CORRELATION OF SHEAR STRENGTH PARAMETERS ~~AT O.M.C.~~ WITH THE PLASTICITY CHARACTERISTICS OF SOILS

THESIS

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE AWARD OF DEGREE OF
MASTER OF ENGINEERING
IN
SOIL MECHANICS AND FOUNDATION ENGINEERING

By
R. N. SACHAN

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE; INDIA
1964

CORRELATION OF SHEAR STRENGTH PARAMETERS ~~AT O.M.C~~. WITH THE PLASTICITY CHARACTERISTICS OF SOILS

by

R.N. SACHAN

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF ROORKEE, ROORKEE
INDIA

1964

CORRELATION OF SHEAR STRENGTH PARAMETERS ~~AT O.M.C.~~ WITH PLASTICITY CHARACTERISTICS OF SOILS.

By.

R. N. SACHAN

A

DISSERTATION

Submitted in partial fulfilment of the Requirements for the award of degree of MASTER OF ENGINEERING

IN

SOIL MECHANICS AND FOUNDATION ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY OF ROORKEE

ROORKEE ; INDIA

1964

CERTIFICATE

Certified that the dissertation entitled "CORRELATION OF SHEAR STRENGTH PARAMETERS ~~AT O.M.C.~~ WITH PLASTICITY CHARACTERISTICS OF SOILS" which is being submitted by Sri R.N. Sachan in partial fulfilment of the requirements for the award of Master of Engineering Degree in Soil Mechanics and Foundation Engineering of University of Roorkee, is the record of his own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is further certified that he has worked for a period of *Six* months from *June, 63* to *1st Jan*, 1964 in connection with the preparation of this dissertation.

KB Agarwal

(K.B. Agarwal)
Reader in Civil Engineering
University of Roorkee
Roorkee, India

Roorkee
Dated *26/6/* 1964

CONTENTS

Contd.

A B S T R A C T

When soil is used as construction material, the important property required is the shear strength for particular condition of the soil in field. The conventional method of determining the shear strength is by tri-axial testing which is quite tedious and time taking. Hence it would be worthwhile if the shear strength can be determined indirectly from correlations with simple properties of soil like plasticity characteristics. The obvious advantage will be that these tests done for the classification of soil for the project, can be utilised for estimating the shear strength readily. More over correlations of shear strength parameters C and Ø with the plasticity characteristics help us in understanding the basic behaviour of the soil.

In the present investigation attempts have been made to correlate the apparent shear strength parameters C and Ø (quick test) of cohesive soils with their plasticity characteristics.

Fifty soils from North India have been collected from different sources. Their O.M.c., liquid limit and plastic limit have been determined by the usual standard methods.

Then the soils were compacted at O.M.C. at standard Proctor's. At O.M.C., undrained (Quick) tests have been performed in triaxial machine and their apparent cohesion C and angle of internal friction Ø have been obtained. Then these C and Ø, have been correlated with liquid limit, plastic limit and plasticity index by statistical analysis.

Of the above trials, the best correlations on the basis of statistical analysis of data, seems to be the correlations of C and Ø with liquid and plastic limits combined.

Nomograms have also been developed for the above correlations for easy prediction of C and Ø from plasticity characteristics of the soil.

ACKNOWLEDGMENTS

The author wishes to express his gratitude and sincere thanks to Sri K.B. Agarwal, Reader in Civil Engineering University of Roorkee, for suggesting the problem and his valuable guidance and encouragement in the preparation of this dissertation.

The author is thankful to Dr. Jagdish Narain, Professor in Soil Mechanics, University of Roorkee for his useful suggestions and help in the experimental work.

Author also expresses his thanks to the Soil Mechanics Laboratory staff for their help during experimental work.

Finally, the author is grateful to the University Grants Commission for awarding Scholarship to facilitate Post-Graduate studies.

R.N. SACHAN

LIST OF ILLUSTRATIONS

NOTATION

a - Additive constant of equations.

b - Multiplying constant of equations.

C - Apparent cohesion in psi. at O.M.C.

$\bar{C}$ - Mean value of apparent cohesion.

C' - Calculated value of apparent cohesion.

I_p - Plasticity Index.

$\bar{I}_p$ - Mean value of plasticity index.

N - Total number of observation.

r - Product moment correlation coefficient.

R - Multiple correlation coefficient.

S_c - Standard error of estimate for apparent cohesion.

S_ϕ - Standard error of estimate for apparent angle of internal friction.

W_l - Liquid limit.

$\bar{W}_l$ - Mean value of liquid limit.

W_p - Plastic limit.

$\bar{W}_p$ - Mean value of plastic limit.

ϕ - Apparent angle of internal friction in degrees.

ϕ' - Calculated value of ϕ.

$\bar{\phi}$ - Mean value of ϕ.

σ_c - Standard deviation for values of C.

σ_c' - " " " " " C'.

σ_I - " " " " " I_p.

σ_l - " " " " " W_l.

σ_ϕ - " " " " " ϕ.

σ_ϕ' - " " " " " ϕ'.

Σ - Sum of quantities.

Σ' - Corrected sum of quantities.

I. INTRODUCTION

The strength characteristics of compacted cohesive soils have become of major importance in recent years, as the activities in the construction of earth structures such as embankments for railway and highways and earth dams have increased. For satisfactory and economical design of these structures, the knowledge of the behaviour of compacted soils in shear is essential.

The purpose of the present investigation is to correlate the shear strength characteristics of compacted soils with some fundamental soil properties which can be easily, economically and quickly determined. The conventional method of determining the shear strength of soils is by direct shear or by triaxial testing which are in general costly and time consuming and require a well-equiped laboratory. Several attempts have been made to determine the strength characteristics of soil by simpler methods such as vane shear test, cone penetration test etc. The aim of the present investigation is to develop simple economic and quick method of determining, the values of apparent cohesion and angle of internal friction, without performing triaxial test for which adequate laboratory facilities are required, and also to help in understanding the strength behaviour of soils with respect to their plasticity characteristics.

The liquid limit, plastic limit and plasticity index are regarded as important engineering properties of cohesive soils. Moreover these tests are invariably performed for the classification of soil in all important projects. In this investigation attempts have been made to develop correlations between the quick or undrained shear strength parameters i.e. 'C' and 'Ø', for cohesive soils compacted at O.M.C to standard Proctor's density; with the plasticity characteristics of the same soils viz. the liquid limit, the plastic limit and the plasticity index. Fifty soil samples obtained from the different parts of U.P. have been tested to obtain the results. Seven correlations have been developed on the basis of the statistical analysis in which 'C' and 'Ø' have been correlated with the liquid limit, plastic limit and plasticity index. The statistical tests revealed that the correlation of 'C' and 'Ø' with liquid and plastic limit; combined are the best correlations for the plasticity ranges of the soils tested.

II. REVIEW OF LITERATURE

Shear Strength of Soils.

In 1773 Coulomb (31)* suggested an empirical law for the shear strength characteristics of a soil which could be represented by the equation :

$$S = C + \sigma \tan \phi$$

where in the modern nomenclature :

S denotes shear strength

C denotes apparent cohesion.

σ denotes total pressure normal to the shear plane and ϕ denotes apparent angle of shearing resistance.

In the above equation, 'C' and 'ϕ' are empirical constants, the value of which for any given soil, depend upon the conditions under which the soil is stressed; whether the soil is allowed to drain during shearing process or otherwise.

In a more fundamental form, first put forward by Hvorslev (31) in 1937, coulomb's equation is rewritten as :

$$S = C_e + (\sigma - u) \tan \phi_e$$

where C_e denotes true cohesion

ϕ_e denotes true angle of internal friction

and $(\sigma - u)$ denotes effective stress normal to the shear plane.

The cohesion and internal friction will in general depend upon the void ratio of the soil at the instant of failure.

---

* Figures in parantheses refer to the Bibliography given on page 77.

Thereafter many modifications (13) in the effective stress law were proposed by Terzaghi, Bishop and Eldin (1950), Skempton (1954), Jenning and Knight (1957), Lambe and whitman (1959) and various other investigators, for different conditions of voids of the soil mass.

Whether or not this view of the physics, of shear strength is wholly acceptable, the Coulomb-Hvorslev equation has been confirmed experimentally, and it still forms the basis of the fundamental considerations of shear strength of the soil.

The measurement of 'C_e' and 'ϕ_e' is however, a matter of some difficulty in many soils. Moreover, an analysis of stability based on these basic properties is likely to be rather elaborate in practical use, though ultimately such analysis will be carried out in engineering. But at present time the usual method of procedure is (31):-

(i) To determine the values of C and ϕ in Coulomb's equation under a definite conditions of water content change during shear, namely no water content change (Undrained Test) or full water content change (Drained Test).

(ii) To use these values of C and ϕ as if they denoted the cohesion and internal friction of the soil: where practical conditions approximate to zero water content change the undrained test parameters are used with respect to total stresses: where practical conditions approximate to full water content change, the drained test parameters are used with respect to effective stresses: where practical conditions cannot be even approximately represented by either drained or undrained test, both tests should be made and approximate strength deduced from a knowledge of the degree of consolidation under field conditions.

This procedure is semi-emperical : its justification must be judged by the following three criteria:-

(a) Simplicity.

(b) Reliability in practice.

(c) Small errors as compared with a more rigorous analysis based on C_e and ϕ_e and knowledge of pore pressure, U.

Factors Affecting Strength of Compacted Soils

1. Physical Factors:-

The physical component of the shear strength of soil is customarily attributed to frictional resistance and interlocking between particles. The interlocking is further divided (Rosenquist) into two parts:

(a) A large scale interlocking between particles which necessitates appreciable movements of particles normal to the shear plane accompnied by volumetric expansion in order that failure might occur.

(b) A small scale interlocking due to particle surface roughness, necessiating only small movements normal to the shear plane in order that failure might occur.

Although classed as a physical factor, even the resistance due to friction may be regarded to some extent as a physico-chemical effect. The magnitude of friction and interlocking effects in a soil are dependent on more fundamental factors, reflected by soil composition. The nature of minerals present and their surface characteristics will determine the magnitude of true friction. Since particle size, shape, size distribution and packing are functions of the composition, the volumetric expansion is dependent on composition. It is further affected by orientation of particles, which depend, in addition to the nature of particles present, on the history of the soil, the ambient condition and the void ratio.

2 - Physico-Chemical Factors:-

A second component of soil strength is primarily attributed to physico-chemical conditions in the soil and is referred to as 'Cohesion'. Cohesion in a soil is taken to mean that part of the soil strength that is present independently of any applied pressures, either mechanical or capillary, and would remain though not necessarily permanently, if all applied pressures were removed. Cohesion is a bonding of particles with in soil mass by physico-chemical mechanism of inter-atomic, intermolecular or interparticle nature.

The cohesion present in the soil may be attributed to interparticle attractive forces that resist relative displacements of clay particles having larger surface to mass ratio. Although the precise nature of cohesion and the mechanism by which it is developed have not yet been clarified, it seems to be generally agreed that it is a function of the net interparticle forces. These in turn are determined by the resultant effects of the variables in the soil-water-air-electro-lyte system as outlined below:

(a) Total Interparticle Attractive Forces:- Micheals and Rosenqvist (11) are of the opinion that Vander Walls' forces of attraction are of a magnitude more than adequate to account for cohesion in clays. Other possible interparticle attractive force mechanisms such as Coulombic attraction between negative surfaces and positive edges and particle-cation-particle linkages have been suggested.

(b) Interparticle Repulsive Forces:- Interparticle repulsive forces arise from the interaction of double layers surrounding adjacent particles. The double layer theory as presented by Verway and Overbeck and Bolt (11), shows that an increase in dielectric constant of the pore fluid or a decrease in electrolyte concentration, ion-valence or temperature should lead to increased repulsive forces. In addition Lambe points out that an increase in size of hydrated ion in double layer, pH, or anion adsorption, will also lead to decreased repulsive forces.

(c) Water:- The role of water in clay cohesion has been discussed by Michaels (11) It is argued that cohesion occurs in spite of rather than because of presence of water. Spontaneous adhesion of particles will occur if they are brought into sufficiently close proximity. Water is however strongly attracted to clay surfaces by any or all of the several mechanisms as outlined by Low and Lovell (11) It appears, therefore, that its role is that of a filler separating particles and resisting close approach. Thus a lesser adhesive bond is formed than would exist if water is removed from clay.

Since the shear plane in clay will pass through the water between particles, the characteristics of the water in the force fields between clay particles must also be considered. This water is known to posses properties different from those of normal water.

(d) <u>External Forces and Stress History</u>:- Externally applied effective compressive forces undoubtedly influence the development of cohesive bonds, since they help to determine the particle orientation and spacing, and thereby affect the interparticle attractive and repulsive forces. Since such compression is not a reversible phenomanon in normal clay soils, the particle spacing under a condition of decreasing external forces will depend on the previous stress application and thus on stress history of the soil

(e) <u>Chemical Factors</u>:- Cohesion is also attributed due to interparticle cementation. Most soils are known to contain measurable amounts of free iron, aluminum oxide and carbonates. These compunds may act as cementing agents at points of interparticle contact.

3 - <u>Influences of Moulding Water Content and Methods of Compaction</u>:-

In order, for the double layer around the clay particles to develop fully, it is necessary that there be sufficient water present in the soil and therefore interparticle repulsion is affected. The amount of water present during compaction will also affect the structural arrangement of the soil mass and the strength.

Similarly methods of compaction will affect the structural arrangement of particles in the soil mass depending upon the amount of shear strains induced during compaction.

Plasticity Characteristics of Soils.

Plasticity is one of the major characteristic of the cohesive soils. In 1911, Swedish Scientist, A. Atterberg published his results on the investigations of the plasticity of fine-grained soils. He found that plasticity is a two dimensional property which can be best defined by the upper and lower limits of plastic range, namely liquid and plastic limits respectively. The tests due to Atterberg, orginally developed for agricultural work, have won wide acceptance in the field of soil engineering. He suggested two simple tests to determine these limits. But, later on, it was found difficult to achieve reproducible values of these limits by Atterberg's methods of test.

In 1932, A. Casagrende modified the procedure for determining the liquid limit by developing a new device which gave the same values of liquid limit for the soil as obtained by Atterberg's methods. Since then liquid limit test has become a standard test. The plastic limit test is the same as suggested by Atterberg except that the threads are now rolled to 1/8" dia.

Definitions of limits:-

The liquid limit (W_1) of the soil is the moisture content at which the soil is practically liquid but posses a certain small amount of shear strength (25 gms/Sq.cm), this arbitrarily chosen strength being presumably the smallest value that is feasible to measure by a standard procedure. According to the standard liquid limit device developed by A. Casagrende, liquid limit is defined as the moisture content at which 25 blows will just close a groove of standard dimensions for half an inch length which is cut in by a standard grooving tool.

The plastic limit is the smallest value of the moisture content at which a soil is plastic. It is obtained by rolling out samples at slowly decreasing moisture content untill that moisture content is reached at which the soil thread 1/8" in dia. just begins to crumble.

The plasticity index (I_p) which gives the range of moisture content with in which the soil is plastic, is the difference between liquid and plastic limits.

Factors on which plasticity Characteristics of Soil depend.

The plasticity characteristics in general depend on the type of soil and the amount of clay and organic matter present in the soil. Grim (6), Norton (7), Johnson (8) and Scott Blair (9) indicated that plasticity of soils is affected by -

(1) Clay minerals.

(2) Non-mineral composition.

(3) Electrolyte content, amount and kind of exchangeble bases and soluble salts.

(4) Organic matter content.

(5) Miscellaneous textural characteristics such as shape of grains etc.

But for detailed study we shall consider separately the factors on which the liquid limit, the plastic limit and the plasticity index of the soil depend.

Liquid Limit:-

Liquid limit depends on the proportions of clay fractions in the soil directly.

The type of clay present also affects the liquid limit. Finer and flatter, the grains of clay, the greater will be the surface area and higher amount of water will be required to coat the grains. The liquid limit of such clays will therefore be high.

The presence of organic matter, in general, increases the liquid limit of the soil. The liquid limit of the organic soil is significantly reduced by over drying since most of organic matter is oxidised.

Plastic limit:-

Davidson and Sheeler (10) have pointed out that by increasing the clay content, the plastic limit of the soil decreases. The activeness of the clay also affects the plastic limit, the clay which is more active will have higher plastic limit.

When organic matter is present in the soil, the plastic limit is comparatively increased.

Plasticity Index:-

Plasticity index being the numerical difference of liquid limit and plastic limit, represents the range over which the soil mass is plastic. It is more or less independent of type of clay minerals present in the soil. The amount of clay mineral affects the plasticity index. Increasing amount of clay proportion in soil, increases plasticity index as pointed out by Davidson (10).

Organic matter does not have much effect on the value of plasticity index, as the liquid and plastic limits both increase nearly in the same proportion.

Earlier Attempts

Rosenqvist (14) has pointed out in his discussion in the 4th International Conference on Soil Mechanics and Foundation Engineering; that the liquid limit of the soil depends solely upon the following three factors.

(1) The amount and nature of the minerals.

(2) The degree of the electrochemical saturation and

(3) Polarizability of the adsorbed ions.

The shear strength of the soil depends upon factors (1), (2), (3) - the same factors as are influencing the liquid limit, but also upon the stress condition and stress history, the water content and the diagenitic cementation between the minerals. This shows that there exists a close correlation between the plasticity characteristics and the shear strength at some standard water content (O.M.C. in the present investigat on), of the soil, and this formed the basis of the present investigation.

Bjerrum and Simons (12) have also shown that there exists and approximate tendency of the angle of shearing resistance (with respect to effective stresses) to follow a straight line correlation with the plasticity index, on the results of few soils that they have tested.

Present Investigation and its Significance.

In the present investigation the undrained (Quick) tests have been performed on 50 soils compacted at O.M.C. with standard Proctor's energy - conforming to most of the cases usually met in the field. Their plasticity characteristics have also been determined. Attempts have been made to correlate the undrained strength parameters C and Ø with the plasticity characteristics of soils.

Corrolation of one property with another has two distinct advantages. First, it helps to understand the fundamental properties clearly and secondly if one property is known, the other may be predicted with the help of correlation, avoiding difficult and time consuming testing of soil, both in laboratory and in the field, and giving more information in the field economically and expediently.

The soils studied include clays, Silts and also a few sandy clays.

The problems of the field likely to utilise the results of this investigation are foundation of structures, embankments and earthen dams provided that consolidation during construction is negligible, and design of walls, and cuttings; where factor of safety is required for conditions during or immediately after construction. The stability analysis is carried out with respect to total stresses and with apparent shear strength parameters C and ϕ.

III. EXPERIMENTAL STUDY

General.

The apparent cohesion (C) and apparent angle of internal friction (Ø) for each soil have been determined by performing undrained (Quick) tests on a minimum of three samples of each soil at different cell pressures in the triaxial testing machine. The soil is compacted at O.M.C. in the mould with Proctor's standard energy (British Standard) (3) and then the samples are extruded from the mould. Glycerine has been used for applying different cell pressures. British Standard (3) methods have been used for determining O.M.C., liquid limit and plastic limit of each soil.

Efforts have been made to study various soils which could be classified in different groups of Casagrende's plasticity chart, to cover a wide range of plasticity characteristics.

Soil Studied.

Fifty soils have been tested. In Fig. No. 1, they are plotted on the plasticity chart (W_1 v/s I_p). These soils include soils of each group of Casagrende's plasticity chart as follows:-

(i) Inorganic clays of low plasticity...............6
(ii) Inorganic clays of medium plasticity............20
(iii) Inorganic clays of high plasticity...............6
(iv) Inorganic silts of low plasticity ....Nil
(v) Inorganic silts of medium plasticity or organic silts..9
(vi) Inorganic silts of high plasticity or organic clays....4
(vii) Sands with clay content..............................5

No soil belonging to group 'silts of low plasticity' was available.

All soils belong to the geological region known as Indogangetic Plane of India.

As number of soils obtained were limited, seven soils were prepared by mixing two or more types of soils to obtain intermediate plasticity characteristics.

Preparation of Soils

About 15 lbs. of each soil was taken. After breaking it into pieces, the soil was dried in an oven at a temperature of 105^{0} to 110 C^{0}, for 24 hours. The dried soil was further broken by wooden hammer and sieved with U.S. Sieve No. 4 for subsequent experiments.

Determination of plasticity Characteristics.

About 200 gms. of dried soil passing U.S. Sieve No. 40 (I.S.S. No. 40) is taken. The British Standard procedure described in H.M.S.O. (3) which is also adopted by I.S.S. is used for the determination of liquid limit and plastic limit for each soil. The flow curve for each soil has been drawn as shown in Fig. Nos. 22 to 26 of Appendix A. The apparatus used is shown in Photo No. 1.

Determination of O.M.C.

Standard Proctor's test as described by Lambe (2) is used with the following modifications:-

(1) To have uniformity and to avoid the error due to personal factors, automatic mechanical compactor was used as shown in Photo No. 2. In this apparatus uniformly distributed blows were applied by a rammer weighing 5.5 lbs. The fall of rammer was kept 12".

(2) The base plate was kept fixed on the apparatus and only mould was removed and then placed on the other base plate for trimming off the soil and then weighed with it. This was done to avoid adjustment of base plate after every observation.

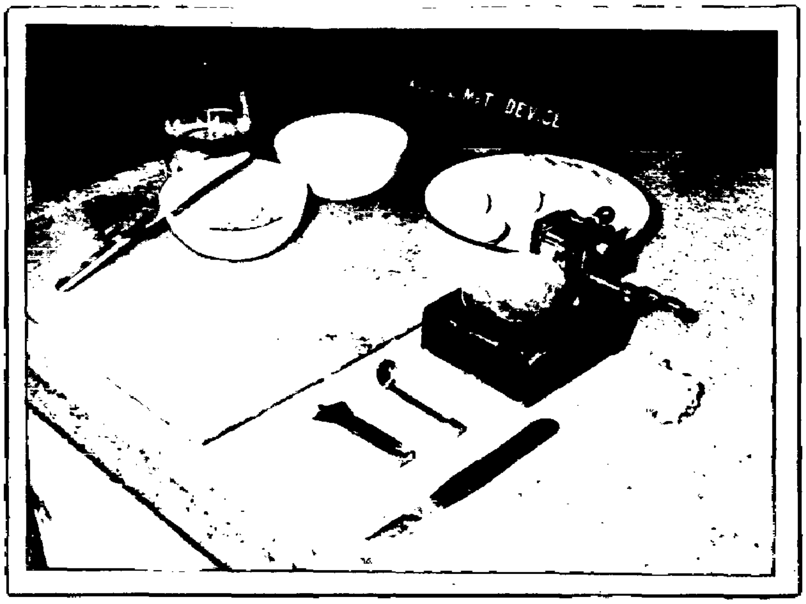


Photo No. 1 - Liquid limit device.

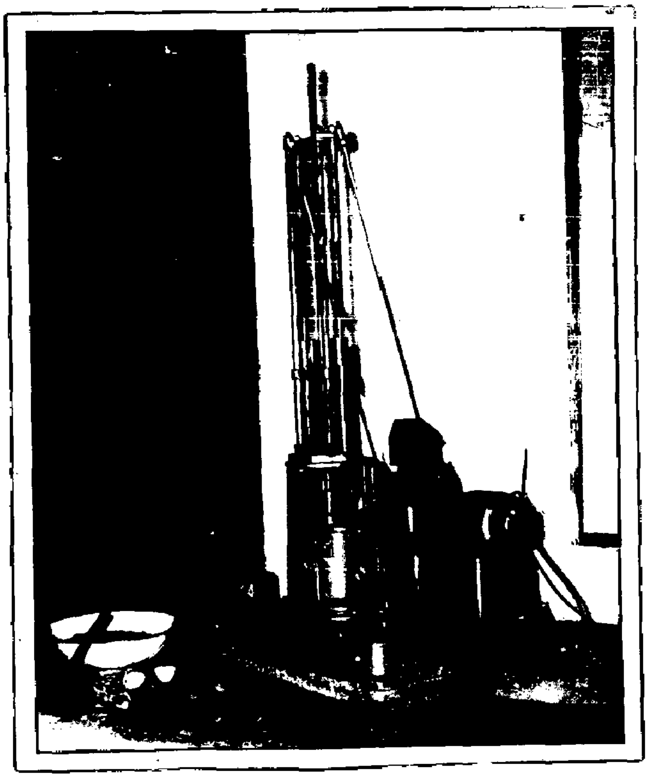


Photo No. 2 - Mechanical Compactor.

For every soil the moisture content v/s dry density curve was plotted as shown in Fig. Nos. [illegible] to [illegible] of Appendix A, and O.M.C. with maximum dry density was obtained.

Preparation of Samples for triaxial testing.

200 gms of dried soil was taken which had previously been cooled to room temperature in closed [illegible] [illegible] avoid the entry of the moisture from the atmosphere. Calculated amount of water to give O.M.C. plus 0.5% additional amount of water was added to counteract loss of moisture during mixing and compaction. In all the cases the moisture content of the failed triaxial samples was determined and it was found that this moisture content very well agreed with the calculated one, the error not exceeding ± 0.3% of moisture content. In some cases where the difference was found greater than 0.5%, the testing was repeated. After compaction of the soil the top of the mould was trimmed off and samples were taken out by means of the sampler shown in Photo No. 4. Three samples of 1½" diameter were extruded and each cut to 3" length and kept inside the moist membrano by means of membrane stretcher (Photo No. 4) and kept for testing in triaxial machine.

Testing in triaxial machine.

Photo No. 3 shows the general arrangement of the apparatus. For each soil, a minimum of three samples 1½" dia. and 3" in length have been tested and each sample under different cell pressure, varying from 0 to 60 psi. Glycerine is used for applying confining pressure to avoid leakage. Vaccum pump was used to evacuate the glycerine from the cell quickly. Two [illegible], one at each end of the sample, were

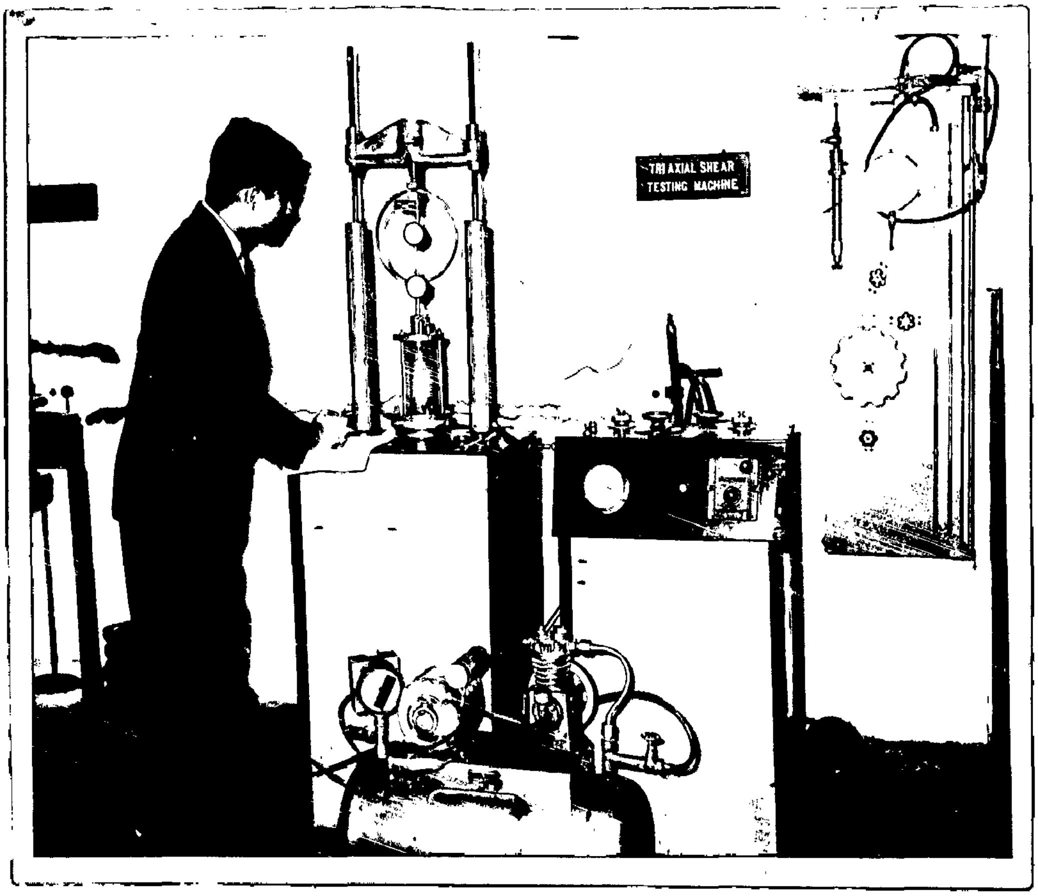


Photo No. 3 - Triaxial Testing Machine with Bishop's pore pressure measuring device.

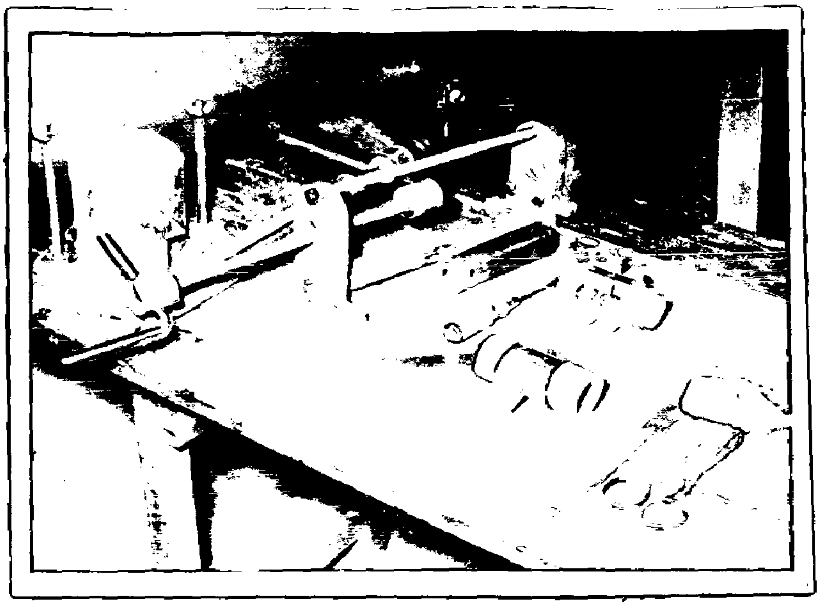


Photo No. 4 - Sample Extruder, Membrane Stretcher etc

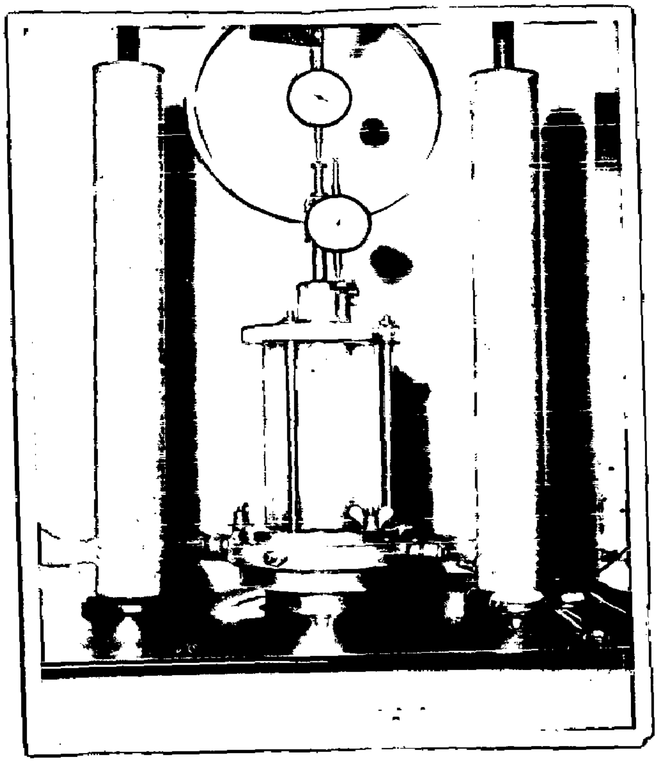


Photo No. 5 - Close up view of the Soil Sample
in triaxial machine.

placed to avoid any drainage or change in moisture content. The rate of strain was kept 0.1"/min, through out. Due to some defects in the strain controlling unit, some times the fluctuations in the rate of strain was found as much as 20%. But as pointed out by Henkel (1) that so far as laboratory practice is concerned the variation in the rate of strain or loading in an undrained tests are of little consequences. A considerable number of experiments by Biship and Skempton (31) indicate that differences in strength obtained in test carried out 8 times faster or 8 times slower than standard rate, do not amount to more than about 5" or in extreme case 10 percent. The Mohr's envelop is drawn for each soil approximately touching the three circles as shown in Fig. No. 39 to 56 of Appendix A. Skempton and Biship(31) have pointed out that in most soils under partially saturated condition (as the present case is), the Mohr envelop is slightly curved, but it may be taken as linear over the range pressure under investigation. Therefore in all cases best fitting straight lines have been drawn and for each soil apparent cohesion and apparent angle of internal [illegible].

[illegible] have also been measured by means of Biship's pore pressure measuring device as shown with the triaxial machine in Photo No. [illegible]. For these soils Mohr envelop for effective stresses have been drawn and true values of cohesion and angle of internal frictions have been obtained.

Photo No. 5 shows a close up view of the triaxial cell with glycerine and failed sample inside it. Photos No. 6 and 7 show few typical failures of soil samples.

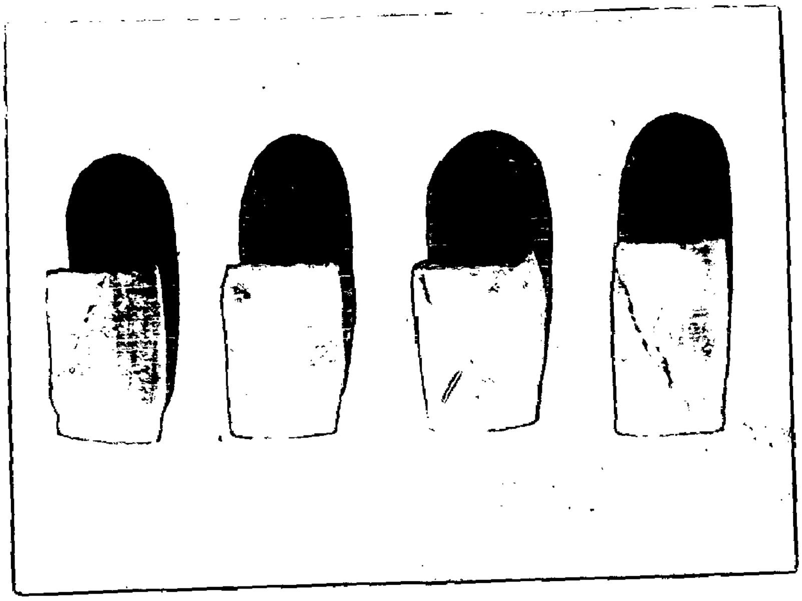


Photo. No. 6 - Typical modes of failure of Samples I

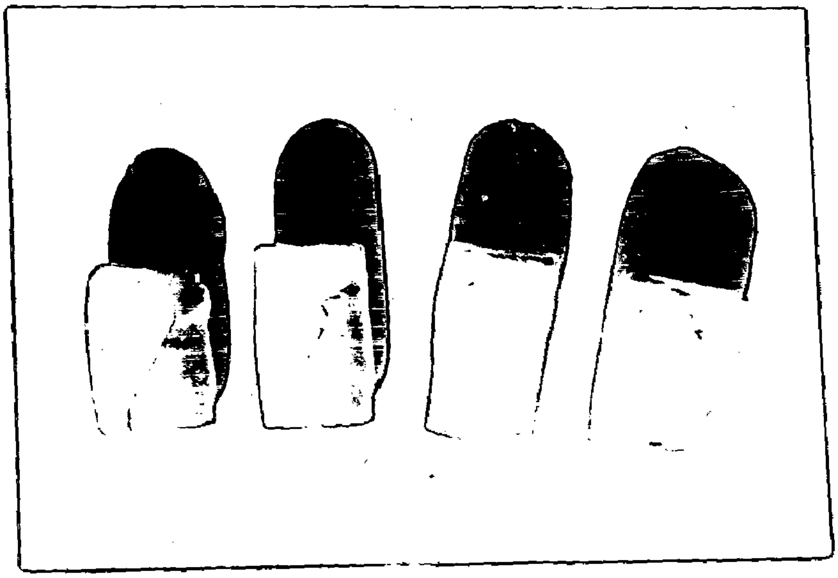


Photo No. 7 - Typical modes of failure of Samples II

T A B L E N O. 1

E X P E R I M E N T A L R E S U L T S

Soil Number.	Liquid-Limit %	Plastic-Limit %	Plasticity-Index. %	Dry-Density lbs/Cft.	Optimum-Moisture Content %	Cohesion Psi.	Angle of Internal Friction in Degrees
1	2	3	4	5	6	7	8
1	59.0	28.0	31.0	106.4	17.5	24.0	14.5
2	50.0	26.3	23.7	105.4	18.5	16.0	21.5
3	62.0	29.4	32.6	99.8	22.0	28.0	8.0
4	41.5	25.3	16.2	107.3	18.0	20.0	24.0
5	43.0	25.8	17.2	105.3	18.25	15.0	25.0
6	61.0	33.3	27.7	99.5	21. 5	21.0	18.0
7	52.2	30.7	21.5	105.8	19.0	24.0	14.0
8	60.3	33.4	26.9	98.8	20.0	27.0	14.0
9	36.7	22.9	13.8	106.4	17.25	17.0	27.0
10	16.8	15.4	1.4	119.4	10.0	8.0	37.0
11	44.5	26.4	18.1	104.5	19.5	16.0	31.0
12	57.8	30.0	27.8	101.9	21.75	22.0	15.0
13	20.0	18.2	1.8	110.9	11. 3	12.0	28.0
14	45.8	25.0	20.8	108.5	17. 0	18.0	21.5
15	34.1	25.1	9.0	106.0	13. 5	17.5	30.0
16	18.8	15.6	3 .2	118.8	11.5	8.0	35.0
17	32.8	23.4	9.4	109.3	15.5	13.0	33.0
18	21.5	17.1	4.4	118.3	12.0	12.5	30.0
19	44.3	25.8	18.5	106.4	19.7	17.0	16.0
20	48.2	26.4	21.8	102.15	21.0	22.0	20.0
21	40.8	28.2	12.6	100. 3	20.75	14.0	28.0
22	18.5	15.7	2 .8	118.0	11.25	7.0	33.0
23	52.0	30.2	21.8	103.3	21. 5	17.5	16.0
24	45.0	28.7	16.3	99.2	23.25	18.5	15.0
25	48.9	26.8	22.1	104.6	20.25	21.0	20.0
26	41.8	25.9	15.9	103.7	18.75	15.0	25.0
27	53.1	27.5	25.6	101.15	22.25	20.5	13.0
28	44.6	27.1	17.5	102.8	21. 0	16.5	14.0
29	37.7	27.2	10.5	106.75	16.75	14.0	28.0
30	30.6	20.4	10.2	112. 8	13.75	16.0	32.0
31	56.0	28.9	27.1	100.0	23. 5	21.0	15.0
32	41.0	25.6	15.4	107.2	17.75	14.0	32.0
33	41.3	25.8	15.5	107.0	17. 0	17.0	27.0
34	51.1	29.4	21.7	102.9	21. 0	19.0	24.0
35	15.4	12.9	2.5	113.4	13. 0	7.0	35.5

Contd.

Table No. 1 (Contd.)

1	2	3	4	5	6	7	
36	39.4	27.1	12.3	104.6	18.0	13.0	30.0
37	37.1	31.2	5.9	97.0	25.25	16.0	25.0
	29.6	22.7	6.9	103.2	19.8	13.0	20.0
39	28.1	19.1	9.0	113.1	15.6	12.0	30.0
40	19.4	15.1	4.3	113.4	13.6	13.5	30.5
41	34.1	24.9	9.2	108.7	18.2	18.0	31.0
42	33.6	22.2	11.4	111.4	15.5	17.0	34.0
43	37.3	29.4	7.9	101.5	23.0	17.0	28.5
44	24.1	17.3	6.8	115.25	13.8	16.0	[illegible]
45	32.2	22.2	10.0	106.1	17.7	13.6	[illegible]
46	39.9	25.0	14.9	108.35	16.8	15.0	26.0
47	39.2	23.1	16.1	108.1	17.0	14.5	26.5
48	40.2	30.0	10.2	105.2	17.5	16.5	[illegible]
49	38.3	21.8	16.5	111.1	15.25	17.5	29.0
50	26.1	17.7	8.4	120.15	11.5	16.5	32.0

TABLE NO. 2

Results of 5 Soils tested with pore pressure measurements.

Sl. No.	Soil No.	True Cohesion C_t in psi.	True angle of internal friction ϕ_t in degrees.
1.	34	21.0	23.0
2.	37	17.5	25.0
3.	38	14.0	17.0
4.	39	13.0	24.5
5.	40	15.5	30.0

— —

IV. TRAILS OF CORRELATION

General.

The fifty soils investigated have been found to posses the ranges for apparent Cohesion (c) and angle of internal friction (Ø) at O.M.C., liquid limit, Plastic limit, Plasticity Index, O.M.C. and dry density at Proctoer's Standard Compaction energy, as indicated in the table below:-

TABLE NO. 3

The minimum and maximum values of observed soil properties.

Sl. No.	Property	Minimum Value	Maximum Value
1	C in psi.	7.0	28.0
2	Ø in degrees	8.0	37.0
3	W_l (%)	15.4	62.0
4	W_p (%)	12.9	33.3
5	I_p (%)	1.4	32.6
6	Dry density in lbs./cft.	97. 0	120.15
7	O.M.C. (%)	10. 0	25.25

Refering to Fig. No. 1, it can be seen that the soils cover a fairly wide range of plasticity characteristics. The correlations of C and Ø with different plasticity characteristics obtained on the basis of these soils, may be expected to be more or less applicable to all soils in the above ranges.

The following correlations have been tried.

1. C with W_l
2. C with I_p
3. C with W_l and W_p

4. ϕ with W_1

5. ϕ with I_p

6. ϕ with W_1 and W_p

7. ϕ with W_1 in parts

8. $\text{Log}_{10}\ \phi$ with W_1

TABLE NO. 4

Required data for Statistical analysis.

Sl. No.	Quantity	Value	Sl. No.	Quantity	Value
1	Σc	825.1000	15	$\bar{I}_p$	14.6820
2	Σc^2	14605.7100	16	$\Sigma c \times W_1$	34784.1700
3	$\bar{c}$	16.5020	17	$\Sigma c \times I_p$	13623.9500
4	$\Sigma \phi$	1246.0000	18	$\Sigma c \times W_p$	21160.2200
5	$\Sigma \phi^2$	33626.0000	19	$\Sigma \phi \times W_1$	45354.3500
6	$\bar{\phi}$	24.9200	20	$\Sigma \phi \times I_p$	15926.6500
7	ΣW_1	1966.7000	21	$\Sigma \phi \times W_p$	29427.7000
8	ΣW_1^2	84842.3300	22	$\Sigma W_p \times W_1$	51218.8800
9	$\bar{W}_1$	39.3340	23	σ_c	4.4496
10	ΣW_p	1232.6000	24	σ_ϕ	7.1773
11	ΣW_p^2	31636.0200	25	σ_1	12.2345
12	$\bar{W}_p$	24.6520	26	σ_p	4.9998
13	ΣI_p	734.1000	27	σ_i	8.0772
14	ΣI_p^2	14040.1900	28	N	50

N.B. - Above data were obtained from Table No. 10 to 19 of Appendix B and Appendix C.

Correlation of C with W_1

The plot between cohesion and liquid limit is shown in Fig. No. 2. The following trial is made to correlate C with W_1 by straight line law, the equation expressing the relationship is assumed of the form -

$$C' = a + bW_1$$

The object is to get the best slope and best intercept, which is obtained by generally accepted criterian of 'least squires'. The required data are given in Table No. 4.

The additive (a) and the multiplying (b) constants of the straight line relation are obtained by solving the following two normal equations, based on the method of least squares.

$$\Sigma C = a.N + b\Sigma W_1$$

and $$\Sigma C \times W_1 = a\Sigma W_1 + b\,\Sigma W_1^2$$

By solving the above two equations for 'a' and 'b' , we get :

$$a = \frac{(\Sigma W_1)\ (\Sigma C.W_1) - (\Sigma W_1^2)\ (\Sigma C)}{(\Sigma W_1)^2 - N\ (\Sigma W_1^2)}$$

$$\text{or, } a = \frac{\frac{(\Sigma W_1)\ (\Sigma C x W_1)}{N} - \frac{(\Sigma C)\ (\Sigma W_1^2)}{N}}{\frac{(\Sigma W_1)\ (\Sigma W_1)}{N} - \Sigma W_1^2}$$

$$\text{or} \quad a = \frac{(\overline{W}_1)\ (\Sigma C.W_1) - (\overline{C})\ (\Sigma W_1^2)}{(\overline{W}_1)\ (\Sigma W_1) - \Sigma W_1^2}$$

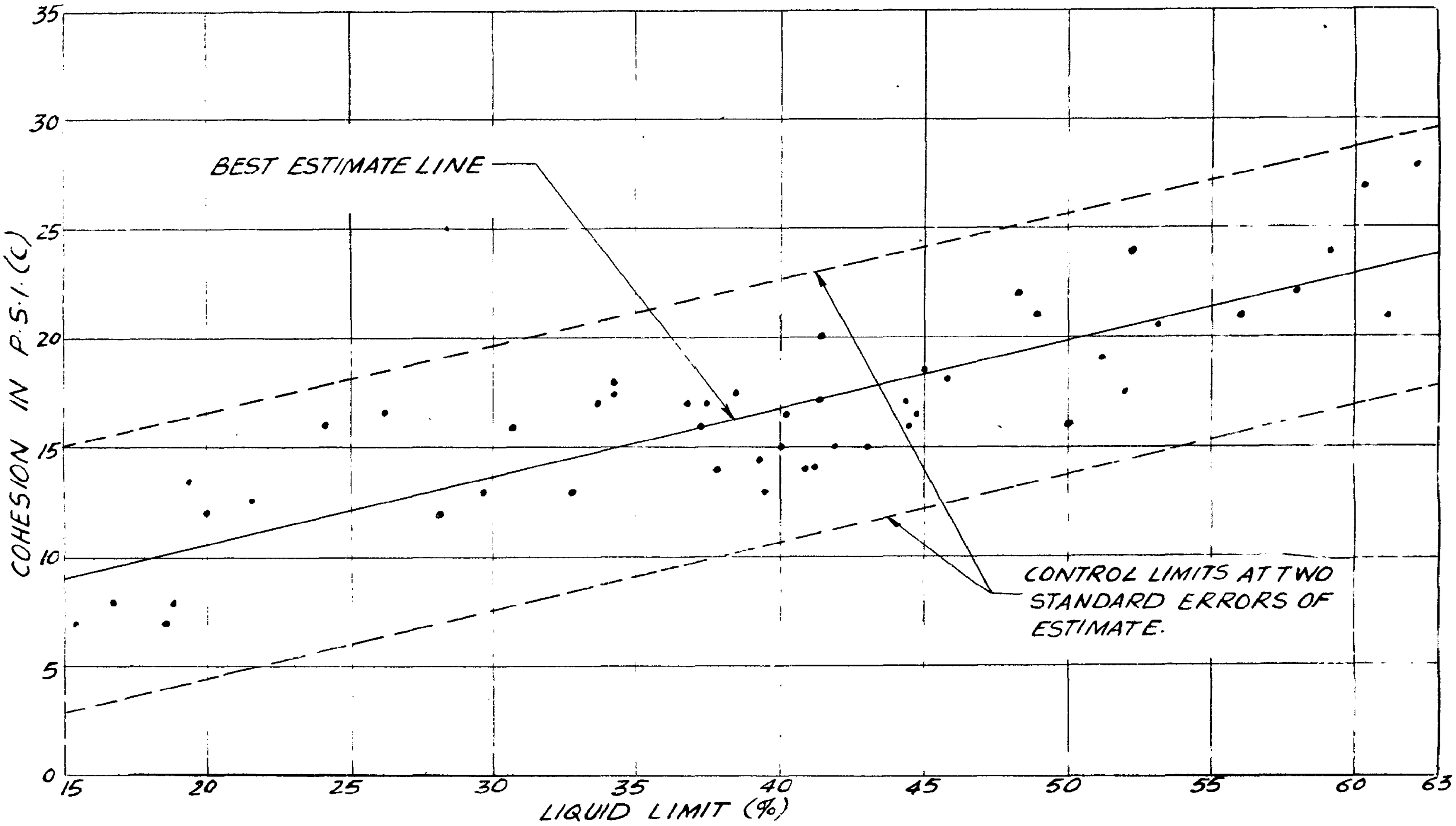


FIG. NO. 2 COHESION AT O.M.C V/S LIQUID LIMIT

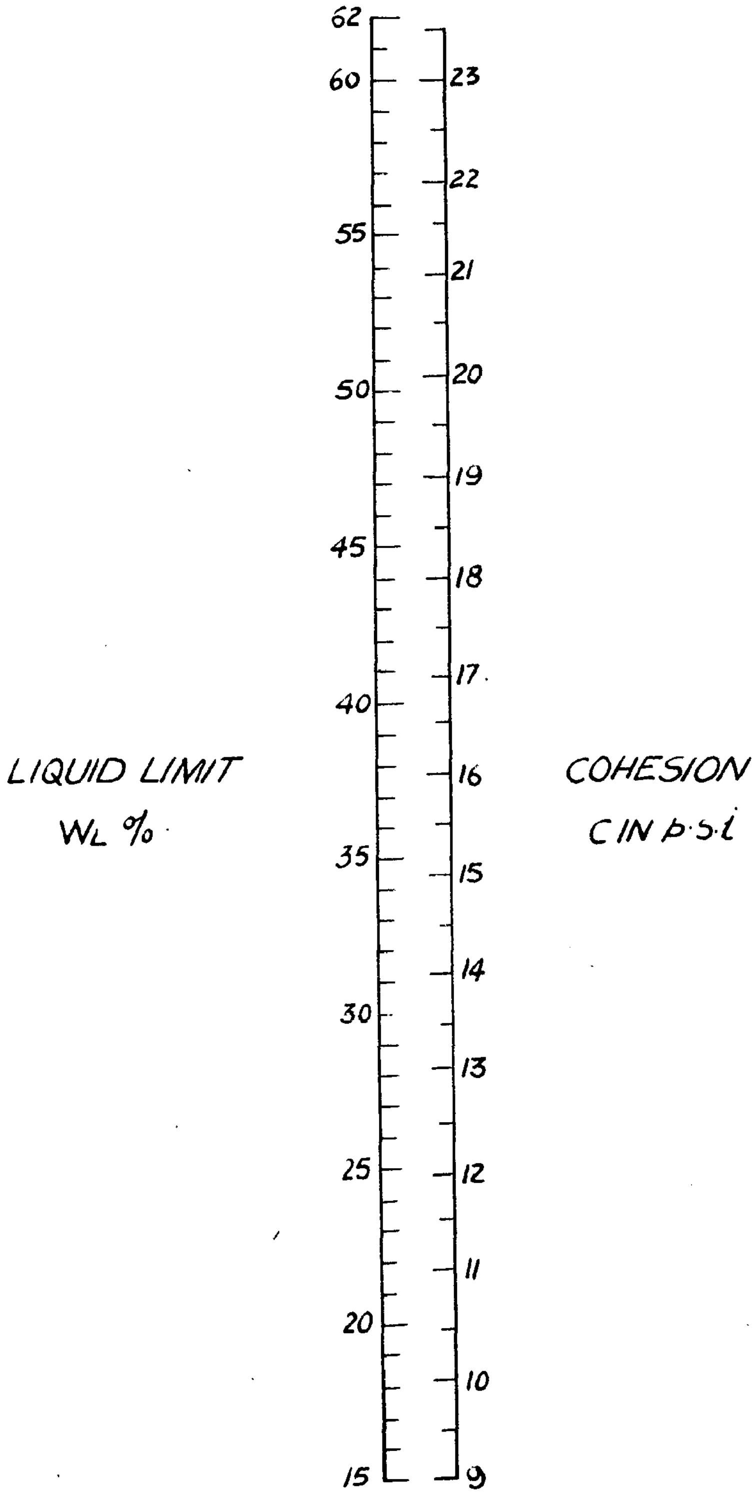


FIG. NO. 3 NOMOGRAM FOR CALCULATING COHESION FROM LIQUID LIMIT OF THE SOIL and $$b = \frac{\Sigma C . W_1 - \frac{(\Sigma C)(\Sigma W_1)}{N}}{\Sigma W_1^2 - \frac{(\Sigma W_1)(\Sigma W_1)}{N}}$$

$$= \frac{\Sigma C . W_1 - (\bar{C})(\Sigma W_1)}{\Sigma W_1^2 - (\bar{W}_1)(\Sigma W_1)}$$

On substitution of numerical values from table No. 4, we got :

$$a = \frac{(39.334)(34784.17) - (16.502)(84842.33)}{(39.334)(1966.70) - (84842.33)}$$

$$= 4.258$$

and, $$b = \frac{(34784.17) - (16.502)(1966.70)}{(84842.33) - (39.334)(1966.70)}$$

$$= 0.3113$$

Therefore the equation of correlation is

$$C' = 4.258 + 0.31113\ W_1$$

For various observations the values of C are obtained from the above relation and are shown in Table No. 8.

The nomogram of correlation is shown in Fig. No. 3. The method of drawing nomogram is explained in Appendix D_1.

Product Moment Correlation Coefficient:-

The degree of correlation measured by so called product moment correlation coefficient, which is expressed as :

$$r = \frac{\frac{1}{N} \Sigma (C-\bar{C})(W_1 - \bar{W}_1)}{(\sigma_c)(\sigma_1)}$$

The numerical value of r cannot exceed +1 or be less than -1. The value of r equal to ±1 represents that there exists a perfect functional relationship between two variables. When value of r is zero it signifies that there is no relationship at all between the two variables. Other intermediate value of r indicates that there is no strict functional relationship between two variables, but there is a trend.

The product moment correlation can be written as :

$$r = \frac{\frac{1}{N} \sum C.W_1 - \bar{C}.\bar{W}_1}{(\sigma_c)\ (\sigma_1)}$$

On substitution of the various values from table No. 4, we get :

$$r = \frac{\frac{34784.17}{50} - (16.502)\ (39.334)}{4.4406 \times 12.2345}$$

$$= 0.8558$$

Now for the test of the significance of the product moment correlation coefficient r, the minimum significant value of r is 0.361 for 48 degrees of freedom. The above value of r obtained is highly significant and this reveals that there exists a very good correlation between cohesion (c) and the liquid limit of the soil. The positive sign of r indicates that cohesion increases as liquid limit increases.

Standard Error of Estimate:-

The regression line gives only the 'best estimate' of the value of quantity in question. The degree of uncertainity in this estimate is calculated by so called standard error of estimate and is expressed as :-

$$S_c = \sigma_c \sqrt{1 - r^2}$$
$$= 4.4496 \sqrt{1 - (0.8558)^2}$$
$$= 2.303 \text{ psi.}$$

Thoritically for normal distribution of quantities at least in 95% of the cases, the actual value will be within plus or minus two standard errors of the estimated value given by the regression equation. Almost without exception, the actual value will be found to depart from the estimated value by not more than three standard errors. In Fig. No. 2, the lines plotted parallel to regression line at distances equal to twice the standard error on either side, indicate that all 50 points out of 50 tie within the limits. Thus we are definitely correct in making the claim that actual values of C will lie within $\pm$ 2x2.303 = $\pm$ 4.606 psi. in atleast 95% cases, from the estimated values given by the regression equation of C, in the specified range.

Suppose for example we want to estimate the value of C for a soil with liquid limit W_1 = 40%

Then we have :

$$C' = 4.258 + 0.3113 \times 40$$
$$= 16.71 \text{ psi.}$$

Since the standard error of estimate is 2.303 psi., we should expect that for all soils with the liquid limit of 40% , at least 95% would show that cohesion C will be between 12.104 psi. and 21.316 psi. we should almost be certain that value of C will NOT be less than 9.801 psi. and NOT more than 23.619 psi. for all soils tested under these conditions.

The correlation equation thus obtained can only be applied within the limits of observed values. We cannot claim for the equation to hold good outside the limits of experimental values. Hence it can be cancluded that from the equation obtained the value of cohesion can be obtained for soils having liquid limit between 15.4% and 62%.

Correlation of C with I_p

The plot between cohesion and plasticity Index shows a tendency towards a straight line relation as shown in Fig. No. 4. And so trial is made to correlate cohesion with plasticity Index by equation of the form :-

$$C' = a + b\, I_p$$

In this case

$$a = \frac{(\bar{I}_p)\ (\Sigma C.I_p) - (\bar{C})\ (\Sigma I_p^2)}{(\bar{I}_p)\ (\Sigma I_p) - \Sigma I_p^2}$$

and

$$b = \frac{\Sigma C.I_p - (\bar{C})\ (\Sigma I_p)}{\Sigma I_p^2 - (\bar{I}_p)\ (\Sigma I_p)}$$

By substituting the numerical values in the above equations from Table No. 4, we get :

$a = 9.7066$

$b = 0.4628$

Therefore the equation of correlation is

$$C' = 9.7066 + 0.4628\ I_p$$

For various observations C' is obtained and shown in Table No. 8.

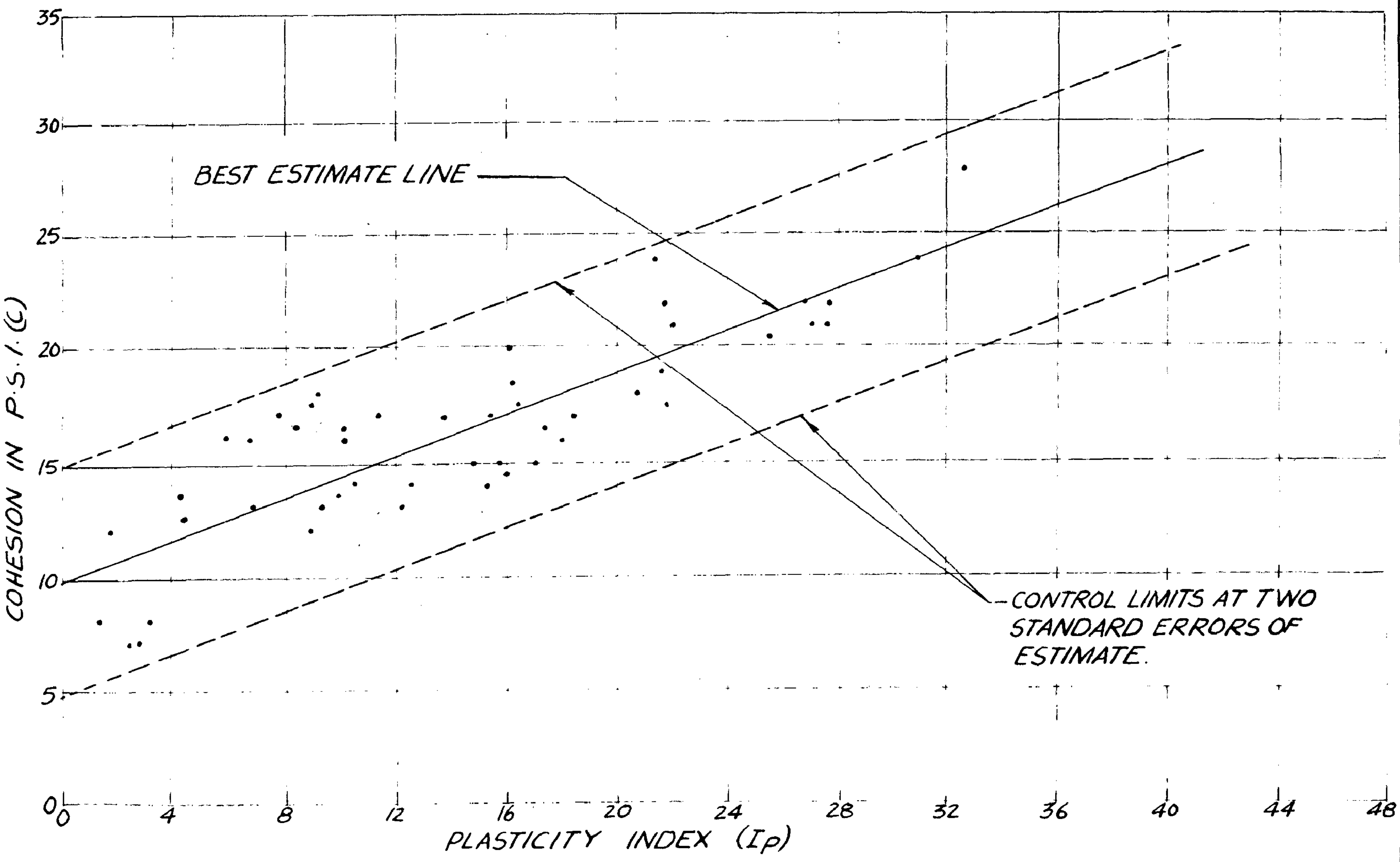


FIG. NO. 4 COHESION AT O.M.C. V/s PLASTICITY INDEX

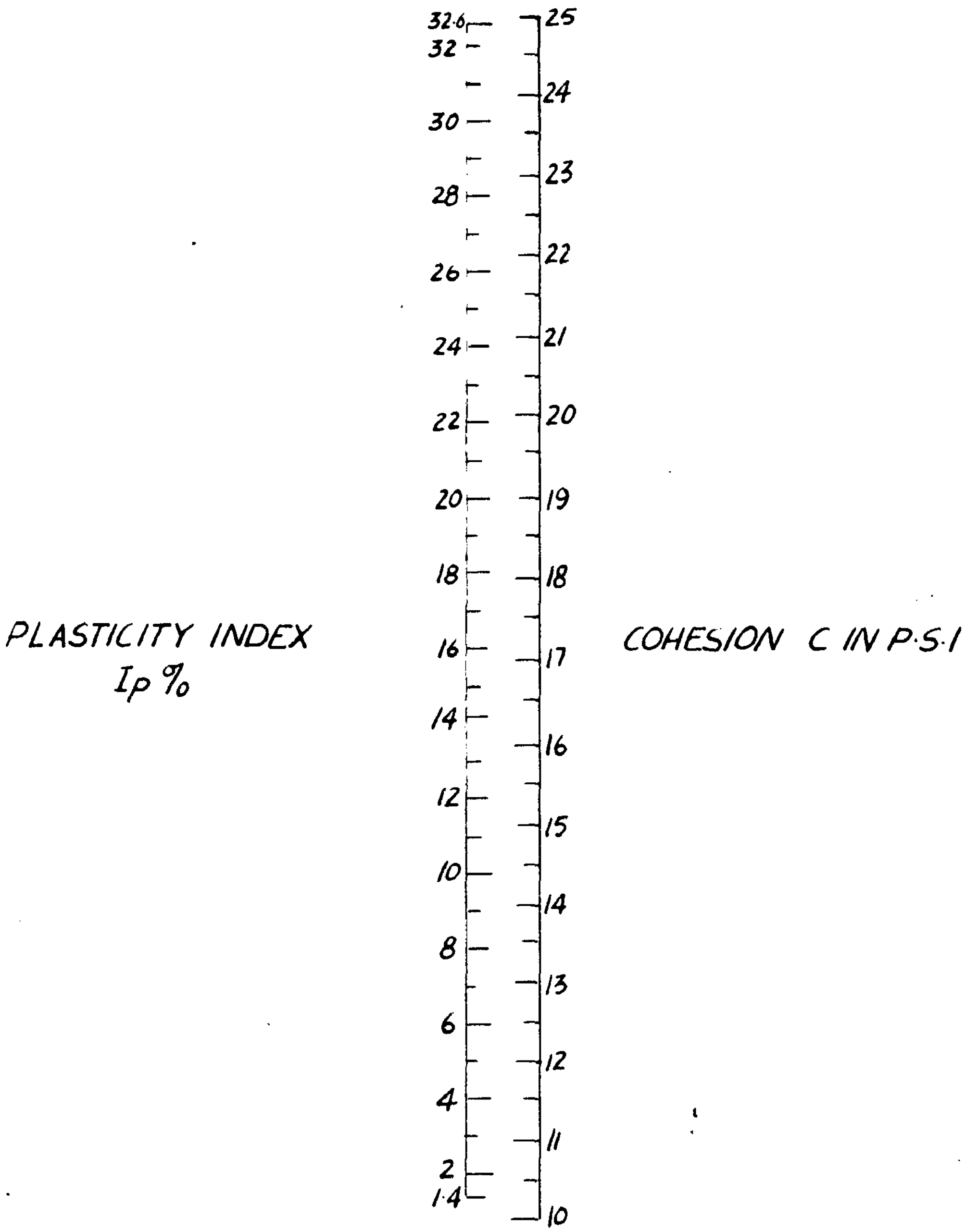


FIG. NO. 5 NOMOGRAM FOR CALCULATING COHESION FROM PLASTICITY INDEX OF THE SOIL

The nomogram of correlation is given in Fig. No. 5. It can be used to calculate cohesion from plasticity index of soil directly.

The product moment correlation coefficient is obtained from the relation

$$r = \frac{\frac{1}{N}\sum C.I_p - \bar{C}\,\bar{I}_p}{(\sigma_C)\ (\sigma_I)}$$

Substituting the various values and solving, we get:

$$r = 0.8401$$

Which reveals that relation obtained is fairly good positive correlation.

The standard error of estimate in this case

$$S_c = \sigma_c \sqrt{1 - r^2}$$
$$= 4.4496 \sqrt{1 - (0.8401)^2}$$
$$= 2.41 \text{ psi.}$$

From Fig. No. 4, it can be seen that 100% values lie within plus or minus 2 x 2.41 = 4.82 psi. from the estimated values of cohesion. Therefore we can be sure in 95% the maximum variation will not exceed 4.82 psi.

Correlation of C with W_1 and W_p

Figures No. 2 and 4 indicate that there exists a fair degree of straight line relation between cohesion and liquid limit and plasticity index which is the difference between liquid and plastic limits, separately. Therefore it is considered worthwhile to develop the correlation of C with W_1 and W_p.

Assuming that C is best related with W_1 and W_p by a partial regression equation of the type.

$$(C' - C) = c(W_1 - \bar{W}_1) + d(W_p - \bar{W}_p)$$

Where c and d are partial regression coefficients. The constant 'c' denotes, by how much C depends on W_1 with W_p remaining constant. Likewise, if W_1 remains constant, the amount by which C is dependent on W_p is represented by the coefficient d. The two unknowns c and d are found by framing and solving the two simultaneous equations as shown in the following steps.

(1) Rewriting the partial regression equation in the form :

$$\Sigma(C - \bar{C}) = c.\Sigma(W_1 - \bar{W}_1) + d.\Sigma(W_p - \bar{W}_p)$$

or $$\Sigma C - \Sigma\bar{C} = c\,\Sigma W_1 - c\,\Sigma\bar{W}_1 + d\,\Sigma W_p - d\,\Sigma\bar{W}_p$$

or $$C - \Sigma\frac{\Sigma C}{N} = c\,\Sigma W_1 - c.\Sigma\frac{\Sigma W_1}{N} + d\,\Sigma W_p - d\Sigma\frac{\Sigma W_p}{N} \quad \text{.......(i)}$$

(2) Multiplying the equation (i) by W_1 throughout, we get the following equation :-

$$\Sigma C.W_1 - \Sigma\left(\frac{\Sigma C}{N}\right)(W_1) = c\left[\Sigma W_1^2 - \Sigma\left(\frac{\Sigma W_1}{N}\right)(W_1)\right] + d\left[\Sigma W_p.W_1 - \Sigma\left(\frac{\Sigma W_p}{N}\right)(W_1)\right]$$

or $$\Sigma C.W_1 - \frac{\Sigma C.\Sigma W_1}{N} = c\left[\Sigma W_1^2 - \frac{(\Sigma W_1)^2}{N}\right] + d\left[\Sigma W_p.W_1 - \frac{\Sigma W_p.\Sigma W_1}{N}\right]$$

Inserting the sign Σ' (corrected sum of quantities) which is explained and calculated in Appendix E. , we get :

$$\Sigma' C.W_1 = c\,(\Sigma' W_1^2) + d\,(\Sigma' W_1.W_p) \text{..........(ii)}$$

(3) Next by multiplying the equation No. (i) by W_p throughout and inserting Σ', we get :-

$$\Sigma' C.W_p = c\ (\Sigma' W_l . W_p) + d\ (\Sigma' W_p^2) \ldots\ldots\ldots\ldots\ldots\ldots (iii)$$

(4) Inserting the numerical values from Table No. 5, we get :-

$$2329.69 = 7484.15c + 2735.80\ d$$

and

$$819.86 = 2735.80\ c + 1738.07\ d$$

by solving the above equations

$$c = 0.3270$$

$$d = -0.0430$$

(5) Substituting the values of c and d in the regression equation, we get :-

$$(C' - \bar{C}) = 0.327\ (W_l - \bar{W}_l) - 0.0430\ (W_p - \bar{W}_p)$$

Substituting the values of $\bar{C}$, $\bar{W}_l$ and $\bar{W}_p$ from Table No. 4, we get the required regression equation :-

$$C' = 4.7 + 0.3270\ W_l - 0.0430\ W_p$$

This is final equation which may be used in predicting the cohesion C from the data of liquid limit and plastic limit for the soil. The values of C obtained from the equation and their comparison with the actual observed values is shown in Table No. 8.

The nomogram of correlation is shown in Fig. No. 6. The method of drawing and using nomogram is explained in Appendix D_2.

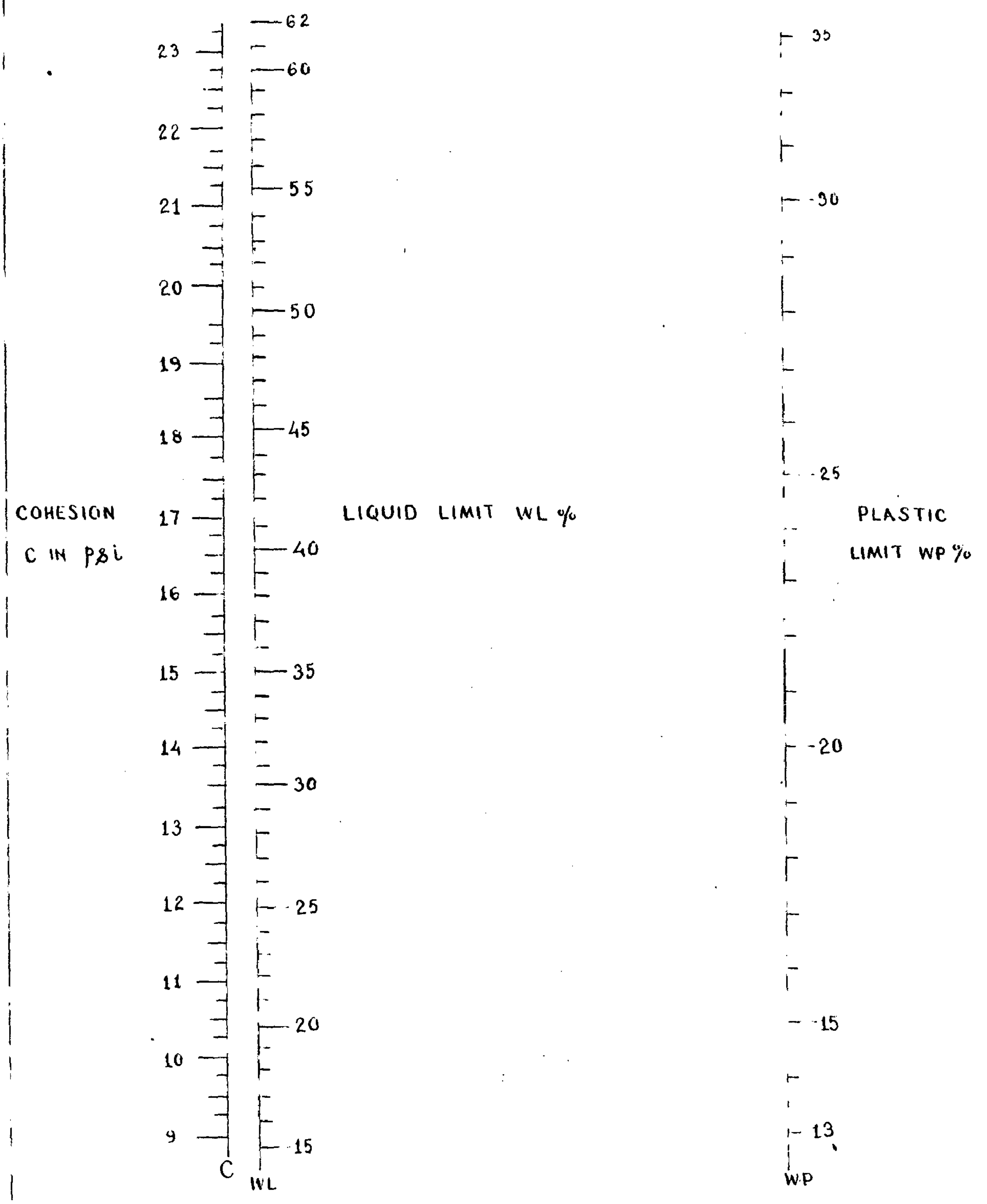


FIG NO. 6 NOMOGRAM FOR CALCULATING COHESION FROM LIQUID AND PLASTIC LIMITS OF SOIL

T A B L E N O. 5

Correlated Sums.

Sl. No.	Quantity	Value	Sl. No.	Quantity	Value.
1	$\Sigma' C^2$	989.91	6	$\Sigma' C.W_1$	2329.69
2	$\Sigma' \phi^2$	2575.68	7	$\Sigma' C.W_p$	819.86
3	$\Sigma' W_1^2$	7484.15	8	$\Sigma' \phi.W_1$	-3415 .81
4	$\Sigma' W_p^2$	1738.07	9	$\Sigma' \phi.W_p$	-1288.69
5	$\Sigma' W_1.W_p$	2735.80			

Multiple Correlation Coefficient

Since the values predicted from the partial regression equation, while approximating actual values differ some what from them, we shall find a correlation coefficient between actual and predicted values. Such a correlation coefficient called a multiple correlation coefficients.

The multiple correlation coefficient R is given by

$$R = \frac{\frac{\Sigma C.C'}{N} - (\bar{C})(\bar{C}')}{\sqrt{\left\{ \left(\frac{\Sigma' C^2}{N} \right) \left(\frac{\Sigma' C'^2}{N} \right) \right\}}}$$

Substituting the various numerical values, we get :-

$R = 0.8616$

The standard error of estimate

$$S_c = \sigma_c \sqrt{1 = - R^2}$$

$$= 4.4496 \times 0.5075 = 2.258 \text{ psi.}$$

Whenever we make a prediction, therefore we shall be correct 95 times out of 100 if we say that the actual value of cohesion will be within 2 x 2.258 = 4.516 psi. either sides of the value arrived by using the partial regression equation.

Correlation of ϕ with W_1

The plot between the angle of internal friction ϕ at O.M.C. and liquid limit shows a tendency towards a straight line as shown in Fig. No. 7. So trial is made to correlate them by a straight line of the type -

$$\phi' = a + b.W_1$$

In this case

$$a = \frac{(\bar{W}_1)(\Sigma \phi.W_1) - (\bar{\phi})(\Sigma W_1^2)}{(\bar{W}_1)(\Sigma W_1) - \Sigma W_1^2}$$

and

$$b = \frac{\Sigma \phi.W_1 - (\bar{\phi})(\Sigma W_1)}{\Sigma W_1^2 - (\bar{W}_1)(\Sigma W_1)}$$

By substituting the various values in the above equation from Table No. 4, we get :-

$$a = 44.1336$$

and

$$b = -0.4884$$

Therefore the equation of correlation is

$$\phi' = 44.1336 - 0.4884\, W_1$$

For various observations ϕ' is obtained and is shown in Table No. 9.

The nomogram of correlation is given in Fig. No. 8. It can be used to calculate ϕ from liquid limit of the soil directly.

The product moment correlation coefficient is given by the relation.

$$r = \frac{\frac{1}{N}\Sigma \phi.W_1 - \bar{\phi}.W_1}{\sigma_\phi . \sigma_1}$$

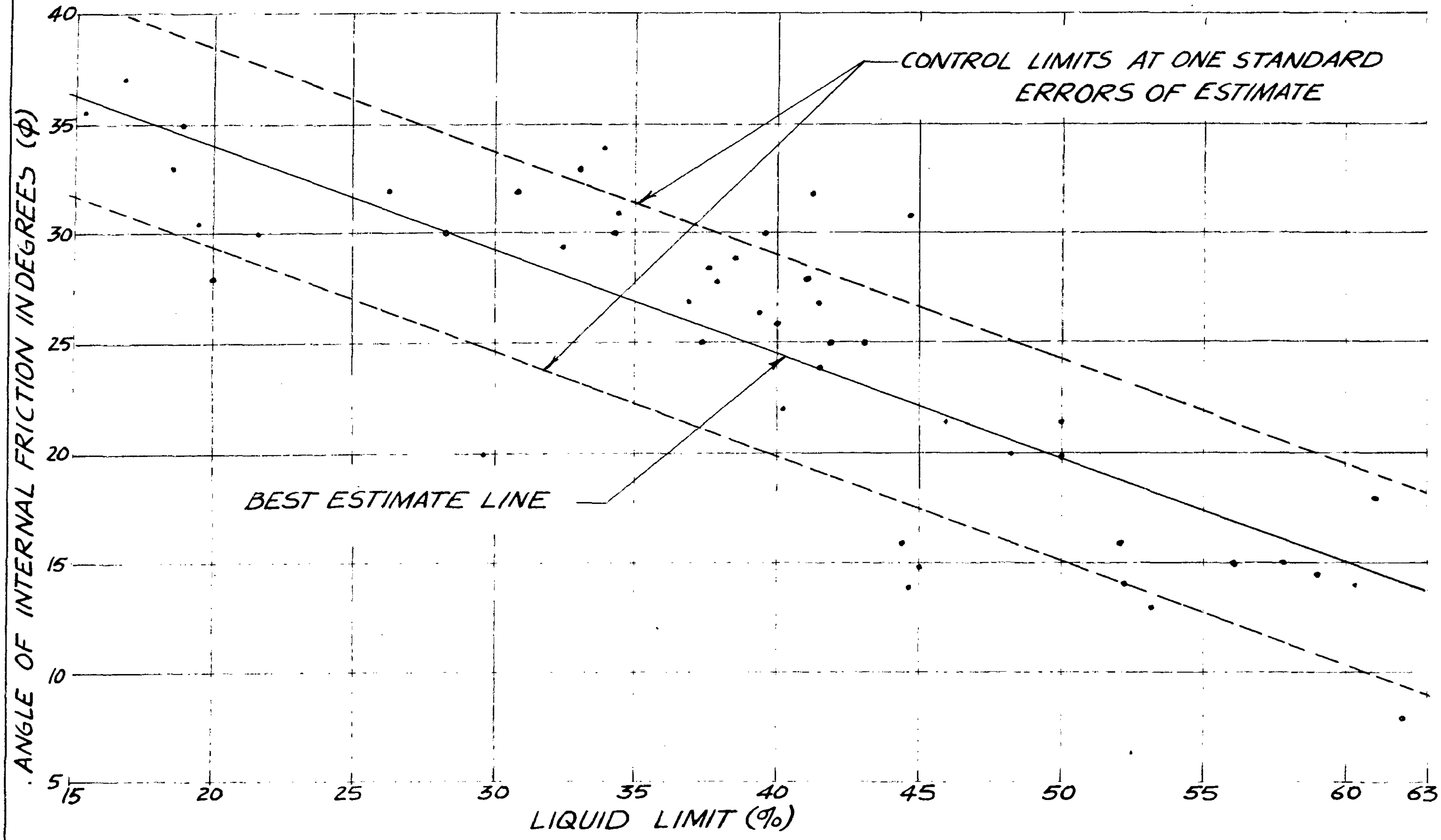


FIG. NO. 7 ANGLE OF INTERNAL FRICTION (ϕ) V/S LIQUID LIMIT (W_L)

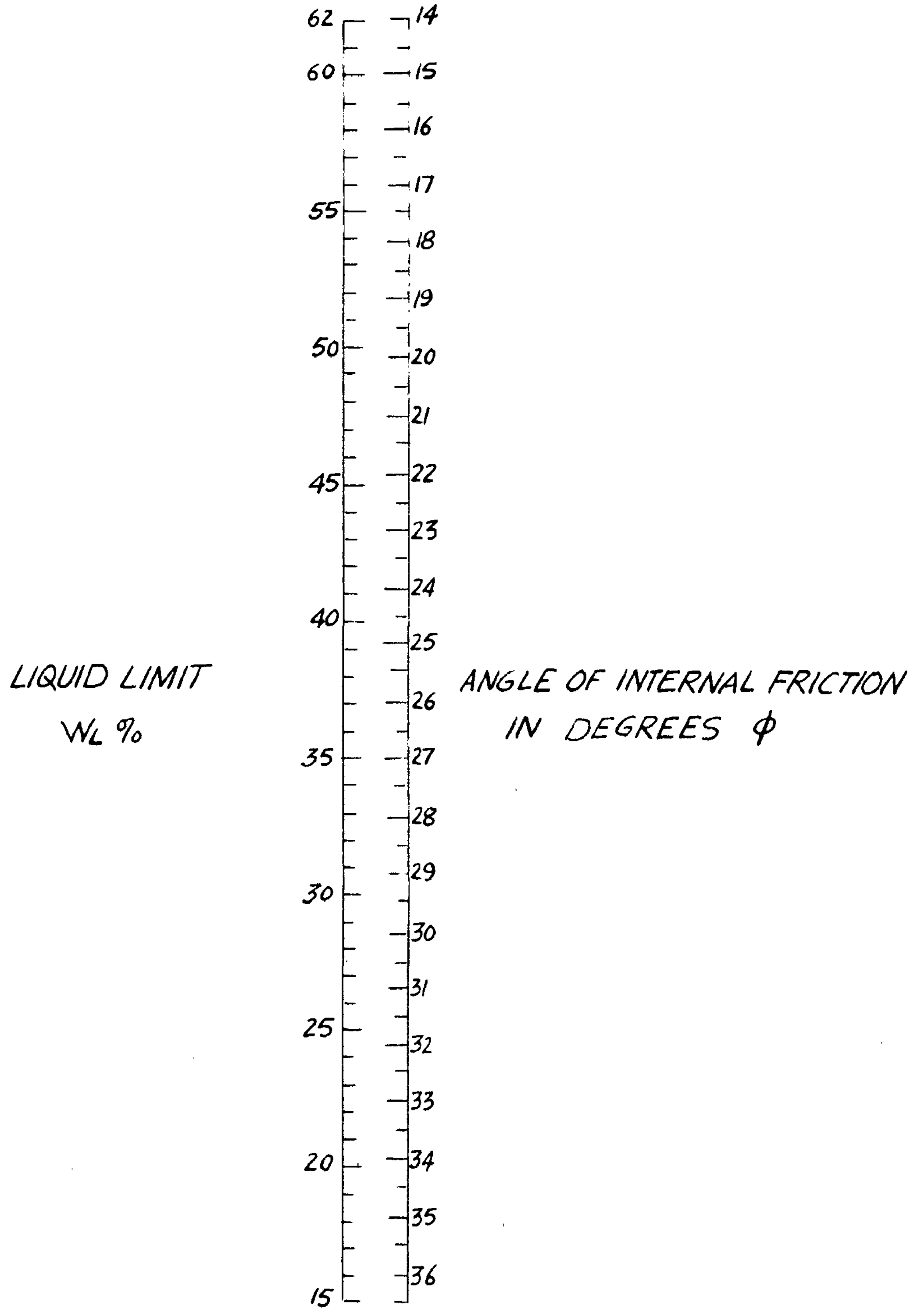


FIG. NO. 8 NOMOGRAM FOR CALCULATING THE ANGLE OF INTERNAL FRICTION FROM LIQUID LIMIT OF THE SOIL.

Substituting the values from Table No. 4, we get :-

$r = -0.8320$

which reveals that relation obtained is fairly good negative correlation, i.e. as liquid limit increases the value of ϕ decreases.

The standard error of estimate is given by the relation

$$
\begin{aligned}
S_{\phi} &= \sigma_{\phi} \sqrt{1 - r^2} \\
&= 7.1773 \sqrt{1 - (-0.8320)^2} \\
&= 3.98^{0}
\end{aligned}
$$

Theoretically for normal distribution of values 65% values should be covered at the deviation of an standard error i.e. 3.98^{0}. From Fig. No. 7 it can be seen that 74% cases are covered at one standard error, and 100% cases will be covered at two standard error. Thus we can be sure that in 95% cases the actual values of ϕ will not differ from the calculated value by more than 7.96 degrees.

<u>Correlation of ϕ with I_p</u>

The plot between the angle of internal friction ϕ at O.M.C. and plasticity index shows a tendency towards a straight line as shown in Fig. No. 9. Therefore trial is made to correlate them by a straight line law of the type -

$$\phi' = a + b I_p$$

Here

$$a = \frac{(\bar{I}_p)(\Sigma \phi . I_p) - (\bar{\phi})(\Sigma I_p^2)}{(\bar{I}_p)(\Sigma I_p) - (\Sigma I_p^2)}$$

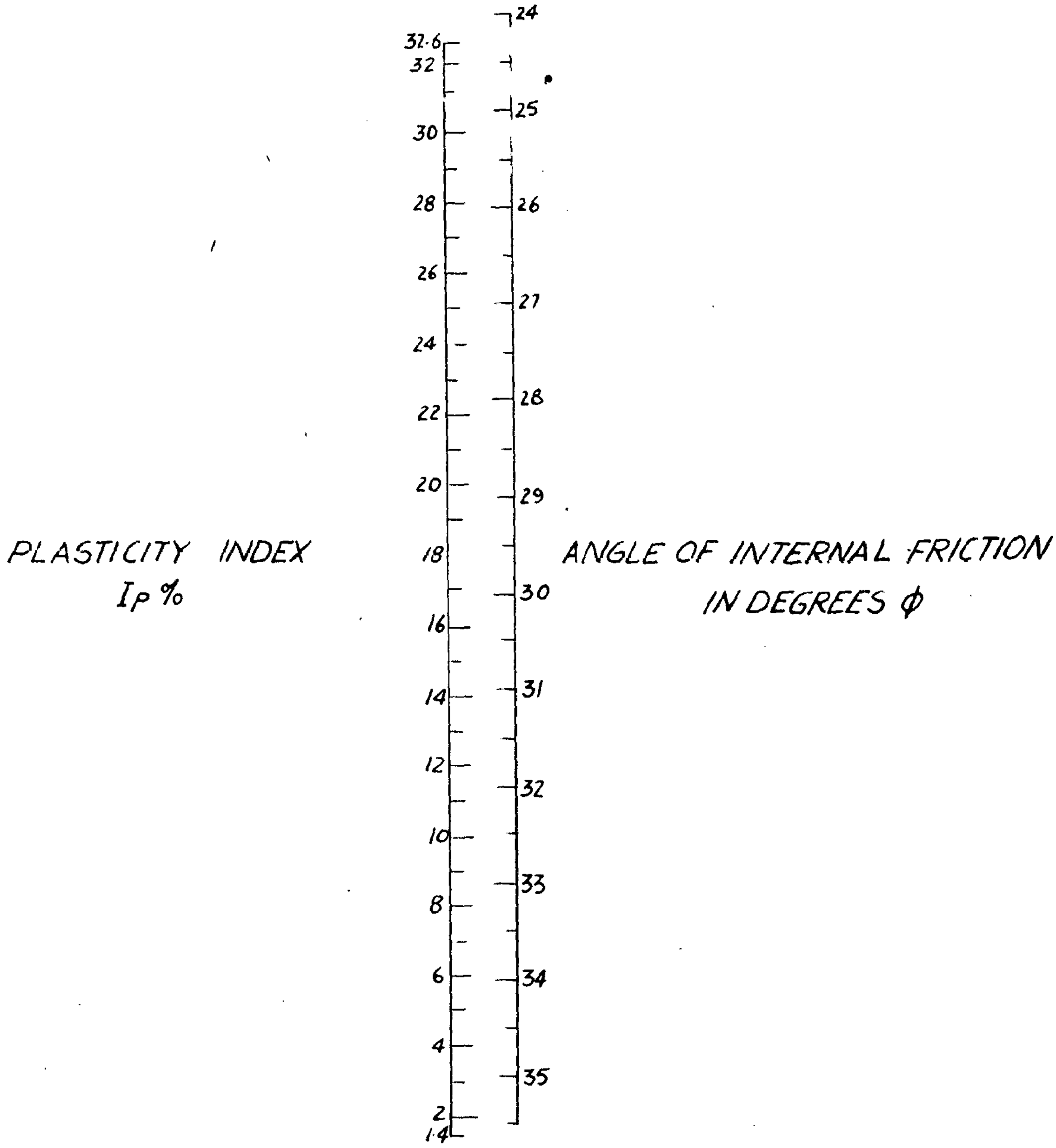


FIG. NO. 10 NOMOGRAM FOR CALCULATING THE ANGLE OF INTERNAL FROM PLASTICITY INDEX OF THE SOIL and $b = \dfrac{\Sigma \phi . I_p - (\bar{\phi})(\Sigma I_p)}{\Sigma I_p^2 - (\bar{I_p})(\Sigma I_p)}$

By substituting various values in the above equations from Table No. 4, we get

$a = 35.5737$

and $b = -0.7256$

Therefore the equation of correlation is :-

$$\phi = 35.5737 - 0.7256 \, I_p$$

For various observations ϕ is obtained and is shown in Table No. 9 .

The nomogram of correlation is given in Fig. No. 10. It can be directly used to calculate ϕ from the plasticity index of the soil.

The product moment correlation coefficient is given by the equation

$$r = \frac{\frac{1}{N} \Sigma \phi . I_p - \bar{\phi} \bar{I}_p}{(\sigma_{\phi}) . (\sigma_I)}$$

Substituting the values from Table No. , we get :-

$r = -0.8166$

which reveals that relation obtained is fairly good negative correlation i.e. plasticity index increases ϕ decreases.

The standard error of estimate is given by the relation:

$$S_{\phi} = \sigma_{\phi} \sqrt{1 - r^2}$$

$$= 7.1773 \sqrt{1 - (-0.8166)^2}$$

$$= 4.1436$$

As shown in Fig. No. 9, in 96% cases the actual values of ϕ lie within plus or minus 8.2872 degrees from the estimated values given by the regression equation. Therefore we can be sure that in 95% cases the maximum variation will not exceed two standard error. And almost for 100% case the variation in any value will not exceed three standard error of estimate.

Corralation of ϕ with W_1 and W_p

Figures No. 7 and 9 indicate that there is a straight line trend of ϕ with W_1 and I_p separately, where as I_p is self the difference between W_1 and W_p. Therefore trial to correlate ϕ with W_1 and W_p is made.

Assuming the following regression equation -

$$(\phi' - \bar{\phi}) = c\,(W_1 - \bar{W}_1) + d\,(W_p - \bar{W}_p)$$

The partial regression coefficients c and d are determined from the following two equations.

$$\Sigma' \phi . W_1 = c\,(\Sigma' W_1^2) + d\,(\Sigma' W_1 . W_p)$$

and $$\Sigma' \phi . W_p = c\,(\Sigma' W_1 . W_p) + d\,(\Sigma' W_p^2)$$

Substituting numerical values from Table No. 5, we get :-

$$c = -0.4365$$

and $$d = -0.0543$$

And therefore the partial regression equation is

$$(\phi' - \bar{\phi}) = -0.4365\,(W_1 - \bar{W}_1) - 0.0543\,(W_p - \bar{W}_p)$$

Substituting the numerican values of $\bar{\phi}$, $\bar{W}_1$ and $\bar{W}_p$ from Table No. 4, we get the final partial regression equation -

$$\phi' = 43.428 - 0.4365\,W_1 - 0.0543\,W_p$$

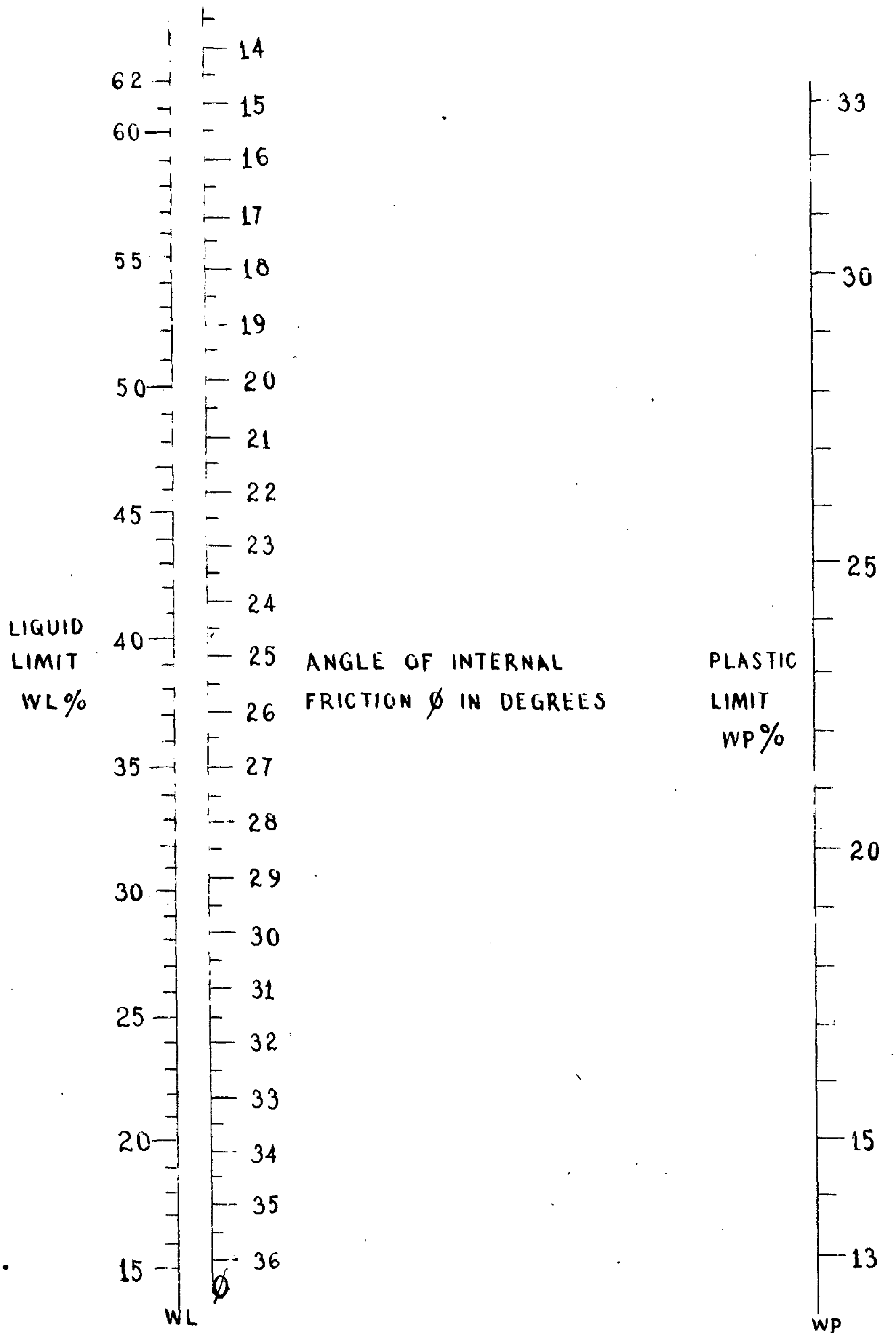


FIG. NO. 11 NOMOGRAM FOR CALCULATING ANGLE OF FRICTION FROM LIQUID AND PLASTIC LIMITS OF SOIL

From the above equation ϕ' can be calculated from liquid and plastic limit of the soil. For comparison the observed and the calculated values of ϕ are shown in Table No. 9.

The nomogram of correlation is given in Fig. No. 11, which can be used to calculate ϕ from the observed values of liquid and plastic limits of the soil. The method of drawing and using the nomogram is explained in Appendix D_2.

Multiple correlation coefficient is given by :-

$$R = \frac{\frac{1}{N}\sum \phi \cdot \phi' - (\bar{\phi})(\bar{\phi}')}{\sqrt{\left\{ \left(\frac{1}{N}\Sigma'\phi^2\right) \left(\frac{1}{N}\Sigma \phi'^2\right) \right\}}}$$

Substituting the numerical values

$$R = 0.833$$

The standard error of estimate is given by

$$S_\phi = \sigma_\phi \sqrt{1 - R^2}$$

$$= 7.1773 \sqrt{1 - (0.833)^2}$$

$$= 3.97^0$$

In 95% of the cases the actual value of ϕ will lie within plus or minus $2 \times 3.97 = 7.94^0$ from the estimated value given by the regression equation.

Correlation of $\text{Log}_{10}\phi$ with W_1

The plot between the logarithim to the base 10 of the angle of internal friction ϕ and the liquid limit W_1 in ordinary scale shows a tendency towards a straight line as shown in Fig. No. 12. Therefore trial is made to correlate them by a straight line on semilog scale of the type -

$$\text{Log}\ \phi' = a + b W_1$$

In this case : -

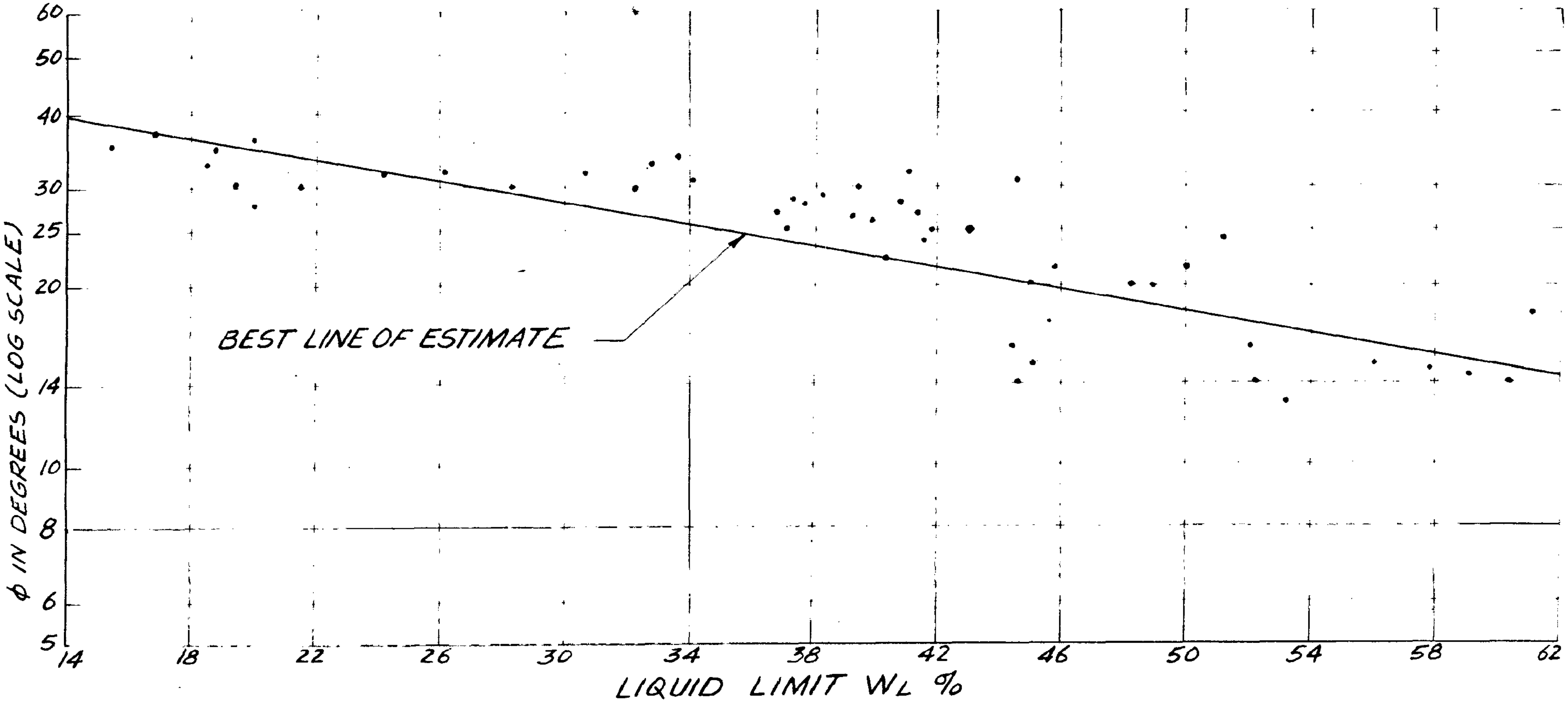


FIG. NO. 12 ANGLE OF INTERNAL FRICTION φ IN DEGREES V/S LIQUID LIMIT W_L %

$$a = \frac{(\overline{W}_1)\left\{\Sigma\left[(\mathrm{Log}_{10}\phi)\,(W_1)\right]\right\} - (\overline{\mathrm{Log}_{10}\phi})\,(\Sigma W_1^2)}{(\overline{W}_1)\,(\Sigma W_1) - \Sigma W_1^2}$$

and
$$b = \frac{\Sigma\left\{\mathrm{Log}_{10}\phi . W_1\right\} - (\overline{\mathrm{Log}_{10}\phi})\,(\Sigma W_1)}{\Sigma W_1^2 - (\overline{W}_1)\,(\Sigma W_1)}$$

By substituting the v·rious numerical values in the above equations, we get :-

$a = 1.7554$

and $b = -0.00962$

Therefore equation of correlation is

$\mathrm{Log}_{10}\phi' \; + = 1.7554 - 0.00962\,W_1$

For various observations ϕ' is obtained and is shown in Table No. 9.

The product moment correlation coefficient is given by :-

$$r = \frac{\frac{1}{n}\Sigma(\mathrm{Log}_{10}\phi . W_1) - (\overline{\mathrm{Log}_{10}\phi})\,(\overline{W}_1)}{(\sigma_{\log_{10}\phi})\,(\sigma_1)}$$

$= -0.8062$

Which reveals that the relation obtained is fairly good negative correlation i.e. as liquid limit increases $\mathrm{Log}_{10}\phi$ decreases.

The standard error of estimate is given by

$$S_{\log_{10}\phi} = \sigma_{\log_{10}\phi}\sqrt{1 - r^2}$$

$$= 0.1460\sqrt{1 - (-0.8062)^2}$$

$$= 0.08637$$

In 95% of the cases the difference in Log of ϕ to the base 10, will not be more than two standard error of log ϕ i.e. $2 \times 0.08637 = 0.1727$ from the calculated value of $\log_{10}\phi$ from the regression equation.

Correlation of ϕ with W_1 in parts.

From the plot between angle of internal friction ϕ and liquid limit W_1 as shown in Fig. No. 13, it is clear that it will be more accurate to fit a straight line between liquid limit 15% to 30% and another straight line between liquid limit 30% to 62%. This is probably due to marked difference in clay content of the soils below liquid limit of 30%.

Let the equation of the straight line below liquid limit 30% is of the type

$$\phi_1' = a + b\,W_{11}$$

Here only those soils be considered whose liquid limit below 30%, but their liquid limit be represented by adding one additional suffix 1 i.e. by W_{11} and ϕ by ϕ_1.

Therefore

$$a = \frac{(\bar{W}_{11})\ (\Sigma\,\phi_1.W_{11})\ -\ (\bar{\phi}_1)\ (\Sigma\,W_{11}^2)}{(\bar{W}_{11})\ (\Sigma\,W_{11})\ -\ \Sigma\,W_{11}^2}$$

and

$$b = \frac{\Sigma\,\phi.W_{11}\ -\ (\bar{\phi}_1)\ (\Sigma\,W_{11})}{\Sigma\,W_{11}^2\ -\ (\bar{W}_{11})\ (\Sigma\,W_{11})}$$

By substituting the various numerical values from Table No. 6, we have :-

$$a = 46.5830$$

$$b = -0.7109$$

Therefore the equation, of correlation is

$$\phi_1' = 46.5830 - 0.7109\,W_1$$

The product moment correlation coefficient is given by the relation :-

$$r = \frac{\frac{1}{N_1} \Sigma \phi_1 . W_{11} - \bar{\phi}_1 . \bar{W}_{11}}{\sigma_{\phi_1} . \sigma_{11}}$$

$$= -0.595$$

Which reveals that there exists a straight line correlation but not so good, due to smaller number of observations and larger scattering. As the no. of observation in this region is only 11, the equation cannot be relied for the estimation of ϕ even for this region.

Standard error of estimate is given by :-

$$S_{\phi_1} = \sigma_{\phi_1} \sqrt{1 - r^2}$$

$$= 4.3715 \sqrt{1 - (-0.595)^2}$$

$$= 3.5134^0$$

However the standard error is smaller in comparison to the previously derived single straight line equation, therefore for this region the values of ϕ calculated from this equation are liable to be subjected to lesser amount of error.

Now let the equation of straight line between liquid limit 30% to 62% is

$$\phi_h = a + b W_{1h}$$

Here only those soils will be considered whose liquid limit is above 30%, let their liquid limit be represented by an additional suffix h i.e. W_1 by W_{1h} and ϕ by ϕ_h.

In this case

$$a = \frac{(\bar{W}_{1h})(\Sigma \phi_h . W_{1h}) - (\bar{\phi}_h)(\Sigma W_{1h}^2)}{(\bar{W}_{1h})(\Sigma W_{1h}) - (\Sigma W_{1h}^2)}$$

and,

$$b = \frac{\Sigma \phi_h \cdot W_{1h} - (\bar{\phi}_h)(\Sigma W_{1h})}{\Sigma W_{1h}^2 - (\bar{W}_{1h})(W_{1h})}$$

Substituting the various numerical values from Table No. 6, we
we get :-

$a = 53.1922$

and $b = -0.6777$

Therefore the equation of correlation is

$$\phi'_h = 53.1922 - 0.6777\, W_1$$

The product moment correlation coefficient is given by

$$r = \frac{\frac{1}{N_h} \phi_h \cdot W_{1h} - \bar{\phi}_h \cdot \bar{W}_{1h}}{\sigma_{\phi h} \times \sigma_{Ih}}$$

$$= -0.8517$$

Which reveals that relation obtained is fairly good, negative correlation i.e. as liquid limit increases value of ∅ decreases.

The standard error of estimate is given by :-

$$S_{\phi h} = \sigma_{\phi h} \sqrt{1 - (-0.8517)^2}$$

$$= 2.39^0$$

The standard error of estimate in this case is less than that from a single straight line equation derived earlier. Therefore for calculating ∅ for soils having liquid limit greater than 30% this formula will given more accurate results.

From both above equations the values of ∅ have been calculated and for comparison with observed values have been shown in Table No. 9. This can be seen that these calculated values are more close to the observed values than that calculated from single straight line equation to cover the whole range derived earlier.

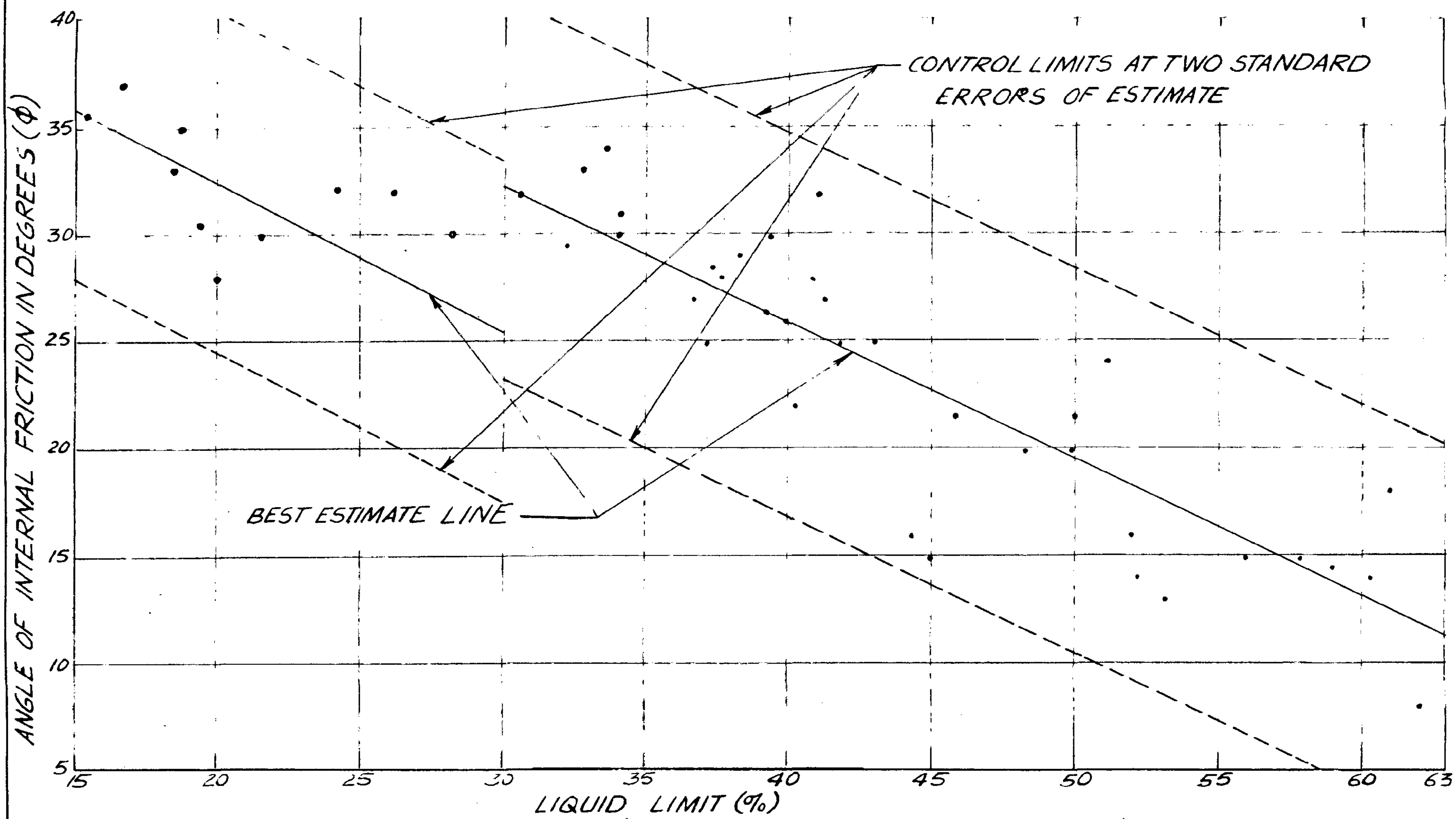


FIG. NO. 13 ANGLE OF INTERNAL FRICTION (φ) V/S LIQUID LIMIT (W_L) (IN PARTS)

From Fig. No. 13 it can be seen that 100% points lie inside the two standard errors of estimate for the respective region. Thus we can be sure that for 95% cases the error will not exceed the two respective standard errors of estimate.

V DISCUSSION ON CORRELATIONS OBTAINED.

The following are the equations of correlation obtained for C :-

1. $C' = 4.258 + 0.3113\, W_1$
2. $C' = 9.7066 + 0.4628\, I_p$
3. $C' = 4.70 + 0.3270\, W_1 - 0.0430\, W_p$

and for ϕ :-

4. $\phi' = 44.1336 - 0.4884\, W_1$
5. $\phi' = 35.5737 - 0.7256\, I_p$
6. $\phi' = 43.428 - 0.4365\, W_1 - 0.0543\, W_p$
7. $\log_{10} \phi' = 1.7554 - 0.00962\, W_1$

and also for soils with

$W_1 = 15\%$ to 30%

8. $\phi' = 46.5830 - 0.7109\, W_1$

and with $W_1 = 30\%$ to 62%.

9. $\phi' = 53.1922 - 0.6777\, W_1$

The values of standard errors and coefficients of correlations for various equations are :-

Equation No.	Standard Error	Correlation Coefficient.
1	2.303 psi.	0.8558
2	2.410 psi.	0.8401
3	2.258 psi.	0.8616
4	3.98^{0}	-0.832
5	4.1436^{0}	-0.8166
6	3.97^{0}	0.833
7	$\log_{10} \phi = 0.08637$	-0.806
8	3.5134^{0}	-0.595
9	2.[illegible]	-0.8517

Hence in order of accuracy for cohesion equation - 3 is the best and then equation -1 and -2 follow. Table No. 8 gives the observed as well as calculated values of C from different relations for all 50 soils.

For Ø in order of accuracy equation - 6 is the best and then equations -4, -5 and -7 follow. However equations -8 and -9 are more accurate for their specified regions, but due to smaller number of observations comparatively they cannot be relied. Equation No. 9 can be used in its specified region.

In both the cases it has been observed that equations -3 and -6 give better results comparatively, probably because in both these equations, both the liquid and plastic limits of the soil have been considered. Both the observed amd calculated values of C and Ø from equations -3 and -6 respectively have been plotted in Fig. No. 14 and 15.

The standard error of estimate in equation -3 is 2.258 psi. and so its double is 4.516 psi. and the mean value of C is 16.502 psi.

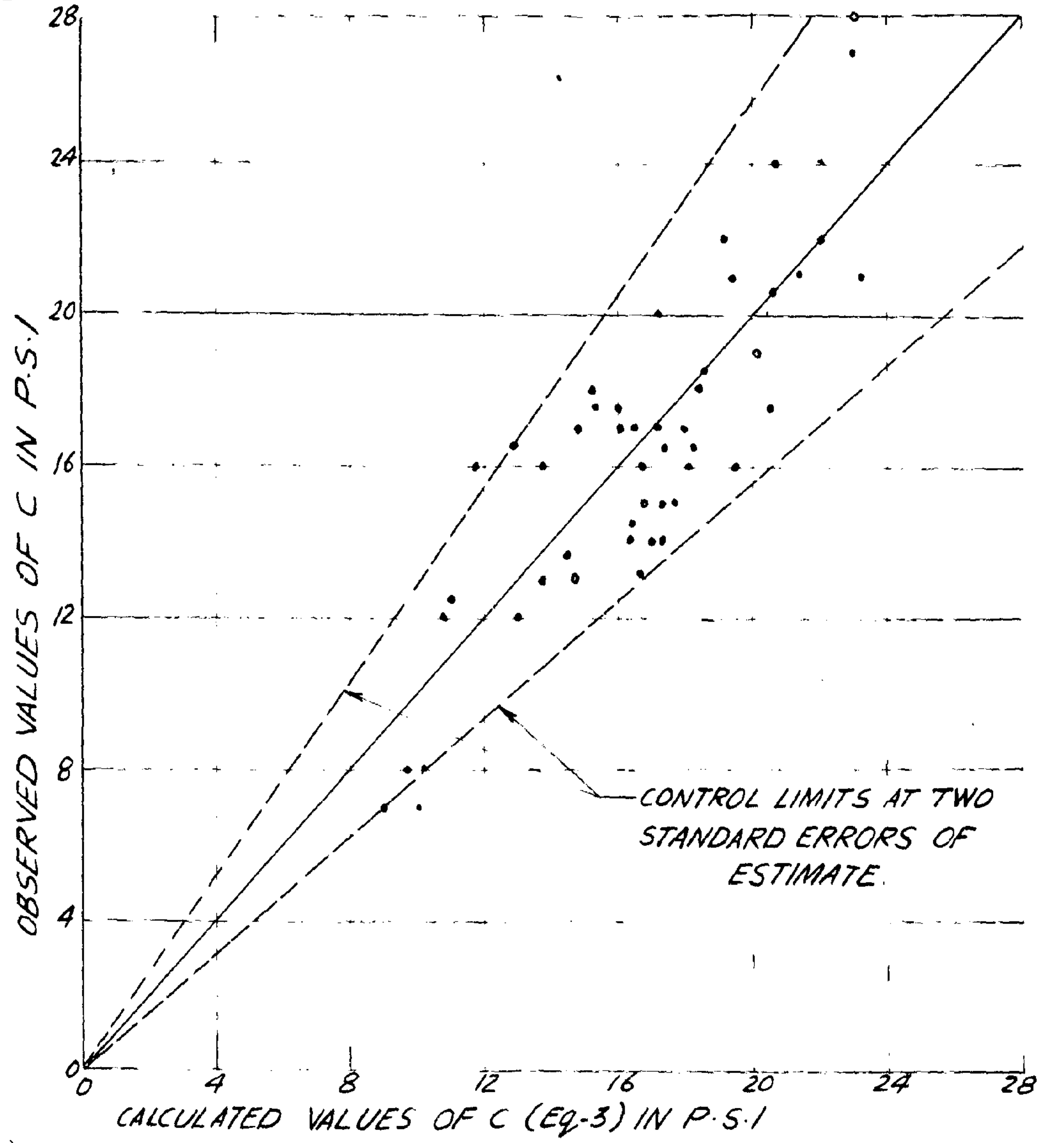


FIG. NO. 14 COMPARISION OF OBSERVED & CALCULATED VALUES (Eq-3) OF C

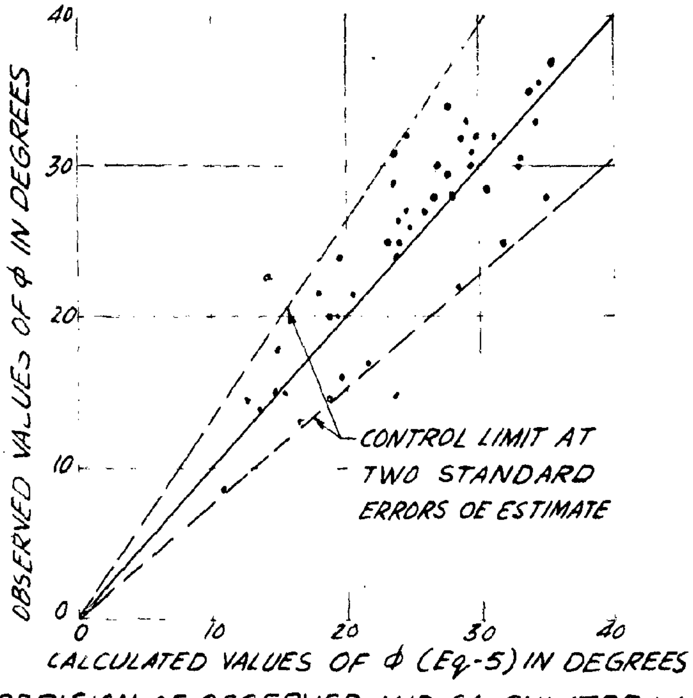


FIG. NO. 15 COMPARISION OF OBSERVED AND CALCULATED VALUES OF ϕ

So present error is :-

$$= \frac{4.516}{16.502} = 27.4\%$$

This error is plotted on either side of the 45^0 line in Fig. No. 14. Out of 50 points 49 lie inside the limits i.e. 98% of cases. Hence we can expect a maximum of 27.4% error in 95% cases.

Similarly standard error of estimate in equation -6 is 3.97 and so its double is 7.94 degrees, and the mean value of ϕ is 24.92 degrees. So present error is

$$= \frac{7.94}{24.92} = 31.8\%$$

This error is plotted on either side of the 45^0 line in Fig. No. 15. Out of 50 points 48 lie inside these limits. Hence we can expect a maximum of 31.8% error in 95% cases.

The best equation for calculating cohesion is :-

$$C = 4.70 + 0.3270\,W_1 - 0.0430\,W_p$$

In the above equation giving different numerical values to one variable, the relation between the other two variables have been plotted.

Fig. No. 16 shows lines of constant C on the $W_1 - W_p$ chart.

Fig. No. 17 shows change of C with liquid limit for constant values of plastic limit.

Fig. No. 18 shows change of C with plastic limit for constant values of liquid limit. This indicates that rate of change of C is more with change of liquid limit than the corresponding change in pl stic limit.

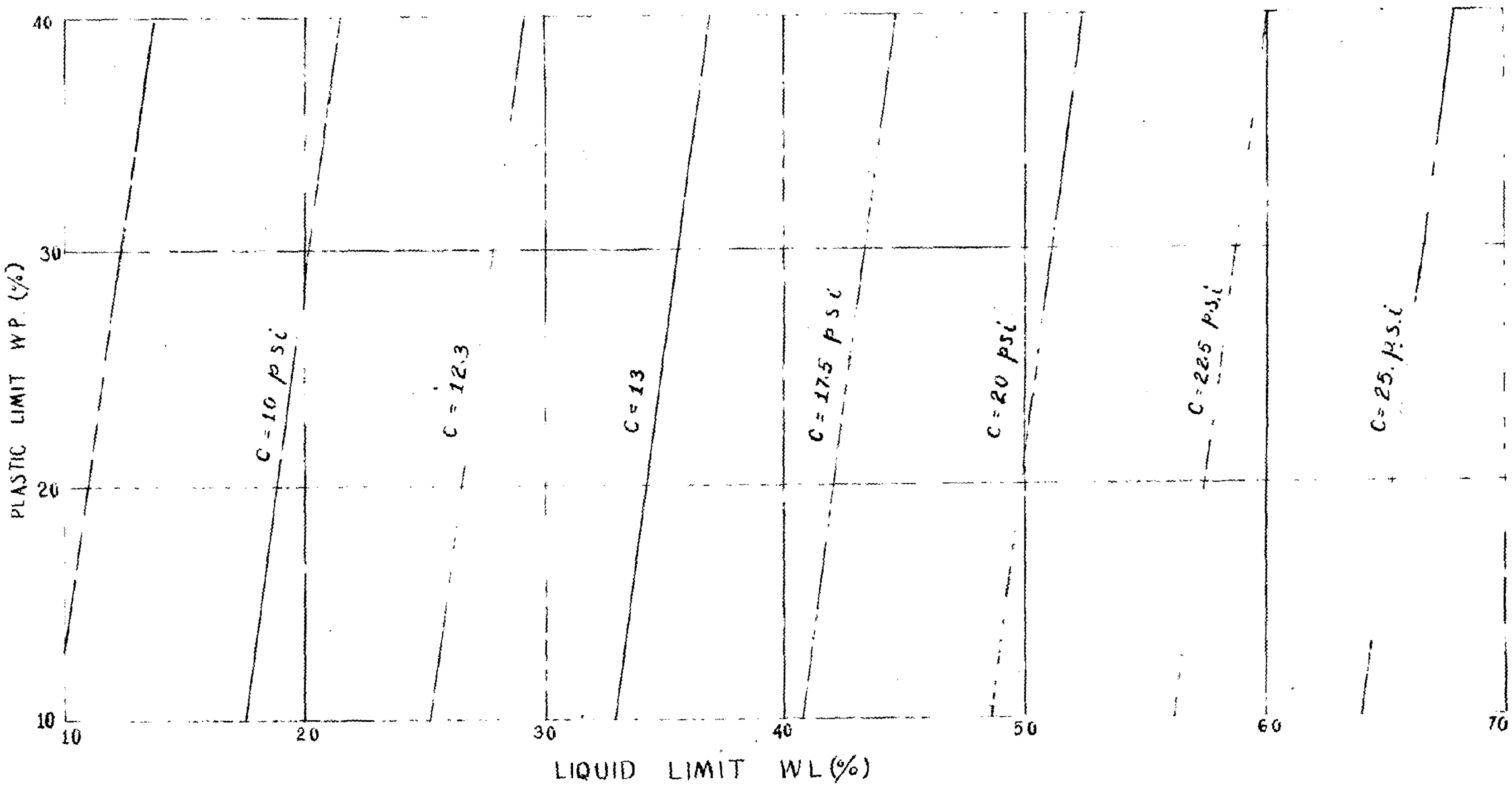


FIG. NO. 16 CONSTANT COHESION LINES ON LIQUID LIMIT - PLASTIC LIMIT CHART

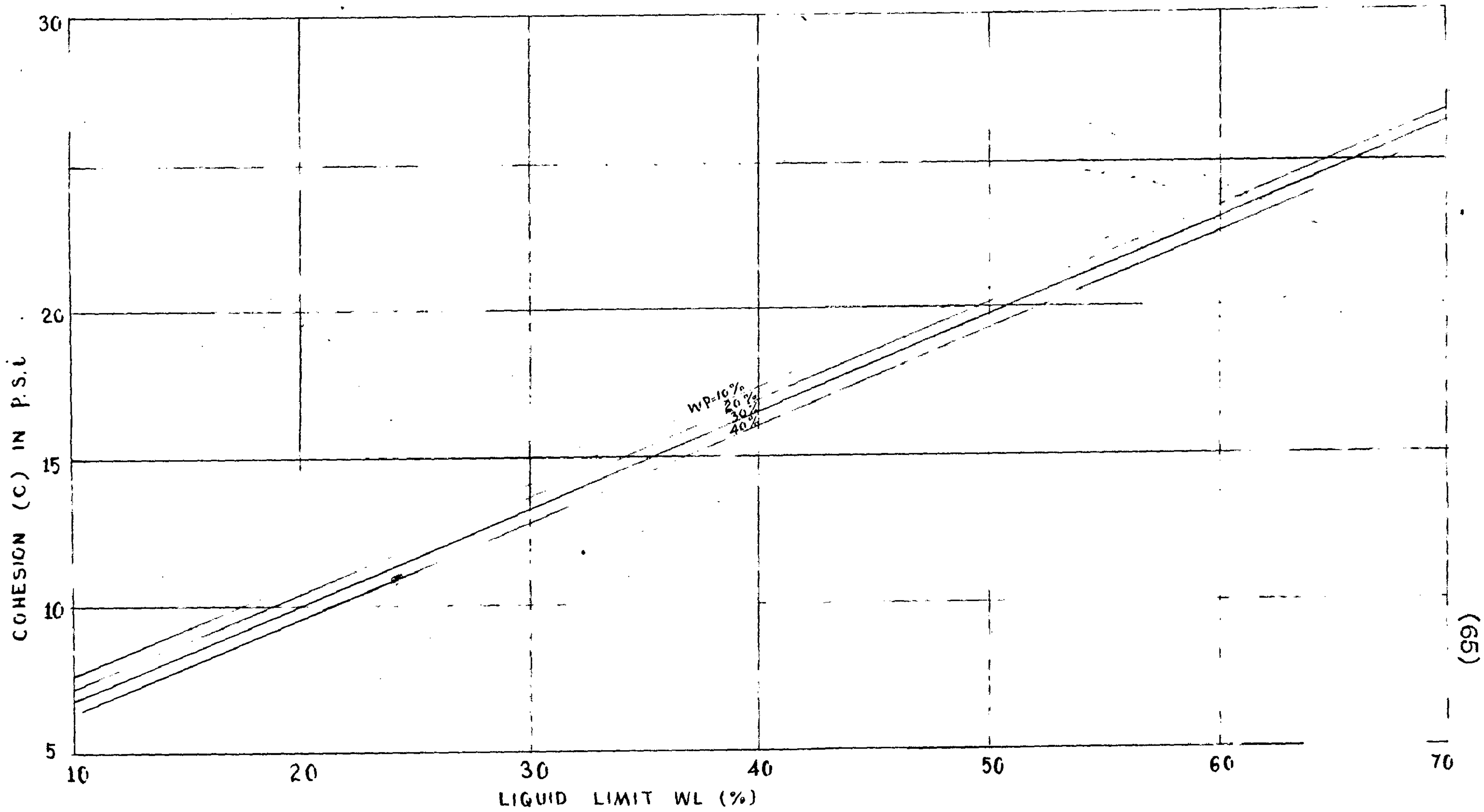


FIG. NO. 17 VARIATION OF COHESION WITH LIQUID LIMIT FOR CONSTANT PLASTIC LIMIT VALUES

187941

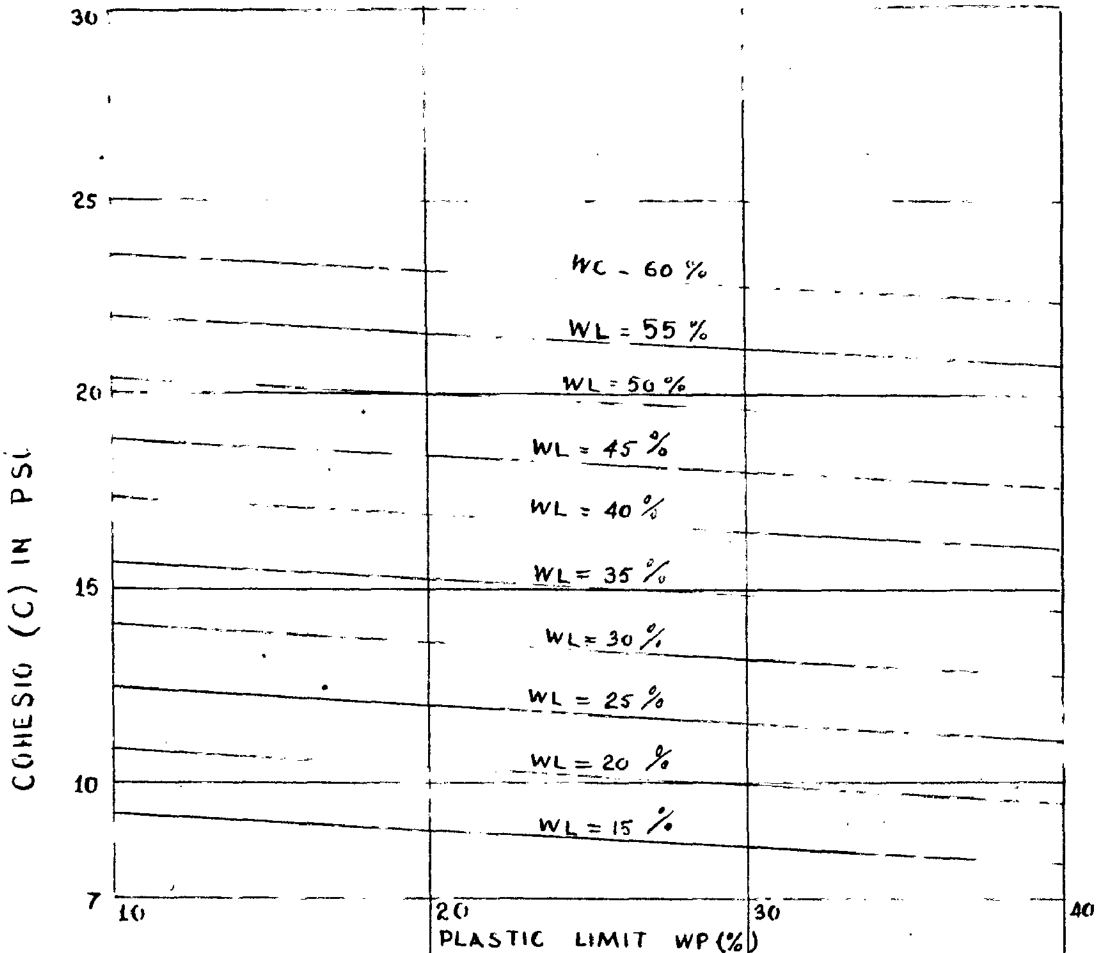


FIG. NO. 18 VARIATION OF C WITH WP FOR CONSTANT WL VALUES

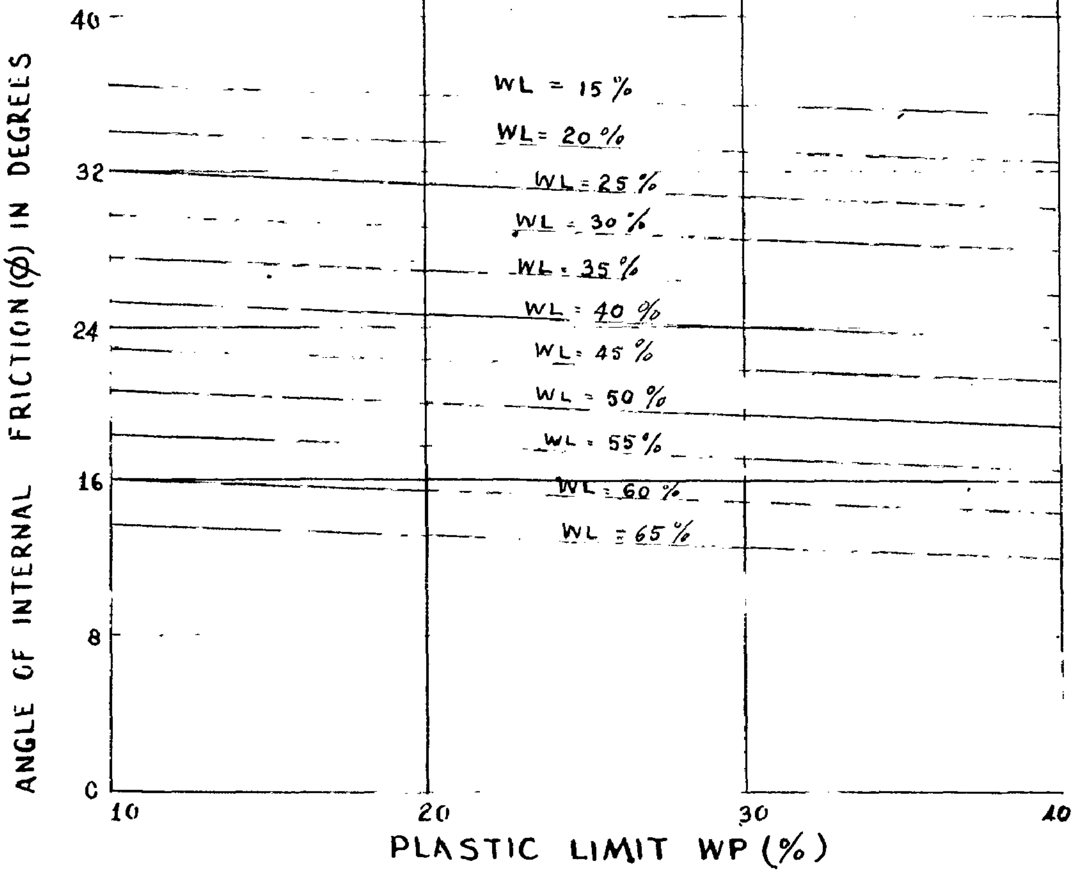


FIG. NO. 19 VARIAT OF φ WITH WP FOR CONSTANT WL VALUES

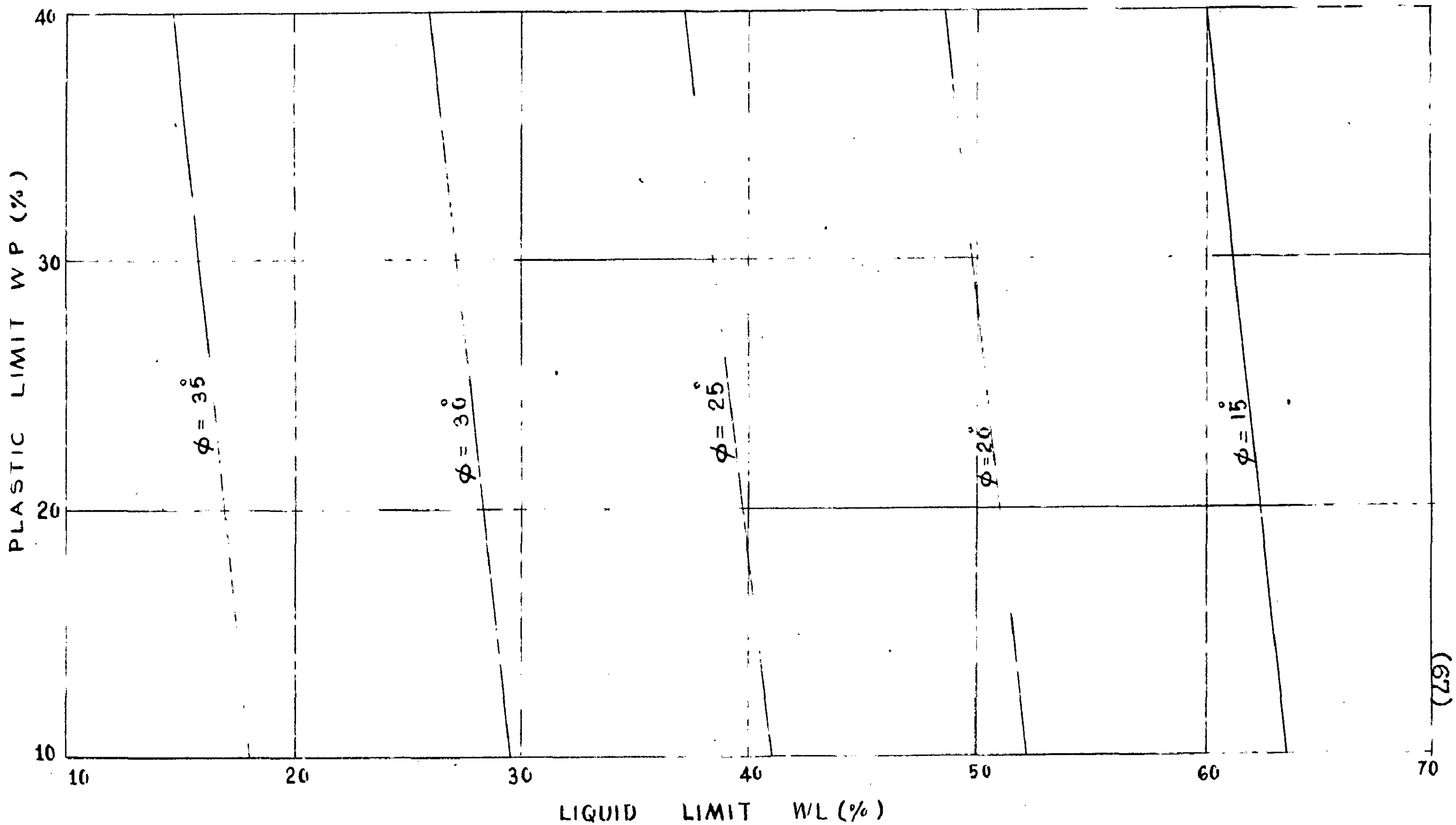


FIG NO. 20 CONSTANT φ LINES ON LIQUID LIMIT - PLASTIC LIMIT CHART.

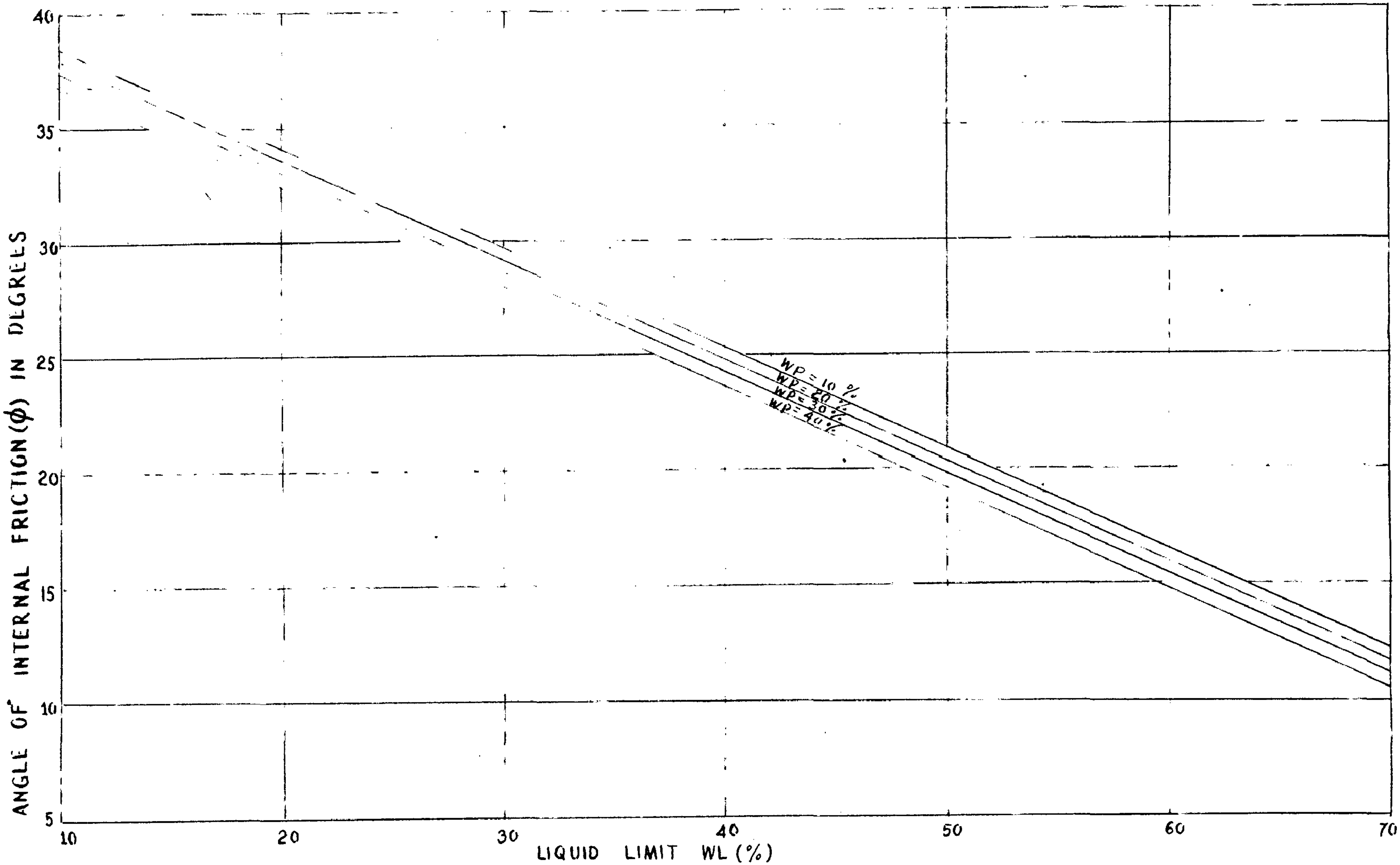


FIG. NO. 21 VARIATION OF ϕ WITH LIQUID LIMIT FOR CONSTANT PLASTIC LIMIT VALUES

Similarly best equation for ϕ is

$$\phi' = 43.428 - 0.4365 W_l - 0.0543 W_p$$

Giving different numerical values to one variable in the above equation the relation between the other two have been plotted.

Fig. No. 19 shows change of ϕ with plastic limit for constant values of liquid limit. This indicates that ϕ decreases with the increase in liquid and plastic limits.

Fig. No. 20 shows lines of constant ϕ on W_l - W_p chart.

Fig. No. 21 shows change of ϕ with liquid limit for constant values of plastic limit.

DISCUSSION OF RESULTS.

The standard error of estimate in various equations is for observed values by one operator and we have assumed no standard deviation in observation due to operational techniques. Mr. Agarwal (29) has pointed out that standard deviation for plastic limit values of soils by ten operators is 1.32% moisture content. But no such experiments seem to have been done for liquid limit, C and ϕ, in view of the above factors the correlations developed are expected to give reliable values of C and ϕ.

TABLE NO. 8

Comparison of observed values of apparent cohesion and its calculated value from the various developed relations.

Soil No.	Observed value of C in psi.	Calculated value of C in psi. from its relation with Liquid limit and plastic limit.	Liquid limit	Plasticity Index.
1	2	3	4	5
1	24.0	22.69	22.7	20.05
2	16.0	19.82	19.9	20.65
3	28.0	23.71	23.6	24. 8
4	20.0	17.18	17.2	17. 2
5	15.0	17.64	17.7	17.65
6	21.0	23.21	23.3	22. 5
7	24.0	20.45	20.6	19.65
8	27.0	22.98	23.1	22.15
9	17.0	15.71	15.7	16.08
10	8.0	9.53	9.5	10.34
11	16.0	18.11	18.1	18.07
12	22.0	22.31	22.3	22. 6
13	12.0	10.46	10.5	10.53
14	18.0	18.63	18.6	19.33
15	17.5	14.77	14.9	13.86
16	8.0	10.18	10.1	11.17
17	13.0	14.42	14.5	14.05
18	12.5	11.00	11.0	11.74
19	17.0	18.08	18.1	18.26
20	22.0	19.33	19.3	19.76
21	14.0	16.73	17.0	15.54
22	7.0	10.07	10.0	10.99

Contd.

Table No. 8 (Contd.)

1	2	3	4	5
23	17.5	19.40	20.5	19.78
24	18.5	18.18	18.3	17.25
25	21.0	19.54	19.5	19.92
26	15.0	17.25	17.3	17.05
27	20.5	20.88	20.1	21.53
28	16.5	18.15	18.2	17.8
29	14.0	15.89	16.0	14.55
30	16.0	13.83	13.8	14.42
31	21.0	20.77	21.7	22.25
32	14.0	17.01	17.0	16.83
33	17.0	17.10	17.1	16.87
34	19.0	20.15	20.2	19.75
35	7.0	9.18	9.1	10.85
36	13.0	16.38	16.5	15.4
37	16.0	15.49	15.8	12.43
38	13.0	14.40	13.5	12.89
39	12.0	13.07	13.0	13.86
40	13.5	10.39	10.3	11.69
41	18.0	14.78	14.9	13.95
42	17.0	14.73	14.7	14.94
43	17.0	15.62	15.9	13.35
44	16.0	11.84	13.8	12.84
45	13.6	14.26	14.3	14.33
46	15.0	17.67	16.7	16.6
47	14.5	14.53	16.5	17.1
48	16.5	16.38	16.8	14.42
49	17.5	16.29	16.2	17.35
50	13.5	12.42	12.4	13.58

TABLE NO. 9

Comparison of observed values of apparent angle of internal friction Ø and its calculated value from the various developed relations.

Soil No.	Observed values of Ø in degrees.	Calculated values of Ø in degrees from its relation with				
		Liquid-limit & Plastic-limit.	Liquid-limit.	Liquid-limit (Log relation)	Liquid-limit (in parts)	Plasticity-Index
1	2	3	4	5	6	7
1	14.5	16.15	15.33	15.0	13.19	13.07
2	21.5	20.17	20.73	18.8	19.29	18.37
3	8.0	14.77	13.88	14.5	11.19	11.81
4	24.0	23.94	23.88	22.3	25.07	23.30
5	25.0	23.16	23.13	21.5	24.04	23.07
6	18.0	15.00	14.38	14.8	11.89	15.47
7	14.0	18.98	18.68	17.9	17.79	19.97
8	14.0	15.30	14.73	15.0	12.39	16.07
9	27.0	26.19	26.23	25.0	28.35	25.56
10	37.0	35.26	35.93	39.0	34.60	34.55
11	31.0	22.57	22.38	21.0	23.04	22.42
12	15.0	16.57	15.88	16.0	13.99	15.37
13	28.0	35.71	34.37	38.8	32.40	34.54
14	21.5	22.95	21.73	20.0	22.04	20.47
15	30.0	27.21	27.48	26.5	29.69	29.03
16	35.0	34.37	34.96	37.7	33.00	33.25
17	33.0	27.84	28.13	27.2	30.99	28.74
18	30.0	33.11	33.63	35.5	31.30	32.37
19	16.0	22.69	22.53	21.0	23.19	22.15
20	20.0	20.96	20.58	19.0	20.56	19.73
21	28.0	24.08	24.23	22.6	25.54	26.42
22	33.0	34.50	35.10	38.0	33.40	33.53
23	16.0	19.09	18.73	17.8	17.97	19.72
24	15.0	22.23	22.18	20.4	22.69	23.72

Contd.

Table No. 9 (Contd.)

1	2	3	4	5	6	7
25	20.0	20.63	20.20	19.0	19.39	19.52
26	25.0	23.78	23.71	22.0	24.84	24.02
27	13.0	18.76	18.23	17.5	17.14	16.97
28	14.0	22.49	22.35	21.0	22.89	22.70
29	28.0	25.52	25.73	24.2	27.64	27.93
30	32.0	28.99	29.00	29.0	32.45	28.16
31	15.0	17.41	16.83	16.3	15.19	15.87
32	32.0	24.14	24.13	22.6	25.39	24.37
33	27.0	24.00	23.98	22.2	25.21	24.32
34	24.0	19.53	19.15	18.0	18.56	19.87
35	35.5	36.01	36.63	40.5	35.60	33.75
36	30.0	24.76	24.93	23.2	26.54	26.64
37	25.0	25.54	26.03	24.8	28.04	31.29
38	20.0	29.27	29.68	29.6	25.60	30.56
39	30.0	30.13	30.41	30.5	26.70	29.03
40	30.5	34.14	38.01	37.0	32.80	32.45
41	31.0	27.19	27.51	26.5	30.09	28.89
42	34.0	27.56	27.73	26.9	30.39	27.27
43	28.5	26.55	25.88	24.5	27.91	29.83
44	32.0	31.97	32.36	33.5	29.50	30.63
45	29.5	28.17	28.41	27.9	31.34	28.31
46	26.0	24.65	24.54	23.0	26.19	24.73
47	26.5	25.06	24.98	23.5	26.60	23.87
48	22.0	25.25	24.48	23.0	25.94	28.16
49	29.0	25.54	25.43	24.0	27.24	23.57
50	32.0	31.07	31.38	32.0	28.10	29.47

VI. CONCLUSIONS

Out of nine correlations developed, following are recommended for use in order of preference:-

For apparent Cohesion C :-

1. $C' = 4.70 + 0.3270\, W_1 - 0.0430\, W_p$ ....(3)
2. $C' = 4.258 + 0.3113\, W_1$ ....(1)

For apparent angle of internal friction ϕ:-

1. $\phi' = 43.428 - 0.4365\, W_1 - 0.0543\, W_p$ ....(6)
2. $\phi' = 44.1336 - 0.4884\, W_1$ ....(4)

For the soils having liquid limit between 30% to 62%, better results can be obtained from the following equation

$$\phi' = 53.1922 - 0.6777\, W_1 \quad \text{.........................(9)}$$

Since the study was limited to only fifty soils, a wide range of soils could not be covered. The equations are effective for the soils having liquid limit from 15.4% to 62% and the plastic limit from 12.9% to 33.3%. The applicability of the equations may not hold out side these ranges.

As the pore pressure measurements were limited to only five soils, no comment can be made with certainity for the true values of C and ϕ. However on the basis of five soils tested, it is observed that there is increase in true cohesion of the soil from apparent cohesion, due to shifting of Mohr's circles towards the origin; and there is decrease in the true angle of internal friction from apparent ϕ, though comparatively of small magnitude.

These correlations were obtained from the soils of Indo-Gangetic Plain (U.P.). The correlations can therefore be applied to the soils of this geological region.

The author is of the opinion that, if such equations are developed for soils of each geological region, satisfactory results may be obtained.

VII. SCOPE FOR FURTHER STUDY

(1) The triaxial tests can be performed on compacted soils with pore water and pore air pressure measurements, and true cohesion and angle of internal friction can be obtained which can be correlated with plasticity characteristics of the soils.

(2) Tests can be made on the soils for modified Proctor's compaction. So correlation can be developed for finding C and ϕ in that case, from plasticity characteristics of the soils.

(3) The maximum dry density could also be correlated with C and ϕ for particular conditions.

(4) The cohesion can be obtained for completely saturated case of compacted clays which can be correlated with plasticity characteristics. Quick saturation can be obtained by means of recently developed back pressure technique.

(5) The standard deviations for various plasticity characteristics tests can be obtained, by collecting the test results for the same soil by different operators. This will help in testing the effectiveness of correlations.

(6) Correlations of plasticity characteristics may be found with important fundamental property such as permeability, and also with emperical soil properties as C.B.R., bearing capacity, modulus of subgrade reaction etc. Such correlations will help in understanding the soil behaviour and will give different soil properties by one or two simple tests.

BIBLIOGRAPHY

1. Bishop, A.W. and Henkel, D.J. ; " Measurement of soil-Properties in the Triaxial Test ". Edward Arnold Ltd. London.
2. Lambe, T.W. ; " Soil Testing for Engineers ", John Wiley & Sons Inc. New York.
3. H.M.S.O. ; " Soil Mechanics for Road Engineers " London, Reprinted 1961.
4. Casagrande, A. ; " Research on the Atterberg limits of Soils" Public Roads 13, (1932)
5. Proctor, R.R. ; " Design and Construction of Rolled Earth Dams " Engineering News Record, Vol. III (1933) pp. 245 and 286.
6. Grim, R.E. ; " Clay Mineralogy " McGraw Hill Book Co. (1953)
7. Norton, F.H. ; " Fundamental studies of clay VII a new theory for plasticity of clay water mass ". Am. Soc. of Ceramics Vol. 31 (1948)
8. Johnson, A.L. and Nortan, F.H. ; " Plastical Drying Proportion of certain clays as influenced by Electrolyte content ", Jl. of Ame Ceramic Society Vol. 24 (1941).
9. Scott Blair, G.W. ; " Measurement of Plasticity of Clays " Jl. of Physical Chemistry Vol. 35 : 374.
10. Davidson, T.D. and Sheeler, J.B. ; " Clay Fraction in Engineering Soils III Influence of amount of properties.' Proc. H.R.B. Vol. 31, 1952, pp. 558.
11. Seed, H.B. and Michell J.K. and Chau, C.K. ; " The strength of compacted cohesive soils ". Research Conference on shear strength of cohesive soils, Soil Mechanics and Foundation Div. A.S.C.E., June 1960, pp. 877.

12. Bjerrum, L. and Simons, N.E. ; " Comparison of shear strength characteristics of Normally consolidated clays ". Research conference on shear strength of cohesive soils (A.S.C.E.) June 1960.

13. Jenning, J.E. ; ' A revised effective stress law for use in the prediction of the Behaviour of unsaturated soils ' " Pore Pressure and Suction in Soils " Butterworths, London 1961.

14. Rosenqvist, Th. (Norway); 4th Internation Conference of Soil Mechanics and Foundation Engg. Vol. III pp. 257.

15. Rosenqvist, I. Th. ' Physqico-Chemical Properties of Soils : Soil Water Systems ". A.S.C.E. Proc. Paper No. 2000, April 1959.

16. Leonards, G.A. ; 'Strength characteristics of compacted clays ' Trans. A.S.C.E. Paper No. 2780, Vol. 120, 1955.

17. Lambe, T.W. " The Engineering Behaviour of Compacted Clays " A.S.C.E. Proc. Paper Nos. 1654 and 1655, May 1958.

18. Gibbs, H.J. and Hilf, J.W. ; Discussion of strength characteristics of compacted clays ' by G.A. Leonard, Trans. A.S.C.E. Vol. 120, 1955.

19. Seed, H.B. and Chan, C.K. ; " Structure and strength characteristics of compacted clays " A.S.C.E. Proc. Paper 2216, Oct. 1959.

20. Lambe, T.W. "Compacted clay structure", Trans. A.S.C.E. 1960.

21. Terzaghi, K. and Peck, R.B. ; " Soil Mechanics in Engg. Practice " Asia Publishing House, Second Edition 1960.

22. Taylor, D.W. ; " Fundamentals of Soil Mechanics " Asia Publishing House, 1962.

23. Morney, M.G. ; " Facts from Figures " Penguin Book, 1951, Reprinted 1959.

24. Toft, L. and McKay, A.D.D. ; " Practical Methematics Part one and two ". Sir Isaac Pitman and Sons Ltd. Asia Edition.

25. Arkin and Cotton ; ' An Outline of Statistical Methods '. pp. 74.

26. Freund, John E. ; " Modern Elementary Statistics ". pp. 258

27. Kenney and Keeping ; ' Mathematics of Statistics '. pp. 75 and 252.

28. Weatherburn, C.E. ; " A First Course in Mathematical Statistics Cambridge University Press 1949.

29. Agarwal, K.B. ; " Improved Methods of determining Atterborg limits " Thesis for M.E. Degree ; Civil Engg. Dept. , University of Roorkee.

30. Rajoria, K.B. ; " Correlation of O.M.C. with Plasticity characteristics of soils " Thesis for M.E. Degree ; Civil Engg. Dept. University of Roorkee, 1963.

31. Skempton A.W. and Bishop, A.W. ; " The measurement of shear strength of soils "; Geotechnique Vol. II (1950-51)

A P P E N D I X E S.

APPENDIX A

TABLE NO. 10

Sums of W_1 and W_1^2

Soil No.	W_1	W_1^2	Soil No.	W_1	W_1^2
1	59.0	3481.00	26	41.8	1747.24
2	50.0	2500.00	27	53.1	2819.61
3	62.0	3844.00	28	44.6	1989.16
4	41.5	1722.25	29	37.7	1421.29
5	43.0	1849.00	30	30.6	936.36
6	61.0	3721.00	31	56.0	3136.00
7	52.2	2724.84	32	41.0	1681.00
8	60.3	3636.09	33	41.3	1705.69
9	36.7	1346.89	34	51.1	2611.21
10	16.8	282.24	35	15.4	237.16
11	44.5	1980.25	36	39.4	1552.36
12	57.8	3340.84	37	37.1	1376.41
13	20.0	400.00	38	29.6	876.16
14	45.8	2097.64	39	28.1	789.61
15	34.1	1162.81	40	19.4	376.36
16	18.8	353.44	41	34.1	1162.81
17	32.8	1075.84	42	33.6	1128.96
18	21.5	462.25	43	37.3	1391.29
19	44.3	1962.49	44	24.1	580.81
20	48.2	2323.24	45	32.2	1036.84
21	40.8	1664.64	46	39.9	1592.01
22	18.5	342.25	47	39.2	1536.64
23	52.0	2704.00	48	40.2	1616.04
24	45.0	2025.00	49	38.3	1466.89
25	48.9	2391.21	50	26.1	681.21
				1966.70	84842.33

T A B L E N O. 11

Sums of W_p and W_p^2

Soil No.	W_p	W_p^2	Soil No.	W_p	W_p^2
1	28.0	784.00	26	25.9	670.81
2	26.3	691.69	27	27.5	756.25
3	29.4	864.36	28	27.1	734.41
4	25.3	640.09	29	27.2	739.84
5	25.8	665.64	30	20.4	416.16
6	33.3	1108.89	31	28.9	835.21
7	30.7	942.49	32	25.6	655.36
8	33.4	1115.56	33	25.8	665.64
9	22.9	524.41	34	29.4	864.36
10	15.4	237.16	35	12.9	166.41
11	26.4	696.96	36	27.1	734.41
12	30.0	900.00	37	31.2	973.44
13	18.2	331.24	38	22.7	515.29
14	25.0	625.00	39	19.1	364.81
15	25.1	630.01	40	15.1	228.01
16	15.6	243.36	41	24.9	620.01
17	23.4	547.56	42	22.2	492.84
18	17.1	292.41	43	29.4	864.36
19	25.8	665.64	44	17.3	299.29
20	26.4	696.96	45	22.2	492.84
21	28.2	795.24	46	25.0	625.00
22	15.7	246.49	47	23.1	533.61
23	30.2	912.04	48	30.0	900.00
24	28.7	823.69	49	21.8	475.24
25	26.8	718.24	50	17.7	313.29
				1232.60	31636.02

TABLE NO. 13

Sums of I_p and I_p^2

Soil No.	I_p	I_p^2	Soil No.	I_p	I_p^2
1	31.0	961.00	26	15.9	252.81
2	23.7	561.69	27	25.6	655.36
3	32.6	1062.76	28	17.5	306.25
4	16.2	262.44	29	10.5	110.25
5	17.2	295.84	30	10.2	104.04
6	27.7	767.29	31	27.1	734.41
7	21.5	462.25	32	15.4	237.16
8	26.9	723.61	33	15.5	240.25
9	13.8	190.44	34	21.7	470.89
10	1.4	1.96	35	2.5	6.25
11	18.1	327.61	36	12.3	151.29
12	27.8	772.84	37	5.9	34.81
13	1.8	3.24	38	6.9	47.61
14	20.8	432.64	39	9.0	81.00
15	9.0	81.00	40	4.3	18.49
16	3.2	10.24	41	9.2	84.64
17	9.4	88.36	42	11.4	129.96
18	4.4	19.36	43	7.9	62.41
19	18.5	342.25	44	6.8	46.24
20	21.8	475.24	45	10.0	100.00
21	12.6	158.76	46	14.9	222.01
22	2.8	7.84	47	16.1	259.21
23	21.8	475.24	48	10.2	104.04
24	16.3	265.69	49	16.5	272.25
25	22.1	488.41	50	8.4	70.56
				734.10	14040.19

TABLE NO. 14

Sums of C and C^2

Soil No.	C	C^2	Soil No.	C	C^2
1	24.0	576.00	26	15.0	225.00
2	16.0	256.00	27	20.5	420.25
3	28.0	784.00	28	16.5	272.25
4	20.0	400.00	29	14.0	196.00
5	15.0	225.00	30	16.0	256.00
6	21.0	441.00	31	21.0	441.00
7	24.0	576.00	32	14.0	196.00
8	27.0	729.00	33	17.0	289.00
9	17.0	289.00	34	19.0	361.00
10	8.0	64.00	35	7.0	49.00
11	16.0	256.00	36	13.0	169.00
12	22.0	484.00	37	16.0	256.00
13	12.0	144.00	38	13.0	169.00
14	18.0	324.00	39	12.0	144.00
15	17.5	306.25	40	13.5	182.25
16	8.0	64.00	41	18.0	324.00
17	13.0	169.00	42	17.0	289.00
18	12.5	156.25	43	17.0	289.00
19	17.0	289.00	44	16.0	256.00
20	22.0	484.00	45	13.6	184.96
21	14.0	196.00	46	15.0	225.00
22	7.0	49.00	47	14.5	210.25
23	17.5	306.25	48	16.5	272.25
24	18.5	342.25	49	17.5	306.25
25	21.0	441.00	50	16.5	272.25
				825.10	14605.71

TABLE NO. 15

Sums of ϕ and ϕ^2

Soil No.	ϕ	ϕ^2	Soil No.	ϕ	ϕ^2
1	14.5	210.25	26	25.0	625.00
2	21.5	462.25	27	13.0	169.00
3	8.0	64.00	28	14.0	196.00
4	24.0	576.00	29	28.0	784.00
5	25.0	625.00	30	32.0	1024.00
6	18.0	324.00	31	15.0	225.00
7	14.0	196.00	32	32.0	1024.00
8	14.0	196.00	33	27.0	729.00
9	27.0	729.00	34	24.0	576.00
10	37.0	1369.00	35	35.5	1260.25
11	31.0	961.00	36	30.0	900.00
12	15.0	225.00	37	25.0	625.00
13	28.0	784.00	38	20.0	400.00
14	21.5	462.25	39	30.0	900.00
15	30.0	900.00	40	30.5	930.25
16	35.0	1225.00	41	31.0	961.00
17	33.0	1089.00	42	34.0	1156.00
18	30.0	900.00	43	28.5	812.25
19	16.0	256.00	44	32.0	1024.00
20	20.0	400.00	45	29.5	870.25
21	28.0	784.00	46	26.0	676.00
22	33.0	1089.00	47	26.5	702.25
23	16.0	256.00	48	22.0	484.00
24	15.0	225.00	49	29.0	841.00
25	20.0	400.00	50	32.0	1024.00
				1246.0	33626.00

TABLE NO. 16

Sum of C x W_1

Soil No.	C	W_1	C x W_1	Soil No.	C	W_1	C x W_1
1	24.0	59.0	1416.00	26	15.0	41.8	627.00
2	16.0	50.0	800.00	27	20.5	53.1	1088.55
3	28.0	62.0	1736.00	28	16.5	44.6	735.90
4	20.0	41.5	830.00	29	14.0	37.7	527.80
5	15.0	43.0	645.00	30	16.0	30.6	489.60
6	21.0	61.0	1281.00	31	21.0	56.0	1176.00
7	24.0	52.2	1252.80	32	14.0	41.0	574.00
8	27.0	60.3	1628.10	33	17.0	41.3	702.10
9	17.0	36.7	623.90	34	19.0	51.1	970.20
10	8.0	16.8	134.40	35	7.0	15.4	107.80
11	16.0	44.5	712.00	36	13.0	39.4	512.20
12	22.0	57.8	1271.60	37	16.0	37.1	593.60
13	12.0	20.0	240.00	38	13.0	29.6	384.80
14	18.0	45.8	824.40	39	12.0	28.1	337.20
15	17.5	34.1	596.75	40	13.5	10.4	261.90
16	8.0	18.8	150.40	41	18.0	34.1	613.80
17	13.0	32.8	426.40	42	17.0	33.6	571.20
18	12.5	21.5	268.75	43	17.0	37.3	634.10
19	17.0	44.3	753.10	44	16.0	24.1	385.60
20	22.0	48.2	1060.40	45	13.6	32.2	437.92
21	14.0	40.8	571.20	46	15.0	39.9	598.50
22	7.0	18.5	129.50	47	14.5	39.2	568.40
23	17.5	52.0	910.00	48	16.5	40.2	663.30
24	18.5	45.0	832.00	49	17.5	38.3	670.25
25	21.0	48.9	1026.90	50	16.5	26.1	430.65
							34784.17

TABLE NO. 17

Sum of C x I_p

Soil No.	C	I_p	C x I_p	Soil No.	C	I_p	C x I_p
1	24.0	31.0	744.00	26	15.0	15.9	238.80
2	16.0	23.7	379.20	27	20.5	25.6	524.80
3	28.0	32.6	912.80	28	16.5	17.5	288.75
4	20.0	16.2	324.00	29	14.0	10.5	147.00
5	15.0	17.2	258.00	30	16.0	10.2	163.20
6	21.0	27.7	581.70	31	21.0	27.1	569.10
7	24.0	21.5	516.00	32	14.0	15.4	215.60
8	27.0	26.9	726.30	33	17.0	15.5	263.50
9	17.0	13.8	234.60	34	19.0	21.7	412.30
10	8.0	1.4	11.20	35	7.0	2.5	17.50
11	16.0	18.1	289.60	36	13.0	12.3	159.90
12	22.0	27.8	611.60	37	16.0	5.9	94.40
13	12.0	1.8	21.60	38	13.0	6.9	89.70
14	18.0	20.8	374.40	39	12.0	9.0	108.00
15	17.5	9.0	157.50	40	13.5	4.3	58.05
16	8.0	3.2	25.60	41	18.0	9.2	165.60
17	13.0	9.4	122.20	42	17.0	11.4	193.80
18	12.5	4.4	55.00	43	17.0	7.9	134.30
19	17.0	18.5	314.50	44	16.0	6.8	108.80
20	22.0	21.8	479.60	45	13.6	10.0	136.00
21	14.0	12.6	176.40	46	15.0	14.9	223.50
22	7.0	2.8	19.60	47	14.5	16.1	233.45
23	17.5	21.8	381.50	48	16.5	10.2	168.30
24	18.5	16.3	301.55	49	17.5	16.5	288.75
25	21.0	22.1	464.10	50	16.5	8.4	138.60
							13623.95

TABLE NO. 18

Sum of $\phi \times W_1$

Soil No.	ϕ	W_1	$\phi \times W_1$	Soil No.	ϕ	W_1	$\phi \times W_1$
1	14.5	59.0	855.50	26	25.0	41.8	1045.00
2	21.5	50.0	1075.00	27	13.0	53.1	690.30
3	8.0	62.0	496.00	28	14.0	44.6	624.40
4	24.0	41.5	996.00	29	28.0	37.7	1055.60
5	25.0	43.0	1075.00	30	32.0	30.6	979.20
6	18.0	61.0	1098.00	31	15.0	56.0	840.00
7	14.0	52.2	730.80	32	32.0	41.0	1312.00
8	14.0	60.3	844.20	33	27.0	41.3	1115.10
9	27.0	36.7	990.90	34	24.0	51.1	1226.40
10	37.0	16.8	621.60	35	35.5	15.4	546.70
11	31.0	44.5	1379.50	36	30.0	39.4	1182.00
12	15.0	57.8	867.00	37	25.00	37.1	927.50
13	28.0	20.0	560.00	38	20.0	29.6	592.00
14	21.5	45.8	984.70	39	30.0	28.1	843.00
15	30.0	34.1	1023.00	40	30.5	19.4	591.70
16	35.0	18.8	658.00	41	31.0	34.1	1057.10
17	33.0	32.8	1082.40	42	34.0	33.6	1142.40
18	30.0	21.5	645.00	43	28.5	37.3	1063.05
19	16.0	44.3	708.80	44	32.0	24.1	771.20
20	20.0	48.2	964.00	45	29.5	32.2	949.90
21	28.0	40.8	1142.40	46	26.0	39.9	1037.40
22	33.0	18.5	610.50	47	26.5	39.2	1038.80
23	16.0	52.0	832.00	48	22.0	40.2	884.40
24	15.0	45.0	675.00	49	29.0	38.3	1110.70
25	20.0	48.9	978.00	50	32.0	26.1	835.20
							45354.35

TABLE NO. 19

Sum of $\phi \times I_p$

Soil No.	ϕ	I_p	$\phi \times I_p$	Soil No.	ϕ	I_p	$\phi \times I_p$
1	14.5	31.0	449.50	26	25.0	15.9	397.50
2	21.5	23.7	509.55	27	13.0	25.6	332.80
3	8.0	32.6	260.80	28	14.0	17.5	245.00
4	24.0	16.2	388.80	29	28.0	10.5	294.00
5	25.0	17.2	430.00	30	32.0	10.2	326.40
6	18.0	27.7	498.60	31	15.0	27.1	406.50
7	14.0	21.9	301.00	32	32.0	15.4	492.80
8	14.0	26.9	376.60	33	27.0	15.5	418.50
9	27.0	13.8	372.60	34	24.0	21.7	520.80
10	37.0	1.4	51.80	35	35.5	2.5	88.75
11	31.0	18.1	561.10	36	30.0	12.3	369.00
12	15.0	27.8	417.00	37	25.0	5.9	147.50
13	28.0	1.8	50.40	38	20.0	6.9	138.00
14	21.5	20.8	447.20	39	30.0	9.0	270.00
15	30.0	9.0	270.00	40	30.5	4.3	131.15
16	35.0	3.2	112.00	41	31.0	9.2	285.20
17	33.0	9.4	310.20	42	34.0	11.4	387.60
18	30.0	4.4	132.00	43	28.5	7.9	225.15
19	16.0	18.5	296.00	44	32.0	6.8	217.60
20	20.0	21.8	436.00	45	29.5	10.0	295.00
21	28.0	12.6	352.80	46	26.0	14.9	387.40
22	33.0	2.8	92.40	47	26.5	16.1	426.65
23	16.0	21.8	348.80	48	22.0	10.2	224.40
24	15.0	16.3	244.50	49	29.0	16.5	478.50
25	20.0	22.1	442.00	50	32.0	8.4	268.80
							15920.65

TABLE NO. 20

Sums of C' and C'²

Soil No.	C'	C'²	Soil No.	C'	C'²
1	22.69	514.8361	26	17.25	297.5625
2	19.82	392.8324	27	20.88	435.9744
3	23.71	562.1641	28	18.15	329.4225
4	17.18	295.1524	29	15.89	252.4921
5	17.64	311.1696	30	13.83	191.2689
6	23.21	538.7041	31	20.77	431.3929
7	20.45	418.2025	32	17.01	289.3401
8	22.98	528.0804	33	17.10	292.4100
9	15.71	246.8041	34	20.15	406.0225
10	9.53	90.8209	35	9.18	84.2724
11	18.11	327.9721	36	16.38	268.3044
12	22.31	497.7361	37	15.49	239.9401
13	10.46	109.4116	38	14.40	207.3600
14	18.60	345.9600	39	13.07	170.8249
15	14.77	217.1529	40	10.39	107.9521
16	10.18	103.6324	41	14.78	218.4484
17	14.42	207.9364	42	14.73	216.9729
18	11.00	121.0000	43	15.62	243.9844
19	18.08	326.8864	44	11.84	140.1856
20	19.33	373.6489	45	14.26	203.3476
21	16.73	279.8929	46	17.67	312.2289
22	10.07	101.4049	47	14.53	211.1209
23	19.40	376.3600	48	16.38	268.3044
24	18.18	330.5124	49	16.29	265.3641
25	19.54	381.8116	50	12.42	154.2564
				822.56	14238.8386

TABLE NO. 21

Sums of ϕ' and ϕ'^2

Soil No.	ϕ'	ϕ'^2	Soil No.	ϕ'	ϕ'^2
1	16.15	260.8225	26	23.78	565.4884
2	20.17	406.8289	27	18.76	351.9576
3	14.77	217.0429	28	22.49	505.8001
4	23.94	573.5236	29	25.52	651.2704
5	23.16	536.3856	30	28.99	840.4201
6	15.00	225.0000	31	17.41	303.1081
7	18.98	360.2404	32	24.14	582.7396
8	15.30	234.0900	33	24.00	576.0000
9	26.19	685.9161	34	19.53	381.4209
10	35.26	1243.2676	35	36.01	1296.7201
11	22.57	509.4049	36	24.76	613.0576
12	16.57	274.5649	37	25.54	652.2916
13	33.71	1136.3641	38	29.27	856.5329
14	22.95	526.7025	39	30.13	907.8169
15	27.21	740.3841	40	34.14	1165.5396
16	34.37	1181.2969	41	27.19	739.2961
17	27.84	775.0656	42	27.56	759.5536
18	33.11	1096.2721	43	25.55	652.9025
19	22.69	514.8361	44	31.97	1022.0809
20	20.96	439.3216	45	28.17	794.5489
21	24.08	579.8464	46	24.65	607.6225
22	34.50	1190.2500	47	25.06	628.0036
23	19.09	364.4281	48	25.25	637.5625
24	22.23	494.1729	49	25.54	652.2916
25	20.63	425.5969	50	31.07	965.3449
				1247.91	32700.9987

TABLE NO. 22

Sum of C x C'

Soil No.	C	C'	C x C'	Soil No.	C	C'	C x C'
1	24.0	22.69	544.560	26	15.0	17.25	208.750
2	16.0	19.82	317.120	27	20.5	20.88	428.040
3	28.0	23.71	663.880	28	16.5	18.15	299.475
4	20.0	17.18	343.600	29	14.0	15.89	222.460
5	15.0	17.64	264.600	30	16.0	13.83	221.280
6	21.0	23.21	487.410	31	21.0	20.77	436.170
7	24.0	20.45	490.800	32	14.0	17.01	238.140
8	27.0	22.98	620.460	33	17.0	17.10	290.700
9	17.0	15.71	267.070	34	19.0	20.15	382.850
10	8.0	9.53	76.240	35	7.0	9.18	64.260
11	16.0	18.11	289.76	36	13.0	16.38	212.940
12	22.0	22.31	490.820	37	16.0	15.49	248.840
13	12.0	10.46	125.520	38	13.0	14.40	187.200
14	18.0	18.60	334.800	39	12.0	13.07	156.840
15	17.5	14.77	258.475	40	13.5	10.39	140.265
16	8.0	10.18	81.440	41	18.0	14.78	266.040
17	13.0	14.42	187.460	42	17.0	14.73	250.410
18	12.5	11.00	137.500	43	17.0	15.62	265.540
19	17.0	18.08	307.360	44	16.0	11.84	189.440
20	22.0	19.33	425.260	45	13.6	14.26	193.936
21	14.0	16.73	234.220	46	15.0	17.67	265.050
22	7.0	10.07	70.490	47	14.5	14.53	210.685
23	17.5	19.40	339.500	48	16.5	16.38	270.270
24	18.5	18.18	336.330	49	17.5	16.29	285.075
25	21.0	19.54	410.340	50	16.5	12.42	204.930
							14204.601

TABLE NO. 23

Sum of ø x ø'

Soil No.	ø	ø'	ø x ø'	Soil No.	ø	ø'	ø x ø'
1	14.5	16.15	234.175	26	25.0	23.78	594.500
2	21.5	20.17	433.655	27	13.0	18.76	243.880
3	8.0	14.77	118.160	28	14.0	22.49	314.860
4	24.0	23.94	574.760	29	28.0	25.52	714.560
5	25.0	23.16	579.000	30	32.0	28.99	927.680
6	18.0	15.00	270.000	31	15.0	17.41	261.150
7	14.0	18.98	265.720	32	32.0	24.14	772.480
8	14.0	15.30	214.200	33	27.0	24.00	648.000
9	27.0	26.19	707.130	34	24.0	19.53	570.720
10	37.0	35.26	1304.620	35	35.5	36.01	1278.355
11	31.0	22.57	699.670	36	30.0	24.76	742.800
12	15.0	16.57	248.550	37	25.0	25.54	638.500
13	28.0	33.71	943.880	38	20.0	29.27	585.400
14	21.5	22.95	493.425	39	30.0	30.13	903.900
15	30.0	27.21	816.300	40	30.5	34.14	1041.270
16	35.0	34.37	1202.950	41	31.0	27.19	842.890
17	33.0	27.84	918.720	42	34.0	27.56	937.040
18	30.0	33.11	993.300	43	28.5	25.55	728.175
19	16.0	22.69	363.040	44	32.0	31.97	1023.040
20	20.0	20.96	419.200	45	29.5	28.17	831.015
21	28.0	24.08	674.240	46	26.0	24.65	640.900
22	33.0	34.50	1138.500	47	26.5	25.06	664.090
23	16.0	19.09	305.440	48	22.0	25.25	555.500
24	15.0	22.23	333.450	49	29.0	25.54	740.660
25	20.0	20.63	412.600	50	32.0	31.07	994.240
							32765.290

TABLE NO. 24

Sums of $Log_{10}\ \phi$ and $(Log_{10}\ \phi)^2$

Soil No.	ϕ	$Log_{10}\phi$	$(Log_{10}\phi)^2$	Soil No.	ϕ	$Log_{10}\phi$	$(Log_{10}\phi)^2$
1	14.5	1.161	1.347921	26	25.0	1.397	1.951609
2	21.5	1.332	1.774224	27	13.0	1.113	1.238769
3	8.0	0.903	0.815409	28	14.0	1.146	1.313316
4	24.0	1.380	1.904400	29	28.0	1.447	2.093809
5	25.0	1.397	1.951609	30	32.0	1.505	2.265025
6	18.0	1.255	1.575025	31	15.0	1.176	1.382976
7	14.0	1.46	1.313316	32	32.0	1.505	2.265025
8	14.0	1.146	1.313316	33	27.0	1.431	2.047761
9	27.0	1.431	2.047761	34	24.0	1.380	1.904400
10	37.0	1.568	2.458624	35	35.5	1.550	2.402500
11	31.0	1.491	2.223081	36	30.0	1.477	2.181529
12	15.0	1.176	1.382976	37	25.0	1.397	1.951609
13	28.0	1.447	2.093809	38	20.0	1.301	1.692601
14	21.5	1.332	1.774224	39	30.0	1.477	2.181529
15	30.0	1.477	2.181529	40	30.5	1.484	2.202256
16	35.0	1.544	2.383936	41	31.0	1.491	2.223081
17	33.0	1.518	2.304324	42	34.0	1.531	2.343961
18	30.0	1.477	2.181529	43	28.5	1.454	2.114116
19	16.0	1.204	1.449616	44	32.0	1.505	2.265025
20	20.0	1.301	1.692601	45	29.5	1.470	2.160900
21	28.0	1.447	2.093809	46	26.0	1.415	2.002225
22	33.0	1.518	2.304324	47	26.5	1.423	2.024929
23	16.0	1.204	1.449616	48	22.0	1.342	1.800964
24	15.0	1.176	1.382976	49	29.0	1.462	2.137444
25	20.0	1.301	1.692601	50	32.0	1.505	2.265025
						68.716	95.504940

TABLE NO. 25

Sum of $Log_{10}\phi \times W_1$

Soil No.	$Log_{10}\phi$	W_1	$Log_{10}\phi \times W_1$	Soil No.	$Log_{10}\phi$	W_1	$Log_{10}\phi \times W_1$
1	1.161	59.0	68.499	26	1.397	41.8	58.3946
2	1.332	50.0	66.600	27	1.113	53.1	59.1003
3	0.903	62.0	55.986	28	1.146	44.6	51.0236
4	1.380	41.5	57.270	29	1.447	37.7	54.5519
5	1.397	43.0	60.071	30	1.505	30.6	46.0530
6	1.255	61.0	76.555	31	1.176	56.0	65.8560
7	1.146	52.2	59.8212	32	1.505	41.0	61.7050
8	1.146	60.3	69.1038	33	1.431	41.3	59.1003
9	1.431	36.7	52.5177	34	1.380	51.1	70.5184
10	1.568	16.8	26.3424	35	1.550	15.4	23.8700
11	1.491	44.5	66.3495	36	1.477	39.4	58.1938
12	1.176	57.8	67.9728	37	1.397	37.1	51.8287
13	1.447	20.0	28.940	38	1.301	29.6	38.5096
14	1.332	45.8	61.0056	39	1.477	28.1	41.5037
15	1.477	34.1	50.3657	40	1.484	19.4	28.7896
16	1.544	18.8	29.0272	41	1.491	34.1	50.8431
17	1.518	32.8	49.7904	42	1.531	33.6	51.4416
18	1.477	21.5	31.7555	43	1.454	37.3	54.2342
19	1.204	44.3	53.3372	44	1.505	24.1	36.2705
20	1.301	48.2	62.7082	45	1.470	32.2	47.3340
21	1.447	40.8	59.0376	46	1.415	39.9	56.4585
22	1.518	18.5	28.0830	47	1.423	39.2	55.7816
23	1.204	52.0	62.6080	48	1.342	40.2	53.9484
24	1.176	54.0	52.920	49	1.462	38.3	55.9946
25	1.301	48.9	63.6189	50	1.505	26.1	39.2805
							2630.8708

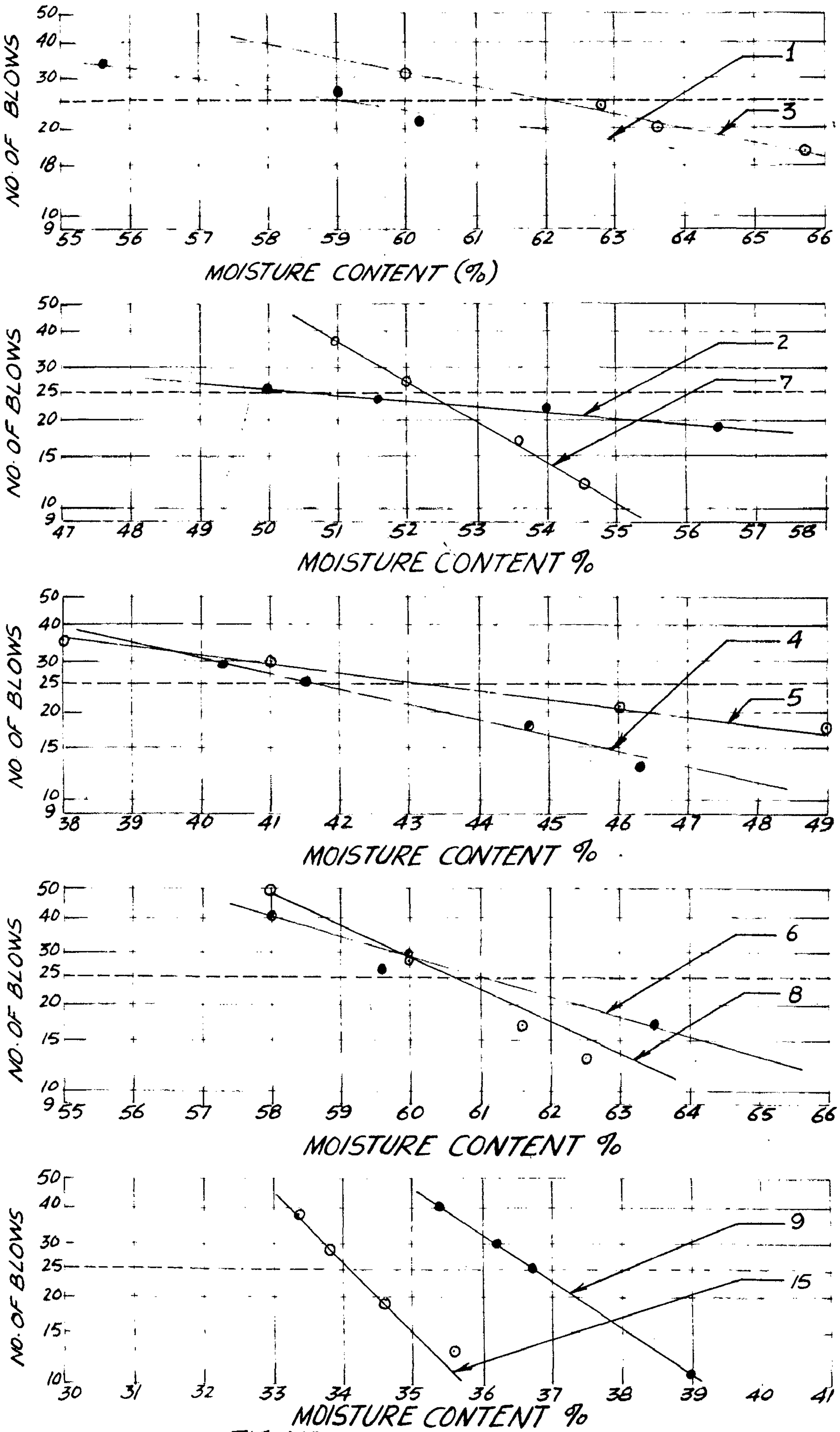


FIG. NO. 22 FLOW CURVES

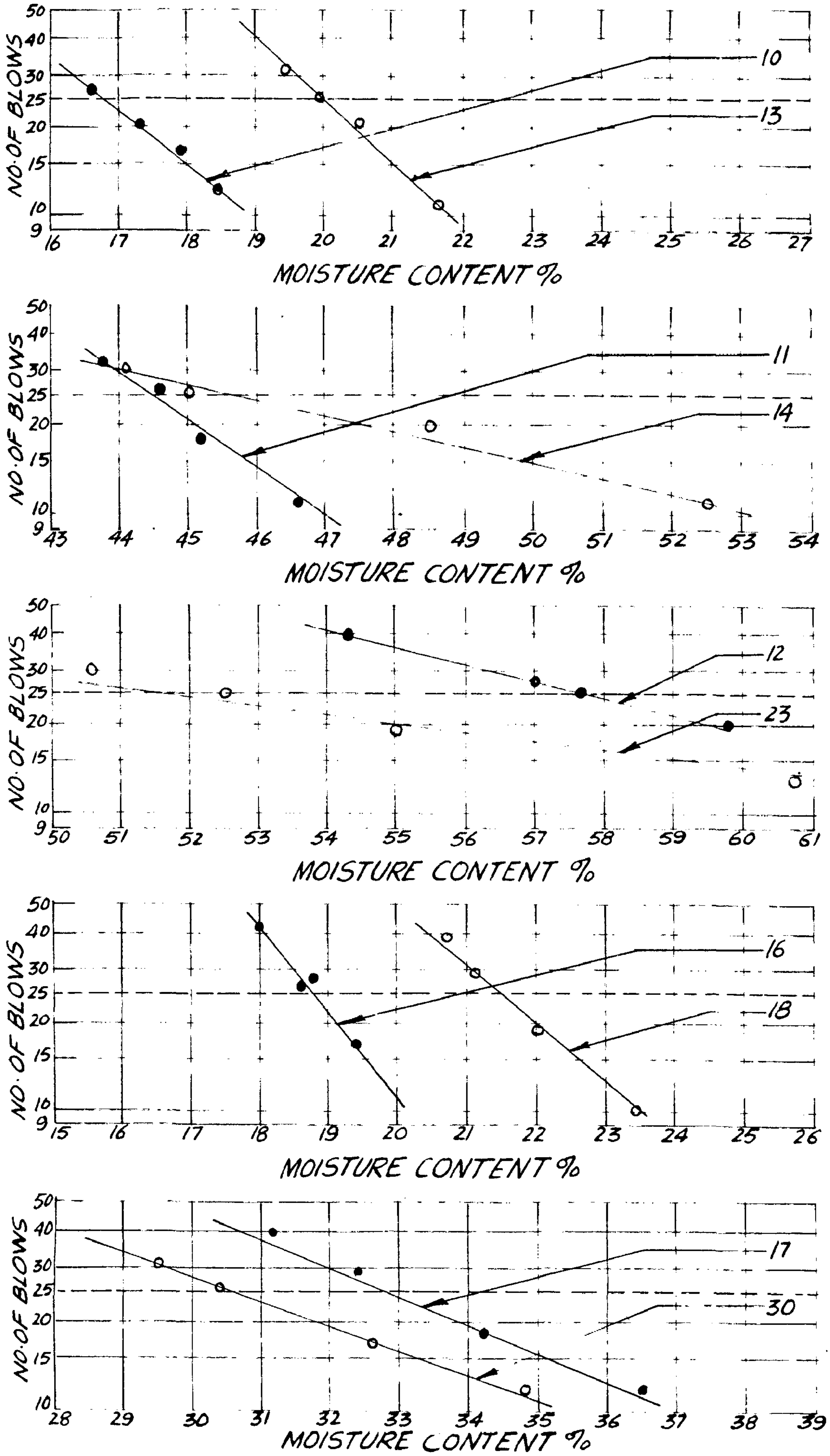


FIG. NO. 23 FLOW CURVES

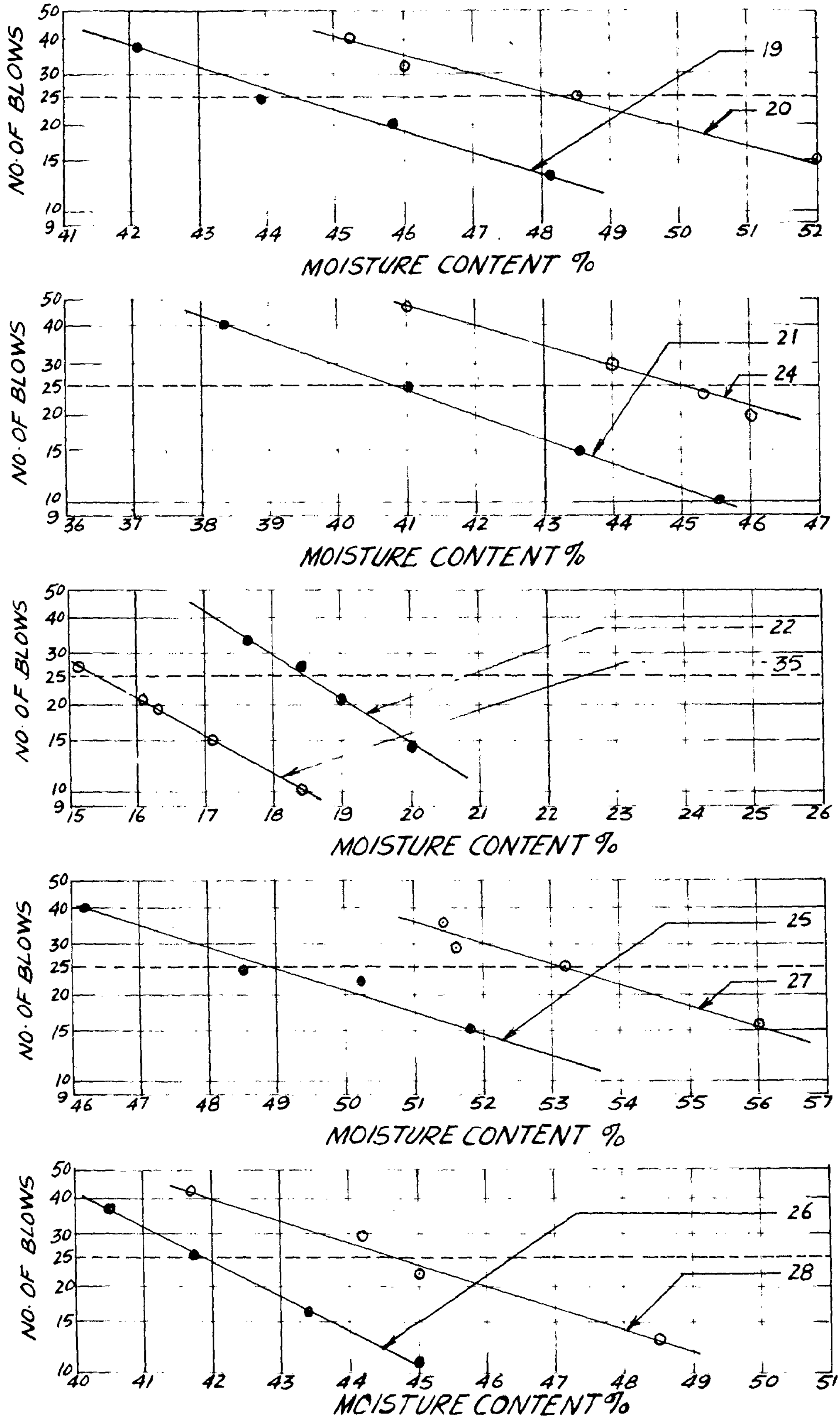


FIG. NO. 24 FLOW CURVES

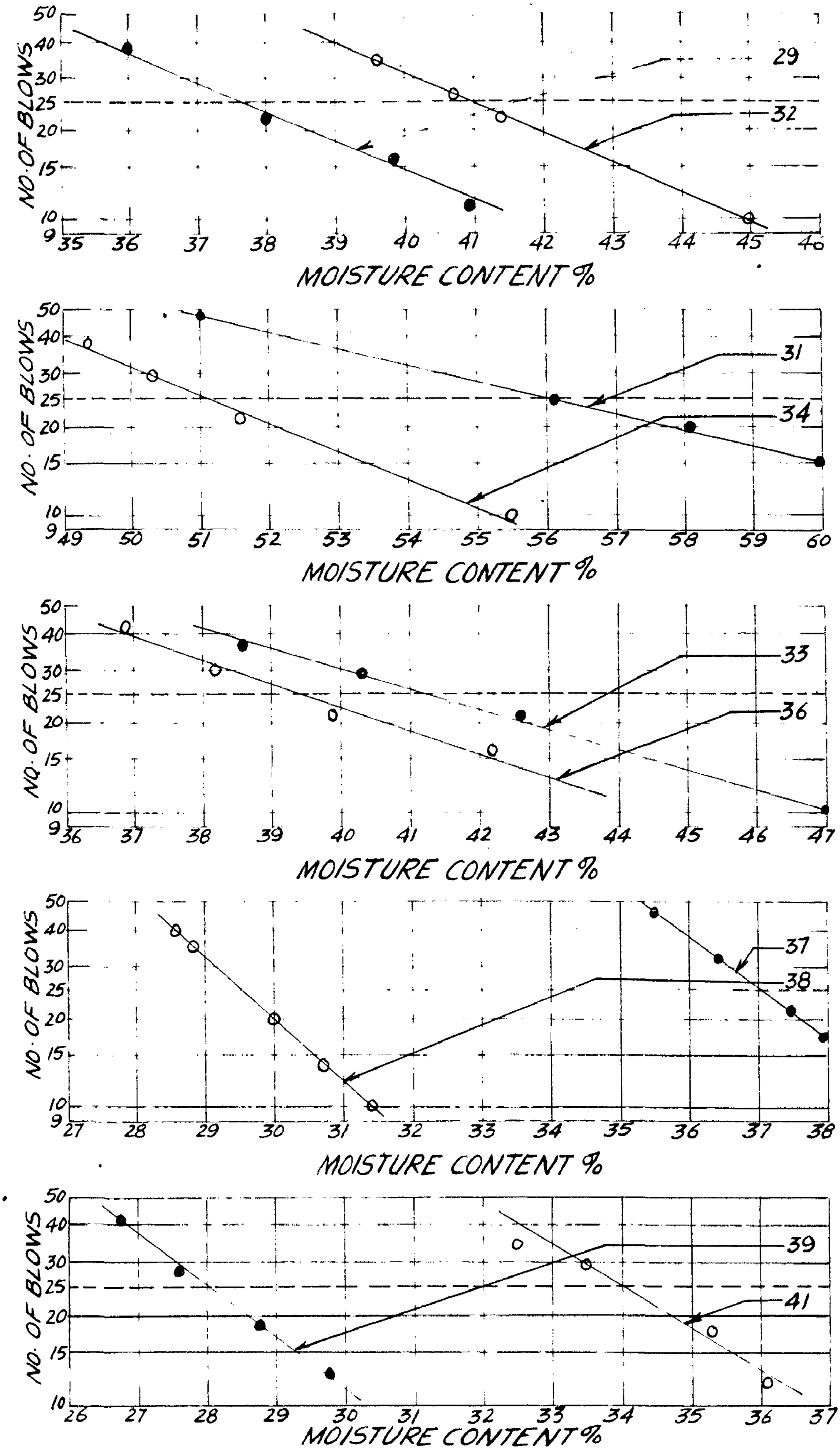
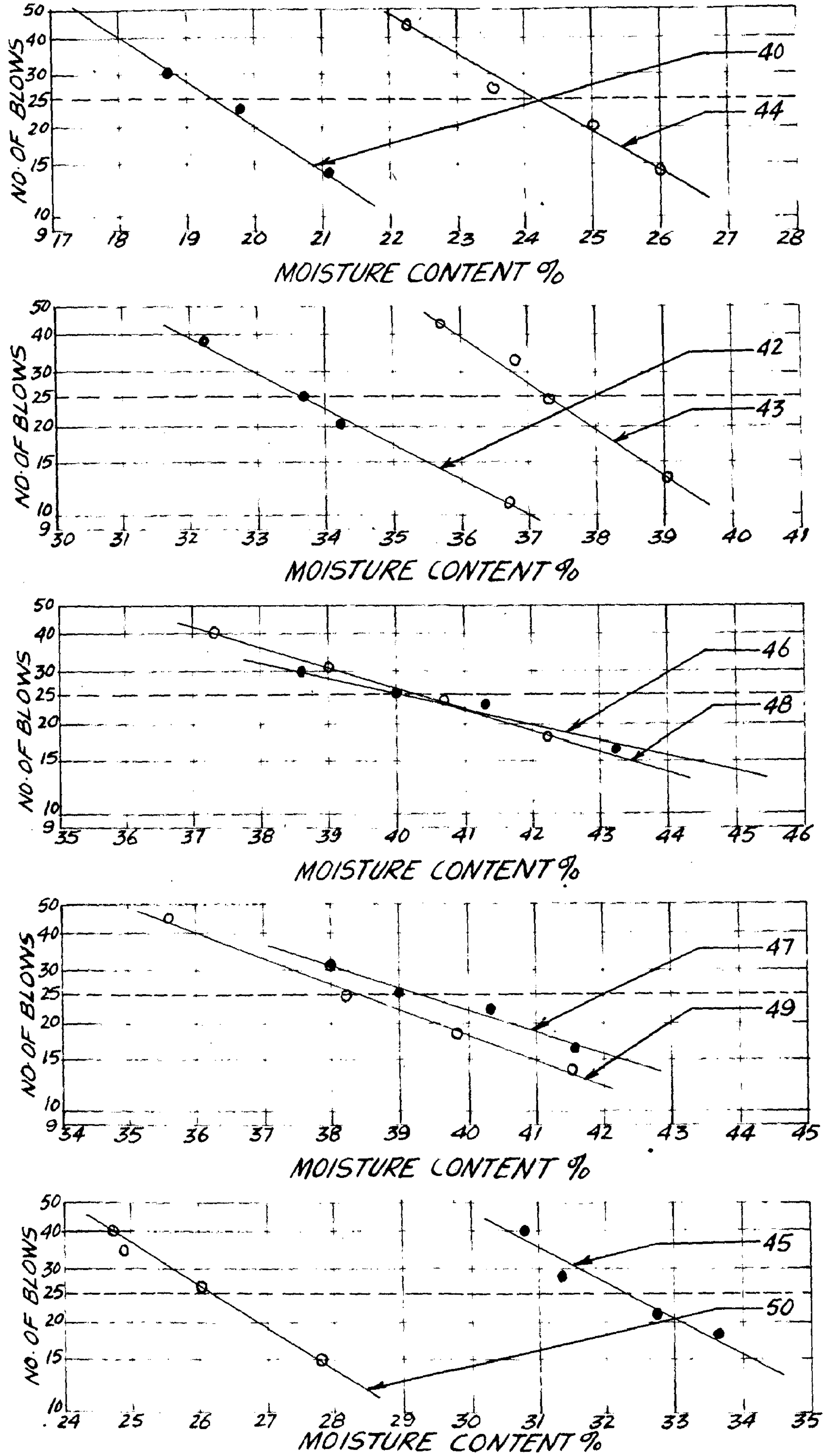


FIG NO.25 FLOW CURVES



FIG·NO·26 FLOW CURVES

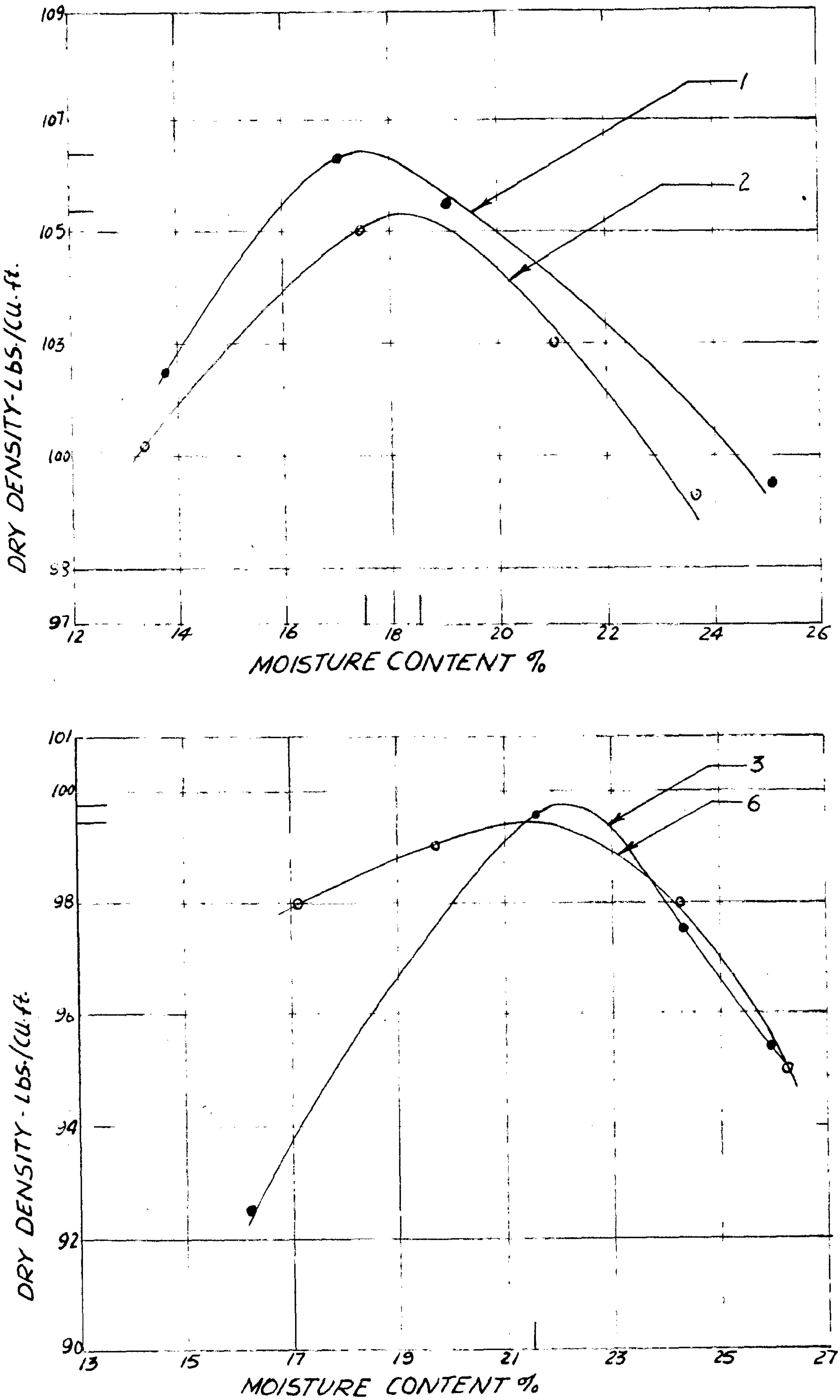
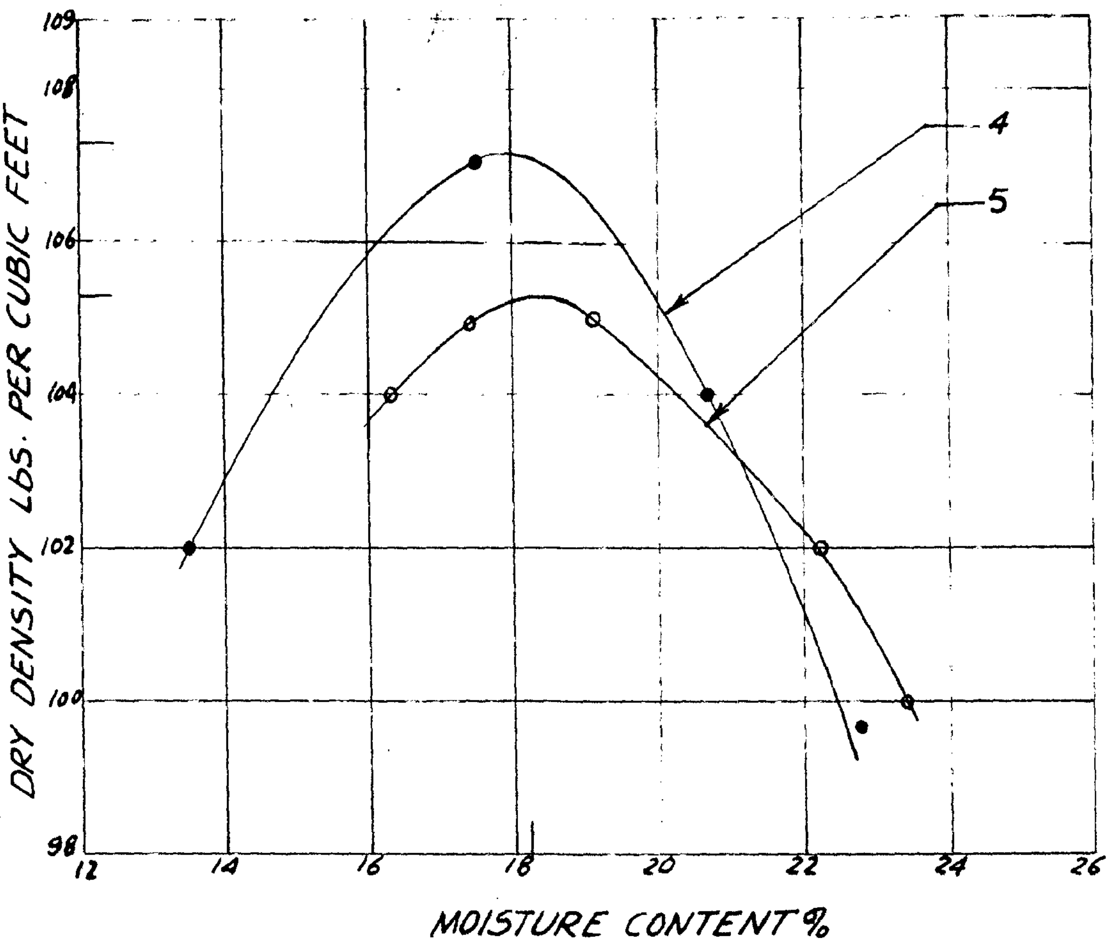


FIG. NO. 27 MOISTURE DENSITY CURVES



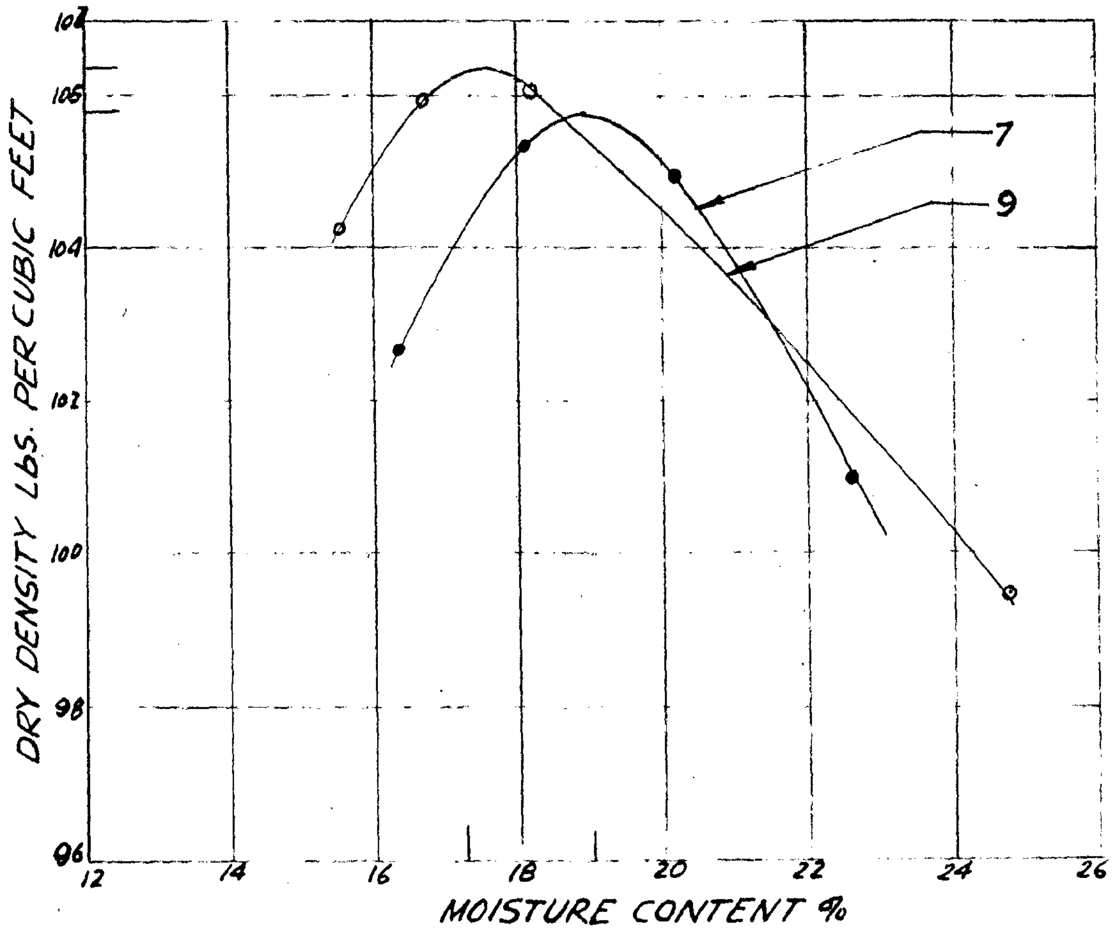
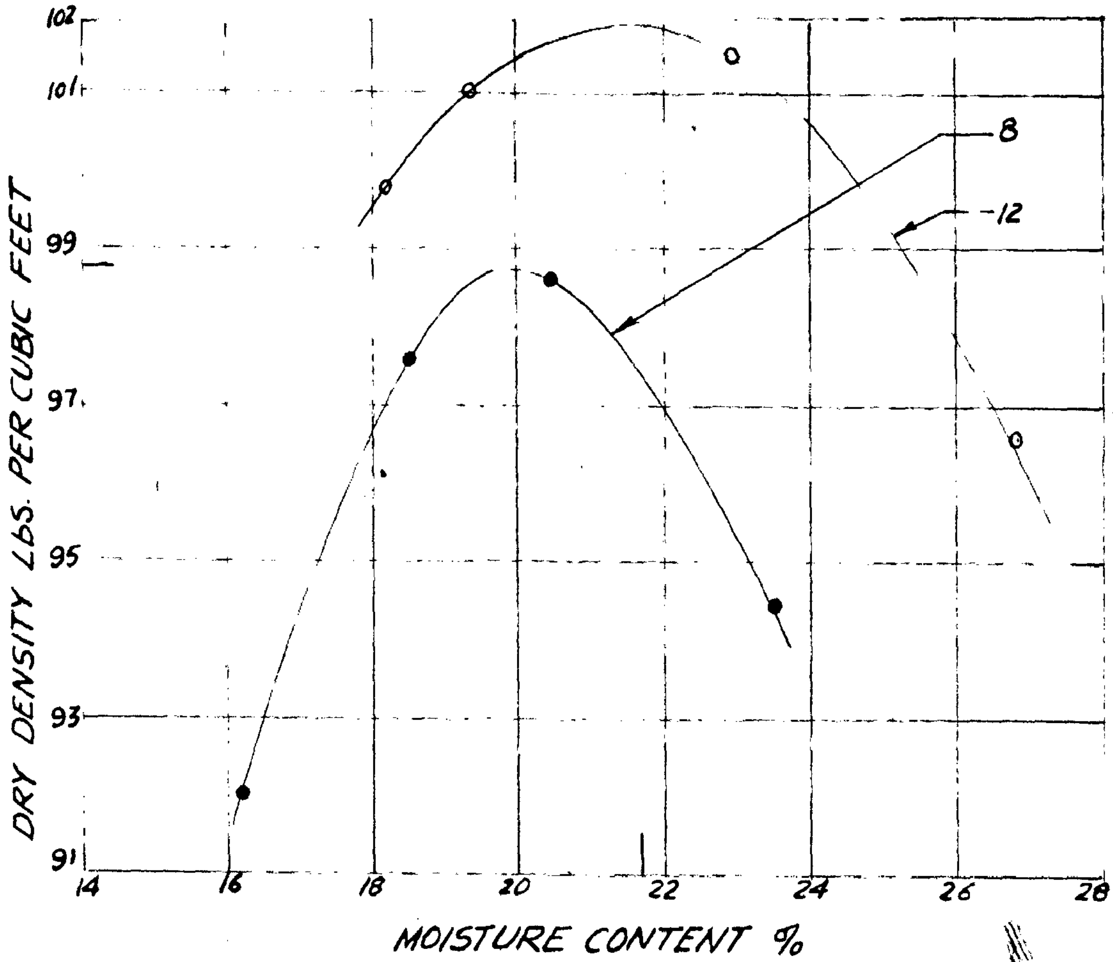


FIG. NO. 28 MOISTURE DENSITY CURVES



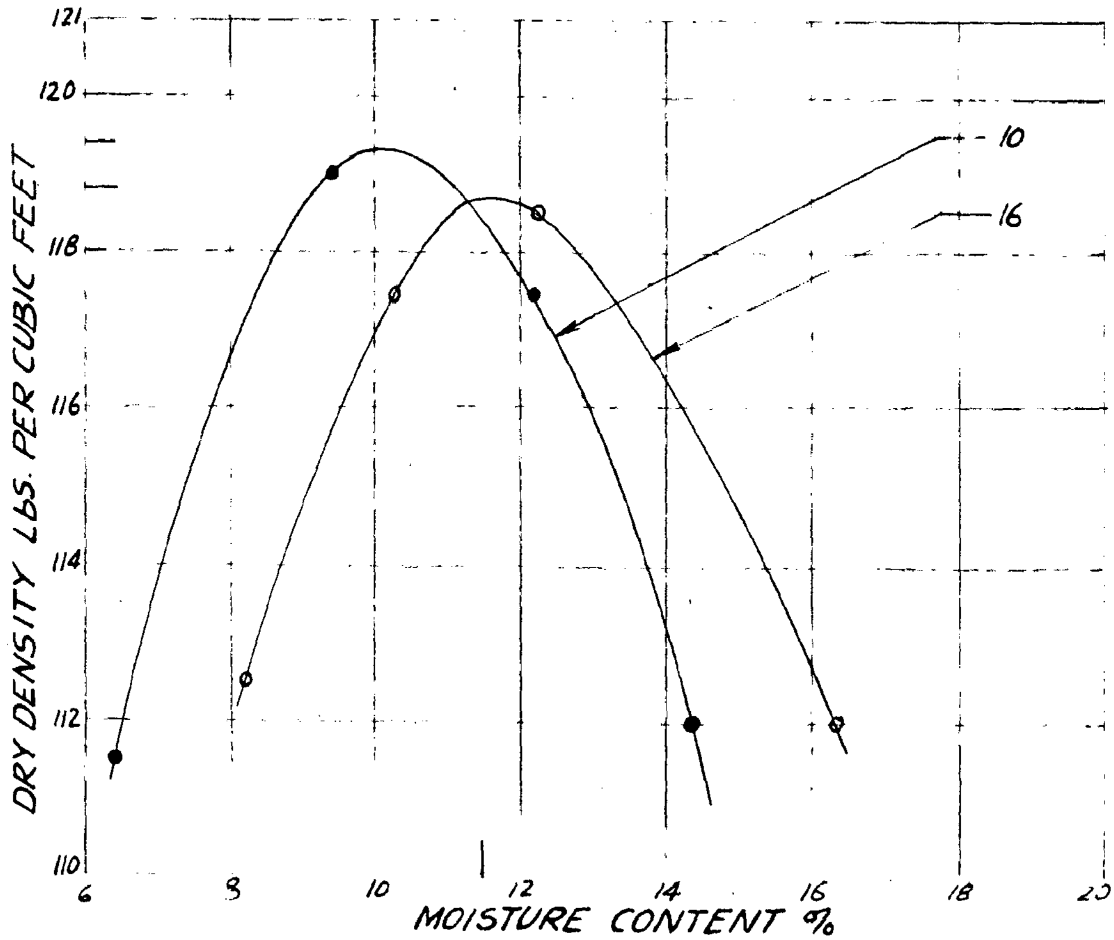


FIG. NO 29 MOISTURE DENSITY CURVE

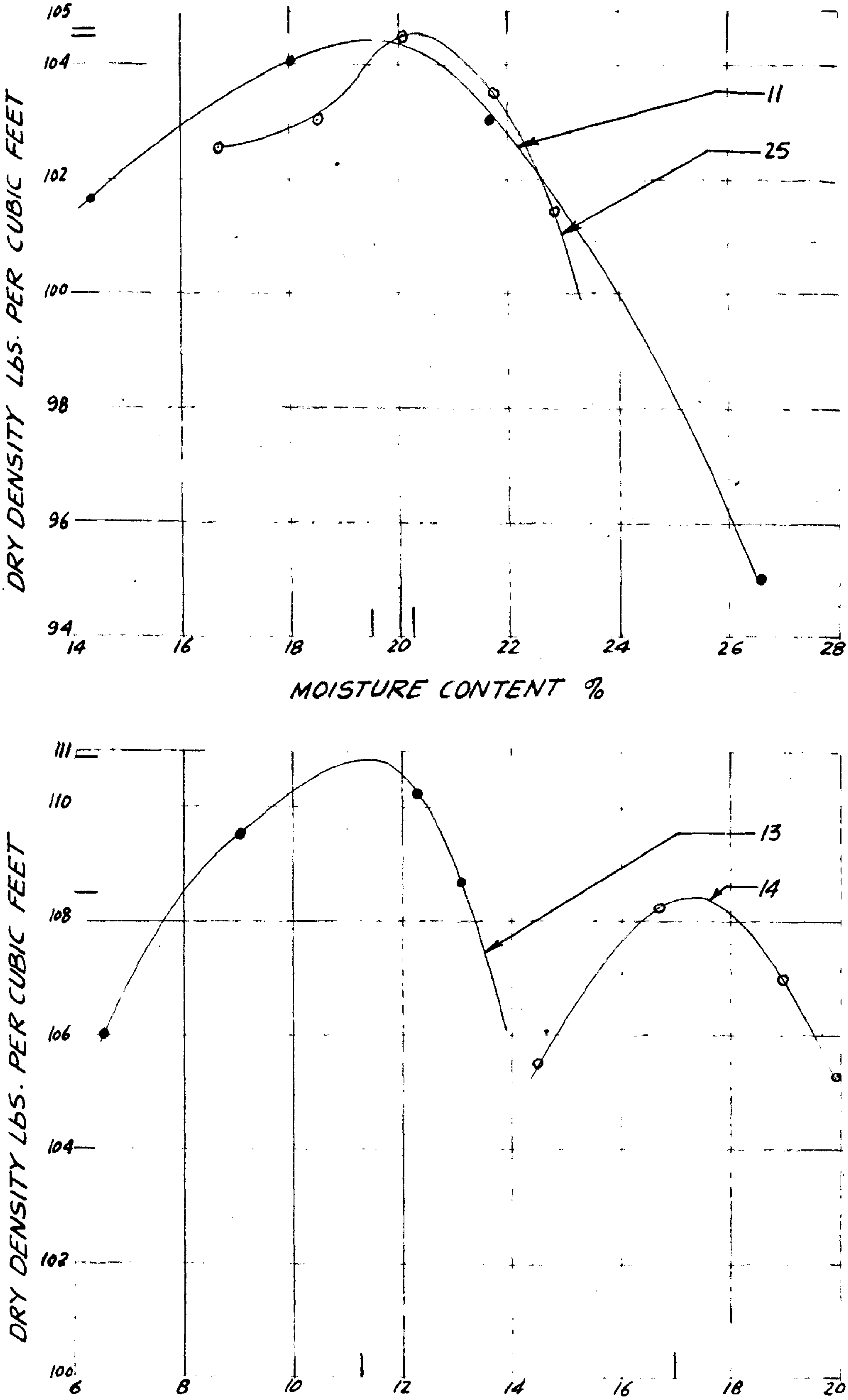
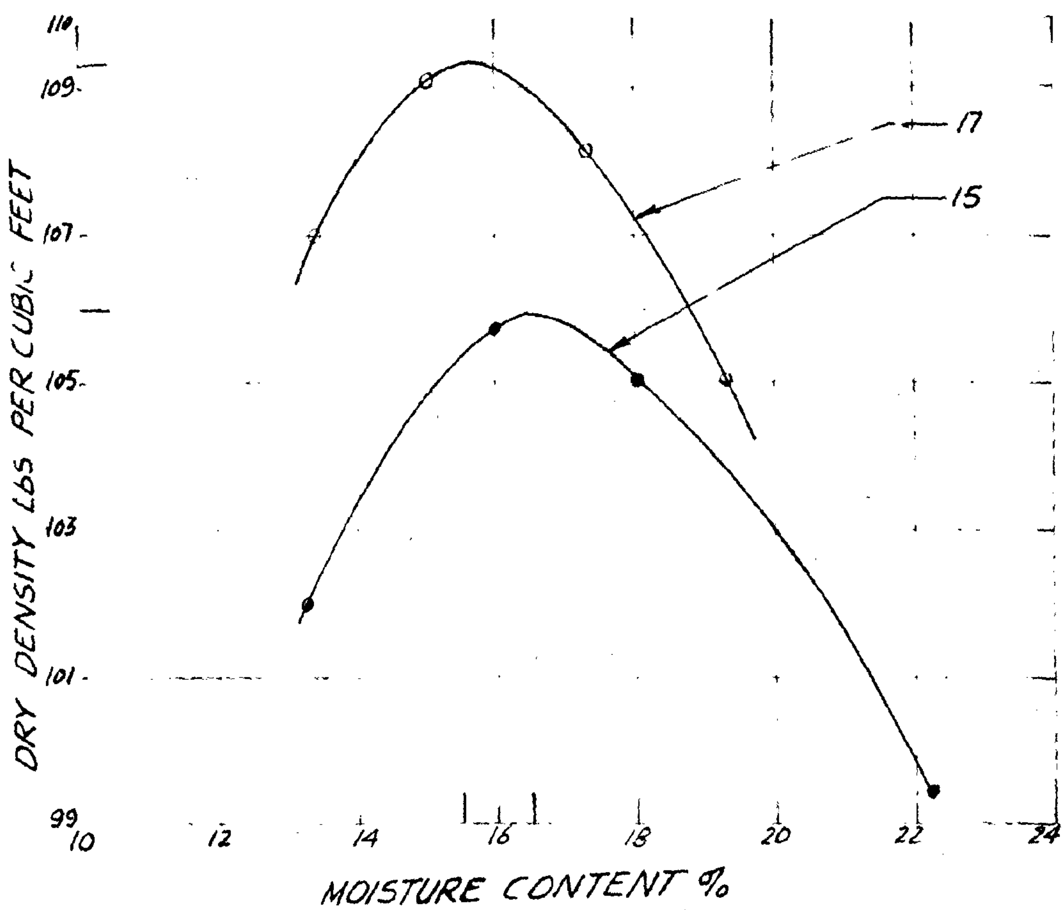
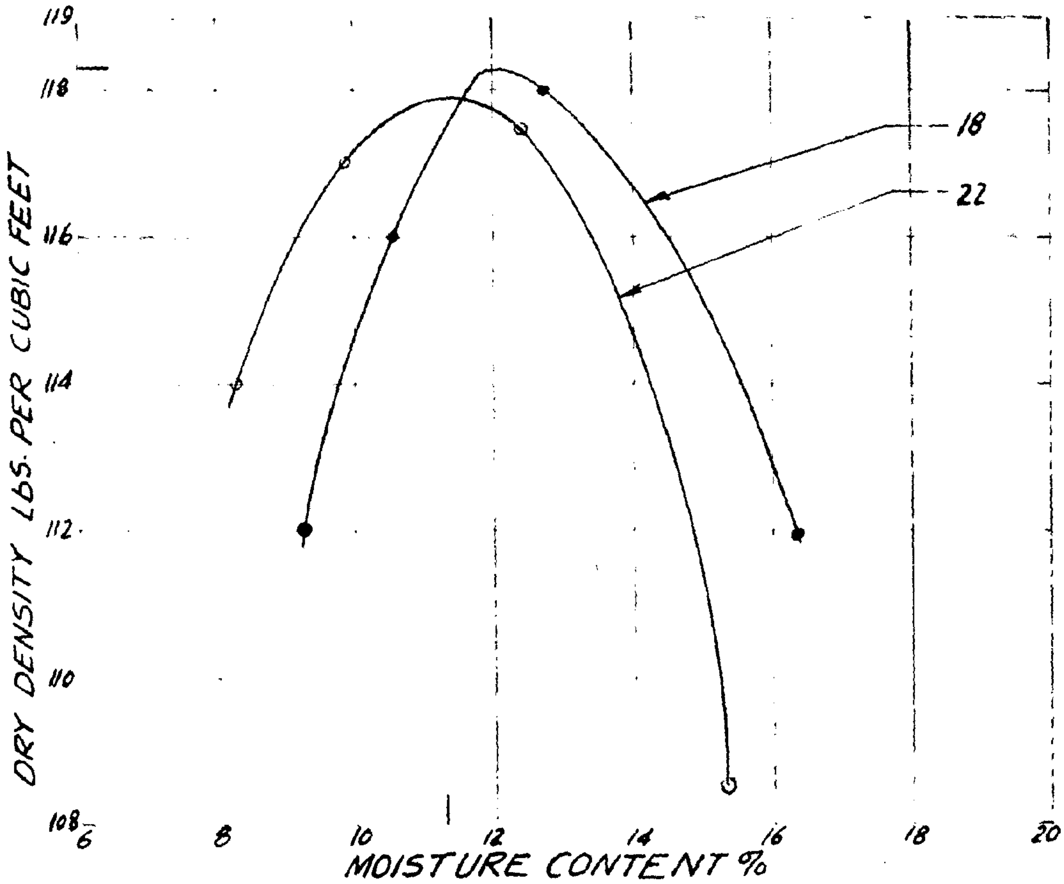


FIG. NO. 30 MOISTURE DENSITY CURVES





FIG·NO·31 MOISTURE DENSITY CURVES

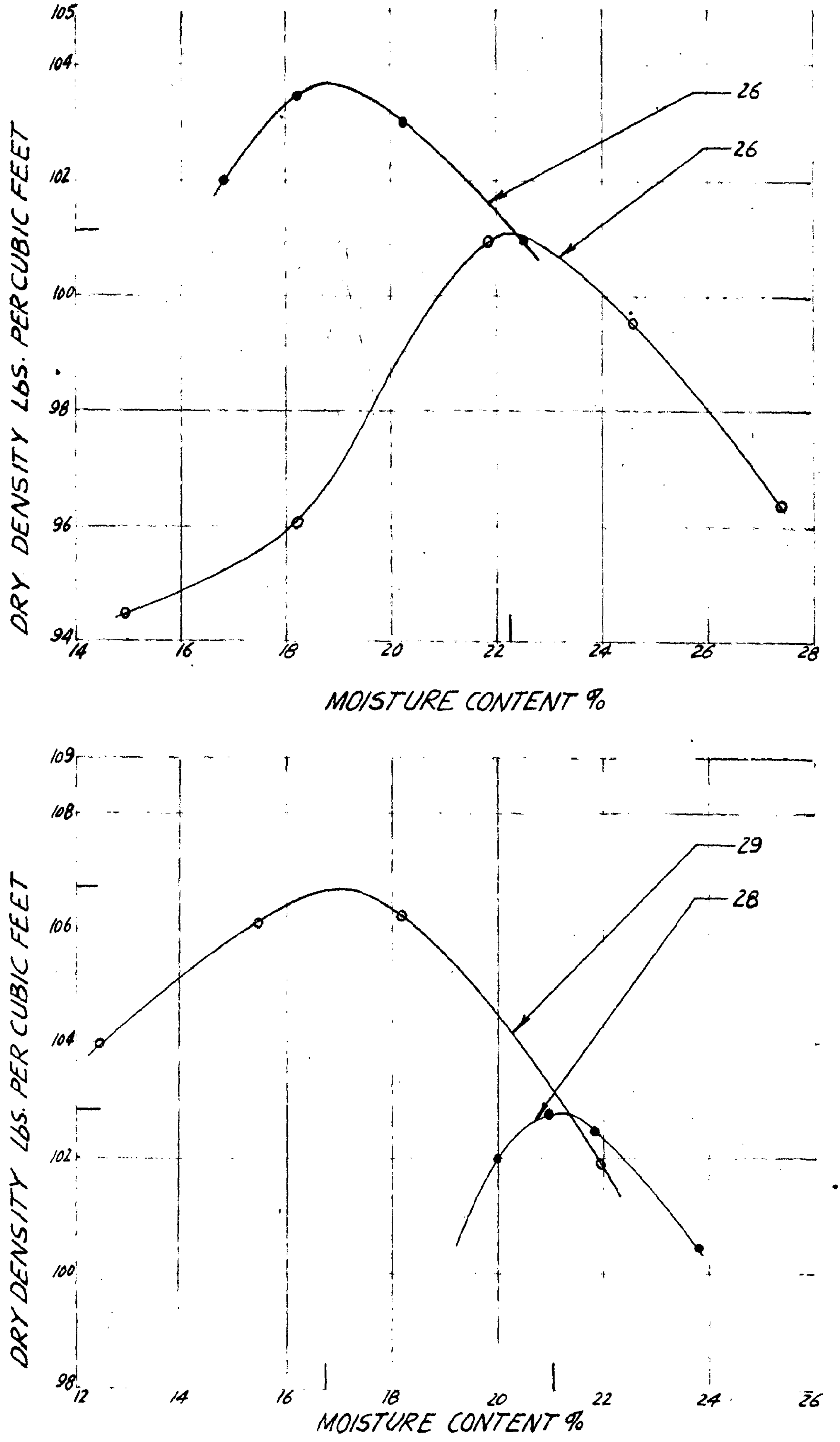
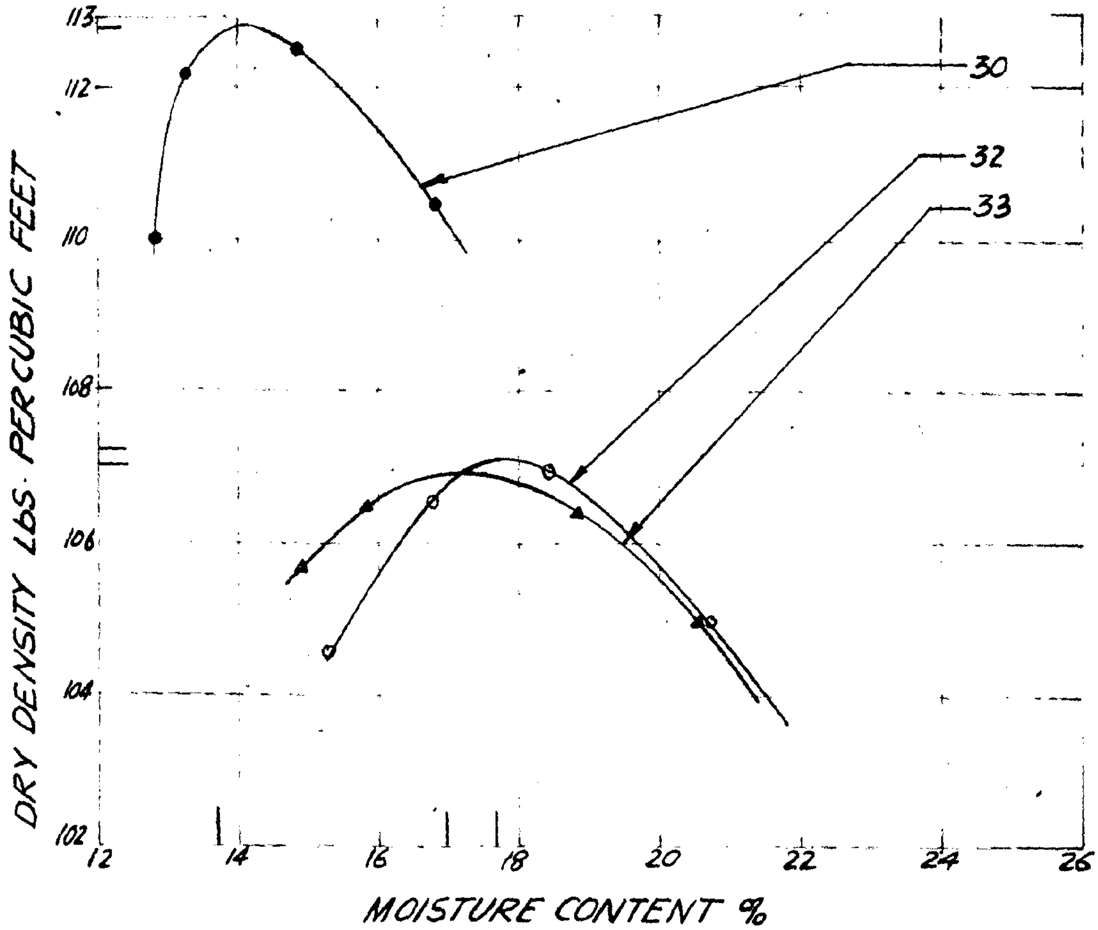


FIG. NO 33 MOISTURE DENSITY CURVE



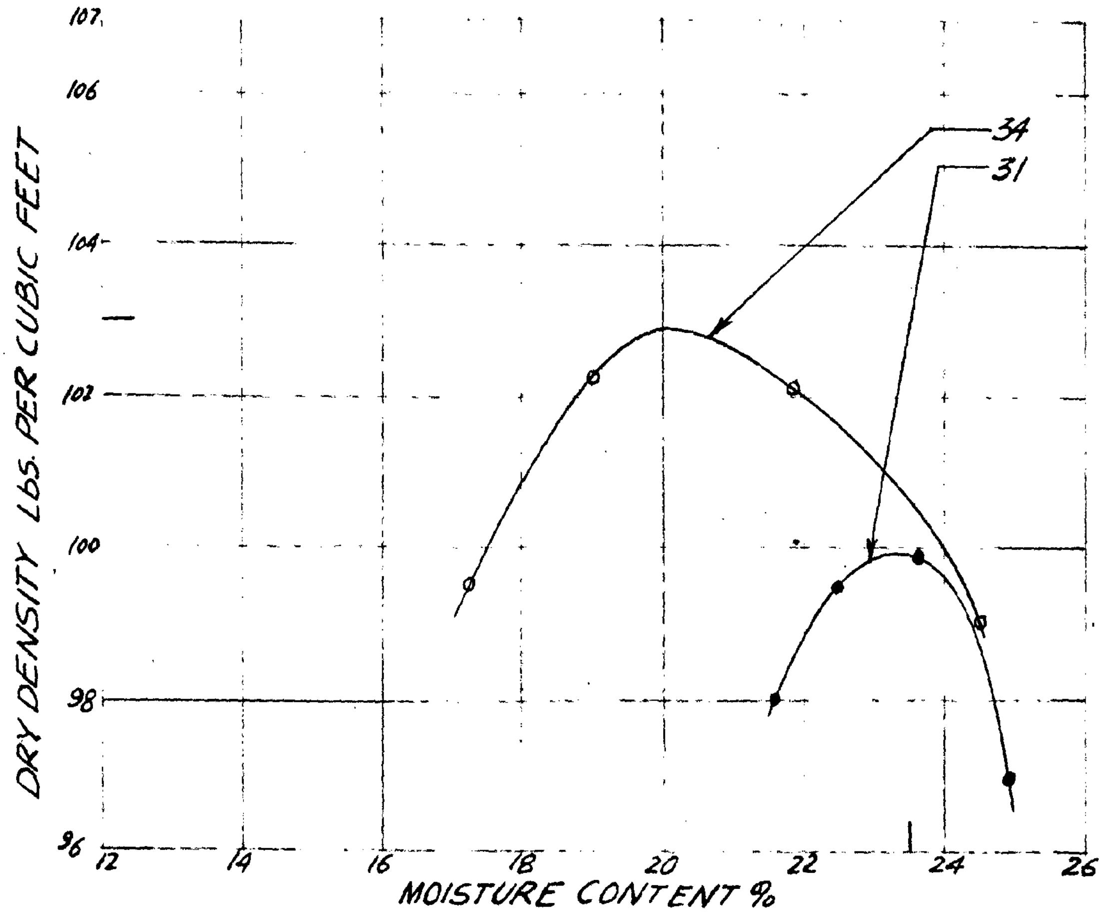


FIG. NO 34 MOISTURE DENSITY CURVES

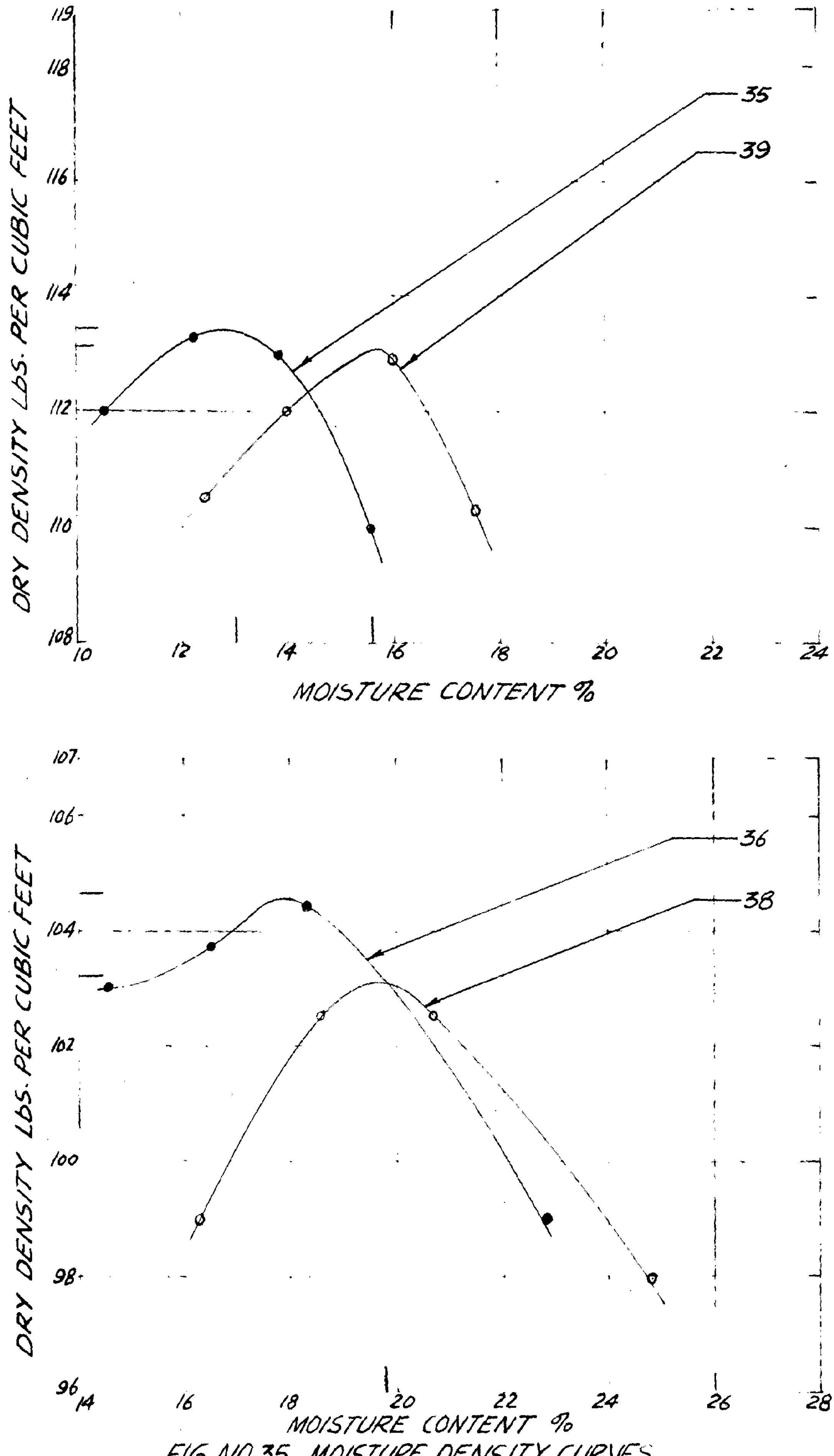
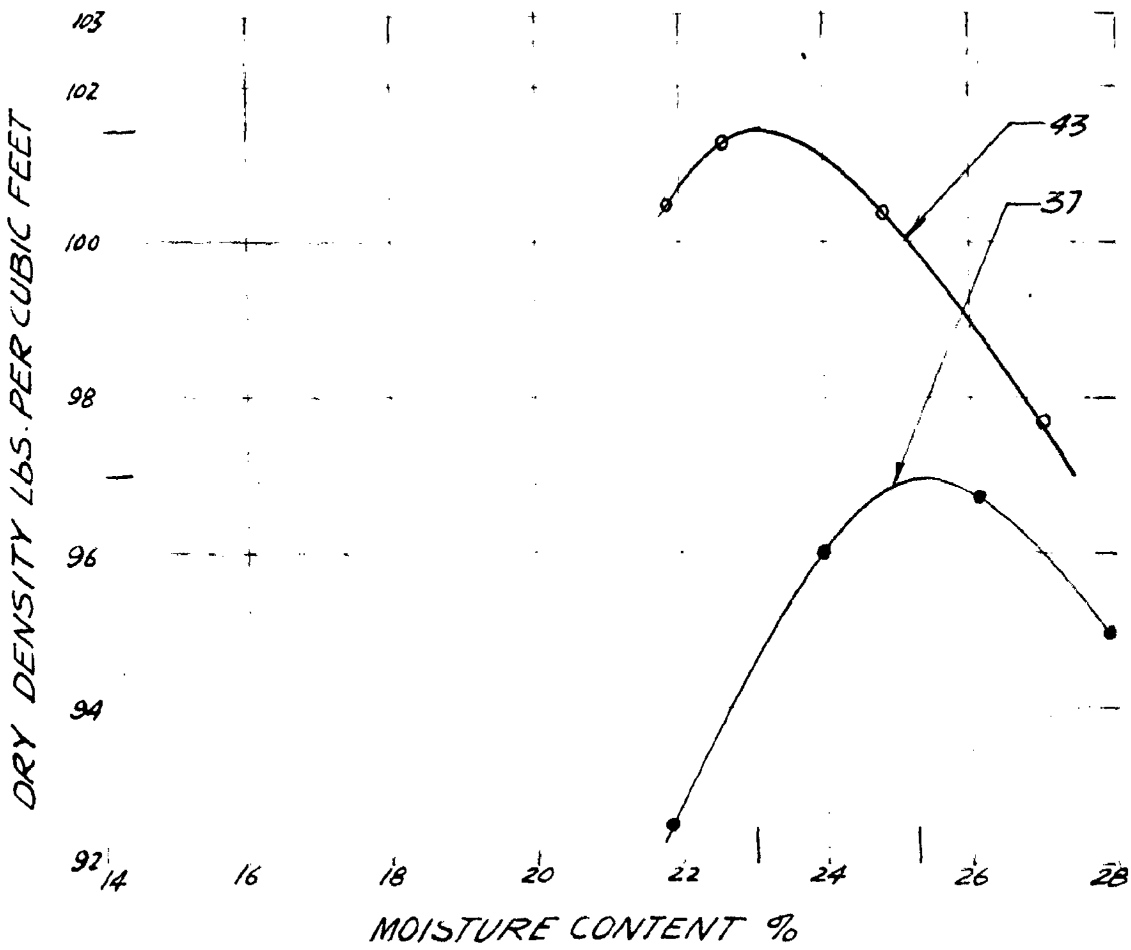


FIG. NO. 35 MOISTURE DENSITY CURVES



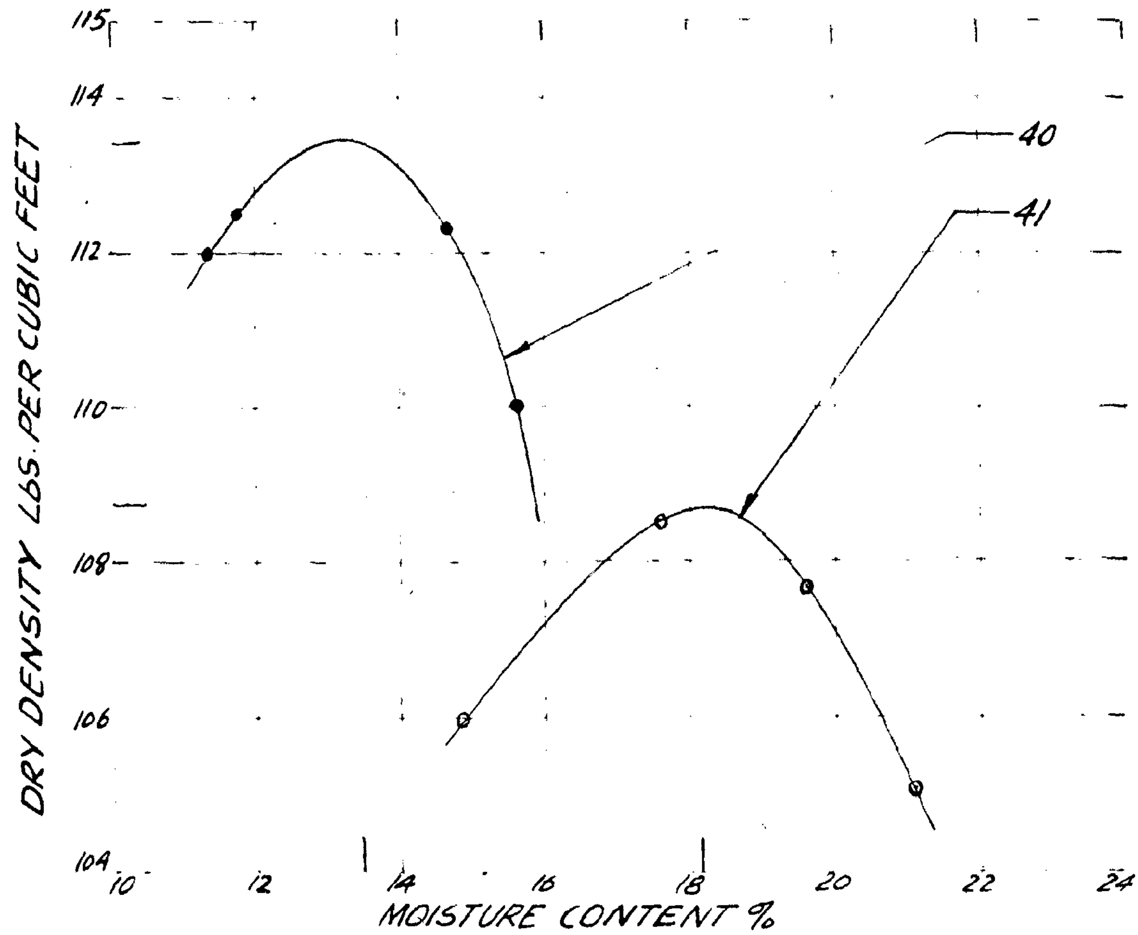


FIG. NO. 36 MOISTURE DENSITY CURVES

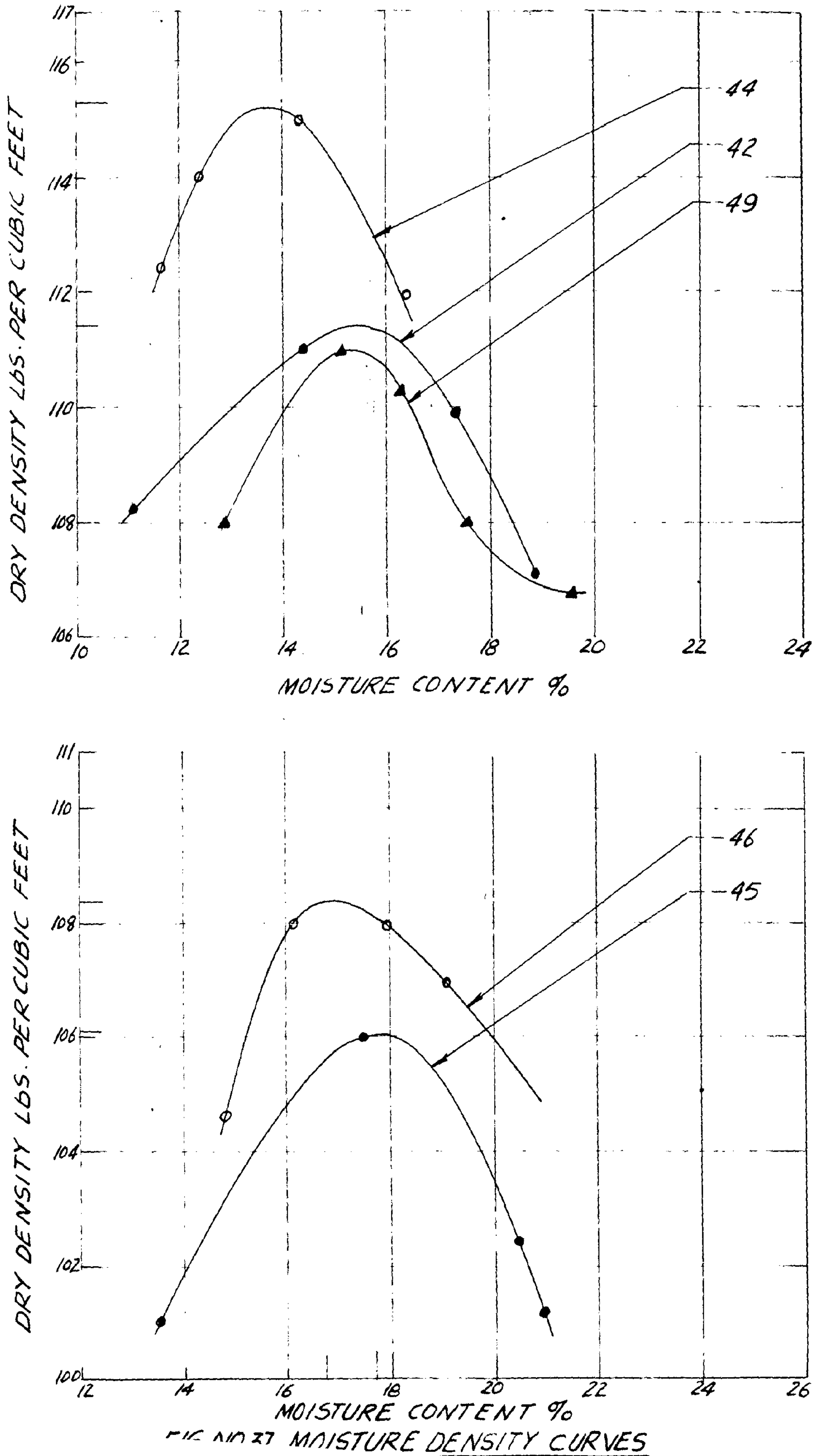


FIG NO 37 MOISTURE DENSITY CURVES

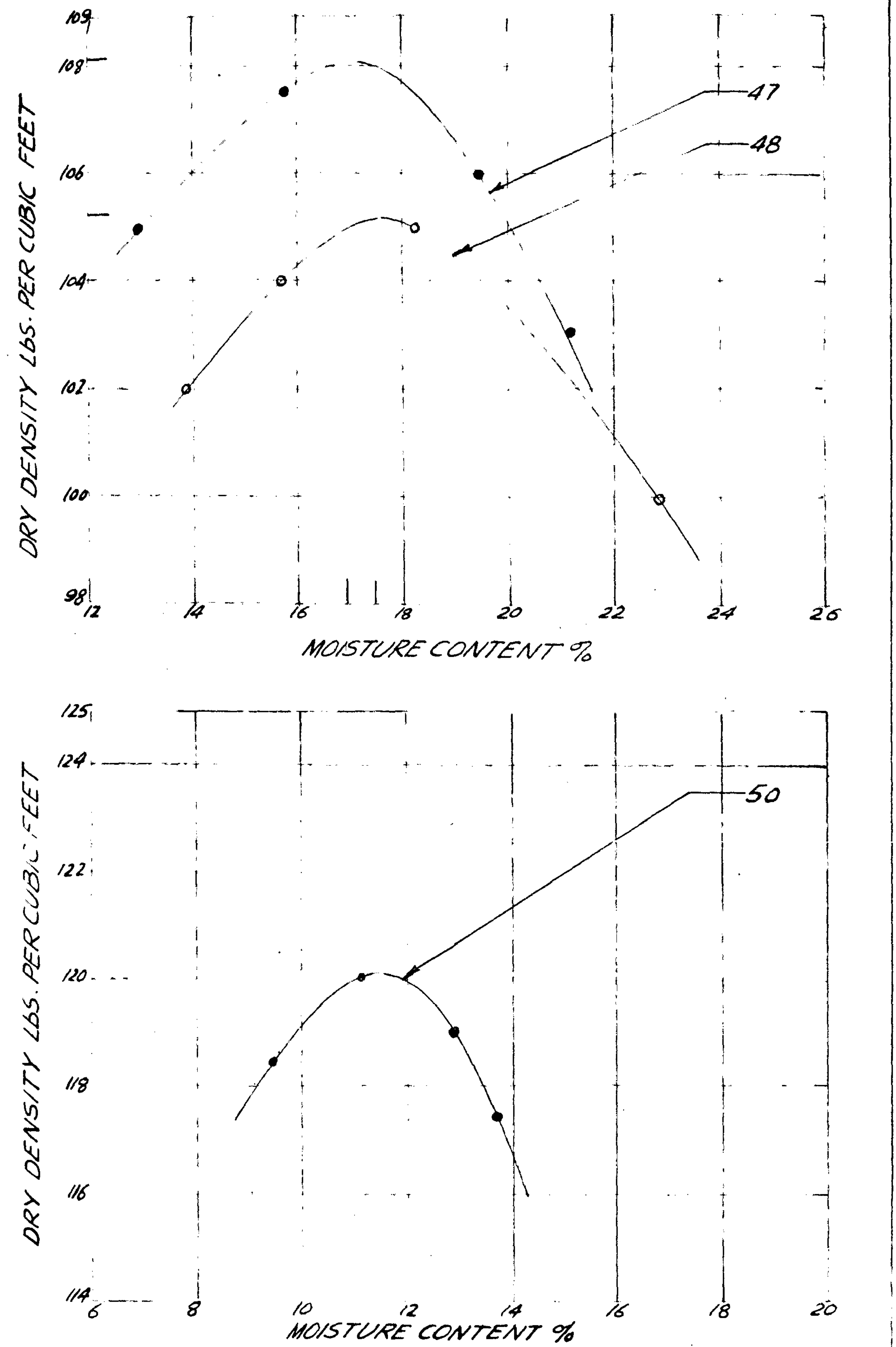


FIG. NO. 38 MOISTURE DENSITY CURVES

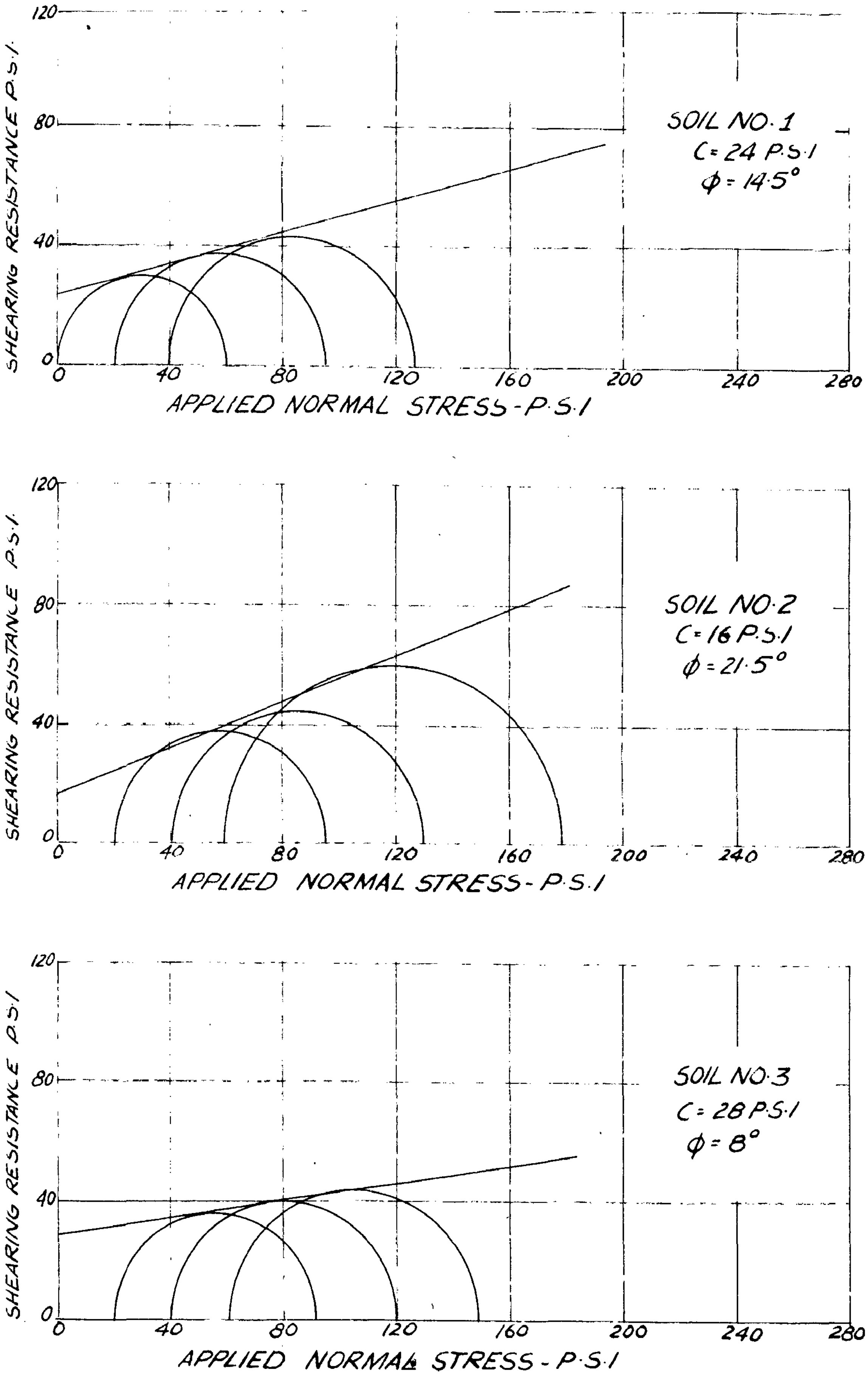
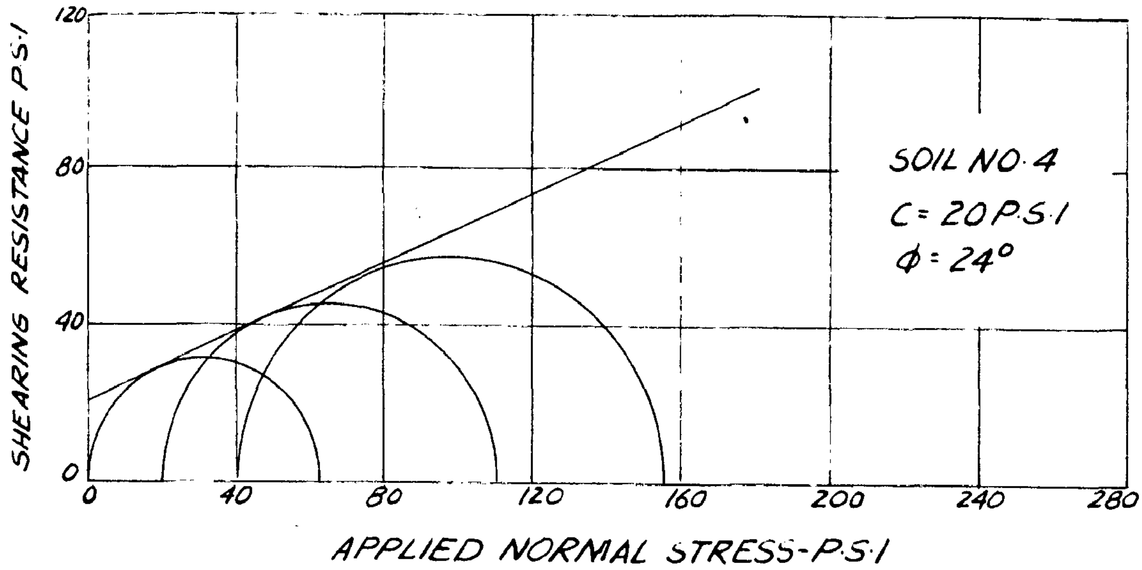
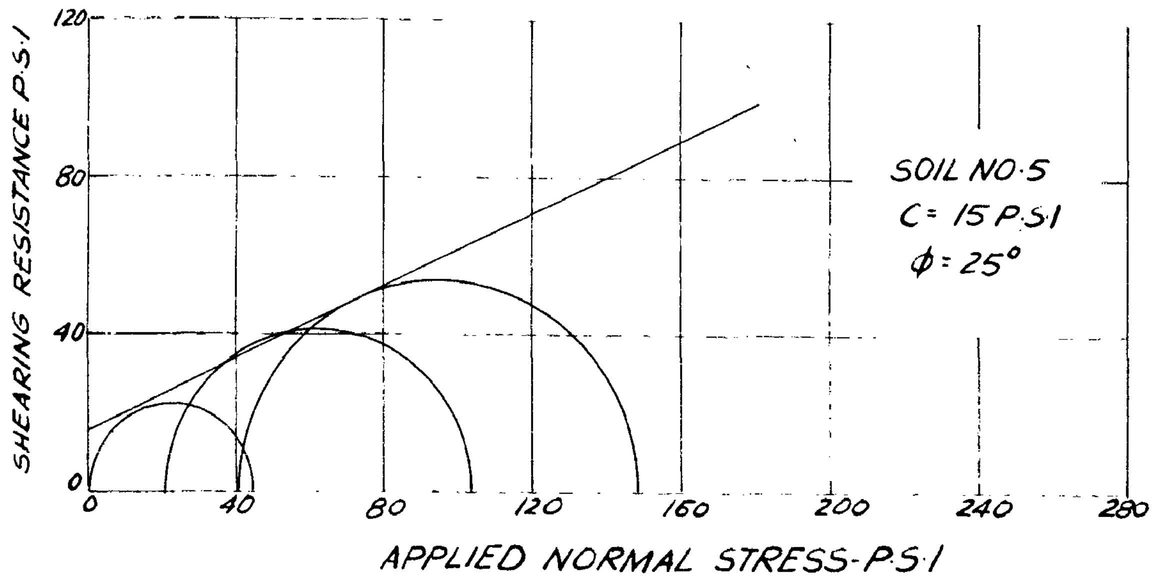
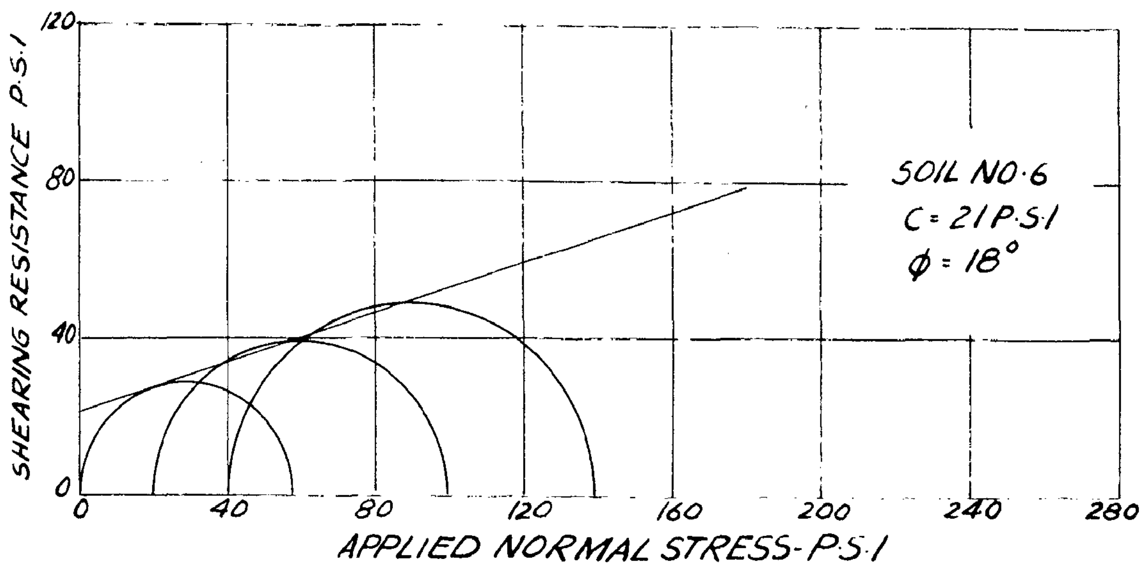


FIG. NO. 39 MOHR'S RUPTURE DIAGRAMS







FIG·NO·40 MOHR'S RUPTURE DIAGRAMS

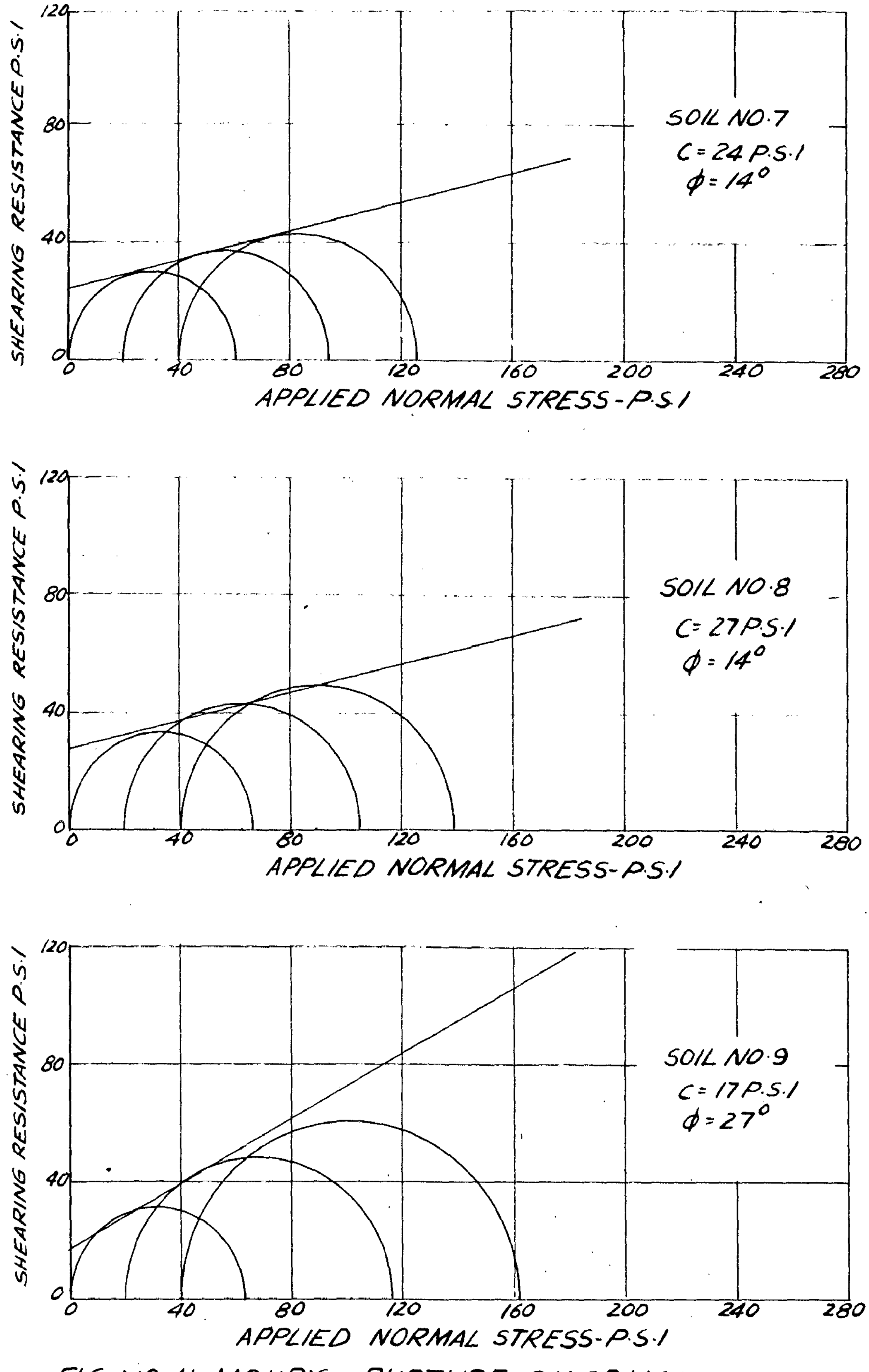


FIG. NO. 41 MOHR'S RUPTURE DIAGRAMS

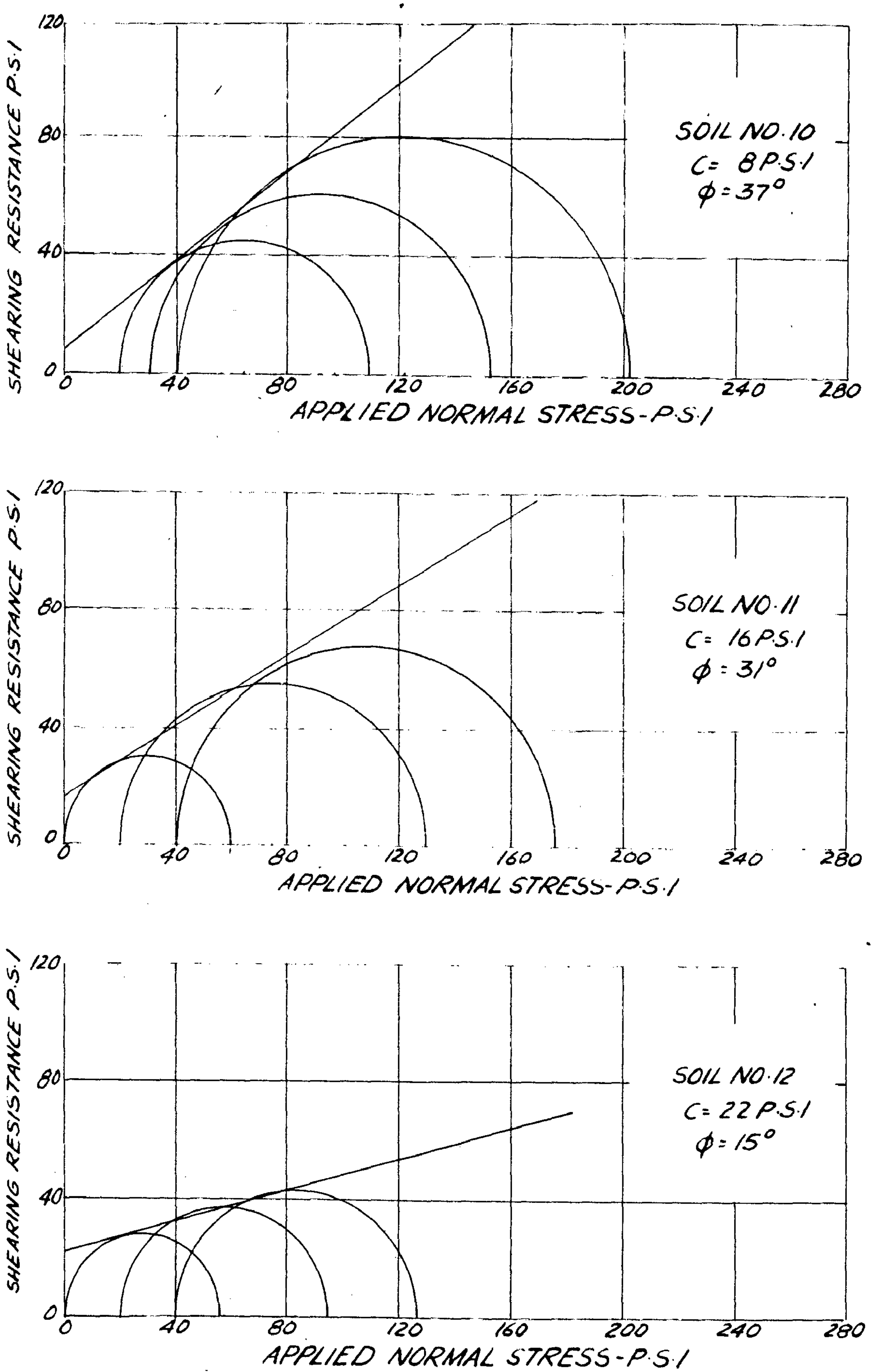


FIG. NO. 42 MOHR'S RUPTURE DIAGRAMS

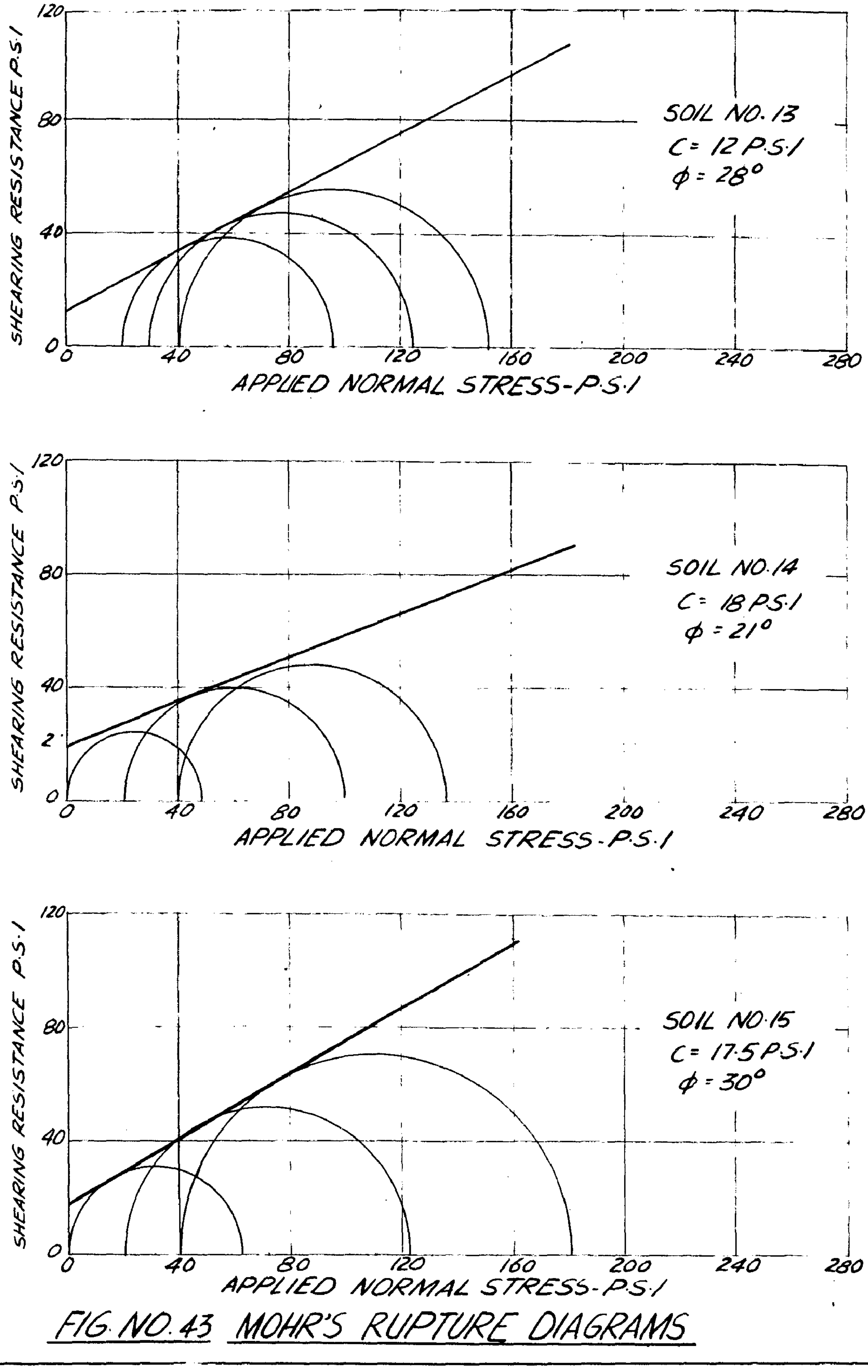


FIG. NO. 43 MOHR'S RUPTURE DIAGRAMS

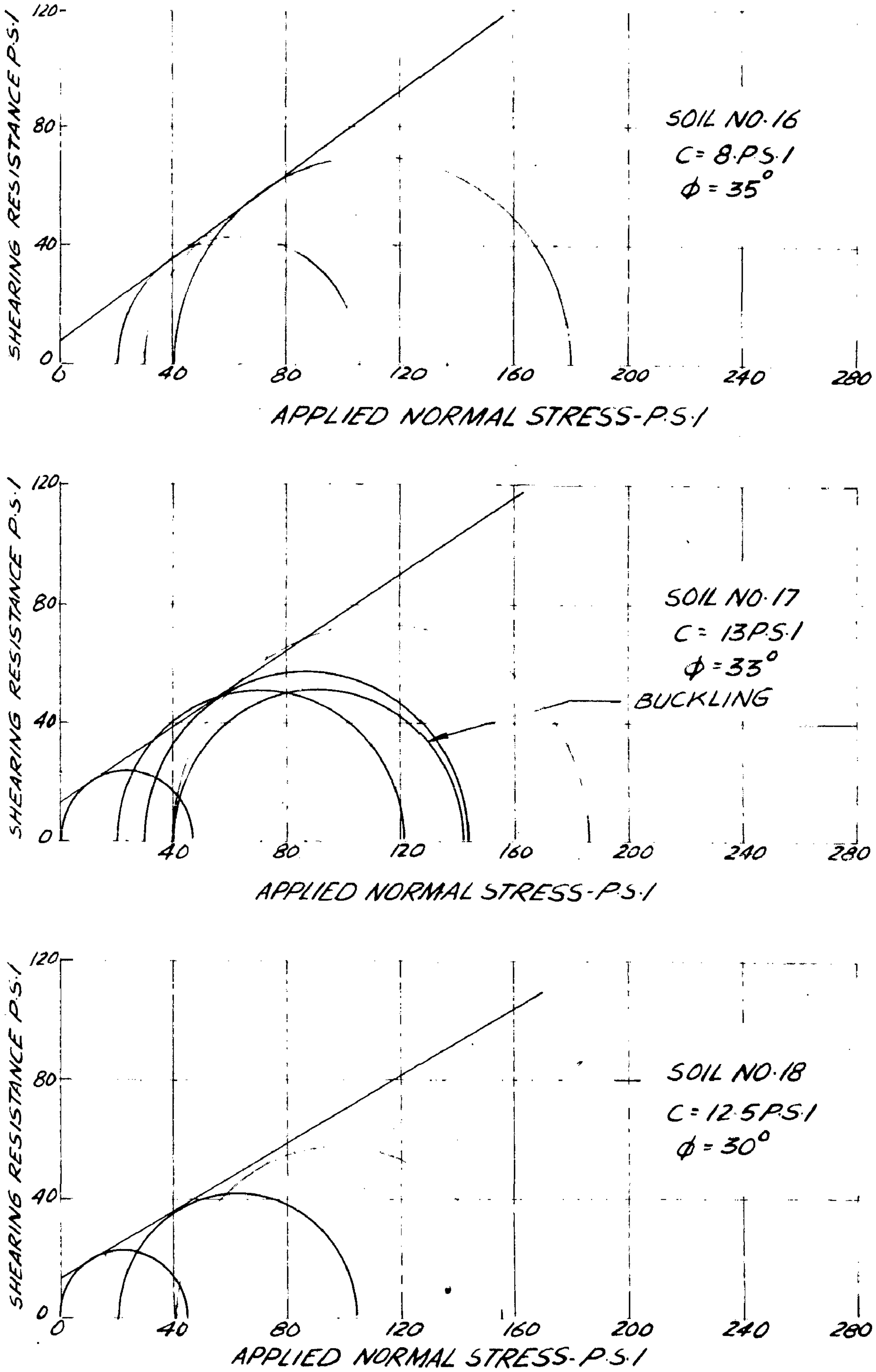


FIG. NO. 44 MOHR'S RUPTURE DIAGRAMS

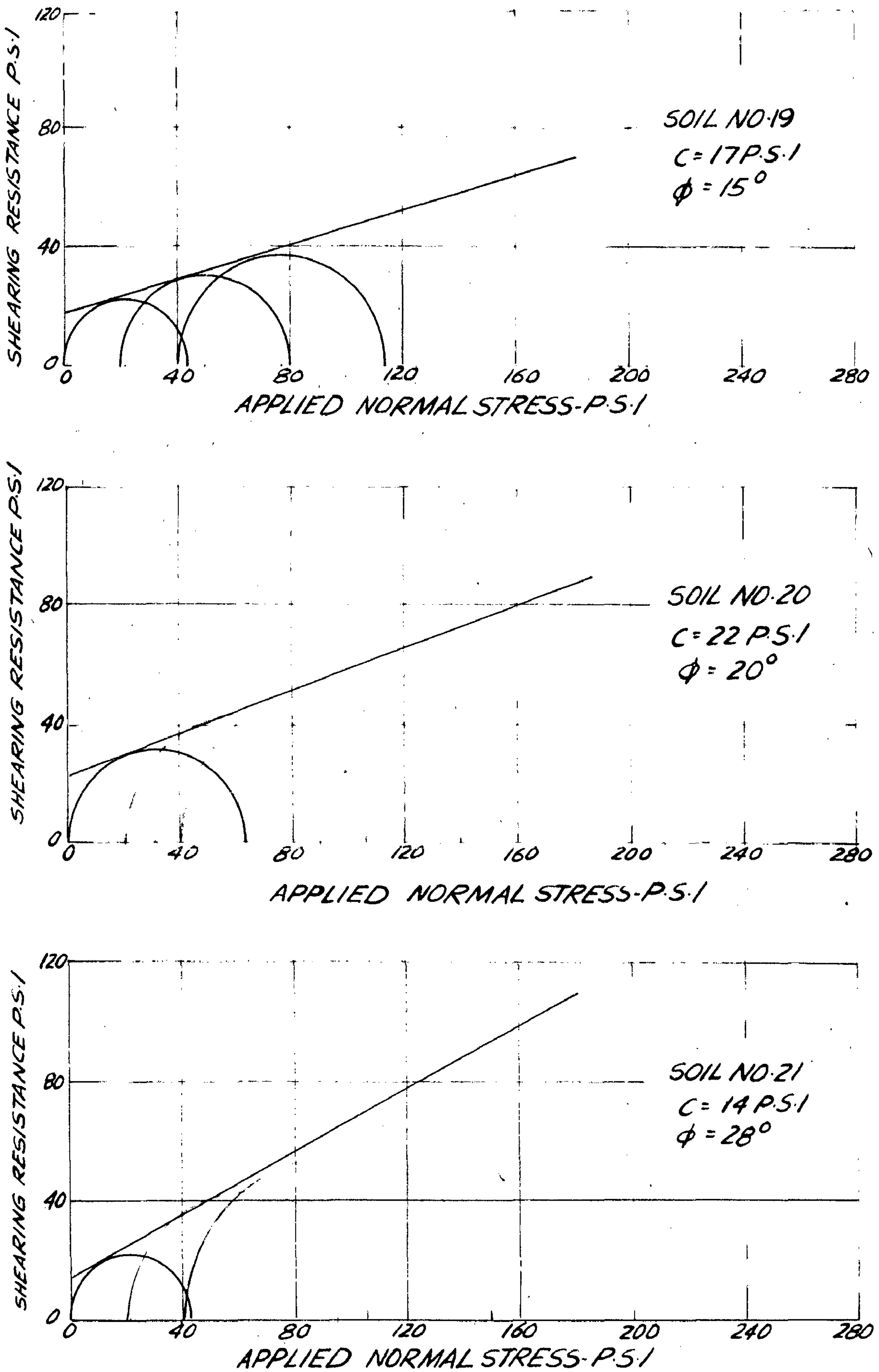


FIG. NO. 45 MOHR'S RUPTURE DIAGRAMS

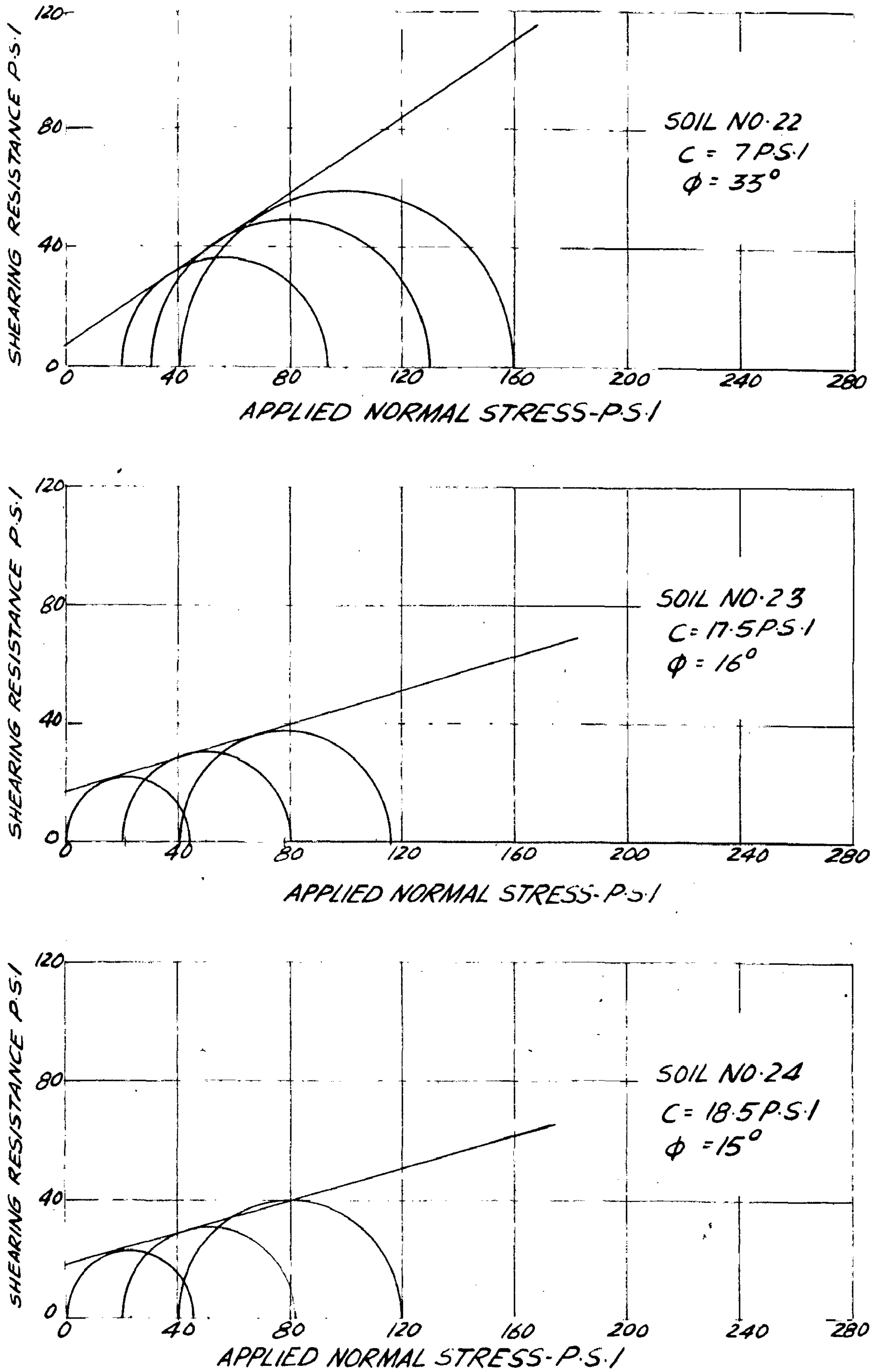


FIG. NO. 46 MOHR'S RUPTURE DIAGRAMS

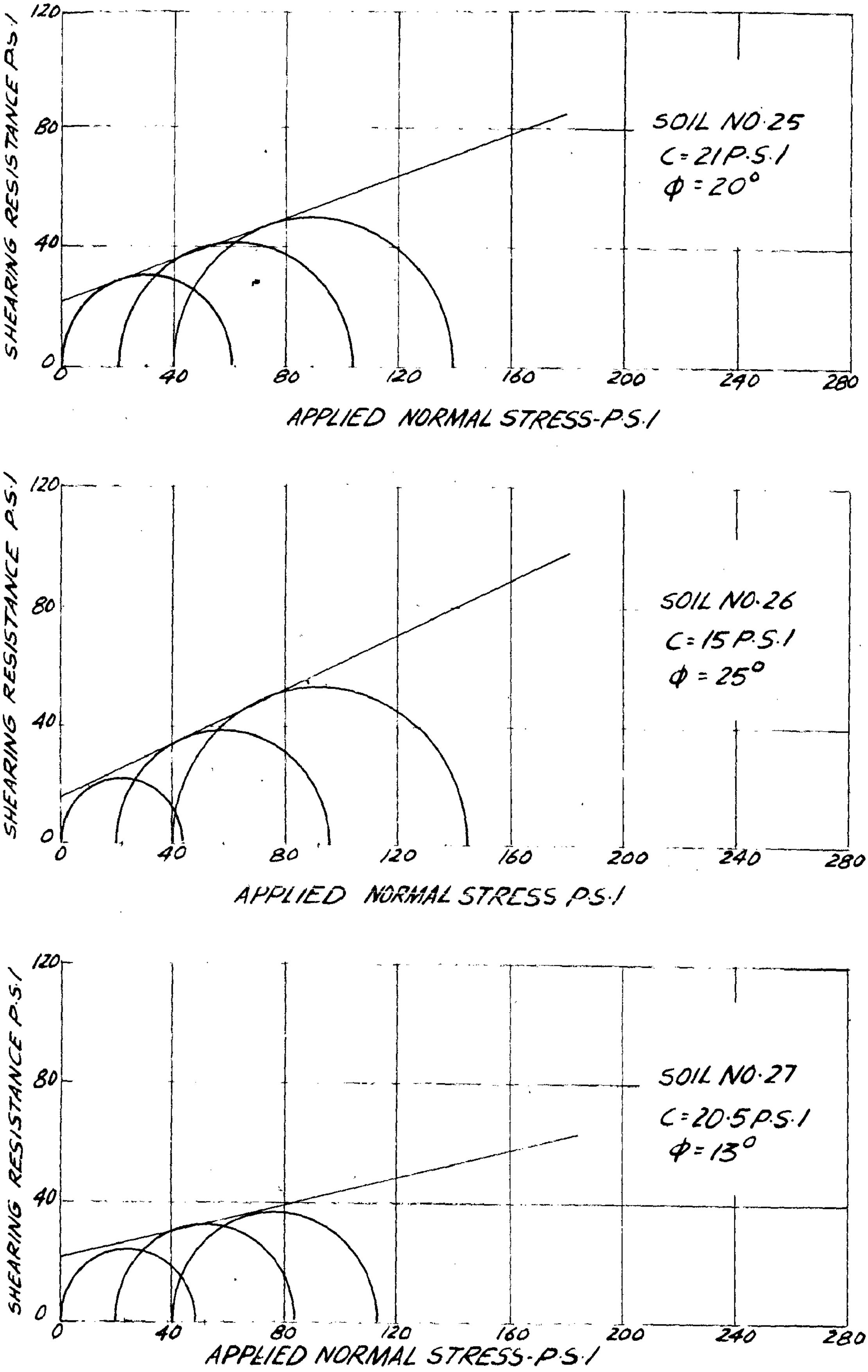


FIG. NO. 47 MOHR'S RUPTURE DIAGRAMS

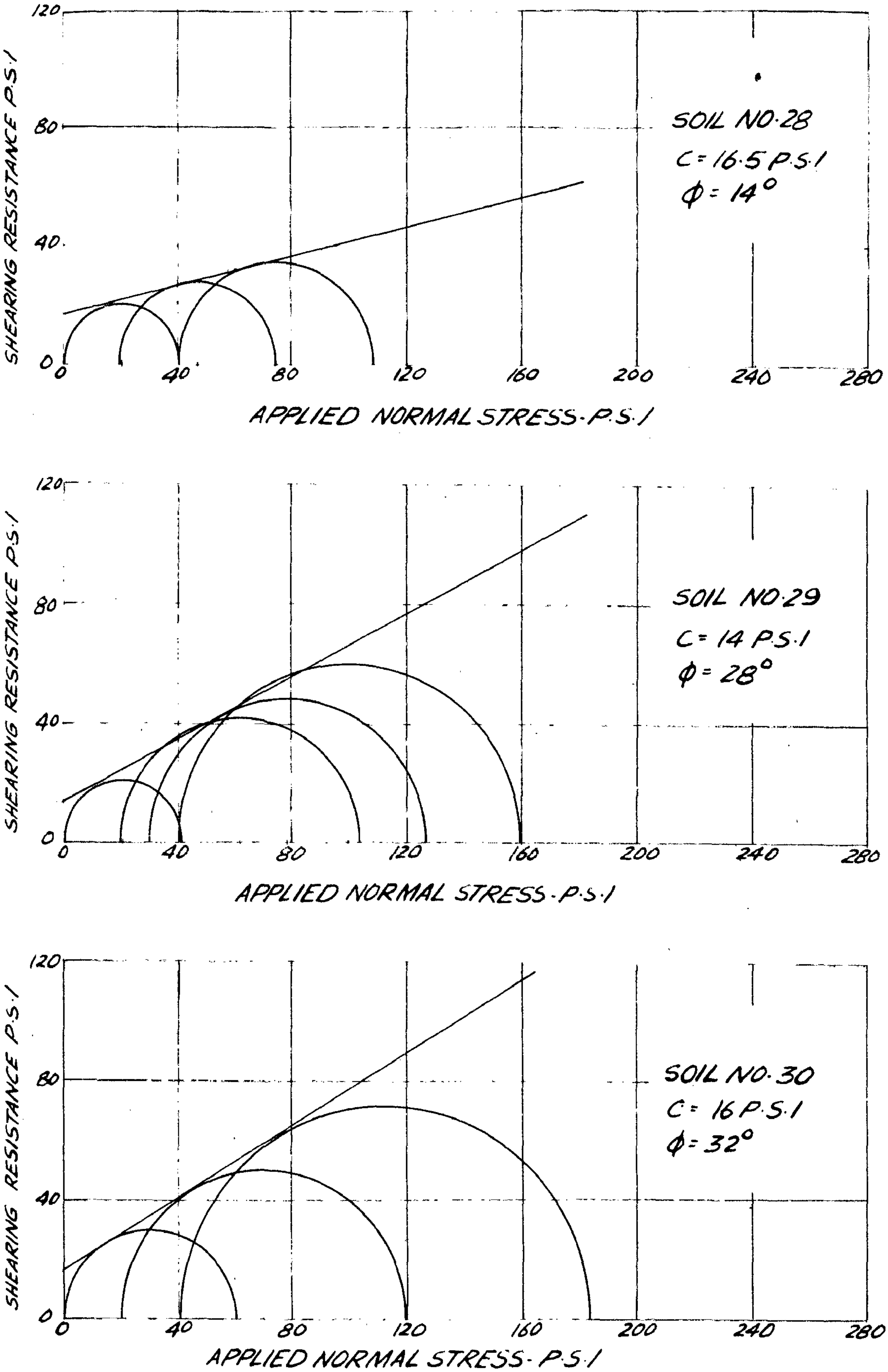
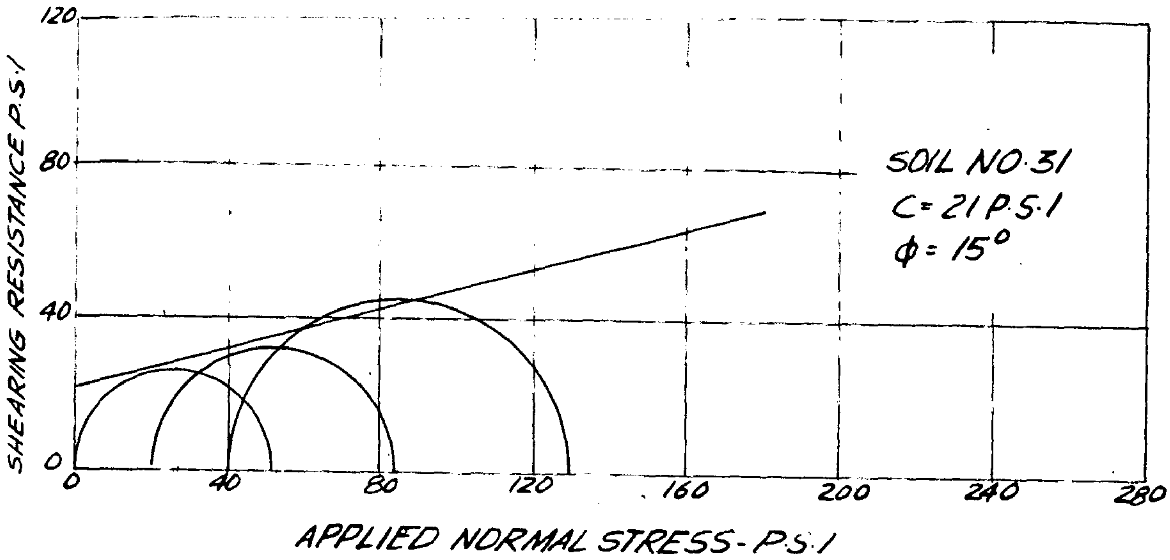
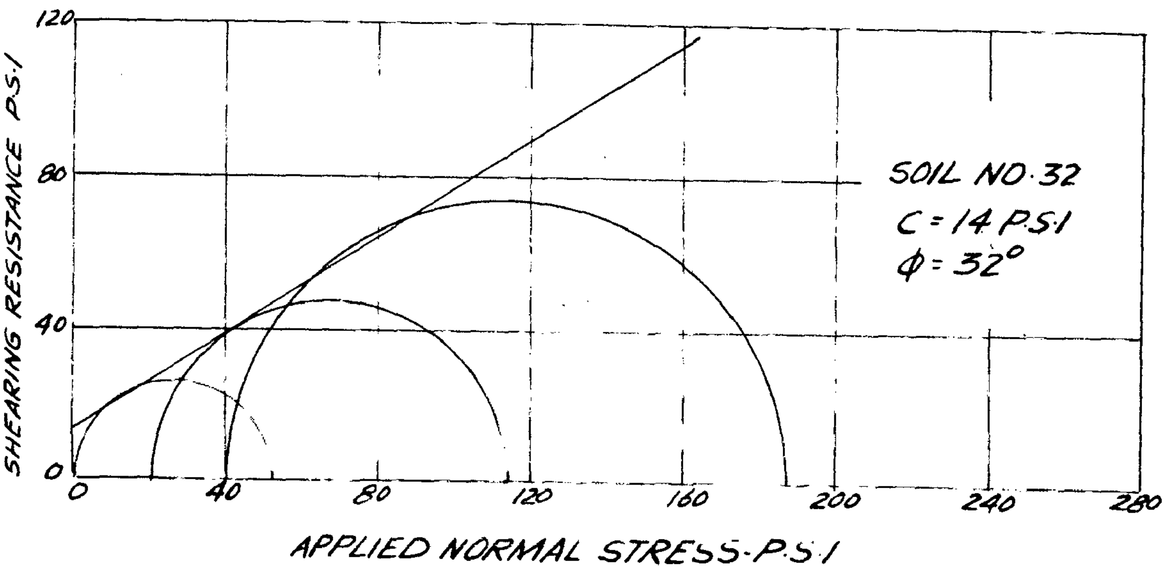


FIG.NO.48 MOHR'S RUPTURE DIAGRAMS





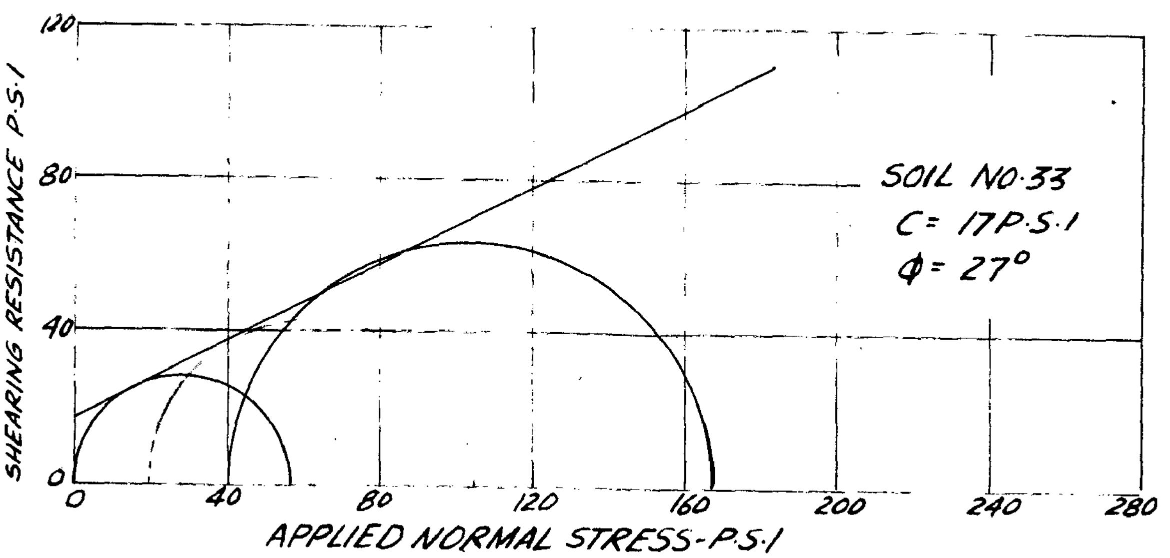


FIG. NO. 49 MOHR'S RUPTURE DIAGRAMS

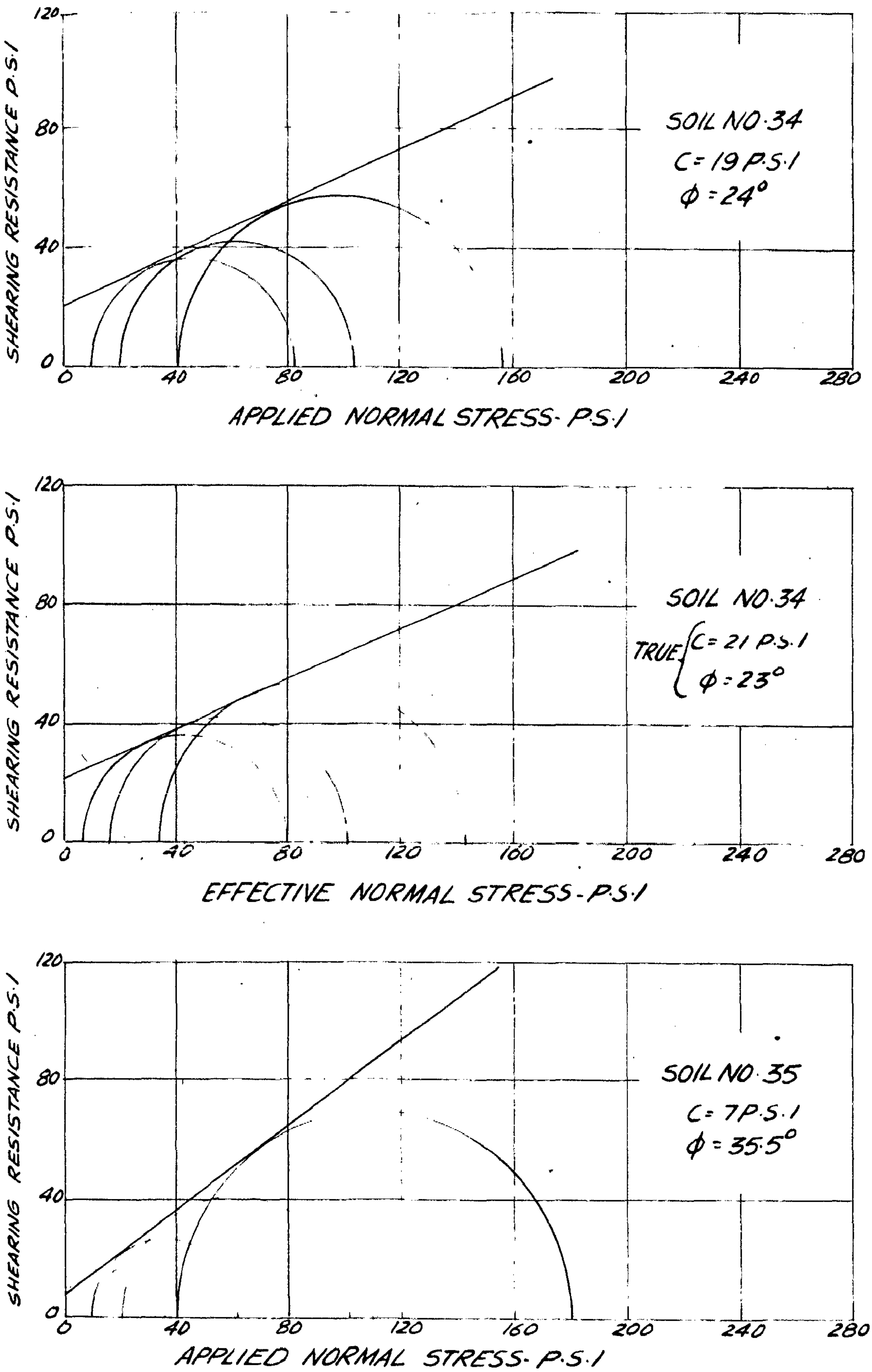


FIG.NO.50 MOHR'S RUPTURE DIAGRAMS

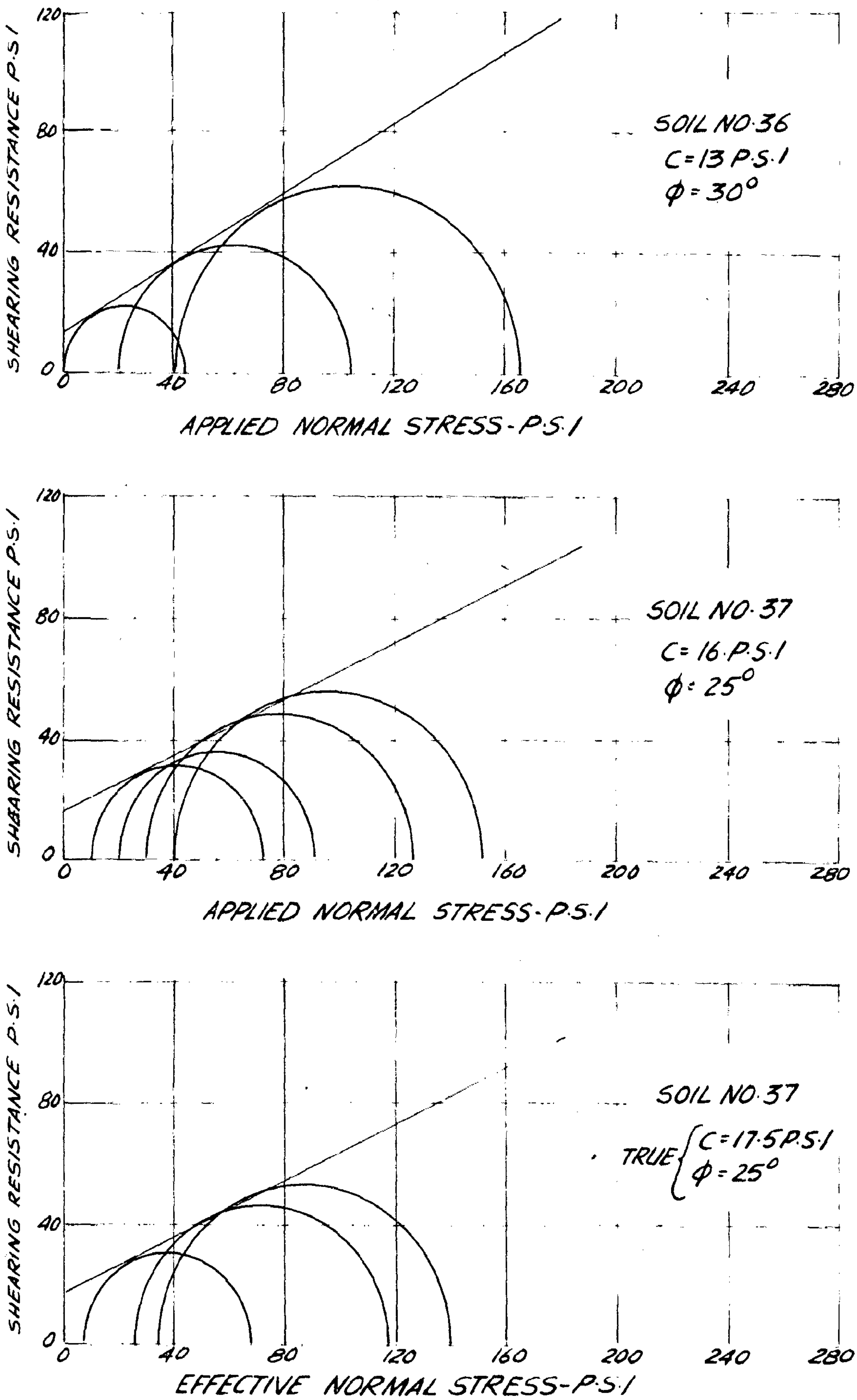


FIG. NO. 51 MOHR'S RUPTURE DIAGRAMS

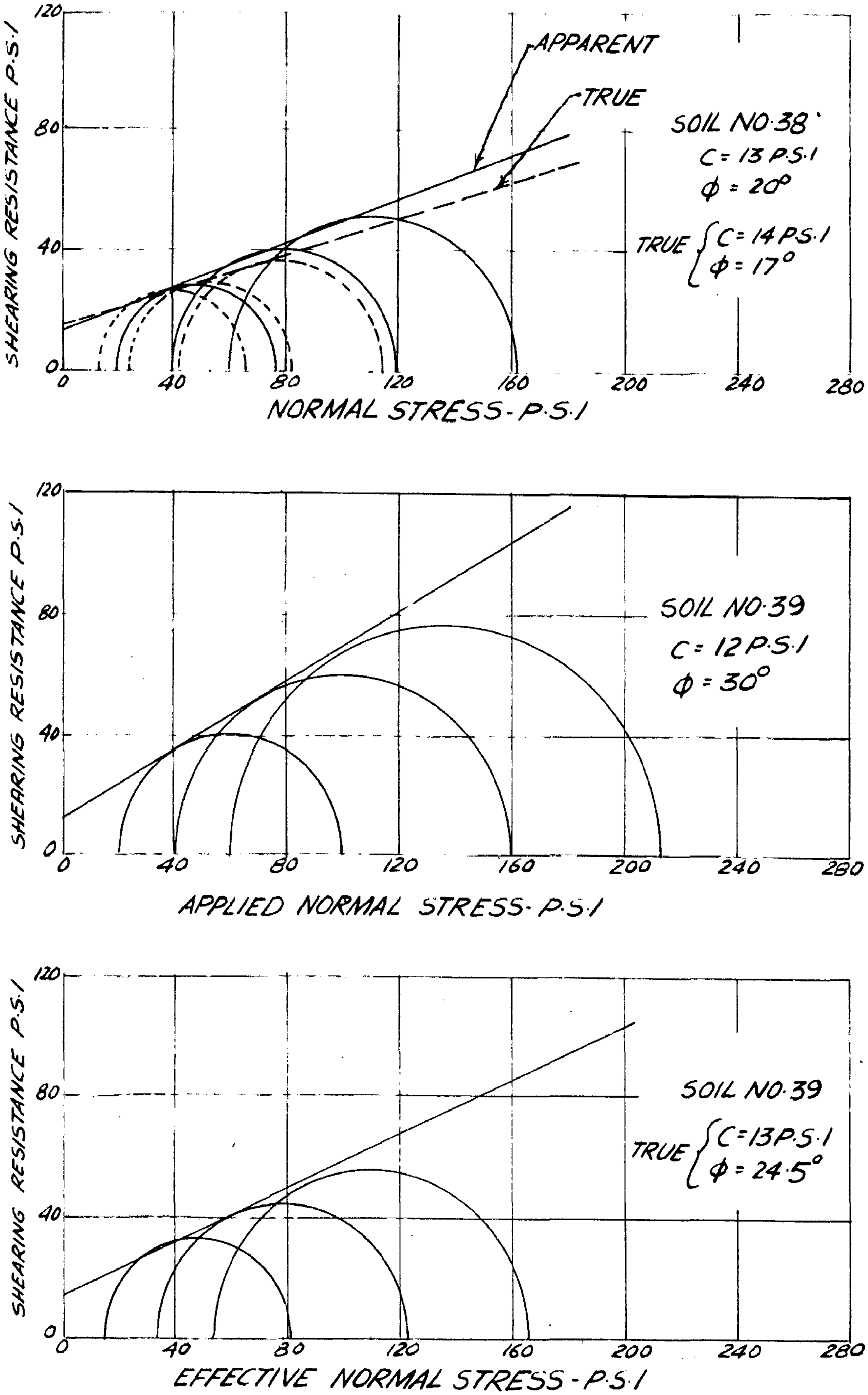


FIG. NO. 52 MOHR'S RUPTURE DIAGRAMS

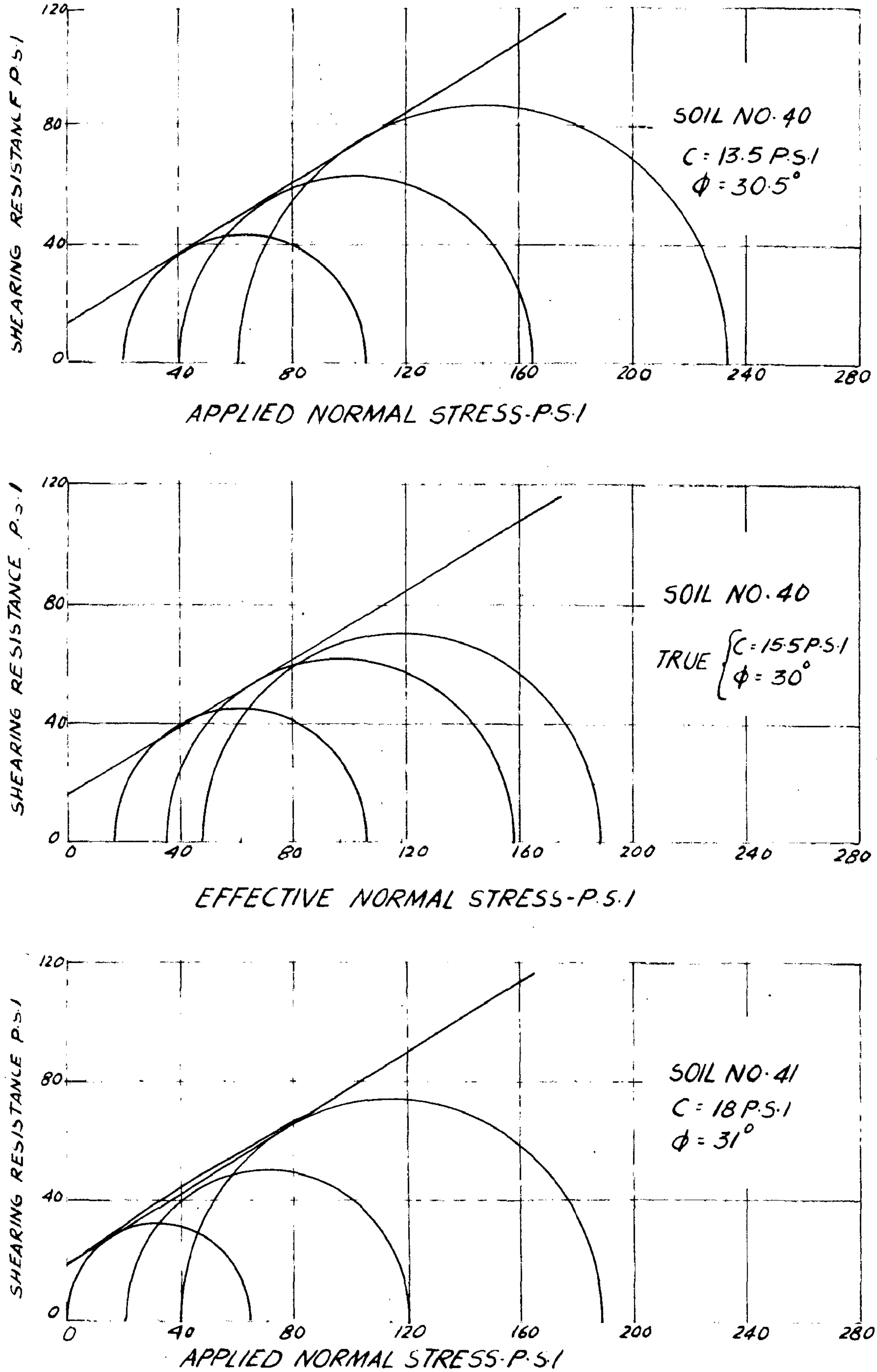


FIG. NO. 53 MOHR'S RUPTURE DIAGRAMS

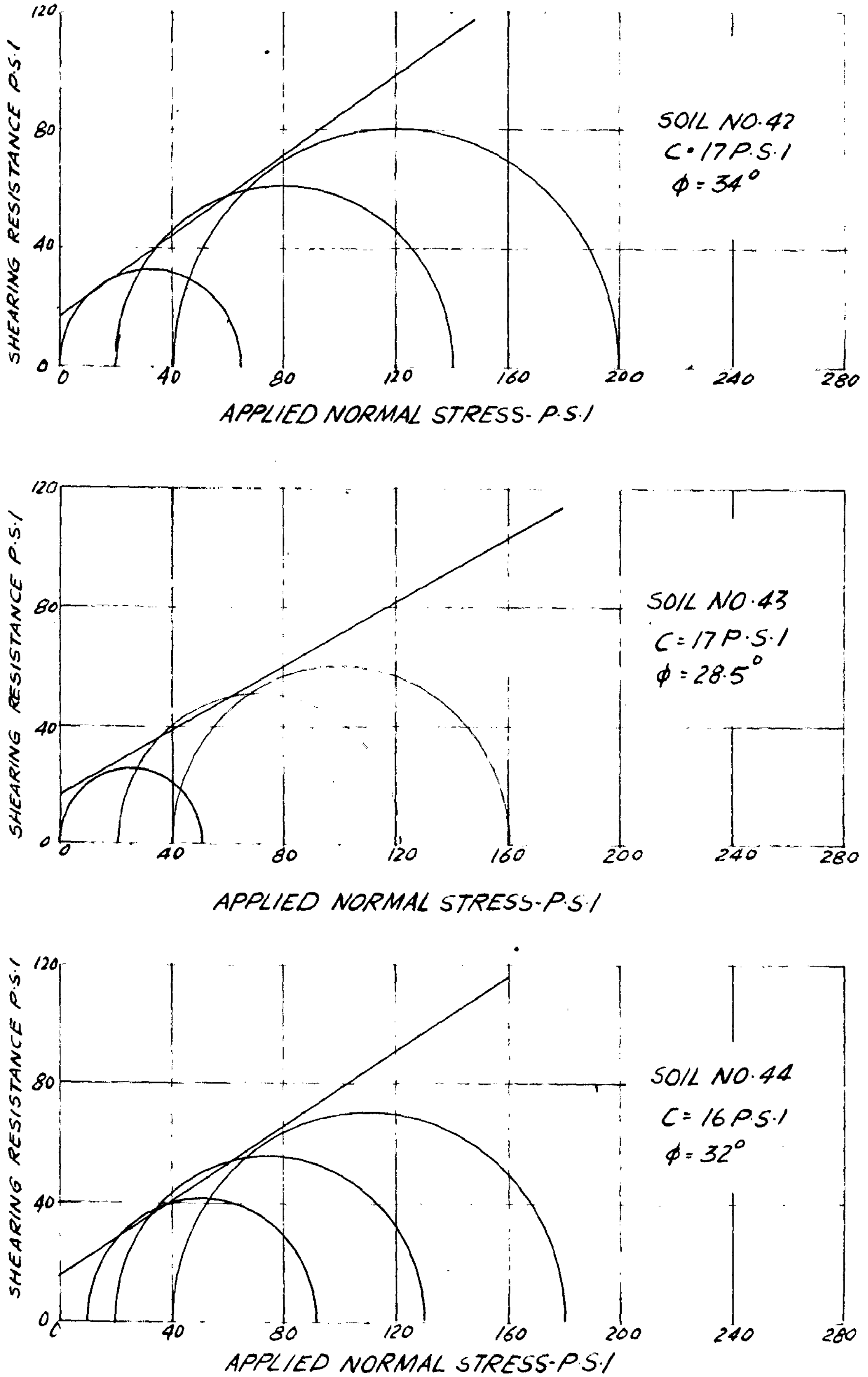


FIG NO. 54 MOHR'S RUPTURE DIAGRAMS

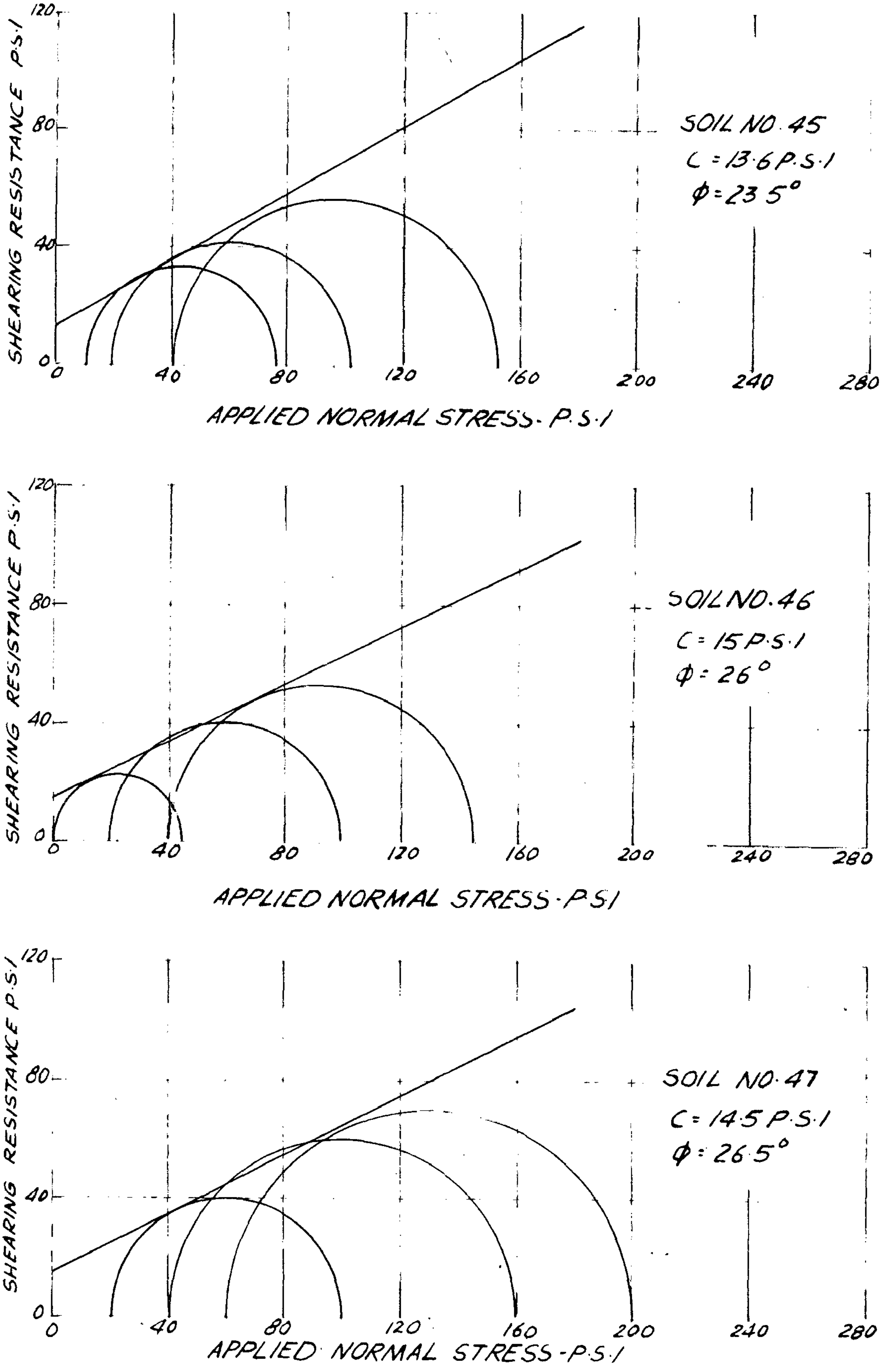


FIG. NO. 55 MOHR'S RUPTURE DIAGRAMS

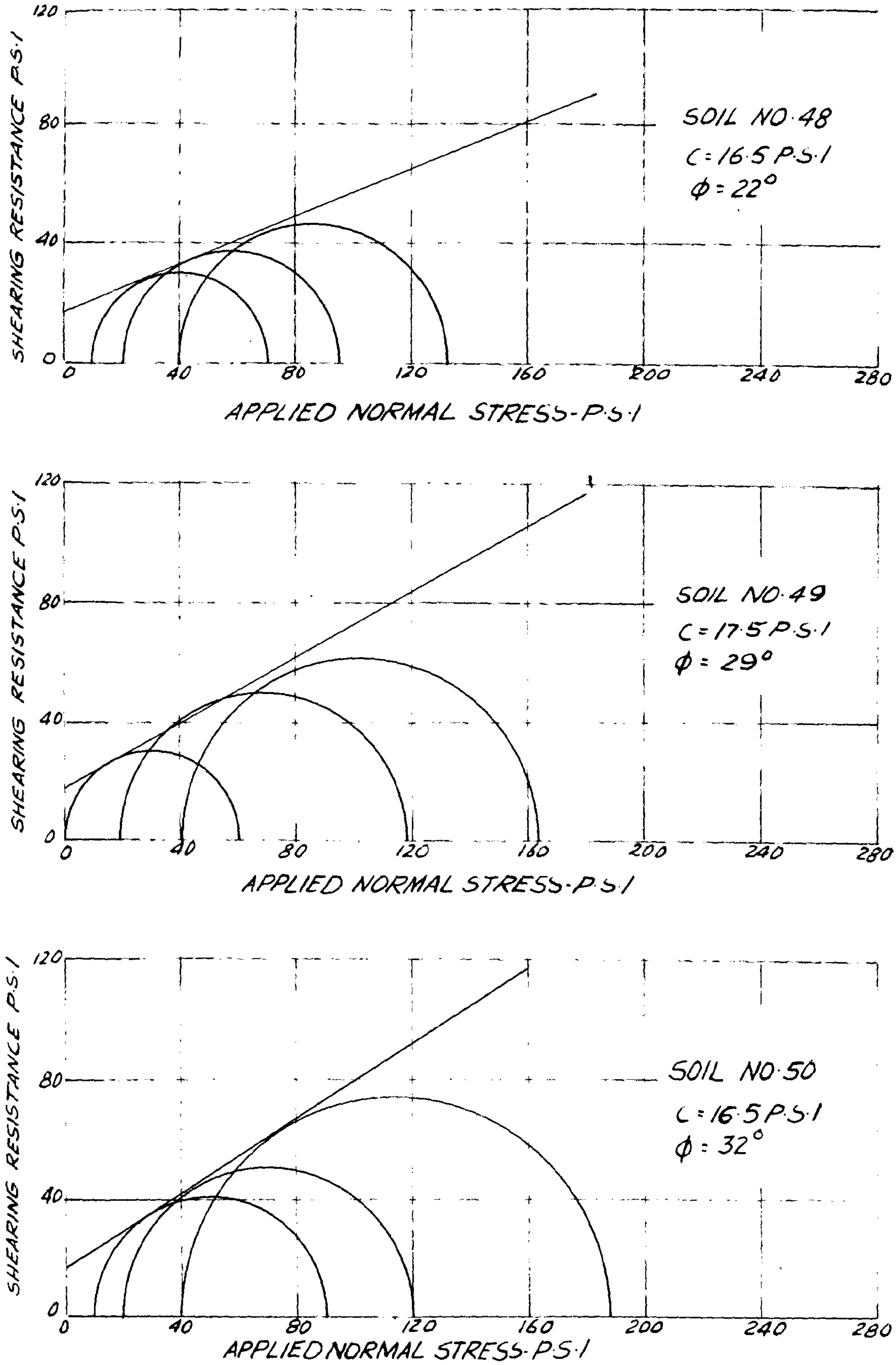


FIG. NO.56 MOHR'S RUPTURE DIAGRAMS

A P P E N D I X C

Calculations for various standard deviations (σ) :-

$$\sigma_c = \sqrt{\left\{\frac{\Sigma c^2}{N} - - \left(\frac{\Sigma c}{N}\right)^2\right\}}$$

$$= \sqrt{\left\{\frac{\Sigma c^2}{N} - \bar{c}^2\right\}}$$

$$= \sqrt{\frac{14605.71}{50} - (16.502)^2}$$

$$= 4.4496$$

$$\sigma_\phi = \sqrt{\left\{\frac{\Sigma \phi^2}{N} - \bar{\phi}^2\right\}}$$

$$= \sqrt{\left\{\frac{33626}{50} - (24.92)^2\right\}}$$

$$= 7.1773$$

$$\sigma_1 = \sqrt{\left\{\frac{\Sigma W_1^2}{N} - \bar{W}_1^2\right\}}$$

$$= \sqrt{\left\{\frac{84842.33}{50} - (39.334)^2\right\}}$$

$$= 12.2345$$

$$\sigma_p = \sqrt{\left\{\frac{\Sigma W_p^2}{N} - \bar{W}_p^2\right\}}$$

$$= \sqrt{\left\{\frac{31636.02}{50} - (24.652)^2\right\}}$$

$$= 4.9999$$

$$\sigma_I = \sqrt{\left\{\frac{\Sigma I_p^2}{N} - \bar{I}_p^2\right\}}$$

$$= \sqrt{\left\{\frac{14040.19}{50} - (14.682)^2\right\}}$$

$$= 8.0772$$

$$\sigma_{Log_{10}\phi} = \sqrt{\left\{ \frac{\Sigma (Log_{10}\phi)^2}{N} - (\overline{Log_{10}\phi})^2 \right\}}$$

$$= \sqrt{1.910098 - 1.8887554}$$

$$= \sqrt{0.0213434}$$

$$= 0.1460$$

$$\sigma_{\phi_1} = \sqrt{\left\{ \frac{\Sigma (\phi_1)^2}{N_1} - \bar{\phi}_1^2 \right\}}$$

$$= \sqrt{\frac{10905.5}{11} - (31.1818)^2}$$

$$= 4.3715$$

$$\sigma_{11} = \sqrt{\left\{ \frac{\Sigma (w_{11})^2}{N_1} - \bar{w}_{11}^2 \right\}}$$

$$= \sqrt{\frac{5321.49}{11} - (21.6636)^2}$$

$$= 5.469$$

$$\sigma_{\phi_h} = \sqrt{\left\{ \frac{\Sigma (\phi_h)^2}{N_h} - (\bar{\phi}_h)^2 \right\}}$$

$$= \sqrt{\frac{22720.5}{39} - (23.1538)^2}$$

$$= 6.817$$

$$\sigma_{1h} = \sqrt{\left\{ \frac{\Sigma (w_{1h})^2}{N_h} - \bar{w}_{1h}^2 \right\}}$$

$$= \sqrt{\left\{ \frac{79460.84}{39} - (44.318)^2 \right\}}$$

$$= 8.566$$

APPENDIX D_1

Nomogram for finding cohesion from liquid limit -

The equation of correlation is :-

$$C' = 4.258 + 0.3113 W_1$$

The range of liquid limit is 15% to 62%

(1) For W_1 = 15%

C' = $4.258 + 0.3113 \times 15$

= 8.9275 psi.

(2) For W_1 = 60%

C' = $4.258 + 0.3113 \times 60$

= 22.936 psi.

Plotting these values correspondingly, and then deviding the scales linearly (since the equation is linear), we get the required nomogram.

APPENDIX D_2

Nomogram for finding cohesion C from liquid limit and plastic limits of the soil.

(1) The equation of correlation is :-

$$C' = 4.7 + 0.3270 W_1 - 0.043 W_p$$

i. Range of liquid limit from 15.4% to 62%

ii. Range of plastic limit from 12.9% to 33.3%

(2) Reducing the equation to the form

$$X + Y + Z = 0$$

We get :-

$$X = 0.3270 W_1$$

$$Y = -(C' - 4.7)$$

$$Z = -0.043 W_p$$

(3) Taking the actual length of nomogram on paper = 18 cms.

Let l, m, and n be the scale factors for W_1, C and W_p respectively.

$18 = l \times 0.327\ (62 - 15.4)$

or $l = 1.181$

and $18 = -n \times 0.043\ (33.3 - 12.9)$

or $n = -20.519$

and $m = -\dfrac{l \times n}{l + n} = \dfrac{1.181 \times 20.519}{1.181 - 20.519}$

$= -1.252$

This gives scale factor for cohesion.

(4) Let a and b be distances of cohesion line from liquid and plastic limit lines respectively.

So $\dfrac{a}{b} = \dfrac{l}{n} = \dfrac{1.181}{20.519} = -0.0575$

also a + b = 8.5 cms.

a = -0.51 cms.

and b = 9.01 cms.

Therefore C axis will be left of W_1 and W_p lines.

(5) The value of cohesion at base line is obtained for the lowest values of liquid and plastic limits.

$C' = 4.7 + 0.327 \times 15.4 - 0.043$

$= 9.18$ psi.

After plotting this value, other values are plotted as scale factor is known.

The method of determining cohesion from this nomogram is - mark the points on the nomogram for the given W_1 and W_p values of soil on respective W_1 and W_p lines, join these two points by a straight line, the point at which it cuts the C line is the required value of C.

APPENDIX D_3

Nomogram for finding ϕ from the liquid and plastic limits of the soil.

(1) The equation of correlation is :-

$$\phi' = 43.428 - 0.4365 W_l - 0.0543 W_p$$

i. Range of liquid limit from 15.4% to 62%.

ii. Range of plastic limit from 12.9% to 33.3%.

(2). Reducing the equation to the form :-

$$X + Y + Z = 0$$

We get :-

$$X = -0.4365 W_l$$

$$Y = -(\phi' - 43.428)$$

$$Z = -0.0543 W_p$$

(3) Taking actual length of nomogram on paper = 18 cms.

Let l, m and n be scale factors for W_l, ϕ' and W_p respectively

$$18 = -l \times 0.4365\ (62 - 15.4)$$

or $l = -0.8849$

and $18 = -n \times 0.0543\ (33.3 - 12.9)$

or $n = -16.2454$

and $m = -\dfrac{l \times n}{l + n} = 0.84$

This gives scale factor for ϕ

(4) Let a and b be distances of ϕ line from liquid and plastic limit lines respectively.

So $\dfrac{a}{b} = \dfrac{l}{n} = 0.054$

Let a + b = 10 cms.

b = 9.487 cms.

and a = 0.514 cms.

Therefore ϕ axis will be between W_l and W_p lines.

(5) The value of ϕ at base line is obtained from the lowest values of liquid and plastic limits.

$$\phi' = 43.428 - 0.4365 \times 15.4 - 0.0543 \times 12.9$$

$$= 36.006 \text{ degrees.}$$

After plotting this value other values are plotted as the scale factor is known.

APPENDIX. E

$$\Sigma' c'^2 = \Sigma c^2 - \frac{(\Sigma c)^2}{N}$$

$$= \Sigma c^2 - \bar{c}.\Sigma c$$

$$= 14605.71 - 16.502 \times 825.10$$

$$= 989.9$$

$$\Sigma' \phi^2 = \Sigma \phi^2 - \bar{\phi}.\Sigma \phi$$

$$= 33626.00 - 24.92 \times 1246.00$$

$$= 2575.68$$

$$\Sigma' W_1^2 = \Sigma W_1^2 - \bar{W}_1.\Sigma W_1$$

$$= 84842.33 - 39.334 \times 1966.70 = 7484.15$$

$$\Sigma' W_p^2 = \Sigma W_p^2 - \bar{W}_p.\Sigma W_p$$

$$= 31636.02 - 24.256 \times 1232.60 = 1738.07$$

$$\Sigma' W_1 \times W_p = \Sigma W_1.W_p - \frac{(\Sigma W_1)(\Sigma W_p)}{N}$$

$$= \Sigma W_1.W_p - \bar{W}_1.\Sigma W_p$$

$$= 51218.88 - 39.334 \times 1232.60 = 2735.80$$

$$\Sigma' c.W_1 = \Sigma c.W_1 - \bar{c}\Sigma W_1$$

$$= 34784.17 - 16.502 \times 1966.70 = 2329.69$$

$$\Sigma' c.W_p = \Sigma c.W_p - \bar{c}.(\Sigma W_p)$$

$$= 21160.22 - 16.502 \times 1232.60 = 819.86$$

$$\Sigma' \phi.W_1 = \Sigma \phi.W_1 - \bar{\phi}.\Sigma W_1$$

$$= 45354.35 - 24.92 \times 1966.70 = -3415.81$$

$$\Sigma' \phi.W_p = \Sigma \phi.W_p - \bar{\phi}.\Sigma W_p$$

$$= 29427.70 - 24.92 \times 1232.60 = -1288.69$$

$$\Sigma' c'^2 = \Sigma c'^2 - \bar{c}'.\Sigma c'$$

$$= 14238.8386 - 822.56 \times 16.4512 = 706.74$$

$$\Sigma' \phi'^2 = \Sigma \phi'^2 - \bar{\phi}'.\Sigma \phi'$$

$$= 32700.9957 - 24.958 \times 1247.91 = 1555.41$$

THE END.

ACKNOWLEDGMENTS

The author wishes to express his gratitude and sincere thanks to Sri K.B. Agarwal, Reader in Civil Engineering University of Roorkee, for suggesting the problem and his valuable guidance and encouragement in the preparation of this dissertation.

The author is thankful to Dr. Jagdish Narain, Professor in Soil Mechanics, University of Roorkee for his useful suggestions and help in the experimental work.

Author also expresses his thanks to the Soil Mechanics Laboratory staff for their help during experimental work.

Finally, the author is grateful to the University Grants Commission for awarding Scholarship to facilitate Post-Graduate studies.

R.N. SACHAN

LIST OF TABLES

Substituting the values from Table No. 4, we get :-

$$r = -0.8320$$

which reveals that relation obtained is fairly good negative correlation, i.e. as liquid limit increases the value of ϕ decreases.

The standard error of estimate is given by the relation

$$S_\phi = \sigma_\phi \sqrt{1 - r^2}$$
$$= 7.1773 \sqrt{1 - (-0.8320)^2}$$
$$= 3.98^0$$

Theoretically for normal distribution of values 65% values should be covered at the deviation of an standard error i.e. 3.98^0. From Fig. No. 7 it can be seen that 74% cases are covered at one standard error, and 100% cases will be covered at two standard error. Thus we can be sure that in 95% cases the actual values of ϕ will not differ from the calculated value by more than 7.96 degrees.

<u>Correlation of ϕ with I_p</u>

The plot between the angle of internal friction ϕ at O.M.C. and plasticity index shows a tendency towards a straight line as shown in Fig. No. 9. Therefore trial is made to correlate them by a straight line law of the type -

$$\phi' = a + b I_p$$

Here
$$a = \frac{(\bar{I}_p)(\Sigma \phi . I_p) - (\bar{\phi})(\Sigma I_p^2)}{(\bar{I}_p)(\Sigma I_p) - (\Sigma I_p^2)}$$

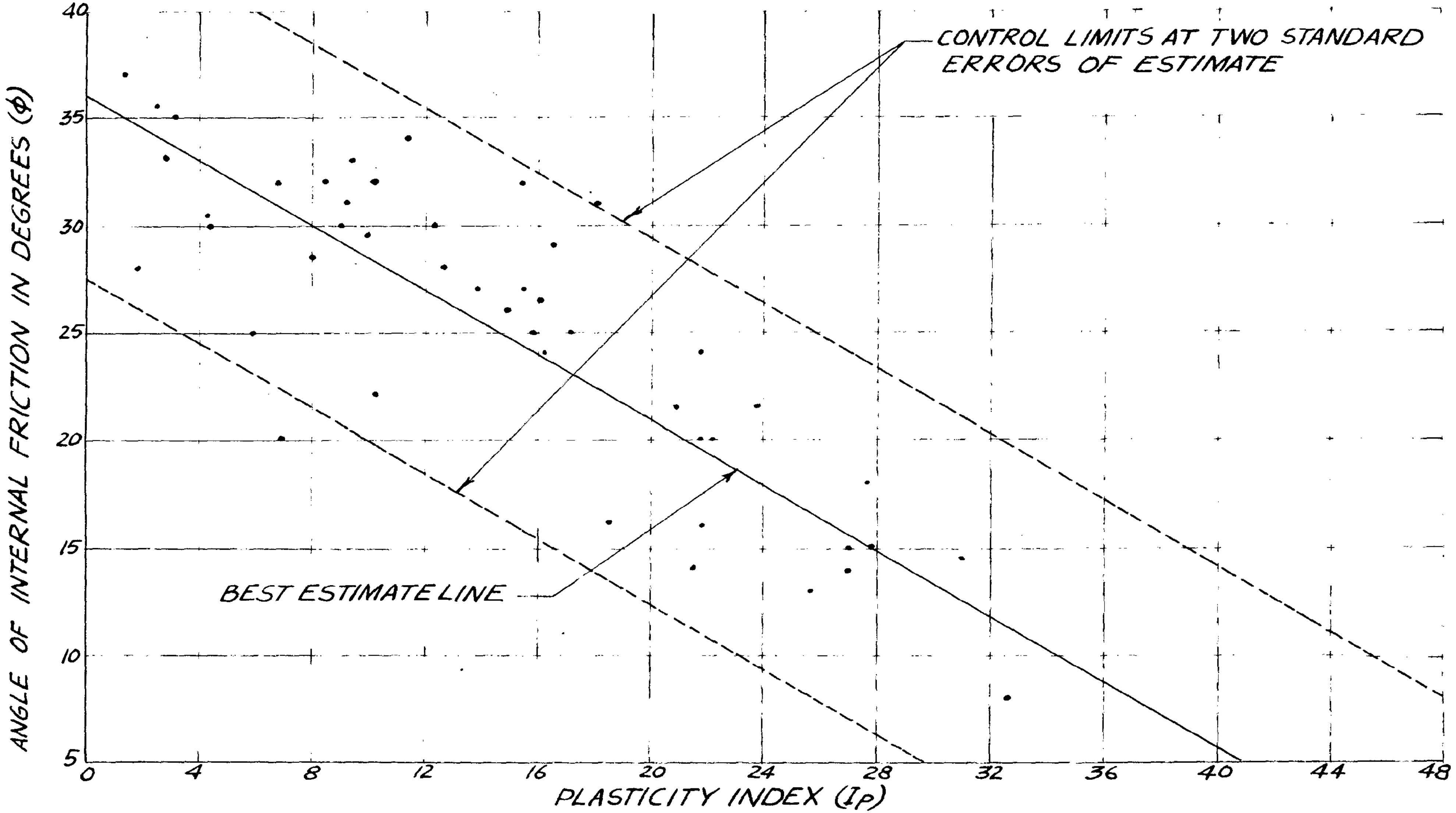


FIG. NO. 9 ANGLE OF INTERNAL FRICTION (Φ) V/S PLASICITY INDEX (I_p)

Correlation of ϕ with W_1 in parts.

From the plot between angle of internal friction ϕ and liquid limit W_1 as shown in Fig. No. 13, it is clear that it will be more accurate to fit a straight line between liquid limit 15% to 30% and another straight line between liquid limit 30% to 62%. This is probably due to marked difference in clay content of the soils below liquid limit of 30%.

Let the equation of the straight line below liquid limit 30% is of the type

$$\phi_1' = a + b W_{11}$$

Here only those soils be considered whose liquid limit below 30%, but their liquid limit be represented by adding one additional suffix 1 i.e. by W_{11} and ϕ by ϕ_1.

Therefore

$$a = \frac{(\bar{W}_{11})(\Sigma \phi_1 . W_{11}) - (\bar{\phi}_1)(\Sigma W_{11}^2)}{(\bar{W}_{11})(\Sigma W_{11}) - \Sigma W_{11}^2}$$

$$\text{and} \quad b = \frac{\Sigma \phi . W_{11} - (\bar{\phi}_1)(\Sigma W_{11})}{\Sigma W_{11}^2 - (\bar{W}_{11})(\Sigma W_{11})}$$

By substituting the various numerical values from Table No. 6, we have :-

$a = 46.5830$

$b = -0.7109$

Therefore the equation, of correlation is

$$\phi_1' = 46.5830 - 0.7109 W_1$$

TABLE NO. 6

Additional data required for statistical analysis in parts.

Sl. No.	Quantity	Value	Sl. No.	Quantity	Value
1.	$\Sigma \phi_1$	343.00	11.	$\Sigma \phi_h^2$	22720.50
2.	$\Sigma \phi_1^2$	10905.50	12.	$\bar{\phi}_h$	23.1538
3.	$\bar{\phi}_1$	31.1818	13.	ΣW_{1h}	1728.40
4.	ΣW_{11}	238.000	14.	ΣW_{1h}^2	79460.84
5.	ΣW_{11}^2	5381.49	15.	$\bar{W}_{1h}$	44.318
6.	$\bar{W}_{11}$	21.6636	16.	$\Sigma(\phi_h.W_{1h})$	38079.45
7.	$\Sigma(\phi_1.W_{11})$	7274.90	17.	$\sigma_{\phi h}$	6.817
8.	$\sigma_{\phi 1}$	4.3715	18.	σ_{1h}	8.566
9.	σ_{11}	5.469	19.	N_1	11
10.	ϕ_h	903.00	20.	N_h	39

TABLE NO. 7

Soil No.	ϕ_1	ϕ_1^2	W_{11}	W_{11}^2	$\phi_1.W_{11}$	Remarks.
10	37.0	1369.00	16.8	282.24	621.60	The corresponding values for the soils having liquid limit greater than 30% have been obtained by substracting these sums from the total sums.
13	28.0	784.00	20.0	400.00	560.00	
16	35.0	1225.00	18.8	353.44	658.00	
18	30.0	900.00	21.5	462.25	645.00	
22	33.0	1089.00	18.5	342.25	610.50	
35	35.5	1260.25	15.4	237.16	546.71	
38	20.0	400.00	29.6	876.16	592.00	
39	30.0	900.00	28.1	789.61	843.00	
40	30.5	930.25	19.4	376.36	591.70	
44	32.0	1024.00	24.1	580.81	771.20	
50	32.0	1024.00	26.1	681.21	835.20	
11	343.0	10905.50	238.3	5381.49	7274.90	

TABLE NO. 11

Sums of W_p and W_p^2

Soil No.	W_p	W_p^2	Soil No.	W_p	W_p^2
1	28.0	784.00	26	25.9	670.81
2	26.3	691.69	27	27.5	756.25
3	29.4	864.36	28	27.1	734.41
4	25.3	640.09	29	27.2	739.84
5	25.8	665.64	30	20.4	416.16
6	33.3	1108.89	31	28.9	835.21
7	30.7	942.49	32	25.6	655.36
8	33.4	1115.56	33	25.8	665.64
9	22.9	524.41	34	29.4	864.36
10	15.4	237.16	35	12.9	166.41
11	26.4	696.96	36	27.1	734.41
12	30.0	900.00	37	31.2	973.44
13	18.2	331.24	38	22.7	515.29
14	25.0	625.00	39	19.1	364.81
15	25.1	630.01	40	15.1	228.01
16	15.6	243.36	41	24.9	620.01
17	23.4	547.56	42	22.2	492.84
18	17.1	292.41	43	29.4	864.36
19	25.8	665.64	44	17.3	299.29
20	26.4	696.96	45	22.2	492.84
21	28.2	798.24	46	25.0	625.00
22	15.7	246.49	47	23.1	533.61
23	30.2	912.04	48	30.0	900.00
24	28.7	823.69	49	21.8	475.24
25	26.8	718.24	50	17.7	313.29
				1232.60	31636.02

TABLE NO. 12

Sum of $W_l \times W_p$

Soil No.	W_l	W_p	$W_l \times W_p$	Soil No.	W_l	W_p	$W_l \times W_p$
1	59.0	28.0	1652.00	26	41.8	25.9	1082.62
2	50.0	26.3	1315.00	27	53.1	27.5	1460.25
3	62.0	29.4	1822.80	28	44.6	27.1	1208.66
4	41.5	25.3	1049.95	29	37.7	27.2	1025.44
5	43.0	25.8	1109.40	30	30.6	20.4	624.24
6	61.0	33.3	2031.30	31	56.0	28.9	1618.40
7	52.2	30.7	1602.54	32	40.0	25.6	1049.60
8	60.3	33.4	2014.02	33	41.3	25.8	1065.54
9	36.7	22.9	840.43	34	51.1	29.4	1502.34
10	16.8	15.4	258.72	35	15.4	12.9	198.66
11	44.5	26.4	1174.80	36	39.4	27.1	1067.74
12	57.8	30.0	1734.00	37	37.1	31.2	1157.52
13	20.0	18.2	364.00	38	29.6	22.7	671.92
14	45.8	25.0	1145.00	39	28.1	19.1	536.71
15	34.1	25.1	855.91	40	19.4	15.1	292.94
16	18.8	15.6	293.28	41	34.1	24.9	848.89
17	32.8	23.4	767.52	42	33.6	22.2	745.92
18	21.5	17.1	367.65	43	37.3	29.4	1096.62
19	44.3	25.8	1142.94	44	24.1	17.3	416.93
20	48.2	26.4	1272.84	45	32.2	22.2	714.84
21	40.8	28.2	1150.56	46	39.9	25.0	997.50
22	18.5	15.7	290.45	47	39.2	23.1	905.52
23	52.0	30.2	1570.40	48	40.2	30.0	1206.00
24	45.0	28.7	1291.50	49	38.3	21.8	834.94
25	48.9	26.8	1310.52	50	26.1	17.7	461.97
							51218.88

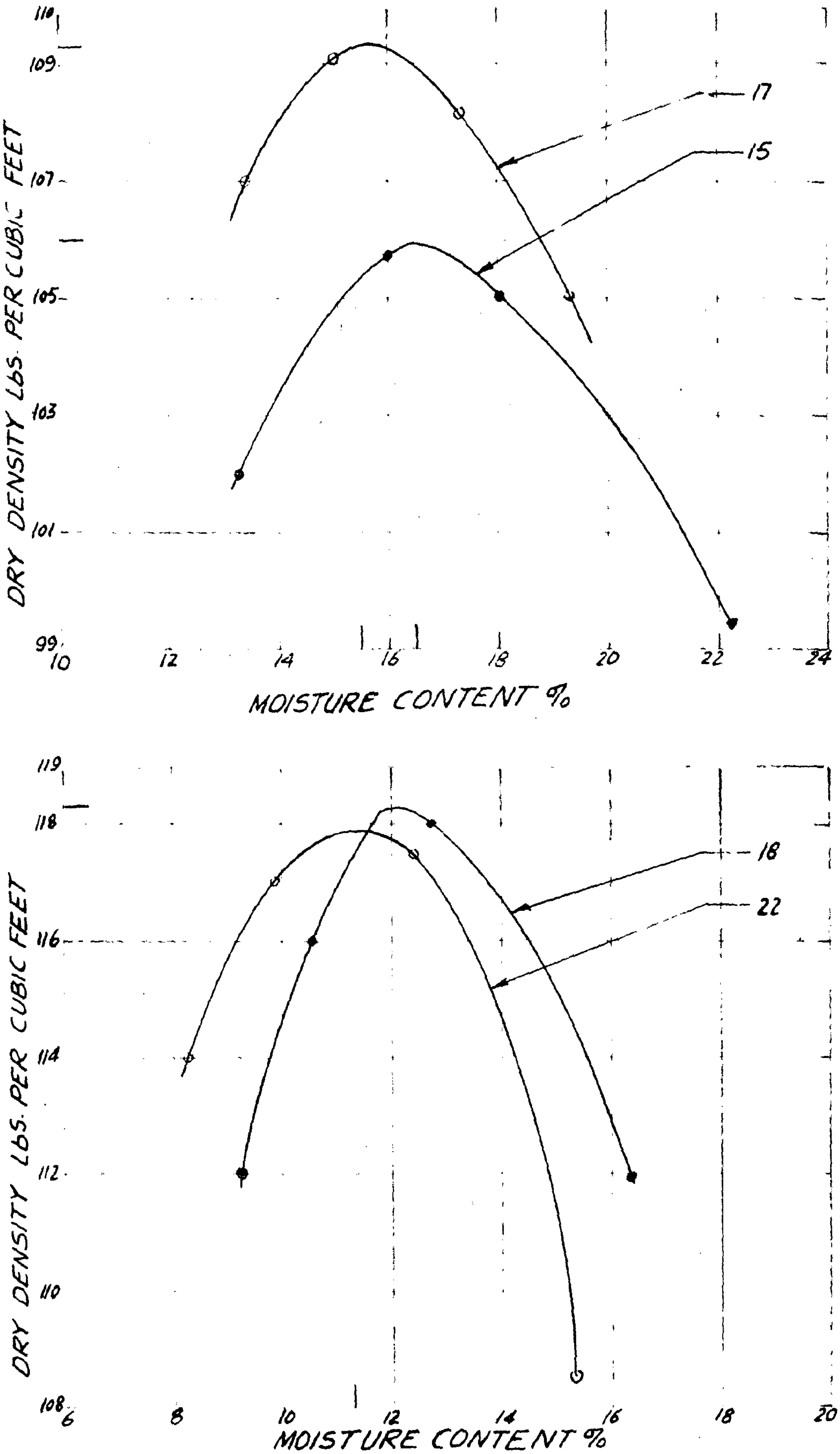


FIG. NO. 31 MOISTURE DENSITY CURVES

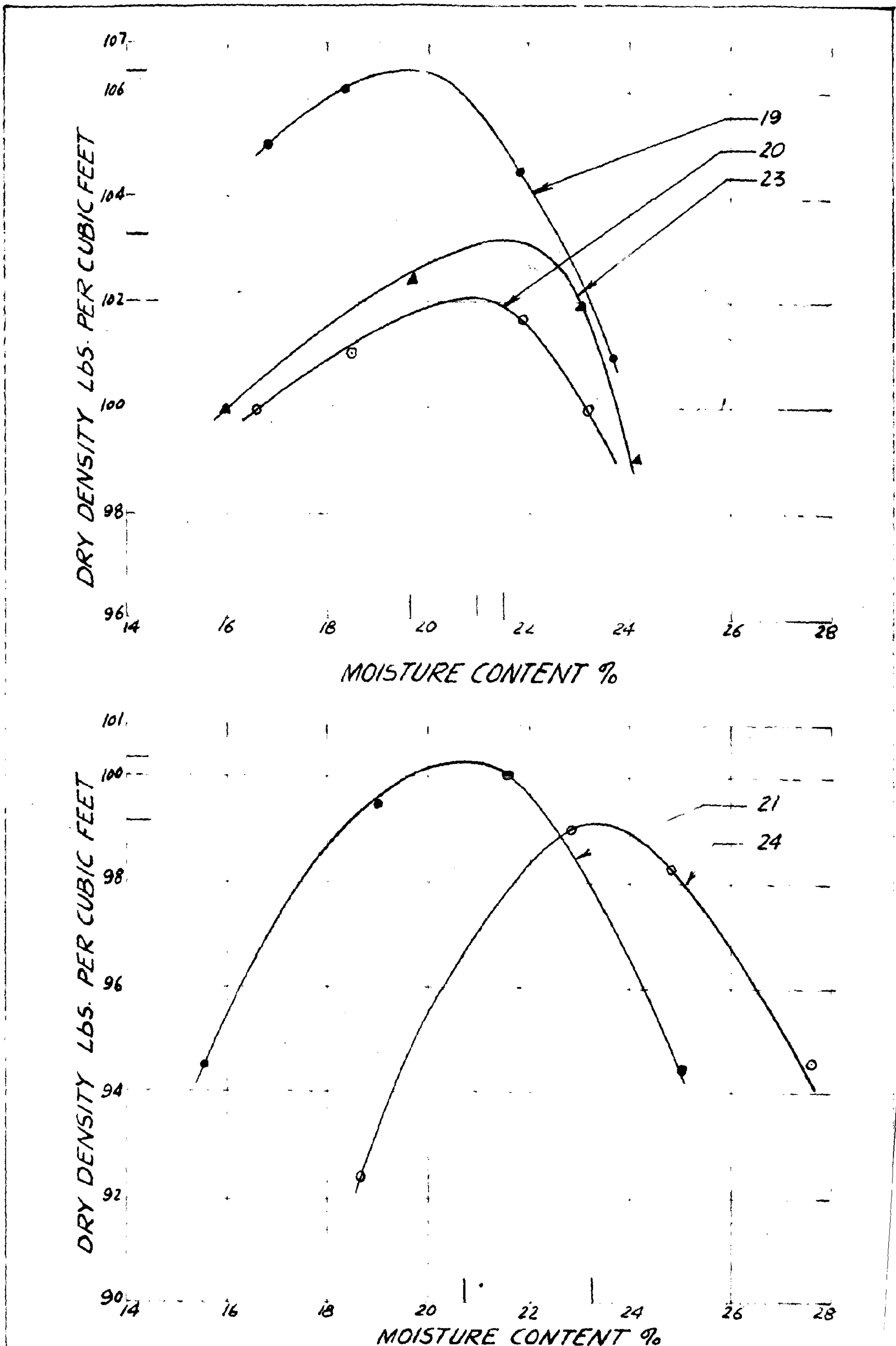


FIG. NO. 32 MOISTURE DENSITY CURVES