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16. Abstract

A criterion for anticipating the performance of shales in embankments according to simple slaking indexes is presented. The basis for this criterion is information on service performance of numerous highway embankments of generally known construction in relation to the slake-durability index or jar-slake index of associated shales. This evaluation procedure is offered for further study and field trial at the state level.

This volume is the third in a series. The others in the series are:

Volume	FHWA No.	Title
1	RD-75-61	Survey of Problem Areas and Current Practices
2	RD-75-62	Evaluation of Remedial Treatment of Compacted Shale Embankments

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PREFACE

The study, "Design and Construction of Compacted Shale Embankments," is a project being conducted by the Soils and Pavements Laboratory (S&PL), U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, for the Federal Highway Administration (FHWA). This report on slaking indexes was prepared as a part of that project by Dr. R. J. Lutton, Engineering Geology and Rock Mechanics Division (EGRMD), S&PL. Mr. W. E. Strohm, Jr., EGRMD, is project coordinator and Mr. A. F. DiMillio, Materials Division, FHWA, is contract manager. Chief of EGRMD, S&PL, is Mr. D. C. Banks, and Mr. J. P. Sale is Chief, S&PL.

Mineralogical examinations and their interpretation were provided by Mr. G. S. Wong, Concrete Laboratory, WES. Personnel of the state highway organizations of Arizona, Colorado, Indiana, Kansas, Kentucky, Montana, New Mexico, Oklahoma, Ohio, South Dakota, Tennessee, Texas, Utah, Virginia, West Virginia, and Wyoming provided valuable information for the study and assistance in obtaining shale samples.

Directors of the WES during the conduct of this study and the preparation of the report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
angstroms	1×10^{-10}	metres
tons (2000 lb, mass)	907.1847	kilograms

DESIGN AND CONSTRUCTION OF COMPACTED SHALE EMBANKMENTS

SLAKING INDEXES FOR DESIGN

PART I: INTRODUCTION

1. Shale* is often among the most troublesome materials for construction of highway embankments by virtue of its weakness in comparison with other rocks and the possible further deterioration of its low strength over the service life of the embankment. It follows that treatment of shale as rock in embankments can result in costly failures. Conversely, not all shale has such adverse characteristics. Some instead may hold up quite satisfactorily over a long term and can be treated as rock. Consequently, fixed conservative design and construction procedures might be unnecessarily costly. The Indiana State Highway Commission, following research by Purdue University,[1] now uses a slake-durability test procedure to help determine whether shale will be compacted in embankments as soil (maximum 8-in.** loose lifts) or in much thicker lifts as rock. Such indexes distinguishing the degree of durability show promise of being even more useful in the future. This report examines shales collected on a nationwide basis and relates their slaking characteristics to the construction and performance of associated embankments.

Background

2. The work covered in this report is a part of a comprehensive study of compacted shale embankments undertaken by the U. S. Army Engineer Waterways Experiment Station for the Federal Highway Administration. The scope of the overall study is outlined in Table 1. The first year's

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* Unless otherwise noted, the term "shale" in this report refers to all weak fine-grained, sedimentary rocks such as claystone, mudstone, and siltstone.

** A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page vi.

Table 1

Scope of Research Study and Schedule

PHASE I - IDENTIFICATION OF FACTORS RESPONSIBLE FOR THE DETERIORATION OF COMPACTED SHALES
(FY 1975, Vol. 1)

Task A

1. Review existing literature and reports pertinent to compaction and performance of compacted shale mixtures in embankments.
2. Contact Federal and State agencies concerned with highway construction in areas where problems have been encountered for the purpose of identifying the sources of the problem and discussing, as well as describing, the state-of-the-art design, construction, maintenance, and remedial treatment of compacted shale embankments.

Task B

1. Identify the geologic, stratigraphic units and the specific geographic localities of shales that have caused problems in compacted embankments.
2. Accomplish preliminary identification and validation of the intrinsic and extrinsic factors and combinations of these factors causing the problems.

Task C

Perform field and laboratory study to determine the probable natural variability of intrinsic properties of stratigraphic units of shales of different geologic ages that have caused problems to embankments.

PHASE II - STABILITY EVALUATION AND REMEDIAL TREATMENT OF EXISTING EMBANKMENTS
(FY 1975, Vol. 2)

Task A

Review and evaluate available experience on appropriate methods for evaluating the stability of existing compacted shale embankments.

Task B

Review and evaluate available experience on appropriate methods for remedial treatments of existing embankments.

PHASE III - DEVELOPMENT OF DESIGN CRITERIA AND CONSTRUCTION CONTROL TECHNIQUES
(FY 1976-1978)

Task A

Develop, evaluate, and recommend the appropriate shale sampling program for obtaining embankment design data and preparation of compaction specifications.

Task B

Develop new index tests or improve existing tests and evaluate them as techniques for obtaining compaction specifications for shale mixtures.

PHASE III (continued)

Task C

Develop, evaluate, and recommend an appropriate laboratory specimen preparation methodology, a laboratory compaction methodology, and a laboratory testing technique for determination of shear strength and compressibility properties of compacted shale mixtures for the end-of-construction condition of the compacted shale mixture. These are to be used when:

1. The grain-size distribution of the laboratory specimen approximates that of the compacted shale mixture in the embankment.
2. The particles in the laboratory specimen are substantially smaller than particles in the compacted shale mixture in the embankment.

Task D

1. Develop a methodology for evaluation of the end-of-construction shear strength and compressibility of the shale mixtures compacted in test strips.
2. Conduct field tests to evaluate methodology developed in D-1 above.

Task E

Develop, evaluate, and recommend tests to quantitatively evaluate the long-term strength and compressibility properties for compacted shale mixtures for specimens prepared and compacted either in the laboratory or in a field test strip.

Task F

Develop, evaluate, and recommend a methodology to use for extrapolating the laboratory preparation and compaction techniques to field compaction specifications for shale mixtures and also a field compaction control methodology. These are to be used when:

1. The grain-size distribution of the laboratory specimen approximates that of the compacted shale mixture in the embankment.
2. The particles in the laboratory specimen are substantially smaller than particles in the compacted shale mixture in the embankment.

Task G

Evaluate and make recommendations concerning the effectiveness of different kinds of pretreatment techniques and compaction equipment for compaction of different types of shales.

Task H

Review, evaluate, and condense results of other tasks to provide detailed guidance and recommended methodology for the following:

1. Determining the design strength and compressibility parameters from test data.
2. Performing the stability analysis.
3. Selecting design features.

effort in FY 1975 produced two reports[2,3] that reviewed generally the problems, practice, evaluation, and remedial treatment of shale embankments. The present portion of the study falls under Phase III, Task B, in Table 1 and concerns index tests that show promise in distinguishing deteriorating shales from durable shales.

Purpose of Study (Task B)

3. The purpose of this task was to develop a procedure for simply indexing any shale for valid predictions of the behavior of that shale in highway embankments. With the capability of predicting behavior, certain aspects of highway embankment design and construction can be planned on new highway projects for improved embankment service. Establishing useful design procedures was thus an important associated purpose of the task.

Scope of Report

4. This report outlines the task investigation and its findings and recommends a testing procedure for indexing shales for purposes of highway embankment evaluation and design. Because emphasis has been given to presentation of results in a timely manner, evaluation of the recommended procedure by extensive on-the-job trial is not yet complete, though field experiences were used in its development. In fact, individual state highway departments may want to modify or supplement the evaluation procedure for their own local shales and construction methods.

5. Of particular value to this study is the collection of construction and service information assembled from state highway departments. These data on existing embankments are mostly new information gathered specifically for this task and closely tied to the sampling and testing program. The combination of test data on shales and construction and performance experience from embankments constructed of the same material provided the basis for developing the shale indexing criteria.

Evaluation of Problem

6. During the conduct of Phase I investigations,[2,3] a definition of specific problems in compacted shale embankments was developed. The following five classes of problems within embankments are proposed in view of Phase I reviews and subsequent discussions with highway department personnel.

- a. Short-term settlement of embankment.
- b. Long-term, continued slow settlement of embankment.
- c. Small, but serious, settlement of bridge approach embankment.
- d. Deep-seated shear failure within the embankment.
- e. Relatively shallow slide along the side slope of embankment.

7. At the start of the task, the scope was defined to include embankment problems only and not those resulting from the foundation. Consequently, highway departments were specifically queried about problems thought to be localized within embankments only. In some states, this limitation reduced the number of pertinent cases drastically, particularly in shear failure type problems which often began with weakness in the foundation.

8. Some consideration was devoted to the likelihood that embankment settlement problems and shear failures are directly related. Although a coherent picture of gradual internal breakdown and settlement and later reduction of shear strength to the point of failure is an attractive hypothesis, very little subsurface data are available to develop this concept. Therefore, most of the effort in this task has been directed to cases of settlement. Cases described as involving shear problems are included in the working data, but they may or may not be directly comparable.

9. Unfortunately, the documentation of fill settlement is usually not thorough unless the fill is located adjacent to a structure such as a bridge where even minor differential settlement will be critical. Minor short-term settlement is to be expected in cut-and-fill

embankments, and settlement measurements are not usually made. This suggests that a fruitful field for further study is in quantifying the minor settlement that will occur in satisfactory embankments. Such research would help to refine the conclusions of the present study, but until such time as permissible settlement has been quantified, the broad degrees of settlement in this report should remain useful.

10. The consensus that developed from interviews with highway department personnel and from the prevailing concept of shale deterioration is that settlement and eventual shearing occur as a result of intake of moisture by intact shale pieces and consequential sloughing of shale fragments to fill interfragmental voids and reduce overall volume. This incidentally impedes drainage and aggravates the process. The process of breakdown may take place during lift-by-lift construction or it may develop slowly over a period of years while the embankment is in service.

11. Where deterioration takes place rapidly, material should be treated and compacted as soil, with or without extra prewetting, disking, and working. The problem of long-term deterioration is less obvious, yet serious, and was basically the target of this study. The test procedures outlined in Part III were chosen to simulate on an accelerated scale the process of deterioration in the embankment. The samples selected for the study are described in Part II; they were selected to cover the entire range of shale types and geological ages.

Data Collection

12. Data for this report were obtained by field sampling and observations and by requests to highway departments. Selection of shale samples required special care to obtain groups of fresh samples representative of each formation. The key information on performance of associated embankments was developed in coordination with state highway departments but was still difficult to assemble. Necessary, detailed information on as-built conditions was often not available in records.

13. The best sources of information were commonly the former

project engineers or their assistants. Many of these individuals had progressed to new positions in the highway departments or private construction, or had retired, and locating them usually required considerable persistence. In view of the useful results obtained from this approach, however, it seems that experience data collection should be continued in the future, at least at the state level.

PART II: SAMPLE SELECTION AND FIELDWORK

14. A major part of the Task B field effort was directed towards sampling and describing various stratigraphical settings for shale and examining variability of intrinsic properties of shales. Numerous shale units were sampled, ranging in geological age from Precambrian to Tertiary. The collection of 158 samples is listed and briefly described in Table 2. Tables 3 and 4 present associated test and mineralogical data which are discussed later.

Distribution of Shales

15. The samples for study and the number obtained within broad age and location groups are as follows:

Geologic Age	Location	Number
Tertiary	Wyoming	4
Tertiary	Eastern Colorado	3
Cretaceous	Montana, Wyoming, South Dakota	8
Cretaceous	Utah, Western Colorado	17
Cretaceous	Central Colorado	8
Cretaceous	Eastern Colorado, Oklahoma, Kansas	14
Jurassic	Utah	3
Triassic	Utah	5
Triassic	Arizona	2
Permian	Oklahoma	1
Pennsylvanian	Oklahoma	2
Pennsylvanian	West Virginia	1
Pennsylvanian	Tennessee	6
Pennsylvanian	Western Kentucky	7
Pennsylvanian	Eastern Kentucky	5
Mississippian	Oklahoma	1
Mississippian	Indiana	7
Mississippian	Western Kentucky	2
Mississippian	Eastern Kentucky	3
Mississippian	West Virginia	7
Mississippian	Ohio	1
Devonian	Kentucky, Tennessee, Ohio, Oklahoma	5
Devonian	Virginia	3
Silurian	Oklahoma	1
Silurian	Eastern Kentucky	3
Silurian	Western Kentucky	3
Ordovician	Kentucky, Indiana, Ohio	19
Ordovician	Virginia	1
Ordovician	Oklahoma	1
Ordovician	Tennessee	1
Cambrian	Tennessee	13
Precambrian	Montana	1

Table 2

Shale Sample Descriptions

Shale Number	Water Content percent	Color	Structure	Fragment Shape	Texture*	Formation	Geological Age
				Kentucky			
KY 1	8.8	Greenish gray	Bedded	Platy	Silty	Osgood	Silurian
KY 2	12.6	Greenish gray	Bedded	Small pieces	Soft, sandy	Osgood	Silurian
KY 3	18.7	Yellowish gray	Indistinct	Irregular	Soft clay	Osgood	Silurian
KY 4	4.1	Brownish black	Thinly fissile	Platy	--	New Albany	Devonian
KY 5	9.5	Greenish gray	Indistinct	Pebbles	--	New Providence	Mississippian
KY 6	4.1	Medium gray	Laminated	Tabular	Siltstone	New Providence	Mississippian
KY 7	3.5	Olive gray	Faintly bedded	Thinly platy	Sandy	Tradewater	Pennsylvanian
KY 8	13.6	Brownish gray	Indistinct	Irregular	--	Tradewater	Pennsylvanian
KY 9	12.9	Medium gray	Indistinct	Irregular	Soft, silty	Tradewater	Pennsylvanian
KY 10	12.4	Medium yellowish brown	Indistinct	Blocky	Silty	Tradewater	Pennsylvanian
KY 11	6.5	Medium gray	Indistinct	Platy	--	Tradewater	Pennsylvanian
KY 12	7.8	Olive black	Laminated	Thinly platy	Silty	Tradewater?	Pennsylvanian
KY 13	9.9	Medium dark gray	Indistinct	Tabular	--	Tradewater?	Pennsylvanian
KY 14	5.9	Dark greenish gray	Indistinct	Platy	--	Crab Orchard	Silurian
KY 15	10.9	Greenish gray	Fissile	Tabular	Silty	Crab Orchard	Silurian
KY 16	13.7	Greenish gray	Faintly bedded	Blocky	--	Crab Orchard	Silurian
KY 17	18.6	Greenish gray	Indistinct	Blocky	Silty	Preacherville	Ordovician
KY 18	3.0	Brownish black	Thinly fissile	Platy	--	New Albany	Devonian
KY 19	6.0	Greenish gray	Fissile	Platy	Siltstone	Nada	Mississippian
KY 20	5.1	Dark gray	Indistinct	Thinly platy	--	Breathitt	Pennsylvanian
KY 21	5.3	Greenish gray	Indistinct	Tabular	Silty	Nada	Mississippian
KY 22	5.5	Dark reddish brown	Fissile	Thinly platy	Siltstone	Crider Clay	Pennsylvanian
KY 23	8.0	Dark greenish gray	Fissile	Tabular	--	Crider Clay?	Pennsylvanian
KY 24	4.4	Dark greenish gray	Indistinct	Platy	Silty	New Providence	Mississippian
KY 25	8.4	Greenish gray	Faintly bedded	Blocky	--	Kope	Ordovician
KY 26	12.1	Greenish gray	Indistinct	Prismatic	--	Kope	Ordovician
KY 27	7.5	Greenish gray	Indistinct	Tabular	--	Kope	Ordovician
KY 28	11.4	Dark greenish gray	Indistinct	Prismatic	--	Kope	Ordovician
KY 29	8.2	Greenish gray	Faintly bedded	Blocky	--	Kope	Ordovician
KY 30	6.3	Dark greenish gray	Faintly bedded	Blocky	--	Kope	Ordovician
KY 31	--	Dark gray	Indistinct	Irregular	--	Breathitt	Pennsylvanian
KY 32	--	Olive black	Fissile	Platy	--	Breathitt	Pennsylvanian
				Tennessee			
TN 1	7.6	Yellowish gray	Indistinct	Platy	--	Pumpkin Valley	Cambrian
TN 2	3.9	Greenish gray	Indistinct	Tabular	Siltstone	Nolichucky	Cambrian
TN 3	10.8	Light olive gray	Indistinct	Tabular	Silty	Nolichucky	Cambrian
TN 4	11.9	Light olive gray	Indistinct	Tabular	--	Nolichucky	Cambrian
TN 5	7.8	Pale yellowish brown	Indistinct	Platy	--	Nolichucky	Cambrian
TN 6	6.8	Light olive gray	Indistinct	Blocky	Silty	Nolichucky	Cambrian
TN 7	12.5	Yellowish gray	Faintly bedded	Tabular	Silty	Nolichucky	Cambrian
TN 8	11.2	Pale yellowish brown	Indistinct	Tabular	--	Nolichucky	Cambrian
TN 9	7.7	Grayish orange pink	Indistinct	Prismatic	Silty	Nolichucky	Cambrian
TN 10	10.2	Pale yellowish brown	Indistinct	Platy	--	Nolichucky	Cambrian
TN 11	8.3	Light olive gray	Laminated	Tabular	Silty	Nolichucky	Cambrian
TN 12	--	Medium bluish gray	Bedded	Platy	Sandy	Rome	Cambrian
TN 13	1.2	--	--	--	--	Rome	Cambrian
TN 14	4.8	Medium dark gray	Faintly bedded	Irregular	--	Redoak Mountain	Pennsylvanian
TN 15	--	Olive black	Bedded	Tabular	Siltstone	Redoak Mountain	Pennsylvanian
TN 16	--	Medium dark gray	Indistinct	Tabular	Siltstone	Graves Gap	Pennsylvanian
TN 17	3.3	Medium dark gray	Indistinct	Irregular	--	Cross Mountain	Pennsylvanian
TN 18	--	Olive black	Thinly fissile	Platy	--	Chattanooga	Devonian
TN 19	--	Medium dark gray	Faintly bedded	Platy	Sandy	Sevier	Ordovician
TN 20	--	Medium dark gray	Bedded	Tabular	Sandy	Slatestone	Pennsylvanian
TN 21	--	Medium dark gray	Bedded	Irregular	Silty	Slatestone	Pennsylvanian
				Ohio			
OH 1	8.1	Dark greenish gray	Indistinct	Prismatic	Silty	Fairview	Ordovician
OH 2	--	Dark greenish gray	Faintly bedded	Irregular	--	Kope	Ordovician
OH 3	--	Greenish gray	Indistinct	Tabular	--	Kope	Ordovician
OH 4	--	Greenish gray	Indistinct	Tabular	Silty	Elkhorn	Ordovician
OH 5	--	Grayish red	Faintly bedded	Prismatic	--	Elkhorn	Ordovician
OH 6	--	Dark yellowish brown	Indistinct	Blocky	--	Bedford	Mississippian
OH 7	--	Brownish black	Faintly fissile	Platy	--	Ohio	Devonian
OH 8	--	Dark greenish gray	Indistinct	Tabular	--	Kope	Ordovician
OH 9	--	Greenish gray	Indistinct	Tabular	--	Kope	Ordovician

(Continued)

Note: ? = Tentative formation identification.
* Texture other than shaly.

(Sheet 1 of 3)

Table 2 (Continued)

Shale Number	Water Content percent	Color	Structure	Fragment Shape	Texture	Formation	Geological Age
			Indiana				
IN 1	--	Greenish gray	Faintly bedded	Tabular	Limestone	Whitewater	Ordovician
IN 2	--	Dark greenish gray	Indistinct	Irregular	--	Dillsboro	Ordovician
IN 3	--	Medium dark gray	Laminated	Tabular	Sandy	Palestine	Mississippian
IN 4	--	Medium dark gray	Fissile	Irregular	--	Palestine	Mississippian
IN 5	--	Dark greenish gray	Faintly bedded	Tabular	--	Kope	Ordovician
IN 6	--	Dark gray	Laminated	Irregular	Silty	Palestine	Mississippian
IN 7	--	Medium dark gray	Faintly bedded	Tabular	--	Palestine	Mississippian
IN 8	--	Medium dark gray	Faintly bedded	Tabular	Sandy	Palestine	Mississippian
IN 9	--	Dark greenish gray	Indistinct	Irregular	--	Dillsboro	Ordovician
IN 10	--	Dark gray	Finely laminated	Platy	--	Palestine	Mississippian
IN 11	--	Dark gray	Well bedded	Irregular	Silty	--	Mississippian
IN 12	--	Greenish gray	Faintly bedded	Irregular	Sandy	Dillsboro	Ordovician
			Virginia				
VA 1	--	Dark gray	Laminated	Tabular	Siltstone	Brallier	Devonian
VA 2	--	Dark gray	Bedded	Tabular	--	Millboro	Devonian
VA 3	--	Medium dark gray	Indistinct	Tabular	--	Millboro	Devonian
VA 4	--	Medium dark gray	Fissile	Platy	--	Edinburg	Ordovician
			West Virginia				
WV 1	--	Blackish red	Indistinct	Irregular	--	Conemaugh (Clarksburg)	Pennsylvanian
WV 2	--	Light olive gray	Well bedded	Tabular	Siltstone	Hinton	Mississippian
WV 3	--	Grayish red	Indistinct	Irregular	Silty	Hinton	Mississippian
WV 4	--	Light olive gray	Indistinct	Tabular	--	Hinton	Mississippian
WV 5	--	Olive gray	Indistinct	Tabular	--	Hinton	Mississippian
WV 6	--	Brownish black	Laminated	Tabular	--	Hinton	Mississippian
WV 7	--	Pale brown	Laminated	Irregular	Sandstone	Hinton	Mississippian
WV 8	--	Medium dark gray	Indistinct	Irregular	Silty	Hinton	Mississippian
			Colorado				
CO 1	--	Olive gray	Indistinct	Irregular	Siltstone	Raton	Cretaceous
CO 2	--	Olive black	Faintly bedded	Irregular	Silty	Vermejo	Cretaceous
CO 3	--	Medium dark gray	Indistinct	Irregular	Sandy	Pierre	Cretaceous
CO 4	--	Olive gray	Indistinct	Irregular	Silty	Poison Canyon	Tertiary
CO 5	--	Olive black	Indistinct	Irregular	Silty	Pierre	Cretaceous
CO 6	--	Dark gray	Fissile	Tabular	--	Raton	Tertiary
CO 7	--	Brownish black	Indistinct	Irregular	Silty	Vermejo	Cretaceous
CO 8	--	Brownish black	Bedded	Tabular	Siltstone	Vermejo	Cretaceous
CO 9	--	Olive black	Indistinct	Irregular	--	Pierre	Cretaceous
CO 10	--	Brownish black	Fissile	Platy	--	Benton	Cretaceous
CO 11	--	Olive gray	Indistinct	Irregular	Silty	Pierre	Cretaceous
CO 12	--	Brownish black	Faintly laminated	Irregular	Silty	Pierre	Cretaceous
CO 13	--	Dark gray	Indistinct	Irregular	--	Pierre	Cretaceous
CO 14	--	Dark gray	Faintly laminated	Irregular	Silty	Pierre	Cretaceous
CO 15	--	Brownish black	Well bedded	Irregular	Silty	Pierre	Cretaceous
CO 16	--	Brownish black	Faintly bedded	Irregular	--	Pierre	Cretaceous
CO 17	--	Dusky yellowish brown	Well bedded	Irregular	Silty	Pierre	Cretaceous
CO 18	--	Brownish black	Bedded	Irregular	Silty	Pierre	Cretaceous
CO 19	--	Brownish black	Faintly bedded	Irregular	Silty	Pierre	Cretaceous
CO 20	--	Olive gray	Indistinct	Irregular	Silty	Mancos	Cretaceous
CO 21	--	Brownish gray	Faintly bedded	Tabular	Sandy	Mancos	Cretaceous
CO 22	--	Medium dark gray	Laminated	Irregular	Silty	Mancos	Cretaceous
CO 23	--	Olive gray	Well bedded	Platy	--	Mancos	Cretaceous
CO 24	--	Dark yellowish brown	Faintly bedded	Irregular	Silty	Pierre	Cretaceous
CO 25	--	Grayish brown	Fissile	Tabular	Silty	Laramie	Cretaceous
CO 26	--	Light olive brown	Indistinct	Irregular	Silty	Denver	Tertiary
			Utah				
UT 1	--	Brownish black	Faintly laminated	Platy	--	Mancos	Cretaceous
UT 2	--	Brownish gray	Faintly laminated	Tabular	Sandy	Mancos	Cretaceous
UT 3	--	Brownish black	Bedded	Tabular	Sandy	Mancos	Cretaceous
UT 4	--	Dark gray	Indistinct	Irregular	Clayey	Mancos	Cretaceous
UT 5	--	Medium grey	Laminated	Irregular	Silty	Mancos	Cretaceous

(Continued)

(Sheet 2 of 3)

Table 2 (Concluded)

Shale Number	Water Content percent	Color	Structure	Fragment Shape	Texture	Formation	Geological Age
			Utah (Continued)				
UT 6	--	Light bluish gray	Bedded	Blocky	Silty	Moenkopi	Triassic
UT 7	--	Greenish gray	Fissile	Platy	--	Moenkopi	Triassic
UT 8	--	Reddish brown	Bedded	Irregular	Siltstone	Moenkopi	Triassic
UT 9	--	Grayish red	Bedded	Irregular	Siltstone	Moenkopi	Triassic
UT 10	--	Olive gray	Faintly bedded	Irregular	--	Chinle	Triassic
UT 11	--	Medium dark gray	Indistinct	Irregular	--	Cedar Mountain	Cretaceous
UT 12	--	Dark grey	Faintly bedded	Irregular	Sandy	Mancos (Ferron)	Cretaceous
UT 13	--	Pale red	Indistinct	Irregular	--	Morrison	Jurassic
UT 14	--	Dark gray	Indistinct	Irregular	Silty	Mancos	Cretaceous
UT 15	--	Grayish red purple	Indistinct	Irregular	--	Morrison	Jurassic
UT 16	--	Blackish red	Indistinct	Tabular	Silty	Summerville	Jurassic
UT 17	--	Olive gray	Bedded	Irregular	Sandy	Mancos	Cretaceous
UT 18	--	Brownish black	Laminated	Tabular	Siltstone	Blackhawk	Cretaceous
UT 19	--	Brownish black	Faintly bedded	Platy	Siltstone	North Horn	Cretaceous
UT 20	--	Olive black	Bedded	Irregular	Silty	Mancos	Cretaceous
UT 21	--	Medium dark gray	Faintly bedded	Tabular	Silty	Mancos	Cretaceous
			Wyoming				
WY 1	--	Yellowish gray	Indistinct	Irregular	Siltstone	Wasatch	Tertiary
WY 2**	--	Very pale orange	Indistinct	Irregular	Silty	Wasatch	Tertiary
WY 3	--	Light olive gray	Indistinct	Platy	Silty	Cody	Cretaceous
WY 4**	--	Olive gray	Bedded	Platy	Silty	Cody	Cretaceous
WY 5	--	Yellowish gray	Indistinct	Irregular	Siltstone	White River	Tertiary
WY 6**	--	Yellowish gray	Indistinct	Irregular	Siltstone	White River	Tertiary
			Montana				
MT 1	--	Light olive gray	Fissile	Irregular	Silty	Carlile	Cretaceous
MT 2	--	Light olive gray	Bedded	Irregular	Silty	Carlile	Cretaceous
MT 3	--	Light brownish gray	Fissile	Irregular	Silty	Carlile	Cretaceous
MT 4	--	Olive gray	Faintly bedded	Tabular	Silty	Greenhorn	Cretaceous
MT 5	--	Olive black	Indistinct	Irregular	--	Bearpaw	Cretaceous
MT 6	--	Pale red purple	Bedded	Platy	Siltstone	Spokane	Precambrian
			Oklahoma				
OK 1	--	Grayish black	Faintly bedded	Tabular	--	Chattanooga	Devonian
OK 2	--	Medium dark gray	Faintly fissile	Platy	--	Atoka	Pennsylvanian
OK 3	--	Light olive gray	Indistinct	Irregular	Silty	Boggy	Pennsylvanian
OK 4	--	Dusky yellow green	Indistinct	Prismatic	--	Missouri Mtn	Silurian
OK 5	--	Grayish black	Fissile	Platy	--	Caney	Mississippian
OK 6	--	Pinkish gray	Fissile	Platy	Silty	Womble	Ordovician
OK 7	--	Medium dark gray	Faintly bedded	Tabular	Silty	Washita	Cretaceous
OK 8	--	Moderate reddish brown	Indistinct	Irregular	Silty	Hennessey	Permian
			Kansas				
KS 1	--	Olive gray	Fissile	Tabular	--	Blue Hill	Cretaceous
KS 2	--	Dark gray	Faintly fissile	Tabular	--	Graneros	Cretaceous
			Arizona				
AZ 1	--	Grayish red	Indistinct	Irregular	Silty	Chinle	Triassic
AZ 2	--	Medium dark gray	Indistinct	Irregular	Silty	Chinle	Triassic
			South Dakota				
SD 1	--	Light olive gray	Indistinct	Platy	--	Pierre	Cretaceous

** WY 2, 4, and 6 are apparently duplicates of WY 1, 3, and 5, respectively.

(Sheet 3 of 3)

Types of Shales

16. The following stratigraphical categories of shale formations were sampled and studied:

- a. Thick uniform shale.
- b. Shale interbedded with limestone.
- c. Shale with sandstone, siltstone, and coal.
- d. Shale with sandstone and siltstone but without coal.
- e. Carbonaceous black shale.

The categorization in this manner is given for most formations in paragraphs 49-88.

17. It has been pointed out by Shamburger, Patrick, and Lutton[2] that generalizations apply among the various categories of shale. Each category may have its own combination of properties and subtle characteristics that tends to set it apart from adjacent rock units and even other shale. On the other hand, certain variations appear to exist within each shale formation or category. In some cases, these variations are manifested in physical test results and elsewhere as subtle differences in mineralogy. For example, a series of samples of the troublesome Kope formation near Cincinnati exhibit a general trend of increasing slake durability and increasing calcite content with increasing depth.

18. Most of the examples for this study came from flat-lying strata that, except for age effects, have undergone approximately the same simple history since deposition. This selection of flat-lying units for sampling and testing was designed to exclude structurally or historically complex materials. The following samples were exceptions, coming from structurally complex areas where bedding was inclined appreciably and/or a degree of metamorphism had been imposed.

Sample No.	Geological Age
OK 2	Pennsylvanian
OK 5	Mississippian
WV 2-8	Mississippian
VA 1-3	Devonian
OK 4	Silurian

(Continued)

Sample No.	Geological Age
VA 4	Ordovician
OK 6	Ordovician
TN 19	Ordovician
TN 1-13	Cambrian
MT 6	Precambrian

Association with Embankment Problems

19. Emphasis throughout the sampling program was on materials known to have given problems at least locally in compacted shale embankments. However, numerous shale samples associated with no problems were also collected in the course of this study to provide a balance between problem and no-problem shales, but the sampled problem shales are still clearly more numerous than in proportion to their actual relative abundance. The manner of analysis of test results and correlation with highway embankment service has kept this bias from being detrimental. Thus, in Part V it is assumed that a different construction technique (e.g., smaller lift thickness) would have eliminated most of the problems associated with the sampled shales.

PART III: SAMPLE TESTING AND EXAMINATION

20. Numerous standard and nonstandard tests were critically reviewed[2] prior to initiation of index testing. Selections of tests to use were based upon the following factors: previous success, general acceptability, time requirements, costs, simplicity of procedure, and approximation to the inferred problem mechanism (paragraphs 7-11).

21. Samples were first described in a systematic manner to reveal any consistent differences in color, structure, fragment shape, and texture. Later, these samples were subjected to relatively simple indexing tests selected from those tests that alone or in combination approximate processes thought to be involved during shale breakdown in embankments. Selected samples were also carefully examined by X-ray diffraction analysis to provide a semiquantitative mineralogical composition, mineralogy being important to shale durability.

Sample Descriptions

22. Portions of one-third of the samples were sealed in jars in the field and subsequently tested for water content in the laboratory. Water that normally sweats out after removal of samples from the ground was retained in the jars, so these water contents are representative of field conditions. A complete set of water contents was determined later during the process of slake-durability indexing (Table 3). These water contents do not appear to differ substantially from field water contents despite the sample sweating that had occurred in the plastic sample bags between the time of sampling in the field and the laboratory determination.

23. Each sample was examined visually in the laboratory and described as follows in Table 2:

- a. Color was determined on a representative hand specimen according to the Munsell color system, and the nomenclature used in Table 2 is according to that system.
- b. The term "structure" refers to either bedding or fissility. The particular terms chosen for this description are intended to indicate the degree of intact fabric structuring.

Table 3

Shale Test Results

Shale Number	Water Content Before Test, percent 1	2	3	Avg	Jar-Slake Index Damp	Dry	Slake-Durability Index, percent 1	2	3	Avg	Scleroscope Index Parallel Damp	Parallel Dry	Perpendicular Damp	Perpendicular Dry	Test Water pH* Cycle 1	Cycle 2	Avg
									Kentucky								
KY 1	6.9	8.4	5.9	7.1	6	2	30	5	10	15	--	--	15	26	8.6	--	--
KY 2	21.1	19.6	--	20.3	3	1	11	6	--	9	--	--	--	--	9.0	9.4	9.2
KY 3	18.4	18.0	18.4	18.3	4	2	2	2	29	11	--	--	--	--	9.6	9.2	9.4
KY 4	4.1	4.7	3.2	4.0	6	6	99	99	99	99	25	29	40	54	6.8	4.5	5.6
KY 5	6.2	7.0	7.7	7.0	6	4	82	73	78	78	14	20	18	27	7.7	7.7	7.7
KY 6	3.6	3.5	3.0	3.4	5	6	92	93	95	93	24	27	--	--	9.3	9.0	9.2
KY 7	5.4	5.2	5.8	5.5	6	6	89	90	89	89	--	--	14	22	6.8	7.3	7.0
KY 8	17.0	8.3	8.2°	11.2	6	3	15	11	6	11	--	--	--	--	6.1	6.5	6.3
KY 9	7.2	7.7	--	7.5	5	1	0	0	--	0	--	--	10	21	3.0	--**	3.0
KY 10	11.8	12.3	10.9	11.7	6	4	62	48	47	52	12	18	--	20	6.7	6.3	6.5
KY 11	6.0	6.1	6.7	6.3	5	4	25	21	20	22	--	--	18	21	6.1	6.1	6.1
KY 12	6.4	--	--	6.4	6	6	84	--	--	84	--	--	--	--	7.8	7.2	7.5
KY 13	9.0	9.3	8.8	9.0	6	4	51	55	54	53	13	14	17	31	7.0	7.3	7.2
KY 14	3.1	2.7	4.1	3.3	6	5	70	84	42	65	--	--	14	--	8.1	8.2	8.2
KY 15	8.3	8.5	8.2	8.3	6	2	5	5	2	4	12	15	18	23	7.3	7.3	7.3
KY 16	15.3	15.9	13.2	14.8	6	1	0	0	0	0	11	14	--	--	7.6	7.1**	7.6
KY 17	6.6	7.1	7.1	6.9	6	1	1	1	1	1	14	17	18	26	8.6	-- **	8.6
KY 18	3.0	4.6	4.0	3.9	6	6	99	99	98	99	--	--	35	37	4.9	5.3	5.1
KY 19	4.4	4.7	4.5	4.5	6	6	95	93	96	95	--	--	22	43	7.4	7.5	7.4
KY 20	4.7	5.0	4.8	4.8	6	4	92	91	90	91	--	--	20	29	7.0	7.4	7.2
KY 21	5.4	5.1	4.3	4.9	6	5	78	88	94	87	22	--	22	26	7.8	7.8	7.8
KY 22	5.2	5.5	5.3	5.3	6	4	75	78	64	72	--	--	20	25	7.2	7.6	7.4
KY 23	8.0	9.4	8.4	8.6	6	1	9	2	6	6	13	--	17	32	9.2	7.0**	9.2
KY 24	4.7	4.6	4.3	4.5	6	4	76	72	73	74	--	--	20	32	8.1	8.4	8.2
KY 25	8.8	8.0	8.5	8.4	6	4	63	49	62	58	11	17	16	26	8.5	--	--
KY 26	8.4	8.3	8.5	8.4	5	5	59	60	37	52	10	14	16	27	8.6	8.4	8.5
KY 27	6.7	6.5	6.7	6.6	4	3	68	73	61	67	14	20	20	27	9.0	9.0	9.0
KY 28	10.5	10.6	11.1	10.7	6	1	28	26	22	25	13	15	17	25	8.8	8.6	8.7
KY 29	8.9	8.8	8.4	8.7	6	2	26	22	25	24	11	19	16	29	8.2	8.8	8.5
KY 30	5.6	5.9	5.8	5.8	6	4	17	17	19	18	17	22	22	25	7.4	8.7	8.0
KY 31	9.4	7.4	8.8	8.5	-	3	40	59	49	49	--	--	--	--	7.4	7.6	7.5
KY 32	6.2	5.9	--	6.1	-	6	92	91	--	91	--	--	--	--	--	--	--
									Tennessee								
TN 1	8.3†	5.2	7.1	6.2	6	6	41†	75	73	74	--	--	16	26	6.6	6.3	6.4
TN 2	3.2	3.0	3.1	3.1	6	5	93	92	93	93	25	32	--	--	6.9	6.8	6.8
TN 3	10.3	7.6	8.7	8.9	5	3	63	74	70	69	--	--	24	30	6.4	6.2	6.3
TN 4	10.3	10.3	10.2	10.3	6	3	55	56	54	55	15	24	16	33	6.3	5.6	6.0
TN 5	7.0	6.8	9.0	7.6	5	2	75	72	65	71	12	18	12	26	6.0	7.2	6.6
TN 6	3.9	4.0	5.4	4.4	6	5	84	89	86	86	17	25	--	--	6.5	6.6	6.6
TN 7	12.6	12.4	11.2	12.1	6	4	73	74	70	72	--	--	12	30	6.1	6.3	6.2
TN 8	9.7	9.7	11.3	10.2	5	5	83	84	85	84	12	17	15	30	5.8	5.8	5.8
TN 9	6.8	6.8	7.6	7.1	5	2	80	83	79	81	15	--	18	26	5.6	6.1	5.8
TN 10	8.6	8.7	9.7	9.0	6	3	49	43	34	42	16	22	24	40	6.1	6.2	6.2
TN 11	10.3	12.0	11.6	11.3	6	3	77	87	86	83	14	19	15	22	6.8	6.6	6.7
TN 12	1.7	2.1	1.6	1.8	6	5	80	78	86	81	--	--	13	13	6.8	6.9	6.8
TN 13	0.8	0.8	1.3	1.0	6	2	87	83	70	80	20	21	--	--	6.5	6.3	6.4
TN 14	5.8	6.0	5.3	5.7	6	5	46	49	33	43	15	21	16	20	4.2	6.3	5.2
TN 15	3.7	3.6	3.6	3.6	6	5	93	93	92	93	17	23	19	27	6.5	6.3	6.4
TN 16	3.4	3.3	3.7	3.5	6	5	89	91	88	89	18	25	25	28	7.7	6.6	7.2
TN 17	1.8	2.0	1.1	1.7	6	6	97	97	97	97	25	35	30	44	6.2	6.6	6.4
TN 18	0.6	0.6	0.4	0.5	6	6	99	99	99	99	30	38	40	45	5.6	6.1	5.8
TN 19	1.0	1.0	--	1.0	-	6	99	99	--	99	--	--	--	--	--	--	--
TN 20	3.0	3.1	--	3.1	6	6	96	96	--	96	--	--	--	--	--	--	--
TN 21	2.0	1.9	--	2.0	-	-	98	98	--	98	--	--	--	--	8.0	8.0	8.0
									Ohio								
OH 1	4.4	4.5	5.0	4.6	6	4	73	75	62	70	14	26	18	29	7.8	8.6	8.2
OH 2	7.1	7.1	8.0	7.4	6	4	3	2	24	10	12	17	18	28	8.6	8.7	8.7
OH 3	8.3	6.8	6.7	7.3	-	3	39	37	32	36	15	21	16	28	--	8.7	--
OH 4	3.4	3.3	3.6	3.4	4	3	52	59	69	60	--	--	--	--	6.5	--	--
OH 5	8.0	8.3	8.3	8.2	5	2	15	16	21	17	14	18	23	38	8.7	--	--
OH 6	9.2	8.4	8.7	8.8	-	3	50	71	63	61	13	18	17	25	--	8.2	--
OH 7	1.5	1.0	2.3	1.6	6	6	99	99	99	99	24	31	28	50	6.3	--	--
OH 8	7.4	7.6	7.7	7.6	6	2	40	21	13	24	--	--	--	--	7.0	7.9	7.5
OH 9	9.4	9.4	--	9.4	6	3	31	33	--	32	--	--	--	--	--	--	--

(Continued)

* pH of distilled water used in test was 5.3 to 6.8; pH of tap water was approximately 7.
** pH of cycle 2 insignificant because of small amount of material from cycle 1; disregarded in average.
† Anomalous material; disregarded in average.

(Sheet 1 of 3)

Table 3 (Continued)

Shale Number	Water Content Before Test, percent 1	2	3	Avg	Jar-Slake Index Damp	Dry	Slake-Durability Index, percent 1	2	3	Avg	Scleroscope Index Parallel Damp	Dry	Perpendicular Damp	Dry	Test Water pH Cycle 1	Cycle 2	Avg
Indiana																	
IN 1	1.5	1.1	2.2	1.6	6	6	96	98	95	96	--	--	--	--	8.5	8.1	8.3
IN 2	8.6	8.5	7.5	8.2	5	4	25	34	47	35	13	14	16	30	8.7	8.5	8.6
IN 3	2.1	2.1	2.0	2.1	5	6	87	87	93	89	--	--	27	34	6.6	6.6	6.6
IN 4	3.7	3.7	3.3	3.6	6	3	88	88	88	88	15	25	14	38	7.0	7.3	7.2
IN 5	7.2	8.6	11.8	9.3	6	4	46	36	31	38	13	17	14	25	--	--	8.2††
IN 6	4.7	5.0	4.8	4.8	6	5	76	82	77	78	20	24	16	27	6.7	7.2	7.0
IN 7	4.9	4.8	4.9	4.9	6	3	79	74	74	76	19	22	23	30	6.0	6.1	6.0
IN 8	4.8	4.9	4.8	4.8	4	3	81	79	76	79	18	20	20	31	6.8	6.3	6.6
IN 9	5.9	6.2	12.6	8.2	6	2	24	18	6	16	17	20	16	20	8.9	8.3	8.6
IN 10	5.3	5.8	5.6	5.6	6	2	20	17	21	19	15	23	15	33	6.3	6.7	6.5
IN 11	2.9	--	--	2.9	-	-	77	--	--	77	--	--	--	--	6.4	6.7	6.5
IN 12	7.3	6.2	--	6.8	6	2	10	6	--	8	--	--	--	--	--	--	--
Virginia																	
VA 1	1.0	0.8	1.5	1.1	6	6	98	98	98	98	33	40	39	51	4.5	4.6	4.6
VA 2	0.6	0.4	0.9	0.6	6	6	99	99	99	99	25	40	37	40	6.0	6.2	6.1
VA 3	1.3	1.3	1.5	1.4	6	5	97	98	97	97	--	35	44	--	5.1	5.3	5.2
VA 4	0.2	0.2	0.6	0.3	6	6	98	99	97	98	--	--	--	--	8.2	8.4	8.3
West Virginia																	
WV 1	3.7	2.8	4.2	3.6	-	1	3	7	6	6	--	--	--	--	7.2	7.1	7.2
WV 2	2.2	1.9	2.0	2.0	-	6	97	97	97	97	--	--	--	--	7.1	6.9	7.0
WV 3	3.9	4.1	3.9	4.0	-	2	50	50	52	51	--	--	--	--	6.9	6.8	6.9
WV 4	7.8	8.1	--	8.0	6	2	74	71	--	73	--	--	--	--	7.9	--	7.9
WV 5	8.1	7.6	--	7.8	6	2	52	59	--	56	--	--	--	--	7.9	8.0	8.0
WV 6	6.3	5.3	--	5.8	6	4	29	47	--	38	--	--	--	--	7.5	7.4	7.5
WV 7	7.9	7.7	--	7.8	6	6	86	88	--	87	--	--	--	--	7.5	7.6	7.5
WV 8	2.2	2.2	--	2.2	6	6	97	94	--	96	--	--	--	--	7.8	8.0	7.9
Colorado																	
CO 1	3.2	3.3	3.1	3.2	-	6	95	95	94	95	20	24	26	25	6.8	6.8	6.8
CO 2	7.3	7.6	7.1	7.4	-	2	35	31	59†	33	10	16	10	25	6.8	6.5	6.6
CO 3	3.7†	2.9	2.8	2.9	-	6	81†	95	95	95	29	44	16	31	8.7	8.9	8.8
CO 4	4.8	4.5	--	4.7	-	3	45	40	--	43	10	22	10	18	8.1	7.9	8.0
CO 5	5.0	4.1	3.8	4.6	-	5	69	85†	67	68	16	25	22	21	9.0	9.0	9.0
CO 6	7.0	6.8	--	6.9	5	1	14	21	--	18	10	19	15	25	9.1	9.0	9.1
CO 7	4.8	5.0	--	4.9	-	2	23	15	--	19	21	33	24	38	9.4	9.2	9.3
CO 8	4.4	4.5	--	4.5	-	4	67	72	--	70	19	25	--	20	7.1	7.6	7.4
CO 9	11.6	11.8	--	11.7	-	1	0	0	--	0	9	--	14	--	8.6	--**	8.6
CO 10	12.0	12.4	--	12.2	-	2	9	4	--	7	--	--	--	--	4.0	5.2**	4.0
CO 11	8.6	8.5	--	8.6	-	2	75	76	--	75	10	18	10	25	8.8	8.9	8.9
CO 12	2.0	1.9	--	2.0	6	5	95	95	--	95	18	20	19	34	7.6	7.7	7.7
CO 13	2.3	2.4	--	2.4	-	5	98	98	--	98	18	20	15	30	8.5	8.0	8.3
CO 14	2.3	2.3	--	2.3	-	5	98	98	--	98	19	26	18	30	8.2	8.7	8.5
CO 15	2.0	1.9	--	2.0	-	5	98	98	--	98	20	27	15	24	8.0	8.1	8.1
CO 16	1.9	1.7	--	1.8	-	5	98	98	--	98	20	26	20	28	9.1	7.3	--
CO 17	1.2	1.2	--	1.2	-	6	99	99	--	99	29	30	17	30	8.4	8.7	8.6
CO 18	1.4	1.6	--	1.5	-	6	99	99	--	99	25	29	20	36	8.3	8.4	8.4
CO 19	1.5	1.3	--	1.4	-	6	99	99	--	99	30	42	36	34	8.7	6.4	--
CO 20	9.5	9.2	--	9.4	-	1	0	0	--	0	9	15	17	20	9.5	9.0**	9.5
CO 21	1.6	1.6	--	1.6	-	6	97	97	--	97	21	26	27	35	9.3	9.2	9.3
CO 22	2.4	2.3	--	2.4	-	4	95	93	--	94	19	21	20	30	9.3	9.2	9.3
CO 23	9.0	8.3	--	8.6	-	2	22	19	--	20	--	--	--	--	7.9	8.4	8.2
CO 24	16.6	16.6	--	16.6	-	3	63	69	--	66	--	--	--	--	--	--	--
CO 25	22.2	23.0	--	22.6	-	1	0	0	--	0	--	--	--	--	--	--	--
CO 26	21.0	21.0	--	21.0	-	1	0	1	--	0	--	--	--	--	--	--	--
Utah																	
UT 1	3.2	3.4	--	3.3	-	4	97	97	--	97	15	23	16	32	8.7	9.4	9.1
UT 2	3.7	3.9	--	3.8	-	5	95	95	--	95	18	25	14	26	9.1	9.2	9.2
UT 3	3.3	3.4	--	3.4	-	6	96	95	--	95	15	25	16	33	9.3	9.4	9.4
UT 4	7.6	8.0	--	7.8	-	3	76	80	--	78	10	20	10	24	8.8	9.1	9.0
UT 5	2.1	2.0	--	2.1	-	5	97	97	--	97	15	25	20	28	9.3	9.4	9.4

(Continued)

** pH of cycle 2 insignificant because of small amount of material from cycle 1; disregarded in average.
† Anomalous material; disregarded in average.
†† Cycle not identified on one pH test.

(Sheet 2 of 3)

Table 3 (Concluded)

Shale Number	Water Content Before Test, percent 1	2	3	Avg	Jar-Slake Index Damp	Dry	Slake-Durability Index, percent 1	2	3	Avg	Scleroscope Index Parallel Damp	Dry	Perpendicular Damp	Dry	Test Water pH Cycle 1	Cycle 2	Avg
								Utah (Continued)									
UT 6	2.0	2.2	--	2.1	-	6	96	94	--	95	40	56	31	30	8.8	9.1	9.0
UT 7	3.5	3.4	--	3.5	-	3	69	73	--	71	12	21	17	26	8.4	8.8	8.6
UT 8	4.2	4.1	--	4.2	-	5	81	81	--	81	16	21	18	16	9.2	9.3	9.3
UT 9	1.2	1.5	--	1.4	-	5	85	90	--	88	20	22	22	30	9.3	9.4	9.4
UT 10	4.3	4.0	--	4.2	-	1	4	6	--	5	15	17	18	24	9.2	9.2	9.2
UT 11	9.3	8.8	--	9.0	-	1	0	0	--	0	--	--	--	--	9.2	--**	9.2
UT 12	0.4†	2.5	--	2.5	-	2	83	81	--	82	16	20	15	30	7.4	7.4	7.4
UT 13	3.3	3.2	--	3.3	-	4	97	97	--	97	18	23	20	20	8.1	7.3	7.7
UT 14	4.2	4.5	--	4.4	-	2	25	30	--	28	6	7	7	15	9.0	8.8	8.9
UT 15	3.6	3.9	--	3.7	-	1	26	17	--	22	15	21	19	16	8.2	8.1	8.2
UT 16	7.4	7.0	--	7.2	-	1	0	0	--	0	8	13	10	16	8.7	7.0**	8.7
UT 17	3.6	4.7	--	4.1	-	2	93	90	--	91	16	25	17	25	8.8	9.2	9.0
UT 18	2.5	2.5	--	2.5	-	6	97	97	--	97	28	50	38	50	9.0	9.3	9.2
UT 19	0.8	0.4	--	0.6	-	6	99	99	--	99	50	58	--	--	--	--	--
UT 20	6.8	7.0	--	6.9	-	2	67	63	--	65	--	--	--	--	--	--	--
UT 21	2.0	3.1	--	2.6	3	2	80	81	--	81	--	--	--	--	--	--	--
								Wyoming									
WY 1	4.7	4.8	--	4.8	-	1	0	0	--	0	--	--	--	--	6.0	6.4**	6.0
WY 2	6.9	6.7	--	6.8	-	1	0	0	--	0	--	--	--	--	5.6	6.3**	5.6
WY 3	3.7	3.9	--	3.8	-	1	30	26	--	28	--	--	--	--	9.8	9.6	9.7
WY 4	3.6	4.0	--	3.8	-	1	35	27	--	31	--	--	--	--	9.8	9.8	9.8
WY 5	4.7	5.1	--	4.9	-	4	92	92	--	92	17	18	20	26	9.4	8.3	8.9
WY 6	5.5	5.1	--	5.3	-	3	80	88	--	84	--	--	--	--	9.5	9.3	9.4
								Montana									
MT 1	5.6	5.5	--	5.6	-	1	49	43	--	46	--	--	--	--	5.5	5.5	5.5
MT 2	5.7	6.0	--	5.9	-	1	1	4	--	3	6	11	7	15	8.2	8.2	8.2
MT 3	7.3	7.1	--	7.2	-	1	0	0	--	0	--	--	--	--	4.8	6.4**	4.8
MT 4	4.0	4.3	--	4.2	-	1	64	67	--	66	8	10	10	17	8.8	9.0	8.9
MT 5	14.9	15.1	--	15.0	-	1	40	41	--	40	--	--	--	--	--	--	--
MT 6	0.6	0.6	--	0.6	6	6	98	99	--	98	--	--	--	--	--	--	--
								Oklahoma									
OK 1	1.5	1.6	--	1.6	-	6	99	99	--	99	15	25	28	35	6.3	6.2	6.2
OK 2	3.5	3.6	3.5	3.5	-	2	55	40†	58	56	15	15	11	15	4.7	4.5	4.6
OK 3	9.1	9.4	9.0	9.1	-	1	47	25†	55	51	7	20	8	17	7.7	7.3	7.5
OK 4	4.1	3.4	--	3.8	-	5	85	86	--	86	64	54	41	73	6.4	6.3	6.4
OK 5	10.0†	7.6	--	7.6	-	4	34†	22	--	22	--	--	--	--	4.4	4.6	4.5
OK 6	5.2	5.7	--	5.5	-	6	94	93	--	94	7	10	19	20	6.7	6.4	6.5
OK 7	16.0	16.2	--	16.1	-	1	6	6	--	6	--	--	--	--	--	--	--
OK 8	13.4	12.3	--	12.8	-	1	4	10	--	7	--	--	--	--	--	--	--
								Kansas									
KS 1	16.5	16.6	--	16.6	4	1	0	0	--	0	7	15	10	23	--	--	--
KS 2	19.5	19.7	--	19.6	-	3	46	52	--	49	7	14	10	22	--	--	--
								Arizona									
AZ 1	7.1	7.4	--	7.3	-	1	12	7	--	9	--	--	--	--	--	--	--
AZ 2	13.9	14.3	--	14.1	-	1	0	0	--	0	--	--	--	--	--	--	--
								South Dakota									
SD 1	28.1	29.7	--	28.9	-	1	0	0	--	0	--	--	--	--	--	--	--

** pH of cycle 2 insignificant because of small amount of material from cycle 1; disregarded in average.
† Anomalous material; disregarded in average.

(Sheet 3 of 3)

_c_. Under "fragment shape," the following self-explanatory terms were used for description: "thinly platy," "platy," "tabular," "prismatic," "blocky," and "irregular."

_d_. Texture was described as "clayey," "silty," or "sandy" with emphasis on departures from a "shaly" texture. More than half of the samples were shale or mudstone. The remaining samples were silty or sandy, though mostly still basically shale. Where discrete thin silty or sandy laminae were evenly dispersed, the material was considered simply as silty or sandy shale rather than a mixture of siltstone, sandstone, and shale laminae.

_e_. The formation is also identified in Table 2. In a few cases, this identification was tentative at best.

Index and Associated Tests

24. The slake-durability test and two supplemental index tests chosen for their simplicity were selected to obtain indexes representing the pertinent physical behavior of shale. Since dry-wet cycling is a conspicuous deleterious environmental factor, the slake-durability test appeared to be well suited to the study. A simple jar-slake test was conducted for comparison with slake-durability results. A second simple test was for an index of hardness which might relate to strength and elasticity as obtained with a scleroscope. Additional supplemental determinations of water content before slake-durability testing and of the acidity of the test water after testing were made.

25. A basic portion of the testing program was the slake-durability test described by Franklin and Chandra.[4] This test measures resistance of rock to weakening and disintegration as a result of two cycles of drying and agitation in a water bath. The test is accepted as a standard by the International Society of Rock Mechanics. The apparatus for conducting the test consists essentially of:

_a_. A solid-ended drum cage of 2-mm standard mesh, 100 mm long and 140 mm in diameter, with axis interrupted and extending outward from each end plate of the cage.

_b_. A rectangular box trough to be partially filled with water and to contain the drum cage in a horizontal position.

c. A motor drive capable of rotating the drum 20 rpm.

26. In the standard procedure, a representative group of ten rounded lumps of the rock, each weighing 40 to 60 g and together totaling 450 to 550 g, is placed in the drum and dried to a constant weight at 105°C. In the present study, where the same pair of drums was used for running an overlapping sequence of tests, all drying and weighing were done in trays outside the drum. The sample was then placed in the drum and the drum mounted in the partially filled trough and coupled to the motor. The trough was filled to 20 mm below the drum axis with either distilled or tap water* and the drum was rotated at 20 rpm for 10 min.

27. The drum was then removed from the trough and unloaded. The sample was dried in the oven and weighed. Two cycles were conducted to obtain slake-durability index (I_D):

$$I_D = \left(\frac{\text{Dry weight after two cycles}}{\text{Dry weight before testing}}\right) \times 100$$

Water content of the material was obtained from the moisture loss determined during the first drying for slake-durability testing. The material remaining after testing (Figures 1-12) gives some suggestion of the manner of breakdown that may take place in embankments.

28. Jar samples were taken from the water bath shortly after the end of agitation for both cycle one and cycle two of slake-durability testing and sent to the chemical laboratory for determination of the pH of the test water. The water samples were obtained 10 sec to 10 min after completion of test agitation. A delay in sampling allowed coarse and gritty materials to settle out completely, but the water was still cloudy from suspended fine material. After a day of settling, this suspended material formed a thin layer of clay at the bottom of the jar.

29. A hardness index (termed "scleroscope index" in Table 3) was determined using a Shore scleroscope, which is designed to measure an

* All eastern shale samples and samples CO 1-8, 11, 14, and 20 and UT 14, 16, and 19 were tested with distilled water.

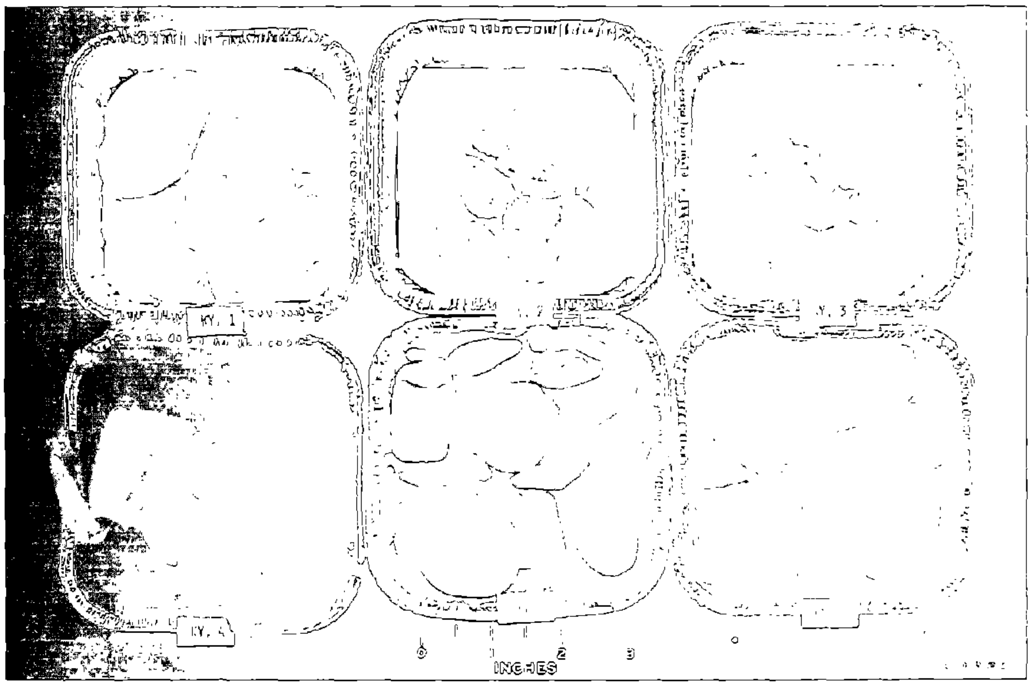


Figure 1. Remainder from slake-durability testing on samples KY 1 to KY 12

Figure 2. Remainder from slake-durability testing on samples KY 13 to KY 24

Figure 3. Remainder from slake-durability testing on samples KY 25 to KY 30 and OH 1 to OH 6

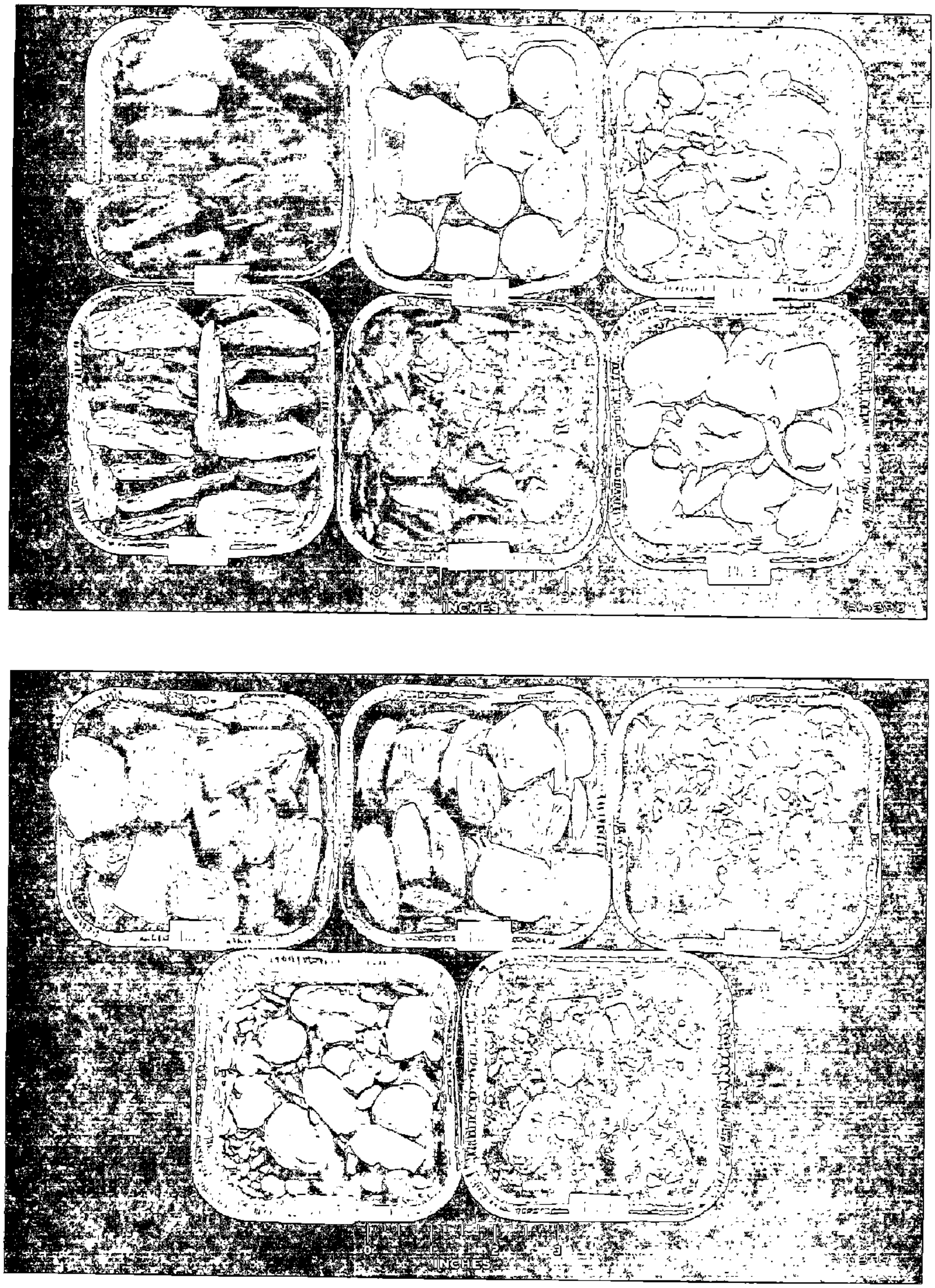


Figure 4. Remainder from slake-durability testing on samples OH 7 and IN 1 to IN 10

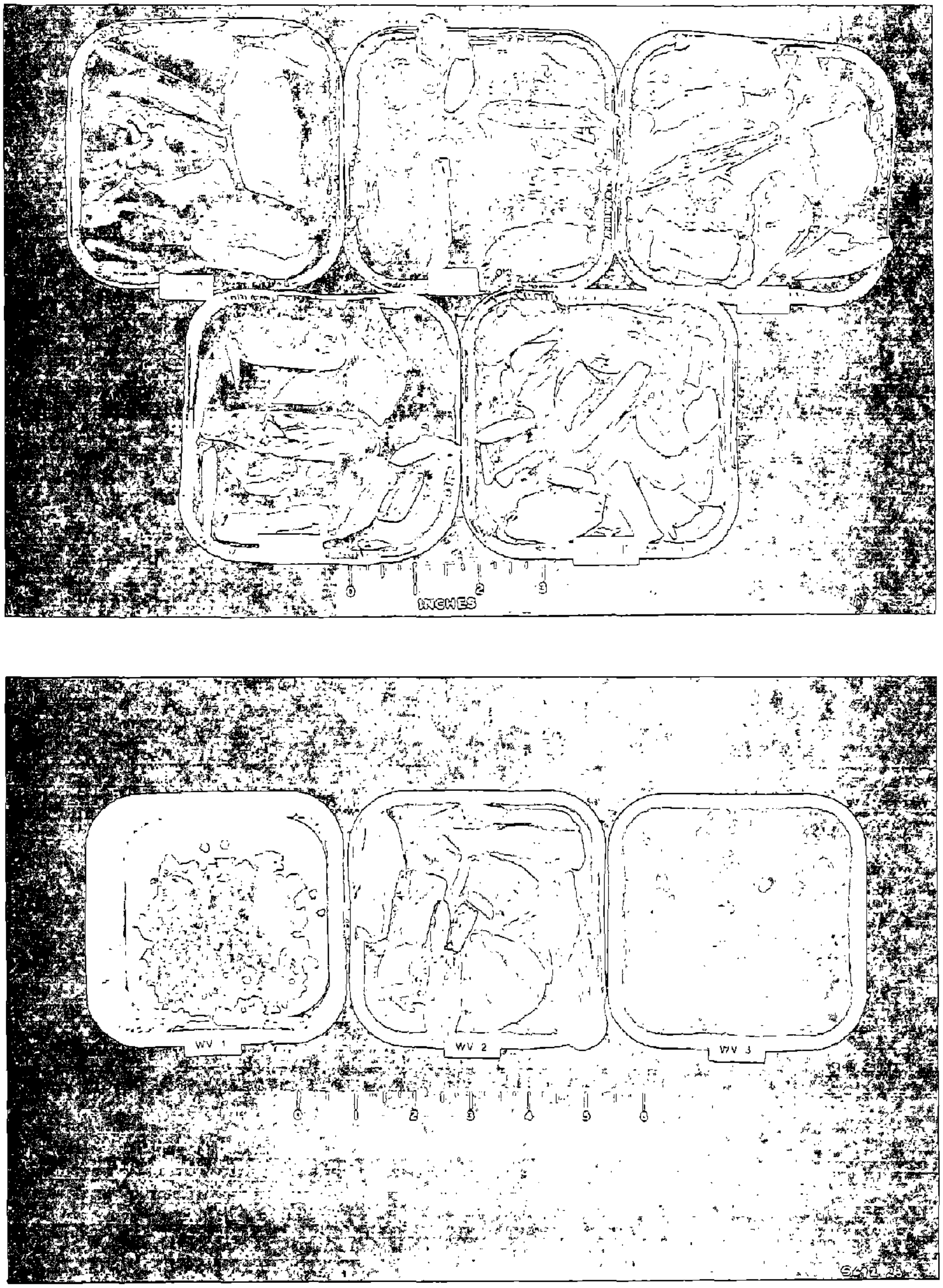


Figure 5. Remainder from slake-durability testing on samples VA 1 to VA 4 and WV 1 to WV 3

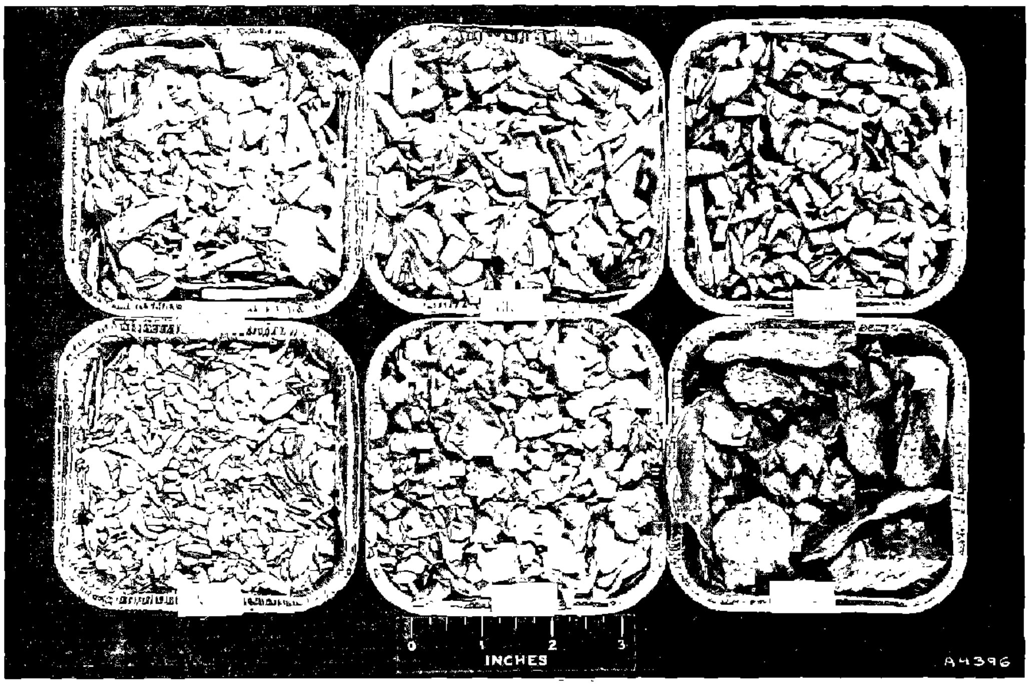


Figure 6. Remainder from slake-durability testing on samples TN 1 to TN 12

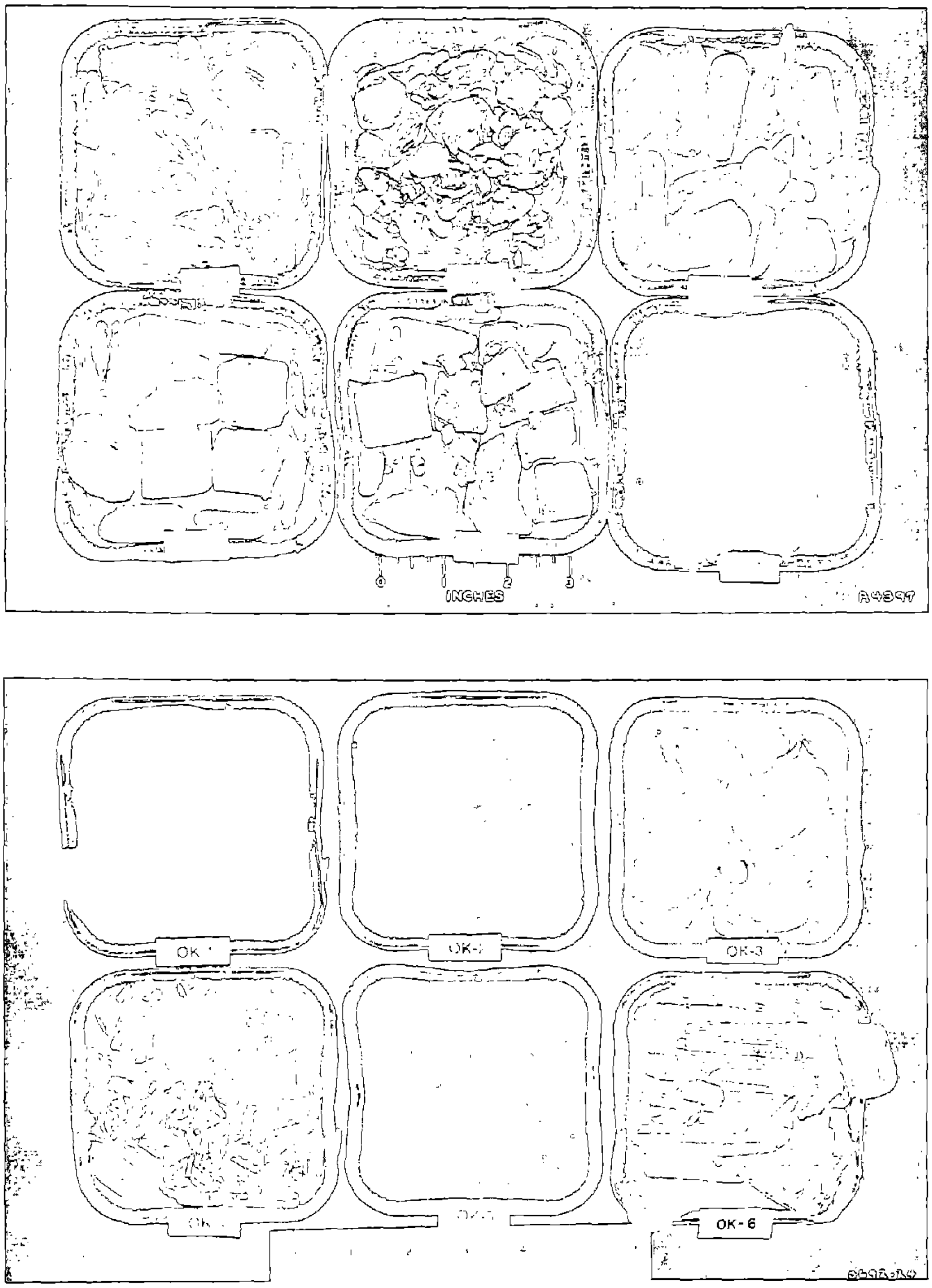


Figure 7. Remainder from slake-durability testing on samples TN 13 to TN 18 and OK 1 to OK 6

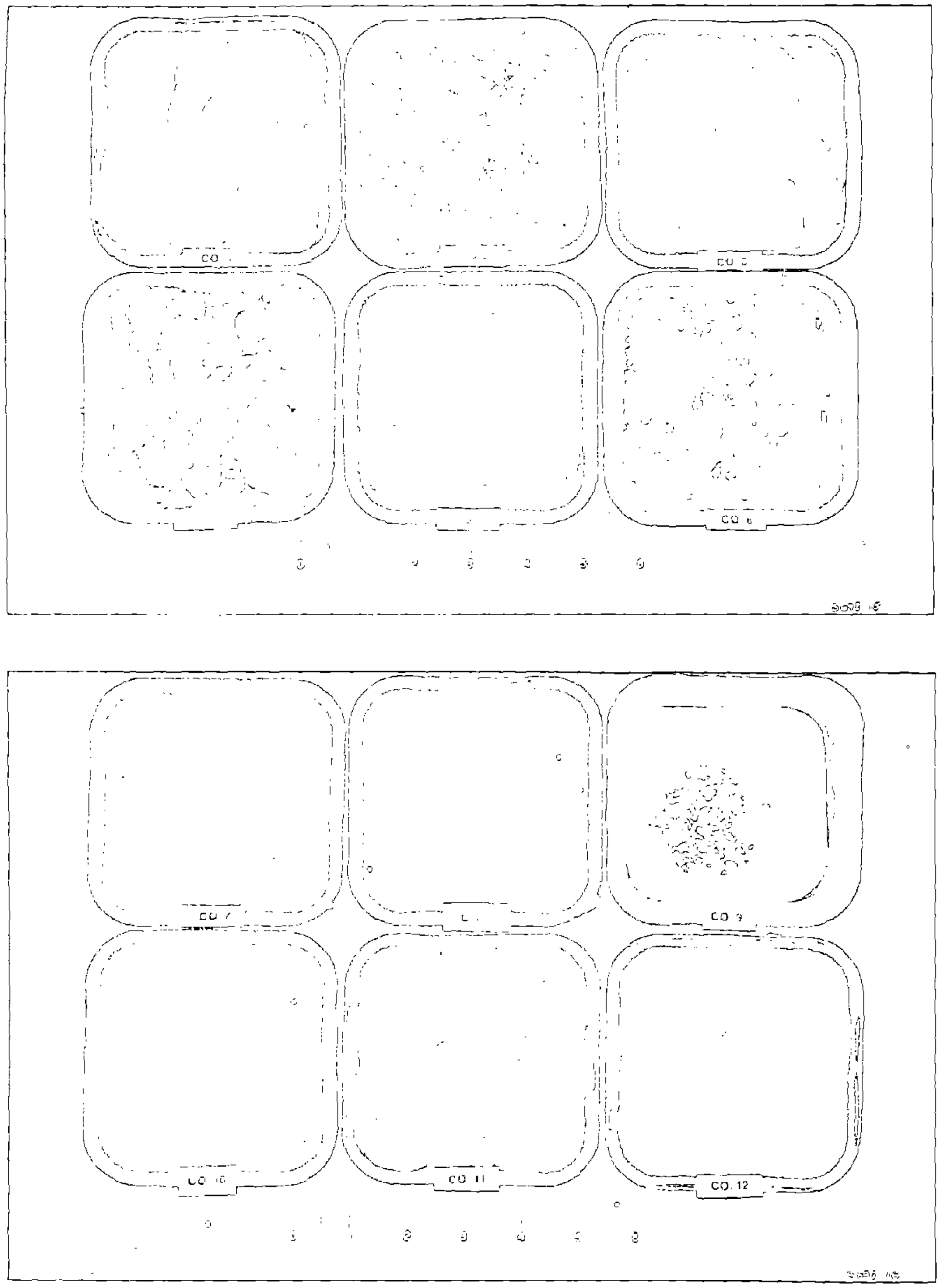


Figure 8. Remainder from slake-durability testing on samples CO 1 to CO 12

Figure 9. Remainder from slake-durability testing on samples CO 13 to CO 23 and UT 1

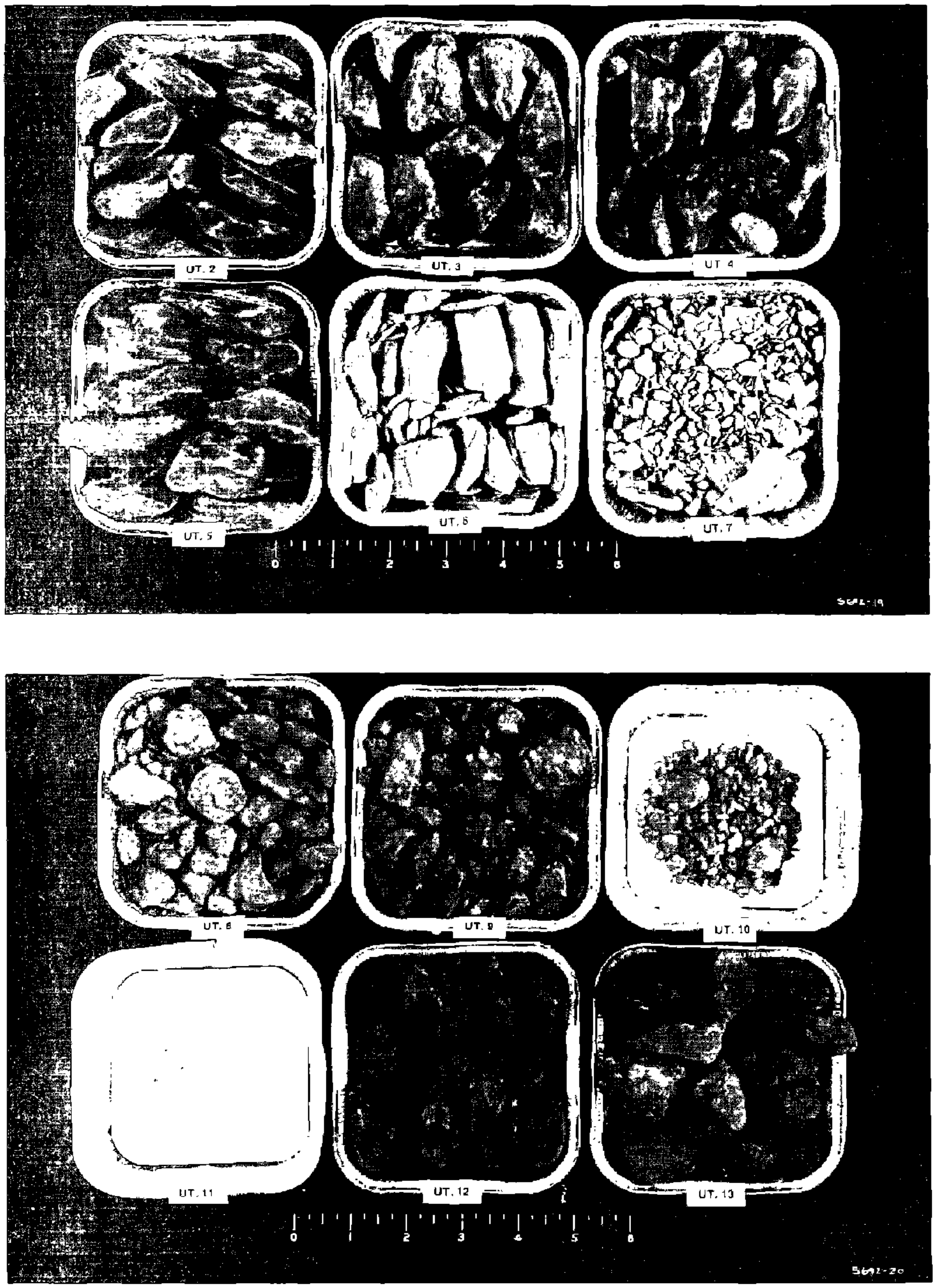


Figure 10. Remainder from slake-durability testing on samples UT 2 to UT 13

Figure 11. Remainder from slake-durability testing on samples UT 14 to UT 19 and MT 1 to MT 4

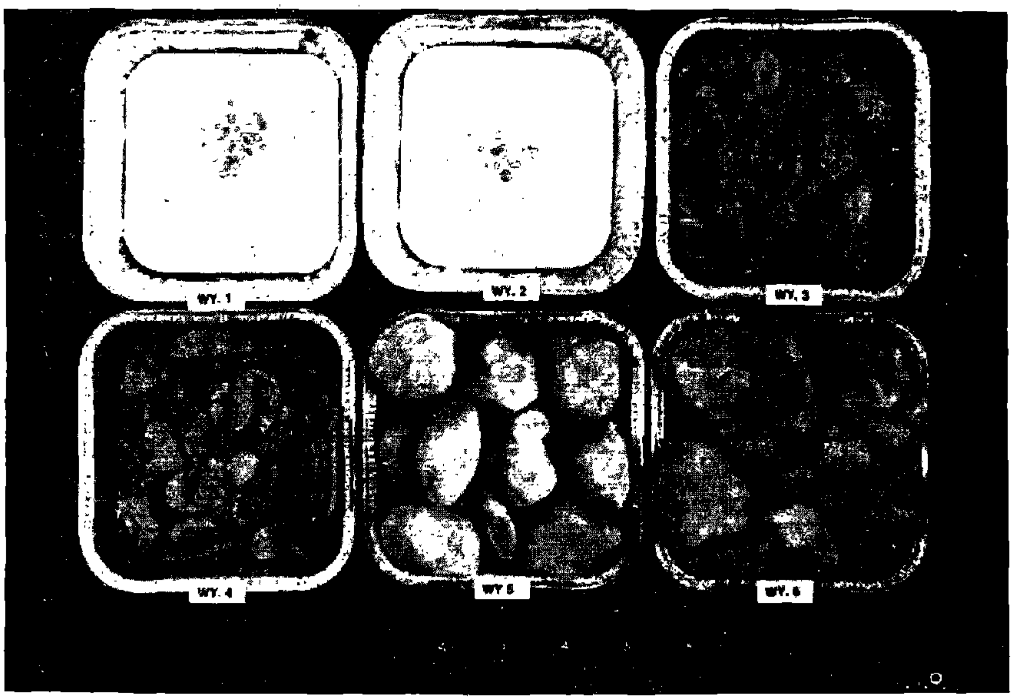


Figure 12. Remainder from slake-durability testing on samples WY 1 to WY 6

index of hardness of metals somewhat similar to and correlatable with Rockwell hardness. The Shore scleroscope (Model D) is a nondestructive, hardness measuring device which indicates relative values of hardness by the height of rebound of a small diamond-pointed piston dropped vertically approximately 1 cm within a tube onto the test surface. The height of rebound is indicated on a scale of 0 to 140 divisions. The sample is held fixed on the flat metal base during testing by impingement of the tube cranked down against it.

30. A specimen weighing about 50 g was used for the scleroscope index tests on the shale samples. The readings judged most reliable were obtained from pieces cut with parallel surfaces. Each impact damaged the surface so that a new test area was required. The sets of data indicated in Table 3 are for tests parallel and perpendicular to bedding or fissility and at moist and oven-dried conditions. Ideally, a number of impacts should be averaged for best scleroscope indexes; however, condition and configuration of the test blocks in this study were often poor, and the values listed in Table 3 are based on what was judged to be a reasonable degree of reproducibility of test results.

31. A fifth test conducted on the shale samples was a jar-slake test producing values for direct comparison with slake-durability test results. As formulated for this study, the simple test consisted of immersing an irregular fragment of the material weighing about 20 g in distilled or tap water and describing the resulting behavior by means of the following six jar-slake index (I_J) values.

I_J	Behavior
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

The test was conducted on both damp and oven-dried material but the damp material generally was insensitive as shown in Table 3. It was concluded that oven-dried material should be used to obtain a rapid evaluation of slaking potential. Where a reaction occurred, it usually happened largely within the first 10 min. Thus, careful observations were made during the first 30 min. Further breakdown was very subordinate, and the only other observation necessary was the final condition after 24 hr. The only jar-slake behaviors that were observed were fracturing and flaking. Some samples experienced a subtle softening, but no attempt was made to identify this behavior systematically.

Mineralogical Examination

32. Almost all eastern shales and about half of the western shales were examined mineralogically (Table 4) using X-ray diffraction. Representative portions of samples were crushed and quartered. Ten grams were ground to pass a No. 325 sieve, packed in a holder to minimize preferred orientation, and then X-rayed.

33. A second portion of each raw sample, amounting to 25 g, was agitated for 5 min in 500 ml of distilled water with a blender. Another 500 ml of distilled water was added and settling behavior was observed. If settling was visible, the top one-fourth of the suspension was siphoned into an 800-ml beaker after 4 hr and enough distilled water was added to fill the beaker. Sedimented slides prepared by leaving glass slides in the suspension overnight were air-dried and then X-rayed. If settling was not visible, 500 ml of slurry was diluted again by adding 500 ml of distilled water. If the settling was still too slow, 2 to 20 drops of a dispersing agent were added and the sedimented slides were prepared and X-rayed.

34. Samples with a 14-Å spacing were treated with glycerol, allowed to stand overnight, and then X-rayed again. Where the 14-Å spacing was caused by montmorillonite, absorption of the glycerol increased the spacing to about 17 Å.

35. The remaining examination of clay minerals, in particular that distinguishing kaolinite and chlorite, was accomplished selectively within groups of related samples. Chlorite can be positively identified

Table 4

Shale Mineralogy and Semiquantitative* Composition

Shale No.	Clay Minerals: Clay-Mica	Chlorite	Kaolinite	Montmorillonite	Nonclay Minerals: Quartz	K-Feldspar	Plagioclase	Calcite	Dolomite	Siderite	Pyrite	Hematite
						Kentucky						
KY 1	C	Tr	R	--	C	--	R	--	M	--	--	--
KY 2	C	--	R	--	C	--	R	--	M	--	--	--
KY 3	C	Tr	R	M†	C	--	R	--	M	--	--	--
KY 4	Not examined											
KY 5	C	R	Tr**	--	A	--	M	--	--	Tr	--	--
KY 6	C	R	Tr	--	A	--	C	C	--	Tr	--	--
KY 7	C	--	C	--	A	--	M	--	--	M	--	--
KY 8	C	M	M	--	C	--	M	--	--	R	--	--
KY 9	M	--	M	R†	A	--	R	--	--	R	--	--
KY 10	C	M	M**	--	A	--	M	--	--	R	--	--
KY 11	C	M	M	--	A	--	M	--	--	R	R	--
KY 12	C	M	M**	--	A	R	R	--	--	R	--	--
KY 13	C	M	M**	--	C	--	M	--	--	M	--	--
KY 14	C	R	--	--	C	R	--	--	C	--	R	--
KY 15	C	R	--**	--	C	--	R	--	M	R	--	--
KY 16	C	R	--**	--	C	--	R	--	R	--	--	--
KY 17	C	M	--	--	C	--	R	--	C	R	--	--
KY 18	C	Tr	M	--	A	--	M	M	--	R	M	--
KY 19	C	R	--	--	A	R	M	--	--	--	--	--
KY 20	C	M	M**	R	A	--	M	--	--	R	--	--
KY 21	C	M	--**	--	A	R	R	R	--	--	--	--
KY 22	C	--	M	R†	A	M	R	M	--	R	--	--
KY 23	C	--	M**	--	A	M	M	--	--	R	M	--
KY 24	C	M	M	--	A	--	M	--	M	--	--	--
KY 25	C	M	--**	--	C	--	M	M	M	--	R	--
KY 26	C	M	--	--	C	--	R	C	--	--	R	--
KY 27	C	M	--**	--	C	--	M	C	M	--	--	--
KY 28	C	M	--**	--	C	--	M	C	R	R	R	--
KY 29	C	M	--	--	C	--	M	M	R	R	--	--
KY 30	C	M	--**	--	C	--	M	M	--	--	R	--
						Tennessee						
TN 1	C	--	--	--	--	A	--	--	--	--	--	--
TN 2	C	R	--**	--	M	C	--	--	--	--	--	--
TN 3	C	R	--**	--	C	M	--	--	--	--	--	--
TN 4	C	R	--**	--	C	M	--	M	--	--	--	--
TN 5	C	R	--	--	C	M	--	--	--	--	--	--
TN 6	C	R	--**	--	C	M	M	--	--	--	--	--
TN 7	C	R	--**	--	C	M	--	--	--	--	--	--
TN 8	C	--	--	--	C	R	--	Tr††	--	--	--	Tr††
TN 9	C	--	--	--	C	R	R	Tr††	--	--	--	--
TN 10	C	R	--**	--	C	R	--	--	--	--	--	--
TN 11	C	R	--	--	C	R	--	--	--	--	--	--
TN 12	C	R	--**	--	C	C	--	--	--	--	--	--
TN 13	Not examined											
TN 14	C	M	M	--	A	--	M	--	--	R	--	--
TN 15	C	M	M**	--	A	--	M	--	--	M	--	--
TN 16	C	M	M**	--	C	--	C	--	--	M	--	--
TN 17	C	M	M	--	A	--	M	--	--	M	--	--
TN 18	C	--	M	--	A	--	C	--	--	R	M	--
						Ohio						
OH 1	C	M	--**	--	C	--	M	M	M	--	--	--
OH 2	C	M	--**	--	C	--	R	R	M	--	R	--
OH 3	C	M	--**	--	C	--	M	C	M	--	R	--
OH 4	C	M	--	--	M	--	R	--	A	--	R	--
OH 5	C	M	--	--	C	R	--	--	M	--	--	M
OH 6	C	M	M**	--	A	--	M	--	--	--	--	--
OH 7	C	Tr	M	--	A	--	M	--	--	R	M	--

(Continued)

* Relative amounts determined by X-ray diffraction peak intensities; (A) abundant, greater than 50 percent; (C) common, about 25-50 percent; (M) minor about 10-25 percent; (R) rare, about 5-10 percent; (Tr) trace, less than 5 percent; (--) not present.

** Composition projected from associated samples; no acid treatment for distinguishing kaolinite from chlorite.

† Mixed-layer clay (montmorillonite and clay-mica).

†† Tentative mineral identification.

Table 4 (Concluded)

Shale No.	Clay Minerals: Clay-Mica	Chlorite	Kaolinite	Montmorillonite	Nonclay Minerals: Quartz	K-Feldspar	Plagioclase	Calcite	Dolomite	Siderite	Pyrite	Hematite
						Indiana						
IN 1	M	Tr	--	--	M	R	--	A	M	--	--	--
IN 2	C	M	--**	--	C	--	R	M	M	--	R	--
IN 3	C	R	M	--	A	--	C	--	--	M	--	--
IN 4	C	R	M**	--	A	--	C	--	--	M	--	--
IN 5	C	M	--**	--	C	R	M	M	--	R	R	--
IN 6	C	M	--	--	A	--	M	--	--	R	R	--
IN 7	C	R	--**	--	A	--	M	--	--	M	--	--
IN 8	C	R	M**	--	C	--	M	--	--	M	--	--
IN 9	C	M	--**	--	C	--	M	R	M	--	--	--
IN 10	M	R	C	--	A	M	--	--	R	R	Tr	--
						Virginia						
VA 1	C	M	--**	--	A	--	M	--	--	R	R	--
VA 2	C	M	--	--	A	--	M	R	R	R	R	--
VA 3	C	R	--**	--	A	--	M	R	R	R	R	--
VA 4	M	M	--	--	M	--	R	A	--	--	--	--
						Colorado***						
CO 1	Tr	--	M	Tr	A	--	R	--	--	--	--	--
CO 2	Tr	--	M	Tr	A	Tr	Tr	--	--	--	--	--
CO 3	Tr	Tr	R	--	A	M	M	--	Tr	--	--	Tr
CO 4	R	Tr	M	Tr	A	R	R	--	R	Tr	--	Tr
CO 5	Tr	Tr	R	Tr	A	--	R	--	R	Tr††	--	--
CO 6	Tr	Tr	M	Tr	A	R	R	--	--	--	--	--
CO 9	Tr	Tr	R	Tr	A	R	R	--	R	Tr	--	Tr
CO 11	Tr	Tr	R	Tr	A	Tr	M	--	R	Tr	--	Tr
CO 12	R	Tr	R	--	A	--	M	--	M	Tr	--	R
CO 16	R	Tr	R	Tr	A	--	M	--	M	Tr	--	Tr
CO 20	Tr	Tr	Tr	Tr	A	--	R	M	M	--	--	--
CO 21	Tr	Tr	Tr	Tr	C	--	Tr	C	M	Tr	--	Tr
CO 22	Tr	Tr	Tr	Tr	A	--	R	M	M	Tr	--	Tr
						Utah***						
UT 4	Tr	Tr†††	Tr	Tr	A	--	R	--	M	R	--	Tr
UT 5	R	Tr	Tr	Tr	A	--	R	M	M	Tr	--	Tr
UT 7	R	--	R	--	C	R	R	--	C	--	--	R
UT 12	Tr	Tr	Tr	Tr	A	--	R	--	--	Tr	--	Tr
UT 15	Tr	--	R	R	C	--	--	--	--	--	--	Tr
UT 20	Tr	Tr	Tr	Tr	C	Tr	Tr	C	M	Tr††	--	--
UT 21	Tr	Tr	Tr	Tr	A	Tr	Tr	M	M	Tr	--	Tr

** Composition projected from associated samples; no acid treatment for distinguishing kaolinite from chlorite.

*** All samples from Colorado and Utah except UT 7 also contained mixed-layer clays.

†† Tentative mineral identification.

††† Chlorite and/or vermiculite.

by the presence of its 4.7-Å spacing. The prominent and diagnostic spacing for kaolinite at about 7 Å, however, is shared with chlorite. Representative samples containing chlorite were treated with a solution of 1 HCl:4 H_2O. The slurry was allowed to react for 6 hr at 80°C. The residue was then washed and put on a slide, air-dried, and X-rayed. This procedure removed the chlorite. The only other way kaolinite was identifiable was in the absence of chlorite in the original sample, in which case there is no superimposition of two mineral peaks at 7 Å.

36. Many samples were not acid-treated, and the identification of kaolinite was by association and therefore not confirmed. These samples were studied in related groups, and apparently representative samples were selected from each group for acid treatment. The abundance of kaolinite determined in these representative samples was then projected to the other samples in the group. These projected compositions of kaolinite are indicated by two asterisks in Table 4.

37. The minerals searched for at least selectively are listed in Table 4 in two groups, clay minerals and nonclay minerals. The nonclay minerals were determined from X-ray diffraction of the bulk sample. The clay minerals were determined from the sedimented slides, with or without treatment. One sample was examined for possible halloysite because of its especially moist condition; no halloysite was found.

PART IV: TEST RESULTS

38. In this part, shale sample characteristics and ranges in characteristics are reviewed. The results of the laboratory work conducted on the total collection of problem and no-problem shales are tabulated in Tables 2-4. Since samples are tabulated by state in chronological order of collection, no meaningful trends will be found in proceeding down each column. Similarly, the average values of characteristics given below are not intended to do more than generalize the entire heterogeneous collection.

Sample Descriptions

39. Natural water content of eastern shales as sampled in the field (Table 2) varied between values of approximately 1 and 19 percent; 45 determinations average 8.46 percent (standard deviation $S = 3.90$) but these include nine values of greater than 12 percent which quite possibly were affected by surface weathering. The remaining 36 determinations average 7.05 percent ($S = 2.69$).

40. Color of shales varied widely although there was a preponderance of greenish gray in some formations and neutral gray in others. The degree of bedding or fissility varied from relatively structureless to highly laminated material. The internal structure was manifested to some degree in the shape of fragments that resulted during natural or test degradation, i.e., tabular and platy fragments reflecting internal anisotropy.

41. The texture or fabric grain size of the rock was typically shaly but often with a silty component. The texture reflects to some degree the intentional selectivity exercised in the field sampling program where shales were sought.

Results of Physical Tests

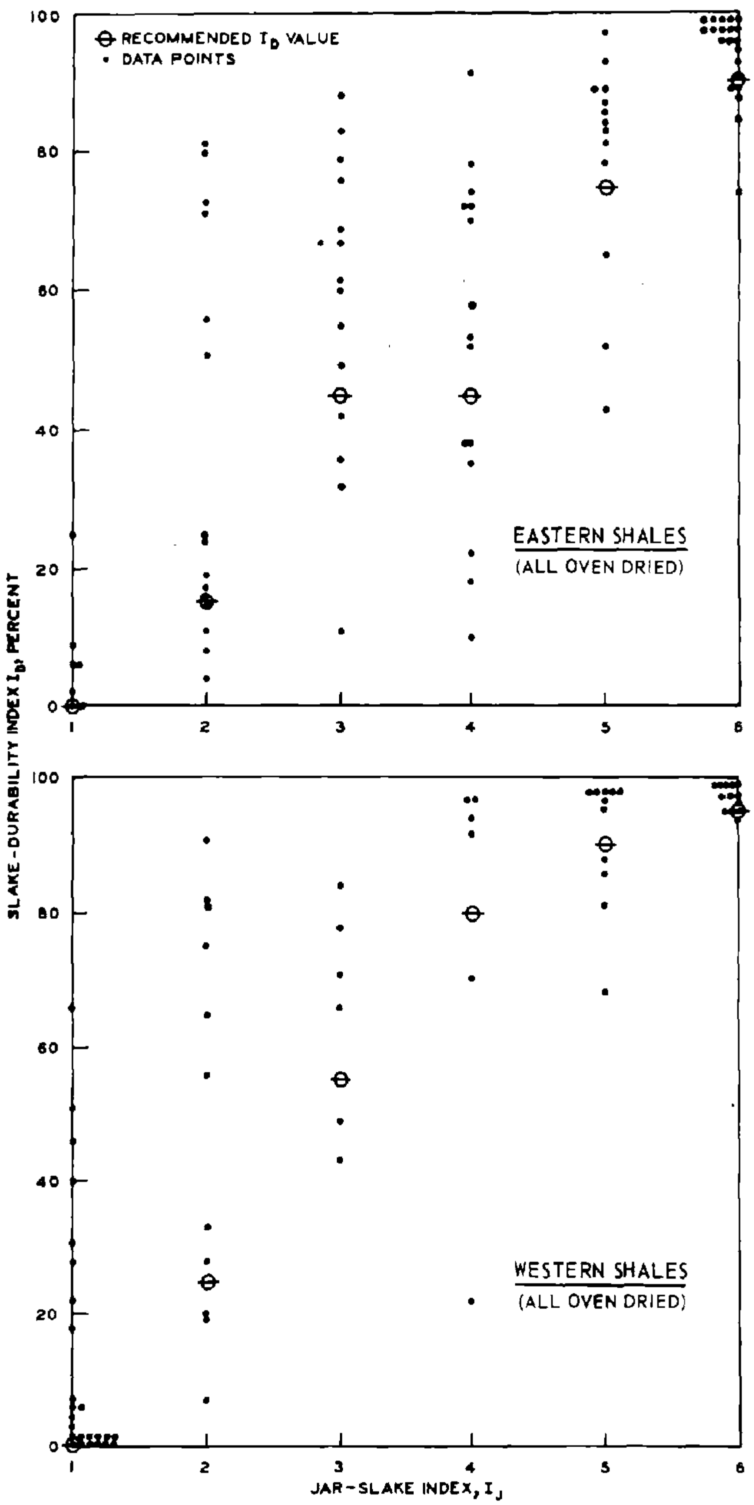
42. Table 3 indicates the results of physical tests on the shales and associated determinations of water content and test water pH.

The water content was determined before each slake-durability test, and an average value is also given. The range of average water contents was from 0.3 to 28.9 percent, but certain samples were abnormally high in water as though they had been softened by surface weathering processes. A more meaningful arrangement of values of water content averages is shown in the groupings of samples according to formation. Such groupings are discussed in paragraphs 48-88.

43. Figures 1-12 show material remaining after slake-durability testing. I_D values for the two or three individual slake-durability tests are given in Table 3 along with average values. These indexes ranged between extremes of 0 and 99 percent. Differences in I_D among the two or three tests on portions of the same material indicate that the testing did not always realize the reproducibility to within 5 percent claimed by Franklin and Chandra.[4] Reproducibility was quite high among the more resistant rocks, but this was expected since these rocks did not degrade appreciably. Where agreement was poor between the two tests for each sample of western shale, a third test was conducted and the anomalous value ignored in averaging.

44. The results of pH determinations on slake-durability test water after each of two cycles are indicated in Table 3. These values are also averaged, except in cases where little material remained from cycle 1 to influence the pH of cycle 2. Again, a wide dispersion of values reflects the wide variation of shale types sampled in the program. When pH values are grouped according to particular formations, the dispersion is reduced considerably and within a particular formation is not very great. It is interesting to note, however, that problem shales can produce either acidic or alkaline water in the slake-durability test.

45. The jar-slake test gave a full range of I_J values from 1 to 6. The relationship between I_J and I_D was explored in Figure 13 to determine usefulness of the jar-slake test as a simpler substitute for the slake-durability test. The figure indicates a poorly defined correlation. The I_D points along constant I_J lines are widely dispersed. A conservative correlation, assuming that I_D is the more accurate measure of durability, places an appropriate single value of I_D on the lower



EASTERN SHALES

GIVEN I_J	RECOMMENDED* I_D
1	0
2	15
3	45
4	45†
5	75
6	90

† SAME AS FOR 3

WESTERN SHALES

GIVEN I_J	RECOMMENDED* I_D
1	0
2	25
3	55
4	80
5	90
6	95

*NOTE: THE BASIS FOR RECOMMENDING VALUES OF I_D CORRESPONDING TO TEST VALUES OF I_J IS: (1) ASSUMPTION THAT I_D IS MORE ACCURATE MEASURE OF DURABILITY, AND (2) "CONSERVATIVE" DISTRIBUTION OF APPROXIMATELY THREE-FOURTHS OF I_D VALUES ABOVE RECOMMENDED VALUE (AN EXCEPTION BEING AT I_J = 4 FOR EASTERN SHALES).

Figure 13. Correlation of indexes of jar-slake and slake-durability tests

half of the I_D distribution, in this case (Figure 13) with about three-fourths of the I_D values greater than the chosen value. Separation of eastern and western shales distinguished separate correlations; western shales experienced relatively greater breakdown in the jar-slake test (considered at constant I_D). It seems that the small size (relatively high surface area) of the test material and the long test time in jar-slake testing may be more conducive to deterioration of montmorillonite contained preferentially in the western shales (paragraph 47).

46. A considerable amount of judgment was necessarily exercised in arriving at representative scleroscope index values. Irregular surfaces, sample sizes, and cracking all had major effects on the index and were hard to compensate. It was possible to obtain an average based on several closely agreeing impacts in about half of the tests. The test was generally not very useful in characterizing shales since so many values fell in the narrow range 11-25 and yet the test precision is relatively poor.

Results of Mineralogical Analyses

47. The results of the mineralogical analyses are indicated in Table 4. Gross characteristics of the collection as a whole include an abundance of quartz in approximately half the samples. In fact it is apparent, at least as far as the semiquantitative values go, that quartz often exceeded the total content of clay minerals. Among clay minerals, clay-mica (usually illite) almost always dominated in Paleozoic shales. Chlorite was usually second in abundance followed by kaolinite. Only four Paleozoic samples contained significant montmorillonite, and in three of these cases the montmorillonite was in mixed-layer relationship with clay-mica. On the other hand, montmorillonite is usually an important clay mineral in shale samples of younger age (western shales). Among the three carbonates that were identified (calcite, dolomite, and siderite), the first two are most characteristic of marine shale and may actually represent fragmental fossil debris. Siderite was the dominant carbonate in sampled Mississippian and Pennsylvanian formations

and particularly in coal-bearing strata. Siderite may largely constitute a cementing material, and therefore it was considered subsequently in regard to possible strengthening and increased slake durability. Pyrite was commonly found in marine shale.

Comparisons with Stratigraphy and Location of Problems

48. As mentioned earlier, the extensive data presented in the tables are best compared within the confines of individual formations. The sampling program produced sample groups of modest size from five relatively confined stratigraphic sequences: the Upper Ordovician around Cincinnati, Ohio; the Middle Cambrian near Knoxville, Tenn.; the Middle Pennsylvanian in western Kentucky; the Upper Cretaceous in southeastern Colorado; and the Upper Cretaceous in Utah. Numerous smaller groups were obtained from thinner sequences of shales. Figures 14-25 show most of the sampled strata and general lithology along with sample characteristics that sometimes correlate with stratigraphic position and/or problem localization.

Kope formation

49. The Upper Ordovician in the vicinity of Cincinnati consists of several hundred feet of marine limestone and shale in thinly alternating beds.[5] The sequence occurs over a wide area and has caused embankment problems of considerable magnitude in the past. The base of the sequence of interest is the Point Pleasant or Cynthiana limestone (Figure 14) and the top is the Brassfield limestone at the base of Silurian strata. Stratigraphical names that have been or are being used are indicated in the figure, along with the approximate positions of 17 samples used in this study.

50. Pertinent characteristics of the samples are shown graphically on the side for comparison and in relation to stratigraphical position. The top three samples in the set are of lesser importance than those below because of their anomalous lithology and/or remote position with respect to problems. It can be seen that, upward in the lower two-thirds of the sequence, I_D varies from intermediate values of about

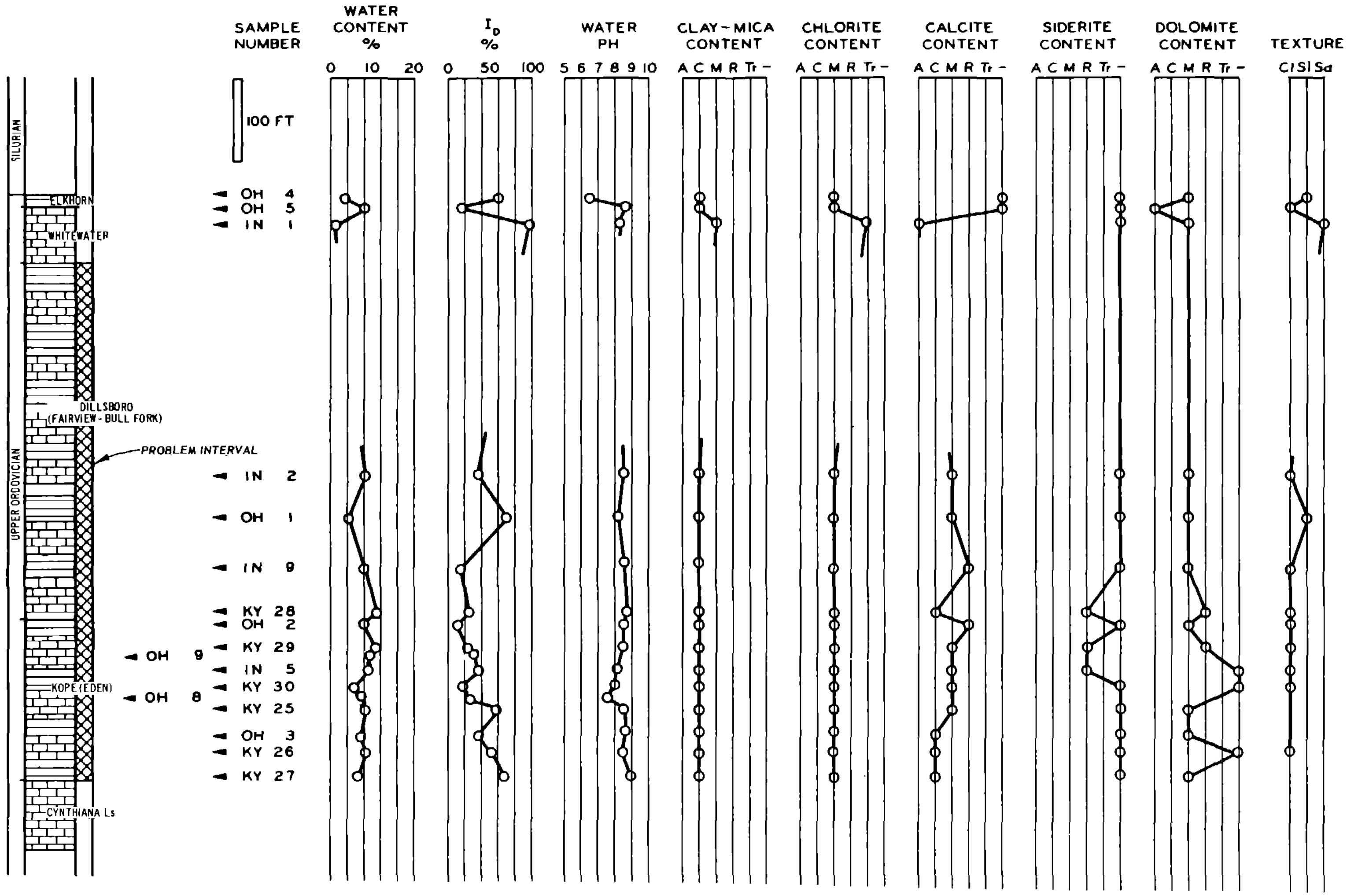


Figure 14. Test results and characteristics of shales of the Dillsboro and Kope formations

70 percent to low values. Personnel in the Kentucky Department of Transportation offered the opinion that, if there is a most troublesome portion of these strata, it probably is the upper Kope formation. The principal Ordovician problem in Indiana involved shale embankments constructed of material taken near the Kope-Dillsboro contact. Low I_D thus appears to be most characteristically obtained for this problem interval.

51. Calcite is a minor mineralogical constituent for the most part in the shale of the sequence but, like I_D, seems to increase in the lower 50 ft of the Kope formation. The other constituents of the rock appear to have no relationship to I_D and localization of problems, with the possible exception of water. Water content seems to be somewhat higher in the top of the Kope than in the bottom. The presence of calcium carbonate within or adjacent to the shale layers accounts for the higher pH, between 8 and 9. The pH values do not appear to correlate with I_D.

Tradewater formation

52. Lower and Middle Pennsylvanian strata in western Kentucky consist of the Caseyville, Tradewater, and Carbondale formations and generally represent the shale type associated with sandstone, siltstone, and coal (paragraph 16). In some areas these formations are clearly defined (Figure 15), but elsewhere, as a consequence of intricate facies changes characteristic of this type of strata, the units are apparently contemporaneous with one another. The Tradewater is regarded as a major problem formation.

53. Tradewater sandstone is light to medium gray and micaceous.[6] The siltstone is light to medium gray and interbedded with thin-bedded sandstone. Shale is apparently quite subordinate to siltstone but does occur consistently in association with coal beds. Seven samples of Tradewater formation were obtained in the field (Figure 15), but this sampling was not extensive enough nor positions well enough established that the results in the figure can be taken as more than a first approximation. Sample KY 9 contained coaly material and probably was located near one of several coal beds found in these strata, probably that known as No. 6 coal.

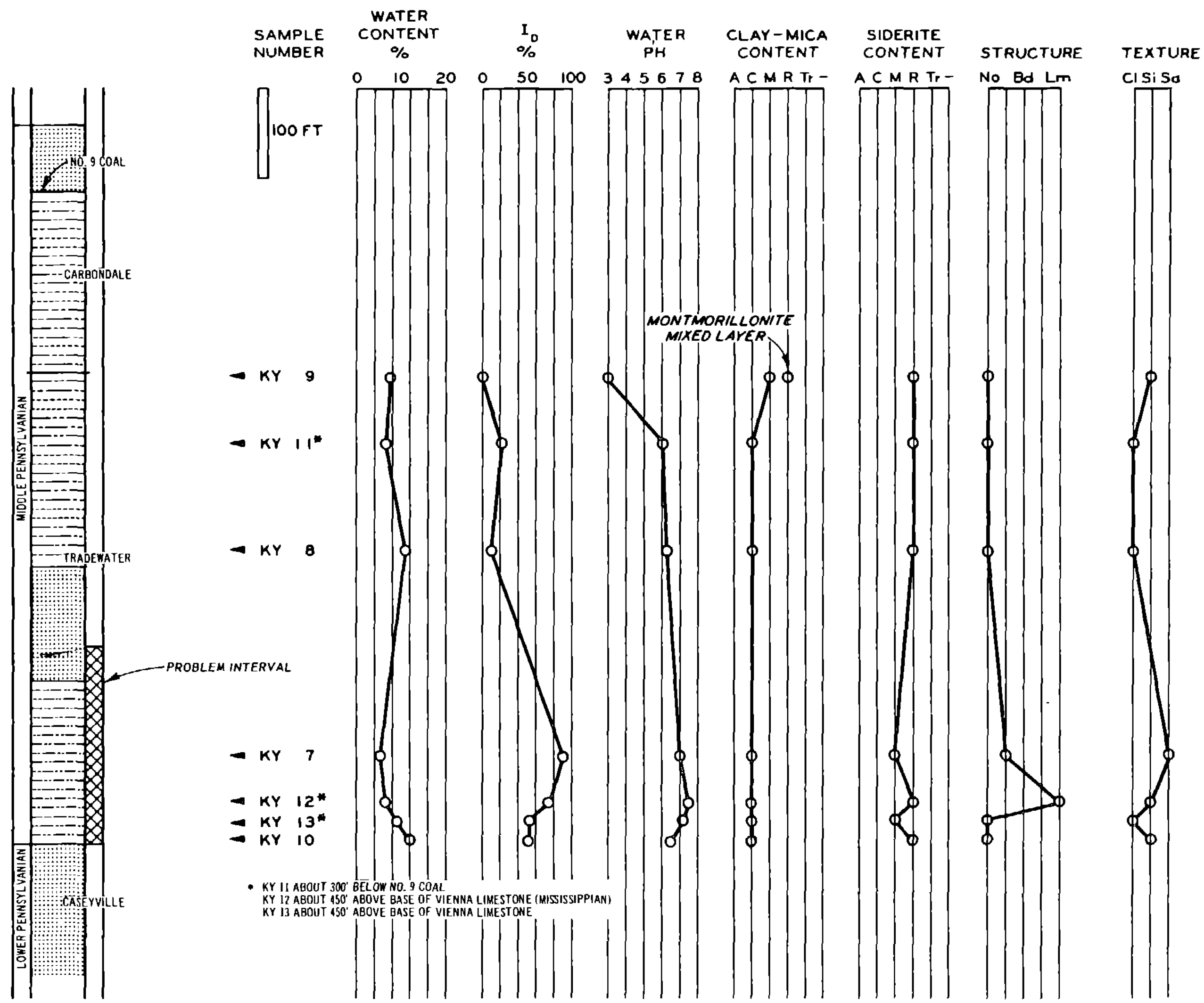


Figure 15. Test results and characteristics of shale of the Tradewater formation

54. I_D results indicate an interesting distinction between upper and lower groups. The upper samples have I_D's of 0 to 22, whereas indexes of the lower samples are all above 50. However, the three lowest samples came specifically from cuts that provided material used in embankments that had failed; thus, the lower Tradewater would seem to be more troublesome, despite I_D's suggesting faster deterioration in the upper group.

55. The group of Tradewater samples shows a prominent correlation between I_D and test water pH. This is revealed graphically in Figure 15 by the approximately parallel trends of these two parameters from sample to sample. The other mineralogical and physical characteristics plotted in the figure tend to be either constant or erratic through the strata and therefore suggest no reasons for a consistent difference in the behavior of portions of this formation.

<u>Nolichucky shale</u>

56. The Nolichucky shale was one of several Cambrian units specified by the Tennessee Department of Transportation for which problems had been experienced within compacted embankments. Two of the other specified units were the Rogersville and Rome shales lying several hundred feet lower stratigraphically. Sampling in the field was conducted along a relocated section of Tennessee Highway 92 south of Jefferson City, Tenn. The Nolichucky represents a thick shale according to the types proposed in paragraph 16.

57. Ten samples were taken from fresh cut surfaces along the route. Stratigraphic positions (Figure 16) were deduced on the basis of known geological structure. Four of the samples were taken apart from the others, and their positions in Figure 16 depend on the effects of two thrust faults believed to cut the sampling traverse. If the thrusting is insignificant, samples TN 8, 9, 10, and 11 are out of position and should be located in the Rogersville shale. Actually, the Rogersville is very similar to the Nolichucky, and they are conventionally grouped together with other units in the Conesauga group when details for subdivision are lacking.

58. The Nolichucky consists of well-bedded, yellowish to

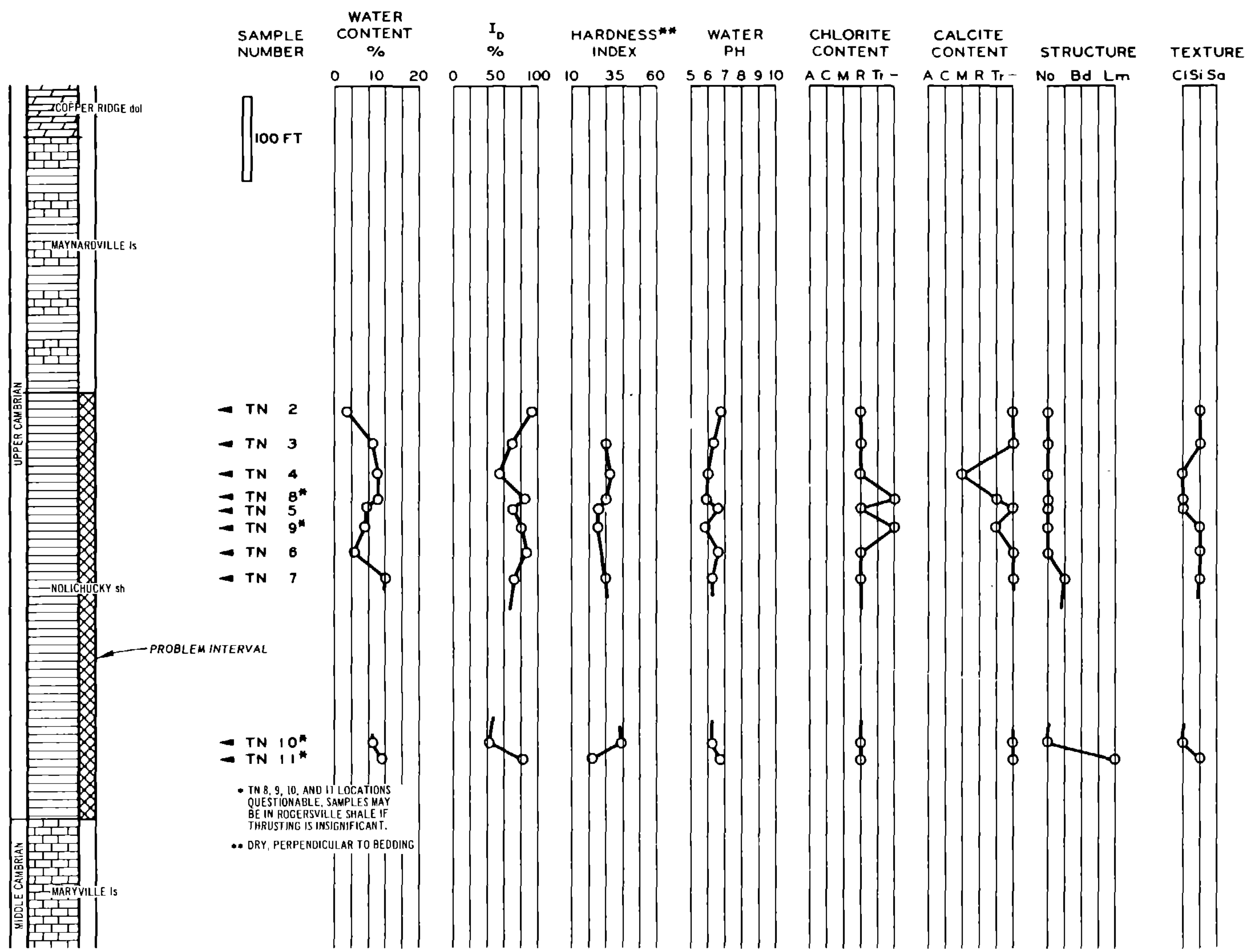


Figure 16. Test results and characteristics of shale of the Nolichucky formation

olive-green calcareous shale. Beds of limestone to a few inches in thickness are said to occur at irregular intervals.[7] In the sampling program, a variation in texture was noted, as indicated in Figure 16.

59. I_D's were relatively high, usually well over 50. Nolichucky shale behaved distinctly different from almost all other samples by bulking conspicuously upon breakdown in slake-durability testing. The shale (Figure 6, samples TN 2 through TN 10) characteristically degraded into flakes about 1/2 in. broad but did not degrade enough to pass through the screen of the slake-durability apparatus. No well-defined trend in I_D is apparent through the strata. Test water pH shows a correlation with I_D, and the pretest water content seems to be inversely related to I_D. Hardness, structure, texture, and chlorite and calcite contents are shown in Figure 16 but apparently have no consistent variation from top to bottom. Because of the uniformity in appearance and test results, the Nolichucky is inferred to be uniform in its behavior in embankments.

New Providence formation

60. The New Providence formation occurs in eastern and western Kentucky and has been responsible for embankment problems in both areas. The New Providence is approximately 200 ft thick and constitutes the lower half of the Borden formation in recent stratigraphic nomenclature.[8] Figure 17 shows the arrangement and position of this formation in the stratigraphical column in the vicinity of Morehead, Kentucky, but a similar sequence occurs in western Kentucky between Devonian black shale (New Albany) and limestone of the Meramecian series.[9]

61. The New Providence consists of shale and siltstone that is dark greenish gray to bluish gray in color and is of the thick shale type as proposed in paragraph 16. The siltstone may have thin bedding, and ironstone lenses and concretions are common. The New Providence grades upward into the Brodhead formation by an increase in the siltstone percentage, and above that lies the Muldraugh formation, a third member in the newly defined Borden formation. At the top is a thin shale in eastern Kentucky known as the Nada member. The Muldraugh

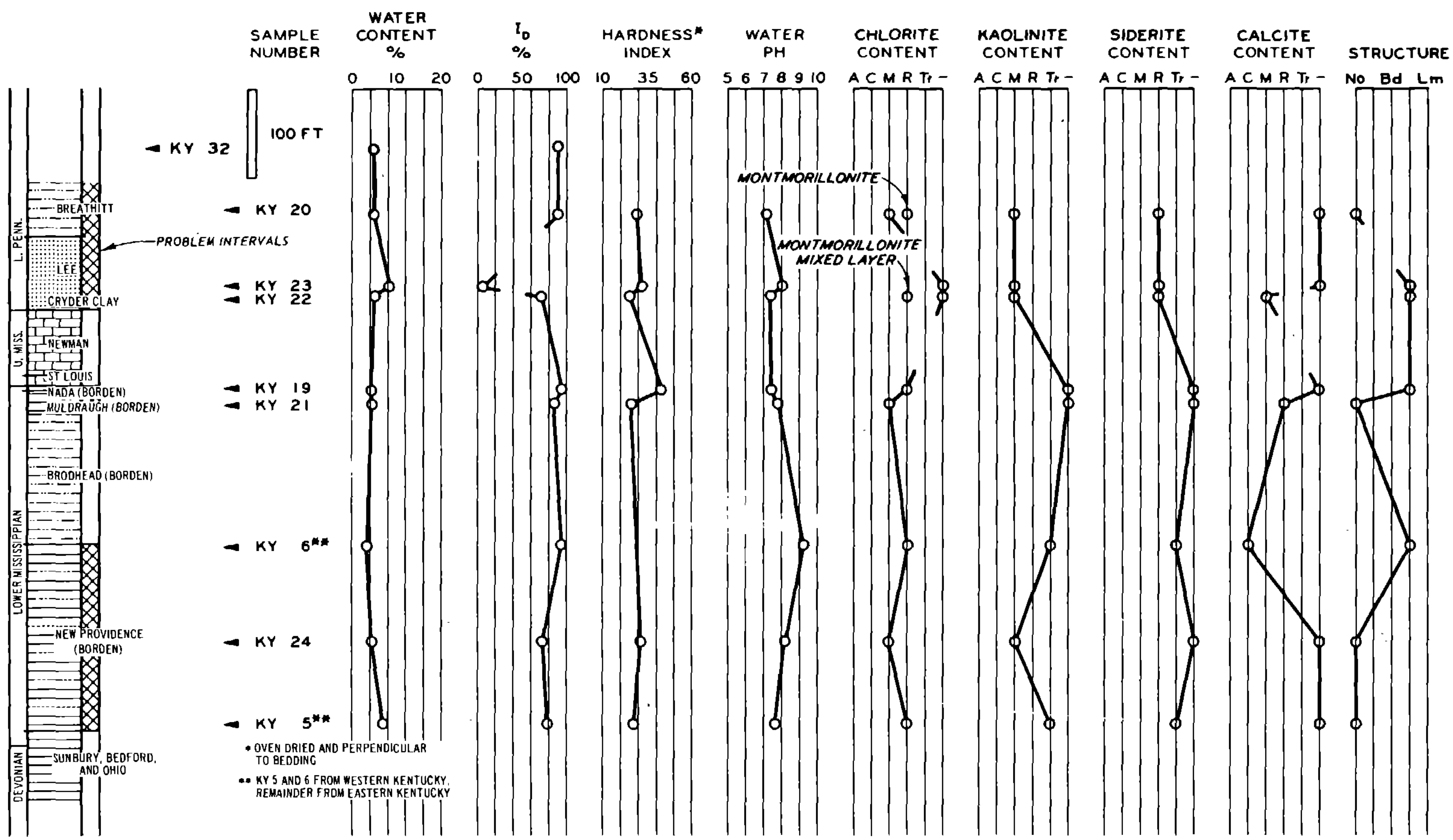


Figure 17. Test results and characteristics of shales of the New Providence, Nada, Lee, and Breathitt formations

formation contains an appreciable percentage of limestone in complicated facies arrangements with siltstone.

62. Five samples were collected from New Providence and associated formations. Two of these were taken in western Kentucky and three in eastern Kentucky, but they are combined in Figure 17 because of the similarity in nature of the formations in the two areas. Three samples of superjacent rock in the Lower Pennsylvanian are shown also. The kaolinite and siderite contents of the eight samples appear to show a distinction between the Lower Pennsylvanian and Lower Mississippian shales. The Lower Pennsylvanian shales are richer in kaolinite and siderite as a group.

63. During the collection of samples, failed embankments of New Providence and related shales were noted but the most troublesome portions of the shale strata could not be pinpointed. Apparently all shale from the Breathitt downward to the top of the Devonian black shale has potential for causing trouble. It is perhaps not surprising, therefore, that the slake-durability and hardness tests for those materials show uniformity of results, and among other characteristics, no consistent trend is apparent in progressing downward through the strata.

Lower Pennsylvanian
<u>formations of eastern Kentucky</u>

64. Three samples of shale from Lower Pennsylvanian strata were collected in eastern Kentucky. The shales were identified as problem shales by state highway representatives. The Breathitt and interfingering Lee formations are composed of shale, siltstone, and sandstone with coal.[8] Sample locations are shown in Figure 17 along with those of underlying Mississippian rocks.

65. The three Pennsylvanian samples show inconsistent characteristics except in the content of kaolinite and siderite. Kaolinite is apparently characteristically present in minor amounts and siderite in rare amounts, but both occur in greater amounts than in the underlying Mississippian. The outstanding characteristic of these Lower Pennsylvanian strata appears to be a measurable content of montmorillonite, either alone or in mixed-layer relation with clay-mica.

Redoak Mountain and
associated formations

66. A thick sequence of Middle Pennsylvanian formations was sampled in eastern Tennessee. According to state highway representatives, these coal-bearing shale and sandstone units had given problems in past embankments and are viewed with minor concern for future construction. Samples were obtained at random over a stratigraphic thickness of 1000 ft, which can be regarded as typical of the entire 4000 ft of Middle Pennsylvanian.[10]

67. The characteristics and test results in Figure 18 provided useful information not only about this sequence but for comparison with Pennsylvanian strata in Kentucky (Figures 15 and 17). The I_D was high in three of the four samples. Correspondingly, the water content was low. Samples TN 14 and 17 were freshly broken rock in coal strip mines and gave representative water contents. One of the factors that may account for the high I_D is the comparative abundance of siderite, to the exclusion of calcite and dolomite. The siderite probably constitutes a cementing agent holding the shale together and resisting slaking.

Crab Orchard formation

68. The shaly material lying immediately above the Brassfield dolomite is called the Crab Orchard formation in eastern Kentucky and the Osgood formation in western Kentucky. Both units are regarded as troublesome by the Kentucky Department of Transportation and were considered together in this study. Three samples were obtained from each part of the state, and they are shown in their relative positions in Figure 19. This figure is based on the stratigraphic column in the vicinity of Owingsville in eastern Kentucky;[8] the comparable Osgood section in the west is less than half as thick.

69. As described by Peterson,[11] the Osgood in western Kentucky consists of interbedded shale and dolomite. The shale is greenish gray and pale red and is nonfissile dolomitic shale and mudstone and weakly fissile clay shale. The unit grades into the underlying Brassfield dolomite by interbedding of shale and dolomite. Serious embankment problems have occurred in both the Osgood and the Crab Orchard formations in the

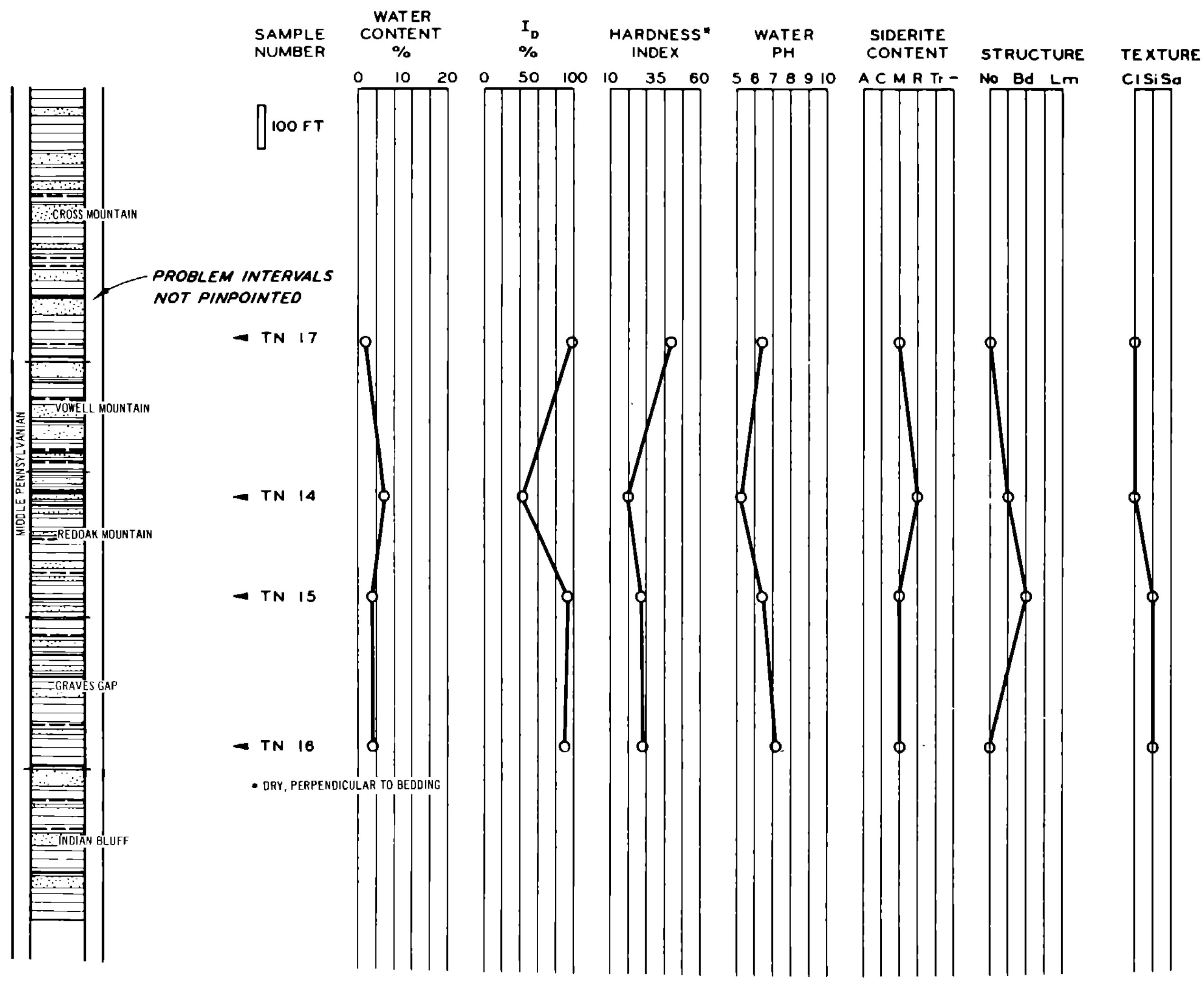


Figure 18. Test results and characteristics of Pennsylvanian shales of eastern Tennessee

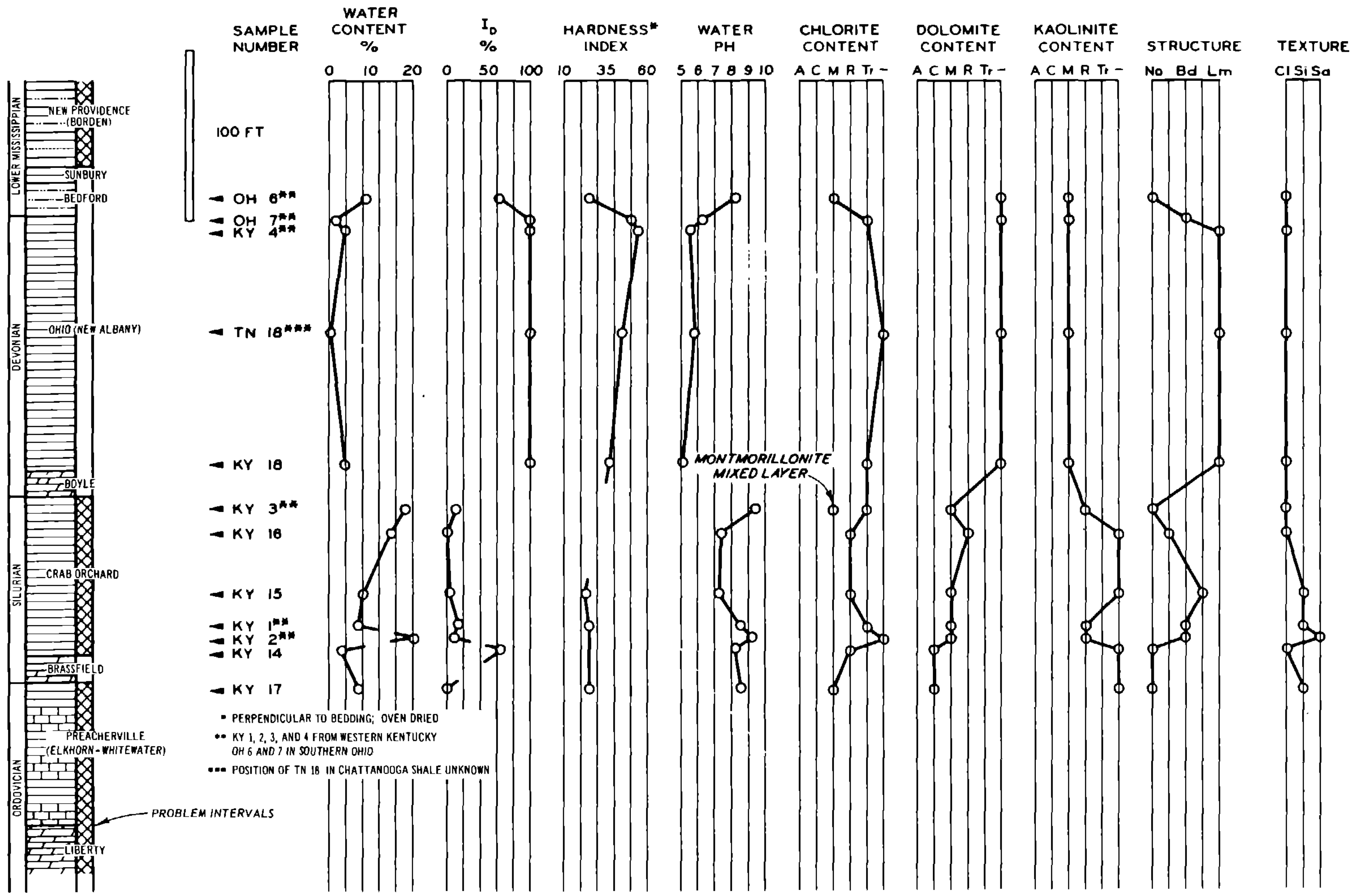


Figure 19. Test results and characteristics of shales of the Ohio (New Albany) and Crab Orchard (Osgood) formations

vicinity of the sampling sites. The entire group of samples therefore can be regarded as problem shale.

70. The problem nature appears reflected in test results since five of six samples average less than 20 in I_D. Figure 19 shows this trend in stark contrast to results from the overlying Ohio shale. The slake-durability test water was generally alkaline, but there was considerable variability. Dolomite content is particularly interesting with a rather consistent decrease upward through the Crab Orchard-Osgood. This trend apparently is related to the presence of dolomite in the shale and the transitional contact with the underlying Brassfield dolomite. One of the Osgood samples contained montmorillonite in mixed-layer relation with clay-mica.

Ohio shale

71. The Ohio (New Albany and Chattanooga) shale is relatively thin but very persistent and widespread black carbonaceous shale. The geological age is Upper Devonian. Thickness ranges from about 50 to 150 ft in the Ohio-Kentucky-Tennessee region. The shale is grayish black, very carbonaceous, brittle, and fissile. Four samples that were collected and tested came from three states but are shown together in Figure 19 in relation to the Crab Orchard formation. A fifth sample, Chattanooga shale from Oklahoma, is equivalent and could be included generally with the others.

72. In contrast to most of the other shale units, this widely distributed black shale has relatively uniform characteristics. The water content is 4 percent or less, I_D is consistently near 100, water pH is slightly acidic, and scleroscope hardness is high.

73. The mineralogy of the unit is also consistent as far as sampling in this study shows. Quartz is abundant, and the dominant clay mineral is clay-mica (illite). Chlorite is subordinate to kaolinite. A substantial amount of pyrite was present in the four samples examined mineralogically.

Palestine formation

74. Six samples identified as the Palestine formation from southern Indiana were supplied for study by the Indiana State Highway

Commission. The Palestine formation is not considered a problem shale but under different construction procedures could conceivably be one. The samples were taken along a section of about 4 miles and their stratigraphic positions within the thin Palestine formation were not established. In Figure 20, they are shown only as a group, providing no information on variation through the formation.

75. Figure 20 shows that the water content and I_D, with one exception, are fairly uniform among the samples. Similarly, the pH of test water and the chlorite content are uniform. The material contained an appreciable amount of siderite, but only one sample contained dolomite. It is interesting to note that this one sample with a small percentage of dolomite gave anomalously low slake-durability results.

Pierre formation

76. The Pierre formation constitutes a major portion of Upper Cretaceous strata on the Great Plains of eastern Colorado. According to the classification of shales in paragraph 16, the Pierre is of the thick uniform type. Sandstone facies are also present but quite subordinate. Five samples of the Pierre were obtained in the field along with samples of the Upper Cretaceous formations immediately above and below (Figure 21).

77. According to Colorado State Highway Department personnel, the Pierre formation has not generally caused settlement in embankments in recent years. A local problem involving Pierre shale in embankments was identified north of Dillon, Colorado (discussed in following paragraph), and eight samples of shale associated with this problem were taken. Salient physical characteristics of Pierre shale as revealed in Figure 21 are the apparently great variability in I_D and the associated inverse relation of this index to water content. Test water pH is consistently high. Sample CO 3 is probably not so representative of Pierre shale in view of the fact that it was located just below the Trinidad sandstone and, apparently by association, has a high sand content.

78. The eight samples of Pierre shale (Figure 22) north of Dillon, Colorado, may be somewhat anomalous and more like contemporaneous Mancos shale to the west (compare Figures 8 and 9). The basal part

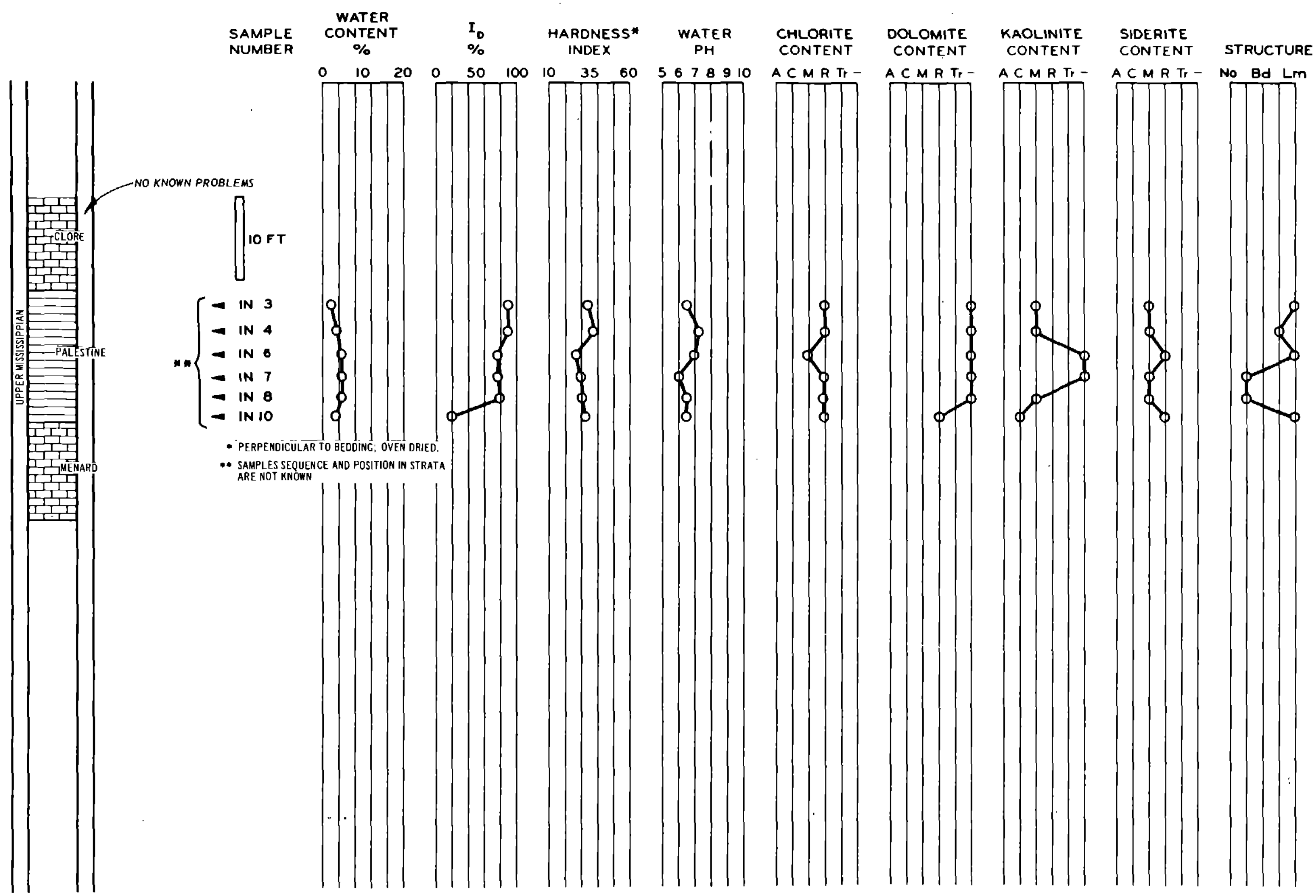


Figure 20. Test results and characteristics of shale of the Palestine formation

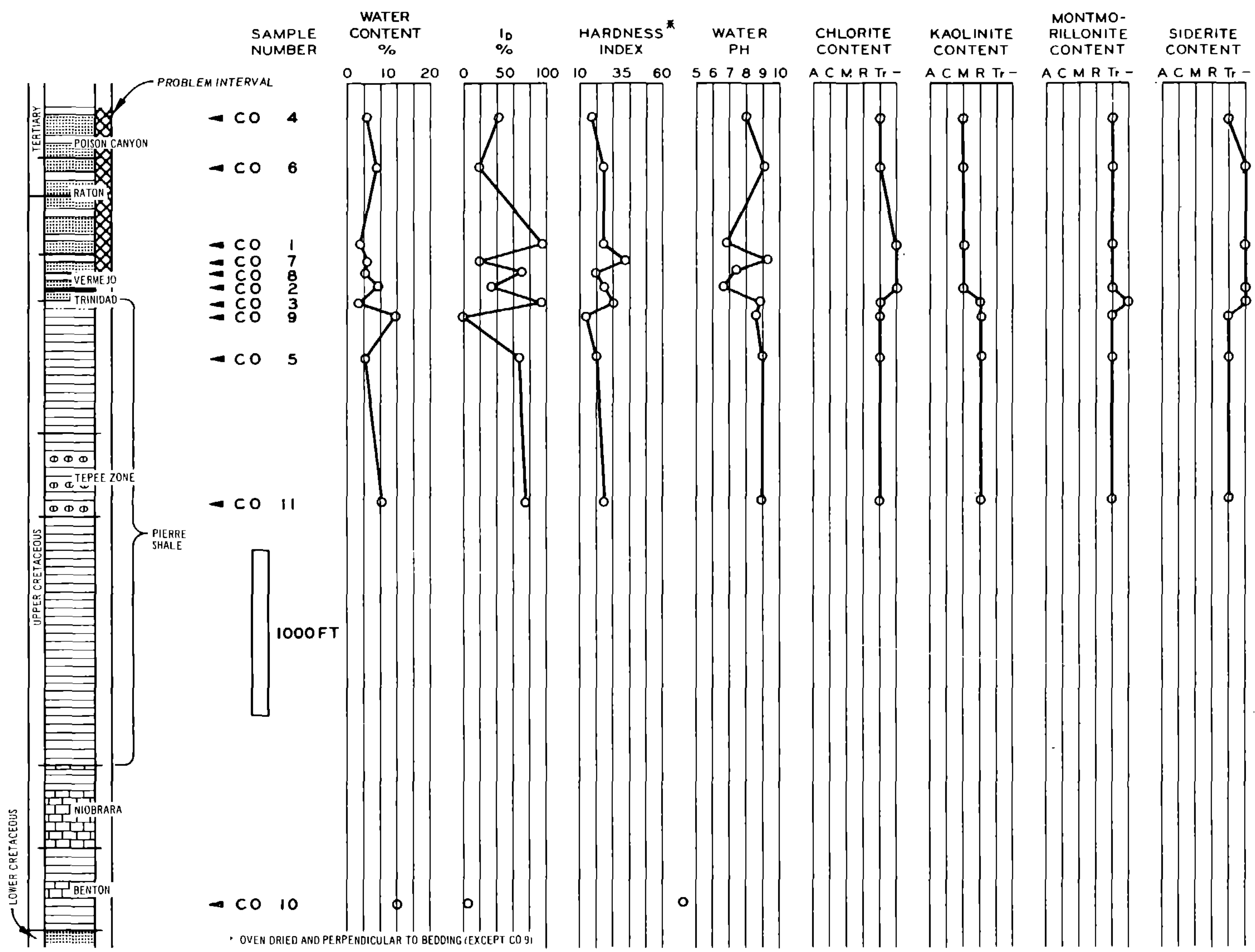


Figure 21. Test results and characteristics of Cretaceous shales of southern Colorado

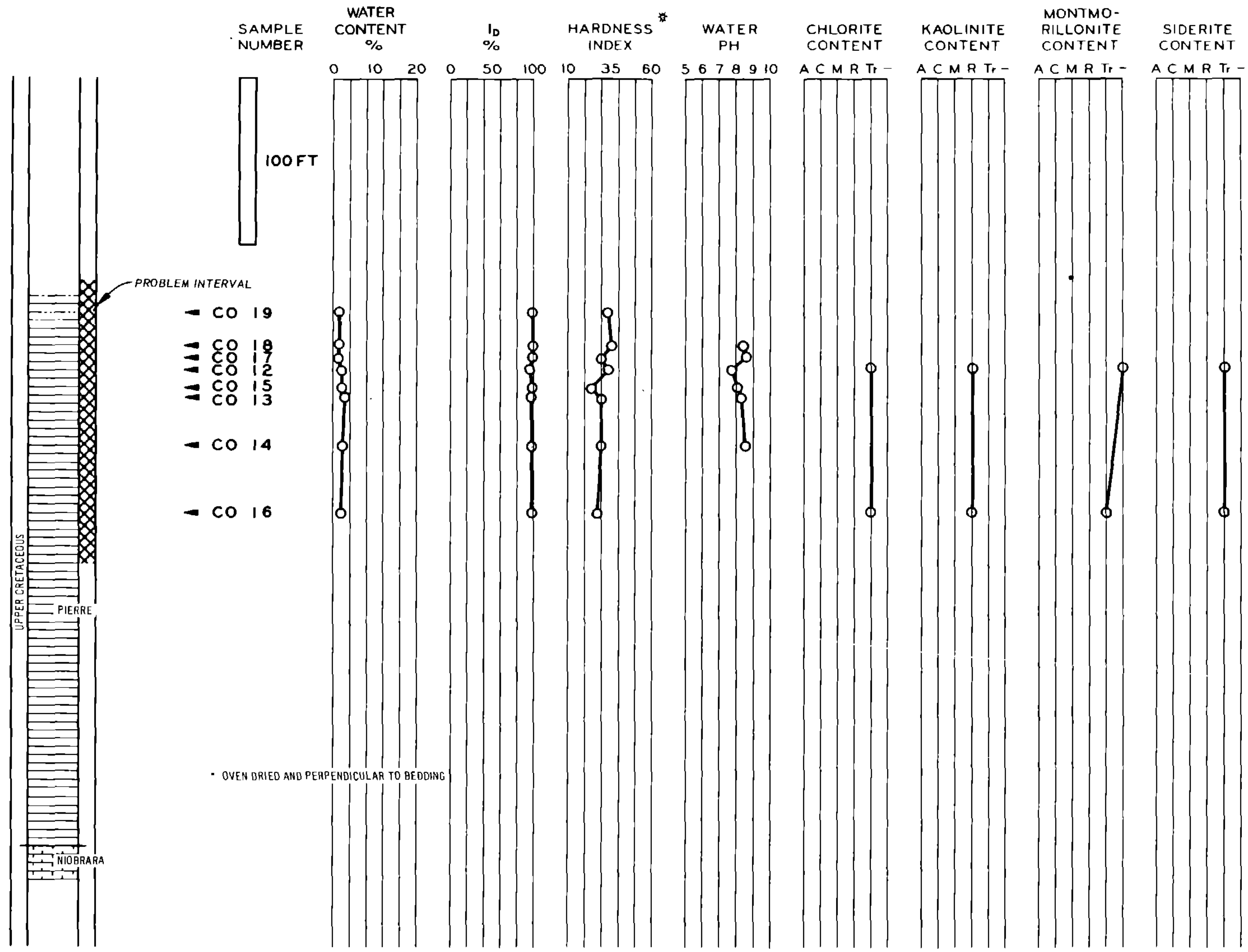


Figure 22. Test results and characteristics of shale of the Pierre formation in central Colorado

of a flat-lying section of Pierre shale, measuring at least 4900 ft nearby at Kremmling,[12] is traversed by State Highway 92 along the side of Green Mountain Reservoir. Local settlement problems developed in embankments shortly after construction in 1959. The Pierre shale along the highway consists of hard, massive shale that shows laminated structure, but no appreciable strength anisotropy. Only about 300 ft of strata were sampled and within this narrow interval no gross departures in lithology were noted except for one or two zones in which a few limy concretions are developed.

79. An interesting characteristic of the Pierre shale at Green Mountain Reservoir is the modest degree of induration, presumably brought about by localization in a region of thrust faulting and moderate igneous activity. The induration is indicated by consistently low water content. The formation as sampled has uniformly high I_D and alkalinity of testing water.

Vermejo-Raton formations

80. The Vermejo and Raton formations complete the Upper Cretaceous stratigraphy in southeastern Colorado (Figure 21), where they lie immediately above the Trinidad sandstone, upon the Pierre shale. The Vermejo has been identified as a problem shale in discussions with personnel of the Colorado State Highway Department. Sampling in the field was conducted along Highway I-25 and at some fresher excavations in the vicinity of Trinidad Dam. Shales of the Vermejo and Raton are of the type associated with sandstone, siltstone, and coal (paragraph 16), and provide for an interesting comparison of this type of shale with similar, older units in the eastern United States.

81. Six samples of the Vermejo and Raton formations are included in Figure 21. The formations show considerable variability in their properties and mineralogy. This variability probably reflects the characteristic facies changes and typically gradational nature of silty and sandy shale lithologic types. The average water content varies from 3 to 7 percent, as tested, and I_D is even more variable, between 18 and 95. Water pH is also quite variable, but in comparison with that of other western shales that were sampled, generally more acidic. The

greater acidity seems to agree with findings in coal-bearing strata in the eastern United States (Figures 15 and 18), and therefore may be more or less characteristic of such strata universally.

Mancos formation

82. The Mancos formation is a very widespread and monotonously thick shale in Utah, western Colorado, and portions of New Mexico and Wyoming. Two sections were sampled separately. The Mancos strata in the vicinity of Grand Junction, Colorado, are approximately 4000 ft thick (Figure 23) and four samples were obtained from the lower half to near the base (Young*). A larger collection of Mancos samples (Figure 24) was obtained in central Utah in the vicinity of Green River and Price.[13] Again, the thickness of the Mancos shale in Utah is approximately 4000 ft, and there is a gross continuity of some strata from the one area to the other. The source of sediments that formed shales was to the west, and there is thought to be a subtle difference in some beds farther from the source in the vicinity of Grand Junction. However, the facies changes up and down in the strata are at least as notable, and samples from both areas can sensibly be lumped together in order to represent the various shale types.

83. The Mancos shale consistently produced an alkaline test water; the pH averaged above 9. Otherwise, the Mancos shale is rather variable in physical characteristics. Samples having I_D greater than 90 were commonly obtained, but there are several with I_D much lower. The Utah Department of Transportation has recognized an occasional problem in shale embankments, particularly where the material has been broken and incorporated in the embankment in large blocks. Generally, Utah's experience has been that the Mancos causes most of its problems as a consequence of its expansive behavior, and the problems are mostly localized in cut sections or at the cut-fill transition.

84. At the top of Mancos strata at both Grand Junction and in Utah and elsewhere, uniform thick shale grades to the coal-bearing strata of the Mesa Verde formation. The relationship is clearly one

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* R. G. Young, personal communication to R. J. Lutton, 18 November 1975.

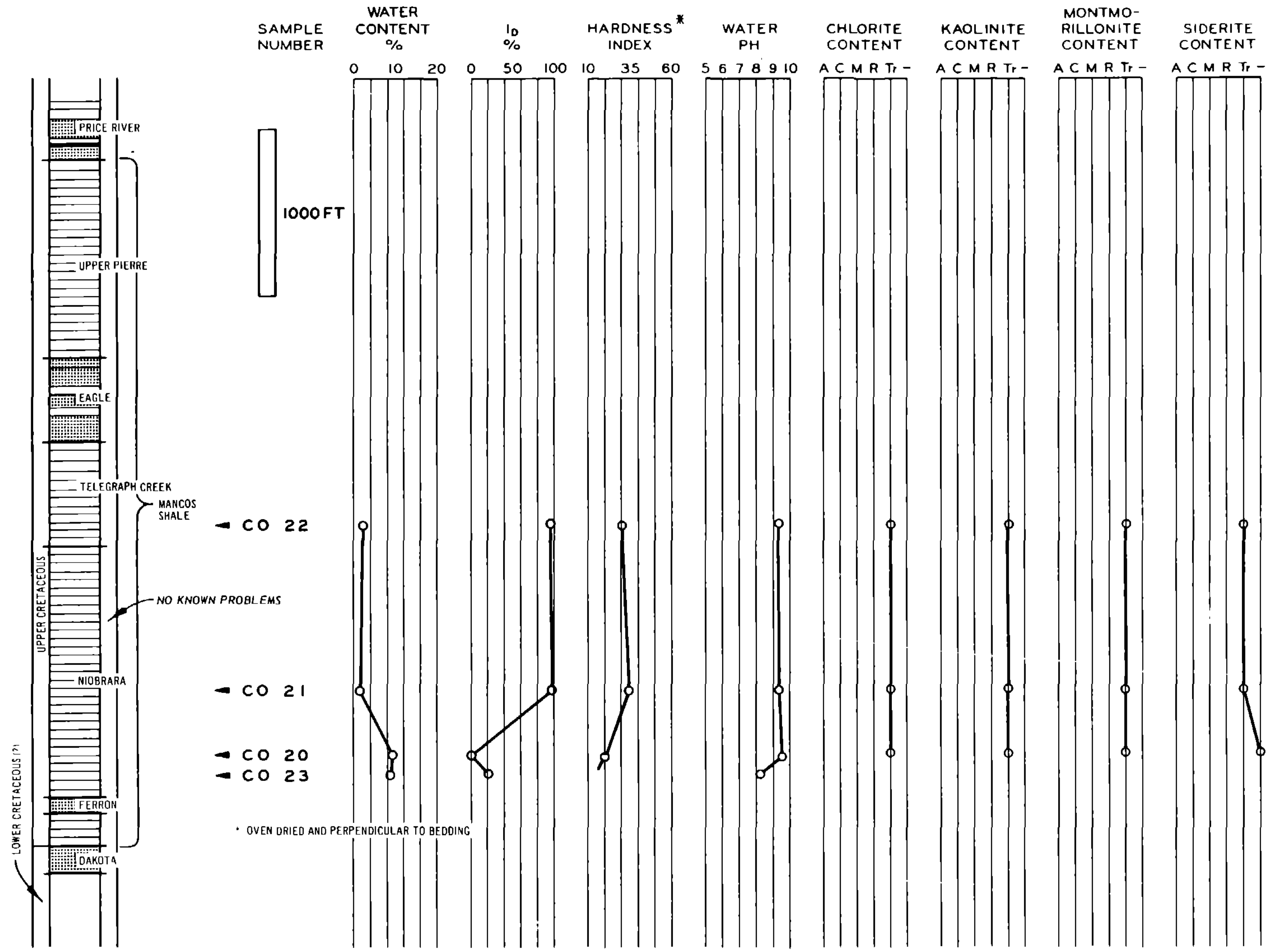

Figure 23. Test results and characteristics of shale of the Mancos formation in western Colorado

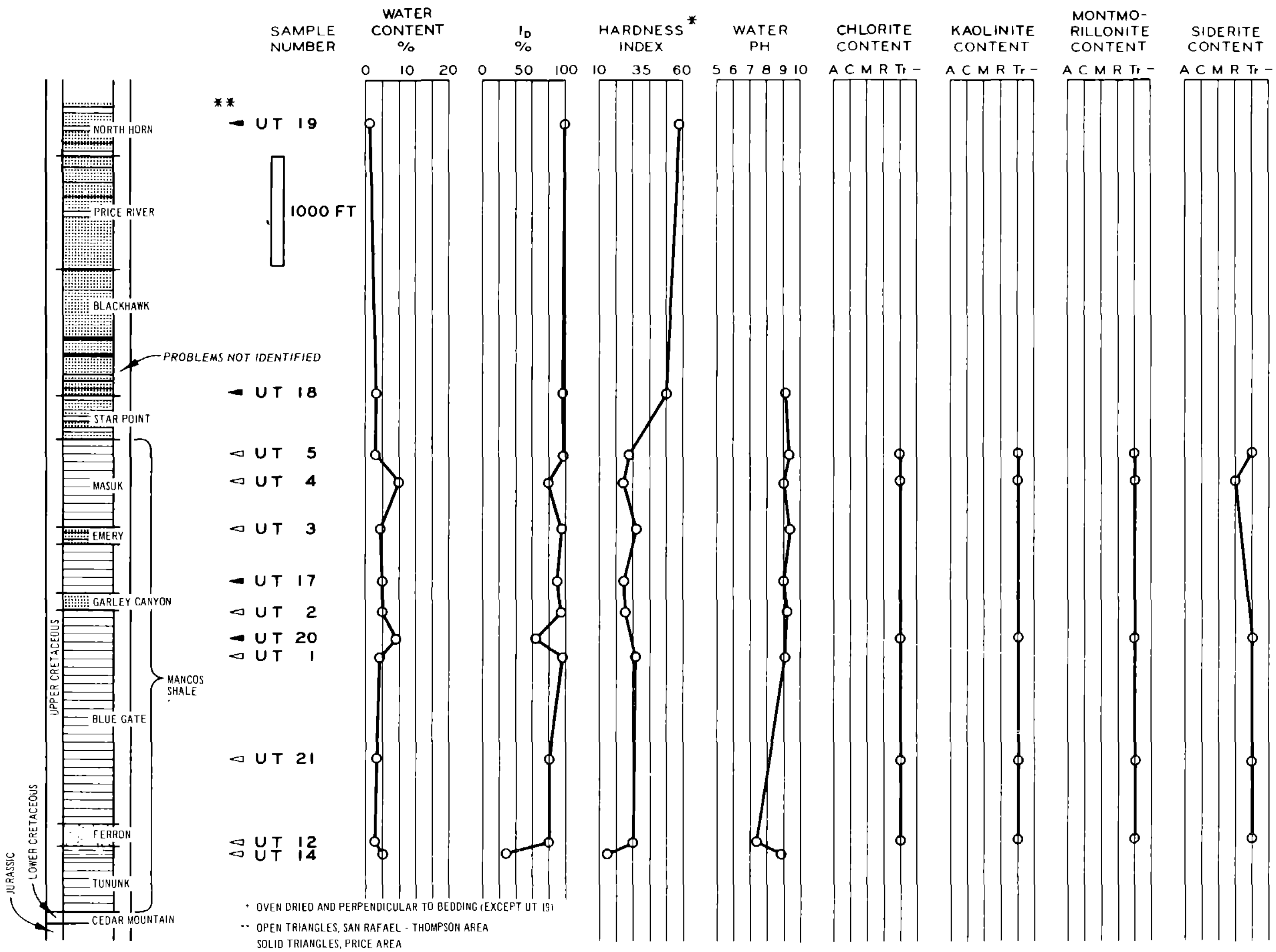

Figure 24. Test results and characteristics of shale of the Mancos formation in Utah

between facies representing different geological environments of deposition such as within the Mancos shale itself (paragraph 82). Commonly the Mancos shale interfingers as tongues within the Mesa Verde. The interrelationship of the two formations is such that coal-bearing strata are developed in the west more abundantly, whereas progressing at one horizon to the east, one may find a gradual change from Mesa Verde to Mancos type shale.

85. The samples collected in the Mesa Verde may be contrasted with the Mancos samples taken below or they may be compared with the similar Raton and Vermejo formations in southeastern Colorado (Figure 21).

Morrison and
Summerville formations

86. A small collection of samples was made in central Utah where it was reported by Utah Department of Transportation personnel that mid-Mesozoic strata were actually more troublesome than the adjacent Mancos shale. The strata sampled are composed of sandstone, siltstone, and shale without coal. They are however somewhat anomalous in two characteristics. The strata contain an unusually large amount of montmorillonite as an alteration product of volcanic material and the formations are largely nonmarine. Figure 25 reveals that the strata are weak, but otherwise similar to shales in general.

Moenkopi formation

87. A group of five samples was obtained in central Utah from the Moenkopi and overlying Chinle formations. The four samples from the Moenkopi are in a sequence of interbedded sandstone, siltstone, and shale that contains at least one interval of dolomitic strata. The shale appears to contain an abundance of finely disseminated pyrite.

88. The physical distinction of the shales of the Moenkopi seems to be principally a greater durability in comparison with the Morrison shale samples higher in the Mesozoic strata.

Conclusions from Testing and Variability Study

89. The laboratory tests and examinations explored the composition, short-term strength and elasticity, durability, and slaking

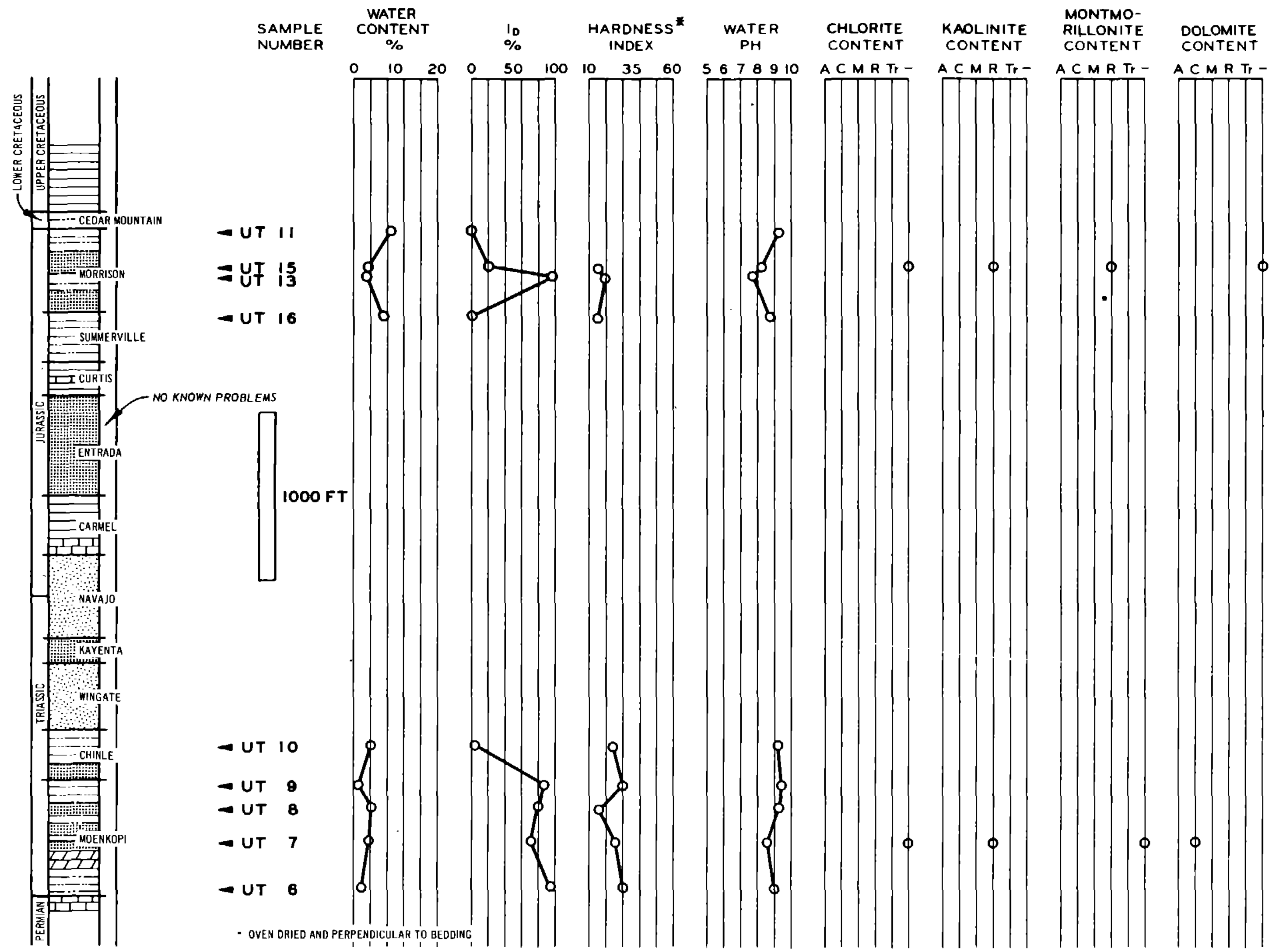

Figure 25. Test results and characteristics of shales of the Moenkopi, Summerville, and Morrison formations

behavior of shale. The short-term strength and elasticity indexes show marginal promise for predicting the important long-term behavior of shale. Details of the mineralogy provide some general background and a feel for behavior to be expected of some shale in service within an embankment, but the principal promise for quantitative indications of shale behavior appears to lie in the slaking indexes. The range of I_D results from 0 to 99 percent obtained in this study indicated that a relatively subtle distinction can be made among shales in this pertinent characteristic.

90. I_J shows promise as a simple substitute for I_D; however, Figure 13 indicates that the correlation is diffuse. Specific values are given in the figure in order to assure reasonable conservatism in using I_J in place of I_D in the design procedures proposed in Part V.

PART V: EMBANKMENT EXPERIENCES AND RELATION TO TEST INDEXES

91. In order to evaluate the use of slaking test results described in Part IV to predict embankment performance or to design new embankments, information on construction practice and performance of representative existing fills was required. Accordingly, contacts were made with highway departments requesting specific information on existing embankments constructed of the shales used in the testing program.

92. Ideally, each specific embankment to be documented should lie adjacent to a sample site for assurance that the shale in the fill was the same as that tested. Since this ideal situation was not always attainable, the contact was asked to substitute when necessary information on an appropriate fill containing shale appearing to be the same as that sampled. In a few cases, embankments more than 5 miles away were used where they were considered to be of the same material.

Construction and Performance

93. The information assembled from field visits and contacts with highway departments is presented in Table 5. Numerous construction techniques have been used, but in general they conformed to accepted practice prevailing at the time of construction. Variations in construction techniques seemed to correlate with differences in the local nature of shale or shale-rock mixtures. Thus, in much of the western United States, the areally important shales are mostly young (Cretaceous) in geological age and relatively weak, and lifts for embankment construction are commonly about 8 in. in loose thickness. In areas where the shale is stronger and is excavated in rocklike blocks, lifts were as much as 3 ft thick.

94. A generally preferred procedure for constructing embankments with shale or mixtures of shale and other materials consists of placing in 8- to 12-in. loose lifts, controlling moisture addition, and compacting with special equipment such as tamping or heavy rubber-tired rollers.

Table 5

Shale Embankment Data

Embankment	Height ft	Materials	Construction History: Date	Construction History: Lift Thickness in.	Construction History: Compaction Method	Construction History: Moisture Control	Side Slopes	Performance	Location
					Wyoming				
EWY 1	6	100% Shale	1937	6 (estimated)	Sheepsfoot roller	No	1 on 2	Very good	S-59, 8 mi north of Reno Junction
EWY 2	50	80% Shale	1962	8-12	Sheepsfoot roller	Yes	1 on 2	Continued settlement up to 1.5 ft	I-90, 15 mi east of Buffalo
EWY 3	15	90% Shale	1969	8	Compaction equipment	Yes	1 on 2	Good	S-120, 10 mi south of Cody
EWY 4	14	75% Siltstone and Shale	1965	8	Sheepsfoot roller	Yes	1 on 2	Good-very good	I-25, 4 mi north of Orin Junction
					West Virginia				
EWV 1	204	100% Shale	1971	8-24 (mostly 24)	Vibratory and paddlefoot rollers on thin lifts	Rather dry	1 on 2	25-in. settlement	US-460, sta 534, east of Princeton
EWV 2	45	70% Shale 30% Sandstone	1975	12	Harrowea, tamped, and rolled	Yes	1 on 3.5	No unexpected settlement	Beech Fork Lake Dam random zone
					New Mexico				
ENM 1	35	45% Shale 15% Sandstone 40% Bouldery clay	1965	12 (occasional blocks to 36)	Sheepsfoot and 50-ton proof rollers	Yes	1 on 1.5 (with berm on lower side)	Minor settlement	I-25, 1.6 mi south of Raton Pass summit
					Virginia				
EVA 1	108	90% Shale	1969	48	Placement and spreading equipment (possibly sheepsfoot roller)	No	1 on 2	>3-ft settlement	I-64 bridge approach at Clifton Forge
EVA 2	80+	70% Shale (+4) 30% Soil	1974	6-24	Sheepsfoot and tired rollers	Yes	1 on 2	No problems	I-64 bridge approach over US 81
					Texas				
ETX 1	18	90% Shaly clay 10% Clay	1970	6 (compacted)	Sheepsfoot roller	Yes	1 on 2	No settlement or swell visible	US-287 at FM 1763 at Harrold

(Continued)

Sheet 1 of 8

Table 5 (Continued)

Embankment	Height ft	Materials	Construction History: Date	Lift Thickness in.	Compaction Method	Moisture Control	Side Slopes	Performance	Location
					Indiana				
EIN 1	40	75% Shale 25% Limestone	1961	48	No special compaction	No	1 on 2	Major settlement and sliding	I-74, 1.2 mi east of S-1 interchange
					Tennessee				
ETN 1	25	65% Shale 35% Limestone	1934	6	10-ton minimum	Yes	1 on 1	Good	US-11 W, 1.7 mi north of S-70
ETN 2	15	85% Shale 15% Ls-clay	1946	12	Sheepsfoot roller	Yes	1 on 1.2	No appreciable change	Old S-92, 1.5 mi north of I-40 interchange
ETN 3	12	50% Shale 50% Ls-clay	1946	12	Sheepsfoot roller	Yes	1 on 1	Very minor settlement	Old S-92, 1.2 mi north of I-40 interchange
ETN 4	7	70% Shale 30% Limestone	1946	12	Sheepsfoot roller	Yes	1 on 1.5	Good	Old S-92, 1 mi north of I-40 interchange
ETN 5	28	50% Shale 50% Siltstone	1967	6+	Sheepsfoot roller	Yes	1 on 1.5	No settlement	US-11 W, 0.6 mi north of S-66
ETN 6	35	60% Shale 40% Siltstone	1941	12	Sheepsfoot roller	Yes	1 on 1.5	Very good despite partial submergence	US-25 E, 0.3 mi north of US-11 W
ETN 7	16	60% Shale-clay 40% Sandstone	Before 1942	<36	Horses and wagons	No	1 on 1	Minor slumps; generally good	S-63, 0.5 mi east of S-2344
ETN 8	15	80% Shale 20% Sandstone	Before 1942	<36	Horses and wagons	No	1 on 1.5	Fair to good; no major settlement	S-63, 1.6 mi west of S-2344
ETN 9	20	85% Shale 15% Sandstone	Before 1942	<36	Horses and wagons	No	1 on 1.7	Shear failure	S-63, 2.2 mi west of S-2344
ETN 10	10	50% Shale 50% Sandstone	1941	12	Sheepsfoot roller	Yes	1 on 1.5	Good; no noticeable settlement	US-25 E, 1.8 mi north of US-11W
ETN 11	10	75% Shale-clay 25% Sandstone	1941	12	Sheepsfoot roller	Yes	1 on 1.5	Good; possibly minor settlement	US-25 E, 2 mi north of US-11W
ETN 12	105	100% Shale and siltstone	1966	18-36	Haulers, spreaders, and sheepsfoot roller	No	1 on 1.5	Major settlement with cracking	I-75, sta 964 near Stinking Creek exit

(Continued)

Sheet 2 of 8

Table 5 (Continued)

Embankment	Height ft	Materials	Construction History: Date	Lift Thickness in.	Compaction Method	Moisture Control	Side Slopes	Performance	Location
					Oklahoma				
EOK 1	10	90% Shale 10% Limestone	1940	8	Haulers and sheepsfoot roller	No	1 on 1.5	Minor dips	US-69, Durant to Bokchito
EOK 2	20	90% Shale 10% Limestone	1940	8	Haulers and sheepsfoot roller	No	1 on 1.5	Slumps common	US-69, Durant to Bokchito
EOK 3	8	85% Shale 15% Sandstone	1950	8	Mostly hauling equipment	No	1 on 3	Some minor undulations	S-51, Kingfisher to Logan County line
EOK 4	10	60% Shale 40% Sandstone	1950	8	Mostly hauling equipment	No	1 on 2	No problems	US-59, Sallisaw to Adair County line
EOK 5	20	60% Shale 40% Sandstone	1950	8	Mostly hauling equipment	No	1 on 2	Considerable slumps; very little settlement	US-59, Sallisaw to Adair County line
EOK 6	25	70% Shale 30% Sandstone	1964	8	Haulers and sheepsfoot rollers	Yes	1 on 2.5	Settlement undulations	US-69, McAlester to Checotah
					South Dakota				
ESD 1	10	75% Weathered shale 25% Soil	1963	12	Sheepsfoot roller	Yes	1 on 4	No problems	S-47W, sta 232 north of Reliance
					Arizona				
EAZ 1	10	50% Shale 50% Blowsand	1970	6-8	Sheepsfoot roller	No	1 on 2	Excellent	S-180 at MP 323.5
EAZ 2	5	40% Shale 60% Blowsand	1961	6-8	Sheepsfoot roller	No	1 on 4	Good	I-40 at MP 323.0
					Kansas				
EKS 1	6	50% Shale 50% Soil	1963	6 (compacted)	Sheepsfoot roller	Yes	1 on 3	No problems	US-183, 11.5 mi north of I-70

(Continued)

Sheet 3 of 8

Table 5 (Continued)

Embankment	Height ft	Materials	Construction History: Date	Lift Thickness in.	Compaction Method	Moisture Control	Side Slopes	Performance	Location
					Ohio				
EOH 1	100	80% Shale 20% Limestone	1974	8	Dozers, scrapers, and sheepsfoot rollers	Yes	1 on 2 plus counterberm	Foundation failure	I-74, I-275 interchange west of Miamitown
EOH 2	45	75% Shale 25% Limestone	1961	8	According to specifications to obtain compaction	No	1 on 2	No settlement	Columbia Parkway over Penn Central RR
EOH 3	35	100% Shale	1974	24	Spread with bulldozer	Yes	1 on 2	No settlement; minor sloughing	I-675 Greene County sta 863-881
EOH 4	40	100% Shale	1971	8	Scrapers, dozers, and sheepsfoot rollers	Yes	1 on 2	No problems	US-23, sta 806-810, Ross County
EOH 5	40	100% Shale	1972	8	Scrapers, dozers, and sheepsfoot rollers	Yes	1 on 2	No settlement	S-124, sta 1258-1288, Adams County
EOH 6	40	75% Shale 25% Limestone	1962	8-36	Scrapers, dozers, and sheepsfoot rollers	No	1 on 2	Major approach fill settlement; some in foundation	I-74 at Wesselman Road, Hamilton County
EOH 7	55	75% Shale 25% Limestone	1961	8	Tamping roller and 50-ton tired roller	Yes	1 on 2	Insignificant settlement in approach fill	I-74 over S-128, Hamilton County
EOH 8	30	30% Shale 70% Limestone	1959	8	According to specifications with 90-day waiting period	Yes	1 on 2	Settlement probably in foundation	I-75, north of S-63 at Penn Central Railroad
EOH 9	70	<50% Shale >50% Sandstone	1960	8	Bulldozers and sheepsfoot rollers	No	1 on 2	Approach fill settlement up to 12" in 10 years	S-57 over Black River, Lorain County
					Montana				
EMT 1	60	100% Argillite and quartzite	1962	24-36	End-dumped and dozed to spread	No	1 on 1.5	1- to 2-ft settlement first year only; foundation probably involved	I-15, 10 mi north of Helena
EMT 2	50	100% Shale	1959	6-12	Spread, blended, and compacted	Yes	1 on 1.5	Good; only minor settlement	US-191, about 5 mi south of Missouri River

(Continued)

Table 5 (Continued)

Embankment	Height ft	Materials	Construction History: Date	Lift Thickness in.	Compaction Method	Moisture Control	Side Slopes	Performance	Location
					Colorado				
ECO 1	25	100% Shale	1968	8	Sheepsfoot roller	Yes	1 on 3 (max) 1 on 4	No settlement	US-285, 3 mi southeast of Morrison
ECO 2	20	90% Shale	1952	6-8	Sheepsfoot roller	Yes	1 on 2	No settlement	I-25, 2.1 mi south of Fountain interchange
ECO 3	50	100% Shale	1960	8 12 (maximum)	Sheepsfoot roller	Yes	1 on 2	No significant settlement	I-25, sta 1720, north of Walsenburg exit
ECO 4	15	60% Shale 40% Soil	1965	8	Buffalo compactor	Yes	1 on 3	No settlement	I-25, 0.5 mi south of Graneros Canyon exit
ECO 5	40	60% Shale 40% Rock	1967	12-18	Sheepsfoot roller	Yes	1 on 2	Minor settlement over pipe	I-25, sta 600 north of port-of-entry
ECO 6	40	50% Shale 50% Sandstone	1974	18 (average) 24 (maximum)	Compactors	Yes	1 on 2	No problems except settlement in abutment fill	S-12 near Cokedale, west of Trinidad
ECO 7	80	50% Shale 50% Sandstone	1973	12	Disced and rolled	Yes	1 on 2	No problems	Trinidad Lake, sta 168 on railroad relocation
ECO 8	35	40% Shale 60% Sandstone	1965	36 (many blocks)	Compacted (but blocky)	Partial	1 on 1.5	Local dips and general settlement	I-25, sta 170 (and 235) south of Trinidad
ECO 9	112	70% Shale and Soil 30% Sandstone	1964	12	Disced and rolled	Yes	1 on 2	Good service	I-25, sta 84 south of Trinidad
ECO 10	4	100% Shale	1959	8	Haulers and rollers	Yes	1 on 4	Minor distress	I-70 MP 357, west of Limon
ECO 11	20	100% Shale	1958	8	Sheepsfoot roller	Yes	1 on 2	Considerable distress	I-70, exit 96 west of Limon
ECO 12	50	100% Shale	1958	8-24	Sheepsfoot roller	Yes	1 on 2	Good service	S-9, 3.7 mi south of Grand-Summit County line
ECO 13	50	100% Shale	1958	8-72 >24 (75%)	Sheepsfoot roller	Ineffective	1 on 2	Settlement and bumps	S-9, 4.6 mi south of Grand-Summit County line

(Continued)

Sheet 5 of 8

Table 5 (Continued)

Embankment	Height ft	Materials	Construction History: Date	Construction History: Lift Thickness in.	Construction History: Compaction Method	Construction History: Moisture Control	Side Slopes	Performance	Location
					Colorado (Continued)				
ECO 14	12	100% Shale	1972	8	Self-loading high speeds and sheepsfoot rollers	Yes	1 on 2	Good	S-141, just north of US-50 intersection
ECO 15	6	100% Shale	1966	8	High speeds and waffle-iron rollers	Yes	1 on 4	Fair	I-70, 1 mi east of Airport interchange
ECO 16	25	100% Shale	1970	8	High speeds and sheepsfoot rollers	Yes	1 on 2	Ramps good; some settlement just off abutments	I-70 Loma interchange
					Kentucky				
EKY 1	70	75% Shale 25% Limestone	1962	12-18	Sheepsfoot and paddlefoot rollers	No	1 on 2	No problems	I-75 NBL at MP 148.5
EKY 2	60	70% Shale 30% Limestone	1962	12-18	Sheepsfoot and paddlefoot rollers	No	1 on 2	With dips and 3-in. pavement separation	I-75 SBL at MP 148.5
EKY 3	70	75% Shale 30% Limestone	1962	36	Dozers and haulage equipment only	No	1 on 2	About 1 ft general settlement; patched	I-75 SBL at MP 150.2
EKY 4	60	70% Shale 30% Limestone	1962	36	Dozers and haulage equipment only	No	1 on 2	About 1.5 ft general settlement and dips; patched	I-75 SBL at MP 151.2
EKY 5	60	60% Shale 40% Limestone	1960	24	Sheepsfoot and paddlefoot rollers	No	1 on 2	Minor settlement and dips; no patch	I-75 SBL at MP 156.0
EKY 6	60	50% Shale 50% Limestone	1959	24	Sheepsfoot and paddlefoot rollers	No	1 on 2	Only minor dips; no patches	I-75 NBL at MP 160.8
EKY 7	30	50% Shale 50% Sandstone	1971-72	18-24	Vibratory roller	No	1 on 2	No problems	I-64 WBL at MP 178.6
EKY 8	80	70% Shale 30% Sandstone	1967	18-24	Vibratory roller	No	1 on 2	Broad, modest settlement and dips	I-64 EBL and WBL at MP 163.2
EKY 9	90	50% Shale 50% Sandstone	1967	18-24	Vibratory roller	No	1 on 2	Generally good; very minor dips	I-64 EBL at MP 164.0

(Continued)

Sheet 6 of 8

Table 5 (Continued)

Embankment	Height ft	Materials	Construction History: Date	Lift Thickness in.	Compaction Method	Moisture Control	Side Slopes	Performance	Location
					Kentucky (Continued)				
EKY 10	70	65% Shale 35% Sandstone	1970	18-24	Paddlefoot roller	Very little	1 on 2	Minor broad dips	I-64 WBL at MP 152.8
EKY 11	40	50% Shale 50% Sandstone	1970	18-24	Vibratory roller	No	1 on 2	No problems	I-64 WBL at MP 151.2
EKY 12	70	50% Shale 50% Siltstone	1968	36	Dumped and pushed; not rolled	No	1 on 2	No problems	I-64 EBL at MP 145.5
EKY 13	60	50% Shale 50% Limestone	1966	24	Haulage equipment only	No	1 on 2	Major settlement approach embankment; may involve foundation	I-64 EBL and WBL at MP 134.8
EKY 14	30	100% Shale	1967	36 (60 on bottom)	Split-wheel rolling by pushover dozer spreader	No	1 on 2	No problems	I-64 at MP 130.0
EKY 15	45	70% Shale, Soil 30% Limestone	1966	---	---	---	1 on 2	About 1 ft settlement	I-64 at MP 122.7
EKY 16	40	40% Shale 60% Dolomite	1964	---	---	No	1 on 2	General settlement; with patches	Blue Grass Parkway at MP 16.9
EKY 17	50	60% Shale 40% Dolomite	1964	---	---	No	1 on 2	No problem	Blue Grass Parkway at 13.7
EKY 18	25	--	1964	---	---	No	1 on 2	Major settlement of approach fill	Blue Grass Parkway at MP 10.3 over L&NRR
EKY 19	40	100% Shale	1964	---	---	No	1 on 2	No problem	Blue Grass Parkway at MP 5.3
EKY 20	70	50% Shale, Soil 50% Sandstone	1962	18-30 (12 on top)	Rolled upper 20 ft with tired roller	No	1 on 2	No problems	Western KY Parkway at MP 92.9 (Do Stop)

(Continued)

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Table 5 (Concluded)

Embankment	Height ft	Materials	Construction History: Date	Lift Thickness in.	Compaction Method	Moisture Control	Side Slopes	Performance	Location
					Kentucky (Continued)				
EKY 21	70	90% Shale 10% Sandstone	1962	12	Rubber-tired roller	No	1 on 2	No problems	Western KY Parkway at MP 91.0 (Dog Cr)
EKY 22	25	50% Shale 50% Sandstone	1962	---	---	No	1 on 2	No problems	Western KY Parkway at MP 78.9
EKY 23	25	50% Shale 50% Sandstone	1962	24	Sheepsfoot roller	No	1 on 2	No problems	Western KY Parkway at MP 23.7
EKY 24	50	50% Shale 50% Sandstone	1962-63	24-30	Little or no rolling	No	1 on 2	Minor dips	Western KY Parkway at MP 20.1
EKY 25	20	70% Shale 30% Sandstone	1962-63	24-30 (48 on bottom)	Little or no rolling	No	1 on 2	Appears OK but said to have failed	Western KY Parkway at MP 19.8
					Utah				
EUT 1	20	100% Shale (minor gravel)	1969	12	Self-propelled sheepsfoot roller	Yes	1 on 2	Few rough spots from expansion	I-70 at and just east of S-10
EUT 2	40	100% Shale	1965	12-18	Sheepsfoot roller	Yes	1 on 2	Good	I-70 EBL 1.9 mi east of S-24
EUT 3	20	50% Shale 50% Sandstone	1965	18-24	Sheepsfoot roller	No	1 on 2	Good	S-24 approach over I-70, Emery County
EUT 4	10	100% Shale	1959	8-12	Sheepsfoot roller	Yes	1 on 2	Soft spots due to seepage	I-70 WBL just west Crescent Jct
EUT 5	15	100% Shale	1956	12-36	---	Yes	1 on 2	Good	US-6-50 approach fill 500 ft south of S-139 at Helper
EUT 6	50	100% Shale	1968	8-24	Hauling equipment, dozers, and sheepsfoot roller	Yes	1 on 2	Good	US-6-50 approach over railroad 5 mi south of Woodside.
EUT 7	40	80% Shale 20% Gravel	1968	8-24	Hauling equipment and dozers	Yes	1 on 2	Good	S-10 0.5 mi south of north end of S-155

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There does seem to have been common variations in the side slopes used on highway fills from place to place. Frequently the side slopes are designed on the basis of experience or slope stability analysis. Thus some weak western shale embankments are constructed 1V on 4H whereas embankments of apparently stronger shale are commonly constructed 1V on 2H. The side slope inclination is included in Table 5 because this factor can also be important in the performance of embankments, particularly in regard to potential shear failure. However, since this report emphasizes settlement (paragraph 8) with or without subsequent shear failure, the side slope is not considered in detail.

95. Mixtures of shale and rock often require special procedures to allow compaction in thin lifts. Interbedded sandstone or limestone commonly breaks and is later incorporated in shale-rock fills in oversized blocks. One procedure is to scatter these blocks evenly about and compact around them in the usual thinner lifts. Special care is needed in compacting fine material adjacent to the blocks, since voids left in this critical area have been suspected of leading to problems in some fills. Such mixtures also cause problems in moisture control and often result in a nonuniform distribution of moisture.

96. Elsewhere mixtures of shale and rock have been treated by separate compaction of thick lifts of blocky rock interlayered with the thin lifts of finer shale and soil. This procedure has been known to lead to excessive seepage and consequent instability in fills,[14] but in embankment ECO 9 (see Table 5) a satisfactory result was obtained using this method locally in the embankment. Obviously the attention to details of material and setting and the care exercised during construction may make the difference between good and bad results from the same general technique.

Test Results in Relation to Experience

97. This section presents an analysis of the interrelations of three factors: durability index, construction lift thickness, and embankment performance. The analysis, graphically introduced in Figure 26,

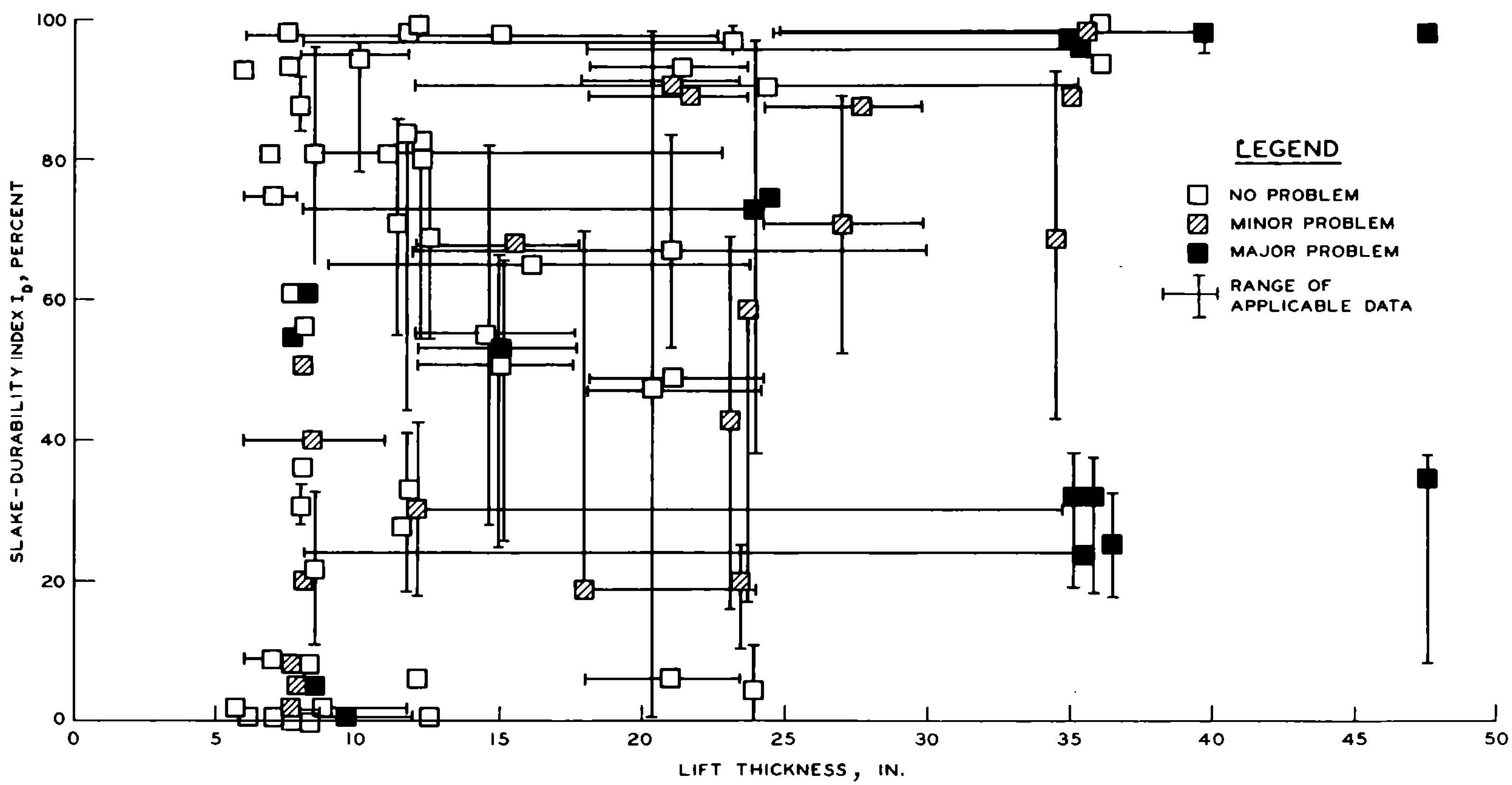

Figure 26. Relationship between slake-durability index (I_D), lift thickness, and performance of embankment

was developed on the basis of the evaluation of the problem as indicated in paragraphs 6-8. Representative I_D values for shale samples are plotted against construction lift thicknesses of associated fills (Table 6), and the performance of each fill is indicated by the pattern shown for each point. One conclusion of this graphical analysis is that no firm relationship exists among all three chosen factors. Much time was spent in finding sources of construction information, in sampling and testing representative shales, and in observing or interviewing about present conditions of specific embankments. Nevertheless the suspected relationship (see next paragraph) did not materialize clearly on the plot except possibly from a subjective point of view, i.e., a grouping of five problem embankments at the lower right in Figure 26 and a grouping of no-problem embankments at the upper left.

98. Experience information of a more general nature has been introduced in Figure 27. A survey of state highway departments[2] established that prevailing construction procedures for embankments typically limit lift thickness for rock, including hard shale, to 36 in. Similarly, construction lifts, using soil or degradeable shale, conventionally range from 6 to 12 in. and average 8 in. in loose thickness. These preferred construction lift thicknesses, representing many department-years of experience among the numerous states, constitute two well-established end points that should be accommodated on any meaningful linear or curvilinear relationship that might have developed on the graph (i.e. rock, with I_D = 100 percent and lift thickness of 36 in.; and soil, with I_D = 0 percent and lift thickness of 8 in.). Accordingly, the specific data points on the figure might ordinarily be expected to show some preferred distributions with respect to a line connecting the end points.

99. In Figure 27 a linear relationship connecting the two end points has been added (linear for simplicity) for comparison with the specific embankment data collected in this study. This line amounts to a hypothetical criterion for judging optimum lift thickness considering only material durability and embankment lift thickness. Accordingly, an embankment constructed of a given material would be anticipated to

Table 6

Embankment and Sample Associations for Analysis

Embankment	Lift Thickness* in.	Associated Samples	Range** of Average I_D %	Problem Class
EWY 1	6	WY 1, 2	0	None
EWY 2	8-12	WY 1, 2	0	Major
EWY 3	8	WY 3, 4	28-34	None
EWY 4	8	WY 5, 6	84-92	None
EWV 1	8-<u>24</u>	WV 2-8	38-97	Major
EWV 2	12	WV 1	6	None
ENM 1	<u>12</u>-36	CO 4, 6	18-43	Minor
EVA 1	48	VA 1-3	97-99	Major
EVA 2	6-24	VA 4	98	None
EIN 1	48	IN 2, 5, 9, 12	8-38 (35)	Major
ETN 1	6	TN 2	93	None
ETN 2	12	TN 8-11	42-84 (83)	None
ETN 3	12	TN 8-11	42-84 (83)	None
ETN 4	12	TN 3-7	55-86 (71)	None
ETN 5	6+	TN 12, 13	80-81	None
ETN 6	12	TN 12, 13	80-81	None
ETN 7	<36	TN 14, 15	43-93	Minor
ETN 8	<36	TN 16	89	Minor
ETN 9	<36	TN 17	97	Major
ETN 10	12	TN 18	99	None
ETN 11	12	TN 18	99	None
ETN 12	18-36	TN 20, 21	96-98	Major
EOK 1	8	OK 7	6	Minor
EOK 2	8	OK 7	6	Major
EOK 3	8	OK 8	7	Minor
EOK 4	8	OK 2	56	None
EOK 5	8	OK 2	56	Major
EOK 6	8	OK 3	51	Minor
ESD 1	12	SD 1	0	None
EAZ 1	6-8	AZ 2	0	None
EAZ 2	6-8	AZ 1	9	None
EKS 1	6	KS 1	0	None
EOH 2	8	OH 3	36	None
EOH 3	24	OH 4, 5	17-60 (60)	Minor
EOH 4	8	OH 6	61	None

(Continued)

* Prevalent thickness underlined in range of values.

** Typical value indicated in parenthesis where range is large.

(Sheet 1 of 3)

Table 6 (Continued)

Embankment	Lift Thickness in.	Associated Samples	Range of Average I_D %	Problem Class
EOH 5	8	OH 7	99	None
EOH 6	8-36	OH 8	24	Major
EOH 7	8	OH 2, 9	10-32	None
EOH 9	8	OH 6	61	Major
ECO 1	8	CO 26	0	None
ECO 2	6-8	CO 11	75	None
ECO 3	8-12	CO 9	0	None
ECO 4	8	CO 10	7	None
ECO 5	12-18	CO 3, 5	68-95 (68)	Minor
ECO 6	18-24	CO 7, 8	19-70 (19)	Minor
ECO 7	12	CO 2	33	None
ECO 8	36	CO 2, 6	18-33	Major
ECO 9	12	CO 4, 6	18-43	None
ECO 10†	8	CO 24	66	Minor
ECO 11	8	CO 25	0	Minor?
ECO 12	8-24	CO 12-19	95-99 (98)	None
ECO 13	8-72 >24 75%	CO 12-19	95-99 (98)	Major
ECO 14	8	CO 20	0	None
ECO 15	8	CO 22	94	None
ECO 16	8	CO 23	20	Minor?
EKY 1	12-18	KY 25-27; OH 3, 8	24-67 (52)	None
EKY 2	12-18	KY 25-27; OH 3, 8	24-67 (52)	Major
EKY 3	36	KY 29, 30; IN 5; OH 9	18-38 (32)	Major
EKY 4	36	KY 29, 30; IN 5; OH 9	18-38 (32)	Major
EKY 5	24	KY 28; OH 2	10-25	Minor
EKY 6	24	IN 2, 9; OH 1	16-70	Minor
EKY 7	18-24	KY 31	49	None
EKY 8	18-24	KY 32	91	Minor
EKY 9	18-24	KY 32	91	None
EKY 10	18-24	KY 20	91	Minor
EKY 11	18-24	KY 23	6	None
EKY 12	36	KY 19	95	None
EKY 13	24	KY 24	74	Major
EKY 14	36	KY 18	99	None
EKY 20	12-30	KY 12, 13	53-84	None

(Continued)

† Not plotted because of low embankment height.

(Sheet 2 of 3)

Table 6 (Concluded)

Embankment	Lift Thickness in.	Associated Samples	Range of Average I_D %	Problem Class
EKY 21	12	KY 12, 13	53-84	None
EKY 23	24	KY 8, 9	0-11	None
EKY 24	24-30	KY 7, 10	52-89	Minor
EKY 25	24-30	KY 7	89	Minor?
EMT 1	24-36	MT 6	98	Minor?
EMT 2	6-12	MT 5	40	Minor
EUT 1	12	UT 21	81	None
EUT 2	12-18	UT 12, 14	28-82	None
EUT 3	18-24	UT 13, 15, 16	0-97	None
EUT 4	8-12	UT 3-5	78-97	None
EUT 5	12-36	UT 17	91	None
EUT 6	8-24	UT 1, 20, 21	65-97	None
EUT 7	8-24	UT 20	65	None

(Sheet 3 of 3)

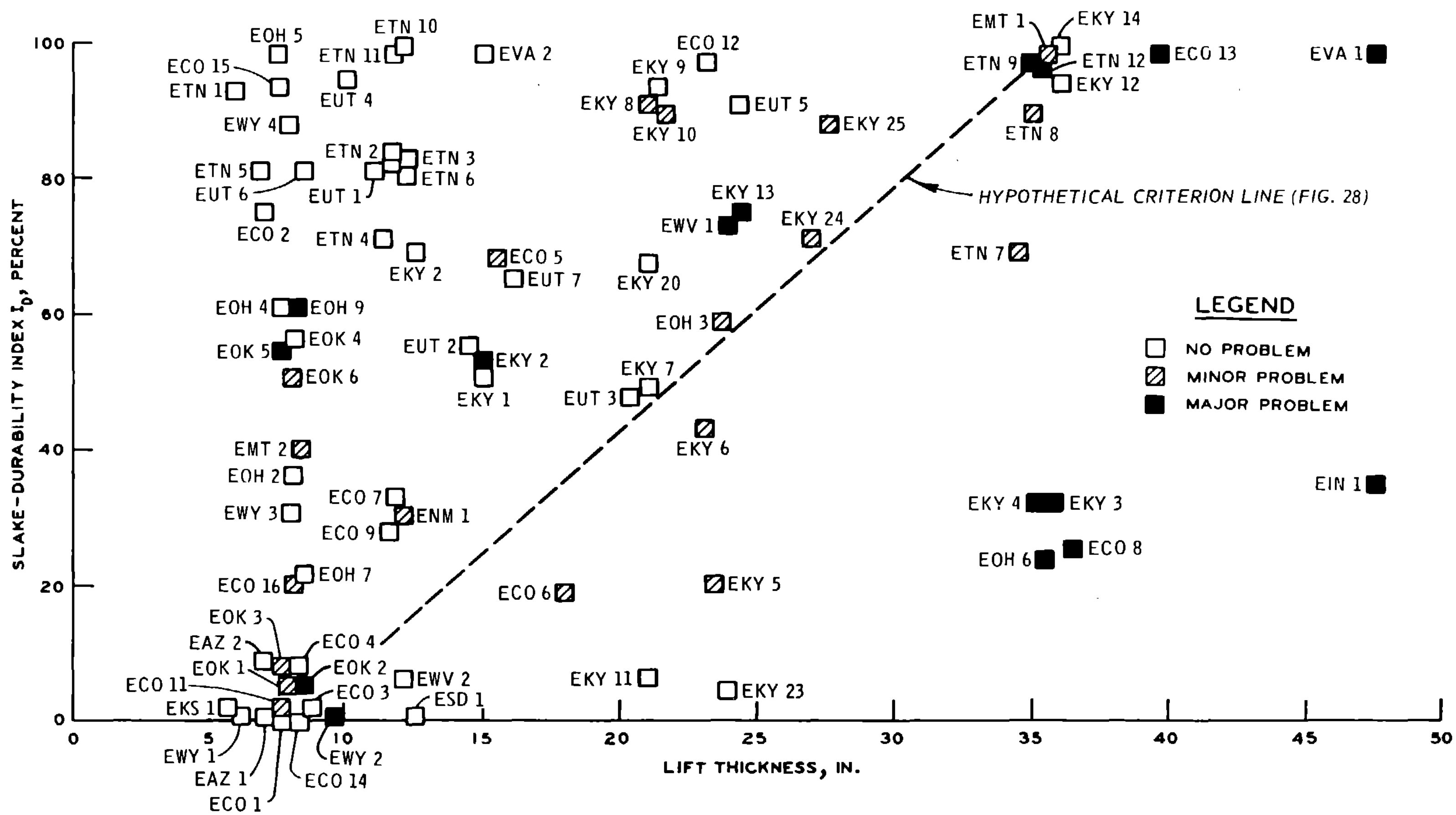

Figure 27. Relationship between slake-durability index (I_D), lift thickness, and performance of embankments with hypothetical criterion line of Figure 28 superimposed

perform satisfactorily or unsatisfactorily according to whether it lies to the left or to the right of the hypothetical criterion line, respectively. Actually other construction variables are included besides lift thickness since thin-lift construction normally implies a greater effort to compact mechanically the material and to manipulate the water content in the process. Thick-lift construction in practice is less demanding or sophisticated in regard to these other variables of construction technique.

Review of Specific Embankments with Respect to Hypothetical Performance Criterion

100. According to the discussion above, the hypothetical criterion line should separate approximately the embankments with no problems from those with major problems. Cases of borderline behavior (minor problems in this study) should be expected to cluster as a group along the criterion line, but with many intrinsic and extrinsic variables capable of exerting a predominant effect wide departures are expectable. The principal features of Figure 27 that require critical consideration are those points for embankments either with no problems or with major problems that are located anomalously on the figure with respect to the criterion line. Possible explanations for the positions of ten anomalous points in Figure 27 are considered below. Major-problem embankments anomalously on the no-problem side of the hypothetical criterion line are EWV 1, EKY 2, EKY 13, EOH 9, and EOK 5. No-problem embankments falling anomalously on the problem side are EKY 11, EKY 12, EKY 23, EWV 2, and ESD 1.

Anomalous major-problem embankments

101. The two most serious anomalies on the no-problem side of the hypothetical criterion line in Figure 27 represent embankments EOH 9 and EOK 5. Validity of EOH 9 may legitimately be questioned on two points. First, the material is said to have contained more than 50 percent sandstone, yet was inferred indirectly to have been placed in 8-in. lifts; lifts may actually have been 3 ft thick as is common for rock. Second, the location of the sample near Chillicothe, Ohio, was over

150 miles from the embankment location and the association is tenuous. Embankment EOK 5, with considerable slumping, came from Oklahoma where according to an earlier survey[2] stability is not a problem in shale embankments. Also, these old embankments were reported to have been placed like soil but without the usual control of moisture, and hence are not to be expected to endure so well but to be potentially troublesome.

102. Less serious anomalies on the no-problem side of the line are embankments EKY 2, EKY 13, and EWV 1. Actually EKY 2 and EWV 1 reach across the line into the problem field when the entire range of slake-durability test results is considered. Of more significance for EKY 2, however, is the fact that it was one of a pair of embankments side by side constructed essentially the same by one contractor, and the other embankment (EKY 1) has given no problems in the same interval. An explanation of anomalous EKY 13 is suggested by the suspicion that this embankment rested partly on a poor foundation of mucky alluvium.

Anomalous no-problem embankments

103. The two grossly anomalous no-problem points on the problem side of the hypothetical criterion line (Figure 27) represent embankments EKY 11 and EKY 23. According to the criterion these two might have been expected to have problems but they did not. The high rock contents (50 percent) of these embankments and one of the three less severe anomalies (EKY 12) may account for their good performance. Where the rock is of such abundance and gradation as to form a continuously contacted framework of durable rock fragments, the embankment may resist settlement indefinitely. Also, somewhat better compaction may have been achieved with the vibratory rolling undertaken on EKY 11.

104. Embankment EWV 2 presents no particular problem in explanation since it is unique in being part of a high rock-fill dam where requirements of compaction, moisture addition, and quality control are generally more severe than in a highway embankment. The point for embankment ESD 1 is also rather unique since it is based on a sample (SD 1) with an unusually high water content. Apparently, this sample was already approaching soil in consistency and satisfactory compaction

could be obtained with no difficulty, even in 12-in. lifts.

Influence of other factors

105. In an attempt to detect the possible influence of other factors, the information in Table 5 on embankment height, side slope, compaction method, and moisture control was noted on separate plots of I_D versus lift thickness similar to Figure 26. Although most of the results did not show effects manifested in different performance categories, compaction method did show an overall trend. Compaction equipment was used on 43 of the 48 no-problem embankments, on 10 of the 17 minor-problem embankments, and on 8 of the 15 major-problem embankments. It would be expected that the compaction effort would be a major factor, especially if large quantities of fine-grained materials were generated during construction. Since the compaction effort and quantity of fine-grained materials were unknown, their relative influence in combination with shale durability could not be assessed. The development or refinement of durability versus lift thickness criteria for use in a particular area, as an extension of this study, would benefit from specific information on compaction effort and quantity of fine-grained materials so that the influence of these factors in relation to shale durability could be assessed.

Use of the Settlement Criterion

106. As explained earlier, the empirical predictive or design service criterion is a line or band (Figure 28) separating problem fills from no-problem fills (Figure 27) as nearly as possible. The position of the criterion will vary according to the particular type of fill or its function. Accordingly the concept of a criterion band as shown in Figure 28 is probably more realistic. For bridge approach fills and other sensitively located fills, only a minor settlement can be tolerated, and therefore the criterion line will be displaced to the left in the band on the graph to generally lesser lift thicknesses. On secondary highways and in other places where minor settlement is tolerable, it may be possible to shift the criterion line to the right in the band to generally greater thicknesses.

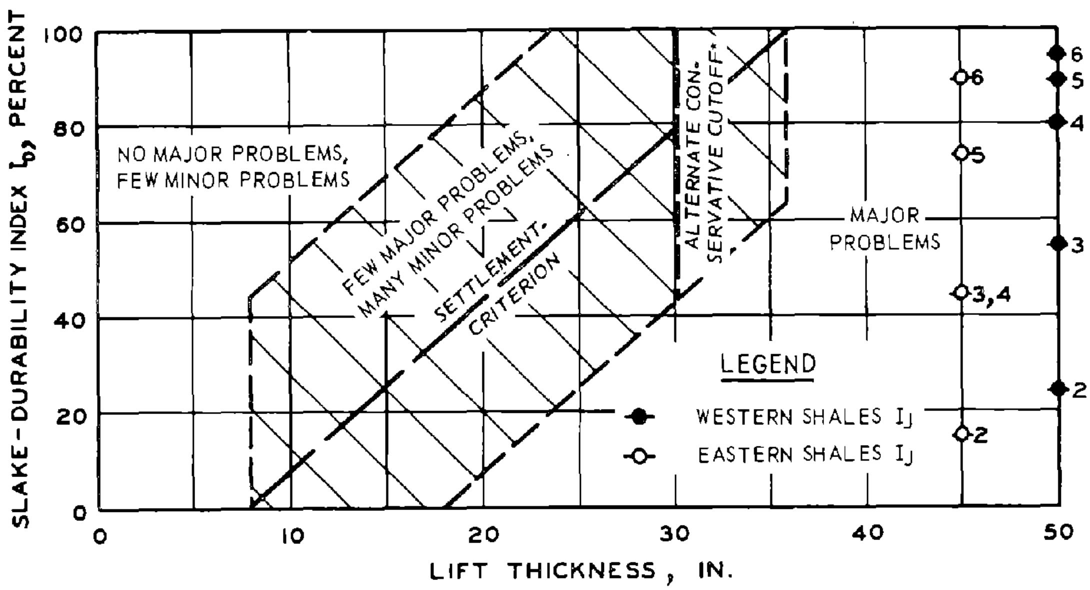

Figure 28. Criterion for evaluating embankment construction on basis of slaking behavior of materials. (*Note: With cognizance of the few cases of major problems for 36-in. lifts at high I_D, the criterion band may be truncated at 30 in.)

107. The durability index service criterion can be used both in predicting the behavior of existing embankments and in estimating design of new construction. For prediction of future behavior of embankments, the known lift thickness used in construction of the fill is correlated with the I_D or I_J of fresh material from the source cut. Those materials falling on the graph above the criterion line may be expected to undergo settlement somewhat in relation to the plotted distance from the criterion line. For use in the design stage, the average I_D or I_J or range of values from materials sampled in areas to be cut provide the input. Depending on the requirements of the project, the designer may determine the maximum lift thickness at an appropriate distance from the criterion line.

108. Hypothetical examples (Figure 29) help illustrate the use of the criterion band for design in coordination with engineering judgment. In example I, testing has indicated $I_D = 66$ percent and therefore lift thicknesses of 14 to 36 in. may be acceptable (depending partly on acceptable postconstruction maintenance). Little variation among I_D values is indicated and the designer is willing to accept the

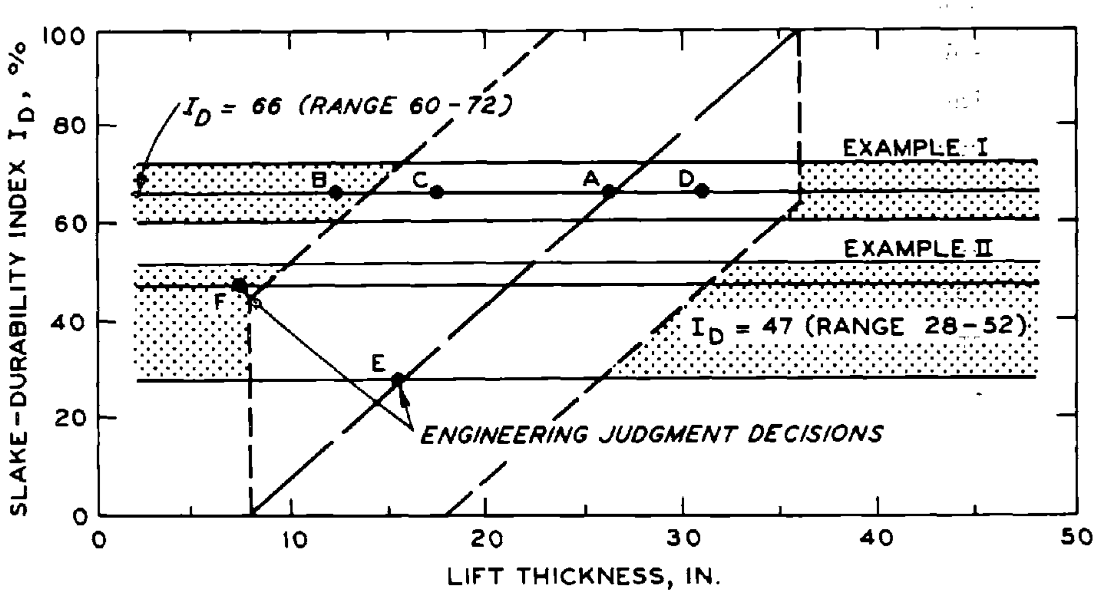

Figure 29. Hypothetical examples of determining suitable lift thickness from test results

possibility of some postconstruction maintenance; accordingly, he chooses 26-in. lifts (point A) directly on the criterion line. For bridge approach fills where a more conservative stance is preferred, the choice would probably be more like 12- or 17-in. lifts (points B and C). Only in cases where special favorable construction practices are assured in some way, or where the consequences of settlement are regarded as insignificant, would the designer ordinarily consider values like point D in the half-band to the right of the criterion line. In Example II (Figure 29), the broad range of I_D values from that one considered as average might necessitate a cautious approach in the engineer's judgment. He might, for example, choose 16-in. lifts (point E) on the lower extreme of the I_D range. Or perhaps an expectation of difficult construction control would suggest values on the edge or left of the criterion band (point F).

109. Since the slake-durability test is relatively time-consuming and there is a distinct advantage in having nearly continuous sample coverage in highway cut sections, the simpler jar-slake test may have decided advantages in many cases. As shown in Figure 13, the slake-durability test and the jar-slake test provide results that correlate

directly on the whole. Therefore, it is suggested that I_J might effectively be substituted for I_D in most cases (Figure 28), especially for field testing. Quick oven drying such as in a microwave oven (except for iron-bearing shales) might further reduce the test time. The I_D test can be reserved for those cases where sophistication is required. It should be useful to work the two tests together, with abundant rapid I_J results providing continuous coverage and the I_D results providing intermittent values to the nearest one percent for confirmation and refinement.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

110. It is concluded that I_D and/or I_J show promise for characterizing shale for use in compacted shale embankments, and accordingly it is recommended that the use of the slaking tests for embankment behavior be subjected to field trial and/or further critical analysis as in this report. Either I_D or I_J may be used to obtain directly maximum lift thickness according to the criterion shown graphically in Figure 28; the reliability of the criterion is yet to be established. The jar-slake test has the advantage of providing inexpensive, quick results and therefore could be used advantageously for continuous characterization of material. The slake-durability test, being somewhat more expensive and time-consuming, is recommended as an intermittent check for confirmation and refinement.

111. The tentative criterion has been developed from a comprehensive study of certain characteristics and mineralogy of shales throughout the United States. One hundred and fifty-eight samples were obtained from 14 states, mostly in the course of fieldwork for this study. The age range of samples was from Precambrian to Tertiary. Sampling covered the following categories of shales: interbedded limestone and shale; sandstone, siltstone, shale, and coal; sandstone, siltstone, and shale without coal; thick, uniform shale; and black, carbonaceous shale. Most samples came from structurally undeformed areas that, except for age effects, have undergone approximately the same history since deposition. The collection appears to represent a broad range of common shale types.

112. Subtle differences were found among shales of various types. More subtle differences were even evident within individual shale units, confirming the value of indexing for characterizing shales and other weak rocks.

REFERENCES

1. Wood, L. E. and Deo, P., "A Suggested System for Classifying Shale Materials for Embankments," Association of Engineering Geologists Bulletin, Vol 12, No. 1, 1975, pp 39-55.

2. Shamburger, J. H., Patrick, D. M., and Lutton, R. J., "Design and Construction of Compacted Shale Embankments; Vol I, Survey of Problem Areas and Current Practices," FHWA-RD-75-61, Aug 1975, Federal Highway Administration, Offices of Research and Development, Washington, D. C.

3. Bragg, G. H., Jr., and Zeigler, T. W., "Design and Construction of Compacted Shale Embankments; Vol 2, Evaluation and Remedial Treatment of Shale Embankments," FHWA-RD-75-62, Aug 1975, Federal Highway Administration, Offices of Research and Development, Washington, D. C.

4. Franklin, J. A. and Chandra, R., "The Slake-Durability Test," International Journal Rock Mechanics and Mining Science, Vol 9, No. 3, May 1972, pp 325-341.

5. Gray, H. H., "Lithostratigraphy of the Maquoketa Group (Ordovician) in Indiana," Special Report 7, 1972, Indiana Geological Survey, Bloomington, Ind.

6. Kehn, T. M., "Geologic Map of the Dawson Springs Quadrangle, Western Kentucky," Map GQ-573, Scale 1:24,000, 1966, U. S. Geological Survey, Department of the Interior, Washington, D. C.

7. Bridge, J., "Stratigraphy of the Mascot-Jefferson City Zinc District, Tennessee," Professional Paper 277, 1956, U. S. Geological Survey, Department of the Interior, Washington, D. C.

8. Hoge, H. P. and Chaplin, J. R., "Geologic Map of the Morehead Quadrangle, Rowan Co., Kentucky," Map GQ-1022, Scale 1:24,000, 1972, U. S. Geological Survey, Department of the Interior, Washington, D. C.

9. Peterson, W. L., "Geologic Map of the Nelsonville Quadrangle, Central Kentucky," Map GQ-564, Scale 1:24,000, 1966, U. S. Geological Survey, Department of the Interior, Washington, D. C.

10. Johnson, R. C. and Luther, E. T., "Strippable Coal in the Northern Cumberland Plateau Area of Tennessee," Report RI 34, 1972, Tennessee Division of Geology, Department of Conservation, State of Tennessee, Nashville, Tenn.

11. Peterson, W. L., "Geologic Map of the Bardstown Quadrangle, Nelson Co., Kentucky," Map GQ-825, Scale 1:24,000, 1969, U. S. Geological Survey, Department of the Interior, Washington, D. C.

12. Griffits, M. O., "Zones of Pierre Formation of Colorado," American Association of Petroleum Geologists Bulletin, Vol 33, No. 12, Dec 1949, pp 2011-2028.

13. Doelling, H. H., "Central Utah Coal Fields: Sevier-Sanpete, Wasatch Plateau, Book Cliffs, and Emery," Monograph 3, 1972, Utah Geological and Mineralogical Survey, Salt Lake City, Utah.

14. Clark, P. C., Crumpton, C. F., and Gilliland, W. J., "Water Drainage from Highway Fills," Report No. 72-1, 1974, State Highway Commission of Kansas, Topeka, Kans.