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TECHNICAL REPORT S-71-6

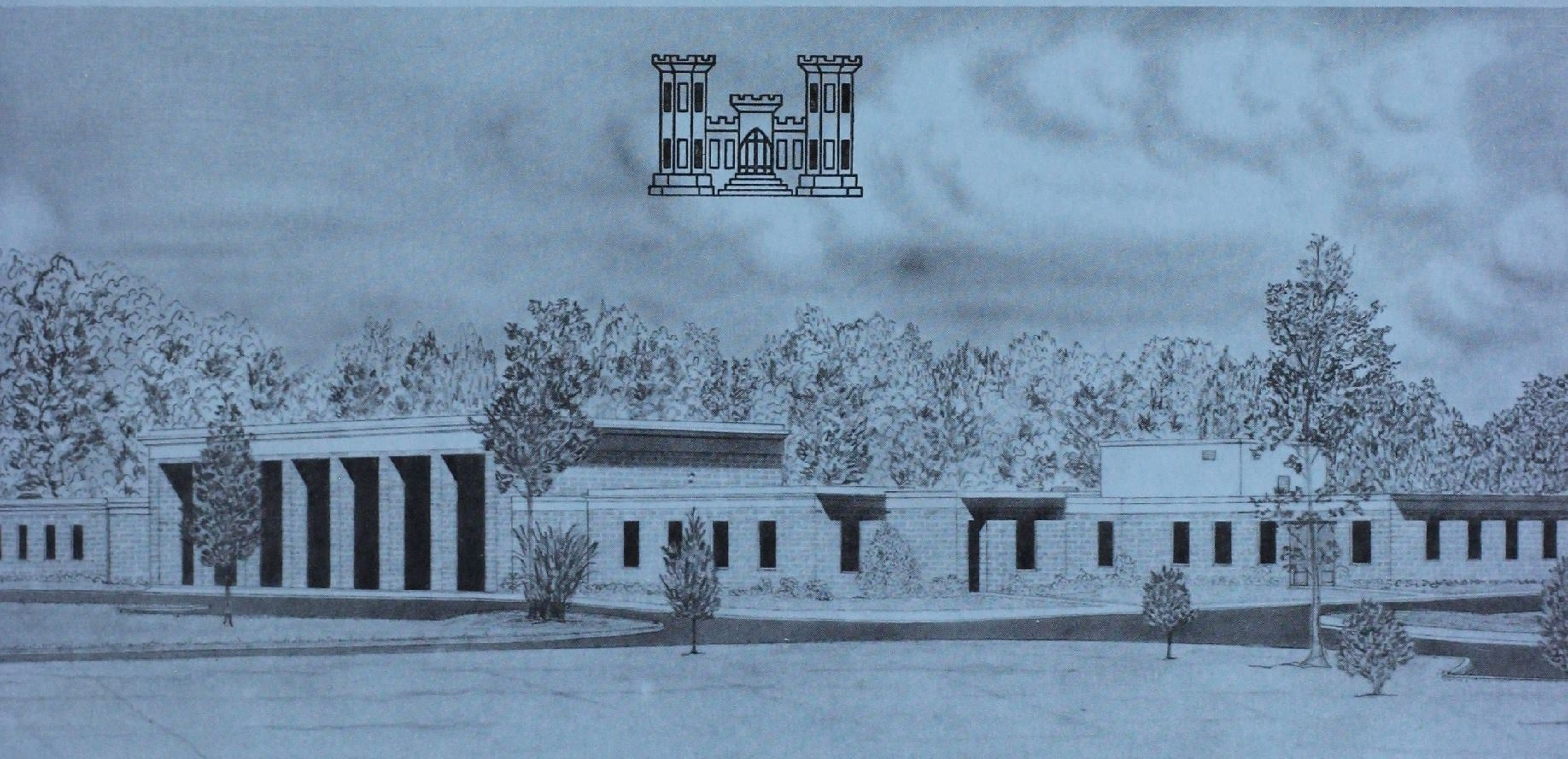
ENGINEERING PROPERTIES OF CLAY SHALES

Report 1

DEVELOPMENT OF CLASSIFICATION INDEXES FOR CLAY SHALES

by

W. Heley, B. N. MacIver



June 1971

Sponsored by **Office, Chief of Engineers, U. S. Army**

Conducted by **U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi**

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ARMY-MRC VICKSBURG, MISS.

FOREWORD

Laboratory investigations of the properties of clay shales by the U. S. Army Engineer Waterways Experiment Station (WES) were requested and authorized by the Office, Chief of Engineers (OCE), in fiscal year 1965 under ES 529 and later under ES 542.

The study of clay shale properties has consisted of both laboratory testing by WES and the review of laboratory test results from other offices of the Corps of Engineers. Particularly helpful in providing information have been Messrs. A. H. Feese of the Southwestern Division and G. S. Spencer of the Missouri River Division. Work at WES was performed by Mr. B. N. MacIver, Project Engineer, and 1LT William Heley, both formerly of the Embankment and Foundation Branch, Soils Division.

This report was prepared by 1LT Heley and Mr. MacIver under the direction of Mr. J. R. Compton, Chief, Embankment and Foundation Branch, and Mr. A. A. Maxwell, Acting Chief, Soils Division, and was reviewed by Mr. S. J. Johnson, Special Assistant, Soils Division.

Directors of WES during the conduct of the study and the preparation of this report were COL John R. Oswalt, Jr., CE; COL Levi A. Brown, CE; and COL Ernest D. Peixotto, CE. Technical Directors were Messrs. J. B. Tiffany and F. R. Brown.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
square feet	0.092903	square meters
gallons	3.785412	cubic decimeters
tons	907.185	kilograms
pounds per square inch	0.070307	kilograms per square centimeter
pounds per square foot	4.88243	kilograms per square meter
pounds per cubic foot	16.0185	kilograms per cubic meter

SUMMARY

Characteristics of clay shales are reviewed with regard to construction and maintenance problems encountered on Civil Works projects of the Corps of Engineers. Confusion in the description and definition of clay shale results from the variable character of the material and the subjectivity of most classification methods. It is considered inadequate to distinguish only good shales from bad shales; rather, standardized indexes are required for the quantitative classification of shales.

From consideration of the several factors controlling the characteristics of clay shales, both qualitative and quantitative indexes are defined and standardized apparatus, procedures, and descriptors for each index are proposed. Particular emphasis is given to the methods for disaggregating clay shale material for index tests and the apparatus and procedures for measuring residual shear strength.

It is recommended that Atterberg limits and particle-size analysis be performed on material processed (a) from undried material, (b) after a single cycle of air-drying and slaking, and (c) after disaggregation by a high-speed food blender. Oven-drying and cyclic air-drying procedures are not believed to provide as useful information as these three methods. Detailed procedures are suggested for the three standardized methods for disaggregating material, including specific equipment and operating requirements for high-speed blending.

Apparatus and procedures for performing repeated direct shear and annular (or rotational) shear tests are reviewed and compared. Variations in measured residual shear strength with type of test, type of specimen, normal stress, and rate of shear displacement are discussed and illustrated with test results. The concept of both a frictional component and a geometrical component to measured residual shear strength is introduced and used to interpret the effect of reversing the direction of shear displacement in the repeated direct shear test. Details of a standardized method for determining residual shear strength are proposed, and objectives for future investigation are suggested.

ENGINEERING PROPERTIES OF CLAY SHALES

DEVELOPMENT OF CLASSIFICATION INDEXES FOR CLAY SHALES

PART I: INTRODUCTION

Background of Study

1. The Corps of Engineers (CE) has long had a direct interest in construction and maintenance problems associated with clay shales. Massive landslides along the Panama Canal began when excavation in clay shales was begun by the CE in 1905, and the slides have never completely stopped. Later, under an expanding Civil Works program, many flood control projects in the central United States required slopes and tunnels to be excavated through clay shales and large water-impounding embankments and structures to be supported on clay shales. Besides problems encountered at dams constructed on the Missouri River, difficulties and uncertainties have attended the construction of dams and appurtenances along the Kansas and Arkansas Rivers and in central Texas. In 1961, a major slide occurred in the clay shale foundation of Waco Dam in Texas during construction.

2. The Office, Chief of Engineers (OCE), initiated an investigation in November 1962 under the program of Engineering Studies (ES) designated ES 529 and entitled "Shear Strength Characteristics of Clay-Shale Foundations." The original purpose of this investigation, which was assigned to the U. S. Army Engineer District, Fort Worth, was "to detect and evaluate the effect of testing techniques on the strength values of clay shales." ES 529 was directed mainly toward the difficulty of correlating results of laboratory tests on clay shales with in situ behavior of such materials. Direct shear (and other) tests of the Pepper and Del Rio shales from the foundation of Waco Dam were performed by the Southwestern Division Laboratory from late 1962 through 1964. The results of this work have been published in part.[1]

3. The U. S. Army Engineer Waterways Experiment Station (WES) was authorized in November 1964 to design and construct an annular shear apparatus to study the residual shear strength of clay shales. From July 1965 (when ES 529 was transferred to WES) through 1968, the work at WES was devoted almost entirely to development of apparatus for residual shear strength determinations. The high-capacity annular shear apparatus presented many difficult design and fabrication problems, as did special equipment needed to trim the annular specimens from intact samples of stiff to hard materials. However, by late 1968, the techniques of specimen preparation had been developed and testing of clay shales was started.

4. ES 529 was terminated in 1968. However, the need for more knowledge of the properties and behavior of clay shales resulted in a new study, having broader objectives than ES 529, that was initiated by OCE in July 1968 as ES 542, entitled "Engineering Properties of Clay Shales."

Objectives of Study

5. One of the several long-range objectives of this study is to establish satisfactory and standardized procedures for the quantitative classification and identification of clay shales by CE offices. An investigation of tests and test procedures useful in identifying and classifying clay shales forms the subject of the present report. The significance of residual shear strength as a measure of long-term stability and as a classification index for clay shales is being studied along with methods for determining residual shear strength. Portions of this study are included in this report. Another objective is to develop information on the macrostructure of clay shales and the effect of gross geological features on in situ behavior. The mass shear strength of clay shale is a difficult property to evaluate. A study of this property will be complicated by the need to reproduce in situ conditions of stress and strain, as well as to test sufficiently large specimens to include

representative geological features. At the present time, little knowledge is available on in situ stresses in clay shale formations, or on the relationship between stress conditions and fissures or slickensides. Experimental investigations of the development of excess pore water pressures must be considered as yet another objective of this study, particularly in view of the high piezometric pressures measured at both Fort Peck and Waco Dams. Stress deformation-time relationships for clay shales also require study.

6. The above-described objectives are being pursued by a variety of methods. One activity is a continuing collection, review, and evaluation of available information on clay shale properties and behavior. Information copies of laboratory reports, field investigations, and design memoranda related to clay shales are obtained from various CE offices; correspondence is being maintained by WES with private firms, educational institutions, and other governmental agencies involved with clay shale problems; and published literature is being studied. This growing fund of information, besides being a source of input to the several separate phases of the study, provides a basis for the long-range objective of correlating field behavior with laboratory test results.

Scope of Report

7. This report is directed solely toward the problem of classification indexes and determination of residual shear strength for clay shales. In the parts that follow, currently used classification indexes, both qualitative and quantitative, are defined and discussed, together with recommended methods for determining them. In some definitions, arbitrary and specific restrictions are introduced to provide standardization. Investigation of classification indexes is continuing under ES 542.

PART II: DEFINITIONS AND CHARACTERISTICS OF CLAY SHALES

8. As described by Underwood,[2] shales are often considered to fall into either of two groups: the good shales or the bad shales. These two groups are also recognized by differentiating shales as rock-like or soil-like, inactive or active, cemented or compacted, stable or unstable, and nonproblem or problem. Unfortunately, this is only a subjective, relative grouping since some shales have definitely good or bad behavioral histories while others have mixed records. However, it is this variable character of shales which causes confusion in the description and definition of shale and which requires quantitative indexing.

9. Shale is defined in one dictionary[3] as "a fissile rock that is formed by the consolidation of clay, mud, or silt, has a finely stratified or laminated structure, and is composed of minerals essentially unaltered since deposition." Underwood[2] defined shale as "the fissile equivalent of claystone and/or siltstone." While these are correct definitions from a geological viewpoint, they do not adequately describe the characteristics which give the words "clay shale" special meaning to engineers. For the Specialty Session on Engineering Properties and Behavior of Clay Shales at the Seventh International Conference on Soil Mechanics and Foundation Engineering,[4] Peterson defined clay shale as "uncemented bedrock containing a high proportion of illite and montmorillonite which has been highly overconsolidated and breaks down on weathering to form a clay." Taylor stated that the material must incorporate some litho relics of the original shale or else it would have to be considered as merely an overconsolidated clay. In an unpublished conference at WES in June 1969, Beene (of OCE) suggested that "clay shale is an uncemented or poorly cemented, highly overconsolidated primary sedimentary rock comprised of predominantly clay minerals."

10. The difficulty with the term "shale" lies in its application to material which is considered a soil by one person and a rock by another. Obviously, there can be no clearly drawn line between soil and unaltered sedimentary rock; materials can be found which represent every stage in the continuous process of densifying an initially soft sediment into an

eventually hard rock. During a particular period in the densifying process, the material may possess considerable strength because of consolidation and, possibly, cementation, but bonds between particles may not ensure permanence of that strength. A shale may appear as substantial as rock, but the engineer is often uncertain whether the material will behave like soil or like rock. This from an engineering viewpoint is the potentially treacherous material to be called "clay shale."

11. For the purposes of this study, clay shales having a wide variation in properties must be investigated to seek correlations between these properties and in situ behavior. Both uncemented and somewhat cemented materials must be examined, as well as materials of different mineralogical composition. Thus the definition of clay shale adopted for this study must not be too restrictive; it must cover both the good and the bad types. Clay shale will be considered to be, first, a heavily overconsolidated sediment. Second, when the material is completely disaggregated into individual particles, it has the properties of clay (that is, the position of its Atterberg limits values on a plasticity chart is above the A-line). Materials included in this study may be massive, fissile, laminated, or slickensided. Degree of cementation, degree of overconsolidation, mineralogical composition, degree of weathering, etc., cannot be specified at this time.

12. The character of shales is so strongly influenced by stress history that many of the common bases for differentiating earth materials are inadequate. The geological age of a material is not a significant indicator, even though most of the formations containing troublesome shales belong to the Cretaceous or Tertiary period. Formation names must be used with care. Most formations that are identified with troublesome clay shales also contain members that are not clay shales but limestones and sandstones. For example, the Pierre Formation consists of eight different members, and only a small part of the total formation consists of the clay shales which have given the formation a bad reputation. Therefore, it is misleading to refer categorically to the behavior of a formation when the intended reference is to the behavior of a member that may constitute only a small part of a given formation. Also, the conditions under which a member of a formation occurs

at one locality may be so different from the conditions under which the same member occurs at another location as to preclude correlation of behavior between the two.

13. Chemical analyses are of limited value in classifying shale since the average chemical composition of all shales is essentially the same: 60 percent silica (SiO_2), 17 percent aluminum oxide (Al_2O_3), 5 to 10 percent ferric oxide (Fe_2O_3), 2 percent magnesium, 2.5 to 3.8 percent potassium monoxide (K_2O), and other salts (Tourtelot, as reported in ref 2). Mineralogical analyses, despite the progress being made with these, are of questionable value in predicting behavior. In some instances, troublesome clay shales have been found to have montmorillonite as the predominant clay mineral,[5,6] though such predominance was not found in the Pepper shale from the foundation of Waco Dam.[7]

14. Underwood[2] proposed that shales could be evaluated for engineering purposes only by assessing the relative values of a number of physical properties. Some of these properties, such as shear strength and permeability, are poorly defined and probably cannot be related with in situ values because of the influence of geological discontinuities. The remainder, however, can be considered to be indexes, amenable to definition and standardized procedures for determination. The need, therefore, is to develop standardized indexes which eventually can be related to the characteristics of clay shales.

PART III: FACTORS CONTROLLING THE CHARACTERISTICS OF CLAY SHALES

15. The physical properties and behavioral tendencies of a clay shale depend on complex mineralogical, chemical, and structural features. These cannot be evaluated directly to provide a basis for computing the overall condition and future behavior of a clay shale. Instead, indexes must be obtained which reflect certain combinations of the factors controlling its physical properties. Since almost every index is affected by more than one factor, no single index can describe a material, and a number of indexes must be used and compared. The following discussion is intended to identify mineralogical and structural characteristics which are considered to be of primary importance in a clay shale. Each factor must be viewed with regard to the geological history of the material. In particular, the dependence of structural patterns and features on past and present stress systems should be recognized.

Character of Individual Particles

16. The first factor to be considered must be the type and size of individual particles comprising the material. A large percentage of clay-sized particles would indicate a potentially more bothersome material than one containing large amounts of coarser particles. However, the quantity of clay-sized particles is not necessarily significant by itself; the type of clay-sized particles present must also be considered. A relatively small percentage of the more active types of clay minerals (such as montmorillonite and illite) can influence the properties of a material more than a larger percentage of less active types of clay minerals (such as kaolinite and chlorite). Mineralogical analyses can detect the presence of different types of clay minerals and can establish the relative quantity of each type present. While these analyses require complex equipment and interpretation by highly qualified specialists, they yield information that is helpful in classifying a material.

17. The quantity and type of clay-sized particles in a soil are typically evaluated by a combination of particle-size analysis and Atterberg limits. The presence of a very active clay mineral would be indicated by a high plasticity index resulting from even a relatively small percentage of clay-sized particles. In the case of a clay shale, however, the strength of interparticle bonds may not permit determination of gradation or plasticity characteristics of its individual particles. These determinations may, in fact, be made on aggregations of particles, giving rise to index values which depend on the effort used to disaggregate the material. While the change in index values with increasing effort to disaggregate is a measure of interparticle bond strength, the meaning of the values themselves is less clear.

Fabric

18. The geometrical arrangement of particles in a clayey material is mainly controlled by the depositional environment and by the stress history following deposition. Material deposited in a brackish or marine environment will become flocculated and produce a fabric of randomly oriented particles. Upon consolidation, such a material can develop high strength, but it will tend to be brittle and sensitive. In addition, clays with randomly oriented particles, having a high percentage of edge-to-face interparticle contacts, are capable of storing considerable strain energy by the flexure of particles and, therefore, produce shales which can be troublesome. Clays deposited in water with low salt contents tend to have less randomly oriented particles; that is, the particles are oriented in a largely parallel fashion with a low percentage of edge-to-face contacts. While high strength and high modulus can develop in a fresh water deposit, such material would not show high sensitivity, and it would not be capable of storing a large amount of recoverable strain energy.

19. Interparticle geometrical relationships are important to the behavior of a clay shale, particularly when considered together with the

interparticle bonding. A qualitative evaluation of fabric is possible by microscopy using thin sections of the material. Recent developments in the scanning electron microscope provide striking displays of fabric with great clarity and depth perception.[8] Methods for making quantitative measurements of fabric by X-ray diffraction are being perfected,[9] and these measurements may eventually prove extremely valuable for the classification and identification of clay shale. Indirect methods for indexing fabric, such as shrinkage and swell characteristics, compression moduli, etc., also reflect the type of clay particles and strength of interparticle bonds, so that rather general assessment of the effect of fabric is possible.

Character of Interparticle Bonds

20. The significance of interparticle bonding on the behavior of overconsolidated clays and clay shales was emphasized by Bjerrum[10] in his explanation of the mechanism of progressive failure. He described the relationship between the strength of the bonds (weak, strong, or permanent) and the capacity of a material to store recoverable strain energy. The reduction in strength of interparticle bonds due to accelerated weathering following excavation releases strain energy and, as a result, causes time-dependent movements of the material.

21. Little is known about the physicochemical character of the bonds between clay particles or about the process, termed "diagenesis," by which these bonds develop and strengthen. Bjerrum[10] postulates that "in the zone of contact between particles the stresses are very large and recrystallation occurs, causing each pair of contacting surfaces to physically conform to one another, and here there might develop adhesion resulting from molecular bonds." Depending on the type of clay particles, the magnitude of the overburden stress, environmental conditions, etc., extremely strong bonds can form over periods of thousands of years. Cementing agents of various types (calcareous, siliceous, etc.) may further strengthen the bonds and, in some instances, produce a permanently

bonded material which must be considered rock rather than soil or clay shale.

22. Visual examination of interparticle bonds is not possible, nor can the strength between two given particles be measured. Instead, the overall strength of interparticle bonding must be indexed by indirect methods. As discussed later, the stronger the bonding, the more effort is required to disaggregate the material. With increasing disaggregation, classification indexes such as particle-size distributions and Atterberg limits will increasingly reflect the character of individual particles rather than clumps of particles. Therefore, the relative strengths of interparticle bonds can be evaluated by the change in measured index properties with increasing effort to disaggregate the material. The type of bonds (whether uncemented or, if cemented, the type of cementing agent) can be revealed to a limited extent by chemical tests.

Macrostructure

23. The type, intensity, and geometrical pattern of discontinuities through a clay shale depend to a large extent on the stress and tectonic histories of the formation. However, depositional patterns and conditions may produce bedding or fissility in a clay shale which is essentially independent of past or present stresses. Clay shale formations were consolidated under high overburden stresses accompanied by high horizontal stresses and will, because of residual horizontal stresses, rebound horizontally toward slopes cut by rivers. Horizontal shear movements following stress relief will produce patterns of fractures and shear surfaces related to (a) the magnitude and direction of the stress relieved, (b) the capacity of the material to store and to release strain energy, and (c) the distance from the slope formed. The intensity of slickensides in clay shales along the Missouri River decreases with depth and with horizontal distance from the river, a very low intensity being found below the river bottom.

24. Additional discontinuities are formed in clay shales by faulting

and sliding. Because of the effect of local conditions, structural discontinuities cannot be used as indexes of an entire formation. Yet, when samples of the same formation are taken at different depths and distances from an eroding river, differences in macrostructure among the samples provide information helpful for classification purposes.

25. Macrostructure is still an essentially qualitative index, subject to the interpretation of individual observers. However, this important factor merits the closest attention. Means for quantitatively evaluating macrostructure eventually may be developed through the application of X-ray techniques. For an example, a radiograph of a piece of Dawson shale from the site of Chatfield Dam in Colorado is shown in fig. 1. Details of intensity and orientation of discontinuities revealed by the density-sensitive X-rays cannot be detected by visual inspection of the shale. The graphical display of these discontinuities provides a basis for direct measurement and statistical analysis.

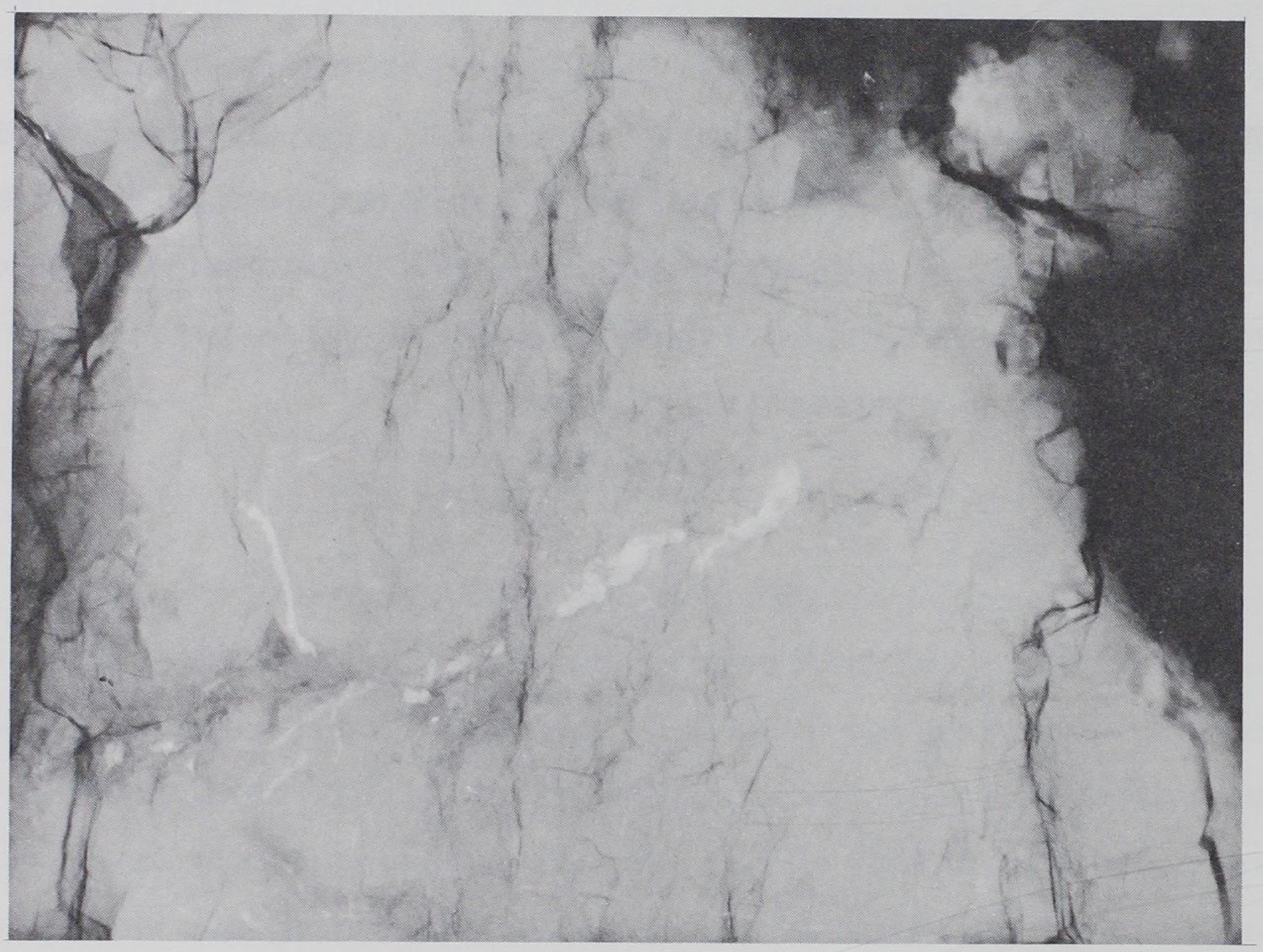

Fig. 1. Radiograph of 2-cm-thick specimen of Dawson shale

PART IV: QUALITATIVE CLASSIFICATION INDEXES

26. The first step in examining and testing an intact soil sample is to prepare a description of the material. This description, by itself, yields information helpful in classifying the material. By performing a number of simple, standardized operations on pieces of the sample, the examination can produce a complete set of qualitative indexes; in many instances, these indexes may be sufficient to classify the material. No special equipment is required to obtain the information, and the examination may be made in the field as readily as in the laboratory. However, standardization of the meaning of the descriptive words is essential to ensuring the value of these indexes. In the following paragraphs are defined the qualitative classification indexes which appear to be the most important and, at the same time, the simplest and most amenable to standardization.

Color

27. The color of a material at its natural water content should be described as completely as possible, since it is indicative of certain minerals or organic matter and the degree of weathering. Charts are available to guide the description of color.[11,12] This description should be limited to the continuous portions of the material and should not include any difference in color on or near discontinuities; the discoloration of fissures and slickensides should be given under the description of the structure of the material.

Consistency

28. The resistance of a material to distortion or compression is a reflection of the strength of interparticle bonds. Gross structural discontinuities should not be permitted to affect the measurement of consistency; only the resistance of intact pieces of material should be

determined. Several scales of consistency have been used, often oriented toward a limited range of local soil types. However, it is believed that the ASTM standard definitions of soil consistency[19] should be followed rather than to introduce special definitions applicable only to clay shales. The standard definitions are given in table 1, with a single modification: the addition of a "Very Hard" category to distinguish materials which are essentially rocklike in character.

29. Two determinations of consistency (made either with the hands or with a pocket penetrometer) are required to indicate sensitivity. One should be performed on an intact piece of material at natural water content, while another should be performed on the same piece of material after it has been thoroughly remolded without reduction in water content. The difference between these two determinations, of course, is a measure of the sensitivity of the material. Such a comparison of consistencies may not be possible for many clay shales, but both determinations should be attempted in order to provide documentation of the character of a material not obvious to an engineer who cannot have the advantage of handling a piece of the material.

30. When an unconfined compression test is performed on a specimen of the material, as discussed later, the results of that test should be used to indicate consistency. For relatively soft materials, a remolded specimen could also be tested in unconfined compression to provide a quantitative measure of sensitivity.

Dry Strength

31. An indirect measure of the quantity and type of clay-sized particles in a soil is given by the crushing strength of a piece of the material after it has been remolded to near the liquid limit and then air-dried. High dry strength is indicative of high plasticity caused by the presence of active clay minerals. A similar test of dry strength on an intact piece of material should also provide an index of the fabric and interparticle bonding. It is suggested that this second test be included in a standard classification procedure, especially since

Table 1

Quantitative and Qualitative Definitions of Consistency[13]

Consistency	Unconfined Compressive Strength kg/sq cm	Identification Procedure
Very soft	< 1/4	Easily penetrated several inches by fist
Soft	1/4 - 1/2	Easily penetrated several inches by thumb
Firm	1/2 - 1	Can be penetrated several inches by thumb with moderate effort
Stiff	1 - 2	Readily indented by thumb but penetrated only with great effort
Very stiff	2 - 4	Cannot be indented by thumb; readily indented by thumbnail
Hard	4 - 8	Indented with difficulty by thumbnail
Very hard	> 8	Cannot be indented by thumbnail

intact pieces are to be air-dried for other purposes.

32. The recommended procedure would be to test two types of specimens as follows:

a. An intact piece at natural water content at least 1 cu cm in volume (preferably a cube cut by a knife).

b. A cube or ball at least 1 cu cm in volume of material remolded with the addition of distilled water to a water content approximately equal to the liquid limit.

Each specimen should be dried to a constant weight at a temperature less than 50 C and then tested by crushing between the thumb and fingers. The following standard definitions[13] should be used to describe the dry strength of the specimen:

Very low	Crumbles with any attempt to handle
Low	Crumbles into powder with little finger pressure
Medium	Considerable finger pressure required to crush into powder; usually, a smear of powder can be easily rubbed from a smooth surface of the specimen
High	Cannot be crushed into powder by finger pressure, but can be broken into pieces; usually, it is not possible to rub a smear of powder from a smooth surface of the specimen
Very high	Cannot be broken between thumb and hard surface

Gloss

33. The degree of polish or gloss that can be produced on the surface of a clayey material is an indicator of the quantity and type of clay minerals present. Two methods have been used to produce surfaces for estimating gloss: (a) cutting with a knife into a piece of intact material at natural water content and (b) rubbing a fingernail on a ball of material remolded to slightly below the plastic limit.[14] For the sake of simplicity and to keep the number of indexes to the minimum required, it is suggested that gloss should be estimated only by remolding the material with the addition of distilled water to a water content slightly below the plastic limit and then repeatedly rubbing a ball (about 1 cm

in diameter) upon the thumbnail. The following standard descriptors for gloss are recommended:

None	No discernible reflection of light
Low	Slight reflection of light, as from a sheet of vellum
Medium	Similar to an unpolished fingernail
High	Similar to glazed porcelain

Reaction to Hydrochloric Acid

34. If the cementing agent in a clay shale is calcareous (that is, consists of calcium carbonate), this can be revealed by the reaction of the material with a dilute hydrochloric acid. The reaction, expressed as $CaCO_3 + 2\ HCl \longrightarrow CO_2 + H_2O + Ca\ Cl_2$, produces carbon dioxide, which bubbles and froths in a drop of acid placed on the surface of the material. This examination should be applied to the clayey material, rather than to discrete inclusions, for identifying the type of cementing agent; however, the reaction to hydrochloric acid of any inclusions should be noted separately.

35. To provide a standardized procedure for detecting the presence of calcium carbonate, it is suggested that an intact piece of the material, with at least one plane surface cut with a knife or a saw, should be air-dried (that is, dried to a constant weight at a temperature less than 50 C), and then a single drop of 0.1 N hydrochloric acid be placed on the horizontal plane surface. The reaction should be observed (preferably using 10- to 20-power magnification) from the moment the drop is placed. The following descriptors are suggested:

None	No discernible reaction
Slight	A very few, discrete bubbles detected in drop
Slow	Many bubbles formed, but process continues slowly for several minutes
Rapid	Foaming and frothing completed within a minute or two

Slaking Behavior

36. The disintegration of an intact piece of clayey material upon immersion in water reflects the type of clay minerals present, the fabric of the material, and the character of the interparticle bonds. Several investigations have been and are being made on slaking with regard to the effect of drying before immersion, the type of liquid used for immersion, and the result of repeated drying and immersing. Until these investigations are completed, it is suggested that slaking behavior be indexed using at least the following two types of slaking tests:

a. Immerse in distilled water an intact piece (at least 1 cu cm in volume) of the material at natural water content and describe its behavior.

b. Immerse in distilled water an intact piece (at least 1 cu cm in volume) of air-dried material (dried to a constant weight at a temperature less than 50 C) and describe its behavior.

37. To describe the slaking behavior, three effects must be noted: (a) the volume of material which has become completely disaggregated (that is, reduced to individual particles), (b) the rate at which the slaking proceeds, and (c) the size and shape of the pieces that were not disaggregated. Suggested standard descriptors are as follows:

a. The volume of material reduced to individual particles should be estimated and compared to the initial volume of material. The degree of disaggregation is described as follows:

None	No discernible reaction
Slight	Less than 5 percent of the volume disaggregated
Some	Between 5 and 25 percent of the volume disaggregated
Much	More than 25 percent but not all of the volume disaggregated
Complete	No intact pieces of the material remain (sand particles should not be confused with pieces of clayey material)

b. The rate of slaking is described as follows:

Slow	Action continuing for several hours
Medium	Action completed within 1 hr

Rapid	Action completed with 2 min
Sudden	Violent, explosive-like reaction

c. The character of remaining pieces of material is described as follows:

No change	Initial piece of material remains intact
Plates remain	Material broken into platy fragments of essentially uniform thickness
Flakes remain	Flaky or wedge-shaped fragments of uneven thickness.
Chunks remain	Bulky fragments all larger than 3 mm (1/8 in.)
Grains remain	No pieces larger than 3 mm remain

Structure

38. A complete description of discontinuities in a clay shale is very important, though rather difficult to prepare. Even the size of the sample to be examined cannot be specified as this will depend on the spacing of the discontinuities. Nevertheless, every effort should be made to work (with fingers and knives) a sufficiently large sample into smaller pieces to expose the type and intensity of structural discontinuities present in that sample.

39. In general, it is necessary to distinguish two types of material: fissile, with cleavage or parting having a parallel orientation, and massive, with no preferred direction of cleavage. For a fissile material, the average spacing of theparting surfaces and the shape of the resulting fragments (plates or flakes) should be observed. For a massively bedded material, the details of the description are more critical. The following types of observations are suggested:

a. The pattern of joints, that is, whether the joints appear to occur randomly or whether there is a preferred orientation or variation in intensity with direction.

b. The average spacing of joints (as a measure of intensity). In most cases, this would be an estimate of the average dimension of the average-sized fragment of material produced by separating the sample along discontinuities. Where a preferred orientation of joints is noted, it is necessary to estimate the average spacing in more than one direction.

c. The continuity of joints. Joints which pass through the entire sample should be distinguished from those which have a limited extent. Where both continuous and short-length joints are found, the percentage of each type (based on the total area of joint surfaces present) should be estimated.

d. The character of the joint surfaces. This description must include the following three factors:

   (1) Texture. Roughness, undulations, striations, whorls, etc., should be observed.

   (2) Gloss. The relative shininess of the surfaces should be estimated using the descriptors suggested previously. If a marked variation is found in the gloss of joint surfaces through the material, the percentage of the highest gloss surfaces (based on the total area of joint surfaces present) should be estimated.

   (3) Color. Discoloration along joint surfaces (whether due to weathering or the deposition of soluble minerals) should be described. If only a portion of the joint surfaces show coloration different from the intact material, the percentage of discolored surfaces (based on the total area of joint surfaces present) should be estimated.

PART V: QUANTITATIVE CLASSIFICATION INDEXES

40. While the qualitative determinations described previously can be helpful in identifying potentially troublesome materials, especially when in the field, quantitative indexes determined by standardized procedures have more specific meaning and are less subject to bias and inconsistency. The quantitative classification indexes defined and discussed in the following paragraphs are proposed to provide the complete suite of values necessary to characterize a specific material. Determination of all these indexes can be made on a single 6-in.-diam core of clay shale about 2 ft long.

Natural Water Content

41. The simplest and easiest property of a material to determine is natural water content.[15] Besides being simple to measure, it is also quite valuable. The water content of every sample being classified should always be determined, and frequent (less than 2-ft depth intervals) determinations should be made through the entire formation. The variation in water content adjacent to major discontinuities and shear planes should be determined from closely spaced (about 2-in. depth intervals) specimens. Thin layers of bentonite can be detected from their high natural water contents.

Dry Unit Weight

42. When the sample of material has been obtained from below the groundwater table and can be considered completely saturated, the natural water content is an adequate indicator of the density of the material. If the sample is not completely saturated, the dry unit weight (or density) of the material will have to be determined separately, and the water content then used to compute the degree of saturation.

43. Determining the dry unit weight requires a volumetric measurement which is time consuming since the volume of a sample must be

determined with considerable precision. However, the preparation and measurement of specimens for other tests (unconfined compression, free swell, and residual shear) provide both weight and volume determinations as a matter of course. It is suggested that data from other tests (preferably the unconfined compression test) be used to compute the dry unit weight rather than making a special volumetric measurement.

Minus 2μ Fraction

44. Particle-size distributions, based on hydrometer analyses, are typically used in a rather qualitative manner; that is, the relative positions of several gradation curves show which materials contain more finer or coarser particles. To obtain a numerical value from a gradation curve, it is necessary to select a reference value of either particle size or the percentage of particles finer than the given size. One of the more common reference values is the particle size of 2μ (0.002 mm) which is often taken to be the upper limit of clay-sized particles. It is suggested that the percentage of particles finer than 2μ be used to summarize the results of particle-size analyses for classification of clay shales.

45. The minus 2μ fraction should be a measure of the percentage of clay-sized particles present, but interparticle bonding will produce aggregations of particles and, thus, will produce an apparently coarser material. The strength of interparticle bonds can perhaps be evaluated by the increase in the minus 2μ fraction with increasing effort to break the bonds.

46. It is recommended that three conditions be standardized for the hydrometer analyses used to classify clay shales: (a) material processed without drying from the natural water content, (b) material air-dried and slaked in distilled water a single time, and (c) material air-dried and slaked in distilled water a single time and then subjected to a standardized duration of dispersion in a high-speed food blender. These three conditions of the material are hereafter referred to as (a) undried, (b) air-dried, and (c) blenderized. Recommended procedures for

disaggregating clay shale material for particle-size and Atterberg limits determinations are given in Appendix A together with a review of procedures used previously.

47. While laboratory investigations have shown that increased durations of blenderizing and repeated air-drying and slaking will both increase the disaggregation of a clay shale and the measured clay fraction, the number of variables allowed to influence this classification index must be minimized by standardized procedures to prevent the classification of each material becoming a minor research project in itself. The three recommended conditions are thought to cover an adequate range of disaggregation efforts to assess the strength of the interparticle bonds, and yet are attainable by simple, inexpensive laboratory methods.

Atterberg Limits

48. The liquid limit and the plastic limit constitute two important quantitative indexes of the potential behavior of a clay shale. However, the determination of these limits (particularly the liquid limit) will be affected by interparticle bonding in the same way that the particle-size analysis is affected. Therefore, it is suggested that the liquid limit and the plastic limit be determined on material processed by the three methods (undried, air-dried, and blenderized) described in Appendix A.

49. Increased effort to disaggregate will increase the liquid limit more than the plastic limit, so the plasticity index will be increased. Since the increased effort will increase the minus 2μ fraction also, it is of interest to determine the variation in activity ratio of the material with increasing effort. The expression "activity ratio" is preferred for the ratio of the plasticity index to the minus 2μ fraction instead of "activity," as originally defined by Skempton,[16] in view of the frequent qualitative applications of the word active.

Compressive Strength

50. Results of unconfined compression tests can be considered as classification indexes as well as strength data. For classification of clay shale, it is recommended that the standard unconfined compression test[15] be performed on specimens approximately 6 in. in diameter (that is, nominal 6-in.-diam samples without peripheral trimming). Any variation from this standard size should be clearly noted. The specimen should be prepared as rapidly as possible and encased in a thin rubber membrane during the test to minimize deterioration due to drying. Complete stress-strain data should be recorded and plotted for each test so that a modulus of deformation can be determined graphically.

51. Anisotropy of strength is a very significant characteristic of a clay shale, and the classification of a material would be incomplete without an assessment of strength anisotropy. However, no standardized method can be applied in all cases, so the tests to determine anisotropy of strength cannot be prescribed until a detailed description (particularly with regard to macrostructure) of the material is available. Samples should be reserved at an early stage in the exploration program from which shear test specimens can be trimmed with axes inclined at different angles from the horizontal or from bedding planes.

Modulus of Deformation

52. The modulus of deformation, as determined in the unconfined compression test, reflects the strength of interparticle bonds and may help in identifying a cemented material. In addition, a logarithmic plot of modulus versus compression strength, which has been widely accepted for the classification of hard rocks,[17] is believed to be equally applicable to clay shales. To ensure consistency with the classification method for hard rocks, the tangent modulus of deformation (the slope of a straight line tangent to the stress-strain curve at the point where the axial stress is 50 percent of the compressive strength) should always be

determined rather than the secant modulus (the slope of a straight line from the origin through the point on the stress-strain curve where the axial stress is 50 percent of the compressive strength).[18]

Residual Friction Angle

53. The different apparatus and procedures currently being used for determining residual shear strength are discussed in Appendix B along with recommendations for standardizing these determinations. The residual shear strength, besides being a measure of the minimum shearing resistance of a soil, is considered in this report to be an important classification index. For this purpose, the expression "residual friction angle" is suggested for the angle having a tangent equal to the ratio of the residual shear strength to the corresponding normal stress. The magnitude of the residual friction angle, if it were dependent only on the character of individual particles, should be independent of normal stress, though it might be affected by strain rate. However, as discussed earlier, interparticle bonding may result in this angle being a measure of the shearing resistance between clusters of particles instead of between individual particles. In that case, an increase in normal stress could cause increased disaggregation of the material and, in turn, a reduction in residual friction angle. Any effort to disaggregate the material (such as air-drying and slaking) would reduce the residual friction angle for a material with strong interparticle bonds.

54. For classification purposes, the residual friction angle should be determined under a standardized normal stress and at a standardized rate of strain, as discussed in Appendix B. Additional information can be gained, on an optional basis, by determining the change in the standard residual friction angle caused by increasing the normal stress and, in another stage, by decreasing the strain rate; procedures for these additional determinations are also recommended in Appendix B.

Linear Shrinkage

55. The percent reduction in the dimensions of a piece of intact material upon air-drying from the natural water content should be indicative of the quantity and type of clay-sized particles present. Also, the difference in the amount of shrinkage in different directions should be a reflection of the fabric of the material and be related to in situ stress conditions. Some measurements of linear shrinkage are being made at present,[14,19] and these values are believed to be helpful indexes. To provide a standardized procedure, it is suggested that two prisms about 4 cm long by 2 cm wide by 1 cm high (approximately 1.5 in. by 1.0 in. by 0.5 in.) should be trimmed from intact material at its natural water content with the longest axis of one prism parallel to the bedding (or horizontal) and the longest axis of the other prism perpendicular to the bedding (or vertical). All surfaces should be essentially plane and end surfaces of each prism should be essentially parallel. Using a caliper or a dial comparator, the length of each prism should be measured and recorded. The prisms should then be dried to a constant weight at a temperature less than 50 C and their lengths measured again. The results of the tests should be reported as (a) the shrinkage (as a percentage of the initial dimension) parallel to the bedding (or in the horizontal plane) and (b) the average shrinkage perpendicular to the bedding (or in a vertical direction).

Swell Potential

56. Several types of tests can be performed in a consolidometer to provide bases for estimating the potential rebound or swelling pressure of a clay shale.[20,21] These are not classification tests, and they must be carefully planned with regard to the depth of each sample and the expected changes in conditions caused by construction. For classification purposes, either of two types of measurements might be used: (a) the pressure required to prevent a consolidation test specimen from swelling

upon inundation and (b) the change in height of a consolidation test specimen when permitted to swell under a low pressure upon inundation. Each has major disadvantages. Measurements of swell pressure using a single specimen are difficult because of the problem of completely preventing volume change; a very small increase in specimen height can produce a substantial reduction in pressure. A relatively close estimate of the swell pressure has been found possible by inundating a specimen while under a pressure equal to the computed overburden stress and then adjusting the applied pressure manually to counter any tendency for the specimen to swell.[22] In the other case, where swelling is permitted, considerable time may be required to complete the test, and friction on the wall of the consolidation ring may be sufficient to restrain a portion of the swelling movement. However, these problems may be solved in part by using a specimen with as small a height as possible and by using a well-polished consolidation ring.

57. It is believed that the amount and rate of swell under a low stress are more closely related to the important in situ behavioral tendencies of clay shales than is swell pressure. Thus, a free-swell test would be preferable to a swell-pressure test for classification purposes. However, the swelling pressure should be determined as a part of the standard consolidation test.

58. For a standardized measure of swell potential, it is suggested that a thin, large-diameter specimen of intact material at natural water content be trimmed to fill a rigid consolidation ring. The cross sectional area of the specimen should be at least 100 sq cm (4.44 in. in diameter) and, if possible, should be as large as 150 sq cm (5.44 in. in diameter). The height of the specimen should be no more than 2.5 cm (1 in.) and, if possible, should be as small as 1 cm (0.4 in.). The inside surface of the rigid ring should be highly polished or have a hard ceramic or chromium plating to minimize friction. The top and bottom surfaces of the specimen should be trimmed parallel to the bedding (or horizontal). Preparation of the specimen, of course, should be as rapid as possible to avoid drying effects.

59. The ring containing the specimen should be placed in an empty water reservoir between two air-dry, rigid porous disks. The ring should not be fastened against the lower disk, but permitted to "float" so that the material can swell from both the top and the bottom of the ring. A dead weight should be placed on the upper porous disk to apply a total stress on the specimen of 0.1 kg per sq cm (for a specimen 4.44 in. in diameter, a weight of about 22 lb would be required). A dial indicator should be rapidly mounted and adjusted at the center of the dead weight. Then, the specimen should be inundated with distilled water, and changes in specimen height with elapsed time should be measured until a straight-line secondary time effect can be clearly defined.

60. The following values from the standardized free swell test should be reported:

a. Amount of primary swelling. This is the increase in specimen height, expressed as a percentage of the initial height, during the period of primary reaction, that is, until the reversal in curvature of a plot of height change versus the logarithm of elapsed time.

b. Rate of secondary swelling. This is the increase in specimen height, expressed as a percentage of the initial height, during a tenfold increase in elapsed time (one logarithmic cycle) after a straight-line secondary time effect has been established.

61. The first of these two values should be related to in situ stress conditions. That is, some portion of the elastic rebound of the material upon removal from the ground should be resisted by tension induced in the pore water. Destroying the pore water tension by inundation should permit an additional rebound in proportion to the preexisting stress. The value of the rate of secondary swelling is suggested as a possible index of the tendency for long-term rebound of a clay shale.

Calcium Carbonate Content

62. The qualitative evaluation of the presence of calcareous cementing material by the reaction with dilute hydrochloric acid was described previously. A quantitative measure of the percentage of calcium carbonate

contained in a clay shale would be helpful, though the most satisfactory method for making this measurement has not been established. One method being used is to soak a specimen for several hours in dilute hydrochloric acid at an elevated temperature (about 40 C) and determine the percentage reduction in dry weight.[14,19]

Predominant Clay Minerals

63. Results of mineralogical analyses are included under quantitative indexes, although they are often used only in a qualitative sense. Mineralogical studies are not within the capabilities of most soils laboratories, though some CE laboratories are equipped to perform chemical, X-ray diffraction, differential thermal, and spectrographic analyses. The results of these analyses must be evaluated by an expert to indicate the types of clay minerals present and the quantity of each (expressed as a percentage of the total dry weight of material). Identification of the predominant clay minerals may be valuable information, and obtaining such information should be encouraged.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

64. At present the reliability of applying the results of laboratory tests in theoretical analyses for predicting in situ behavior is not well established. One of the few exceptions is a stability analysis where sufficient previous sliding has occurred to permit the assumption that only the residual shear strength could be mobilized. For most other cases an essentially empirical approach must be followed. That is, the future behavior of a material must be assumed to correspond with the past behavior of a similar material. A key element in the empirical approach is evidence that the materials are similar. Another equally important element is the evidence that the conditions of materials are similar; however, this evidence (joints, faults, stresses, etc.) must be obtained from field mapping and geologic surveys which are beyond the scope of this report. To provide the required evidence of similar material, a number of index properties specifically applicable to clay shales must be compared. The importance of these indexes for the classification of clay shales is apparent in the studies conducted by the CE relative to a prospective sea-level interoceanic canal through the Central American isthmus.

65. Classification indexes become valuable only when such determinations have been made on a large number of projects involving different types of materials with widely varying properties and behavior records. In addition, the method for determining each index must be standardized or the value of an index from one project cannot be related to the value from another project. A common basis is needed among CE offices regarding, first, which indexes should be used for the classification of clay shales and, second, how the chosen indexes should be determined. Once established and employed, such standards should result in the accumulation of information of much greater value from each future Civil Works project and, under special studies such as ES 542, valid comparisons can be made relating both good and bad records of behavior.

66. It is recommended that both the qualitative and quantitative classification indexes described and defined in this report be used as

the basis for standardization. However, considerably more work will be required before reliable correlations between indexes and behavior can be established. A large quantity of data from which to seek correlations is being produced in several active studies of clay shales. The first of these is a study of slopes along the upper Missouri River valley involving field and laboratory investigations by the Nuclear Cratering Group, Missouri River Division, and WES.[22] The second is an extensive program of laboratory classification, examination, and testing by the South Atlantic Division of clay shales from along several possible routes of the prospective interoceanic canal.[23] The third is a study of slopes along the Panama Canal being conducted by WES for the Panama Canal Company and the Jacksonville District,[24] and being continued under the Soil Mechanics Engineering Studies program. Thorough analysis and synthesis of the data from these studies should be a major effort under ES 542.

67. Two difficulties in determining standard index test values are the methods employed for disaggregating clay shale materials and for determining residual shear strengths. These methods are discussed, respectively, in Appendixes A and B, together with recommended procedures. Disaggregating a well-bonded and possibly a partially cemented material to evaluate the character of individual particles requires a technique which gives complete, yet expeditious, separation of the particles but does not alter the character of the individual particles. It is recommended that all CE division laboratories be encouraged to disaggregate clay shale materials, in investigations for Civil Works projects, by the methods suggested in Appendix A.

68. Investigation of methods for determining residual shear strengths should continue, using the variety of laboratory apparatus required and now available. The objective of highest priority should be to evaluate the adequacy and efficiency of the repeated direct shear test on precut specimens. This work will require comparative annular and repeated direct shear tests on essentially identical specimens. Where differences are found between the results of such tests, further study will be needed to determine the reasons for the differences and to establish criteria for

equipment and procedures which will give the most satisfactory measurements of residual shear strength.

69. Another objective of the study should be to evaluate the suitability of residual shear strength determinations obtained by using remolded clay shale material. If remolded specimens yield appropriate values, relatively inexpensive annular shear apparatus could be used for expeditious determinations of residual shear strength in the manner being studied at Harvard University.[25] It is believed that the difficulty in preparing annular specimens of undisturbed clay shales may limit the possible use of annular shear tests by CE division laboratories to remolded material.

70. Other aspects of the residual shear strength test must continue to be examined. Factors to be considered include the magnitude of the normal stress, the influence of the rate of shear displacement, the extrusion of material from between the two halves of the shear box, and many details in the procedures for preparing specimens and performing the tests. These aspects, as well as methods for determining all other classification indexes, must be investigated by testing clay shales from an adequate number of formations, including both those with good reputations and those whose names have become notorious in foundation engineering.

71. It is recommended that the procedures described in Appendix B serve as a basis for the introduction of a standardized residual shear strength test. Some standardization is needed immediately to provide comparable results from the different CE division laboratories. However, the initial restrictions should not be so inflexible as to stifle the interest and freedom of individual laboratories to investigate alternative procedures.

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APPENDIX A

METHODS FOR DISAGGREGATING CLAY SHALE MATERIAL FOR INDEX TESTS

1. Determinations of such classification indexes as Atterberg limits and particle-size distributions are based on the presumption that individual clay and silt particles are free to move relative to each other in a slurry. In most instances, this condition can be readily obtained by manipulating a remolded material while increasing the water content. However, the interparticle bonds in clay shale material cannot always be broken by normal manipulation, and some of the material will remain in the form of aggregations or clusters of individual particles. The measured index properties will depend, in this case, on the effort used to disaggregate the material.

Variations in Procedure

2. While the procedures for determining Atterberg limits and particle-size distributions of soils are standardized among CE offices,[15*] this does not ensure consistent or correct results for clay shale materials due to the dependence of results upon techniques of sample preparation. In addition, the variation in procedure permitted in the hydrometer analysis would affect the results obtained on clay shales since the analysis can be performed on material that has been either processed from its natural water content or oven-dried and slaked. Thus merely following the standard CE laboratory procedures is no assurance of comparable results.

3. Special procedures have been developed for processing clay shale material, and the development of these procedures is continuing in the laboratories of MRD, SAD, SWD, and WES. In general, the objective of the processing is to disaggregate the material so that the classification

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* Raised numbers refer to similar numbered items in Literature Cited which follows the main text.

indexes reflect the character of individual particles to the greatest extent possible. Variations in procedures currently in use for clay shales are discussed in the following paragraphs.

Missouri River Division

4. The MRD standard method for preparing clay shale material for Atterberg limits is to shave a piece of material at its natural water content using a salad grater and allow the shavings to air-dry for 48 hr. Then, the dry material is ground in a mortar with a rubber-tipped pestle (or a steel pestle, when needed) to pass the No. 40 sieve. The powder is slaked in distilled water for 48 hr. After reducing the water content to a point still well above the liquid limit, the material is worked in a thin layer on a glass plate with a steel spatula to crush any remaining lumps.

5. As part of a study of slopes in clay shale sponsored by NCG,[22] MRD determined Atterberg limits on material (a) processed from natural water content, that is, undried, (b) after oven-drying and slaking, (c) after one cycle of air-drying and slaking (the MRD standard method), (d) after several cycles of air-drying and slaking, and (e) after air-drying, slaking, and blenderizing. The procedure for preparing oven-dried material was identical to the MRD standard method except that the shavings were oven-dried rather than air-dried.

6. Material processed from natural water content was shaved using a salad grater and the shavings were immediately placed in distilled water for 48 hr. Then, the material was ground while wet in a mortar with a rubber-tipped pestle to pass the No. 40 sieve (a steel pestle being used on harder portions) and the resulting breakdown microscopically inspected for any breakdown of nonclay material. After reducing the water content, the material was worked on a glass plate with a steel spatula to crush any remaining lumps.

7. For repeated air-drying and slaking, the material at natural water content was broken into pieces approximately 1 in. in diameter or smaller. The pieces were then alternately air-dried for 48 hr and slaked in distilled water for 48 hr until judged, by feeling for lumps with the fingers, to be

completely disaggregated. After reducing the water content, the material was worked on a glass plate with a steel spatula.

8. Material to be blenderized was first treated in the standard MRD method: shaved, air-dried, ground to pass the No. 40 sieve, and slaked. The slurry was then blenderized for 20 min in a food blender (Sunbeam make) having a no-load speed of 18,000 rpm; the resulting breakdown was microscopically inspected for any breakdown of nonclay material. After reducing the water content to a point still well above the liquid limit, the material was worked on a glass plate with a steel spatula. Results of these different preparation methods are discussed in subsequent paragraphs.

9. All material for the hydrometer analysis was prepared similar to the MRD standard method, except that a quantity of the dry powder was removed from the batch and split into two equal parts; one part was slaked in distilled water for 48 hr to serve as the specimen for analysis, while the water content of the second part is used to compute the oven-dry weight of the first part. Thus the particle-size analysis is performed on material air-dried but neither oven-dried nor worked on a glass plate with a steel spatula.

South Atlantic Division

10. SAD has conducted extensive laboratory testing of clay shales for the Atlantic-Pacific Interoceanic Canal Commission studies.[19] For Atterberg limits determinations, SAD processed the material in essentially the same way as MRD did under the NCG study: (a) from natural water content, (b) after oven-drying and slaking, (c) after one cycle of air-drying and slaking, (d) after several cycles of air-drying and slaking, and (e) after air-drying, slaking, and blending. Air-drying by SAD was done in a special room with a high temperature (38 C) and a low relative humidity (about 10 percent). For cyclic air-drying and slaking, SAD used ten cycles. Blending times of both 10 and 20 min were tried when using the high-speed blender (Waring make). All material for Atterberg limits determinations was worked on a glass plate with a steel spatula.

11. Material for the particle-size analysis was taken from the batch

disaggregated by cyclic air-drying and slaking, and worked on a glass plate with a steel spatula in the same manner as used for limit determinations. Dispersing the material for the hydrometer analysis was accomplished by the high-speed blender (for approximately 4 min) instead of the standard milk-shake stirrer.[15]

Southwestern Division

12. Classification tests on clay shales are typically performed by SWD with only the minimum required departure from standard CE procedure.[15] For both Atterberg limits determinations and hydrometer analyses, material at natural water content is soaked overnight in distilled water and, then, is either (a) worked wet in a mortar with a pestle to pass the No. 40 sieve or (b) blended for 1 or 2 min in a high-speed food blender (Oster make) to pass the No. 40 sieve.[26] The water content is reduced to just above the liquid limit, and the material is tempered overnight before testing. No special attention is given to working the material with a steel spatula, though some working is inherent in the liquid limit test.

13. Special methods for processing clay shale material are being developed by SWD for specific projects.[7,26,27] These include air-drying and oven-drying the material and the use of the high-speed food blender and an ultrasonic bath for varying periods of time. Some results of these methods are discussed in subsequent paragraphs.

Waterways Experiment Station

14. Clay shales tested by WES in 1968 for the Panama Canal Company[28] were broken into 1-in.-diam pieces (or smaller), air-dried for 96 hr, and slaked in distilled water for 24 hr. The material was then subjected to an additional three to five cycles of air-drying for 48 hr and slaking for 24 hr. Atterberg limits were determined on the repeatedly slaked material following each of four types of further processing: (a) worked on a glass plate with a steel spatula, (b) not worked on a glass plate, (c) oven-dried, slaked in distilled water overnight, and worked on a glass plate with a steel spatula, and (d) blended for 5 min in a high-speed food blender (Hamilton-Beach make). All material was washed through the No. 40 sieve before testing.

15. Particle-size analyses were performed on the repeatedly slaked material following each of three types of additional processing: (a) worked on a glass plate with a steel spatula, (b) not worked on a glass plate, and (c) blended for 5 min in a high-speed food blender.

16. Subsequent testing of clay shales by WES for the Panama Canal Company is being done in accordance with the MRD procedures.[14]

Effects of Drying and Slaking

17. The results of the work by MRD,[22] as shown in table A1, indicate clearly the increased disaggregation of the material by air-drying and slaking. This is dramatically shown by the liquid limit of the cemented bentonite of the Claggett formation which more than doubled in value. Oven-drying and cyclic air-drying of chunks produced results which are difficult to interpret; in one instance the liquid limit would be higher than that produced by the MRD standard procedure, while in another instance it would be lower. The source of this variability may be incomplete drying of material before slaking. Where oven-dried material produced a higher liquid limit than air-dried (rather than a lower value as reported by Casagrande[29] for Bearpaw shale from Canada), this might be an indication that the air-dried material was simply not sufficiently dry (perhaps due to a high relative humidity of the air) to give a strong slaking action.

18. The results from the WES laboratory test program on the bentonitic Cucaracha shale from the Hodges Hill investigation in Panama[28] showed that oven-drying produced increases in liquid limits by 3 to 16 points over the air-dried method. These results are shown in table A2. The minus 2μ fraction also increased with mixing effort. Working the material on a glass plate with a steel spatula raised the minus 2μ fraction as much as 20 percent.

19. Results of tests by SWD on the Dawson shale showed a distinct increase in liquid limit due to air-drying and oven-drying, while the plastic limit remained unchanged.[26] Tests performed by WES on the Dawson

Table A1

Effect of Disaggregating Effort* on Atterberg Limits of Clay Shales from Upper Missouri River Valley[22]

Formation	Undried		Air-Dried and Slaked**		Oven-Dried and Slaked		Cyclic Air-Drying and Slaking of Chunks		Air-Dried, Slaked, and Blenderized	
	LL	PL	LL	PL	LL	PL	LL	PL	LL	PL
Colorado	33	20	42	20	39	21	45	21	42	20
Claggett	52	25	83	22	90	23	95	21	112	21
Claggett (cemented bentonite)	75	36	171	35	173	34	142	38	200	37
Bearpaw	64	20	81	21	93	20	89	18	117	19
Fort Union	115	23	133	22	113	22	111	21	145	22
Pierre	85	34	143	34	130	36	142	36	168	36

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* Descriptions of the procedures for disaggregating the materials are given in paragraphs 4 thru 8.

** MRD standard procedure for clay shales.

Table A2

Effect of Disaggregating Effort* on Atterberg Limits and Gradation of Cucaracha Shale

Sample No.**	Atterberg Limits								Minus 2μ Fraction		
	Air-Dried and Slaked Only		Air-Dried, Slaked, and Worked with Spatula		Oven-Dried, Slaked, and Worked with Spatula		Air-Dried, Slaked, and Blenderized		Air-Dried and Slaked Only	Air-Dried, Slaked, and Worked with Spatula	Air-Dried, Slaked, and Blenderized
	LL	PL	LL	PL	LL	PL	LL	PL	%	%	%
5	29	28	38	20	39	20	51	18	2	13	18
7	35	25	43	22	44	24	53	21	4	20	30
13	40	27	52	26	45	30	67	28	5	24	41
16	42	23	49	22	49	26	61	24	3	25	37
17	42	22	54	23	47	24	61	24	2	23	36
23	39	29	48	28	49	34	66	32	6	17	40
55	56	35	57	31	58	32	72	31	12	16	27

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* Descriptions of the procedures for disaggregating the material are given in paragraphs 14 and 15.

** All samples from boring No. CRW-15, Hodges Hill Investigation.

shale (using MRD procedures) produced liquid limits of 58 for undried material, 63 for air-dried material, and 59 for oven-dried material. Tests by SWD on Pepper shale from Waco Dam produced much the same results[7]; however, the material from Warm Springs Dam showed essentially no change due to drying.[27]

Effects of Mechanical Dispersion

20. An even greater amount of disaggregation than that produced by drying and slaking appears to occur when a high-speed food blender is used to disperse the material. Blenderizing was used by MRD in their study for NCG, and these results are shown in table A1. WES has also used a high-speed blender, and some results are given in table A2. With a single exception (MRD tests of the Colorado formation), no other method produced a liquid limit or a minus 2μ fraction as high as that produced by blenderizing. Liquid limits were increased by as much as 70 percent over values obtained after only air-drying and slaking. Tests performed by WES under ES 542 showed the liquid limit of Bearpaw shale from Gardiner Dam to increase from 132 after only air-drying and slaking to 152 after 2 min of blenderizing and then to 196 after an additional 15 min of blenderizing.

21. Considerable work was done by SWD to evaluate the effects of blenderizing on Dawson shale, Pepper shale, and the foundation material from Warm Springs Dam. The effect of blenderizing on particle-size distributions and Atterberg limits was examined as a function of cumulative time of blenderizing combined, in some instances, with a curing period between increments of blenderizing. SWD also used an ultrasonic bath to disaggregate one material. It should be noted that the materials disaggregated mechanically by SWD were all processed from natural water content without drying.

22. The first material systematically tested by SWD was Dawson shale. Figure A1 shows a summary of the results of liquid limits tests conducted after different blenderizing periods. However, the curing periods between blenderizing and testing were not constant. The trend toward an ultimate

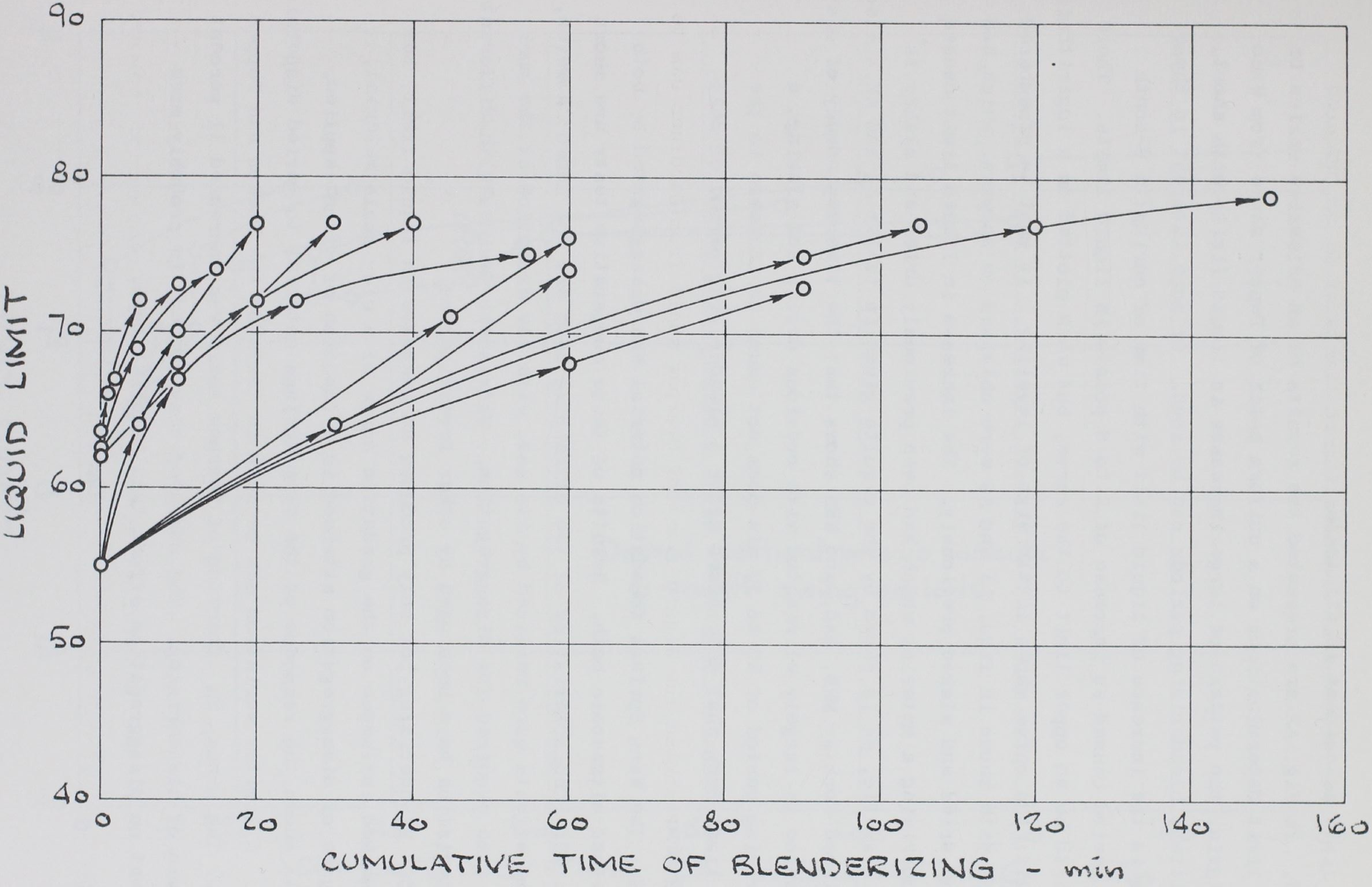

Fig. A1. Effect of time of blenderizing on liquid limit of Dawson shale[26] liquid limit is evident in all tests.

23. In fig. A2 are presented the results of an extensive series of liquid limit determinations on a uniform batch of Pepper shale from Waco Dam. Again, the pattern of large increases in liquid limits with short, intermittent blenderizing periods can be seen. Of more interest in these results is the increase of liquid limit with time of curing; a 6-month curing period caused an increase of 2 to 6 points in liquid limits. There appears to be an upper limit to the curve, but when plotted on a logarithmic time axis, the curve shows little sign of leveling. It must be remembered that the data shown in figs. A1 and A2 were obtained on material which had not been dried and slaked previously. The increase in liquid limit caused by blenderizing a material which had been previously dried and slaked is not so dramatic, as is shown by the results given in tables A1 and A2. Also, unpublished work by MRD, SAD, and WES shows that the time-dependency of disaggregation is largely eliminated with previous drying and slaking; a blenderizing period of 20 to 30 min does not cause an increase in the liquid limit from that determined after a blenderizing period of only 5 to 10 min.

24. The Warm Springs foundation material was disaggregated by both blender and ultrasonic bath. Results of these comparative tests are shown in fig. A3. Characteristics of the ultrasonic bath are not known; however, the same effects were realized by its use, with the exception of the much longer time required for disaggregation. Ultrasonic devices with different characteristics have been used by other investigators.[30,31]

25. Blenderizing not only produces an increase in liquid limit, but has a marked influence on the gradation curve of a clay shale material. The degree of disaggregation attained is a function of effort applied. Table A3 shows the response of the Warm Springs material to varied dispersive effort. A similar variation can be seen in tests on the Dawson and Pepper shales. The minus 2μ fraction of Bearpaw shale was increased 11 percent by 17 min of blenderizing. The measured clay content is probably more dependent on disaggregation effort than material type.

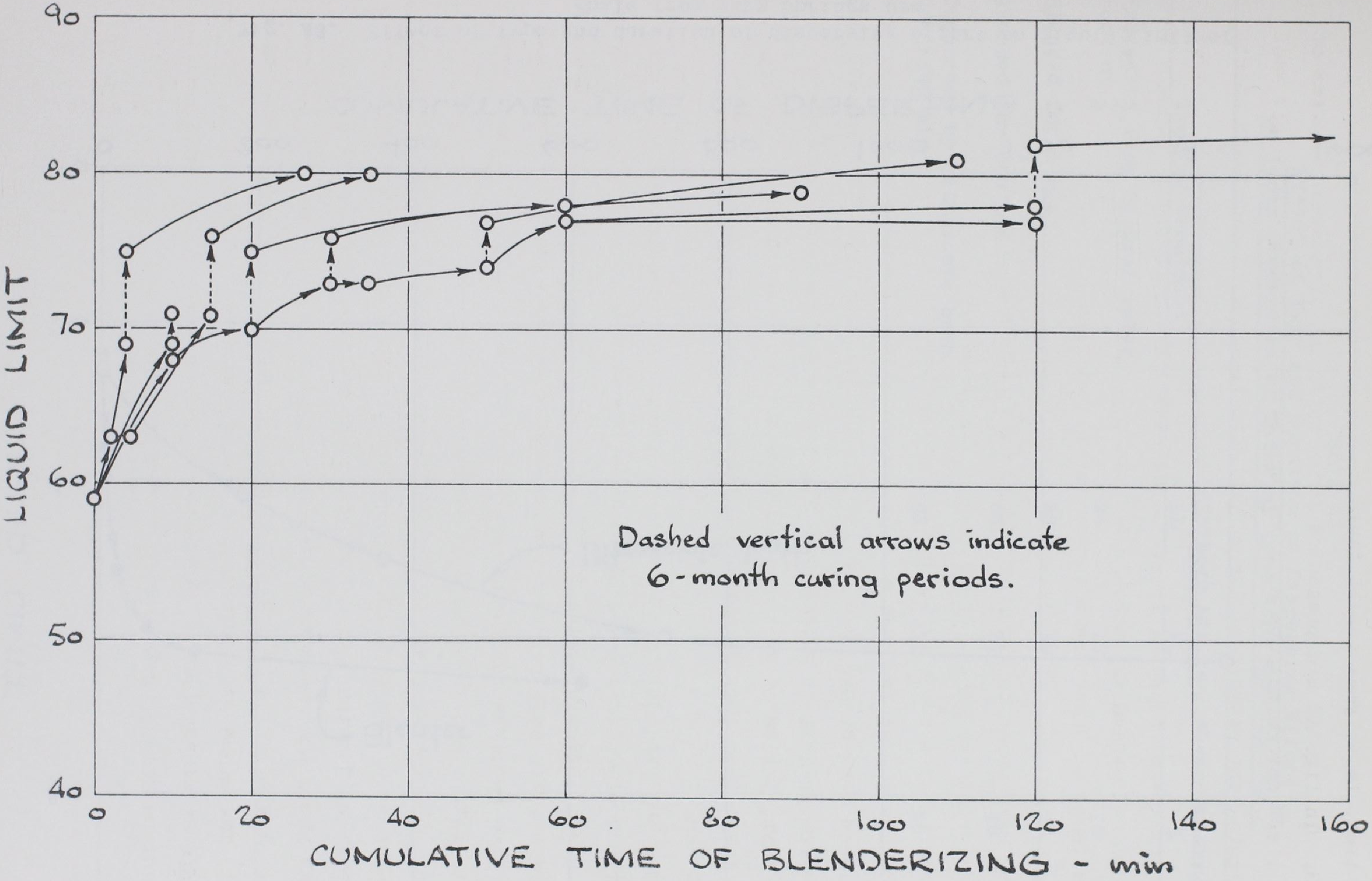

Fig. A2. Effect of time of blenderizing on liquid limit of Pepper shale

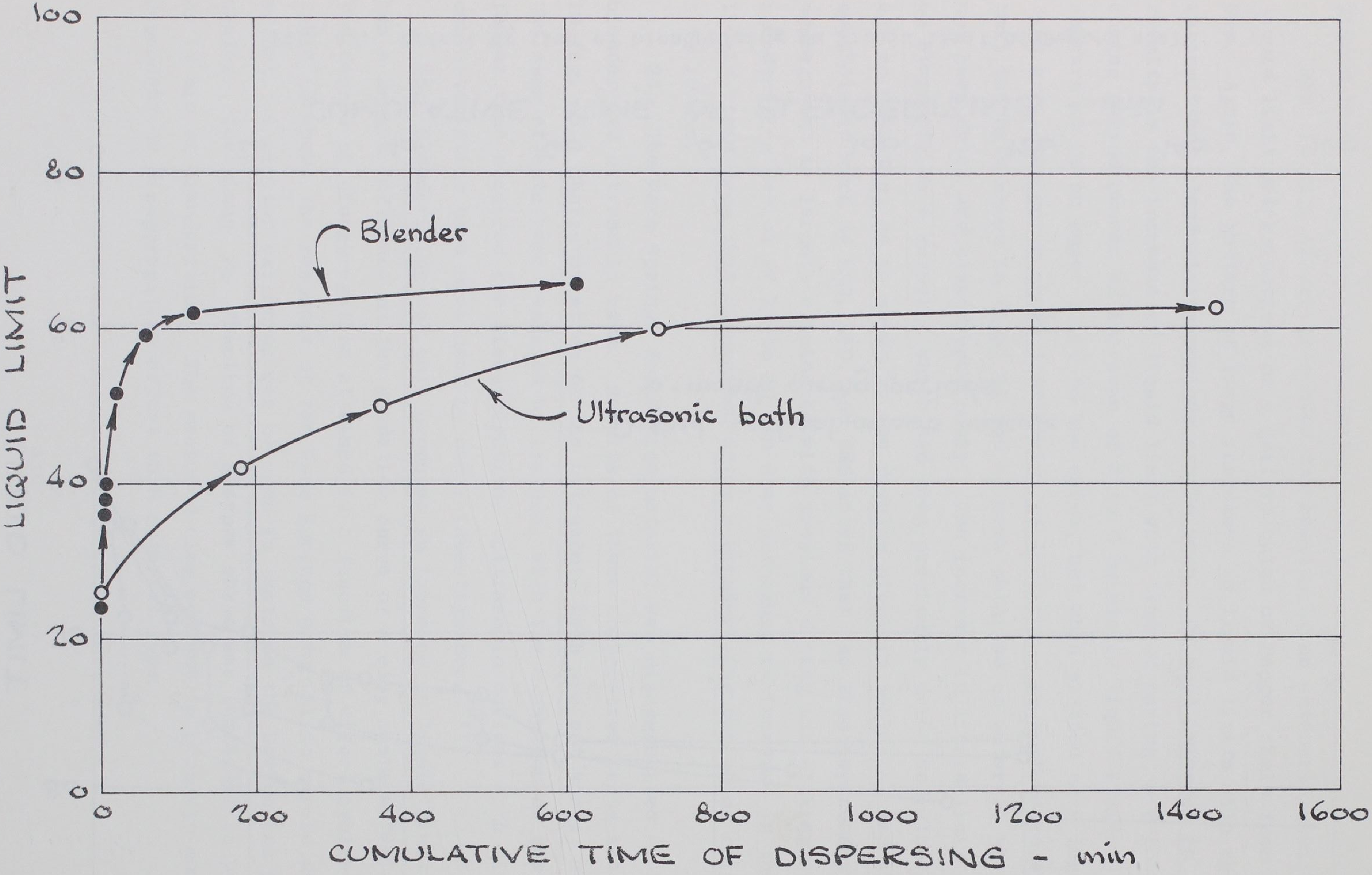

Fig. A3. Effect of type and duration of dispersing effort on liquid limit of shale from Warm Springs Dam

Table A3

Effect of Type and Duration of Dispersing Effort on Index Properties of Material from Warm Springs Dam[27]

Type of Treatment	Atterberg Limits LL	Atterberg Limits PL	Minus 2μ Fraction %
Processed from natural water content	24	17	10
Blended for 5 min	38	19	25
Blended for 600 min	65	21	49
Dispersed by ultrasonic bath for 1440 min	63	21	50

Suggested Standardized Procedures

26. Currently, it is difficult to correlate classification indexes of clay shales between laboratories due to variations in preparation methods allowed by standard CE testing procedures and by further variations being introduced by the laboratories specifically for clay shales. It seems paradoxical to specify the dimensions of a liquid limit grooving tool to close tolerance if one laboratory dries and slakes all its material while another works from the natural moisture, or if one laboratory oven-dries its material for hydrometer analyses while another does not. Unless uniform procedures are followed, there can be no simple indexes for classification.

27. Investigations are showing that classification indexes are affected by air-drying and slaking, by oven-drying and slaking, by the type and duration of mechanical dispersing, and by other variations in procedure. While the methods for preparing clay shale material for testing should cover a sufficient range of disaggregation efforts to assess the strength of interparticle bonds, the number of variables allowed to influence the indexes must be minimized by standardized procedures to prevent the classification of each material becoming a minor research project in itself. Therefore, it is recommended that only three methods of processing clay shale material be considered for standardization. First, to provide a reference value, the material should be tested without any drying. Second, a single cycle of air-drying and slaking should be used to disaggregate the material, similar to the MRD standard procedure for clay shales. Finally, to provide an essentially complete disaggregation, the material should be subjected to high-speed blenderizing. Oven-drying and cyclic air-drying and slaking merit additional investigation, but the value of these two methods does not appear as great as that of the three recommended methods. Cyclic air drying and slaking, of course, require several weeks to complete and appear too cumbersome for normal usage.

28. Suggested standardized procedures for preparing clay shale

material are as follows:

a. Undried. Material at essentially natural water content should be shaved or shredded, immediately placed in distilled water, and allowed to soak for at least 48 hr. After removing excess water by decanting, the wet material should be ground in a mortar with a rubber-tipped pestle and washed through the No. 40 sieve. Excess water should be removed using a plaster-of-paris dish lined with filter paper. The sieved material, at a water content above the liquid limit, should be worked in a thin layer on a glass plate with a steel spatula until no further reduction in the size of lumps can be achieved.

b. Air-dried. Material at essentially natural water content should be shaved or shredded and dried to a constant weight in an atmosphere with a temperature less than 50 C (120 F) and a relative humidity less than 30 percent. (The drying atmosphere may be produced by a low-temperature oven, a dessicator, or a controlled-humidity room.) After a constant weight is attained (and after a drying period of at least 48 hr), the material should be soaked in distilled water for at least 48 hr. After removing excess water by decanting, the wet material should be ground in a mortar with a rubber-tipped pestle and washed through the No. 40 sieve. Excess water should be removed using a plaster-of-paris dish lined with filter paper. The sieved material, at a water content above the liquid limit, should be worked in a thin layer on a glass plate with a steel spatula until no further reduction in the size of lumps can be achieved.

c. Blenderized. Material at essentially natural water content should be shaved or shredded and dried to a constant weight in an atmosphere with a temperature lessthan 50 C and a relative humidity less than 30 percent. After a constant weight is attained (and after a drying period of at least 48 hr), the material should be soaked in distilled water for at least 48 hr. The slurry should be placed in a high-speed food blender having a no-load speed of 15,000 to 20,000 rpm. The material should be blenderized without interruption for a period of 10 min and then washed through the No. 40 sieve. Material retained on the sieve should be discarded. Excess water should be removed using a plaster-of-paris dish lined with filter paper. The sieved material, at a water content above the liquid limit, should be worked in a thin layer on a glass plate with a steel spatula until no further reduction in the size of lumps can be achieved.

29. When material is to be prepared by all three methods, care should be exercised that the parent material for the batches is similar.

The piece of sample selected should be divided by a vertical cut into two parts with one piece about twice as large as the other. The smaller piece should be shaved into distilled water to produce the undried batch, and the larger piece used to produce the other two batches. Figure A4 shows a flow diagram of the three preparation methods and indicates when separation of batches is required.

30. Material may be taken from each of the three batches and used for Atterberg limits determinations without further processing. Dry strength and gloss determinations should be made on material taken for Atterberg limits determinations. Material for a hydrometer analysis should be removed from each batch and soaked overnight in distilled water containing a sufficient amount of a suitable chemical dispersant (such as sodium tripolyphosphate or sodium hexametaphosphate) to prevent flocculation. Dispersion should be made in a milk shake stirrer or with an air jet, but not with a high-speed food blender.

31. The use of a high-speed blender for soil dispersion introduces a large number of variables which have not yet been evaluated. However, most of the variables (size and shape of container, size and shape of blades, no-load speed, variation of speed with load, etc.) can be avoided by specifying a single make and model of blender. Most blenders on the market are household appliances, and the operating characteristics of models being sold at different times could very well change. The only blender really intended for laboratory use, and available from every laboratory supply company, is the Waring "Blendor." It is recommended that the standardized procedure for disaggregating clay shale material by blenderizing should utilize the standard one-speed Waring Blendor with the 1000-ml glass container. Specifying this make of blender would give the manufacturer no significant economic advantage since only a few CE laboratories would require one and the unit price is modest, about $35.

32. If the make of the blender were specified, the remaining variables would be (a) the amount of wear to be permitted on the blades, (b) the quantity of the soil-water slurry to be placed in the container, and (c) the water content of the slurry. To provide a starting point for

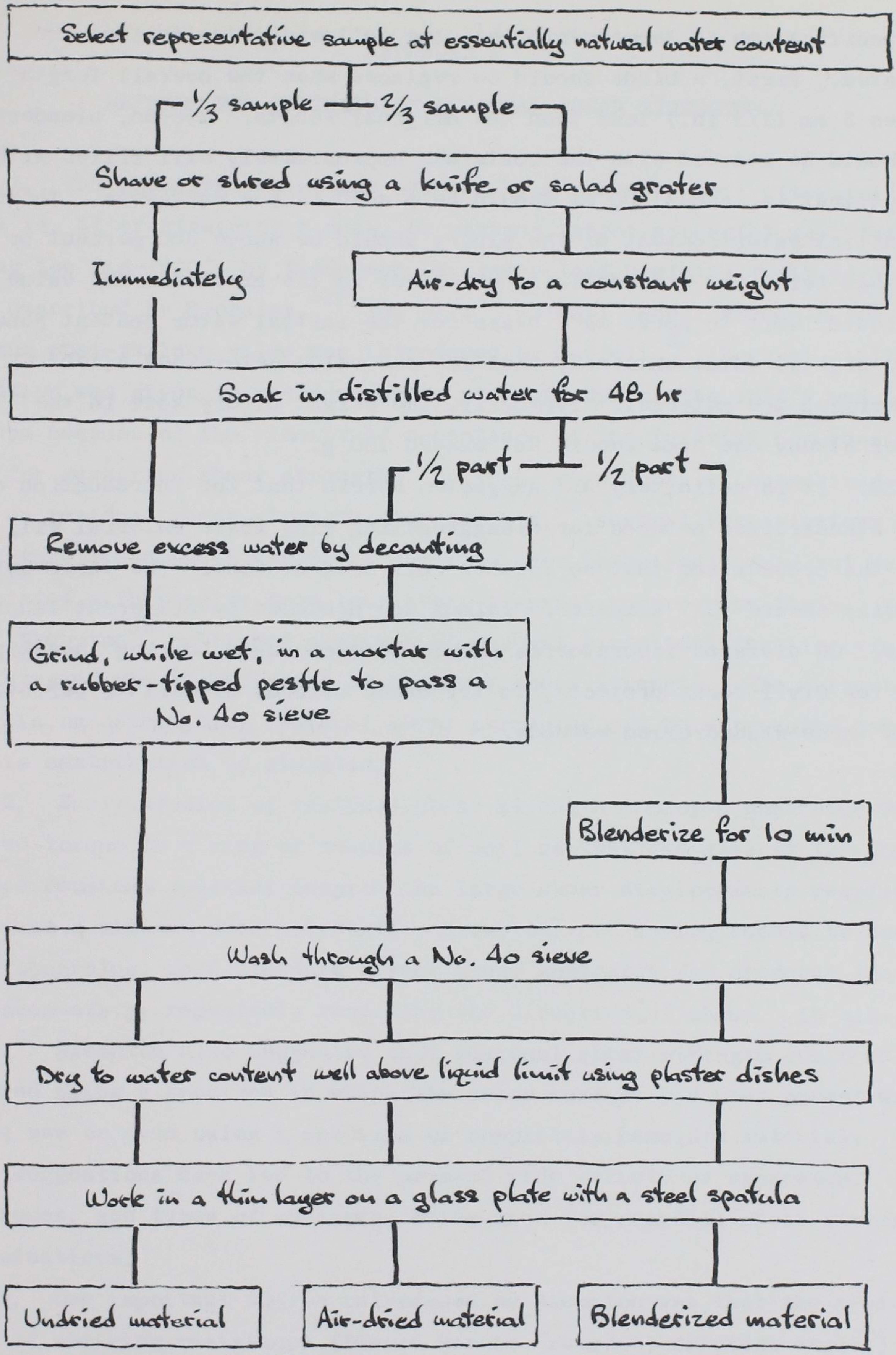

Fig. A4. Flow diagram of the three suggested standardized procedures for disaggregating clay shale material the specification of these variables, the following restrictions are suggested. First, a blade should be replaced when the overall length becomes 3 mm (1/8 in.) less than the original length. Second, blenderizing should be started with the container approximately half filled with slurry; that is, about 500 ml should be placed in the container. Third, the initial water content of the slurry should be above 300 percent or more than twice the liquid limit, whichever is the greater. The value of the liquid limit to serve as a basis for the initial water content should be the highest value obtained, that is, the value determined after blenderizing the material. Typically, the weight of dry soil in the blender at any one time should not exceed 150 g.

33. It is definitely not suggested herein that the introduction of three standardized methods for disaggregating clay shale material will solve the problem and that no further work need be done. The three methods only will ensure that comparable values are produced by different laboratories. CE division laboratories should be encouraged, during investigations for Civil Works projects, to try other methods as well as variations in the three standardized methods.

APPENDIX B

METHODS FOR DETERMINING RESIDUAL SHEAR STRENGTHS

1. The shearing resistance offered by a cohesive soil after failure (that is, after attaining a peak, or maximum, shear strength) was studied during the mid-1930's by Tiedemann, Hvorslev, and Haefeli; their work has been described by Hvorslev.[32*] The term "residual" shear strength for the minimum post-failure value was introduced by Haefeli.[33] However, little attention was given to residual shear strength during the 1940's and 1950's, perhaps because of the widespread acceptance of the triaxial compression test for measuring shear strength. By 1960, when Hvorslev summarized his work on residual shear strength measurements,[34] several investigators had found that field shear strengths computed from landslides could not be correlated with results from laboratory triaxial compression tests. In 1964, Skempton[35] published analyses of several landslides that forcefully demonstrated the significance of residual shear strength. The current emphasis on determining residual shear strengths can be attributed largely to this contribution by Skempton.

2. Early studies of residual shear strength employed apparatus which applied torque to a ring or annulus of soil so that the area of the shear surface remained constant despite the large shear displacements required to attain a minimum shear strength. Skempton, not having access to annular shear apparatus, used standard direct shear apparatus and produced the large displacements by repeatedly reversing the direction of shear. In his 1964 paper,[35] Skempton also suggested that residual shear strength could be measured using a specimen in which the shear surface had been precut with a wire saw or even using a specimen of completely remolded material. These suggestions have led to the present wide variety of apparatus, techniques, and types of specimens being used for residual shear strength determinations.

3. One important notion introduced by Skempton was that the residual angle of shearing resistance (termed herein "residual friction angle")

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* Raised numbers refer to similar numbered items in Literature Cited which follows the main text.

should be independent of the stress history of the material and depend solely on the nature of particles comprising the material. This led to the concept of residual friction angle being an index property as well as an engineering property. Thus it was widely concluded that residual friction angle is uniquely related to the mineralogical composition of a material and is independent of the type of specimen (intact, precut, or remolded), normal stress, and rate of strain as long as there is sufficient displacement to produce a minimum shear strength; however, many of these conclusions are speculative to some degree.

4. The need for standardization of residual shear strength determinations by CE offices is clear and urgent. Standardization, however, should not only provide for the most satisfactory measurements, but also ones that are simple and inexpensive to make. Apparatus and procedures that have been used for residual shear strength measurements are reviewed in the following paragraphs, along with information on the effect of variations in test conditions on the measured values.

Variations in Apparatus and Procedures

5. Two basic types of apparatus are discussed below: (a) translational or direct shear apparatus, which require reciprocal movement to produce large displacements and (b) rotational shear apparatus, which produce large displacements without reversing the direction of movement. The use of triaxial compression apparatus for determining residual shear strengths is not considered here, although it has been used for this purpose.[36,37,38] Differences in testing procedure are primarily associated with reversing the direction of shear with direct shear apparatus.

Direct shear apparatus

6. Following the example of Skempton, many investigators started using available direct shear apparatus for residual strength tests. Difficulties were encountered from the very first due to the limitation of most direct shear apparatus to provide movement in only one direction. In some cases, this limitation was overcome by removing or reducing the

normal stress at the end of each shear movement and manually returning the unit to its initial position; this is the procedure commonly used by WES. Other solutions involved rotating the shear box 180 deg at the end of each stroke (used by the laboratory of the Kansas City District) or by modifying apparatus to permit movement in both directions (used by SWD). Eventually, laboratories designed and constructed apparatus for the specific purpose of repeated direct shear testing, in which the directions of shear displacements are sequentially reversed.

7. One of the earlier repeated direct shear apparatus was developed by the Massachusetts Institute of Technology (MIT) under a CE contract study of the properties of clay shales.[39] The MIT quadruple-unit repeated direct shear apparatus, shown in fig. B1, accepts specimens 2.00 in. square and 0.75 in. high. Maximum normal and shear stresses on the 26-sq-cm specimen are 16.0 kg per sq cm. Rates of strain in either direction of movement can be varied from 280 in. per day to 0.001 in. per day.

8. Several special double-unit repeated direct shear apparatus, shown in fig. B2, were constructed by the SAD laboratory. The specimen size of 3.00 in. square by 0.50 in. high is in accordance with the CE standards for laboratory testing,[15] though specimens up to 1.00 in. in height can be accepted. The area of contact between the upper and lower halves of the shear boxes is an 0.031-in.-wide lip around all four sides of the specimen. Normal stresses up to 38 kg per sq cm are applied to the 58-sq-cm specimen using a commercial pneumatic cylinder, while shear displacements (as great as 0.5 in. to either side of the center) are produced by pushing on the upper half of the shear box with one of the two separate controlled-strain drives provided for each shear box (a separate drive is provided for displacement in each direction). Rates of strain can be varied from 18 in. per day to 0.14 in. per day, and greater variation can be obtained by replacing gears.

9. In fig. B3 is shown one of the three double-unit repeated shear apparatus constructed by the MRD laboratory. This apparatus also accepts specimens 3.00 in. square with heights as great as 1.00 in. Normal stresses up to 30 kg per sq cm are applied pneumatically through a rolling

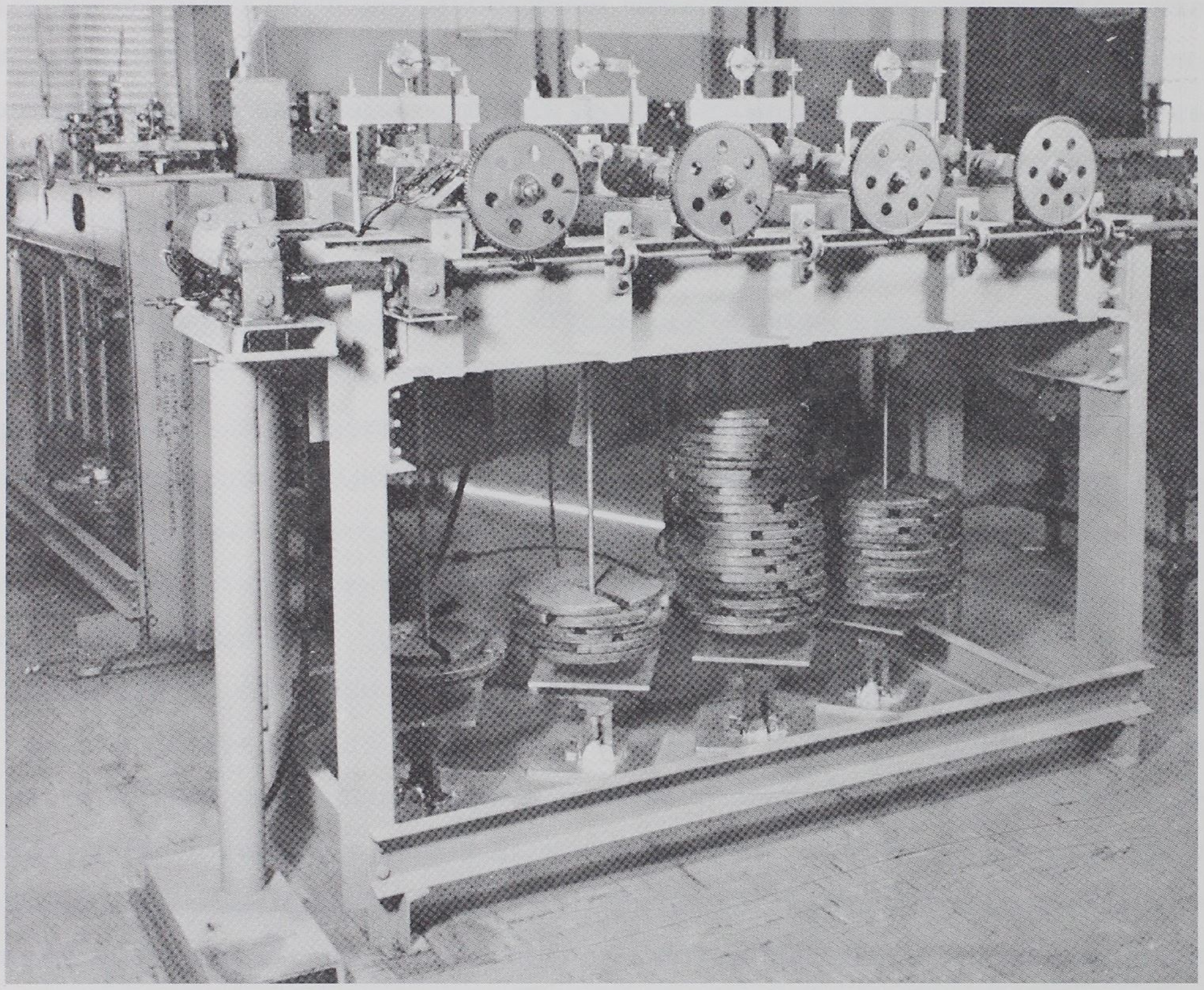


Fig. B1. MIT quadruple-unit repeated direct shear apparatus

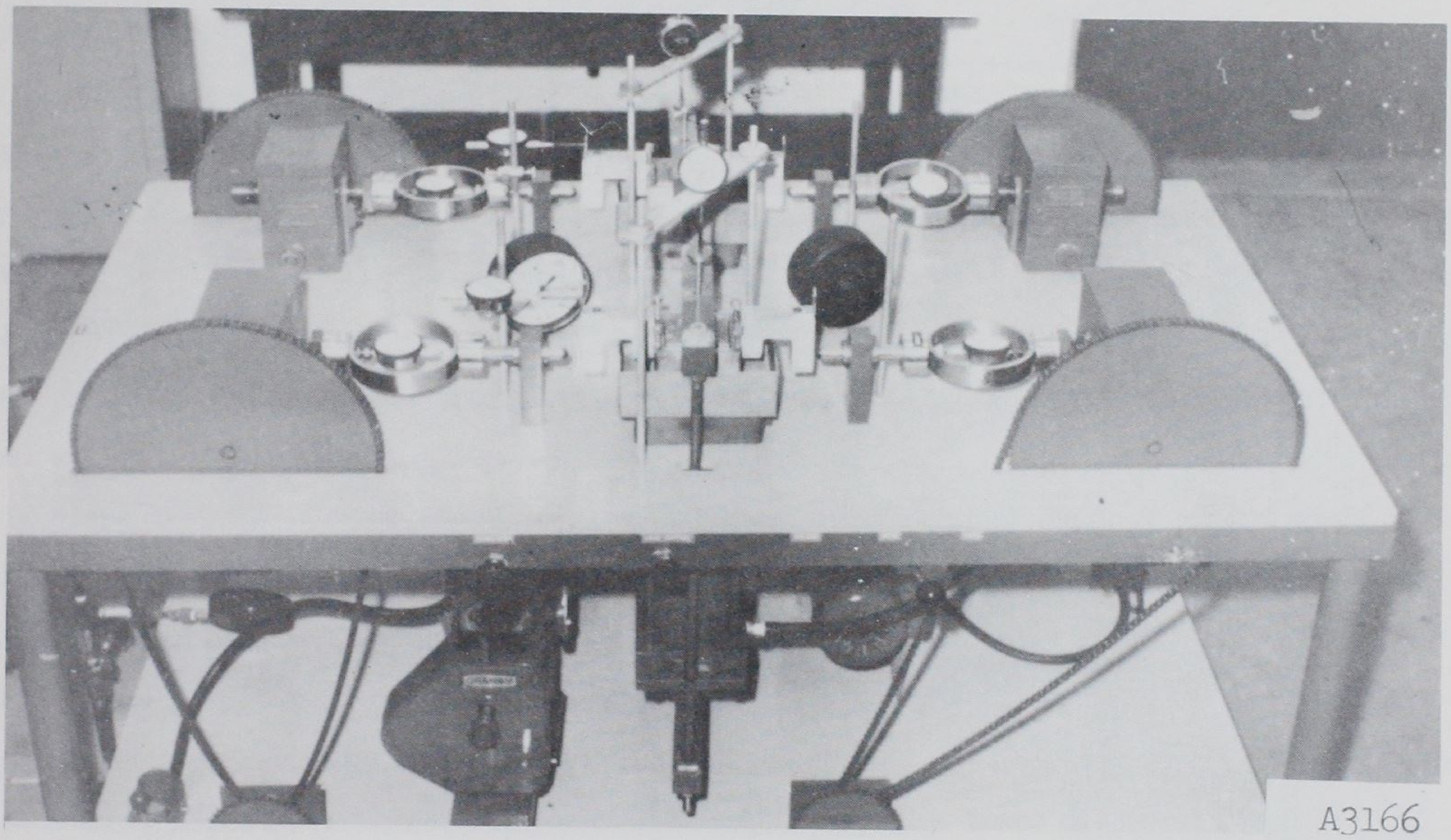


Fig. B2. SAD double-unit repeated direct shear apparatus

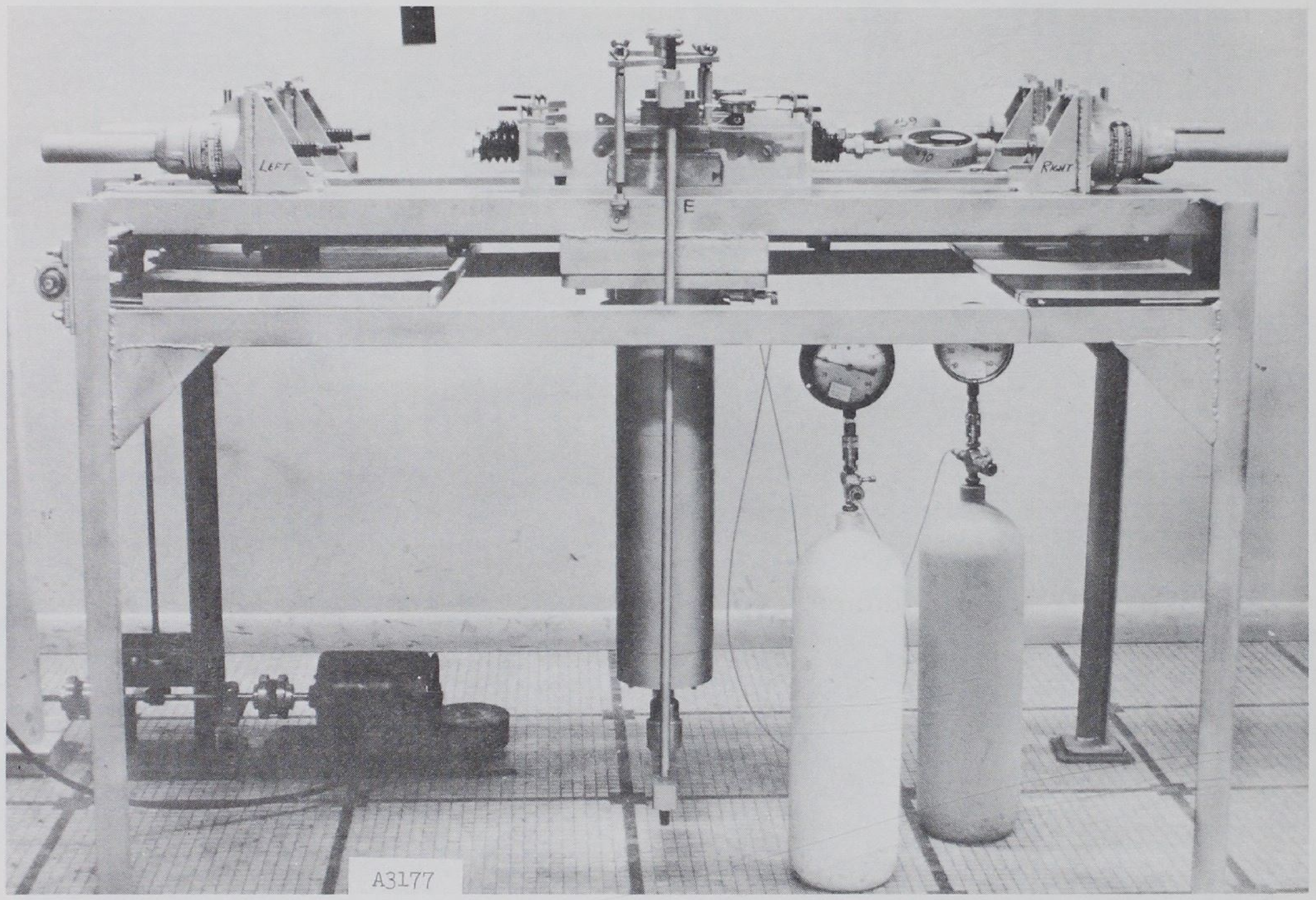


Fig. B3. MRD double-unit repeated direct shear apparatus diaphragm connected to the piston of the shear box by very long tie rods; this connection minimizes the angular deflection that otherwise accompanies shear displacement. As in the SAD apparatus, two controlled-strain drives are provided for shear displacements of each box. The MRD apparatus produces shear displacements up to 0.5 in. either side of center by pulling the upper half of the shear box. Rates of strain can be varied from 3 in. per day to 0.1 in. per day (greater variation in strain rate requires the replacement of gears).

10. A direct simple-shear apparatus produced commercially by Geonor, AS, in Norway was obtained by WES in 1966. This apparatus shears a 50-sq-cm circular specimen, 1.5 cm high, encased in a wire-bound rubber membrane to permit uniform shear strain over the full height of the specimen.[40] In 1968, the apparatus was modified for repeated direct shear testing by replacing the original specimen holders with a direct shear box; a simpler modification of a similar apparatus had been made by the Norwegian Geotechnical Institute in 1965 to permit residual shear strength measurements.[41] The modification by WES, as shown in fig. B4, permits the testing of a specimen 2.78 in. square (to maintain the original specimen area of 50 sq cm) and 0.59 in. (1.5 cm) high. Normal stresses, up to a maximum of 16.0 kg per sq cm, are applied through a force gage by a dead-weight lever system. Maximum shear stress is 8.0 kg per sq cm. Shear displacements in each direction, up to 0.3 in. either side of center, are provided by a single, reversible drive that moves the top half of the shear box through a yoke. Strain rates from 7 in. per day to 0.004 in. per day can be produced with the six-speed gear box and by interchanging the small synchronous motors. Cables can be attached to the shear stress yoke and passed over removable sheaves to a deadweight hanger for controlled-stress testing. In addition, a small jack below the normal stress hanger permits varying the normal stress during shear to accomplish a constant-volume (or undrained) test.

11. Several apparatus designed especially to perform repeated direct shear tests have been fabricated and operated at Imperial College in England. However, details of the apparatus have not been published.

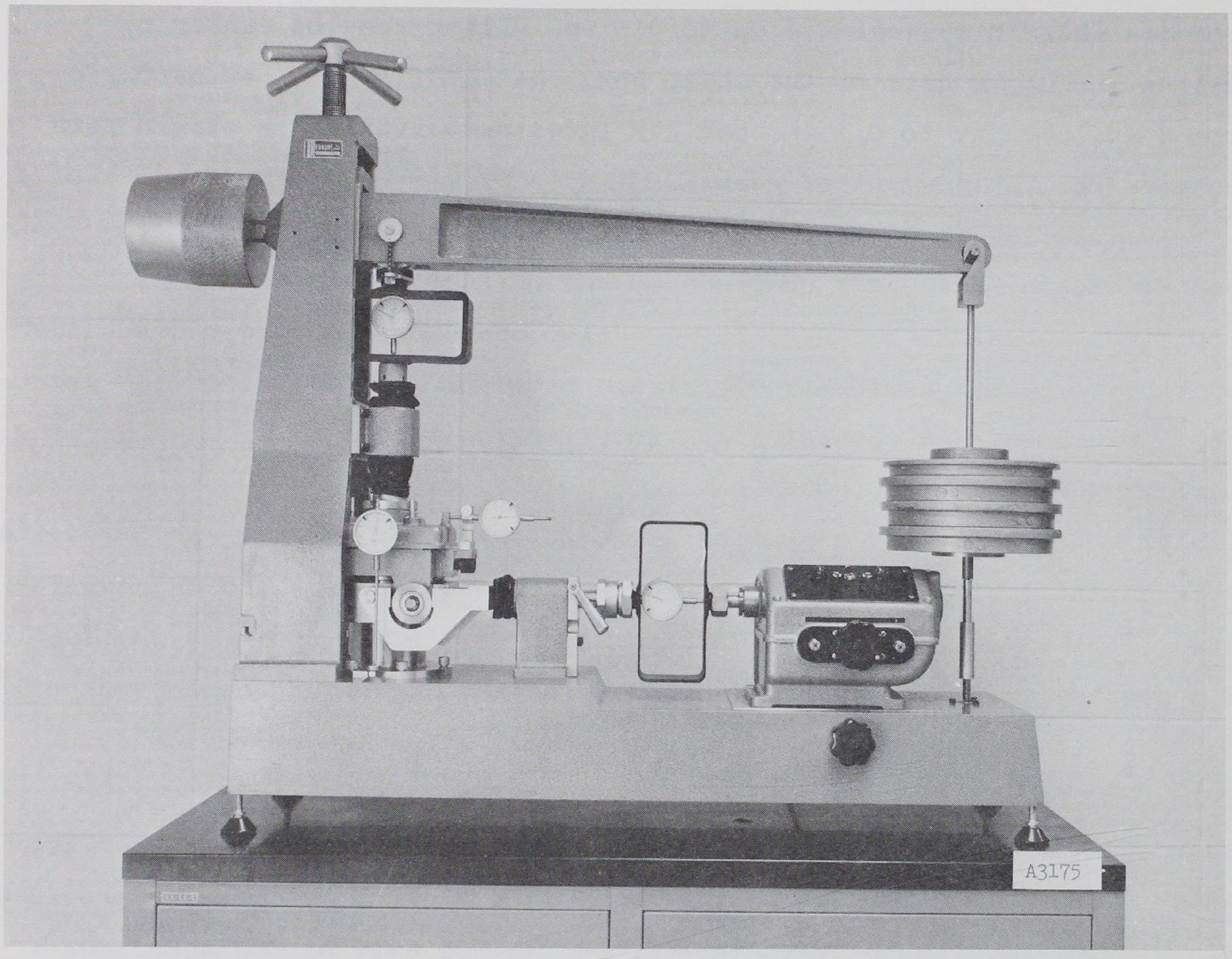


Fig. B4.. Geonor direct simple-shear apparatus as modified by WES for repeated direct shear testing

Apparently, specimens have large length-to-width ratios to minimize the influence of the boundary conditions at the front and rear edges of the shear box.

12. In a repeated direct shear test, the shear displacement may be accumulated by either of two methods. First, the upper half of the shear box may be moved from the initial, aligned position to a point some distance from the initial position and then moved back to the starting point; in other words, all shear movement is made at one side of the initial position. Second, the upper half of the shear box may be moved during each stroke, after the first half stroke, from one side of the initial position, through the initial position, to the other side of the initial position. The first of these methods is regularly used by SWD and WES, while the second method is used by MRD and SAD. In addition, movement in both directions may be under the same normal stress (MRD, SAD, and SWD) or the movement back to the initial position may be under a reduced normal stress (WES). Movement in both directions may be at the same rate of displacement (MRD and SAD) or the movement back to the initial position may be at a higher (WES) or lower (SWD) rate than used for the movement away from the initial position. The influence of these variations in procedures is discussed in subsequent paragraphs.

Rotational shear apparatus

13. The development of torsion and annular shear apparatus during the 1930's has been described in detail by Hvorslev.[32] In 1947, Hvorslev designed an annular shear apparatus that was constructed at WES for testing soft, organic clay from the Panama Canal Zone.[42] This unit accepts a specimen 4.50 in. in outside diameter, 2.50 in. in inside diameter, and 0.75 in. in height. Normal stress capacity on the 71-sq-cm specimen is 5.0 kg per sq cm and the maximum shear stress is 2.0 kg per sq cm. Both controlled-stress and controlled-strain tests can be performed. The apparatus was modified in 1968, as shown in fig. B5, to provide rates of strain variable from 200 in. per day to 0.004 in. per day.

14. The WES 1966 annular shear apparatus, shown in fig. B6, is generally similar in design and operation to the WES 1947 apparatus.

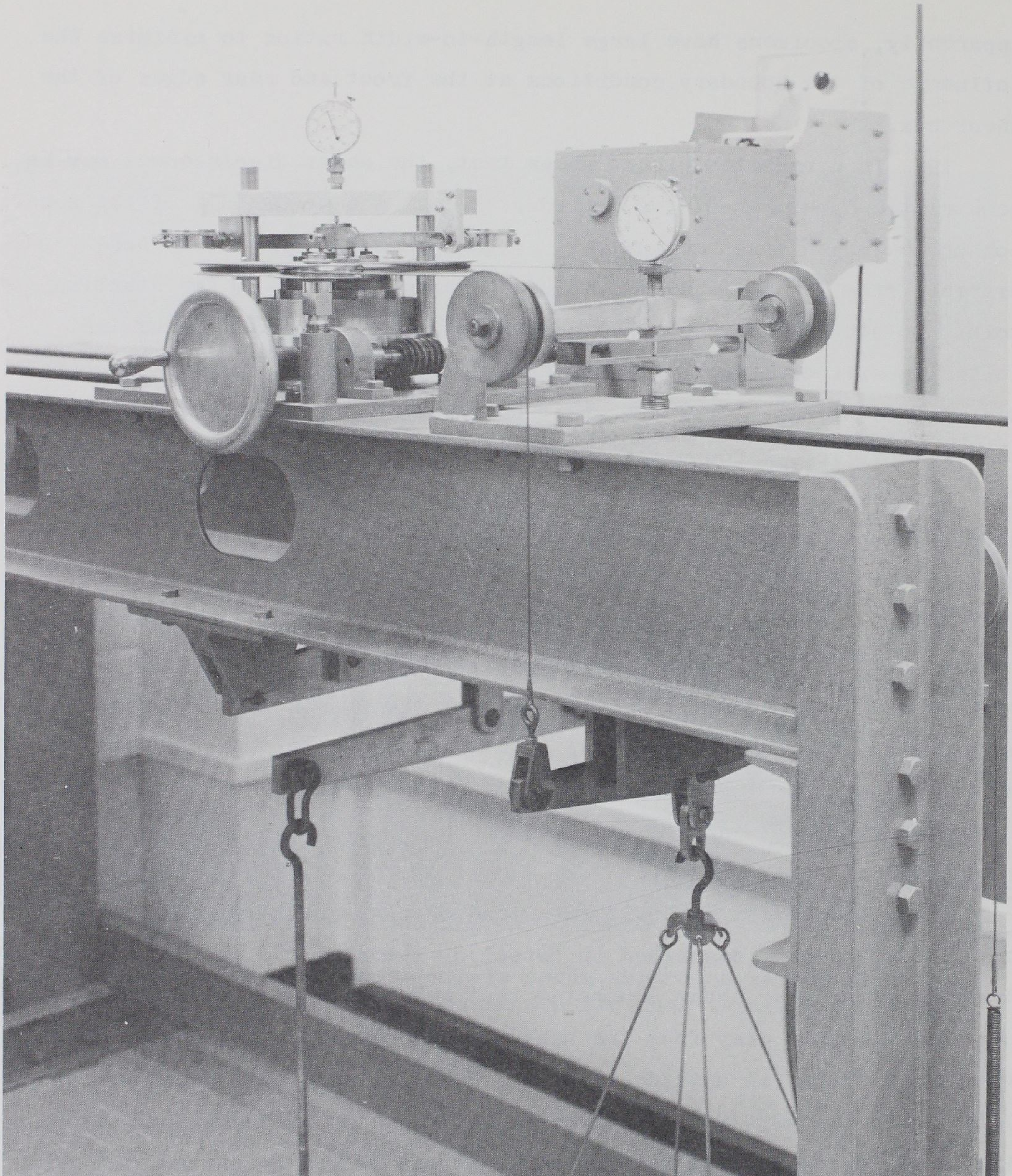


Fig. B5. WES 1947 annular shear apparatus

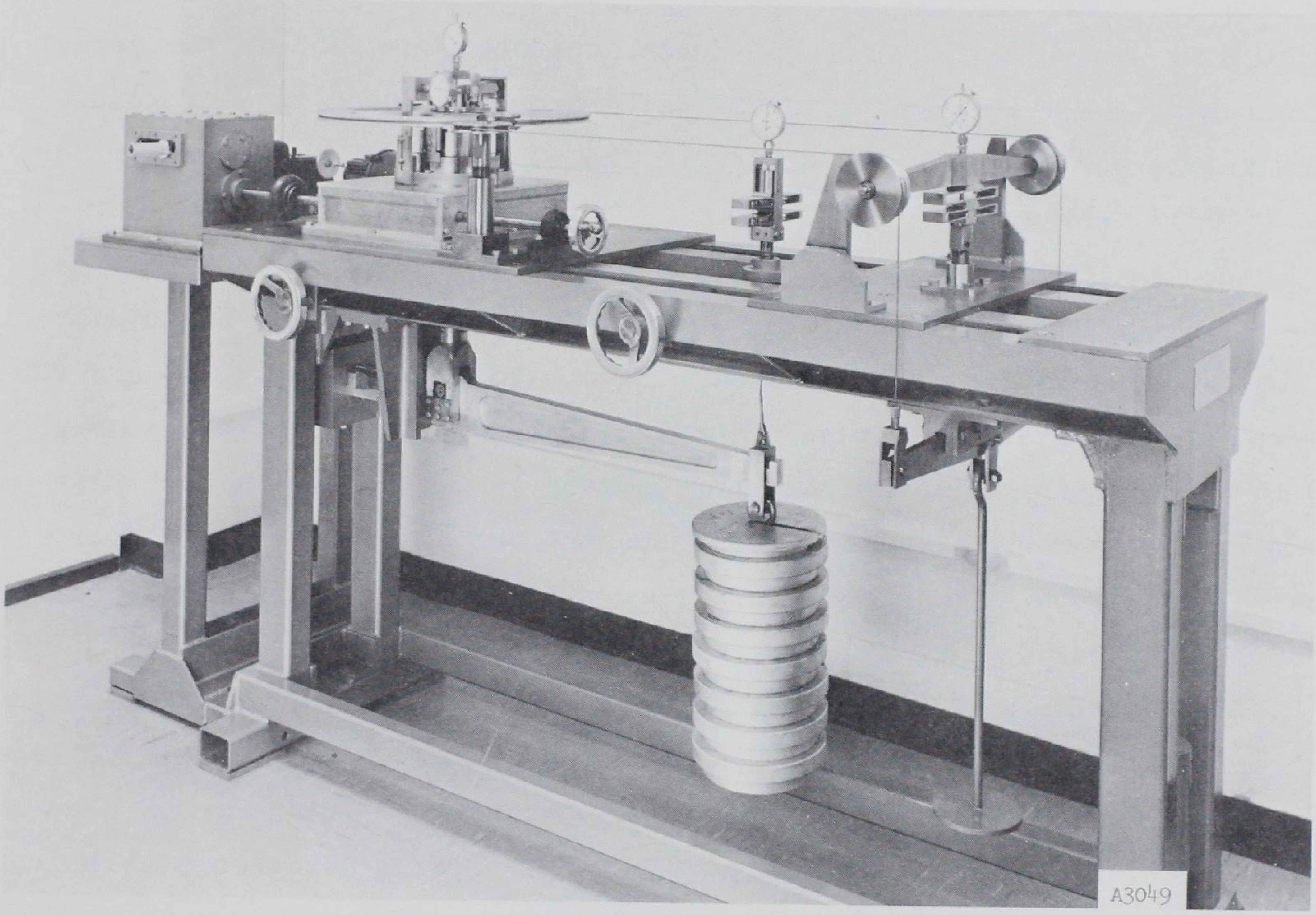


Fig. B6. WES 1966 annular shear apparatus

Cables connected to a torque wheel above the specimen pass around horizontal and vertical sheaves to a force gage and a deadweight hanger to permit both controlled-stress and controlled-strain testing. The specimen has an outside diameter of 5.50 in. (permitting a specimen to be trimmed from a nominal 6-in.-diam sample), an inside diameter of 3.25 in., and a height which is variable from 0.50 to 1.00 in. Maximum normal stress on the 100-sq-cm specimen is 20.0 kg per sq cm and the maximum shear stress is 10.0 kg per sq cm. A jack and force gage are mounted over the normal stress hanger for varying the normal stress during shear to perform a constant-volume test. Rates of strain can be varied from 60 in. per day to 0.003 in. per day.

15. In 1967 WES constructed a triple-unit annular shear apparatus, shown in fig. B7. This apparatus accepts specimens 4.00 in. in outside diameter, 2.04 in. in inside diameter, and 0.75 in. in height. A maximum normal stress of 5.0 kg per sq cm can be applied by dead weights to the 60-sq-cm specimen. The maximum shear stress is 2.5 kg per sq cm; this stress is measured by a torque plate mounted above the specimen. Only controlled-strain tests can be performed, with rates of strain variable from 170 in. per day to 0.34 in. per day.

16. Geonor, AS, is producing commercially an annular shear apparatus, as shown in fig. B8 (photograph taken of the apparatus at Imperial College in London). Development of this apparatus started in 1964 through a cooperative effort by Imperial College and the Building Research Station in England and the Norwegian Geotechnical Institute. The specimen is 6.00 in. in outside diameter, 4.00 in. in inside diameter, and 0.75 in. in height. (The large outside diameter of the specimen precludes testing intact material from nominal 6-in.-diam cores.) Normal stresses up to 10.0 kg per sq cm are applied to the 102-sq-cm specimen by a deadweight lever system (contained in the rectangular base casting shown in fig. 8). Shear stresses, to a maximum of 5.0 kg per sq cm, are measured by a torque bar above the specimen acting against two balanced force gages. This controlled-strain apparatus can be operated at rates of strain from 28 in. per day to 0.08 in. per day. Constant-volume shear tests can be performed

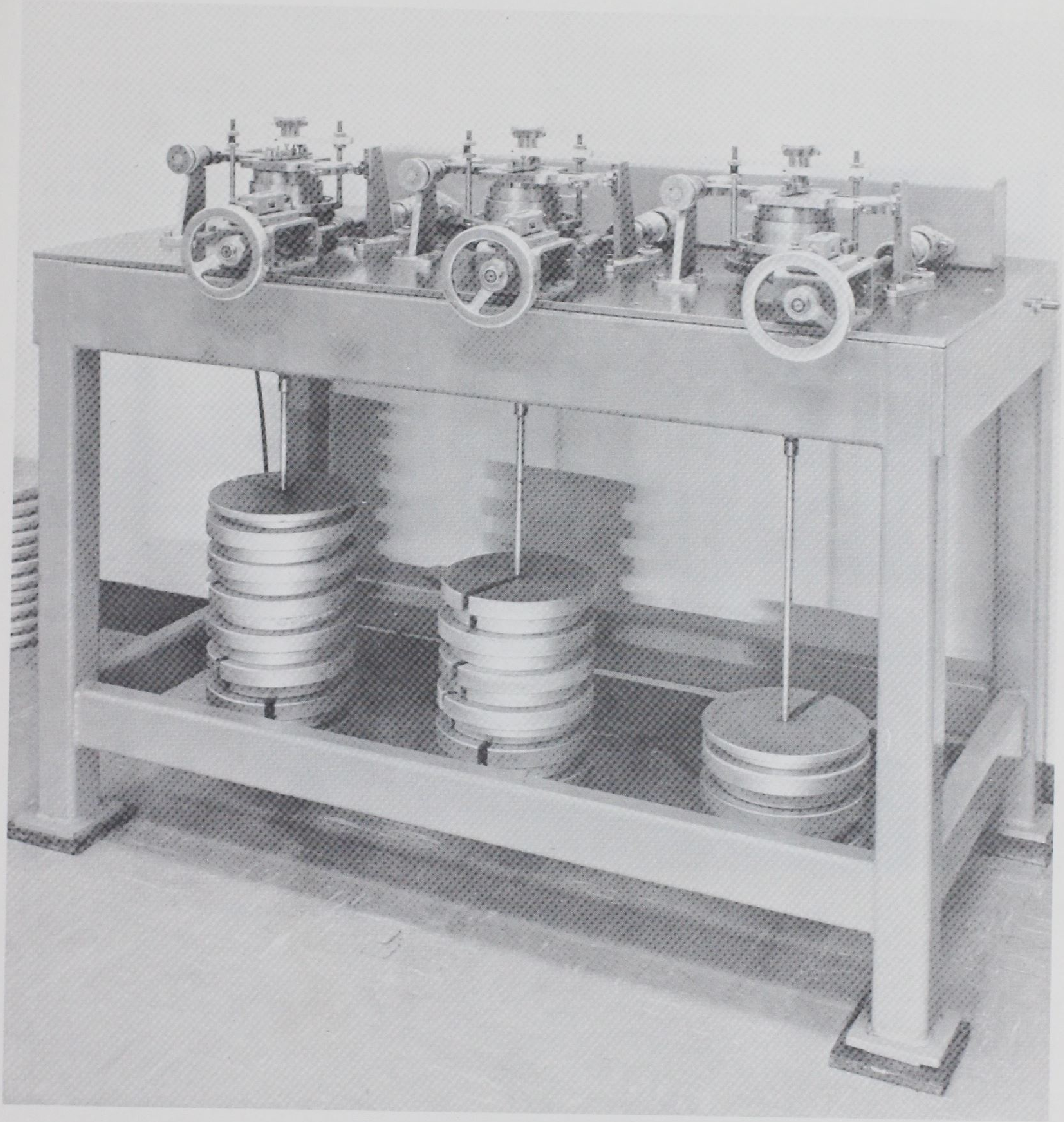


Fig. B7. WES 1967 triple-unit annular shear apparatus

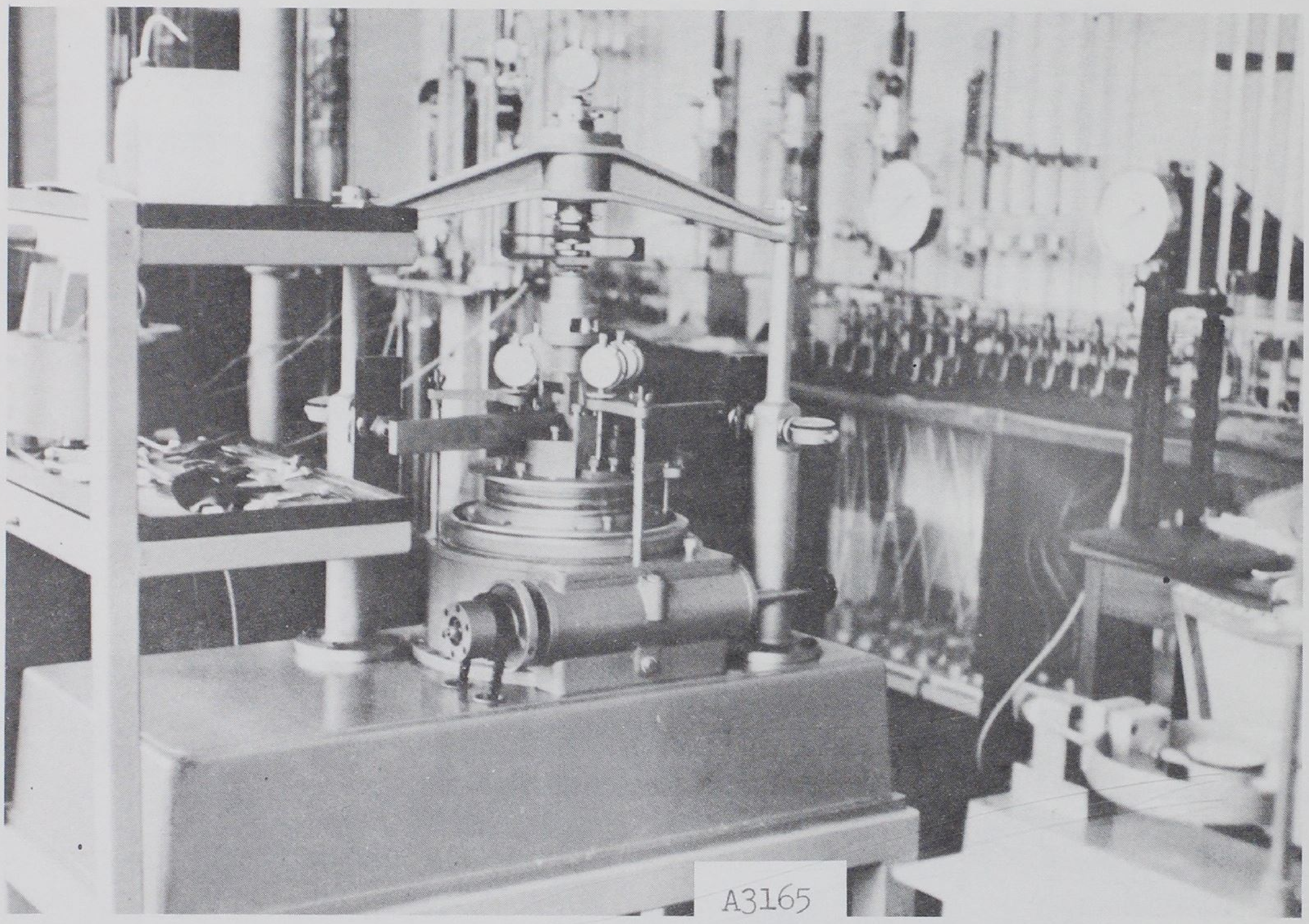


Fig. B8. Geonor annular shear apparatus

with the apparatus as well as drained tests.

17. Under a CE research contract,[25] Harvard University developed the rotation shear apparatus shown in fig. B9. Three of these devices have been received from Harvard University for further research testing at WES. The test specimen is a disk (typically of remolded rather than intact material), 2.80 in. in diameter and variable in height from 0.05 in. up to a maximum of 1.00 in. Normal stresses, up to a maximum of 25.0 kg per sq cm, are applied to the 40-sq-cm disk by a dead-weight level system. Shear stresses, up to a maximum of 20.0 kg per sq cm on the disk-shaped specimen, are measured by the reaction of two balanced, electrical force transducers to a torque bar mounted on the top of the specimen. Shear displacements are produced by rotating the porous disk at the bottom of the specimen with a controlled-strain drive system. Rates of peripheral displacement can be varied from 320 in. per day to 0.32 in. per day.

18. Annular specimens with any inside diameter less than 2.80 in. can be tested in this apparatus through the use of adaptors. At Harvard, tests have been performed on annular specimens 2.00 in. in inside diameter, giving a specimen area of 20 sq cm. When using an annular specimen, the rate of linear displacement measured at the mean diameter of the specimen can be varied from 270 to 0.27 in. per day. One of the main advantages of this apparatus is the capability for controlling the gap between the upper and lower specimen-confining rings to prevent extrusion of material.

19. Annular shear testing at the Belgian Geotechnical Institute of Ghent is performed on specimens 8.0 cm (3.15 in.) in outside diameter, 4.0 cm (1.58 in.) in inside diameter, and 1.8 cm (0.71 in.) in height.[43] Test results reported show normal stresses as high as 4.0 kg per sq cm being applied to the 38-sq-cm specimen and shear stresses as high as 1.6 kg per sq cm being measured. Rates of strain can be varied at least from 2.0 in. per day to 0.37 in. per day.

Effect of Specimen Type

20. Residual shear strength may be determined using the three basic

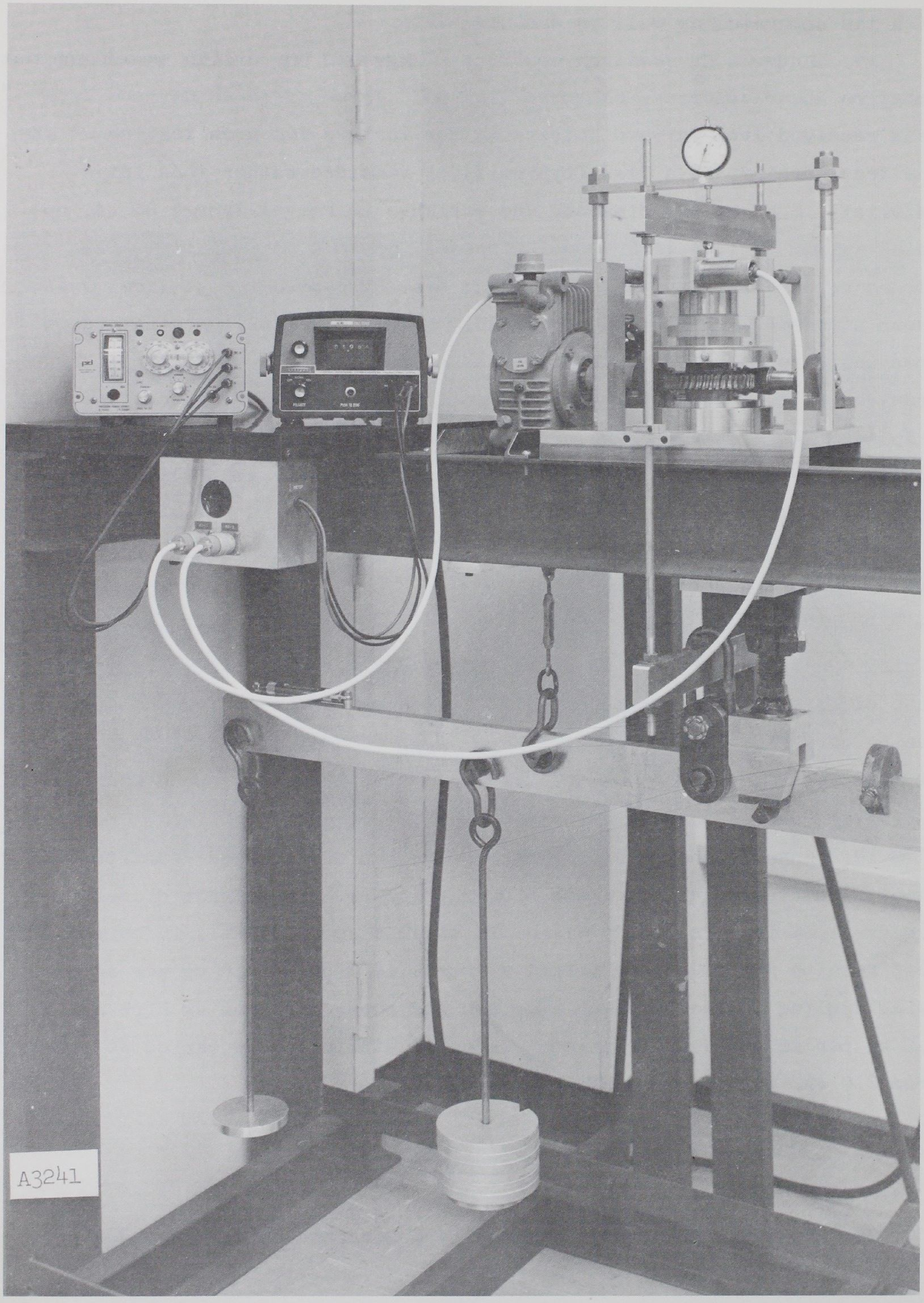


Fig. B9. Harvard rotation shear apparatus types of specimens defined as follows:

a. Intact. An intact piece of material at natural water content is subjected to a shear test so that the residual shear strength is determined on a surface formed naturally by shearing action.

b. Precut. Two pieces of intact material at natural water content are placed into uniform contact over a plane area and, then, one piece is moved over the surface of the other so that the residual shear strength is determined on a surface which is initially plane. The two pieces may be trimmed separately before being placed in the shear apparatus, or a single piece may be cut in two using a small-diameter wire after the piece is placed in the shear apparatus.

c. Remolded. The material is thoroughly disaggregated, slurried, and reconsolidated to either a normally or an overconsolidated state to form a specimen. The resulting specimen is subjected to a shear test so that the residual shear strength is determined on a surface formed naturally by shear. An unspecified factor here is the procedure for disaggregating the material.

21. If the residual shear strength were indeed independent of stress history, the same value should be found with tests on all three types of specimens. In that case, the most convenient type of specimen could be chosen for testing. However, experimental investigation of the effect of specimen type is required. One such investigation was reported by de Beer,[43] who found that annular shear tests of a stiff fissured clay gave residual friction angles of 24.3 deg using intact specimens and 19.3 deg using precut specimens, all values being determined at a rate of shear displacement of 0.37 in. per day. But the significance of this difference is uncertain because of the lack of details regarding the test procedure. Additional uncertainty is caused by the fact that the angles using both intact and precut specimens decreased about 4 deg when the rate of shear displacement was increased to 2.0 in. per day. Companion direct shear tests on precut specimens performed by the Danish Geotechnical Institute measured friction angles of about 11 deg, but there is, again, insufficient published information to evaluate these findings.

22. The Prairie Farm Rehabilitation Administration (PFRA) of Canada sent intact samples of Bearpaw shale from the left slope of the spillway at Gardiner Dam (formerly South Saskatchewan River Dam) to WES, MRD, and

Harvard University for residual shear strength determinations to compare with results being obtained by PFRA. The comparative results, as given in table B1, suggest that essentially the same values can be obtained with either precut or remolded specimens.[44]

23. Several annular and repeated direct shear tests have been performed by WES on both intact and precut specimens as a part of ES 542. The results of some of these tests, as given in table B2, are included here to help in evaluating the effects of specimen type and other variables. However, most of these tests were performed to develop the testing techniques and do not reflect current procedures. For example, some of the tests were started with very high rates of shear displacement so the measured friction angle is a function of elapsed time (to permit dissipation of excess pore water pressure) rather than shear displacement. Difficulties with the amount of gap between the upper and lower confining rings marred several tests. Because of time limitations, few tests were carried under the constant conditions of normal stress and rate of displacement sufficiently long to reach a real state of equilibrium.

24. Figure B10 presents the strength versus displacement curves from annular shear tests on intact specimens of Dawson shale from Chatfield Dam. The displacement scale in this figure is logarithmic (following a practice introduced by LaGatta[25]) to aid in determining when a minimum shearing resistance has been obtained. Breaks in curvature are the results of adjusting the gap between the confining rings. Under high normal stress, extrusion of remolded soil from the gap was too excessive to permit a residual condition to be attained. In addition, the tests were all terminated before sufficient shear displacement had occurred to obtain a minimum shearing resistance. Figure B11 shows such curves from tests on precut specimens conducted on three different apparatus. Excessive extrusion did not occur, though the results are inconclusive since the tests were ended too soon. While all specimens were trimmed from a single block sample, variations in properties among the specimens must be expected in view of the nonuniform character of the weathered Dawson shale.

25. In fig. B12 are shown results of annular shear tests of both

Table B1

Residual Friction Angles of Bearpaw Shale Measured by Different Laboratories

Laboratory	Type of Apparatus	Type of Specimen	Sample No.	Atterberg Limits		Normal Stress kg/sq cm	Total Shear Displacement cm	Residual Friction Angle deg
				LL	PL			
WES	Annular shear	Precut	5B TP 4102	175	27	6	30	2.6
				144	25	6	103	3.6
Harvard	Annular shear	Remolded	6 TP 4102	165	28	2	-	4.0
						4	< 100	3.8
						4	-	2.9
						8	< 100	3.3
MRD	Repeated direct shear	Precut	5A TP 4102	181	24	6	15-23	5.2
						6	15-23	4.9
						18	15-23	4.3
PFRA	Repeated direct shear	Field shear plane	TP 4102	170	28	-	-	2.5 - 3.0
				129	25			
PFRA	Repeated direct shear	Remolded	RD 2300	125	23	-	-	5.0 - 6.0
PFRA	Repeated direct shear	Remolded	C 4039	124	25	-	-	4.0 - 4.2

Table B2

Results of Shear Tests Performed by WES on Dawson Shale

(Box U-18 from Chatfield Dam)

Test No.	Type of Apparatus	Type of Displacement	Type of Specimen	Stage No.	Normal Stress kg/sq cm	Rate of Shear Displacement cm/day	Displacement During Stage cm	Minimum Friction Angle deg
6	Annular	Continuous	Intact	1	6	0.1	0.6	-
				2	6	1	9.7	8.9
				3	6	0.1	0.5	8.7
				4	6	1	2.0	8.8
				5	18	0.1	0.4	10.0
				6	18	1	4.7	10.0
				7	18	10	3.2	10.4
				8	18	0.1	0.3	9.7
				9	6	1	13.5	10.6
				10	2	1	6.7	15.0
8	Annular	Continuous	Intact	1	6	10	36.0	8.3
				2	18	100	0.9	-
				3	6	100	115.2	5.7
9	Annular	Continuous	Intact	1	6	0.1	0.5	-
				2	6	1	10.7	6.3
				3	18	1	1.8	6.4
				4	6	1	6.0	7.1
				5	6	10	69.7	6.0
				6	2	10	9.5	6.8
12	Annular	Continuous	Intact	1	20	0.1	0.5	-
				2	20	0.316	1.3	-
				3	20	1	25.5	7.1
				4	6	1	4.6	7.2
7	Annular	Continuous	Precut	1	2	100	10.6	9.6
				2	2	10	25.2	7.3
				3	2	100	27.4	7.3
				4	2	0.1	0.6	6.4
				5	6	100	31.7	6.1
				6	6	1	6.5	5.1
				7	18	100	33.4	6.6
				8	18	1	7.5	5.9
				9	18	100	28.3	6.9
				10	18	1	0.7	5.8
				11	6	1	3.9	6.0
				12	6	100	108.6	6.2
				13	2	1	1.9	6.2
				14	2	100	89.1	6.6
13	Annular	Repeated	Precut	-	6	1.707	36.8	5.7
		Continuous		-	6	1.707	52.1	4.8
16	Direct	Repeated	Precut	1	6	1.163	9.2	4.9
				2	6	0.593	8.5	4.6

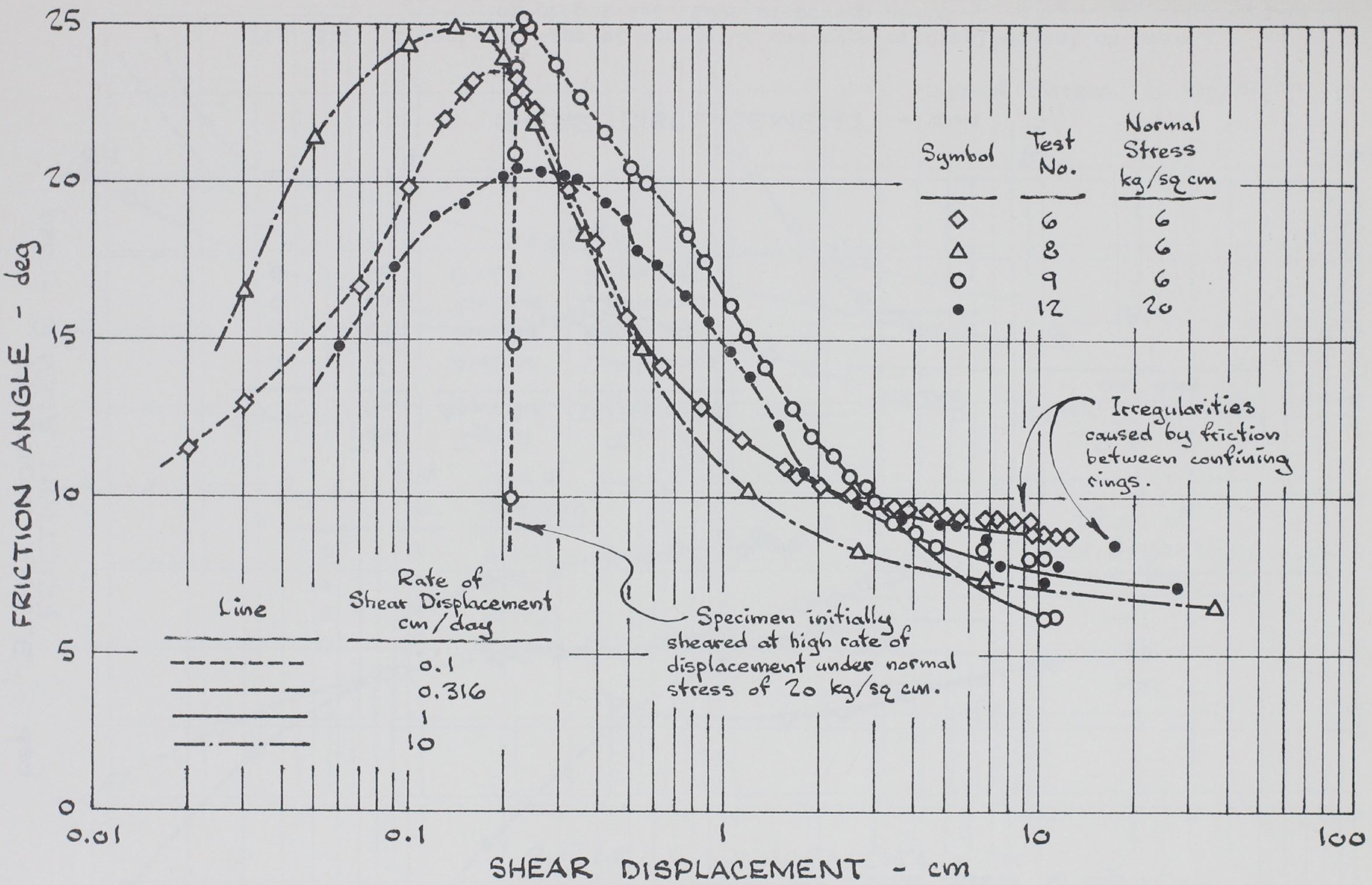


Fig. B10. Results of annular shear tests of intact specimens of Dawson shale

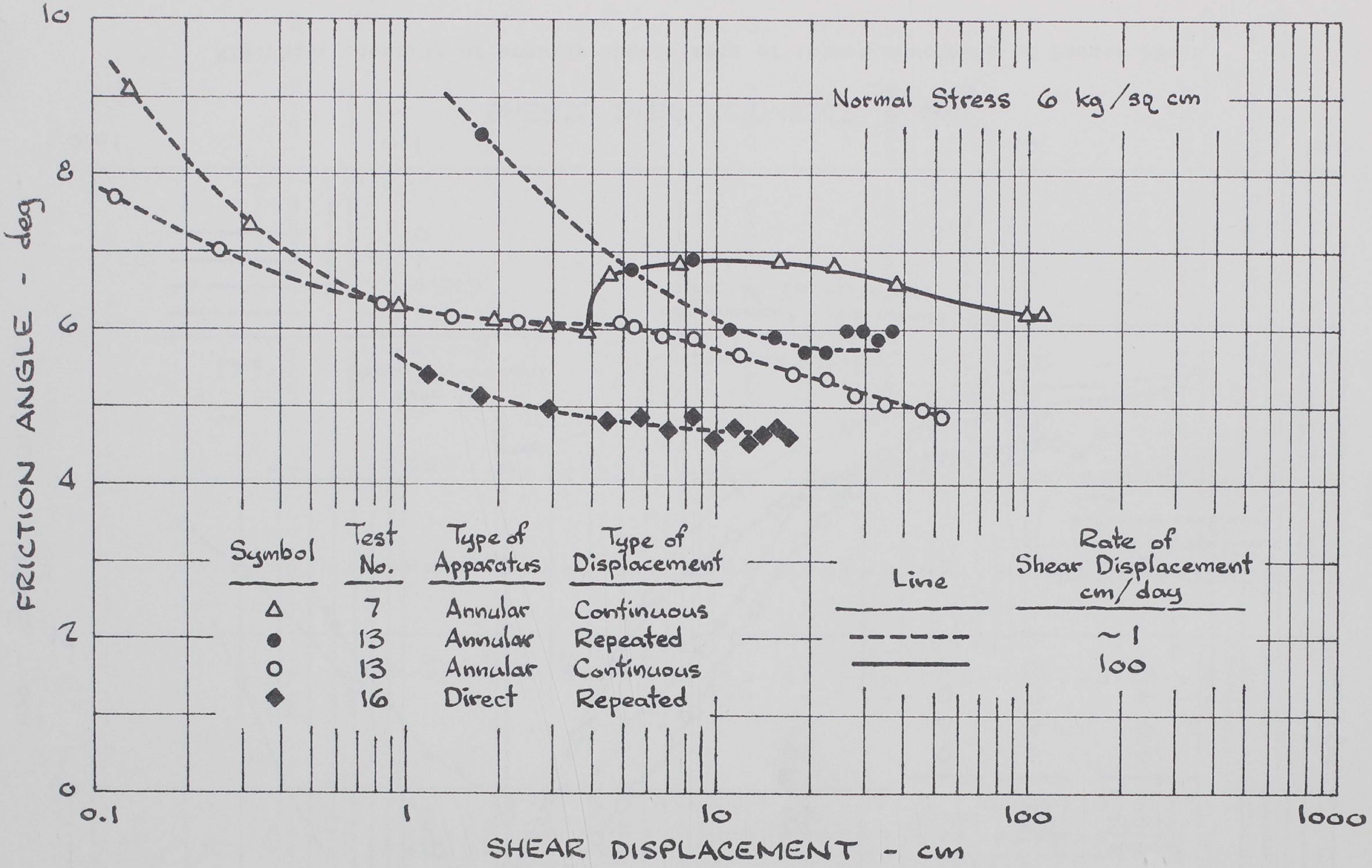


Fig. B11. Effects of type of apparatus and type of displacement on tests of precut specimens of Dawson shale

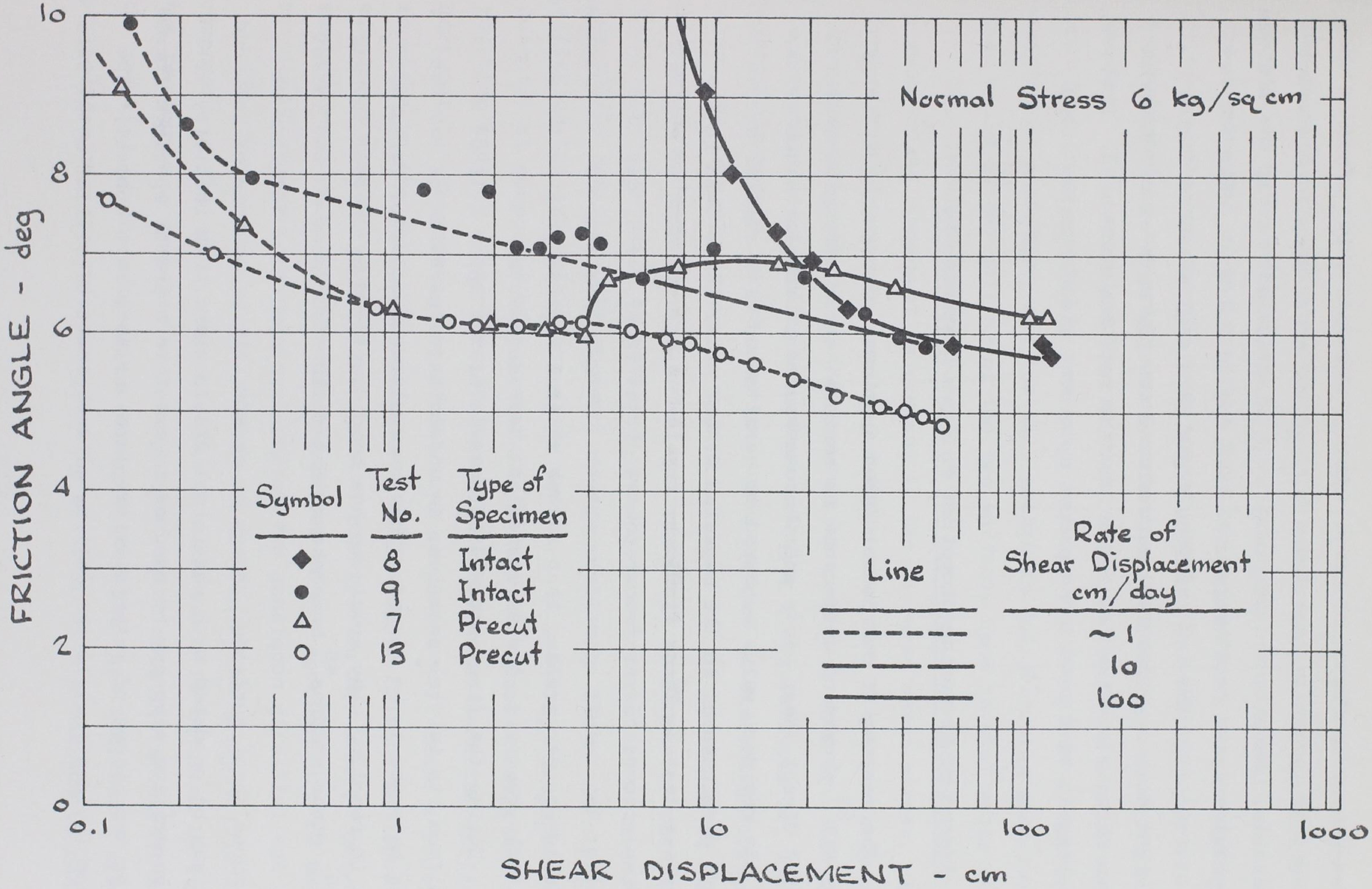


Fig. B12. Comparison of results from annular shear tests of intact and precut specimens of Dawson shale intact and precut specimens of Dawson shale. The data shown are from the later stages of the tests (see table B2), so the shear displacements are not comparable. Despite the differences in displacement rates, the minimum friction angles agree relatively well (5.8 deg to 6.2 deg), with the exception of test 13. The low friction angle (4.8 deg) measured during test 13 might have resulted from maintaining the low rate of displacement; test 7 was showing similar results before the rate was increased. However, the data suggest that intact and precut specimens yield equally valid results.

Effect of Reversing Direction of Shear Displacement

26. The testing of overconsolidated specimens of resedimented clay shales by MIT[39] showed no difference in residual shear strengths measured in repeated direct shear tests and those measured in annular shear tests. However, the residual value appeared to be attained with smaller accumulative shear displacement in the repeated direct shear tests than in the annular shear tests. These findings, together with the shape of typical stress-displacement curves from repeated direct shear tests, can lead to a concept of the nature of residual shear strength measurements, as discussed in the following paragraphs, that may be helpful in interpreting the effects of repeatedly reversing the direction of shear movements.

27. During the first shear displacement of the upper half of a specimen from its initial position, an undulating separation of the two halves is believed to be formed. This irregular character of failure surfaces in remolded clay specimens has been displayed by several investigators.[45] Other studies[46] have shown that failure surfaces in any intact material are initially nonplanar due to the development of families of discontinuous shear surfaces, though an essentially plane zone of remolded material may be produced with sufficient displacement. An initially irregular separation also can be assumed to exist in a precut specimen formed by placing two pieces of material with plane surfaces into contact. The phenomenon is identical to the galling of two pieces of similar metal when

rubbed together under pressure; minor surface irregularities interlock and cause flakes and slivers to be torn from each of the pieces as controlled by microfractures or other incipient discontinuities. While the development of an initially nonplanar separation in a precut specimen of clay shale has not yet been investigated, its existence can be demonstrated by the presence of striations on the shear surfaces after testing. The irregularities at right angle to the direction of movement must have been created by irregularities in the direction of movement which existed at some time, and the only mechanism for producing such irregularities would be the galling of the two surfaces upon initial shear displacement.

28. Because the two halves of the specimen have undulating surfaces, a geometrical component is present in the measured shear stress. As the irregular surfaces are displaced farther in either direction away from their initial, mating position, the geometrical component will increase due either to irregularities sliding upward on matching irregularities or, when displacements become larger, the increased contact of dissimilar irregularities. Also, the irregularities may not be oriented in the direction of shear movement so a binding or a rotational effect is introduced. When the direction of movement is reversed and the two surfaces are returned toward the mating position, the geometrical component will lower the measured shear stress as the irregularities slide downward on matching irregularities; the geometrical component will vanish as the surfaces pass through the initial position and the vector sum of the shear stresses between the surfaces is horizontal. Therefore, the geometrical component will cause a continuous increase in the measured shear stress as the upper half of the specimen is displaced from one side of its initial position to the other. Only the shear stress measured when the two halves of the specimen are in their initial vertically aligned position is valid.

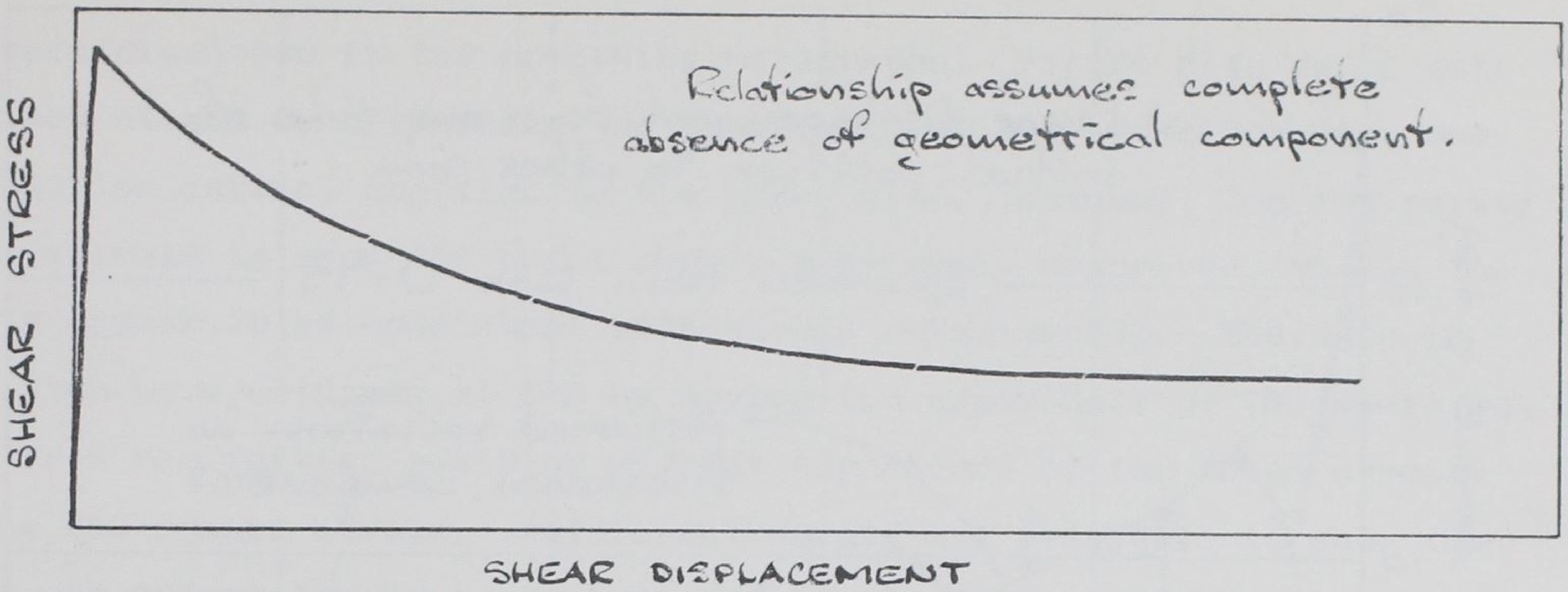
29. The purpose of the test is to determine the minimum frictional component of the shear stress. This minimum value is obtained by rubbing the two surfaces together with sufficient total relative movement that the material at the contact is disaggregated and that individual clay particles along the interface develop a fabric with a maximum of parallel

orientation in the direction of movement. An idealized relationship between the frictional component and the shear displacement is shown in fig. B13a; this relationship presumes a perfectly plane separation between the two halves of the specimen.

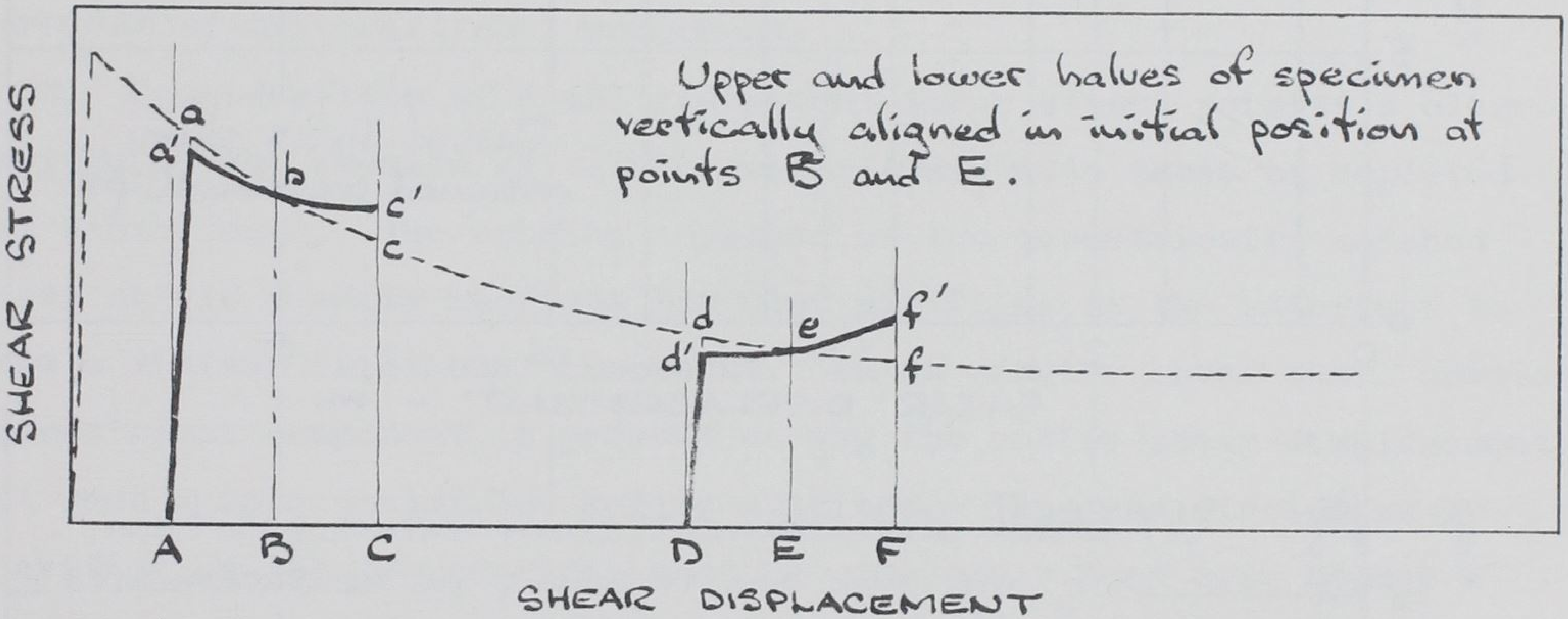
30. In fig. B13b is shown the idealized influence of the geometrical component on the measurement of the frictional component during two different strokes of a repeated direct shear test. During stroke AC, the actual decrease in the frictional component from a to c is altered by the geometrical component to cause the measured shear stress to decrease from a' to c' ; only at b is the measured shear stress equal to the unaffected frictional component. During stroke DF , however, the increase in the geometrical component is greater than the decrease in the frictional component, so the continuously decreasing relationship from d to f is obscured by a measured shear stress continuously increasing from d' to f' .

31. The third component of the shear stress measured in the repeated direct shear test is illustrated in fig. B13c. The nature of this flip-over effect is not known. It is certainly more than a mere static friction; a test stopped and then restarted in midstroke shows an insignificant rise in shear stress required for the resumption of movement. Thus the effect is caused by reversing the direction of movement, but the effect disappears after a very small shear displacement (less than half a millimeter), and the stress-displacement relationship thereafter appears unaffected by the reversal in direction. This is an important point, and it needs to be emphasized. Reversing the direction of shear movement does not appear to undo the tendency toward parallel orientation of clay particles displayed during the preceding stroke, save for the short-lived flip-over effect. If one would conceive of the development of a minimum shearing resistance as being similar to the bending and flattening of the bristles on a brush under the stroke of a hand, it does not appear that reversing the direction of the stroke lifts and rebends every bristle.

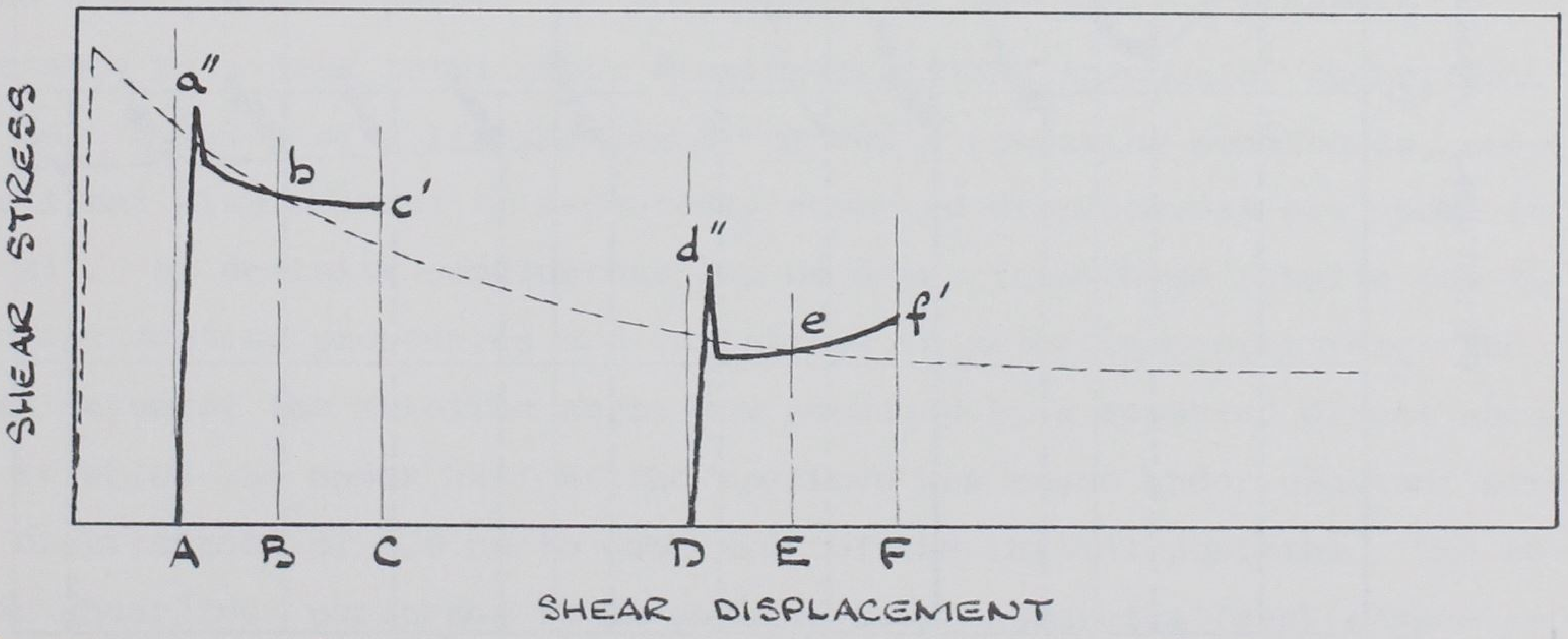
32. Two sets of stress-displacement curves from repeated direct shear tests on Dawson shale are shown in fig. B14 to demonstrate the



(a) Decrease in frictional component of shear stress with displacement



(b) Effect of geometrical component during two strokes of repeated direct shear test



(c) Flip-over effect (a" and d") when direction of movement is reversed

Fig. B13. Idealized expressions of the three components of shear stress measured in the repeated direct shear test

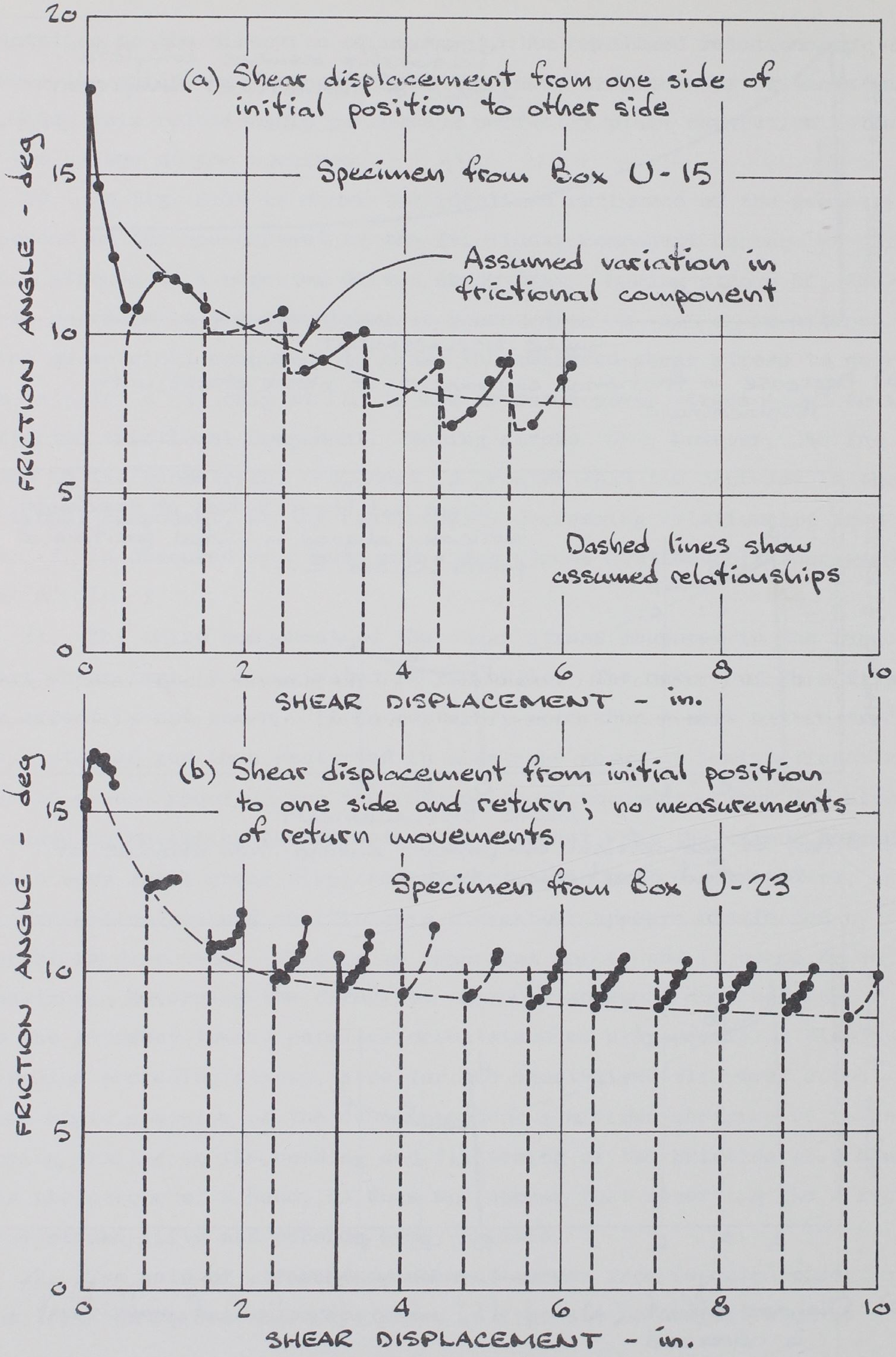


Fig. B14. Stress-displacement curves from two repeated direct shear tests on Dawson shale[26] concepts discussed in the preceding paragraphs. Figure B14a shows data obtained at MRD by displacing the upper half of the shear box from one side of the initial position to the other side. However, too few points are available to show the relationship previously described, though the points appear to be consistent with such a relationship. The data in fig. B14b were obtained at SWD by moving the upper half of the shear box away from the initial position without any record of the shear stress during the return stroke. Sufficient points are available to show the flip-over effect for some strokes, and it is apparent that the geometrical component is influencing the results. By starting each stroke from the initial position, the flip-over effect is imposed upon the only valid measurement of the frictional component.

33. Consideration of a multicomponent shear stress permits a clearer comparison of the results of annular shear tests with those of repeated direct shear tests. The rubbing together of two geometrically matched surfaces should readily reorient the clay particles at the interface to produce a minimal frictional component. In an annular shear test, however, the geometrical component is present during the entire shear displacement except when a rotation of 360 deg is attained. Thus the dissimilar irregularities on the two surfaces must be completely worn away before a valid measurement of the frictional component is possible. This suggests that a repeated direct shear test, by a more efficient action of one surface on the other, should permit the measurement of the minimum shearing resistance with less total shear displacement than an annular shear test.

34. Results of a limited number of tests comparing continuous, one-directional displacement to repeatedly reversed displacement are shown in fig. B11. No definite conclusions can be drawn from these results due to imperfect testing procedures and variations in material properties. The lowest value of the friction angle was produced by a repeated direct shear test in which the upper half of the specimen was moved under constant stress to a displacement of 0.6 cm to each side of the initial position. The repeated shear test performed in an annular shear apparatus (each stroke made from the initial position with the return stroke accomplished rapidly under

a constant normal stress) did not attain an equally low value, probably because of the testing procedure used. When continuous, one-directional movement was applied to the same specimen, the shear stress decreased slowly with displacement, and would probably have reached the value measured in the repeated direct shear test had not the movement been prematurely discontinued.

Effect of Normal Stress

35. Several studies[25,39] have shown that the relationship between residual shear strength and normal stress is not always constant; that is, the measured residual friction angle may decrease with increasing normal stress. Such a tendency would agree with the concept that both normal and shear stresses are contributing to the disaggregation of the material and the increase in parallel orientation of particles in the direction of shear displacement. Also, under a higher normal stress, irregularities on the surfaces of each half of a test specimen would be more rapidly and completely worn away. Tests performed at MIT showed that the residual shear strength is attained with less shear displacement under a higher normal stress.[39]

36. Residual friction angles determined by several CE laboratories on different clay shales are plotted in fig. B15 as a function of normal stress. While there is a trend of decreasing residual friction angle with increasing normal stress, the difference for any material would not significantly alter the value of this angle as an index for classification purposes.

37. In fig. B16 are shown results from three stages of an annular shear test on a precut specimen of Dawson shale. Although a slight decrease in residual friction angle with increasing normal stress may be noted, the effect was obscured by test irregularities.

38. Besides the possible inherent decrease in residual friction angle with increasing normal stress, the difficulties in measuring residual shear strengths are influenced by the normal stresses used. Under a low

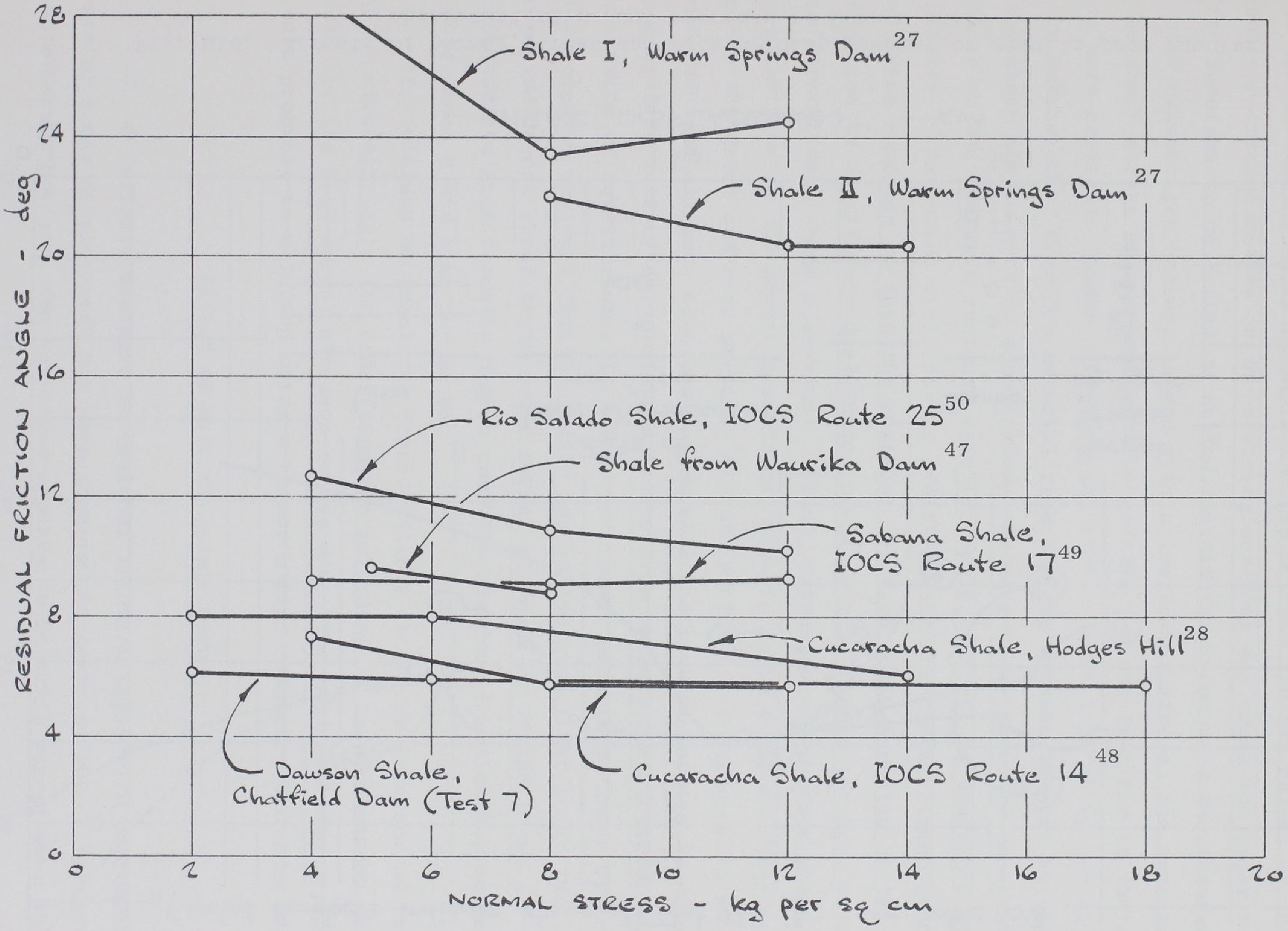


Fig. B15. Summary of results of repeated direct shear tests performed by various laboratories showing the influence of normal stress on residual friction angle

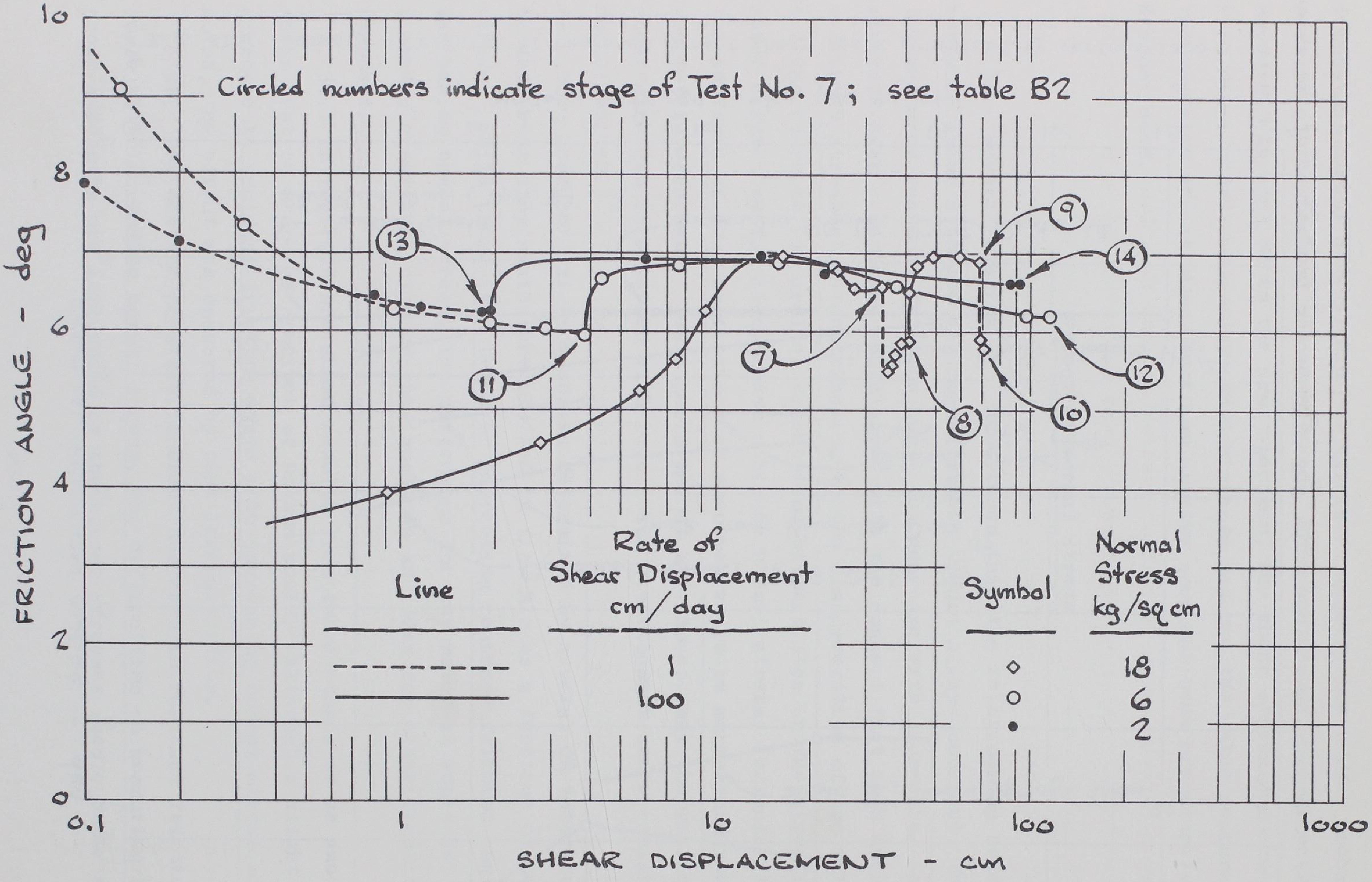


Fig. B16. Effects of normal stress and rate of displacement on results from annular shear test of precut specimen of Dawson shale normal stress (less than 2 kg per sq cm), a specimen of clay shale may tend to swell, causing an increase in the gap between the two halves of the shear box, or irregularities on the shearing surfaces may cause the upper half of the specimen to be lifted or tilted, permitting water from the reservoir to enter between the halves. Also, with a low normal stress, the accuracy of the shear stress measurement must be greater and any friction in the system is more critical. Under a high normal stress (more than 15 kg per sq cm), the extrusion of remolded material from the gap between the two halves of the shear box is greatly accelerated. Extrusion may have two possible effects on the measured residual friction angle. First, as described by LaGatta,[25] extrusion will cause a redistribution of normal stress over the shearing surfaces so that the residual friction angle computed on the assumption of a uniformly distributed normal stress may be too low, especially in a rotational shear apparatus. Second, extrusion may produce gross irregularities on the shearing surfaces, especially in a direct shear apparatus where the front and rear portions of both surfaces are unsupported at the ends of each stroke. Also, extrusion will continuously remove the disaggregated, well-oriented clay particles from between the surfaces, and a condition of equilibrium will not be possible. Because of these effects, the computed residual friction angle may be too high. MRD found that repeated direct shear tests under normal stresses of 15 and 30 kg per sq cm resulted in significantly higher computed residual friction angles than tests under 4 and 8 kg per sq cm.[22]

39. Because of practical considerations in the performance of residual shear strength tests for classification purposes, it is recommended that both low and high normal stresses be avoided. The most satisfactory results would probably be obtained using a normal stress between 4 and 8 kg per sq cm.

Effect of Rate of Displacement

40. A definite decrease in residual friction angle with decreasing rate of shear displacement has been observed in tests at MRD,[22] Harvard,[25] and others. However, the variation appears to be small except when the

rate is increased to the order of, say, 10 cm per day. The results shown in fig. B16 indicate a decrease of about 15 percent in the shear stress (1 deg change in the friction angle) with a hundred-fold decrease in displacement rate, though there was insufficient displacement under each of the different rates to be sure that equilibrium had been obtained. Contrary results were obtained at the Belgian Geotechnical Institute where a five-fold decrease in displacement rate caused an increase of about 25 percent in the shear stress (4 to 5 deg change in the friction angle).[43]

41. Several laboratories use relatively high rates of displacement to accumulate large shear displacements within a reasonable period and then reduce the rate for a valid measure of shear stress. In these instances, the shear stresses measured initially in tests with high rates may be affected by incomplete dissipation of excess pore water pressures (as shown by the initial portions of the curves in fig. B16) in addition to a rate-dependent viscosity of remolded clay. Measurements of shear stresses at low rates (0.1 cm per day) are seldom feasible because of the great length of time needed to obtain sufficient displacement at such rates to ensure an equilibrium condition.

42. While further investigation of the effect of displacement rate is warranted, it is not believed that this effect would be significant in determinations of residual friction angles as long as the rate was sufficiently slow (less than 1 cm per day) to provide essentially complete dissipation of excess pore water pressures. Also, if much lower rates of displacements were to be used, the durations of tests would become excessive for determinations of classification indexes.

Suggested Standardized Procedure

43. Until more comparative residual shear strength tests have been performed, it is suggested that either a direct shear or an annular shear apparatus be used in a standard method for determining the residual friction angle. Furthermore, it is recommended that a precut specimen of intact material at natural water content should be used in the standard method.

Details of the procedure for a standardized test are suggested in the following paragraphs.

44. The specimen should consist of two pieces of intact material trimmed to fill the inside of the shear box or confining ring. The two pieces should be of approximately equal height and have a total height not in excess of 1 in. (preferably, the total height should be 0.5 in., but this is often not practical for stiff, fissured materials). The top and bottom surfaces of each piece should be plane and parallel. Only a reasonably close fit of each piece to the inside of the shear box* is necessary for stiff-to-hard materials which must be cut to shape with a bandsaw or, in the case of very hard materials, with a diamond wheel. The lower half of the specimen should be firmly seated against the porous plate in the lower half of the shear box. A slight (0.010 to 0.020 in.) projection of the lower half of the specimen above the lip of the box is desirable; certainly the top of this half of the specimen should not initially be below the lip. Then the upper half of the specimen should be placed in the shear box, the upper porous plate added, and the remainder of the shear apparatus assembled.

45. Alternatively, a specimen of softer material may be precut inside the shear box. In this case, an intact specimen is firmly seated between saturated porous plates in the apparatus and, then, a plane should be cut with a small-diameter (0.008- to 0.014-in.-diam) steel wire through the specimen at the separation between the upper and lower halves of the box. After cutting, the two halves of the specimen should be separated and the cut surfaces inspected for planeness. Any irregularities should be removed with a straightedge.

46. Once the apparatus is completely assembled around the precut specimen, the normal stress should be applied and, then, the specimen should be inundated with distilled water. For a standardized method of determining the residual friction angle, it is suggested that a single value of normal stress should be used. A standard value of about 6 tons per sq ft is recommended as being high enough to prevent the swelling of most clay shales, yet low enough to minimize the problem of material

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* In the following paragraphs, the term "shear box" should be considered to include the specimen-confining rings of an annular shear apparatus.

extruding from between the two halves of the box during shear. The specimen should be allowed to consolidate or swell to essentially an equilibrium condition under the normal stress; a minimum period of 16 hr should be allowed before shear.

47. When the consolidation phase is completed, a gap should be formed between the two halves of the box to ensure that normal and shear stresses are borne only by the specimen. This gap should be kept rather small (0.015 to 0.025 in.) to minimize extrusion of remolded material from the shearing surface. Periodically during the test, the gap can be checked by inserting thickness gages, and adjustments can be made. Closure of the gap is quite critical in an annular shear test since friction between the two outer confining rings acts with a large moment akin to increasing the measurement of torque disproportionately.

48. Horizontal displacement of one half of the specimen relative to the other should be initiated at a controlled rate not in excess of 0.5 in. per day (about 0.0003 in. per min). Shear movement under constant normal stress should be continued, either by uninterrupted movement in a rotational apparatus or by repeatedly reversed movement (with about 0.25 in. displacement to each side of the initial, center position) in a translational apparatus, until a minimum shearing resistance is attained. A semilogarithmic plot of shear stress (arithmetic scale) versus cumulative shear displacement (logarithmic scale) should be maintained during the test to show when a minimum value has been reached. When a direct shear apparatus is used for the test, only the shear stress measured when the two halves of the shear box are vertically aligned (at the midpoint of each stroke) should be plotted.

49. If, after completing the standard test, the effects of increased normal stress and decreased displacement rate are to be determined, this additional information should also be obtained according to standardized procedures. First, the effect of increased normal stress should be determined as follows. After the minimum resistance has been attained under a normal of about 6 tons per sq ft and at a displacement rate less than 0.5 in. per day, the normal stress should be approximately doubled

while the two halves of the shear box are vertically aligned and the specimen allowed to consolidate for at least 16 hr. Then, shear displacement should be resumed at the previous rate and be continued until a minimum shearing resistance corresponding to the increased normal stress is reached, as previously described.

50. Next, the effect of decreased rate of displacement should be determined as follows. After the minimum shearing resistance has been reached under the high normal stress (approximately 12 tons per sq ft) and at a displacement rate less than 0.5 in. per day, the rate of displacement should be reduced to a tenth of the standard rate (that is, to less than 0.05 in. per day) without any change in the normal stress, and shear displacement should be resumed until the minimum shearing resistance is developed. When a direct shear apparatus is used for the test, the rate of displacement should be reduced soon after the upper half of the shear box has passed through the initial, vertically aligned position. Movement at the reduced rate should continue to the end of the stroke and then, on the return stroke, pass through the initial position again. The shear stress measured when the two halves of the box are vertically aligned this second time should be used to compute the residual friction angle for the decreased displacement rate.

51. At the end of the test, after the shear force has been removed, the water reservoir should be emptied and all free water removed from the specimen. Then, the normal stress should be removed and the two halves of the specimen separated. The shear surfaces should be carefully inspected, and the condition of the surfaces (texture, gloss, irregularities, etc.) should be described. Two final water contents should be determined: one on material scraped from both shear surfaces and another on the remainder of the specimen.

52. While not yet believed appropriate for a standard classification procedure, the residual friction angle could be determined using remolded material prepared by the same three methods (initial, air-dried, and blended) applied to determinations of particle-size distributions and Atterberg limits. Results of this type are being produced; the typical

method used at Harvard University to prepare residual shear test specimens is to reconsolidate material that has been air-dried and slaked. Some study of the effects of air-drying and of blending on the residual friction angle may be needed to assist in establishing correlations between residual friction angle and Atterberg limits.

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13. ABSTRACT

Characteristics of clay shales are reviewed with regard to construction and maintenance problems encountered on Civil Works projects of the Corps of Engineers. Confusion in the description and definition of clay shale results from the variable character of the material and the subjectivity of most classification methods. It is considered inadequate to distinguish only good shales from bad shales; rather, standardized indexes are required for the quantitative classification of shales. From consideration of the several factors controlling the characteristics of clay shales, both qualitative and quantitative indexes are defined and standardized apparatus, procedures, and descriptors for each index are proposed. Particular emphasis is given to the methods for disaggregating clay shale material for index tests and the apparatus and procedures for measuring residual shear strength. It is recommended that Atterberg limits and particle-size analysis be performed on material processed (a) from undried material, (b) after a single cycle of air-drying and slaking, and (c) after disaggregation by a high-speed food blender. Oven-drying and cyclic air-drying procedures are not believed to provide as useful information as these three methods. Detailed procedures are suggested for the three standardized methods for disaggregating materials, including specific equipment and operating requirements for high-speed blending. Apparatus and procedures for performing repeated direct shear and annular (or rotational) shear tests are reviewed and compared. Variations in measured residual shear strength with type of test, type of specimen, normal stress, and rate of shear displacement are discussed and illustrated with test results. The concept of both a frictional component and a geometrical component to measured residual shear strength is introduced and used to interpret the effect of reversing the direction of shear displacement in the repeated direct shear test. Details of a standardized method for determining residual shear strength are proposed, and objectives for future investigation are suggested.

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