally increases with depth as does the proportion of large coarse fragments (>10-inch or 25-centimeter size). The proportion of the smaller coarse fragments (<3/4-inch or two-centimeter size) decreases with depth, while the distribution of intermediate size fractions is more variable. Total coarse fragment content and proportions of various size classes, based on visual estimates made in the field, are presented as a function of depth in Figures 9-7 through 9-9.

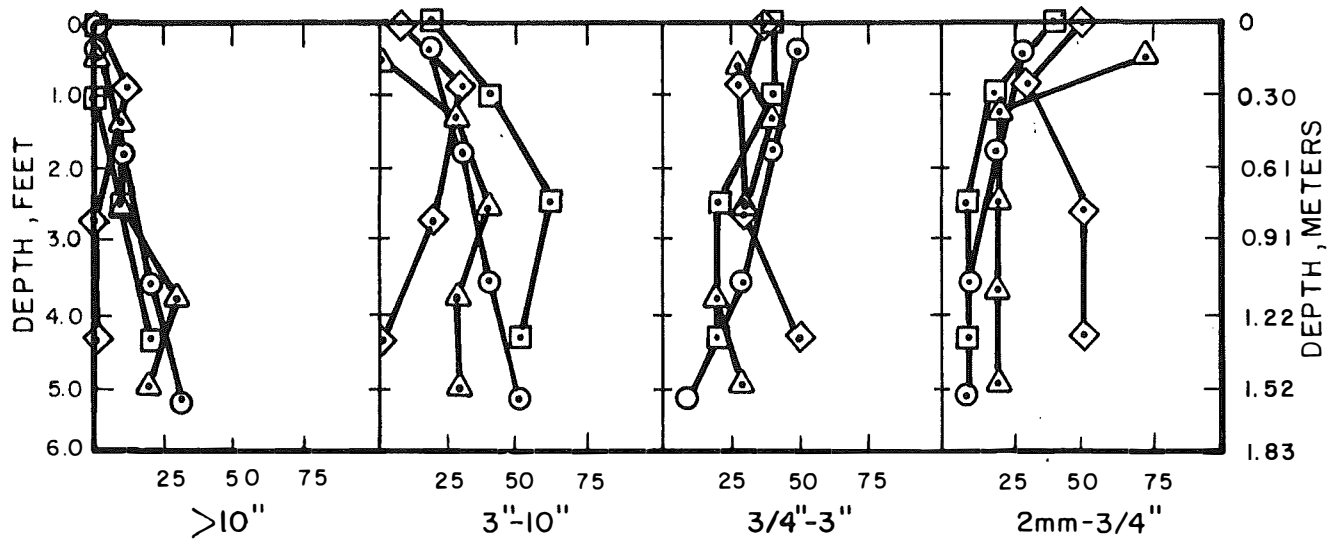
At Site A, total coarse fragment content increases with depth on all but the ten-year spoils. The decreasing coarse fragment content with depth on this spoil appears to result more from spoil placement techniques than in situ slaking. The proportion of coarse fragments greater than 10-inch (25-centimeters) size and three- to ten-inch (7.5- to 25-centimeters) size generally increases with depth indicative of near surface slaking of these size fractions. The proportion of 3/4- to three-inch (two- to 7.5-centimeters) and 3/4- to 5/64-inch



- LEGEND**
- 0 YEAR SPOIL
 - 2 YEAR SPOIL
 - △ 5 YEAR SPOIL
 - ◇ 10 YEAR SPOIL

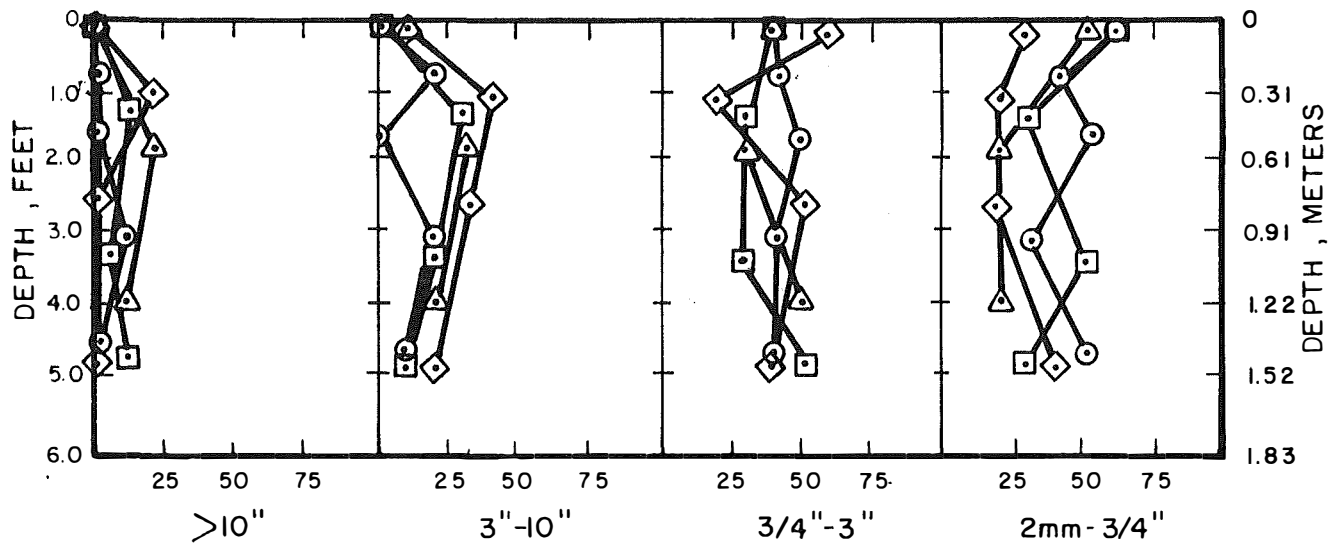
NOTES: (1) PERCENTAGE BASED ON VISUAL ESTIMATES.
 (2) COARSE FRAGMENT SIZE INCLUDES ALL PARTICLE SIZES > 5/64 INCH (2mm)

PERCENT TOTAL COARSE FRAGMENT CONTENT vs DEPTH



COARSE FRAGMENTS BY SIZE CLASSES (%)

a) SITE - A



COARSE FRAGMENTS BY SIZE CLASSES (%)

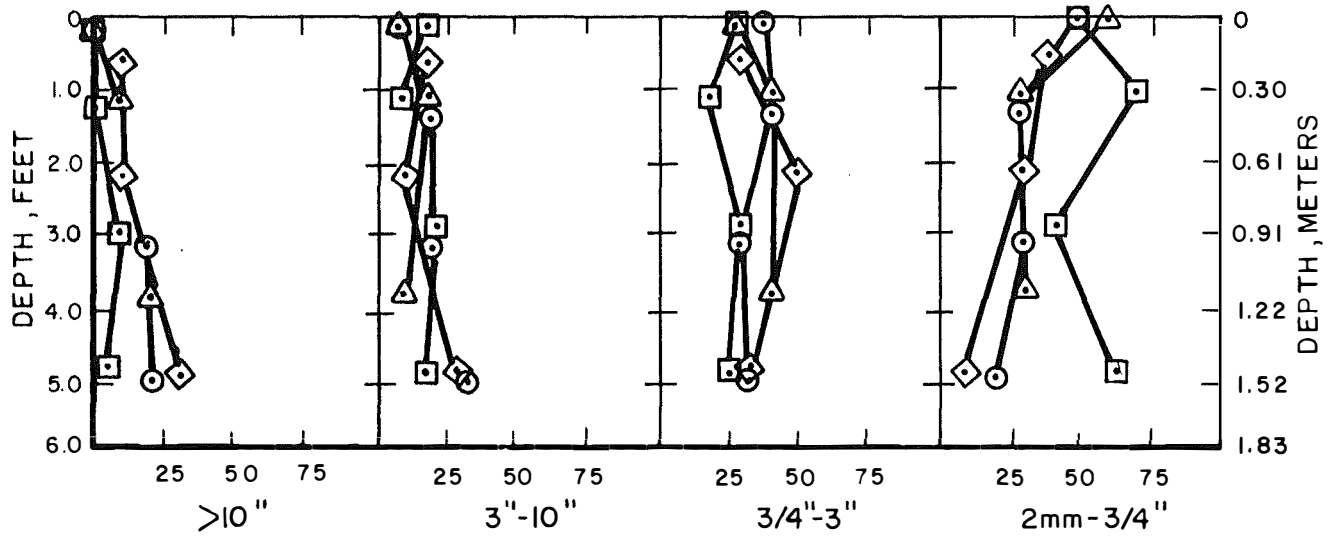
b) SITE - B

- LEGEND
- - 0 YEAR SPOIL
 - - 2 YEAR SPOIL
 - △ - 5 YEAR SPOIL
 - ◇ - 10 YEAR SPOIL

NOTE:
PERCENTAGES BASED ON VISUAL ESTIMATES

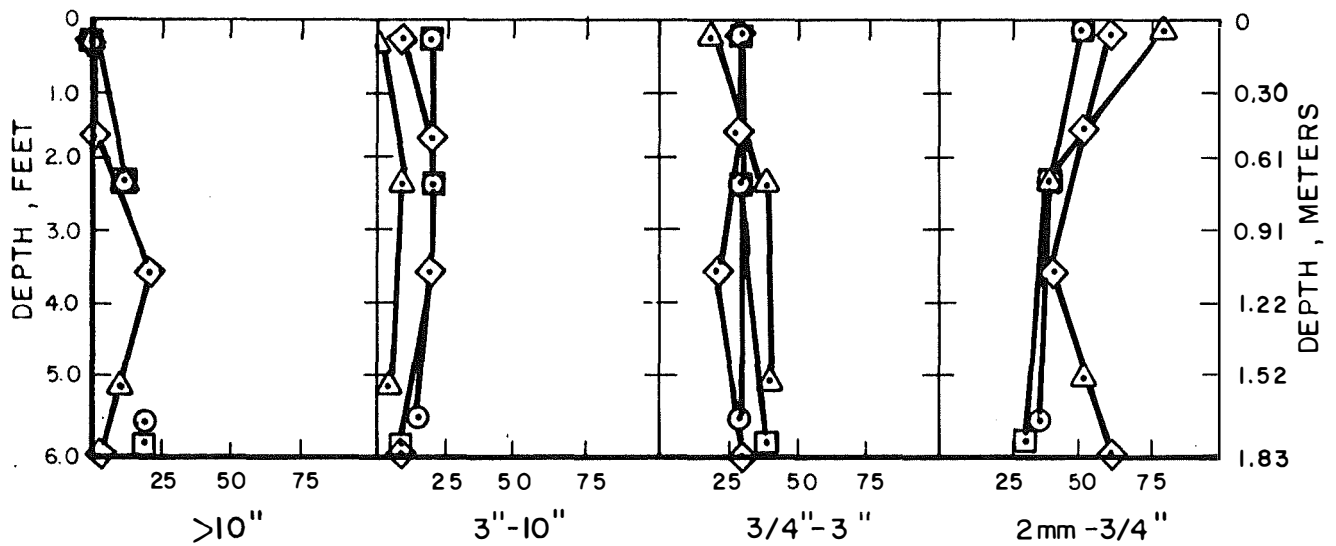
PERCENT COARSE FRAGMENT SIZE vs DEPTH

SITES A and B



COARSE FRAGMENTS BY SIZE CLASSES (%)

a) SITE - C



COARSE FRAGMENTS BY SIZE CLASSES (%)

b) SITE - D

- LEGEND
- ⊙ - 0 YEAR SPOIL
 - - 2 YEAR SPOIL
 - △ - 5 YEAR SPOIL
 - ◇ - 10 YEAR SPOIL

NOTE:

PERCENTAGES BASED ON VISUAL ESTIMATES

PERCENT COARSE FRAGMENT SIZE vs DEPTH
SITES C and D

(two-centimeters to two-millimeters) size coarse fragments generally decreases slightly with depth, suggesting that these size fractions may be relatively unaffected by slaking over time. The content of 3/4- to 5/64-inch (two-centimeters to two-millimeters) 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 upon reaching the 3/4- to 5/64-inch size fraction. Slaking of large coarse fragments at all sites was observed to occur principally along natural zones of weakness such as bedding planes, fractures, and weakly cemented grains. It is believed that such zones of structural weakness may not exist in the smaller fragments, thus substantially reducing the rate of slaking.

At Site B, total coarse fragment content is at a maximum at a depth of one to two feet (0.3 to 0.6 meter) and decreases below this depth. The near-surface zone of high coarse fragment content is thought to be a function of spoil placement methods rather than intensive slaking at depth; however, no direct evidence was found to support this. The greatest proportion of larger coarse fragments (i.e., greater than 3 inches or 7.5 centimeters) was encountered at a depth of approximately one foot (0.3 meter). The content of 3/4- to 3-inch (2- to 7.5-centimeters) coarse fragments with depth is somewhat variable, but generally remains constant or declines slightly. The proportion of 3/4- to 5/64-inch (two-centimeters to two-millimeters) coarse fragments is also variable, but generally decreases slightly with depth, suggesting that this size fraction may represent the equilibrium point in the slaking process mentioned above.

At Site C, coarse fragment content in the surface layers averages approximately 30 percent and increases to 50 to 60 percent at depths of four to five feet (1.2 to 1.5 meters) in all spoils except the two-year spoils. The proportion of coarse fragments greater than ten inches (25 centimeters) increases slightly with depth on all ages suggesting more intensive slaking of large fragments in the near surface. The proportion of fragments from three to ten inches (7.5 to 25 centimeters) in diameter increases with depth on fresh spoil and is variable on older spoils. The proportion of 3/4- to 3-inch (2- to 7.5-centimeters) coarse fragments generally decreases with depth on the fresh and two-year spoil while it increases slightly or remains constant in the five- and ten-year spoil, suggesting that slaking has proceeded to greater depths in the older spoils. The proportion of 3/4- to 5/64-inch (two-centimeters to two-millimeters) size coarse fragments generally decreases with depth regardless of spoil age. The near-surface increase may be a result of material derived from coarser fragments and substantiates the idea of an equilibrium particle size mentioned previously.

At Site D, total coarse fragment content generally increases with depth in all age spoils. Slight decreases at depths of five to six feet (1.5 to 1.8 meters) on five- and ten-year spoils may be a result of spoil placement methods (i.e., partial haulback with minimal regrading);

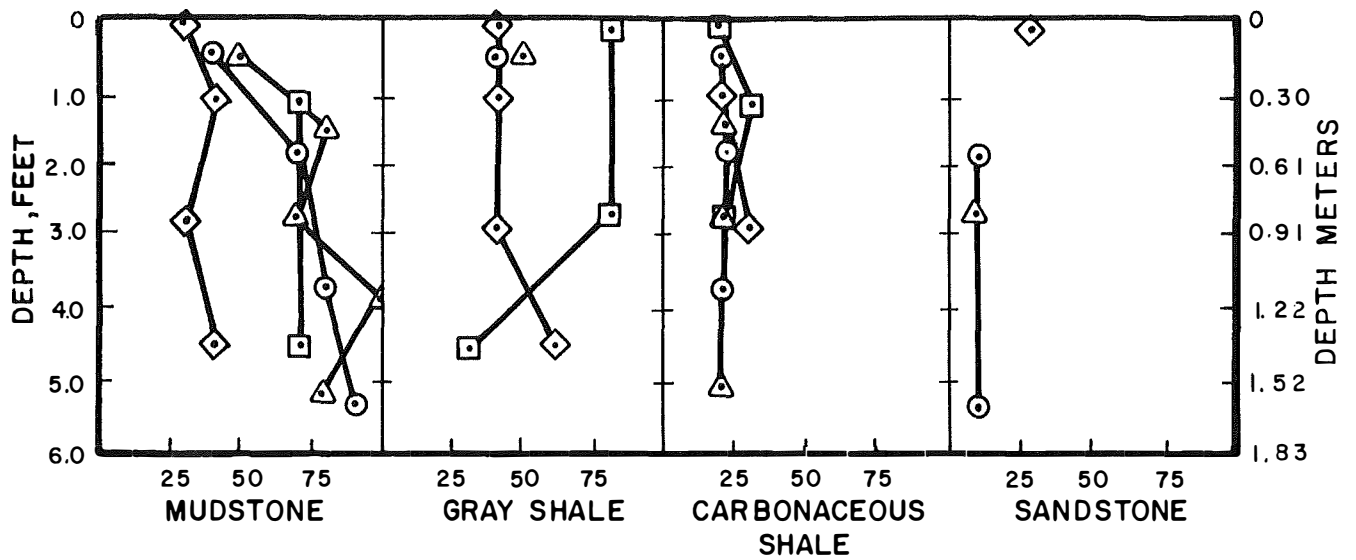
however, supportive information for this conclusion could not be obtained. The proportion of large (>10-inch or 25-centimeters) coarse fragments generally increases with depth on all age spoils while the three- to ten-inch (7.5- to 25-centimeters) and 3/4- to three-inch- (two- to 7.5-centimeters-) diameter fragments remains approximately constant with depth. The proportion of 3/4- to 5/64-inch (two-centimeters to two-millimeters) coarse fragments, as with the other sites, generally decreases with depth on all spoil ages.

Lithologic composition within the spoil profile also can be partially correlated to depth of burial. Lithologies highly prone to slaking, such as the mudstones at Site D, were relatively lacking in the near-surface layers and increased with depth. More durable lithologies remained relatively constant with depth, or varied as a function of spoil placement or composition. These relationships are depicted in Figures 9-10 and 9-11.

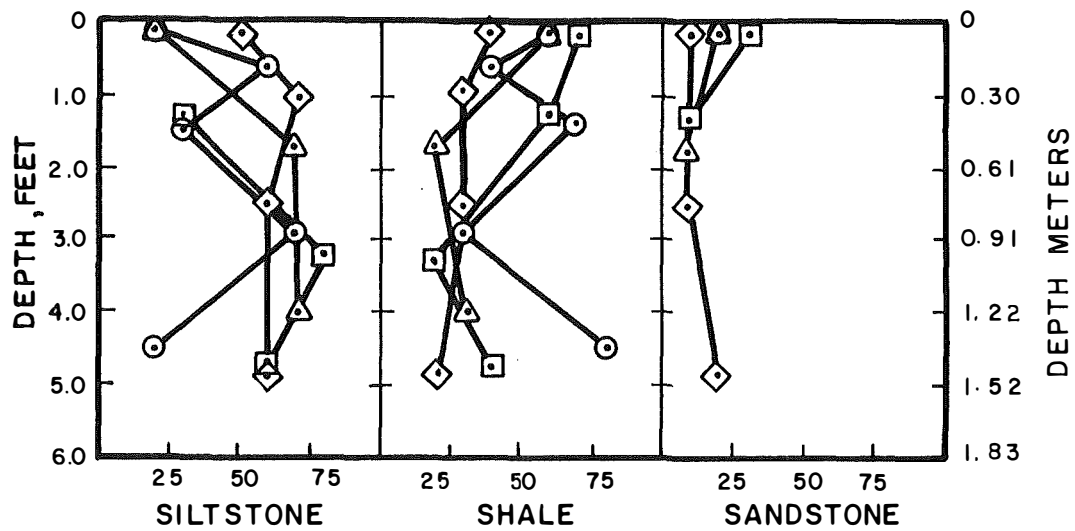
At Site A, the mudstone content generally increases with depth on fresh and five-year spoil, suggesting near-surface slaking of this lithology. However, in the two- and ten-year spoils, the mudstone content remains relatively constant with depth, with no apparent reason. The content of carbonaceous shale, gray shale, and sandstone remains relatively constant with depth on all spoils. Variable gray shale content at about five feet (1.5 meter) on two- and ten-year spoils is believed to be a result of spoil placement methods and spoil composition.

At Site B, the content of siltstone and shale is variable with depth in fresh spoil but generally increases on the two-, five-, and ten-year spoils, suggesting near-surface slaking of this lithology. The content of fissile shale-like chips, which are the product of slaking of siltstone materials, generally decreases with depth except on the fresh spoil. Determination of lithotype was difficult between the dominant siltstone and lesser-prevalent shale due to the similarity in slaking characteristics, especially in the smaller particle sizes. The small amounts of sandstone which are present remain relatively constant with depth.

At Site C, the percentage of siltstone generally increases with depth on the fresh spoil, indicative of slaking near the surface. Siltstone content, however, decreases with depth on other age spoils where spoil placement methods are believed to have concentrated siltstone materials near the surface. Sandstone content on fresh and two-year spoils remains relatively constant with depth, while five- and ten-year spoils increase with depth where spoil was placed so as to bury the sandstone. Mine personnel stated that sandstone materials were covered with siltstone materials in the belief that the latter would enhance revegetation by providing a more favorable physical growth medium, primarily through a decrease in large fragments and improved moisture holding capacity. The content of carbonaceous shale is constant with depth in all spoils, while mudstone content in fresh spoil increases with depth indicative of near-surface slaking. No mudstone was observed in



LITHOTYPE COMPOSITION (%)
a) SITE A

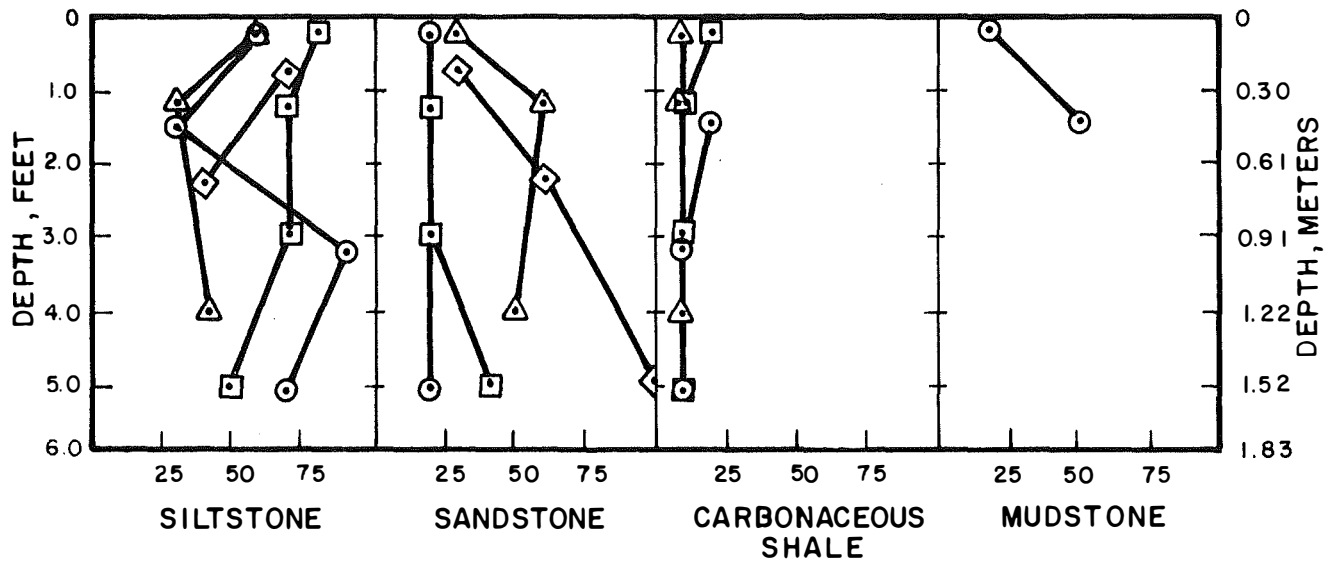


LITHOTYPE COMPOSITION (%)
b) SITE B

- LEGEND**
- - 0 YEAR SPOIL
 - - 2 YEAR SPOIL
 - △ - 5 YEAR SPOIL
 - ◇ - 10 YEAR SPOIL

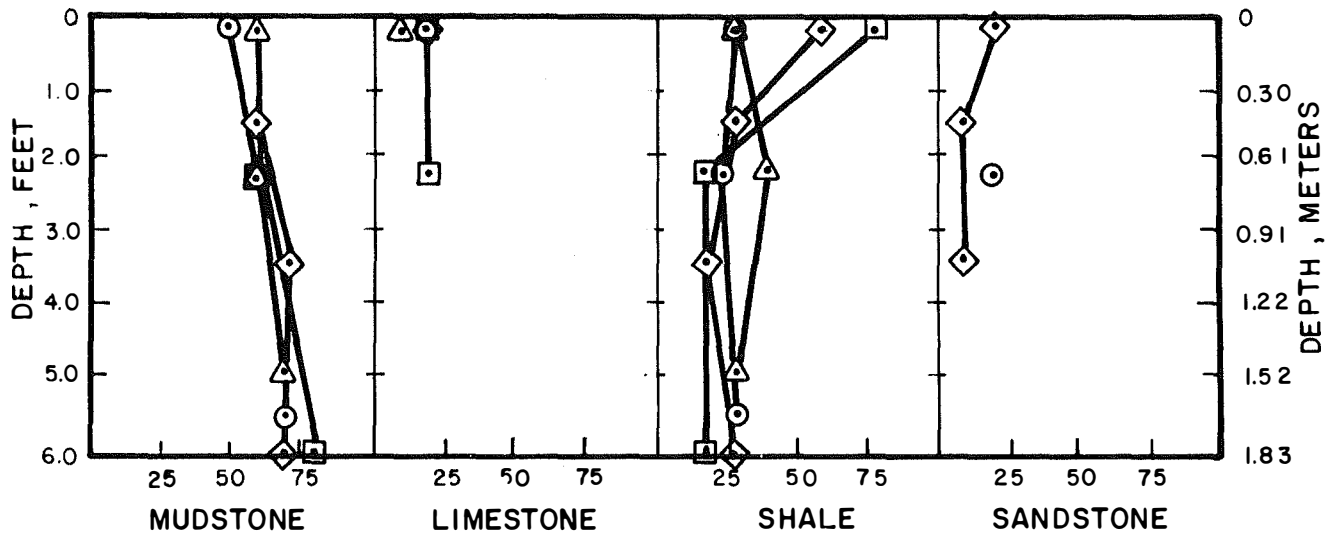
NOTE:
PERCENTAGES BASED ON VISUAL ESTIMATES OF MATERIAL > 5/64 INCH (2 mm) DIAMETER.

PERCENT COARSE LITHOTYPE COMPOSITION vs DEPTH
SITES A and B



LITHOTYPE COMPOSITION (%)

a) SITE C



LITHOTYPE COMPOSITION (%)

b) SITE D

LEGEND

- - 0 YEAR SPOIL
- - 2 YEAR SPOIL
- △ - 5 YEAR SPOIL
- ◇ - 10 YEAR SPOIL

NOTE:

PERCENTAGES BASED ON VISUAL ESTIMATES OF MATERIAL < 5/64 INCH (2 mm) DIAMETER

PERCENT COARSE LITHOTYPE COMPOSITION vs DEPTH
SITES C and D

older spoils due either to placement methods or complete slaking of this material over time.

At Site D, the mudstone content increases with depth, suggesting near-surface slaking of this lithology. The shale content decreases with depth or remains nearly constant. The high shale content near the surface reflects the incorporation of some mudstone which had "chip slaked," thus skewing the lithotype distribution. The content of limestone and sandstone remains constant with depth where present in the spoils.

Several relationships between slaking and physical characteristics seemed common to all study sites even though different mining and spoil handling techniques were used. Lithology appears to be a major factor influencing the potential for slaking to occur. Fine-grained lithologies exhibited the greatest degree of slaking as evidenced by examination of size distribution and quantities in spoil profiles. Carbonaceous shales, however, exhibited little evidence of slaking. Careful study of coarse fragment size and distribution and lithology with depth revealed the following relationships with some exceptions at all sites on all age spoils:

- Slake resistant large fragments will persist at or near the surface while slakable lithologies generally occur in large fragments deeper in the spoil profile.
- Total coarse fragment content generally increases with depth.
- Particle size distribution usually becomes coarser with depth.
- Some lithologies, chiefly shales, mudstones, and siltstones, can undergo a rapid decrease in fragment size. However, when fragments reach 3/4- to 5/64-inch (two-centimeter to two-millimeter) size, further degradation apparently occurs at a much slower rate, suggesting that these fragments have approached equilibrium with their environment.
- Slaking intensity is inversely related to depth and appears to be minimal below a depth of about five feet. Although these general trends were common to all study sites, exceptions did occur. Differences in mining and spoil handling methods are probably responsible for the behavioral variation.

9.1.5 Observed Environmental Effects of Slaking

Slaking of mine spoils produces a variety of associated environmental effects. Some, such as accelerated erosion, may adversely affect local environmental quality. Other effects may favorably impact the mine site and surrounding area. 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.
- Vegetational impacts.
- Variations in slope stability.
- Variations in off-site damage.
- Changes in spoil hydrology.

The presence of a pebble pavement on the spoil surface was characteristic of all sites studied. Fragments ranged from 1/4 inch (six millimeters) to several feet in size, but were commonly 1/2 to three inches (1.2 to 7.5 centimeters) in diameter. The pebble pavement usually consisted of fragments of slake-resistant lithologies such as limestone or silica-cemented sandstone. The pebble-pavement ranged from as little as 30 to essentially 100 percent areal cover. Total or near total pebble cover appeared to assist erosion control, moisture conservation, and seed germination.

Spoils which had not been topsoiled commonly exhibited a crusted layer immediately beneath the pebble pavement. The crust usually consisted of materials which had slaked to their inherent grain size. The thickness and compactness of the crust are a function of the proportion of materials present that slake to their inherent grain size, the amount of machinery traffic traversing the area, and moisture content at the time of traffic crossing. In general, spoils containing greater proportions of materials which exhibited this type of slaking and sustained heavy traffic when wet had a thicker and more compact surface crust. Spoils commonly displayed crusts from 1/2 to five inches (one to 13 centimeters) thick. The development of a surface crust appeared most pronounced where mudstone materials comprise a large amount of the surface spoil, as at Site D. Mudstones at this site slaked rapidly to their constituent grain size (principally silt and clay). The fine particle size and mudlike consistency of moist slaked mudstone appeared to promote compaction by machinery traffic and the formation of the surficial crust. Crusting appeared to be somewhat alleviated over time by the establishment and continued growth of vegetation with vigorous root systems. This conclusion is based on observations of two-year (recently vegetated) spoil and ten-year (established vegetation) spoil at Site D. In contrast to Site D, spoils containing a high percentage of durable chips or slabs in the surface, as at Site B, exhibited the least crusting. The presence of durable fragments (e.g. shale/siltstone chips or limestone/sandstone fragments) appeared to partially offset compaction and crust formation at the spoil surface.

Sheet, rill, and gully erosion was observed to occur to varying degrees on all spoils. Spoils containing a high proportion of materials which 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. Concentrated surface water movement either by diversion or as a result of topographic configurations created numerous rills and occasional deep gullies. This was most noticeable on spoils with a high proportion of materials which slake to their inherent grain size, as at Site D. As previously mentioned, the presence of a durable pebble pavement was observed to be effective in controlling sheet erosion and is a significant erosion control factor on many spoils, in particular at Sites B and C. Spoils at these sites, consisting principally of durable siltstone and sandstone with a high percentage (e.g., greater than 70 percent) of pavement cover, appeared to have few erosion problems. Rock riprap in drainage and diversion ditches, where composed of slake-resistant rocks, prevents down-cutting. Stable rock riprap generally results in U-shaped ditches, while slake-prone riprap typically yields V-shaped ditches with active down-cutting. Some stream diversions at Site D were observed to have failed or exhibited significant erosion due to a lack of durable riprap.

Slaking in mine spoils creates both adverse and beneficial effects on vegetation. Adverse effects include dense crusting of the surface which impedes seed germination, root proliferation, and moisture infiltration. Where spoils consist of a high proportion of materials which slake to their inherent grain size, compact, dense sublayers also occur, impeding deep root penetration. Beneficial effects include the production of fine particles resulting 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. Spoils containing approximately equal proportions of materials which slake to their inherent grain size and rocks which chip slake or slab or block slake generally provide an excellent physical medium for plant growth. Although it could not be observed directly in the field, it is probable that slaking also increases plant-available nutrients in spoils. Since slaking involves a decrease in fragment size, specific surface area increases, thus exposing more material to chemical weathering and subsequent mobilization of plant nutrients.

Slope stability also was found to be related to the slaking mode of spoils. This is irrespective of the variations in bulk density which are known to affect stability (Section 9.1.4). Spoils in which chip, slab, or block slaking dominates generally had little or no stability problems. Spoils in which chip slaking is dominant appeared to be exceptionally stable. The chips form an interlocking matrix which is very resistant to bulk movement. The same phenomenon of interlocking fragments occurs, to a lesser extent, in slab or block slaking materials. Spoils which slake to their inherent grain size may have stability problems as evidenced by slips, bulges, slides, or similar features.

Off-site damage may occur as a result of slaking in mine spoils, particularly when materials which slake to their inherent grain size are present in large quantities. It is often associated with excessive erosion rates and occurs in the form of increased sediment loads and stream siltation. Chip slaking and slab or block slaking were not observed to significantly contribute to off-site damage.

Spoil hydrology and its interaction with slaking were observed to be a complex process. Contrary to the general opinion that spoils are highly permeable, free draining, and retain little water, spoils were found to be effective water reservoirs; perched water tables were found within five feet of the surface in several test pits. Generally, this condition is related to slaking as a decrease in particle size and an increase in near-surface density.

Surface water infiltrates the spoil surface by two means including capillary action of small pores and entry into large cracks and voids. Capillary action is the most important means of infiltration; however, gravity drainage of water into larger surface voids such as shrinkage cracks was observed to occur.

Within the spoil profile, water moves by one of three ways:

- Capillary action
- Gravitational drainage
- Vapor transport.

Vapor transport could not be directly observed in the field; however, 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 seen in numerous profiles; this type of water movement is usually concentrated in large voids and pores. Rock fragments present in and around these voids appeared to slake more rapidly or to a greater extent as a result of exposure to relatively large quantities of water.

Eastern and midwestern coal fields receive precipitation fairly well distributed throughout the year (Chapter 6.0). Consequently, cyclic wetting and drying appear to be confined to approximately the upper four to five feet (1.2 to 1.5 meters) of the spoil profile, and extreme desiccation is limited to the top two feet (1.2 meters). 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. Although the temperature variations differ between sites, any impact of ice formation, if it existed, was masked by other slaking actions.

9.2 LABORATORY TESTING PROGRAM

As described in Chapter 8.0, the principal aims of the laboratory program were directed toward:

- Assessing the applicability of specific accelerated rock weathering tests to predict long-term field behavior.
- Determining relationships that may exist between simple index or sophisticated quantitative techniques and the observed laboratory durability behavior.
- Quantifying, if possible, the time-dependent relationships that exist between laboratory rock degradation and observed performance under field conditions.

The first two points will be addressed in the following subsections while the latter point will be examined in Section 9.3.

9.2.1 Durability Tests

The durability tests selected for study consisted of jar slake, cyclic wet/dry, cyclic rate of slaking, and the slake durability tests (Section 8.2). These tests were selected because the influence of a wide range of parametric effects could be closely examined using procedures that had proven previous success. The various parametric factors consist of the following:

- Sample Size - Coarse sample fragments ranging from 1-1/2 to two inches (38 to 51 millimeters) and fine sample fragments ranging from 1/4 to 3/4 inch (six to 19 millimeters).
- Slaking Fluid - Distilled water and 50 percent solutions of ethylene glycol (jar slake) and sodium sulfate (cyclic wet/dry).
- Temperature - 65 and 110 degrees Celsius (cyclic rate of slaking test only).
- Energy Input - Varying from negligible (jar slake), to moderate (cyclic wet/dry and rate of slaking), to substantial (slake durability test).

Because each of these factors may control, to some degree, the slaking behavior of geologic materials, and surface mine spoils in particular, the testing program represents a comprehensive attempt to identify the key factors affecting this behavior.

As shown in Table 9.2, 128 individual durability tests were conducted using 14 lithologic units collected from four different active surface mining sites. These lithologic units included four sandstones, two limestones, two siltstones, three mudstones, and three shales.

TABLE 9.2
SUMMARY OF DURABILITY TEST RESULTS

SITE	LITHOTYPE	DURABILITY TEST(1)													
		JAR SLAKE(2)				CYCLIC WET/DRY(2)				CYCLIC RATE OF SLAKE(2)				SLAKE DURABILITY	
		COARSE		FINE		COARSE		FINE		COARSE		FINE		I _{d2} ⁽³⁾	1-I _{d2}
		WATER	ETHYLENE GLYCOL	WATER	ETHYLENE GLYCOL	WATER	SODIUM SULFATE	WATER	SODIUM SULFATE	65°C	110°C	65°C	110°C		
A	Brown Sandstone	0	2.7	0.5	0.5	2.0	4.9	0.8	0.3	0	0	0.8	0.3	99.0	1.0
	Gray Shale	11.7	14.8	0.4	0.3	31.6	34.2	0.7	0.7	40.9	52.5	1.2	1.8	87.6	12.4
	Green Mudstone	●	●	47.5	51.9	76.6	■	56.6	30.7	●	●	48.7	58.6	87.1	12.9
	Black Carbonaceous Shale	21.8	26.2	0.5	0.2	42.1	52.1	2.1	0.8	■	35.2	1.9	1.2	97.6	2.4
	Gray Limestone	●	●	●	●	●	●	●	●	●	●	●	●	99.3	0.7
B	Gray Siltstone	3.7	0	1.6	0	75.2	72.2	26.5	16.4	0	76.2	12.1	24.3	98.5	1.5
C	Yellow Sandstone	0	0.3	●	●	0	0	●	●	0	0	●	●	97.1	2.9
	White Sandstone	0	0	0.3	0.3	0	0	0.6	0.7	0	0	1.2	0.5	97.7	2.3
	Gray Siltstone	31.4	25.4	●	●	24.4	25.7	7.5	3.0	26.8	31.6	●	●	94.3	5.7
D	Brown Sandstone	5.4	3.4	●	●	0	18.1	●	●	10.4	7.5	●	●	99.5	0.5
	Gray Shale	38.3	32.6	13.5	16.9	41.9	64.4	42.0	32.6	80.5	87.5	45.7	57.6	98.3	1.7
	Green Mudstone	13.3	9.7	19.5	10.9	20.6	21.8	27.4	15.3	2.3	24.2	21.2	22.6	75.7	24.3
	Red/Green Mudstone	85.6	●	●	●	92.7	●	●	●	●	●	●	●	63.4	36.6
	Gray Limestone	●	●	●	●	●	●	●	●	●	●	●	●	99.7	0.3

(1) All numbers expressed as percent.

(2) Numbers in columns represent Degradation Index (DI) values.
(See Appendix A.4.0 for computational procedure.)

(3) 2-cycle slake durability index.

LEGEND

● - No test performed.

■ - Test performed; sample crushed for X-ray prior to sieving.

Because the deterioration of limestone typically does not occur through physical modes, durability testing for this rock type was limited to two-cycle slake durability tests. Durability testing of other lithotypes was limited only by the availability of the required quantities and sizes of materials. When necessary, coarse samples using distilled water as a slaking fluid were given preference because sample particle size affects the amount and rate of deterioration and distilled water is more readily available for testing than the other slake fluids.

The degradation index (DI) was used to quantify the deterioration of the tested materials for the jar slake, cyclic wet/dry, and cyclic rate of slaking tests. Values of the degradation index for these tests were readily obtained from the results of grain size analyses made prior to and following slake testing. The limits for this index range from zero (no breakdown) to 100 percent (complete breakdown). The slake durability index (I_d), which represents the percent ratio of the retained dry sample weight following testing to the initial dry sample weight, was used to define the slake durability test results. Numerical subscripts to I_d (e.g., I_{d2}) are presented to indicate the number of testing cycles used to determine the index value. For purposes of comparison with the other durability test results, however, the term $(1 - I_{d2})$ is used to define a degradation index for the slake durability test.

9.2.1.1 Jar Slake Test

Thirty-seven jar slake tests were conducted to ascertain the suitability of this testing procedure for predicting field slaking behavior. Of the several testing procedures employed during this program, the jar slake test represents a static testing method that involves negligible energy input in the form of either heat or mechanical effort. Accordingly, the potential range of values (DI) that might be expected is smaller than for the other test types. As such, this test might be most closely related to spoil materials located at depth and within a constant humidity or totally saturated environment.

As shown in Table 9.2, values of the degradation index ranged from 0 to 85.6 percent. The mean DI for all jar slake tests is 15.5 percent and can be used as a relative measure of the severity of other slake tests. The value may be somewhat biased by the limited quantities of sample available for the green (Site A) and red/green (Site D) mudstones. In general, the DI values were the smallest for the sandstones (indicating the greatest durability) and the largest for the mudstones. The siltstones and shales were within these extremes and indicated no readily apparent trends.

The summary of DI values for the jar slake tests (Table 9.2) shows the influence of fragment size, using either of the slaking fluids, particularly for the less durable lithologies. This suggests that materials smaller than a particular particle size (Section 9.1.4) may attain an equilibrium with the surrounding environment and thereby resist further breakdown. This factor was most readily observed for the shale

and siltstone samples which broke down along randomly spaced bedding planes within several hours to days following immersion. The series of photographs in Figure 9-12 documents this behavior. It should be noted that the two sample baskets shown in each portion of Figure 9-12 contain the total sample weight for each lithotype and do not represent separate tests.

The impact of slaking fluids for these tests was not as influential as the size effect. The greater degradation indices were typically achieved using distilled water as the slaking solution. For most tests using a coarse fragment size sample, the difference in DI for the two solutions is generally less than five percent and somewhat smaller for the fine fraction.

Several additional parameters (e.g., water content and fluid pH) were examined in relation to the jar slake test, as with all the durability tests. These will be discussed in Section 9.2.2.

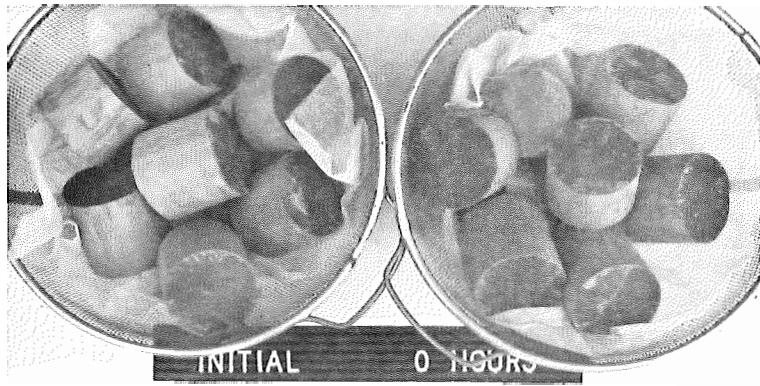
9.2.1.2 Cyclic Wet/Dry Test

The cyclic wet/dry test represents an attempt to model the conditions that may exist near or at the surface of spoil piles. The behavior of spoils within this zone will most likely be controlled by alternate wetting and drying from rainfall and infiltration followed by evaporation.

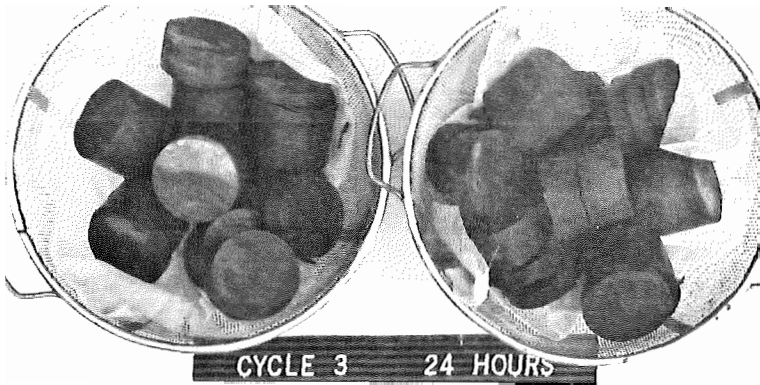
The energy input for the cyclic wet/dry test is significantly greater than the minimal effort imparted during the jar slake test and, therefore, represents a more severe testing procedure. The alternate wetting and drying cycles can lead to a gradual breakdown along planes of weakness for anisotropic sediments (siltstones and shales) or sudden to gradual disaggregation for more homogeneous or isotropic materials (mudstones). Because of this, the degree of slaking is expected to be greater for this test.

As shown in Table 9.2, 41 cyclic wet/dry tests were conducted on all the lithologies used for the jar slake tests. The overall range of degradation index values was generally higher (mean DI = 24.7 percent) for this testing method than observed for the jar slake tests. This conclusion is typically true for both sample sizes and slaking fluids. As noted previously for the jar slake tests, sandstones suffered very little deterioration and mudstones the greatest; siltstones and shales again occur between the extremes. The most noticeable difference developed from this test versus the jar slake test was for the coarse shale and siltstone samples which are particularly sensitive to the wetting and drying process. A typical example of this was the significantly greater breakdown of the gray siltstone from Site B.

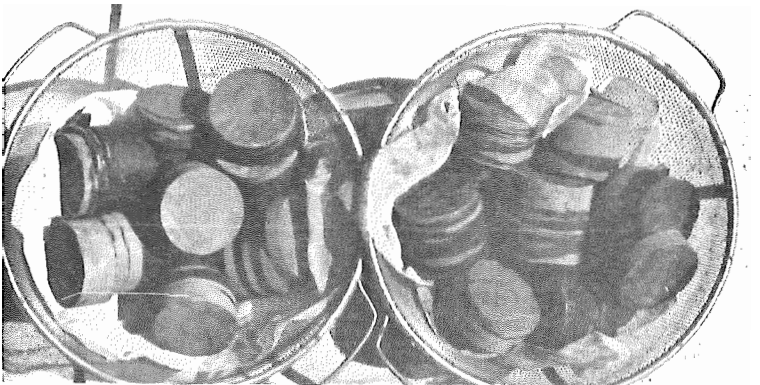
Figures 9-13 and 9-14 clearly show the pattern of breakdown and the influence of cyclic wetting and drying from the initial condition to the completion of the fifth cycle. The pattern of deterioration was



INITIAL



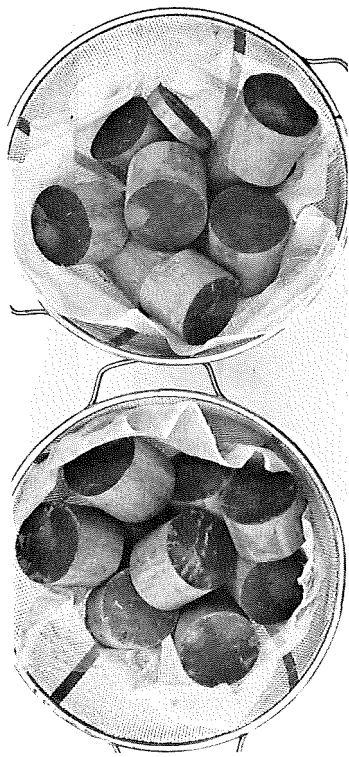
END OF DAY 3



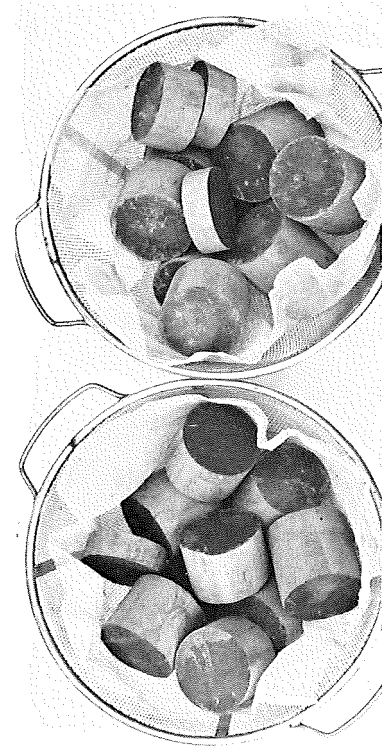
END OF DAY 5

GRAY SILTSTONE -SITE B
FRAGMENT SIZE: COARSE
SLAKE FLUID: WATER

EXAMPLE OF JAR SLAKE TEST RESULTS



INITIAL



END OF
CYCLE 1

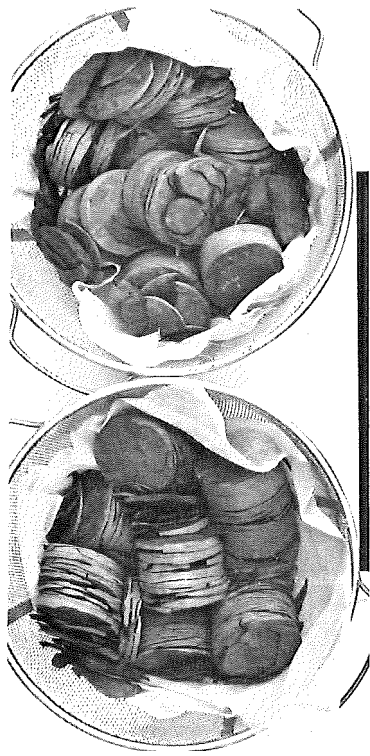


a) SLAKE FLUID: WATER

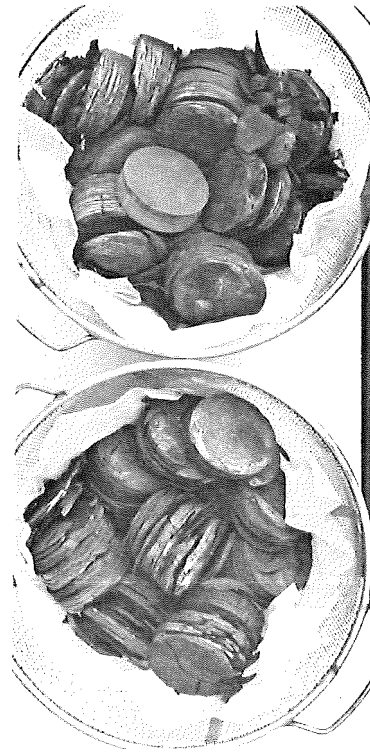
b) SLAKE FLUID: SODIUM SULFATE

GRAY SILTSTONE - SITE B
FRAGMENT SIZE: COARSE

EXAMPLES OF CYCLIC WET/DRY TEST RESULTS
SLAKE FLUID EFFECTS - INITIAL, CYCLE 1



END OF
CYCLE 3



END OF
CYCLE 5



a) SLAKE FLUID: WATER

b) SLAKE FLUID: SODIUM SULFATE

GRAY SILTSTONE - SITE B
FRAGMENT SIZE: COARSE

EXAMPLES OF CYCLIC WET/DRY TEST RESULTS
SLAKE FLUID EFFECTS - CYCLE 3, CYCLE 5

initially similar to that observed previously at the conclusion of jar slake tests for shales and siltstones (Figure 9-12). However, with increasing numbers of cycles, the breakdown was more complete resulting in fractures along thinly spaced bedding planes (approximately 1/8- to 1/4-inch [three- to six-millimeters] thick). Subsequent breakage across bedding planes was also observed for a few individual rock fragments.

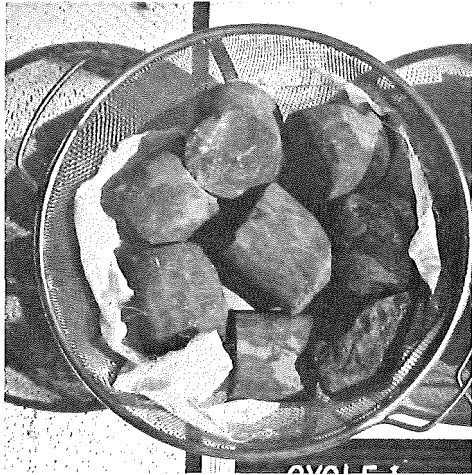
The breakdown for the coarse mudstones followed a different pattern that apparently was uncontrolled by any observable rock fabric. The slaking behavior for the mudstones was manifested by nearly complete disaggregation along random planes as depicted in Figures 9-15 and 9-16. For the red/green mudstone from Site D (Figure 9-15), the process began almost instantaneously upon immersion, while the green mudstones broke down more slowly requiring one or more complete soaking cycles for initiation. The pattern of disintegration for the green mudstone from Site A (Figure 9-16) was also slightly different in that certain pieces remained nearly intact with only a small amount of cracking and surficial rounding. Breakdown for the fine fraction was generally less severe but followed the same general pattern observed for the coarse samples.

The influence of sample size was similar to that observed for the jar slake tests. DI values for the coarse fraction were greater than corresponding values determined for the fine sample components. With the exception of the mudstones, the durability of the various lithologies was strongly affected by sample size, indicating that at particle sizes of 3/8 to 1/2 inch (10 to 13 millimeters) and smaller, the influence of rock fabric was minimal. Conversely, the mudstones continued to break down with increasing numbers of cycles.

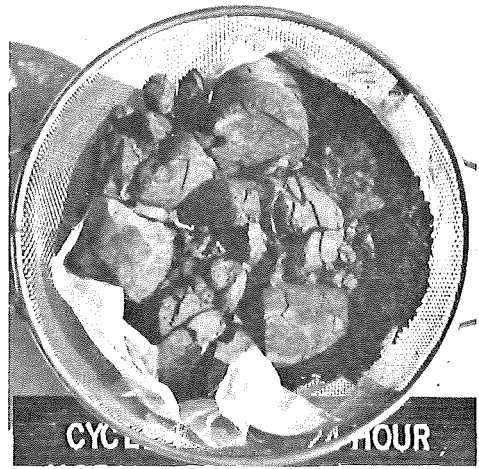
The selection of a 50 percent saturated solution of sodium sulfate as a slaking fluid resulted in slightly greater breakdown compared with similar samples in distilled water. This is attributable to the effect of alternate dissolution and recrystallization of the sodium salt. Application of a more concentrated solution would likely provide little additional advantage over the observed results and may possibly have masked them by causing very complete breakdown for all samples except the most durable. Based upon the results attained for both solutions, wetting and drying effects are dominant over the influence of sodium sulfate.

9.2.1.3 Cyclic Rate of Slaking Test

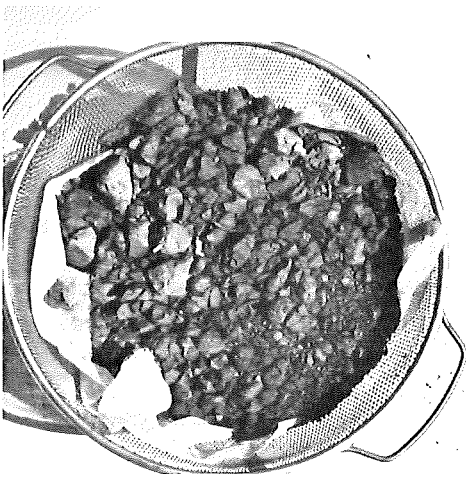
The cyclic rate of slaking test is designed to model the effects of temperature and duration of wetting on the slaking process. Because surface mine spoils, particularly within the upper portions, are subjected to frequent but incomplete wetting and drying cycles, this test method may most accurately represent surficial in situ field conditions of all the durability tests.



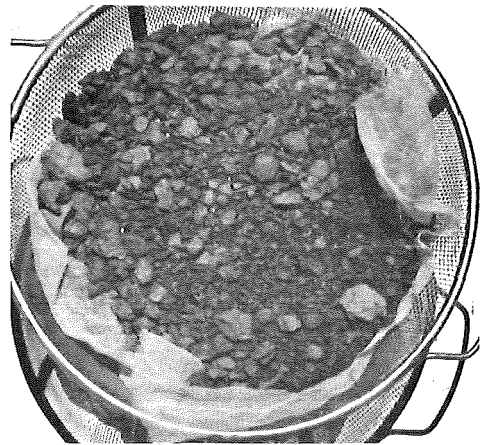
INITIAL



END OF CYCLE 1



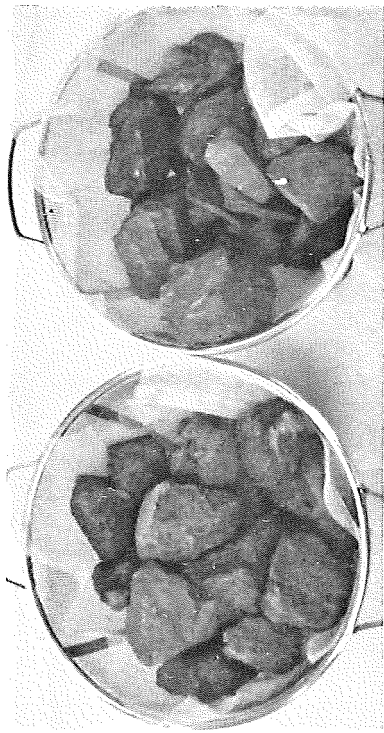
END OF CYCLE 3



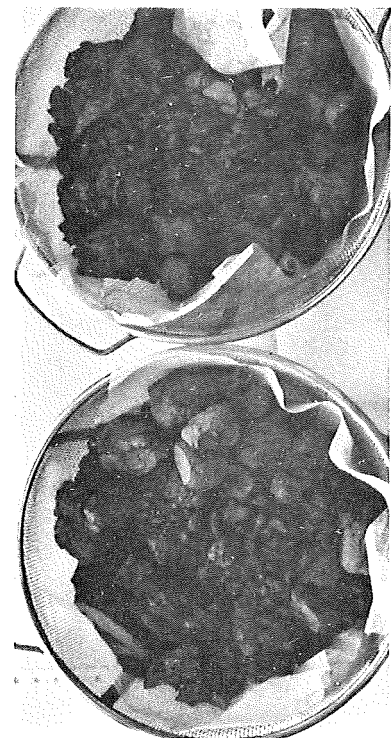
END OF CYCLE 5

FRAGMENT SIZE: COARSE
SLAKE FLUID: WATER

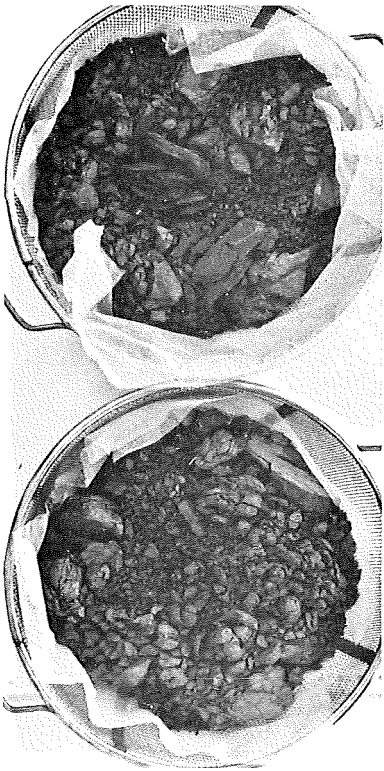
EXAMPLE OF CYCLIC WET/DRY TEST RESULTS
RED/GREEN MUDSTONE - SITE D



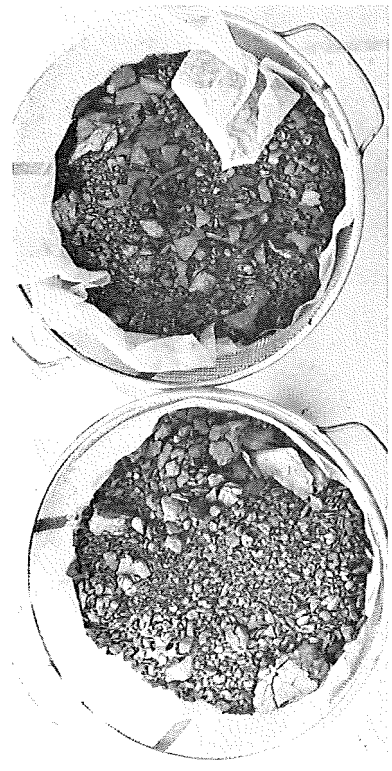
INITIAL



END OF CYCLE 1



END OF CYCLE 3



END OF CYCLE 5

FRAGMENT SIZE: COARSE
SLAKE FLUID: WATER

EXAMPLE OF CYCLIC WET/DRY TEST RESULTS
GREEN MUDSTONE - SITE A

The primary differences between the cyclic wet/dry test in water and the cyclic rate of slaking test are the duration of soaking (eight hours versus two hours) and the drying temperature (110 degrees versus 65 degrees Celsius and 110 degrees Celsius). Because the duration of soaking, drying temperature, and number of cycles have an effect in controlling the durability behavior, the test procedure which imparts the lowest energy level to the sample is expected to cause the smaller amount of sample distress.

From the results of 36 cyclic rate of slaking tests summarized in Table 9.2, the impact of the shorter soaking cycle and lower drying temperature (for 65 degrees Celsius only) is small but noticeable compared with the cyclic wet/dry tests in water. The average DI for these tests is 22.6 percent with values ranging from 0 to 87.5 percent. As noted with the cyclic wet/dry test results, the sandstones exhibited the least deterioration while the siltstones, shales, and mudstones achieved greater degrees of breakdown. Also, the observed patterns of breakdown for these samples were nearly identical to those described for the wet/dry tests.

The impact of drying temperature was generally small for all lithologies and fragment sizes, but was nonetheless apparent. The most readily discernible effect was observed in the least durable materials (e.g., siltstones, shales, and mudstones). As expected, degradation indices tended to increase with higher temperatures and coarser samples.

9.2.1.4 Slake Durability Test

The slake durability test was originally developed to provide information regarding the potential weatherability or slakability of geologic materials. The testing procedure requires that small rock fragments are subjected to cyclic wetting and drying combined with a mechanical tumbling action. For surface mine spoils, this process may be indirectly considered as part of the excavation, placement, and aging aspects of spoil pile degradation (Section 7.2.2).

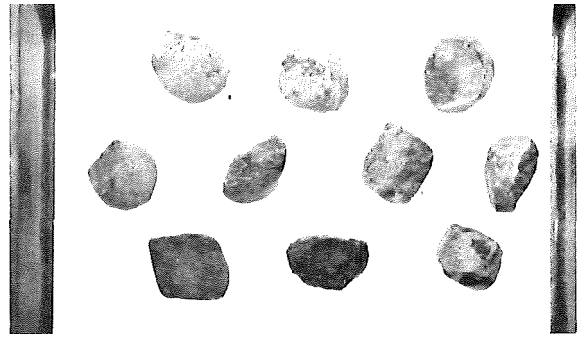
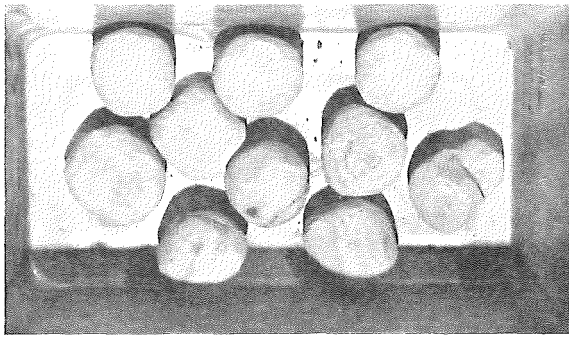
Table 9.3 presents the results of 14 slake durability tests in the form of one- and two-cycle slake durability indices (I_{d1} and I_{d2}) and a two-cycle durability description (Gamble, 1971). Table 9.2 presents a slight variation (I_{d2} and $1-I_{d2}$) to allow for comparison with the degradation index values developed for the jar slake, cyclic wet/dry, and cyclic rate of slaking tests.

Values of I_{d2} range from 99.7 percent (gray limestone - Site D) to 63.4 percent (red/green mudstone - Site D). These values generally fall within the very high to medium high durability range and, with the exception of the green and red/green mudstones from Site D, reveal little variation for the wide range of tested materials. The limestones and sandstones all indicate high to very high durability while the mudstone durabilities range from medium to medium high (Figure 9-17). As observed for the other durability tests, the siltstones and shales fall between these boundaries.

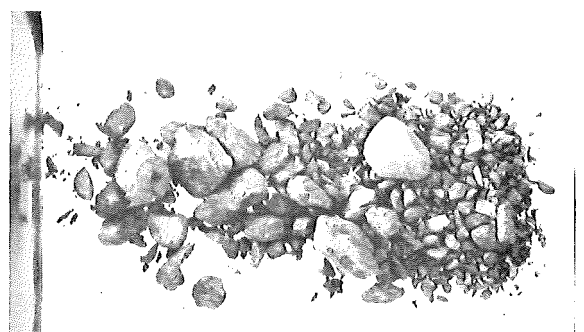
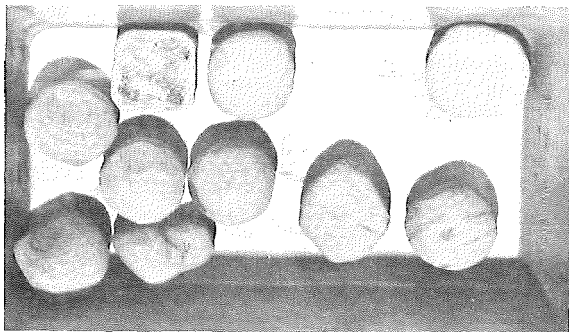
TABLE 9.3
SUMMARY OF SLAKE DURABILITY TEST RESULTS

SITE	LITHOTYPE	SLAKE DURABILITY INDEX		2-CYCLE DESCRIPTION ⁽¹⁾
		1-CYCLE I_{d1} (%)	2-CYCLE I_{d2} (%)	
A	Brown Sandstone	99.4	99.0	Very High
	Green Mudstone	94.5	87.1	Medium High
	Gray Limestone	99.5	99.3	Very High
	Gray Shale	97.0	87.6	Medium High
	Black Carbonaceous Shale	99.3	97.6	High
B	Gray Siltstone	99.1	98.5	Very High
C	Gray Siltstone	97.1	94.3	Medium High
	Yellow Sandstone	98.2	97.1	High
	White Sandstone	98.7	97.7	High
D	Gray Limestone	99.8	99.7	Very High
	Brown Sandstone	99.7	99.5	Very High
	Gray Shale	99.2	98.3	Very High
	Green Mudstone	91.0	75.7	Medium
	Red/Green Mudstone	85.1	63.4	Medium

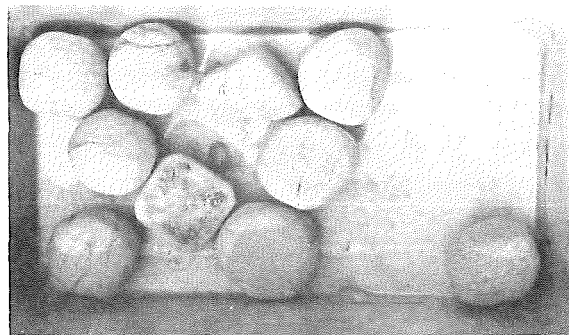
(1) Gamble, 1971.



INITIAL



END OF CYCLE 1



END OF CYCLE 2

a) BROWN SANDSTONE - SITE A

b) RED/GREEN MUDSTONE - SITE D

EXAMPLES OF SLAKE DURABILITY TEST RESULTS

With the exception of tests performed for the limestones and shales, values of $1-I_{d2}$ (Table 9.2) do not show a strong correlation with corresponding DI values determined using the other durability test procedures. In a few cases, a similarity does exist between DI values for the fine component (e.g., green mudstone - Site D). The existence of poor correlation between slake durability tests and the other methods, in most cases, suggests that this method may not properly simulate in situ conditions.

9.2.1.5 Summary of Durability Test Results

The principal objective of the durability testing program was directed toward evaluating each of several testing procedures to ascertain the method or methods for best identifying and ultimately predicting the durability of geologic sediments comprising surface mine spoils. To do this, a wide range of parameters was selected for study and examined in detail. These include rock fragment size, slake fluid, soaking and drying cycles, temperature, and energy input imparted during the testing procedure. Each of these factors is evaluated below by comparing similar test results as presented in Table 9-4).

- Fragment Size - The size of sample fragments was shown to be important for all durability tests in which this parameter was considered. In general, the coarse samples developed greater breakdown for all fluids and temperature conditions. The most noticeable changes occurred for thinly bedded, anisotropic sediments, such as siltstones and shales. Consequently, for a complete identification of slaking potential to be made, consideration must be given to testing samples of sufficient coarseness and representative of the expected sample size following excavation and spoiling. The results of these tests suggest that samples with fragment sizes approximately one inch (25 millimeters) or larger be used and that some modification of the slake durability test may be required to accommodate this recommendation.
- Slaking Fluid - From the results of these tests, the application of 50 percent solutions of either sodium sulfate or ethylene glycol can lead to slightly greater breakdown compared to distilled water. However, distilled water is recommended for future studies because it is more readily available, easier to handle, and its influence during testing was observed to be only slightly less than that of the chemical fluids.

TABLE 9.4
SUMMARY OF DEGRADATION INDICES (DI) FOR COMPARABLE TEST CONDITIONS⁽¹⁾

SITE	LITHOTYPE	FRAGMENT SIZE	DEGRADATION INDEX, DI (%)			SLAKE DURABILITY TEST 1-I _{d2} ⁽²⁾ (%)
			CYCLIC WET/DRY TEST	JAR SLAKE TEST	CYCLIC RATE OF SLAKING TEST (110°C)	
A	Brown Sandstone	Coarse	2.0	0	0	1.0
		Fine	0.8	0.5	0.3	
	Gray Shale	Coarse	31.6	11.7	52.5	12.4
		Fine	0.7	0.4	1.8	
Green Mudstone	Coarse	76.6	●	●	12.9	
	Fine	56.6	42.5	58.6		
Black Carbonaceous Shale	Coarse	42.1	21.8	35.2	2.4	
	Fine	2.1	0.5	1.2		
B	Gray Siltstone	Coarse	75.2	3.7	76.2	1.5
		Fine	26.5	1.6	24.3	
C	Yellow Sandstone	Coarse	0	0	0	2.9
		Fine	●	●	●	
	White Sandstone	Coarse	0	0	0	2.3
Fine		0.6	0.3	0.5		
Gray Siltstone	Coarse	24.4	31.4	31.6	5.7	
	Fine	7.5	●	●		
D	Green Mudstone	Coarse	20.6	13.3	24.2	24.3
		Fine	27.4	19.5	22.6	
	Gray Shale	Coarse	41.9	38.3	87.5	1.7
		Fine	42.0	13.5	57.6	
Brown Sandstone	Coarse	0	5.4	7.5	0.5	
	Fine	●	●	●		
Red-Green Mudstone	Coarse	92.7	85.6	●	36.6	
	Fine	●	●	●		

● - No test performed because of insufficient sample quantity.

(1) Slake fluid for all tests was distilled water.

(2) Inserted for relative comparison with DI values from other slake durability tests.

- Soaking versus Alternate Wetting and Drying - With the exception of the slake durability test, cyclic wetting and drying provided the greatest assurance of breakdown. Of the cyclic tests, the cyclic rate of slaking procedure at 110 degrees Celsius is the most severe which indicates that short soaking periods causing only partial saturation are more effective for the tested samples. An advantage of this method is the shorter soaking observation period, reducing the overall time required for testing. The range of degradation index values obtained for the jar slake test was narrower than for the cyclic tests making the analysis more difficult and subjective. Therefore, cyclic testing is preferred to the static jar slake test.

- Temperature - The cyclic rate of slaking test results represented the only opportunity to study the relationship between drying temperatures and slake durability behavior. These tests indicate that a reduction in durability occurs with increasing drying temperatures. This pattern is stronger for the coarse size fraction which also demonstrates the influence of particle size in affecting the durability of the tested sediments. Although elevated oven drying temperatures such as 110 degrees Celsius are far more severe than would ever be realized within surface mine spoils, their application is recommended as a reference base and as part of the accelerated weathering that is integral to the majority of slake durability testing schemes.

- Energy Input - With the possible exception of the slake durability tests, greater degrees of breakdown were realized with test procedures providing the greatest energy effort. This effort was developed by several means including fluid infiltration, oven drying, chemical attack, and mechanical agitation. Of the durability tests considered for study, both the cyclic wet/dry and cyclic rate of slaking tests at 110 degrees Celsius provided a broad range of breakdown (DI values ranging from 0 to 93 percent) with sufficient sensitivity to characterize relationships within these boundaries. The influence of chemical attack through variation in slake fluid, and elevated drying temperatures (see above) are recognizable causing further breakdown beyond baseline conditions.

Based upon the test results, two apparently anomalous trends exist. The first is a reduction in sample breakdown with increasing mechanical agitation while the second trend is a decrease in deterioration with increasing soaking periods during cyclic testing. The first may be attributable to either the sample size required for the slake durability test (10 rock fragments, 40 to 50 grams each) or the definition for the slake durability index, I_d . Possible improvement might be realized by subjecting the retained dry sample to a grain size analysis and modifying the I_d accordingly. An alternate to this may be to incorporate larger rock fragments into the test procedure to account for the greater breakdown that was observed throughout the entire testing program for coarser sized samples. This, however, is in disagreement with Chandra (1970) who found that "smaller lumps, due to more exposed surface area tend to accelerate weathering."

The influence of soaking time was generally found to decrease with increasing durability for the cyclic durability tests. This trend is apparent (particularly for siltstones and shales) by examining Table 9.4. Although it would be expected that an extended soaking period prior to drying would represent a more severe test condition, the opposite appears to be true. A shortened soaking period would most likely cause a reduction in the degree of saturation below that obtained for samples immersed for a longer length of time. Since the pore air pressure decreases (becomes more negative) with decreasing degrees of saturation, the overall pressures exerted on samples immersed for shorter periods of time may actually be greater. This behavior is closely related to the negative pore air compression slaking mechanism described in Chapter 2.0 and may be related to the behavior observed during the cyclic durability tests.

9.2.2 Identification Tests

Knowledge of the physical, chemical, and mineralogical composition of geologic materials can provide considerable information regarding their slake durability behavior. Several test procedures were incorporated into the laboratory program which have found previous success and often provide corroborative information. The major goal of identification tests conducted in this study was to identify procedures that can be used with confidence as part of an overall slake durability predictive model.

The tests that were considered include several routinely performed geotechnical tests (i.e., moisture content, grain size of disaggregated samples, Atterberg limits, and unit weight), agronomic tests (i.e., 1:1 (soil) pH, methylene blue analysis, and cation exchange capacity) and several specially selected or sophisticated testing procedures (i.e., thin-section petrographic examination, and X-ray diffraction). The results of each of these methods are summarized below.

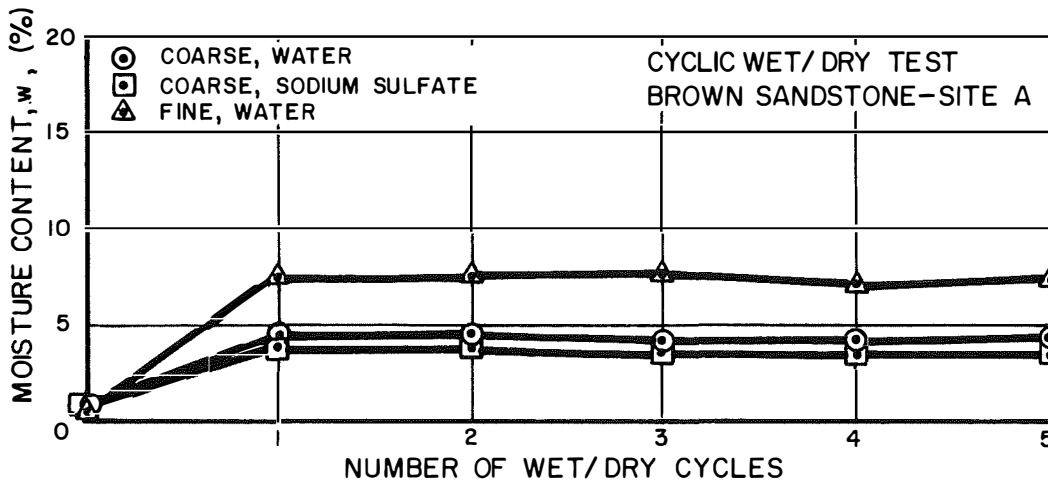
9.2.2.1 Moisture Content

Several general moisture content relationships were observed throughout the durability testing program. Moisture content is used herein to represent a more general term for water content since two chemical solutions were used for portions of the durability testing. The major observed trends follow while examples which typify these trends are shown in Figure 9-18.

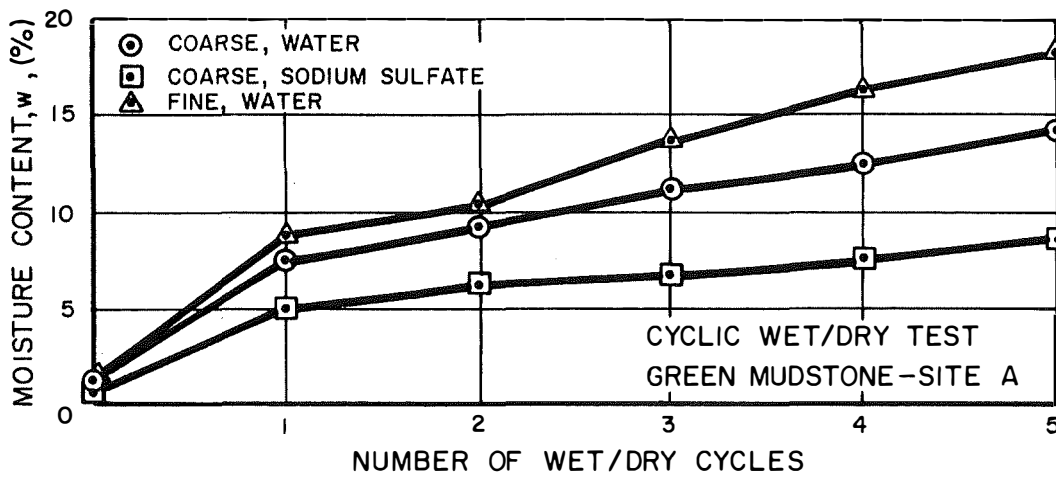
- Variations in moisture content with increasing numbers of cycles of durability tests generally follow two trends. For sandstones and more durable (low DI values) siltstones and shales, the moisture content increased to an equilibrium value within one or two cycles and then randomly varied about that value (Figure 9-18a). All other fine-grained sediments exhibited an increased moisture content with increasing numbers of cycles (Figure 9-18b). Accordingly, these patterns can be correlated with durability.
- Moisture contents for samples consisting of fine fragment size always exceeded the coarse fraction moisture content for corresponding samples and solutions (Figures 9-18 a and b). The smallest increases were realized for sandstones and the largest for mudstones. For samples in water, these values ranged from one to eight percent depending on the test method.

The principal factor controlling the coarse/fine fragment-moisture content behavior is the influence of surface area to volume relationships. With the soaking period identical, the finer samples more readily achieved higher moisture contents. Tests performed using either ethylene glycol (jar slake) or sodium sulfate (cyclic wet/dry) typically revealed slightly lower moisture contents than corresponding tests in water. These lower moisture contents may be attributed to the greater viscosity of ethylene glycol and osmotic pressure effects created between the sodium sulfate solution and the sample fragments.

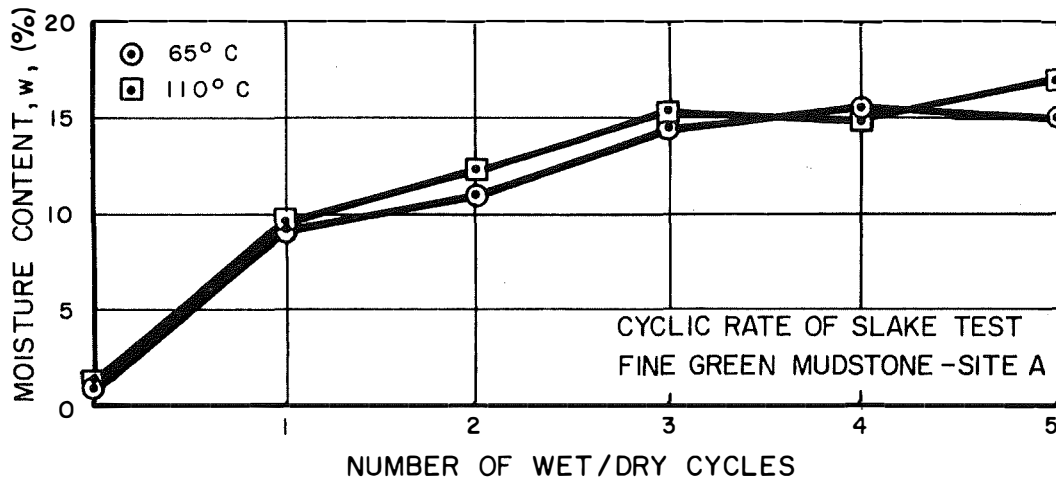
- As indicated in Figure 9-18c, little variation was noted in the amounts of water driven from the sample utilizing temperatures of either 65 or 110 degrees Celsius. Despite the lack of a strong trend between water content and temperature, temperature did appear to impact durability as discussed in Section 9.2.1.5.



a)



b)



c)

SUMMARY OF TYPICAL MOISTURE CONTENT BEHAVIOR
 CYCLIC DURABILITY TESTS

FIGURE 9-18

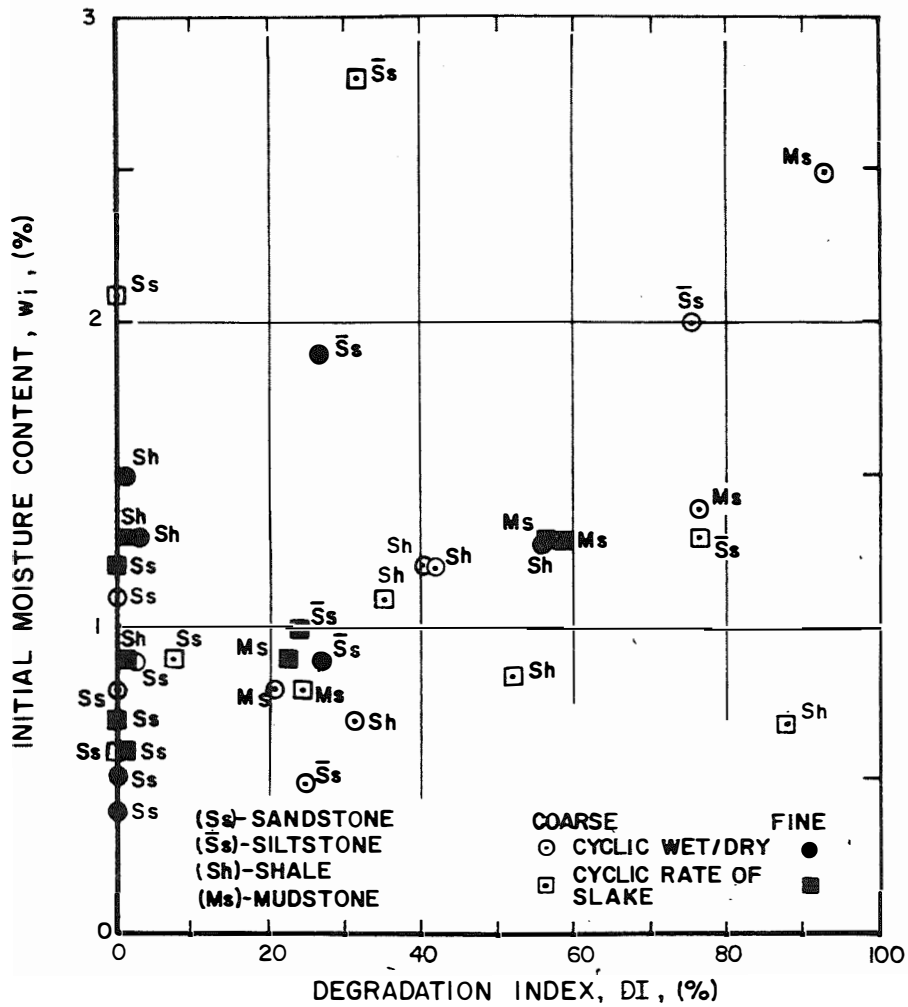
- The relationship of moisture content variation with increasing time for jar slake tests is not as reliable as for other durability tests. Moisture content determinations for these tests were limited to point load test samples and a wet sieve analysis of the entire sample following the completion of testing. Therefore, the moisture contents are somewhat biased toward the coarser and more durable samples used for point load tests (Section 9.2.3.1) and the coarser fraction of the sieved sample. These were likely lower than the overall moisture content.

Since the cyclic durability tests (wet/dry and rate of slake) provided the most reliable moisture content information and the most directly comparable degradation index values (in water), these data were used to help identify relationships that might exist between moisture content and durability. The initial and final moisture contents for coarse and fine samples immersed in distilled water as related to the five-cycle degradation index obtained for each test are shown in Figure 9-19.

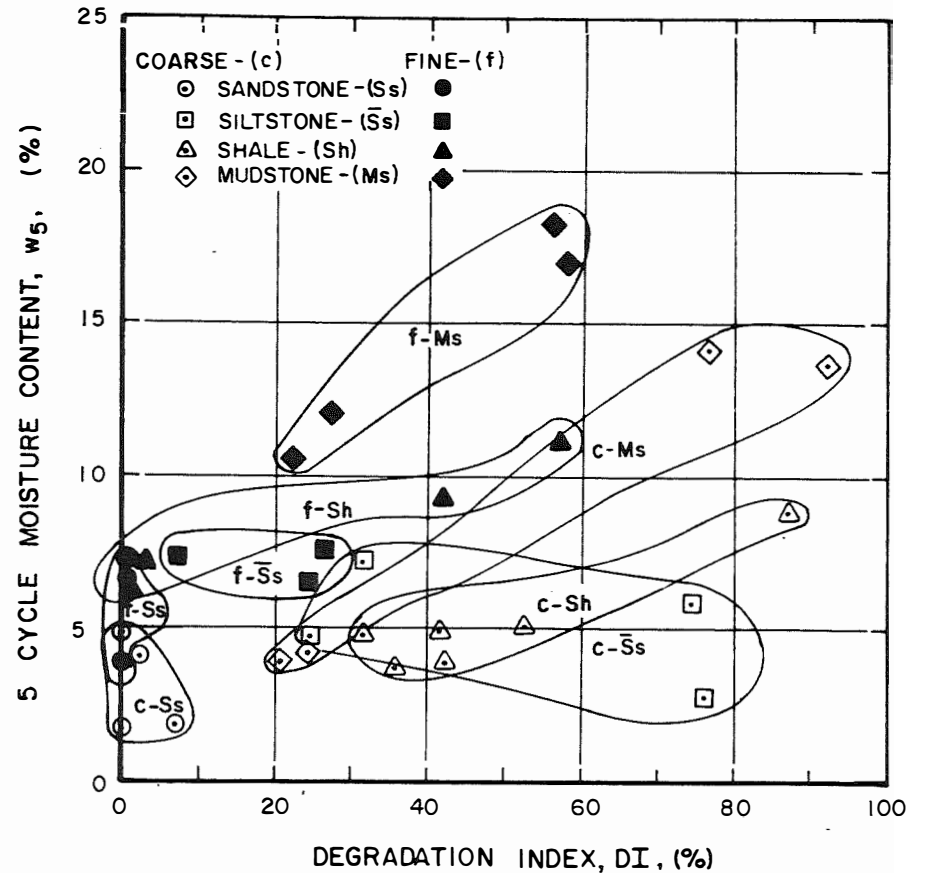
Figure 9-19a indicates that a general trend may exist between the initial moisture content (W_i) and DI. As noted in Section 8.1, the results may be affected to some degree by the need to mix fresh highwall and recent spoils to provide a sufficient quantity of sample for testing. It is very likely that the recent spoils were drier than the in situ sediments. Because the tested samples were combined from both components, no definite conclusions can be drawn. The spread of sandstone (S_s) values reflects a range of W_i values wider than might be expected. This is most likely the influence of drilling water entering the sample during coring operations. Because the other lithotypes tested are more impervious, the influence of drilling operations is probably small.

Relationships between the five-cycle moisture content (w_5) and DI for the cyclic durability tests are presented in Figure 9-19b and show many of the general trends outlined above. Test results are grouped by lithology and fragment size. The basic conclusions drawn from this figure include the following:

- Increasing moisture content occurs with decreasing fragment size.
- Sandstones cluster within relatively small zones at low moisture contents and DI values.
- Mudstones generally attain the highest moisture content levels for equivalent fragment sizes.
- Values for fine-grained lithotypes vary more than do those for sandstones.



a) INITIAL MOISTURE CONTENT vs. DEGRADATION INDEX.



b) 5 CYCLE MOISTURE CONTENT vs DEGRADATION INDEX (SLAKE FLUID: WATER)

MOISTURE CONTENT - DURABILITY RELATIONSHIPS FOR CYCLIC DURABILITY TESTS

- Breakdown of coarse siltstones and shale fragments, and to a lesser degree fine shale fragments, seems to be structurally controlled (i.e., bedding). This is indicated primarily by the relatively constant five-cycle moisture contents that were attained for each particular lithotype and fragment size.

9.2.2.2 Grain Size (Disaggregated) and Atterberg Limits

As described in Section 9.2.1, the samples that were subjected to the greatest deterioration during the durability testing program were predominantly the fine-grained sediments. Therefore, determination of grain size distributions and Atterberg limits was limited to siltstones, shales, and mudstones. The results of these tests are presented in Figure 9-20.

The range of the test results for the various lithologic units is remarkably small and generally bears little relationship to the wide range of durability behavior that was observed. The grain size analyses suggest that all of the fine-grained sediments are composed primarily of silt size particles (75 to 2 microns) and have measured clay fractions ranging from approximately 9 to 22 percent. This is somewhat dependent upon sample preparation and may not truly reflect presedimentation grain size. The only observable relationship from these tests shows that the red/green mudstone (Site D) had the highest clay content. No other similar conclusions could be drawn. The Atterberg limits are clustered close to the "A" line with liquid limits ranging from 20 to 26 percent and plasticity indices ranging from 6 to 8 percent. These results indicate a relatively inactive clay mineralogy which was confirmed through X-ray diffraction analysis (Section 9.2.2.7).

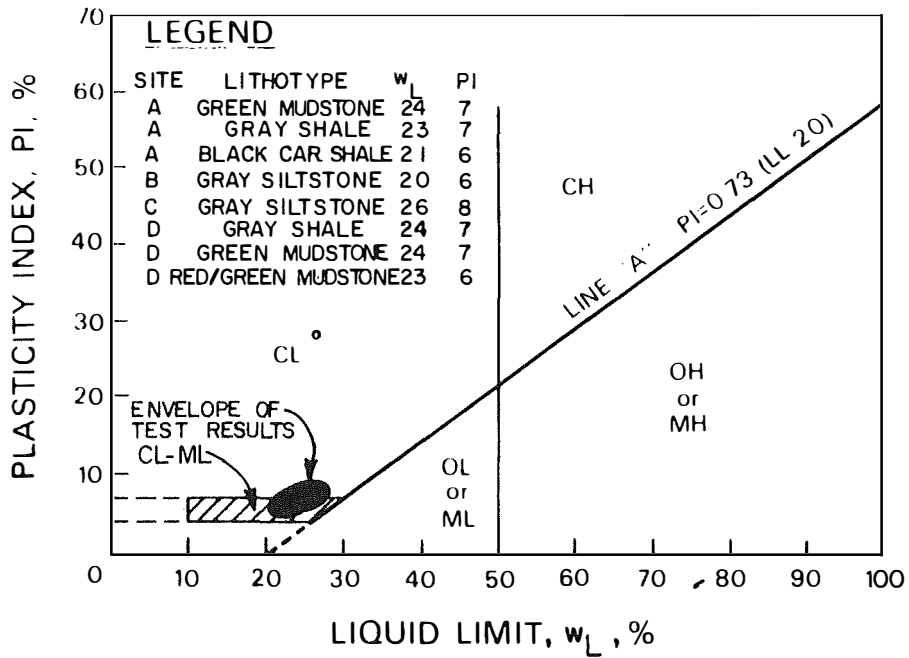
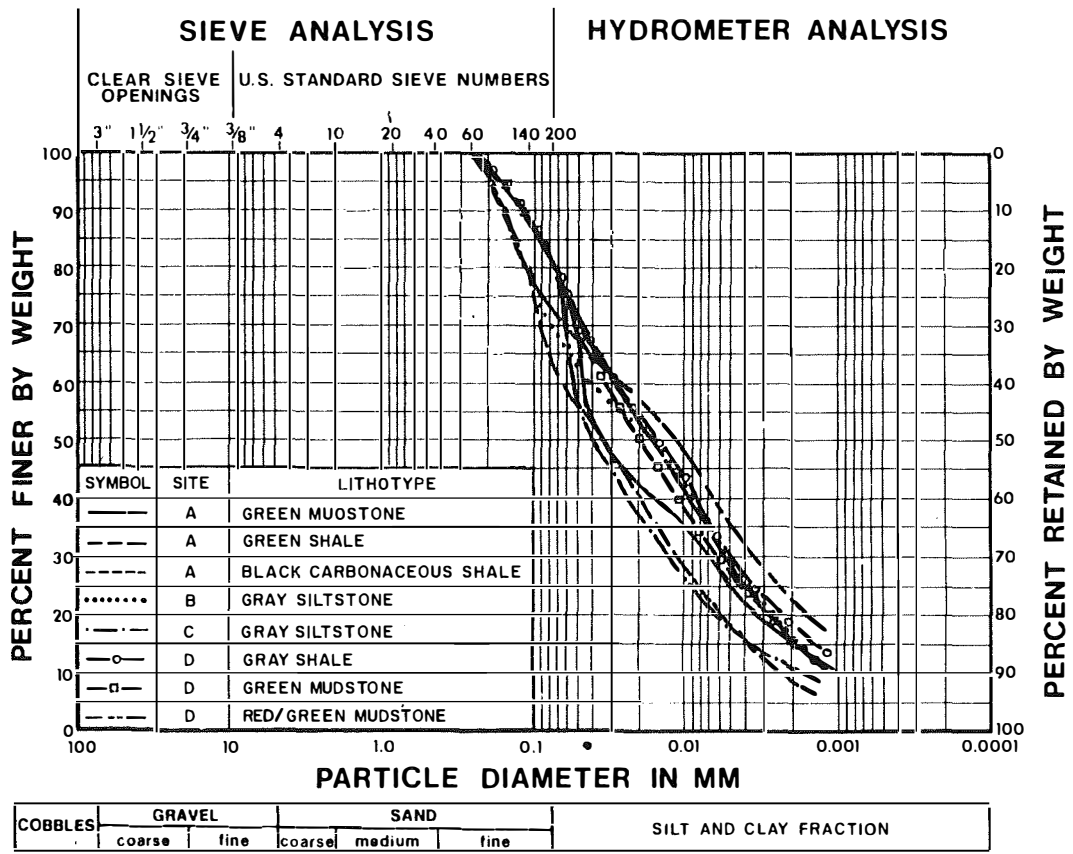
As mentioned, the results of these tests may have been affected by the method of disaggregation used. Although the results might shift if another procedure were selected (e.g., ultrasonic disaggregation), the change is expected to be small and the observed trends would be very similar.

9.2.2.3 Unit Weight

A summary of the sample unit weights of individual lithotypes obtained using the water displacement method ISRM (1979) is presented in Table 9.5. The unit weights of rock fragments range from 134 to 167 pcf (252 to 314 kN/m³). Based on these data, a correlation with durability could not be made; therefore, the use of unit weight as a indicator of slaking potential is considered unlikely.

9.2.2.4 1:1 (Soil) pH

Soil pH is a measure of the hydrogen ion activity in a mixture of disaggregated rock and distilled water; as the pH increases, the hydrogen ion activity decreases. The resulting value is largely dependent



DISAGGREGATED GRAIN SIZE DISTRIBUTIONS
AND ATTERBERG LIMITS
FINE-GRAINED LITHOTYPES

TABLE 9.5
SUMMARY OF UNIT WEIGHT AND 1:1 pH DETERMINATIONS

SITE	LITHOTYPE	DRY UNIT WEIGHT γ_d		1:1 pH ⁽¹⁾
		(pcf)	(kN/m ³)	
A	Brown Sandstone	148	279	ND ⁽²⁾
	Gray Shale	164	309	7.70
	Green Mudstone	141	265	8.40
	Black Carbonaceous Shale	134	252	7.60
	Gray Limestone	166	312	ND
B	Gray Siltstone	167	314	8.76
C	Yellow Sandstone	155	292	ND
	White Sandstone	157	295	ND
	Gray Siltstone	154	290	7.56
D	Brown Sandstone	165	311	ND
	Gray Shale	158	297	8.37
	Green Mudstone	160	302	8.20
	Red/Green Mudstone	140	263	8.88

(1) Average of two values.

(2) ND = Not determined.

upon the mineralogy of the samples being tested and, therefore, if slaking is related to mineralogical composition, soil pH may be an indicator of slaking potential. Table 9.5 presents 1:1 pH values for the fine-grained lithotypes encountered at each site.

Mineralogical composition of all samples was determined by X-ray diffraction analysis (Section 9.2.2.7). From these data, a fair correlation was observed between increasing carbonate mineralogical composition and soil pH. However, the equilibrium pH of calcite (the most soluble carbonate phase with a high equilibrium pH found in the samples) is 8.2 to 8.4 when equilibrium with atmospheric carbon dioxide is reached. Soil pH values above 8.2 to 8.4 are probably controlled by hydrogen ion exchange for other cations on mineral phases with significant ion exchange capacities. Figure 9-21 is a plot of 1:1 pH versus cation exchange capacity. A correlation between exchange capacity and soil pH does appear to be evident for the limited number of samples. Therefore, soil pH appears to be affected by both soluble carbonates and mineral phases such as clays which exchange cations for hydrogen ions.

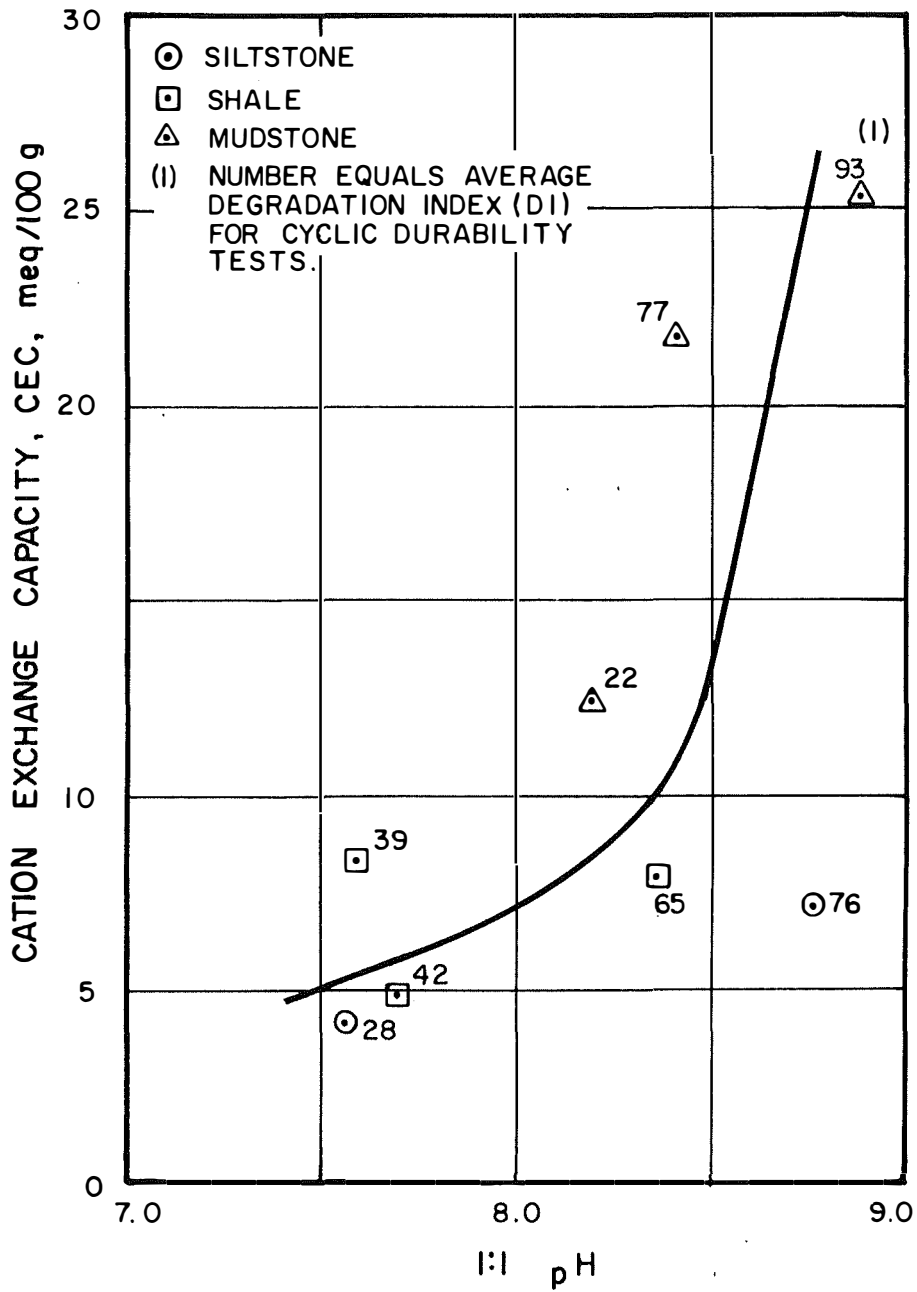
Figure 9-22a illustrates the relationship observed between 1:1 pH and the degradation index. This is most likely due to dissolution of carbonate cements and/or cation exchange. Because of this trend, soil pH may provide a quick and inexpensive determination of slaking potential. It should be noted, however, that this correlation is based on limited data and further studies should be conducted to increase the number of observations as well as develop the rationale behind the postulated mechanisms.

9.2.2.5 Exchange/Adsorption Capacity

Relationships have been demonstrated in previous studies (Chapter 7.0) between ion exchange/dye adsorption capacity and such properties as surface area, swell potential, and dry bond strength. If the slaking potential is related to any of these properties, the cation exchange capacity (CEC) and methylene blue adsorption (MBA) measurements should be an indication of slaking potential. Furthermore, if a good correlation could be achieved between these two types of analyses, then MBA could confidently be substituted for CEC and thus provide a less expensive testing procedure for determining slake potential.

Previous work (Nevins and Weintritt, 1967) has shown that a very good correlation exists between CEC and MBA values. However, an analysis of Table 9.6 indicates that a similar correlation did not exist for this study. Possible reasons for this poor correlation follow:

- Material type and preparation techniques for previous studies differed from those used in this program. Literature values represent generally pure, relatively active single phase clay systems which did not require grinding to achieve an equivalent soil texture.



CATION EXCHANGE CAPACITY vs 1:1 pH
 FINE - GRAINED LITHOTYPES

159

(i) VALUE OBTAINED FROM CYCLIC WET/DRY TEST ONLY; CYCLIC RATE OF SLAKE TEST NOT CONDUCTED.

LEGEND
 AVERAGE COARSE DI VALUE
 DI RANGE FROM CYCLIC DURABILITY TEST

Degradation Index, DI (%)	pH 1:1
20	8.2
25	7.6
35	7.6
40	7.7
65	8.4
75	8.4
75	8.8
90	8.9

a) 1:1 pH VS. DEGRADATION INDEX

LEGEND
 AVERAGE COARSE DI VALUE
 DI RANGE FROM CYCLIC DURABILITY TEST

(i) VALUE OBTAINED FROM CYCLIC WET/DRY TEST ONLY; CYCLIC RATE OF SLAKE TEST NOT CONDUCTED

Degradation Index, DI (%)	Cation Exchange Capacity, CEC, meg/100g
20	12
25	4
35	8
40	5
65	8
75	7
75	22
90	26

b) CATION EXCHANGE CAPACITY VS. DEGRADATION INDEX

1:1 pH AND CATION EXCHANGE CAPACITY RELATIONSHIPS WITH DEGRADATION INDEX

FIGURE 9-22

TABLE 9.6
SUMMARY OF EXCHANGE/ADSORPTION CAPACITY
TEST RESULTS

SITE	LITHOTYPE	EXCHANGE/ADSORPTION CAPACITY ⁽¹⁾		
		CEC ⁽²⁾	MBA ⁽³⁾	MBI ⁽⁴⁾
A	Gray Shale	4.9	1.5	2.2
	Black Carbonaceous Shale	8.3	1.3	3.5
	Green Mudstone	21.7	2.6	4.0
B	Gray Siltstone	7.1	1.1	2.8
C	Gray Siltstone	4.1	1.4	3.0
	Green Mudstone	12.4	1.8	3.3
D	Gray Shale	7.8	2.3	3.0
	Red/Green Mudstone	25.3	4.3	7.8

(1) Conducted prior to durability testing and expressed as meq/100 g of dry sample.

(2) Cation Exchange Capacity (Black, 1965).

(3) Methylene Blue Adsorption (Nettleton, 1974) - 33 percent slurry.

(4) Methylene Blue Index (ASTM, Part 17, C 837, 1977) - 1 percent slurry.

- Although the same CEC method was used in all studies, variation in material properties could affect the final results. For example, the procedure does not take into account the contribution to the CEC from dissolution of calcite (CaCO_3) or other slightly soluble mineral phases. Therefore, those samples with carbonate or sulfate mineral phases probably exhibit higher CEC values than is possible based on available exchange sites. Additionally, the CEC can be affected by organics which may be present. Pure clay systems would not encounter these problems.
- Solid rock samples were disaggregated or ground to equivalent soil texture or grain size. This sample texture (approximately 60 mesh) was used for the determination of both CEC and MBA. Therefore, no difference in surface area existed for samples in either determination. As surface area increases, so does CEC and MBA values. The rate of increase, however, may not be the same. Therefore, better correlations may be realized for various sample textures.
- MBA values were obtained by two different methods (Nettleton, 1974; ASTM, Part 17, C 837-76, 1977), to determine the effect of procedure on the correlation with CEC. Even though the results of these determinations (Table 9.6) indicate that MBA increases with decreasing soil slurry concentration (i.e., MBI values), the effective correlation with CEC remained unchanged.

Although the observed correlation between CEC and MBA was not strong, the less expensive MBA procedure is still a possible predictive measure of slaking potential. However, the effects of soil slurry concentration and sample texture upon analytical results of MBA and CEC determinations need to be investigated. Further study must also be done to define the effect of typical spoil composition (as compared to standards) on MBA results prior to its utilization as a practical tool.

Figure 9-22b depicts the observed correlation between CEC and degradation index. Based on the limited samples tested, a weak correlation exists. This suggests further research is warranted.

9.2.2.6 Petrographic (Thin Section) Examination

The results of thin-section petrographic examination of the sandstone and limestone units studied as part of the laboratory program strongly support the results of the durability tests. The sandstones were observed to be well-graded and comprised of predominantly angular,

fine- to medium-size quartz grains with trace amounts of various clay minerals, micas, carbonates, and coal stringers. Most of the sandstones examined were tightly packed with "welded" grain boundaries and little matrix material. No significant variations were observed between perpendicular and parallel-to-bedding orientations. The limestones are fine-grained, massive, and slightly fossiliferous. The texture is dense and devoid of partings or voids which suggests extremely high durability.

9.2.2.7 X-Ray Diffraction

To provide the necessary foundation for potential correlation between durability and mineralogy, X-ray analyses were performed on all 14 lithotypes. The results are presented in Table 9.7. After close examination only one general trend was discernable; increasing carbonate content (primary calcite) with increasing DI. This correlates with those relationships mentioned previously in conjunction with 1:1 pH (Section 9.2.2.4). A second series of analyses was run on posttest samples to provide data to analyze the effect of sample position within the test chamber (Section 9.2.3.4). However, no significant differences were noted between the pretest and posttest analysis.

9.2.3 Ancillary Tests

Additional testing was performed concurrently with the durability testing program. This included point load tests, and analyses of pH and specific conductance of the slake fluid. These various techniques were relatively simple to perform and were thought to possibly provide additional data for understanding the slaking phenomenon. In addition to those, postdurability testing (i.e., X-ray diffraction, CEC, and MBA) was undertaken to determine the effects of sample position within the durability testing equipment.

9.2.3.1 Point Load Test

One hundred thirty-six point load tests were conducted on rock core fragments obtained from active highwall zones, spoils of various ages, and samples subjected to durability testing (i.e., jar slake, cyclic wet/dry, and rate of slake). The results of these tests performed perpendicular to bedding are summarized in Table 9.8. The test results have been sequentially ordered to reflect the relative durability of the materials.

Initially it was hoped that point load testing would provide a semiquantitative basis to evaluate the effect of time on a given lithology. However, because it was not possible to attain adequately sized fine-grained material for the range of spoil ages, this correlation was not possible.

Although the pattern of data points presented in this table seems to be somewhat scattered and random, the following trends are discernible:

TABLE 9.7
SUMMARY OF X-RAY DIFFRACTION ANALYSES^(1,2)

SITE	LITHOTYPE	CLAY MINERALS				NONCLAY MINERALS						
		KAOLINITE	ILLITE	CHLORITE	MIXED LAYER AND/OR MONTMORILLONITE	QUARTZ	FELDSPAR	CALCITE	DOLOMITE	SIDERITE	ANKERITE	PYRITE
A	Brown Sandstone	<5	10-25	<5	10-25	>50	ND ⁽³⁾	ND	<5	ND	ND	ND
	Green Mudstone	5-10	25-50	5-10	5-10	>50	<5	<5	ND	ND	ND	ND
	Gray Limestone	ND	10-25	ND	ND	10-25	ND	10-25	25-50	ND	ND	ND
	Gray Shale	5-10	10-25	5-10	10-25	>50	ND	ND	ND	ND	ND	ND
	Black Carbonaceous Shale	5-10	5-10	5-10	5-10	25-50	ND	ND	ND	10-25	ND	<5
B	Gray Siltstone	5-10	10-25	5-10	10-25	>50	ND	ND	<5	ND	ND	ND
	Gray Siltstone	5-10	10-25	5-10	10-25	>50	ND	ND	ND	ND	ND	ND
C	Yellow Sandstone	10-25	10-25	5-10	5-10	>50	ND	ND	<5	ND	ND	ND
	White Sandstone	10-25	10-25	5-10	5-10	>50	ND	ND	ND	ND	ND	ND
	Gray Limestone	<5	ND	ND	ND	<5	ND	>50	10-25	ND	ND	ND
	Brown Sandstone	5-10	5-10	5-10	5-10	>50	ND	10-25	ND	ND	ND	ND
D	Gray Shale	5-10	10-25	5-10	5-10	>50	ND	ND	ND	<5	ND	ND
	Green Mudstone	<5	10-25	5-10	10-25	>50	ND	ND	ND	5-10	ND	ND
	Red/Green Mudstone	<5	5-10	ND	5-10	>50	ND	5-10	ND	<5	5-10	ND

(1) Predurability test samples only.

(2) Estimated amounts (%) were determined using X-ray diffraction peak intensities.

(3) Not detected.

- The point load strength index (I_s) generally increases with increasing durability. This is reflective of the shift of data values downward to the right.
- Values of I_s may be typically aligned by sample condition; that is: I_s (in situ) = I_s (jar slake) < I_s (spoil) < I_s (cyclic tests). These trends indicate that the moisture content condition of the rock fragment at the time of testing strongly controls the measured strength. Accordingly, rock fragments sustaining the greatest amount of drying provide the highest point load strengths. Therefore, point load tests taken on jar slake and fresh highwall samples generally indicate weaker materials than those from aged spoil and cyclic durability tests, respectively.
- Point load results for the fine-grained sediments may be somewhat biased toward the more durable fragments. This is true for both aged spoil fragments and samples subjected to any durability test. Examination of Table 9.8 shows that tests conducted for the low durability materials are predominantly from jar slake tests or tests on freshly cored rock samples. This may be attributed to the large amount of breakdown that occurs for the low durability materials following spoil placement or during durability testing which provides an insufficiently sized fragment for testing. Conversely, with increasing durability, the variety of test results becomes more complete and provides a larger sampling base for analysis.

It was observed during the point load testing program that the fracture pattern for shales and siltstones loaded perpendicular to bedding frequently did not fracture entirely through the axis of loading. Instead, the loading points of the test apparatus indented slightly into the rock fragment and then the sample failed along a bedding plane 1/2 inch (12 millimeters) or less from either end of the tested sample. Because it was not possible to fail the sample in the conventional manner, even after repeated attempts, the point load index value was determined assuming the usual procedures. Although this approach is not theoretically correct, it does provide a reference index value that is comparable to test results for other lithotypes. Point load tests were also run parallel to bedding for fine-grained sediments; however, failure occurred along the bedding planes with the resulting values typically below the limits of equipment sensitivity and were considered unreliable.

9.2.3.2 Slake Fluid pH

Measurements of the slaking fluid pH were routinely recorded as part of the entire durability testing program. Although the variation of pH with increasing time or number of cycles followed certain trends, no specific relationships could be established between durability (measured by DI or I_{d2}) and the pH of the various slaking fluids.

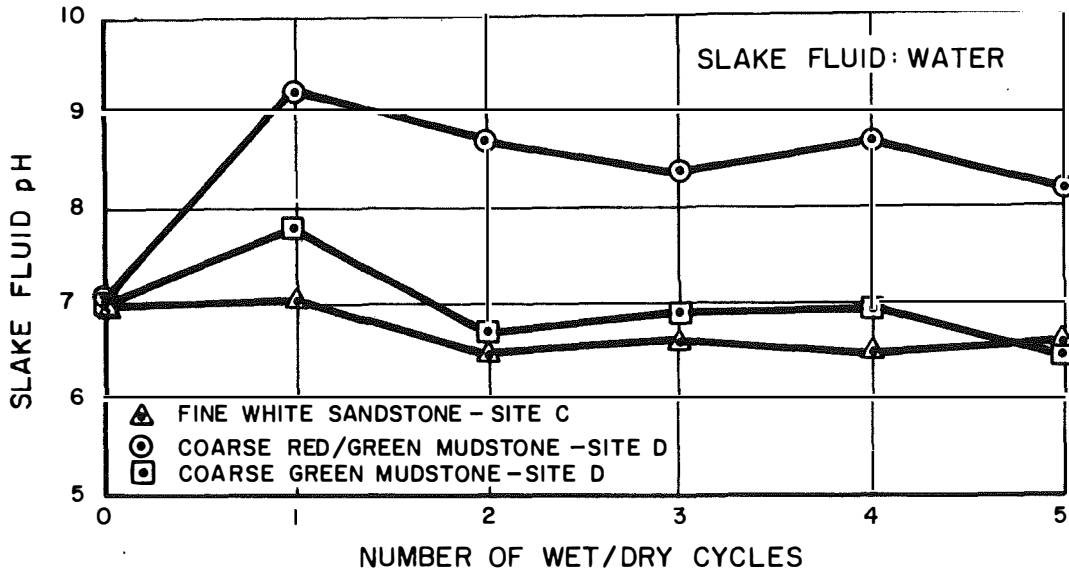
Tests conducted with water typically followed two trends: the slake fluid pH either decreased from neutrality (pH = 7.0) to values typically between 6.0 and 6.5, although higher and lower readings were recorded, or increased slightly and then returned to near neutrality. Exceptions to these trends were observed for the red/green mudstone (Site D) and the green mudstone (Site A). For these samples, the fluid pH increased sharply to 8 or 9 and then decreased with increasing cycles or time but remained high (7.5 to 8.5). Figure 9-23a shows examples of this behavior.

For durability tests in which a chemical solution was used, the fluid pH decreased with increasing cycles or time from about 9 to 9.5 to 7.5 to 8.5. As observed above for the two cited mudstone samples, the final pH values were higher than all other tests which reflect the basic chemistry of these sediments.

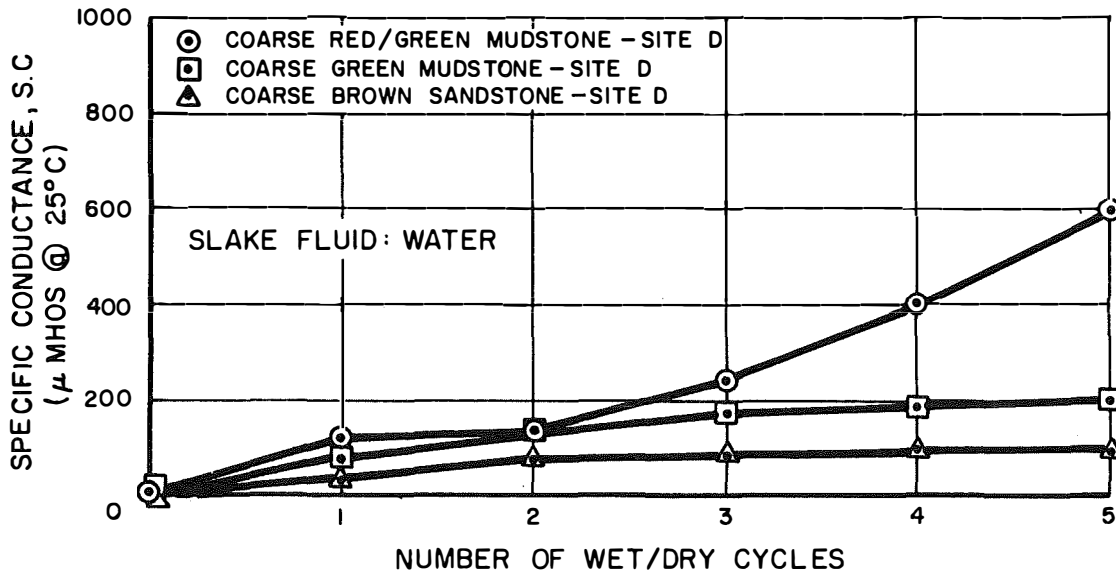
9.2.3.3 Specific Conductance

The specific conductance test is an instrumental method designed to measure the conductivity of fluids by measuring the current between two electrodes immersed in a solution. Because the conductivity is proportional to the concentration of dissolved salts in the fluid, the test provides an indirect means for determining the rate of dissolution of samples during durability testing.

Specific conductance measurements were obtained only during the cyclic wet/dry tests for Sites B, C, and D. Tests conducted in both ethylene glycol and sodium sulfate revealed a gradual to rapid increase in specific conductance with increasing numbers of wetting and drying cycles. For tests in distilled water, specific conductance ranged from initial values of 5 to 9 μmhos to 100 to 600 μmhos at the end of five cycles of testing. Specific conductance values in sodium sulfate ranged from 35,000 to 40,000 μmhos prior to testing to 60,000 to 80,000 μmhos upon the completion of testing. All readings are corrected for temperature effects to 25 degrees Celsius. Based upon the small amount of information available from these few tests, the rate of change and magnitude of specific conductance typically increases with decreasing durability. Examples of this behavior are shown in Figure 9-23b. Tests conducted in water provided a much better indication of this behavior because the readings are directly related to the dissolution of samples rather than the interaction that occurs between sample fragments and the chemical slake fluid. The high specific conductance of sodium sulfate tends to mask the effects of sample dissolution and thereby inhibits the



a)



b)

TYPICAL RESULTS OF CYCLIC WET/DRY TESTS
SLAKE FLUID pH AND SPECIFIC CONDUCTANCE

applicability of this test when salt solutions are employed as slaking fluids. Increased levels of conductance also may have resulted from evaporation of the fluid; however, its impact is believed minimal.

9.2.3.4 Postdurability Testing

It was observed that during the durability testing, the amount of degradation within a given test sample varied from fragment to fragment. Some coarse sample fragments (principally consisting of the green mudstones) degraded to a lesser degree than did the majority of the sample material. This may be a result of natural inhomogeneity of the sample, the influence from the test procedure employed, or some combination of both. Therefore, a series of compositional tests was undertaken using samples that had either degraded completely or had suffered only marginal deterioration. These included X-ray diffraction, 1:1 pH, MBA, and CEC. The results of these tests suggested that the observed variability in slaking behavior could not be attributed to compositional difference.

Because of the quantity of sample that was needed for several of the durability tests (i.e., jar slake, cyclic wet/dry, and cyclic rate of slake), it was necessary to place three to five pounds (one to two kilograms) of coarse rock fragments in porous basket containers. Accordingly, some portions of each sample had a more direct access to slake fluids and circulating dry air (in the case of the cyclic tests). Based upon the results of the compositional tests, it was concluded that the quantity of sample tested may have some influence on the test results.

9.3 COMBINED FIELD AND LABORATORY RESULTS

Some previous studies of slaking have failed to correlate laboratory test results with observed field behavior. This has often led to incomplete recognition of several of the prime factors that control the breakdown of geologic materials. Furthermore, because of the similitude and time effect problems associated with laboratory programs, the implications of several factors (e.g., sample size and accelerated weathering) in relation to field behavior are not completely understood. Therefore, this section will attempt to relate the behavior of aged spoil materials examined during the field program with "undisturbed" samples tested in the laboratory. By studying a range of geologic materials and environmental regimes, the implications for extending these results to other locations can then be evaluated.

Field observations of durability and modes of slaking were generally substantiated by and in agreement with the laboratory program. In addition, several of the slaking and supplemental physical/chemical tests discussed in Section 9.2 were found to be good indicators of expected field behavior. Based on the field observations and laboratory results, a method for classifying geologic materials according to durability behavior can be established as a means for identifying potentially problematic materials.

9.3.1 Durability and Slaking Modes

Several lithologies were identified during the course of the field program and relative durability of each was evaluated based on the examination of various aged spoils. The mode of slaking was found to be largely controlled by the rock type and the mining disposal practices observed at each site.

At Site A, lithologies were identified by slaking mode and ranked in terms of field slaking behavior or degradation from lowest to highest as follows:

- Brown sandstone - slab or block slakes.
- Black carbonaceous shale - chip slakes.
- Gray shale - chip slakes.
- Green mudstone - slakes to inherent grain size.

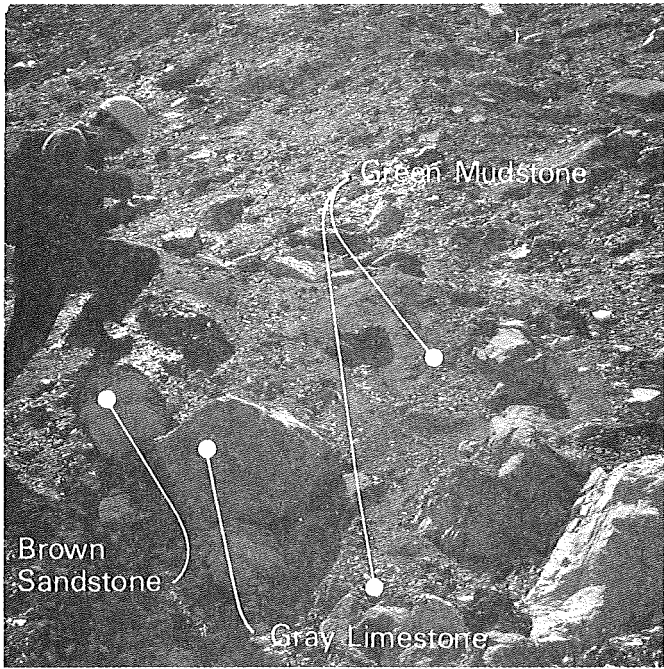
The breakdown of all these materials in the field compares favorably with the observed laboratory behavior.

The sandstone showed very little breakdown either in the field or laboratory. In the field, sandstone particles undergo block slaking to fragments four to eight inches (100 to 200 millimeters) in size similar to those shown in Figure 9-24a and c. Breakdown below this size range is negligible and in excellent agreement with observed slake test behavior.

The degradation indices for all tests conducted on the green mudstone were high and show the tendency for this material to slake to a fine constituent grain size that is uncontrolled by the initial fragment size. Figure 9-24b and d compares the field and laboratory behavior and reflects the complete and rapid breakdown that occurs both in situ and within a controlled laboratory environment.

Slaking of the gray shale and black carbonaceous shale followed very similar patterns in the field and laboratory and was strongly controlled by the initial fragment size. Deterioration along bedding planes causes fragmentation to thin, angularly shaped chips and platelets. During the laboratory program, this size effect and breakdown pattern was evidenced by the relative lack of slaking for the fine fraction. Extremely low degradation indices were obtained as compared with those of the coarse sized fractions. In the field, coarse gravel and cobble sized particles readily break down by chip slaking while smaller or fine fragments undergo little additional deterioration. As samples reach this stage, an equilibrium level is achieved between forces tending to cause further slaking and those limiting additional disintegration (e.g., particle size and cementing). Figure 9-25 demonstrates this behavior.

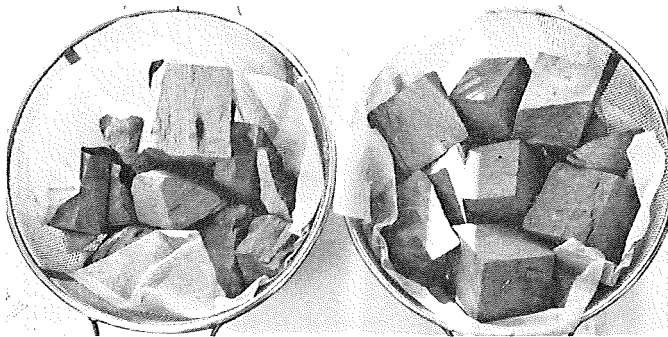
At Site B, the gray siltstone is initially massive with no apparent bedding and high RQD values (Figure 6-2). When subjected to slaking



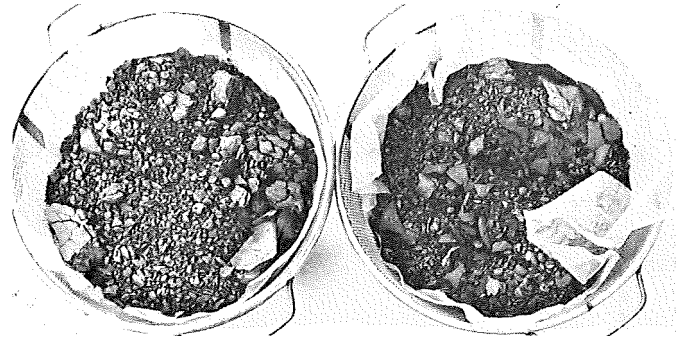
a) FIELD - RECENT SPOIL



b) FIELD - 5 YEAR SPOIL WITH NO SOIL COVER ; GREEN MUDSTONE



c) LABORATORY - BROWN SANDSTONE
CYCLIC WET/DRY TEST (WATER)
END OF CYCLE 5

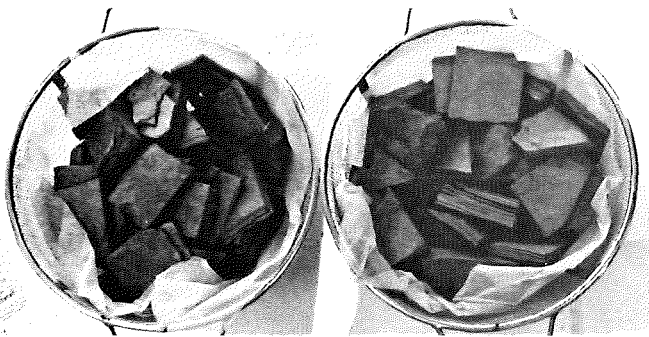


d) LABORATORY - GREEN MUDSTONE
CYCLIC WET/DRY TEST (WATER)
END OF CYCLE 5

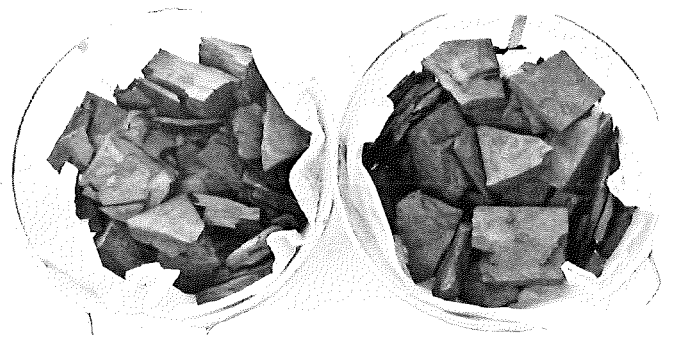
COMPARISON OF FIELD AND LABORATORY BEHAVIOR
SANDSTONE AND MUDSTONE - SITE A



a) FIELD - 10 YEAR SPOIL WITH NO SOIL COVER BLACK CARBONACEOUS AND GRAY SHALE



b) LABORATORY - GRAY SHALE
CYCLIC WET/DRY TEST (WATER)
END OF CYCLE 5



c) LABORATORY - BLACK CARBONACEOUS
SHALES
CYCLIC WET/DRY TEST (WATER)
END OF CYCLE 5

COMPARISON OF FIELD AND LABORATORY BEHAVIOR SHALES - SITE A

stresses, however, this siltstone undergoes chip slaking which was seen both in the field and the laboratory (Figure 9-26). This behavior is strongly controlled by structure (thin bedding planes) originating during deposition of the sediments. The coarse fractions subjected to laboratory testing showed high degradation indices while the fine fractions were more durable with DI values equal to approximately one third those of the coarse samples. This is generally consistent with the observed field behavior as the fine chips appeared to resist further degradation.

At Site C, both the yellow and white sandstones had extremely high durability as reflected by all of the laboratory test methods. Sandstones were observed in the field to remain in blocks in all aged spoils and exhibited little or no evidence of breakdown (Figures 9-27a, b, and d). Laboratory tests of the gray siltstone indicated intermediate DI values (24 to 32 percent) for the coarse fraction and low values for the fine component. As mentioned previously, slaking of the shales and siltstones is strongly controlled by the bedding planes. The coarse-sized rock fragments eventually degrade by chip slaking. This behavior was witnessed both in the field and in the laboratory. Siltstone particles of chip size generally showed little tendency for further degradation because the effect of bedding is insignificant at this and smaller particle sizes. Figure 9-27a, b, and c shows several of these features.

At Site D, lithologies were field ranked according to slaking potential ranging from greatest to least as follows:

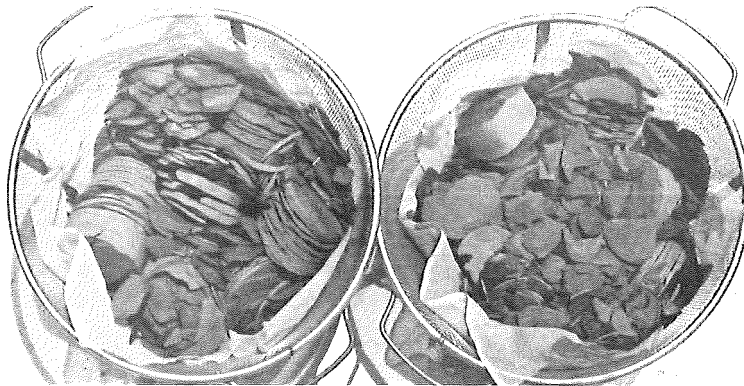
- Red/green mudstone - slakes to inherent grain size.
- Green mudstone - chip slakes then slakes to inherent grain size.
- Gray shale - chip slakes.
- Sandstone - slab slakes.

Although the lithology of the red/green mudstone and green mudstone is similar, the rate of deterioration was far more rapid for the red/green mudstone as evidenced by the general lack of this material in even recent spoil piles. This was supported by the very rapid disintegration that developed in the laboratory following immersion. However, the impact of this lithotype within the spoils is negligible because it represents less than five percent of the highwall materials. As can be seen in Figure 6-4, the RQD's for the red/green mudstone were extremely high. This suggests that RQD and similar classification systems do not accurately reflect slaking potential. Similar results were obtained for other lithotypes throughout the study.

The observed pattern for both mudstones at Site D, however, is similar since neither appears to be affected by fragment size or structural control as shown by the breakdown that occurs for each lithology.



a) FIELD - 5 YEAR SPOIL WITH NO SOIL COVER

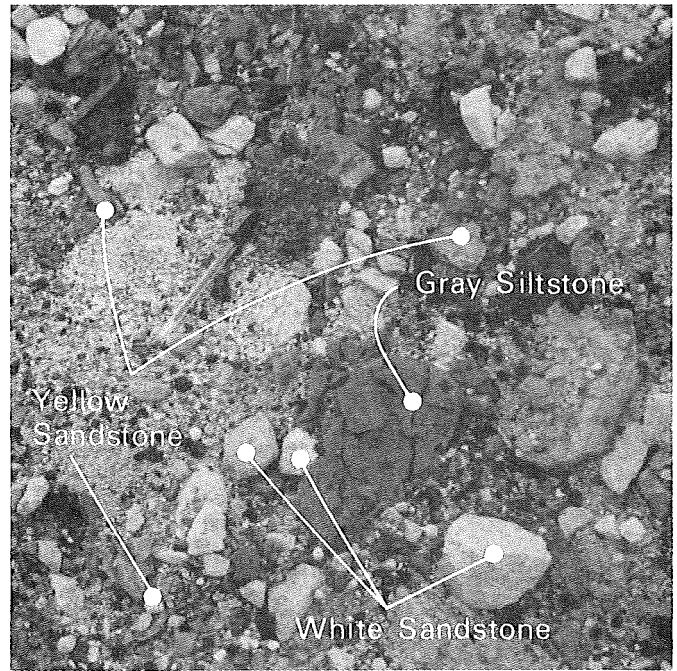


b) LABORATORY
CYCLIC WET/DRY TEST (WATER)
END OF CYCLE 5

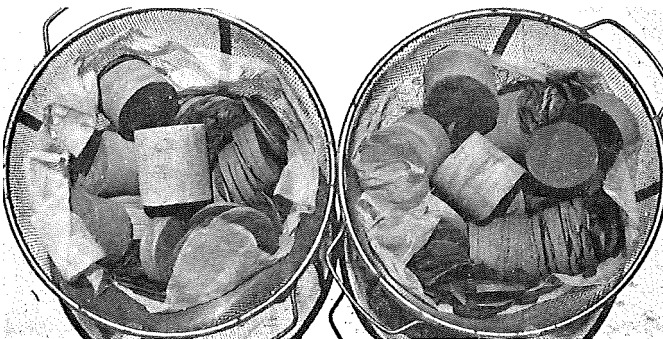
COMPARISON OF FIELD AND LABORATORY BEHAVIOR
GRAY SILTSTONE - SITE B



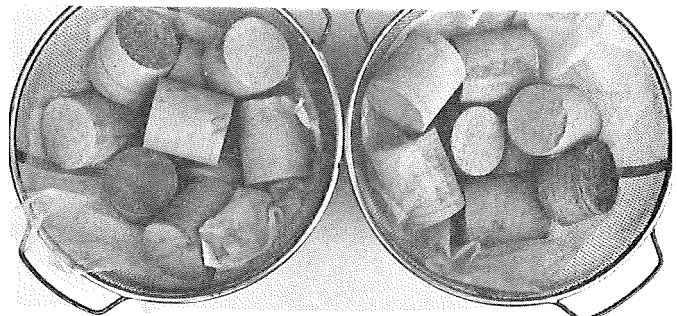
a) FIELD - 5 YEAR SPOIL - VEGETATED,
NO TOPSOIL COVER



b) FIELD - 5 YEAR SPOIL WITH NO SOIL
COVER



c) LABORATORY - GRAY SILTSTONE
CYCLIC WET/DRY TEST (WATER)
END OF CYCLE 5



d) LABORATORY - WHITE SANDSTONE
CYCLIC WET/DRY TEST (WATER)
END OF CYCLE 5

COMPARISON OF FIELD AND LABORATORY BEHAVIOR
SILTSTONE AND SANDSTONES - SITE C

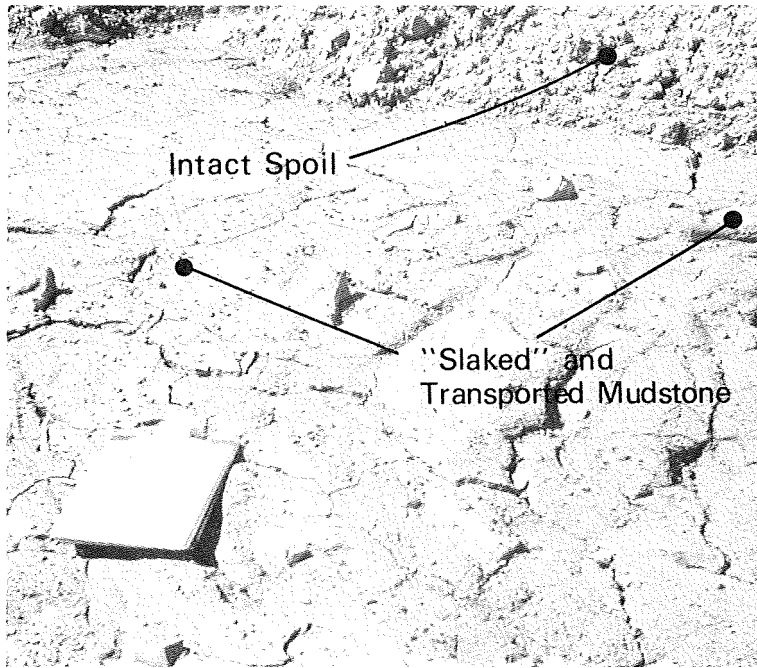
Even though the green mudstone initially undergoes chip slaking in the field, it slakes with time to its constituent particle size. Figure 9-28 shows examples of the pattern of slaking for these mudstones in the field and laboratory.

The gray shale at Site D slakes in a manner very similar to the pattern shown for other shales and siltstones. The breakdown exhibited by the gray shale is structurally controlled by the "bedding" of intact samples and slakes by chipping. This is indicative of the high DI values obtained for coarse sized rock fragments compared to the low to medium values observed for the fine fraction.

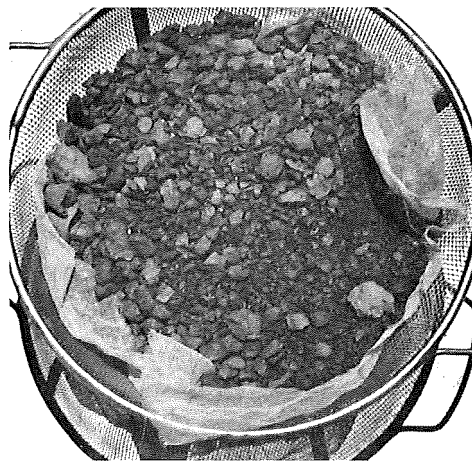
The sandstone has low DI values which is consistent with field observations. The sandstone, where present, occurred as slabs or blocks which showed little or no evidence of further degradation. No deterioration of the gray limestone was observed either in the field or laboratory.

Fragment or sample size appears to have a major impact on the degree and rate of slaking obtained in the laboratory and field. With the exception of the green mudstone at Site D, coarse fraction laboratory samples of slakable lithologies exhibit a greater degree of slaking as measured by the degradation index than did the finer samples. The same trend was observed in the field program. No morphologic characteristics of the green mudstone at Site D were observed in the field or laboratory that could account for the lack of degradation of this lithology. The durability of this material may have been related to a strongly interlocking matrix or attributable to strong cementing agents. Either of these hypotheses could be confirmed through petrographic studies. Large fragments of slakable lithologies evidenced greater breakdown, while finer fractions appeared to undergo less degradation. This may be in response to an approach to a state of equilibrium (Section 9.1.4) with the surrounding environmental conditions. The equilibrium concept, described in Section 9.1.4, may result from a relative lack of zones of weakness (i.e., bedding planes, fractures, weak cementation of grains) in small fragments as compared to coarser materials providing fewer sites within the small fragments for slaking to proceed.

Based upon these trends, the impact of mining procedures can be important if slakable geologic materials are present in sufficient quantities. For example, sites which practice poor spoiling techniques (e.g., insufficient breakdown during excavation, transport, and burial or inefficient surface drainage) may encounter serious environmental problems caused by material breakdown. Lithologies which attain the greatest degree of deterioration do so because of the size effects of the spoils materials; therefore, compaction or crushing of these rock types may largely eliminate slaking as an environmental problem. However, those lithologies which slake to their inherent grain size will continue to weather after mechanical breakdown, particularly if moisture is available. Therefore, if such materials are encountered, control of surface water by grading and ditch construction is important.



a) FIELD - RECENT SPOIL



b) LABORATORY
CYCLIC WET/DRY TEST (WATER)
END OF CYCLE 5

COMPARISON OF FIELD AND LABORATORY BEHAVIOR
MUDSTONES - SITE D

Although many of the lithologies studied for this project might be considered problematic upon initial examination, in fact, few if any adverse effects were observed. This may be attributed to the level of supervision and management planning exhibited by the mine sites that were visited.

10.0 CONCLUSIONS AND RECOMMENDATIONS

Although the primary purpose of this study was to evaluate the environmental effects of slaking on surface mine spoils, other subjects had to be addressed to accomplish this goal. The first step was to study the slaking phenomenon to understand the various processes which occur and their relationship to the mechanisms responsible. Section 10.1 summarizes this portion of the study. Having recognized the processes, either through actual field and laboratory observation or by theoretical evaluation, the environmental effects could then be addressed. Conclusions relative to these impacts are presented in Section 10.2.

Subsequent to the assessment of these impacts as well as the processes associated with the slaking phenomenon, a classification system was developed which can be used to predict durability of overburden materials. This classification scheme combines information obtained in both laboratory and field programs and consists of a series of decision filters (Section 10.3). With this system available, an assessment of problematic materials can be made. If the materials are present, then specialized technology may be required during spoiling and reclamation activities. Section 10.4 provides a synopsis of such techniques.

10.1 SUMMARY OF THE SLAKING PHENOMENON

Slaking is a short-term physical disintegration process that may occur in some geologic materials following stress relief (excavation). This disintegration generally results from an increase in internal stresses. Each of the important mechanisms causing slaking (Chapter 2.0), except confining stress relief, is related to the activity of water, cyclic drying and wetting, or the ions contained in pore fluids.

The rate and degree of the disintegration are directly related to material characteristics and local environmental conditions. The physical and chemical characteristics of argillaceous (clayey) sediments significantly increase the probability of slaking over that in other common sedimentary materials. Argillaceous materials which have closely spaced bedding planes may disintegrate rapidly following exposure, producing small chips. This was found to be typical for many of the siltstones and shales that were studied. Certain argillaceous materials may experience almost complete disintegration very soon after exposure (e.g., the red/green mudstone at Site D), producing soft clays. Disintegration may begin almost immediately after stress relief and proceed over several years.

Many sandstones are composed of relatively inert particles or particles which weather very slowly relative to slaking processes. They are also generally more cemented than argillaceous materials and have porosity and permeability characteristics which do not favor the development of certain types of stress conditions typically found in argillaceous materials (e.g., pore air compression, negative pore pressures).

Therefore, sandstone disintegration is commonly not a problem, as evidenced during the field and laboratory portions of this study.

Argillaceous sandstones, however, may undergo slaking (Heald, et al., 1974). Sandstones with argillaceous partings along bedding planes may break rapidly into slabs and plates of irregular shape (Davies, 1973). Sandstones weakly cemented with calcium carbonate may also disintegrate after exposure with the rate dependent on bond strength, water movement, and the acidity of leaching waters. An occurrence of this type of slaking was encountered during the preliminary reconnaissance at Site C. A fine-grained sandstone of limited lateral extent was observed to have slaked to its inherent grain size upon exposure, forming small talus deposits at the base of the outcrop.

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 limestones are relatively slow and are not considered to be a part of the slaking processes.

The release of confining stress will, in most cases, create partial openings and cracking along existing planes of weakness, allowing more rapid water penetration or drying. Partial or extreme desiccation of nearly saturated, highly argillaceous materials may cause additional disintegration due to negative pore pressure development. Extreme desiccation followed by rapid wetting will cause pore air compression and may lead to additional failure, particularly in nonswelling or kaolinitic materials. Materials with low water contents or low void ratios, moderate to low contents of montmorillonite, or high contents of illite may suffer disintegration upon wetting (or cyclic wetting and drying) as a result of clay mineral hydration forces. Compounding these stress effects is the reduction of structural strength caused by the decrease in surface energy which results when initially dry surfaces are wetted.

The relationship between the slaking process, surface mining, and spoil handling practices has been one of the major topics of this investigation. The most active zone of slaking for spoil piles is generally located within three to four feet (approximately one meter) of ground surface. This is typically the zone most affected by climatic conditions (e.g., humidity, wetting and drying, and freeze-thaw cycles). This conclusion is supported by observations reported for colliery spoils in Great Britain (Spears, et al., 1972, Rodin, 1973).

Although the slaking phenomenon is caused by many complex and interrelated variables, certain factors continually play a large role in determining the slake potential of overburden materials at surface mine sites. These include:

- Inherent Particle Size - Although other factors may affect the slaking of geologic materials, finer-grained sediments are more susceptible to

breakdown and at higher rates than coarse-grained sedimentary materials.

- Mineralogy - In conjunction with the particle size effects, the mineralogical composition of fine-grained sediments, and especially argillaceous sediments, affects the nature, degree, and rate of slaking. Typically, small amounts of active clay minerals (e.g., montmorillonite, mixed-layer clays, and chlorite) can exert a significant influence over the ultimate behavior because of their interlayer water absorption characteristics and the type of ions adsorbed on exchange sites.
- Rock Fabric - The microscopic structure of lithified sediments is a function of the depositional environment, mineralogy, and diagenetic stress conditions and can control the slaking pattern of these materials. Similarly, anisotropic fine-grained sediments (e.g., shales) slake by breakdown along thin bedding planes to form angular platy-shaped fragments while homogeneous, well-graded sediments (e.g., mudstones) slake in a pattern unrelated to any apparent structural control.
- Size of Spoil Rock Fragments - The effect of rock fragment size within spoil piles can be important for thinly bedded and poorly cemented sediments (i.e., fine sandstones, siltstones, and shales). If these materials are not sufficiently broken down during excavation, handling, and placement, subsequent disintegration by various slaking processes can result in a loose assemblage of rock fragments that can cause detrimental settlement and stability problems in reclaimed spoils.
- Water Control - Besides compaction, the principal controllable factor that determines the ultimate performance of overburden spoils is surface and groundwater control. The impact of potential slaking can be greatly limited if adequate measures are taken (e.g., topographic control, open and well-graded ditch lines, and a stable surface cover) to prevent the infiltration of water into the spoils.

Despite the impact of many of these factors, the significance of slaking in surface mine spoils appears to be minimized by the mixing of various slakable and nonslakable materials that usually occurs during

the spoiling operations. A typical example of this is the spoils examined at Site D which consisted of 60 to 70 percent mudstone, 20 to 30 percent shale, and the remainder sandstone and limestone. Although the slake potential of the mudstones was observed to be quite high both in the field and laboratory, the overall behavior of this lithotype within the excavated spoils of all ages showed little if any effect in the reclaimed areas. Apparently, the interaction of slakable sediments with other more stable lithotypes can play a strong role in controlling the success of particular mine spoil reclamation operations.

10.2 ENVIRONMENTAL EFFECTS OF SLAKING

Slaking of mine spoils can produce a variety of environmental effects. Some may adversely affect local environmental quality while others may favorably impact the mine site and surrounding area. There has been very little quantitative correlation and documentation of these effects directly attributable to slaking, particularly with respect to surface mine spoils. Therefore, the assessment of these relationships relevant to surface mining is based largely on field observations from this study (Section 9.1.5) and a general technical understanding of the slaking phenomenon. This is supported, when possible, by existing documentation. The lack of significant data on the slaking behavior of surface mine spoils is a major factor providing the impetus for this study. It should also be noted that this lack of documentation may reflect the rarity of such environmental problems caused by slaking; particularly in spoils handled and reclaimed by currently used methods. This is partially substantiated by the minimal impacts observed at each site during the entire field program (Chapter 6.0).

The observed effects are related to the decrease in particle size with a resulting change in the hydrologic regime of the spoil pile. Spoil disintegration may ultimately lead to the collapse and filling of voids and thus increased density of the mass. Settlement and decreased permeability may result directly from these alterations and a decrease in slope stability may occur from a reduction in shear strength following slaking. Decreased particle size may lead to increased erosion if readily slakable materials are left exposed at the surface. Additionally, material disintegration within plant root zones may affect vegetation.

Slaking of surface mine spoils has been linked to four types of environmental effects. Although there exists an interrelationship between these potential effects, the following discussion considers each separately:

- Hydrological impacts
- Slope instability and settlement
- Erosion and sedimentation
- Vegetation relationships

10.2.1 Hydrological Impacts

Slaking within surface mine spoils may alter the existing hydrologic regime and cause surface instability and malfunctioning of various designed structures or systems within the pile. The hydrogeologic characteristics of the pile (e.g., porosity, permeability, and specific yield) are greatly influenced by particle size and shape, packing, and sorting. With time, the disintegration of spoil pile materials results in a decrease in particle size, angularity, and sorting and an increase in packing. The overall effect of these alterations is a decrease in value for the various hydrologic parameters. However, because slaking is predominantly restricted to near-surface layers, these hydrologic impacts are usually surficial in extent.

Alteration in water storage and seepage characteristics of the spoil pile may result in the following impacts:

- Decrease in infiltration of surface water, thus increasing the potential for surface erosion and eventual siltation of streams.
- Formation of perched water tables and surface ponding in localized zones of relatively impervious materials.
- Clogging of filter systems by fine-grained materials.
- Chemical alteration of groundwater due to increased dissolved solids.
- Increase in unit weight and decrease in spoil pile stability resulting from particle saturation and structural weakening during deterioration.

With time, the slaking process can create conditions within the hydrologic regime of a spoil pile which will influence proper functioning and postreclamation land use of these structures. Only through proper planning and correct spoil handling techniques can the disadvantages of slaking be reduced and the positive effects be maximized.

10.2.2 Slope Instability and Settlement

The impact of slaking on earth structures can be severe in certain cases. To date, the most widely documented studies on the effect of slaking have been for highway embankments constructed mostly of shale (e.g., Shamburger, et al., 1975). For these cases, slaking has shown the greatest impact when embankments have been built using rock-fill construction procedures that typically include large lift thicknesses and minimal compaction efforts.

The construction of overburden spoil piles during surface mining operations typically entails far less design (if any) and supervision than for highway embankments. Accordingly, these piles may experience many of the same types of deterioration found in highway embankments. The importance of such changes in spoil piles, particularly those with postmining land uses that are not very susceptible to impact by settlement or those without steep outer slopes, may be insignificant in many cases.

If degradation of fill materials causes settlement within the spoil, drainage may be impeded and water ponded at the surface. In turn, the effects of water may aggravate and accelerate the breakdown of materials to compound both the settlement and drainage problems. The degradation may reach a stage so that the strength of the intact spoil materials no longer controls stability; stability instead may be governed by greatly reduced strength parameters and increased pore pressures that can ultimately lead to progressive surficial or deep-seated slope instability. However, a study of weathering effects on the engineering properties of coal measure rocks (Spears and Taylor, 1972) showed that measurable deterioration in spoil piles occurred only at relatively shallow depths (typically six feet [2 meters] or less) and within a short period of time. Similar findings were reported by the National Coal Board (1972). The major conclusion from this work showed that cohesion is the most susceptible strength parameter to change during weathering; therefore, the influence of slaking can be significant. However, if reasonable spoiling practices are used and if problematic materials can be identified, the impact can be greatly minimized or eliminated.

There is only a limited amount of existing evidence to support the occurrence of this type of impact on spoil piles. Brawner, et al. (1975), for example, has described the need to identify slakable sedimentary materials as a part of overburden analysis prior to surface mining of coal. Research and documentation related to slaking in nonmining applications may be used to help direct similar investigations involving surface mine spoils. Other studies relating to disintegrated shale embankments have been performed by Coates and Yo (1977), Kennard, et al. (1967), and Strohm (1978).

A survey of state highway organizations (Shamburger, et al., 1975) has shown that the major causes of embankment instability may be attributed to one or more of the following:

- Excessive lift thicknesses which result in a loose arrangement of particle sizes with high void ratios that can enhance the amount of future settlement.
- Inadequate compaction (effects are similar to excessive lift thicknesses).

- Physical and chemical deterioration, primarily of argillaceous materials.
- Expansive characteristics related to the mineralogy of the material comprising a fill.
- Inadequate drainage considerations.
- Excessive side slopes constructed near the angle of repose which may lead to side-hill sloughing or sliding to maintain equilibrium.
- Lack of field and laboratory testing procedures to identify and quantify long-term behavior after placement.

Surface mine spoils are quite variable with regard to both materials and placement control. Therefore, the use of refined or sophisticated analytical models is believed unwarranted because variations in consistency and distribution of material type and degree of slaking can have a significant impact upon predicted behavior.

In the field program conducted for this study, slope stability was also found to be related to the slaking mode of spoils. Spoils in which chip slaking or slab or block slaking dominates generally were found to exhibit little or no stability problems. Spoils in which chip slaking is dominant appear to be relatively stable. The chips form an interlocking matrix which is very resistant to bulk movement. The same phenomenon of interlocking fragments occurs, to a lesser extent, in slab or block slaking materials. Spoils which slaked to their inherent grain size were found to have stability problems as evidenced by slips, bulges, slides, or similar features. Degradation processes controlling settlement and stability behavior also may be influenced by various surface mining and spoil handling methods. In general, methods which involve some mechanical crushing and compaction (if only by trucks and dozers) will most likely exhibit less deterioration following placement than spoils disposed of by simple dumping. This relates to an increase in bulk density (lower void ratios), thereby reducing contact of spoil materials with air and water. In conjunction with compaction, reclamation procedures involving proper drainage away from the spoil pile will minimize the influence of slaking on stability and settlement.

10.2.3 Erosion and Sedimentation

The production of fine-grained soil-like material as a result of disintegration of surface mine spoils will likely lead to increased rates of sediment loss (erosion) if the materials are exposed at the surface. Reclamation practices may reduce this impact depending upon the rate of vegetation establishment and the slaking properties of the materials. Current surface mining design practices require incorporation of settling ponds and other forms of siltation control, but there

is no generally accepted technique for assessing the potential impact of slaking on the size of sediment containment facilities or the erosion control practices that may be required.

In the field program performed for this study, sheet, rill, and gully erosion were observed to occur to varying degrees on all spoils. Those containing a high proportion of materials which 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. Concentrated surface water movement either by diversion or as a result of topographic configurations created numerous rills and occasional deep gullies. This was most noticeable on spoils with a high proportion of materials which slake to their inherent grain size. The presence of a pebble pavement was observed to be effective in controlling sheet erosion and was a significant overall erosion control factor on many spoils. To a certain extent, surficial crusting also played a role in erosion control. Rock riprap in drainage and diversion ditches, where composed of slake-resistant rocks, prevented downcutting. Stable rock riprap generally resulted in U-shaped ditches, while slake-prone rock riprap typically yielded V-shaped ditches with active down-cutting.

Off-site damage can occur as a result of slaking in mine spoils, particularly when materials slake to their inherent grain size. It is often associated with excessive erosion rates and occurs in the form of increased sediment loads and stream siltation. The time of maximum sedimentation appears to correlate with initial placement and periods of disturbance prior to the establishment of vegetation. Chip slaking and slab or block slaking were not observed to significantly contribute to off-site damage.

Surface erosion estimates are often based on the slope gradient and length, rainfall distribution (either generalized for annual or seasonal conditions or based on single high-intensity storms), runoff coefficient, bare soil area ratio (related to vegetation or erosion control) and the erodibility characteristics of the surficial materials (Beasley, 1972; Komura, 1976). Except for potential changes in slope characteristics by mass wasting (Section 5.1), the most important influence of slaking on any of these variables is on the material erodibility which is a direct function of grain size distribution, organic matter content, structural characteristics of the material, and permeability (Wischmeier, et al., 1971). Fresh spoil materials generally have negligible amounts of recently decomposed organic matter and the fine-grained fraction of the spoils is considered to be structureless. Therefore, slaking can influence the erodibility and total sediment loss of spoil materials because it affects grain size distribution and permeability; permeability being, in part, a function of grain size.

Komura (1976) proposed a technique for erosion prediction which is particularly useful for steep slopes and materials with "mixed" particle sizes. He indicated that erosion losses are inversely related to the

median grain size of a material (D₅₀) which is the diameter at which 50 percent of the sample is finer by weight. The utilization of this method in surface mining is only an approximation of the erodibility of spoil materials due to slaking. However, it is believed that a rough estimate, such as provided by this technique, is the best approach to premining design. Sediment loss can be substantially increased by poor planning; however, rapid application of good reclamation practices (including mulching and revegetation) will counteract the tendencies toward increased sediment loss with time.

10.2.4 Vegetation Relationships

The relationships between vegetation in reclaimed areas and slaking of the underlying surface mine spoils are very complex. Essentially, three types of relationships can exist. These follow:

- A well developed vegetative cover and rapid application of prudent reclamation practices will decrease the rate and/or degree of slaking of the underlying materials.
- Slaking can have adverse effects on vegetation. It may lead to development of poor physical and/or chemical soil conditions in the root zone (directly or indirectly) or to significant surface erosion. Examples of this noted during the field program include dense crusting of the surface which impedes seed germination, root proliferation, and moisture infiltration. Where spoils consist of a high proportion of materials which slake to their inherent grain size, compact, dense sublayers may also occur, impeding deep root penetration.
- Slaking can have beneficial effects on vegetation. It may favor the establishment of vegetation and improve soil conditions within the plant root zone. Positive effects include the production of fine particles resulting 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 and nutrients.

A fourth possibility, that vegetation encourages slaking, may exist. Although plant roots can force rock fragments apart in certain circumstances, the high void ratios typical of most spoil piles provide paths of lesser resistance and, therefore, root development probably would not be impeded. In the event that such plant root stresses exist, they are unlikely to be a significant contributor to slaking. The acidic environment provided by plant roots, although it does cause some

weathering of soil and rock materials, is also unlikely to be a significant factor in the slaking process, particularly in light of increased acidic rainwater and frequent occurrence of acidic spoils.

A number of site-specific factors can influence the slaking-vegetation relationships cited above and include the following:

- The position of potentially slakable materials in the spoil pile with respect to the plant root zone.
- The presence or absence of a natural topsoil surface layer (placed during reclamation), its thickness, and the spoil surface preparation techniques utilized prior to topsoil placement.
- The rate and, more importantly, the degree of disintegration of spoil materials within or close to the plant root zone.
- The characteristics of materials susceptible to slaking, including their inherent grain size, clay mineralogy, and content of sulfide minerals (e.g., pyrite).
- The slope of the spoil pile surface and the interface between topsoil and slakable materials, if present.
- The nature of the topsoil-slakable material interface, if present, particularly with respect to very abrupt changes in soil texture (grain size), structure, density, and pore size distribution. Topsoil-spoil interfaces typically consist of relatively fine-grained material overlying coarser materials. Most water movement within topsoil materials occurs by capillary action whereas gravitational flow is dominant within spoil materials. Because capillarity is often broken at the topsoil-spoil interface, excess water accumulates at this point which can accelerate the slaking process and thus affect the physical properties of the material.
- Various environmental factors, including specific characteristics of the vegetation itself (particularly the nature of the root system) and local surface hydrologic relationships (e.g., rainfall distribution, runoff). The nature and extent of the root system is important to the slaking process. Taproot plants, including legumes and

many tree and shrub species, produce relatively few large roots that may extend to greater depths than plants with fibrous root systems. The fibrous root systems, therefore, could broadly affect near-surface spoil materials while slaking effects from taproot species would be more concentrated in isolated areas within the spoil.

Ground cover may also affect local hydrology. Plants which provide a high percentage of ground cover, such as grasses and legumes, reduce the impact of raindrops on the spoil surface, reduce runoff, and increase infiltration. Local topography may increase runoff or cause ponding, sheet flow or channel flow, and influence runoff velocity. These local hydrologic features may increase or decrease the impact on slaking and erosion depending on site conditions.

These factors should be evaluated during mine planning to optimize reclamation procedures and resulting impacts of slaking.

10.3 PROPOSED CLASSIFICATION SYSTEM

The slaking of surface mine spoils has been shown to be a complex problem with several interrelated variables. Because information provided from both field and laboratory investigations is necessary to accurately assess the impact of many of these factors, a complete classification scheme must include both aspects. For example, bedrock exposures or aged spoils may be examined to study the influence of time and climatic conditions on different materials while laboratory tests can provide detailed information regarding specific behavioral characteristics under controlled and accelerated conditions. Accordingly, the proposed classification system outlined below incorporates the strongest and most reliable aspects of the field and laboratory investigations conducted for this study to predict the ultimate behavior of material in surface mine spoils. Finally, the predicted behavior is used to address design measures that can minimize potentially adverse environmental effects of slaking.

Based on the field observations and laboratory results, a ranking of slaking potential by degradation index was first developed. The ranges for the various categories have been designed so as to group lithologies of similarly observed behavior. It is based on analysis of coarse size samples using either the cyclic wet/dry or cyclic rate of slaking tests in water. The coarse size sample is recommended in view of the size effects on test results as discussed previously. The tests were selected based on the agreement between laboratory test results and observed field behavior as well as the simplicity of required testing methods.

The proposed ranking of slaking potential by degradation index is as follows:

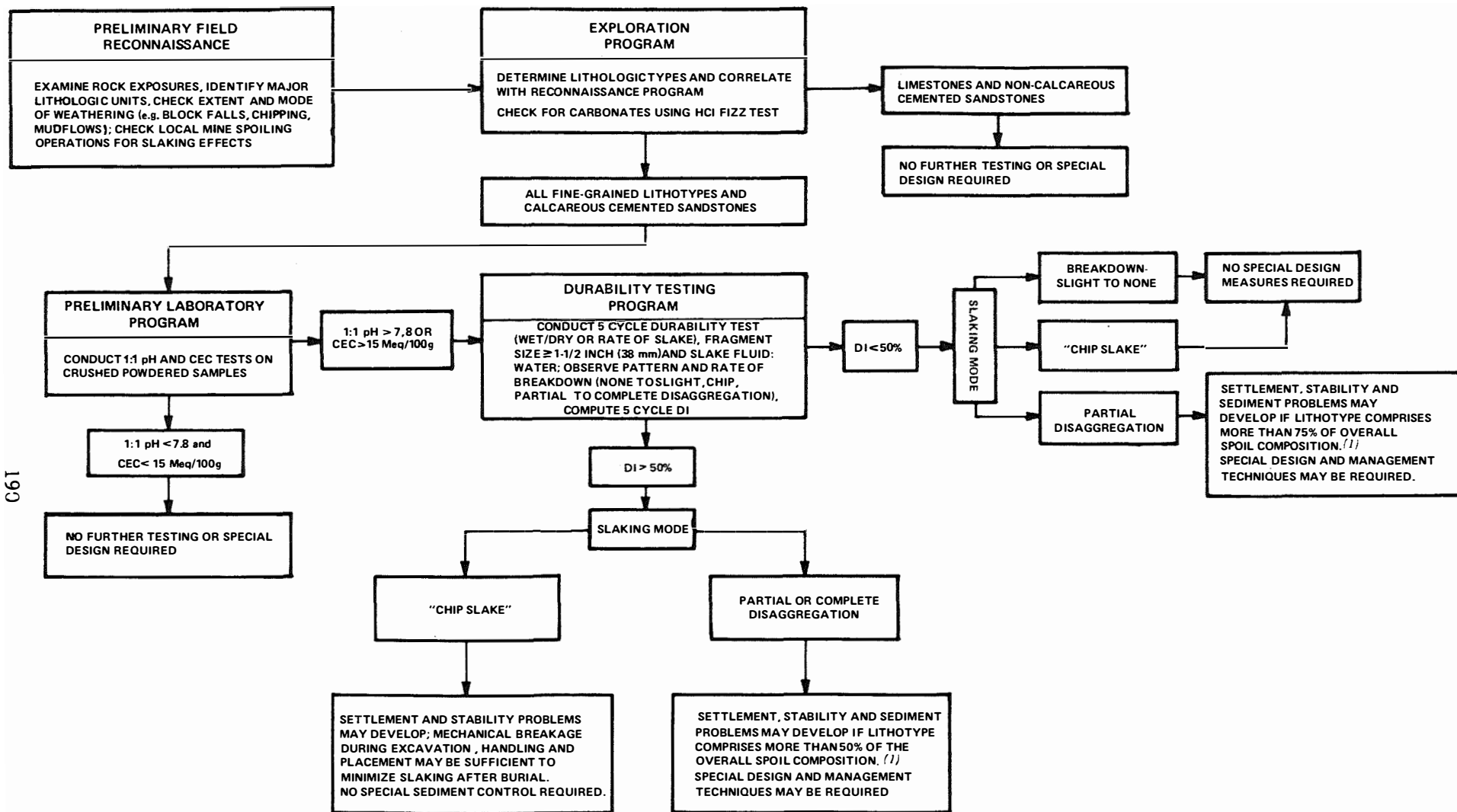
- DI = 0 to 10 percent, Very Low Slaking Potential
- DI = 10 to 25 percent, Low Slaking Potential
- DI = 25 to 50 percent, Moderate Slaking Potential
- DI = 50 to 100 percent, High Slaking Potential

Lithologies with a very low slaking potential typically are resistant to breakdown over relatively long periods of time when placed in spoil and can be expected to cause few, if any, adverse environmental effects. Lithologies with low slaking potential undergo some breakdown; however, the rate and degree of slaking is generally insufficient to cause adverse environmental effects. Lithologies with moderate slaking potential exhibit significant breakdown either in terms of rate or degree. Adverse environmental effects may result depending on the proportion of material present at any one location, mode of slaking, and site-specific features. Lithologies with a high slaking potential typically exhibit extreme breakdown with potentially adverse environmental effects resulting. These impacts depend on slaking mode and site-specific features such as the lithotype percentage in the overburden and mining techniques. The degradation index is a fundamental input parameter in the classification system outlined below.

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

The proposed system is presented in Figure 10-1 and includes those techniques that were found to reliably predict the slaking potential and behavior of geologic materials. It is divided into field and laboratory phases and utilizes relatively simple inspection and routine test procedures that are often a part of surface mine permitting programs.

Examination of bedrock outcrops can provide much useful information regarding the behavior of geologic materials upon exposure and is included as a major component of the preliminary field reconnaissance program. Information pertaining to the type and quantity of various lithologic units within the overburden can be determined and the impact of slaking can be partially assessed. Of particular importance are the type and quantity of fine-grained sediments because these factors bear a direct relationship to the nature of problems that may be encountered following spoiling operations. Because various lithotypes have shown tendencies to deteriorate by particular slaking modes (e.g., siltstones and shales by chip slaking), deviation from these patterns may indicate



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FIGURE 10-1

(1) BASED ON HOMOGENEOUS MIXING OF LITHOTYPES DURING PLACEMENT

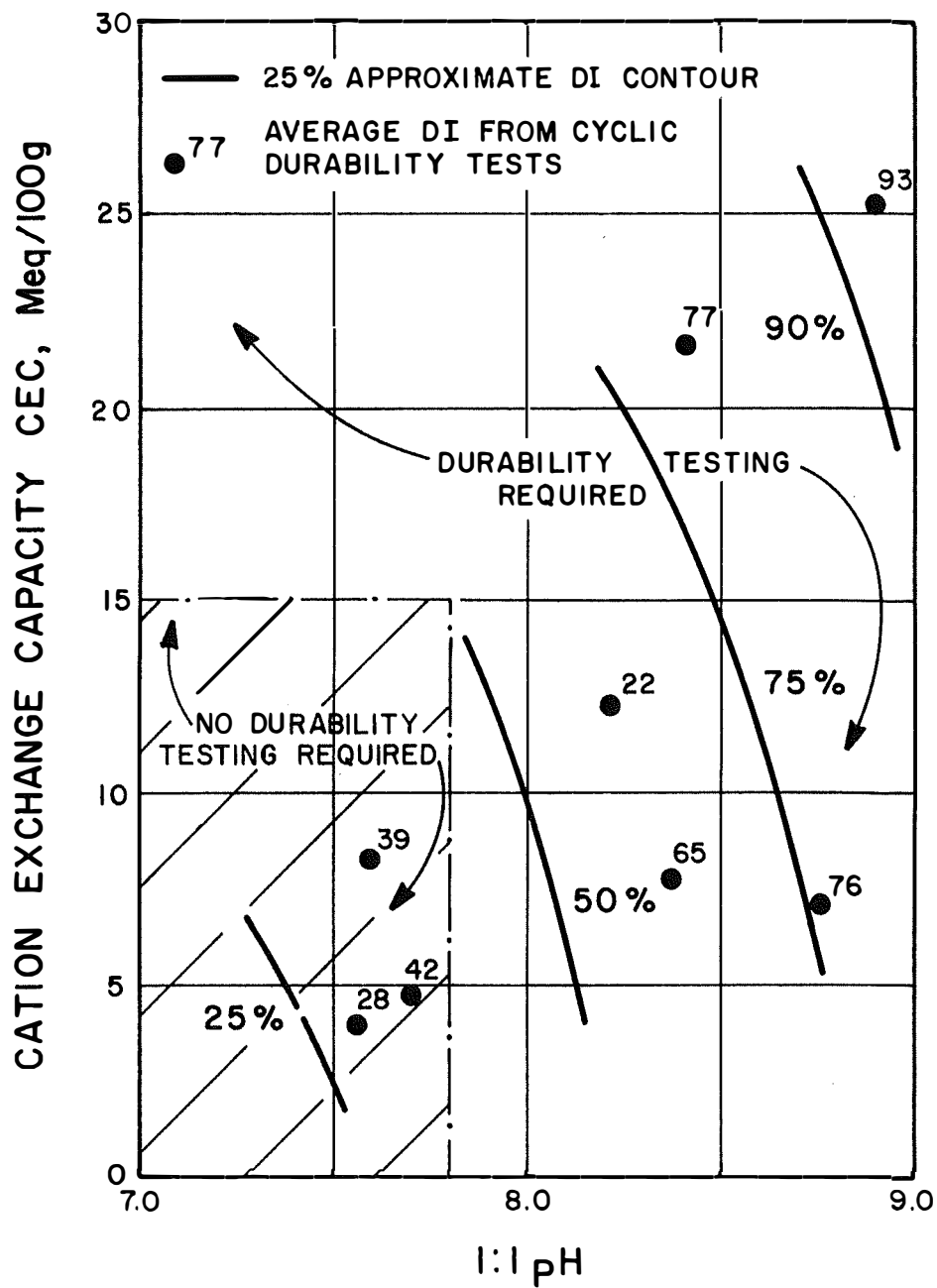
PROPOSED CLASSIFICATION SYSTEM

unusual compositional properties. Finally, a reliable indication as to the ultimate behavior of spoil materials can be obtained through examination of existing local surface mining operations.

Drilling programs that are routinely implemented as part of many environmental or exploration activities represent an excellent opportunity to compare fresh rock samples to the behavior observed in bedrock exposures. Because the carbonate content of many rock types appears to be related to durability, fresh rock core should be tested with dilute hydrochloric acid (HCl) to provide useful information regarding the chemical composition of the cementing agent of these materials. Accordingly, if nonargillaceous sandstones show very little to no reaction with HCl and rock exposures indicate relatively good durability, the need for further testing or special design considerations can be eliminated. The behavior of sandstones with carbonate cements or fine-grained sediments cannot be reliably ascertained at this stage. Therefore, one or more laboratory phases must be used to further delineate their slake potential.

The laboratory testing program is designed as a two-phase filtering system. The principal purpose is intended to separate durable from non-durable geologic materials based on two tests using crushed, powdered rock samples (1:1 pH and cation exchange capacity). As described previously (Section 9.2.3), a relationship exists between CEC and 1:1 pH that can be extended to include rock durability based on a five-cycle degradation index (DI). Figure 10-2 demonstrates that the DI increases with increasing 1:1 pH and CEC. This behavior is related to the influence of carbonates and various clay mineral phases. To incorporate this behavior into the proposed classification scheme, a DI value of 50 percent (representing the delineation between moderate and high degradation levels) was selected as a threshold. This value, in conjunction with the chemical performance of the suite of materials tested, suggested that maximum limits of 7.8 (1:1 pH) and 15 meq/100 g (CEC) be utilized, as indicated in Figure 10-2, as criteria to assess the need for durability testing. If, for a particular sample, the preliminary test results fall below these boundaries (cross-hatched zone in Figure 10-2), no further testing is necessary nor special design measures beyond normal practical requirements expected. If either of these bounds is exceeded, then further testing is required.

The final stage in this classification system utilizes durability testing. This may be readily and simply accomplished by subjecting the remaining samples to either of the cyclic durability test procedures (i.e., cyclic wet/dry or cyclic rate of slaking at 110 degrees Celsius) described previously. Based on results from the laboratory program, it is recommended that these tests be conducted using coarse fragments, 1-1/2 inches (38 millimeters) or larger, and water as the slaking medium. Intensity and mode of breakdown then can be identified, compared with the results of the field reconnaissance, and appropriate design considerations can be implemented to minimize potential environmental impacts of spoiling these materials.



PRELIMINARY LABORATORY CLASSIFICATION FILTER

The evaluation of the durability test results is based upon the intensity of slaking and the breakdown mode. If the degradation index is less than 50 percent, no special problems are likely to arise unless samples that partially disaggregate are expected to comprise more than 75 percent of the spoil. In this case, some degree of settlement/stability or sedimentation/erosion problems may arise. More serious problems may be encountered if degradation index values of 50 percent or more are attained unless special design or management techniques are implemented. This is partially true for those spoils which are comprised of more than 50 percent of lithotypes that partly or completely disaggregate during testing. Although settlement/stability problems may be encountered with siltstone and shale, sediment control is expected to be minimal because these materials appear to slake to an equilibrium size which minimizes the quantity of fine sediment.

The assessment of spoil management control measures for the above categories was developed from the field program conducted at Sites A through D. At each of these sites, the reclamation procedures that are practiced follow relatively routine patterns that seem to provide sufficient amounts of breakdown and densification to minimize slaking effects. These result in relatively minor problems (mostly surficial) despite the fact that some lithotypes developed higher than expected DI values (e.g., gray siltstone at Site B) or were present in sampled spoils in relatively high amounts (e.g., 60 to 70 percent mudstone at Site D). This suggests that the effort expended during excavation, handling, and placement and the intermixing of durable and nondurable sediments can control, to a large degree, the ultimate behavior of geologic materials. Therefore, present spoiling and reclamation practices may overcome the majority of problems that could be associated with low durability materials. Section 10.4 suggests various techniques which may be implemented to control the slaking process if standard procedures are inadequate.

This classification system was developed using information provided from a few sites selected to cover a broad range of conditions that may be encountered at other surface coal mining areas in the eastern and central United States. Accordingly, application of this scheme to other locations will provide necessary expansion of baseline data and a better definition of the various relationships used as a foundation. With sufficient data, the pH/CEC/DI correlation can then be reevaluated. If it remains relatively constant, then the durability testing portion of the proposed system can be eliminated and engineering assessment can be made based upon this empirically derived relationship.

10.4 MANAGEMENT TECHNOLOGY

A variety of alternative management techniques is available if standard spoiling procedures are insufficient to control slaking. The most viable alternative for any particular situation will depend on a variety of factors. However, based on the results of this study, three general principles will assist in controlling slaking. These follow:

- Maintain reclamation activities as concurrent as possible with active mining operations.
- Optimize material handling during mining and reclamation operations.
- Minimize the area disturbed at any one time.

Maintaining reclamation concurrent with mining operations minimizes the time period from initial excavation to final reclamation. Spoils generally are most susceptible to slaking during this time because little or no vegetative cover is available and minimum compaction exists. Reducing the amount of time when slaking agents can exert a maximum effect on spoils will not only reduce slaking and adverse environmental effects but will also insure that reclamation proceeds in a timely and cost-effective manner.

Reduction of material handling will reduce the crushing, grinding, and weakening of spoil materials and, therefore, minimize the resulting sedimentation problems which occur during excavation, movement, placement, and grading of spoils. An increase in sedimentation problems can be correlated with the advent of laws which require extra handling and a general increase in the weight, capacity, and power of stripping equipment. However, explosive casting in which overburden is blasted to fall where it can be reclaimed without being transported by equipment is one recently developed technique used to minimize material handling.

Although a reduction in initial environmental impacts, such as sedimentation, can be realized by minimizing the material handling or machine contact, long-term effects may be increased. This occurrence is related to "size equilibrium" mentioned in Chapter 9.0. The final fragment size (slabs, blocks, chips, or inherent particles) is a function of material properties. Once excavated, the duration of slaking is partially governed by initial fragment size; the larger it is, the longer it takes before "equilibrium size" is obtained. Therefore, minimizing the material handling is not always the best solution; it is better to optimize material handling based on the slakability of the lithotypes present in the spoils.

Because most slaking appears to be confined to the near surface zones of spoil piles, materials placed at depth will undergo little slaking. However, those materials placed in the "near surface" zones (i.e., influenced by slaking processes) should be subjected to additional machinery traffic. This would create a surface layer that would almost instantaneously reach the equilibrium size and reduce future impacts of slaking. Increased traffic or handling can also increase the surface density, thus minimizing atmospheric effects on the underlying spoils. To avoid sedimentation problems, revegetation should occur directly following these procedures.

Minimizing the area disturbed at any one time will reduce the volume of material subjected to maximum stress from slaking agents. Even if undesirable environmental effects do occur, they will be of a magnitude where they can be more easily and efficiently controlled. Mining and reclamation activities will also proceed in a more orderly and efficient manner.

Selection of a specific alternative to control slaking in surface mine spoils should consider the following factors:

- The significance of slaking and related problems.
- Material heterogeneity.
- Simple, direct methods which can be integrated into a mining plan.
- Cost effectiveness.

The significance of slaking and related problems may be evaluated by field observations and laboratory testing (Section 10.3) or indirect means such as citizen complaints or bond release problems. Slaking-related problems which have serious or major adverse effects may require extensive modification to standard procedures or implementation of innovative techniques. Minor problems may be rapidly and inexpensively alleviated.

Material heterogeneity is a function of mining methods and overburden characteristics. Where a slakable lithology is mixed with non-slakable material in spoils and adverse effects are encountered, remedial techniques become expensive due to the large volume of material involved. Segregation of problem materials during excavation may be a more efficient and effective technique when slaking is of a magnitude to warrant such treatment.

Simple, direct control methods which can easily be integrated into an ongoing or proposed mine plan will be the most efficient and also the most readily accepted and implemented by mining company personnel. Methods which are easy to initiate and carry out will have the greatest potential for success.

Management techniques to control slaking of problematic materials include but are not limited to the following:

- Stockpiling of slake-prone materials.
- Isolation within slake-resistant materials.
- Segregation with extra stabilization techniques.

- Modification of blasting and excavation procedures.
- Containment within temporary or permanent structures.
- Improved hydrologic controls.
- Chemical or physical treatments.
- Accelerated slaking under controlled conditions.

The application of any of the preceding control measures may require a variance from federal or state laws and regulations.

Stockpiling slake-prone materials can be a viable alternative where instability of fresh spoil causes slides into the working pit, degrades water quality, or otherwise affects coal production and reclamation. Slake-prone materials can be removed and stockpiled using procedures similar to those now employed for topsoil stripping and stockpiling. As mining progresses, stockpiled material can be disposed of by deep burial within the backfill area. The relative ease with which stockpiling and subsequent disposal can be conducted depends on the extent and location of the slakable lithologies, blasting patterns, and stripping equipment. Stockpiling could most easily be utilized where the slakable lithologies are located near the top of the highwall, near a coal seam, or where the overburden is shot in a series of lifts. The major disadvantage of stockpiling is the requirement for double handling of the material.

Slaking may also be controlled by isolating slakable lithologies within more resistant materials. This technique is similar to stockpiling except that slakable materials would be placed immediately after excavation in the area previously mined. This technique could be conducted in a manner similar to that used for disposal of partings, carbonaceous roof shales, and other potentially acidic materials by burial in the backfill area or layering of the slakable material between more durable lithologies. The principal advantage to this method is that disposal of slake-prone materials proceeds concurrently with mining and direct exposure to the environment is minimized. The relative ease of implementing this control technique is dependent on location and extent of lithologies and blasting and excavation techniques.

Slaking may be controlled by segregation of materials in conjunction with other techniques which include but are not limited to terracing, use of diversion ditches, heavy mulching rates, and compaction. These measures control slaking by controlling the volume and velocity of water flow over and through the spoil area. The principal disadvantages to this control method include the machinery and manpower requirements to segregate the slakable materials and the costs for periodic maintenance of hydrologic structures.

Modification of excavation techniques can be performed as a separate control measure or in conjunction with other techniques. Excavation techniques can be modified to optimize materials handling, which will improve efficiency as well as reduce the overall effects of slaking. Optimal spoil handling methods will differ depending on site characteristics but may include varying the exposure time of slakable lithologies. Prompt excavation and controlled placement at sites with large quantities of slakable material could minimize slaking and associated adverse effects. At other sites, induced breakdown of materials by handling, transport, and traffic prior to final reclamation may be desirable to provide conditions suitable for vegetative growth. Modified excavation procedures may be necessary when stockpiling, isolation, or segregation techniques are used as discussed previously.

Slake-prone materials may be controlled by containment within temporary or permanent structures. Embankments, fills, or other properly designed structures, can be used to hold slake-prone materials. This control method can be conducted in a manner similar to techniques used for coal waste disposal or head-of-hollow fill construction. Design, construction, and maintenance costs are the principal disadvantages of this technique.

Improved hydrologic controls may be a viable technique for controlling adverse environmental effects of slaking. Current state and federal regulations require sediment ponds and other hydrologic structures. Strategically placed sediment ponds, terraces, diversion ditches with nonslakable rock riprap, or other properly designed structures, can significantly reduce slaking-related problems. This technique is relatively inexpensive to implement and can easily be incorporated into a mining and reclamation plan.

Chemical or physical treatments may be considered as alternative control methods. The use of mulches, binder emulsions, netting, fencing, flocculents, or other means may be employed to control slaking and adverse environmental effects. The use of nonslakable lithologies acting as a rock mulch, which is a naturally occurring phenomenon on most mine sites, should also be considered. The feasibility of using any of these treatments depends on the availability and cost of materials as well as the amount of slakable lithologies.

Accelerated slaking under controlled conditions may also be a viable alternative in some instances. This technique would involve placing slake-prone material in an environment where it is exposed to wet-dry cycles. Slaked materials are controlled by sediment ponds, embankments, or other features, with the slaked material ultimately disposed of by burial within a fill area. Such a technique would require periodic monitoring, maintenance of structures, and disposal.

Slaking is controlled on most mine sites by current mining and reclamation techniques. Blasting, excavation, and placement techniques commonly result in the blending of slake-prone lithologies with more

durable materials. This results in a relatively stable matrix which contains or controls adverse environmental slake-related effects. Most adverse effects result from slaking occurring at or near the surface of the placed spoil. Mulching, the rapid establishment of a thick vegetative cover, sediment ponds, and other reclamation activities significantly reduce these impacts.

Specific mine sites may have more severe slaking-related problems which cannot be adequately controlled by routine reclamation techniques. In these instances, the use of alternative control measures such as those discussed previously should be considered. Mine site conditions including overburden and spoil characteristics, mining methods, and available equipment will determine which alternative will be the most effective and efficient technique to implement.

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Agricultural soil physics reference text; reviews the relationships between soil structure, soil aeration, and plant growth which are relevant to potential impacts of slaking on reclamation vegetation roof development. Does not specifically consider the slaking process.

Beasley, R. P., 1972, Erosion and Sediment Pollution Control, Iowa State University Press, Ames, Iowa, 320 pp.

Soil erosion reference text; reviews the Universal Soil Loss Equation (USLE) and input parameter evaluation relevant to assessing the potential impact of slaking on sediment loss in certain situations. Does not specifically consider the slaking process.

Berkovitch, I., M. Manackerman, and N. M. Potter, 1959, "The Shale Breakdown Problem in Coal Washing: Part I. - Assessing the Breakdown of Shales in Water," Journal of the Institute of Fuel, Vol. 32, pp. 579-589.

An investigation into shale durability in British coal washeries; concludes that exchangeable ion content of the shale, the hardness, and the free moisture content are the most significant properties which correlate with the ease of breakdown in water; a rotating drum durability device was utilized.

Bertram, G. E., 1973, "Field Tests for Compacted Rockfill," Embankment Dam Engineering - Casagrande Volume, R. C. Hirschfeld and S. D. Poulos, eds., John Wiley and Sons, Inc., New York, New York, pp. 1-19.

A general review of field tests for assessing the quality of rock-fill embankments. Particular emphasis is placed on density and gradation tests on large sample volumes for boulder- and cobble-size materials.

Birkeland, P. W., 1974, Pedology, Weathering, and Geomorphological Research, Oxford University Press, London, England, 285 pp.

A review text on the weathering of geologic materials and soil formation; provides a synthesized review of generalized weathering mechanisms which serves as a perspective for assessment of slaking mechanisms.

Bishop, A. W., 1973, "The Stability of Tips and Spoil Heaps," Quarterly Journal of Engineering Geology, Vol. 6, No. 3-4, pp. 335-376.

Extensive case history analysis of stability problems in spoils derived from a wide range of types of geologic materials and mining methods; the major emphasis urges utilization of geotechnical analysis and proper management of mine spoils in fills.

Bjerrum, L., 1967, "Progressive Failure in Slopes of Overconsolidated Plastic Clay and Clay Shales," Journal of the Soil Mechanics and Foundation Engineering Division, ASCE, Vol. 93, No. SM5, pp. 3-49.

A case history analysis of progressive slope failure; major topics reviewed include mechanisms of progressive failure in natural slopes, properties of overconsolidated clays and clay shales; slides in unweathered clay, and creep in slopes in overconsolidated clays.

Black, C. A., ed., 1965, "Methods of Soil Analysis," Agronomy Monograph No. 9, 2 vols., American Society of Agronomy, Madison, Wisconsin, 1572 pp.

A comprehensive reference work on methods of analysis applicable to geologic materials as well as soils; reviews techniques useful for assessing physicochemical index properties which may affect slaking.

Blatt, H., G. Middleton, and R. Murray, 1972, Origin of Sedimentary Rocks, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 634 pp.

A reference text on sedimentary rocks, including reviews of geologic/taxonomic classifications of sedimentary rocks.

Brant, R. A., 1964, "Geological Description and Effects of Strip Mining on Coal Overburden Material," Ohio Journal of Science, Vol. 64, No. 2, pp. 68-75.

Discusses properties of coal-bearing units in Ohio and the relationship between lithologies and rate of disintegration of mine spoil.

Brawner, C. O., D. L. Pentz, and D. B. Campbell, 1975, "Ground Stability in Surface Coal Mines," Mining Congress Journal, Vol. 61, No. 6, pp. 42-53.

A review paper with analysis of five case histories; focuses on highwall stability and heave (flat and dipping coal seams), tailings impoundments, and waste embankments; considerations include geotechnical analysis, design, and monitoring for instability.

Broch, E. and J. A. Franklin, 1972, "The Point-Load Strength Test," International Journal of Rock Mechanics and Mining Sciences, Vol. 9, pp. 669-697.

A thorough evaluation of the point load test, including a suggested standard testing procedure; includes detailed review of apparatus design and various testing techniques; aspects of testing procedures that were investigated included size and shape effects, measurement of anisotropy, and the influence of water content on strength results.

Brook, N., 1977, "The Use of Irregular Specimens for Rock Strength Tests," International Journal of Rock Mechanics and Mining Sciences, Vol. 14, pp. 193-202.

Three major types of rock strength tests (point load, crushing, and impact strength) are described so that irregular rock fragments can be used; for the point load and impact tests, similar strength indices may be obtained as for prepared regular specimens.

Carroll, D., 1970, "Clay Minerals: A Guide to Their X-Ray Identification," Special Paper 126, The Geological Society of America, Boulder, Colorado, 80 pp.

A general survey text incorporating background information regarding the principal crystallographic features of clay minerals, application of X-ray techniques for identification, and discussion of specific laboratory procedures.

Caspall, F. C., 1975, "Soil Development on Surface Mine Spoils in Western Illinois," Third Symposium on Surface Mining and Reclamation, National Coal Association, Vol. 2, Paper No. R-726, 8 pp.

An evaluation of soil development on mine spoils from a revegetation/reclamation viewpoint; major emphasis is on A-horizon development and organic matter accumulation; does not directly assess slaking.

Chandra, R., 1970, "Slake-Durability Test for Rocks," Master's Thesis, Imperial College, London University, London, England, 55 pp.

Reviews the problems of rock durability, principles of durability test design, and slaking mechanisms; outlines the development of a single-cycle, 20-rotation per minute/10-minute duration slake durability test and proposes a classification system for results.

Chapman, D. R., 1975, "Shale Classification Tests and Systems: A Comparative Study," JHRP-75-11, Indiana State Highway Commission and Purdue University, Engineering Experiment Station, Joint Highway Research Project, West Lafayette, Indiana, 90 pp.

A review and analytical comparison of laboratory techniques for assessing shale durability; major techniques evaluated included slake durability, slaking tests with different slaking fluids, Atterberg limits, Los Angeles abrasion, Schmidt hammer hardness, and the Washington degradation test; slake durability, rate of slaking, and slake index are concluded to be the most useful for shale classification.

Chenevert, M. E., 1970a, "Adsorptive Pore Pressures of Argillaceous Rocks," Rock Mechanics--Theory and Practice, W. H. Somerton, ed., American Institute Mining Engineers, New York, New York, pp. 599-627.

A theoretical investigation into the measurement of adsorptive (negative) pore pressures developed in shales and clayey sandstone upon drying; major emphasis is on geotechnical analysis of true effective stresses rather than on durability evaluation.

Chenevert, M. E., 1970b, "Shale Alteration by Water Adsorption," Journal of Petroleum Technology, Vol. 22, pp. 1141-1148.

A theoretical study of stresses and strains resulting from hydration of shales; water adsorption by confined shales generated stresses which led to hydrational spalling, vertical fracturing, and compressive strength reduction; illitic and chloritic shales, in addition to montmorillonitic shales, showed significant degrees of alteration.

Chorley, R. J., 1969, "The Role of Water in Rock Disintegration," Water, Earth and Man, R. J. Chorley, ed., Chapter 11, Methuen and Company, Ltd., London, England, pp. 135-155.

A general review of rock weathering processes related to water; does not directly consider slaking but reviews important mechanisms including hydration, crystal growth, and cement alteration.

Coates, D. F. and Y. S. Yo, 1977, "Pit Slope Manual, Chapter 9--Waste Embankments," CANMET Report 77-1, Canadian Center for Mineral and Energy Technology, Ottawa, Ontario, Canada, 129 pp.

A comprehensive engineering manual for waste embankments (including tailings dams and rock/overburden/soil piles) prepared for use in Canada; major emphasis is on site and laboratory investigations, design, construction, and operation.

Cook, F. and W. Kelly, 1976, "Evaluation of Current Surface Coal Mining Overburden Handling Techniques and Reclamation Practices," Open File Report 28-77, U.S. Department of the Interior, Bureau of Mines, Washington, D.C., 318 pp.

A summary report for three coal mining regions (eastern, central, and western) in the United States; major emphasis is on classification of mining systems within the broad categories of area and steep slope systems; the study is based on evaluation of 159 randomly sampled surface coal mines; the major implications of the study are improvement of operating procedures for productivity increase.

Cottiss, G. I., R. W. Dowell, and J. A. Franklin, 1971a, "A Rock Classification System Applied in Civil Engineering, Part 1," Civil Engineering and Public Works Review, Vol. 66, No. 779, pp. 611-614.

A summary review of a multiparameter technique for developing rock quality scores; tests are aimed at evaluating three generalized properties (brokenness, hardness, and durability); tests included slaking (jar-slake test), porosity, density, specific gravity, sound, velocity, Schmidt rebound hardness, Brazilian strength, uniaxial compressive strength, and petrological properties.

Cottiss, G. I., R. W. Dowell, and J. A. Franklin, 1971b, "A Rock Classification System Applied in Civil Engineering, Part 2," Civil Engineering and Public Works Review, Vol. 66, No. 780, pp. 736-743.

Application of the multiparameter classification system to five examples is reviewed.

Daniel, T. W., Jr. and M. H. Fies, 1970, "Strippable Coal in the Fabius Area, Jackson County, Alabama," Bulletin 96, Geological Survey of Alabama, Division of Economic Geology, University, Alabama, 81 pp.

Detailed description of the stratigraphic section in the Plateau coal field of Alabama.

Davies, W. E., 1968, "Coal Waste Bank Stability," Mining Congress Journal, Vol. 54, No. 7, pp. 19-24.

A generalized review of coal refuse embankment stability problems in Appalachia; relates rate of observed particle breakdown to material properties in a general fashion; reviews geotechnical implications of embankment water conditions and emphasizes need for engineered fills.

Davies, W. E., 1973, "Geologic Factors in Waste Bank Stability," Mining Congress Journal, Vol. 59, No. 1, pp. 43-46.

A generalized review of factors related to stability of coal refuse embankments in Appalachia; describes observations on the rate of breakdown of shale and sandstone spoils; emphasizes shale as a problematic material.

Davis, S. N. and R. J. M. DeWiest, 1966, Hydrogeology, John Wiley & Sons, Inc., New York, New York, 463 pp.

Basic principles of hydrogeology, including discussions of factors affecting permeability of porous media.

Deere, D. U., A. H. Merritt, and R. F. Coon, 1969, "Engineering Classification of In-Situ Rock," Technical Report No. AFWL-TR-67-144, U.S. Air Force Systems Command, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, 272 pp.

A review of techniques for in situ classification of a wide range of rock types for engineering purposes; major emphasis is on rock quality designation (RQD) and velocity index (square of the ratio of in situ to laboratory sonic velocities).

Deo, P., 1972, "Shales as Embankment Materials, Final Report," JHRP-72-45, Indiana State Highway Commission and Purdue University, Engineering Experiment Station, Joint Highway Research Project, West Lafayette, Indiana, 202 pp.

A comprehensive review of shale classification approaches and shales of Indiana, and an evaluation of testing methods for classifying shales; degradation-type tests included air slaking, cyclic jar-slake tests, slake durability tests, modified soundness, and modified abrasion tests; additional tests included soil type identification tests and compaction and load-deformation tests; a flow-chart-type classification system for shales is proposed.

Dunn, J. R. and P. P. Hudec, 1965, "The Influence of Clays on Water and Ice in Rock Pores," Report RR-65-5, Part 2, New York State Department of Public Works, Bureau of Physical Research, n.p., 138 pp.

An investigation into the theoretical considerations of freezing behavior and sorption behavior in argillaceous rocks, primarily argillaceous limestone and carbonate rocks used for aggregate in New York; the major conclusion is that freezing of water is not likely to be the mechanism of disruption for the majority of unsound rocks tested.

Dunn, J. R. and P. P. Hudec, 1972, "Frost and Sorption Effects in Argillaceous Rocks," Frost Action in Soils, Highway Research Record No. 393, Highway Research Board, National Academy of Sciences, Washington, D.C., pp. 65-78.

A summary review of theoretical investigations into freezing behavior of water in argillaceous rocks in New York, including durability effects; it is concluded that sorptive interactions with water vapor or liquid water are far more destructive of shales, siltstones, and argillaceous carbonate rocks than are freezing and thawing.

Eigenbrod, K. D., 1972, "Progressive Failure in Overconsolidated Clays and Mudstones," Ph.D. Dissertation, University of Alberta, Edmonton, Alberta, Canada, 295 pp.

An investigation into the nature of strength reduction in overconsolidated argillaceous materials in Canada; a detailed evaluation of material classification is included; tests developed and/or evaluated

included rate of slaking test, jar-slake test with water content measurement, and standard compression softening tests; two classification systems are proposed, including one based on standard compression softening test results and one based on rate of slaking test results.

Fenneman, N. M., 1938, Physiography of Eastern United States, McGraw-Hill Book Co., New York, New York, 714 pp.

Overview of various physiographic provinces in the eastern portion of the United States with general descriptions of geology and geomorphology responsible for the formation of characteristic land forms.

Fookes, P. G., W. R. Dearman, and J. A. Franklin, 1971, "Some Engineering Aspects of Rock Weathering with Field Examples from Dartmoor and Elsewhere," Quarterly Journal of Engineering Geology, Vol. 4, pp. 139-185.

A case study of field and laboratory tests to assess weathering and weatherability with suggestions for designating rock quality for mapping and core logging; materials considered included granite, dolerite, limestone, and mudstone; weathering grade and fracture spacing receive major consideration; point load testing and Schmidt hammer testing were utilized for strength evaluation; the case location is in southwest England.

Franklin, J. A., 1970, "Classification of Rock According to Its Mechanical Properties," Ph.D. Dissertation, Imperial College, University of London, London, England, 155 pp.

A thorough review of major aspects of rock evaluation for engineering purposes, including development and/or assessment of approaches to durability and strength testing; field investigations and laboratory investigations are addressed, in addition to a detailed discussion of the triaxial strength of rock (techniques, strength criteria, and classification).

Franklin, J. A., E. Broch, and G. Walton, 1971, "Logging the Mechanical Character of Rock," Institution of Mining and Metallurgy (London) Transactions, Vol. 80, pp. A1-A9.

A review of field and laboratory procedures for describing rock materials with a brief discussion of applications; logging techniques include geologic description, fracture spacing indices, strength logging with a point load device, strength anisotropy index, and slake-durability index; applications described include drilling, blasting, excavation, rock structure stability evaluation, rock aggregate selection, and rock quality designation.

Franklin, J. A. and R. Chandra, 1972, "The Slake-Durability Test," International Journal of Rock Mechanics and Mining Science, Vol. 9, pp. 325-341.

A description of slake-durability test, details of the apparatus, and suggestions for interpretation and classification of the results obtained.

Gamble, J. C., 1971, "Durability-Plasticity Classification of Shales and Other Argillaceous Rocks," Ph.D. Dissertation, University of Illinois, Urbana, Illinois, 161 pp.

A thorough review of shale classification systems for engineering applications and material properties affecting degradation, including the development of internationally standardized techniques for slake durability assessment and classification; the major conclusion is that a combination of plasticity classification with durability classification is most practical for a generalized prediction of problems with low durability, swelling, rebound, and low shear strength.

Gipson, M., Jr., 1963, "Ultrasonic Disaggregation of Shale," Journal of Sedimentary Petrology, Vol. 33, No. 4, pp. 955-958.

An investigation into the application of ultrasonic disaggregation techniques for subsequent mechanical (grain size) analysis; the major conclusion is that considerable grain alterations may occur in the clay-sized particles but that this has no major effect on the final results for proportions of total sand, silt, and clay.

Goodman, R. E., F. E. Heuze, R. K. Thorpe, and J. M. Chatoian, 1974, "The Design of Highway Cuts in Intermediate Quality Rock, Rock Testing Techniques Related to the Performance of Highway Cuts in Shales and

Sandstone," CA-DOT-TL-2137-1-75, University of California-Berkeley, Department of Civil Engineering, Geological Engineering Group for California Department of Transportation, Sacramento, California, 128 pp.

A report discussing the applicability of various testing techniques for assessing the behavior of partially weathered shales and sandstones. The investigation includes borehole jack measurements, slake durability, point load strength, radial permeability, and direct shear tests. With the possible exception of the radial permeability tests, these tests generally provided a good indication of weathered rock behavior.

Gray, H. H., W. J. Wayne, and C. E. Wier, 1970, "Geologic Map of the 1° x 2° Vincennes Quadrangle and Parts of Adjoining Quadrangles, Indiana and Illinois, Showing Bedrock and Unconsolidated Deposits," Regional Geologic Map No. 3, Vincennes Sheets, Scale 1:250,000, Indiana Department of Natural Resources, Geological Survey, Bloomington, Indiana.

Map showing the bedrock geology of coal-bearing units in Indiana.

Grice, R. H., 1968, "The Effect of Temperature-Humidity on the Disintegration of Nonexpandable Shales," Bulletin of the Association of Engineering Geologists, Vol. 5, pp. 69-77.

A report of progress in an investigation of techniques for qualitative measurement of progressive fissuring and disintegration of shales by use of controlled temperature-humidity cabinets and determining the change in surface area as a weight change after exposure to 100 percent humidity; definitive conclusions are not reported.

Harrison, J. L. and H. H. Murray, 1964, "Clays and Shales of Indiana," Bulletin 31, Indiana Department of Conservation, Geological Survey, Bloomington, Indiana, 40 pp.

Publication lists clay mineralogy and other properties of selected Indiana shales and clays.

Heald, M. T., G. E. Arnold, and R. M. Smith, 1974, "Sandstone Weathering on Surface Mine Spoil," Green Lands, Vol. 4, No. 3, pp. 19-20.

A brief report of field observations of sandstone disintegration/durability in West Virginia mine spoils; major conclusions are that calcareous sandstones in West Virginia generally remain intact, although voids may develop and that argillaceous sandstones are the least durable, with breakage primarily along argillaceous partings; emphasis is on the usefulness of field observations of natural local outcrops in predicting sandstone behavior.

Heley, W. and B. N. MacIver, 1971, "Engineering Properties of Clay Shales, Report 1: Development of Classification Indexes for Clay Shales," Technical Report No. S-71-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 104 pp.

A review of qualitative and quantitative classification indices useful for clay shales, with detailed summaries of methods for disaggregating shales for index tests and for determining residual shear strengths; quantitative tests considered included water content, unit weight, grain size, Atterberg limits, compressive strength, modulus of deformation, residual friction angle, linear shrinkage, swell potential, calcium carbonate content, and clay mineral analysis; slaking behavior is considered as a qualitative index.

Huddle, J. W., E. J. Lyons, H. L. Smith, and J. C. Ferm, 1963, "Coal Reserves of Eastern Kentucky," Bulletin 1120, U.S. Department of the Interior, Geological Survey, Washington, D.C., 247 pp.

Overview of the coal fields in Eastern Kentucky with detailed descriptions of structure, stratigraphy, and available coal resources.

Hudec, P. P., 1978, "Development of Durability Tests for Shale Embankments and Swamp Backfills," RR 216, Ontario Ministry of Transportation and Communication, Research and Development Division, Downsview, Ontario, Canada, 51 pp.

An investigation of Ontario shales and an assessment of a wide range of testing techniques for durability prediction; test procedures included freeze/thaw, slake durability, wet/dry deterioration, rate of slaking, water adsorption, abrasion loss and dry bulk density, and a dielectric heating test; the wet/dry test and slake durability tests were concluded to be the most generally useful.

Hudec, P. P. and J. R. Dunn, 1967, "Rock Deterioration: Frost Versus Sorption Sensitivity," presented at the Highway Research Board Meeting, Washington, D.C., 39 pp.

A discussion of investigations into the freezing behavior of water in argillaceous rocks in New York; the major conclusion is that adsorptive forces are often more important than freezing of pore fluids in causing deterioration in rocks believed to be frost sensitive.

Ingram, R. L., 1953, "Fissility of Mudrocks," Bulletin, Geological Society of America, Vol. 64, pp. 869-878.

A review of the breaking characteristics of mudrocks, including a triangular diagram classification system with massive, flaky-fissile, and flaggy-fissile end members; type of fissibility was not found to correlate with clay mineral type; cementing agents were the principal cause of observed differences.

International Society for Rock Mechanics, Commission on Standardization of Laboratory and Field Tests, 1979, Committee on Laboratory Tests, "Suggested Methods for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling, and Slake-Durability Index Properties," International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, Vol. 16, No. 2, pp. 148-156.

A detailed description of standardized testing techniques which allows flexibility in the development or improvement of techniques.

Jensen, M. E., ed., 1974, Consumptive Use of Water and Irrigation Water Requirements, American Society of Civil Engineers, Technical Committee on Irrigation Water Requirements of the Irrigation and Drainage Division, New York, New York, 215 pp.

A review of theory and applications related to water balances in the soil-plant-atmosphere system; although primarily for use in irrigation engineering, the principles are also applicable to evaluation of water transfers in the near-surface portion of mine spoil piles.

Keller, W. D., 1957, The Principles of Chemical Weathering, Lucas Brothers Publishers, Columbia, Missouri, 111 pp.

A reference text on chemical weathering processes and products of weathering which provides a perspective for a consideration of slaking mechanisms; does not directly consider the slaking process.

Kennard, M. F., J. L. Knill, and P. F. Vaughan, 1967, "The Geotechnical Properties and Behavior of Carboniferous Shale at the Balderhead Dam," Quarterly Journal of Engineering Geology, Vol. 1, No. 1, pp. 3-24.

A detailed case study of shale materials used as fill in a dam; the geotechnical investigation included an assessment of the weathering and disintegration of the shale materials and provided observations supporting negative pore pressures and cement alterations as slaking mechanisms.

Keystone Coal Industry Manual, 1978, Mining Informational Services, McGraw-Hill Mining Publications, New York, New York, 1265 pp.

A reference manual for the coal mining industry, including listings of all mines and data on coal seams, overburden thickness, and other items where available.

Kezdi, A., 1968, "Problems of Soil Mechanics in Open Cast Mining, Part 2: Tip Stability Tests," Bergbautechnik, Vol. 8, p. 398, trans. by National Coal Board, Translating and Interpreting Branch, Trans. A-2758/HSA, National Coal Board, London, England, 9 pp.

A theoretical investigation of the stability of tipped material derived from open-cast mining operations. General consideration is given to the height and slope of tips, the strength of spoil and foundation materials, groundwater conditions, and the degree of spoil compaction.

Komura, S., 1976, "Hydraulics of Slope Erosion by Overland Flow," Journal of the Hydraulics Division, ASCE, Vol. 102, No. HY10, pp. 1573-1586.

Description of a computational equation for predicting slope erosion rates; potentially useful for conditions where the Universal Soil Loss Equation may not be accurate; major parameters include the mean grain size, runoff coefficient, rainfall intensity, slope length and gradient, bare-soil ratio, and an erodibility coefficient.

Krause, R. R., 1973, "Predicting Mined-Land Soil," Ecology and Reclamation of Devastated Land, R. J. Hutnik and G. Davies, eds., Vol. 1, Gordon and Breach, Science Publishers, Inc., New York, New York, pp. 121-131.

A general discussion of the relationship between overburden weathering, soil development, and reclamation; suggests that exposed highwalls are better than artificially weathered core-drill samples for predicting spoil disintegration.

Krinitzsky, E. L. and C. R. Kolb, 1969, "Geological Influences on the Stability of Clay Shale Slopes," Proceedings of the 7th Annual Engineering Geology and Soils Engineering Symposium, Idaho Department of Highways, University of Idaho and Idaho State University, pp. 160-175.

A general discussion of natural clay shale slope stability, using case examples; considers the importance of slaking and structural relaxation (recoverable strain energy) along with other factors.

Krumbein, W. C. and L. L. Sloss, 1963, Stratigraphy and Sedimentation, 2nd ed., W. H. Freeman and Co., San Francisco, California, 660 pp.

A reference text on sedimentary materials, including a detailed review of geologic/taxonomic classifications of sedimentary materials.

Laguros, J. G., 1972, "Predictability of Physical Changes of Clay-Forming Materials in Oklahoma, Final Report," Oklahoma Study No. 68-03-2, OURI Project 1677, University of Oklahoma Research Institute for Oklahoma Department of Highways and Department of Transportation, Federal Highway Administration, 168 pp.

An investigation into the behavior of Oklahoma shales; ultrasonic disaggregation techniques were utilized; durability index tests included the sand equivalent method, a soaking method, and a hydrogen pyroxide method; the general conclusion is that component grain size distribution of shales is a major factor affecting behavior and should be used to select subsequent testing parameters.

Lessing, P. and R. D. Thomson, 1973, "Clays of West Virginia, Part I," Mineral Resources Series No. 3, West Virginia Geological and Economic Survey, Morgantown, West Virginia, 190 pp.

Summary of mineralogical, chemical, and economical analyses of selected shale and clay samples of various geologic units.

Lowry, G. L., 1961, "Some Physico-Chemical Properties of Weathering Coal Spoils and Their Influence on the Growth of Pine Seedlings," Ph.D. Thesis, Michigan State University, East Lansing, Michigan, 141 pp.

An investigation into the weathering and vegetation relationships of 19 spoils from Ohio; the major conclusion regarding spoil weathering is that spoil pH has the greatest effect on the rate of weathering.

Lutton, R. J., 1977, "Design and Construction of Compacted Shale Embankments, Vol. 3: Slaking Indexes for Design, Interim Report," Report No. FHWA-RD-77-1, U.S. Army Engineer Waterways Experiment Station, Soils and Pavement Laboratory for U.S. Department of Transportation, Federal Highway Administration, Offices of Research and Development, Washington, D.C., 88 pp.

An investigation of 158 shales collected throughout the United States and techniques for predicting their behavior in embankments; the major conclusion is that the slake durability index or the jar-slake index provides the best indication of durability behavior.

Mathematica, Inc., 1976a, "Evaluation of Current Surface Coal Mining Overburden Handling Techniques and Reclamation Practices, Phase II: Central United States," Contract Report S0144081, Mathematica, Inc., for U.S. Department of the Interior, Bureau of Mines, Washington, D.C., 110 pp.

An interim report on the classification of mining systems in the central United States; the objectives of the study were to provide baseline information for development of a surface coal mining and reclamation research program.

Mathematica, Inc., 1976b, "Evaluation of Current Surface Coal Mining Overburden Handling Techniques and Reclamation Practices, Phase III: Eastern United States," Contract Report S0144081, Mathematica, Inc., for U.S. Department of the Interior, Bureau of Mines, Washington, D.C., 185 pp.

An interim report on the classification of mining systems in the eastern United States; the objectives

of the study were to provide baseline information for development of a surface coal mining reclamation research program.

Marachi, N. D., C. K. Chan, and H. B. Seed, 1972, "Evaluation of Properties of Rockfill Materials," Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 98, No. SMI, pp. 95-114.

A general discussion of a modeling technique to determine the properties of rock-fill materials. The results indicate that field behavior can be predicted with a high degree of accuracy. The technique consists of modeling the field gradation using laboratory samples with a parallel gradation. Test results show that the angle of friction and compressibility is only slightly affected if the proposed method is employed.

McKee, E. D. and E. J. Crosby, coords., 1975a, "Paleotectonic Investigations of the Pennsylvanian System in the United States, Part I, Introduction and Regional Analysis of the Pennsylvanian System," Professional Paper 853, U.S. Department of the Interior, Geological Survey, Washington, D.C., 349 pp.

Geological description of the entire Pennsylvanian section in the continental United States. Included in the study are structural and stratigraphic interpretations such as sandstone-shale ratios for each unit.

McKee, E. D. and E. J. Crosby, coords., 1975b, "Paleotectonic Investigations of the Pennsylvanian System in the United States, Part II, Interpretive Summary and Special Features of the Pennsylvanian System," Professional Paper 853, U.S. Department of the Interior, Geological Survey, Washington, D.C., 192 pp.

Overview of special features peculiar to individual Pennsylvanian basins. Presented as a series of short papers, each dealing with a different basin and/or feature.

McKee, E. D. and E. J. Crosby, coords., 1975c, "Paleotectonic Investigations of the Pennsylvanian System in the United States, Part III, Plates," Professional Paper 853, U.S. Department of the Interior, Geological Survey, Washington, D.C., 17 plates.

Maps and cross sections detailing the thicknesses and lithologies of various Pennsylvanian units as

well as structural history during and following deposition and diagenesis.

Metzger, W. J., 1965, "Pennsylvanian Stratigraphy of the Warrior Basin, Alabama," Circular 30, Geological Survey of Alabama, Division of Paleontology, Stratigraphy, and Geophysics, University, Alabama, 80 pp.

Detailed description of stratigraphy in the Warrior Basin related to coal-bearing units. Includes detailed description of the Pennsylvanian section as well as a generalized stratigraphic column.

Mitchell, J. K., 1976, Fundamentals of Soil Behavior, John Wiley and Sons, New York, New York, 422 pp.

A reference text on soil behavior from a physical and engineering perspective, including detailed reviews of behavior mechanisms potentially important in slaking (e.g., double-layer repulsion force); does not directly consider the slaking process.

Morgenstern, N. R. and K. D. Eigenbrod, 1974, "Classification of Argillaceous Soils and Rock," Journal of the Geotechnical Engineering Division, ASCE, Vol. 100, No. GT10, pp. 1137-1156.

A summary review of an investigation of behavior of shales, primarily from Alberta, Canada; two types of classification systems are proposed, including one based on the standard compression softening test and one based on the rate of slaking test (change in liquidity index) and liquid limits.

Moriwaki, Y., 1974, "Causes of Slaking in Argillaceous Materials," Ph.D. Dissertation, University of California, Berkeley, California, 291 pp.

A comprehensive review of slaking, swelling, and dispersion phenomena in argillaceous materials, and a detailed mechanistic investigation of slaking behavior utilizing prepared mixtures of clay minerals with different exchangeable ion distributions; major parameters considered included physico-chemical (mineralogy, adsorbed cations, electrolyte concentrations, and slaking fluid pH), air-evacuation, relative humidity, consolidation pressure and compaction, silt content, and grain size distribution; major slaking modes considered included swelling slaking, dispersion slaking, surface slaking, and body slaking.

Murayama, S. and N. Yagi, 1966, "Swelling of Mudstone Due to Sucking of Water," Proceedings of the 1st Congress of the International Society of Rock Mechanics, Vol. 1, pp. 495-498.

A theoretical investigation of mechanisms causing failure of new slopes or tunnel walls in mudstone and claystones; hypothesizes that failure may be caused by local unequal expansion related to the unequal distribution of sucked water.

Nakano, R., 1967, "On Weathering and Change of Properties of Tertiary Mudstones Related to Landslide," Soil & Foundations, Vol. 7, pp. 1-14.

A theoretical investigation into causes of softening of mudstones in a landslide area in Japan; materials were predominantly montmorillonitic; pore air compression was concluded not to be a significant cause of softening; release of Gibb's free energy upon hydration was concluded to be the major factor in softening of mudstones.

National Coal Board, 1972, "Review of Research on Properties of Spoil Tip Materials," Lab. Reference No. S/7307, Wimpey Laboratories, Ltd., Hayes, Middlesex, England.

A summary of British research on the behavior of coarse and fine coal refuse; major considerations include shear strength, mechanical breakdown, weathering within refuse piles, permeability, consolidation, and design studies for lagoon banks.

Nettleton, A. F. S., 1974, "An Investigation into a Physico-Chemical Aspect of the Slake Durability Weathering Test," UNICIV Report No. R-128, University of New South Wales, Kensington, New South Wales, Australia, 39 pp.

A comparison study of the slake durability test; recommendations include the use of high pH-dispersing agent solutions for a slaking fluid, presoaking for 24 hours, and the use of the methylene blue absorption test as a simple physico-chemical classification test for prediction of durability.

Nevins, M. J. and D. J. Weintritt, 1967, "Determination of Cation Exchange Capacity by Methylene Blue Adsorption," American Ceramic Society Bulletin, Vol. 46, No. 6, pp. 587-592.

An investigation of the applicability of the methylene blue adsorption test for determining the cation exchange capacity of aqueous drilling fluids. Experiments showed the method to be simple, rapid, and accurate. Results compared favorably with those obtained by the conventional ammonium acetate method.

Noble, D. F., 1977, "Accelerated Weathering of Tough Shales, Final Report," VHTRC-78-R20, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, 38 pp.

An investigation of techniques for differentiation between apparently tough but potentially rapidly weatherable shales; materials included shales from Virginia; a modified sodium sulfate soundness test and a sulfuric acid test are recommended for classification of tough shales.

Ollier, C. D., 1969, Weathering, Longman Group, Ltd., London, England, 304 pp.

A reference text on weathering processes, including detailed discussions of physical, chemical, and biotic mechanisms; discussion of hydrology-weathering relationships and rates of weathering is also included.

Olson, R. E. and G. Mesri, 1970, "Mechanisms Controlling Compressibility of Clays," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, No. SM6, pp. 1863-1878.

A laboratory investigation of compressibility relationships to mineralogy and adsorbed cations/pore fluid chemistry; prepared samples consisted of sodium or calcium illite, kaolinite, and smectite; the highest swelling indices were for Na-smectite, with Na-illite, Ca-illite, and Ca-smectite showing intermediate values, and both Na-kaolinite and Ca-kaolinite had very low swelling indices.

O'Neill, B. J., Jr., D. M. Lapham, M. G. Jaron, A. A. Socolow, R. D. Thomson, and H. P. Hamlin, 1965, "Properties and Uses of Pennsylvania Shales and Clays," Bulletin M51, Fourth Series, Pennsylvania Department of Environmental Resources, Topographic and Geologic Survey, Harrisburg, Pennsylvania, 448 pp.

Summary of mineralogical, chemical, and economical analyses of select clay and shale samples located within Pennsylvania.

Parate, N. S., 1973, "Influence of Water on the Strength of Limestone," Transactions, Society of Mining Engineers, AIME, Vol. 254, pp. 127-131.

A theoretical investigation into mechanisms of strength reduction caused by wetting of limestones; surface energy reduction is concluded to be a significant factor in the reduction of compressive, tensile, and shear strengths.

Penner, E., J. E. Gillott, and W. J. Eden, 1970, "Investigation of Heave in Billings Shale by Mineralogical and Biogeochemical Method," Canadian Geotechnical Journal, Vol. 7, pp. 333-338.

An investigation of the causes of shale heave in basement floors in Ottawa, Canada; expansion upon weathering of pyrite in the presence of autotrophic bacteria was concluded to be the principal cause of heave.

Pettijohn, F. J., 1957, Sedimentary Rocks, 2nd ed., Harper and Row Publishers, New York, New York, 718 pp.

A reference text on sedimentary rocks, including a detailed review of geologic/taxonomic classification systems.

Philbrick, S. S., 1950, "Foundation Problems of Sedimentary Rocks," Applied Sedimentation, P. D. Trask, ed., Chap. 8, John Wiley and Sons, Inc., New York, New York, pp. 147-167.

A general summary of steps that are required to evaluate foundation conditions with particular emphasis on sedimentary rock sites. A general discussion of the testing, investigation, and classification procedures that can be used is presented. A small portion of the testing section relates to the need for weathering tests to determine the susceptibility of sedimentary rocks to deterioration by weathering processes.

Piper, A. M., 1933, "Groundwater in Southwestern Pennsylvania," Bulletin W-1, Pennsylvania Topographic and Geologic Survey, 406 pp.

Summary of water-bearing formations. Includes general descriptions of various stratigraphic units in the Pennsylvania section.

Plass, W. T. and W. G. Vogel, 1973, "Chemical Properties and Particle Size Distribution of 39 Surface Mine Spoils in Southern West Virginia," Research Paper NE-276, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, 8 pp.

An investigation of chemical (ph, phosphorus, exchangeable acidity, fertilizer response) and physical (grain size) characteristics of mine spoils; grain size distributions were not correlated with age of spoils.

Quigley, R. M., J. E. Zajic, E. McKyes, and R. N. Yong, 1973, "Oxidation and Heave of Black Shale," Journal Soil Mechanics and Foundations Division, ASCE, Vol. 99, No. SM5, pp. 417-421.

An investigation into the causes of floor slab heave caused by expansion of shale in Ottawa, Canada; it was concluded that oxidation of pyrite and the ultimate formation of gypsum were the principal causes of heave.

Reidenouer, D. R., 1970, "Shale Suitability, Phase II, Interim Report No. 1," Research Report No. 68-23, Pennsylvania Department of Transportation, Bureau of Materials, Testing and Research, Harrisburg, Pennsylvania, 198 pp.

An investigation of shale suitability for use as granular material in highway construction in Pennsylvania; tests utilized included gyratory compaction, wet-dry slake, Washington degradation, ethylene glycol soaking, specific gravity, percent absorption, mineralogical and chemical analysis, and petrographic analysis; major conclusions for the materials tested were that durability is not significantly correlated with percentage of specific clays or total clay, but that durability is directly correlated to the thickness of laminations.

Reidenouer, D. R., E. G. Geiger, Jr., and R. H. Howe, 1974, "Shale Suitability, Phase II, Final Report," Research Report 68-23, Pennsylvania Department of Transportation, Bureau of Materials, Testing and Research, Harrisburg, Pennsylvania, 146 pp.

A summary review of research on the evaluation of shales for use as construction materials in Pennsylvania; the ultrasonic disaggregation test is concluded to be the most sensitive indicator of durability; a two-phase procedure is recommended for durability evaluation, with field evaluation of

lamination thickness and weathering characteristics used as a screening phase prior to using an ethylene glycol soaking test and the Washington degradation test for final evaluation.

Reidenouer, D. R., E. G. Geiger, Jr., and R. H. Howe, 1976, "Suitability of Shale as a Construction Material," Living with Marginal Aggregates, Special Technical Publication STP 597, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 59-75.

A summary of research on shale evaluation for use as construction materials; field evaluation of lamination thickness and weathering characteristics is recommended to screen samples for testing by ethylene glycol soaking and the modified Washington degradation procedure; limiting values of the Washington degradation factor are selected for specific uses of shale in construction.

Rodin, S., 1973, "Tip Materials and Stability Researched," Ground Engineering, Vol. 6, No. 1, pp. 14-16.

A brief discussion of highlights of British research on coal refuse pile stability; topics reviewed include the breakdown and weathering of coarse refuse, shear strength of coarse refuse, pore pressures, flow slides, and design studies for lagoon banks.

Rothrock, H. E., 1949, "Geology and Coal Resources of the Northeast Part of the Coosa Coal Field, St. Clair County, Alabama," Bulletin 61, 2 Parts, Geological Survey of Alabama, University, Alabama, 163 pp.

Detailed analysis of structure, stratigraphy, and coal resources. Includes a stratigraphic section of the Coosa field.

Russell, E. W., 1973, Soil Conditions and Plant Growth, 10th ed., Longman, London, England, 849 pp.

A reference text on soil physics, chemistry, and biology as related to plant growth; includes a review of soil physical conditions related to root development relevant to the relationship between mine spoil disintegration and revegetation success.

Sangrey, D. A., D. K. Noonan, and G. S. Webb, 1976, "Variation in Atterberg Limits of Soils Due to Hydration History and Specimen Preparation," Soil Specimen Preparation for Laboratory Testing, Special Technical Publication STP 599, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 158-168.

A laboratory investigation of the effect upon Atterberg limit determinations by drying and rewetting soils prior to testing; rehydration was found to be time dependent, and a 24-hour rewetting time may be insufficient; the research recommended that the ASTM standard allow for testing of nondried samples.

Saunders, M. K. and P. G. Fookes, 1970, "A Review of the Relationship of Rock Weathering and Climate and Its Significance to Foundation Engineering," Engineering Geology, Vol. 4, pp. 289-325.

A review of rock weathering related to engineering problems with an international scope; includes a summary of various approaches to describing in situ grades of weathering for rock materials.

Seed, H. B., J. R. Woodward, and R. Lundgren, 1964, "Clay Mineralogical Aspects of Atterberg Limits," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 90, No. SM4, pp. 107-131.

An investigation of the utility of Atterberg limits for soil behavior evaluation utilizing prepared clay mixtures; activity of a clay (plasticity index divided by percent total clay) is shown to be a useful parameter and the activity is shown to be related to the mineralogical composition; higher activities are indicative of greater swelling behavior.

Shamburger, J. H., D. M. Patrick, and R. J. Lutton, 1975, "Design and Construction of Compacted Shale Embankments, Volume 1: Survey of Problem Areas and Current Practices, Interim Report," Report No. FHWA-RD-75-61, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 288 pp.

A comprehensive review of shale highway embankment problems in the United States related to material degradation; includes discussions of shale classification, slaking mechanisms, laboratory testing techniques, and distribution of known problem shales.

Shaver, R. H., A. M. Burger, G. R. Gates, H. H. Gray, H. C. Hutchison, S. J. Keller, J. B. Patton, C. B. Rexroad, N. M. Smith, W. J. Wayne, and C. E. Wier, 1970, "Compendium of Rock-Unit Stratigraphy in Indiana," Bulletin 43, Indiana Department of Natural Resources, Geological Survey, Bloomington, Indiana, 229 pp.

Listing and description of coal-bearing units in Indiana.

Shaw, D. E., J. B. Case, and J. J. Gusek, 1978, "Engineering and Economic Evaluation of Explosive Casting of Overburden for Surface Mining," Contract No. JO177081, D'Appolonia Consulting Engineers, Inc., for U.S. Department of the Interior, Bureau of Mines, Washington, D.C., 216 pp.

An engineering and economic feasibility investigation of explosive casting techniques for overburden removal to a spoil pile without additional handling.

Sisler, J. O., 1961, "Bituminous Coal Fields of Pennsylvania, Part II, Detailed Description of Coal Fields," Bulletin M6, Fourth Series, Pennsylvania Department of Internal Affairs, Topographic and Geologic Survey, Harrisburg, Pennsylvania, 511 pp.

Summarizes coal reserves by county. Gives detailed analyses of each minable seam and a short description of the interburden stratigraphy.

Skempton, A. W., 1964, "Long-Term Stability of Clay Slopes," Geotechnique, Vol. 14, No. 2, pp. 77-101.

A detailed review of long-term stability of cut slopes with particular emphasis placed on overconsolidated clays. The impact of peak and residual strength, previous stress history (i.e., previous slope movement), fractures or fissures, and groundwater is considered. Failures typically occur by a progressive failure mechanism which continues until residual strength conditions are reached and is manifested by a gradual reduction of the effective cohesion.

Smith, R. M., E. H. Tryon, and E. H. Tyner, 1971, "Soil Development on Mine Spoil," Bulletin 604T, West Virginia University, Agricultural Experiment Station, Morgantown, West Virginia, 47 pp.

A review of laboratory and field investigations of soil development in spoils at two West Virginia locations; topics addressed included bulk densities,

particle sizes, nitrogen, acidity, cation exchange, mineralogy, infiltration, field moisture trends, root development, site quality, and various interrelationships.

Sokolov, A. A. and T. G. Chapman, eds., 1974, "Methods for Water Balance Computations, An International Guide for Research and Practice," Studies and Reports in Hydrology No. 17, Unesco Press, Paris, France, 127 pp.

A comprehensive review of methods for prediction of water transfers in the soil-plant-atmosphere system; does not address slaking influences but methods are relevant to an assessment of water balances in near-surface portions of mine spoil piles.

Sowers, G. F., R. C. Williams, and T. S. Wallace, 1965, "Compressibility of Broken Rock and the Settlement of Rock Fills," Proceedings of the Sixth International Conference on Soil Mechanics and Foundation Engineering, Vol. 2, pp. 561-565.

An investigation of rock-fill settlement at 14 dams; settlements were found to be similar to secondary compression of soils; laboratory tests showed that settlement rates were accelerated by wetting and by shock; settlement apparently resulted from crushing of points of contact.

Spears, D. A. and R. K. Taylor, 1972, "The Influence of Weathering on the Composition and Engineering Properties of In-Situ Coal Measure Rocks," International Journal of Rock Mechanics and Mining Science, Vol. 9, pp. 729-756.

A summary of detailed field and laboratory investigations at a single site in England; major topics discussed include visual assessment of weathering, mineralogy, geochemistry, fundamental grain size, Atterberg limits, specific gravity, density and standard penetration tests, shear strength, and deformation moduli.

Stimpson, B., R. G. Metcalfe, and G. Walton, 1971, "A New Field Technique for Sealing and Packing Rock and Soil Samples," Quarterly Journal of Engineering Geology, Vol. 3, pp. 127-133.

A field technique is described for sealing and packing soil and rock cores in a rigid plastic foam; absolute moisture content losses of less than 1.0 percent over six months should be obtainable.

Stout, W., 1947, "Generalized Section of Rocks of Ohio," Information Circular 4, Fourth Series, Ohio Department of Natural Resources, Columbus, Ohio.

Descriptions of various coal-bearing stratigraphic units.

Strohm, W. E., Jr., 1978, "Design and Construction of Compacted Shale Embankments, Vol. 4: Field and Laboratory Investigations, Interim Report," Report No. FHWA-RD-78-140, U.S. Army Waterways Experiment Station, Geotechnical Laboratory for U.S. Department of Transportation, Federal Highway Administration, Office of Research and Development, Washington, D.C., 152 pp.

A summary of field and laboratory investigations of six shale embankments (in Tennessee, West Virginia, Kentucky, and Ohio); unweathered shales were used for jar soaking and slake-durability tests, point load tests, compaction tests, and soaked compression tests; pressure meter tests were also run; point load tests appeared promising for field classifications; soaked compression tests of minus 3/4-inch compacted shale correlated with slake durability and can be used to estimate long-term settlement.

Strohm, W. E., Jr., G. H. Bragg, and T. W. Ziegler, 1978 (in press), "Design and Construction of Compacted Shale Embankments, Vol. 5: Technical Guidelines," Report No. FHWA-RD-78-141, U.S. Army Waterways Experiment Station for U.S. Department of Transportation, Federal Highway Administration, Office of Research and Development, Washington, D.C.

A discussion of considerations for shale embankment design; major topics covered include field exploration and sampling of shales, index tests, and durability classification criteria, shale formation excavation characteristics, shale embankment design, shale embankment construction, evaluation of existing shale embankments, and remedial treatment of shale embankments.

Taylor, R. K., 1973, "Compositional and Geotechnical Characteristics of a 100-Year-Old Colliery Spoil Heap," Transactions, Institution of Mining Metallurgy, Vol. 82, pp. A1-A14.

A summary of field and laboratory investigations of a single coal refuse heap in England; detailed mineralogical, chemical, and particle size investigations were performed; shear strength and stability investigations were also performed; in nonburnt

spoils, physical and chemical changes could be most reasonably attributed to original differences in the refuse, whereas burnt spoils experienced significant mineralogical and strength changes.

Taylor, R. K., 1974, "Colliery Spoil Heap Materials, Time Dependent Changes," Ground Engineering, Vol. 7, No. 4, pp. 24-27.

A review of British research on coal refuse weathering and alterations; includes mechanistic discussion of physical disintegration; chemical changes, burnt and partly burnt spoils, large shear displacements, and relationships of changes to disposal point versus spoil heap placement are also discussed.

Taylor, R. K., 1975, "English and Welsh Colliery Spoil Heaps - Mineralogical and Mechanical Interrelationships," Engineering Geology, Vol. 9, pp. 39-52.

A review of investigations of 74 triaxial test specimens from 15 British coal refuse piles; mineralogical and chemical (exchangeable cations) analytical results were related to strength test results, moisture content, bulk density, and plasticity indices; major conclusions were that expandable mixed-layer clays and clays with high levels of exchangeable sodium are most susceptible to disintegration and that physical changes in spoils become relatively dormant once the spoils are deeply buried.

Taylor, R. K. and D. A. Spears, 1970, "The Breakdown of British Coal Measure Rocks," International Journal of Rock Mechanics and Mining Science, Vol. 7, pp. 481-501.

A review of mechanisms and intrinsic material properties related to disintegration of coal measure rocks in England; major topics discussed include the role of structures in disintegration, mineralogical influences (clay minerals, pyrites, carbonates), the role of fabric in disintegration, and relationships to various rock types.

Townsend, F. C. and D. C. Banks, 1974, "Preparation Effects on Clay Shale Classification Indexes," Preprint Paper 2140, ASCE Water Resources Engineering Conference, Los Angeles, California, 31 pp.

A comparative laboratory investigation of sample preparation effects on Atterberg limits and grain size analyses; three major techniques were considered (undried, air dried, and blenderized); plastic limits were found to be relatively unaffected by technique; liquid limits and clay percentages decreased in the following order: blenderization (highest), air drying to undried (lowest).

Treworgy, C. G., L. E. Bengal, and A. G. Dingwell, 1978, "Reserves and Resources of Surface-Minable Coal in Illinois," Circular 504, Illinois State Geological Survey, Urbana, Illinois, 44 pp.

Summary of strippable coal reserves by county and unit in Illinois.

Underwood, L. B., 1967, "Classification and Identification of Shales," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM6, pp. 97-116.

A review of geologic/taxonomic classifications for shales; includes a review discussion of significant engineering properties of shales, including strength, modulus of elasticity, moisture/density/void ratio, permeability, swell potential, and activity ratio; also includes a discussion of in situ behavior evaluation (state of stress, slope stability, rebound, disintegration, and pore pressure).

U.S. Department of the Interior, Bureau of Mines, 1971, "Strippable Reserves of Bituminous Coal and Lignite in the United States," Information Circular 8531, USDI, Bureau of Mines, Washington, D.C., 148 pp.

Summary of strippable coal reserves in the United States. Included are breakdowns of reserves by state geologic unit and county as well as a general description of the physical setting by state.

Van Eeckhout, E. M., 1976, "The Mechanisms of Strength Reduction Due to Moisture in Coal Mine Shales," International Journal of Rock Mechanics and Mining Sciences, Vol. 13, pp. 61-67.

A theoretical investigation of moisture effects on shale strength with primary interest in deep mine roof failures; mechanisms considered include fracture energy reduction, capillary tension decrease, pore pressure increase, frictional reduction, and chemical and corrosive deterioration.

Van Eeckhout, E. M. and S. S. Peng, 1975, "The Effect of Humidity on the Compliances of Coal Mine Shales," International Journal of Rock Mechanics and Mining Sciences, Vol. 12, No. 11, pp. 335-340.

A theoretical and laboratory investigation of strength and compliance changes in shales with changes in humidity, with major interest in deep mine roof shales; Young's moduli values for dry specimens were two to three times those for wet specimens; mechanisms for shale breakage upon drying/contraction are summarized.

Wanless, H. R., 1975a, "Appalachian Region, Paleotectonic Investigations of the Pennsylvanian System in the United States, Part 1: Introduction and Regional Analysis of the Pennsylvanian System," Professional Paper 853-C, U.S. Department of the Interior, Geological Survey, Washington, D.C., pp. 17-62.

Geologic overview of the Pennsylvanian System in the Appalachian Basin. Gives thicknesses of various coal-bearing units.

Wanless, H. R., 1975b, "Illinois Basin Region, Paleotectonic Investigations of the Pennsylvanian System in the United States, Part 1: Introduction and Regional Analysis of the Pennsylvanian System," Professional Paper 853-E, U.S. Department of the Interior, Geological Survey, Washington, D.C., pp. 71-95.

Geologic description of the Pennsylvanian System in the Illinois Basin.

Wier, C. E. and H. H. Gray, 1961, "Geologic Map of the Indianapolis 1° x 2° Quadrangle, Indiana and Illinois, Showing Bedrock and Unconsolidated Deposits," Regional Geologic Map, Indianapolis Sheet, Scale 1:250,000, Indiana Department of Conservation, Geological Survey, Bloomington, Indiana.

Map showing geology of coal-bearing strata in Indiana.

Willman, H. B., J. C. Frye, J. A. Simon, K. E. Clegg, D. H. Swann, E. Atherton, C. Collinson, J. A. Lineback, and T. C. Buschbach, 1967, "Geologic Map of Illinois," State of Illinois, Department of Registration and Education, Illinois State Geological Survey, Urbana, Illinois.

Map showing areal extent of coal-bearing strata in Illinois.

Wilmoth, B. M. and P. E. Ward, 1968, "Ground-Water Hydrology of the Monongahela River Basin in West Virginia," River Basin Bulletin 1, West Virginia Geological and Economic Survey, 54 pp.

Provides description of Pennsylvanian units in the northern portion of West Virginia.

Wischmeier, W. H., C. B. Johnson, and B. V. Cross, 1971, "A Soil Erodibility Nomograph for Farmland and Construction Sites," Journal of Soil and Water Conservation, Vol. 26, No. 5, pp. 189-193.

A description of a technique useful for evaluating the soil erodibility factor for use in the Universal Soil Loss Equation; does not address the slaking process; procedure is based on grain size, organic matter content, and structural characteristics of the soil mass or soil aggregates.

APPENDIX A
TEST PROCEDURES

APPENDIX A
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APPENDIX A
TEST PROCEDURES

A.1.0 JAR SLAKE TEST

1. Scope

This test is intended to provide a qualitative and quantitative indication of the slake resistance of rock samples of various sizes soaked in two slaking fluids.

2. Apparatus

- (a) Jars or trays to contain the slaking fluids
- (b) A balance of adequate capacity to weight samples to an accuracy of 0.01 percent of the sample weight
- (c) An oven capable of maintaining a temperature of $110^{\circ}\text{C} \pm 3^{\circ}\text{C}$ for a minimum of 24 hours
- (d) Point load test apparatus
- (e) Standard sieves ranging in size from 2 inches (50.8 mm) to No. 200 (0.075 mm)
- (f) Camera

3. Procedure

- (a) Prepare a quantity of sample material in the following manner:
 - (1) From a ten pound sample of 1-1/2 to 2-inch (38 to 51 mm) diameter particles, conduct three point load tests on randomly selected samples prior to immersion. If bedding or other structure is observed for the entire sample, three point load tests shall be performed both parallel and perpendicular to the observed structure. The initial water content of the coarse sample shall be obtained from the point load test samples.
 - (2) Using a 1,500 gram (3.3 pounds) sample of 3/4 to 1/4 inch (19 to 6 mm) size particles, place 1,000 grams (2.2 pounds) in a slake container. The remaining 500 gram (1.1 pound) sample is used for a moisture content determination. The test sample shall be composed of approximately 2/3 and 1/3 portions of 3/4 to 3/8 inch (19 to 10 mm) and 3/8 to 1/4 inch (10 to 6 mm) size particles respectively.

- (b) Immerse the samples with the slake fluid such that the fluid level is approximately 1/2 inch (13 mm) above the sample. Slaking fluids will consist of distilled water and ethylene glycol.
- (c) Observe the condition of the sample at several time intervals and note the condition of the sample. The time intervals shall be approximately 1/4, 1/2, 1, 2, 4, 8, and 24 hours following immersion and then daily for a total of five days after immersion. Condition of the sample will be classified as follows:

<u>Category</u>	<u>Behavior</u>
1	Degrades to a pile of flakes or mud
2	Breaks rapidly and/or forms many chips
3	Breaks slowly and/or forms few chips
4	Breaks rapidly and/or develops several fractures
5	Breaks slowly and/or develops few fractures
6	No change

- (d) Point load tests shall be performed on randomly selected 1-1/2 to 2-inch (38 to 51 mm) diameter samples at time intervals of 0, 2, and 24 hours following immersion and at five days following immersion. Three samples at each time interval shall be tested to obtain a quantitative relationship between the observed behavior and the strength-time behavior of individual particles based on the point load test results. If bedding or other structure is observed for the entire sample, three point load tests shall be performed both parallel and perpendicular to the observed structure.
- (e) Following point load testing, a water content determination shall be made for each individually tested sample.
- (f) At the conclusion of soaking, both the fine fraction and the remaining coarse fraction shall be wet sieved to obtain the grain size distribution of each sample to quantify the degree of breakdown. The moisture content for portions retained on each sieve shall be obtained so that the grain size distributions can be represented on a dry weight basis. Determine the degradation index using the initial and final grain size distributions.
- (g) Photographic documentation will include a record of the initial sample condition plus the sample condition at the conclusion of 1-, 3-, and 5-day soaking periods.

A.2.0 CYCLIC WET-DRY TEST

1. Scope

This test is intended to provide a qualitative and quantitative indication of the slake resistance of various sample sizes by subjecting the samples to alternating cycles of wetting and drying in two slaking fluids.

2. Apparatus

- (a) Open bottom or screened containers (e.g., colander)
- (b) Trays to contain the slaking fluids
- (c) Balance of adequate capacity to weigh samples to an accuracy of 0.01 percent of the total sample weight
- (d) An oven capable of maintaining a temperature of $110^{\circ}\text{C} \pm 3^{\circ}\text{C}$ for a minimum of 24 hours
- (e) Point load test apparatus
- (f) Standard sieves ranging from 2 inches (50.8 mm) to No. 200 (0.075 mm)
- (g) Camera

3. Procedure

- (a) Prepare a quantity of sample material in the following manner:
 - (1) From a ten pound sample of 1-1/2 to 2 inch (38 to 51 mm) diameter particles, conduct three point load tests on randomly selected samples prior to immersion. If bedding or other structure is observed for the entire sample, three point load tests shall be performed both parallel and perpendicular to the observed structure. The initial water content of the coarse sample shall be obtained from the point load test samples.
 - (2) Using a 1,500 gram (3.3 pounds) sample of 3/4 to 1/4 inch (19 to 6 mm) size particles, place 1,000 grams (2.2 pounds) in a screened container. The remaining 500 gram (1.1 pound) sample is used for a moisture content determination. The test sample shall be composed of approximately 2/3 and 1/2 portions of 3/4 to 3/8 inch (19 to 10 mm) and 3/8 to 1/4 inch (10 to 6 mm) size particles respectively.

- (b) Immerse the sample and screened containers in the trays containing the slaking fluid so that the fluid level is approximately 1/2 inch (13 mm) above the sample. The slaking fluids will consist of distilled water and a 50 percent solution of sodium sulfate.
- (c) The samples shall remain immersed in the slaking fluid for approximately eight hours. During this time, the sample condition will be observed at various time intervals and notes will be made of the general sample condition. The time intervals shall be approximately 1/4, 1/2, 1, 2, 4, and 8 hours, following immersion. Condition of the samples will be classified as follows:

<u>Category</u>	<u>Behavior</u>
1	Degrades to a pile of flakes or mud
2	Breaks rapidly and/or forms many chips
3	Breaks slowly and/or forms few chips
4	Breaks rapidly and/or develops several fractures
5	Breaks slowly and/or develops few fractures
6	No change

- (d) Remove the remaining samples from the soaking trays and oven dry for a minimum of 16 hours at 110°C +3°C. Observe and record the condition of the oven dried samples. Three point load tests shall be performed on randomly selected 1-1/2 to 2 inch (38 to 51 mm) diameter samples following the initial soaking cycle. If bedding or other structure is observed for the entire sample, three point load tests shall be performed both parallel and perpendicular to the observed structure.
- (e) Following point load testing, a water content determination shall be made for each individually tested sample.
- (f) Following oven drying and any additional testing, resubmerge all samples materials and follow step (c) above.
- (g) Repeat the cyclic wetting and drying and observations, as in (c), for a total of five cycles. Conduct point load tests on the coarse fraction as outlined in (d) above following the third and fifth wetting cycles.
- (h) Following the last drying cycle, the remaining sample material shall be drained for 15 minutes and then placed in an oven for a moisture content determination.

- (i) Following oven drying, a grain size analysis will be performed on both the remaining coarse fraction and the total fine fraction to determine the degree of sample deterioration during soaking. Determine the degradation index (DI) using the initial and final grain size distributions.
- (j) Photographic documentation will include a record of the initial sample condition plus the sample conditions at the conclusion of cycles 1, 3, and 5.

A.3.0 RATE OF SLAKING TEST

1. Scope

This test is intended to provide a quantitative measure and qualitative indication of the slake resistance of rock samples of various sizes soaked in water.

2. Apparatus

- (a) Open bottom or screened containers (e.g., colanders)
- (b) Filter paper or filter cloth
- (c) Trays to contain water
- (d) A balance of adequate capacity to weight samples to an accuracy of 0.01 percent of the sample weight
- (e) Two ovens: one capable of maintaining a temperature of $65^{\circ} +3^{\circ}\text{C}$ for a minimum of 24 hours, and a second capable of maintaining a temperature of $110^{\circ} \pm 3^{\circ}\text{C}$ for a minimum of 24 hours
- (f) Sieves ranging in size from 2 inch (50.8 mm) to No. 200 (0.075 mm)
- (g) Camera

3. Procedure

- (a) Prepare a quantity of sample material in the following manner:
 - (1) Using a 3 pound (1,360 Kg) sample of 1-1/2 to 2 inch (38 to 51 mm) diameter particles, place approximately 2 pounds (900 g) in a screened container lined with filter cloth. The remainder of the sample is used for a moisture content determination. Weigh individually the container, filter cloth and sample.
 - (2) Using a 1,500 gram (3.3 pounds) sample of 3/4 to 1/4 inch (19 to 6 mm) size particles, place 1,000 grams (2.2 pounds) of the sample in a screened container lined with filter cloth. The remainder of the sample is used for a moisture content determination. The test sample shall be composed of approximately 2/3 and 1/3 portions of 3/4 to 3/8 inch (19 to 10 mm) and 3/8 to 1/4 inch (10 to 6 mm) particles, respectively. Weigh individually the container, filter cloth and sample.

- (b) Submerge each sample in distilled water for two hours. At the end of soaking, remove the containers from the water and drain for 15 minutes. Weigh each container and dry to a constant weight (approximately 4 to 6 hours) at a temperature of 65°C.
- (c) Determine the dry sample container weight to obtain the water content of the sample.
- (d) Obtain a representative sample from both the coarse and fine fractions to obtain a water contents at 110°C.
- (e) Repeat steps (b) and (c) for an additional four cycles.
- (f) Following the completion of step (e), sieve both the coarse and fine fractions to quantify the degree of sample breakdown during testing. Determine the degradation index (DI) using the initial and final grain size distributions.
- (g) Photographic documentation will include a record of the initial sample condition plus the sample condition at the conclusion of cycles 1, 3, and 5.

4. Calculations

- (a) Determine the change of water content at 110°C and 65°C as follows:

$$\Delta w(110) = *w_i(110) - *w_{i-1}(110)$$

$$\Delta w(65) = w_i(65) - w_{i-1}(65)$$

where

$\Delta w(110)$ = Change of water content determined at 110°C,

$\Delta w(65)$ = Change of water content determined at 65°C,

$w_i()$ = Water content for Cycle i determined at temperature (),

$w_{i-1}()$ = Water content for Cycle (i-1; previous cycle) determined at temperature ().

A.4.0 COMPUTATIONAL PROCEDURE FOR DEGRADATION INDEX (DI)

1. Purpose

To quantify the deterioration of samples subjected to jar slake, cyclic wet/dry, and cyclic rate of slake durability tests. The procedure, as suggested by Bailey (1976), uses mean equivalent mesh sizes from sieving operations before and after slake testing as weighing factors to produce a degradation index which is a measure of the amount of sample breakdown.

2. Apparatus

- (1) A balance of adequate capacity to weight samples to an accuracy of 0.01 percent of the sample weight.
- (2) Standard sieves ranging in size from two inches (50.8 mm to No. 200 (0.075 mm)).

3. Procedure

- (a) Group series covering expected sample gradational range from largest to smallest.
- (b) Determine the mean equivalent mesh size for each group. The mean value is equal to the weighing factor for each sieve size group.
- (c) Conduct sieve analysis prior to testing. Multiply the percent retained for each group by the appropriate weighing factor. Sum the factored percents for each group to obtain the sum before (Σ_B).
- (d) Perform slake test.
- (e) Repeat Step 3 using the sample remaining following slake testing. Multiply the percent retained on each sieve by the corresponding weighing factor and sum the factored percents retained to obtain the sum after (Σ_A).
- (f) Compute the degradation index (DI).

4. Calculation

$$\text{Degradation Index (DI)} = \frac{\Sigma_B - \Sigma_A}{\Sigma_B} = (\%)$$

A.5.0 PREPARATION OF CRUSHED ROCK SAMPLES FOR MATERIAL IDENTIFICATION TESTS

1. Crush rock samples at the natural moisture content using a rock pulverizer. The time of crushing will depend on the characteristics of the sample but will typically be less than five minutes.
2. Sieve the pulverized sample through a No. 60 sieve (0.250 mm). Sample that is retained shall be reprocessed until the grain size is less than 0.250 mm. Sample materials can then be split for further processing for physical-chemical and mineralogical testing.
3. Mix 200 grams of sample material for physical-chemical testing (Atterberg limits and sieve-hydrometer analysis) with 250 ml of distilled water and blenderize for 10 minutes. Place the solution in a plastic container, seal, and agitate for a 24-hour period. Blenderize the solution for an additional 10 minutes and then place the entire solution in an open evaporating dish and dry in an oven at 65°C until the slurry has the consistency of a thick paste. The thickened paste can then be placed in sealed containers until required for testing.
4. Sample material for mineralogical and pH testing shall be air dried and then pulverized until the particle size is less than a No. 200 sieve (0.074 mm). The crushed sample shall then be placed in a sealed container until required for testing.

A.6.0 METHYLENE BLUE ABSORPTION TEST (MBA)
(NETTLETON, 1974)

1. Scope

This test is intended to provide an indirect measure of the equivalent surface area and the cation exchange capacity of crushed natural and weathered rock samples.

2. Apparatus

- (a) A rock crushing device capable of pulverizing rock samples to sizes passing a No. 200 sieve (0.074 mm)
- (b) A balance of adequate capacity to weigh to an accuracy of 0.01 percent of the sample weight
- (c) An oven capable of maintaining a temperature of $110^{\circ}\text{C} \pm 3^{\circ}\text{C}$ for a minimum of 24 hours
- (d) Sealed bottles with a capacity of 100 ml
- (e) Beaker of 100 ml capacity
- (f) Whatman No. 1 filter paper
- (g) Thin diameter glass rod
- (h) 50 cc titration burette

3. Procedure

- (a) A crushed, dried 10-gram sample is placed in a sealed bottle with 30 ml of distilled water to provide a 33% suspension.
- (b) The suspension is agitated in a high-frequency flask agitator for 15 minutes.
- (c) The suspension is allowed to settle for 24 hours at room temperature prior to absorption testing.
- (d) The settled suspension is then acidified with 1 cc of 5N sulfuric acid to sharpen the titration end point.
- (e) The acidified suspension is then diluted to a 10% solution by adding distilled water.
- (f) The suspension is titrated using a 0.005N solution of methylene blue trihydrate dye (prepared by dissolving 1.870 grams of dye powder $[\text{C}_{16}\text{H}_{18}\text{N}_3\text{SCl} \cdot 3\text{H}_2\text{O}]$ in 1 liter of distilled water.

- (g) Spot tests are conducted by placing a small drop of titrated slurry from the end of a glass rod onto the filter paper and observing the results. Spot tests are conducted for every 1 cc of titration and following a 20-second mixing period.
- (h) The end point is indicated when excess dye appears as a sky blue color radiating from the normally darkly colored center point. The end point is then confirmed by observing an identical coloration from a second tests, two minutes after the initial test.

4. Calculation

- (a) The methylene blue absorption index M.B.A. in meq/100 gms of dry soil is computed by:

$$\text{M.B.A.} = \frac{100}{W} \times T \times N$$

where:

- W = dry weight of the soil sample (gms)
- T = volume of titrant (cc)
- N = normality of dye (meq/cc).

Additional Reference: ASTM, Part 17, 1977

A.7.0 POINT LOAD TEST

1. Scope

This test is intended to establish the point load strength of irregularly shaped rock fragments and/or using rock core. The procedure outlined below is for the specific device pictured in Figure 8.3. Other procedures may be required for other devices.

2. Apparatus

Field

- (a) Point load tester
- (b) Moisture proof sample containers

Laboratory

- (a) Point load tester
- (b) A balance of adequate capacity capable of weighting to an accuracy of 0.01 percent of the sample weight
- (c) An oven capable of maintaining a temperature of $110^{\circ}\text{C} \pm 3^{\circ}\text{C}$ for a minimum of 24 hours

3. Procedure

- (a) Select a representative sample for testing. By definition, the sample diameter (D) is the dimension across which failure occurs. The sample length (L) is then the dimension perpendicular to the diameter. If an irregularly shaped sample is used, the diameter should equal 2 inches $\pm 1/2$ inch (51mm ± 13 mm) and have a diameter to length ratio (D/L) ranging from 1.0 to 1.4. For regularly shaped or cored samples, the following criteria are used: axial tests (i.e., load applied parallel to the long direction), D/L equals 1.1 ± 0.05 ; diametral tests, $L > 0.7D$, with the test conducted at midlength of sample.
- (b) The first step for using the point load tester is to fully extend the hydraulic screw piston (upper platen).
- (c) Adjust the lower platen using the handwheel screw. Use the vernier scale to obtain the zero reading and (V_0) and record.
- (d) Loosen the lower platen until the test specimen can be inserted between the platens. Tighten the lower platen until the specimen is held firmly in contact (but subjected to no load) between the platens. Use the vernier scale to obtain the initial vernier reading (V_i). The sample diameter equals the initial reading minus the zero reading.

- (e) Reset the peak load indicator against the gage indicator hand.
- (f) Screw in the upper platen using the hydraulic screw piston until the sample fails. Record the failure load using the peak load indicator reading.
- (g) If the test is conducted in the field, place the failed specimen in a labeled moisture-proof container.
- (h) Determine the water content of the sample in the laboratory.

4. Calculations

- (a) Initial diameter (D_i) = initial vernier reading (V_i) - zero vernier reading (V_0)
- (b) Force at failure (P) = pressure reading (psig) x 5 in² (piston area)
- (c) Point load index (I_g) = P/D^2

List of References

Franklin (1970); Broch and Franklin (1972).