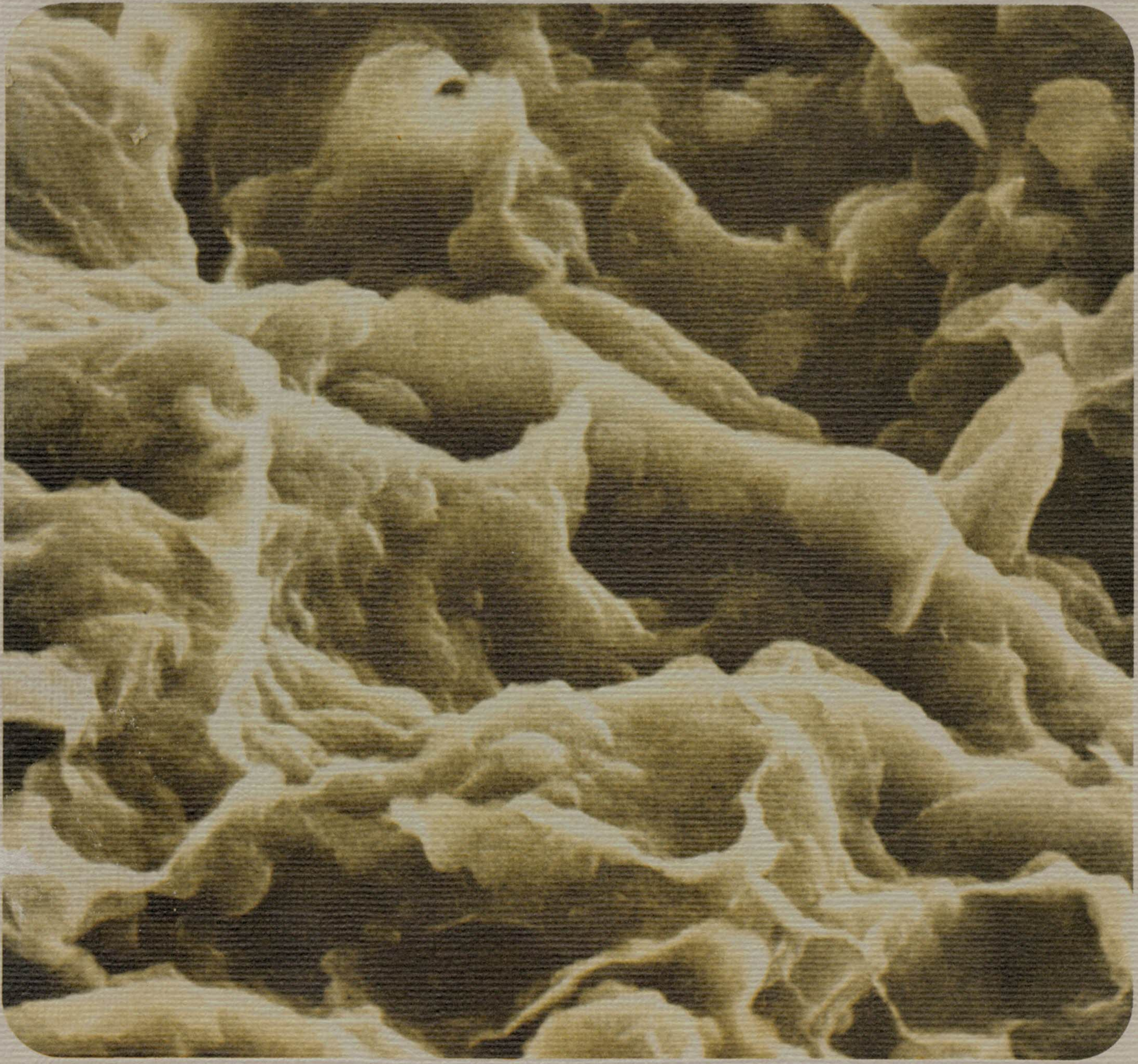
PREDICTABILITY OF PHYSICAL CHANGES OF CLAY-FORMING MATERIALS IN OKLAHOMA

Final Report ☐ Oklahoma Study No. 68-03-2 ☐ Joakim G. Laguros ☐ August, 1972

OKLAHOMA DEPARTMENT OF HIGHWAYS
and DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

UNIVERSITY OF OKLAHOMA RESEARCH INSTITUTE



I Planning, Administration, and Environment

IA. Planning and Administration

•agency organization;•personnel management;•finance and economics;•data and information systems•strategic management•planning process; state, regional, and urban transportation planning;•land use•forecasting, market estimation, and modal selection•travel behavior;•transportation of the disadvantaged•transportation demand management

IB. Energy and Environment

•alternative fuels•fuel economy•ecological systems•noise and air quality•water quality•wetlands•historic preservation,
•hazardous wastes

IC. Transportation Law

•eminent domain and land use•contract law•tort liability•environmental law,
•motor vehicle and traffic law

II Design

IIA. Highway and Facility Design

•photogrammetry, digital mapping, remote sensing, and surveying•highway geometrics•traffic barriers, sign supports, and highway safety appurtenances•environmental design and mitigation•archeology and scenic vistas•utilities accommodation

IIB. Pavement Design, Management, and Performance

•pavement management•flexible and rigid pavement design•rehabilitation strategies•response of pavements to load and environmental forces•pavement data collection and analysis•surface unevenness,
•pavement distress•skid resistance•systems for vehicle counting•classification, and•weigh-in-motion

IIC. Bridges, Other Structures, and Hydraulics and Hydrology

•design of steel, concrete, and timber bridges•bridge safety, economy, and service life•field testing and dynamic responses of bridges•tunnel design, construction, and performance•structural design of culverts and hydraulic structures•structural uses of composite materials•hydrology and hydraulics

III Materials, Construction, and Maintenance

IIIA. Soils, Geology, and Foundations

•exploration, properties, identification, classification, and treatment of surface and subsurface soil and rock•subsurface drainage•earthquakes and landslides•environmental effects on soil•mechanics of soil, rock, and layered systems

IIIB. Materials and Construction

•bituminous materials and mixes•cement and concrete•general materials•mineral aggregates specifications•construction,
•quality control

IIIC. Maintenance

•maintenance management•runway and guidance maintenance•structures, roadway, and roadside maintenance•traffic service maintenance•snow and ice control•equipment maintenance

IV Operations and Safety

IVA. Highway Operations, Capacity, and Traffic Control

•transportation systems operations•traffic flow and highway capacity•law enforcement•parking and parking facilities;
•operating effects of roadway elements;
•traffic control devices and systems;
•railroad-highway grade crossings;
•transportation communications systems;
•traffic measurement and evaluation methods•high-occupancy vehicles•intelligent vehicle-highway systems

IVB. Safety and Human Performance

•system safety•accident countermeasures;
•right-of-way and vehicular design, operations, and maintenance;•human behavior and performance associated with transportation•bicycles•pedestrians•emergency medical services•trauma treatment•work zone safety•measurement of safety performance (e.g., accident data and exposure)•planning, management, and financing of safety

V Aviation

•planning•forecasting•finance•socioeconomics•market analysis•airside and landside airport design and operation•air traffic control•aircraft technology•intergovernmental relations•airlines (including regional and commuter)•business and general aviation•safety•user needs

VI Public Transit

•planning, administration, economics, finance, and performance of rail, bus, and new technology transit systems;
•commuter rail•paratransit•rural public transportation•safety•design, operations, and maintenance of vehicle and fixed facilities

VII Rail

•planning, administration, regulation, safety, and operation of rail systems, both passenger and freight•design, construction, and maintenance of track systems and train control•communication systems

VIII Freight Transportation

•truck, rail, water, pipeline, and intermodal freight transportation•planning, administration, design, construction, maintenance, regulation, operations, and safety•transportation of hazardous materials

KEY WORD LIST

SOILS & GEOLOGY

AGGREGATE
CLAY
DRAINAGE
GEOLOGY
LANDSLIDE
HINERAL
MODULUS
MOISTURE
PERMEABILITY
PORE
PRESSURE
ROCK
SNAD
SETTLEMENT
SHEAR
SILT
SLOPE
SOIL
STABILIZATION
STONE
VOIDS
FORMING PROPERTIES
____
____
____

BITUMINOUS PAVEMENTS

ABRASION
AGGREGATE
ASPHALT
BASE
BEAMS
BEARING
BLEEDING
BITUMINOUS
COMPACTION
CRACKING
DEFLECTION
DENSITY
DISTRESS
ELASTOMER
EMULSION
FABRIC
FAILURE
GRADATION
LATEX
LIFTS
MIX
MODIFIER
MOISTURE
OVERLAY
PATCHING
PAVEMENT
POLYMER
RATING
ROLLER
RUBBER
RUTTING
SEAL
SLURRY
SURFACE
VOIDS
____
____
____
____
____

BRIDGE

ABUTMENTS
APPROCHES
ARCHES
BEAM
BEARINGS
CABLE
CAPACITY
DECKS
DYNAMICS
GROUT
LOAD
MAINTENANCE
PADS
PAINT
PIERS
RAIL
SCOUR
SHAFTS
SPANS
SUSPENSION
TRUSSES
UNDERMINING
WINGWALLS
____
____
____

CONCRETE

ABRASION
ADMIXTURES
AGGREGATE
AIR CONTENT
C.R.C.P.
CEMENT
COMPRESSIVE STRENGTH
CONCRETE
CONSTRUCTION
CREEP
CURING
DESIGN
FLEXURAL STRENGTH
FLY ASH
FREEZE-THAW
JOINTS
LOAD
MACROTEXTURE
OVERLAY
PORTLAND
PRESTRESSED
RECYCLING
REHABILITATION
REINFORCEMENT
RESTORATION
____
ROUGHNESS
SHRINKAGE
SKID RESISTANCE
TENSILE STRENGTH
WATERPROOFING

Final Report

Oklahoma Study No. 68-03-2
OURI Project 1677

PREDICTABILITY OF PHYSICAL CHANGES OF CLAY FORMING MATERIALS IN OKLAHOMA

Prepared by

Joakim G. Laguros, Professor

School of Civil Engineering and Environmental Science

Submitted to

OKLAHOMA DEPARTMENT OF HIGHWAYS
and
DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

From the

UNIVERSITY OF OKLAHOMA RESEARCH INSTITUTE
Norman, Oklahoma
August, 1972

This report was prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration and the State of Oklahoma Department of Highways.

The opinions, findings and conclusions expressed in this publication are those of the author and not necessarily those of the Federal Highway Administration or the State of Oklahoma Department of Highways.

PREFACE

In cooperation with the Oklahoma Department of Highways and the Federal Highway Administration, Department of Transportation, a research project was undertaken on October 8, 1968 by the Oklahoma University Research Institute, Norman, Oklahoma to study the predictability of physical changes in clay forming materials. These materials include shale, claystones and their derivatives.

The main objective of the study was to establish a systematic method of testing and criteria which will permit identification and classification of clay forming materials on the basis of the changes in their properties resulting from engineering processes associated with highway construction and utilization.

The period of this study, initially approved, was three years. In March/April 1971, a request was made and approved to extend the period of study by six months. The final date of completion of this study is February 29, 1972.

Reports were submitted quarterly indicating the progress of the work. Progress reports of more detailed nature were submitted annually during March/April of each year the study was in progress.

In February, 1970, a special report was made on the "Disintegration of Shales Employing Ultrasonics". Much of the information contained herein has already been reported in the reports mentioned above.

The total approved cost of this study project is $98,950.

The personnel actively associated either continuously or periodically with this project include:

1. Dr. Joakim G. Laguros
2. Prof. Joe W. Keeley
3. Mr. William H. Bellis
4. Maj. Thomas J. Anessi
5. Mr. Manickam Annamalai
6. Mr. Subodh Kumar
7. Mr. Sheong-sang Liao

SUMMARY

This study was undertaken to establish methods of testing and criteria which, on the basis of the physical changes resulting from highway engineering processes, will permit identification and classification of clay forming materials. Twenty-four shale samples, selected from various parts of Oklahoma, were subjected to extensive laboratory testing which included determination of index properties and strength related properties. X-ray diffraction and fluorescence methods were used to determine the mineralogy and chemical composition of shales.

Using these test data as criteria and employing engineering judgement and the statistical method of factor analysis, the twenty four shales were categorized into groups, each group containing those shales that displayed similarity of properties. From the resulting groups six shales were selected on the basis of (a) their representativeness within the group and (b) their geographic location within the state.

The selected six shales were further studied and the effects of both ultrasonic disaggregation and durability tests were observed. Electron micrographs and x-ray diffraction patterns were obtained to study the effect of ultrasonic disaggregation on the fabric and mineralogy of shales.

The amount of 2-micron clay in a shale is found to be a very

important parameter in determining the engineering behavior of shales.

The durability index test and the sand equivalent test promise to be important identification and classification tests. The sand equivalent test, however, is preferable since it requires only a two-hour period to run it.

The ultrasonic treatment is found to effectively disaggregate shales. This disaggregation is evidenced by changes in grain size distribution, plasticity characteristics, x-ray diffraction patterns, and fabric of shales as revealed by electron microscopy. For the type of ultrasonic equipment and treatment used the practical optimum treatment time is one hour.

A large number of tests were run and an extensive amount of data were obtained in this study. From this information it is possible to identify a few tests which are more meaningful than others in that they make it possible to characterize shales and group them into "no problem" and "problem" shales.

If the combined amount of silt and clay in a shale is less than 40% then it may be classified as 'no problem' shale. No change in test methods or design procedures are required for such shales.

However, in the case of shales that contain 40% or more combined amount of silt and clay, problems in the field may be expected. Additional testing and modifications in design procedures are required for such shales.

For the problem shales the index properties should be determined not only in the conventional manner but also on the material obtained by subjecting the shale to an equivalent of one-hour ultrasonic treatment. The design procedures should be modified to take account of these changing properties of clay-forming materials used in highway construction.

From the observations made and information gained in this study it would be worthwhile to extend this investigation to a number of other shales for which the field experience is known. Also, worthwhile would be a study related to the stabilization of "problem" shales. Since it has been established in this study that significant changes can take place in clay-forming materials when they are used for highway construction, a time-continuous method of parameter design should be developed to take account of this fact.

CONTENTS

Appendices:

LIST OF FIGURES

CHAPTER I

INTRODUCTION

For some time, the Oklahoma Department of Highways has observed that some clay forming materials, especially shales, manifest increase in expansive tendencies and plasticity when excavated from their location and used elsewhere. The magnitude of increase was greater when these clay forming materials, hereafter referred to as shales, were simply left exposed to the detrimental action of weather. While this behavior was true for shales from certain locations it was not true for shales from other locations. Whenever shales experienced changes, it was observed that the structural integrity of a pavement or stability of slope was adversely affected and consequently maintenance costs increased. The climate, clay mineral composition, and physicochemical behavior of clays change throughout Oklahoma. Thus, it becomes evident that a number of parameters are involved in the change of the shale properties.

Before starting field and laboratory investigations for this study a questionnaire was sent out to all the highway departments excluding Hawaii and Oklahoma, requesting information concerning experience with shales. Specifically, the questions asked were;

1. Has your department had any experience with shales or similar rock materials (hard pan, mudstone, etc.) which tend to break down on exposure to weathering forces, into constituent clay or silt components and thereby cause weakening or failure of highway structures or backslopes?

What is the location of such experience?

2. Have you been able to predict by any suitable testing method, the occurence of such situations?

If so, what testing method was used and what was the treatment used to prevent deterioration?

3. Has your department published anything on the above noted situations? If so, please describe.

4. Please note any other pertinent information, references, etc. which you feel might be of additional use to us.

About half of the responses indicated that problems similar to those encountered in Oklahoma existed in other states too. The experience was related mainly to slope failures, and no replies contained pavement failure as specifically accruing from shale deterioration. However, the existence of such failures was not denied.

In the case of most states where problem shales are located, the methods of testing used are classical and give little or no consideration for deterioration of shales due to weathering. However, Alaska, Indiana, Iowa, Kansas, Missouri, Nevada, Ohio, Utah and Washington incorporate tests which at least partly take weathering into account. The various tests for this purpose include: degradation, expansion pressure, freeze and thaw, imbibometry, linear shrinkage, slaking, soaking, swelling, wear and x-ray.

The treatments employed to correct the failure situation are primarily mechanical and include: benching, use of covering materials, granular overlays, wide ditching, flattening of slopes, retaining walls and asphalt applications. Chemical treatment has been indicated in some replies. In a few cases, the design of slope and treatment of failed slope was based on a thorough evaluation of the weathering response of the soil-shale medium. A summary of various replies received is shown in Appendix A.

CHAPTER II

REVIEW OF LITERATURE

Shales are sedimentary rocks of which silts and clays are large and important constituents. Most shales are regarded as difficult and generally undesirable media for civil engineering purposes. Many shales, on the other hand, have proven to be entirely satisfactory for similar situations (Underwood,67). Thus, there is a great need to develop a system or methodology to identify the shales that may prove to be 'problem shales' for a given project.

Presently, shales are identified and classified by a wide variety of methods. The very absence of a general standard procedure emphasizes the difficulty experienced in characterizing the shales from a material viewpoint and predicting their engineering behavior.

In soils, particularly clays, the double layer interaction forces and the forces of physico-chemical nature control the initial soil fabric. Interparticle bonds form in response to the interparticle contact forces generated by these forces and applied stress acting individually or in conjunction with each other. The interparticle contact is the most significant region between soil particles through which the stresses can be transmitted (Mitchell et al, 69). If left undisturbed, bonds of physico-chemical nature will develop at those contacts and the properties of soil will be altered, for example, the net swell pressure of a clay is a function of the number of such bonds. As the number of bonds increases, the swell pressure decreases (Kassiff & Barker, 71). On the other hand, a destruction of such bonds would be expected not only to permit adverse swelling of soils, but also to affect its strength characteristics. Soderman et al (1968) report a decrease in the value of "elastic modulus for cyclic loads" for Tilbury clay till due to the breakdown of soil structure.

As far as highway subgrade is concerned, immediately following the compaction the soil mass may be in a dispersed condition, an unstable high energy level caused by the excess energy input during compaction. The tendency of the system naturally would be toward the attainment of equilibrium conditions, a condition of low energy level. Consequently, a release of energy takes place, and this is manifested by realignment of water molecules and clay particles (Kassiff & Barker, 71). The end product of energy input and energy release sequence is a degraded soil material. In the case of laterites the effect of working on soil - energy input - causes an apparent breakdown of granular structure, and a high bearing strength, low plasticity and high permeability material transforms into a low bearing strength and high plasticity material with poor drainage qualities (Townsend et al, 69). Thus, excessive working on soil may convert a desirable construction material into an undesirable one. Troubles from shales, mudstones and siltstones, that swell on contact with water has been experienced in parts of western United States (Brakey, 70), and frustrations of traveling on such roads are well known to the drivers of that area.

During highway construction, the natural balance of soil environment is disturbed. For grading operations, the soil is excavated from its original location, transported to the site, spread in thin layers and then compacted at moisture content close to optimum. The steep slopes are flattened or otherwise affected by the removal of soil or rock. During and after these operations the exposed soil is acted on by a number of environment factors, the effect of which on a soil is determined by the mineralogical composition, shape and grain size distribution of its component particles, and the interaction of these particles with each other and with the water molecules (Dumbleton & West, 66).

In general, the changes that will take place are expected primarily to be physical. However, their effect on the structural integrity of pavement or the stability of slopes may be profound.

If through a simple process and in a reasonably short period of time, a material similar to the expected alteration product formed by the effects of relevant environmental conditions, could be obtained, then a study of the physicochemical and engineering properties of this new material could lead to a more realistic, improved design of pavement structures and highway side slopes.

CHAPTER III

SAMPLING OF SHALES

After agreement between the various agencies associated with this project, sampling locations for shales were determined. Most of the sites were chosen where trouble of one sort or another was experienced. The trouble was related mainly to failure of pavements or side slopes. Also, a few of shales were taken from those sites where no trouble was experienced, the purpose being to use the data obtained from these shales as reference. Samples have been obtained from 24 sites (Figure 3.1). Sampling from 19 locations was completed by December 1968; sampling from all the 24 sites was completed by August, 1970. The details of sampling sites and field descriptions of shales are given in Appendix B. The geologic characteristics are presented in Table 3.1.

Undisturbed samples of six-inch diameter were obtained at first but when recovered from tubes, they were of little value for testing. The cores did not possess enough intact length to justify running unconfined compressive strength tests on them, and excessive fragmentation along their bedding planes made them unmanageable for direct shear tests. Effort was made at a later date to obtain 2-7/8 inch core samples, but this attempt also met with very little success. In view of these facts, the idea of obtaining undisturbed field samples was abandoned. Among all the attempts made, only in two cases (samples 17 and 25) was it possible to

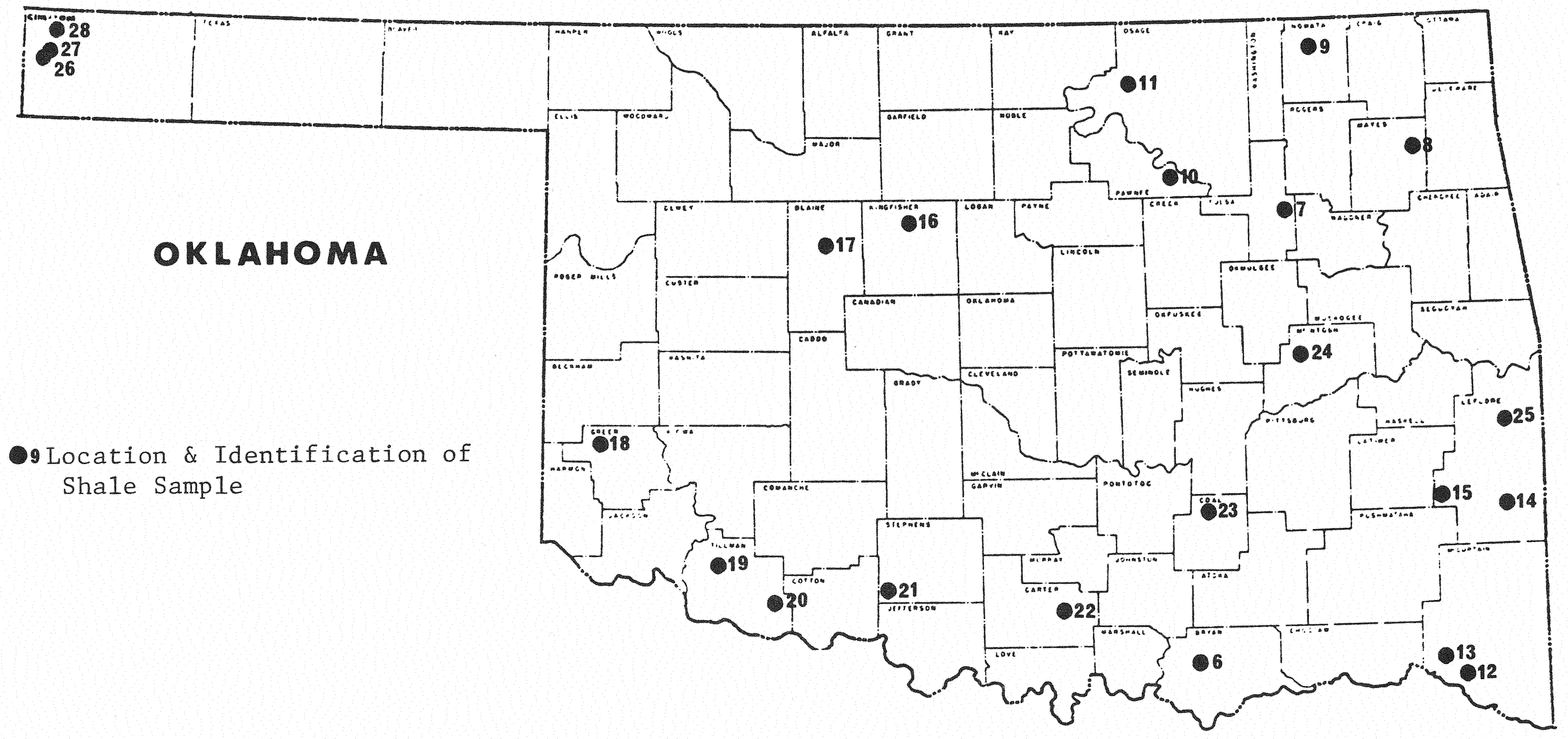


FIG. 3.1: LOCATION AND IDENTIFICATION OF SHALE SAMPLE

TABLE NO. 3.1: GEOLOGIC CHARACTERISTICS OF SHALES

Sample Number	County	Geologic* System	Physiographic* Region	Geologic Unit	Experience Code[a]
6	Bryan	Cretaceous	Red River	Woodbine	PF
7	Tulsa	Pennsylvanian	Prairie Plains	Labette	PF
8	Mayes	Mississippian	Ozark Mountains	Chattanooga	NT
9	Nowata	Pennsylvanian	Prairie Plains	Nowata	PF
10	Pawnee	Pennsylvanian	Sandstone Hills	Vamoosa	SF
11	Osage	Permian	Red Beds Plains	Wellington-Admire	PF
11a	Osage	Permian	Red Beds Plains	Wellington-Admire	PF
12	McCurtin	Cretaceous	Red River	Washita	SF
13	McCurtin	Cretaceous	Red River	Washita	SF
14	LeFlore	Mississippian	Ouachita Mountain	John's Valley	SF
15	LeFlore	Mississippian	Ouachita Mountain	Stanley	NT
16	Blaine	Permian	Gypsum Hills	Flowerpot	ND
17	Kingfisher	Permian	Red Beds Plains	Hennessey	ND
18	Greer	Permian	Gypsum Hills	Flowerpot	ND
19	Tillman	Permian	Red Beds Plains	Hennessey	ND
20	Tillman	Permian	Red Beds Plains	Claypool	ND
21	Stephens	Permian	Red Beds Plains	Claypool	ND
22	Carter	Pennsylvanian	Sandstone Hills	Springer-Gottard	SF
23	Coal	Pennsylvanian	Sandstone Hills	Boggy	SF
24	McIntosh	Pennsylvanian	Prairie Plains	Senora	SF
25	LeFlore	Pennsylvanian	McAlester Basin	McAlester	NT
26	Cimmaron	Cretaceous	High Plains	Kiowa	ND
27	Cimmaron	Jurassic	High Plains	Morrison	ND
28	Cimmaron	Triassic	High Plains	Sloan Canyon	ND

a. PF = Pavement failure, SF = Slope failure
NT = No trouble ND = Not Determined

*From Reference (Sheerar, 32)

obtain adequate size cores. These samples yielded ultimate strengths of 450 psi and 200 psi respectively.

CHAPTER IV

LABORATORY TESTING

Since the main object of this project was to study the clay size particles, the size of the material used in all experiments was finer than U.S. Standard sieve # 10. In case the shale sample was coarser than this size, it was reduced to pass through #10 sieve by grinding.

A. Grain Size Analysis: Grain size distribution was determined in accordance with the AASHO Designation T 88-57, ASTM Designation D-422-63. Calgon was used as the dispersing agent. Iowa jet dispersion apparatus was used to disperse the soil particles. The grain size distribution curves appear in Appendix C. The amounts of silt, 5μ and 2μ size clay particles are presented in Table 4.1.

B. Liquid Limit: The liquid limit tests were run in accordance with AASHO Designation T 89-60, ASTM Designation D 423-66. The results of tests are shown on Table 4.1.

C. Plastic Limit: The plastic limit tests were run in accordance with the AASHO Designation T 90-61, ASTM Designation D 424-65. The values of plastic limits as well as those of plasticity indices are shown on Table 4.1.

D. Shrinkage Limit: The shrinkage limit tests were performed in accordance with the AASHO Designation T 92-60, ASTM Designation D 427-67. The values of shrinkage limits are listed in Table 4.1.

TABLE NO. 4.1: SHALE INDEX PROPERTY DATA

Sample No.	Grain Size Analysis Silt,%	5μClay,%*	2μClay,%	Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit	Specific Gravity	pH
6	28	72	57	36	24	12	16.3	2.80	7.7
7	40	13	8	28	26	2	18.0	2.72	7.8
8	16	3	2	NP	--	NP	14.9	2.51	6.0
9	59	18	10	26	21	5	16.5	2.76	8.4
10	43	51	39	46	23	23	16.0	2.77	7.9
11	46	52	31	44	30	14	17.5	2.76	7.7
11a	48	48	29	40	32	8	18.1		7.5
12	11	88	70	83	45	38	17.0	2.62	7.8
13	35	59	48	43	20	23	10.3	2.73	5.1
14	48	16	8	26	33	7	15.7	2.78	6.8
15	9	18	14	24	22	2	17.0	2.77	7.9
16	31	18	10	38	24	14	24.4	2.75	8.6
17	56	25	19	31	24	7	19.3	2.76	8.5
18	20	79	58	41	30	11	24.0	2.78	8.1
19	48	39	29	39	25	14	17.6	2.76	8.2
20	40	58	39	40	23	17	11.0	2.78	9.4
21	49	39	25	40	26	14	11.3	2.79	8.5
22	14	82	63	64	35	29	17.9	2.68	8.4
23	42	54	34	37	25	12	18.6	2.72	7.5
24	44	23	14	29	23	6	17.4	2.73	7.6
25	49	21	9	30	22	8	16.4	2.63	5.8
26	30	69	54	36	23	13	19.5	2.36	4.4
27	29	14	13	34	29	5	23.5	2.68	7.6
28	31	8	6	NP	--	NP	28.1	2.72	8.3

---

*Indicates total amount less than 5μ clay.

E. Specific Gravity: The tests for determination of specific gravity were made in accordance with the AASHO Designation T 100-60, ASTM Designation D 854-65. The values of specific gravity for various shale samples are shown on Table No. 4.1.

F. pH Value: The tests were run as suggested by Eades and Grim (1966) since no standard specifications cover the tests for the determination of soil pH. In this procedure a 20 gm. portion of oven dried sample of soil passing No. 40 U. S. Standard sieve is placed in a stoppered flask. Then 100 ml. of CO_2 free distilled water (prepared by boiling distilled water for 10 minutes) is added and the flask corked so that all air drawn into the flask during cooling is filtered through a CO_2 absorbing cartridge. The sample is then stirred on a vibratory shaker table at high speed for 30 seconds every 10 minutes. After one hour, the pH of the slurry is measured using a Sargent pH meter. The values of pH for different shale samples are shown on Table No. 4.1.

G. Maximum Dry Density and Optimum Moisture Content: These tests were run in accordance with the AASHO Designation T 99-61, ASTM Designation D 698-66T except that the compaction apparatus used was Harvard Miniature Compaction Apparatus and the sample was compacted using a 20 lb. spring loaded rammer. The main advantage in using this Harvard method is that it requires only about 1 1/2 lb. of soil sample in contrast to about 15 lb. required for Standard Proctor Test. The values of maximum dry density and optimum moisture content are depicted on Table No. 4.2.

TABLE NO. 4.2:   SHALE PROPERTY DATA - STRENGTH RELATED

Sample Number	Maximum Dry Density, pcf.	Optimum Moisture Content,%	Unconfined Comp. Str. psi.	Triaxial Test Data		% Volume Change, in Expansion
				Cohesion psi.	Angle of Friction, °	
6	93.6	28.5	3.6	18	10	13.65
7	116.7	14.7	24.5	18	20	5.97
8	110.8	13.8	0.3	3	14	0.64
9	122.0	13.0	27.5	25	0	3.78
10	108.0	19.2	22.8	17	13	9.32
11	107.6	18.2	28.7	17	8	5.67
11a	103.5	22.0	22.2	9	20	4.12
12	90.1	28.0	34.3	23	14	18.10
13	111.0	18.1	22.5	14	11	10.30
14	118.3	14.5	16.6	13	13	1.85
15	122.7	17.2	2.2	6	13	0.17
16	105.7	21.4	28.3	43	6	1.85
17	107.6	20.4	11.1	12	16	1.35
18	91.8	28.5	19.2	15	10	3.30
19	100.1	23.4	28.3	4	19	3.57
20	109.5	18.7	24.5	15	8	9.26
21	105.5	19.5	31.7	21	9	6.85
22	92.8	27.0	27.8	20	6	15.15
23	107.2	19.5	20.0	16	3	6.35
24	112.3	18.2	26.1	12	16	4.38
25	112.5	14.3	32.1	10	22	7.05
26	102.5	19.5	13.0	11	9	7.62
27	95.2	24.5	5.5	5	9	4.83
28	103.3	19.7	6.0	5	13	0.26

H. Unconfined Compressive Strength Test: The samples for this test were molded at optimum moisture content using the Harvard Miniature Compaction Apparatus. The samples are about 1.4 inch in diameter and 2.8 inch high. The samples were wrapped by Saran wrap and moisture cured at 100% relative humidity in a water filled humidifier for one week to bring about even moisture distribution throughout the sample. After equilibriation the samples were measured for their dimensions and their weights recorded. The samples were tested in Soiltest Unconfined Compression Testing Machine in accordance with the AASHO Designation T 208-64, ASTM Designation D 2166-66. The average values for unconfined compressive strengths are given on Table No. 4.2.

I. Triaxial Compression Tests: Samples for triaxial compression tests were compacted at optimum moisture content using Harvard Miniature Compaction Apparatus. They were then wrapped in Saran wrap and placed in 100% relative humidity for moisture equilibriation. After this, their dimensions and weight was recorded and the samples were tested in Clockhouse Triaxial Testing Machine. The tests were run in accordance with the ASTM Designation D 2664-67 for rock specimens. The rate of loading used was 0.005 inch/minute. For each shale four specimens were prepared and then tested at lateral pressures of 0, 10, 20, and 30 psi. Stress-strain curves were plotted for data from each specimen. Values of maximum principal stress were obtained from these curves. The values of cohesion and angle of internal friction were then obtained by drawing the Mohr's circles; and the former are shown on Table No. 4.2.

J. Volume Change Test: These tests were run in accordance with the AASHO Designation T 116-54. The test is continued for a duration at the end of which the expansion is less than 0.001 inch for 18 hours or a maximum of 7 days. The values of volume change, expressed in percentage of initial volume, are shown on Table No. 4.2.

K. X-ray Diffraction Analysis: The mineralogical composition of shale samples was determined by x-ray diffraction method. Both, the bulk slides and the sedimented slides were used. X-ray diffraction patterns were obtained using Siemens x-ray diffraction unit; Copper K-alpha radiation was used. The mineralogical composition of clays was determined using "area under the peak method". The data on mineralogy of clays is given in Table No. 4.3.

L. X-ray Fluorescence Analysis: The analyses were performed using the Siemens x-ray fluorescence unit SRS-1. Sixteen rock standards from various countries and laboratories are used to set up standard curves. Test shale samples are prepared by grinding the material to make it pass through a No. 200 U. S. Standard sieve. About 3 to 5 grams of this minus 200 material is mixed with 20% polyvinyl alcohol, by weight. The alcohol serves as a binder. The shale-alcohol mixture is then pressed into a briquette under a pressure of 30 tons. The briquette is used for fluorescence analysis. The data from this analysis is shown on Table D.1 (Appendix D). The total iron in a sample is reported as Fe_2O_3 since there is no way to

TABLE NO.4.3: CLAY MINERAL COMPOSITION OF SHALES

(Area Under the Peak, Cm^2)

Sample Number	Illite	Kaolinite	Montmorillonite	Montmorillonite Illite Mixed Layer
6	0.63	1.15	26.85	7.24
7	0.85	0.12	0.12	0.00
8	0.18	0.00	0.00	0.00
9	1.20	0.52	0.32	0.00
10	15.80	5.60	4.90	0.00
11	0.60	0.18	1.80	0.00
11a	1.49	0.49	2.59	4.37
12	3.36	1.30	12.04	4.75
13	0.00	10.96	86.30	0.00
14	0.94	0.32	0.10	0.00
15	0.84	0.35	0.27	0.00
16	1.71	0.11	0.33	0.00
17	3.40	0.45	0.45	0.00
18	3.60	0.18	0.14	0.00
19	3.30	0.42	0.32	0.00
20	5.02	1.26	2.24	3.20
21	1.71	0.76	2.59	6.70
22	3.38	4.81	3.74	6.25
23	3.49	1.26	1.56	1.79
24	1.35	0.55	0.08	0.00
25	1.23	0.59	0.00	0.27
26	0.41	2.22	0.00	0.17
27	1.22	0.00	0.00	1.07
28	1.67	0.00	0.00	0.00

distinguish between ferrous and ferric phases in this analysis.

The values of silica sesquioxide ratios calculated from x-ray fluorescence analysis data are shown on Table D.2 in Appendix D.

M. Electron Microscopy: Electron micrographs were obtained from a JELCO scanning electron microscope. This type of microscope is best suited for the study of argillaceous material since it provides a magnified three dimensional view of the clay surface (Bohor & Huges, 71). A gold-palladium coating, about 100^{o} thick, is applied on the clay surface to provide a conducting surface that prevents building up of electrons on the surface. The depth of focus, for samples under study, was found to reduce appreciably at high magnification and, hence, the magnification was restricted to 2000X-3000X. A polaroid camera attached to the microscope system provides the electron micrograph.

N. Ultrasonic Disaggregation

1. Equipment

In this equipment energy is produced by transducers which change the low frequency electrical energy into a high frequency (20,000 fps or higher) mechanical sound waves. These waves, in turn, pass through the medium of water in a tank (Figs. 4.1 and 4.2), and create alternatingly negative and positive pressures at any one point (Fig. 4.3). As the negative pressure, pressure less than the vapor pressure of water, passes the point, it causes cavitation and half a cycle later a positive condition is created wherein the wave energy causes the vapor bubbles to implode. The quantity of energy

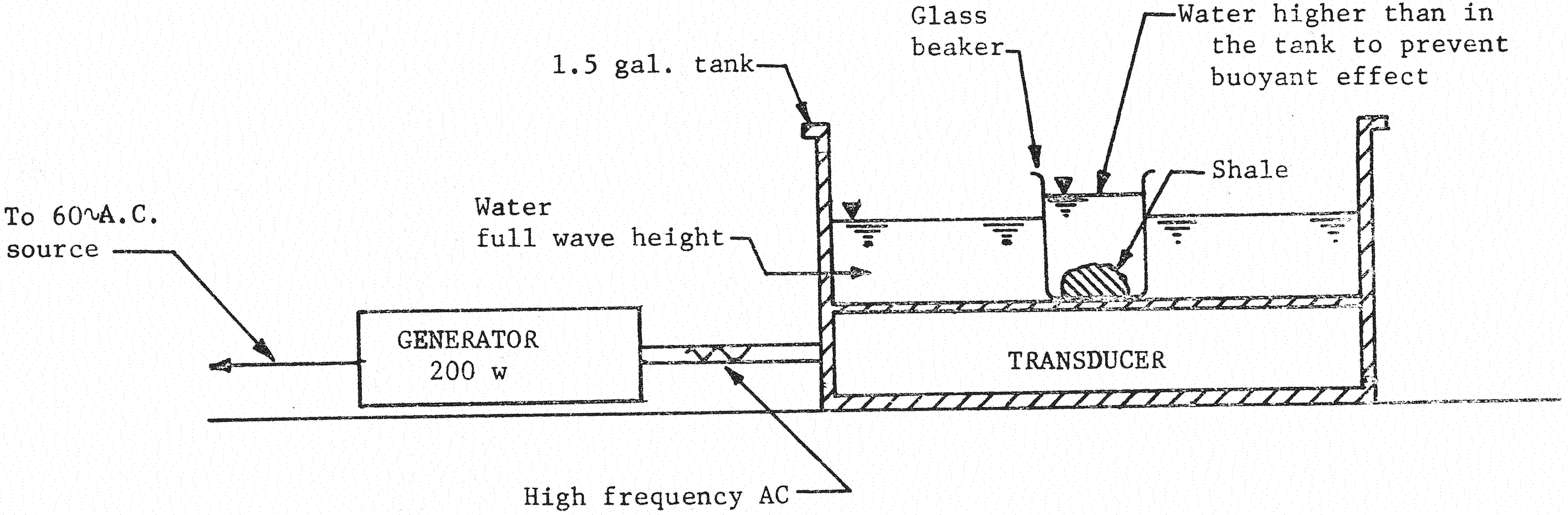


FIG. 4.1: SCHEMATIC DIAGRAM OF ULTRASONIC EQUIPMENT

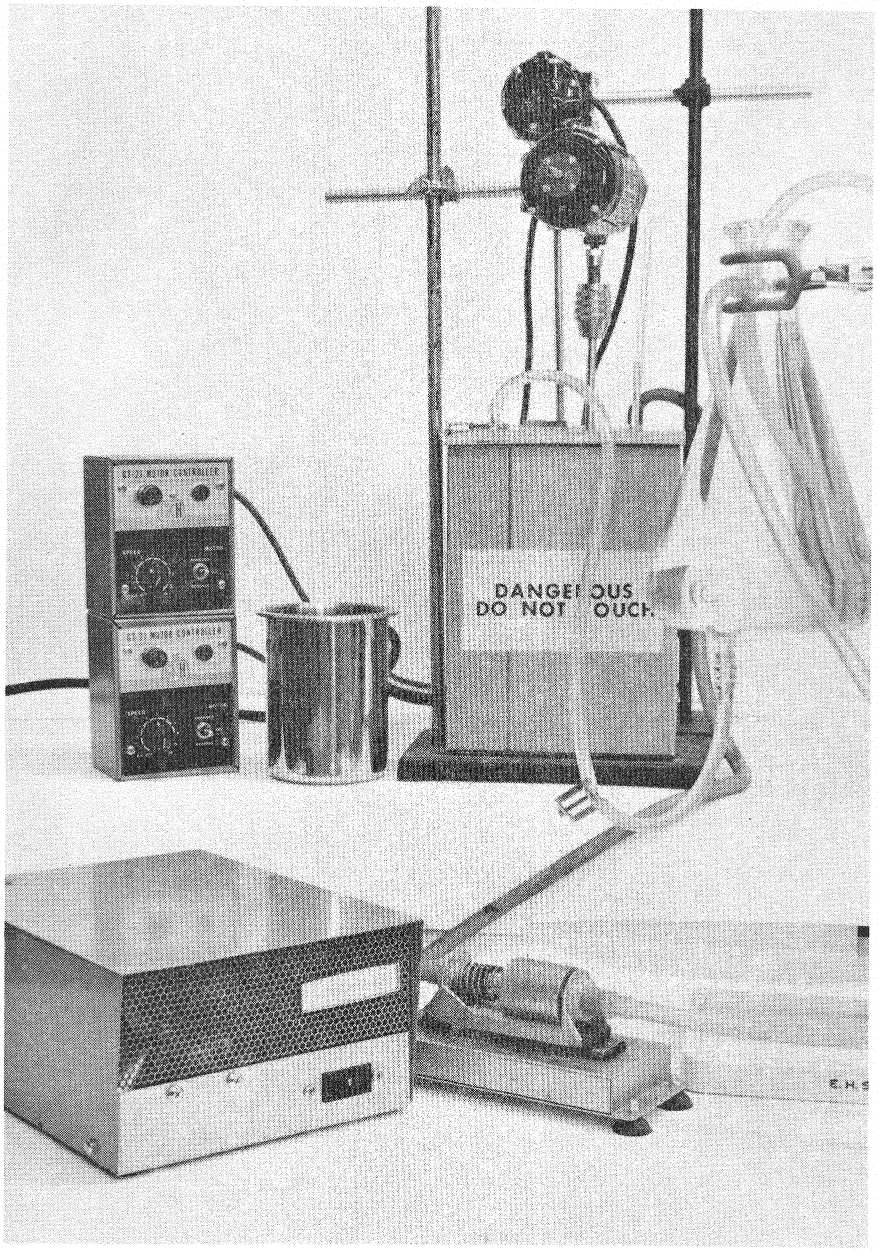


FIG. 4.2: ULTRASONIC EQUIPMENT

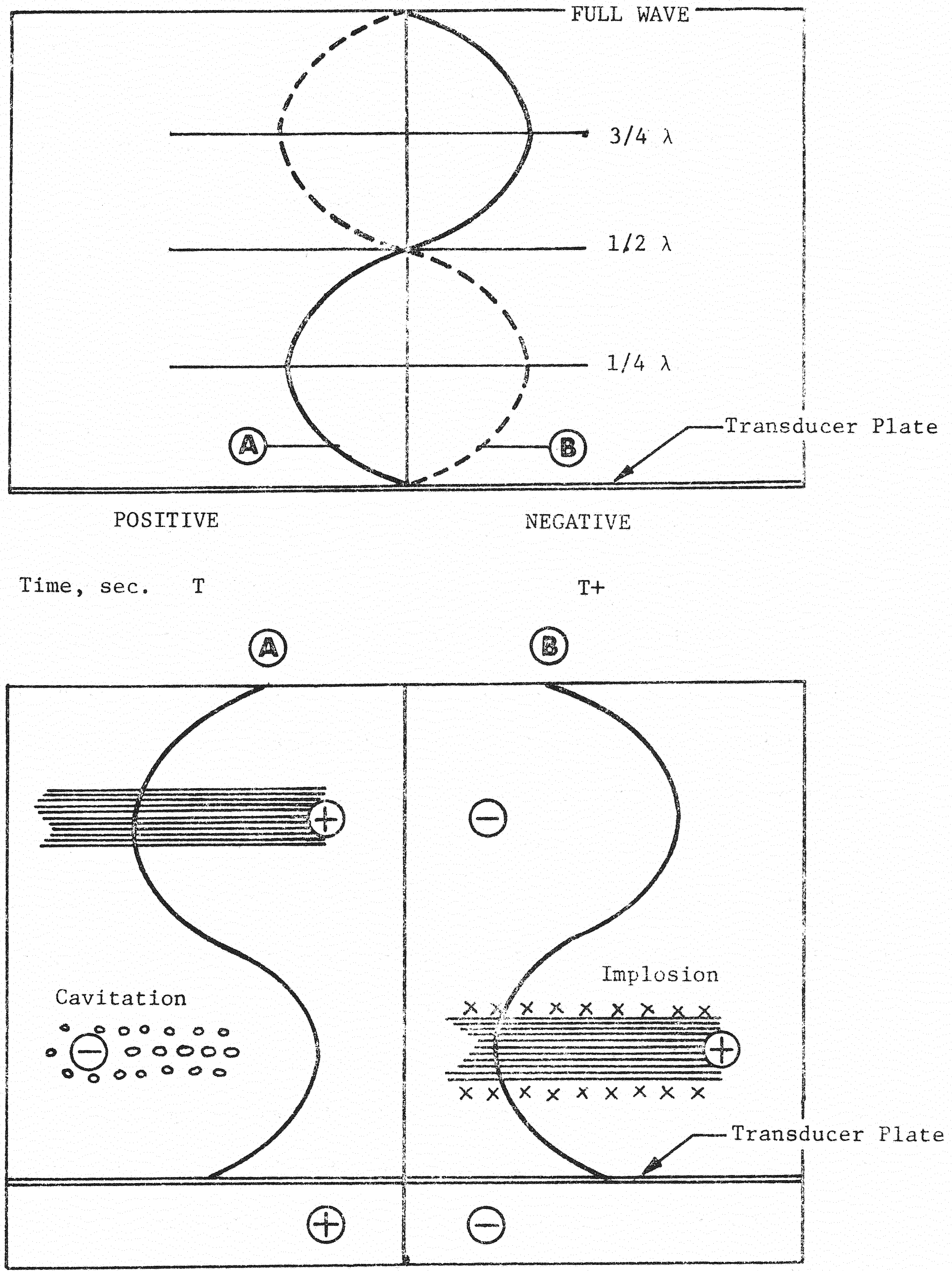


FIG. 4.3: STANDING PRESSURE WAVE

expanded in any one implosion is extremely small, but due to the corresponding small volumes involved, pressures in the order of 10,000 psi and temperatures in the order of 20,000°F are developed and dissipated (Westinghouse, 68). Cavitation causes the bonds between the individual particles making up the shale to break and, thus, separation of particles occurs.

2. Technique

Particle size distribution, liquid limit, plastic limit, x-ray diffraction analysis and electron microscopy were set as tentative criteria for studying the effect of ultrasonic disaggregation.

The shale samples obtained from the field were air dried and crushed to pass U. S. Standard sieve No. 10. Grain size analysis was performed in accordance with standard procedure except with the modification that the sample, after being soaked in sodium hexametaphosphate solution and before transferring to the hydrometer jar, was subjected to ultrasonic treatment for a specified time. For liquid limit and plastic limit determinations 125 gm of the sample was soaked in 125 ml of water for 12-18 hours and then subjected to ultrasonic treatment for a specified time.

The portion of the treated material passing U.S. Standard sieve No. 40 was dried in an oven at 200° - 212°F, crushed again to pass U.S.S. sieve No. 40. The liquid and plastic limits of this material, then, were determined in accordance with the standard procedures. At all times during ultrasonic treatment the material was prevented from settling by means of stirring and, in addition, the temperature in the tank was maintained in the 68°F-72°F range.

A portion of the material prepared for liquid limit and plastic limit was used for x-ray diffraction and electron microscopy work. X-ray diffraction patterns were obtained from sedimented slides. Electron micrographs were obtained on a scanning electron microscope.

The grain size distribution curves for soils afforded ultrasonic treatment are given in Appendix C. The amounts of silt, 5μ and 2μ clays for these soils, along with their liquid limit and plasticity index values are shown in Table No. 4.4.

O. Durability Index Tests: A number of different types of tests are available to determine the durability of aggregates, especially for asphaltic-and cement-concrete work. Some of these tests are:

1. Los Angeles Rattler test
2. Modified Los Angeles Rattler test
3. Washington Degradation test
4. California Durability Index test
5. Struillou's Hydrogen-peroxide method

Most of these tests require that the aggregate be washed clean and then ovendried. All of these methods are not suited to the shale samples under study primarily because they become completely disaggregated and dispersed on contact with water and pass through even the minimum specified sieve. The tests require that some portion be retained, at least, on the smallest size sieve specified. Hence, it is not possible to adopt any of these tests to evaluate the durability of shale clay

TABLE NO. 4.4: INDEX PROPERTIES OF ULTRASONIC TREATED SHALES

Sample Number	Grain Size Analysis			Liquid Limit	Plasticity Index
	Silt, %	5μClay, %	2μClay, %		
6	28	72	56	36	12
7	33	31	20	27	7
8	14	33	23	40	16
9	57	35	22	27	8
10	37	58	47	46	23
11	42	52	34	46	22
11a	40	52	36	50	26
12	2	96	84	84	40
13	27	69	58	55	32
14	38	53	35	27	4
15	14	83	61	46	20
16	24	55	47	39	18
17	44	51	44	32	11
18	2	97	84	49	21
19	9	88	75	40	17
20	25	74	52	49	26
21	22	77	62	45	23
22	9	90	77	72	39
23	34	66	56	37	18
24	12	85	65	47	22
25	31	68	51	35	13
26	27	73	39	50	23
27	24	76	60	--	--
28	29	62	57	27	6

Note: Treatment time in all cases is 8 hours.

samples.

It thus becomes necessary, if durability must be determined, to devise a different test for shales, but one based on the lines similar to those used in other tests. The grainsize of aggregate particles changes when they are subjected to the mechanical abrasion or water action of a weathering test; hence, the grain size distribution can be used as a means of determining durability.

For this investigation three different methods were tried:

1. Sand Equivalent Method: This is a modification of the California Test Method No. 229-E of October 2, 1967. The sample is crushed to pass U. S. Standard sieve No. 4 instead of using the prewashed and oven dried sample.

2. Soaking Method: In this method, the test sample is so graded as to be in accordance with the Oklahoma State Highway Department Specifications for Soil Aggregates (Specification 704:1 of 1967), type A, type B or type C. The amount of graded sample required is 500 gm. It is soaked in 1000 ml. of distilled water and kept so for 12 hours. After soaking, wet sieve analysis is performed to assess the amount of degradation effected by water.

3. Hydrogen-peroxide Method: A 500 gm. graded sample prepared in accordance with the method explained in Test 2 is soaked in a 1000 ml. hydrogen peroxide-water solution (90% distilled water + 10% hydrogen-peroxide) for 30 minutes in a mechanical washing machine. It is then agitated for 10 minutes at 240 strokes per minute. After agitation, wet sieve analysis is performed and grain

size distribution curve obtained for the degraded material.

The values of durability indices are calculated in the manner explained below.

(a) Sand Equivalent Test: The "sand reading" and the "clay reading" are obtained in accordance with the California Test Method No. 217-H of October 7, 1968, and

$$\text{Sand Equivalent Value} = \frac{\text{Sand Readings}}{\text{Clay Readings}} \times 100$$

This index is assumed to estimate the durable properties quantitatively.

(b) For the soaking test and the hydrogen-peroxide test the grain size distribution is obtained by wet sieve analysis. The minimum sieve used is U. S. Standard Sieve No. 200, (opening = 0.074 mm.). If the grain size distribution curves be drawn for both 'before' and 'after' the treatment conditions, in most cases, the intercept between the curves at the particle size corresponding to sieve No. 200 will be the largest for a given treatment. The analysis has been limited to sieve No. 200 because; (a) the hydrometer analysis required for sizes smaller than 0.074 mm is very time consuming, (b) by definition, the durability estimates are made on coarser size particles, and (c) No. 200 sieve demarcates between sand size and finer silt and clay size particles.

If, a = amount percent of soil passing sieve No. 200 before treatment, and
b = percent of soil passing sieve No. 200 after the treatment

then, (100-a) is the percent of soil coarser than the size of sieve No. 200, and is also the amount subjected to treatment. After the treatment, the amount of material coarser than the size of sieve No. 200 is (100-b) percent. The 'amount of fines' produced during the treatment is (b-a) percent. Thus the ratio (b-a)/(100-a) represents the amount of fines produced per unit amount of material subjected to treatment. Thus, a term weatherability index (WI) can be defined as:

$$WI = \frac{(b-a)}{(100-a)} \times 100$$

and Durability Index (DI) may be defined as

$$DI = 100 - WI$$

$$= \frac{100 - b}{100 - a} \times 100$$

The values of Durability Indices determined by the three methods are shown on Table No. 4.5.

The sand equivalent test was run on a more elaborate basis. All the shales, except No. 6, were subjected to this test. Five replicates were used for each test during which "sand readings" and "clay readings" were obtained. Sand Equivalent values were then calculated from these readings. The sand equivalent test data is shown on Table No.4.6.

TABLE NO. 4.5: DURABILITY INDICES FOR SELECTED SHALE SAMPLES

Sample Number	Sand Equivalent Method	Soaking Method	Hydrogen Peroxide Method
7	27	88	90
9	17	79	90
12	2	22	25
13	2	14	39
15	27	92	93
17	16	82	63
21	5	68	52
22	2	66	59
23	5	66	29
24	18	92	78

TABLE NO. 4.6: SAND EQUIVALENT TEST DATA

Shale Number	Sand* Reading	Clay* Reading	Sand Equivalent* Value
7	3.2	11.9	27
8	3.4	3.9	88
9	2.2	13.1	17
10	0.4	13.6	3
11	2.2	13.0	18
11a	2.0	13.0	16
12	0.2	13.5	2
13	0.2	11.6	2
14	2.7	12.5	23
15	3.0	11.4	27
16	3.3	12.0	28
17	2.1	13.6	16
18	0.2	13.4	2
19	1.0	13.5	8
20	1.0	13.2	8
21	0.6	13.4	5
22	0.2	12.6	2
23	0.5	12.9	5
24	2.3	13.2	18
25	2.5	12.8	20
26	2.0	13.0	16
27	1.7	12.4	15
28	3.3	5.3	63

---

*The value indicated is the average of five replicates.

CHAPTER V

SELECTION OF SHALE SAMPLES FOR INTENSIVE STUDY

A. Engineering Judgement

After obtaining the routine engineering and geologic information related to the first 20 shales, it became necessary to narrow the number of shales to be used for further intensive investigations. Many factors had to be taken into account before grouping the shales and then selecting a sample from each group. First attempt toward grouping was based on the AASHO Designation M-145-49. This classification system takes account of the grain size distribution and the plasticity characteristics of soils. This method of selection proved to be very effective, and the groups formed were such that a shale in a group had many other properties common with other shales of the same group.

X-ray diffraction patterns for the samples of each group were then compared. This study in conjunction with the data on volume change and strength tests necessitated introduction of a few modifications. The new grouping in its final form is shown on Table 5.1.

Then, based on a) their representativeness of the group, and b) their geographic location within the state, six samples were selected for further study. The locations of these samples are shown on Fig. 5.1 and the sample descriptions are given in Table 5.2.

TABLE 5.1: GROUPING OF SHALES

Sample No.	AASHO Class.	Experience Code	Dry Density, pcf	Opt. Moist. Content %	% of 2μ clay	Unconf. CompStrPsi	% Vol. Chg. in Exp. Test	Predom. Clay Min.	Group
8	A-1-b	NT	110.8	13.8	2	0.3	0.64	I	1
15	"	"	122.7	17.2	14	2.2	0.17	I	
7	A-4	PF	116.7	14.7	8	24.5	5.97	I	2
9	"	"	122.0	13.0	10	27.5	3.78	I	
14	"	SF	118.3	14.5	8	16.6	1.85	I	
24	"	"	112.3	18.2	14	26.1	4.38	I	
11	A-7(6)	PF	107.6	18.2	31	28.7	5.67	I	3
11a	A-4	"	103.5	22.0	29	22.2	4.12	I	
16	A-6	ND	105.7	21.4	10	28.3	1.85	I	
17	"	"	107.6	20.4	19	11.1	1.35	I	
19	"	"	100.1	23.4	29	28.3	3.57	I	
20	"	"	109.5	18.7	39	24.5	9.26	I	
21	"	"	105.5	19.5	25	31.7	6.85	K	
18	A-7(5)	"	91.8	28.5	58	19.2	3.30	I	
6	A-7(5)	PF	93.6	28.5	57	3.6	13.6	M	4
12	"	SF	90.1	28.0	70	34.3	18.1	I	
22	"	"	92.8	27.0	63	27.8	15.1	K	
10	A-7(6)	SF	108.0	19.2	39	22.8	9.3	I	5
13	"	"	111.0	18.1	48	22.5	10.3	M	
23	A-6	"	107.2	19.5	34	20.0	6.3	I	

a: NT = No Trouble, PF = Pavement Failure, SF = Slope Failure, ND = Not Determined
b: I = Illite, K = Kaolinite, M = Montmorillonite

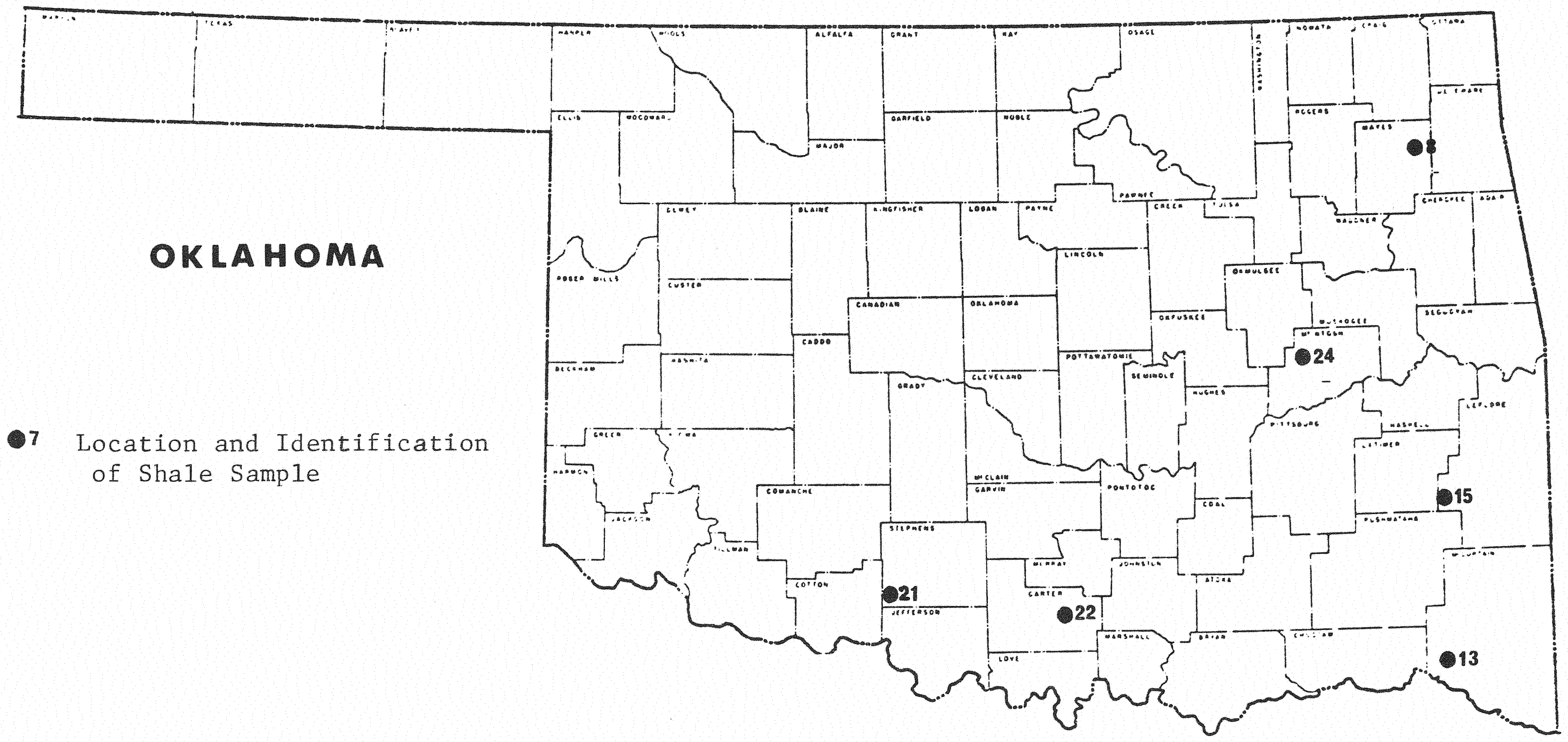


FIG. 5.1: LOCATION AND IDENTIFICATION OF SIX SELECTED SHALE SAMPLES

TABLE 5.2: BRIEF DESCRIPTION OF SIX SELECTED SHALES

Group	Shale Number	County	Geologic Unit	Experience Code
1	8	Mayes	Chattanooga	No Trouble
1	15	LeFlore	Stanley	No Trouble
2	24	McIntosh	Senora	Slope Failure
3	21	Stephens	Claypool	Not Determined
4	22	Carter	Springer-Gottard	Slope Failure
5	13	McCurtin	Washita	Slope Failure

Only one sample has been chosen from each group except Group 1. Two samples have been selected from this particular group since they are to be used as reference shales; it may be noted that the experience code for both these shales is "no trouble".

B. Factor Analysis

1. Definition

Factor analysis encompases the use of statistical techniques to obtain correlations among a set of variables so as to resolve this set of variables into a small number of categories or "factors" and in such a manner that the "factors" convey all the essential information of the original set of variables (Harman, 67). Consequently, the method is uniquely applicable to classification procedures where the data from a large battery of tests are reduced in order to identify a few common factors. Thus, a mathematical model is obtained which hopefully helps explain the underlying behavior of the data.

A satisfactory solution requires that a linear resolution of a set of variables to be obtained in terms of hypothetical factors and the description of these factors in terms of the observed variables be established.

While factor analysis affords a parsimonious description of observed data, it may not discover the complete description because theoretically this cannot be reached. But for all practical purposes a fundamental description is attained.

2. Statistical Methodology

Correlations in engineering are established through the use of multivariate methods which may be classified into two groups:

1. Dependence relations methods which define one criterion or dependent variable and all other variables are treated as predictors.

2. Interdependence relations methods which analyze all variables only in terms of their inter-relationships.

Dependence relations are exemplified by regression analysis while interdependence relations by factor analysis. The inference then is, that factor analysis is silent regarding dependence.

Technically, the principal component technique is used to determine the minimum number of independent dimensions needed to account for most of the variance in the original set of variables. Next, varimax rotation is used to simplify the factor matrix.

Thus, in the factor analytic process, the interrelationships among variables are expressed by a smaller number of categories or factors. The factors are created by linearly combining some or all of the variables depending upon the extent of their interrelations, and thus, a factor is said to be a summary of sets of variables.

3. Application to Shale Properties

The application of factor analysis to the present study assists primarily in the classification of the 20 regional shale samples into smaller groups where in members of a group have common and similar properties.

It is also envisioned that factor analysis will help in assessing and eliminating the redundancy among the various properties measured through engineering and mineralogical tests.

4. Assumptions

The factor analysis model is the consequence of the following fundamental assumptions:

1. The observed variables are linear functions of the factor variables.

2. In the case of non-linearly related variables, a straight line is a good approximation to a monotonic function.

3. Each observed variable is normally distributed.

A corollary condition of these assumptions is that the nature of the data be quantitative. Of the properties (variables) measured in this study the AASHO classification and the type of clay mineral are nonquantitative. Therefore, it became necessary to translate these data into quantitative form. This required making some arbitrary but reasonable assumptions.

To the AASHO classification system an undesirability index scale was assigned as shown in Table E.1 (Appendix E) based on the engineering performance of the materials in a pavement structure.

To quantify clay mineralogy one alternative would be to use the cation exchange capacity of the samples. However, in order to gain greater sensitivity it was decided to design an energy index scale incorporating the areas under the clay mineral peaks of x-ray diffractograms (Laguros, 62) and the average cation exchange capacity for that particular clay mineral. The data for this are given in Table E.2 (Appendix E).

5. Factor Model

In this study the classical factor model in matrix was adopted and the IBM Computer Program (IBM, 66) was employed.

To obtain a better understanding of the influence of the quantified properties through transformation (namely, clay, mineralogy and AASHO classification) and to provide, at least, a tentative evaluation of the level of measurement transformations for these two properties the data were analyzed in three separate schemes (Table E.3; Appendix E) but using the same factorial reference system. In Scheme A all 21 sets of data were used. In Scheme B the clay mineralogy and the AASHO classification system were excluded, resulting in 19 interval scaled properties. In Scheme C only the clay mineralogy was excluded, resulting in a factor analysis of 20 variables.

The results from each scheme are presented in Tables E.4, E.5, and E.6 (Appendix E) respectively. It is interesting to note that differences among the three schemes are very small but of a nature such that they may be significant. In scheme A the 21 variables were reduced to seven factors while in Schemes B and C the 19 and 20 variables, respectively, were reduced to six factors. A comparative summary of the factor analysis for the three schemes is presented in Table E.7 (Appendix E).

6. Discussion

The level of significance of each variable (property) is manifested by the magnitude of the coefficient irrespective of the sign plus or minus. Thus, in scheme A and Factor I the significantly determining properties are maximum dry density, optimum moisture content liquid limit, plasticity index, less than five micron clay content, less than two micron clay content, volume change, and AASHO classification. Again in Scheme A but considering Factor VII the significantly determining property is the angle of shearing friction. Given the limited extent of the analyses, it would be incorrect to interpret this finding as the shearing friction angle being the best predictor property of shale engineering behavior. Rather it indicates that Factor I, in all three schemes accounts for the largest single proportion to total variance among the properties and therefore it becomes the most important factor.

7. Cluster Analysis

The results of the factor analysis were employed to devise a grouping of the twenty sample regions in Oklahoma into a smaller number of regional clusters. Using the approximations permitted in the solutions of communality problems, a similarity index equation was developed which has the form:

$$SI_i = \sum_{j=1}^{n} a_j \frac{(x_{ij} - \bar{x}_j)}{\sigma_j}$$

where, SI = similarity index

i = sample region

j = property (variable)

aj = loading of property j on Factor I

x_{ij} = raw data; sample i, property j

xj = mean of all samples, variable j

σ_j = standard deviation of samples, variable j

The SI equation was then evaluated for each of the 20 sample regions and the SI values were ranked in order of their magnitude. Finally, grouping criteria based arbitrarily on breaks of 5 points and 1.5 points were applied to combine regions. The results are presented in Tables E.8, E.9 and E.10 of Appendix E.

The SI values and associated groupings, provide many interpretations. For example, sample no. 12 is a unique group; 18 and 22 are homogeneous and can be considered as a single sample based on the 5 point break, but they are heterogeneous and must be considered separate based on the 1.5 point break. It, thus, becomes evident that purpose and degree of sensitivity should be clearly defined when using such data for classification.

The result of this analysis proved that the selection of the typical samples presented earlier, using engineering judgement, was sound and reasonable.

CHAPTER VI

PRESENTATION AND DISCUSSION OF DATA

A. Shale Index Property Data

The amount of silt size material is a large and an important constituent of most shales (Underwood, 67). In the shales under study the amount of silt varies from 9% to 59%; but for the majority (11 out of 24) of shales it is between 40% and 50%, and quite a few samples (5 out of 24) have amounts of silt ranging from 28% to 31% (Table 4.1).

The variations in the amounts of 5-micron clay are much greater-from 3% to 88%. On the textural classification chart these shales show a wide variety but most of them (13 out of 24) by conventional methods, still classify as clay (Fig. 6.1) and only one shale--Number 8--has the texture of sand. The variations in the amounts of 2-micron clay are similar to those in the 5-micron clay but, as expected, of smaller magnitude. The variations in this case are from 0% to 63% (Table 4.1).

Only two shales--Numbers 8 and 15-- are known to be "no trouble" shales and for them, in respective order, the amounts of silt are 16% and 9%, the amounts of 5-micron clay are 3% and 18%, and the amounts of 2-micron clay are 2% and 14% (Table 4.1). For both shales the combined amounts of silt and clay-percentage passing U.S. Standard Sieve No. 200-are less than 30%. From this, it appears that the shale No. 28 is also a "no trouble" shale, however, field experience for this sample has not been reported. Thus, it can be expressed that those shales which

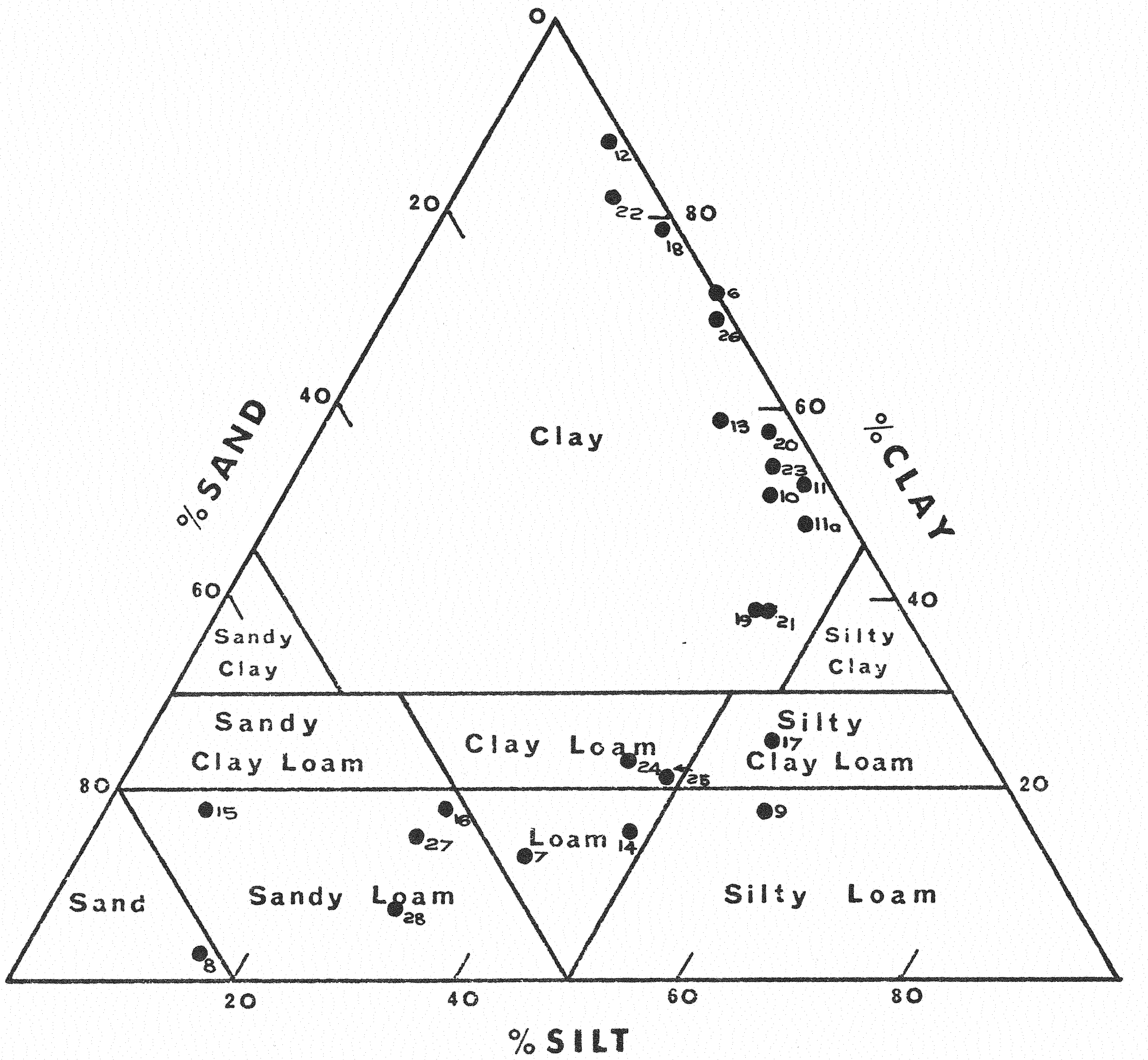


FIG.6.1: U.S.B.P.R. TEXTURAL CLASSIFICATION CHART

contain more than 30% to 40% fraction finer than the size of No. 200 sieve may have the potential for being troublesome.

The liquid limit values range from 24 to 83 (Table 4.1), but for most cases (20 out of 24). They are between 24 and 46 and these values are not considered to be very high for clay soils. The plasticity index values range from 2 to 38 (Table 4.1).

Plasticity index values seem to fall in two groups for most of the shales; for one group the values range from 2 to 8 and for the other from 11 to 14. These values are not very high as far as clay soils are concerned. Most of the shales, on the basis of the Unified Soil Classification Chart (Fig. 6.2) turn out to be either CL or ML. It was not possible to determine the plasticity values for Shale Nos. 8 and 28. Both of these shales have very coarse grained texture. Shale Nos. 12 and 22 are very clayey and stand out on both classification systems mentioned earlier. Apart from these four shales, other shales, in general, have textures of soils containing significant amounts of silt and clay.

The U.S.B.P.R. textural classification, the Unified Soil Classification and the AASHO soil classification for each shale are shown on Table 6.1. It may be noted that the AASHO classification for "no trouble" shales is A-1-b. The classification of Shale No. 28 could not be determined with certainty, but it seems to fall in some category between A-1-b and A-4.

The shrinkage limit values range from 10 to 28, but 17 out of 24 samples have these values between 15 and 19. The specific gravity

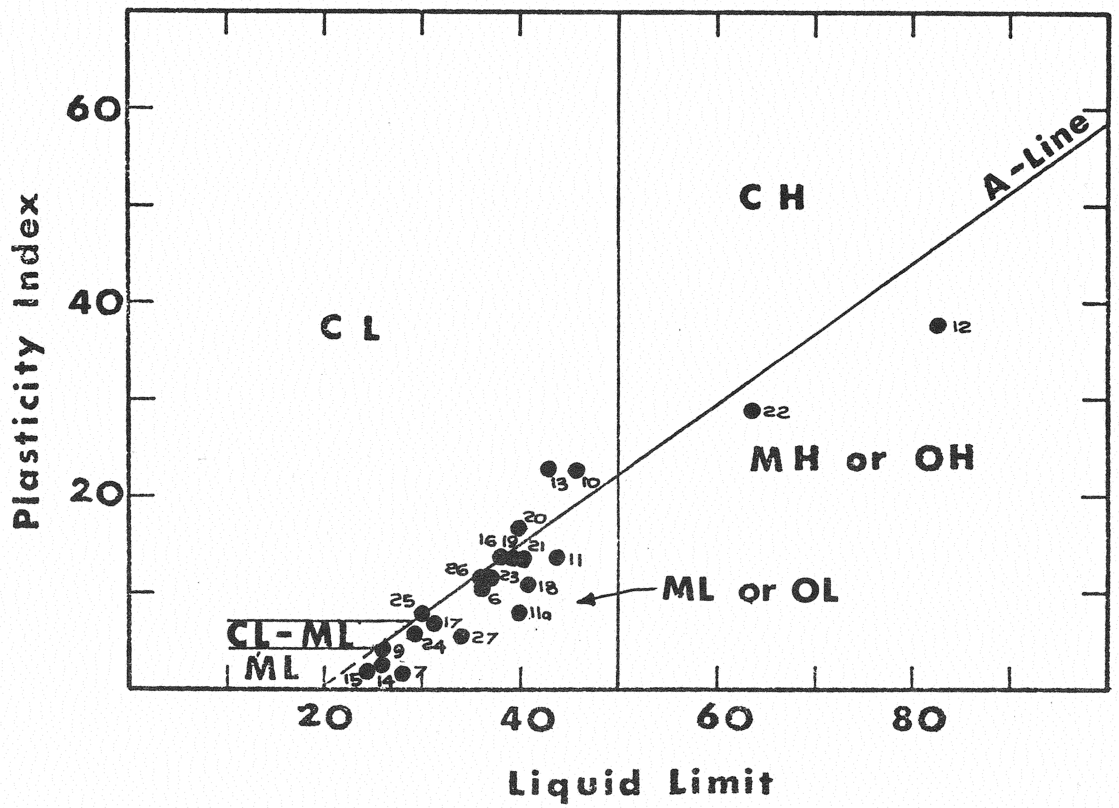


FIG. 6.2: UNIFIED SOIL CLASSIFICATION SYSTEM CHART

TABLE 6.1: CLASSIFICATIONS OF SHALES

Shale Number	USBPR Class.	Unified Soil Class.	AASHO Class.
6	Clay	ML	A-6
7	Loam	ML	A-4
8	Sand		A-1-b
9	Silty Loam	ML	A-4
10	Clay	CL	A-7(6)
11	Clay	ML	A-7(6)
11a	Clay	ML	A-4
12	Clay	MH	A-7(5)
13	Clay	CL	A-7(6)
14	Loam	ML	A-4
15	Sandy Loam	ML	A-1-b
16	Sandy Loam	CL or ML	A-6
17	Si. Cl. Loam	ML	A-6
18	Clay	ML	A-7(5)
19	Clay	ML	A-6
20	Clay	CL	A-6
21	Clay	ML	A-6
22	Clay	MH	A-7(5)
23	Clay	ML	A-6
24	Clay Loam	ML	A-4
25	Clay Loam	CL or ML	A-6
26	Clay	ML	A-6
27	Sandy Loam	ML	A-6
28	Sandy Loam	--	A-4(?)

values range from 2.36 to 2.80 but 17 out of 24 values are between 2.72 and 2.79 (Table 4.1). These values are close to the average value for this property among soils. The pH values range from 4.4 to 9.4 but for most shales they are between 7.5 and 8.5 (Table 4.1) and thus they are slightly basic in nature (pH greater than 7.0). Only five shales exhibit acidic nature (pH less than 7.0) Shale Nos. 8 and 15 do not have the similar nature, and the pH values do not seem to indicate that any significant inference can be made from their data.

From the Index Property Data presented in Table 4.1, it is quite obvious that the grain size characteristics of shales are closely related to their plasticity characteristics but not to any other property. As the amount of silt decreases and the amount of clay increases, the liquid limit increases. The plasticity index values increase approximately linearly with the amount of 2-micron clay, and this relationship (shown on Fig. 6.3) can be expressed as:

$$PI = 0.489(x) - 0.332 \qquad (6.1)$$

where x = percentage of 2-micron clay. The coefficient of correlation for this relationship is 0.930, and the standard error of estimate is 3.687, the data for sample nos. 6, 16, 18 and 26 having been excluded from analysis.

B. Shale Property Data--Strength Related

The maximum dry density values range from 90.1 pcf to 122.7 pcf with a large number (14 out of 24) of values ranging from 102.5 pcf to 112.5 (Table 4.2). The optimum moisture content values range from

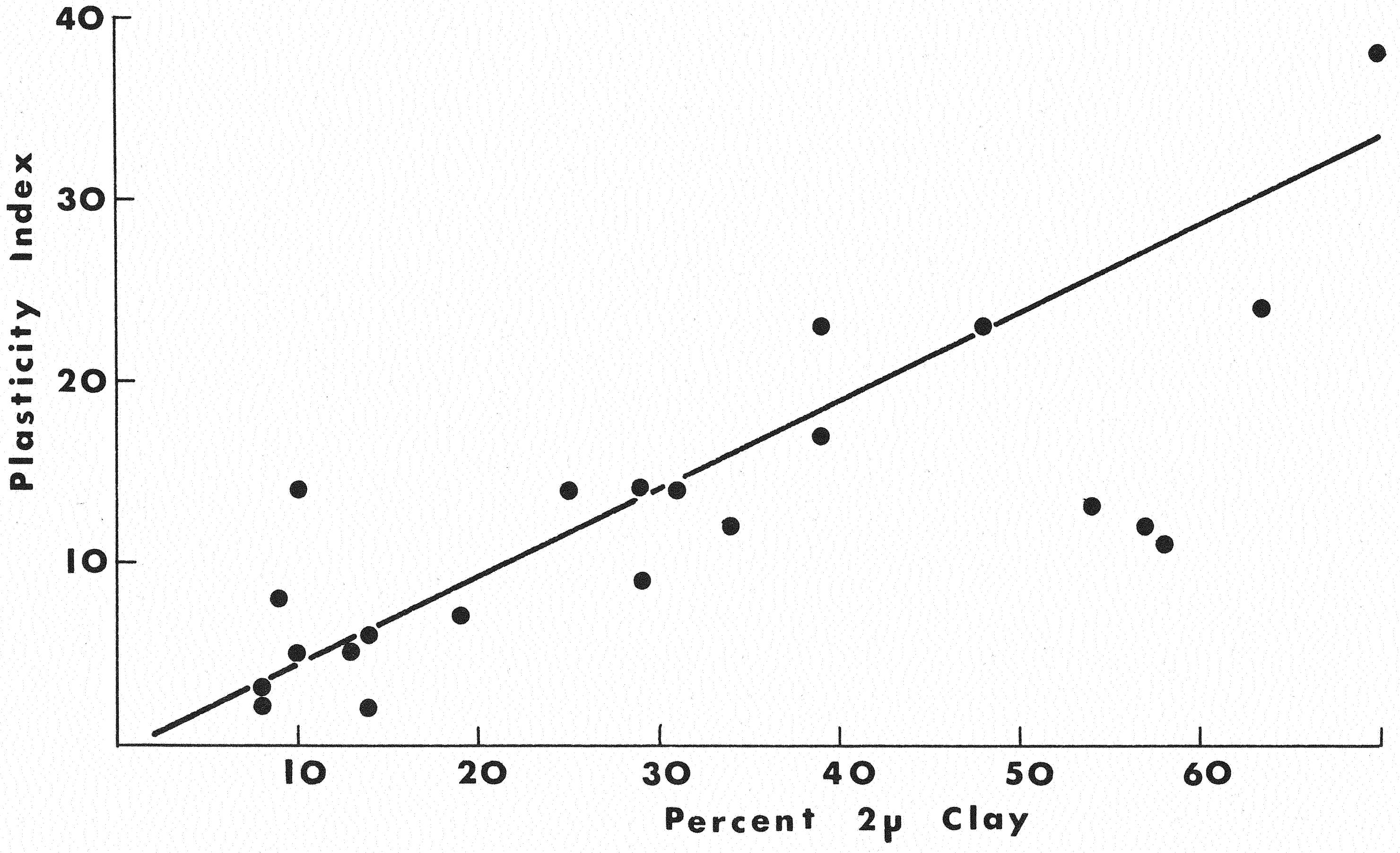


FIG. 6.3: RELATIONSHIP BETWEEN PLASTICITY INDEX AND THE AMOUNT OF 2-MICRON CLAY IN SHALES

13.0% to 28.5% with a substantial number (10 out of 24) of values ranging from 17% to 20% (Table 4.2). These values indicate that most of the shales can be compacted to a relatively high density at moderate percentages of moisture. The relation between maximum dry density (MDD) and optimum moisture content (OMC) is approximately linear (Fig. 6.4) and can be expressed mathematically as:

$$(\mathrm{MDD}) = 142.882 - 1.834(\mathrm{OMC}) \qquad (6.2)$$

For this relationship the coefficient of correlation is 0.965 and the standard error of estimate is 2.353; data for Sample Nos. 8 and 15 having been excluded from analysis. The density decreases with increasing optimum moisture content. It is interesting to note that deviation from this relationship is significant for Sample Numbers 8 and 15 which are texturally significantly different from other shales.

For most of the samples (16 out of 24) the values of unconfined compressive strength (determined on samples compacted at maximum dry density and optimum moisture content) range from 16.6 to 32.1 (Table 4.2). Among the samples that exhibit very low strength, four possess sand or sandy loam texture; and for such materials this type of test does not provide a measure of their actual intrinsic strength.

Triaxial tests were run under unconsolidated-undrained conditions and, thus, they also are not to be expected to provide indication of actual shear strengths of Shale Nos. 8, 15, 27, and 28. Obviously, the strength values for these shales are very low with cohesion ranging from 3 psi to 6 psi while for 18 out of 24 samples the values for cohesion are between 9 psi and 25 psi (Table 4.2). The angle of

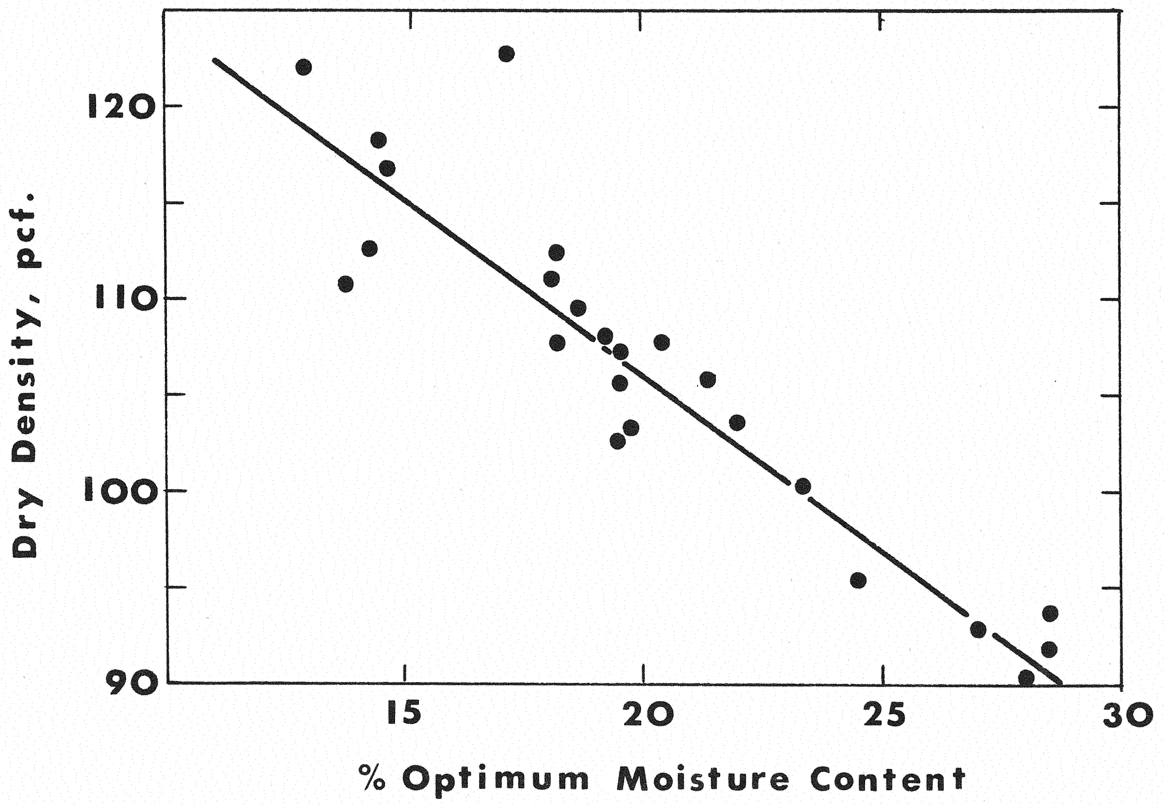


FIG. 6.4: RELATIONSHIP BETWEEN MAXIMUM DRY DENSITY AND OPTIMUM MOISTURE CONTENT OF SHALES

friction values vary from 0-degree to 22-degrees; but 18 out of 24 values range from 6-degrees to 16-degrees (Table 4.2), and this is the usual range of values for clay soils.

The values of volume change in expansion range from 0.26% to 18.10% with most of the values (15 out of 24) ranging between 3.30% and 10.30% (Table 4.2). It is very significant and important to indicate here that for shale numbers 8 and 15 - characterized as "no trouble" shales - the volume change is less than 1%. Change in volume experiment seems to distinctly separate the "no trouble" shales from the "troublesome" ones. Again, as has been mentioned earlier, the Shale No. 28 would be expected to be a "no trouble" shale. The relation between the change in volume (V) and the amount of 2-micron clay (x) is approximately linear (Fig. 6.5), and it can be mathematically expressed as:

$$V = 0.249x - 0.941 \qquad (6.3)$$

For this relationship the coefficient of correlation is 0.942, and the standard error of estimate is 1.734; the data for Sample Numbers 7, 18, 25 and 26 having been excluded from analysis.

It must be pointed out that the volume change experiments were run on samples compacted in laboratory at maximum dry density and optimum moisture content. Thus, data from this experiment could be readily applicable only to the subgrade material below pavements. It is considered opinion that for slope stability, data on volume change can be obtained on undisturbed samples or under conditions simulated to field conditions as far as practical.

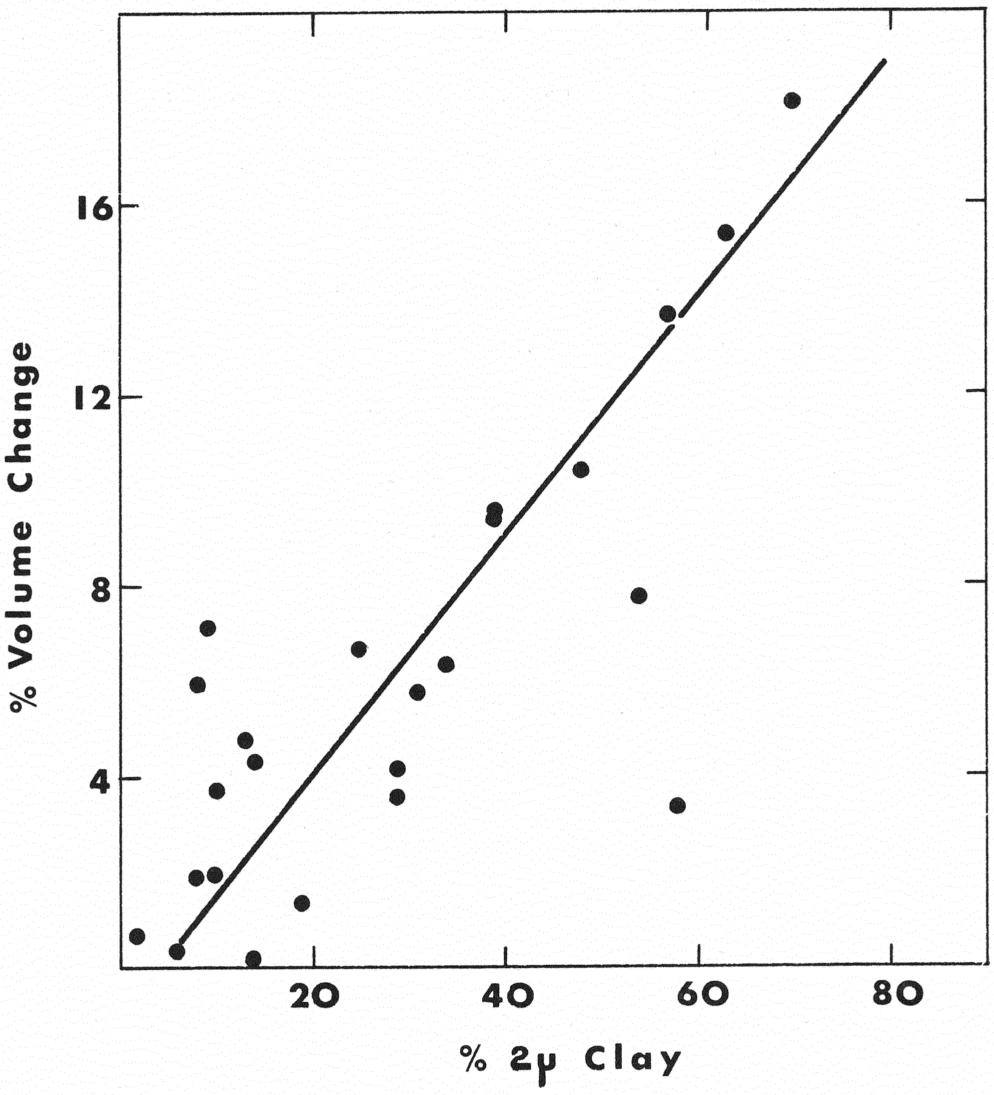


FIG. 6.5: RELATIONSHIP BETWEEN VOLUME CHANGE AND THE AMOUNT OF 2-MICRON CLAY IN SHALES

From an engineering point of view the mineralogical study of the clay fraction of shales is very important (Underwood, 67). The engineering behavior of shales in part will depend on its clay mineral composition. Clay fraction containing high percentages of illite and montmorillonite are usually characterized by low shear strength and high swelling potential (Underwood, 67). Since there are no established correlations between the type and amount of clay mineral and a certain engineering parameter and further, since the determination of actual clay mineral composition is a very complicated process, at best only qualitative results can be expected. It can readily be seen that volume change (Table 4.2) is very high in the case of those shales which contain substantial amount of montmorillonite (Table 4.3). It is, in general, high also in the case of those shales for which the total amount of argillaceous constituents is high.

C. Ultrasonic Disaggregation of Shales

Ultrasonic methods have been found to effect further disaggregation in sandstone and siltstones (Savage, 69) and shales (Gipson, 63). Since soils and shales exposed to the effects of weathering and or traffic to some extent suffer disaggregation, it was considered worthwhile to cause disaggregation of all the 24 shales in laboratory and then study the index properties of the resulting material. Ultrasonic treatment was effected for various lengths of time, and it was found that eight hours was the time by which disaggregation was complete for most of the shales.

The effect of ultrasonic disaggregation on the grain size distribution of shales is shown on Figs. C.1 through C.24 (Appendix C). The changes brought about by this method on the index properties of the shales are shown on Table 6.2.

The ultrasonic method was found to be more effective in breaking down the interparticle bonds in shales than the conventional method. This treatment causes a change in the grain size distribution which indicates increase in the amounts of finer size particles. The amount of silt size fraction decreases, and this decrease causes an augmentation in the amounts of clay size fraction. A direct consequence of this increase in the amount of clay size fraction is increase in the plasticity characteristics of shales.

The effect of ultrasonic treatment on highly clayey shales is difficult to determine becuase, to begin with, their particles are very small and the hydrometer method of determining the particle size does not seem to be sensitive enough to detect any changes in them.

However, the effect of eight hours of ultrasonic treatment is severe. The decrease in the amount of silt size particles is up to 39% increase in the amount of 5-micron clay is up to 65%, and increase in 2-micron clay is up to 51% (Table 6.2). The increases in liquid limit and plasticity index values range up to 20 and 18, respectively.

Small variations in the direction opposite to the general trend of values seem to be due to the inherent variability of all soils

TABLE NO. 6.2: EFFECT OF ULTRASONIC TREATMENT* ON INDEX PROPERTIES OF SHALES

	Increment in Value				
Shale Number	% Silt	%5μ Clay	%2μ Clay	Liquid Limit	Plasticity Index
6	0	0	-1	0	0
7	-7	18	12	-1	5
8	-2	30	21	--	--
9	-2	17	12	1	3
10	-6	7	12	0	0
11	-4	0	3	2	8
11a	-8	4	7	10	18
12	-9	8	14	1	2
13	-8	10	10	12	9
14	-10	37	27	1	1
15	5	65	47	20	18
16	-7	37	37	1	4
17	-12	26	25	1	4
18	-18	18	26	8	10
19	-39	49	46	1	3
20	-15	16	13	9	9
21	-27	38	37	5	9
22	-5	8	14	8	10
23	-8	12	22	0	6
24	-32	62	51	18	16
25	-18	47	42	5	5
26	-3	4	-15	14	10
27	-5	62	47	--	--
28	-2	54	51	--	--

---

*Ultrasonic treatment time is 8 hours.

and shales.

To determine the effect of treatment time on index properties, the shales were subjected to ultrasonic disaggregation for varying periods of time; only the six selected shales were subjected to this intensive study.

The ultrasonic treatment times for all the six shales were 0, ¼, ½, 1, 2, 4, and 8 hours.

Grain Size Analysis: With the exception of small variations, inherent with all soil experiments, the shale samples steadily assumed finer gradations with treatment time (Figs. F.1 through F.6, Appendix F). Tables G.1 through G.6 (Appendix G) indicate the amounts of various soil fractions determined for the samples after specified treatment times. In general, the changes in gradation occur rapidly at first but then tend to reach asymptotically stable values with time (Figs. H.1 through H.6, Appendix H). As is obvious, e.g., for Shale No. 15 (Fig. F.3, Appendix F) the treatment time in excess of one hour does not produce any significantly different size material. Behavior of other shales except Shale No. 8 is similar , and in all cases practically optimum treatment time is 1 hour or less. Shale No. 8 is a highly indurated silty shale which initially has a very low percentage of clay material, and it continues to show signs of significant amount of disaggregation even after 8 hours of ultrasonic treatment.

Liquid Limit & Plastic Limit: The increase in the amount of clay size particles that occurs with ultrasonic treatment time is expected to influence the liquid and the plastic limits. The changes in liquid limit values follow the pattern (Tables G.1 through G.6 in Appendix G and Figs. I.1 through I.6 in Appendix I) described for variations in grain size analysis in that the changes in liquid limit occur rapidly at first and then tend to reach asymptotically stable values with treatment time. No relationship, however, could be established between the liquid limit and the amount of shale particles smaller than a given size. The plastic limit changes significantly only within the first half hour of treatment time but at a lesser rate than the liquid limit. Consequently, appreciable changes in plasticity index values take place usually in the first half hour, and after one hour treatment no significant changes occur in the plasticity characteristics of shales, except for Shale No. 8.

X-ray Analysis: Clay mineral analysis by X-ray diffraction is generally qualitative and gives only semi-quantitative information. The relative proportions of clay minerals in a sample, however, can be approximately estimated from the relative intensities of the peaks on an X-ray diffraction pattern (Gillott, 69). The x-ray diffractograms obtained for all the six untreated and ultrasonically treated shale samples, did not reveal any alterations in clay mineral types. However, the peaks became progressively more defined (Fig. 6.6) Since aggregations cause weakened X-ray reflections (Gillott, 69) it is obvious that ultrasonic treatment effectively disaggregates the particles.

Electron Microscopy: In general, micrographs show a similar pattern for all shales. As shown in Fig. 6.7 for Shale No. 2, appreciable

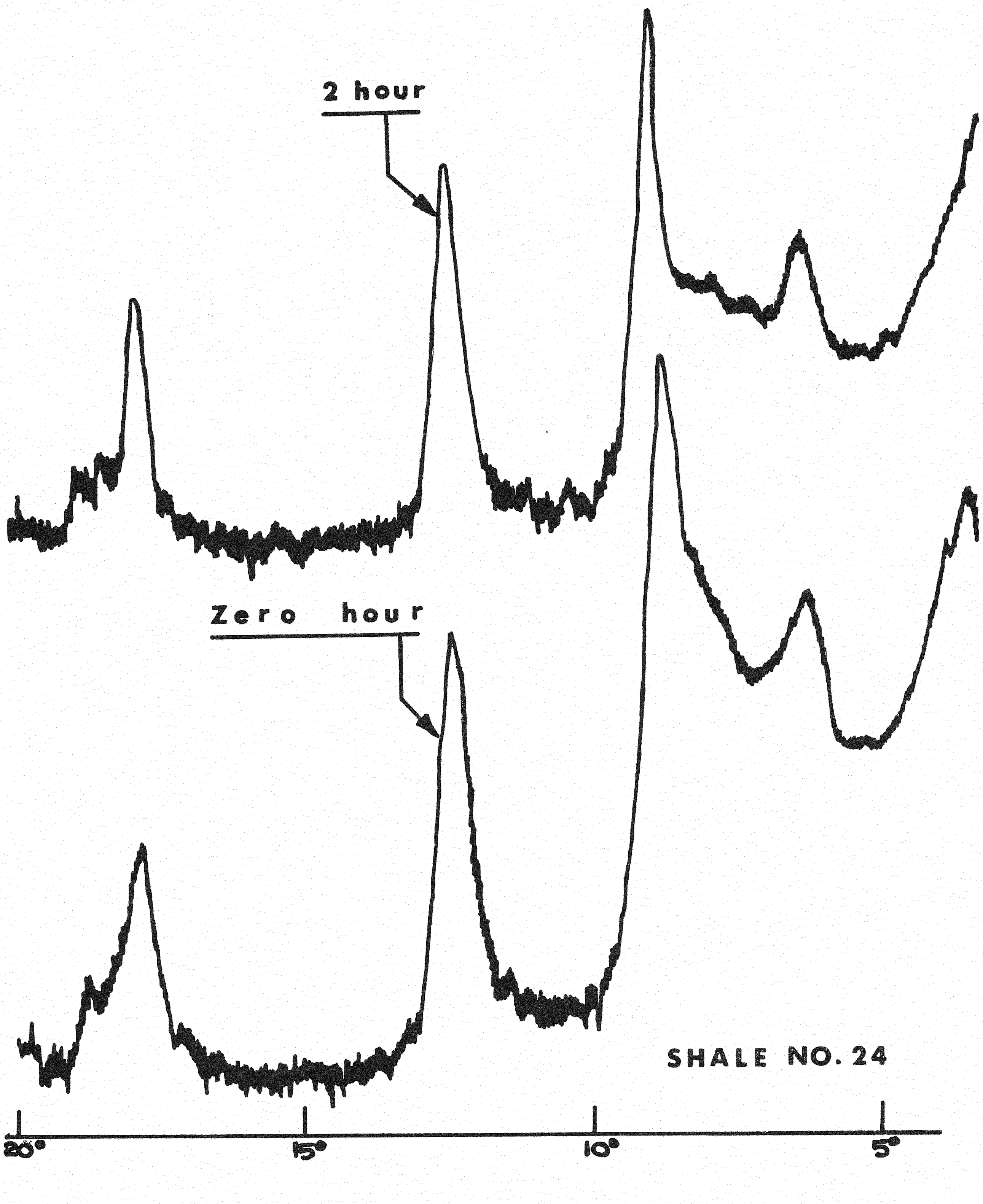
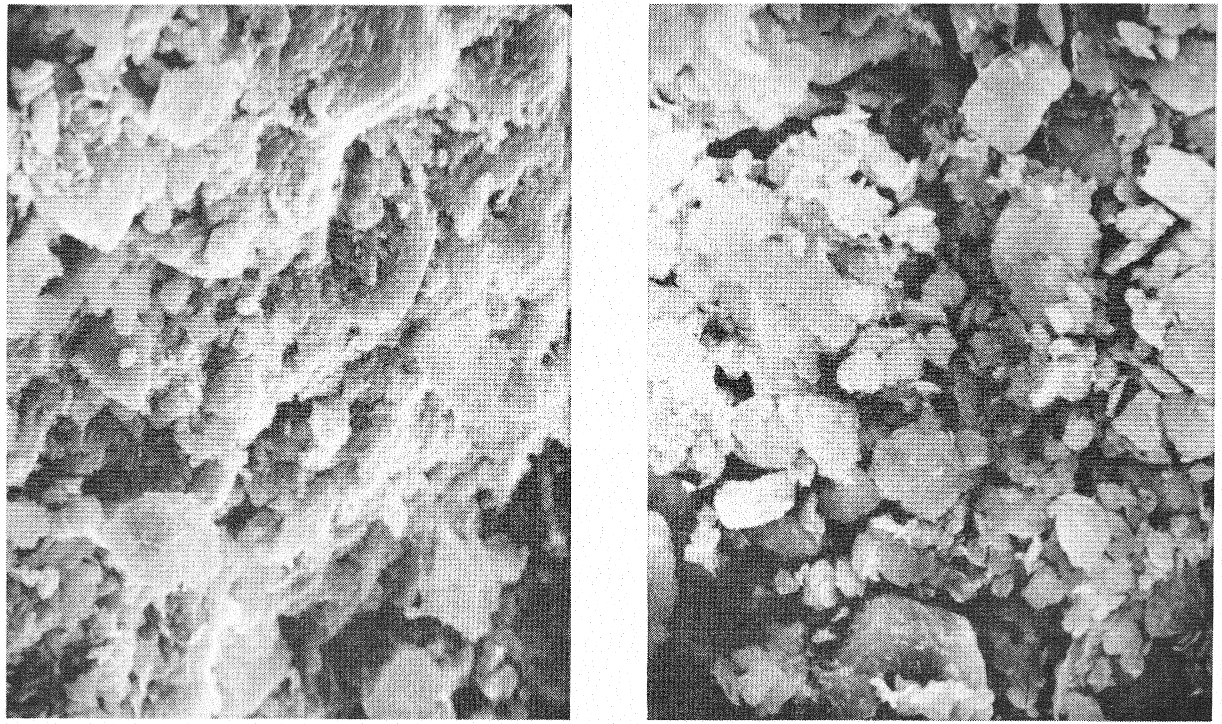


FIG. 6.6: EFFECT OF ULTRASONIC TREATMENT ON X-RAY DIFFRACTION PATTERN FOR SHALE NO. 24



Zero hour

Half hour

SHALE NO. 21

FIG. 6.7: EFFECT OF ULTRASONIC TREATMENT ON FABRIC OF SHALE NO. 21: ELECTRON MICROGRAPH

disaggregation took place within half hour of ultrasonic treatment. For this shale, the micrographs for periods ranging from 1 hour to 8 hours of ultrasonic treatment time do not appreciably differ from each other. Due to the fact that electron micrographs exhibit conditions of a very localized area, the differences in fabrics are not readily discernable in some micrographs.

D. Durability Index Tests

The quantitative assessment of durable properties of the shales is based on the results of the Durability Index Tests under this project.

The values of durability index obtained by Method 2 (soaking the shale sample in water for twelve hours) and Method 3 (soaking the shale sample in hydrogen-peroxide for half-hour)correlate linearly with the index property values of the shales. Included in Appendix J, the following relationships are shown on Figs. J.1 through J.6.

Fig. J.1: % 2-micron clay and Durability Index by Method 2
Fig. J.2: % 2-micron clay and Durability Index by Method 3
Fig. J.3: Liquid Limit and Durability Index by Method 2
Fig. J.4: Liquid Limit and Durability Index by Method 3
Fig. J.5: Plasticity Index and Durability Index by Method 2
Fig. J.6: Plasticity Index and Durability Index by Method 3.

The linearity relationships shown have coefficients of correlation ranging from 0.833 to 0.940, the data for Shale Nos. 12 and 22 being excluded from analysis.

The values of durability index range from 14 to 92 for Method 2 and from 25 to 93 for Method 3. In all cases, Shale Nos. 12 and 22 show great deviations; this may be due to their highly clayey nature

(Fig. 6.1), the amount of 2-micron clay is 70 and 63 for sample Nos. 12 and 22 respectively. The curves (Figs. J.1 and J.2) obtained from regression analyses indicate that the durability index value would be zero when the amount of 2-micron clay is 57% for Method 2 and 55% for Method 3. From the limited amount of test data available that when the amount of 2-micron clay exceeds 50% value these methods of determining durability index value cannot be considered very effective

Data were obtained on 23 shale samples by method 1 (modified sand equivalent test) and is shown on Table No. 6.3. For each shale 5 replicates were run and among these the "sand readings" were found to be consistent. The "clay readings", however, showed considerable scatter - the difference between the maximum and the minimum values among replicates ranged from 0.2 to 2.8. The sand equivalent values reported are the average of values for 5 replicates.

The relationships of sand equivalent values with 2-micron clay, liquid limit and plasticity index are shown respectively on Figs. J.7 through J.10 (Appendix K). In this case also, the test does not appear to be very sensitive if the amount of 2-micron clay exceeds 50%. The 2-micron clay content (x) and the sand equivalent values (SEV) is a linear relationship and can be expressed as

$$x = 41.094 - 1.248\ (\mathrm{SEV}) \qquad (6.4)$$

The coefficient of correlation for this relationship is 0.833. The relation between liquid limit and durability index value also is found to be linear; for the relationship shown (Fig. J.8) the coefficient of correlation is 0.89 and the standard deviation of error of estimate is 3.2, Sample Nos. 12 and 22 having been excluded from analysis.

Linear relationship exists between plasticity index and durability index values as shown (Fig. J.9) but only when plasticity index values less than 10 are considered. When plasticity index exceeds 10, the sand equivalent values show considerable scatter (Fig. J.10: Appendix J) e.g., both the Shale No. 16 and Shale No. 21 have a plasticity index value of 14 but their sand equivalent values are 28 and 5 respectively. Thus, no correlation is found in this case for those shales for which plasticity index is greater than 10.

Attempts were made to interpret the sand equivalent test data in terms of its components, the "sand reading" and the "clay reading". "Sand reading" is a measure of resistance of the soil particles to the application of load in their immersed condition. "Clay reading" estimates the amount of fine clay and silt size particles which are brought readily into suspension. Since most of the shales are predominantly clayey, the "clay readings" for various samples were not much different. They varied only within 9% of their mean in a range of 11.4 to 13.6. The "sand readings", on the other hand, showed variations of 90% from mean and ranged from 0.2 to 3.4. If liquid limit and plasticity index be assumed to vary linearly with both, the "sand reading" and the "clay reading", then the following relationships are obtained by the use of multiple regression analysis:

$$LL = 36.435 - 5.727(SR) + 0.589(CR) \tag{6.5}$$

and

$$PI = 24.745 - 5.587(SR) - 0.428(CR) \tag{6.6}$$

Where

LL = Liquid Limit

PI = Plasticity Index

SR = Sand Reading

CR = Clay Reading

The values of coefficient of multiple correlation for equations 6.5 and 6.6 are 0.88 and 0.84 respectively. The standard deviations of error in estimation of the values are 3.3 and 3.8 for liquid limit and plasticity index respectively; thus if "sand reading" and "clay reading" are known, the plasticity characteristics are predictable within a range of ± 5 points.

The main advantage of the sand equivalent test is its efficiency, it takes only two hours to run it. If the sand reading for a shale happens to be less than 3.0 then it is likely to be a 'troublesome' shale. A 'sand reading' of 1.0 or less indicates the tendency of shale to be prone to attack by water and its immersed strength is likely to be far less than its dry strength. A shale for which the "clay reading" happens to be 10.0 or more is likely to have predominant silt and clay fractions and is expected to be a poor material for highway construction purposes.

E. Weather Cycles

In addition to the data on shales, the data for number of weather cycles for various parts of Oklahoma also was obtained. To determine these cycles, data for ten years (1960-1969) were collected from 16 locations (Table K.3: Appendix K) and then evaluated. The data for the freeze-thaw cycles is shown on Table K.1 and that for wet-dry cycles is shown on Table K.2 of Appendix K.

A freeze-thaw cycle is considered as any period in which the average temperature goes from 32°F or higher to 31°F or lower and back to 32°F or higher.

A methodology similar to freeze-thaw cycle has been adopted for wet-dry cycles. A cycle is defined as a dry period in a 24-hour interval; any rainfall less than 0.10 inch is disregarded unless this rainfall links two 24-hour periods with at least a total of 0.10 inch rainfall.

The third highest number of freeze-thaw or wet-dry cycles is chosen as the number of weather cycles. The number of these cycles for various parts of Oklahoma are shown on Figs. K.1 and K.2 of Appendix K.

CHAPTER VII

CONCLUSIONS

On the basis of the data obtained from laboratory tests on twenty-four shales selected from various parts of Oklahoma, the following principal conclusions may be drawn:

1. The amount of 2-micron clay is a very important parameter in determining the behavior of shales. For most shales, the plasticity index (PI) and the percent and the percent volume change (V) are linearly related to the percentage of 2-micron clay (x) in the following manner, respectively: $PI = 0.489(x) - 0.332$, and $V = 0.249x - 0.941$

2. The behavior of a shale depends also on its clay mineral composition. Volume change is very high for the shales which contain substantial amounts of montmorillonite.

3. The modified durability index test and the sand equivalent test developed for shales show promise to be important classification tests. However, the sand equivalent test seems to be preferable since it can be conducted in less than two hours.

4. The durability index test and the sand equivalent test are not sensitive for the shales containing more than 50-percent 2-micron clay.

5. Linear relationships of the form

$$PI = a - b\ (DI)$$

(a and b are constants)

exist between plasticity index (PI) and durability indices (DI) for shales having plasticity index less than 10.

6. If the "clay reading" obtained from the sand equivalent test is 10 or greater the shale is likely to have predominant silt and clay fractions and is expected to be a poor material for highway construction purposes.

7. A "sand reading" of 1.0 or less obtained from the sand equivalent test indicates the tendency of the shale to be adversely affected by contact with water.

8. Ultrasonic treatment effectively disaggregates the shales. Due to this treatment, changes take place in the index properties of shale; their grain size distribution becomes finer and liquid limit and plastic limit increase. These changes occur rapidly at first but then tend to reach asymptotically stable values with time. Effectiveness of ultrasonic treatment in disaggregating the shales is evidenced in electron micrographs of their fabric, too.

9. The practical optimum time -- for the type of ultrasonic equipment and treatment used in this study -- is one hour.

10. X-ray diffraction methods do reveal the disaggregation effects of ultrasonic treatment on shales but do not indicate any changes in the clay mineralogy due to this treatment.

11. If the combined amount of silt and clay material in shale is less than 40% the shale may be classified as a "no problem" shale. For shales in this classification the volume change in expansion is likely to be less than 1% and the "sand reading"-- in sand equivalent test - more than 3.0. No new tests and design modifications are needed for these shales.

12. For the shales which contain the combined amount of silt and clay material of 40% or more, trouble in field may be expected. Additional testing and new design modifications are necessary for these shales.

13. For "problem" shales, index properties should be determined not only in conventional manner but also on the material obtained by equivalent of one hour ultrasonic treatment. The design procedures should be modified to take account of these changing properties of the clay forming materials.

CHAPTER VIII

RECOMMENDATIONS

1. The present study was limited to 24 shale samples. In order to make this study more meaningful, these investigations should be extended to a great number of other shales for which field experience is definitely known.

2. In most cases, remedial measures are very important in the areas which "problem" shales are encountered. It would be worthwhile to study the effects of various methods and agents for stabilization of these shales. A study in this area and related to ion exchange and electrokinetic phenomena would be of fundamental importance in Soil Engineering.

3. A time-continuous method of pavement design should be developed in which account is taken of the changing properties of the clay forming material below the highway pavement. Important information can be obtained for this purpose from ultrasonic treatment and durability testing methods.

4. To determine more closely the nature and behavior of the material produced by the effects of weathering and traffic when shales are used under the highway pavements, a simulated laboratory study would be of great practical significance.

ACKNOWLEDGEMENT

This research was sponsored jointly by the Oklahoma Department of Highways and the Federal Highway Administration of the Department of Transportation.

During the conduct of this research numerous meetings were held with representatives from the two sponsoring agencies and the author is grateful for all the helpful suggestions and cooperations which he received.

The assistance of the Oklahoma Highway Department during the field sampling phases is gratefully acknowledged and in particular the help of Mr. Willard McCastland is appreciated.

The author would like to thank the School of Geology and Geophysics, and especially Dr. William Bellis for the planning and implementation of the mineralogical and chemical testing program; Professor Joe W. Keeley of Civil Engineering for his constant counsel and Dr. William Southard for assisting in the factor and cluster analysis.

Thanks are due all the graduate and undergraduate research assistants who helped with this study, and in particular Dr. Thomas Anessi, Major, U.S.A.F., Subodh Kumar, and Manickam Annamalai, who carried a major load of the responsibility.

Finally, special mention should be made of Robert T. Alguire's

(a graduate student in Civil Engineering), contribution to this study as he was the first to experiment with and suggest the feasibility as well as the potential of the ultrasonic treatment.

REFERENCES

1. Bohor, B.F. and Hughes, R.E., Scanning Electron Microscopy of Clays and Clay Minerals, Clays and Clay Minerals, Journal of the Clay Minerals Society, Vol. 19, No. 1, Oxford England, March 1971, pp. 49-54.

2. Brakey, B.A., Road Swells: Causes and Cures, Civil Engineering, Vol. 40, No. 12, American Society of Civil Engineers, New York, N.Y., December 1970, pp. 48-50.

3. Dumbleton, M.J. and West, G., Some Factors Affecting the Relation Between the Clay Minerals in Soils and Their Plasticity, Clay Minerals, Journal of the Mineralogical Society of America, Vol. 6, No. 3, Blackwell Scientific Publications, Oxford England, July 1966, pp. 179-193.

4. Eades, J.L. and Grim, R.E., A Quick Test to Determine Lime Requirements for Lime Stabilization, Highway Research Record No. 139, Highway Research Board, Washington, D.C., 1966, pp. 61-72.

5. Gillott, J.E., Clay in Engineering Geology, Elsevier Publishing Company, Amsterdam, Holland, 1968.

6. Gipson, M. Jr., Ultrasonic Disaggregation of Shale, Journal of Sedimentary Petrology, Vol. 33, No. 4, Society of Economic Paleontologists, and Mineralogists, Tulsa, Oklahoma, December 1963, pp. 955-958.

7. Harman, H.H., Modern Factor Analysis, Second Edition; Revised, The University of Chicago Press, Chicago, Illinois, 1967.

8. IBM Application Program: H20-0205-3, System/360 Scientific Subroutine Package (360A-CM-03X) Version III, Programmer's Manual, IBM Technical Publications Department, White Plains, N.Y., 1966.

9. Kassiff, G. and Barker, R., Aging Effects on Swell Potential of Compacted Clays, Journal of the Soil Mechanics and Foundations Division, Vol. 97, No. SM3, American Society of Civil Engineers, New York, N.Y., March 1971, pp. 529-540.

10. Laguros, J.G., Handy, R.L. and Reign, L.L., Effect of Exchangeable Calcium on Montmorillonite Low-Temperature Endotherm and Basal Spacing, Bulletin 349, Highway Research Board, Washington, D.C., 1962, pp. 51-58.

11. Mitchell, J.K., Singh, A. and Campanella, R.G., Bonding, Effective Stresses, and Strength of Soils, Journal of the Soil Mechanics and Foundations Division, Vol. 95, No. SM5, American Society of Civil Engineers, New York, N.Y., September 1969, pp. 1219-1246.

12. Savage, E.L., Ultrasonic Disaggregation of Sandstone and Siltstone, Journal of Sedimentary Petrology, Vol. 39, No. 1, Society of Economic Paleontologists, and Mineraologists, Tulsa, Oklahoma, March 1969, pp. 375-378.

13. Sheerar, L.F., The Clays and Shales of Oklahoma, Vol. 3, No.5, Oklahoma A & M College, Stillwater, Oklahoma, September 1932.

14. Soderman, L.G., Kim, Y.D. and Milligan, V., Field and Laboratory Studies of Modulus of Elasticity of a Clay Till, Highway Research Record No. 243, Highway Research Board, Washington, D.C., 1968, pp. 1-11.

15. Townsend, F.C., Manke, P.G. and Parcher, J.V., Effects of Remolding on the Properties of a Lateritic Soil, Highway Research Record No. 284, Highway Research Board, Washington, D.C., 1969, pp. 76-84.

16. Underwood, L.B., Classification and Identification of Shales, Journal of the Soil Mechanics and Foundations Division, Vol. 93, No. SM6, American Society of Civil Engineers, New York, N.Y., November 1967, pp. 97-116.

17. Westinghouse, 'Ultrasonic - Primer No. 1', Application Data 80-070, Metallurgical Services, Dallas, Texas, ca. 1968.

APPENDIX A

48 STATE SURVEY: QUESTIONNAIRE REPLIES

TABLE 48 STATE SURVEY: QUESTIONNAIRE REPLIES

State	Experience with Shales or Similar Rock Exposure	Testing Methods To predict Occurence of Weathering	Treatments Used To prevent Deterioration	Remarks
Alabama	Yes Northern half of state	Identify by geological formation		
Alaska	Yes (Matanuska formation)	Geologic examination. Lab wear tests Freeze-thaw tests		Upon exposure to weathering it becomes a silt within 5± to 10± years. It is used as an embankment material only.
Arizona	Air slacking Volcanic Shales	Experience		
Arkansas	Yes			
California	Ridge Route Formation			
Colorado	Yes Mancos shale Pierre shale Cretaceous shale Denver Formation Laramie Formation	By experience	Treatment of Mancos Shale with asphalt Membranes	

State	Experience with Shales or Similar Rock	Testing methods To predict Occurence of Weathering	Treatments used To prevent Deterioration	Remarks
Connecticut	No pertinent reply			
Delaware	No			
Florida	No			
Georgia	NW¼ of the state			
Idaho	Yes-North Idaho			
Illinois	Yes			
Indiana	Yes In Southern part of state	Based on the percentage of recovery in cove drilling and the amount of slaking		When these types of materials are encountered, cut back slopes generally are flattened, when used in embankments. Special provisions may require placing in lifts to as little as nine inches thick.
Iowa	Yes Des Moines Series Pennsylvania Shales	2" piece of core is placed in water for 24 hrs. to observe its behavior		
Kansas	Yes In various shales and glacial clays	Hydrometer analysis, Atlerberg limit, Swell test X-ray, Imbibometry	In subgrade, remove shale to a depth of 12"-14" replace with crushed stone.	Hydrated lime is used on soft or weathered shales in subgrade to minimize swell.

State	Experience with Shales or Similar Rock Exposure	Testing methods To predict Occurence of Weathering	Treatments used To prevent Deterioration	Remarks
Louisiana			4:1 slope is used and covered with a clay blanket implanted with grass for erosion protection	
Maryland	Western part	Core boring visual evaluation	Bench design Slope ratio	
Massachusetts			Clear rock Slide area Remove all base rock	
Michigan	No			
Minnesota	Yes	Borings		When dealing with shaley formations the backslope is flattened. Find no remedies to prevent weathering
Mississippi	No			
Missouri	Yes In Kansas city area and along the Mississippi River	Swell and disintegration of core during cut, classification & core disintegration after weathering and slaking in water	Weather wall, wide ditches or benches, flattened slopes	Soundness and weathering tests have been made on shales in the Kansas City Group of the Missourian series.

State	Experience with Shales or Similar Rock Exposure	Testing methods To predict Occurence of Weathering	Treatments used To prevent Deterioration	Remarks
Montana	Yes Fort Union Formation, Hell Creek Formation, Bearpaw Shale, Judith River Formation, Eagle Sandstone, Telegraph Creek, Nioprara, Cody			
Nebraska	Yes Pierre Shale Chadron Formation	Borings by power drill, Visual inspection, standard soil tests		Some hydrated lime stabilization has been used in the Pierre areas but as yet no definite conclusions have been reached.
Nevada	Yes	Expansion-pressure test, Degradation test, Atlerberg limits tests, Swell test	Compact the material at about 2% above optimum & cover 3' of compacted borrow.	Plan to try lime & cement treatment in the future.
New Jersey	Yes Shales Triassic belt	Topography and boring result	Flattened slopes retaining wall crushed stone covering	
New Mexico	Yes	Plastic Limit Liquid Limit Linear Shrinkage Stability tests		

State	Experience with Shales or Similar Rock Exposure	Testing methods To predict Occurence of Weathering	Treatments used To prevent Deterioration	Remarks
New York	Yes Catskill Mts. Southwestern Plateau	Experience	1:1 slope--using pneumatically projected concrete on slopes steeper than 1:1.	
North Carolina	No			
North Dakota	West & Southwest of Mississippi River	Experience	Flattened backslope, Spread topsoil, seeded slope, benching in deep cuts	
Ohio	Yes Southeastern Ohio	Sodium Sulfate soundness loss test, AASHO T 104 5-cycles		
Oregon	Marine basalts sandstone, sedimentary deposits		Treat with asphalt or portland cement	
Pennsylvania	Yes	Observation of the outcrops by trained geologists		Shale samples were tested with gyratory compaction, wet-dry absorption, specific gravity & Washington Degradation tests.
South Dakota	Pierre Shale			Various methods of stabilization conducted on Pierre shale.

State	Experience with Shales or Similar Rock Exposure	Testing methods To predict Occurence of Weathering	Treatments used to prevent Deterioration	Remarks
South Carolina	No			
Tennessee	Yes			
Utah	Yes Mancos shale Chinle formation Uinta formation	Expansive pressures test		
Vermont	Yes Along I89-I91			
Virginia		Experience	2:1 backslope in shale cuts. 12" granular material over shale in road bed.	
Washington	Western Washington, Basalt interbeds in eastern Washington	Past experience. Observing the behavior of fragments when placed in beakers of fresh water		Provided information on over consolidated clays & clay shales.
West Virginia	Yes Western half of state		Multiple benches	
Wisconsin	No			
Wyoming	Yes Cody shale Green River shale	Observation in its natural state. Bury this material within an embankment.		

APPENDIX B

SHALE SAMPLE DESCRIPTION

TABLE B.1 SHALE SAMPLE DESCRIPTION

Sample Number	County	Location	Field Description
6	Bryan	2½ mi so of 69-70 interchng. Ea slope, ea lane. 2' above ditch line, 2' below road grade. F-219 (9) (10). Sta 873 + 75. 2000' So. Sec line, SE¼, NW¼, S12, T7S, R8E.	Fragmented shale, light yellow to olive. Slope, 1½-1. 1' weathered matl removed. Vegetation, prairie grass.
7	Tulsa	F-32 (4)(5). Broken Arrow Expy, left backslp, Left lane, sta. 164+00. 25' below Oologah Limestone cap. 5' above ditch line. SW¼, SW¼, S34, T19N, R14E.	Dark grey fissile shale, slope 1-1. 1' weathered matl removed. No vegetation.
8	Mayes	East Backslp, S.H. 82, SE¼, NE¼, S15, T22N, R21E, .2 mi SW of cut section. 5' above ditch line.	Black blocky Fissile shale, very hard. Considerable iron on fracture faces. Slope, vertical.
9	Nowata	F-193 (11), Sta. 707+25. 15' below Lenapah limestone. 7' above ditch line. So backslope. S.H.10	Grey, blocky fissile shale, slope, 1-1. 1' weathered matl removed. No vegetation.
10	Pawnee	So backslp, U.S. 64, SE¼, SW¼, S16, T21N, R8E. 60' below Elgin Sandstone, 10' above ditch line	Grey-green to brown clay shale Slope 1-1. 1' weathered mat'l removed. No vegetation cover.

Sample Number	County	Location	Field Descriptions
11	Osage	100' N of S.H. 18 and U.S. 60 intersection on E backslp. 3' above ditch line. SW¼, NW¼, S32, T26N, R6E.	Grey Blocky fissile shale. Slope, 1-1 1' weathered matl removed. No vegetation
11a	Osage	"	Grey-olive blocky fissile shale from lower third of 3' layer (11).
12	McCurtin	F-40 (25) pt 1, S.H. 70, 500' N of Sta 1702+00 in borrow pit. 1000' W of Sec line in NW ¼, SE¼, S23, T7S, R23E.	Yellow-olive clay shale. Slope 2-1. 1' weathered material removed.
13	McCurtin	F-40 (21)(22) 2½ mi. SE of Valiant, 1/8 mi N of S.H. 70 SE¼, SE¼, S25, T6S, R21E. Sta. 1013+00 North.	Yellow-gray clay shale. Slope, 1-1. 5' above bottom pit. 1' cover removed.
14	LeFlore	Project FLHW-12(3) Sta. 1116+75. Rt back slope, 5' above ditch line. Talihina Drive. SW¼, NE¼, S23, T3N, R25E.	Grey blocky shale. 1' cover removed. Slope: 1-1. Weathers to tan clay.
15	LeFlore	Rifle Range, SW¼, SE¼, SW¼, S1, T3N, R21E. ¼ mi of Talihina.	Green-grey, blocky shale. Weathers to grey-olive flakes. Slope 1-1. 1' cover removed.
16	Blaine	NE¼, NE¼, NW¼, Sec. 9 T17N, R11W. In road cut on South side of Section Line Road.	Red, Blocky mudstone. Slope: 1-1.
17	Kingfisher	NW¼, NW¼, NW¼, S23, T19N, R7W in borrow pit. 30' below natural ground level. 200' So. of Hwy 51.	Red, blocky mudstone with conchoidal fracture planes, some greenish gray "spots". Slope: 1-1.

Sample Number	County	Location	Field Directions
18	Greer	SE¼, SE¼, SW¼, Sec. 7 T7N, R23W. Road cut on No. side of section line raod.	Green-grey,blocky shale. Weathers red. 2' cover removed. Slope: 1-1.
19	Tillman	NE¼, NE¼, Sec. 25, T1S, R18W, West side of section line road inside gulley, 7' below natural ground line.	Red blocky shale. Sampled 1' into vertical face. Slope: 1-1.
20	Tillman	SW¼, NW¼, NW¼; Sec 28, T3S, R14W, 250' East of highway 36 near upper boundary of Claypool.	Red blocky shale. Slope: 1-1. 1' cover removed.
21	Stephens	NW¼, NE¼, NE¼, Sec.12, T3S R9W, in road cut on So. side of section line road.	"
22	Carter	2350' So. of sec line, SW¼, SE¼, NE¼, Sec 35,T3S , R1E; F.A. I-35-1(47) 033. Rt land, rt bkslp Sta 1965+50, about 3' above ditch line.	Bluish-Olive, blocky, plastic clay shale. Weathers to olive clay. Slope: 1½-1. 1' cover removed.
23	Coal	Coal Co--SW¼, SW¼, Sec. 9 T3N, RIOE: So. bkslp; Ea of landslide.	Gray, blocky shale. Weathers to tan clay. Slope: 1-1.1' cover removed.

Sample Number	County	Location	Field Descriptions
24	McIntosh	McIntosh Co. --NW¼, SW¼, Sec 12, T11N, R14E, No. bkslp of left lane. Sampled from just W. of backslp slide, 4' above ditch line. FAP I-40 -6(45)(46), Sta. 277+00.	Grey, blocky shale. Weathers tan. Slope: 1-1. 1' cover removed.
25	LeFlore	SW¼, SW¼, NW¼; Sec. 6, T7N, R26E; S.H. #112, Sta. 607+50; about 8-12 ft. below top of cut, sampled beneath sandstone cap.	Gray blocky shale, flake to fissile upon removal of over burden
26	Cimarron	Center N½, Sec. 15, T5N, R1E, C.M.	Gray fissile shale, blocky upon fresh excavation, well defined bedding planes, appears carbonaceous.
27	Cimarron	Center West Quarterline; NE¼, Sec. 15, T5N, R1E, C.M.	Green blocky shale, defined bedding planes which rupture upon excavation.
28	Cimarron	SE¼, SE¼, Sec. 20, T6N, R1E, C.M.	Purple, blocky mudstone, jointed, weathers platy, not well cemented.

APPENDIX C

GRAIN SIZE DISTRIBUTION CURVES

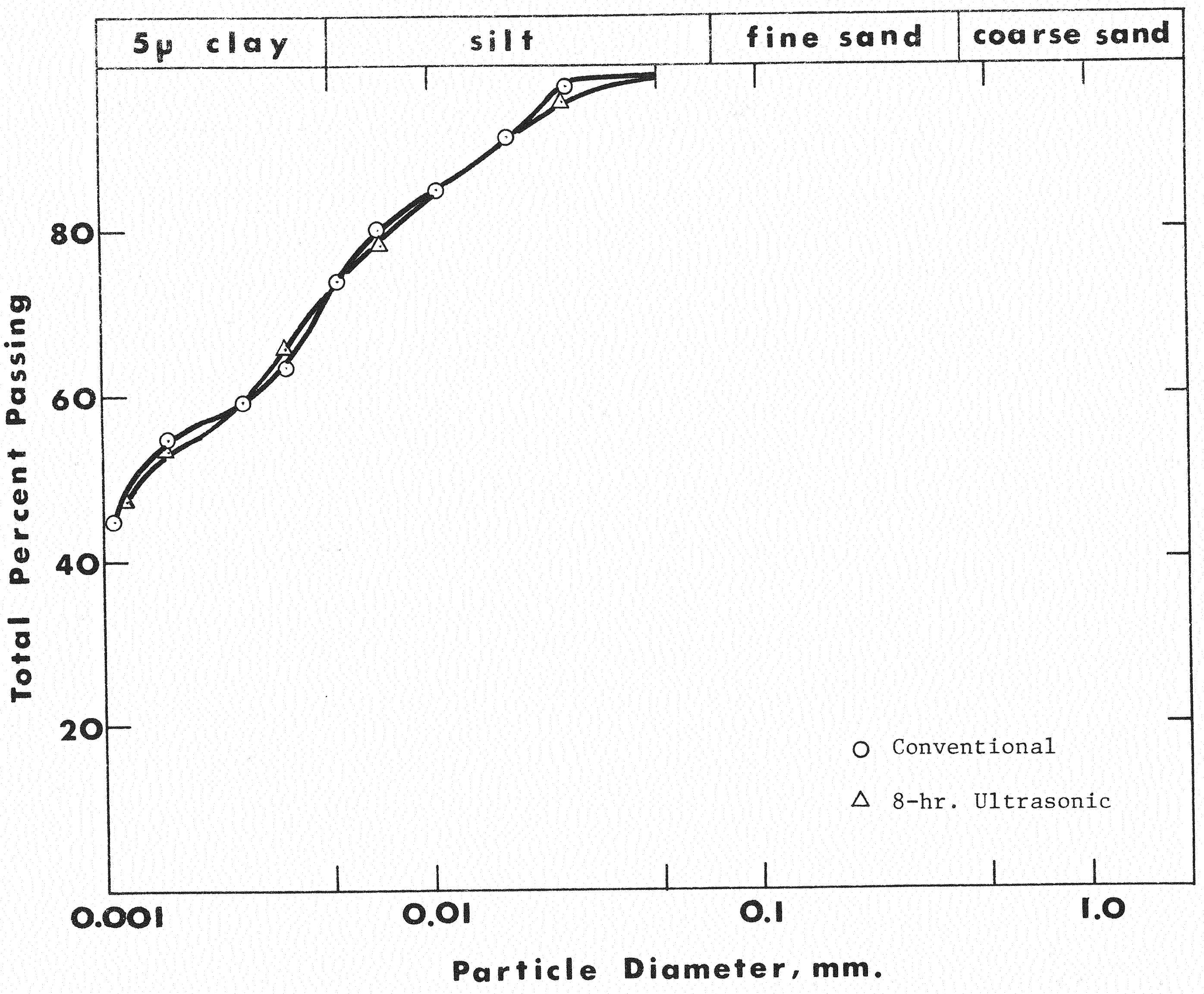


FIG. C.1 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.6

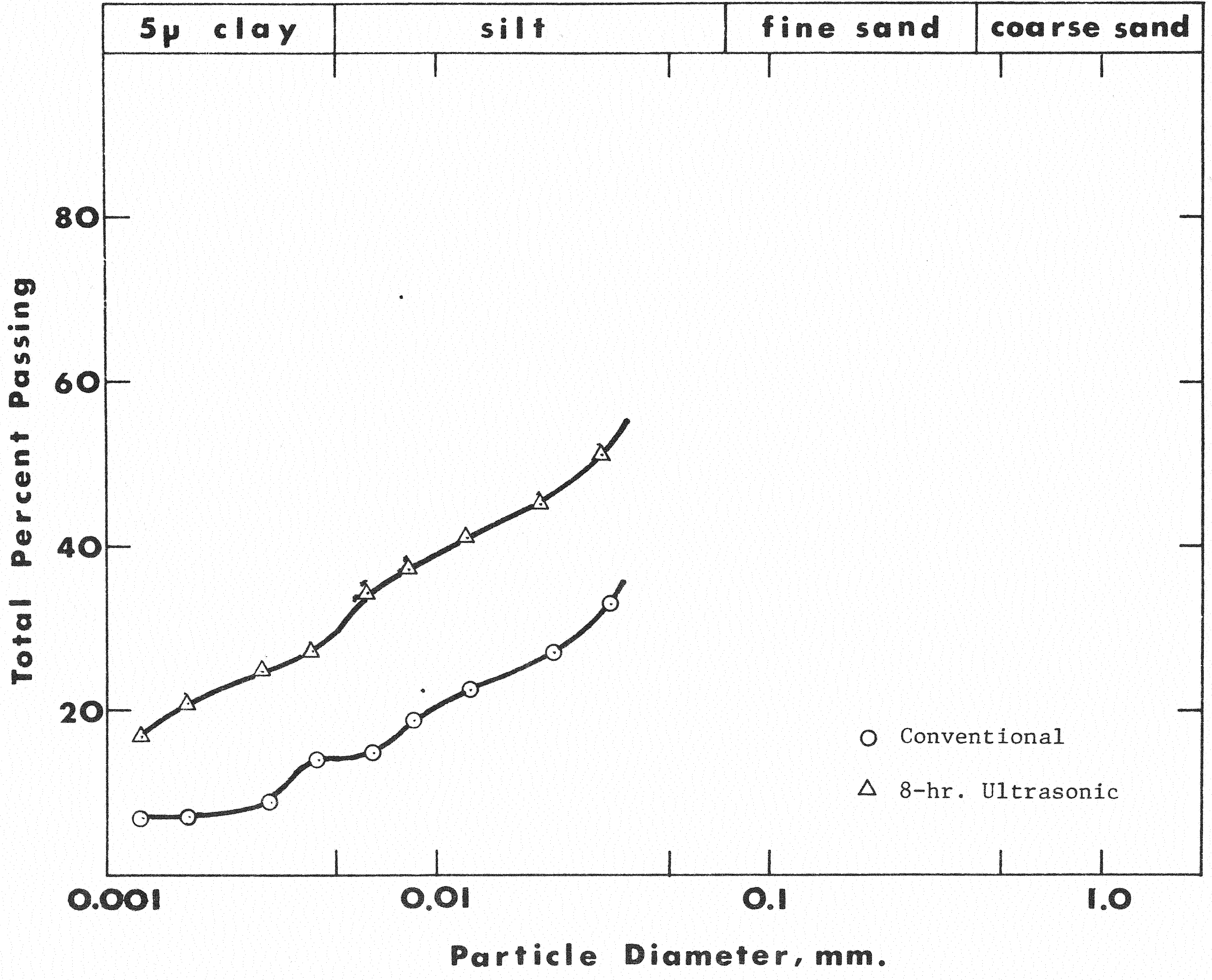


FIG. C.2 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.7

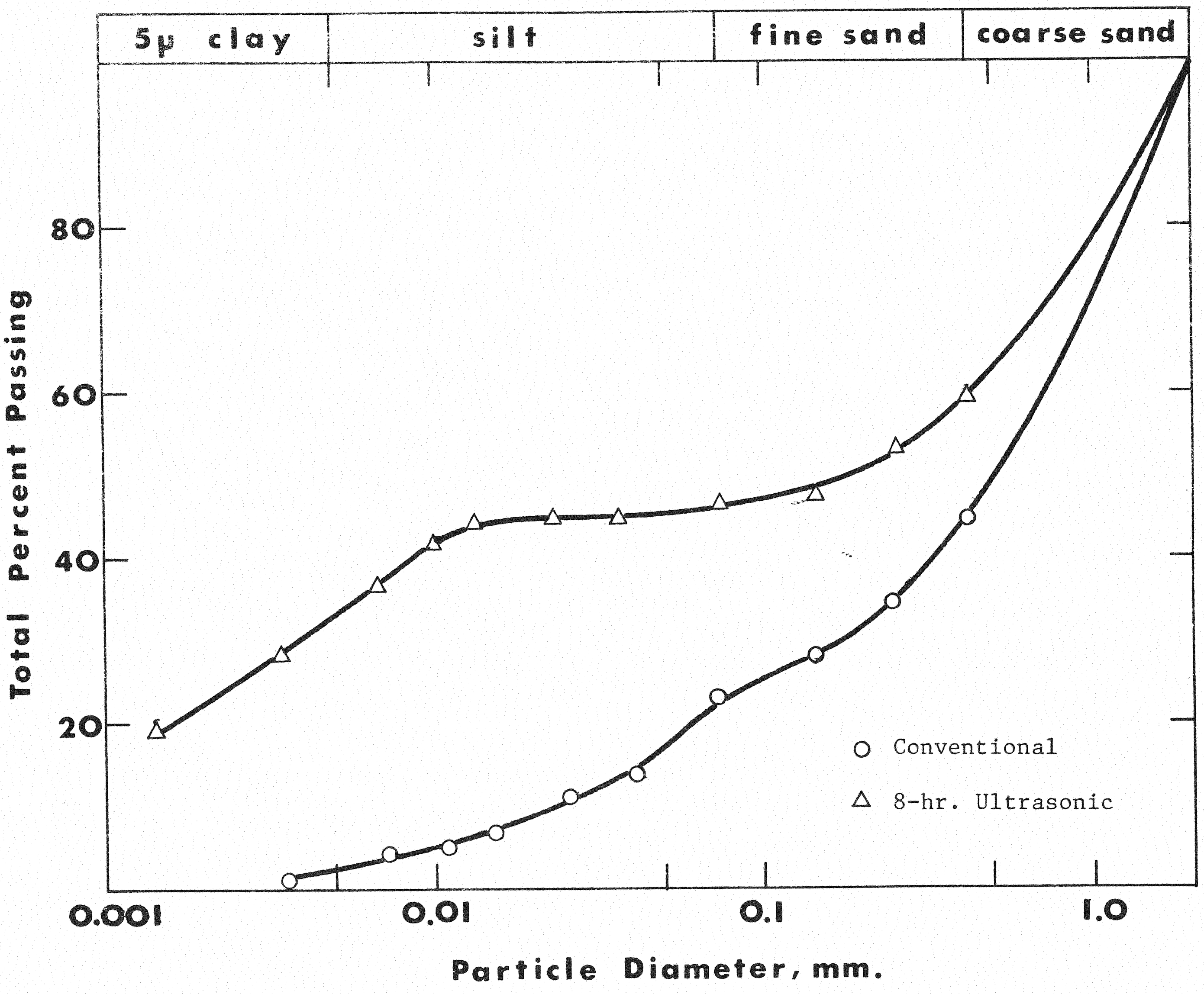


FIG. C.3 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.8

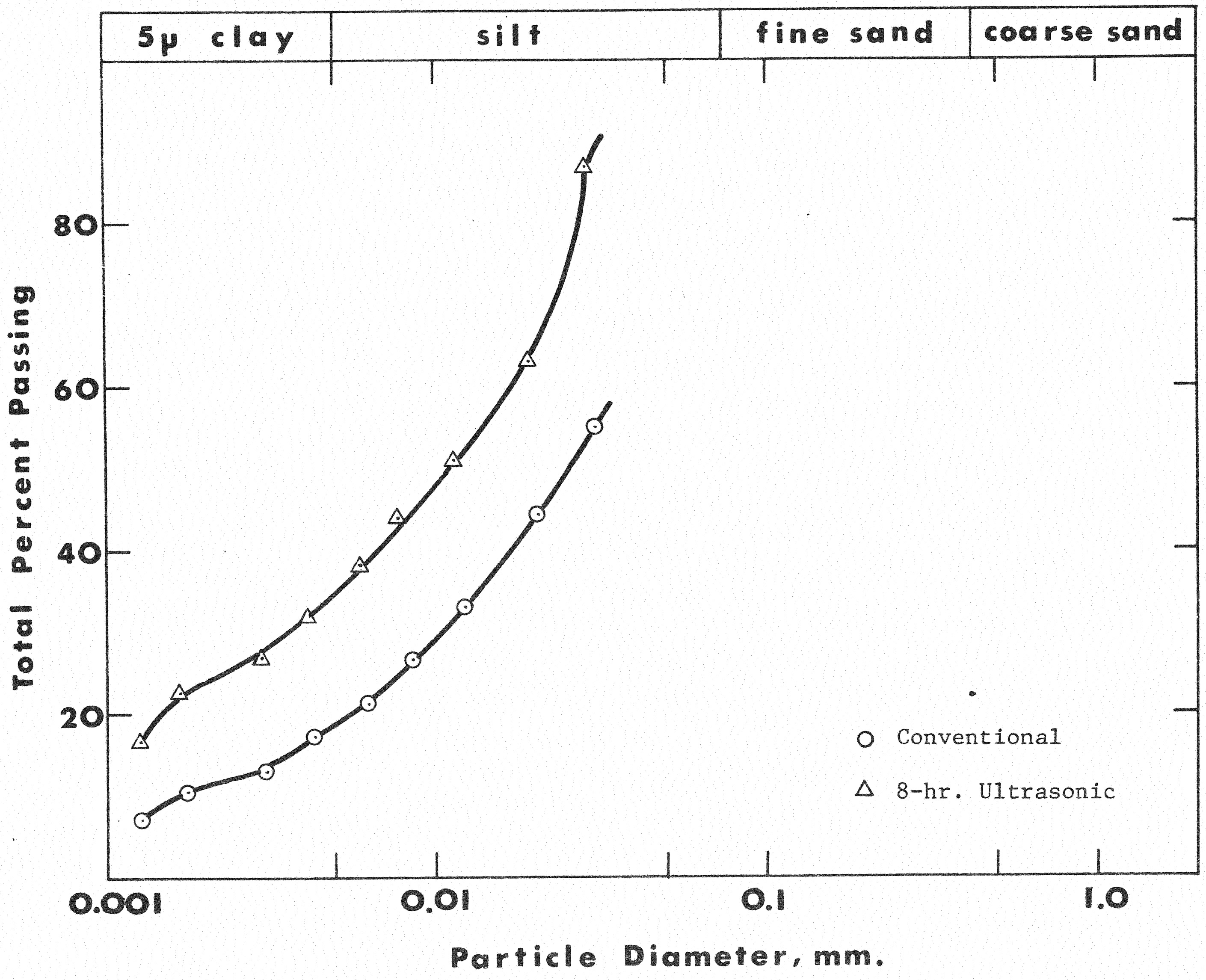


FIG. C.4 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.9

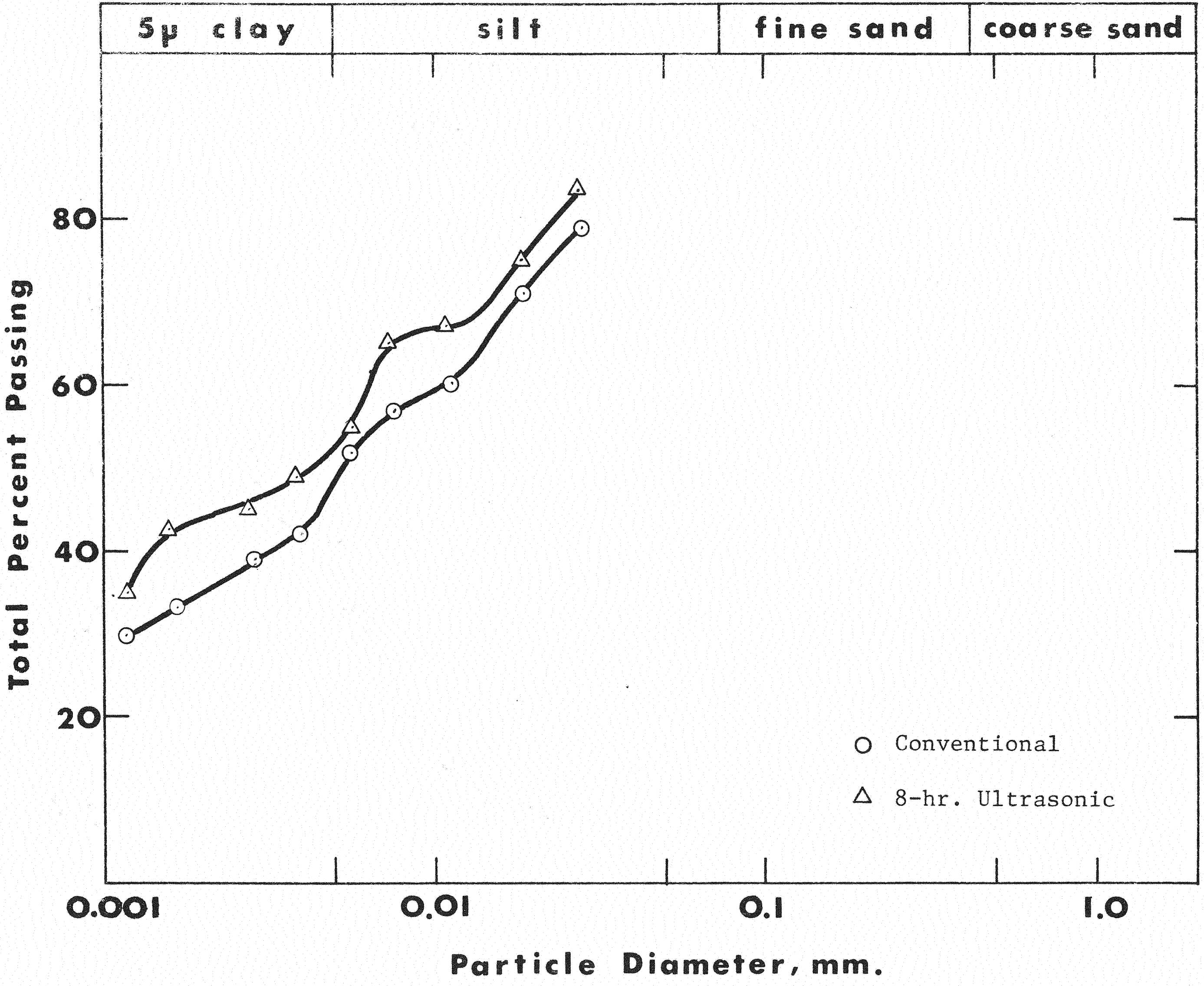


FIG. C.5 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 10

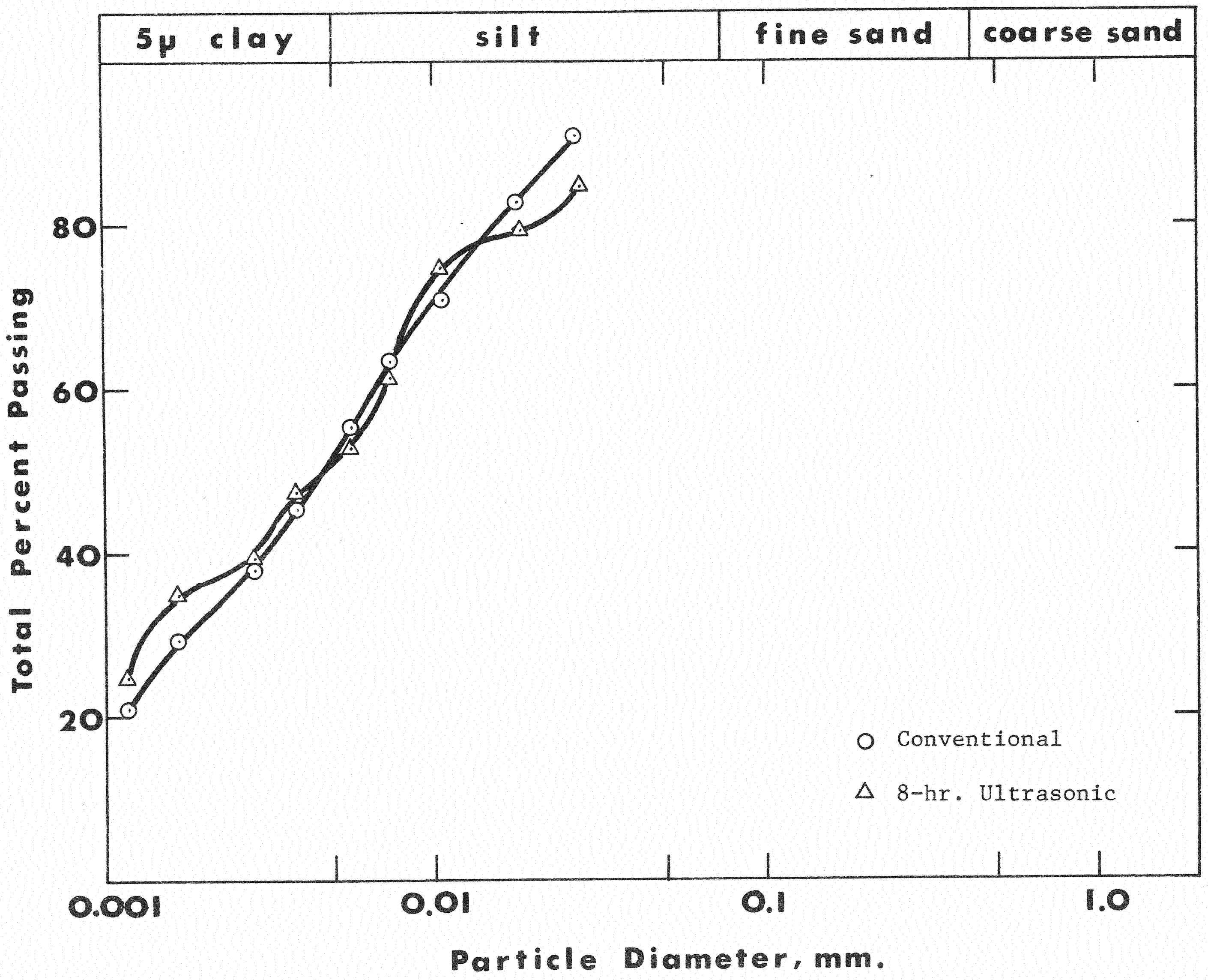


FIG. C.6 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 11

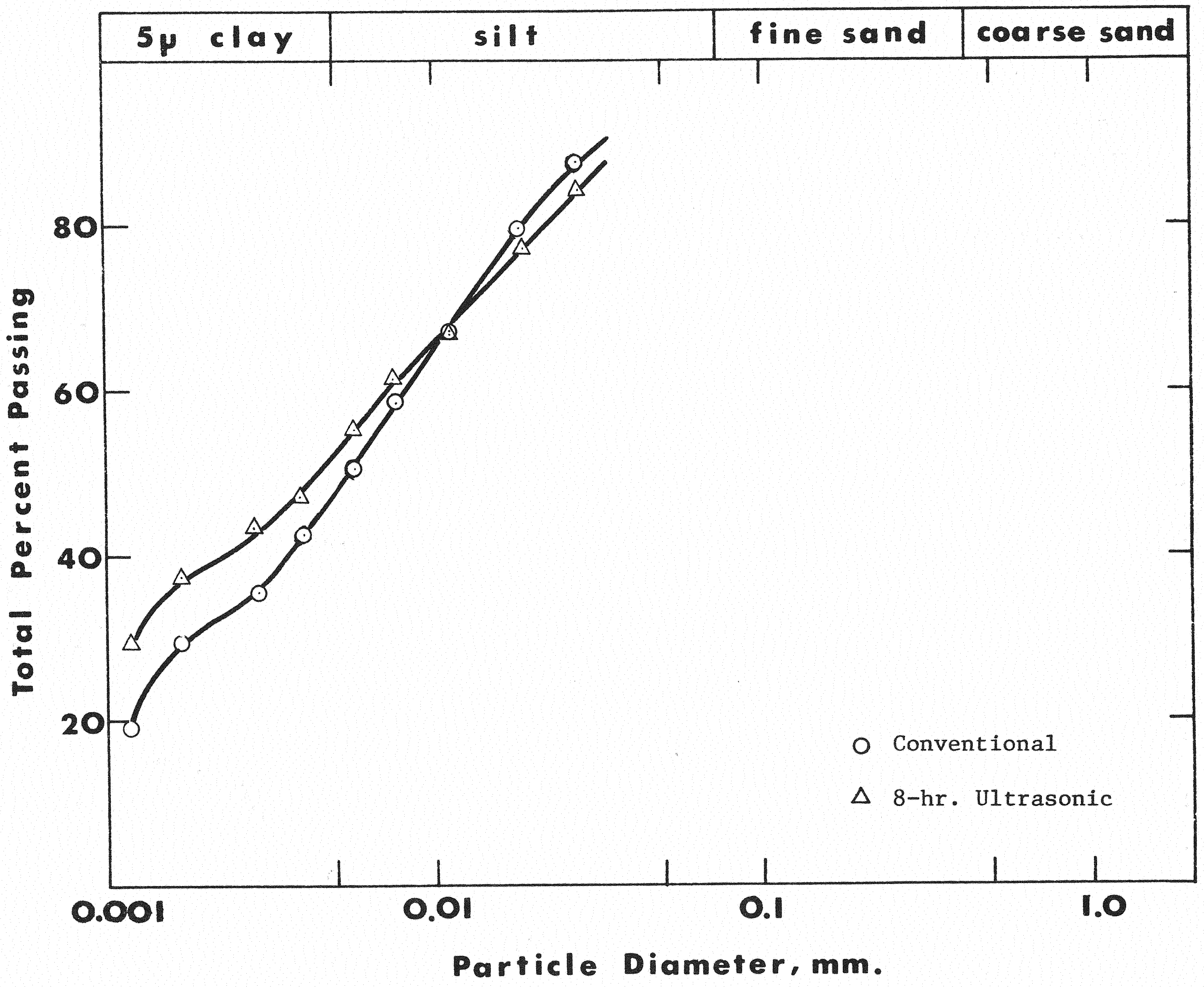


FIG. C.7 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.11a

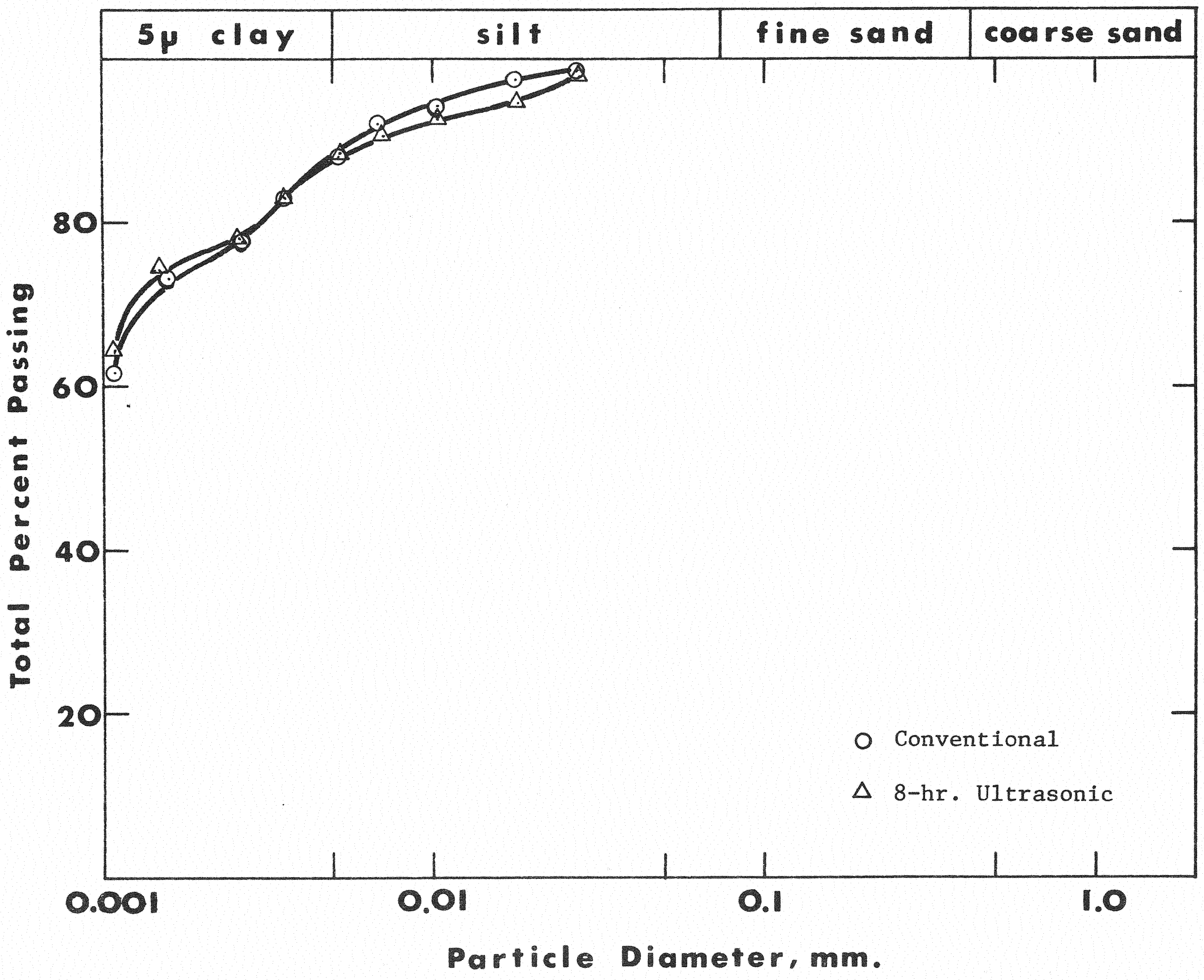


FIG. C.8 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 12

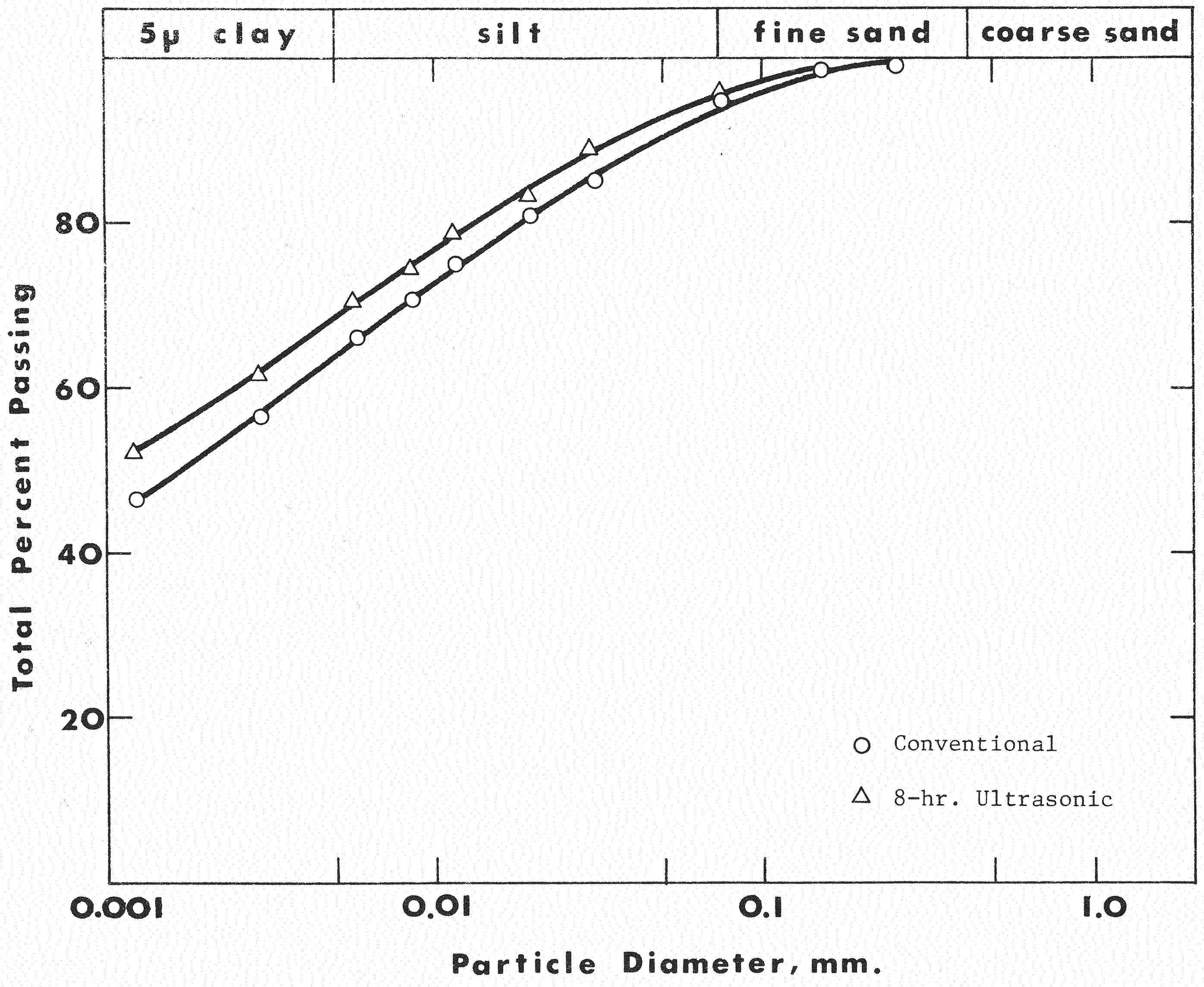


FIG. C.9 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 13

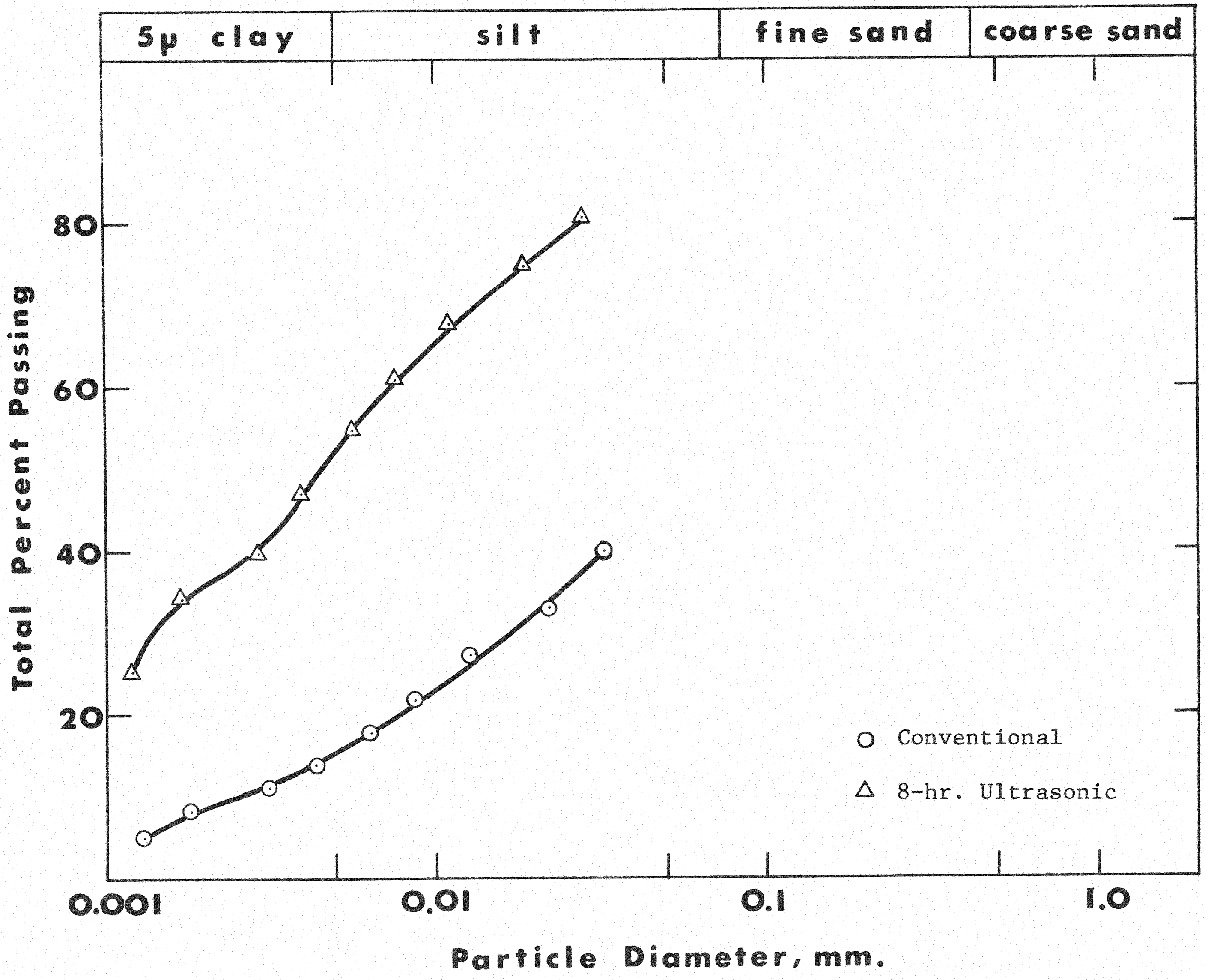


FIG.C.10 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.14

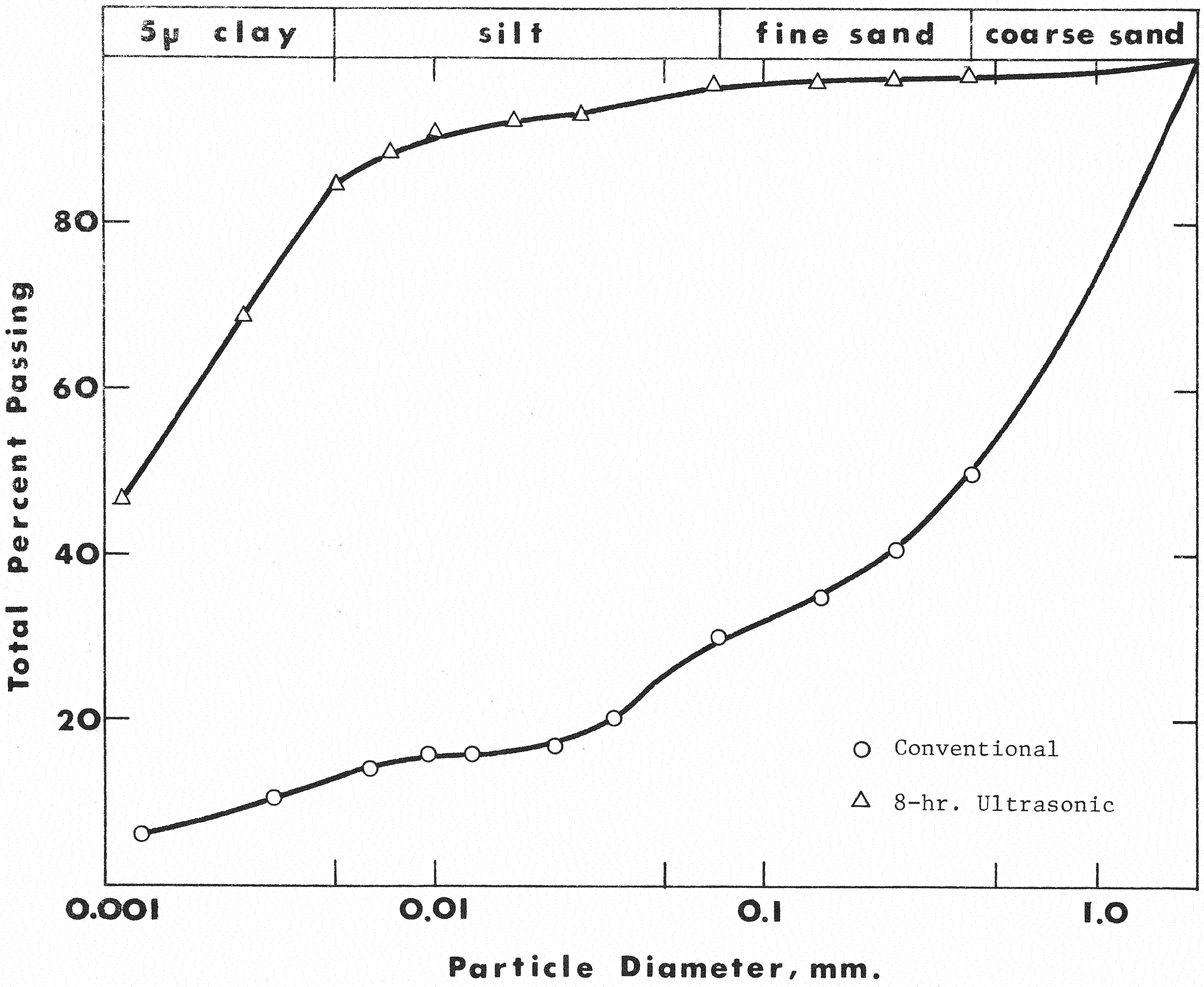


FIG. C.11 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 15

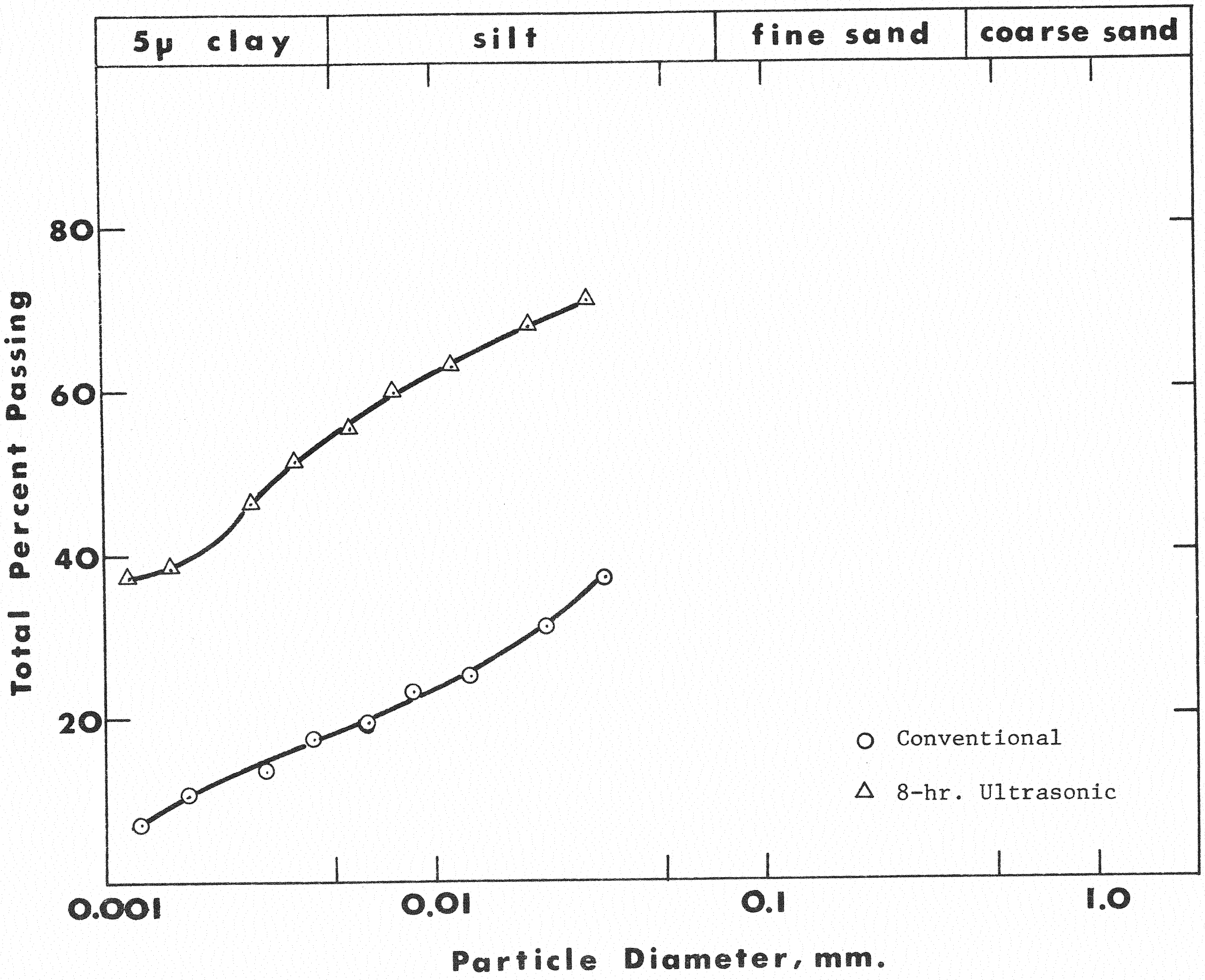


FIG. C.12 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.16

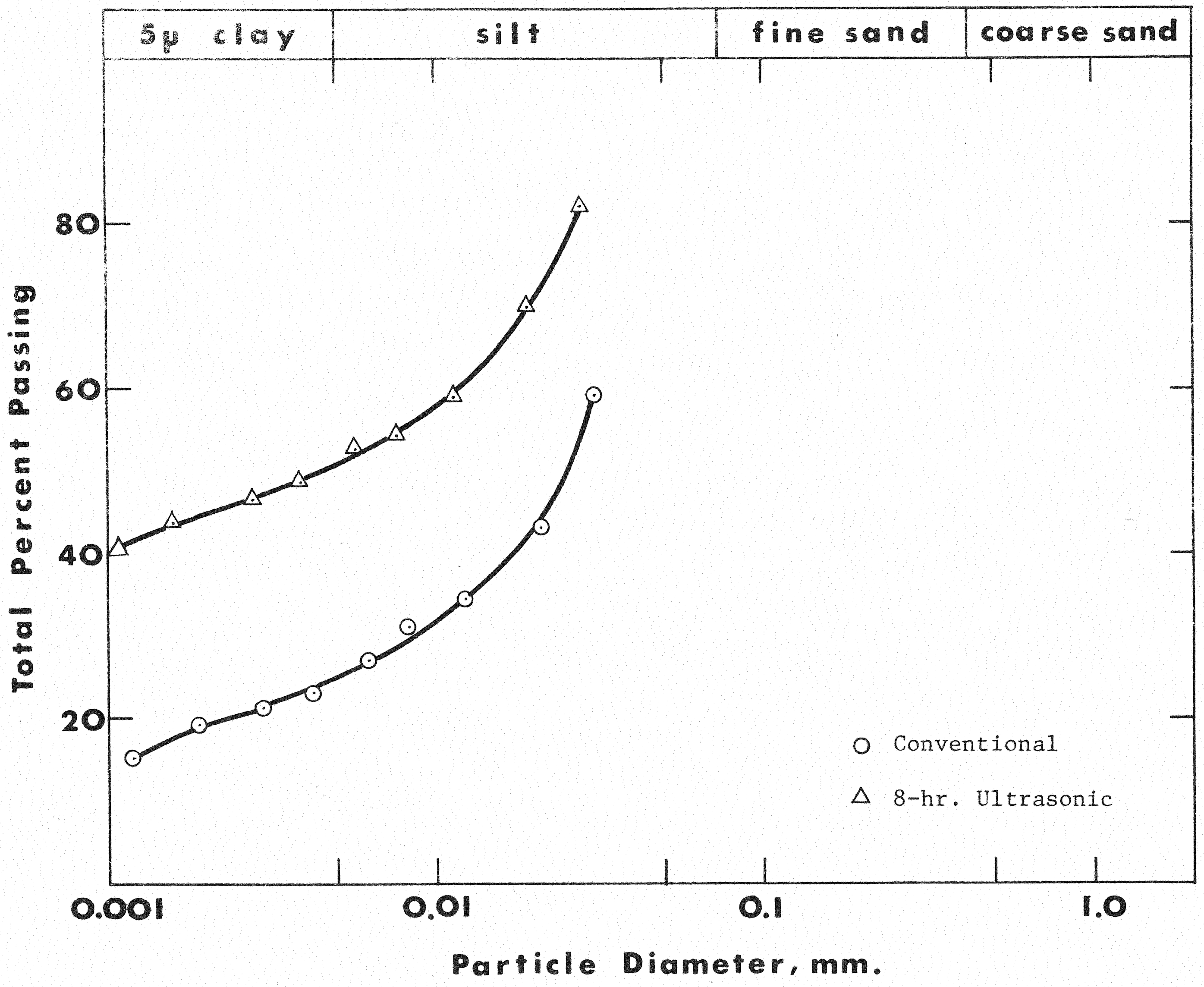


FIG. C.13 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.17

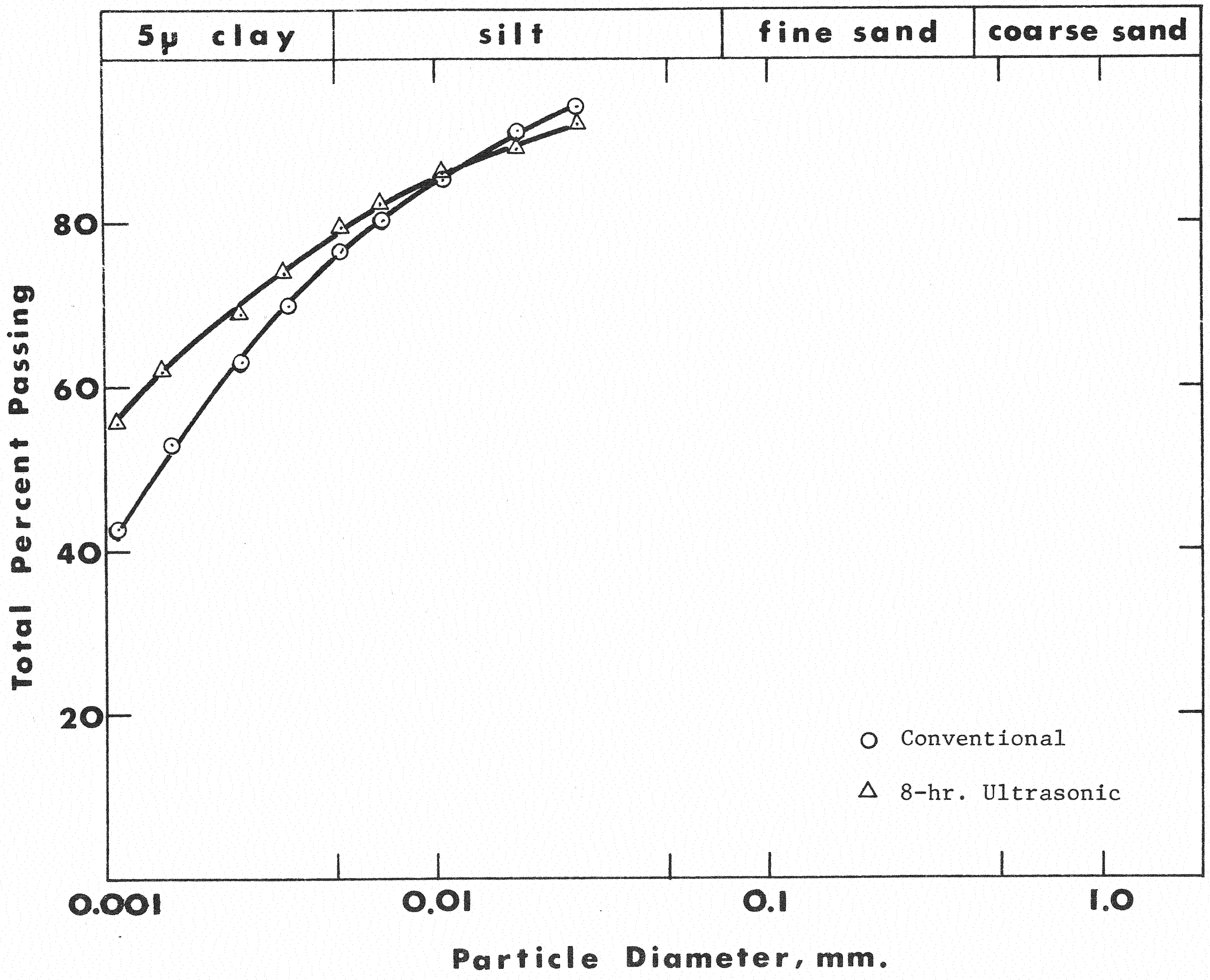


FIG. C.14 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.18

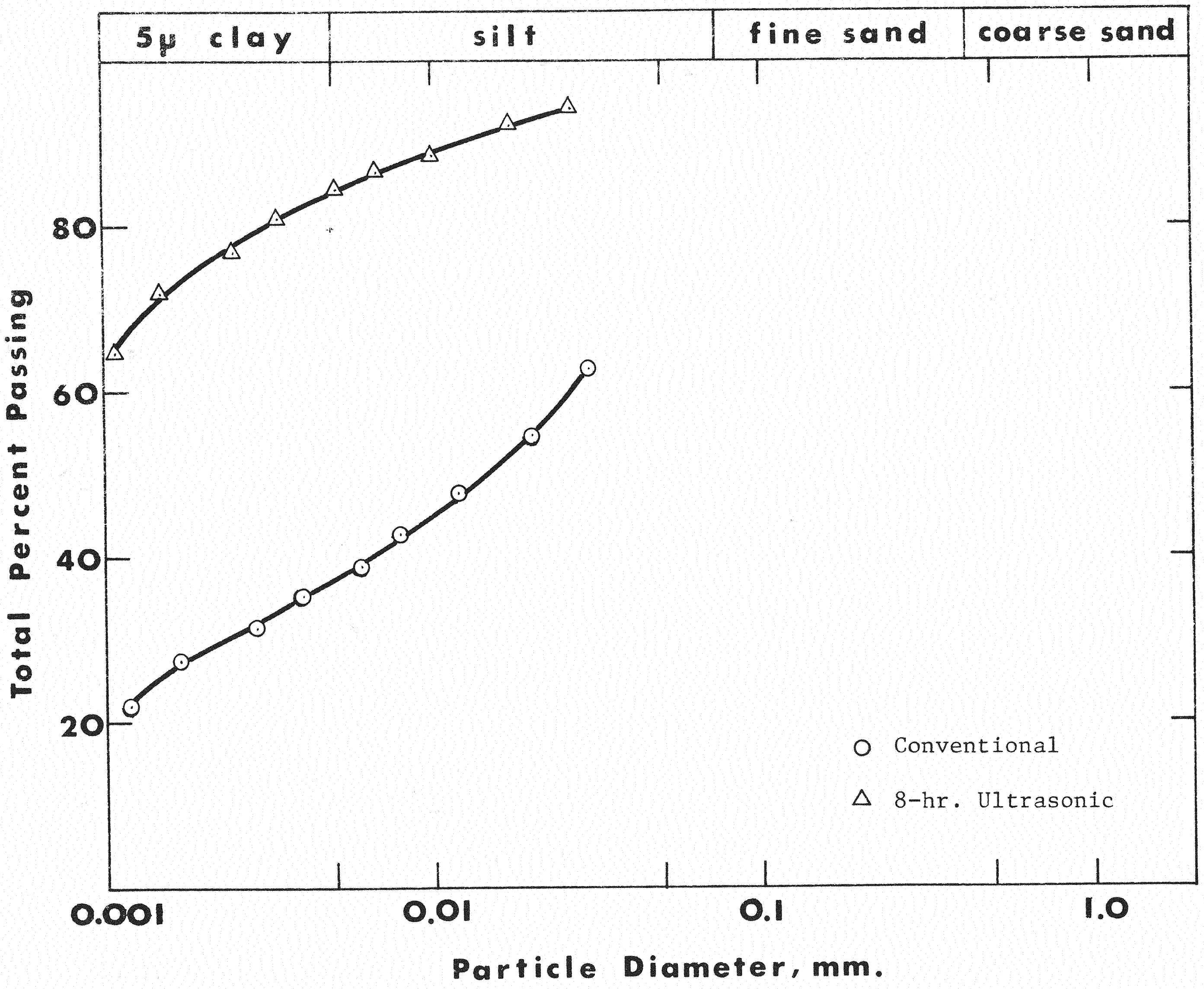


FIG. C.15 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.19

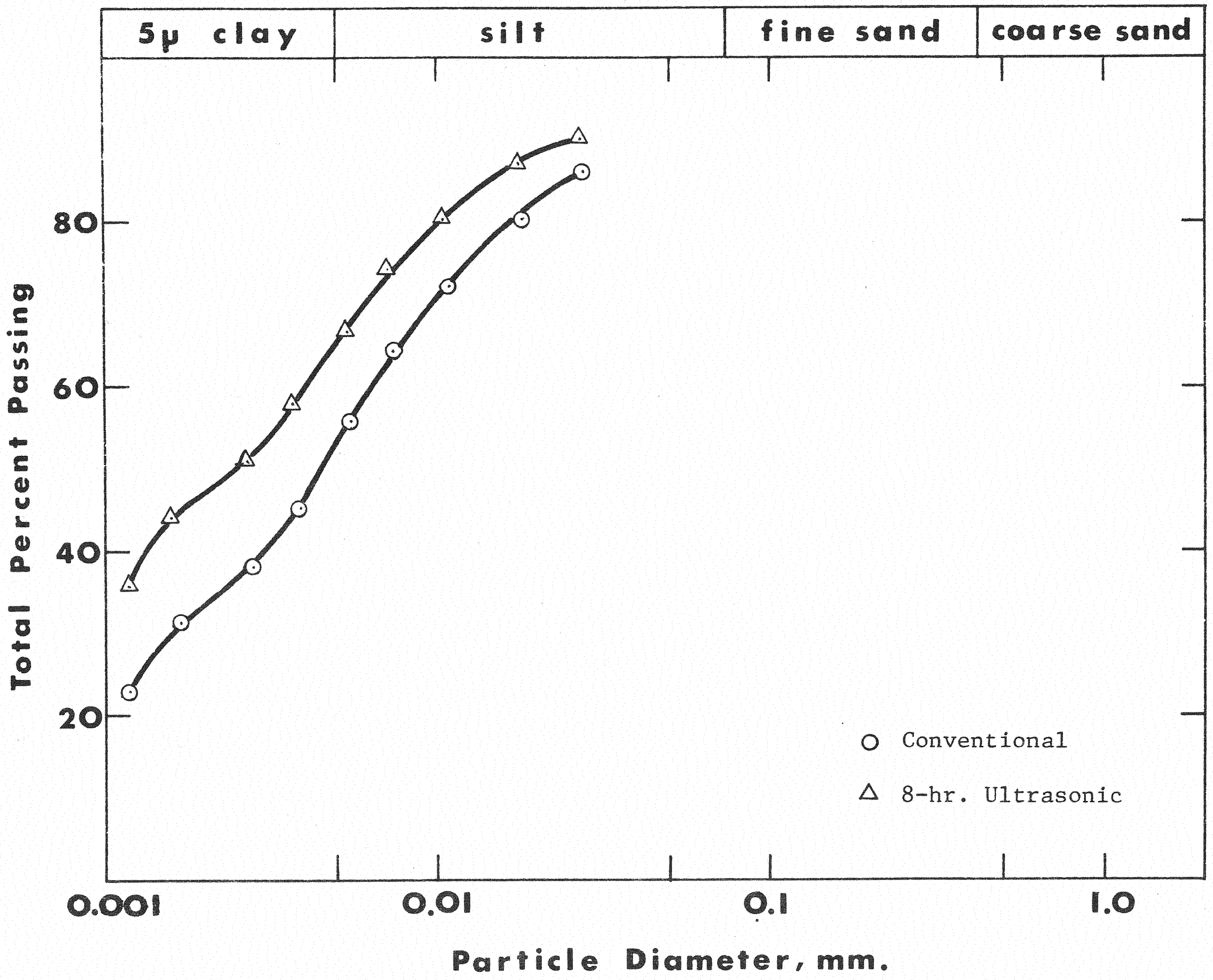


FIG. C.16 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.20

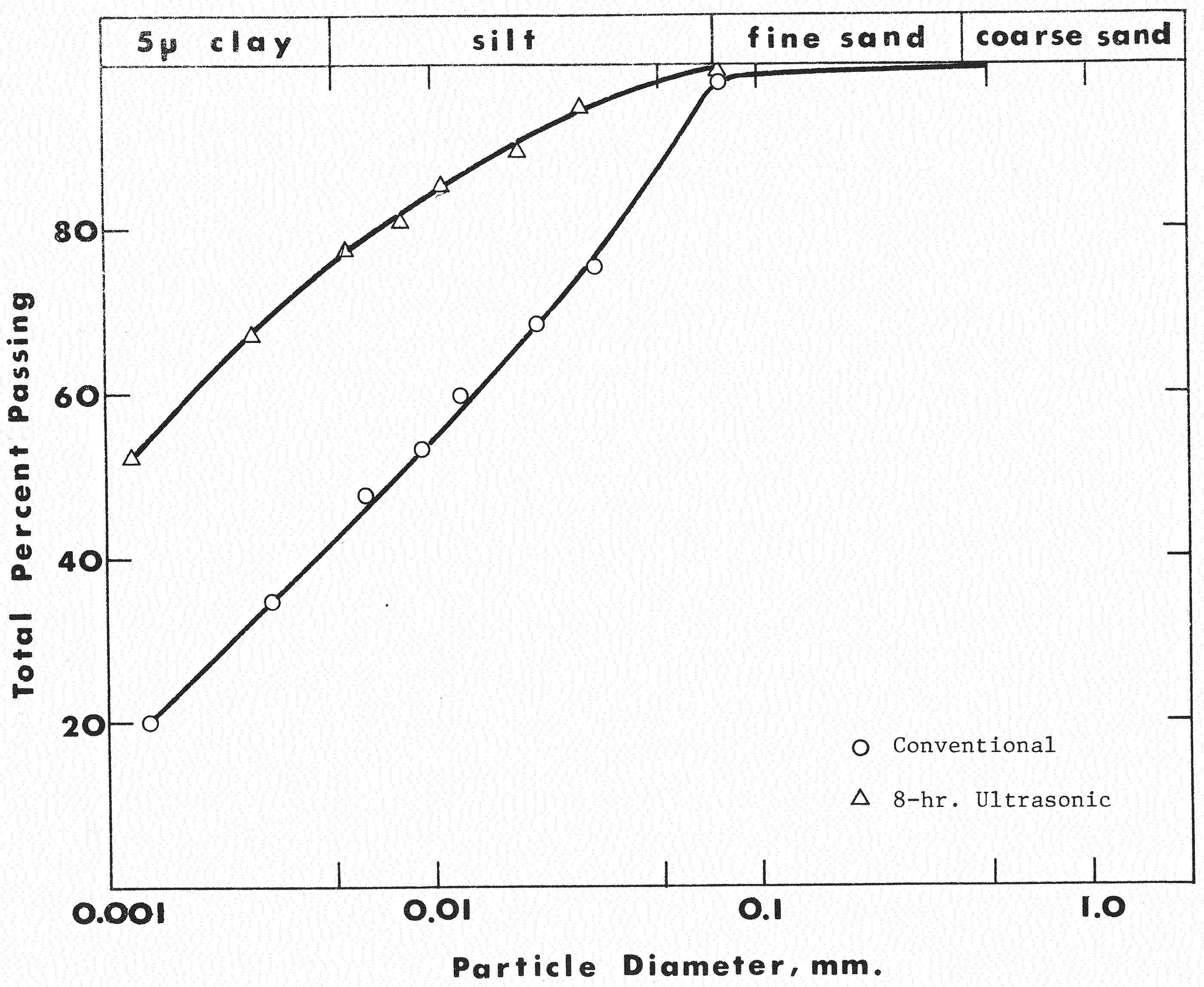


FIG. C.17 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.21

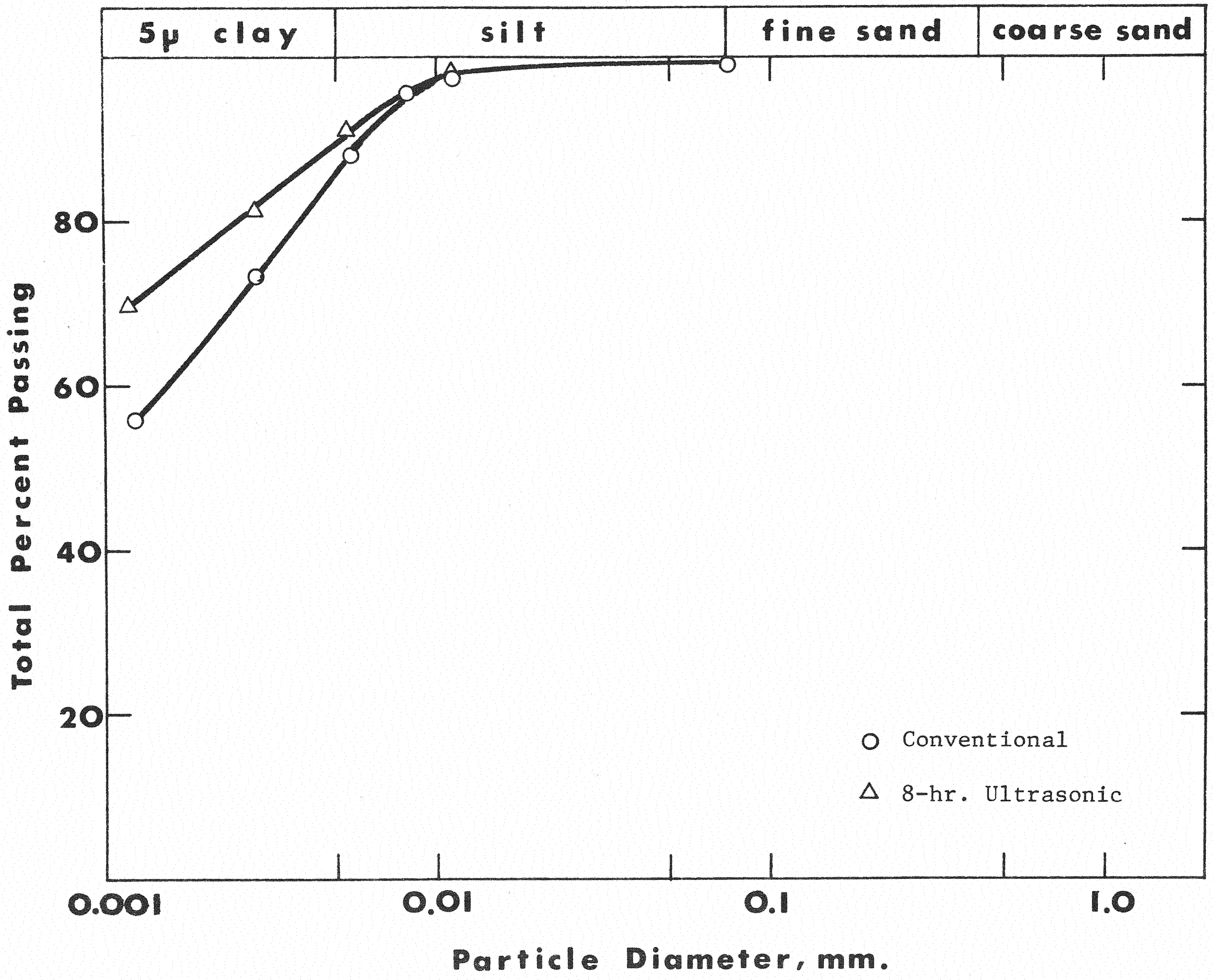


FIG. C.18 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 22

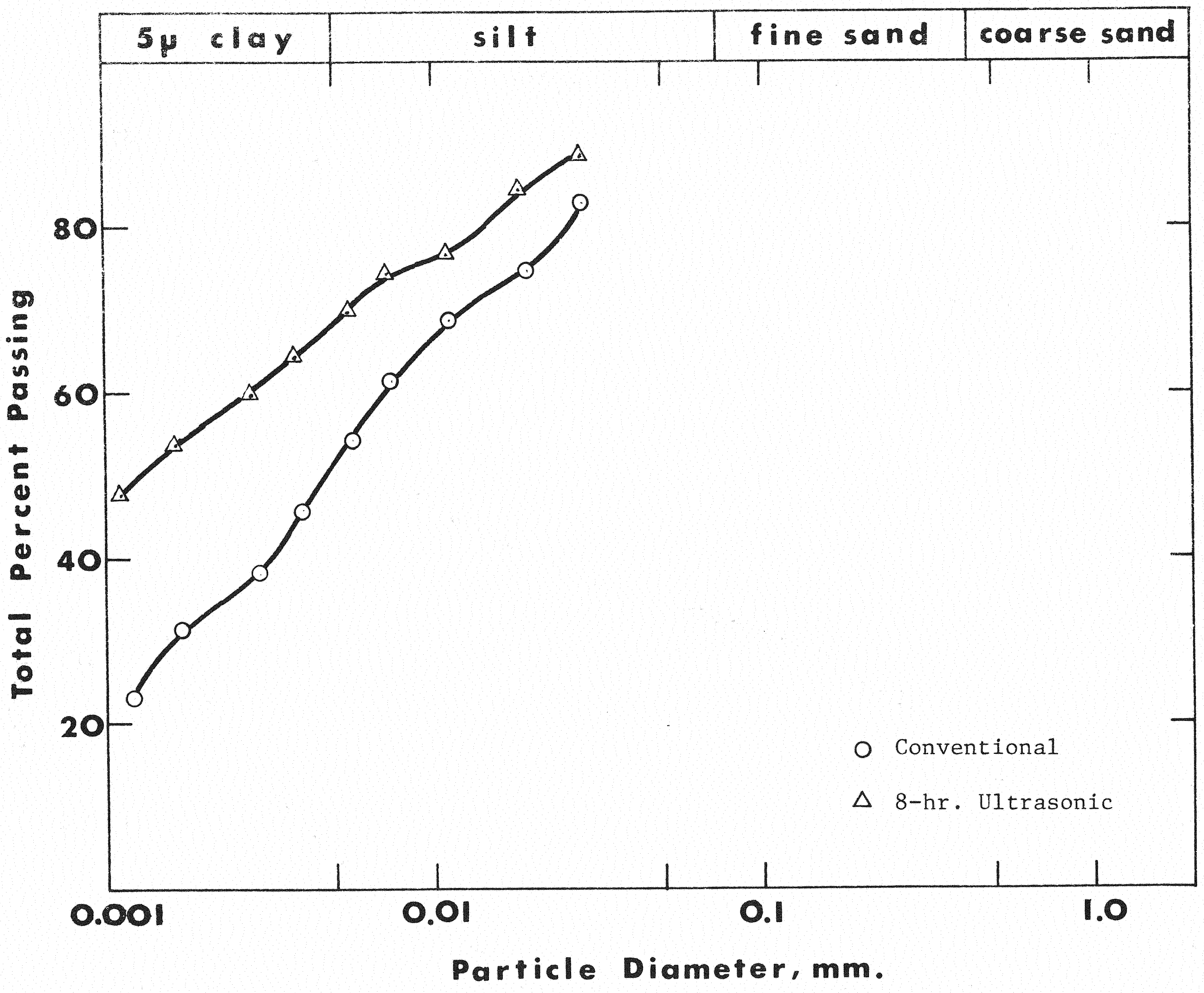


FIG. C.19 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.23

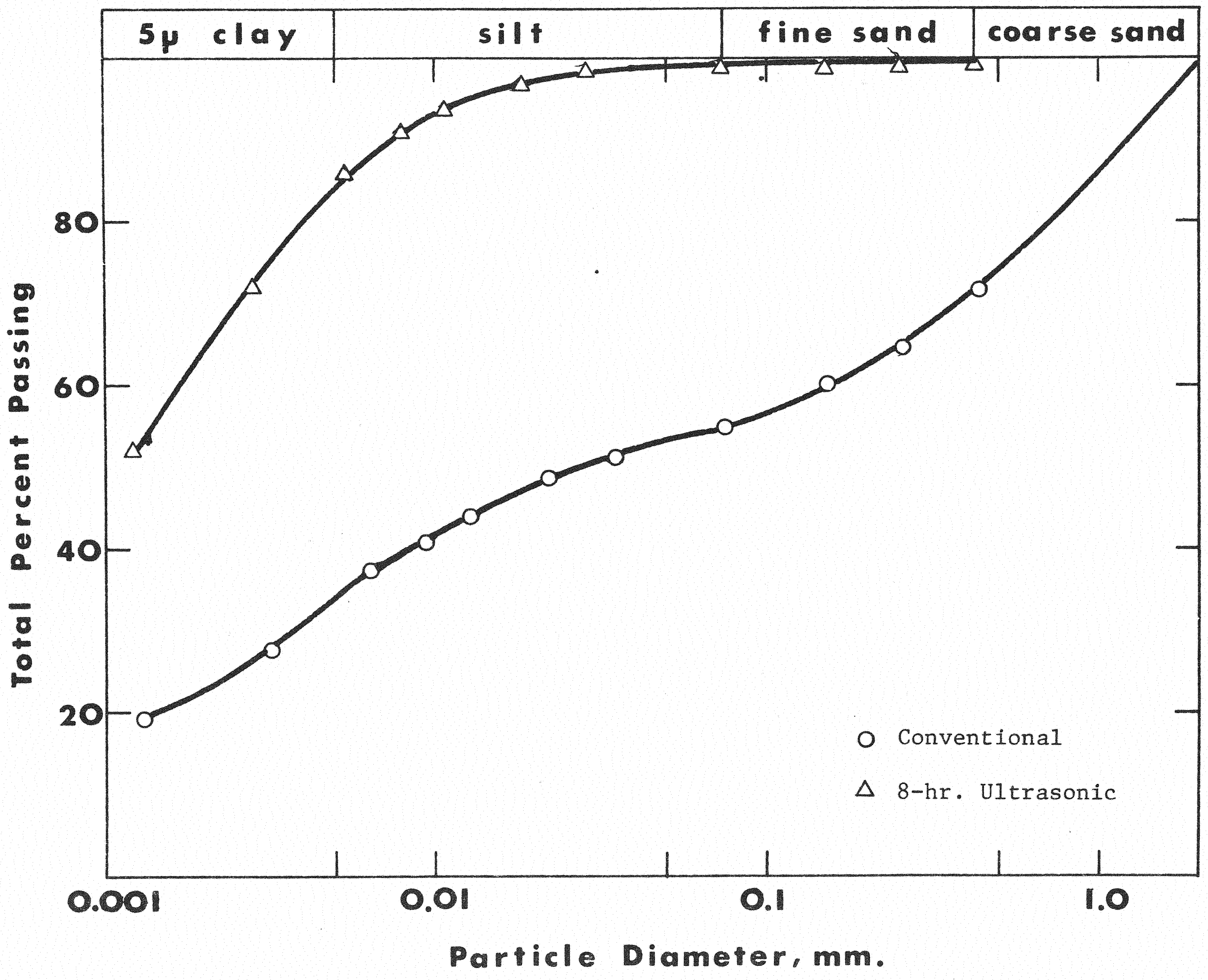


FIG. C.20 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.24

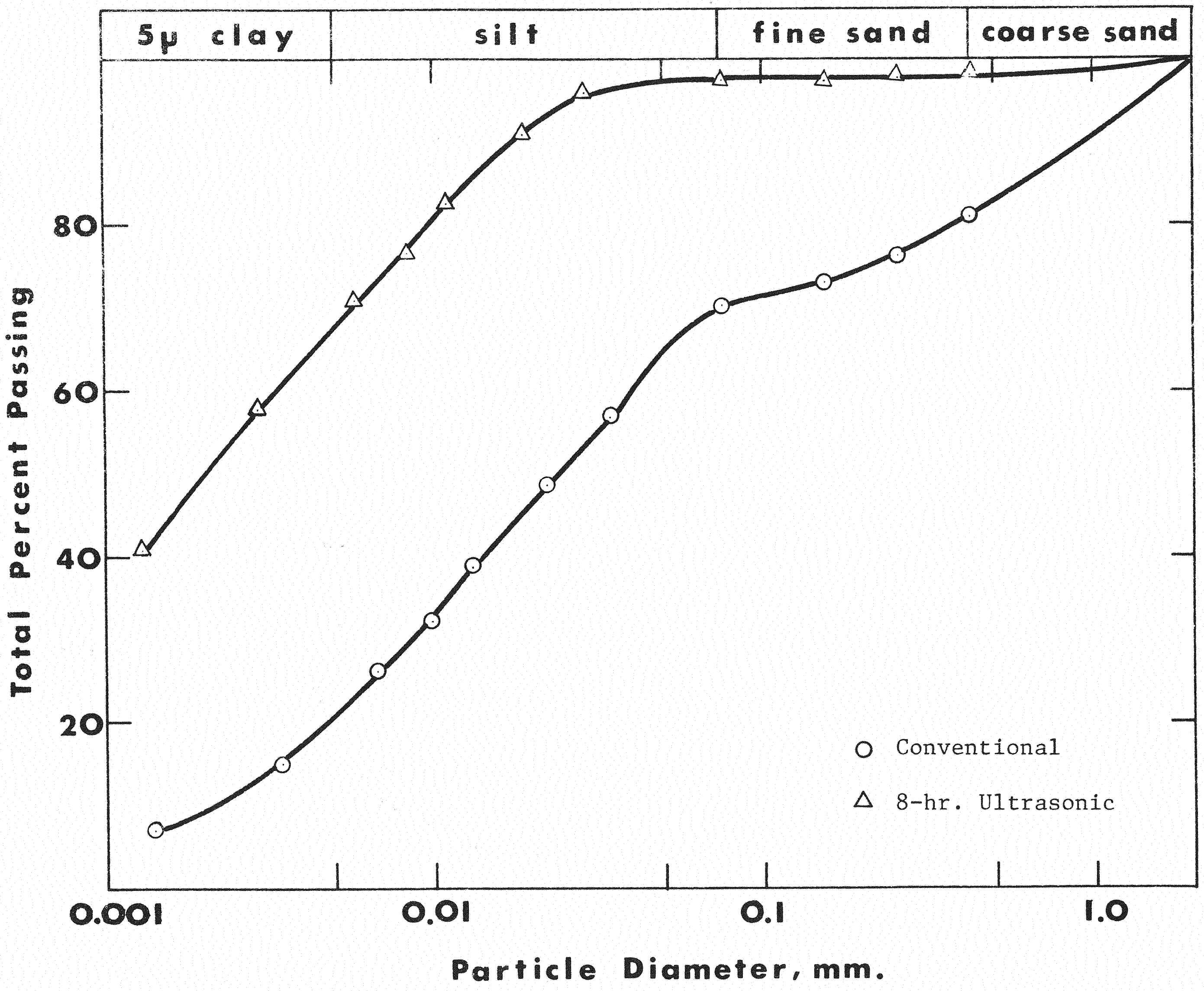


FIG. C.21 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 25

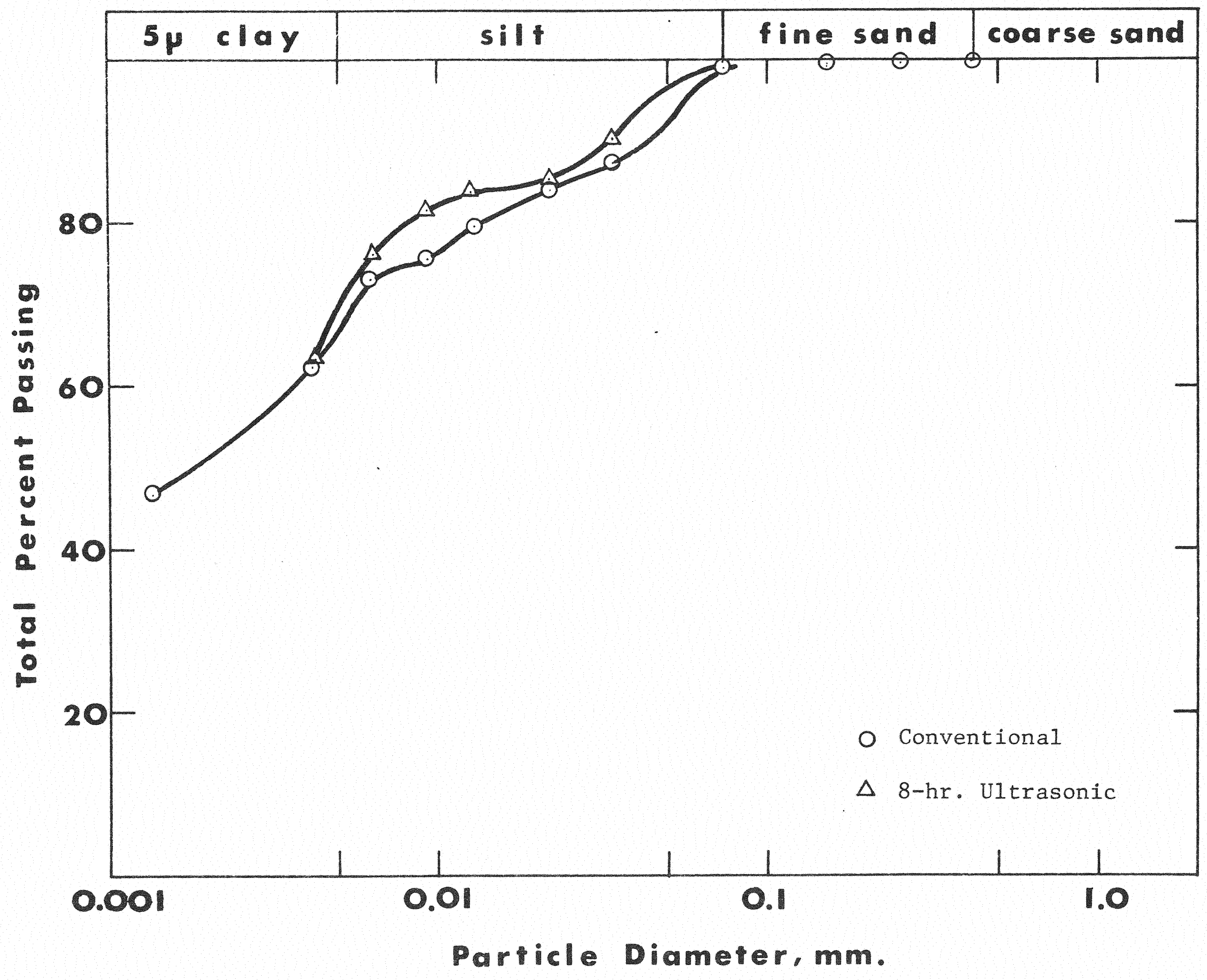


FIG. C.22 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 26

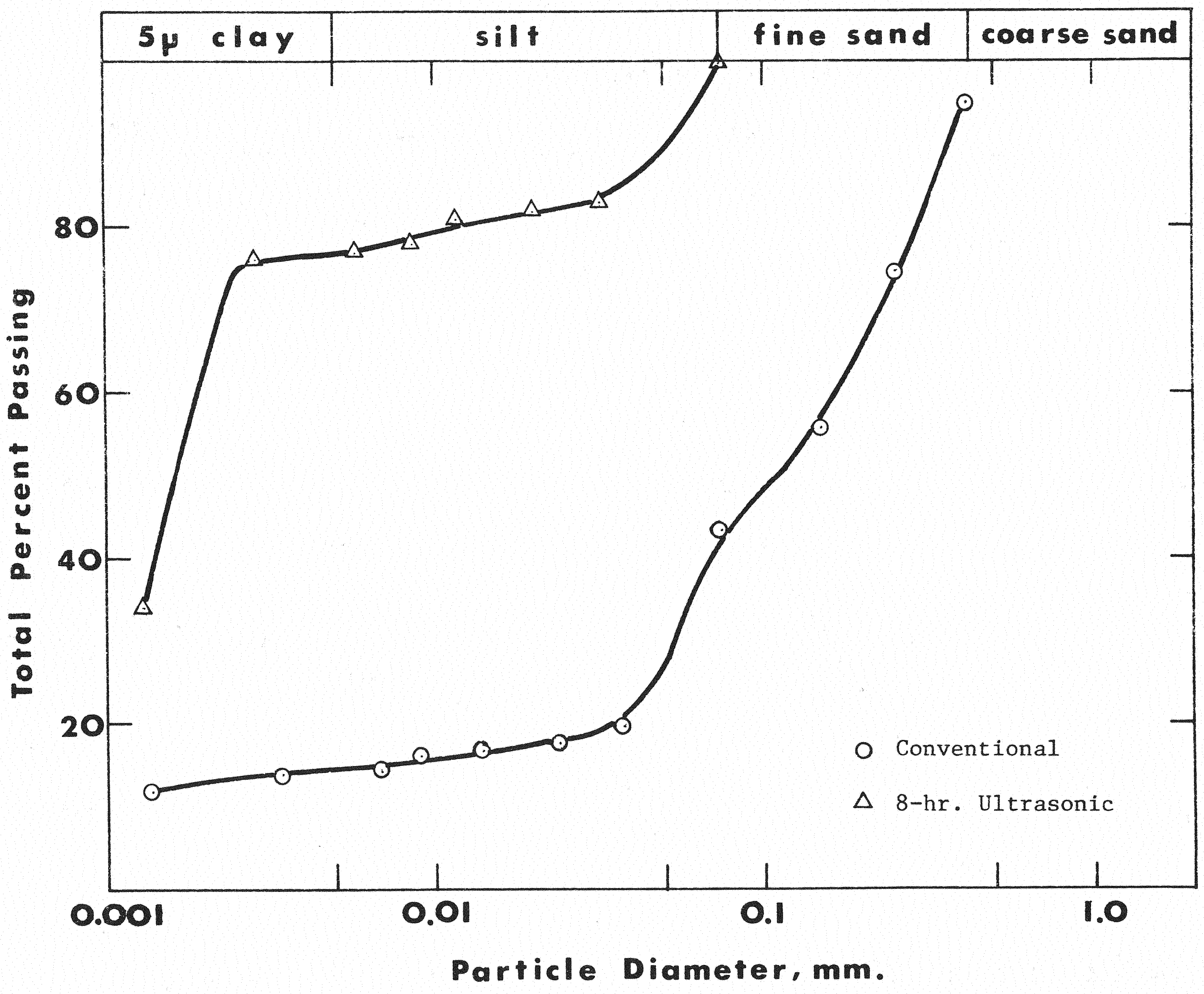


FIG. C.23 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO. 27

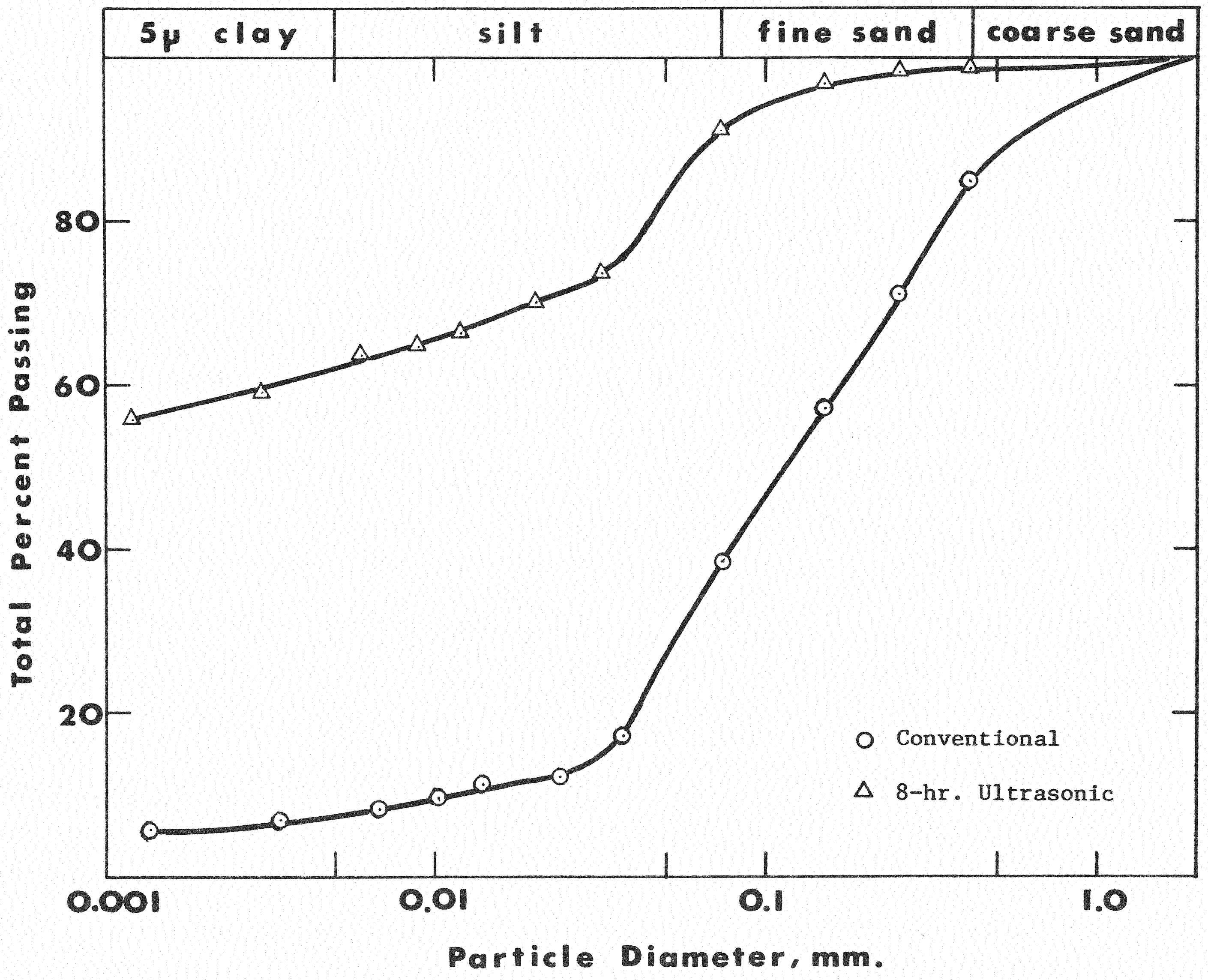


FIG. C.24 GRAIN SIZE DISTRIBUTION CURVES FOR SHALE NO.28

APPENDIX D

CHEMICAL COMPOSITION OF SHALES BY X-RAY FLUORESCENCE ANALYSIS

SILICA SESQUIOXIDE RATIOS OF SHALE SAMPLES

TABLE NO.D.1: CHEMICAL COMPOSITION OF SHALES BY X-RAY FLUORESCENCE ANALYSIS

Percent by Weight

Sample Number	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	CaO	TiO_2	P_2O_5	S	Cl	MnO	LOI	Total
6	55.86	18.50	11.76	1.65	0.04	1.49	1.18	3.96	0.14	0.00	0.00	0.06	7.09	101.73
7	59.70	16.28	7.41	2.59	0.75	3.82	3.50	0.84	0.09	1.59	0.01	0.24	9.63	106.45
8	66.95	14.30	5.99	2.26	0.05	4.77	0.63	0.74	0.04	2.46	0.02	0.03	9.60	107.84
9	59.70	16.71	9.18	2.50	1.05	3.18	2.68	1.09	0.13	0.69	0.01	0.12	6.66	103.70
10	60.55	18.77	8.03	1.41	0.98	2.38	1.73	1.12	0.06	0.02	0.33	0.06	6.12	101.56
11	53.09	13.65	5.19	2.36	0.29	2.19	14.83	0.73	0.13	0.57	0.01	0.06	15.03	108.13
11a	56.28	15.21	5.63	2.52	0.56	2.36	9.98	0.88	0.11	0.05	0.01	0.06	12.02	105.67
12	57.14	17.85	9.72	2.04	0.18	3.21	3.30	0.88	0.15	0.02	0.01	0.35	7.77	102.62
13	65.88	16.19	11.40	0.84	0.08	0.76	0.91	1.26	0.07	0.06	0.01	0.02	4.68	102.16
14	57.35	19.75	9.63	2.08	0.22	3.76	0.56	1.16	0.08	0.51	0.01	0.09	5.94	101.14
15	57.78	17.05	10.60	3.03	1.75	3.48	0.77	1.03	0.12	0.21	0.01	0.06	4.31	100.20
16	58.20	16.79	10.43	3.42	1.53	4.15	0.97	1.07	0.11	0.02	0.01	0.06	4.45	101.21
17	55.65	15.70	9.72	5.00	0.45	3.78	2.00	0.95	0.11	0.02	0.02	0.09	6.75	100.24
18	56.71	16.33	9.36	5.73	0.68	4.88	0.50	0.97	0.10	0.10	0.02	0.06	5.63	101.07
19	55.01	16.29	10.87	4.38	0.49	4.17	1.25	0.98	0.09	0.04	0.04	0.09	7.35	101.05
20	59.06	16.86	13.00	2.58	0.81	2.40	0.43	1.15	0.08	0.01	0.03	0.03	5.20	101.64

TABLE NO. (Cont'd)

21	58.63	16.41	11.76	3.09	0.51	2.41	1.11	1.06	0.07	0.04	0.01	0.04	6.02	101.16
22	53.94	19.49	13.62	1.93	0.18	1.42	1.11	1.52	0.11	0.04	0.01	0.04	9.57	102.98
23	60.76	17.17	9.10	2.07	0.64	3.27	0.56	1.05	0.10	0.05	0.01	0.08	5.85	100.71
24	50.31	17.75	14.86	1.43	0.27	3.50	2.20	1.02	0.26	0.07	0.01	1.12	9.62	102.42

TABLE NO. D.2: SILICA SESQUIOXIDE RATIOS OF SHALE SAMPLES

Shale Number	Silica Sesquioxide Ratio
6	1.8
7	2.5
8	3.3
9	2.3
10	2.3
11	2.8
11a	2.7
12	2.1
13	2.4
14	1.8
15	2.1
16	2.1
17	2.2
18	2.2
19	2.1
20	1.9
21	2.1
22	1.6
23	2.3
24	1.5

APPENDIX E

FACTOR ANALYSIS TABLES

TABLE E.1: AASHO CLASSIFICATION TRANSFORMATION

AASHO CLASSIFICATION	UNDESIRABILITY INDEX
A-1-a	1
A-1-b	1
A-3	2
A-2-4	3
A-2-5	4
A-2-6	5
A-2-7	7
A-4	8
A-5	15
A-6	20
A-7-5	28
A-7-6	30

TABLE E.2: ENERGY INDICES FOR CLAYS

Sample no.	Area Under peak, cm^2				Energy Index[c]				
	K (10)	I (25)	M (115)	ML[a] (70)[b]	K	I	M	ML	Cumulative
6	1.15	0.63	26.85	7.24	1.15	1.57	308.77	50.68	362.17
7	0.12	0.85	0.12	0.00	0.12	2.12	1.38	0.00	3.62
8	0.00	0.18	0.00	0.00	0.00	0.45	0.00	0.00	0.45
9	0.52	1.20	0.32	0.00	0.52	3.00	3.68	0.00	7.20
10	5.60	15.80	4.90	0.00	5.60	39.50	56.35	0.00	101.45
11	0.18	0.60	1.80	0.00	0.18	1.50	20.70	0.00	22.38
11a	0.49	1.49	2.59	4.37	0.49	3.72	29.79	30.59	64.59
12	1.30	3.36	12.04	4.75	1.30	8.40	138.46	33.25	148.16
13	10.96	0.00	86.30	0.00	10.96	0.00	992.45	0.00	1003.41
14	0.32	0.94	0.10	0.00	0.32	2.35	1.15	0.00	3.82
15	0.35	0.84	0.27	0.00	0.35	2.10	3.10	0.00	5.55
16	0.11	1.71	0.33	0.00	0.11	4.27	3.80	0.00	8.18
17	0.45	3.40	0.45	0.00	0.45	8.50	5.18	0.00	14.13
18	0.18	3.60	0.14	0.00	0.18	9.00	1.61	0.00	10.79
19	0.42	3.30	0.32	0.00	0.42	8.25	3.68	0.00	12.35
20	1.26	5.02	2.24	3.20	1.26	12.55	25.76	22.40	56.97
21	0.76	1.71	2.59	6.70	0.76	4.27	29.79	46.90	81.72
22	4.81	3.38	3.74	6.25	4.81	8.45	43.01	43.75	100.02
23	1.26	3.49	1.56	1.79	1.26	8.72	17.94	12.53	40.45
24	0.55	1.35	0.08	0.00	0.55	3.37	0.92	0.00	4.82

[a] K= Kaolinite; I= Illite; M = Montmorillonite; ML = Mixed-layer Illite-Montmorillonite

[b] Average cation exchange capacity of clay mineral (Grim, R.E., Clay Mineralogy, McGraw-Hill Book Company, New York, 1968, p 189.)

[c] Energy Index = Area under peak x avg. CEC, in 10^{-1} cm^2 m.e.g./100 gm.

TABLE E.3: FACTOR ANALYSIS SCHEMES

	Scheme A	Scheme B	Scheme C
Number of Properties	21	19	20
Property[a]			
1. Maximum dry density	1	1	1
2. Optimum moisture content	2	2	2
3. Specific Gravity	3	3	3
4. pH	4	4	4
5. Liquid Limit (conventional)	5	5	5
6. Plasticity Index (conventional)	6	6	6
7. Shrinkage Limit	7	7	7
8. % Silt (conventional)	8	8	8
9. % 5μ clay (conventional)	9	9	9
10. % 2μ clay (conventional)	10	10	10
11. % Silt (ultrasonic)	11	11	11
12. %5μ clay (ultrasonic)	12	12	12
13. %2μ clay (ultrasonic)	13	13	13
14. % Volume Change	14	14	14
15. Unconfined compress. strength	15	15	15
16. Cohesion	16	16	16
17. Angle of Friction	17	17	17
18. Activity coefficient (Conv.)	18	18	18
19. Silica Sesqui-oxide Ratio	19	19	19
20. AASHO Classification	20		20
21. Predominant Clay Minerals	21		

---

[a] The property numbers are those referred to in subsequent tables.

TABLE E.4: FACTOR MATRIX FOR SCHEME A

Property (Variable)	Factors						
	I	II	III	IV	V	VI	VII
1	0.87	-0.00	0.25	-0.15	0.14	-0.09	0.06
2	-0.84	-0.04	-0.33	0.26	-0.08	-0.20	0.03
3	-0.05	0.16	-0.20	-0.55	0.17	-0.75	-0.05
4	-0.18	0.18	-0.09	-0.15	-0.78	-0.39	-0.16
5	-0.87	0.33	0.20	0.05	-0.10	-0.07	0.07
6	-0.85	0.33	0.31	0.14	0.08	0.04	-0.02
7	-0.06	0.26	-0.84	0.14	-0.32	0.04	0.01
8	0.24	0.09	0.05	-0.92	-0.07	-0.10	0.11
9	-0.96	-0.12	0.05	0.07	0.07	-0.08	-0.14
10	-0.95	-0.12	0.07	0.16	0.13	-0.09	-0.12
11	0.31	0.11	0.12	-0.85	0.03	0.07	-0.25
12	-0.83	-0.00	-0.08	0.20	-0.08	-0.44	0.10
13	-0.81	-0.03	-0.14	0.28	-0.06	-0.38	0.17
14	-0.78	0.09	0.47	0.13	0.09	0.02	-0.17
15	-0.43	0.65	0.27	-0.33	-0.24	0.01	0.18
16	-0.17	0.83	-0.12	-0.05	-0.07	-0.06	-0.45
17	0.11	-0.23	-0.04	0.06	0.03	0.06	0.90
18	0.13	0.93	-0.20	-0.06	-0.02	-0.16	-0.11
19	0.23	-0.18	-0.16	-0.11	0.16	0.82	0.07
20	-0.84	0.23	-0.04	-0.18	-0.20	-0.02	-0.11
21	-0.25	-0.01	0.22	-0.05	0.91	-0.07	-0.07

TABLE E.5: FACTOR MATRIX FOR SCHEME B

Property (Variable)	Factors I	II	III	IV	V	VI
1	-.87	-.01	-.34	-.03	-.06	.17
2	.84	-.05	.37	-.22	.03	-.23
3	.02	-.05	.10	-.76	-.06	.50
4	.12	.28	.30	-.61	-.08	.17
5	.86	.40	-.09	-.11	.04	-.03
6	.84	.39	-.25	.04	-.06	-.14
7	.01	.19	.92	-.06	-.00	-.13
8	-.28	.13	-.06	-.17	.14	.89
9	.97	-.09	-.03	-.08	-.14	-.04
10	.97	-.10	-.06	-.07	-.12	-.12
11	-.32	.11	-.12	.05	-.24	.86
12	.81	.02	.08	-.46	.09	-.22
13	.79	-.02	.13	-.40	.16	-.31
14	.81	.16	-.39	.06	-.18	-.08
15	.38	.75	-.13	-.11	.15	.30
16	.12	.77	.22	-.10	-.51	.05
17	-.08	-.18	.03	.11	.91	-.05
18	-.19	.85	.23	-.19	-.19	.02
19	-.22	-.17	.16	.81	.08	.15

TABLE E.6:FACTOR MATRIX FOR SCHEME C

Property (Variable)	Factors					
	I	II	III	IV	V	VI
1	.856	-0.001	-.218	-.003	-.0072	-.310
2	-.825	-.057	.258	-.242	.043	.352
3	-.051	-.068	-.575	-.700	-.083	.124
4	-.104	.281	-.119	-.642	-.066	.274
5	-.856	.388	.067	-.138	.061	-.119
6	-.849	.371	.159	.024	-.042	-.265
7	-.015	.206	.131	-.070	-.003	.908
8	.253	.129	-.909	-.113	.127	-.055
9	-.965	-.101	.068	-.086	-.134	-.045
10	-.960	-.117	.153	-.076	-.115	-.077
11	.310	.133	-.840	.079	-.241	-.136
12	-.814	-.014	.195	-.461	.088	.090
13	-.794	-.049	.279	-.398	.158	.145
14	-.782	.150	.146	.012	-.147	-.437
15	-.390	.742	-.290	-.108	.170	-.153
16	-.137	.782	-.033	-.115	-.495	.149
17	.098	-.187	.061	.102	.906	.035
18	.156	.855	-.054	-.177	-.191	.238
19	.206	-.153	-.120	.843	.066	.171
20	-.854	.205	-.192	.019	-.156	.034

TABLE E.7:FACTOR DEFINITION SUMMARY

Factor	Scheme	Defining Properties
I	A	1,2,5,6,9,10,12,13,14,20
	B	1,2,5,6,9,10,12,13,14
	C	1,2,5,6,9,10,12,13,14,20
II	A	15,16,18
	B	15,16,18
	C	15,16,18
III	A	7
	B	7
	C	8,11
IV	A	8, 11
	B	3,4,19
	C	3,4,19
V	A	4,21
	B	17
	C	17
VI	A	3,19
	B	8,11
	C	7
VII	A	17
	B	
	C	

TABLE E.8: SAMPLE REGION CLUSTERS: SCHEME A

	5-Point Spread	
Cluster	Sample no. and County	Similarity Index
1	8 Mayes	14.6
2	7 Tulsa	9.2
	14 LeFlore	8.8
	9 Nowata	8.7
	15 LeFlore	8.1
	24 McIntosh	5.5
	17 Kingfisher	4.4
3	11a Osage	2.5
	16 Blaine	1.6
	11 Osage	0
	23 Coal	- .6
	21 Stephens	- .9
4	10 Pawnee	-2.8
	20 Tillman	-2.9
	19 Tillman	-3.4
	13 McCurtain	-3.9
	6 Bryan	-7.1
5	18 Greer	-9.9
	22 Carter	-13.5
6	12 McCurtain	-18.3

	1.5 Point Spread	
Cluster	Sample no. and County	Similarity Index
1	8 Mayes	14.6
2	7 Tulsa	9.2
	14 LeFlore	8.8
	9 Nowata	8.7
	15 LeFlore	8.1
3	24 McIntosh	5.5
	17 Kingfisher	4.4
4	11a Osage	2.5
	16 Blaine	1.6
5	11 Osage	0
	23 Coal	- .6
	21 Stephens	- .9
6	10 Pawnee	-2.8
	20 Tillman	-2.9
	19 Tillman	-3.4
	13 McCurtain	-3.9
7	6 Bryan	-7.1
8	18 Greer	-9.9
9	22 Carter	-13.5
10	12 McCurtain	-18.3

TABLE E.9:SAMPLE REGION CLUSTERS: SCHEME B

5 Point Spread

Cluster	Sample no. and County		Similarity Index
1	12	McCurtain	17.68
2	22	Carter	12.73
3	18	Greer	8.99
	6	Bryan	6.72
4	19	Tillman	3.23
	20	Tillman	2.77
	13	McCurtain	2.34
	10	Pawnee	1.88
	21	Stephens	.64
	23	Coal	.46
5	11	Osage	-1.0
	11a	Osage	-1.57
	16	Blaine	-2.32
	24	McIntosh	-4.52
	17	Kingfisher	-4.53
6	15	LeFlore	-6.21
	14	LeFlore	-7.81
	7	Tulsa	-8.17
	9	Nowata	-8.92
7	8	Mayes	-12.45

1.5 Point Spread

Cluster	Sample no. and County		Similarity Index
1	12	McCurtain	17.68
2	22	Carter	12.73
3	18	Greer	8.99
4	6	Bryan	6.72
5	19	Tillman	3.23
	20	Tillman	2.77
	13	McCurtain	2.34
	10	Pawnee	1.88
6	21	Stephens	.64
	23	Coal	.46
7	11	Osage	-1.0
	11a	Osage	-1.57
	16	Blaine	-2.32
8	24	McIntosh	-4.52
	17	Kingfisher	-4.53
9	15	LeFlore	-6.21
10	14	LeFlore	-7.81
	7	Tulsa	-8.17
	9	Nowata	-8.92
11	8	Mayes	-12.45

TABLE E.10: SAMPLE REGION CLUSTERS: SCHEME C

5 Point Spread

Cluster	Sample no. and County		Similarity Index
1	8	Mayes	13.99
	9	Nowata	9.52
2	7	Tulsa	8.94
	14	LeFlore	8.49
	15	LeFlore	7.68
	24	McIntosh	5.34
3	17	Kingfisher	4.26
	11a	Osage	2.38
	16	Blaine	1.88
	11	Osage	- .15
	23	Coal	- .69
4	21	Stephens	- .89
	20	Tillman	-2.91
	10	Pawnee	-2.92
	19	Tillman	-3.35
	13	McCurtain	-3.41
5	6	Bryan	-6.83
	18	Greer	-9.81
6	22	Carter	-13.34
	12	McCurtain	-18.20

1.5 Point Spread

Cluster	Sample no. and County		Similarity Index
1	8	Mayes	13.99
2	9	Nowata	9.52
	7	Tulsa	8.94
	14	LeFlore	8.49
3	15	LeFlore	7.68
4	24	McIntosh	5.34
	17	Kingfisher	4.26
5	11a	Osage	2.38
6	16	Blaine	1.88
7	11	Osage	- .15
	23	Coal	- .69
	21	Stephens	- .89
8	20	Tillman	-2.91
	10	Pawnee	-2.92
	19	Tillman	-3.35
	13	McCurtain	-3.41
9	6	Bryan	-6.83
10	18	Greer	-9.81
11	22	Carter	-13.34
12	12	McCurtain	-18.20

APPENDIX F

EFFECT OF ULTRASONIC DISAGGREGATION ON GRAIN SIZE DISTRIBUTION OF SHALES

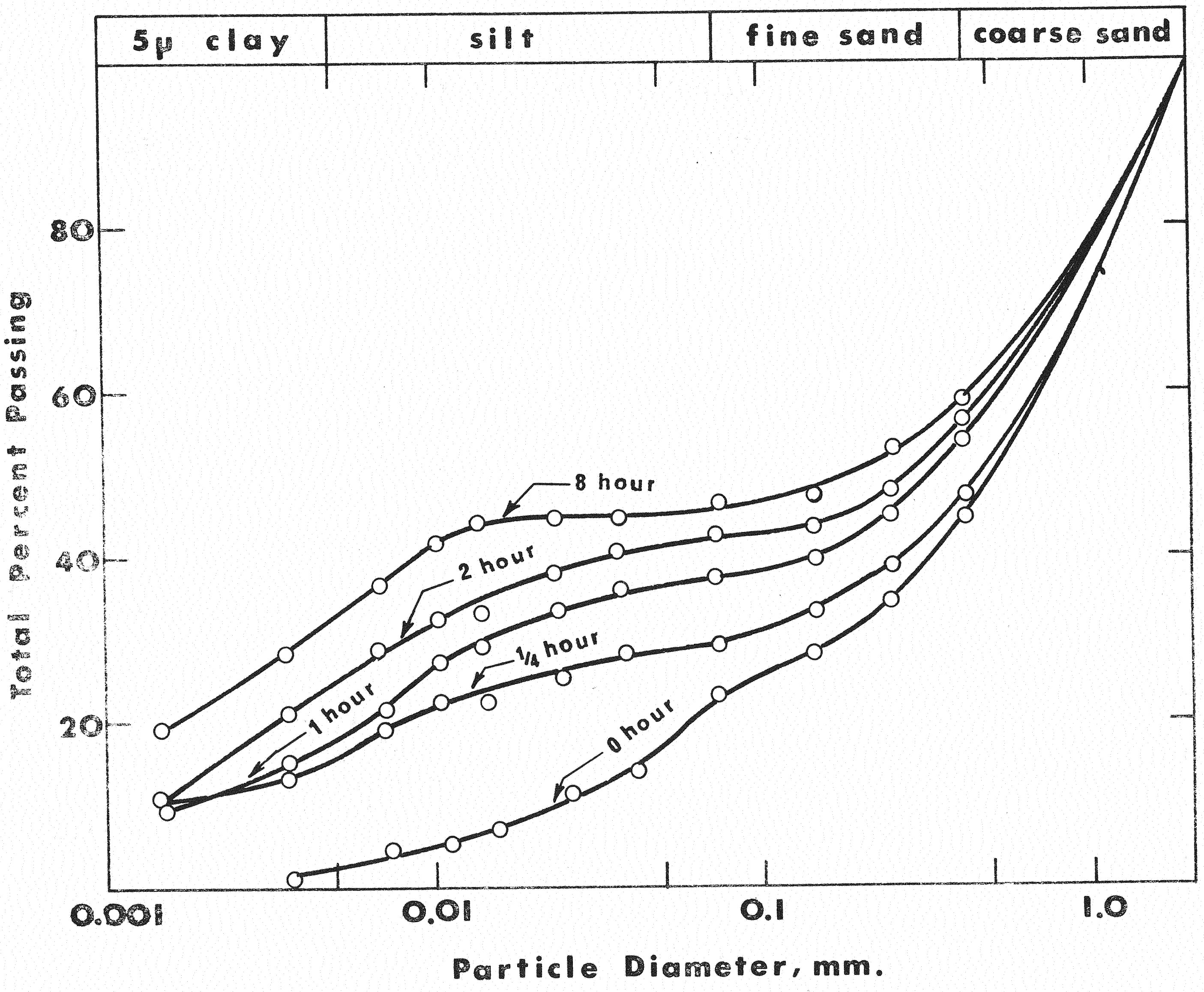


FIG. F.1: EFFECT OF ULTRASONIC TREATMENT ON GRAIN SIZE DISTRIBUTION OF SHALE NO. 8

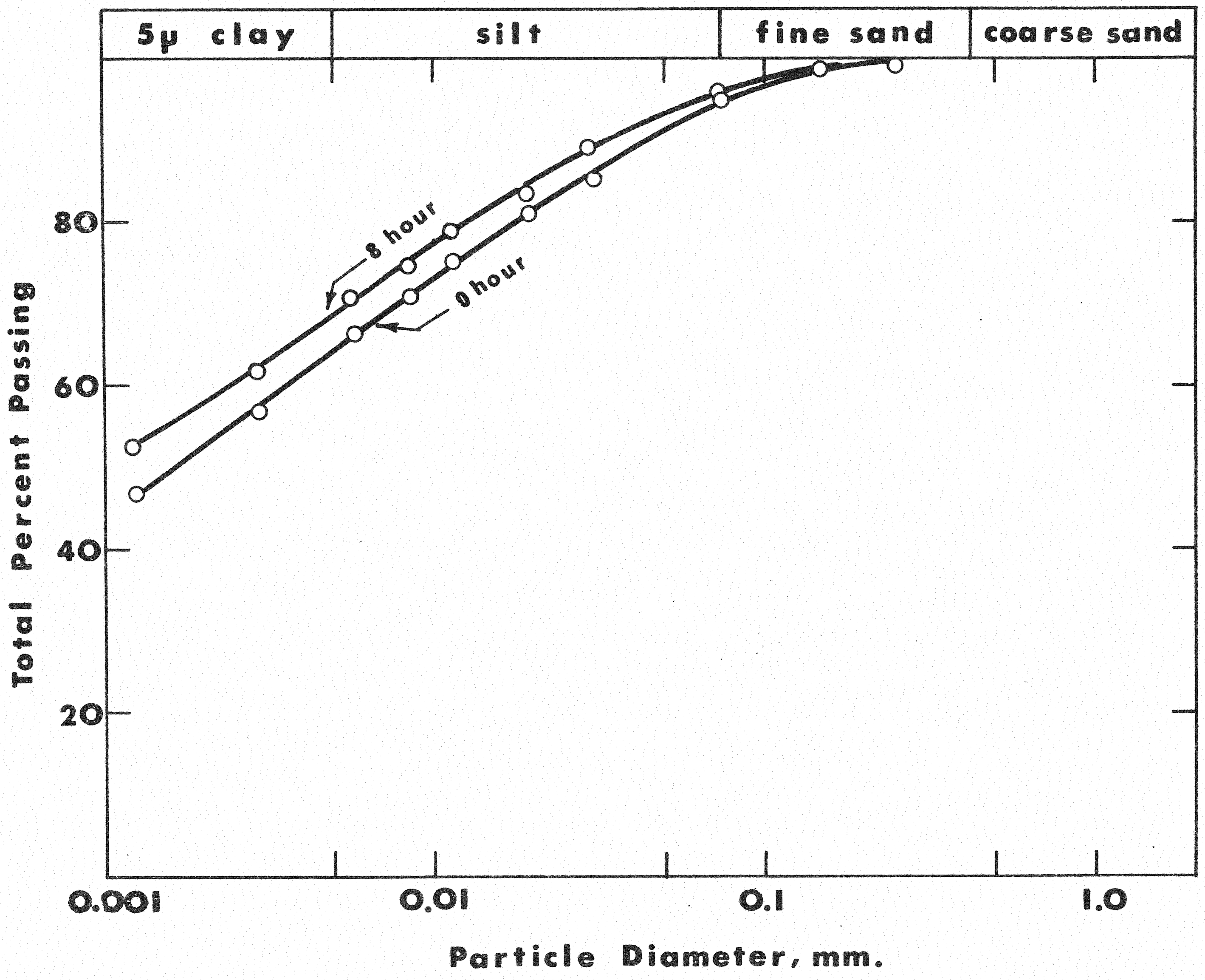


FIG. F.2: EFFECT OF ULTRASONIC TREATMENT ON GRAIN SIZE DISTRIBUTION OF SHALE NO. 13

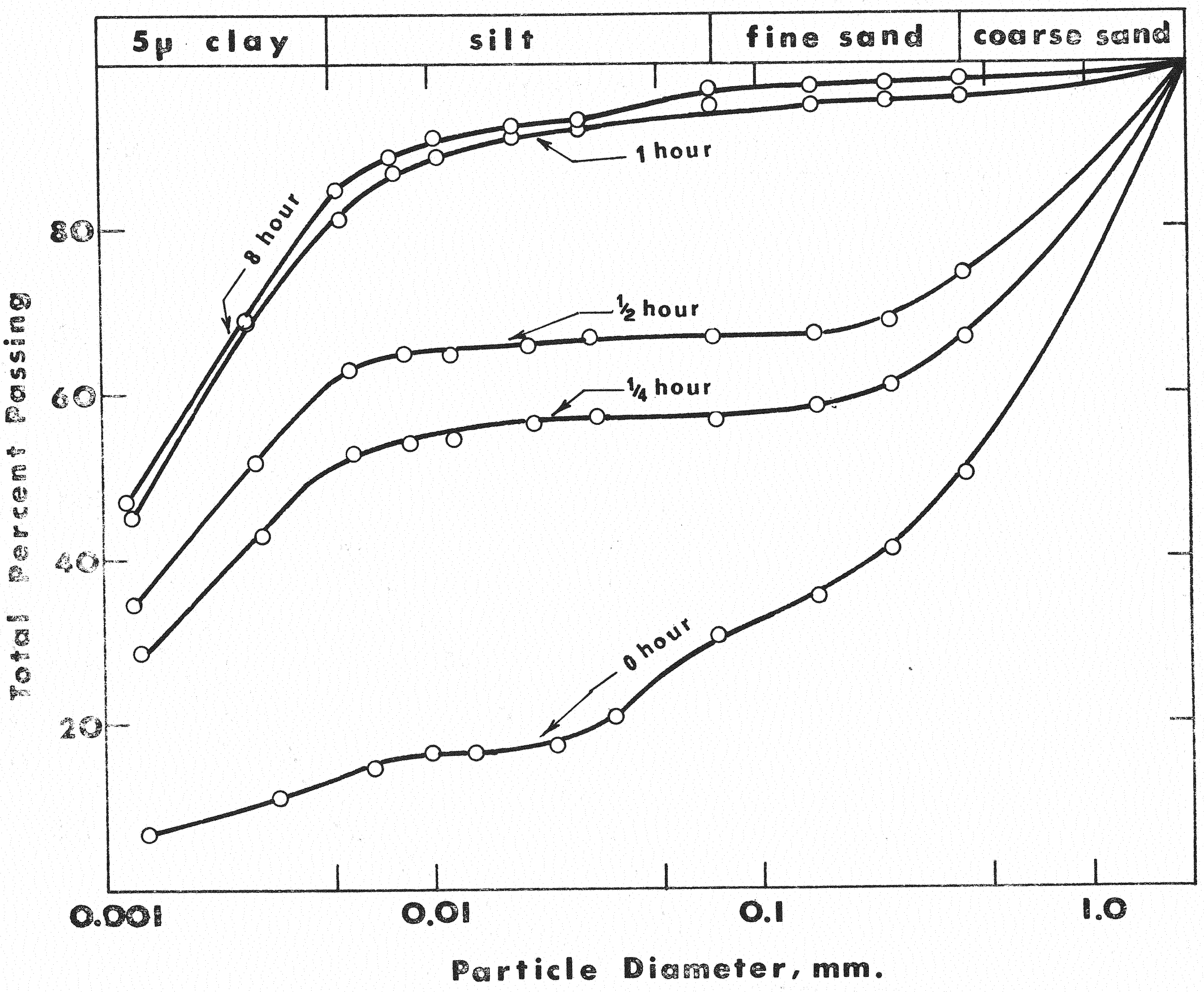


FIG. F.3: EFFECT OF ULTRASONIC TREATMENT ON GRAIN SIZE DISTRIBUTION OF SHALE NO. 15

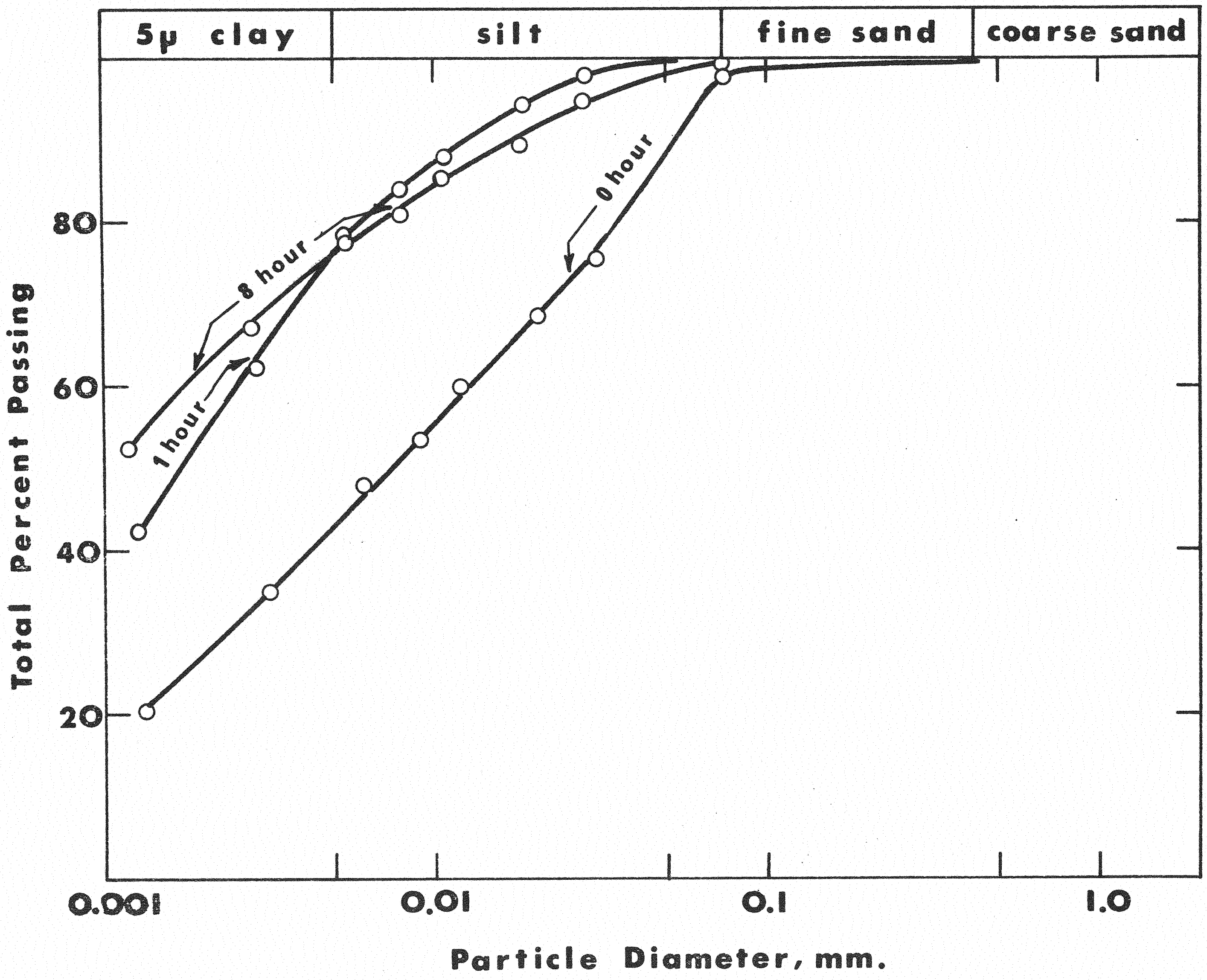


FIG. F.4: EFFECT OF ULTRASONIC TREATMENT ON GRAIN SIZE DISTRIBUTION OF SHALE NO. 21

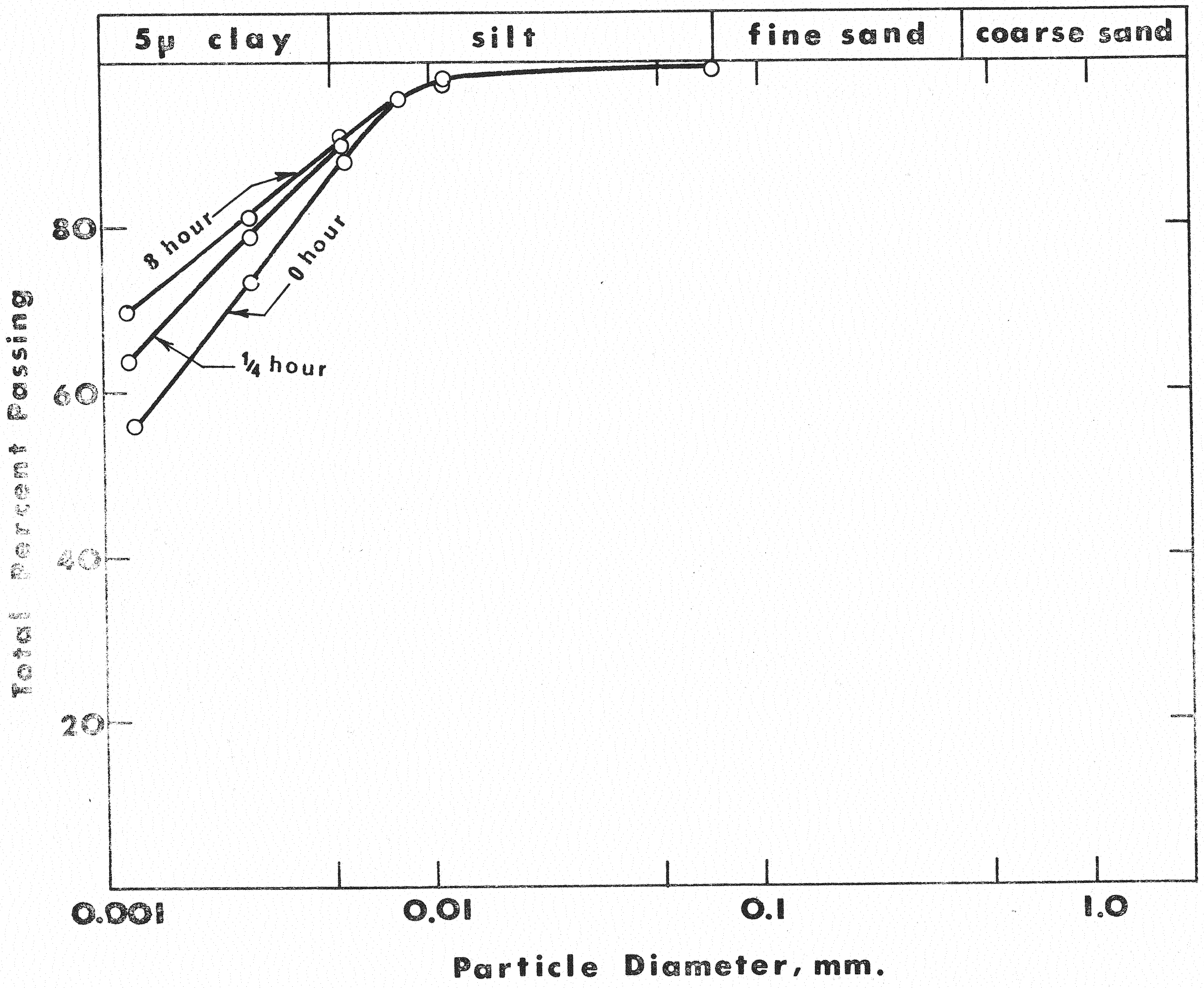


FIG. F.5: EFFECT OF ULTRASONIC TREATMENT ON GRAIN SIZE DISTRIBUTION OF SHALE NO. 22

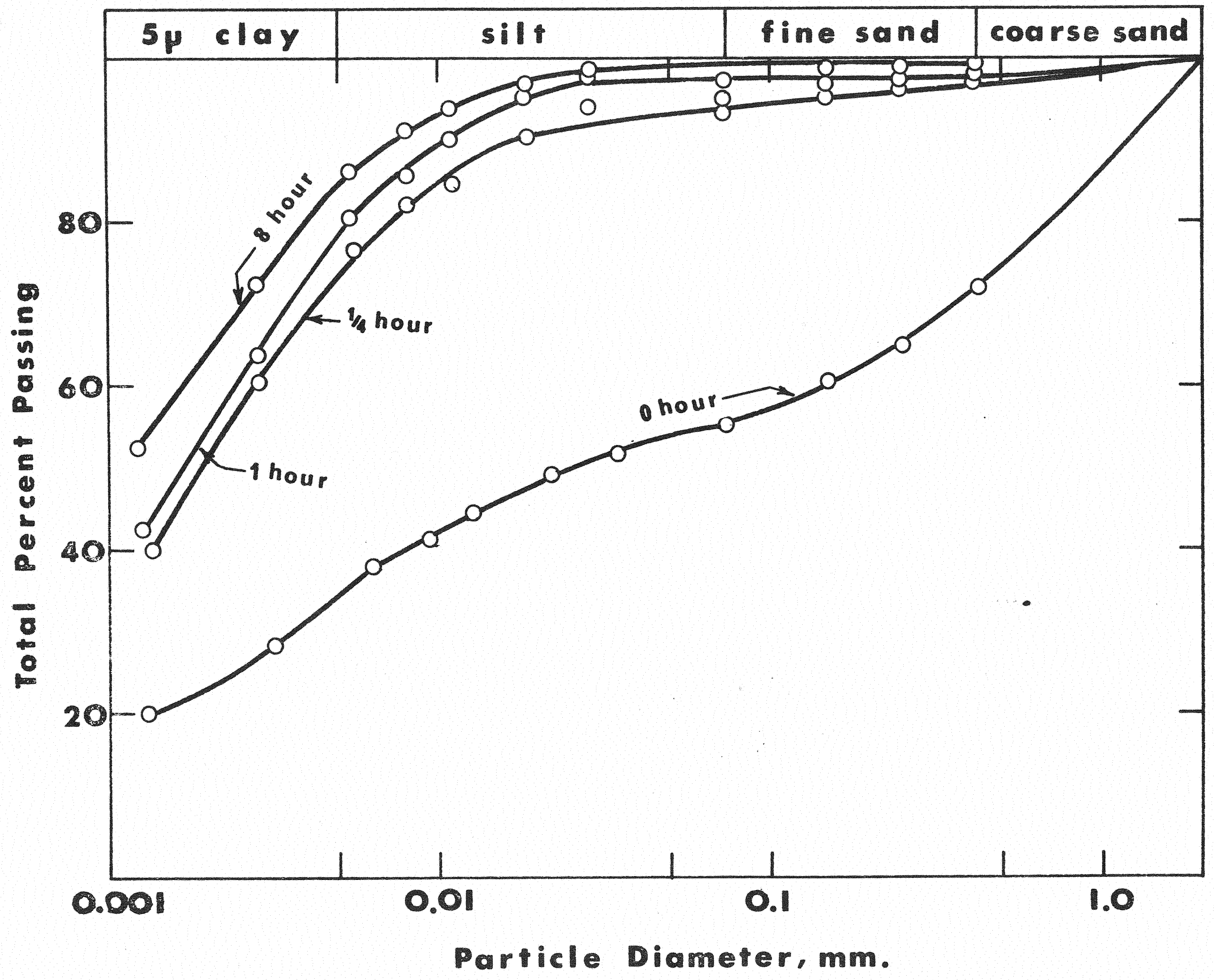


FIG. F.6: EFFECT OF ULTRASONIC TREATMENT ON GRAIN SIZE DISTRIBUTION OF SHALE NO. 24

APPENDIX G

INDEX PROPERTIES OF ULTRASONICALLY TREATED SHALES: TABLES

TABLE NO. G.1 INDEX PROPERTIES OF ULTRASONICALLY TREATED SHALES

A. Percentage Passing Sieve No. 200

Shale Number	Treatment Time, hr.						
	0	¼	½	1	2	4	8
8	23	29	35	37	43	46	47
13	95	95	95	95	95	95	96
15	31	57	57	95	95	96	97
21	97	99	99	99	99	99	99
22	99	99	99	99	99	99	99
24	55	93	95	95	96	97	97

TABLE NO. G.2 INDEX PROPERTIES OF ULTRASONICALLY TREATED SHALES

B. Percent 5-micron Clay

Shale Number	Treatment Time, hr.						
	0	¼	½	1	2	4	8
8	3	15	18	18	25	28	33
13	64	66	70	68	65	64	69
15	14	52	62	80	81	81	83
21	44	74	76	76	76	76	77
22	86	89	89	92	90	93	90
24	34	74	75	79	80	82	85

TABLE NO. G.3 INDEX PROPERTIES OF ULTRASONICALLY TREATED SHALES

C. Percent 2-micron Clay

Shale Number	Treatment Time, hr.						
	0	¼	½	1	2	4	8
8	0	11	12	11	15	17	23
13	52	55	59	57	55	54	58
15	9	35	45	60	60	61	61
21	27	48	54	54	57	59	62
22	66	73	75	78	78	80	77
24	23	51	52	57	57	62	65

TABLE NO. G.4 INDEX PROPERTIES OF ULTRASONICALLY TREATED SHALES

D. Liquid Limit

Shale Number	Treatment Time, hr.						
	0	¼	½	1	2	4	8
8	27	29	30	32	36	37	40
13	47	50	50	51	49	53	55
15	33	41	44	45	46	48	46
21	29	29	32	33	34	35	(45)
22	66	68	69	69	71	72	72
24	38	44	43	47	48	48	47

TABLE NO. G.5 INDEX PROPERTIES OF ULTRASONICALLY TREATED SHALES

E. Plastic Limit

Shale Number	Treatment Time, hr.						
	0	¼	½	1	2	4	8
8	np	np	np	np	21	22	24
13	21	21	22	22	21	22	23
15	20	21	23	25	26	28	26
21	21	21	20	20	20	21	22
22	32	34	33	35	34	32	33
24	25	26	(20)	27	27	28	25

TABLE NO. G.6 INDEX PROPERTIES OF ULTRASONICALLY TREATED SHALES

F. Plasticity Index

Shale Number	Treatment Time, hr.						
	0	¼	½	1	2	4	8
8	--	--	--	--	15	15	16
13	26	29	28	29	28	31	32
15	13	20	21	20	20	20	20
21	8	8	12	13	14	14	(23)
22	34	34	36	34	37	40	39
24	13	18	(23)	20	21	20	22

APPENDIX H

EFFECT OF ULTRASONIC TREATMENT TIME ON VARIOUS SIZE FRACTIONS OF SHALES

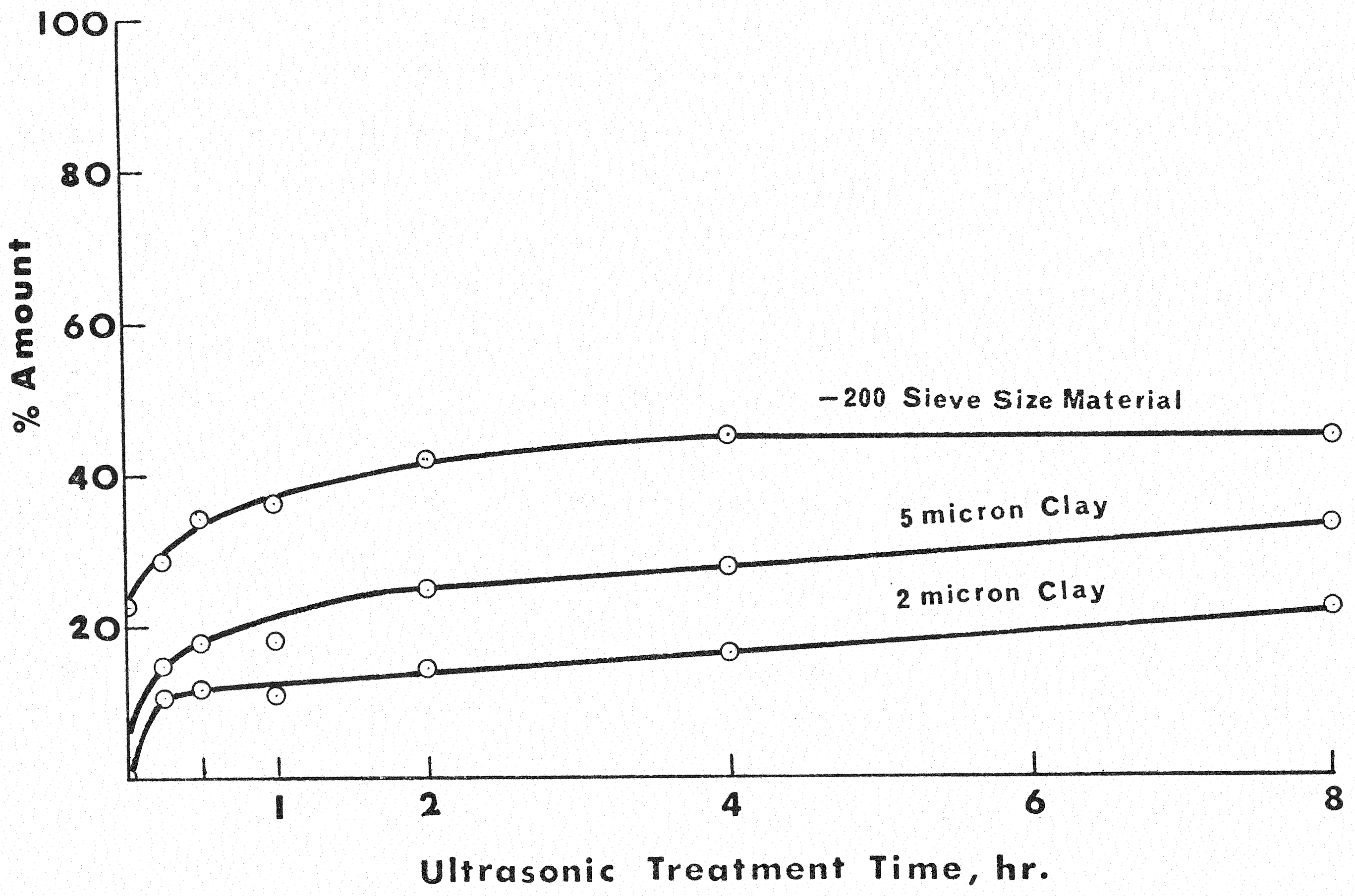


FIG. H.1: EFFECT OF ULTRASONIC TREATMENT TIME ON VARIOUS SIZE FRACTIONS OF SHALE NO. 8

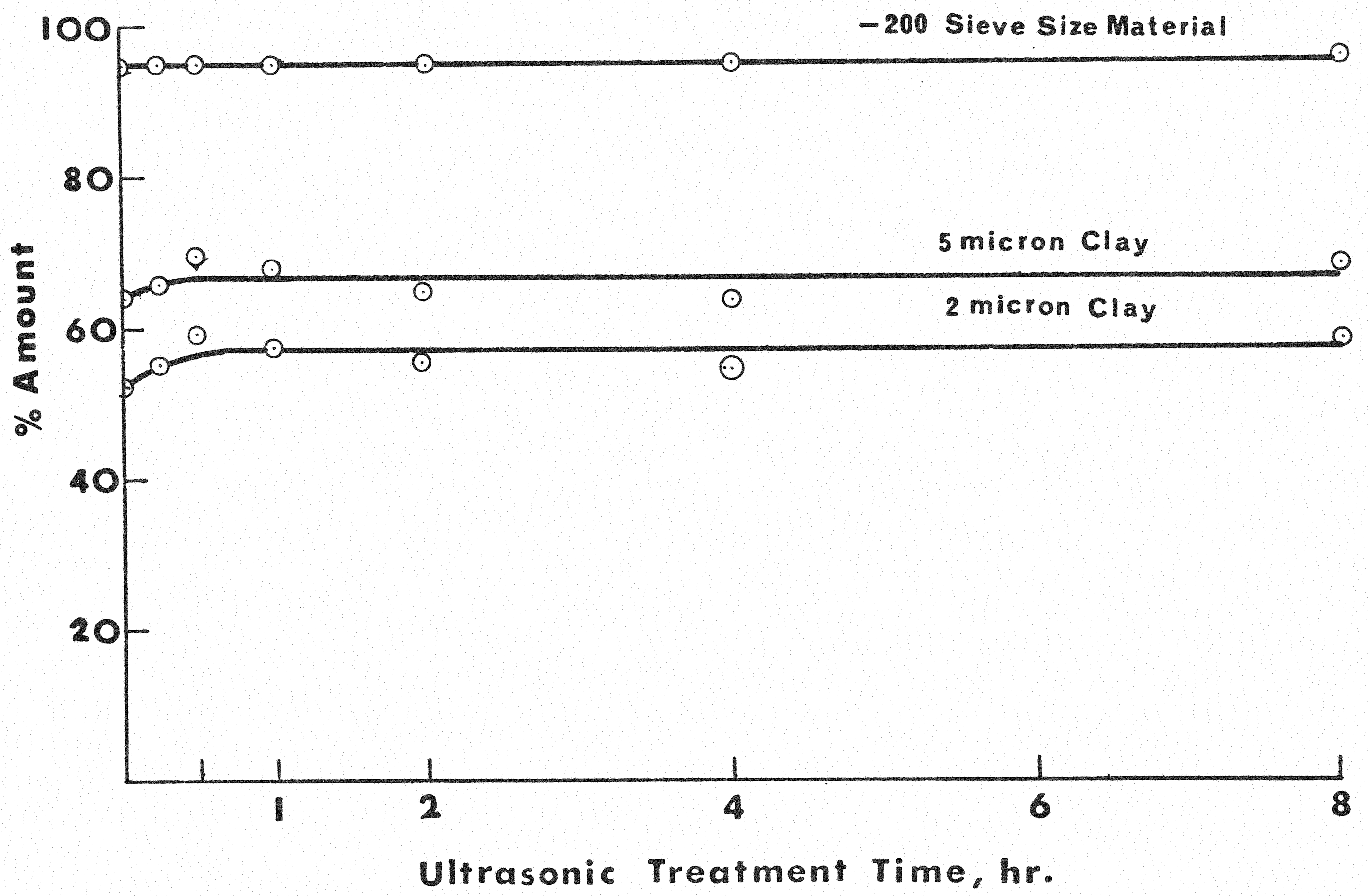


FIG. H.2: EFFECT OF ULTRASONIC TREATMENT TIME ON VARIOUS SIZE FRACTIONS OF SHALE NO. 13

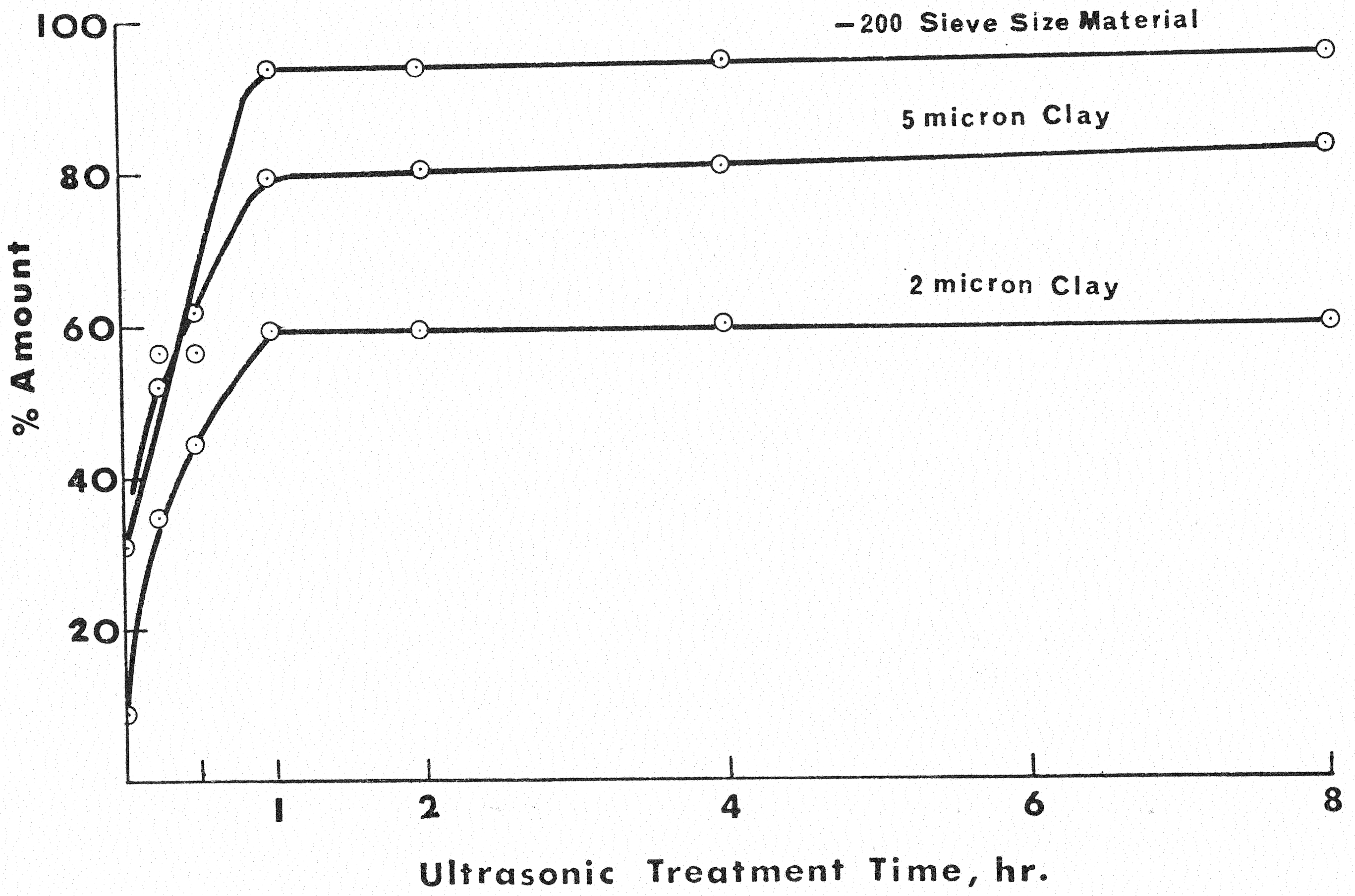


FIG. H.3: EFFECT OF ULTRASONIC TREATMENT TIME ON VARIOUS SIZE FRACTIONS OF SHALE NO. 15

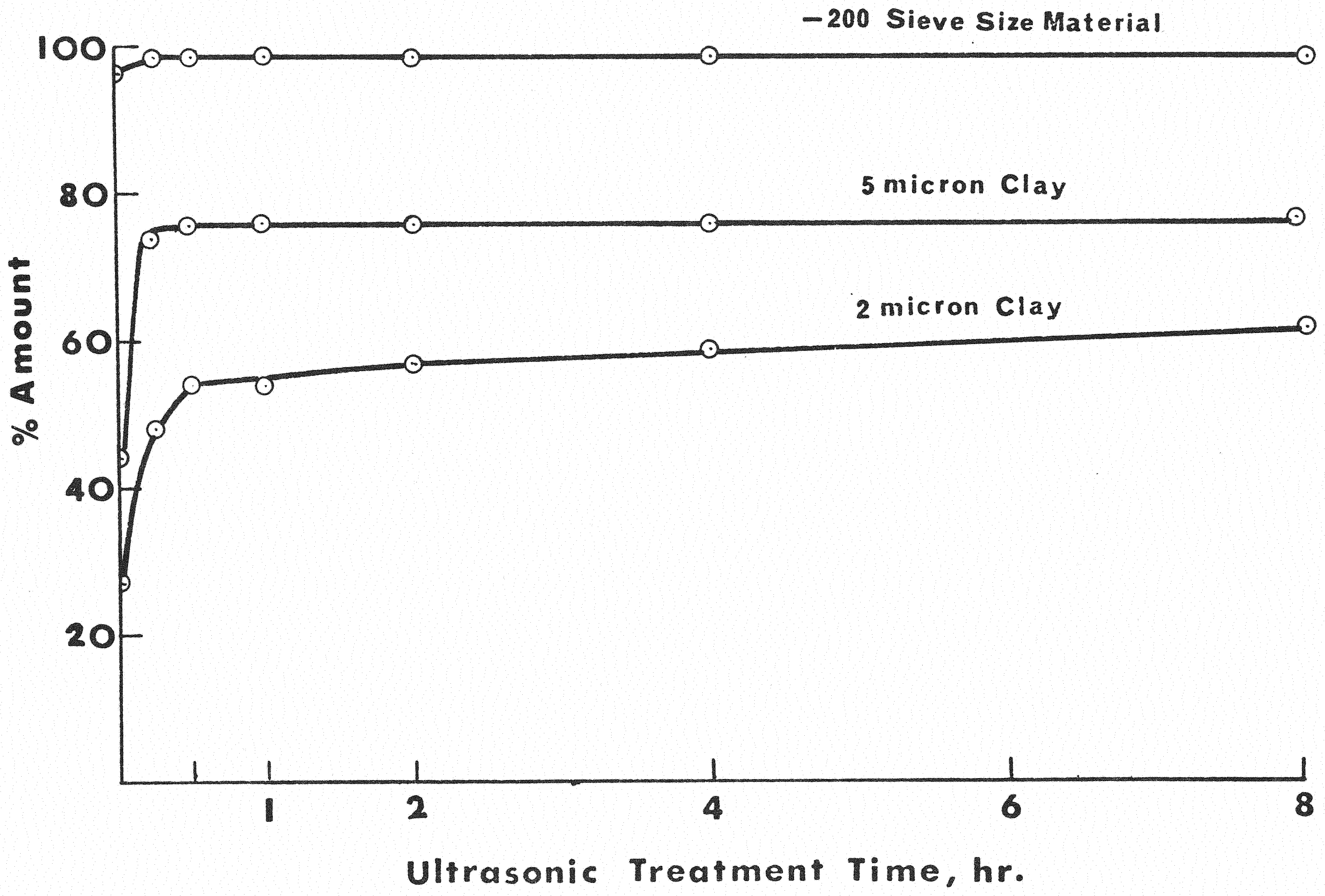


FIG. H.4: EFFECT OF ULTRASONIC TREATMENT TIME ON VARIOUS SIZE FRACTIONS OF SHALE NO. 21

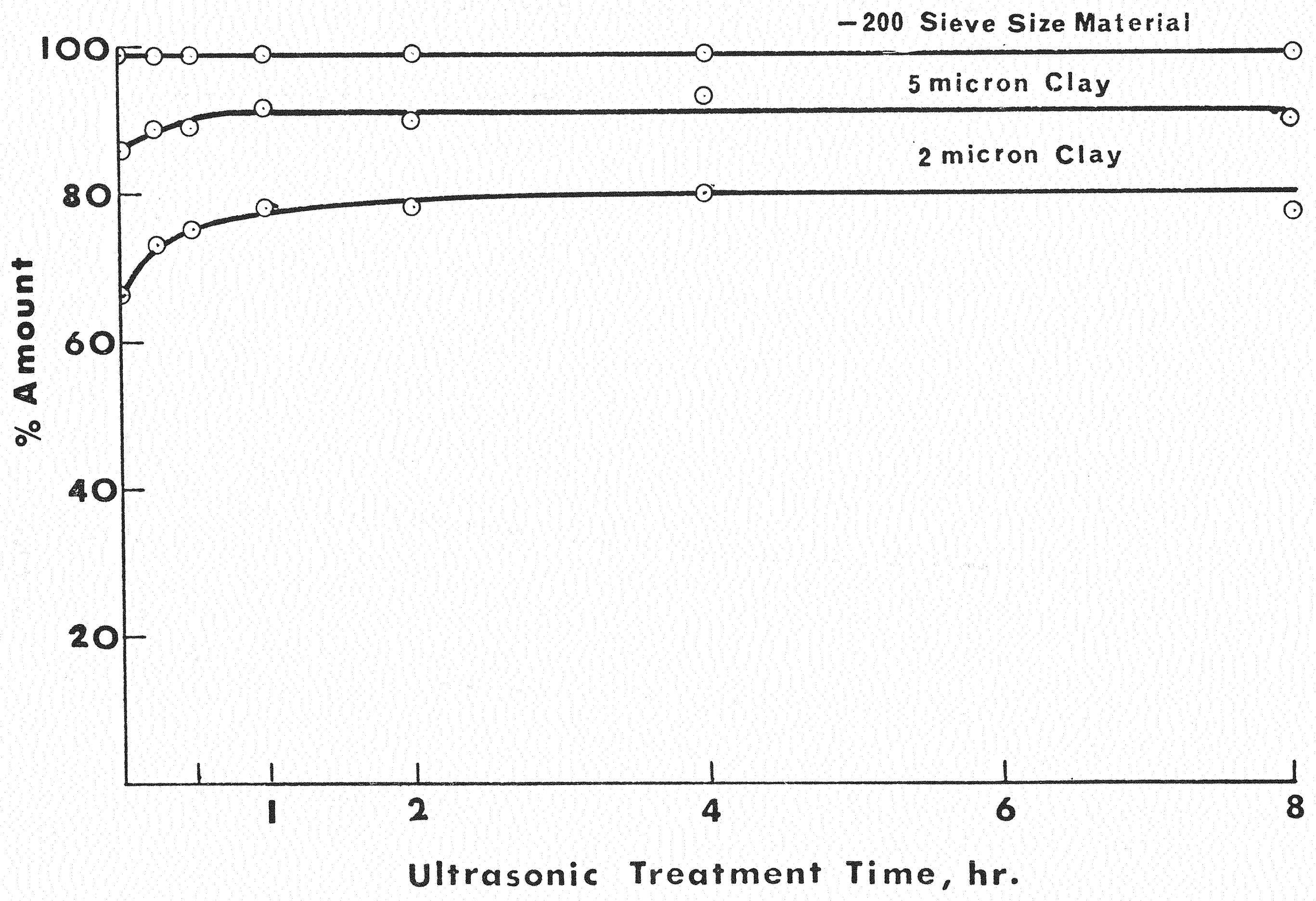


FIG. H.5: EFFECT OF ULTRASONIC TREATMENT TIME ON VARIOUS SIZE FRACTIONS OF SHALE NO. 22

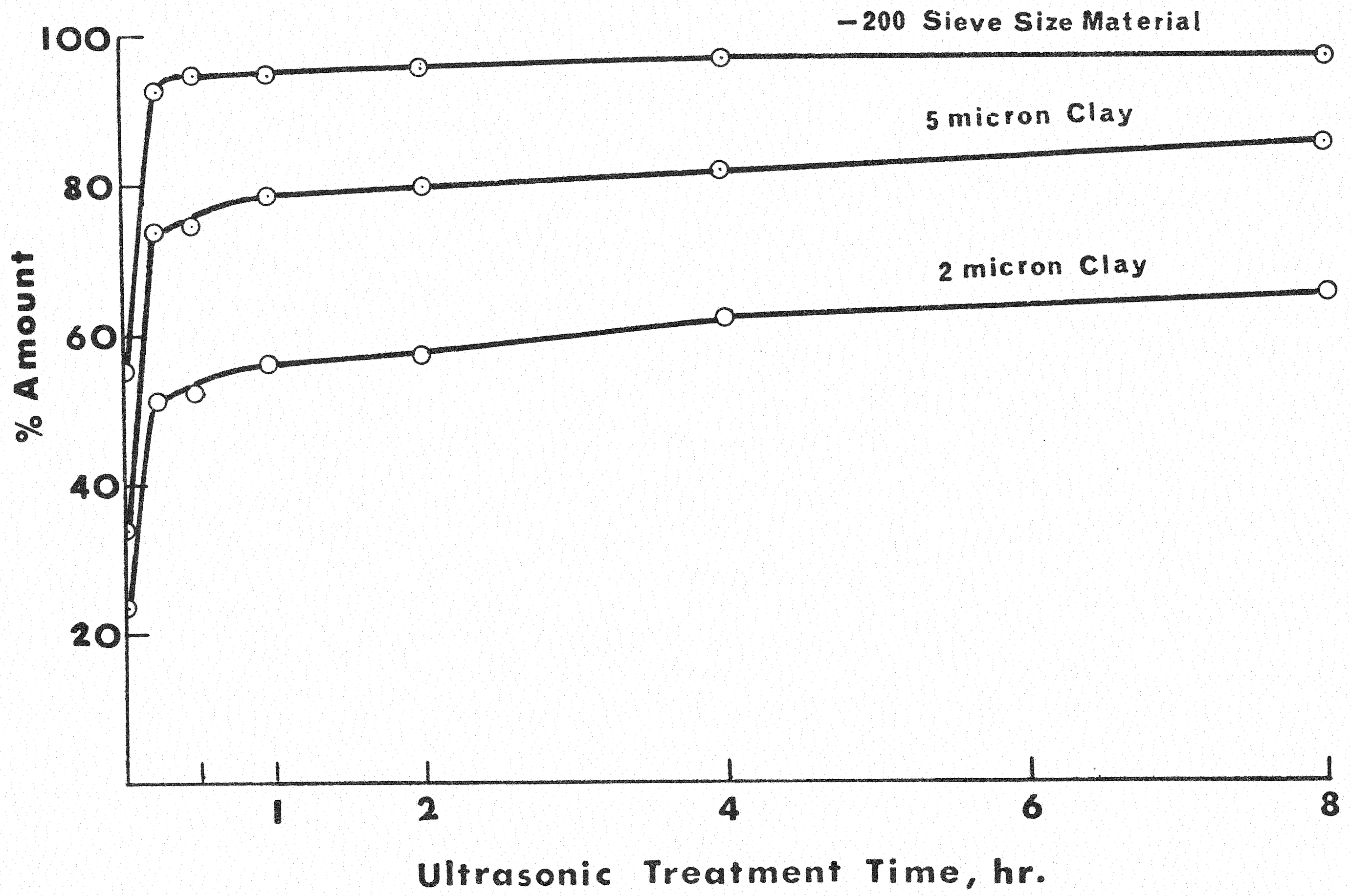


FIG. H.6: EFFECT OF ULTRASONIC TREATMENT TIME ON VARIOUS SIZE FRACTIONS OF SHALE NO.24

APPENDIX I

EFFECT OF ULTRASONIC TREATMENT TIME ON PLASTICITY VALUES OF SHALES

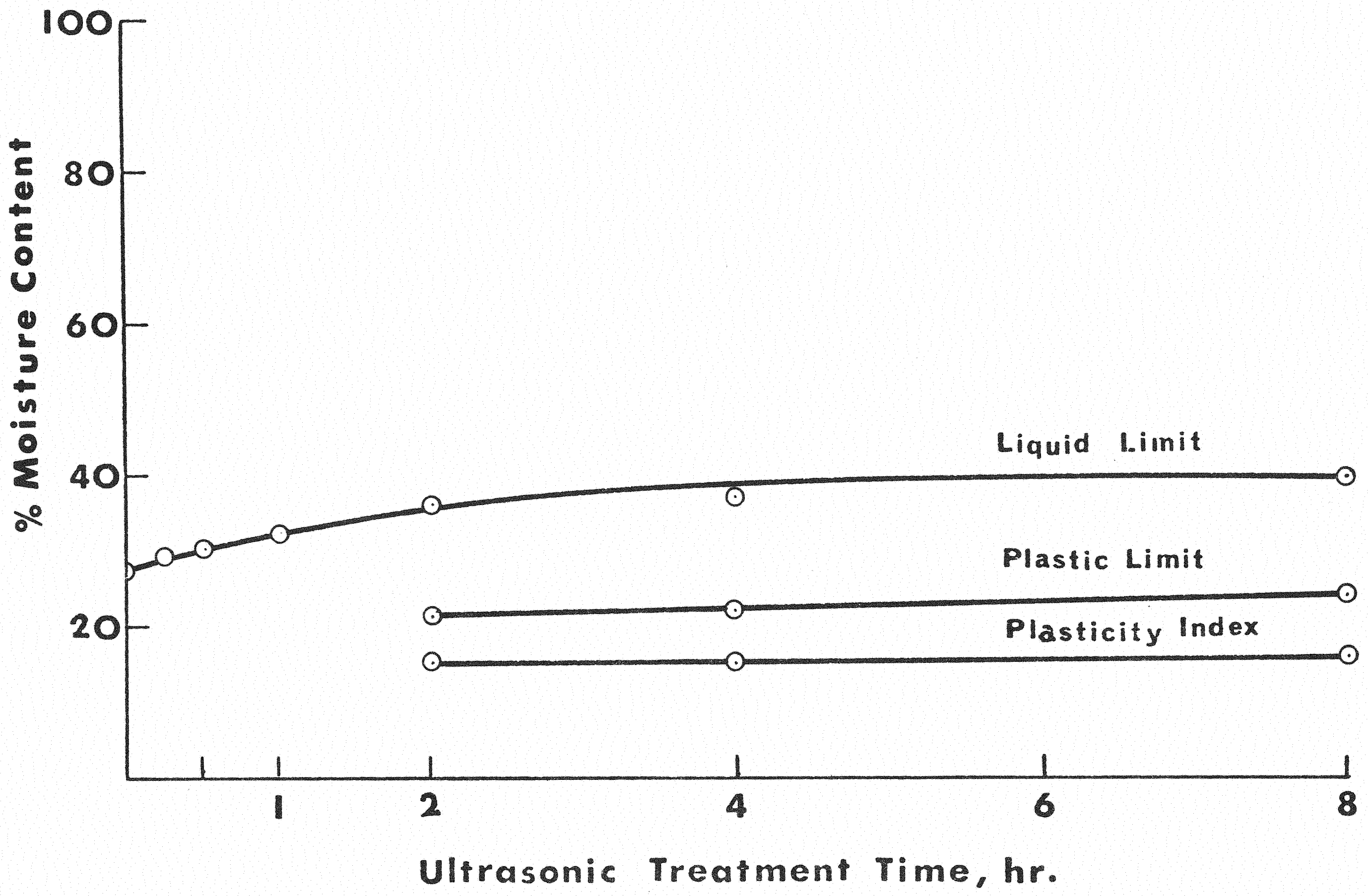


FIG. I.1: CHANGE IN PLASTICITY CHARACTERISTICS WITH ULTRASONIC TREATMENT TIME: SHALE NO. 8

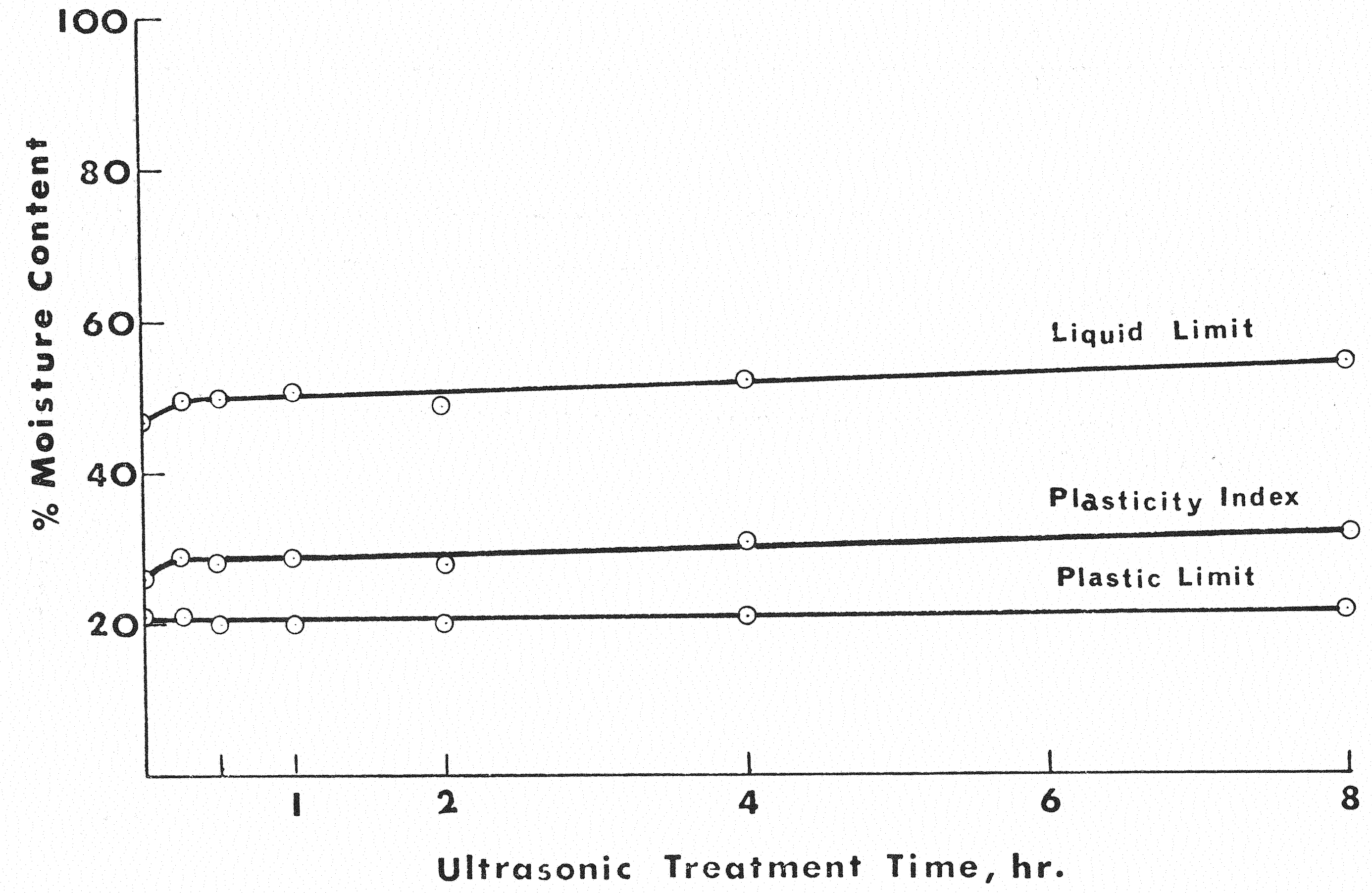


FIG. I.2: CHANGE IN PLASTICITY CHARACTERISTICS WITH ULTRASONIC TREATMENT TIME: SHALE NO. 13

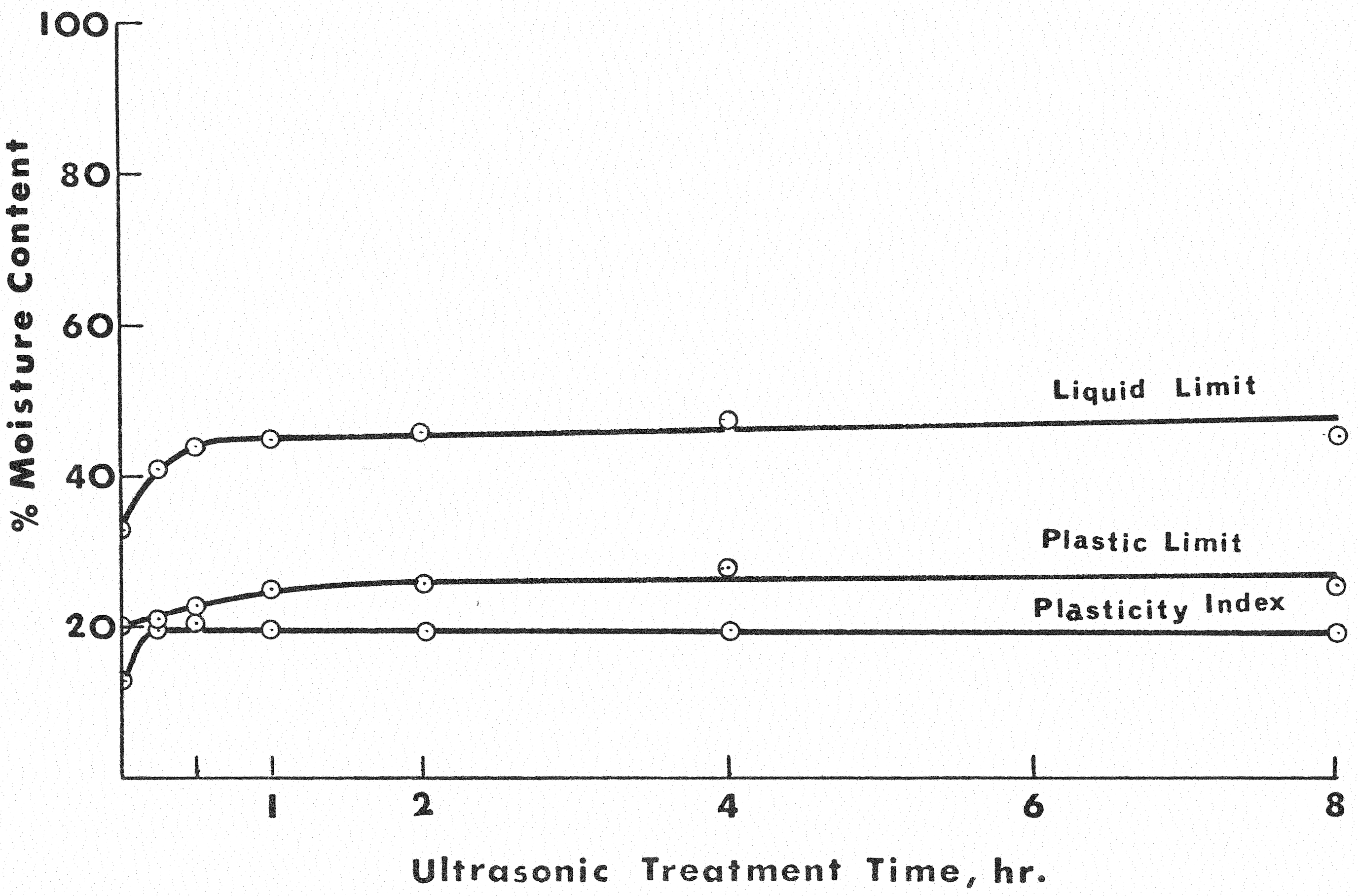


FIG. I.3: CHANGE IN PLASTICITY CHARACTERISTICS WITH ULTRASONIC TREATMENT TIME: SHALE NO. 15

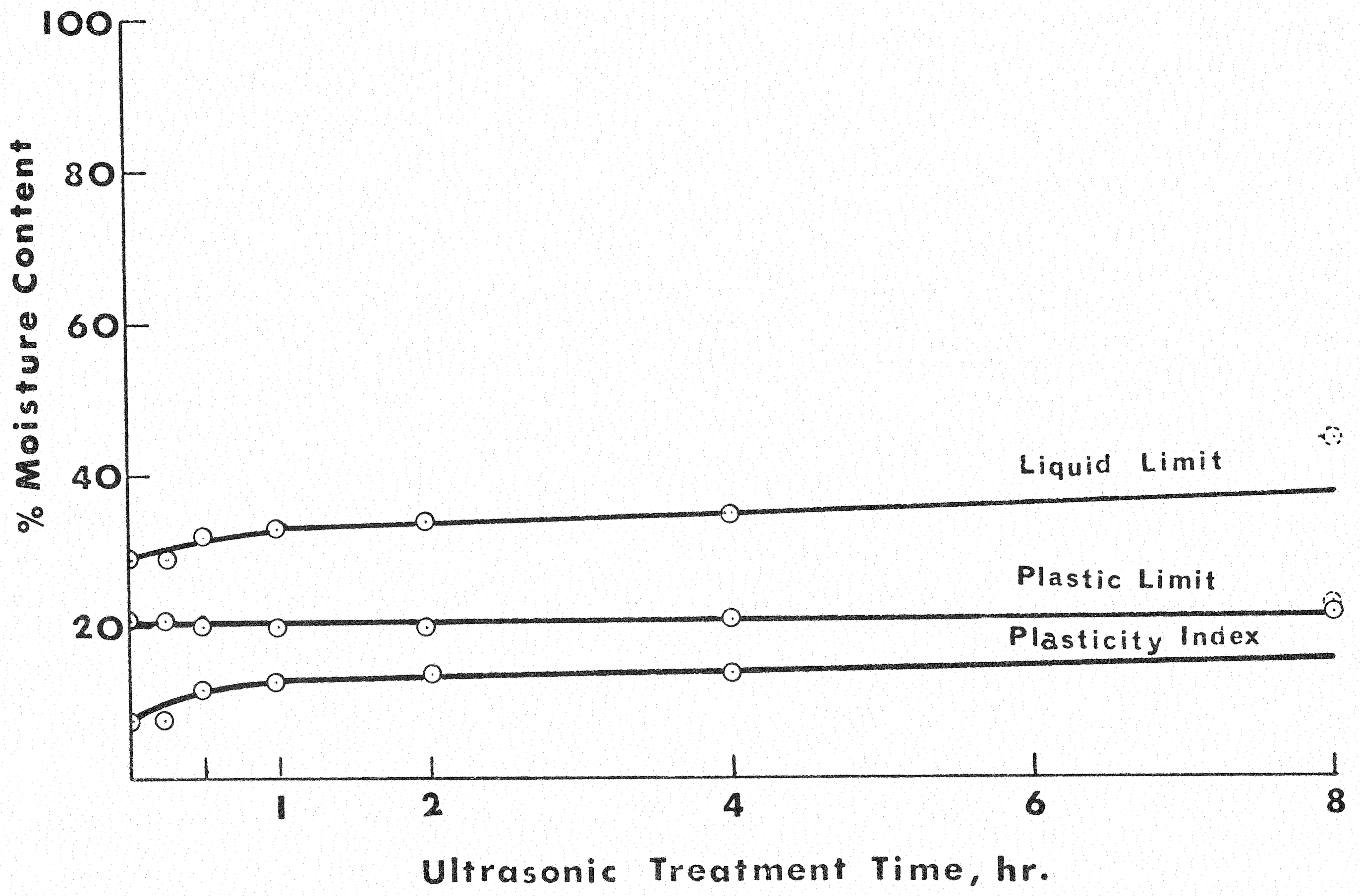


FIG: I.4: CHANGE IN PLASTICITY CHARACTERISTICS WITH ULTRASONIC TREATMENT TIME: SHALE NO. 21

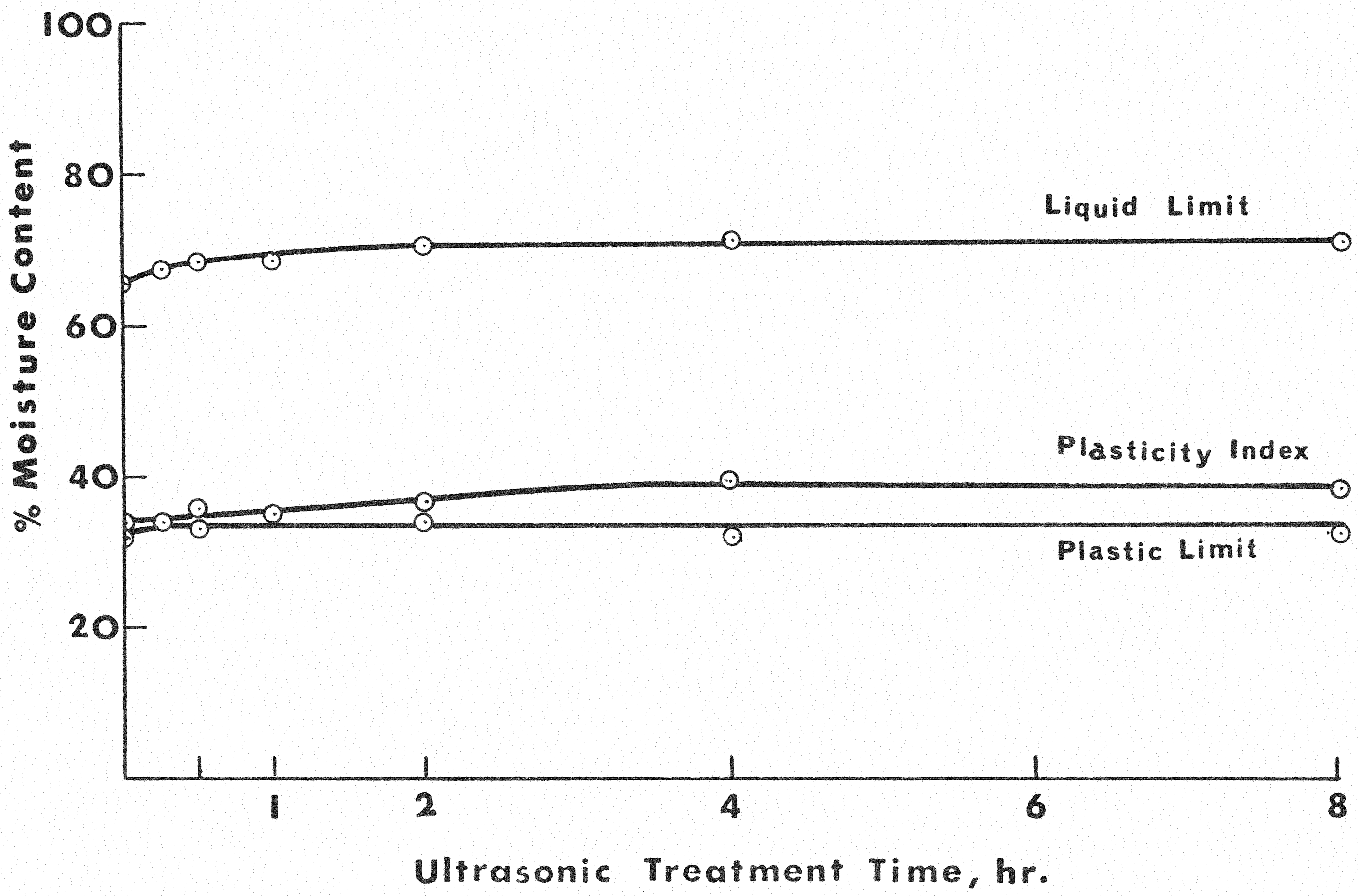


FIG: I.5: CHANGE IN PLASTICITY CHARACTERISTICS WITH ULTRASONIC TREATMENT TIME: SHALE NO. 22

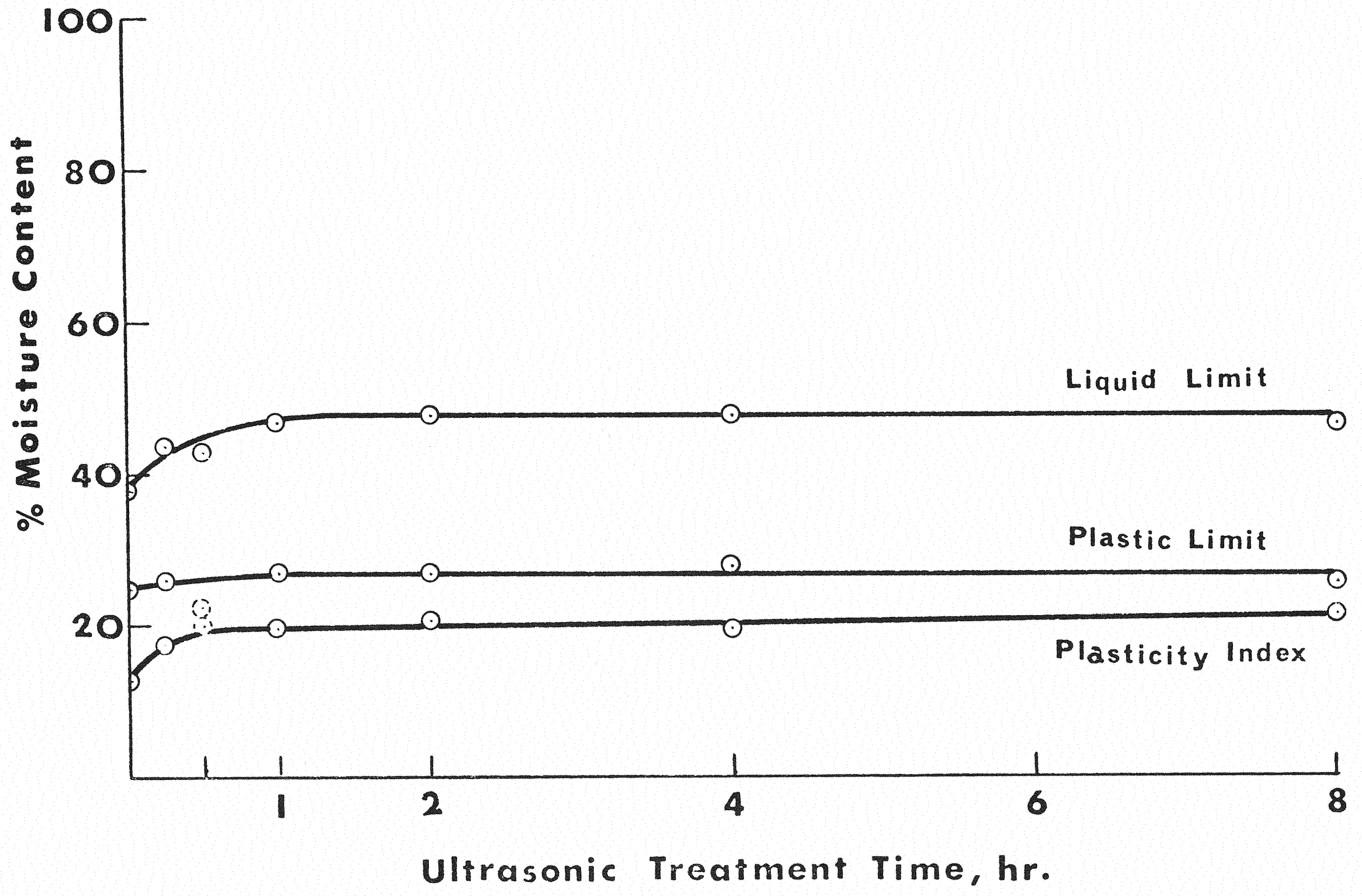


FIG: I.6: CHANGE IN PLASTICITY CHARACTERISTICS WITH ULTRASONIC TREATMENT TIME: SHALE NO. 24

APPENDIX J

RELATIONSHIPS BETWEEN INDEX PROPERTIES AND DURABILITY PROPERTIES OF SHALES

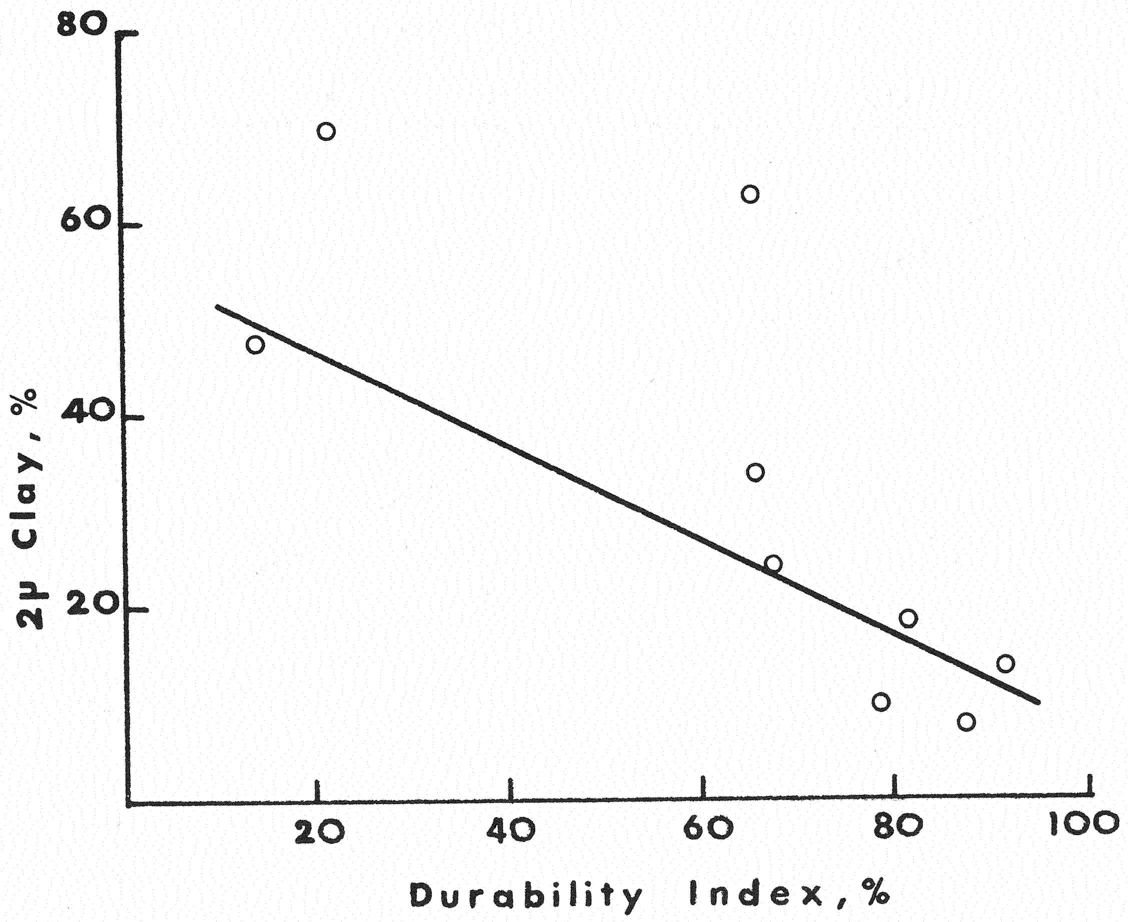


FIG. J.1: RELATIONSHIP BETWEEN THE AMOUNT OF 2-MICRON CLAY AND THE DURABILITY INDEX OF SHALES: METHOD 2

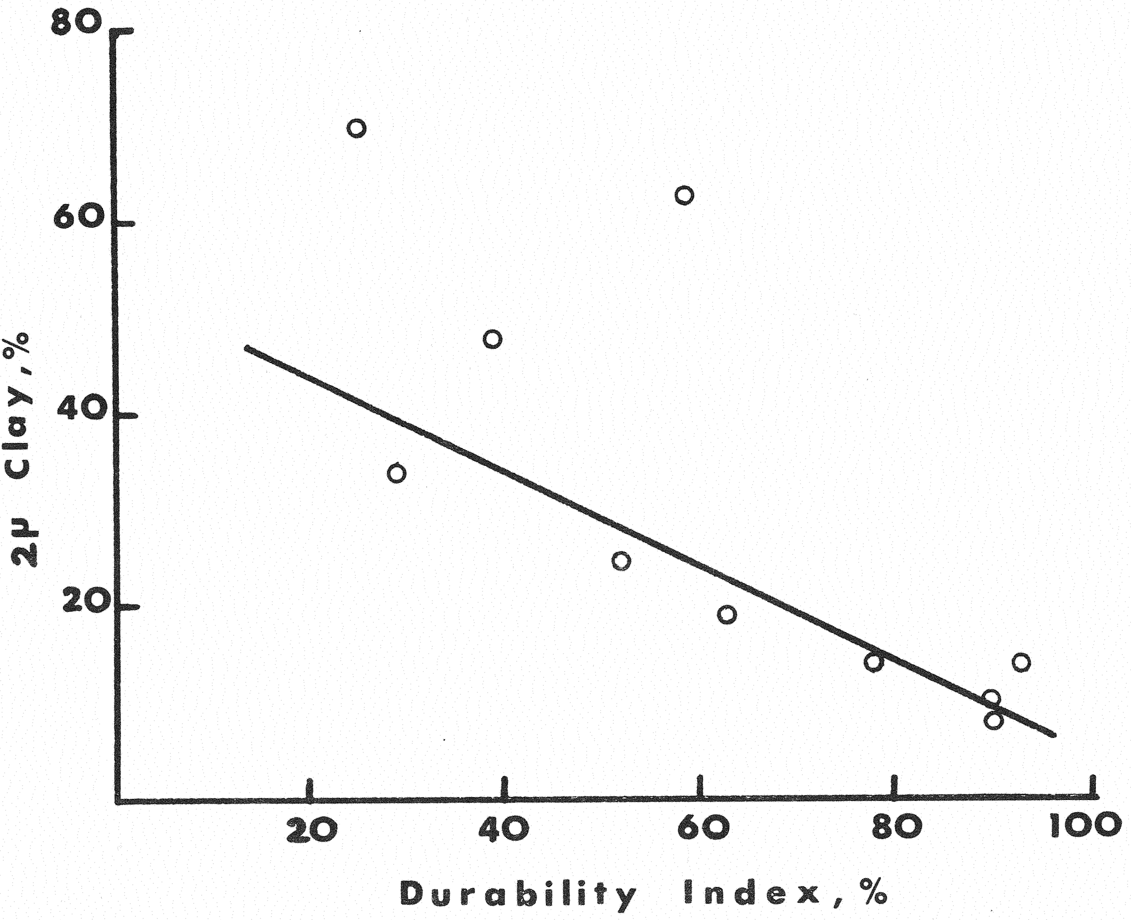


FIG. J.2: RELATIONSHIP BETWEEN THE AMOUNT OF 2-MICRON CLAY AND THE DURABILITY INDEX OF SHALES: METHOD 3

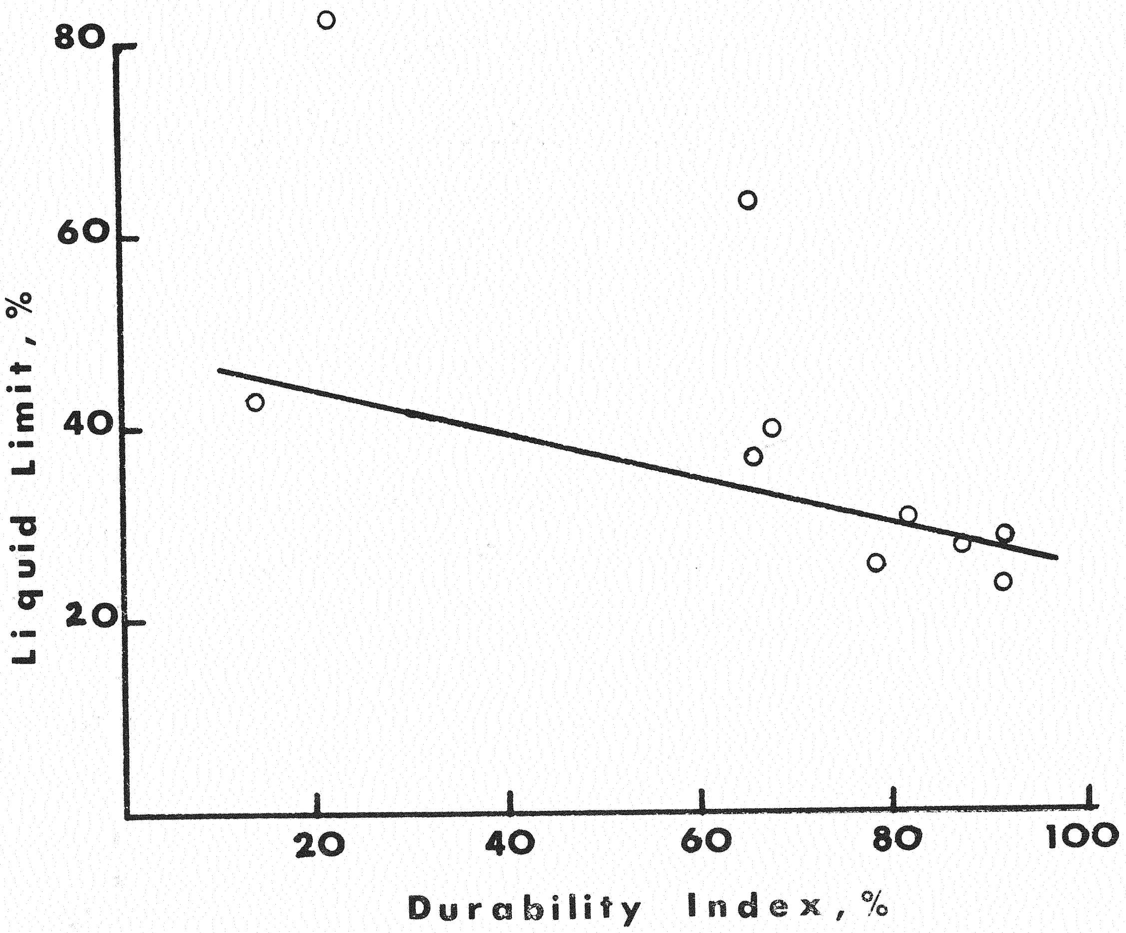


FIG. J.3: RELATIONSHIP BETWEEN THE LIQUID LIMIT AND THE DURABILITY INDEX OF SHALES BY METHOD 2

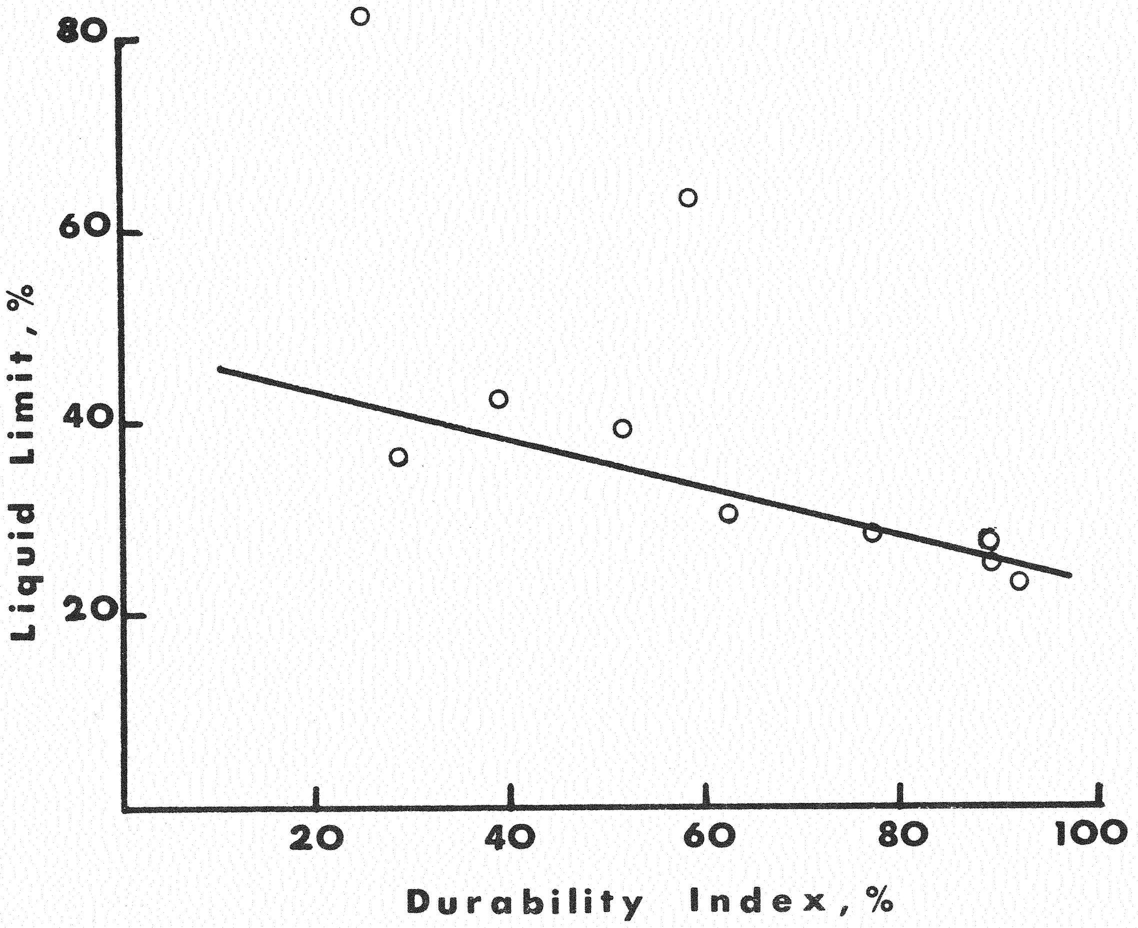


FIG. J.4: RELATIONSHIP BETWEEN THE LIQUID LIMIT AND THE DURABILITY INDEX OF SHALES BY METHOD 3

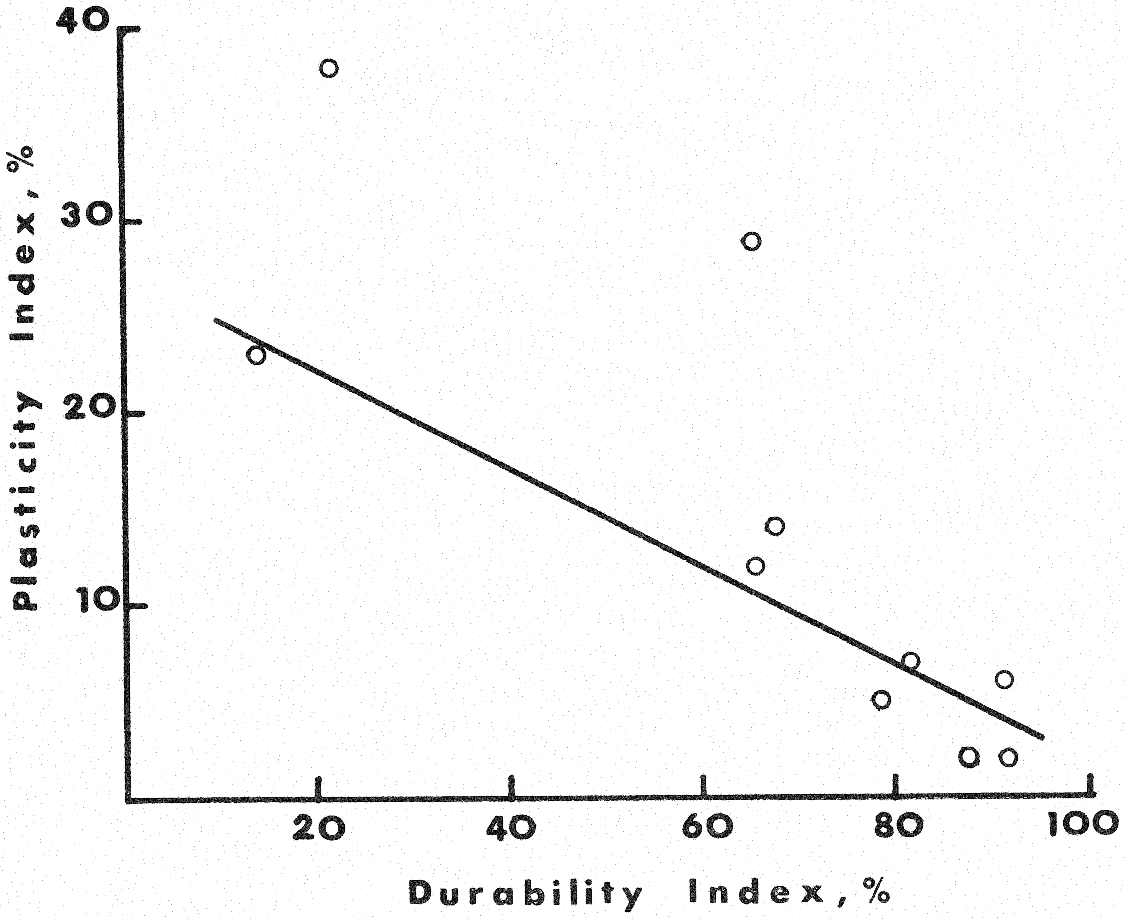


FIG. J-5: RELATIONSHIP BETWEEN THE PLASTICITY INDEX AND THE DURABILITY INDEX OF SHALES BY METHOD 2

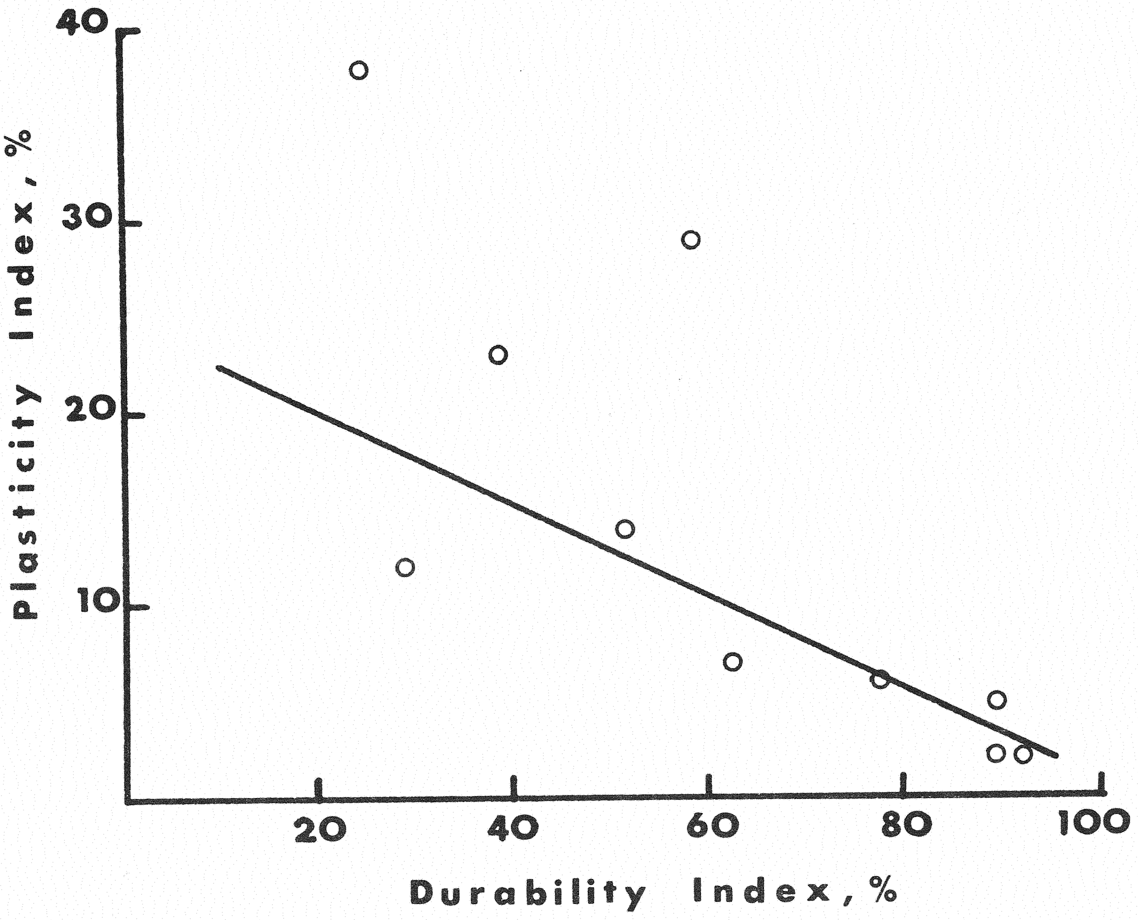


FIG. J.6: RELATIONSHIP BETWEEN THE PLASTICITY INDEX AND THE DURABILITY INDEX OF SHALES BY METHOD 3

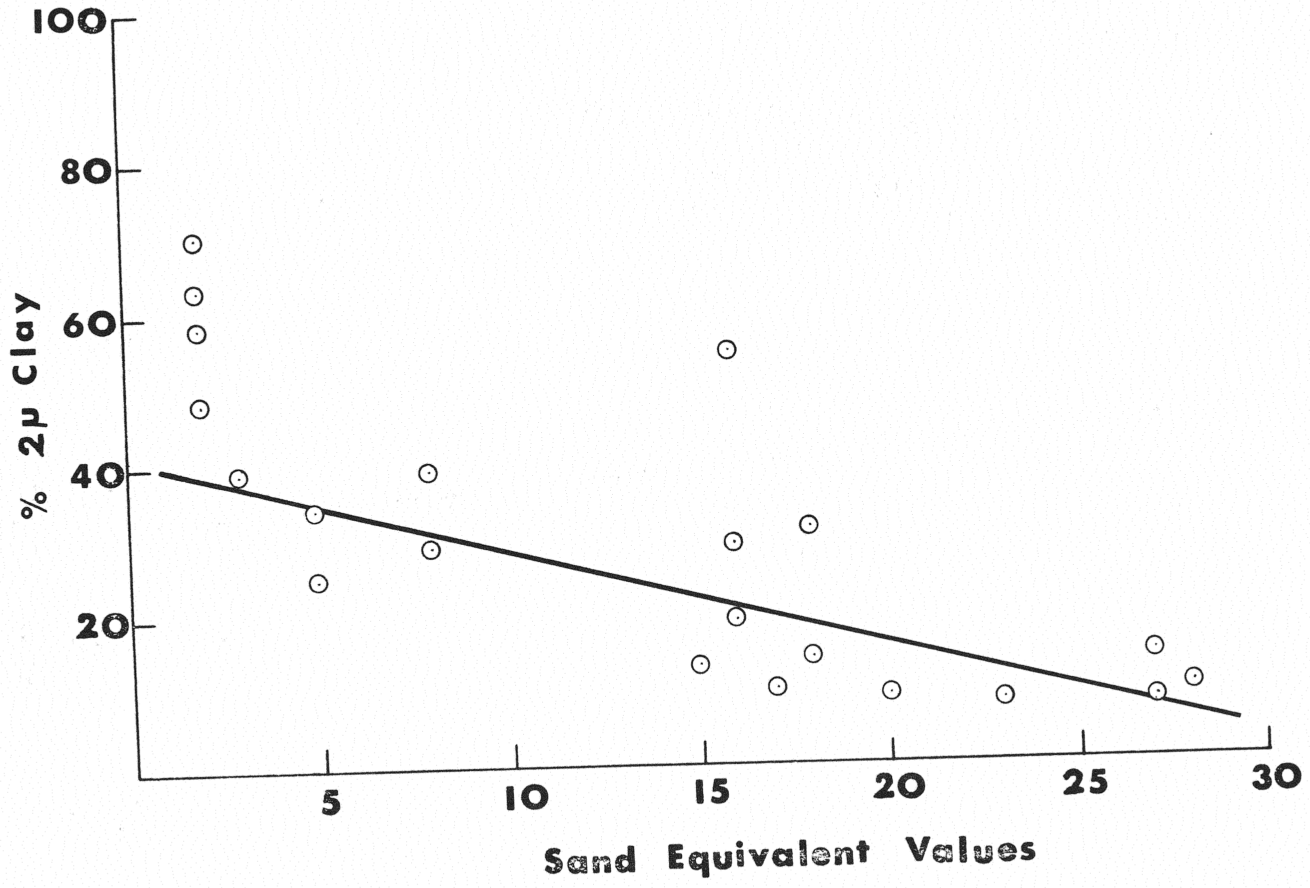


FIG. J.7: RELATIONSHIP BETWEEN THE AMOUNTS OF 2-MICRON CLAY AND THE SAND EQUIVALENT VALUES OF SHALES

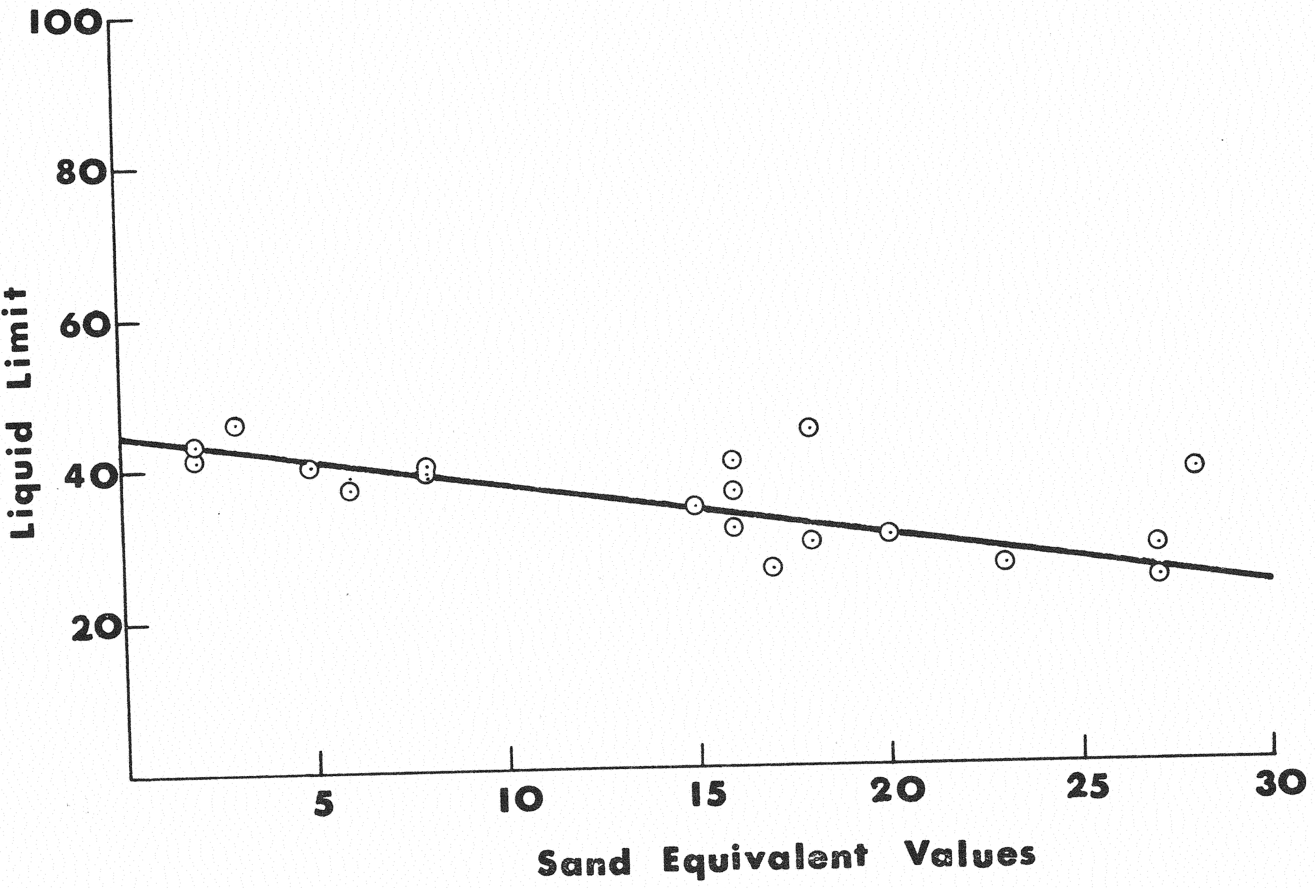


FIG. J.8: RELATIONSHIP BETWEEN THE LIQUID LIMITS AND THE SAND EQUIVALENT VALUES OF SHALES

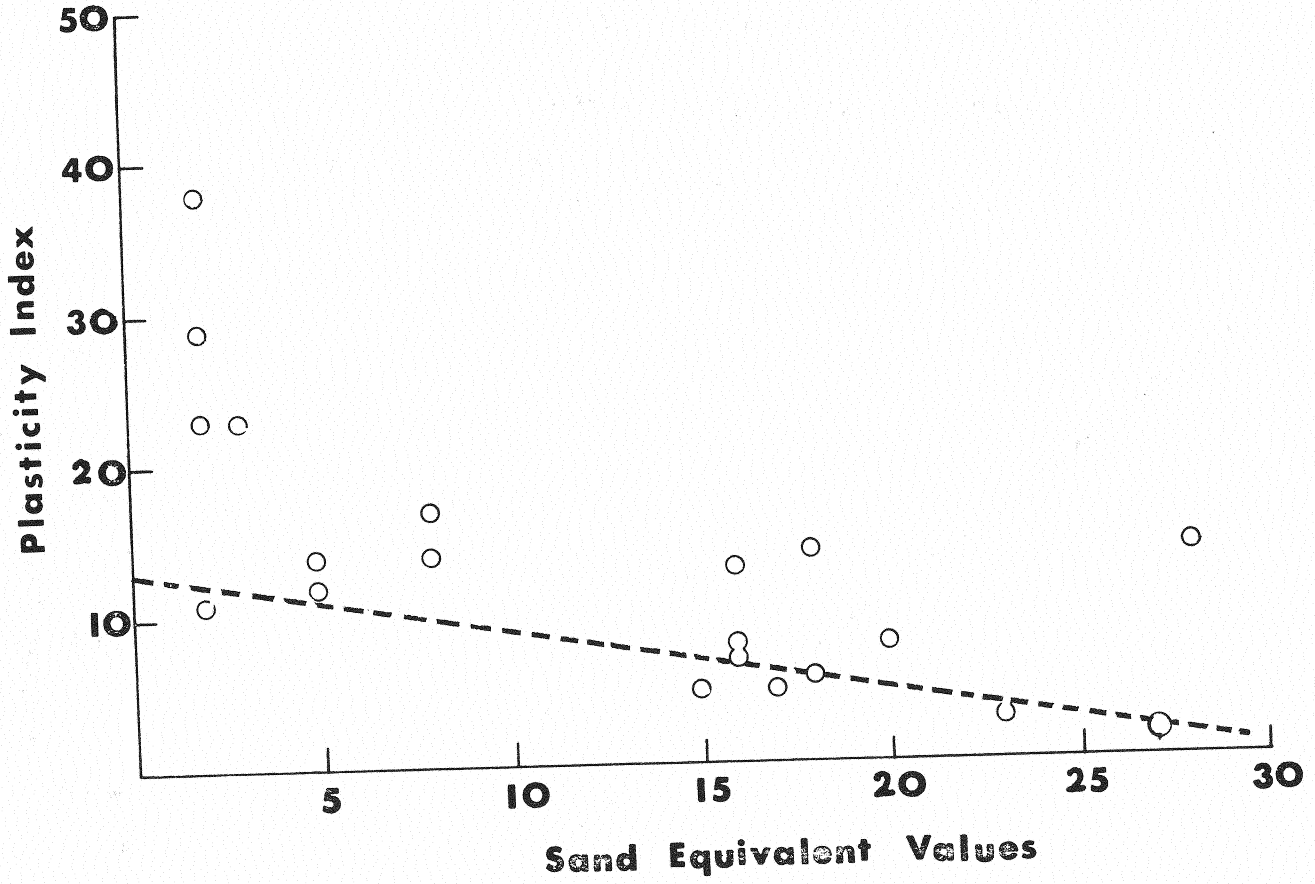


FIG. J.9: RELATIONSHIP BETWEEN THE PLASTICITY INDICES AND THE SAND EQUIVALENT VALUES OF SHALES

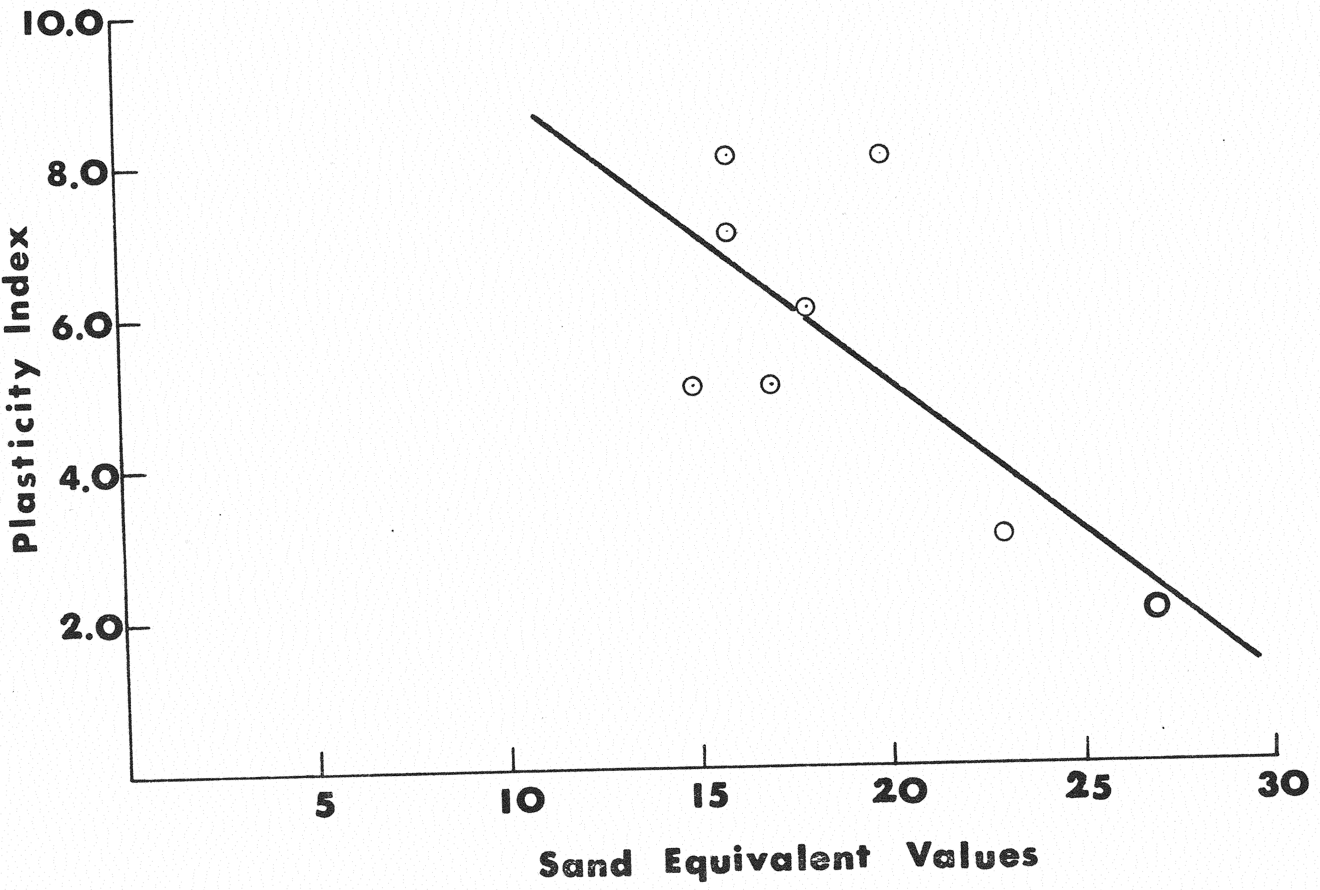


FIG. J.10: RELATIONSHIP BETWEEN THE PLASTICITY INDICES AND THE SAND EQUIVALENT VALUES OF SHALES FOR PI LESS THAN 10

APPENDIX K

WEATHER CYCLES FOR OKLAHOMA

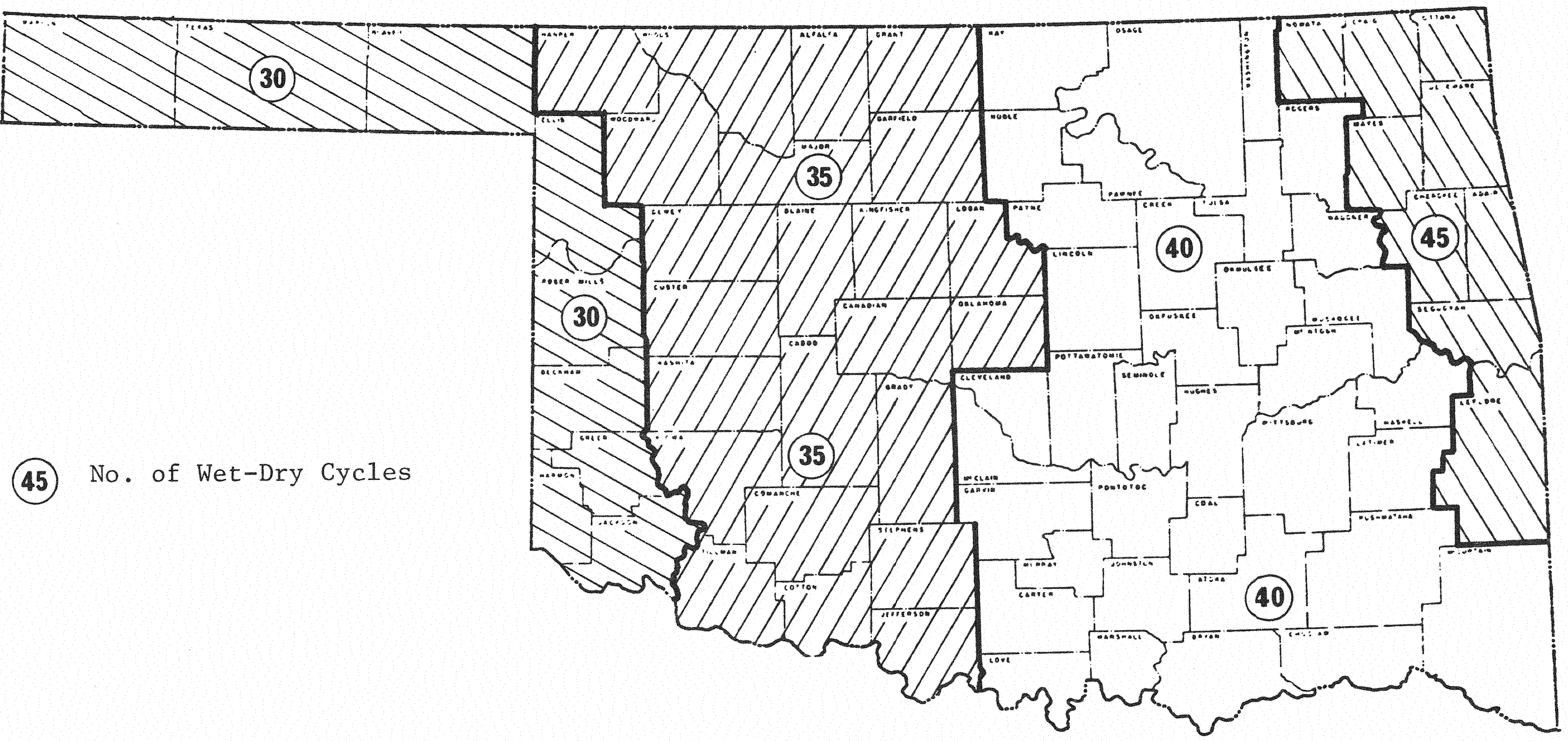


FIG. K.2: WET DRY CYCLES FOR OKLAHOMA

APPENDIX K

WEATHER CYCLES FOR OKLAHOMA

TABLE K.1 WET - DRY CYCLES

LOCATION[a]

YEAR	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1958	38	33	31	39	39	35	30	37	44	45	34	39	40	43	31	47
1960	42	36	41	44	42	34	26	40	39	39	39	38	45	43	37	38
1961	41	29	33	40	35	28	26	29	36	42	36	33	43	37	34	46
1962	35	28	35	41	32	37	29	32	34	38	37	36	44	40	30	37
1963	25	23	29	28	22	33	16	27	28	30	23	37	30	26	30	26
1964	28	23	29	32	27	27	18	26	34	34	42	36	27	33	25	38
1965	36	31	31	35	38	28	31	33	33	32	33	30	38	34	28	34
1966	31	23	30	37	30	23	27	28	35	37	27	27	37	35	27	27
1967	29	20	29	39	36	32	23	31	37	40	40	36	38	35	32	45
1968	43	31	37	49	40	35	25	35	46	41	40	36	42	38	36	39
Third Highest	41	31	35	41	39	35	29	35	39	41	40	37	43	40	34	45
Mean	34.8	27.7	32.5	38.4	34.1	31.2	26.1	18.8	36.6	37.8	35.1	34.8	38.4	36.4	31.0	37.7
Standard Deviation	6.0	5.0	3.9	5.8	6.1	4.2	4.7	4.3	5.1	4.5	5.8	3.7	5.7	4.9	3.6	5.3

---

[a] See Table No. K.3 for Identification of location.

TABLE K.2 FREEZE - THAW CYCLES

YEAR	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	LOCATION[a]															
59-60	8	7	7	7	6	9	14	7	10	9	7	9	9	9	7	10
60-61	5	4	5	3	3	7	11	5	5	5	7	8	4	5	7	9
61-62	8	7	7	7	6	8	11	9	12	9	11	9	10	7	9	11
62-63	7	7	7	6	6	7	9	8	8	9	8	9	7	7	7	11
63-64	5	3	5	4	3	7	15	7	5	5	7	7	5	6	7	11
64-65	10	9	10	6	8	15	18	14	12	12	13	12	9	12	13	14
65-66	4	2	2	2	4	6	8	4	4	4	4	4	3	4	4	6
66-67	8	7	8	6	4	10	10	8	9	12	12	10	8	7	11	14
67-68	8	8	10	6	5	9	12	7	10	7	7	7	7	8	8	10
68-69	7	7	7	5	4	11	11	9	8	9	12	8	7	7	12	11
Third Highest	8	7	8	6	6	10	14	9	10	9	12	9	9	8	11	11
Mean	7	6.1	6.8	5.2	4.9	8.9	11.9	7.8	8.3	8.1	8.8	8.3	6.9	7.2	8.5	10.7
Standard Deviation	2.7	2.2	2.3	1.6	1.5	2.5	2.8	2.6	2.7	2.5	2.8	2.0	2.2	2.1	2.6	2.2

---

[a] See Table No. K.3 for identification of location.

TABLE K.3 EXPLANATION OF LOCATIONS

Reference: Table Nos.

Symbol	Location
A	Ada
B	Altus
C	Anadarko
D	Antlers
E	Ardmore
F	Great Salt Plains
G	Guymon
H	Kingfisher
I	McAlester
J	Muskogee
K	Pawhuska
L	Perry
M	Poteau
N	Seminole
O	Talooga
P	Vinita

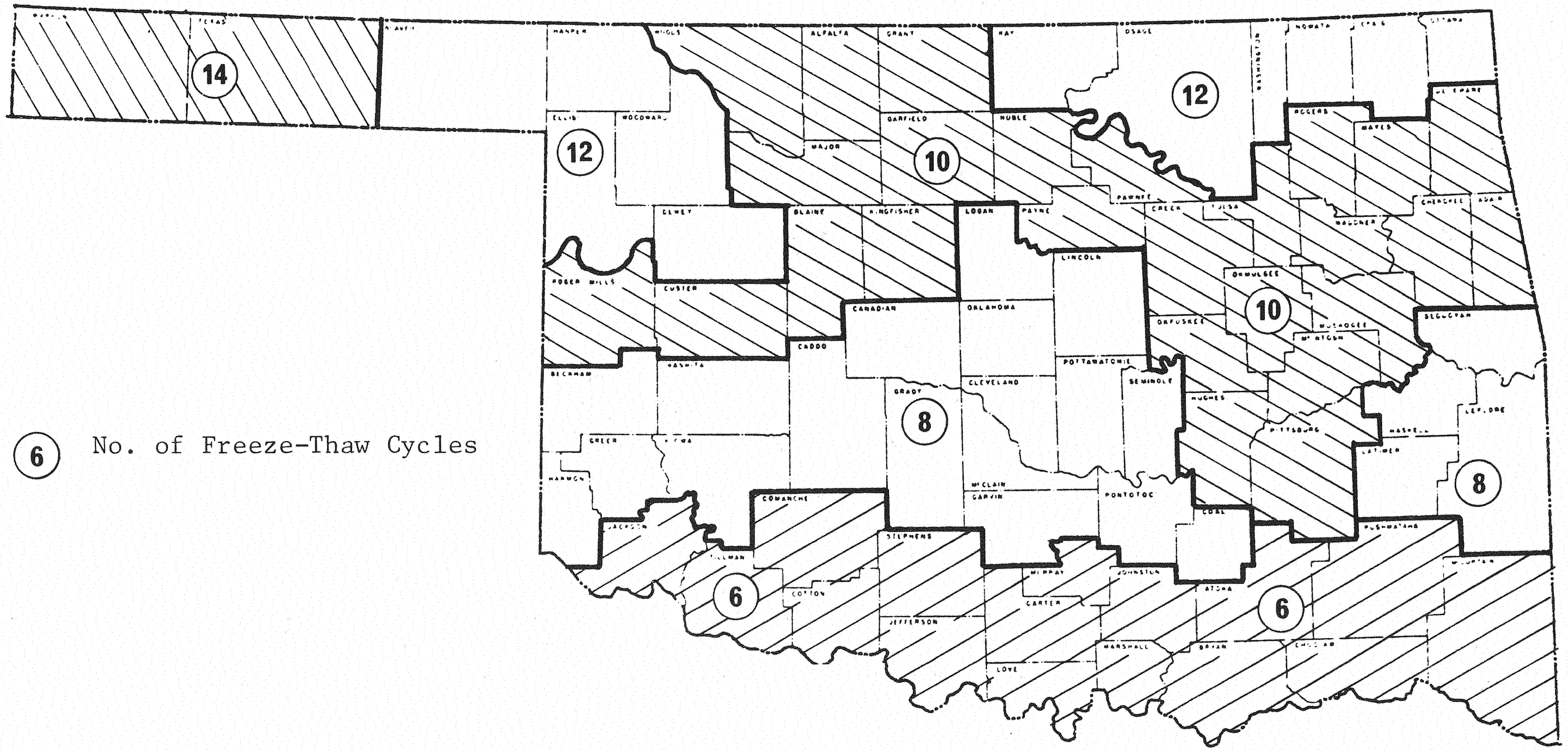


FIG. K.1: FREEZE THAW CYCLES FOR OKLAHOMA

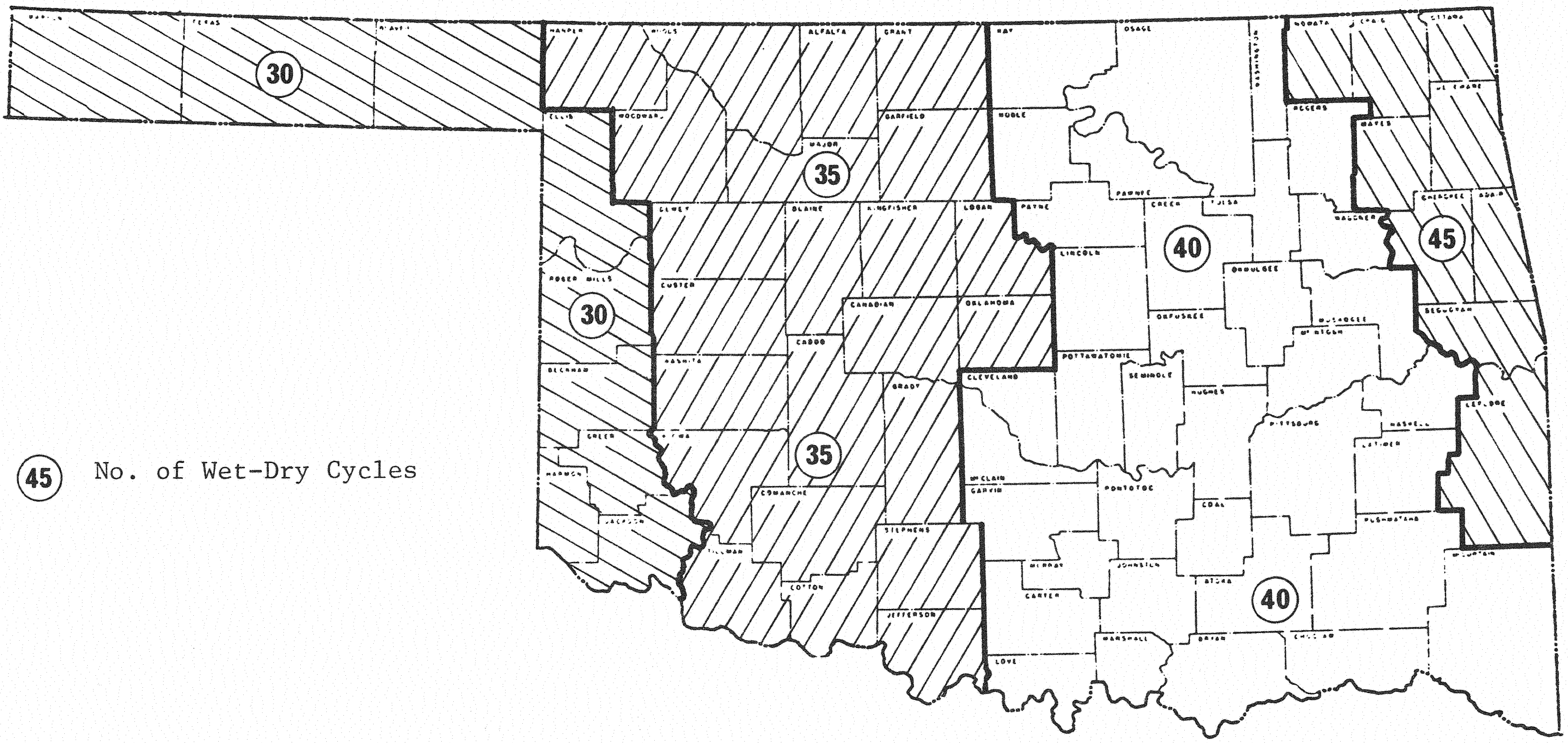


FIG. K.2: WET DRY CYCLES FOR OKLAHOMA