SHALES AS EMBANKMENT MATERIALS

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BY

P. DEO

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INDIANA STATE HIGHWAY COMMISSION

Final Report

SHALES AS EMBANKMENT MATERIALS

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

December 28, 1972

Project: C-36-5J

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The Final Report "Shales as Embankment Materials" is submitted for acceptance as fulfillment of the objectives of the approved JHRP Research Study of the same title. The research and report were performed by Mr. Purushottam Deo, Graduate Instructor in Research on our staff under the direction of Professor C. W. Lovell, Jr.

The Report includes the results of an extensive program of testing shale materials. It is proposed that Indiana shales be classified into four categories. It is recommended that shales as a construction material be viewed as a special material and properly classified as to probable behavior. Actions to take before specifying use of shale materials are outlined and several construction practices are suggested. The Report presents a wealth of information which will be of value to the ISHC when use of shale materials is possible and desirable.

The Report is submitted for acceptance.

Respectfully submitted,

Harold L. Michael

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Project No.: C-36-5J

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LIST OF SYMBOLS

$C_{2\mu}$	Percent particles by weight finer than 0.002 mm
$C_{5\mu}$	Percent particles by weight finer than 0.005 mm
C_{200}	Percent particles by weight finer than No. 200 sieve
$(CBR)_c$	As-compacted California Bearing Ratio at optimum moisture content and Standard Proctor effort
$(CBR)_S$	Soaked California Bearing Ratio at optimum moisture content and Standard Proctor effort
F	Fissility Number
$(I_d)_d$	Durability Index for oven-dried samples
$(I_d)_S$	Durability Index for soaked samples
I_S	Soundness Index
I_P	Plasticity Index
w_ℓ	Liquid Limit
$(N_d)_{d200}$	Durability Number for oven-dried samples at a given number of revolutions, in this case 200
$(N_d)_{S200}$	Durability Number for soaked samples at a given number of revolutions, in this case 200.
R	CBR Ratio = $\frac{(CBR)_S}{(CBR)_C}$ 100%

LIST OF SYMBOLS, continued

S	Percent swell after 96 hours of soaking of CBR sample (from Standard Proctor effort and optimum moisture content)
$(\gamma_m)_{lumps}$	Bulk Unit Weight of oven-dried lumps
$\gamma_{d\ max}$	Maximum Dry Unit Weight at Standard Proctor effort

ABSTRACT

Deo, Purushottam, Ph.D., Purdue University, December 1972, Shales as Embankment Materials. Major Professors: C. W. Lovell, Jr., and L. E. Wood.

Shales have produced major problems in foundations, cut slopes and embankments. This research concentrates on embankment problems produced by shale fill materials.

Representative shale samples were collected from fifteen different locations in Indiana, covering a spectrum from relatively hard and durable ones to those which rapidly weathered into soil. Current state-of-the-art information was gathered from various agencies engaged in embankment construction using soil, shale and other rocks. An extensive testing program was carried out in the laboratory, including degradation, soil type standard identification, compaction and load-deformation, and other types of tests. Standard tests were modified to suit the soft rocks.

Not all the tests yielded useful descriptors. However, experimentally defined values of soaked durability index, soundness index, fissility number, and bulk density seemed to be important descriptors. On the basis of the test results, it is proposed that Indiana shales be classified as "rock like", "intermediate-1", "intermediate-2", or "soil like" shales.

A case history of shale embankment failure on I-74 in southeastern Indiana is presented. The failure was caused by improper placement of the shale, which was in turn caused by a failure to identify the shale and to write special provisions for it.

INTRODUCTION

Shale is the most common rock in the world. It constitutes about 50% of the rock types exposed on the surface of the earth and comprises about 70% of all the sedimentary rocks (1)[1]. In many areas of this country and other parts of the world, shales must be contended with, either insitu as a slope or foundation material, or as the construction material in embankments.

Shales have produced major problems in all of the above uses, viz., foundations (1), cut slopes (16, 25), and embankments (79). However this study focuses on the problems of use of shale in embankments. In such use, the engineer tends to view the shale with suspicion and often recommends design and construction procedures which are conservative, e.g., extra rolling to fragment the material, placing another material between the shale and the atmosphere (encasement), flattening slopes, and using berms. These procedures have reduced, but not eliminated, instabilities of shale embankments (48).

The engineer is unlikely to express satisfaction with the current state of the art. It is probable that current

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[1] Items in parentheses refer to entries in the Bibliography, page 160.

practice is generally too conservative, i.e., some usable shales are being wasted, and the intrinsic strengths of relatively high quality shales are not being used.

Once it is appreciated that shales exhibit a wide spectrum of engineering behavior, there is an obvious motivation to identify and classify shales as to the said behavior. For example, some shales slake almost immediately in moist air (89), while others can withstand numerous cycles of wetting and drying, and are roughly as durable as sandstone or limestone. "Slaking" is the process through which a material disintegrates or crumbles into small particles or flakes when exposed to moisture, and especially when dried and immersed in water.

Since most shales are intermediate in behavior between soil and rock, the tests which suitably classify soils and rocks are not adequate to classify shales. The researcher is thus faced with the need to, (a) modify existing tests, or (b) evolve new tests. Such tests would be both sufficiently simple and discriminating to allow geotechnical engineers to guide the design and construction of shale embankments in a sound and economical manner.

Problems Associated with Embankments

Problems associated with embankments can be grouped in three broad categories.

1. Problems due to the foundation material of the embankment, which include bearing capacity and settlement.

2. Problems of embankments on sidehill locations, where sliding may occur in the foundation material.

3. Problems within the embankment which include:
    a. Settlement due to loading, drying, slaking, or thawing.
    b. Heave caused by wetting or freezing.
    c. Slope instability.
    d. Surface and subsurface erosion.

This research concentrates upon the control of some of the problems of Group 3.

Problems with Shale as Embankment Material

The degree to which shales will demonstrate poor performance depends largely on their service environment, both man-made and natural. For example, unless the material becomes significantly wetter than the placement condition, slaking may not occur. Once exposed to increased moisture, slaking may occur quickly, in many years, or not at all. The practical consequence of the slaking, if it occurs, depends primarily upon the relative abundance of large voids in the compacted mass, into which the slaked material could settle. The size and frequency of large voids is rather directly related in turn to the relative abundance of large chunks of shale in the embankment. If large chunks of slaking shale are placed in the embankment, major problems can be anticipated. If on the other hand, the slaking shale is reduced to small pieces in the construction process, the slaking may produce no unacceptable densifications or surface displacements.

Degradation of material in the embankment can be controlled by effective drainage and/or proper encasement of the embankments. Even relatively nonslaking shales are weakened and made more compressible by increased moisture. Other shales contain enough expansive minerals to cause significant swelling upon wetting and shrinkage upon drying, with potentially harmful effects on the embankment and/or the overlying pavement.

If one is able to assess the general susceptibility of a shale to slaking, volume change, and the like, in the projected service environment, more rational decisions can be reached in the design and construction processes, thereby increasing the probability that satisfactory service will be produced with economy.

RESEARCH PROBLEM AND APPROACH

Statement of the Research Problem

This research involves study of shales in Indiana with a view to assessing their suitability for use in highway embankments. Indiana shales cover a wide spectrum of behavior from relatively hard and durable ones, to those which will rapidly weather into soil. However they are mostly of relatively low plasticity and do not exhibit highly expansible characteristics (38).

A principal activity in the research was the modification of existing tests or development of new tests for the engineering classification of shales. These tests have to be simple and inexpensive, and also be able to rate shales in different embankment-use categories. For example, shales might be grouped in the following four categories.

1. Shales which are very highly susceptible to post-constructional degradation, and when so reduced are actually inferior in performance to normal fine grained soils. The use of these materials in embankments should be restricted.

2. Shales which are about "at par" with normal fine grained soils, if they are rather thoroughly degraded in the construction process, and may be used with normal soil design and construction controls.

3. Shales which are imperfectly degraded in the construction process, and which will be only slightly degraded in service, are stronger than soils, yet can not be placed as rockfill.

4. Shales, which are very difficult to degrade, and can likely be placed as rockfills. These materials are intrinsically superior to soil in fills, if certain construction problems can be overcome.

Not all attempted classification tests were effective in separating shales into groupings such as above. It was therefore necessary to discard certain testing options, while retaining others. The result was to be a recommended simple testing procedure for separating shales into behavioral groups.

After grouping the shales into different categories, the state of the art for soil, rock, and shale embankment in Indiana was reviewed, with the idea that these guidelines could be quantified somewhat depending upon the shale type to be used. However as no field embankments were actually constructed, and the experimental study was limited to laboratory testing, the research stops short of actually recommending revision of design standards or construction specifications for shale embankments in Indiana. This is an obvious next step in the effort to improve the state of the art.

Research Approach

The research effort was divided into three phases.

1. Representative shale samples were collected from different locations in Indiana and in a quantity sufficient for laboratory testing. These shales covered a wide behavioral spectrum, from very hard and durable ones, to those which rapidly weather into soil.

2. Current state of the art information was gathered from various agencies engaged in embankment construction using soil, shale and other rocks. Both verbal and written responses were gathered on problems encountered during and after construction of shale embankments, as well as on the laboratory testing of these materials.

3. Extensive testing was carried out in the laboratory. The testing can be grouped in four categories.

a) Degradation Type Tests measured slaking and other breakdown of the material. As the standard tests were inappropriate for soft rocks, it was necessary to develop new ones, or at least to modify existing ones.

b) Soil Type Standard Identification Tests were conducted on the shales in a thoroughly degraded condition.

c) Compaction and Load-Deformation Tests, principally California Bearing Ratios, were performed on as-compacted and soaked samples.

d) Miscellaneous Type Tests were run which included: 1) absorption-time, 2) bulk density, and 3) certain breaking characteristics of materials.

Not all tests yielded useful descriptors for classifying shales as to their behavior in compacted embankments. Accordingly, only certain tests were selected for use in the recommended engineering classification procedure.

LITERATURE REVIEW

Shale is the most common sedimentary rock on the earth, occurring in various geographic locations that vary from mountain tops to deep ocean trenches. The area of exposure of sedimentary rocks is about 75 percent of the total land area (18). Of the numerous varieties of sediments, only a few are common, so that the three principal types constitute more than 99 percent of all sediments (71). Of these three types, namely, shale, sandstone and limestone, shale is most abundant.

Estimates concerning the relative proportions of the common sediments have been made by Mead (63), Leith and Mead (60), Clarke (18), Schuchert (76), Holmes (42), Kuenen (55), Krynine (54), and Wickman (94). The methods for estimation consist of either actual measurements of many stratigraphic sections, or by calculating the proportions of the "average" shale, sandstone and limestone (plus sea water) that is equivalent in composition to the "average" igneous rock (as the igneous are the parent source of sedimentary rocks). See Tables 1 and 2. Based on this and other general information on the abundance of rock types, it can be concluded that shale comprises about 50 percent of the area of exposed bedrock.

TABLE 1. PERCENTAGE OF SEDIMENTARY ROCKS AS MEASURED.

	Leith and Mead(60)	Schuchert (76)	Kuenen(55)	Krynine(54)
Shale	46	44	56	42
Sandstone	32	37	14	40
Limestone	22	19	29	18

TABLE 2. PERCENTAGE OF SEDIMENTARY ROCK AS COMPUTED.

	Mead(63)	Clarke(18)	Holmes(42)	Wickman(94)
Shale	82	80	70	83
Sandstone	12	15	16	8
Limestone	6	5	14	9

This literature review is presented under the following four headings:

1. Sedimentary rocks, and their relation to shale.
2. Definition, classification, origin and engineering problems of shale.
3. The geology of Indiana shale.
4. Embankments with soil, rock and shale; the state of the art.

Sedimentary Rocks

Sedimentary rocks are formed from the accumulation of sediments (regolith[1]), that have been transported by water, air or ice or precipitated chemically or biochemically, and are subsequently compacted into hard, firm and stratified rocks (43). Sediments may consist of rock fragments of varying sizes, resistant mineral grains, the remains of organisms, and the products of chemical action or evaporation plus various mixtures of this group. Mechanical disintegration of existing rocks produces rock fragments and mineral grains; chemical decomposition produces both debris and materials in solution. The loose mineral grains and rock fragments are transported by water, wind or ice to basins where they are deposited. Some soluble constituents,

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[1] Regolith is the layer of loose, incoherent rock materials, without regard to origin, that forms the land surface and rests on bedrock. It comprises rock waste of all sorts, volcanic ash, glacial drift, alluvium, wind blown deposits, vegetal accumulations, and soils (4).

previously dissolved by water, are precipitated through the action of organisms or when evaporation occurs. Because of their resistance to mechanical and chemical action some particles persist through several cycles of weathering, deposition, and lithification.

Classification of Sedimentary Rocks

Sedimentary rocks may be separated into numerous categories, depending upon their chemical composition, geologic history, mode of deposition, grain size, primary structure and texture, and mineralogical composition. It is, however, beyond the scope of this study to describe all the aspects of sedimentary rock classification. A workable classification based on those by Pettijohn (71) and Huang (43), is shown in Figure 1. Its salient features are described below.

Clastic and Nonclastic Sedimentary Rocks. Sedimentary rocks are classified in two main groups, clastic and nonclastic, based upon the manner in which they are formed (43).

Clastic rocks are produced by mechanical accumulations of rock fragments and mineral grains. Most mechanically deposited sediments consist of land-derived detritus representing the materials of surface weathering and erosion. Many sedimentary rocks, for example sandstone and mudstone, belong to this group. The particles comprising a clastic

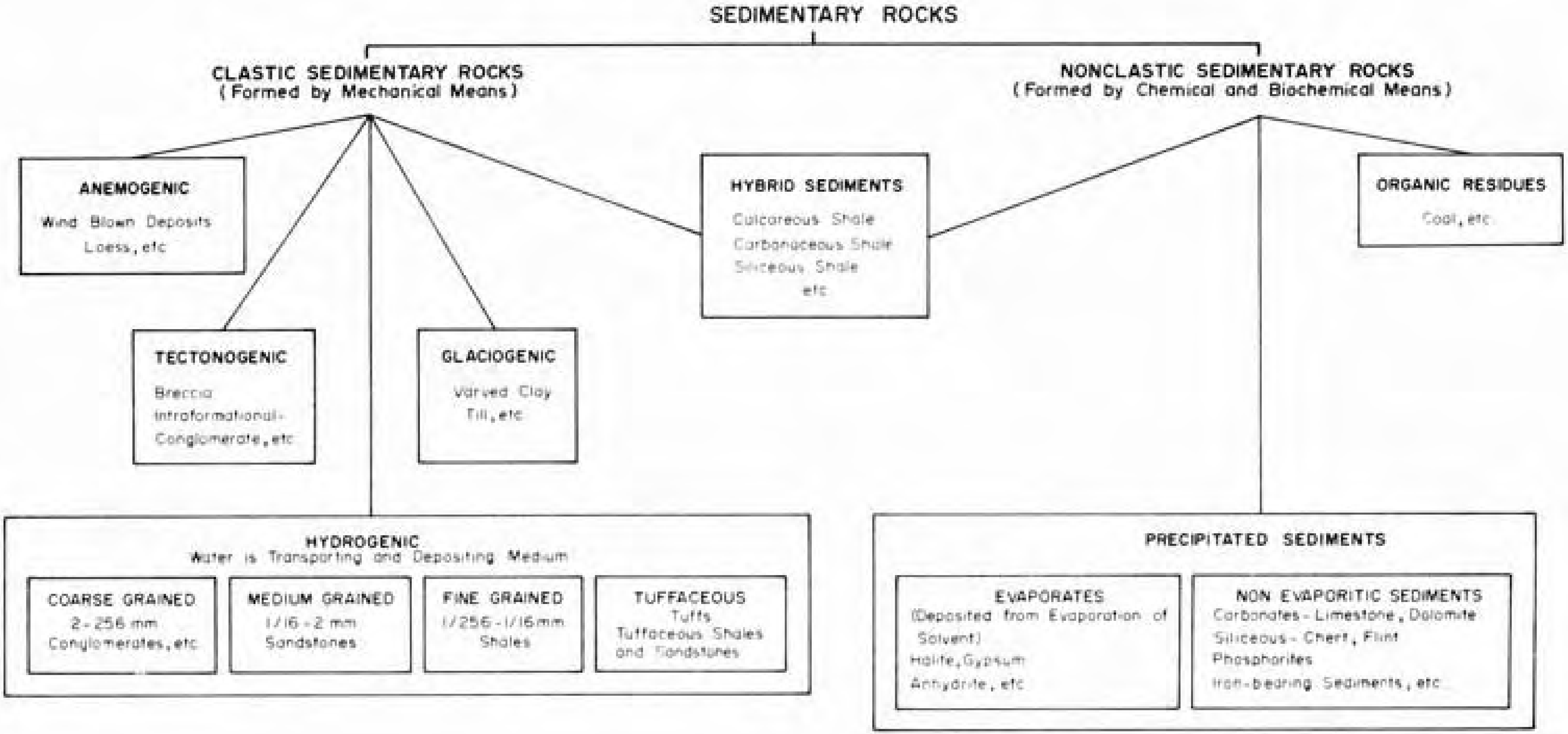

FIGURE I. CLASSIFICATION OF SEDIMENTARY ROCKS (43, 71).

texture may have various forms, sizes, shapes and composition. Clastic sedimentary rocks are produced in a number of ways; they may be wind blown deposits (anemogenic), transported and deposited by water (hydrogenic), or by glacial ice (glaciogenic) or originate from crustal disturbance (tectonogenic). Some sedimentary rocks are formed from the ejecta thrown out from a volcano and subsequently settle out of the air or into standing water. These materials are termed "tuffaceous".

Nonclastic rocks are formed by either chemical or biochemical means, and consist of minerals such as carbonates, hallides, and silica. The rocks are held together by interlocking mineral crystals formed during precipitation. Nearly all nonclastic or chemically deposited rocks originate by chemical precipitation from bodies of surface water. Precipitation may be caused by evaporation of the solvent, by inorganic reaction among dissolved salts, or by organisms such as bacteria, corals and mollusks.

The textures of nonclastic rocks are formed by the following processes acting singly or in combination.

i) Direct crystallization or inorganic reaction among dissolved salts.

ii) Crystal growth and enlargement within an aggregate.

iii) Replacement processes such as dolomitization and silication.

Nonclastic rocks are divided into organic residues such as coal, lignite, and peat; and into precipitated sediments, which include evaporites (halite, gypsum and anhydrite), and rocks precipitated under non-evaporite conditions (carbonates, phosphorites, siliceous and iron bearing sediments).

Some of the sediments have a mixed origin, showing prevalent clastic and nonclastic portions in the rock. These are termed "hybrid sediments" and are given a special designation in the classification.

Engineering Classification of Sedimentary Rocks. In many instances it is important to classify sedimentary rocks from an engineering point of view. However, in only a few instances have specific classifications been proposed. Philbrick (73) classified them into two broad groups, viz., soluble and insoluble rocks, as shown in Figure 2 (90). The limestones, dolomites and evaporites (halite, gypsum, anhydrites) are soluble rocks and natural caverns may develop in them. Sandstone, siltstone, shale and coal are relatively insoluble so that naturally formed caverns are rarely found in these rock units. Philbrick used this relationship to predict the leakage potential of sedimentary rocks.

Shale

Most shales are fine grained clastic rocks of hydrogenic origin, i.e., water is the medium of transport

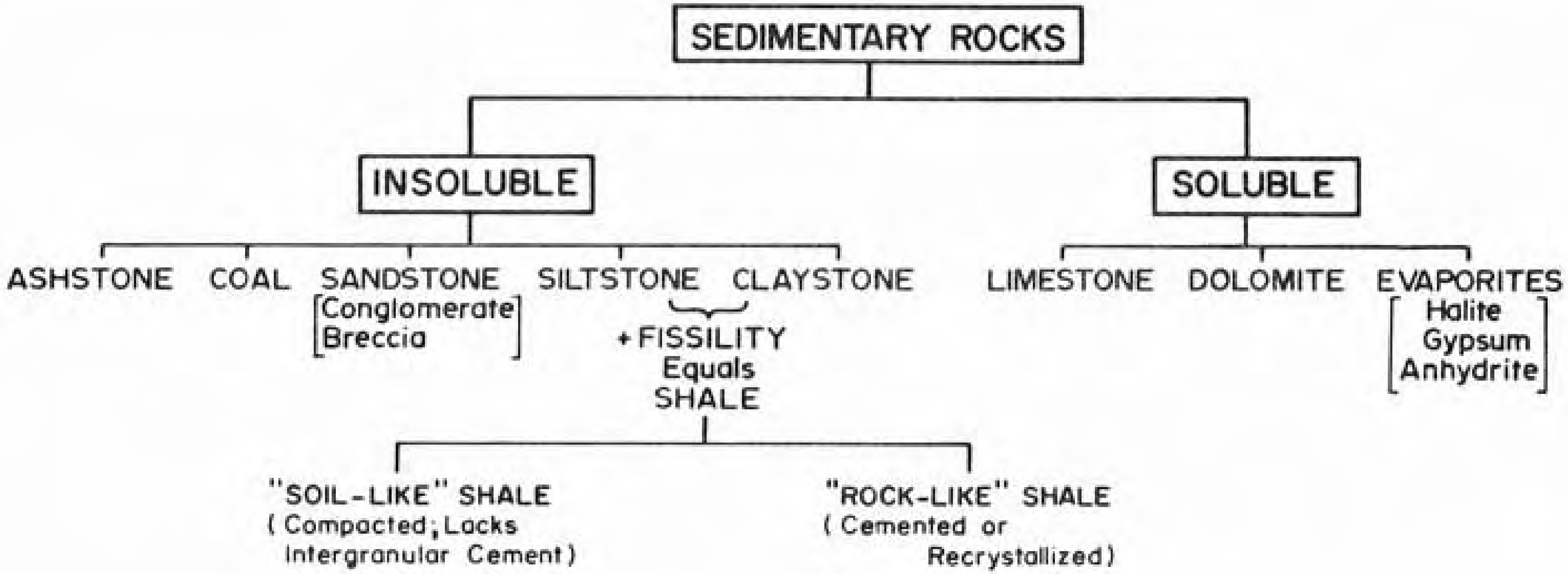

FIGURE 2. AN ENGINEERING CLASSIFICATION OF SEDIMENTARY ROCKS (90).

and deposition. Some shales are however hybrid sediments (Figure 1).

Wide differences of opinion exist in regard to the definition, classification and identification of shales. The definitions of shale supplied by various authors differ drastically. An important aspect is whether shale should be considered soil or bedrock. A judge once made the statement in a court case, "Anyone knows shale is not a rock" (1).

Definition of Shale

The term shale is used by some to designate all argillaceous sediments including claystone, siltstone, mudstone, and marl, whereas others designate the larger group as the mudstone or mudrock group, and classify shale as a member of it (87).

It is interesting to note the definitions of shale given in the literature by various authorities:

"A laminated sediment in which constituent particles are prominently of clay grade" [Holmes (4), p. 262].

"Shales are consolidated fine sediments, usually hardened clay or mud and have a characteristic fracture. Generally dull in appearance, shale can be scratched with a finger nail" [Legget (59), p. 48].

"A product could not be called a shale unless it possesses two properties: When struck with hammer, it should give a clear ring, and when immersed in water its volume should remain unchanged" [Terzaghi (85), p. 20].

"Shale includes the indurated, laminated or fissile claystones and siltstones. The cleavage is that of bedding and such other secondary cleavage or fissility that is approximately parallel to bedding. The secondary cleavage has been produced by the pressure of overlying sediments" [Twenhofel (87), p. 98].

"The term shale is applied to a wide variety of rocks, ranging from consolidated clay and silt to rocks which display thin bedding without regard primarily to texture or composition. Shale includes siltstone and claystone" [Krumbein (53), p. 101].

"The term shales is used in a general sense to refer to the whole group of silty and clayey rocks. Shale is used in a specific sense for rocks composed primarily of silt and clay, with fissility or a tendency to split along fairly close bedding planes" [Deere and Gamble (21), p. 37].

"A fissile rock formed by consolidation of clay, mud or silt, having finely stratified or laminated structure and unaltered minerals" [Webster Dictionary (93), p. 2085].

The definition which has been adopted for this study is:

Shale is a sedimentary rock that: 1) is essentially insoluble, 2) is clastic or hybrid, 3) is fissile and/or laminated, 4) consists primarily of clay and/or silt, and 5) contains minerals essentially unaltered since deposition.

Fissility

Fissility is the property of splitting easily along closely spaced parallel planes (4), and is exhibited by most shales and related rocks. Fissility in shales is usually associated with a parallel arrangement of micaceous clay particles, while nonfissility is associated with a random arrangement of these particles. Experiments and observations indicate (51) that the clay minerals attain a parallel arrangement by gravity settling or by flocculation and compaction, unless the particles are adsorbed on irregularly shaped silica particles or grow randomly in a gel. The nature of the cementing agent determines the degree of fissility. Cementing agents, with the exception of organic matter, cause a decrease in fissility and an increase in the massiveness.

Alling (2), Ingram (51), and McKee and Weir (62) attempted to establish scales of fissility (Table 3). Three dominant types of breaking characteristics were observed by Ingram: massive, flaggy fissile, and flaky fissile.

Massive shales have no preferred direction of cleaving or breaking. Most of the fractured fragments are blocky; a few fragments may be platy, but orientation of these platy fragments in the sample is random.

TABLE 3. FISSILITY SCALES.

Alling (2)	Ingram (51)	McKee and Weir (62)
Massive	Massive	Massive
		Blocky
Platy-Flaggy		
		Slabby
Heavy-Bedded	Flaggy	
		Flaggy
Thin-Bedded		
		Shaly; Platy
Fissile	Flaky	Papery

Flaggy shales split into fragments of varying thickness that have the width and length many times greater than the thickness, and with the two essentially flat sides nearly parallel. Most fragments in flaggy shales have the length and width at least 50 times greater than the thickness. Some shale pieces may break to yield fragments whose description is similar to flaky shales, but these pieces are not as numerous as the flaggy fragments.

Flaky shales split along irregular surfaces parallel to the bedding to form uneven flakes, thin chips, and wedge like fragments, with their length normally less than 3 inches.

Shales combine varying amounts of massiveness, flagginess, and flakiness, producing a continuous range that could be represented on a triangular diagram (Figure 3). However, the quantitative classification of such shales, through the insertion of appropriate percentages and adjectives, has not been accomplished.

Laminations

If the shale is not fissile, it may be laminated (71). Laminations are bands of color or material and range from 0.05 mm to 1.0 mm in thickness; most laminations fall within the range of 0.1 to 0.4 mm. The laminations are of three kinds (71):

i) alternations of coarse and fine particles, such as silt and clay (change in texture);

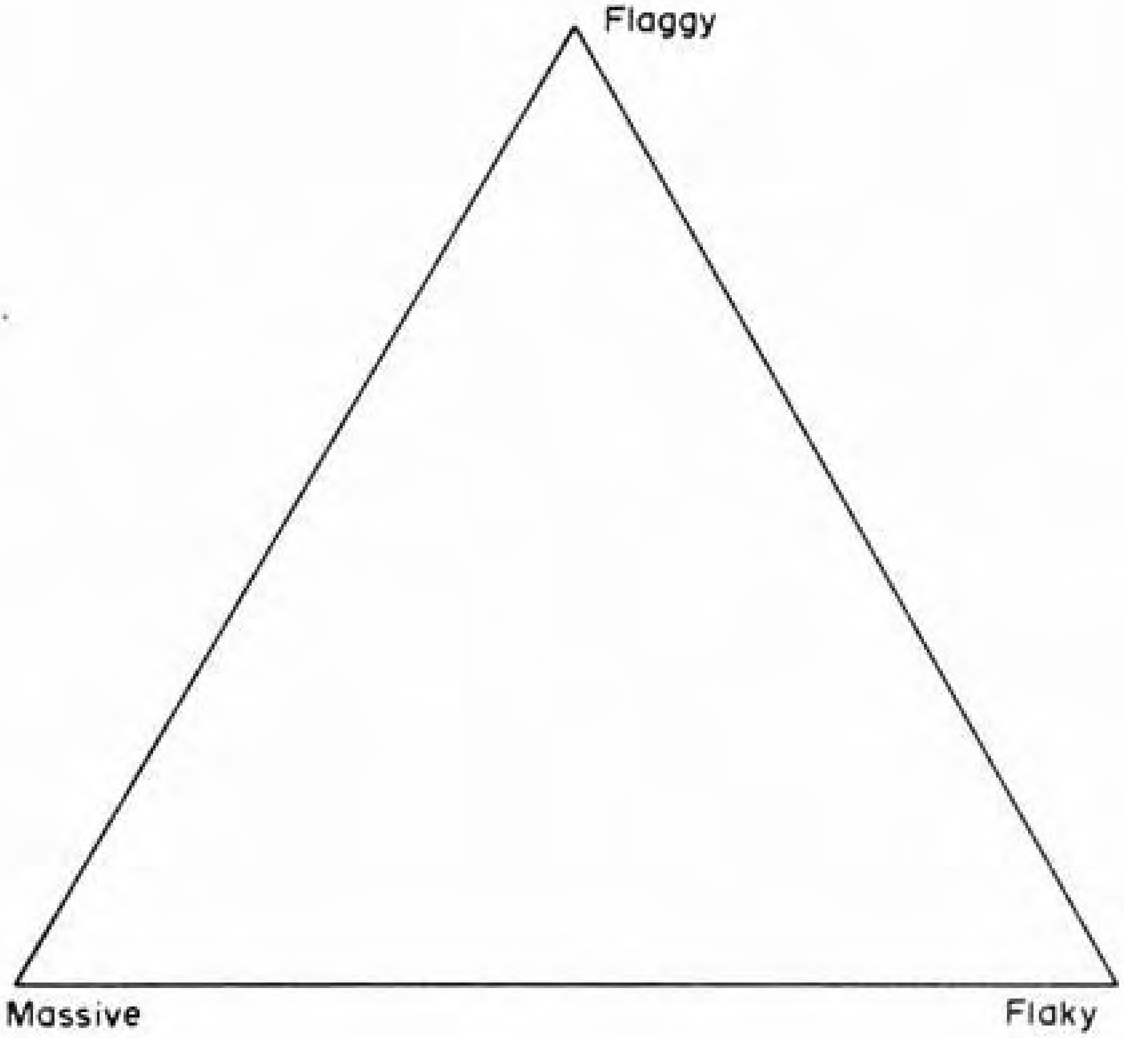

FIGURE 3. TRIANGULAR DIAGRAM FOR MEGASCOPIC CLASSIFICATION OF SHALE BREAKING TYPES (51).

ii) alternations of light and dark layers, distinguished only by their organic contents which are responsible for the color (change in color); and

iii) alternations of silt and calcium carbonate (change in composition).

These alternations are due to changes in proportions of materials being deposited, and are not normally related to either erosion, solution or diffusion. The laminations may or may not indicate cyclic changes (71). If cyclic, they may be caused by storms, floods or other similar occurrences, or are perhaps related to seasonal variations of climate (71).

Other Shale Related Rocks

Twenhofel (87) gives a classification for shale and shale-related rocks as shown in Figure 4. This classification includes indurated[1] silt or clay and their metamorphic equivalents. Underwood (90), Ingram (51), and Gamble (27) have also attempted to differentiate among these rocks. Definitions are given below (51, 27).

<u>Mudrock</u> - Sedimentary rock consisting of at least 50% of either silt or clay with no connotation as to the relative percentages of these constituents or as to the breaking characteristics of the rock.

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[1] Indurated is used to characterize a rock hardened by pressure, cementation or heat; both compaction and cemented shales and mudrocks can be included.

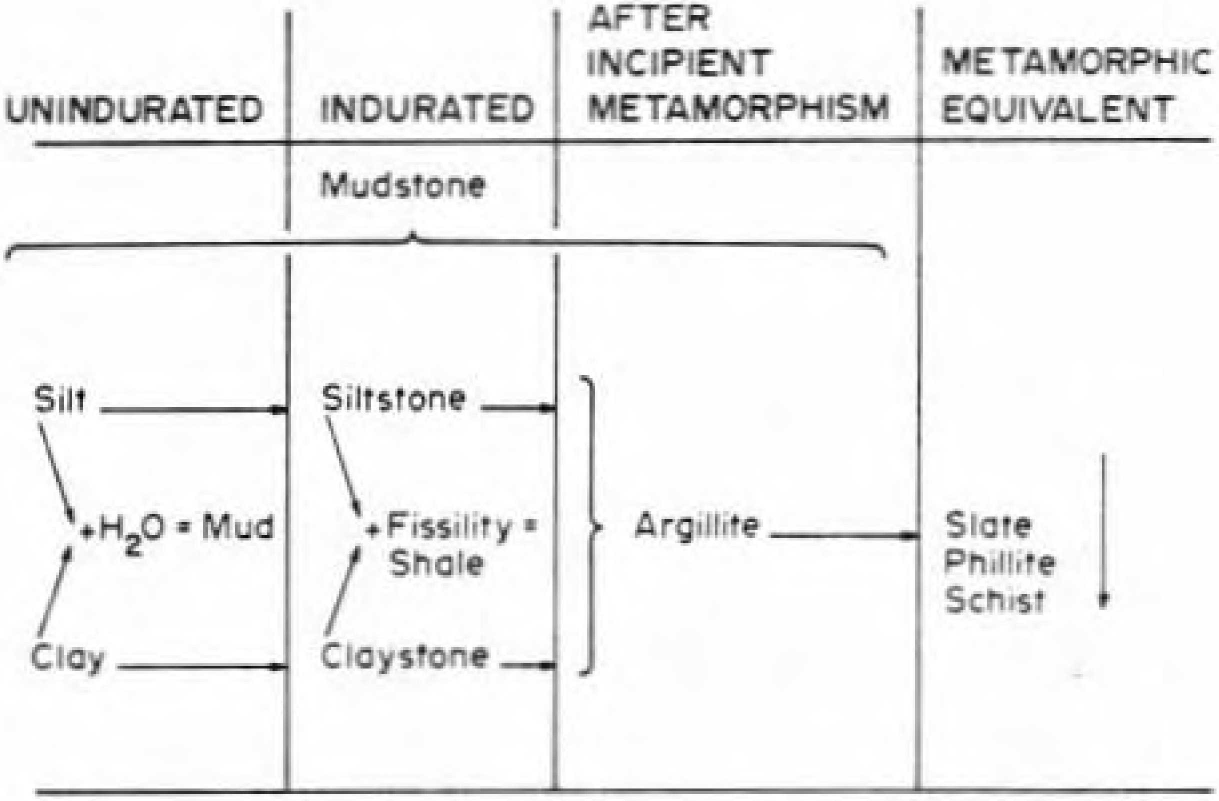

FIGURE 4. CLASSIFICATION OF SHALE AND RELATED ROCKS (87).

Siltrock - Mudrock, in which silt is dominant over the clay.

Clayrock - Mudrock, in which clay is dominant over the silt.

Mudstone - Massive mudrock.

Siltstone - Massive siltrock.

Claystone - Massive clayrock.

Mudshale - Fissile mudrock.

Silt shale - Fissile siltrock.

Clay shale - Fissile clayrock.

Argillite - A rock derived from siltstone or shale that has undergone a higher degree of induration than is present in those rocks. Parting, if any, is parallel to bedding.

Common Word Modifiers for Shale

Attempts have been made (43, 73, 90) to classify shale by use of common word modifiers. Some of the commonly used terms are described below:

Bituminous Shale or Oil Shale - These shales are black or dark brown and contain natural hydrocarbon; on distillation they yield petroleum products.

Alum Shale - A shale impregnated with alum [$Al_2(SO_4)_3$], produced by oxidation and hydration of pyrite.

Arkosic Shale - A shale containing greater than 10% feldspar.

Siliceous Shale - A shale composed mainly of clear, rounded, detrital quartz grains or amorphous silica in silt size.

Red Shale - A shale containing sufficient hematite (Fe_2O_3) to yield a red color.

Micaceous Shale - A shale having muscovite flakes and silty quartz along laminations.

Chloritic Shale - A shale containing chlorite.

Immature Shale - Sediments which are somewhat between clay and shale, with very little cementing material. (Normally, standard soil laboratory testing procedures are applicable to these shales).

Other common words include "heavy" shale, "light" shale, "popcorn" shale, "gumbo" shale, "firm" shale, etc. These terms may be significant to those who regularly use them, but are of doubtful value for general usage.

Origin of Shales

Most shales have a hydrogenic origin, i.e., water is the medium by which the sediment is transported and deposited.

The constituents, which make up shale, are derived from the following sources (71):

a) Products of abrasion (mechanical clay and silt)
b) End products of weathering (residual clays)
c) Chemical and biochemical additions.

The specific nature of the shale formed is determined by the relative contribution of these factors. The kind and proportion of mechanically-derived clay and silt are dependent on rock composition, relief, and climate of the source area. The nature of the residual material that reaches the depositional area is particularly dependent upon climate and drainage.

Theoretically, during the late stages of erosion, when the land surface approaches base level, very little material, other than ionic and colloidal forms, is delivered from the land surface to the basin of deposition. Under such conditions, both silica and iron can accumulate in favorable sites as chemical deposits. Minor uplift leads to partial destruction of the regolith. Sedimentation following such rejuvenation is marked by the deposition of highly aluminous shales. More marked elevation and consequent higher relief interrupts the soil forming process at mid-cycle, so that both weathered and unweathered products are delivered to the basin of deposition (71) and mudrocks are formed.

Under conditions of great crustal stability and low relief, the land derived detrital material is minimal. When this occurs, the sedimentation in adjacent basins will be chiefly chemical. The resulting situation may be deposition of only minor amounts of shale, or if shale or mudrock is formed, it will be richer than normal in chemically or biochemically precipitated materials. Because of such precipitation, the shales contain greater portions of several constituents. If rich in lime, they are calcareous shales; if rich in iron, ferruginous shales; if rich in carbon, carbonaceous shales, etc. Recalculating the rock composition, neglecting this increased chemical and biochemical portion, the remainder yields a more or less normal shale (71).

Figure 5 illustrates the variety of origin processed by shales (71).

Environmental Classification of Shales

Shales can be divided into several groups on the basis of the environment in which they are deposited. This environment in turn influences the thickness, areal extent, and lithology of the deposit. A sedimentary tectonic[1] grouping of shales has been described by Krumbein (53).

Some of the frequently used tectonic elements are defined below (4).

Shelf or Platform - A negative area, usually broad and covered by the sea (Much of the present continental area has been shelf in the geologic past).

Basin - A negative area on the shelf, usually oval shape, that subsided more rapidly than the surrounding shelf.

Geosyncline - An elongate negative area, along the margins of stable regions, that tended to subside rapidly. Positive areas may rise within them from time to time. (Rate of sedimentation may exceed subsidence, e.g., the formation of a delta).

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[1] Tectonic is the term which designates the rock structure and external forms resulting from the deformation of the earth's crust.

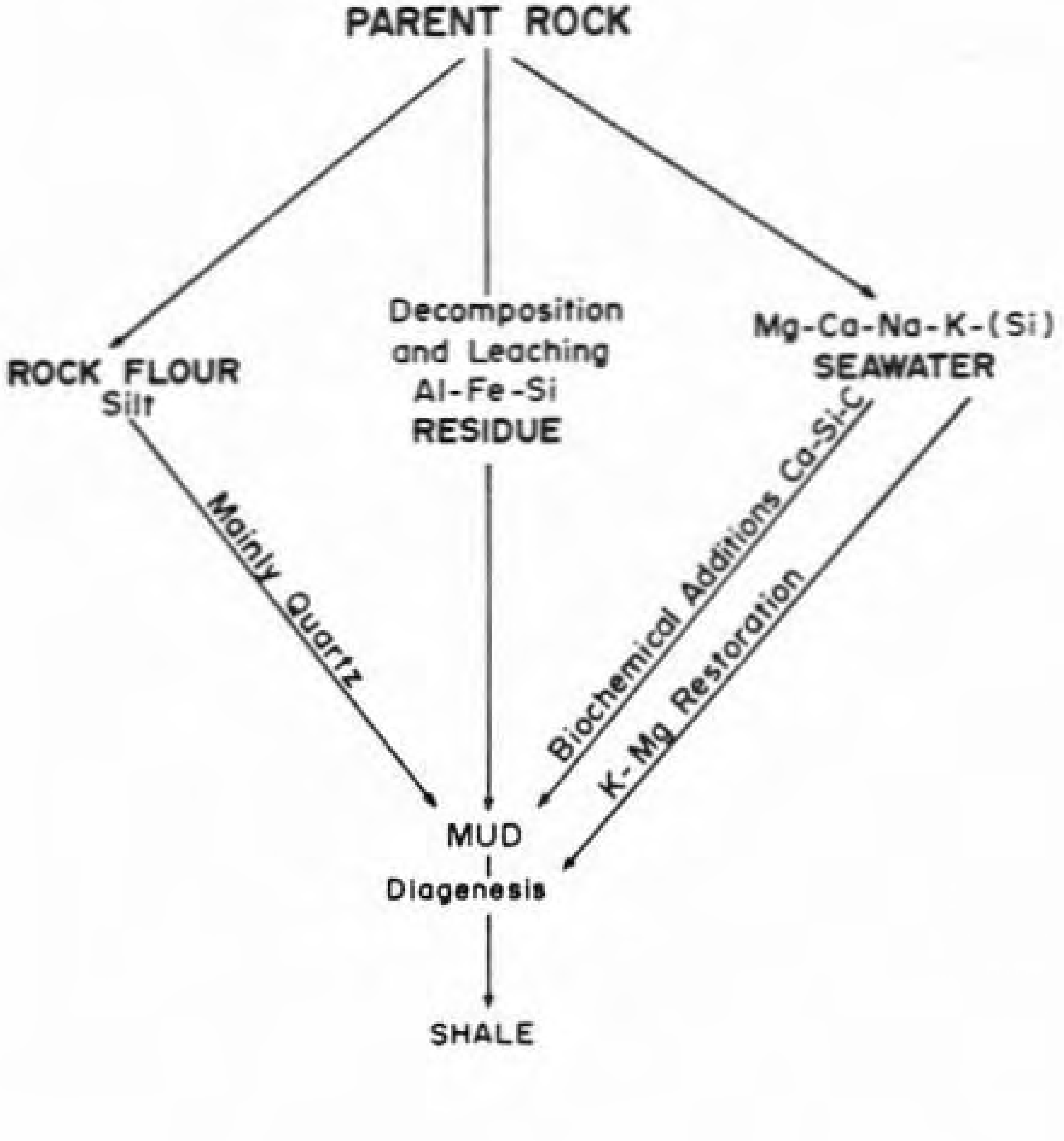

FIGURE 5. ORIGIN OF SHALE (71).

In addition, it should be recognized that a certain combination of shale characteristics may develop under different environmental conditions; and conversely, different shale varieties may develop from similar environments. The common deposit descriptors are:

i) thickness of shaly body,
ii) lateral extent,
iii) lithologic uniformity or variability, and
iv) widespread versus local occurrence.

An example of environmental classification is given in Table 4 (43, 53).

A Shale Classification Based on Degree of Cementation

Mead (64) proposes a classification of shales based on the degree of cementation. He suggests two broad categories: 1. compaction "soil like" shales which have been consolidated by the weight of overlying sediments, and lack a significant amount of intergranular cement; and 2. cemented "rock like" shales in which the cementing material may be calcareous, siliceous, ferruginous, gypsiferous, phosphatic, etc., or if a cementing agent is lacking the shale may be welded or bonded by recrystalization of its clay minerals.

Mead's classification is shown in Figure 6.

Additional Observations about Shale

Shale commonly results from cyclic deposition due to changing water depth and sediment supply. Hence it may be

TABLE 4. ENVIRONMENTAL CLASSIFICATION OF SHALES (43, 54).

Type	Thickness and lithology	Other associations	Condition in depositional site	Inferred Environment of deposition
Abundent rounded quartz; may be calcareous, carbonaceous or glauconite QUARTZOSE SHALE	Uniform thickness and lithology over large area, with some transitional lithologic changes	Quartzose sandstone, cherty limestone, dolomite	Widespread stable platform, no positive areas, very low subsidence	Broad shallow seas or wide flood plains, marginal lagoons; stable shelf deposition
Sandy siltstone to claystone; coarser textures predominate ARKOSIC or FELDSPATHIC SHALE	Thickness and lithology uniform regionally, but with abrupt local changes	Arkosic sandstone, nodular limestone	Locally unstable and subsiding more than surrounding regions	Similar to above; unstable shelf and basin deposition
Sandy siltstone to claystone; mica often; shale may be calcareous or siliceous, etc. MICACEOUS SHALE	Variable thickness and lithology; abrupt changes	Subgraywacke sandstone, argillaceous limestone, gypsum and other salts	Shallow basins, source areas are mildly positive	Shallow seas, alluvial plains, deltas, marginal lagoons; unstable shelf or basin deposition
Sandy siltstone; angular grains; chloritic materials abundant CHLORITIC SHALE	Variable thickness and lithology (usually abrupt change); specific members show transition	Graywacke sandstone, siliceous dark limestones	Tectonically active marginal geosynclines, with strong positive source areas	Range between terrestrial and marine; geosynclinal deposition

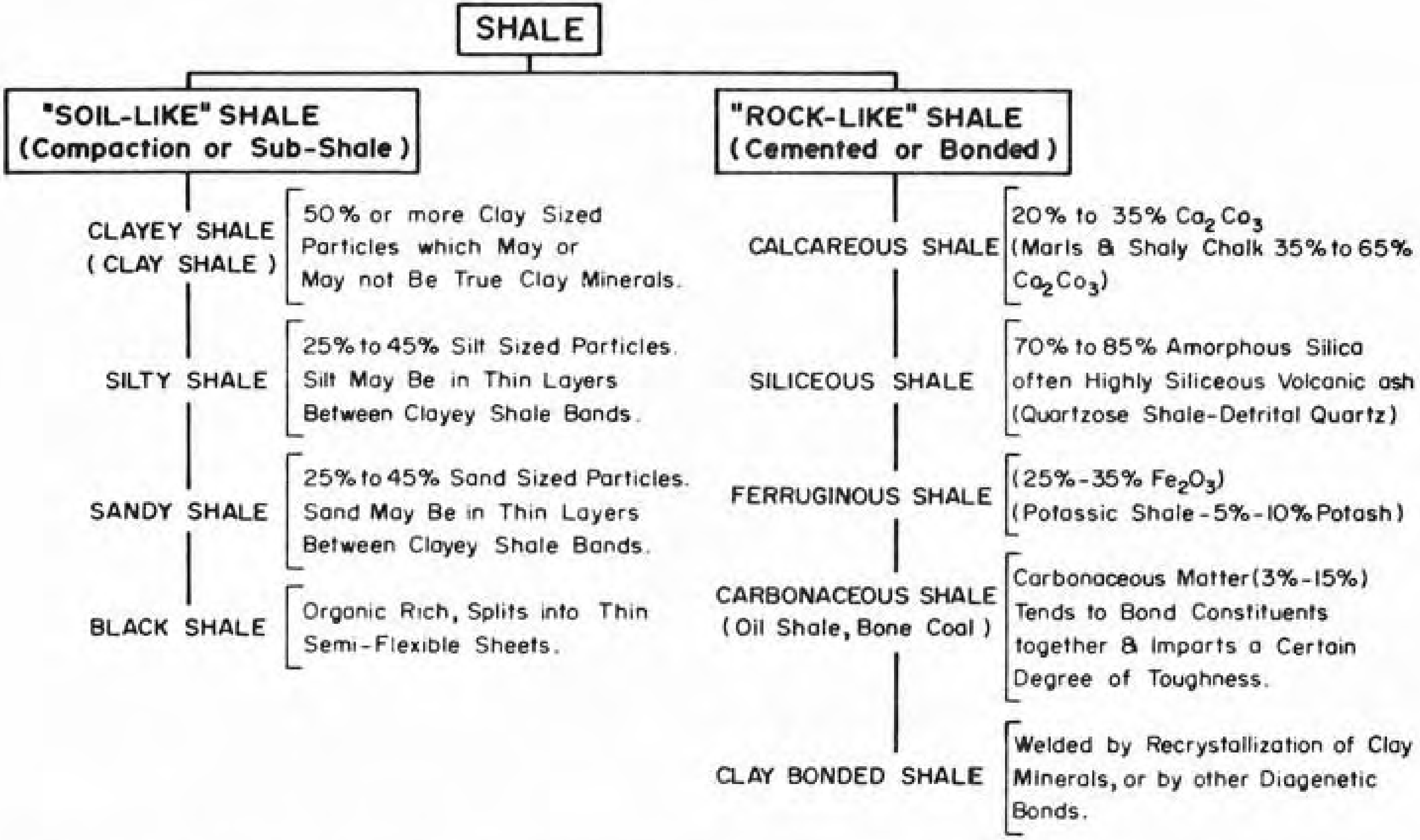

FIGURE 6. A SHALE CLASSIFICATION BASED ON DEGREE OF CEMENTATION (64).

found interbedded in a repeated fashion with other sedimentary rocks. In many locations in Indiana, alternating beds of shale and limestone are found (38). In other areas, coal, sandstone, freshwater limestone, and underclay are the rocks mutually associated with shales, particularly in Pennsylvanian aged rocks (78). These latter sequences are known as cyclotherms. A number of cycles of sedimentation may be present, and this imposes special problems in locating the shale beds. For example, shale may exist as thin beds between massive sandstone or limestone; if it goes undetected and the whole unit is treated as "sound" rock serious problems may develop.

Alling (2) has tried to correlate the ease of splitting and "shaliness" (fissility) with the shale composition. According to that author, an increase in siliceous or calcareous content generally reduced the shaliness. Rubey (75) has also concluded that fissility of shales has an inverse relationship with calcium carbonate content.

Ingram (51) observes that fissility in shales is associated with parallel arrangement of clay particles. The nature of the cementing agent determines whether the shale is flaky or flaggy. If the cementing agent can hold the material in large slabs, the shale will be flaggy. If the amount or the tenacity of the cementing agent is small, the shale will be flaky. Cementing agents other than organic matter tend to hinder cleavage parallel to clay particles, causing a decrease in fissility and an increase in massiveness. Weathering increases the fissility of shales. The type of fissility, however, did not correlate well with the type of clay minerals present in a random collection of mudrocks (51).

Payne (69) and Grim and Cuthbert (35) believe that clay minerals control fissility. According to these authors, sediments composed of illite will have a greater tendency toward fissility than those containing other clay minerals.

Clarke (18) determined chemical composition of an "average" shale from 82 shale samples, and compared it to the composition of an "average" igneous rock. The results are shown in Table 5. It can be concluded that the chemical compositions of the average shale and the average igneous rock are not a great deal different.

Underwood (90) presented a list of properties, and suggested ranges of values to aid in differentiating "problem" from "non-problem" shales with respect to <u>insitu</u> behavior for civil engineering purposes. The engineering properties considered significant were: compressive strength, shear strength, modulus of elasticity, permeability, moisture content, and density. The state of insitu stress and the deterioration of surfaces was also judged to affect engineering performance.

Slickensides are common features in shale and shale-related rocks (71). They are polished or scratched surfaces

TABLE 5. CHEMICAL COMPOSITION OF AVERAGE IGNEOUS ROCK AND AVERAGE SHALE (17).

Constituent	Average Igneous Rock	Average Shale
SiO_2	59.14	58.10
TiO_2	1.05	0.65
Al_2O_3	15.34	15.40
Fe_2O_3	3.08	4.02
FeO	3.80	2.45
MgO	3.49	2.44
CaO	5.08	3.11
Na_2O	3.84	1.30
K_2O	3.13	3.24
H_2O	1.15	5.00
P_2O_5	0.30	0.17
CO_2	0.10	2.63
SO_3	-	0.64
BaO	0.06	0.05
	99.56	99.2

which result from friction along a fault plane. Peterson (70) reported that slickensides are common in the softened surface zone of the Bearpaw shale, and their intensity decreases with depth.

Chenevert (16) reported results of water adsorption tests on several shales. He found that shales showed significant alteration of properties as a result of water adsorption.

Hartmann and Greenwald (39) of the U.S. Bureau of Mines have reported effects of moisture and temperature on roof shales from a coal mine. An uncoated kaolinite shale showed marked expansion with increases in temperature and humidity, while the same material coated with either mortar or paint had significantly less expansion. Changes in humidity also caused disintegration. Fresh samples immersed immediately in water exhibited no deterioration even after 2-1/2 months, while specimens which were first dried and then immersed in water disintegrated in 15 minutes.

Grice (31) reported that nonexpansive shales also disintegrate when subjected to various intensities and duration of wetting and drying. The degree of disintegration varies.

Underwood (88) reported that rapid slaking of the Pierre shale, when exposed to dry air, was prevented during the construction of tunnels at Oahe Dame in South Dakota, by maintaining the humidity of ventilating air at 95 percent.

In a later article (89), he reported that during the construction of Missouri river dams, he encountered some shales which slaked almost immediately after being exposed to moist air.

Deere and Gamble (21) suggested a durability-plasticity classification for shales and argillaceous rocks. The relative durability of these rocks to slaking was measured in an apparatus developed by Franklin and others (26). Oven dried pieces of shale were put in a drum of 2 mm mesh. The drum was rotated in a water trough at 20 rpm for 10 minutes. Slake durability was measured as the percent of the original sample weight retained in the drum after the test. Slake durability was designated as very low, low, medium, medium high, high, and very high. The plasticity index was classified as low, medium, and high. The rocks were subsequently designated according to their slake durability and plasticity index, e.g., medium durability-low plasticity shale or low durability-low plasticity shale, etc.

Engineering Problems of Shales

Shales have produced major problems in foundations (1), cut slopes (25, 36, 56), and embankments (79) throughout the world. The principal problems associated with shales are (1, 73):

1. Weathering into soils when exposed to cycles of wetting and drying, freezing and thawing.

2. Expansion upon wetting.
3. Shrinkage upon drying.
4. Variation in permeability and other properties.
5. Relatively low compressive strength and shear strength (compared to other rocks); degradation under load.
6. Joint systems which either afford high permeability or are sites of swelling clay minerals.

Shales of Indiana

In many parts of Indiana, shales are either exposed at the earth's surface or underlie it at shallow depths that are within the range of engineering considerations. Only shales of the Palezoic Era are present in Indiana and hence the montmorillonitic clays related to more recent rocks, volcanic activity, and weathering in arid regions are not represented.

Shales of Ordovician Age

The oldest geologic system of rocks in Indiana that contain shale of engineering significance is the Ordovician. These rocks are exposed in the southeastern part of the state (Figure 7). One such rock unit of note, the "Dillsboro Formation", lies within the Ordovician (78).

Shale of Dillsboro Formation. This formation consists of alternating beds of shale and limestone (30); at some locations more than five hundred beds of alternating shale

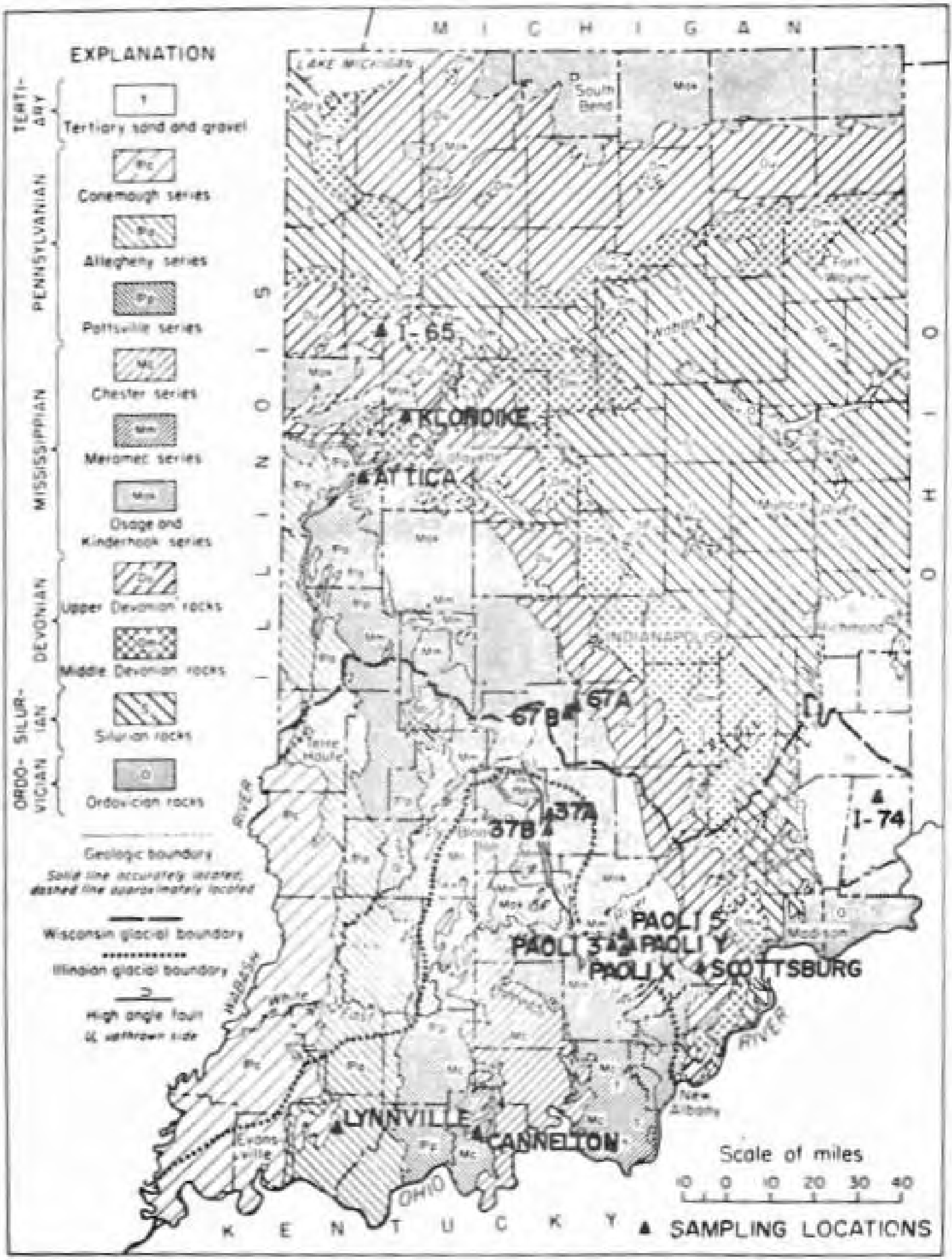

FIGURE 7. BEDROCK GEOLOGY OF INDIANA, AND SHALE SAMPLING LOCATIONS (92).

and limestone can be observed. The thickness of shale beds varies between one inch and two feet (30).

The Dillsboro Formation lies above the Kope Formation and directly below the Saluda Formation. Limestone in the Dillsboro is argillaceous and shales are calcareous (78). Common clay minerals present are illite, kaolinite and chlorite (30).

Generally the shales are highly fissile, and with repeated wetting and drying, they weather into low strength clay. The shale has few open joints, but the limestone is well jointed. The beds of shale and limestone are essentially horizontal (30).

Shales of Silurian Age

The Silurian System is represented in Indiana by a succession of limestones and dolomites. Silurian rocks are exposed at the surface in the southeastern part of the state (Figure 7). North of the Illinoian glacial boundary, glacial drift of varying thickness covers the bedrock surface. In some locations, such as certain creeks and river beds, the glacial drift has been removed by erosion and the bedrock is exposed. Despite the predominance of carbonate rocks in the Silurian, there are two formations with prominent shale lithologies, the "Waldron" and the "Mississinewa" (38).

Waldron Shale. This formation overlies the Laurel Limestone and is overlain in turn by the Louisville Limestone.

It ranges from 5 to 12 feet in thickness. In a few places the Waldron is entirely missing, and the Louisville Limestone rests uncomformably on the Laurel Limestone (78).

Waldron Shale contains the clay minerals kaolinite, illinite, and chlorite; the non-clay fraction consists of quartz, dolomite and calcite. The color of Waldron Shale varies from green to gray. In some places it is massive and soft, but in others, is fissile and hard. It is fine grained and much of the quartz, calcite and dolomite are nearly as fine grained as the clay minerals (38).

Mississinewa Shale. This formation overlies the Louisville Limestone and is overlain in turn by the Liston Creek Limestone. In places along the Mississinewa River it is more than 50 feet thick (78).

Shale in the Mississinewa is mineralogically similar to Waldron Shale, except that the former commonly lacks kaolinite. In many places Mississinewa rocks are primarily dolomite rather than shale, as the dolomite beds consistently comprise more than 50 percent of the sequence (38).

Mississinewa Shale is gray to blue on fresh surfaces and light brown when weathered. The shale is massive and bedding is not apparent. It is dominantly fine grained, but in some places silt or sand give the unit a silty or sandy appearance (38).

Shales of Devonian Age

Similar to the Silurian, the Devonian System is also represented in Indiana by a succession of limestones and dolomites. They are exposed at the surface in southeastern Indiana, but are otherwise covered by glacial drift of varying thickness. There is only one shale formation, the "New Albany", contained in the Devonian sequence (38).

New Albany Shale. This shale is partially Devonian and Mississipian in age, since the unit extends above and below the boundary of these two geologic systems (38). The North Vernon Limestone underlies the New Albany Shale and the Rockford Limestone of Mississippian age overlies it (78).

New Albany Shale varies in thickness from 80 to 150 feet along its outcrop. Illite, kaolinite and chlorite are common clay minerals. Quartz is the most abundant non-clay mineral and is associated with feldspar, calcite, dolomite and phosphate minerals. Pyrite is commonly present as coarse to fine crystals in the form of nodules or concretions (38).

New Albany Shale is dark gray, dark olive green, or black, and weathers to light gray, brown or maroon after a few years of exposure (38). It is found in almost all known locations as thinly bedded to fissile, fine grained shale. Some of its quartz and pyrite grains are large enough to fall within the sand size (38).

Shales of Mississipian Age

Mississipian rocks in Indiana are exposed in a band that trends in a northwest-southeast direction across the approximate center of the state (Figure 7). The oldest rocks (Kinderhook) are at the eastern edge of this band, and the youngest rocks (Chester) are at the western edge. Much of the band of Mississippian rocks is buried by glacial drift.

Rocks of the Mississipian System are assigned to four series in Indiana: Kinderhook, Osage, Meramec, and Chester (38). The only shale of the Kinderhook Series occurs in the top portion of the New Albany Shale, which has been discussed under the Devonian System. Rocks of the Osage Series consist of shales and limestones. Meramec rocks are mostly limestones and dolomites and contain practically no shale. Rocks of the Chester Series are composed of limestones, sandstones and shales (38).

Osage Shales. Rocks of the Osage Series are assigned to the Borden Group and are popularly known as "Borden rocks". The shales of this group occur in two formations, the New Providence Shale, which is the oldest formation of the Borden Group and the Locust Point Formation, which lies directly above the New Providence. These two have a similar lithology and are difficult to distinguish (38).

Rocks of the Borden Group lie in a narrow band about 12 to 15 miles wide trending from New Albany, on the Ohio River, to Lafayette. From the Illinoian glacial boundary northward, glacial drift of varying thickness covers the Borden shales, but they are locally exposed in places (38). The Borden Group overlies either the Rockford Limestone or the New Albany Shale because of a prominent unconformity which cuts across those geologic units.

Borden shales contain illite, kaolinite, chlorite, quartz and feldspar. The non-clay particles in Borden shales are commonly silt size. The color ranges from blue gray to brown. In most places these shales are massive to blocky on fresh surfaces, but on weathered surfaces they display definite partings and break out in small pieces. The shales vary from soft to very hard (38).

Chester Shales. The rocks of the Chester Series consist of shales, sandstones and limestones. This series is more variable in mineralogy, thickness, and physical properties, both laterally and vertically, than the shale units previously described (38).

Chester rocks crop out in a band west of the Borden rocks. The outcrop belt extends from the Ohio River to a point midway between Indianapolis and Terre Haute (Figure 7).

The Bethel Formation is stratigraphically the lowest formation of the Chester Series which contains shale. The

Bethel consists of dark gray shales and argillaceous sandstones, 5 to 30 feet thick. Most of the Bethel shales are soft, and their grain size ranges from coarse to fine (38).

All shales of the Chester Series are variable in physical properties and mineralogy, particularly in the lateral direction (78). In many locations the shale grades laterally into sandstone or limestone in less than a mile, and in other places in a matter of tens of feet (38). The dominant clay minerals are illite, kaolinite and occasionally montmorillonite. Quartz is the main non-clay mineral. Feldspar and calcite may be present in small quantities (38).

Shales of Pennsylvanian Age

Rocks of the Pennsylvanian System lie west of the Mississippian outcrop, in a belt extending from the Ohio River northward to Lafayette, and then westward to the Indiana-Illinois state boundary (Figure 7). North of the Illinoian glacial boundary, glacial drift of varying thickness covers most Pennsylvanian rocks (38).

Pennsylvanian formations are stratigraphically complex because of common changes from one rock type to another over relatively short distances. In addition, rocks of a specific lithologic type are similar mineralogically from one Pennsylvanian formation to another, making it difficult to distinguish between the formations using lithology alone (38).

Two types of shales are found in Pennsylvanian rocks in Indiana: 1) dark-gray to black, fine grained thinly bedded shale; and 2) light-gray silty thick bedded shale (38).

Pennsylvanian shales have less quartz and feldspar than the shales previously discussed. The common clay minerals are illite, kaolinite and chlorite. They also contain traces of iron (38).

Current Placement Technology

Embankments for engineering structures have been constructed of both soil and rock. Shale has been treated sometimes as a soil, sometimes as a rock. Indeed most aspects of design and construction involving shale materials fall within the group of engineering problems for which there are only empirical solutions.

Sherard and others (79) emphasize the importance of proper investigation of the shale material, and handling each as an individual problem. Test embankment sections are recommended to determine the proper design and construction procedures and specifications.

In Indiana there are three agencies actively engaged in the construction of embankments which involve use of shales. These are:

1. Indiana State Highway Commission.
2. Soil Conservation Service, United States Department of Agriculture.

3. Division of Water, Indiana Department of Natural Resources.

Verbal and written information was obtained from these agencies on their problems and practices.

Indiana State Highway Commission

The Indiana State Highway Commission has separate specifications for earth and rock fill embankments (44). They do not, however, have separate specifications for shale in embankments. Nonetheless, when shale is encountered as a fill material, the writing of special provisions is customary.

Soil Fill (44). All soil embankments are constructed with density control. Embankments are compacted to at least 95 percent of maximum wet density as determined by AASHO T-99 (3). The embankment material is placed in uniform level layers with a three wheeled roller weighing not less than 10 tons. Other types of compacting equipment could be used provided they are capable of producing a smooth and even surface on the embankment. Each lift is treated by some mechanical means, which insures the breaking up of existing lumps and clods. The loose depth of each lift is selected such that the required compaction can be obtained, but in no case can it exceed 8 inches. If a tamping roller is used as compaction equipment, the loose depth can not exceed the length of tamper feet. The compaction is accomplished on the dry side of optimum moisture content as determined by AASHO T-99 (3). If the material has a moisture content greater than optimum moisture content, the material is aerated to remove excess moisture.

There are no standard specifications for the side slope. Normally for embankments of height 10 feet or less, side slopes of 4 to 1 are used. For heights greater than 10 feet, side slopes of 3 to 1 are employed (50).

Rock Fill (44). When rock is used in an embankment, the pieces are distributed over the area so as to avoid large and obvious voids or pockets. Voids are carefully filled with small pieces. The top 2 feet of the embankment is composed of suitable soil placed in loose layers of 8 inches or less and compacted to the required density.

If the depth of an embankment exceeds 5 feet and consists entirely of rock, the rock is deposited in lifts not greater than the top size of the material being used, or 4 feet, whichever is less. The voids of the last lift are closed with small broken stone or other suitable material and thoroughly compacted. If the depth of the embankment is less than 5 feet, or where the material being placed does not consist entirely of rock, the material is placed in lifts not greater than the top size of the rock being used, or 2 feet, whichever is less.

Where the rock fill is to be placed over a structure, the structure is first covered with 2 to 4 feet of properly compacted soil.

There is no density control carried out in rock fills; however, side slopes are steeper than for soils. For embankments constructed from sound limestone, 1 to 1 slopes are acceptable. For soft rocks like shale, 2 to 1, or 3 to 1 slopes are commonly used. Such guidelines are quite empirical.

Shale Fill. There are no separate fixed specifications for shale embankments. The Indiana State Highway Commission uses shales in embankments with the following provisions (50).

1. Shales are subjected to thorough breakdown in the process of excavation, hauling, placement and compaction; in other words, treated like soil fill. Occasionally, lift thicknesses are made even smaller than for soil.

2. A non-shale soil encasement of two or three feet is provided on all boundaries of the embankment.

3. The shale-soil mixture, when treated in the specified manner, is considered to be highly competent, and no other special design features are needed.

Such provisions are normally contained in a special construction specification statement, and are often quite qualitative. For example, in the construction of I-65 near

Remington and in the vicinity of the U.S. 24 interchange, shale was used in the embankment. The special provisions are quoted below (45):

"We believe that use of this shale should be based primarily on field evaluations as follows:

1. Construction personnel must be satisfied with the quality of the material.

2. The contractor should agree to process or handle this material in such a manner as to reduce the shale pieces to reasonable sizes that are well compacted in its final position. It may be necessary to place this material in thinner lifts than soil.

3. The shale is to be confined to the interior portion of the fill, with a minimum encasement of two feet of soil both on the side slopes and surface. The upper two feet of subgrade should be soil. The suitable use of this shale will depend primarily on the contractor's operations."

In some cases shale has not been properly identified and specially treated, leading to embankment distress. At least at one location, on I-74 near St. Leon, a non-durable shale was used (1961) with limestone. It apparently was not sufficiently degraded during the construction process and did ultimately slake in service, producing settlement and finally a landslide, which closed the eastbound lanes some 10 years later. The complete case history has been described in Appendix A.

Soil Conservation Service

The Soil Conservation Service, U.S. Department of Agriculture, used shale in construction of small (height less than 40 feet) dams. Though they differentiated between durable and non-durable (soil-like) shales, they have no definite stated criteria to indicate into which group the shale in question should fall. They use shales with the following provisions:

Durable Shales

1. The maximum size of rock fragments used is eighteen inches, provided that such fragments are completely embedded in a matrix of compacted fill.

2. The maximum thickness of rock layers before compaction is twenty four inches.

3. Broken shale and limestone mixtures may be used in rock fill.

4. Rock fill has a cover of weathering resistant material of two to four feet.

5. A minimum compacted dry unit weight of 112.5 pcf was used for two different shales. This number could vary for other shales (81).

Soil like Shales

1. A shale which completely slakes in water in few (about ten) minutes can also be used in embankment provided it is thoroughly broken down to soil during excavation, hauling, placement, and compaction.

2. A minimum encasement of four feet of non-shale soil is needed.

3. The unit weight of the fill should be at least 95 percent of the maximum determined by ASTM D 698-66T (83).

Division of Water

The Division of Water, Indiana Department of Natural Resources, has had limited experience concerning use of shales in embankments. They prefer a thorough breakdown of material, and specify that the broken shale material be processed and compacted in such a manner as to achieve 95 percent of maximum density as determined by the Standard Proctor test, ASTM D 698-66T (22).

None of these agencies has standards for quantitatively examining and classifying the shale for construction. A considerable amount of judgement may be required at the time of construction, and there is a definite potential for being unduly conservative, and even occasionally, erring on the unsafe side.

EXPERIMENTAL MATERIALS

Sampling sites were selected with the aid of concerned agencies, e.g., the Indiana State Highway Commission (ISHC) and the Soil Conservation Service (SCS). At least 24 potential sampling sites were inspected, and 15 of these were ultimately sampled. The quantity of material acquired varied between 150 and 1500 lb, depending upon the type of material and ease in sampling. Fresh and unweathered samples were desired, and this ordinarily meant taking the material during the cutting of an excavation, or immediately after the completion of the excavation. In some cases the sampling was done with the help of the personnel of the Indiana State Highway Commission and Soil Conservation Service.

The sampling locations are shown on an Indiana state highway map in Figure 8. Sampling locations were also shown in Figure 7, which is the bedrock geology map of Indiana. Ten of the fifteen samples, namely, Klondike, Attica, 67A, 67B, 37A, 37B, Paoli 3, Paoli 5, Paoli X, and Paoli Y are Borden shales of the Osage Series, which is early Mississipian in age (about 330 million years). One, the Cannelton shale, is of the Chester Series, which is

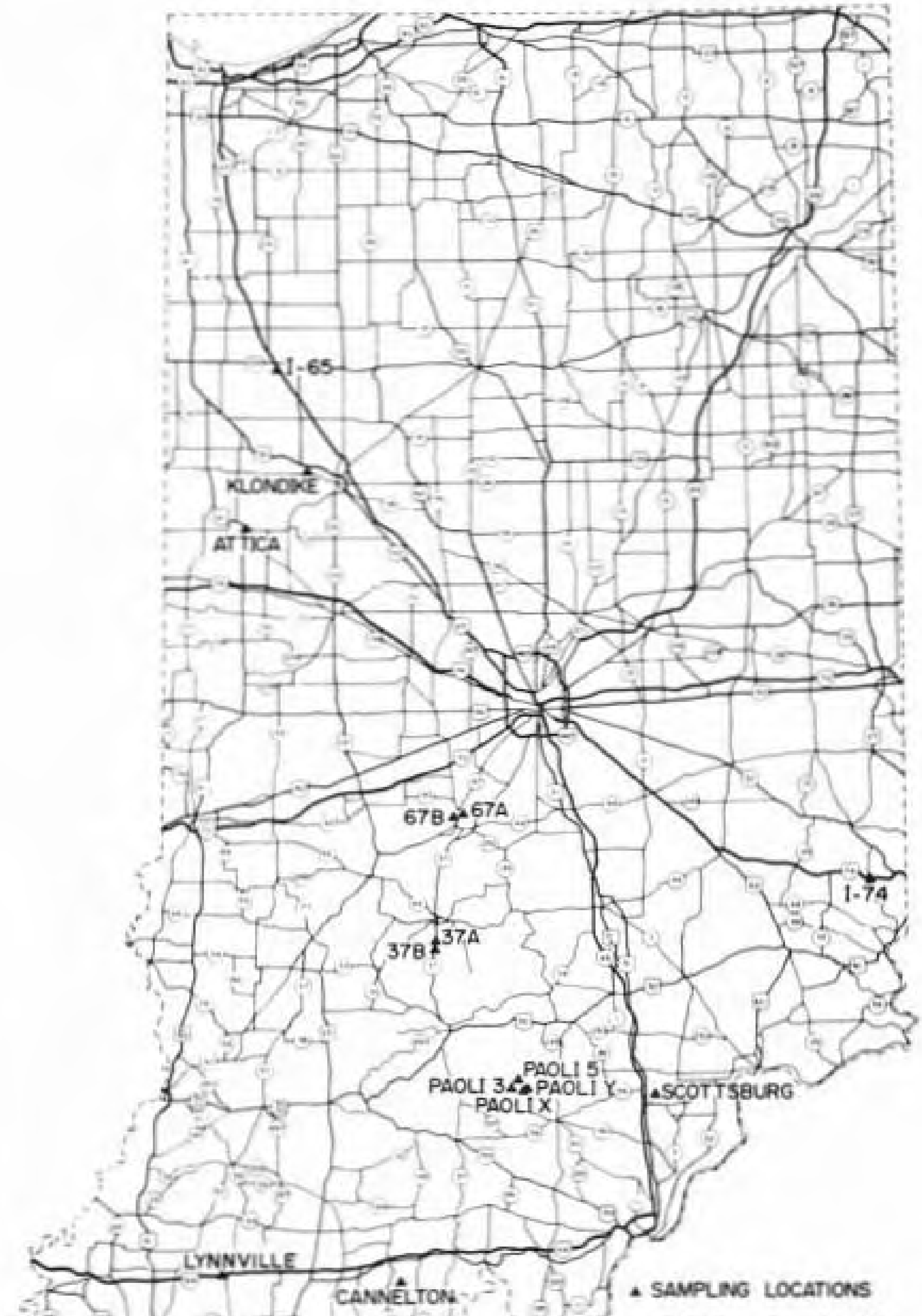

FIGURE 8. HIGHWAY MAP OF INDIANA, AND SHALE SAMPLING LOCATIONS (49).

of late Mississipian age (about 310 million years). Two, I-65 and Scottsburg shales, are of the New Albany Formation of upper Devonian age (about 350 million years). The Lynnville shale is of the Allegheney Series of middle Pennsylvanian age (about 290 million years). The I-74 shale is of the Dillsboro Formation of late Ordovician age (about 430 million years).

Shales of three sites were used as embankment material in small dams by the Soil Conservation Service (Paoli 3, Paoli 5 and Cannelton). Shales from four locations were used in highway embankments by the Indiana State Highway Commission (I-65, I-74, 37A and 37B).

APPARATUS AND TEST PROCEDURES

A battery of engineering tests was run on all the shales to classify them and predict their engineering performance. A description of different tests, their purpose, procedure, and apparatus, is given below.

The tests were in four groups:

1. Degradation type tests
2. Soil type standard identification tests
3. Compaction and load-deformation tests
4. Miscellaneous tests.

Degradation Type Tests

These tests are a measure of the durability of the shales during construction and in the service environment. This group includes different types of slaking tests (in air, water, and a sodium sulfate solution), and mechanical abrasion tests. Each of these will be discussed in turn.

Test for Slaking in Air

It has been reported by Underwood (89) that some shales will slake almost immediately when exposed to moist air. For such shales, there is a rapid deterioration of any exposed surface or excavated material. An examination of the excavated surfaces and stored material revealed that none of the shales collected during this program came under this category.

Test for Slaking in Water in One Cycle of Wetting and Drying

A broken piece of shale weighing between 50 and 60 gm was oven dried at a temperature between 105° and 110°C for at least 8 hours. This broken piece was selected such that it was roughly equidimensional. The shale piece was allowed to cool for 30 minutes at room temperature. It was immersed in water so that it was at least 1/2 in. below the water surface.

After immersion, the shale piece was observed continuously during the first hour; after that, the condition of the piece was checked at two, four, eight, twelve, and twenty four hours. The condition of the piece was recorded as: complete breakdown, partial breakdown, or no change. If the piece seemed intact, the cloudiness of the water was also noted. For any shale which slaked completely or partially, the test was repeated.

Figures 9, 10, and 11 show the extremes of material response in the test.

Test for Slaking in Water with Five Cycles of Wetting and Drying

This test was first suggested by Philbrick (73) to separate "compaction" and "cemented" shales.

FIGURE 9. CANNELTON SHALE BEFORE IMMERSION IN WATER.

FIGURE 10. CANNELTON SHALE AFTER 15 MINUTES OF IMMERSION IN WATER.

FIGURE 11. PAOLI 3 SHALE AFTER 24 HOURS OF IMMERSION IN WATER.

A broken piece of shale weighing between 50 and 60 gm was oven dried at a temperature between 105° and 110°C for at least 8 hours. The broken piece was selected such that it was roughly equidimensional. The shale piece was allowed to cool for 30 minutes at room temperature and then immersed at least 1/2 in. below the water level.

After 16 hours, the shale piece was removed from the water, drained for 10 minutes, and dried at between 105° and 110°C for 8 hours. Five cycles of wetting and drying were repeated, and the condition of the sample was observed at the end of each cycle, and at the conclusion of the test.

Slake Durability Test

The slaking tests discussed previously produce rather qualitative results. The slake durability test, on the other hand, measures a weight loss in water which can be expressed as a durability number (N_d). The durability number values vary not only with the type of shale, but, unfortunately, also with such test details as the initial moisture condition of the shale charge and the testing time (drum revolutions).

The apparatus was developed by Franklin and others at Imperial College London in 1970 (26). The test procedure was further developed and modified to suit Indiana shales.

The apparatus, shown in Figures 12 and 13, consisted of a drum of 2 mm mesh, 10 cm in length and 14 cm in diameter.

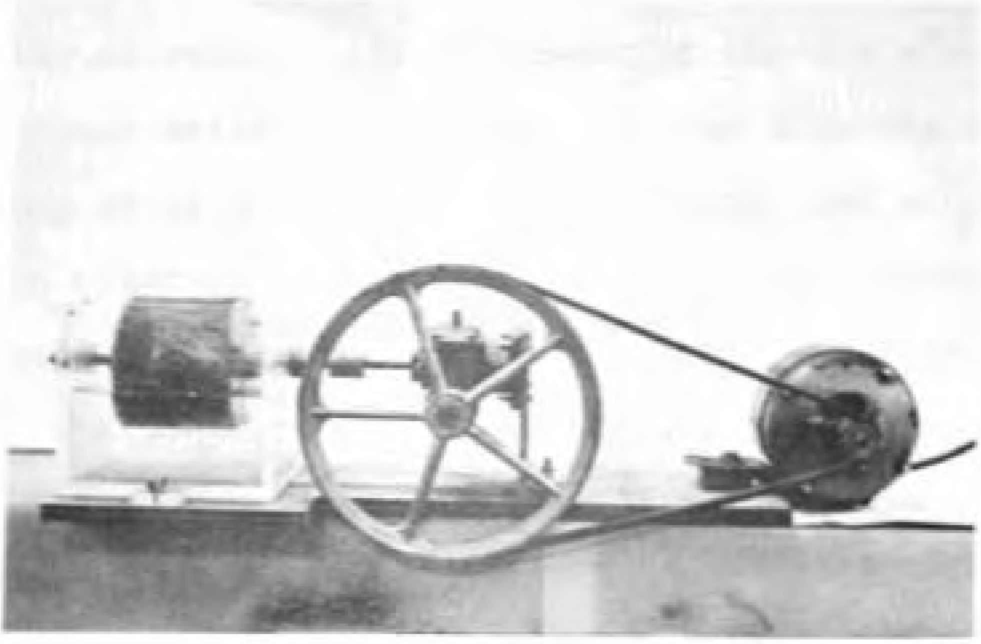

FIGURE 12. SLAKE DURABILITY APPARATUS.

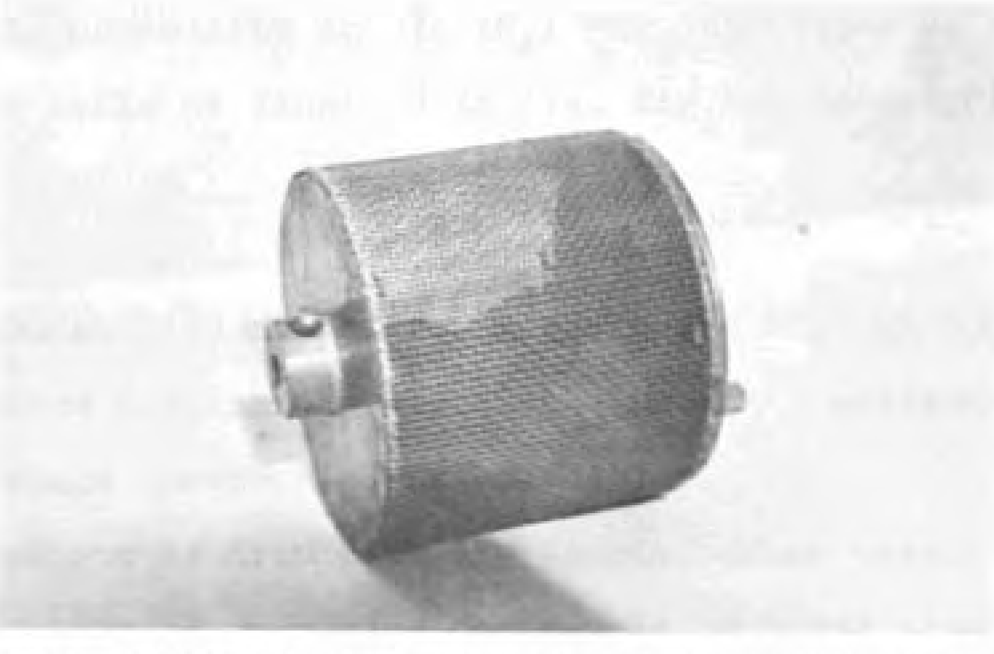

FIGURE 13. TEST DRUM IN SLAKE DURABILITY APPARATUS.

Both ends of the cylinder are solid and incorporate suitable driving dogs. One side plate incorporates a quick release mechanism to permit easy placement of the shale samples.

A motor drive unit attached to the drum was capable of revolving it at a speed of 20 revolutions per minute. The drum was rotated in a water trough which was mounted to the base board. The test drum was supported on water lubricated bearings, allowing 4 cm unobstructed clearance below the drum. The trough water level was 2 cm below the axis of the drum.

A sample of ten representative shale pieces, each weighing 50 to 60 gm, was oven dried and placed in the test drum. The drum was now half immersed in the water bath and rotated. Material detached from the pieces passed through the mesh, i.e., became a sample weight loss.

The durability number (N_d) was calculated as the percentage ratio of final to initial dry sample weights,

$$N_d = \frac{B-C}{A-C} 100 \quad \text{where}$$

N_d = Durability number for a shale for a given number of drum revolutions and given initial conditions of shale (oven-dried or soaked).

A = Weight of drum plus dry sample before test.

B = Weight of drum plus dry sample retained after test.

C = Weight of clean and dry drum.

The test was conducted not only on oven-dried samples, but also on samples which were immersed in water for six hours before testing. Dry sample weights were used in all calculations.

To determine a suitable value for the standard number of revolutions, preliminary tests were conducted on selected samples for 100, 200, 500 and 1000 revolutions of the drum. These results are shown in Appendix B. The weight loss through the meshed drum increases with the number of revolutions, except that at a higher number of revolutions, viz., 1000, the results were not always reproducible. Five hundred revolutions seems a reasonable compromise, since it produced both a wide range of durability numbers among the shales and reproducible results.

The durability number for 500 revolutions was defined as the durability index (I_d). Durability indices both for dry samples, $(I_d)_d$, and for soaked samples, $(I_d)_s$, were determined. At least two tests were run for each combination of variables; values reported are averages. The lower the I_d value, the less durable the shale. Soaked values were always lower than the dry ones.

Modified Soundness Test

This test measures the degradation of shales when subjected to five cycles of alternate wetting and drying in a sodium sulfate solution. It is more severe than the previously mentioned slaking tests, and is more effective in distinguishing among the harder and more durable shales.

The test was modified from ASTM C 88-63 (5), which is used to determine the resistance of aggregates to disintegration by sodium sulfate or magnesium sulfate. The standard test uses a fully saturated solution, but this is too severe for shales, and after a series of trials, the saturation was reduced to 50%.

The charge of shale fragments was 1000 gm, of which 330 gm was between 1/2 in. and 3/8 in., and 670 gm was between 3/4 in. and 1/2 in. Pieces in this size range were roughly equidimensional. Larger pieces tended to be plate shaped, due to the laminated nature of the sediment. Definition of size by a sieving process of course becomes more arbitrary as the pieces depart from a bulky shape. The sample was washed with water, and oven dried at 105 to 110°C before weighing.

A saturated solution of anhydrous granular sodium sulfate was prepared in accordance with ASTM C 88-63 procedures (5). The solution was diluted to 50% saturation by adding an equal amount of water. The solution was prepared at least 24 hours in advance of the start of test.

The sample was immersed in the sodium sulfate solution for not less than 16 hours and not more than 18 hours. The solution covered the shale chunks to a depth of at least 1/2 in. The immersion was conducted at a room temperature of 72° ± 2°F. The sample was removed from the solution, drained for 15 minutes, placed in the drying oven at 105 to 110°C, and dried to constant weight. After the sample had cooled to room temperature, the process was repeated.

Upon completion of five cycles of immersion and drying, the sample was washed with water until free of sodium sulfate, as determined by the reaction of the wash water with barium chloride ($BaCl_2$). It was then dried and fractioned on a 5/16 in. sieve. The weight retained on the sieve was determined. Each test was repeated at least once, and average values are reported.

The Soundness Index, I_s, was defined as the percent retained by weight on the 5/16 in. sieve. Durability is considered to increase with increase in I_s value.

Modified Abrasion Test

The test was modified from the standard Los Angeles abrasion test, ASTM C 131-66 (5). In the standard test, the sample and a defined abrasive charge of steel balls is placed in the abrasion testing machine and rotated for 500 revolutions. The quantity of material finer than the No. 12 sieve, resulting from this process, is called the "wear", and rates the degree of abrasion. High wear values indicate less durable rocks.

The standard test was too severe for the shales used in this study, and changes were introduced. Shale charges were either, a) oven dried or b) soaked.

a) Oven-Dried Sample. The abrasion charge was reduced from 12 to 3 steel balls (each approximately 1-7/8 in. diameter and 445 gm weight), and the sample weight was 2000 gm, with 1000 gm between 1 and 1-1/2 in., and 1000 gm between 3/4 and 1 in. Abrasion loss was determined by sieving through the No. 12 (1.68 mm) U.S. standard sieve after 200 revolutions in the standard drum. (Abrasion loss was also recorded after 50 revolutions.) The weight loss of the sample expressed as a percentage of the original weight was defined as the percent abrasion loss. For some selected samples a complete chunk (grain) size distribution was also determined at the end of the test.

b) Soaked Sample. The abrasion test on soaked shale samples used the same weight and gradation of sample as above. The shale chunks were soaked in water for six hours prior to starting the test. The machine was rotated for only 50 revolutions and no charge was used. After 50 revolutions the material was washed on a No. 4 (4.76 mm) U. S. standard sieve. The material retained on No. 4 sieve was dried and weighed. Using the dry weights, the percent abrasion loss was determined as before.

Soil Type Identification Tests

These tests were run on powdered shale material to determine the behavior of the shale when and if reduced to the soil size. These test results, which are of only limited value, include Atterberg limits, grain size distribution, and X-ray diffraction.

Atterberg Limits

The dried[1] shale was broken down by mechanical means to provide a sufficient sample passing the No. 40 sieve. A mortar and a pestle (with rubber tip) were used for grinding purposes.

The liquid limit was determined in accordance with ASTM D 423-66 (6), and plastic limit and plasticity index were measured using ASTM D 424-59 (6).

Grain Size Analysis

The grain size distribution of various shales was based upon a combined sieve and hydrometer analysis, ASTM D 422-63 (6). The distribution of particles larger than 0.074 mm (retained on the No. 200 sieve) was determined by sieving, while the distribution of particle sizes smaller than 0.074 mm was determined by a sedimentation process using a hydrometer.

The usual mechanical disaggregation preceding the test was both arbitrary and troublesome. Due to the "cemented character" of the shales, it was most difficult to determine the amount of mechanical effort required to separate basic particulate units without fracturing them.

---

1. It was not possible to store the shale samples at controlled humidity.

An alternate technique was developed which consisted of a combination of mechanical and chemical disaggregation. The technique is described below.

A saturated solution of sodium sulfate was prepared, and the shale pieces of about 1 in. size were immersed in it for 16 hours. The shale was dried for 8 hours in an oven. Following the above pattern, three cycles of soaking and drying were repeated. Care was taken during the handling, so that there was no loss of material. At the end of the third cycle, the sample was washed with water till free from sodium sulfate, as determined by the reaction of the wash water with barium chloride.

All the wash water was collected, and a filter paper was used to collect the shale particles. The material retained on filter paper was further washed to insure removal of all sodium sulfate.

The sample was then ground with the mortar and pestle. Since the bonds of the shale particles were weakened due to the sodium sulfate action, the size reduction was easy to accomplish and reproducible test results were obtained. The grain size distribution test was conducted in accordance with ASTM D 422-63 (6).

X-ray Diffraction

The X-ray diffraction test was conducted on powdered shale samples to identify principal clay and nonclay minerals. Powdered shale samples were obtained by mechanical degradation only.

The test samples were further prepared in a special aluminum cell using the McCreery method (61), which is described in Appendix C.

The sample was mounted and the diffractometer adjusted for standard conditions, which are:

Voltage = 50 kilovolt
Current = 32 milliampere
Goniometer Speed = 2°/minute
Beam Slit = 1°
Detector Slit = 0.2 Angstrom
Time Constant = 2 seconds
Chart Speed = 60 inch/hour
Range = 0 to 1000 cycles per second

The diffraction pattern was obtained between 2° and 30° of 2θ values.

A diffraction pattern was also obtained with the paste of powder with glycerol.

After determining the positions of peaks, the interplanar spacings were calculated:

$$d = \frac{\lambda}{2 \text{ Sin } \theta} \qquad \text{where}$$

d = Interplanar spacings for angle 2θ

λ = Wave length of radiation

(For copper radiation K_{α_1}, $\lambda = 1.54$ Å)

2θ = Diffractometer angle in degrees for position of peaks.

Knowing the interplanar spacings, the various minerals are identified.

Compaction and Load-Deformation Tests

Since the embankment materials are placed as a rolled fill, it was desirable to establish some form of the moisture density relationship. Some sort of "strength number" was also needed. Since large pieces of shale may be used in the embankment, the largest practicable laboratory sample was selected. This was the six inch diameter CBR sample and test. CBR values were determined for both as-compacted and soaked samples at different water contents. Swelling after soaking in the CBR mold was also measured.

Test procedures AASHO T 99-61 and T 181-61 (3) were followed for compaction, except that all compaction was accomplished in the CBR mold. Standard AASHO T 193-63 (3) was followed for the CBR testing, with minor modifications.

Apparatus

A 6 in. internal diameter cylindrical mold having a height of 7 in. was used. It had an extension collar 2 in. in height and a perforated base plate that could be fitted to either end of the mold. A circular metal spacer disk, 5-5/16 in. in diameter and 2.416 in. in height was also available. When both the mold and the spacer disk are used, a sample height of 4.584 in. and volume of 1/13.33 (0.075) cu ft are obtained.

Two rammers were used in this study. One had a 2 in. diameter face, weighed 5.5 lb, and was dropped 12 in. The second rammer had a 2 in. diameter face, weighed 10.0 lb, and a drop of 18 in. Figure 14 shows the mold, spacer disk, extension collar, and a rammer.

The loading device consisted of a compression type apparatus, capable of applying a deformation rate of 0.05 in. per minute. The apparatus was used to force a piston of circular cross section having a diameter of 1.95 in. (area = 3 sq in.) into the sample of compacted shale. The loading device is shown in Figure 15.

The apparatus for measuring volume increase, due to the effect of water upon the compacted samples, consisted of a swell plate with an adjustable stem and a tripod support for a dial indicator. The swell plate is made of metal, 5-7/8 in. in diameter and perforated with 1/16 in. diameter holes. The tripod used to support the dial indicator is arranged to fit the mold extension collar. The device is shown in Figure 16.

Test Procedure

The maximum size of shale chunks that could be used in this mold was recommended as 3/4 in. by AASHO T 99-61 (3). Therefore large pieces of shale, about 6 in. across, were

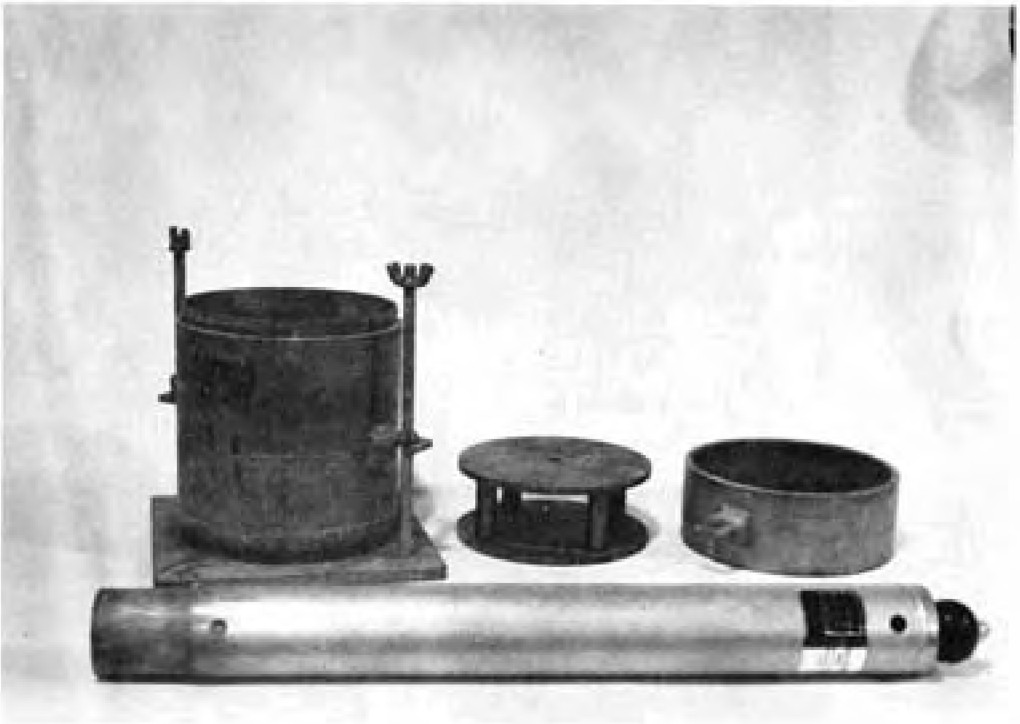

FIGURE 14. MOLD, SPACER DISK, EXTENSION COLLAR AND RAMMER.

FIGURE 15. LOADING DEVICE FOR CBR TEST.

FIGURE 16. DEVICE FOR MEASURING EXPANSION.

passed through a jaw crusher which produced pieces 3/4 in. or smaller. The softer shales gave finer gradations.

A representative air-dried sample weighing at least 18 lb was thoroughly mixed with water to produce the desired compaction water content. The prepared shale was compacted, with the spacer disk at the bottom and the collar attached at the top, such that a compacted height of 5 in. was obtained. A filter paper was placed between the spacer disk and the shale.

The compaction was performed at the four effort levels listed below.

i) Standard effort - 5.5 lb rammer with 12 in. fall, 3 layers, 56 uniformly distributed blows per layer.

ii) 0.5 Standard effort - same as above, but 28 uniformly distributed blows per layer.

iii) 1.8 Standard effort - same as above, but 100 uniformly distributed blows per layer.

iv) 4.5 Standard effort - 10 lb rammer with 18 in. fall, 5 layers, 56 uniformly distributed blows per layer.

After compaction, the extension collar was removed and the surface was trimmed evenly with the help of a straightedge. The weight of the compacted soil sample was determined. The water content of the compacted shale was determined by drying a sample of at least 50 gm.

The as-compacted California Bearing Ratio was now measured. The extension collar was replaced and a surcharge of 10 lb of annular and slotted weights was placed on the sample. The sample was positioned in the loading device, and the penetration dial indicator and load indicator were adjusted to zero.

The piston was forced into the sample at a rate of 0.05 in. per minute. Loads at penetrations of 0.1 and 0.2 in. were recorded, and the sample was unloaded.

The mold was then taken from the loading machine, and the hole caused by piston penetration was filled with shale.

The mold was inverted and put into a soaking tank. The swell plate was put on the compacted shale sample in the mold. A surcharge of 10 lb was applied, the tripod with the dial indicator was placed on the top of the mold, and an initial reading was taken.

In the soaking tank, the water level was maintained 1.0 in. above the top of specimen, which was soaked for 96 hours. At the end of this period the swell or height increase was recorded.

$$\text{Percent swell} = \frac{\text{Change in height in in. during soaking}}{4.584\text{ in.}}\ 100$$

The specimen was now removed from the soaking tank and allowed to drain for 15 minutes. The CBR of the soaked sample was determined as explained earlier.

California Bearing Ratio values are obtained in percent by dividing test load values for 0.10 in. and 0.20 in. penetration by standard loads of 1000 and 1500 psi, respectively, and multiplying these ratios by 100. The greater of the two ratios is taken as CBR. The ratio at 0.10 in. penetration was found to be greater for all samples tested.

The results were obtained at different moisture contents and different compactive effort levels. However, only the Standard compactive effort was used when the sample quantities were limited.

Thus for every test the following information was available.

a) compaction effort;
b) molding water content;
c) dry unit weight as compacted;
d) percent swell;
e) CBR as compacted;
f) CBR soaked;
g) ratio of CBR soaked to CBR as compacted.

Miscellaneous Tests

These tests included water absorption - time characteristics, bulk unit weight, and certain breaking characteristics of the material.

Absorption

Water absorption vs. time curves were obtained on shales which did not slake either fully or partially in water. Five oven-dried pieces, each weighing 50 to 60 gm, and as equidimensional as possible, were covered with at least 1/2 in. of water. The sample was removed from water at various time intervals and rolled in a large absorbent cloth until all visible surface films of water were removed. The sample was weighed and again immersed in water for the subsequent readings at the next time interval. Time intervals of 1/4, 1/2, 1, 2, 5, 10, 24, and 48 hours were used.

After 48 hours, the sample was oven dried and the dry weight was recorded. If the dry weight after the test was less than the original weight, the water content at the end of the test was determined corresponding to this weight, and a proportionate correction was applied for intermediate saturations.

If A_1 = saturation after 48 hr, calculated from initial dry weight of sample;

A_2 = saturation after 48 hr, calculated from final dry weight of sample; and

I = saturation at some intermediate time calculated from initial dry weight of sample

then Correction $C = \frac{I}{A_1} (A_2 - A_1)$.

Therefore the corrected saturation at an intermediate time is $(I + C)$.

Bulk Unit Weight

It is believed that the strength and durability of shale increases with an increase in insitu density. Though insitu density was not determined, the bulk densities of chunks of the various shales were determined in accordance with ASTM D 1188-71 (6). The test sample was a shale chunk weighing between 50 and 60 gm, and as equidimensional as possible. The weight of the specimen was determined after being oven dried and cooled at room temperature for about one hour. The specimen was then coated with melted paraffin sufficiently thick to seal all air voids and cooled to room temperature, after which it was weighed. The weight of the coated specimen submerged in water was recorded.

If A = weight of dry specimen in air, gm;

B = weight of dry specimen plus paraffin coating in air, gm;

E = weight of dry specimen plus paraffin coating in water, gm;

G = specific gravity of paraffin at room temperature;

then

$$\text{Bulk density} = \frac{A}{B-E-(\frac{B-A}{G})} 62.4, \text{ pcf.}$$

Breaking Characteristics

The breaking characteristics may be the most descriptive feature for shales. They can be classified as massive, flaky-fissile and flaggy-fissile. Fissility is associated with a parallel arrangement of clay particles, and non-fissility with a random arrangement (51). The nature of cementing agents is also an important factor influencing fissility.

Massive rocks have no preferred directions of cleaving and breaking. Most of the fragments are blocky. Flaggy rocks will split into fragments of varying thickness, but the width and length are many times greater than the thickness, and the two essentially flat sides are approximately parallel. Flaky shales split along irregular surfaces parallel to the bedding, and into uneven flakes, thin chips, and wedge-like fragments whose length seldom exceeds three inches. The three breaking types are shown in Figures 17, 18 and 19.

Shales were broken by: (a) a hammer having a large area of contact, and (b) by striking pieces of shale against each other. About 1000 gm of shale was broken in this way, and approximately the same breaking effort was applied to each shale.

Shale pieces with massive, flaggy and flaky characteristics were visually separated and weighed. Proportions of the three different breaking types were determined to the nearest 10 percent.

FIGURE 17. MASSIVE BREAKING TYPE.

FIGURE 18 . FLAGGY BREAKING TYPE.

FIGURE 19. FLAKY BREAKING TYPE.

TEST RESULTS AND DISCUSSION

The various test results and their usefulness in classifying shales as to their behavior in compacted embankments will be described in this section. It will be seen that all the tests did not yield useful descriptors, and only certain tests were selected for use in the recommended engineering classification procedure. The relations among the results of various tests will also be discussed.

Degradation Type Tests

This group is comprised of slaking tests (in air, water and a sodium sulfate solution) and mechanical abrasion tests.

Test Results

Simple Slaking Tests. None of the shales collected during this study slaked in moist air, but the results of slaking tests in water showed a wide range of disintegration. The results of one cycle of wetting and drying are reported in Table 6. It will be seen that only two of the fifteen shales were affected by this test.

TABLE 6. RESULTS OF SLAKING TEST IN WATER (ONE CYCLE OF WETTING AND DRYING).

Sample	Slaking Time	Remarks
Cannelton	8-10 minutes.	Completely breaks down.
I-74	Partial slaking in 24 hours.	About one fourth of material is reduced to thin flakes or very small pieces.
Paoli Y	Negligible slaking in 24 hours.	After 24 hours the piece is still intact. However the water becomes somewhat dirty.
Paoli X; I-65; Paoli 3; Paoli 5; Lynnville; Attica; 67A; 67B; 37A; 37B; Scottsburg; and Klondike	No slaking in 24 hours.	No change in piece or surrounding water after 24 hours.

The results of five cycles of wetting and drying are reported in Table 7. Five of the fifteen samples are affected by this test.

Slake Durability Tests. The values of the slake durability index for dry samples $(I_d)_d$ and for soaked samples $(I_d)_s$ are shown in Table 8. The values of $(I_d)_d$ range from 24.0 to 95.0 and those of $(I_d)_s$ range from 0 to 93.6. As these numbers refer to the percent weight retained in the meshed test drum, higher values of I_d refer to more durable shales. For all shales the soaked values are lower than the dry ones.

Modified Soundness Test. The results of this test are shown in Table 9. This test seems more effective than others in distinguishing among the harder and more durable shales. The values of soundness index (I_s) range from 0 to 97.2. As this number refers to the percent weight retained on the 5/16 in. sieve at the conclusion of the test, higher values of I_s refer to more durable shales.

Abrasion Tests. The results of abrasion tests are shown in Tables 10, 11, and 12 and Figure 20. Table 10 shows the abrasion loss for oven-dried samples for 50 and 200 revolutions. The abrasion loss for 200 revolutions is almost four times of that for 50 revolutions. The abrasion loss for the dry sample abrasion test is defined by the material finer than the No. 12 sieve.

TABLE 7. RESULTS OF SLAKING TEST IN WATER (FIVE CYCLES OF WETTING AND DRYING).

Sample	Result
Cannelton	Material slaked completely into uncohering small aggregates during first cycle of wetting.
I-74	Material slaked completely into uncohering small aggregates during third cycle of wetting.
Paoli Y	At the end of fifth cycle, material slaked only partially. Between 30 and 35% of material slaked into very small pieces and thin flakes. Some cracks were visible in the intact piece.
Paoli X	At the end of fifth cycle between 5 and 10% of material slaked into very small pieces. Some cracks were visible.
I-65	No slaking. At the end of fifth cycle some cracks were visible in the shale piece.
Paoli 3; Paoli 5; Lynnville; Attica; 67A; 67B; 37A; 37B; Scottsburg; and Klondike	No visible change in the condition of shale piece.

TABLE 8. VALUES OF SLAKE DURABILITY INDEX FOR DIFFERENT SAMPLES.

Sample	Slake Durability Index Dry Sample, $(I_d)_d$	Slake Durability Index Soaked Sample, $(I_d)_s$
Cannelton	24.0	0.0
I-74	63.0	24.5
Paoli Y	86.1	56.2
Paoli X	88.8	68.7
Paoli 5	93.8	89.1
Lynnville	93.8	87.2
I-65	93.2	78.5
67B	93.8	90.1
67A	94.9	90.3
Paoli 3	94.5	91.0
Scottsburg	94.0	91.1
37A	94.8	93.6
Klondike	94.2	91.2
Attica	95.0	93.5
37B	95.0	93.6

TABLE 9. RESULTS OF MODIFIED SOUNDNESS TEST.

Sample	Percent Weight Passing 5/16 in. Sieve	Soundness Index, I_s (Percent Weight Retained on 5/16 in. Sieve)
Cannelton	100	0
I-74	100	0
Paoli Y	84	16
Paoli X	69	31
Paoli 5	28	72
Lynnville	14	86
I-65	19	81
67B	17	83
67A	16	84
Paoli 3	16	84
Scottsburg	15	85
37A	5.5	94.5
Klondike	5.4	94.5
Attica	5.2	94.8
37B	2.8	97.2

TABLE 10. RESULTS OF ABRASION TEST (OVEN-DRIED SAMPLE).

Sample	Percent Weight Passing No. 12 Sieve	
	After 50 Revolutions	After 200 Revolutions
Cannelton	2.7	11.0
I-74	4.0	15.8
Paoli Y	5.1	20.0
Paoli X	4.0	15.5
Paoli 5	4.0	15.2
Lynnville	2.8	11.0
I-65	3.2	13.1
67B	3.4	13.5
67A	3.4	13.5
Paoli 3	2.4	8.5
Scottsburg	3.5	13.0
37A	2.5	9.5
Klondike	3.2	12.5
Attica	2.6	9.9
37B	2.1	8.0

TABLE 11. RESULTS OF ABRASION TEST (SOAKED SAMPLE).

Sample	Percent Weight Passing No. 4 Sieve After 50 Revolutions
Cannelton	100
I-74	68.5
Paoli Y	39.2
Paoli X	32.3
Paoli 5	20.0
Lynnville	20.6
I-65	23.5
67B	16.0
67A	17.0
Paoli 3	16.8
Scottsburg	15.9
37A	14.0
Klondike	16.0
Attica	14.1
37B	19.5

TABLE 12. RESULTS OF ABRASION TEST; COMPARISON FOR OVEN-DRIED AND SOAKED SAMPLES.

	Percent Weight Passing No. 4 Sieve After 50 Revolutions	
Sample	Oven-Dried Sample	Soaked Sample
Cannelton	3.9	100
Paoli Y	7.1	39.2
Paoli 5	5.2	20.0
I-65	5.0	23.5
Attica	3.1	14.1
37B	2.9	19.5

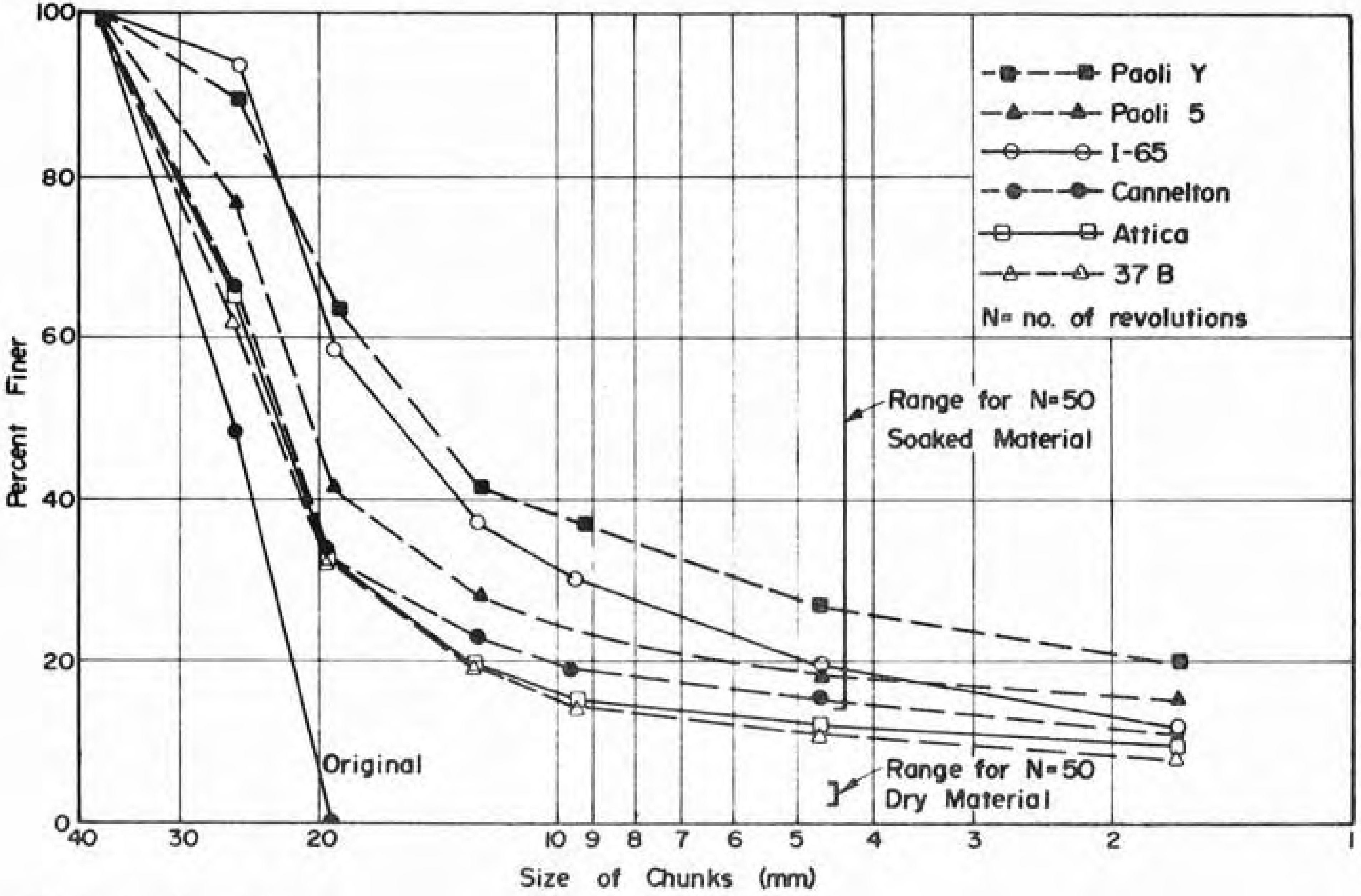

FIGURE 20. THE CUMULATIVE FREQUENCY DISTRIBUTION OF CHUNK SIZES BEFORE AND AFTER THE ABRASION TEST (DRY MATERIAL, N = 200).

Table 11 shows the results of soaked sample abrasion tests. This version of the test employs 50 revolutions and the No. 4 U.S. standard sieve. Corresponding values for selected shale samples in the oven-dried condition were determined for comparison and are reported in Table 12. The range of values for different samples is also shown in Figure 20. The abrasion loss on a soaked sample is much higher than on an oven-dried sample. However, the ranking of shales is not necessarily the same in the two varieties of the test . (see Table 12).

Figure 20 shows the cumulative frequency distribution of chunk sizes before and after the test for selected samples. All the samples had the same gradation of chunks before the test. After the test, the distribution curves for the various materials have about the same shape, but are displaced with respect to each other.

Discussion

Simple Slaking Tests. On the basis of the first three tests, viz., slaking in air, slaking in water in one cycle, and slaking in water in five cycles, all the shales could be classified into three groups.

1. Shales which are severely affected by water, i.e., slake significantly. Only Cannelton, I-74, and Paoli Y are in this category.

2. Shales which are affected by water to a very minor extent during five cycles. Paoli X and I-65 are in this category.

3. Shales which appear totally unaffected by five cycles. Paoli 3, Paoli 5, Lynnville, Attica, 67A, 67B, 37A, 37B, Scottsburg and Klondike fall in this category.

Those shales which slake significantly in the five cycle test should certainly be viewed as non-durable. If used in embankment, they should be accorded special treatment. Groups 2 and 3 perform satisfactorily in these tests, but further examination of their characteristics should be undertaken before specifying design and construction details.

Slake Durability Tests. An examination of the values of durability index on both dry and soaked samples from Table 8 reveals the following points.

1. For the shales which completely or partially slake in water, the slake durability index for dry samples also predicts a severe degradation in water. This is true for the Cannelton and I-74 shales. On the basis of Tables 6, 7, and 8, an $(I_d)_d \leq 85$ would represent shales which are probably non-durable.

2. For the shales which have an $(I_d)_d > 85$, the $(I_d)_s$ is probably a better measure. If the $(I_d)_s$ is between 0 and 50, the material is highly susceptible to breakdown in water. An $(I_d)_s$ between 50 and 70 represents an intermediate susceptibility to water. Values between 70 and 90 represent materials with fair to good relative durability.

3. For materials with $(I_d)_s$ values greater than 90 (or perhaps even 85) the test does not distinguish sufficiently among the materials, and other tests are needed if such distinction is desired.

Modified Soundness Test. By comparing the values of Table 9 with those of Table 8, the soundness test seems to be more effective than the other tests in distinguishing among the harder and more durable shales. Although the test does not simulate weathering actions, it seems to relate well to the effects of weathering, e.g., wetting and drying, freezing and thawing.

When this test was run on a sound, medium grained limestone, it gave a soundness index of 99.2, which shows that even the best shale (37B) is more susceptible to weathering than limestone.

On the basis of this test various groupings of materials are suggested:

1. If I_s is less than 20, the material is very susceptible to weathering, and should probably be treated like a fine grained soil.

2. If I_s is between 20 and 50 (perhaps even 70), the material has a relatively high susceptibility to weathering and the material should probably still be treated as a soil.

3a. Materials having values between 90 and 98 are grouped as "Intermediate-1", and are probably little affected by weathering.

3b. Materials having values between 70 and 90 are termed "Intermediate-2". Both intermediates can be superior to soil as embankment materials, if given adequate treatment in the construction process.

4. If I_s is greater than 98 (no such materials were sampled), the material can probably be treated like a rock.

Abrasion Test. The abrasion test was performed on dry as well as on soaked samples. However on the dry samples the test results showed little difference between the shales (Table 10).

Results of abrasion tests with soaked samples are shown in Table 11. These results reflect a combined effect of mechanical abrasion and water slaking. The slake durability test, which gives $(I_d)_s$, is also a combined effect of the same two phenomena. The results of these two tests are similar, and as seen from Figure 21, their interrelation is approximately linear. A simple linear regression analysis gives the relationship [$(I_d)_s = 109 -$ 1.15 Abrasion Loss], with a correlation coefficient of 0.99. It should be noted that the abrasion test is much more time consuming and expensive than the slake durability test.

It is concluded that the soaked durability index and the soundness index, when taken together, can give a reasonable rating of the durability of shales in a service environment.

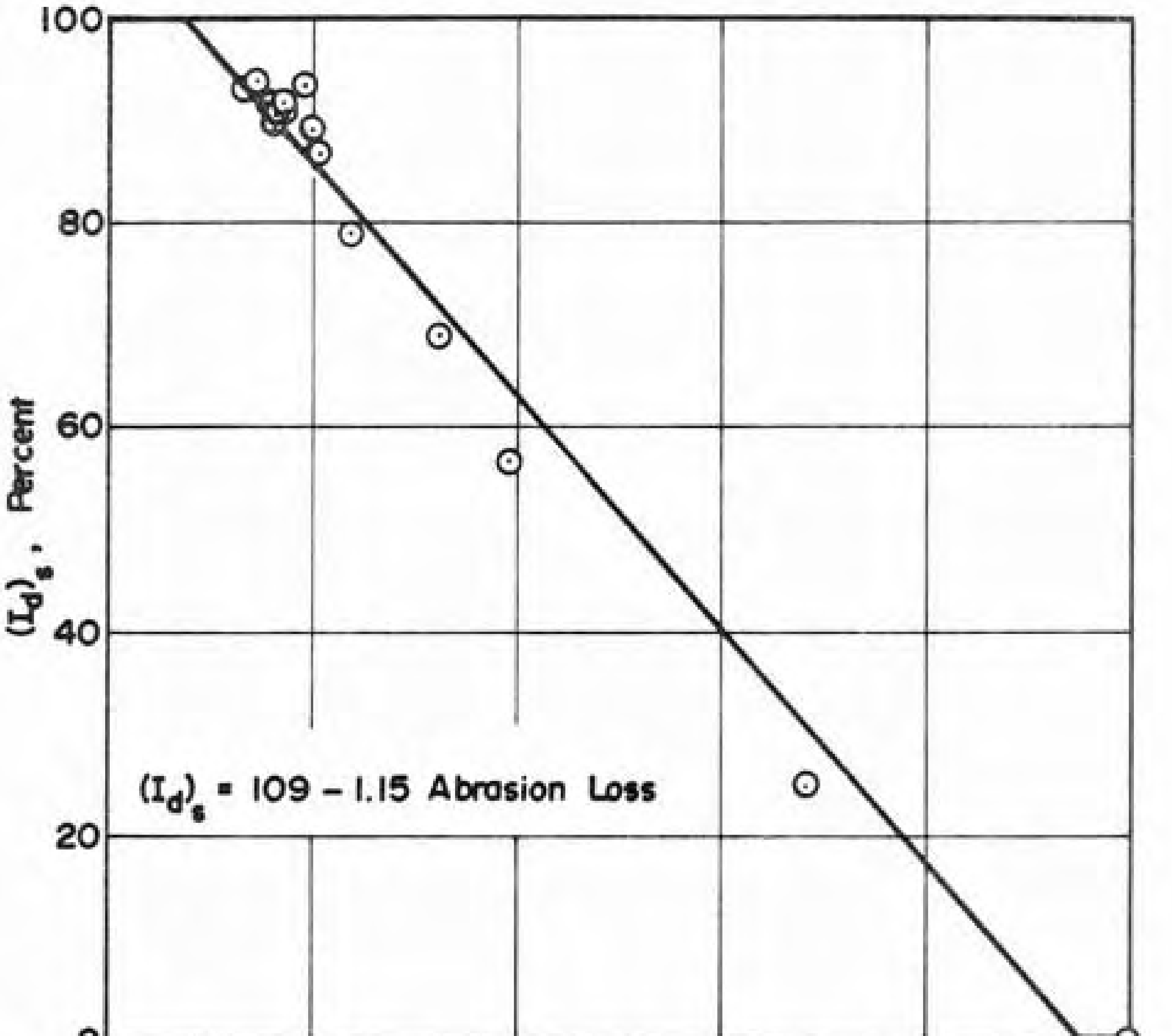

FIGURE 21. RELATIONSHIP BETWEEN SLAKE DURABILITY INDEX AND ABRASION LOSS IN SOAKED TESTS.

Soil Type Identification Tests

This group includes tests for determining Atterberg limits, grain size distribution, and dominant minerals.

Test Results

Atterberg Limits. The values of Atterberg limits on powdered shales are reported in Table 13. The values of liquid limit (w_ℓ) range from 21 to 45 and those of plasticity index (I_p) from 4 to 17.

Grain Size Distribution. Cumulative frequency distribution of grain sizes are plotted in Figure 22. The distribution curves for the various materials are quite different. Table 14 summarizes the percent fractions of sand, silt, clay, and (silt + clay) sizes by weight. The particles finer than 0.002 mm range from 12% for Attica shale to 61% for Cannelton shale. The particles finer than the No. 200 sieve range from 40% for 37A shale to 93% for Paoli Y shale.

X-ray Diffraction. X-ray diffraction patterns were obtained for both dry powder and glycerol paste.

The diffraction patterns were similar, and it was not possible to group the shales in different categories on the basis of their clay mineral composition. Thirteen out of fifteen samples had illite as the dominant clay mineral. Two samples (Cannelton and Klondike) did not give any prominent clay mineral peaks. Since the Cannelton shale had 61% particles finer than 0.002 mm, it was tentatively concluded that this material was amorphous (allophane). The results

TABLE 13. ATTERBERG LIMITS FOR POWDERED SHALE.

Sample	Liquid Limit, w_ℓ	Plasticity Index, I_p
Cannelton	45	17
I-74	36	15
Paoli Y	27	10
Paoli X	21	6
Paoli 5	23	6
Lynnville	36	14
I-65	26	9
67B	23	5
67A	24	10
Paoli 3	21	5
Scottsburg	26	6
37A	25	7
Klondike	28	4
Attica	31	5
37B	24	4

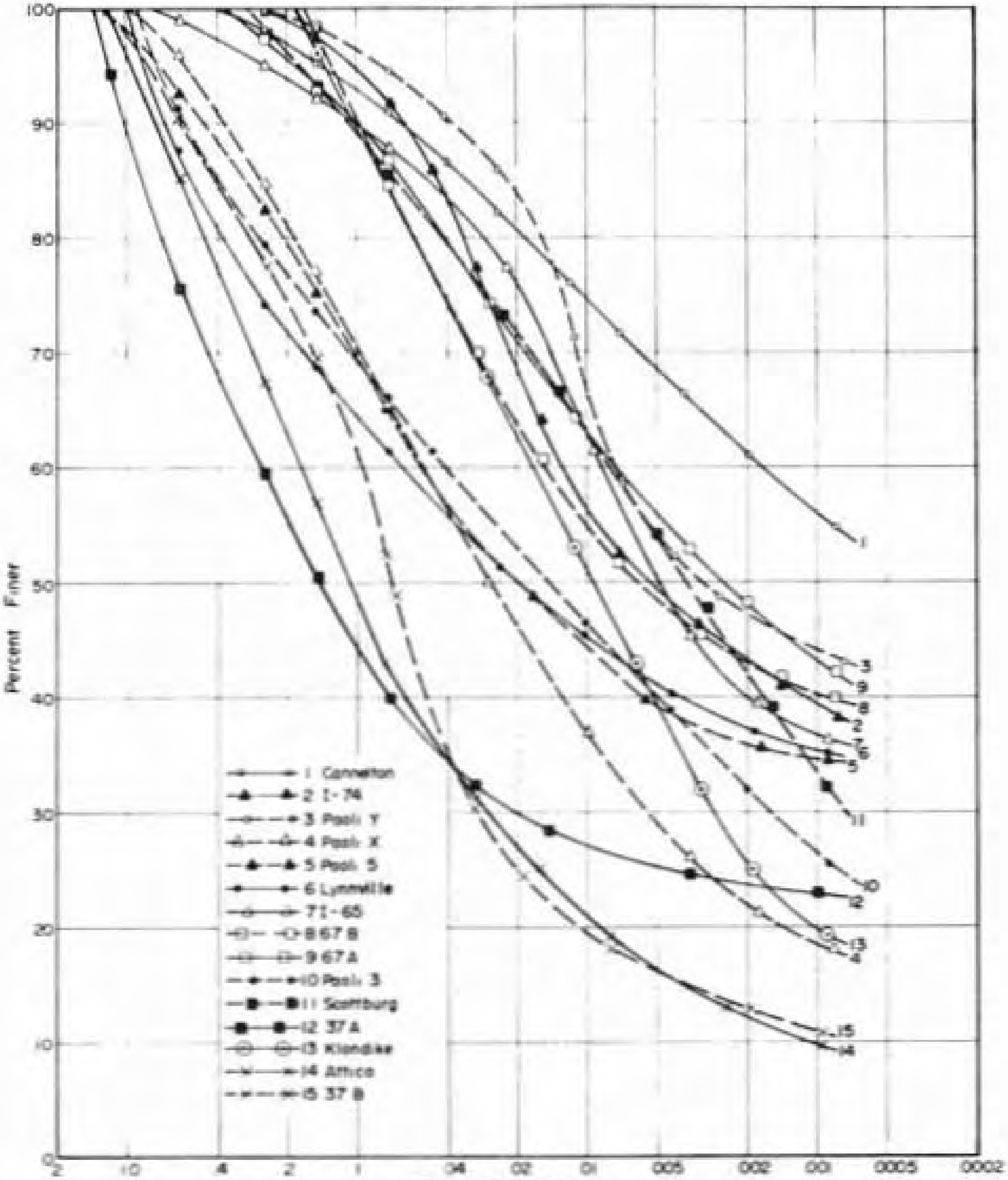

FIGURE 22. GRAIN SIZE CURVE FOR SHALE POWDERS.

TABLE 14. PERCENT FRACTIONS OF SAND, SILT, AND CLAY SIZES FOR SHALE POWDERS.

Clay Size - Smaller than 0.002 mm

Silt Size - 0.074 to 0.002 mm

	Percent by Weight			
Sample	Sand Size	Silt Size	Clay Size	(Silt+Clay) Size
Cannelton	9	30	61	91
I-74	8	49	43	92
Paoli Y	7	46	47	93
Paoli X	34	44	22	66
Paoli 5	35	29	36	65
Lynnville	38	25	37	62
I-65	12	40	48	88
67B	15	42	43	85
67A	13	39	48	87
Paoli 3	34	34	32	66
Scottsburg	14	44	42	86
37A	60	16	24	40
Klondike	15	60	25	85
Attica	57	31	12	43
37B	48	39	13	52

of X-ray diffraction identification of the principal mineral constituents are reported in Table 15. Complete X-ray diffraction patterns are shown in Appendix D.

Discussion

Atterberg Limits and Activity. Though it is realized that the Atterberg limits can vary with the pretest treatment of the soil, e.g., predrying of soil reduces its plasticity (14, 57), they still correlate well with amount and type of clay content (77).

Values of the plasticity index for clay shales as reported in the literature (21, 70) normally range between 50 and 200. A plasticity index as high as 465 is reported by Morton (66). The values of plasticity index from Table 13 show that the sampled Indiana shales have little plasticity, e.g., I_p is from 4 to 17.

The activity ratio for the different shales has been calculated from the data of Table 13 and Figure 22, and is reported in Table 16. Activity is the ratio of the plasticity index to the percent by weight of the minus 0.002 mm fraction of the sample. Skempton divided activity in five groups as follows (33):

Group 1. Inactive, with activity less than 0.5
Group 2. Inactive, with activity 0.5 to 0.75
Group 3. Normal, with activity 0.75 to 1.25
Group 4. Active, with activity 1.25 to 2
Group 5. Active, with activity greater than 2.

TABLE 15. RESULTS OF X-RAY DIFFRACTION ON POWDERED SHALES.

Sample	Principal Constituents
Cannelton	Allophane, Kaolinite, Quartz
I-74	Illite, Kaolinite, Chlorite, Quartz, Feldspar
Paoli Y	Illite, Kaolinite, Quartz, Feldspar
Paoli X	Illite, Kaolinite, Quartz, Feldspar
Paoli 5	Illite, Kaolinite, Chlorite, Quartz, Feldspar
Lynnville	Illite, Kaolinite, Quartz, Feldspar
I-65	Illite, Kaolinite, Quartz, Feldspar
67B	Illite, Kaolinite, Quartz, Feldspar
67A	Illite, Kaolinite, Quartz, Feldspar
Paoli 3	Illite, Kaolinite, Chlorite, Quartz, Feldspar
Scottsburg	Illite, Kaolinite, Quartz, Feldspar
37A	Illite, Kaolinite, Chlorite, Quartz, Feldspar
Klondike	Kaolinite, Quartz
Attica	Illite, Kaolinite, Quartz, Feldspar
37B	Illite, Kaolinite, Chlorite, Quartz, Feldspar

TABLE 16. ACTIVITY FOR POWDERED SHALES.

Sample	Plasticity Index	Percent by Weight Finer than 0.002 mm	Activity
Cannelton	17	61	0.28
I-74	15	43	0.35
Paoli Y	10	47	0.21
Paoli X	6	22	0.27
Paoli 5	6	36	0.17
Lynnville	14	37	0.38
I-65	9	48	0.19
67B	5	43	0.12
67A	10	48	0.21
Paoli 3	5	32	0.16
Scottsburg	6	42	0.14
37A	7	24	0.29
Klondike	4	25	0.16
Attica	5	12	0.42
37B	4	13	0.31

In general, one would expect that active clays would have relatively high water holding capacity, high compressibility and low resistance to shear (33).

Table 16 shows that all the samples have an activity of less than 0.5; therefore all are in group 1, which is most inactive.

According to Grim (33), the values of activity for kaolinite range from 0.01 to 0.41, and for illite from 0.23 to 0.58 (Skempton gives much higher values). From X-ray diffraction on these samples, it was concluded that illite and kaolinite were the main clay minerals in the sampled Indiana shales.

Grain Size Distribution. From the cumulative frequency distribution curves of Figure 22, the powdered materials are classified according to the Indiana State Highway Commission (ISHC) textural (46), Unified (86), and AASHO (96) systems.

According to the ISHC textural classification, soils are sand, loam, silt, clay, or a combination of them depending upon the relative percentage of clay, silt and sand sizes. Clay size is taken as smaller than 0.005 mm, while silt is between 0.074 and 0.005 mm. See Figure 23. The 37A material is classified as sandy clay loam; Attica, as sandy loam; 37B, as loam; and Paoli X, as clay loam. The remaining 11 materials are classified as clay.

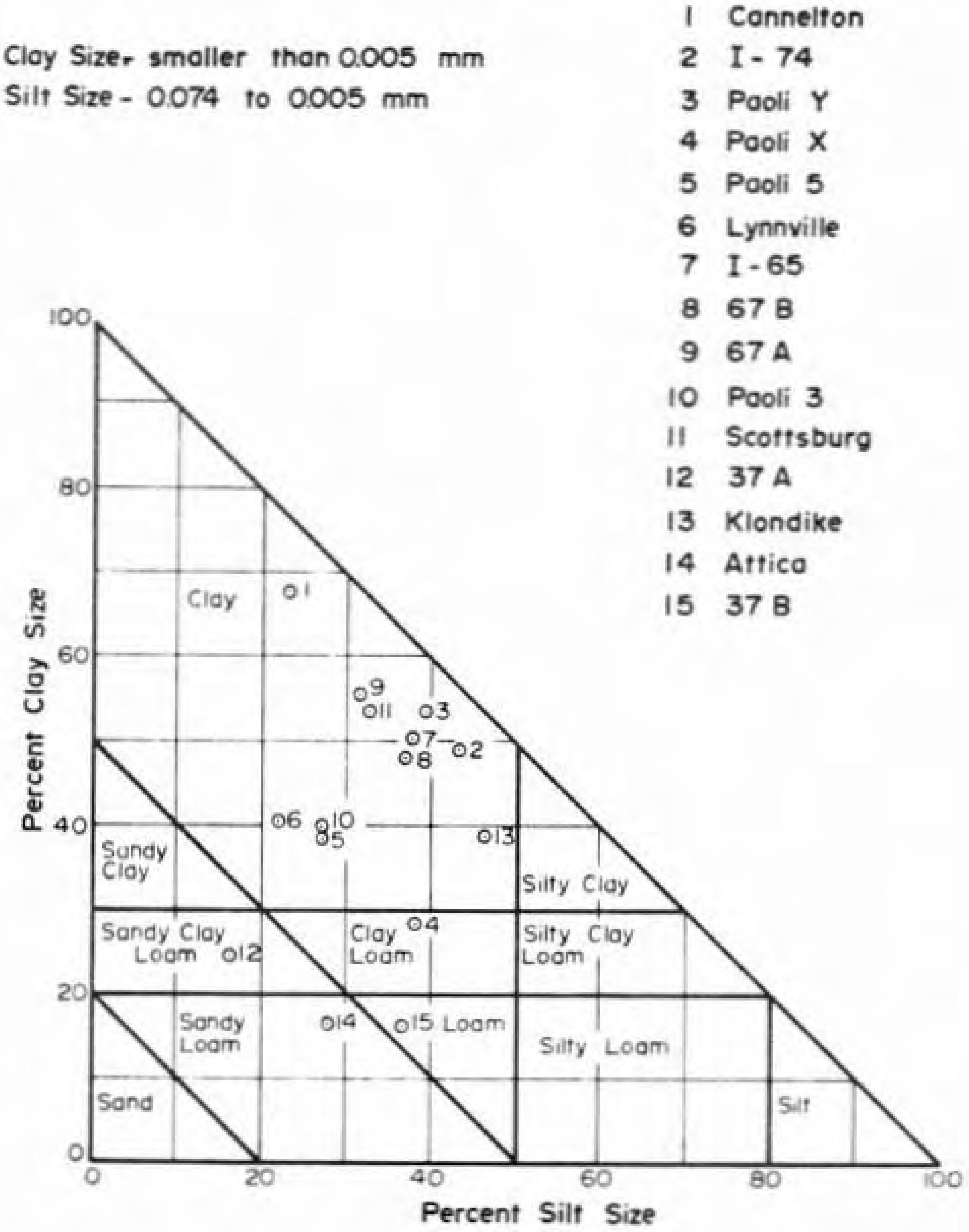

FIGURE 23. TEXTURAL CLASSIFICATION BASED UPON GRAIN SIZE DISTRIBUTION (ISHC).

The Unified classification system (86) is more comprehensive in that it takes into account both grain size distribution and Atterberg limits. The classification of the powdered shale materials according to this system is shown in Figure 24. Six materials, namely, I-74, Paoli Y, Lynnville, I-65, 67A, and 37A are classified as CL or inorganic clays of low compressibility. Three materials, namely, Cannelton, Klondike, and Attica are classified as ML which means inorganic silts and fine sands of low compressibility. The remaining six materials, Paoli X, Paoli 5, 67B, Paoli 3, Scottsburg, and 37B are borderline materials and are represented by a double symbol, CL-ML.

The AASHO Classification system uses seven groups, A-1 through A-7, based upon grain size distribution and Atterberg limits. For the fines, a group index[1] may also be determined. One material (Cannelton) is classified as A-7-6, which is the classification for the poorest inorganic materials. Two materials (I-74 and Lynnville) are classified as A-6, and the remaining 12 materials are classified as A-4, i.e., are silty.

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[1] Group Index (I) is defined as
$I = 0.2a + 0.005\,ac + 0.01bd$ where
a = the portion of soil passing No. 200 sieve greater than 35 percent and not exceeding 75 percent, expressed as a number (from 0 to 40)
b = the portion of soil passing No. 200 sieve greater than 15 percent and not exceeding 55 percent, expressed as a number (from 0 to 40)
c = the portion of liquid limit greater than 40 and not exceeding 60, expressed as a number (from 0 to 20)
d = the portion of plasticity index greater than 10 and not exceeding 30, expressed as a number (from 0 to 20).

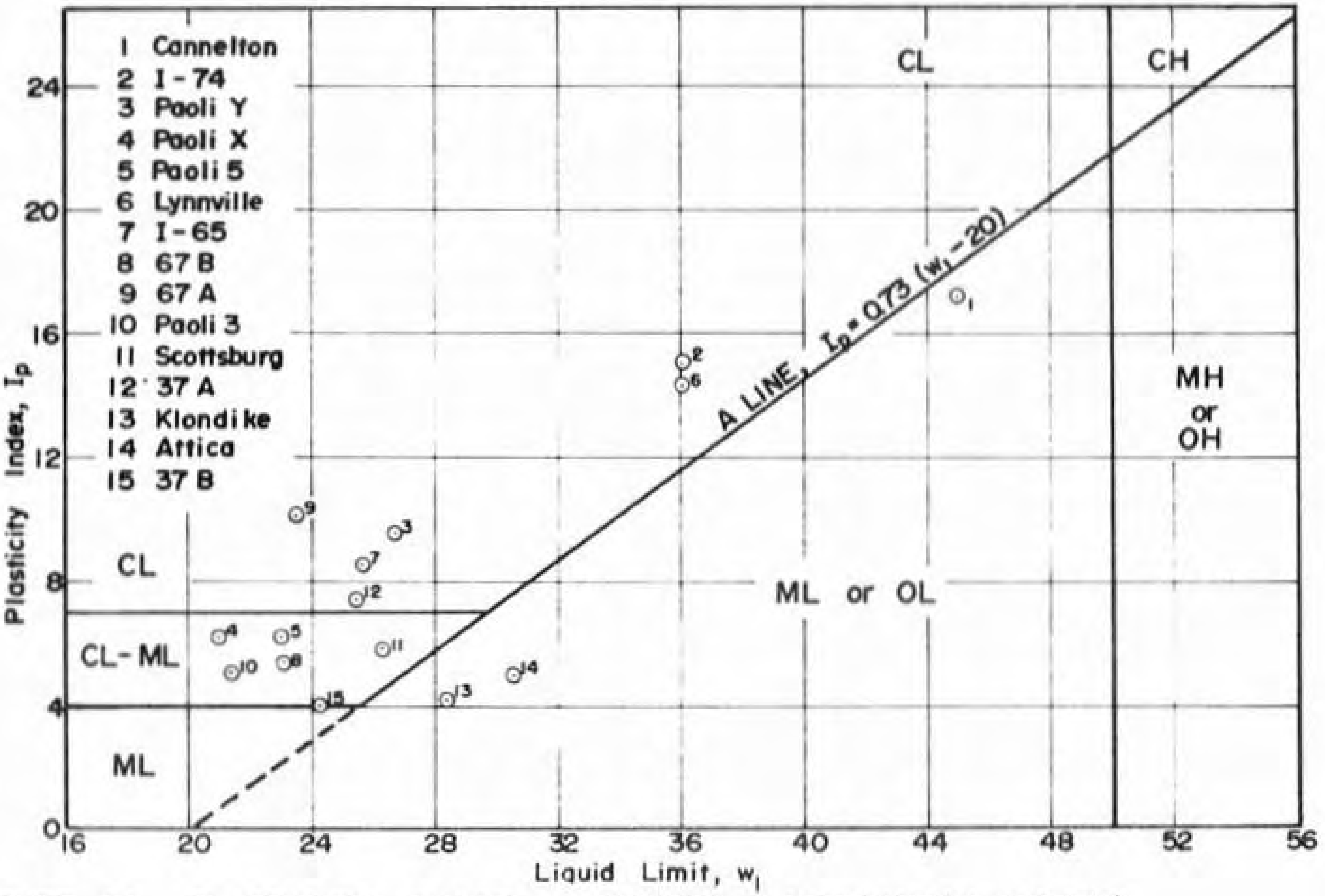


FIGURE 24. PLASTICITY CHART (UNIFIED CLASSIFICATION SYSTEM).

Table 17, summarizes the classification of powdered materials according to the three systems.

X-ray Diffraction. Results of X-ray diffraction showed that none of the shales contained montmorillonite in identifiable quantities. Thirteen out of fifteen samples had illite as the dominant clay mineral. One sample (Cannelton) had allophane. This sample also did not contain feldspar, a common constituent of the others.

Mineral composition probably explains less about the behavior of these shales than cementing materials. Unfortunately, the cementing materials, which will be a very small fraction of the total shale mass, were not determined as this could not be included within the scope of this study.

Compaction and Load-Deformation Tests

These tests were run in a 6 in. diameter CBR mold. The tests were performed at different moisture contents and compactive effort levels. After each test the following results were available. (The first two items were controlled as independent variables.)

1. Compaction effort
2. Molding water content
3. Dry unit weight as compacted
4. Percent axial swell after soaking
5. CBR as compacted
6. CBR soaked
7. Ratio of CBR soaked to CBR as compacted.

TABLE 17. CLASSIFICATION OF POWDERED SHALE MATERIALS ACCORDING TO ISHC, UNIFIED, AND AASHO CLASSIFICATION SYSTEMS.

	Classification		
Sample	ISHC Textural	Unified	AASHO
Cannelton	clay	ML	A-7-6
I-74	clay	CL	A-6
Paoli Y	clay	CL	A-4
Paoli X	clay loam	CL-ML	A-4
Paoli 5	clay	CL-ML	A-4
Lynnville	clay	CL	A-6
I-65	clay	CL	A-4
67B	clay	CL-ML	A-4
67A	clay	CL	A-4
Paoli 3	clay	CL-ML	A-4
Scottsburg	clay	CL-ML	A-4
37A	sandy clay loam	SC	A-4
Klondike	clay	ML	A-4
Attica	sandy loam	SM	A-4
37B	loam	ML	A-4

Test Results

The test results are shown in Figures 25 to 39. Figures 25 to 28 show the molding water contents vs. dry densities and CBR values (both as compacted and soaked) at four effort levels of 0.5, 1.0, 1.8, and 4.5 times the Proctor standard effort for four shales (Cannelton, I-74, 37A, and Attica). Figures 29 to 31 show these relations at two effort levels of 1.0 and 4.5 times the standard effort for three shales (I-65, Paoli 3, and Scottsburg). For the remaining eight shales (Paoli Y, Paoli X, Paoli 5, Lynnville, 67B, 67A, Klondike, and 37B), Figures 32 to 39 show the results for the standard effort only. The values of axial swell were also determined after 96 hours of soaking in water, and are reported in percent on the water content-dry density curves.

The results show that the optimum moisture content for a given effort level varied greatly from shale to shale, as did percent swell. Table 18 summarizes the results at optimum moisture content and standard effort for all the shales.

Discussion

Compaction Behavior. An examination of the moisture-density curves shows that at higher compactive effort levels, higher maximum densities were obtained and at lower optimum moisture contents. This is similar to fine grained soil

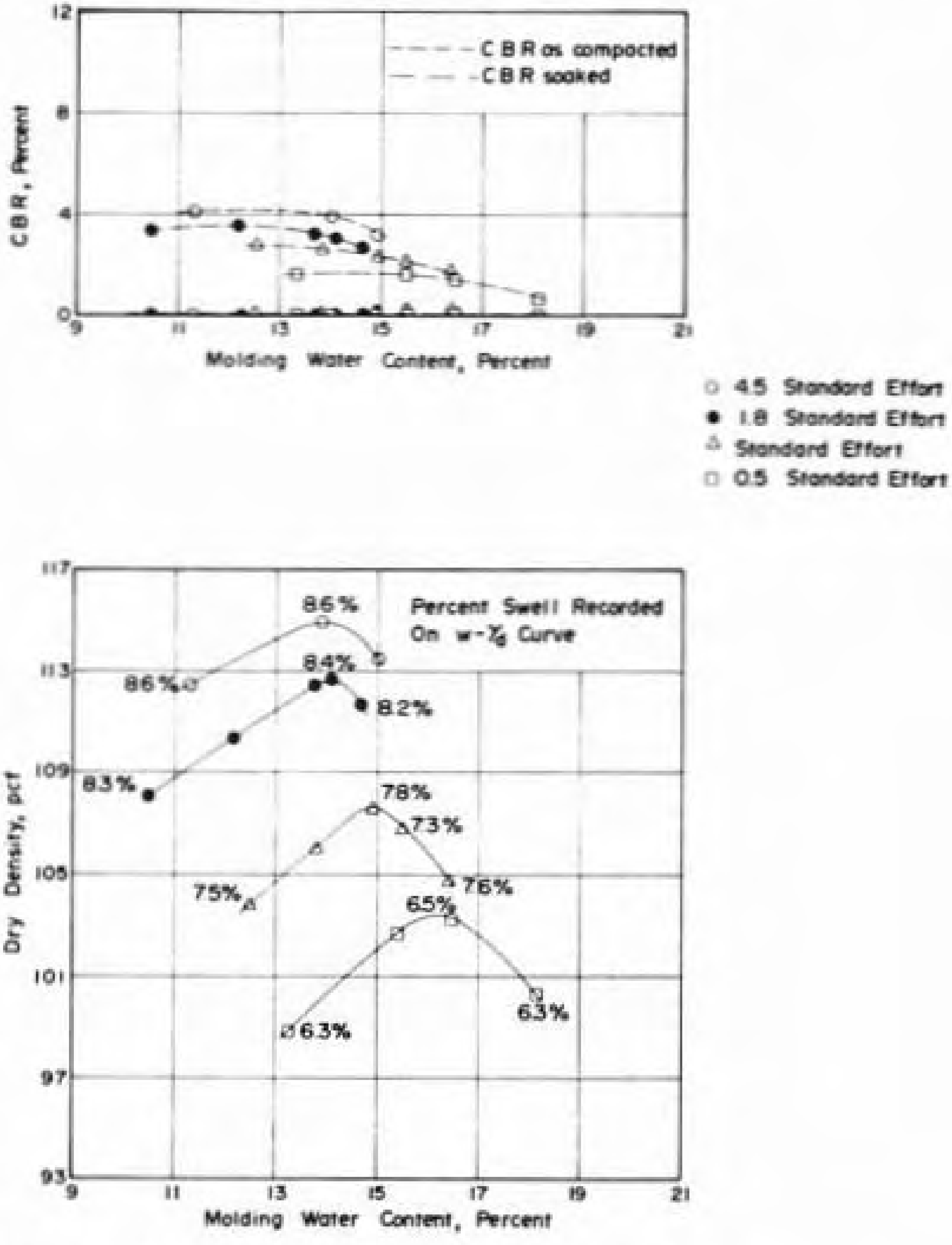


FIGURE 25. C B R TEST RESULTS, CANNELTON SHALE.

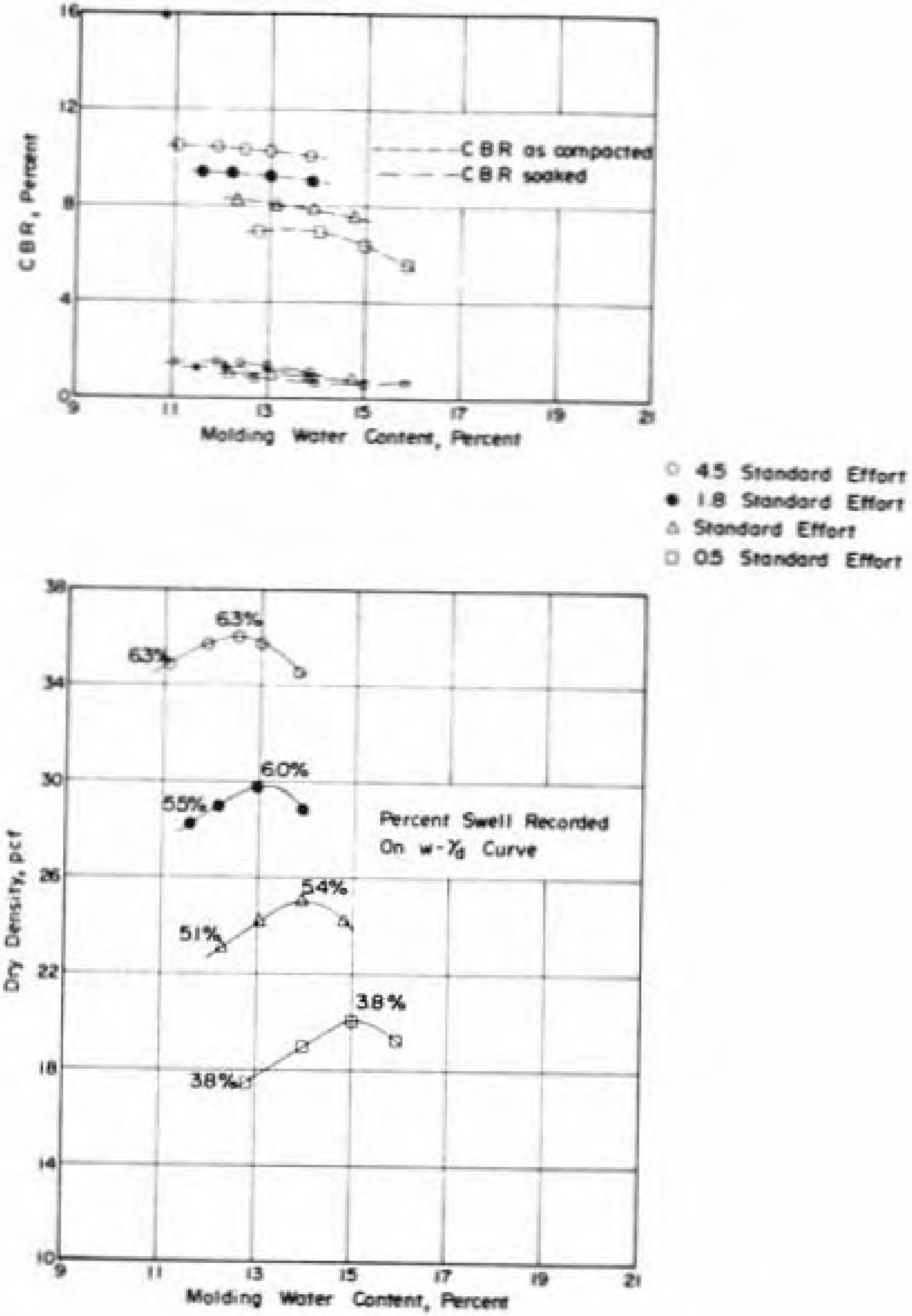


FIGURE 26. C B R TEST RESULTS, I-74 SHALE.

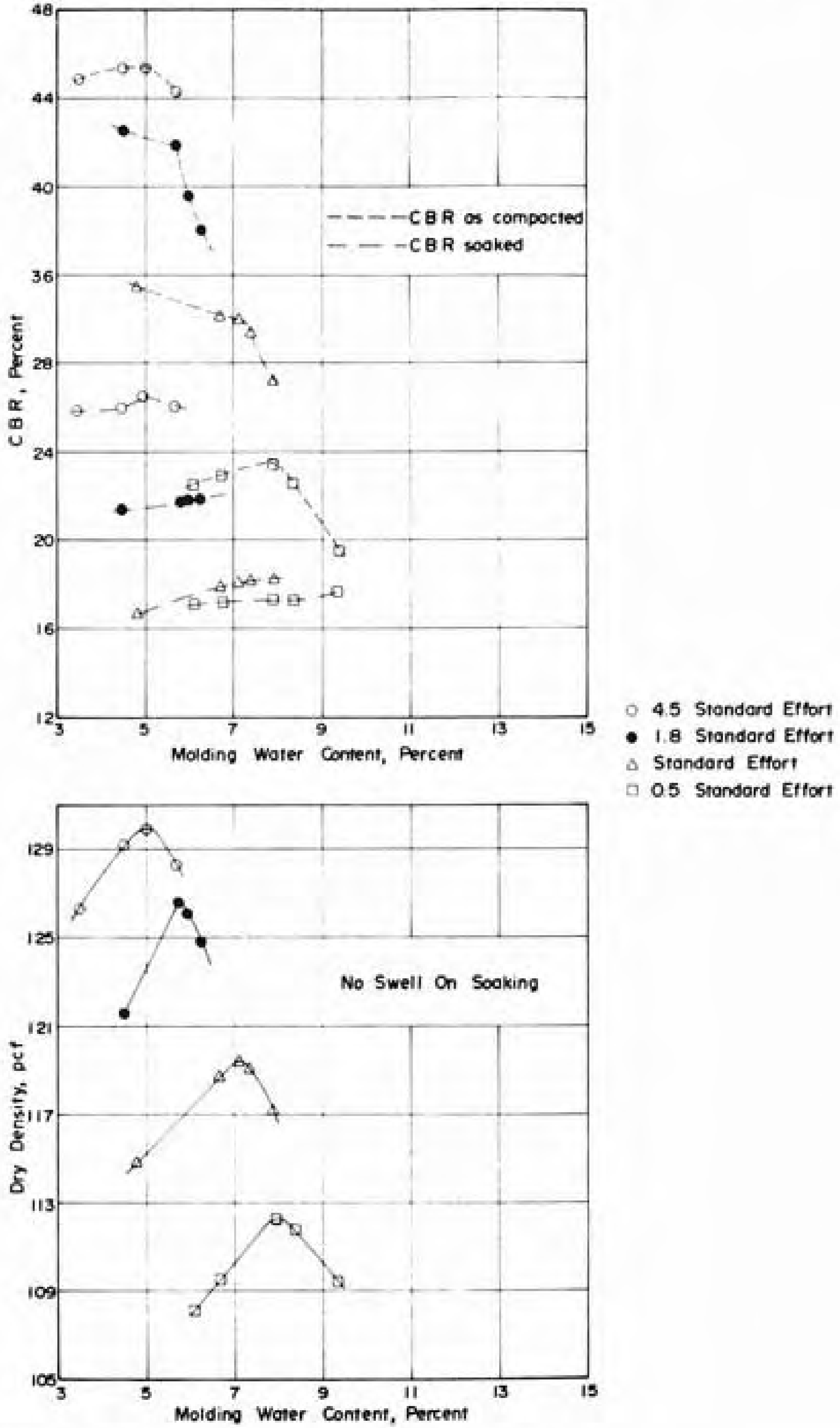


FIGURE 27. C B R TEST RESULTS, 37 A SHALE.

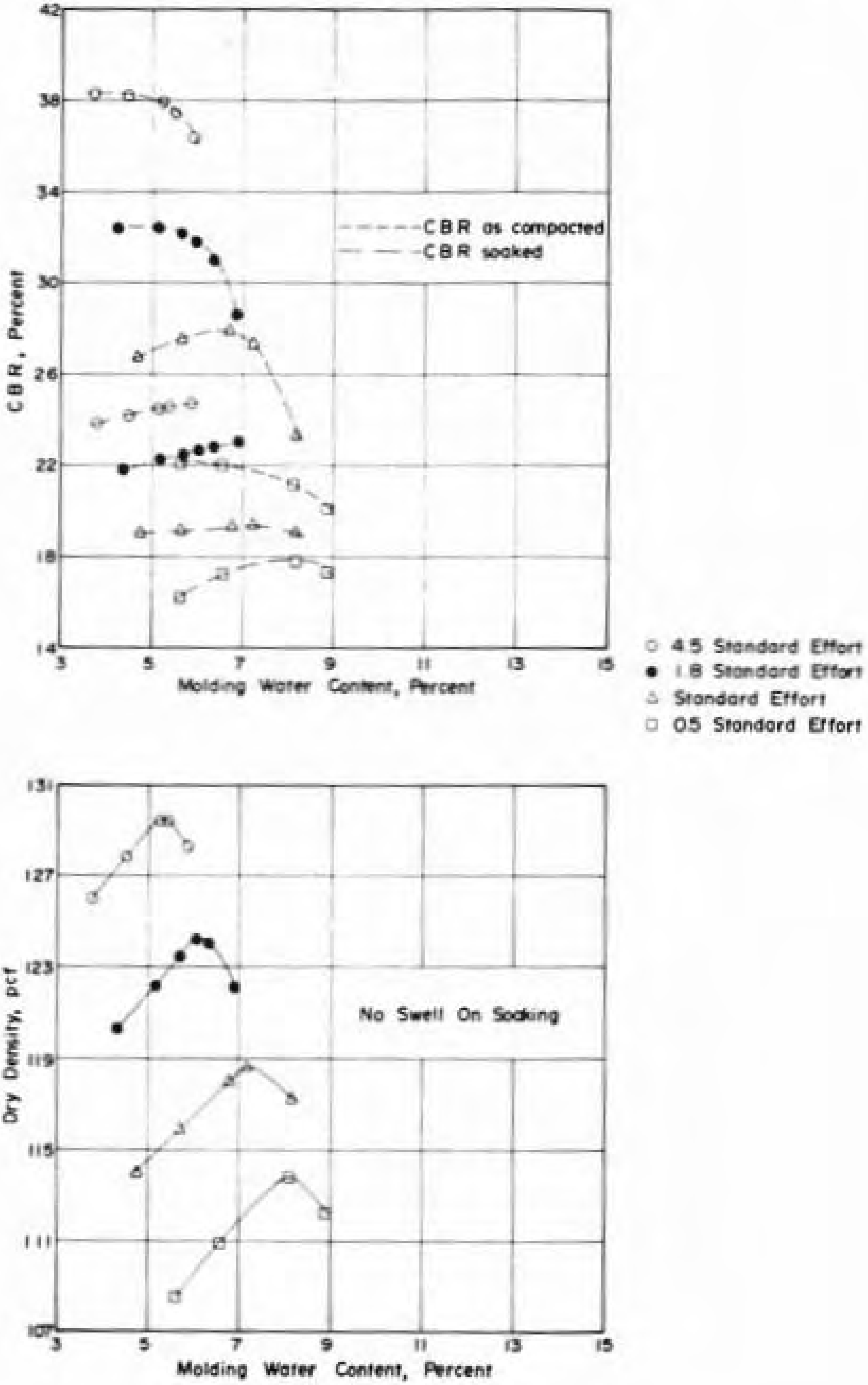


FIGURE 28. C B R TEST RESULTS, ATTICA SHALE.

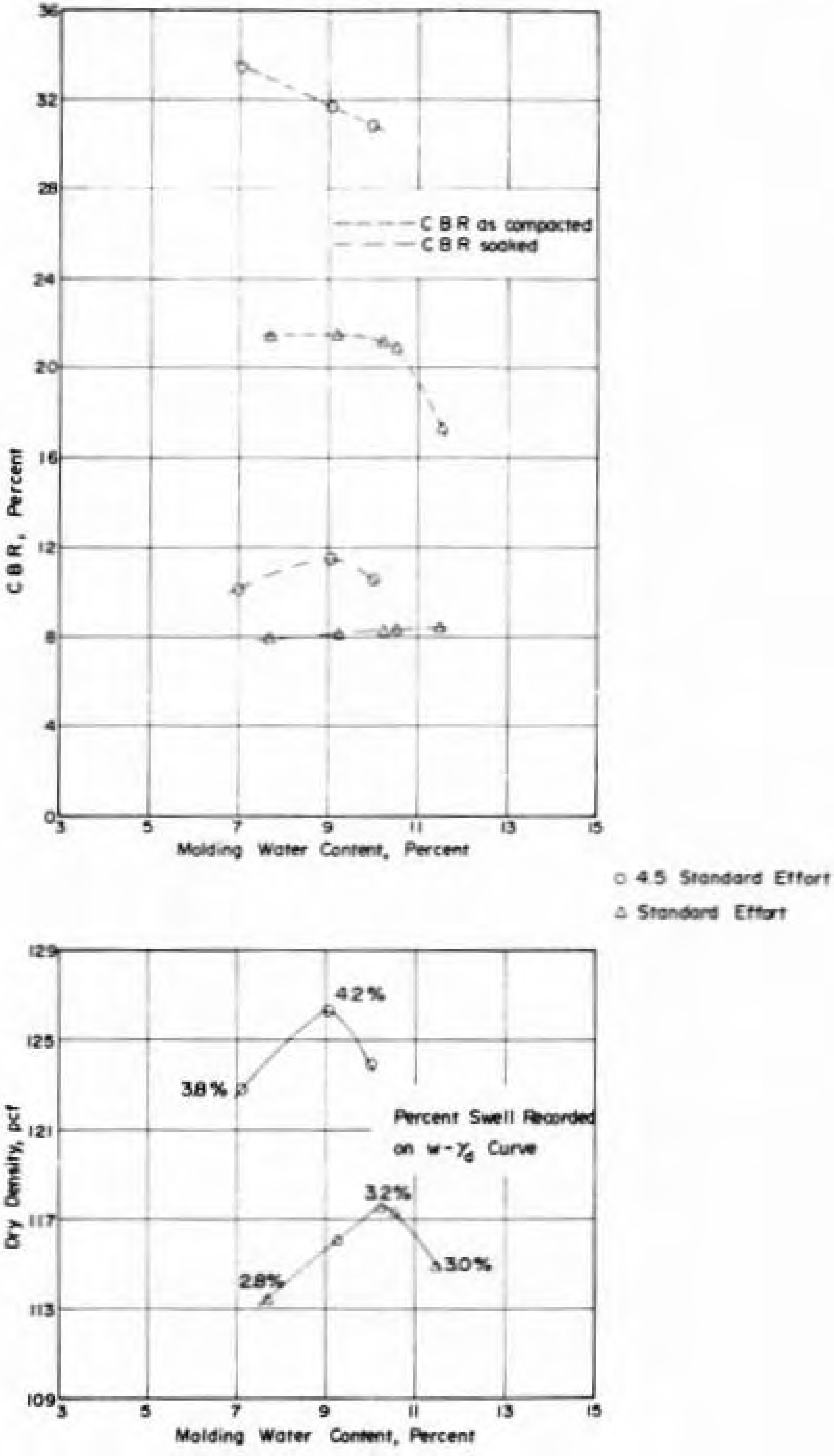


FIGURE 29. C B R TEST RESULTS, I-65 SHALE.

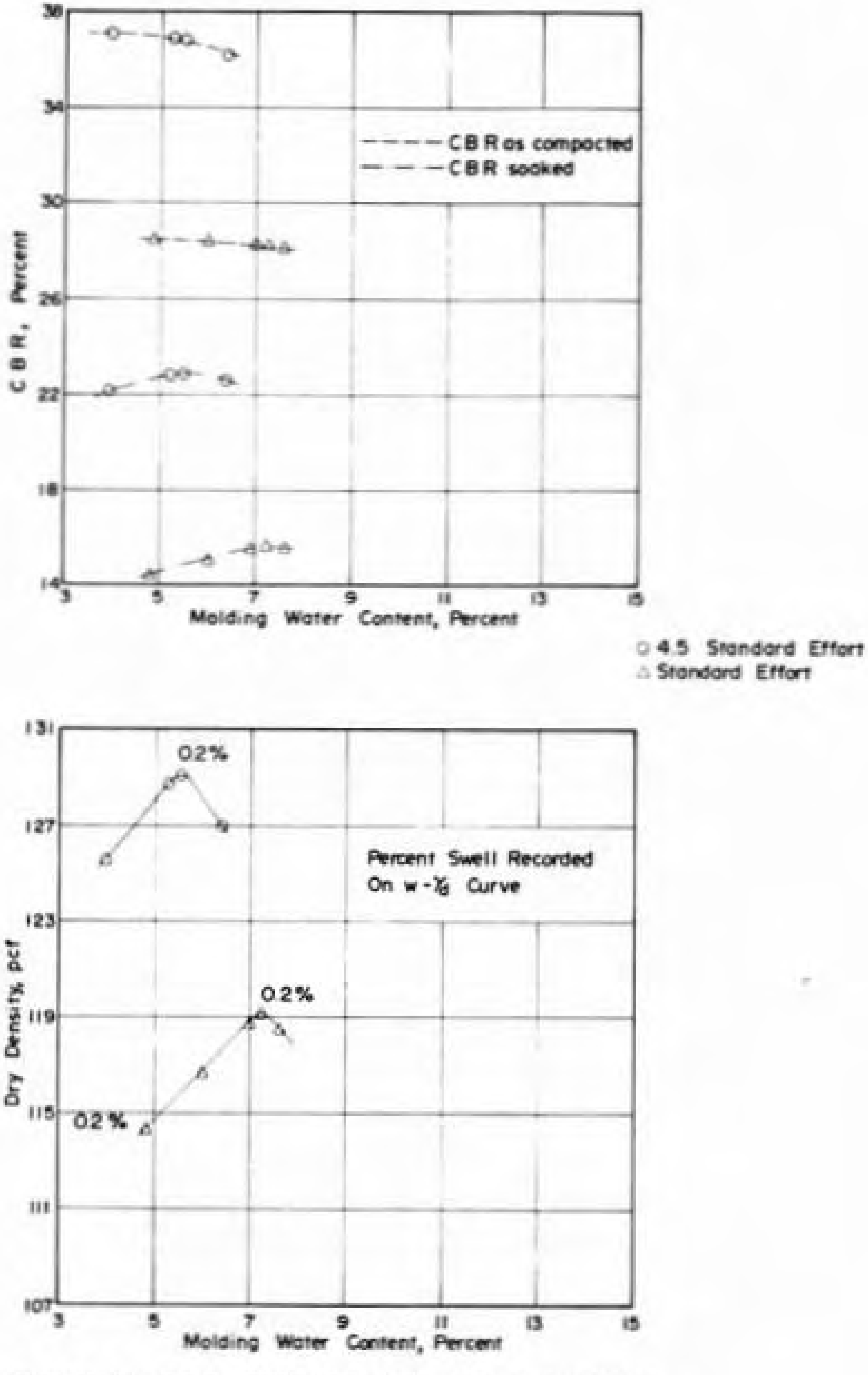


FIGURE 30. C B R TEST RESULTS, PAOLI 3 SHALE.

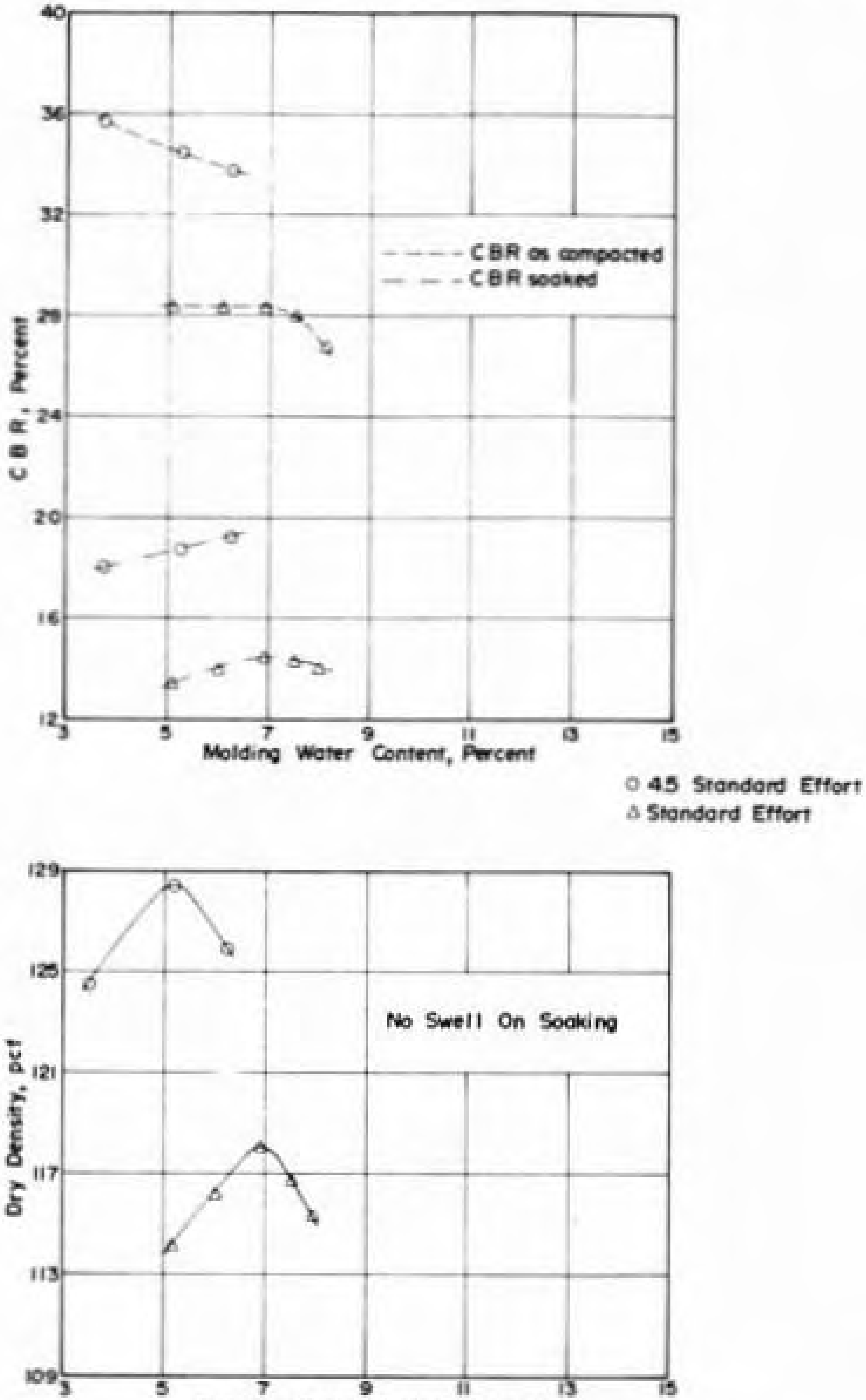


FIGURE 31. C B R TEST RESULTS, SCOTTSBURG SHALE.

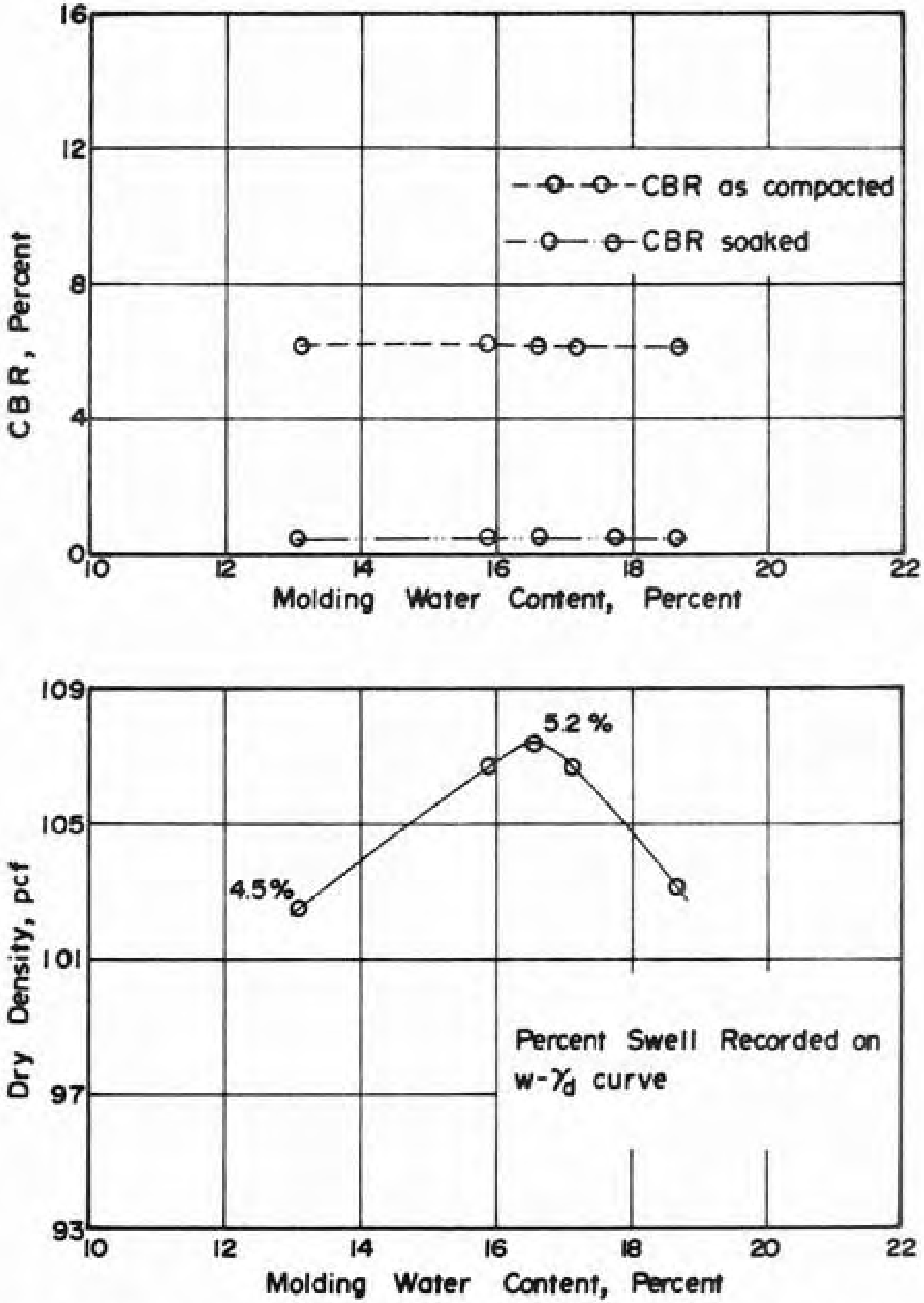
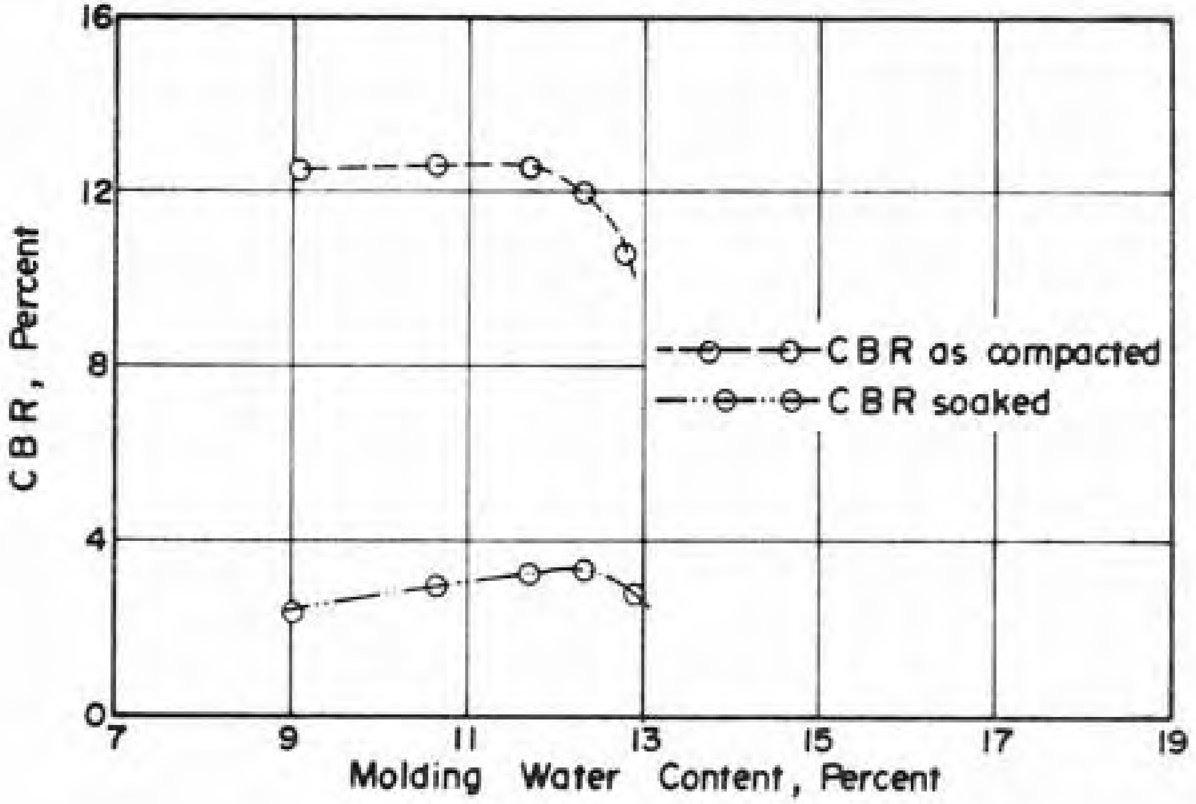


FIGURE 32. CBR TEST RESULTS (STANDARD EFFORT), PAOLI Y SHALE.



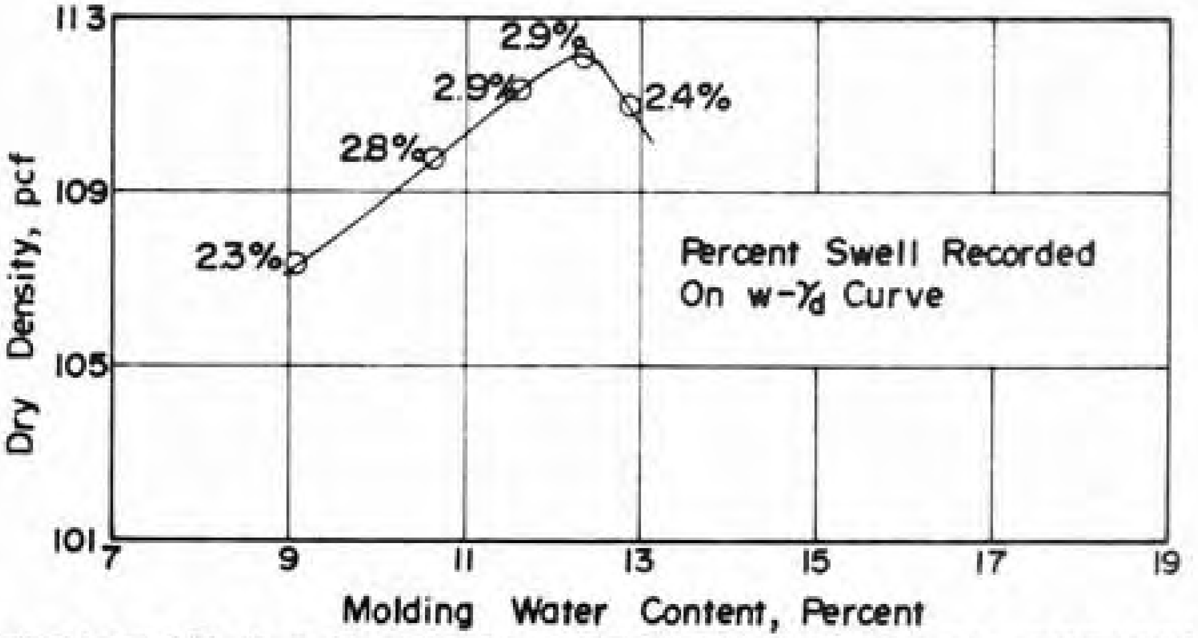


FIGURE 33. C B R TEST RESULTS (STANDARD EFFORT), PAOLI X SHALE.

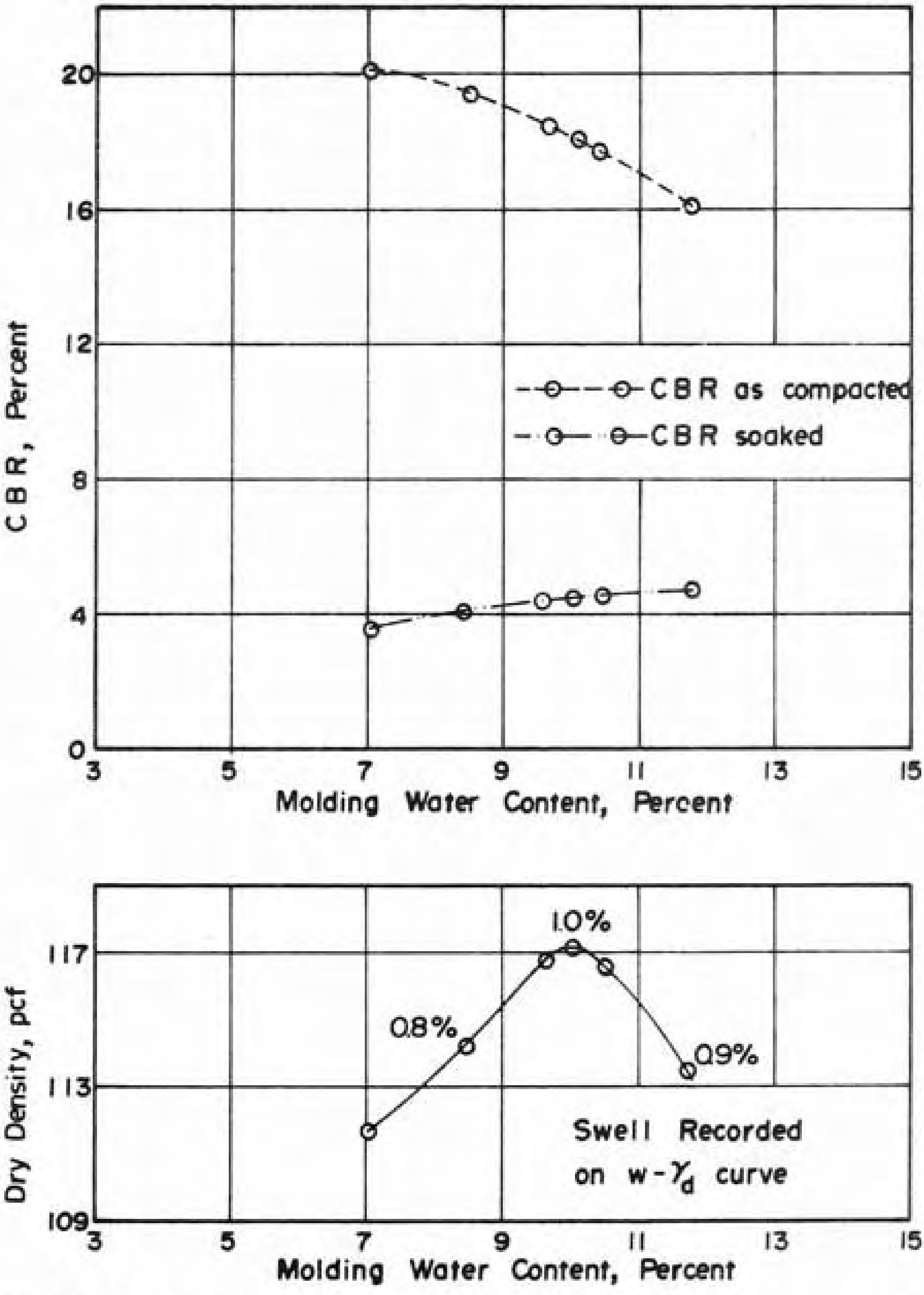


FIGURE 34. C B R TEST RESULTS (STANDARD EFFORT), PAOLI-5 SHALE.

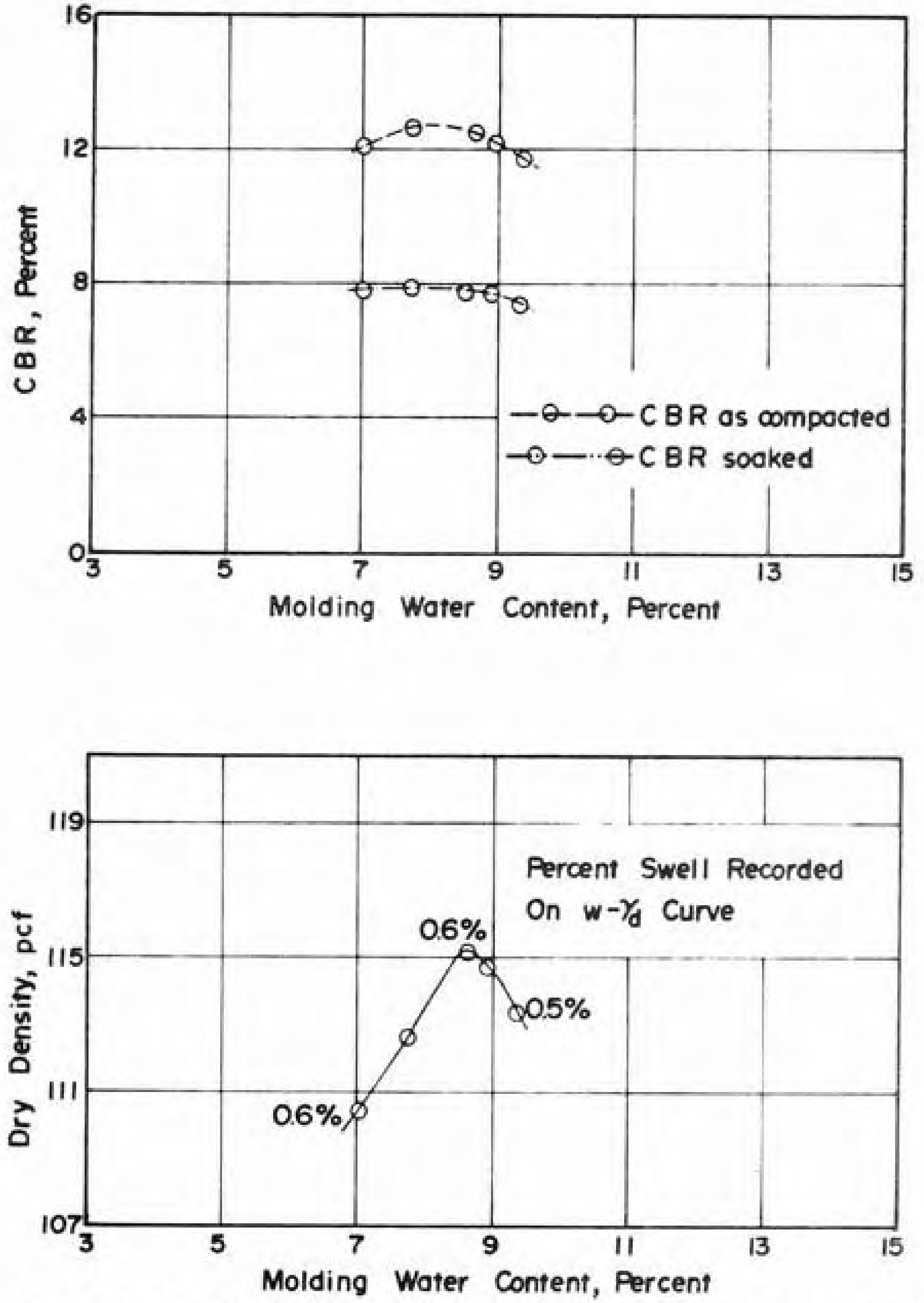


FIGURE 35. C B R TEST RESULTS (STANDARD EFFORT), LYNNVILLE SHALE.

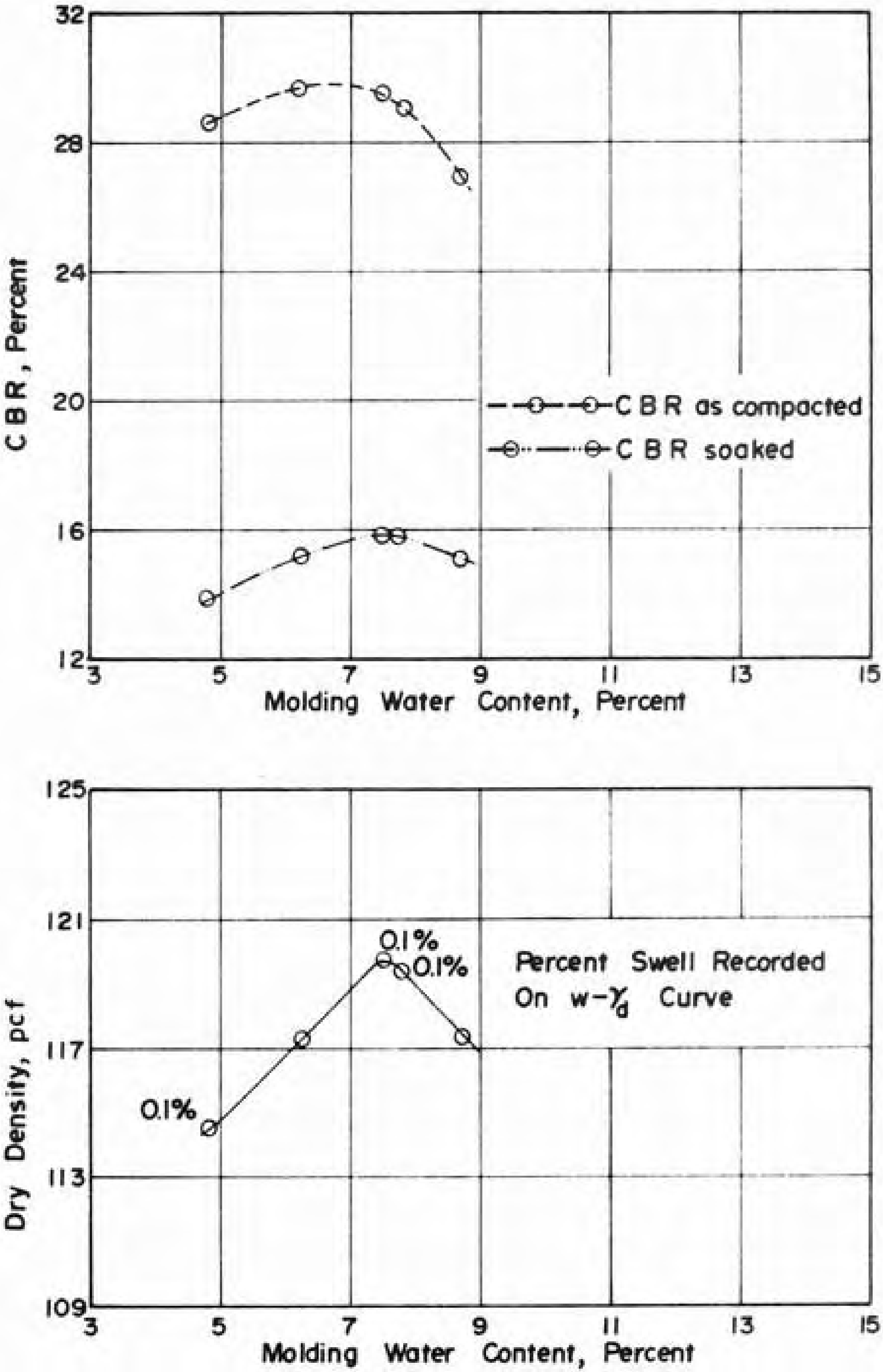


FIGURE 36. C B R TEST RESULTS (STANDARD EFFORT), 67 B SHALE.

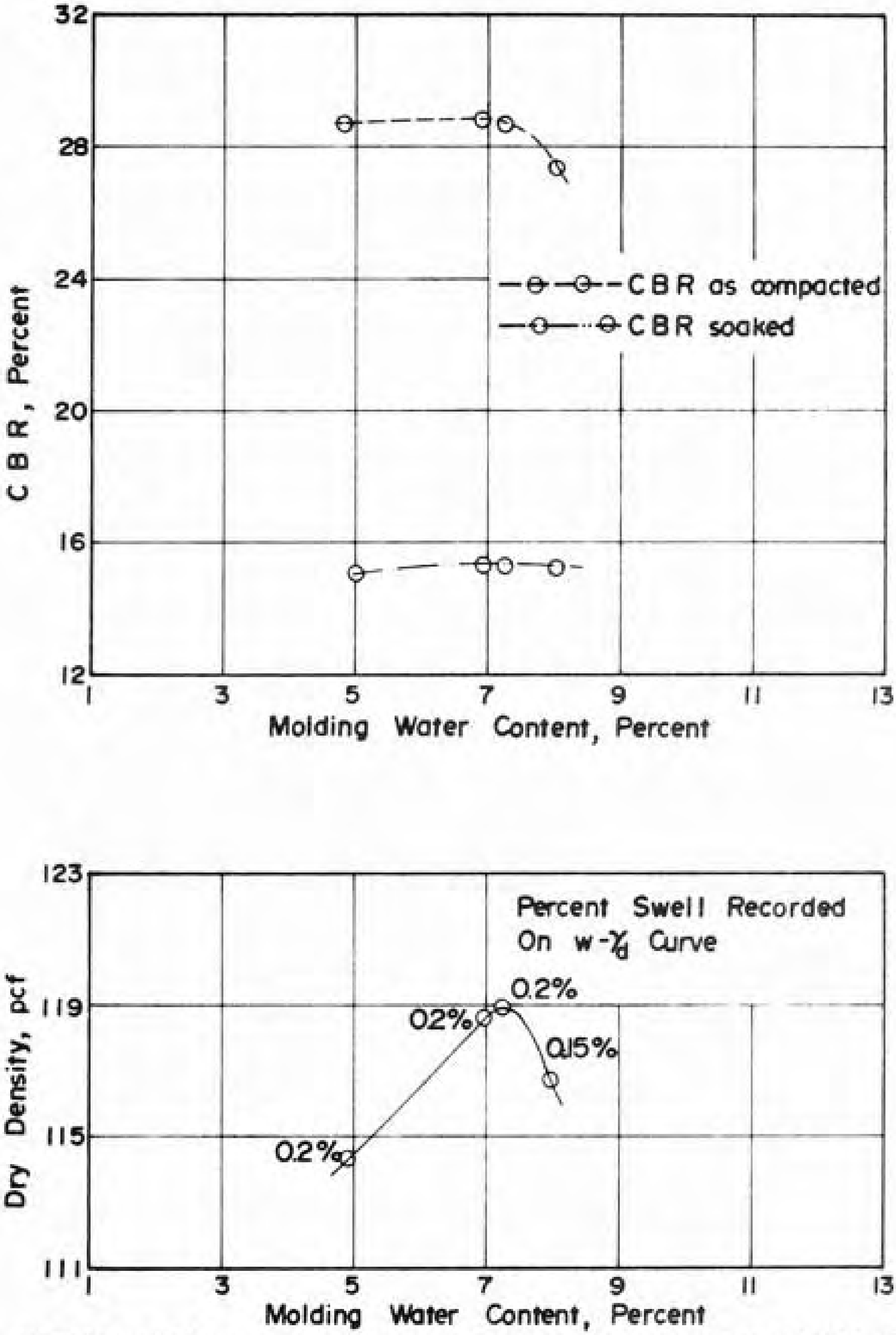
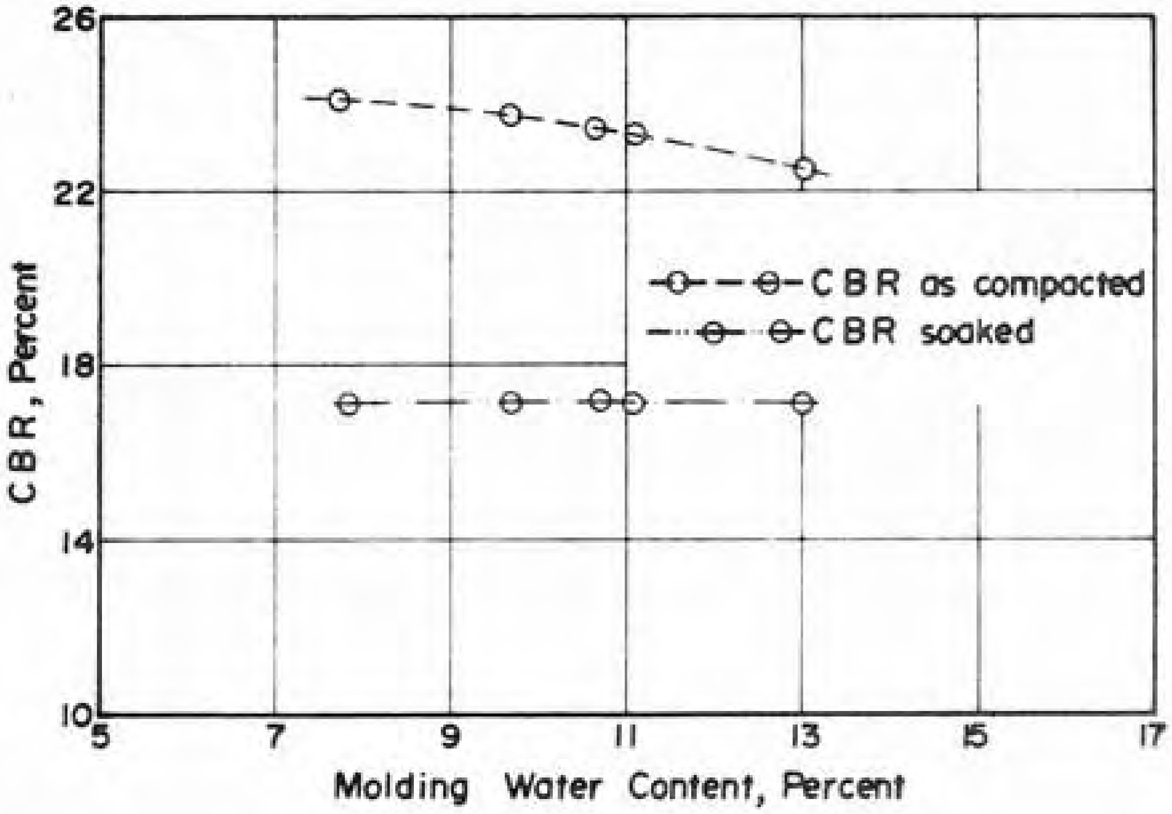


FIGURE 37. C B R TEST RESULTS (STANDARD EFFORT), 67 A SHALE.



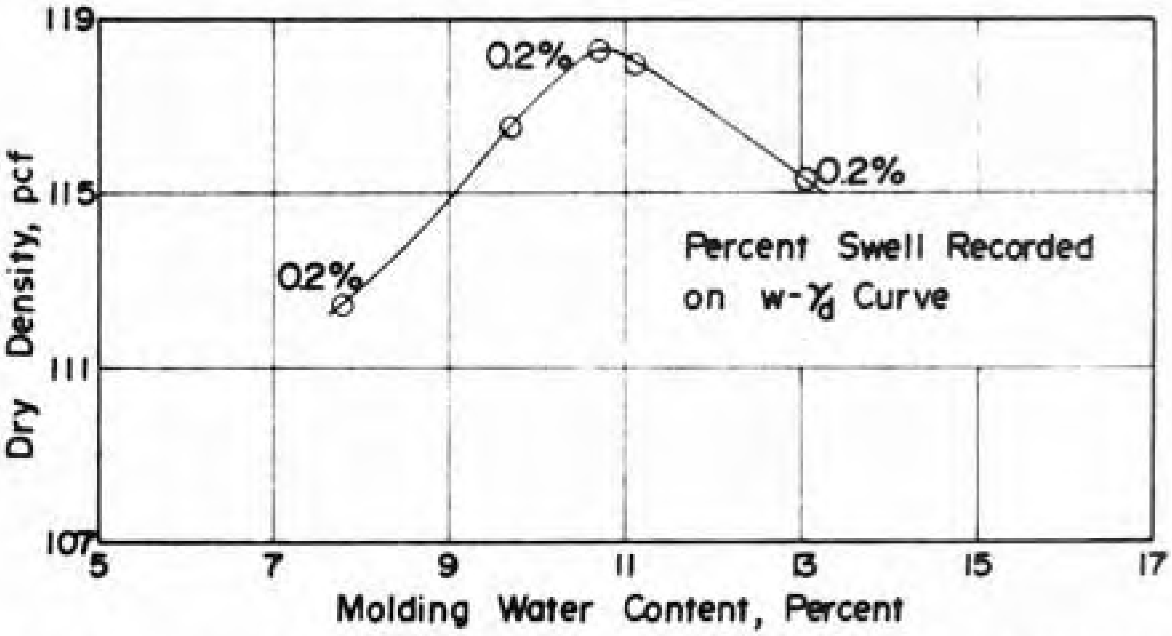


FIGURE 38. CBR TEST RESULTS (STANDARD EFFORT), KLONDIKE SHALE.

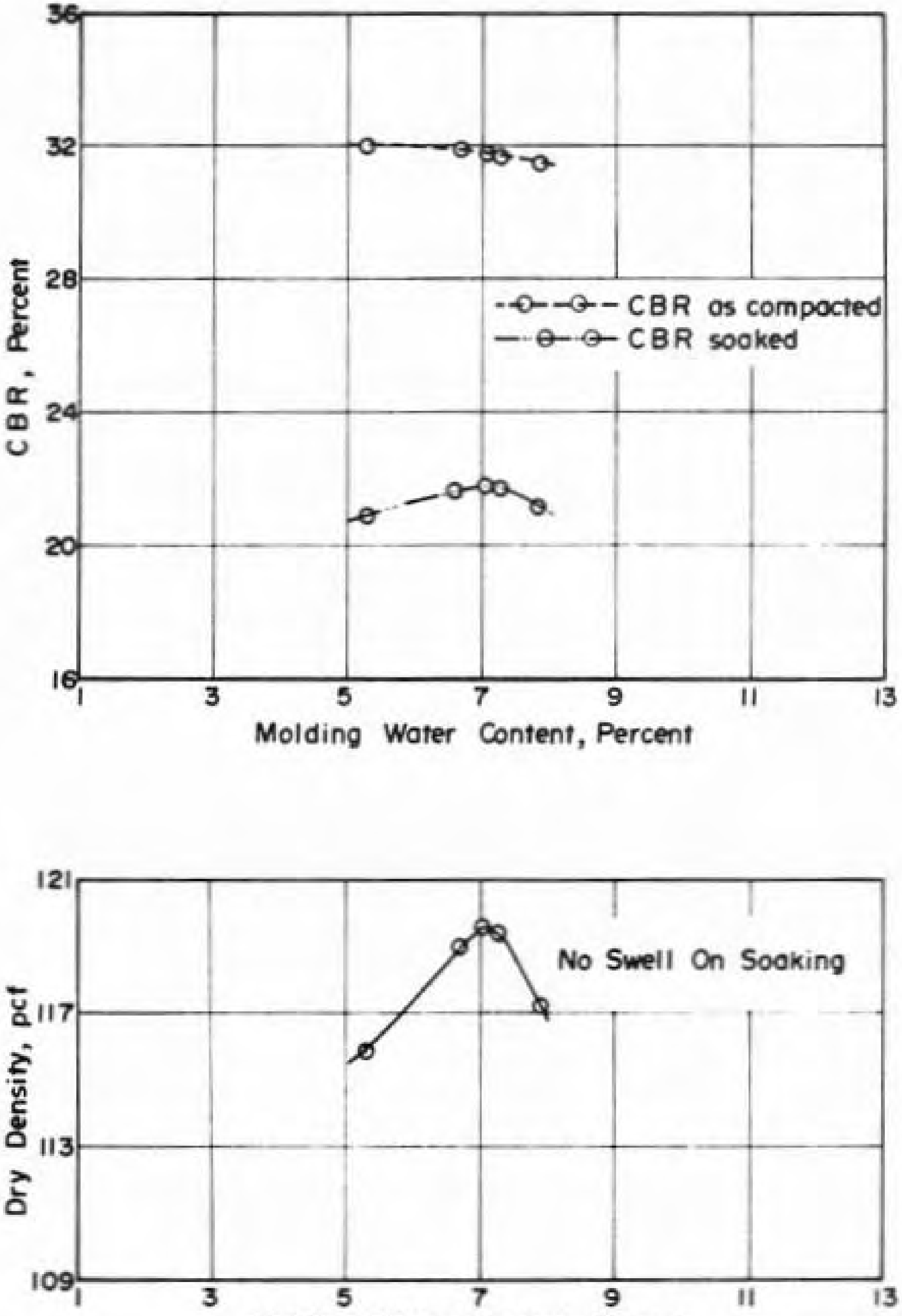


FIGURE 39 CBR TEST RESULTS (STANDARD EFFORT), 37 B SHALE.

TABLE 18. RESULTS OF CBR TEST AT STANDARD PROCTOR EFFORT AND OPTIMUM MOISTURE CONTENT.

Sample	γ_d max pcf	O.M.C. %	CBR as Compacted	CBR Soaked	(CBR Soaked) ÷ (CBR as compacted), R%	Swell %, S
Cannelton	107.8	14.8	2.1	0.0	0.0	7.8
I-74	117.9	13.8	8.0	1.1	13.7	5.4
Paoli Y	107.4	16.6	6.1	0.4	6.6	5.2
Paoli X	112.2	12.6	12.0	3.3	25.7	2.9
Paoli 5	117.0	10.1	19.9	6.2	31.2	1.0
Lynnville	115.3	8.7	12.4	7.8	63.0	0.6
I-65	117.8	10.2	21.2	8.3	39.2	3.2
67B	119.7	7.5	29.5	15.8	53.6	0.1
67A	119.0	7.3	28.8	15.3	53.5	0.2
Paoli 3	119.2	7.2	28.2	14.7	52.0	0.2
Scottsburg	118.2	6.9	28.4	14.5	51.0	0.0
37A	119.6	8.2	30.2	18.3	60.5	0.0
Klondike	118.3	10.7	23.4	17.2	76.5	0.2
Attica	117.5	7.2	27.4	19.4	71.0	0.0
37B	119.6	7.1	31.8	21.8	68.5	0.0

results. At standard effort, the optimum moisture content ranges from 6.9% to 16.6%. At 4.5 standard effort, optimum moisture content ranges from 5.3 to 14.0%. Optimum moisture content was plotted against the percent by weight of particles finer than 0.005 mm determined from grain size analysis of the shale. The plot is shown in Figure 40. Though no mathematical relationship is possible, there is a trend of increasing optimum moisture content with increasing amount of fine particles.

Maximum dry density obtained with standard effort at optimum moisture content ranges from 107.4 to 119.7 pcf.

CBR Results. As expected, CBR values, for both as-compacted and soaked conditions were higher at high compactive effort levels. For as-compacted CBR values, there was not much change on the dry side of optimum moisture, but on the wet side of optimum moisture content values decreased rapidly with the increase of moisture content. Generally, soaked CBR values were smaller on the dry side of optimum moisture content than those at optimum moisture content.

As tests were run on all fifteen samples at standard Proctor effort, these results were more thoroughly examined and compared (Table 18).

The comparisons of the values of as-compacted CBR, soaked CBR, and ratio of soaked CBR and as-compacted CBR show that as-compacted CBR varied between 2.1 and 31.8,

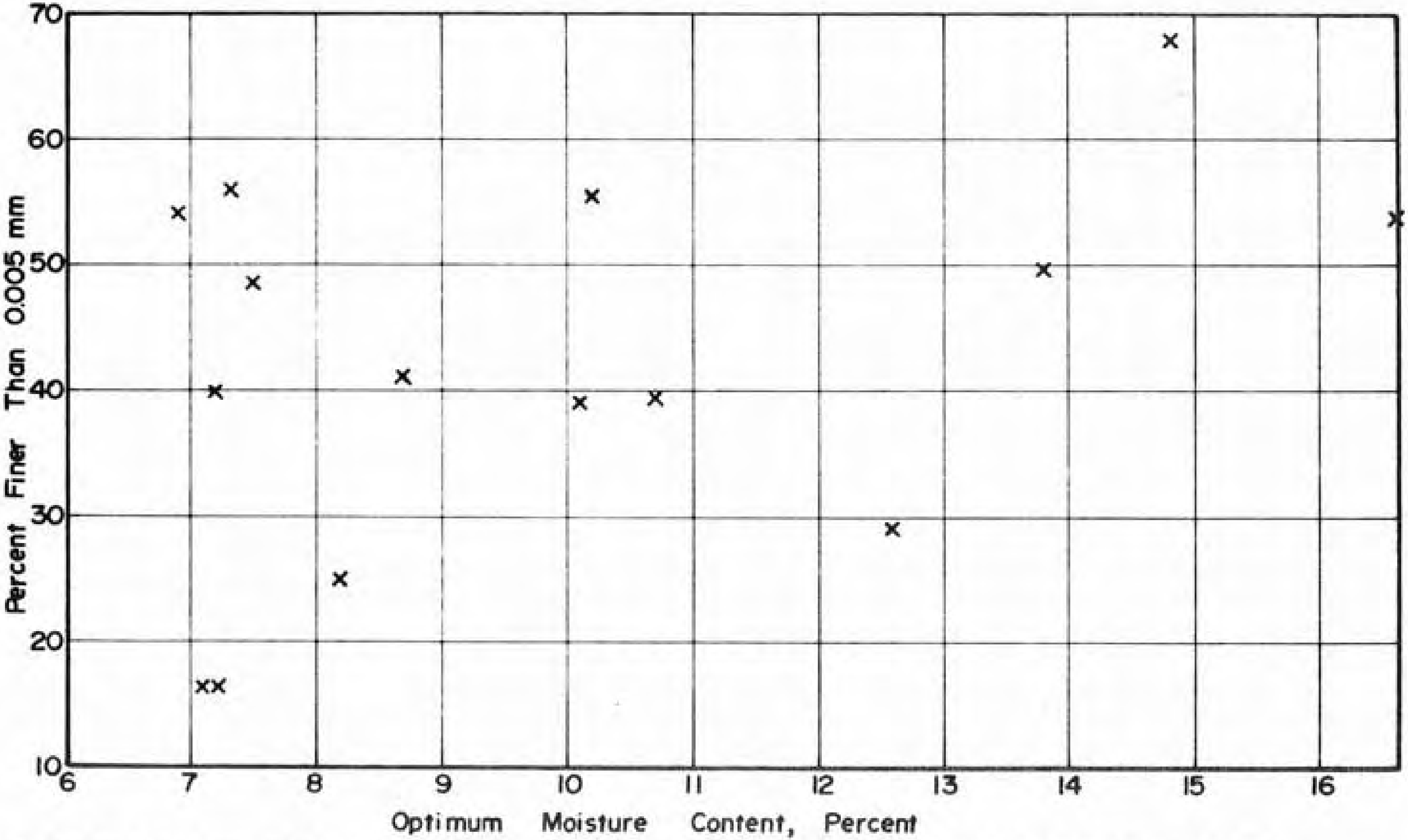


FIGURE 40. RELATIONSHIP BETWEEN PERCENTAGE OF PARTICLES FINER THAN 0.005 MM AND OPTIMUM MOISTURE CONTENT AT STANDARD EFFORT

soaked CBR varied between 0.0 and 21.8 and the ratio of soaked CBR and as compacted CBR varied between 0.0 and 0.765. It is noted that for the three materials which show some slaking in water, the value of soaked CBR is 0.0, 0.4 and 1.1, while the as-compacted CBR values are 2.1, 6.1 and 8.0. These data imply a very weak embankment, should these shales be saturated in service.

The values of soaked CBR varies between 0.0 and 76.5 percent of the as-compacted CBR. As this ratio becomes low, a closer examination of the special provisions for the use of the shale is indicated, e.g., compaction degradation, drainage, and encasement.

Swelling Behavior. Swelling after 96 hours of soaking was recorded. The maximum size of shale lumps used was 3/4 in., and it was thought that a few of the shales might collapse and show a volume decrease upon 96 hours of soaking. However, no such subsidence was noted.

For eight out of fifteen materials there is almost no axial swell. At standard Proctor optimum moisture for the remaining materials, axial swell is 0.6, 1.0, 2.9, 3.2, 5.2, 5.4 and 7.8%. On both sides of optimum moisture content, swell was less than at optimum moisture. Swell also increases with the increase of compaction effort (molding water content constant) and therefore with the increase of dry density. This is similar to fine grained soil results.

An increase in swell is identified with a decrease in the CBR ratio. If results are compared for those shales which give a swell of 1.0% or more, there is linear trend for reduction in ratio with the increase of swell. See Figure 41. A simple linear regression analysis gives a relationship of $R = 42.7 - 5.48S$, with a correlation coefficient of 0.86. The equation shows that at a certain value of swell, in the vicinity of 7.5%, the soaked CBR is reduced to almost zero.

Miscellaneous Tests

This group consists of water absorption, bulk unit weight of lumps, and certain breaking characteristics of materials.

Test Results and Discussion

Absorption tests. On three samples, viz., Cannelton, Paoli Y, and I-74, it was not possible to get reliable results due to the slaking phenomenon. For the other materials, water absorption-time curves are shown in Figure 42. The forty eight hour water content did not vary much from shale to shale, and was between 4.45 and 7.6 percent for all the samples.

Bulk Unit Weight. The results of bulk unit weights of chunks, as determined by the paraffin-coating technique are shown in Table 19.

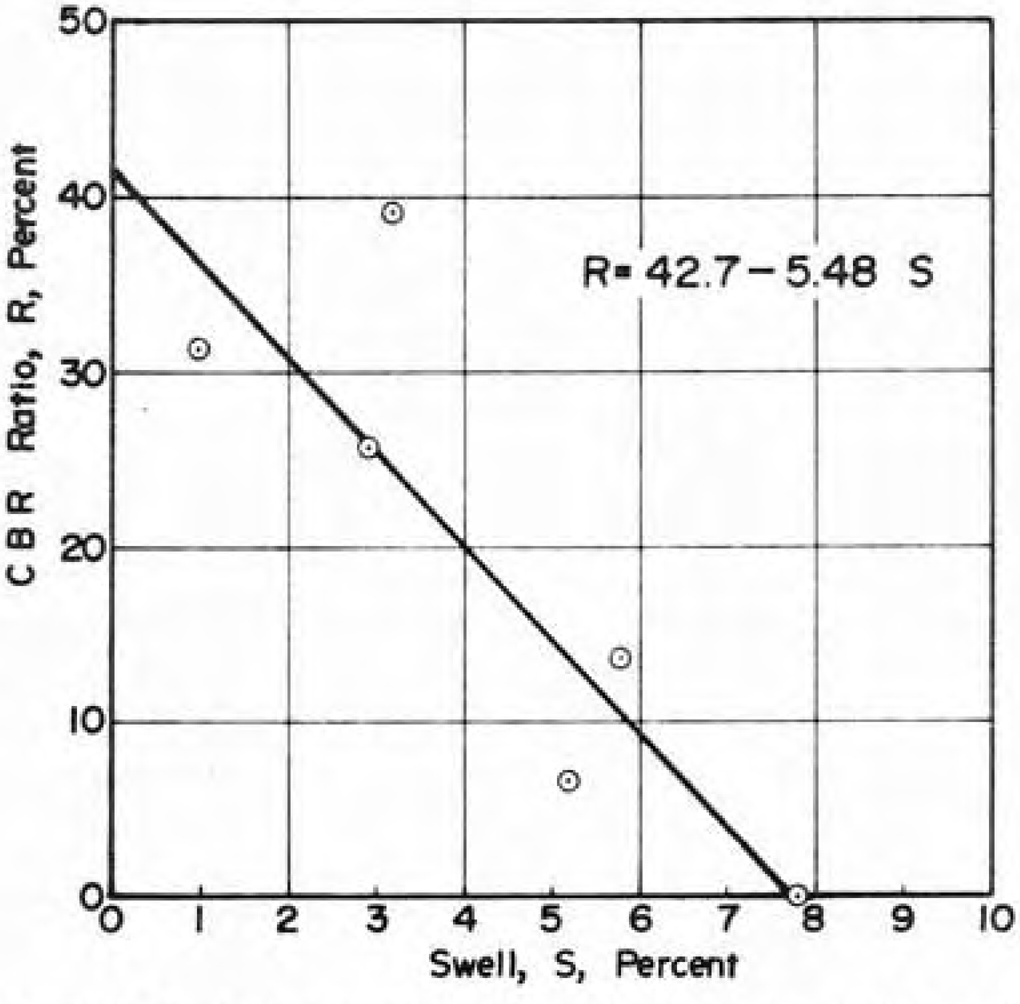


FIGURE 41. SWELL VS. CBR RATIO AT STANDARD PROCTOR OPTIMUM MOISTURE (FOR SHALES WHICH GAVE SWELL GREATER THAN 1%).

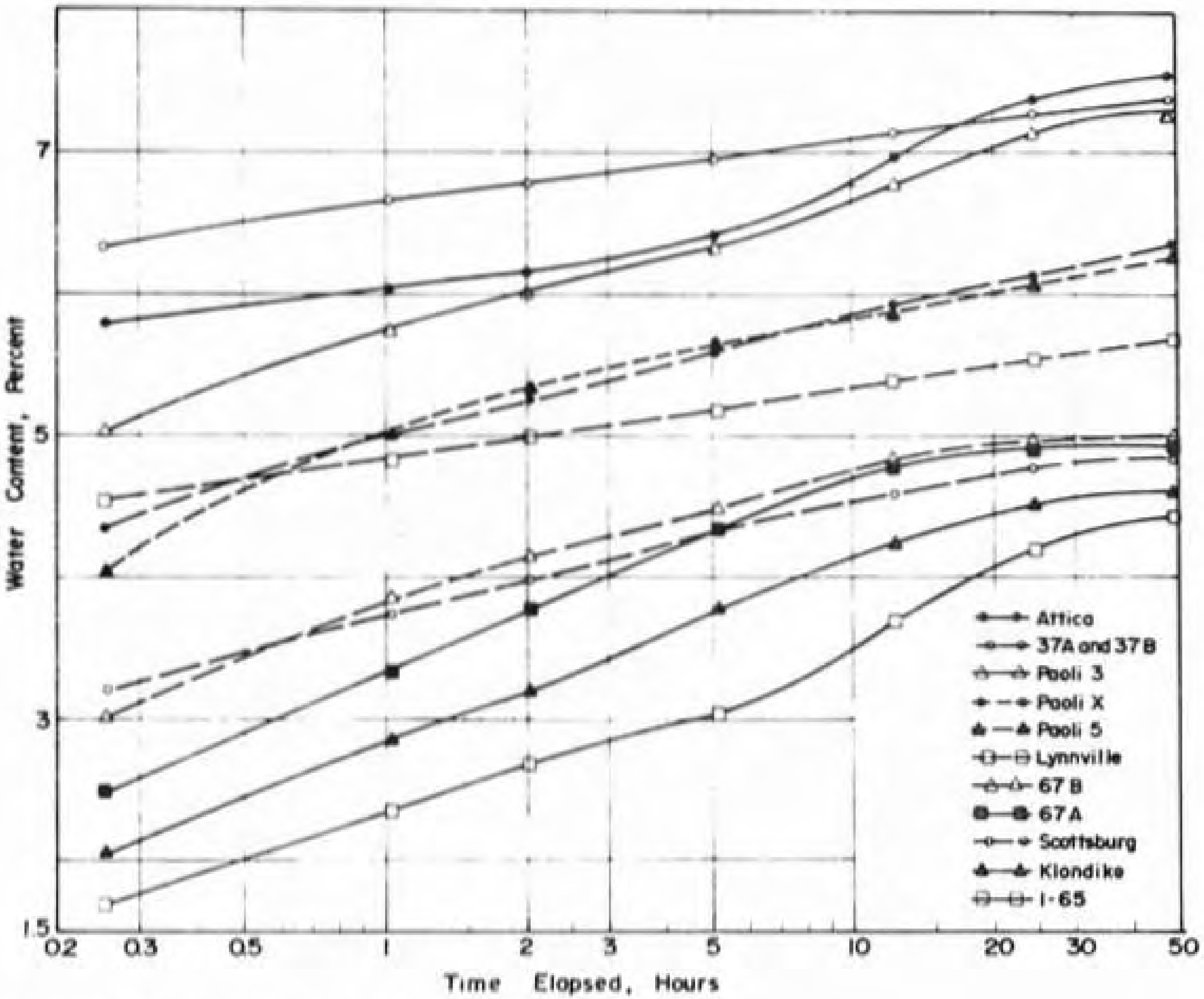


FIGURE 42. WATER ABSORPTION vs TIME CURVES.

TABLE 19. BULK UNIT WEIGHT OF SHALE SPECIMENS.

Sample	Bulk Unit Weight pcf
Cannelton	101.5
I-74	110.5
Paoli Y	102.8
Paoli X	114.6
Paoli 5	119.2
Lynnville	114.5
I-65	116.6
67B	120.4
67A	121.5
Paoli 3	124.1
Scottsburg	119.8
37A	124.6
Klondike	120.2
Attica	118.4
37B	129.9

As reported in literature by Underwood (90) and others (21, 66), the insitu dry unit weight of shale varies from 80 to 160 pcf. The dry unit weight values, which were obtained on chunks of Indiana shales varied from 101.5 to 129.9 pcf.

Higher values were expected, and the probable reasons for lower values are:

1. Many of the shales were sampled from shallow depths.
2. No insitu testing was done. Rather, bulk unit weight was determined on shale chunks after bringing them into the laboratory. Reduction in confining pressure might have increased the volume of chunks (though decrease in water content might also cause them to shrink).

Breaking Characteristics. On the basis of breaking characteristics of shales, the percentage component for each shale having massive, flaggy, and flaky properties was determined and is reported in Table 20.

Flaky and flaggy are two characteristics of fissility, and therefore the fissility number should be some weighted sum of the two. It was assumed that the fissility number should be equal to the percent flaky component plus a constant times the percent flaggy component. Though the size and weight of flaggy or flaky pieces for a given shale varies with the breaking effort, the flaggy pieces will be heavier

TABLE 20. FISSILITY CHARACTERISTICS FOR SHALES.

Sample	% Massive	% Flaggy	% Flaky	Fissility No., F (% Flaky + 0.35 % Flaggy)
Cannelton	0	30	70	81
I-74	10	20	70	77
Paoli Y	0	30	70	81
Paoli X	0	50	50	68
Paoli 5	10	40	50	64
Lynnville	20	30	50	61
I-65	0	50	50	68
67B	10	40	50	64
67A	10	40	50	64
Paoli 3	30	40	30	44
Scottsburg	20	40	40	54
37A	30	50	20	38
Klondike	0	50	50	68
Attica	30	60	10	31
37B	30	60	10	31

than the flaky pieces, for a given breaking effort. Typically the weight of flaky pieces varied between 5 and 100 percent of flaggy pieces, and the average weight of flaky pieces was 0.35 times the average weight of flaggy pieces.

Therefore, the fissility number (F) was defined as the sum of percent flakiness and 0.35 times percent flagginess.

The values of fissility number for Indiana shales ranged between 31 and 68 and are shown in Table 20. It will be shown in subsequent discussion that higher values of fissility number reduce both strength and durability of a compacted shale fill.

Correlation Among the Various Test Results

Attempts were made to correlate the results of one test with those of others. Linear and quadratic regression models were tried. Not all the correlation attempts were meaningful. Correlation attempts among the test results within the same test group have been described under the discussion of these group results. For example, the results of abrasion and slake durability tests on soaked samples were similar, giving a linear interrelation [$(I_d)_s = 109 - 1.15$ abrasion loss], with a correlation coefficient of 0.99 (Figure 21). A simple linear relationship was also possible between the CBR ratio and the axial swell for the shales which had a swell of 1.0% or more (Figure 41). The relationship is: $R = 42.7 - 5.48S$, with a correlation coefficient of 0.86. Principal correlation attempts among the test results of different groups are discussed below.

Fissility and CBR

As-compacted CBR is an indicator of the strength of the shale in the compacted fill, while soaked CBR indicates both in-service strength and durability. CBR ratio (R) is an indicator of the strength loss and the durability. Higher values indicate strong and/or durable shales for embankments.

It is expected that highly fissile rocks are comparatively weak and non-durable. Fissility number was therefore plotted against as-compacted CBR, soaked CBR, and CBR ratio. The plot against CBR ratio is shown in Figure 43, and a simple linear regression analysis gives the relationship $R = 108 - 1.07F$, with a correlation coefficient of 0.85. Regression analysis was also attempted for fissility number vs. as-compacted CBR and fissility number vs. soaked CBR. The relationships are: $(CBR)_c = 48.3 - 0.46F$, with a correlation coefficient of 0.77; and $(CBR)_s = 33.1 - 0.37F$ with a correlation coefficient of 0.83.

Thus, higher values of fissility number tend to reduce as-compacted CBR, soaked CBR, and CBR ratio, implying that embankments, constructed from shales having high fissility numbers, are relatively weak and less durable.

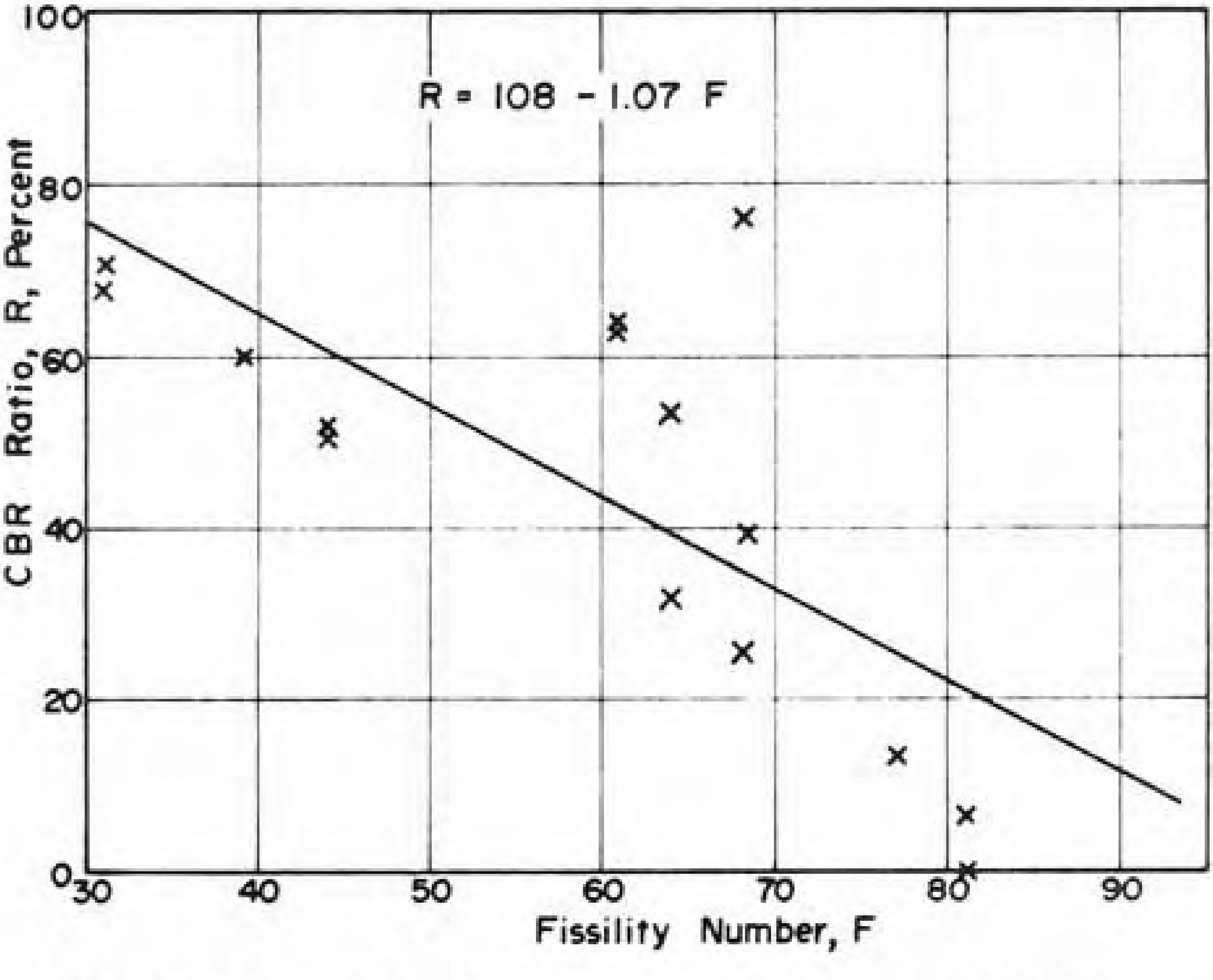


FIGURE 43. FISSILITY NUMBER VS. CBR RATIO.

Soundness Index and CBR

The soundness index was chosen as a simple index of durability because it is more effective than the slake-durability in distinguishing among the materials. By examining the values of soundness index (Table 9), it can be seen that 11 out of 15 shales which do not slake in water, give a soundness index of 70 or greater. The loss in CBR for the four slaking shales is tremendous and no mathematical relationship is attempted. However, for shales with a soundness index greater than 70, linear relationships are possible with the soaked CBR and CBR ratio. (No relationship should be expected with the as-compacted CBR because as-compacted CBR is a measure of strength and not of durability.) The relationships are: $(CBR)_s = -33.0 + 0.55\ I_s$, with a correlation coefficient of 0.83; and $R = -84.7 + 1.63\ I_s$, with a correlation coefficient of 0.92. These relationships are valid only for shales which have a value of I_s between 70 and 98. Figure 44 shows the plot of soundness index vs. CBR ratio.

It is thus seen that the shales which are predicted by the soundness test to be less durable, have lower values of soaked CBR and CBR ratio, i.e., they are predicted to be less durable by the CBR values also.

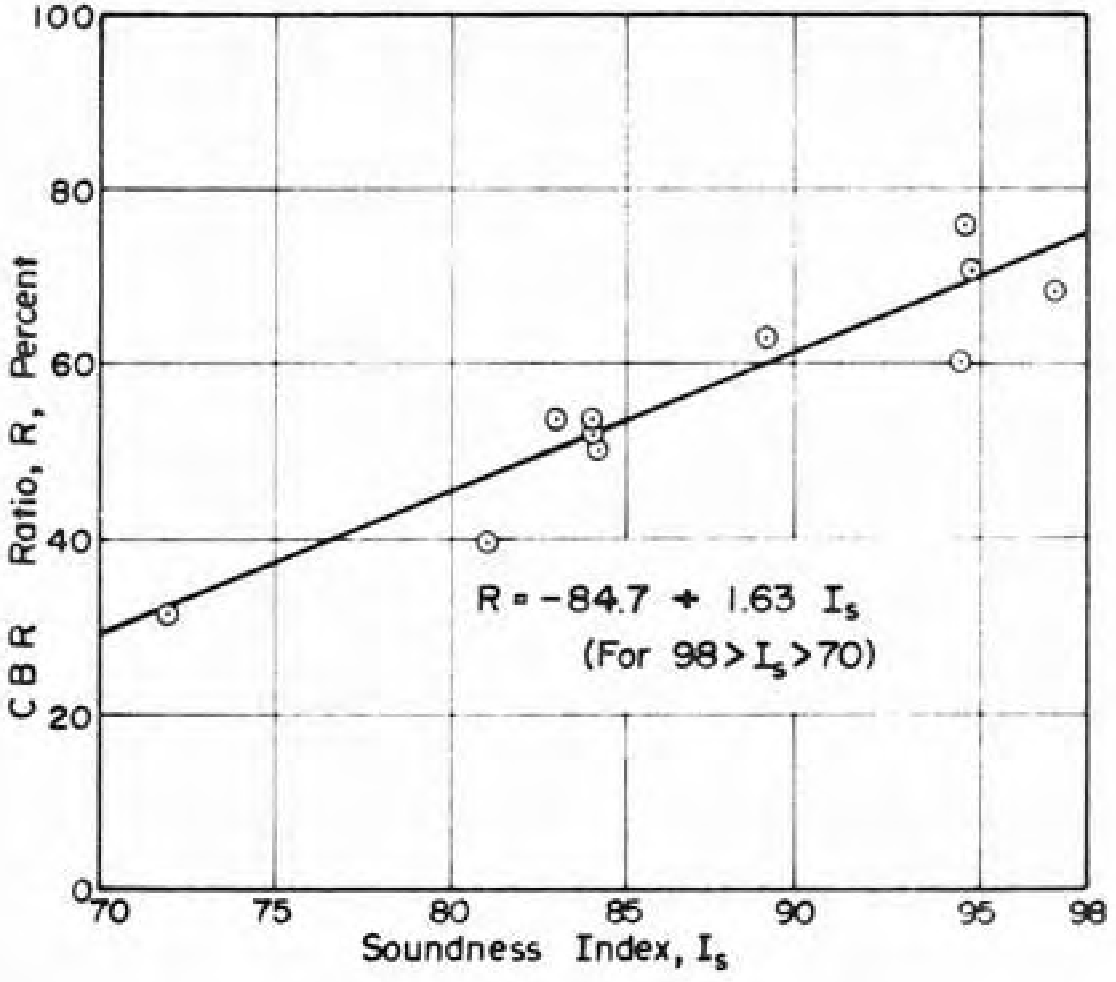


FIGURE 44. SOUNDNESS INDEX VS. CBR RATIO.

Fissility and Soundness Index

Shales with the three highest degrees of fissility were those which slaked most readily in water. Exceptions to the trend are noted, for example, Klondike shale has a high fissility number (F = 68), yet it also showed a relatively high soundness index ($I_s = 94.6$). This may be due to the nature of the cementing materials.

If a shale does not slake in water in one cycle of wetting and drying, and has a fissility number of less than 50, it is probable that it will be a relatively durable embankment material. In addition, all the shales which had a fissility number of less than 68, had a soundness index of greater than 68. A plotting of soundness index and fissility number values is shown in Figure 45. Linear and quadratic regression models were tried but do not give any meaningful relation. However, Figure 45 shows that, at least in a qualitative sense, the fissility number and soundness index have an inverse relationship. The absence of a strong quantitative inverse relationship could be explained by the fact that fissility is not the sole physical material factor influencing durability.

Grain Size Distribution and Indices of Durability

It has been reported by Ollier (68) that fine grained rocks show greater weathering effects than coarse grained ones. Accordingly, the cumulative percentages finer than 0.002 mm, 0.005 mm, and No. 200 sieve were plotted against

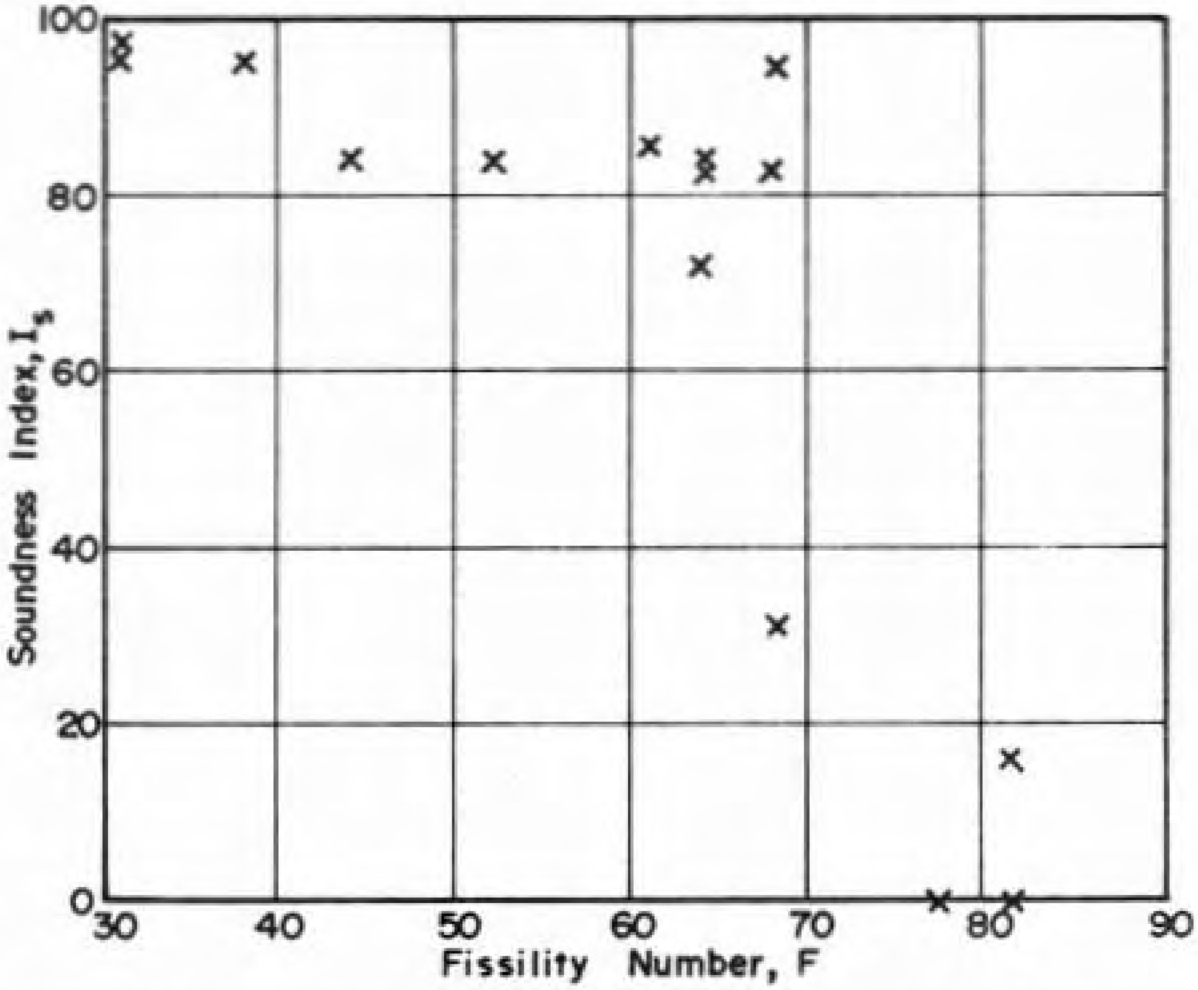


FIGURE 45. FISSILITY NUMBER VS. SOUNDNESS INDEX.

$(I_d)_d$, $(I_d)_s$ and I_s. Linear and quadratic regression models were tried on soundness index, I_s, and percent finer than 0.002 mm ($C_{2\mu}$). The linear regression model gave a relationship $I_s = 114 - 1.33\ C_{2\mu}$, with a correlation coefficient of 0.522. The quadratic model gave a relationship $I_s = 73 + 1.50\ C_{2\mu} - 0.0412\ C_{2\mu}^2$, with a correlation coefficient of 0.565. Such low values of correlation coefficients show that the regression equations have very little meaning. Regression analysis attempts with other measures of grain size ($C_{5\mu}$ and C_{200}), or of durability [$(I_d)_d$ and $(I_d)_s$], also yielded relationships with very low correlation coefficients. However, the data show that, at least in a qualitative sense, fines reduce the durability indices.

Unit Weights and CBR or Soundness Index

It is believed that the strength and durability of shale increases with the increase of insitu density. Insitu density was not determined, but bulk dry unit weight of lumps [(γ_m) lumps] and maximum dry unit weight of Standard Proctor effort ($\gamma_{d\ max}$) were known.

It was therefore attempted to correlate the two dry unit weights with as-compacted CBR, soaked CBR, CBR ratio, and soundness index. No meaningful correlation was possible with the soaked CBR, CBR ratio, or soundness index. However, linear relationships were possible between the as-compacted CBR and the two types of unit weight (Figure 46). The relationships are: $(CBR)_c = -220.7 + 2.07\ \gamma_{d\ max}$, with a correlation coefficient of 0.85; and $(CBR)_c = -120.2 + 1.20\ (\gamma_m)_{lumps}$, with a correlation coefficient of 0.93.

The correlation with as-compacted CBR indicates that the unit weights are related to the strength only and not to the durability.

General Discussion

Several of the degradation type tests distinguish well among the various shales. The soaked durability index and the soundness index seem to be valuable for rating shales as to their relative durability. They apparently reflect a combined effect of various important characteristics of shale, such as, fissility, cementing materials, and amount and type of clay and silt sizes.

Soil type identification tests seemed least promising in predicting the behavior of the various shales. However, it is expected that Atterberg limits would be very useful in identifying clay shales. X-ray diffraction would be useful in identifying montmorillonitic shales (which are likely to swell considerably). However, the shales of this study were neither highly plastic, nor montmorillonitic. Both plasticity and X-ray diffraction results were quite similar for all of them. Yet the shales differed drastically in durability. Probably, the cementing materials,

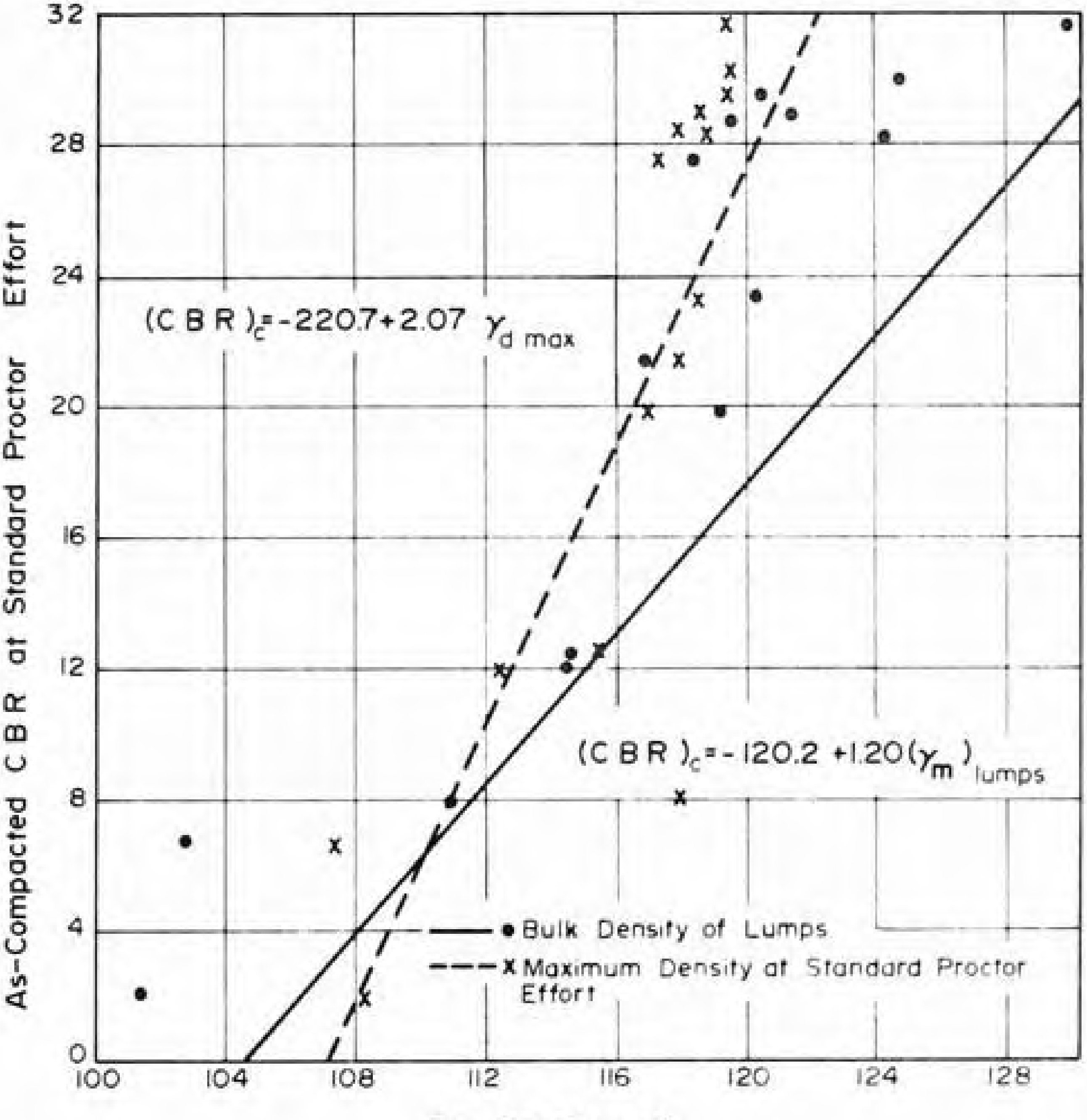


FIGURE 46. DRY DENSITY VS. AS-COMPACTED C B R.

which will be a very small fraction of the total shale mass (and were not determined during this study), have more influence on the behavior of shales than the clay minerals.

Results of CBR tests on various shale samples showed a widespread range in the values of $(CBR)_c$, $(CBR)_s$, R, and $\gamma_{d\ max}$. Higher values of $(CBR)_c$ and $\gamma_{d\ max}$ indicate stronger shales. $(CBR)_s$ is an indicator of both in-service strength and durability, and higher values indicate more strength and durability. Higher values of R predict more durable shales. The results of CBR tests correlate satisfactorily with soundness index and fissility number.

Among the results of miscellaneous tests, fissility number seemed the most promising. Higher values of fissility number tend to reduce as-compacted CBR, soaked CBR, and CBR ratio. Thus higher fissility reduces durability and strength.

The values of bulk unit weight of lumps and maximum dry unit weight of Standard Proctor effort correlated well with the values of CBR as compacted, which is a measure of strength. However, values of bulk unit weight of sampled Indiana shales covered a relatively small range as compared with that reported in the literature. (The values of bulk unit weight of dry lumps of sampled shales ranged between 101.5 and 129.9 pcf, as compared with an insitu dry unit weight range of 80 to 160 pcf (21, 66, 90)).

Therefore bulk unit weight of shale lumps has a limited utility here.

Table 21 summarizes the relative usefulness of various tests. It will be seen that soaked durability index, soundness index, soaked CBR, CBR ratio and fissility number are the descriptors of durability, while as-compacted CBR, bulk dry unit weight of lumps, and maximum dry unit weight of Standard Proctor effort are descriptors of strength.

On the basis of 4 simple degradation type tests, Indiana shales can apparently be classified in the following four groups;

1. Rock like shales
2. Intermediate-1 shales
3. Intermediate-2 shales
4. Soil like shales.

The flow chart for classification is shown in Figure 47.

The range of values of other descriptors for the Intermediate-1, Intermediate-2 and Soil like shales is listed in Table 22. (No Rock like shale was sampled.)

Based upon the experimental data generated by this study, it is possible to make certain qualitative statements about the strength and durability of these shales in embankments. Soil like shales are non-durable and weak. They should be broken down before use and thinner lifts than normally used for soil may be needed. An effective

TABLE 21. USEFULNESS OF VARIOUS TESTS.

Test	Usefulness	Remarks
Slaking in water in one cycle	Useful to measure durability of shales which completely or partially slake in the tests.	Only qualitative results.
Slaking in water in five cycles		
Slake durability (dry sample)		Very simple and inexpensive test.
Slake durability (soaked sample)	Very useful to measure durability of shales which do not slake in water in one cycle.	
Modified soundness		More useful for shales for which $(I_d)_s$ is greater than 80.
Abrasion (dry sample)	Not useful.	-
Abrasion (soaked sample)		Results could be related with slake durability (soaked) test results.
Atterberg limits	Limited.	Useful in case of highly plastic clay shales.
Grain size		-
X-ray diffraction		Useful in identifying montmorillonitic shales (which are likely to swell considerably).
Compaction	Useful Laboratory tests.	Compaction and $(CBR)_c$ for strength, R and $(CBR)_s$ for durability.
CBR		
Swell		Higher swell means less durable.
Absorption	Not useful.	-
Bulk Unit Weight of chunks	Useful for strength.	Higher density means more strength.
Fissility number	Useful for durability and strength.	High fissility number means lower durability and strength.

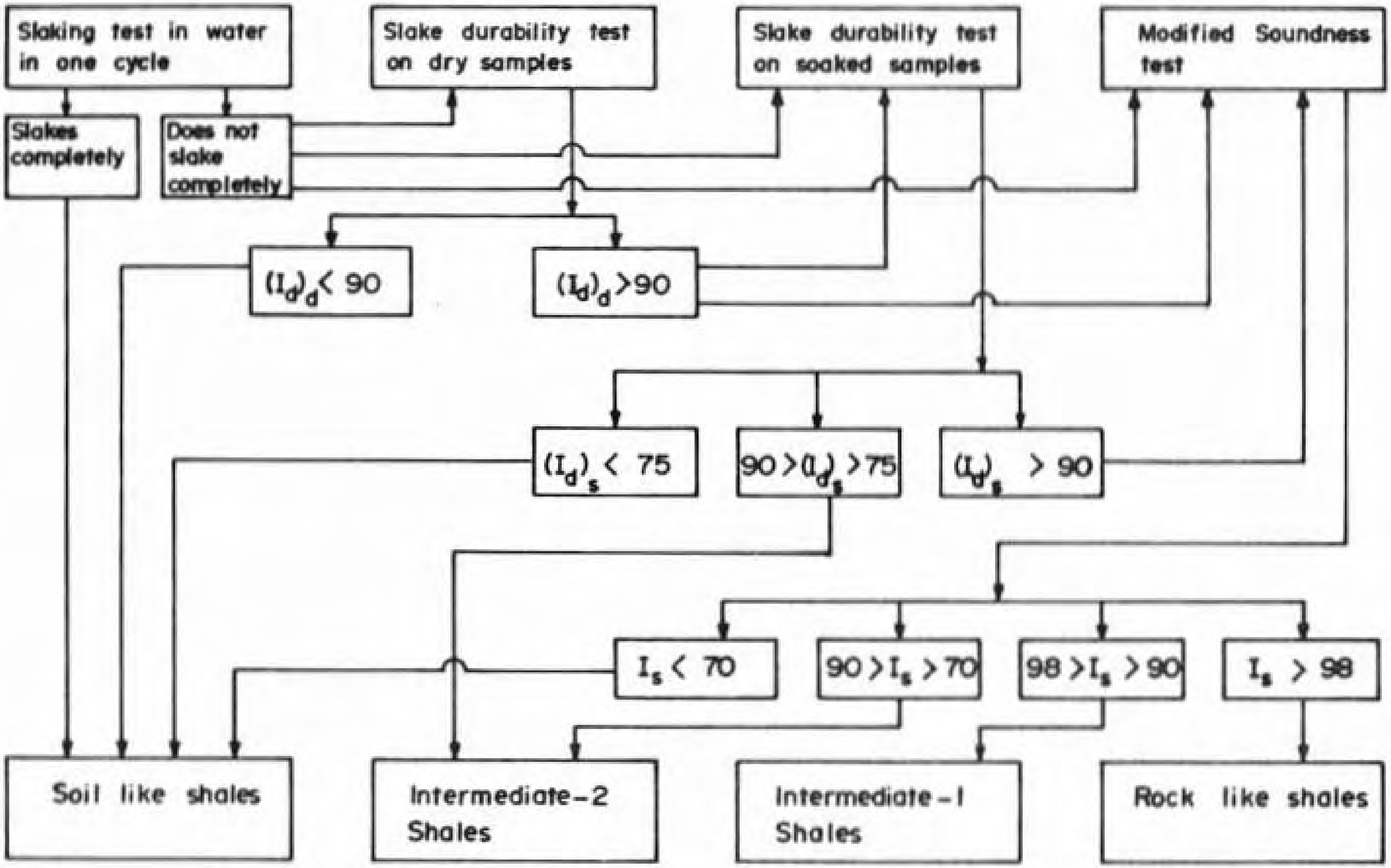


FIGURE 47. PROPOSED CLASSIFICATION OF SHALES FOR EMBANKMENT CONSTRUCTION.

TABLE 22. RANGE OF VALUES OF VARIOUS DESCRIPTORS FOR DIFFERENT SHALE CLASSIFICATION GROUPS.

Classification Group	Samples	$(CBR)_c$	$(CBR)_s$	R,%	S,%	γ_d max pcf.	(γ_m) lumps pcf	F
Intermediate-1	37A; Klondike; Attica; 37B	23.4 to 31.8	17.2 to 21.8	60.5 to 76.5	0.0 to 0.2	117.5 to 119.6	118.4 to 129.9	31 to 68
Intermediate-2	Paoli 5: Lynnville; I-65; 67B; 67A; Paoli 3; Scottsburg	12.4 to 29.5	6.2 to 15.8	31.2 to 63.0	0.0 to 3.2	115.3 to 119.7	114.5 to 124.1	44 to 68
Soil like	Cannelton; I-74; Paoli Y; Paoli X	2.1 to 12.0	0.0 to 3.3	0.0 to 25.7	2.9 to 7.8	107.4 to 117.9	101.5 to 114.6	68 to 81

encasement of non-shale soil may be needed. For the two intermediates, specifications should generally vary between those for soil and those for rock fills. Bigger chunks can be used. In the intermediate-2 shales, it is probably necessary to have better density control and effective encasement.

SUMMARY AND CONCLUSIONS

General

1. Shales are "bad actors" in various degrees. Some shales slake almost immediately when exposed to a higher humidity, while others withstand numerous cycles of wetting and drying.

2. Indiana has some shales which are hard and durable. However, there are others which slake in water and are likely to cause problems in embankments.

3. Most of the Indiana shales sampled during this study are of low plasticity and low activity. Illite and kaolinite are common clay minerals.

4. For the use of shales in embankments there are two principal problems; first, a failure to recognize and properly classify the shale in an engineering sense; second, an inability to specify economic design and construction features to match the predicted engineering response.

5. Within a short distance, laterally or vertically, shales like most other naturally occurring materials vary greatly in appearance and physical properties.

Tests

Not all of the tests yielded useful descriptors for classifying shales as to their probable behavior in compacted embankments (Table 21). $(I_d)_s$, I_s, $(CBR)_s$, R, and F are descriptors of durability. $(CBR)_c$, $(\gamma_m)_{lumps}$, and $\gamma_{d\ max}$ are the descriptors of strength.

Experimental results from the tests lead to the following conclusions.

1. The results of abrasion and slake durability tests on soaked samples are similar, and their interrelation can be approximated by a linear relationship [$(I_d)_s$ = 109 - 1.15 (Abrasion Loss)].

2. With respect to CBR tests, the CBR ratio (R) and percent axial swell (S) show an inverse relationship. For shales which give a swell of 1.0 percent or more, the relationship is approximated by $R = 42.7 - 5.48\ S$.

3. CBR ratio and soaked CBR can be simply related with soundness index (I_s), for the shales which have a soundness index between 70 and 98. The relationships are, $R = -84.7 + 1.63\ I_s$, and $(CBR)_s = -33.0 + 0.55\ I_s$.

4. Fissility number is a highly useful descriptor for shales. Highly fissile shales will have lower soundness index, lower CBR (both as-compacted, and soaked), and lower CBR ratio. The relationships of fissility number with CBR ratio, as-compacted CBR, and soaked CBR can be

approximated respectively as, $R = 108 - 1.07F$; $(CBR)_c = 48.3 - 0.46F$; and $(CBR)_s = 33.1 - 0.37F$.

5. Bulk unit weight of lumps is a useful descriptor for shales. As-compacted CBR and bulk unit weight of lumps have a direct relationship, approximated by $(CBR)_c = -120.2 + 1.20\ (\gamma_m)_{lumps}$.

6. Maximum dry unit weight of Standard Proctor effort and as-compacted CBR have a direct relationship, approximated by $(CBR)_c = -220.7 + 2.07\ \gamma_{d\ max}$.

Classification of Shales

It is proposed that the Indiana shales be classified into the four categories, namely, Rock like, Intermediate-1, Intermediate-2 and Soil like shales (Figure 47).

RECOMMENDATIONS AND SUGGESTED CONSTRUCTION PRACTICES

When shale is considered as a construction material in embankments, it should be viewed as a special material, i.e., something between soil and rock. It should be classified in accordance with its probable behavior in the embankment. Before actually specifying use of this type of material, the following recommendations are made.

1. Review the design and construction standards and specifications which could apply if the embankments material were (a) an average fine grained soil and (b) an average sedimentary rock, i.e., consider the limits for the real material which is generally intermediate.

2. Study the proposed fill material to determine whether it is grossly homogeneous or a mixture of unlike materials, e.g., shale and limestone. There are special hazards in the latter case, and extra special attention is required.

3. Perform the slake durability and modified soundness tests. Classify the material in one of the four groups suggested earlier, i.e., Rock like, Intermediate-1, Intermediate-2 or Soil like.

For different groups of shales, the following construction practices are suggested by the author. (These opinions were derived intuitively on the basis of observations but without any actual field test.)

1. If the material is soil like, the material should be thoroughly broken down before use and thinner lifts than normally used for soil, may be needed. Here, expansive characteristics for the shale should also be determined. (Axial swell in CBR test is a good descriptor.) If the shale powder shows more swelling than that of ordinary clays, it should be accorded the special treatment given an expansive soil embankment and an effective encasement of non-shale material will be needed.

2. For intermediate-1 and intermediate-2 shales, specifications should generally vary between those for soil and those for rock fills. Bigger chunks can be used. In intermediate-2 shales, it is probably necessary to have better density control and to employ an encasement.

3. A mixture of durable and non-durable material should not be used in an embankment, e.g., never mix a rock like with intermediate-2. The two materials will degrade differently during service, causing problems. Only top quality of intermediate-1 shales or rock like can be mixed with limestone or sandstone.

4. If it is not possible to separate good and bad shales, then the whole material should be treated like soil, and should be thoroughly broken down before use.

SUGGESTIONS FOR FURTHER RESEARCH

1. Indiana shales should be categorized as to embankment performance by geologic units, so that geologic mapping can be used to make a first prediction of the shale behavior. Such a program would require systematic sampling and laboratory testing of the general type described in this research.

2. Shales considered for embankment use by the ISHC should be subjected to characterization by test in the general manner described herein. These data can be accumulated and will improve the validity of correlation equations of the type contained in this report.

3. The performance of shale embankments, particularly those constructed with the aid of the guidelines stemming from this study should be monitored, with a view to improving design and construction specifications and standards.

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APPENDICES

Appendix A

Case History

In December 1971 and January 1972, a slope failure occurred on I-74 near St. Leon in Dearborn County, Indiana. This failure forced the closing of the east-bound lane of the highway. It was located within a compacted fill containing both shale and limestone.

The location and geology of the problem site are described herein, along with salient features of the landslide. The construction specifications and properties of the embankment material are also described.

Description of Landslide Area

The failure occurred in southeastern Indiana, near the Indiana-Ohio boundary. The exact location is in the northwestern half of section 13, T-7-N, R-2-W, about 1-1/4 miles east of the interchange with Indiana State Highway 1 (Figure 48).

Bedrock at this point is in the upper part of the Dillsboro Formation (lower part of the Richmond Group), and is late Ordovician in age. This formation consists of thin beds of shale and limestone. The regional dip is about 6 feet per mile westward, and the beds appear practically horizontal to the naked eye (30). In this region, more than 300 beds of alternating shale and limestone are recorded with an average thickness of beds about six inches (30).

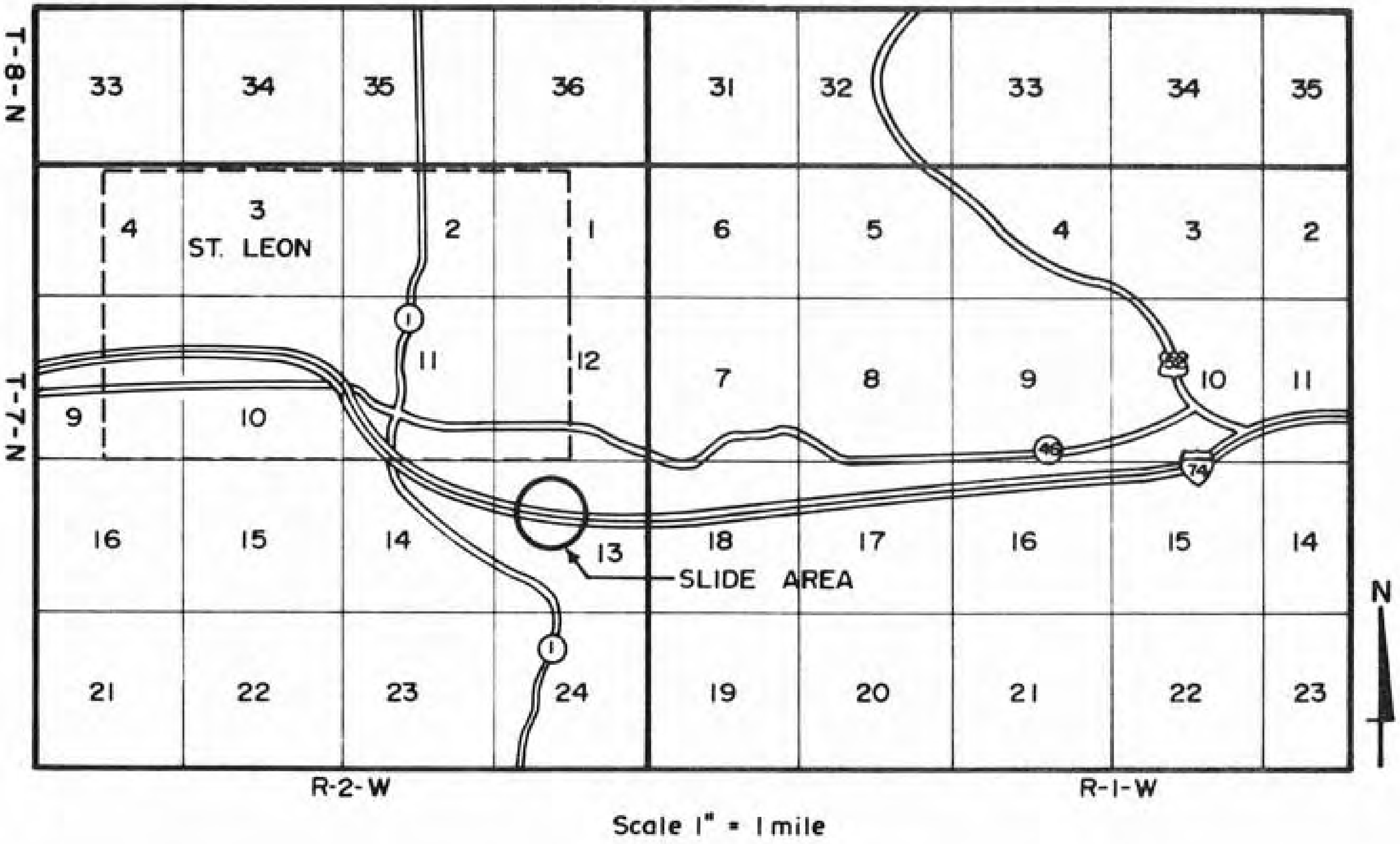

FIGURE 48. LOCATION OF SLIDE AREA.

Several types of limestone are present. Some are granular; some are fine-grained; all contain abundant fossils, fossil-fragments or fine fossil debris. Limestone makes up 55 percent of the exposed rocks, mostly in beds 0.2 to 0.4 feet thick. The greater part of the limestone, however, is in three thick beds that make up the upper 23 feet. Gray soft shale in beds 0.1 to 2.0 feet thick make up the remaining 45 percent of the thickness (30).

The shale has few open joints, but the limestone is well jointed and typically breaks out into slabs with flaggy characteristics. The existence of a master joint system in the area is suggested by prominent parallelism of many of the smaller streams in a N30°W direction; the explanation is that the streams have preferentially eroded along weakened joints (30).

Natural slopes on these rocks are as steep as 35 percent or about 3 to 1. Gray (30) reports that these slopes show little evidence of instability, and steeper cut slopes also appear to be stable. However, Sisiliano (80) concludes that this general area is the most landslide susceptible in the entire state. Landslides are associated with the residual soils of the area, and occur on natural slopes as well as with embankments and cuts.

Soil cover in the area consists of residual weathered materials on the slopes and glacial till on the broader divides. The till is a strong silty clay. The residual soil consists of limestone slabs in a matrix of greenish-brown or yellowish-brown clay, which has weathered principally from shale (30). The insitu soils tend to have good internal drainage. Cuts in this material may cause landslides (8), and erosion is a serious problem on cut slopes (84).

These soils are heterogeneous. Water movement through them tends to follow irregular pathways of least resistance. One part of the soil may be fairly dry, while another part close by is thoroughly saturated. The most important zone of weakness is immediately beneath the soil at the bedrock-soil interface. The reason for this is that the shale is less permeable than the soil, so that water seeping downward through the soil, as well as water seeping toward the outcrops in beds of limestone, tends to collect and move downslope at the bedrock-soil interface as shown in Figure 49 (30).

Embankment Details

The embankment was constructed during 1961. The fill material consisted of the locally available mixture of limestone, shale, and clay weathered principally from the shale. The construction specifications do not directly refer to the shale or to any special treatment for it. Apparently, the shale was placed in large chunks and was not much reduced in size by compaction. The harder

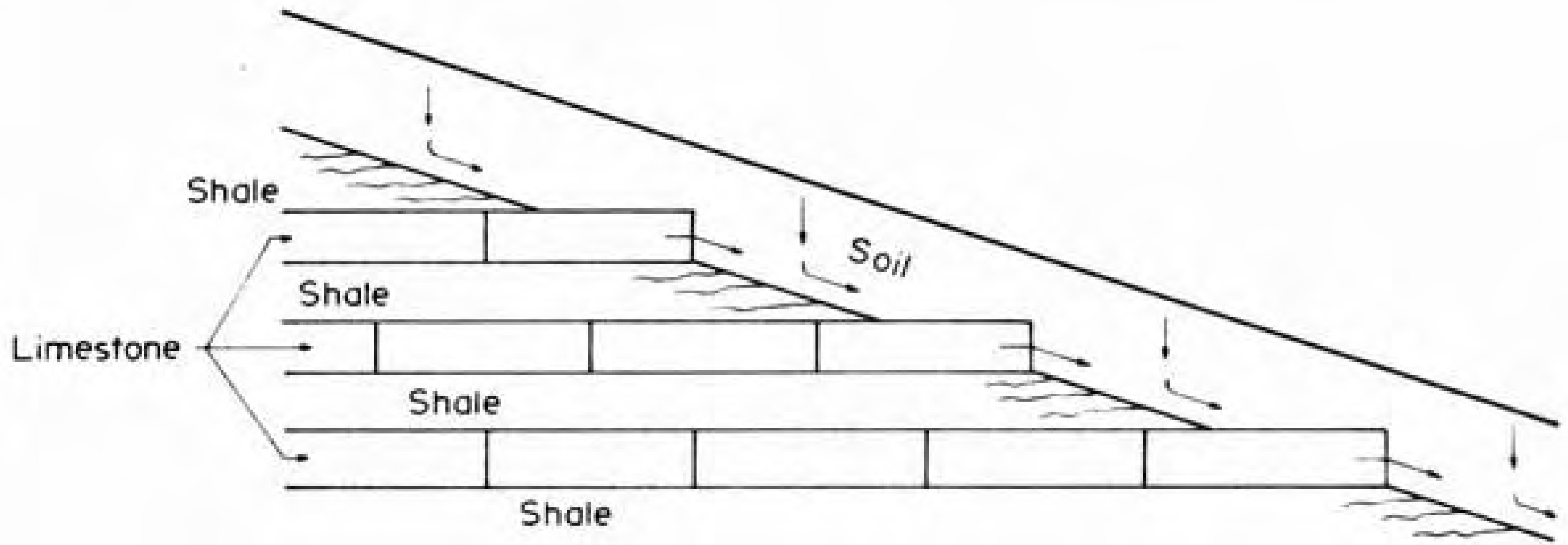

FIGURE 49. MOVEMENT OF WATER AT SOIL-BEDROCK INTERFACE (30).

limestone was present randomly and probably protected the shale by bridging, arching or similar load-distribution action. If the fill were constructed as a rockfill the lifts could have been as thick as four feet (47).

The side slopes were 2 to 1. Figure 50 shows a cross section of the embankment after construction and after failure. According to the classification system proposed by the HRB Landslide Committee (41), the failure is a (rotational) slump slide.

Before the failure occurred, the site experienced large settlements, which severely cracked the pavements and locally altered the drainage pattern. Nearby fills along I-74 have also experienced similar settlements, suggesting that they too ultimately be landslide sites. Figures 51 (a) and (b) show the photographs of failure zones at two locations. Figure 51 (a) shows the main scarp of the slide. The surface is concave upward. Figure 51 (b) shows a close-up of the scarp failure surface. Limestone pieces, shale chunks and soil mixtures could be seen here.

Measurement on Embankment Materials

Material was sampled from the failed embankment and from a nearby shale cut. The material from the embankment consisted of clayey soil, shale, and limestone pieces. All chunks, except the limestone ones, slaked in a single cycle of wetting.

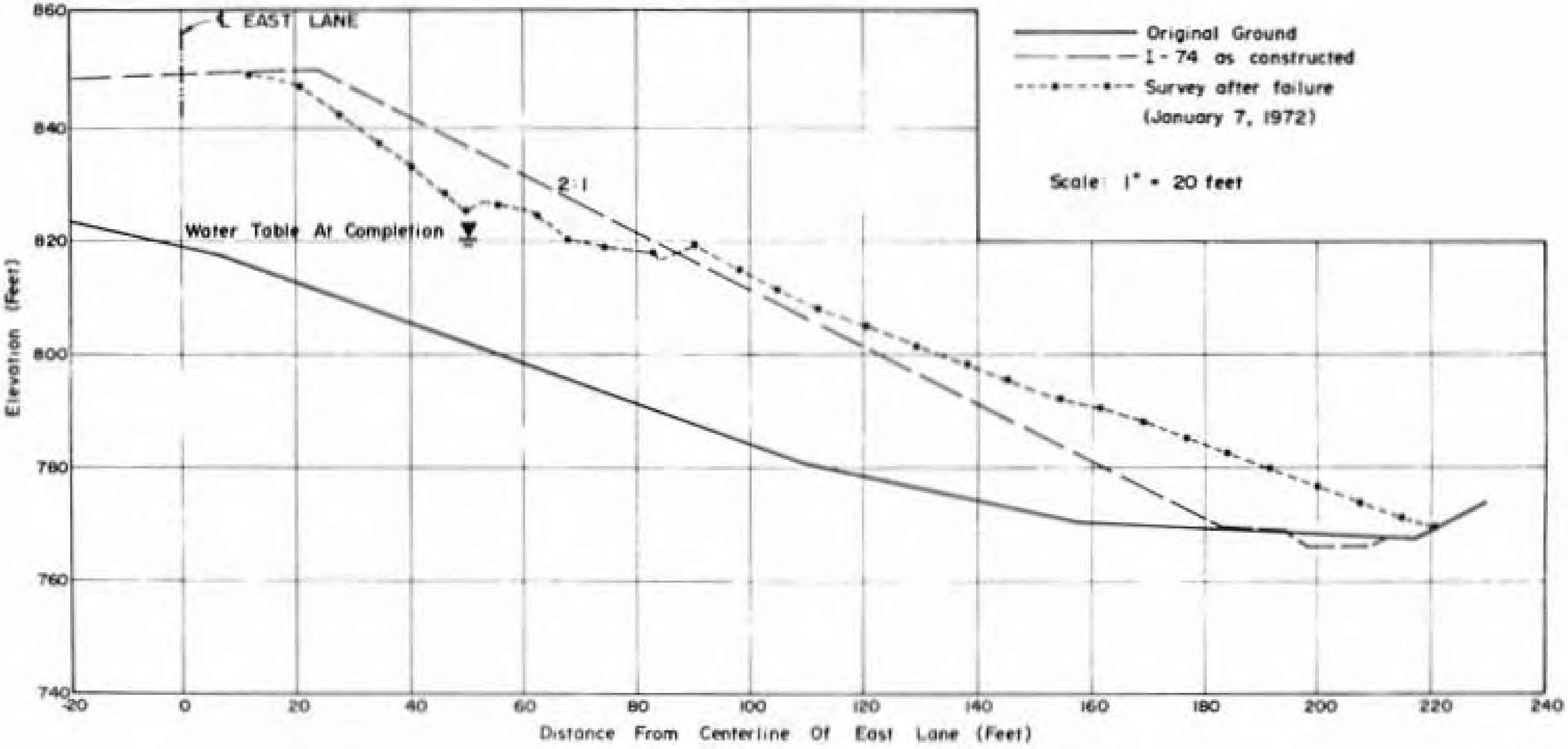

FIGURE 50. CROSS SECTION OF I-74 EMBANKMENT BEFORE AND AFTER SLOPE FAILURE.

(a)

(b)

FIGURE 51 . PHOTOGRAPHS OF FAILURE ZONE AT TWO LOCATIONS.

The material from the shale cut consisted of two types of shale, one was gray in color, while the other was of a brownish color. These materials differed somewhat in properties, however, both were non-durable, slaking completely in three cycles of wetting and drying.

Since it was assumed that the two shales would be used in about equal proportions in an embankment, they were mixed in equal parts prior to testing. Results are collected in Table 23.

According to the proposed classification system, the material is "soil like". Therefore it should be thoroughly broken down at the end of compaction; it should also be encased within the embankment.

Intact samples of 2.8 in. diameter were taken from the enbankment by the ISHC. These samples, while somewhat disturbed, do show large voids within the compacted material, suggesting that shale chunks have slaked in service.

Probable Explanation for Failure

The shale was apparently placed in the embankment without proper identification. It was probably dry enough to be quite resistant to mechanical breakdown. However the shale is very nondurable under wetting and drying.

The large chunks of shale were further protected from breakdown in the rolling process by the limestone pieces in the fill mixture. The presence of large pieces also tended to produce larger voids between them.

TABLE 23. MEASUREMENTS ON SHALE SAMPLED NEAR I-74 EMBANKMENT.

Property	Result
Slaking	Slakes completely in three cycles of wetting and drying in water.
$(I_d)_d$	24.0
$(I_d)_s$	0.0
I_s	0.0
w_ℓ	45.0
I_p	15.0
$C_{2\mu}$	43.0
Activity	0.35
Clay minerals	Illite, Kaolinite and Chlorite
Nonclay minerals	Quartz and Feldspar
Proctor Standard O.M.C.	13.8%
$\gamma_{d\ max}$	117.9 pcf
S	5.4%
$(CBR)_c$	8.0
$(CBR)_s$	1.1
R	13.7%
$(\gamma_m)_{lumps}$	110.5 pcf
Fissility number, F	77

The drainage of the shale was reasonably good and some 8 or 9 years were required to produce serious slaking of the shale. The first evidence of trouble was the large scale settlement resulting from the breakdown. The action probably was progressive, since the settlement disrupted drainage, causing more slaking and settlement, etc.

The embankment was much weakened by the collapse of the shale chunks. The wetter condition of the fill also reduced its strength, as well as increasing the driving force. The result was a slide-slump class of failure.

Remedial Action by Indiana State Highway Commission

The Indiana State Highway Commission is applying three techniques to stabilize the fill, as shown in Figure 52.

1. Improving the drainage. The drainage was disrupted due to the slaking of shales and subsequent settlements in the embankments. To improve the drainage, grade "B" special borrow[1] is placed below the water level as shown in Figure 52.

2. The side slopes are made flatter. Instead of a 2 to 1 slope as used earlier, a 3 to 1 slope is adopted.

3. Stabilizing berms are provided as shown in Figure 52. They will contribute to the resisting forces.

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[1] B borrow material consists of suitable sand, crushed or uncrushed gravel, crushed stone or blast furnace slag, and contains not more than 10% material passing the No. 200 sieve.

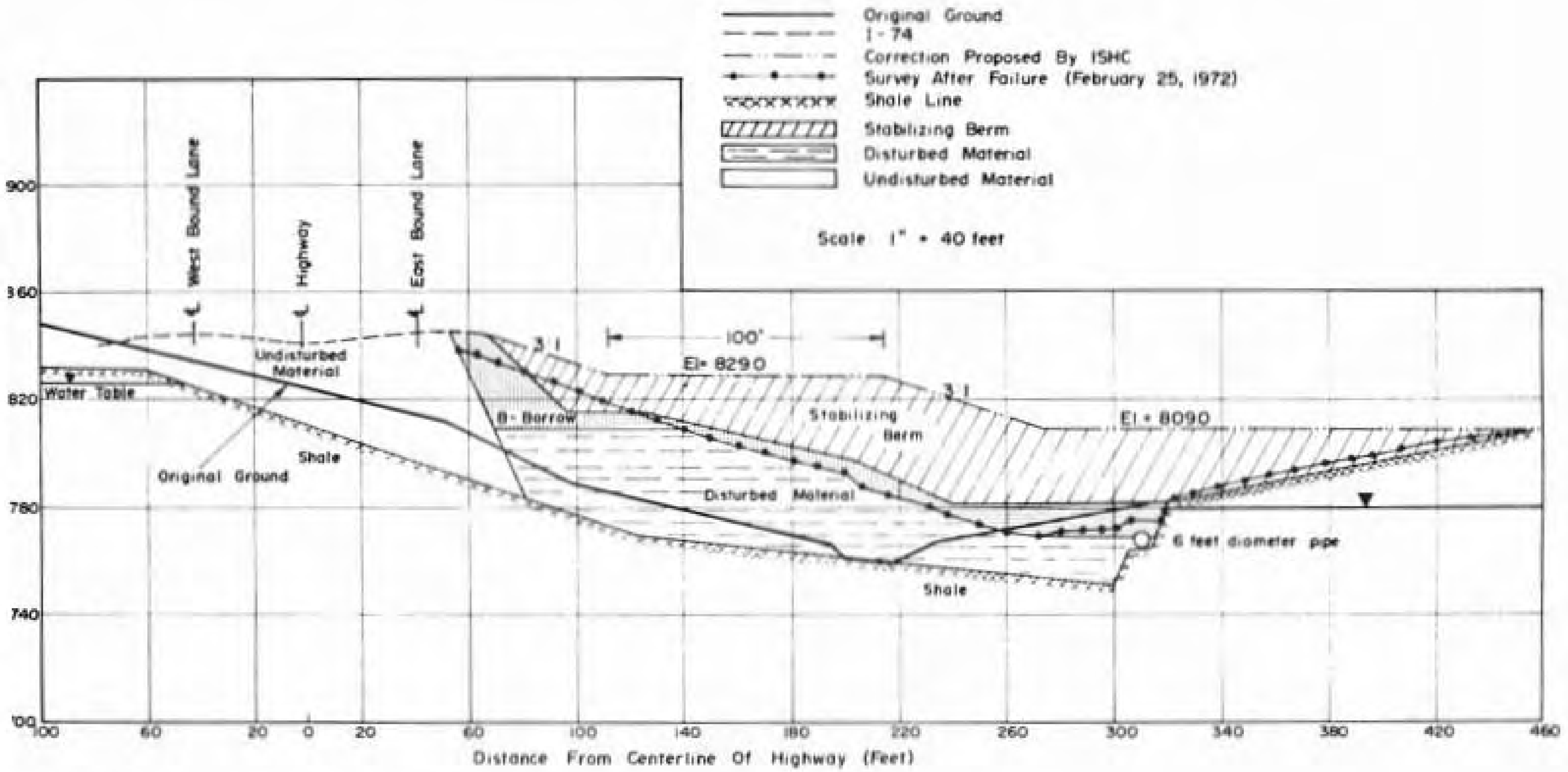

FIGURE 52. CORRECTION APPLIED TO FAILED EMBANKMENT OF I-74.

Conclusions about Failure

The failure was caused by improper placement of the shale, which in turn was caused by a failure to identify the shale and to write special provisions for it. The flattening of slopes and provisions of berms will certainly help in making the structure stable, but future movements may occur since the slaking and interior adjustments to it may not be complete. This incident is an example of how important it is to properly identify and classify the fill material before use, so that design and construction provisions may be adequate for it.

Appendix B

Slake Durability Numbers for Different Numbers of Revolutions

Preliminary tests were conducted on selected shale samples for 100, 200, 500 and 1,000 revolutions of the drum in order to select the standard number of revolutions in the slake durability test. The results are shown in Tables 24 and 25. The weight loss through the meshed drum increased with the number of revolutions. However at a higher number of revolutions, viz., 1000, the results were not always reproducible. Five hundred revolutions seemed a reasonable compromise, as it enabled one to distinguish among the various shales on the basis of the durability numbers. Reproducible results were also obtained.

TABLE 24. VALUES OF SLAKE DURABILITY NUMBER FOR DIFFERENT NUMBER OF REVOLUTIONS ON DRY SAMPLE.

Sample	Slake Durability Number if Number of Revolutions are			
	100, $(N_d)_{d100}$	200, $(N_d)_{d200}$	500, $(N_d)_{d500}$	1000, $(N_d)_{d1000}$
Cannelton	82.0	65.0	24.0	0.0
Paoli Y	97.7	94.3	86.1	71.5
Paoli 5	98.1	96.5	93.8	84.5
I-65	98.1	96.9	93.2	85.3
67A	98.0	96.9	94.9	88.1
37A	98.4	97.2	94.8	89.5
Attica	98.4	97.3	95.0	88.2

TABLE 25. VALUES OF SLAKE DURABILITY NUMBER FOR DIFFERENT NUMBER OF REVOLUTIONS ON SOAKED SAMPLE.

Sample	Slake Durability Number if Number of Revolutions are			
	100, $(N_d)_{s100}$	200, $(N_d)_{s200}$	500, $(N_d)_{s500}$	1000, $(N_d)_{s1000}$
Cannelton	0.0	0.0	0.0	0.0
Paoli Y	94.5	83.0	56.2	14.0
Paoli 5	96.7	95.2	89.1	77.6
I-65	95.0	91.1	78.5	48.6
67A	97.1	95.2	90.3	80.4
37A	98.0	96.3	93.6	86.2
Attica	98.0	96.2	93.5	86.0

Appendix C

Preparation of X-ray Diffraction Samples

Dry Powder

The test samples for X-ray diffraction were prepared in a special aluminum cell using the McCreey method (61), which is described below.

1. Using mechanical grinding with a mortar and pestle, powder as fine as possible was obtained (Powder finer than No. 200 sieve is satisfactory).

2. A special aluminum cell, which is 1-1/2 in. x 1 in. x 1/8 in. thick with a 5/8 in. diameter cavity, was covered on one face with paper and a clean glass slide, which was bound firmly with tape.

3. An excess of shale powder was put in the cavity and tamped thoroughly and gently with the edge of a spatula.

4. The surplus powder was removed with a razor blade.

5. A loose layer of powder about 1/16 in. thick was added and pressed firmly with the flat blade of the spatula.

6. The surplus powder was removed. The aluminum cell was covered with a clean glass slide and then taped.

7. The assembly was turned over, and the glass plate on the first side was removed.

8. The sample was now ready for mounting in the diffractometer.

Glycerol Paste

The test smaple was prepared in the same manner as for the dry sample, with the difference that instead of dry powder, a paste of powder and glycerol was used. Care was taken that powder and glycerol were mixed thoroughly.

Appendix D

X-ray Diffraction Patterns

X-ray diffraction patterns, which were obtained for dry powder and glycerol paste, are shown in Figures 53 to 67.

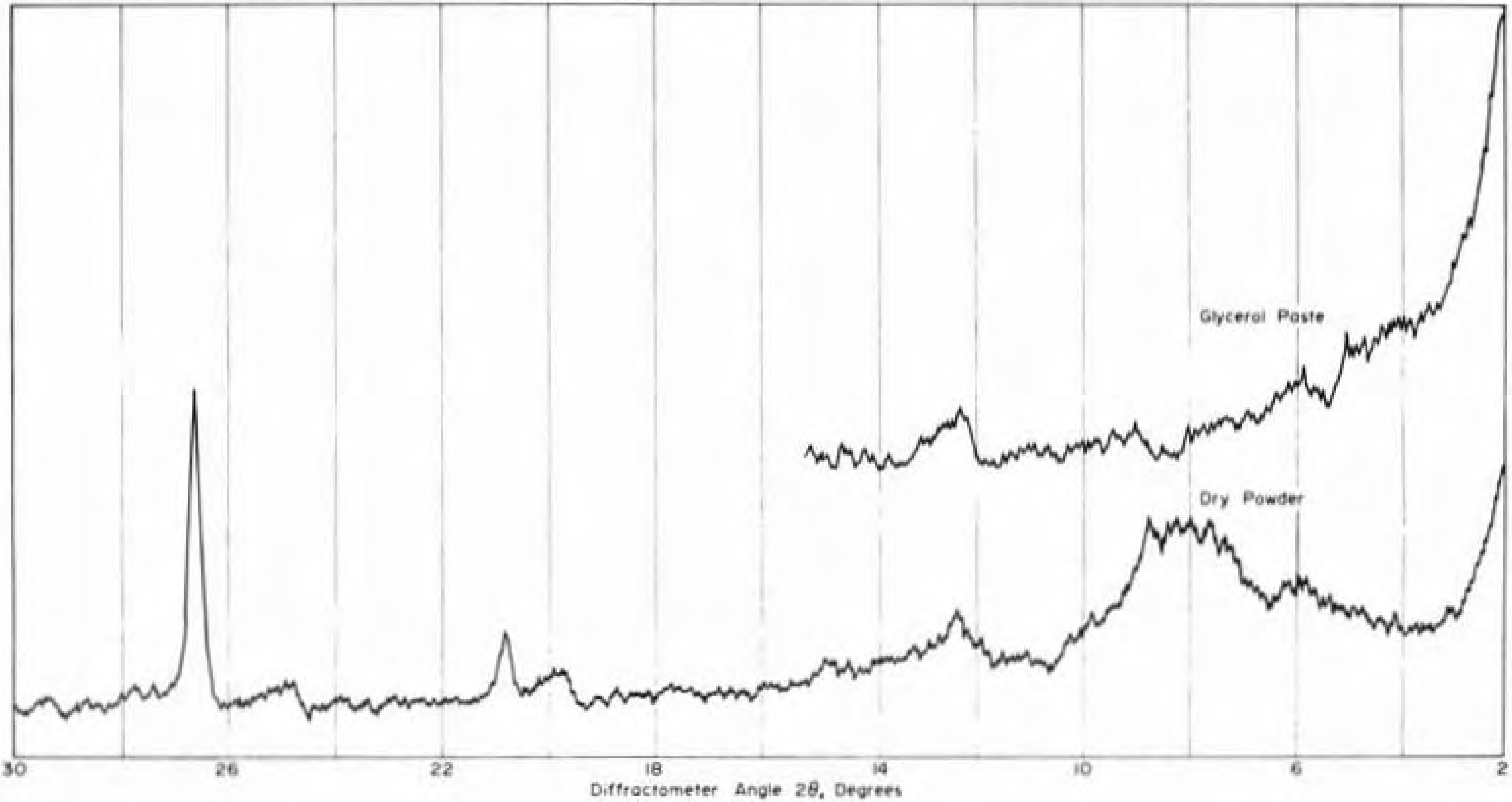

FIGURE 53. X - RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR CANNELTON SHALE.

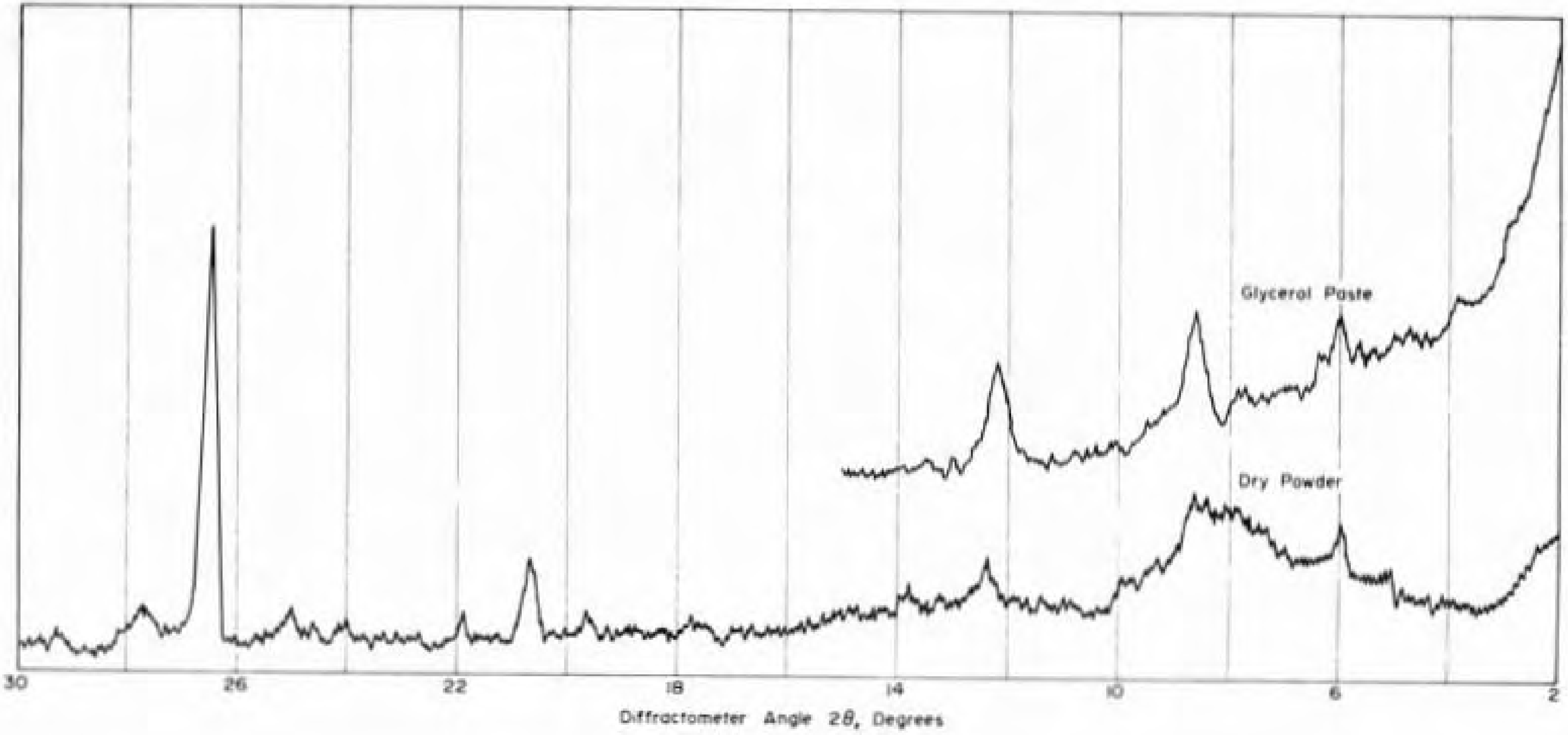

FIGURE 54. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR I-74 SHALE.

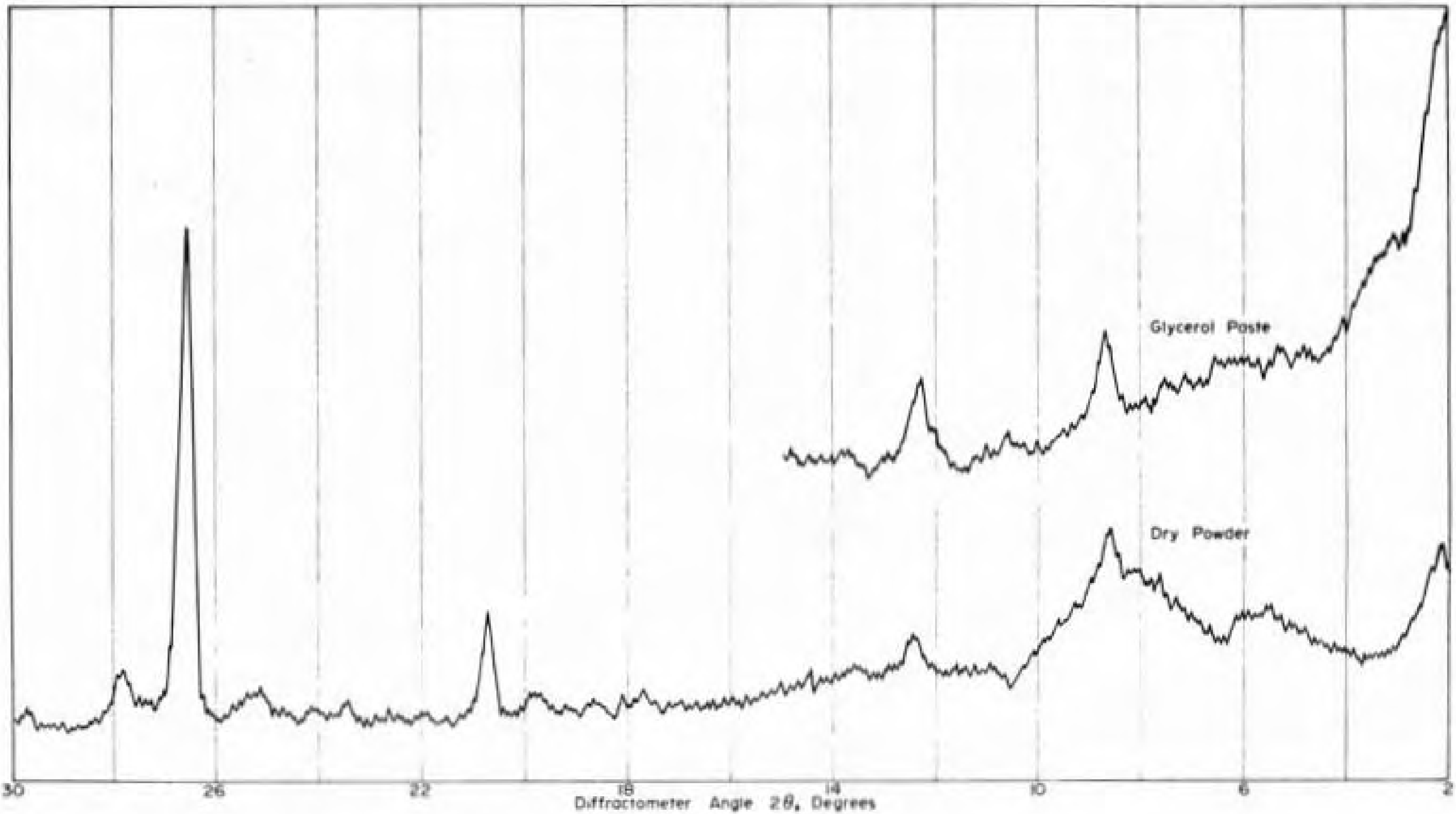

FIGURE 55. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR PAOLI Y SHALE.

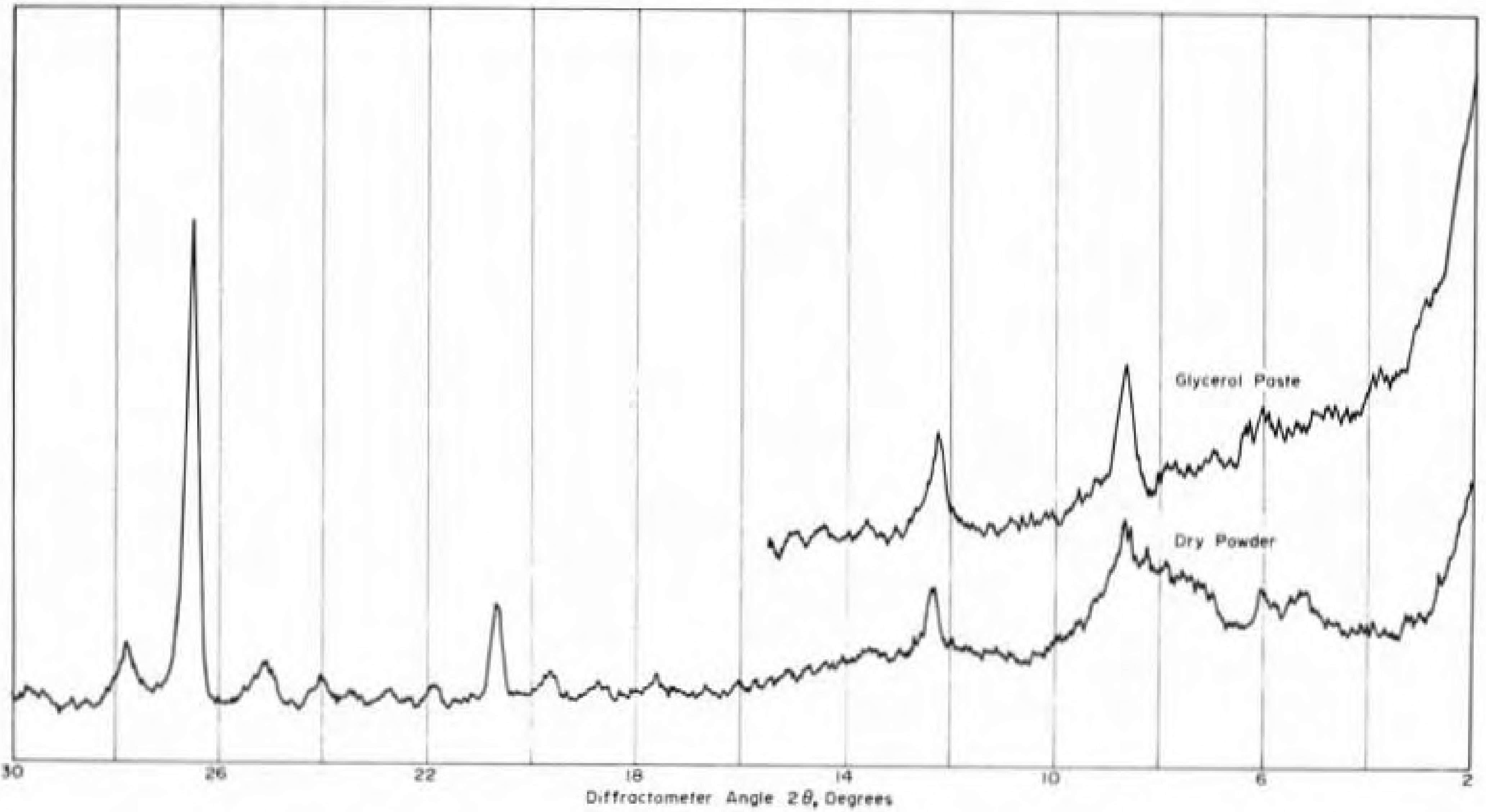

FIGURE 56. X - RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR PAOLI X SHALE.

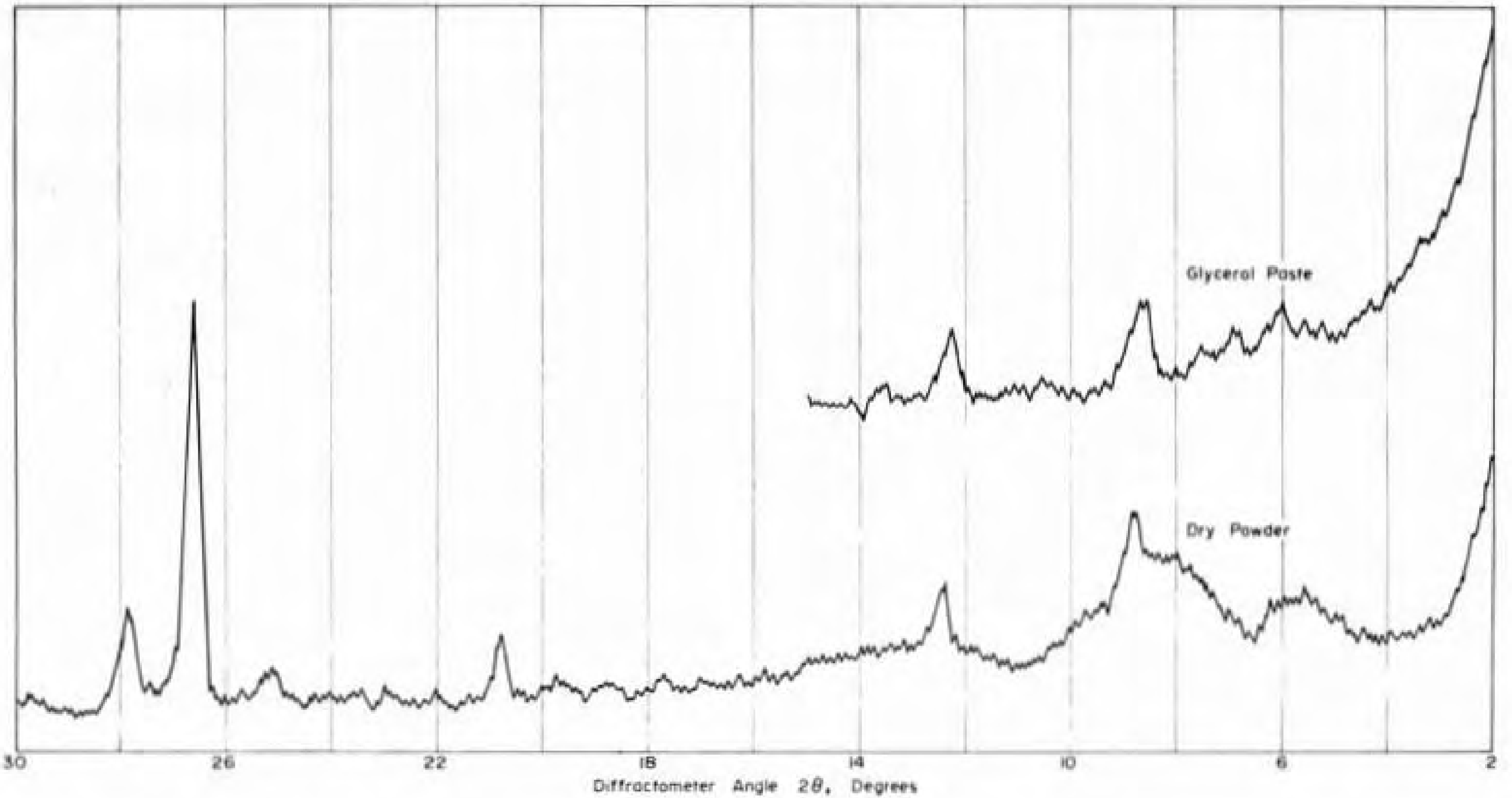

FIGURE 57. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR PAOLI 5 SHALE.

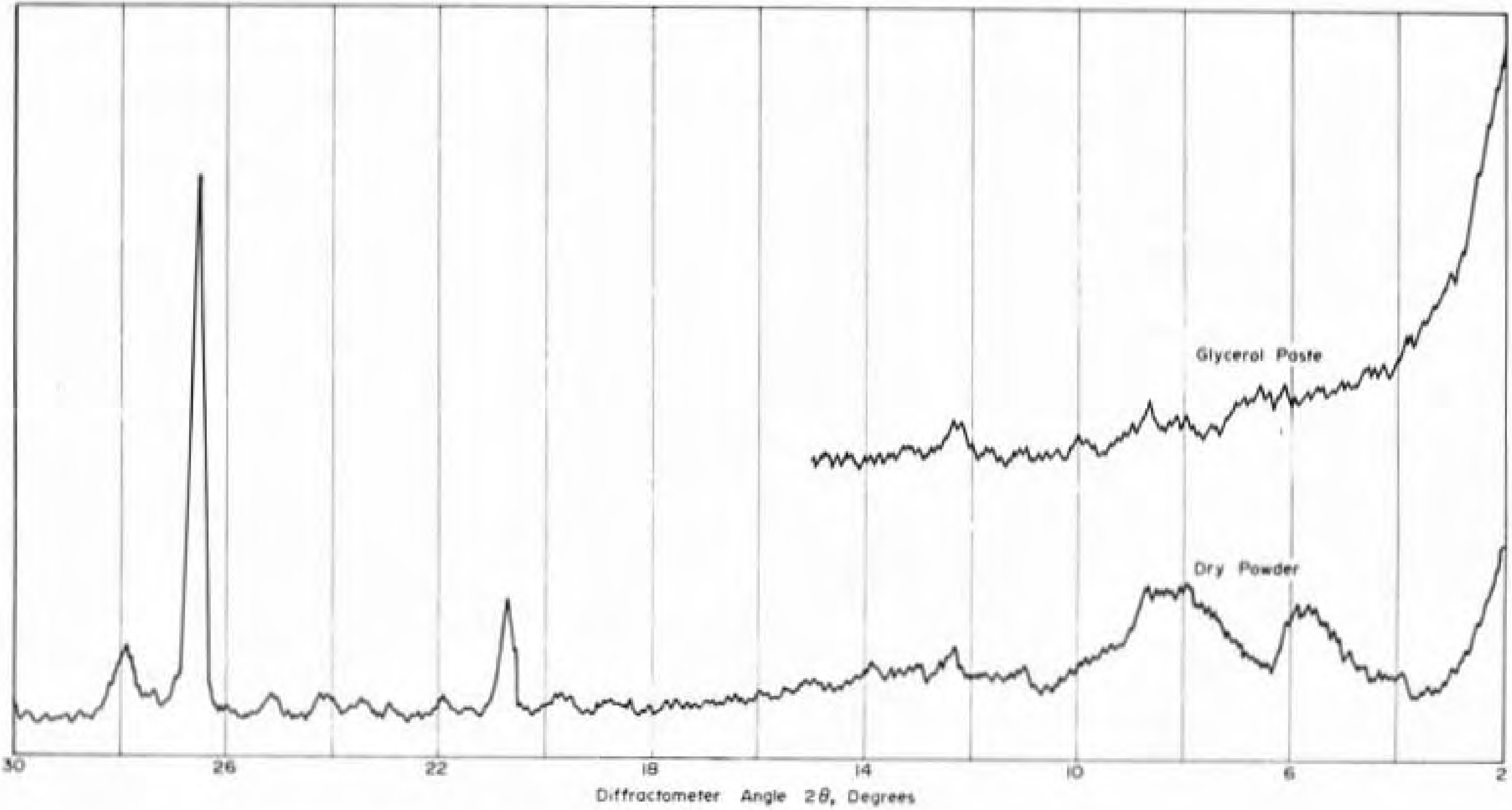

FIGURE 58. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR LYNNVILLE SHALE.

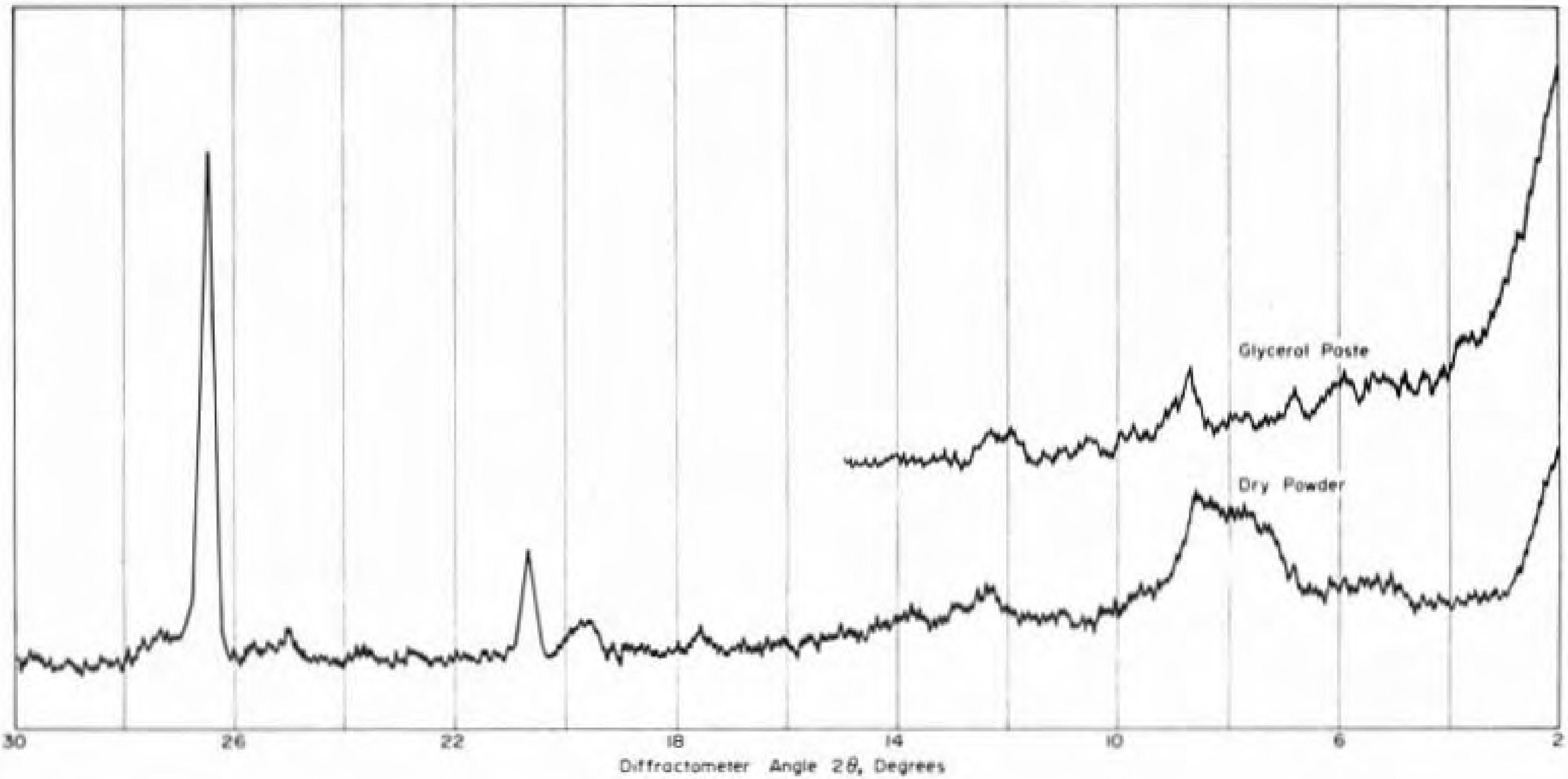

FIGURE 59. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR I-65 SHALE.

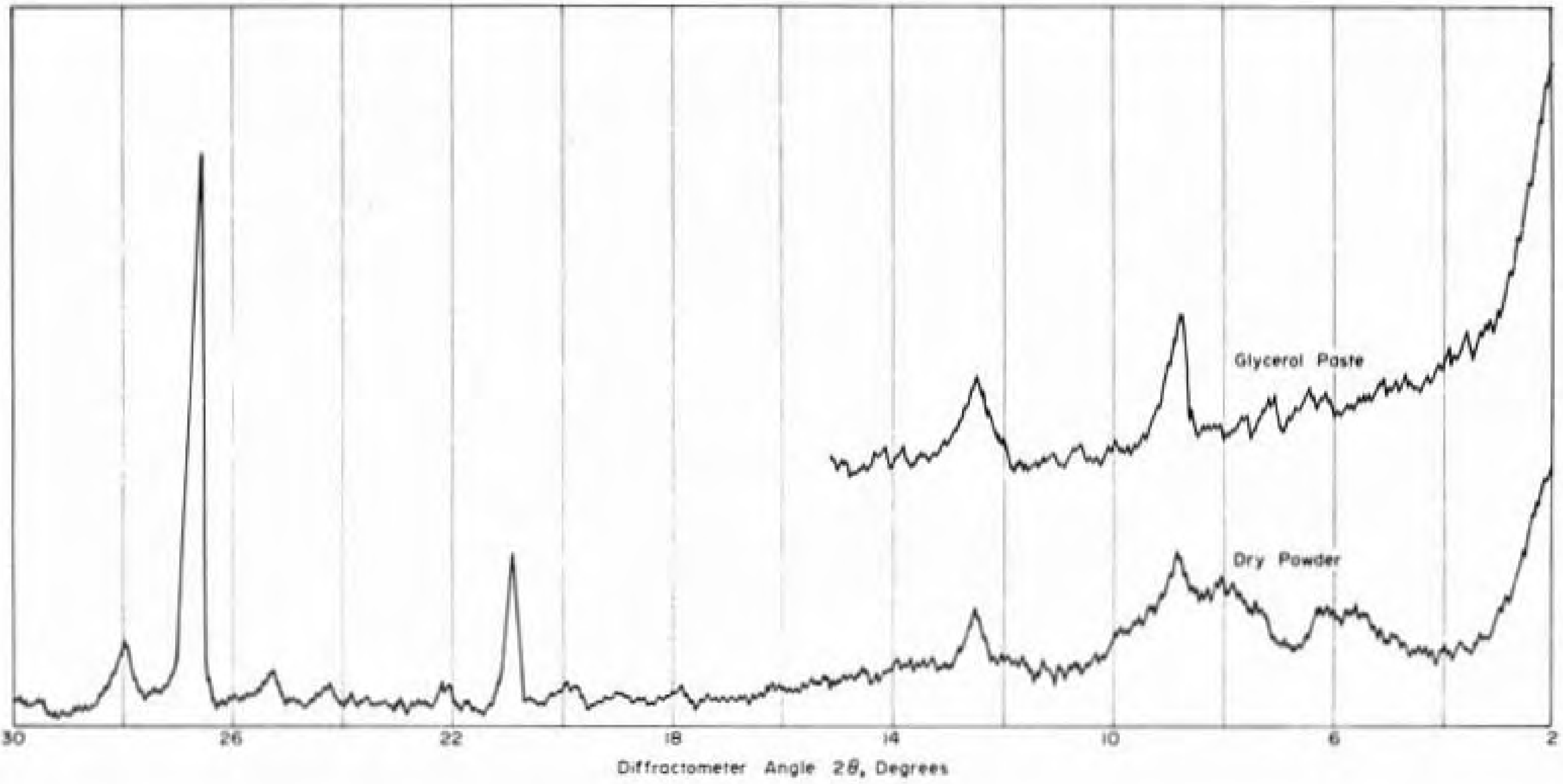

FIGURE 60. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR 67B SHALE.

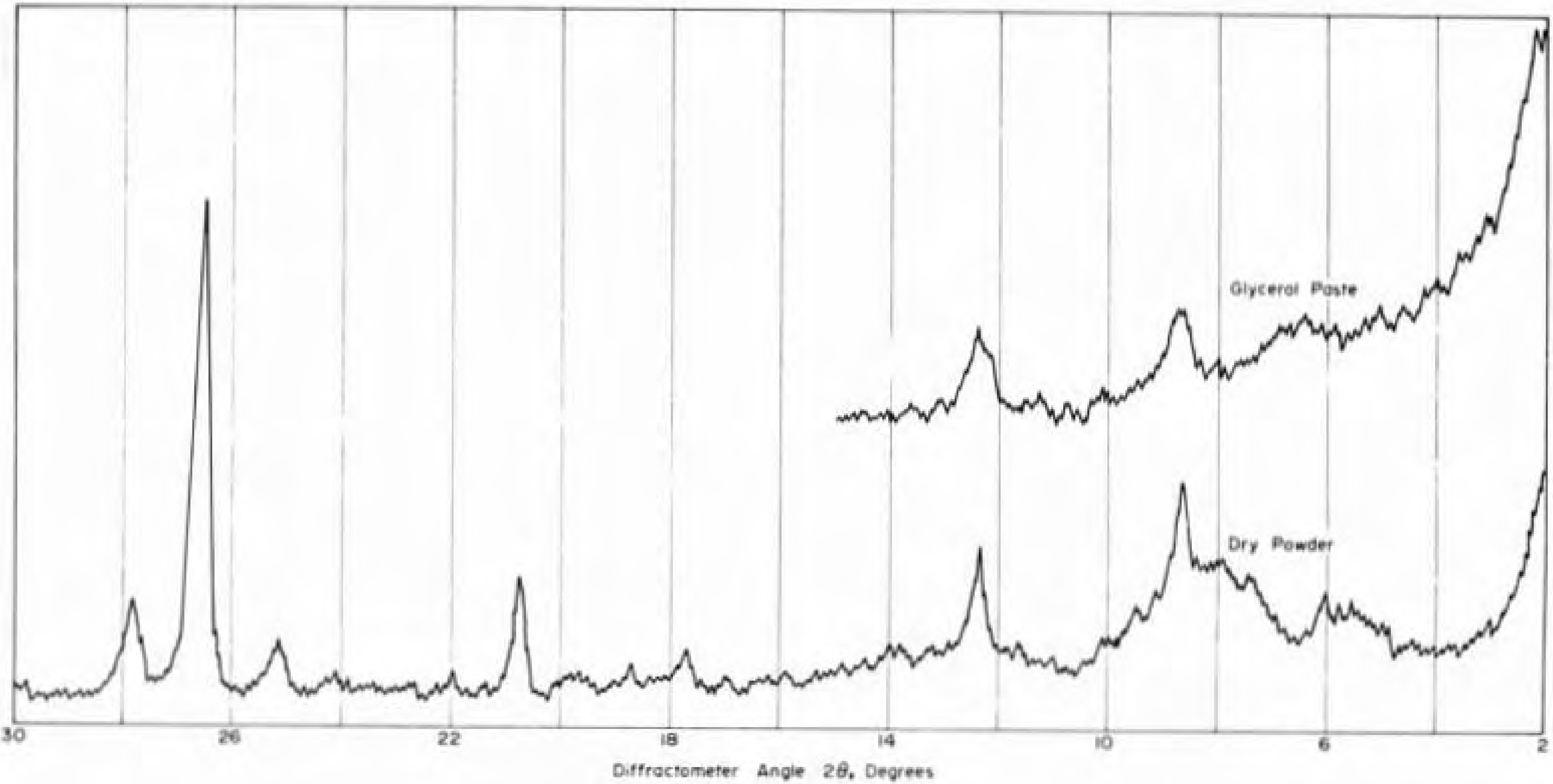

FIGURE 61. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR 67A SHALE.

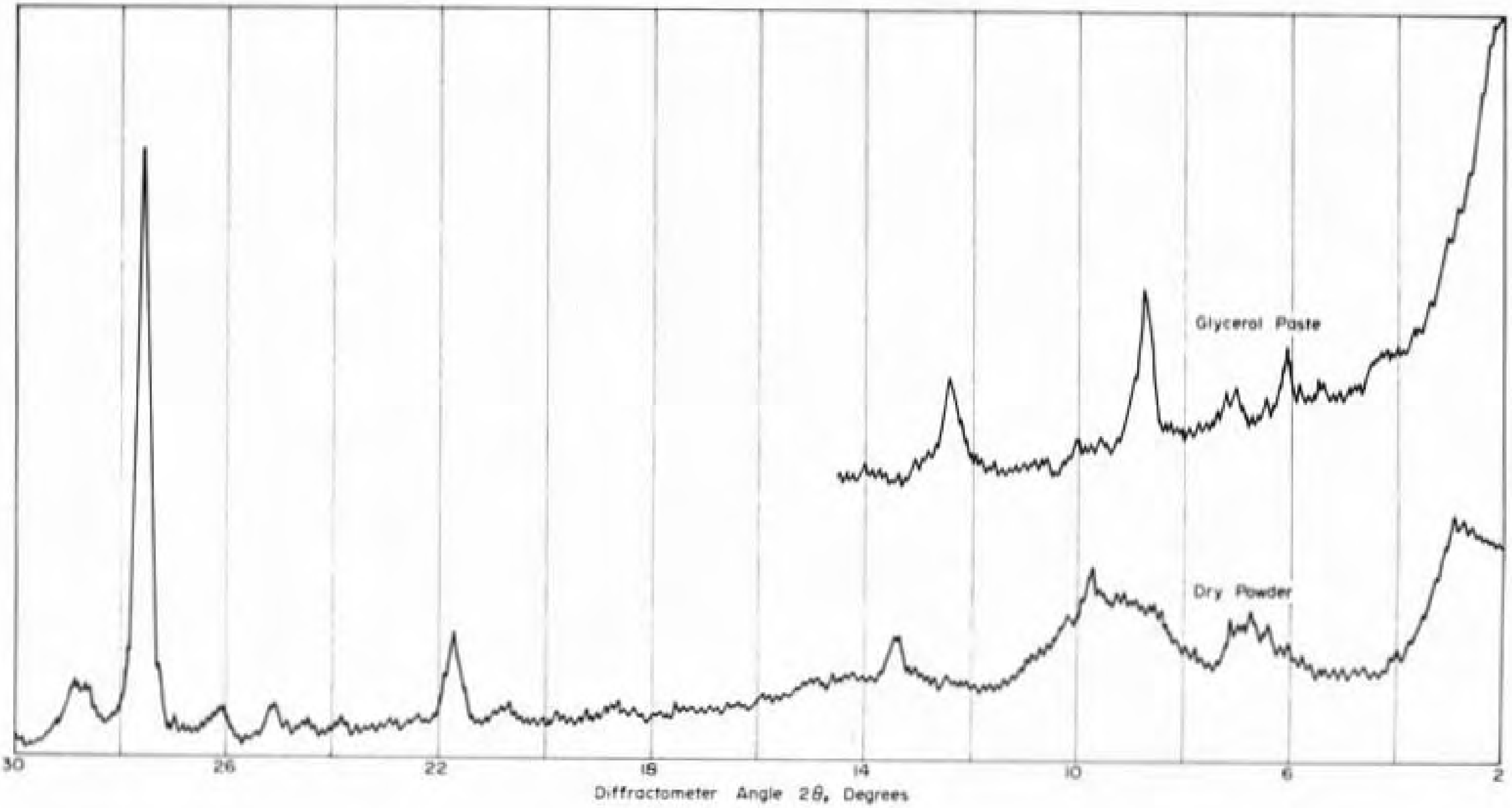

FIGURE 62. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR PAOLI 3 SHALE.

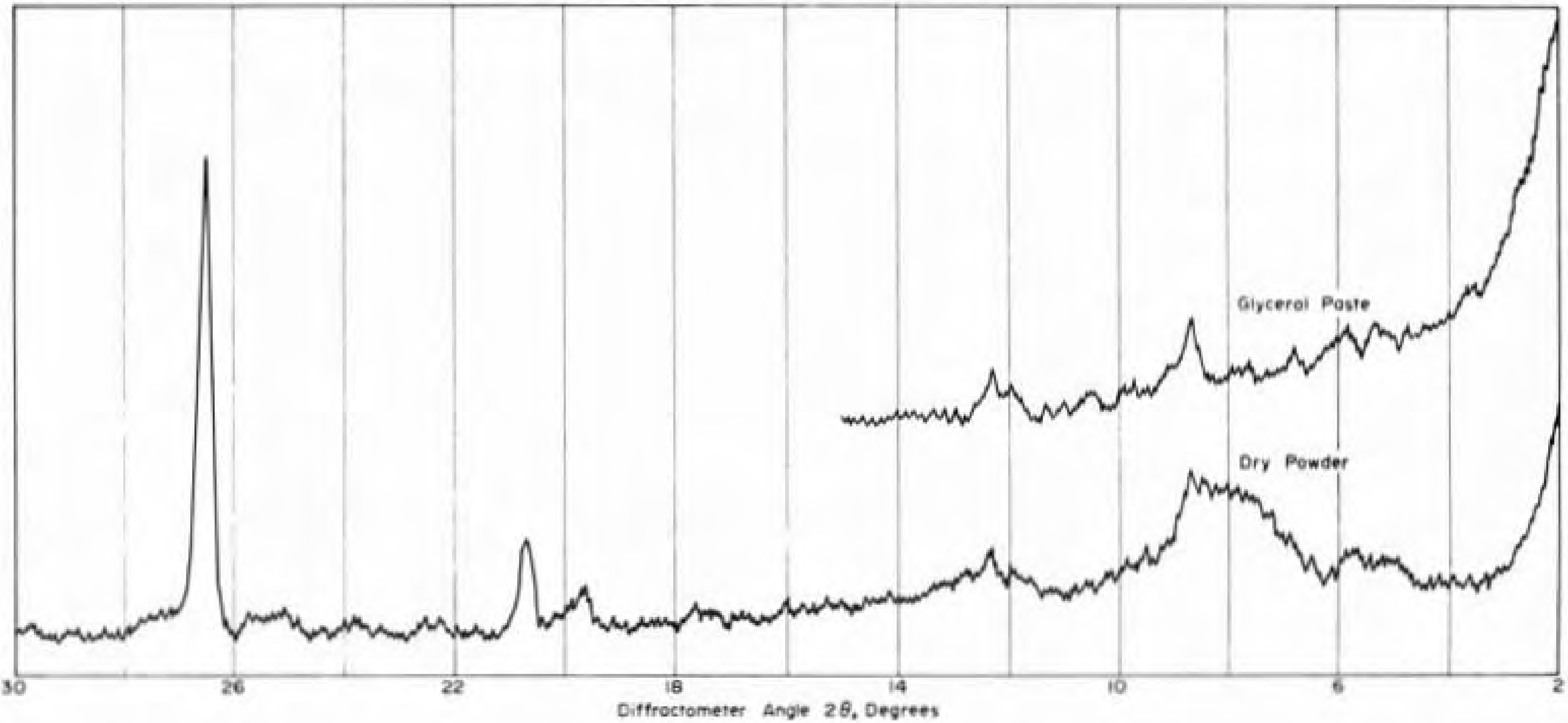

FIGURE 63. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR SCOTTSBURG SHALE.

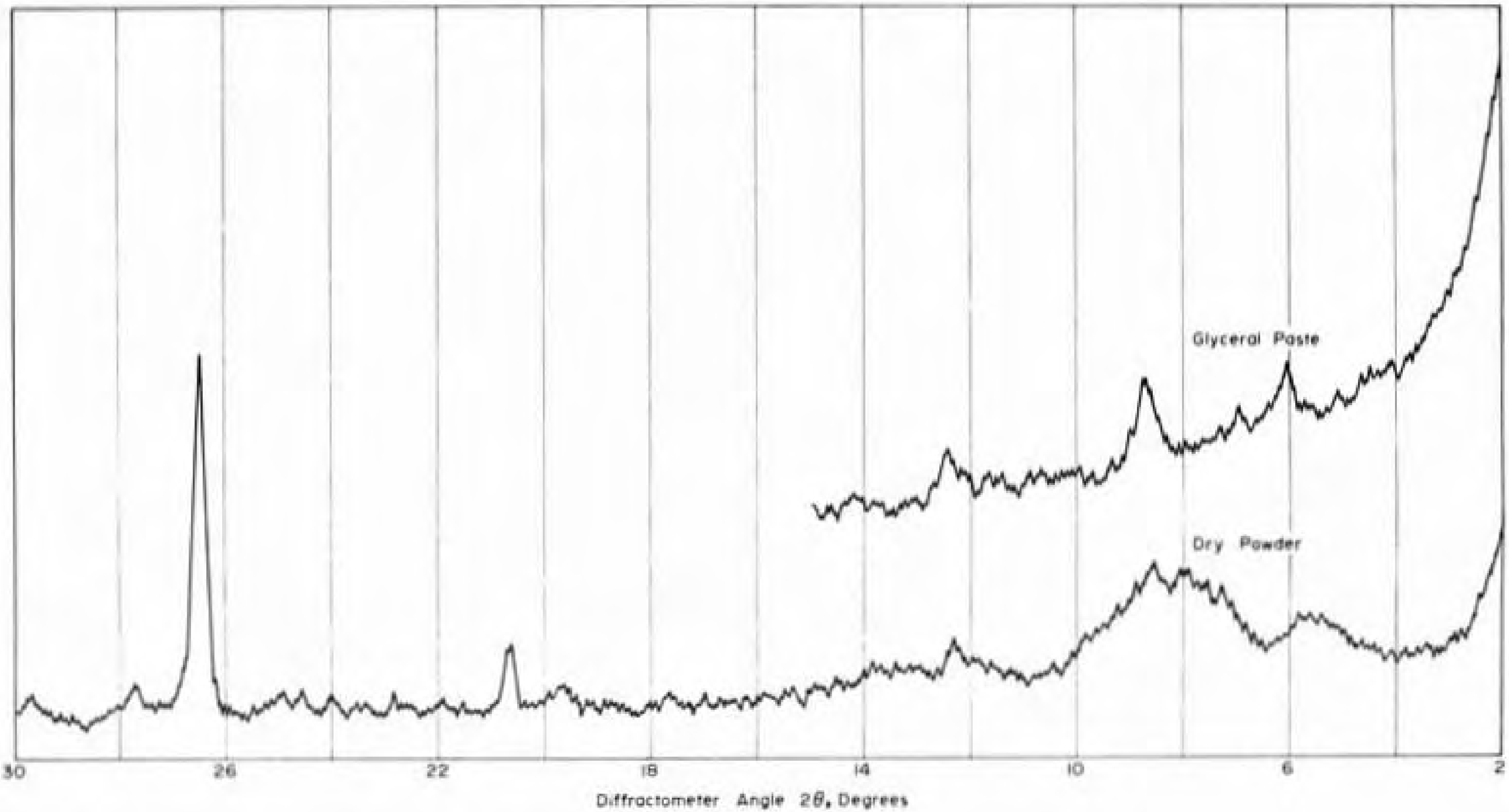

FIGURE 64. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR 37A SHALE.

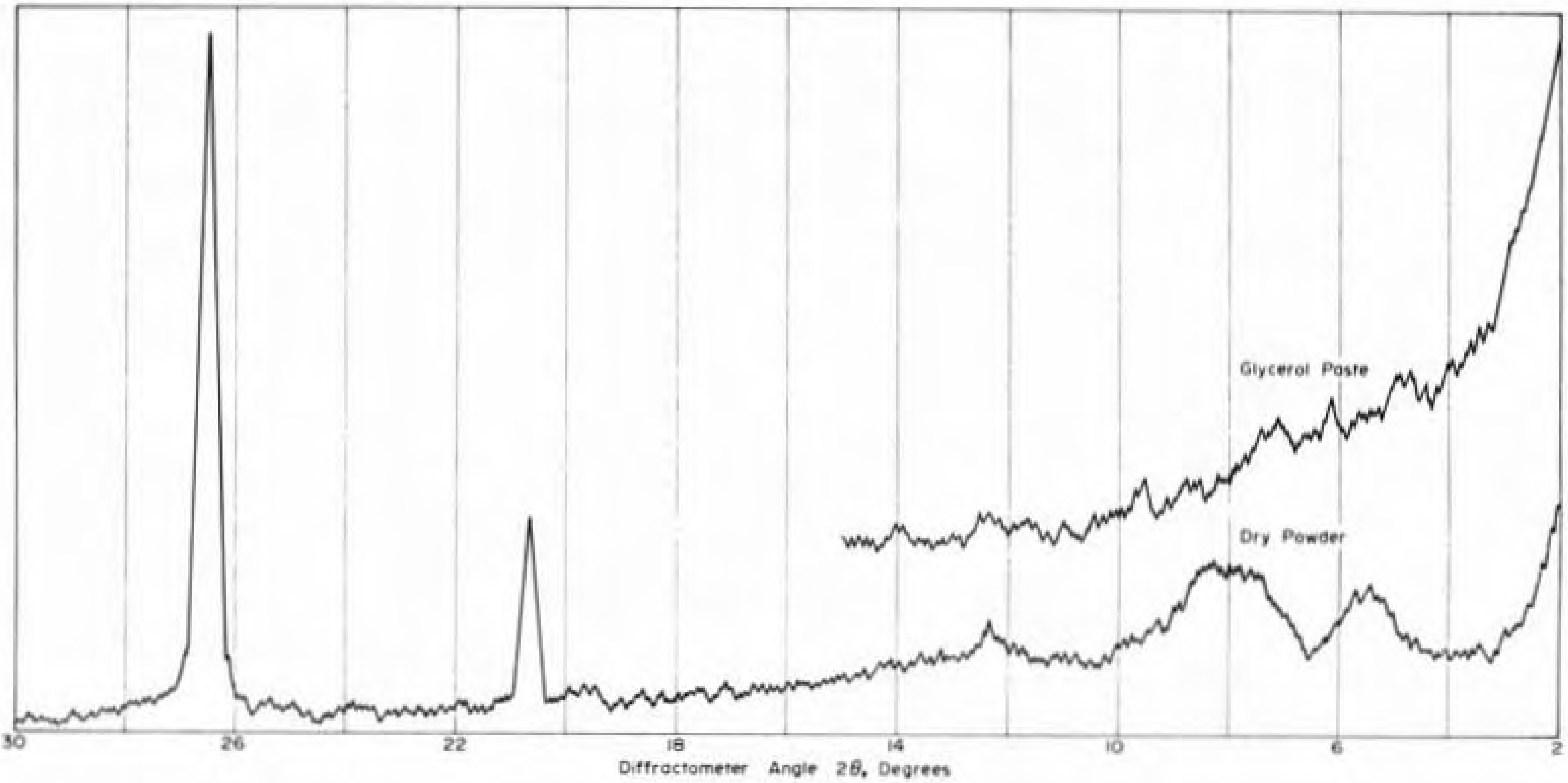

FIGURE 65. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR KLONDIKE SHALE.

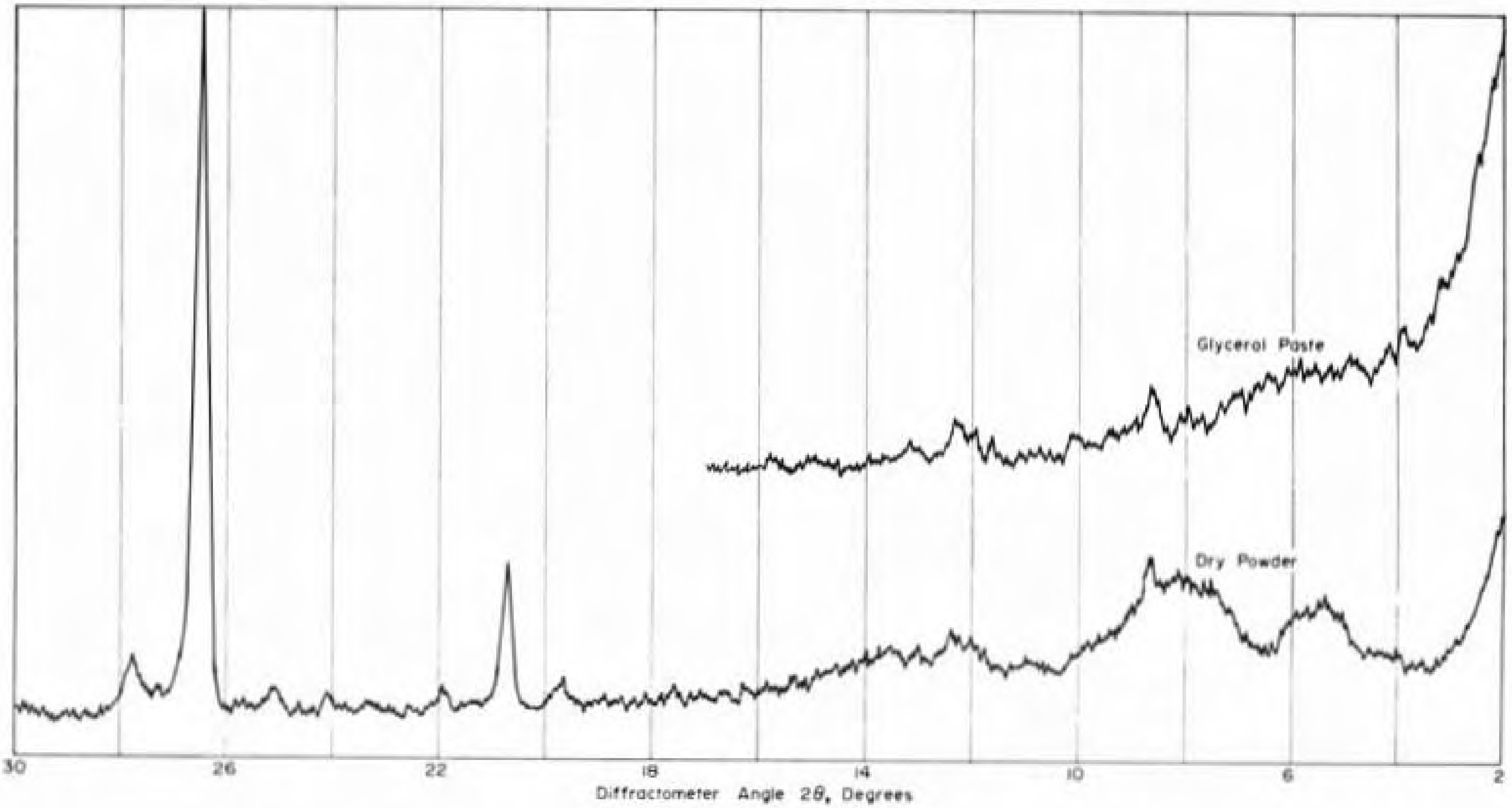

FIGURE 66. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR ATTICA SHALE.

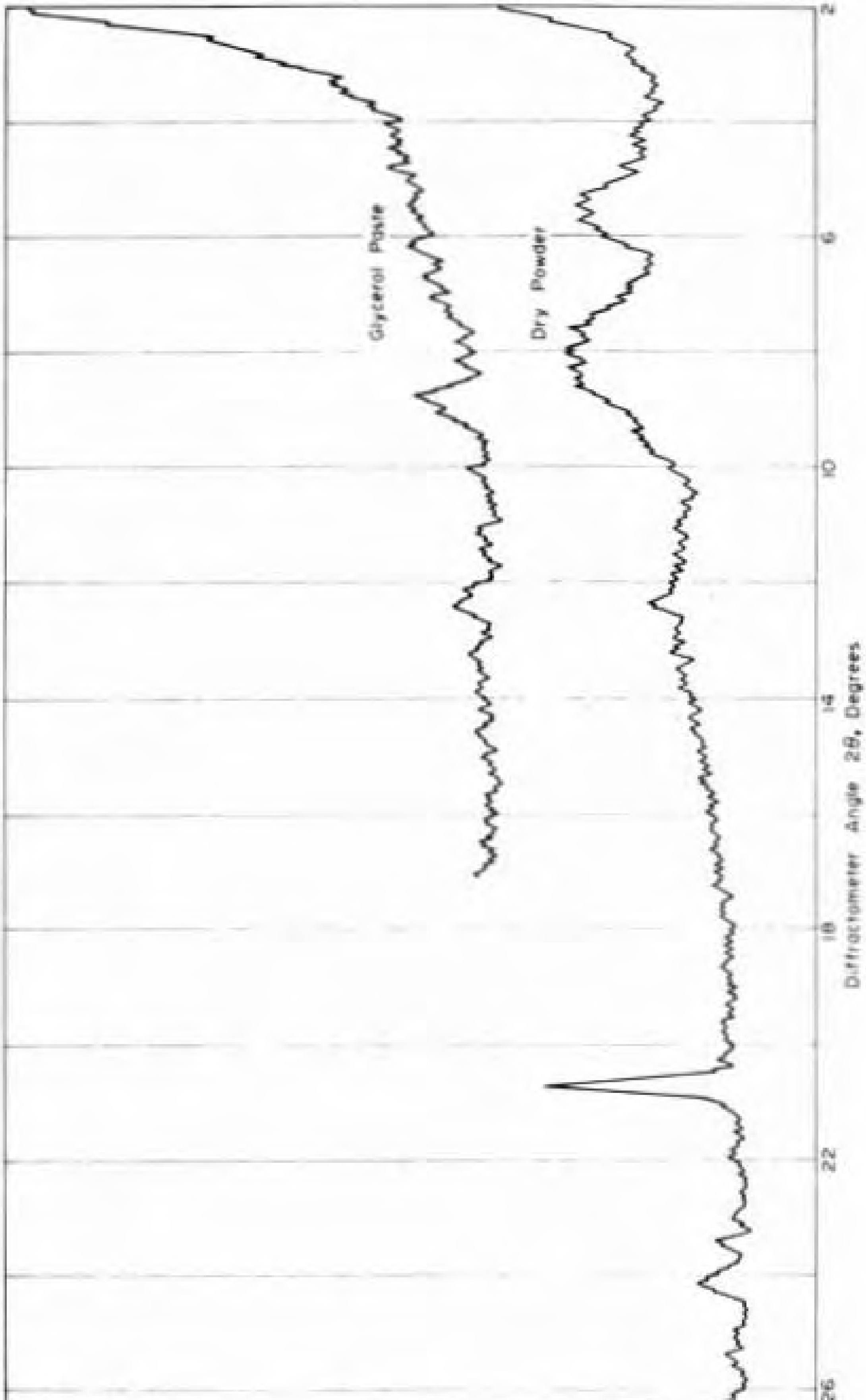

FIGURE 67. X-RAY DIFFRACTOMETER PATTERN (Cu Kα) FOR 37B SHALE.

VITA

VITA

Purushottam Deo was born on January 1, 1943 in Bagpat (U.P.), India. After completing his Intermediate and B. Sc. (I year) education from D. Jain College, Baraut, he joined the University of Roorkee in 1960. He received the Bachelor of Engineering (Civil) degree in 1964. Mr. Deo received government merit scholarships throughout his education from 1955 through 1964.

Upon graduation in 1964, Mr. Deo joined the staff of K. L. Polytechnic, Roorkee, as a lecturer in Civil Engineering. He resigned this position in 1966 to join the University of Roorkee for graduate work, for which he received a research followship. He was awarded the Master of Engineering (Civil) degree with Honours in August 1968.

In September 1968, Mr. Deo entered Purdue University for graduate studies in Civil Engineering. He worked as a teaching and research instructor while at Purdue.

Mr. Deo is a member of Indian Geotechnical Society and an associate member of American Society of Civil Engineers.

In August 1969, Mr. Deo was married to Manjul Jain, who also attended the graduate school at Purdue.

He is a citizen of India.