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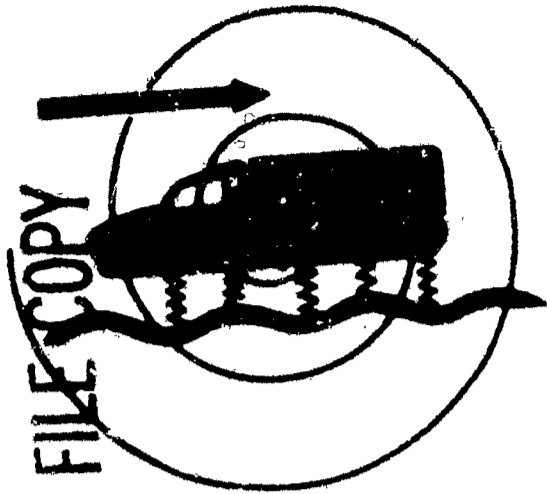
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ARTIFICIAL SOILS
FOR LABORATORY STUDIES
IN LAND LOCOMOTION

BY
B. HANAMOTO

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ARTIFICIAL SOILS FOR LABORATORY
STUDIES IN LAND LOCOMOTION

by
B. HANAMOTO

Ordnance Corps
Land Locomotion Research Branch
Research and Development Division
Ordnance Tank-Automotive Command
15 November 1957

ACKNOWLEDGEMENT

This work was staged by Mr. S. S. Ulrich, formerly associated with the project, within the general program of Land Locomotion Research. He tested many possible mixtures of artificial soils and suggested the use of glycol. He, also, assisted in writing this report.

ABSTRACT

The three types of artificial soils produced and tested in the Land Locomotion Research Laboratory have shown the necessary stability of mechanical properties and great ease in handling over the wide range of values reproduced below:

Soil No.	c	ϕ	k_c	k_ϕ	n
C-32-35	2.05	0°	22.0	17.0	0.16
C-32-40	1.14	0°	18.0	12.1	0.20
C-32-41	0.64	0°	3.6	2.5	0.25
C-32-43	0.25	0°	0.2	0.9	0.40
C-32-50	0.17	0°	0.1	0.3	0.67
CS-33-22	1.06	38°	17.0	9.5	0.15
CS-33-23	0.95	38°	11.6	8.3	0.17
CS-33-24	0.76	38°	8.9	6.2	0.18
CS-33-25	0.38	38°	4.0	1.8	0.20
CS-33-26	0.14	38°	3.4	0.4	0.21
S-34-7.5	0.17	22.5	9.1	20.4	0.42
S-34-10	0.30	14.5	10.8	18.4	0.46
S-34-12.5	0.35	9.5	17.0	11.6	0.52
S-34-15	0.44	8.0	26.5	6.78	0.71

The above data indicate a feasibility of producing artificial soils of any desired properties by using bentonite, sand and glycol, which eliminates the necessity of using unstable and uncontrollable natural soils, and simplifies laboratory work.

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OBJECTIVE

The objective of this investigation is to establish an artificial soil mass which would eliminate the absolute necessity of using natural soils for test purposes in the laboratory, because of the difficulty in their handling and controlling. The aim is to cover the entire range of natural soils, from frictional to cohesive, with this stable and easily producible artificial mixture.

INTRODUCTION

One of the greatest and most urgent needs in soil trafficability investigations by laboratory methods is to overcome the difficulty of working with natural soils. Such soils quickly lose their moisture content, causing changes in the mechanical properties exhibited. Some work has been done in the past in an attempt to reproduce in the laboratory the physical conditions encountered in the field. The Bucyrus-Erie Co. (South Milwaukee, Wis.) has used a mixture of foundry sand and motor oil with some success in investigating the behavior of self-loading scraper-type earthmoving machinery. In most instances, however, these attempts have met with very little success, due to the varied physical and chemical mixtures possible in the natural state.

It, therefore, appears necessary to approach the problem from another angle. Rather than attempt to physically duplicate natural soils, work must be directed toward simulating certain mechanical properties of various soils in their natural site, by formulating such properties into an artificial soil mass. These efforts should result in artificially produced materials whose consistency can be controlled and perhaps varied by accurate formulation from a near-fluid to a near-solid state to cover the major portion of terrain found in off-road operations of land vehicles.

To achieve such desired results, it appears necessary to study and experiment with a wide variety of inert solids and so-called "binders" in mixture or compound form which exhibit the required soil properties and yet remain unaffected by time, usage and normal atmospheric conditions. In such a manner, it is hoped that complete independence of the use of natural soils for laboratory test purposes will be attained.

It should be noted that in all these proposals a secondary, but important advantage other than control of properties, would be gained, i.e., stability of properties. Most natural soils have different cohesion and

friction at different moisture content and compaction, so that accurate control of these two parameters is necessary, in order to obtain reproducible test conditions, and hence reproducible tests. Control of the mechanical properties is obviously necessary for successful experimentation and is one of the most difficult problems in scale-model vehicle testing in soils.

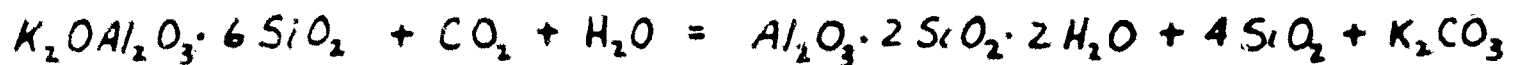
The ideal soil mass would thus have the following characteristics:

- a. Stability of the solid state regardless of time, oxidation or other chemical interaction.
- b. Controllability of the soil values and parameters exhibited.
- c. Reproducibility of the mass in any quantity using standard or easily obtainable materials.

In this report, the available data on mechanical characteristics of natural soils were used in simulating artificial soils. "Artsoil" may be an appropriate name for the proposed artificial soil mass. The following is the description of the progress made.

DISCUSSION OF THE PROBLEM

The term "clay" is applied to certain earthy materials which have been formed by the weathering of rocks containing aluminum silicates, particularly by the weathering of the mineral feldspar. The outstanding property of these materials is their plasticity when wet and their rigidity when dry. Clay is the decomposition product of feldspar or of rocks containing feldspar minerals. It is of variable composition, depending on the parent rock and on its history after decomposition, but in general it contains as its chief ingredient hydrated aluminum silicate, together with some sand and other materials. A typical decomposition reaction is as follows: Reference (1)



Orthoclase
Feldspar

Kaolinite

Sand

In the reaction, it is assumed that decomposition has occurred through atmospheric weathering, with CO₂ being present in the surface water. The major portion of clay, consists of kaolinite and quartz. Kaolinite, Al₂O₃.

$2SiO_2 \cdot 2H_2O$ imparts plasticity to the clay. Quartz is not plastic and, therefore, reduces the plasticity of the clay; an excess of silica destroys the cohesiveness of clay.

Plasticity is the outstanding physical characteristic of clay. This is the property a substance has of deforming continuously under a finite force. Like liquids, plastic solids do not reach a definite deformation under load and then become rigid; they continue to deform indefinitely. Unlike liquids, however, plastic solids will not begin to flow until a definite force is applied; up to that point they are rigid.

It is not easy to explain why clay possesses this property. The chemical composition of kaolinite apparently is not of paramount importance in this connection. It is believed that the fineness of the particles is of significance. Clay particles are extremely small, of the order of magnitude of 1 micron (0.0001 mm). It is believed that these fine particles which have an extremely large surface in the aggregate, absorb a thin layer of water, and that it is this "internal lubrication" which causes the plasticity of clays. (2) In any event, it is known that as the water content of clay is increased, its plasticity increases up to a maximum. This may occur anywhere from 10 to 50%, depending on the nature of the clay. Further increase in the water content causes the clay to become sticky, and then to become a fluid suspension or "slip". (3) Drying the clay down to a dry powder lacking plasticity is also possible. If the drying is conducted at a low temperature, wetting will cause the clay to regain its plasticity. On the other hand, firing causes a permanent loss in plasticity.

The mechanism of plasticization of clays is in dispute, but it seems probable that the major factor is mechanical interference of platy particles dispersed in the water. (4) It has been demonstrated that plastic flow can be induced in liquid suspensions of asymmetric particles, whether needle-shaped or platy, or even mechanical agglomerations of spherical particles. (5) Asymmetric particles can develop mechanical structure in the mass at extraordinarily low volumetric concentrations, particularly if the ratio of the linear dimensions be high. It seems certain that the ratio of inter-particle attraction to the distorting forces likely to act on a single particle increases as size decreases. This is equivalent to saying that forces holding the ultimate particle in place decreases less rapidly with size than do those inducing movement, Figure 1. (6)

Dispersion of the clays is essential to plasticity. It is connected with affinity of the liquid for the clay surface; thus clay resists dispersion in all organic liquids of low polarity. Dispersion is one of the major results of aging and weathering. It is believed that when adequately dispersed, the surface of each ultimate particle is highly hydrated, even where agglomeration is considerable. There is also some parallelism between the base-exchange capacity of clays and plasticity.

(In Table I, the clays are arranged in order of increasing plasticity.)

Table I

<u>Type of Clay</u>	<u>Base Exchange Capacity in Milli-Equivalents/100 Gms.</u>
Kaolin	5
Ball Clay	13
Fire Clay	17.5
Fuller's Earth	27
Bentonite	90

Because air dispersed through the clay-water mixture can greatly decrease plasticity, de-aeration is being adopted in making bricks, refractories and pottery.

The main differences in the physical characteristics of the two primary types of soils may be summarized as follows: (7)

<u>Sand</u>	<u>Clay</u>
Void ratio low	Void ratio high
Negligible cohesion when clean	Marked cohesion, depending on water content
Internal friction high	Internal friction low
Not plastic	Plastic
Only slightly compressible	Very compressible
Compression takes place immediately on application of load	Compression takes place slowly over a long period of time
Permeable to water	Practically impermeable

METHOD AND THE ATTACK UPON THE PROBLEM

To simulate in some way some of the above discussed characteristics of soils, the following ideas were advanced for experimentation:

1. Graded glass beads (available in graded sizes from 0.005 in. to 0.40 in. in diameter) mixed with varying quantities of silicone fluids of varying viscosities.

2. Modeling clay with various admixtures of oils to vary its strength.
3. Colloidal iron in a liquid binder and subject to a variable field wherein the mechanical properties could be controlled by the strength of the electro-magnetic field.
4. Shots of various sizes and materials with a binder to achieve varying densities.
5. Binder constituents (Vehicle):
 - a. Liquid or pasty materials as mineral oil, fat and wax combinations; asphaltum; b. synthetics as glycols, "Plastics", etc.
6. Solid constituents (Body)
 - a. Chemically inert powders having high slippage properties as: Talc (steatite); Mg. Al silicates; titanium and zinc oxides; kaolin and magnesium carbonate.
 - b. Chemically inert powders having high frictional properties as: Pumice, quartz (sand); slate flour (hydrated aluminum silicates); emery, tripoli, corundum; mica; crushed garnet; boron and silicon carbides; aluminum, chromium, and tin oxides.
7. Materials to add plastic character to artsoil. Plasticity of clay seems to develop only in particles below 10 micron size. (8)
 - a. The effectiveness of various materials listed below as possible ingredients was determined by:
 - (1) Comprehensive literature survey conducted to evaluate the physical and chemical properties of the various substances.
 - (2) Preliminary laboratory experiments to aid in the selection of the components.
 - b. Laboratory Investigations were conducted to evaluate:
 - (1) Degree of cohesion and friction and stress-strain relationships as defined by the soil parameters c , ϕ , k_c , k_ϕ , and n , (9).
 - (2) Effect on the parameters by varying the percentages of the soil mass constituents.

The following are the materials tested as possible ingredients for artsoil:

Solid Constituents

Asbestos
Calcite
Charcoal
Feldspar
Fuller's Earth
Glass, Powdered
Graphite
Iron Oxide (Red & Black)
Iron, Filings
Infusorial Earth
Kaolin
Mica
Magnesium Oxide
Quartz
Rotienstone
Silicon Carbide
Soapstone Talc
Tripoli
Tin Oxide
Zinc Oxide

Liquid Constituents

Ethylene Glycol
Glycerin
Mineral Oil
Paraffin
Petrolatum

At the present stage, the three ingredients decided upon to be used for the artsoil were volclay, sand, and antifreeze. Volclay, a bentonite clay, is readily available in the clay group. It represents the cohesive ingredient of soils. Sand, which exhibits frictional characteristics, represents the frictional component. Antifreeze was chosen as the liquid constituent because of its low volatility, its inertness when mixed with sand or clay and its ease of availability. The general characteristics of these materials are shown in Appendix I.

The mixing of the ingredients was done in a Hobart S601 Mixer, shown in the center of the "Soil Processing Room" photograph (Fig. 8). The mixing procedure was as follows:

1. Weigh and put volclay into mixer.
2. Start mixer.
3. Weigh and add antifreeze gradually.
4. After all of the antifreeze has been added, continue mixing for 1/2 hour.

The same mixing procedure was followed for all batches to keep them consistent and the mixture was transferred to a 4' x 4' x 2" box and tamped to get an even consistency throughout the batch. Shear and sinkage tests were made on the samples in the box.

The test procedure was as follows:

1. Sinkage:

- a. Three different sized footings.
- b. Three runs per each footing.
- c. Tamp the sample after each sinkage reading.

2. Shear:

- a. Place 5" x 5" shear plate in sample making sure of complete contact of plate and grousers with the artsoil.
- b. Load plate with three to five varying loads and record force necessary to move the shear plate for each load. Movement of the plate indicates point of rupture or shear of the sample.

The Bevameter used for the sinkage test is shown in the photograph entitled "Load Sinkage - Shear Test Device", Fig. 9. The shear plate was attached to a spring scale to record the force. The sinkage and shear test on the sand and antifreeze mixture was made with the combination hydraulic sinkage-shear test apparatus, shown in the "Load Sinkage - Shear Test Device" photograph, Fig. 10.

To avoid a repetition of the theoretical reasoning behind the soil value parameters, the reader is referred to the investigations by Mr. M. G. Bekker. (11) The equation used in relation with the sinkage tests to determine soil values is:

$$p = \left(\frac{k_c}{b} + k_\phi \right) z^n \quad (1)$$

where

- p = Pressure (Loaded track or wheel)
 k_c = Cohesive Modulus of Deformation
 b = Breadth of the Footing
 k_ϕ = Frictional Modulus of Deformation
 z = Sinkage
 n = Exponent of Sinkage

The equation used to determine soil values with data from the shear tests is:

$$H = cA + W \tan \phi \quad (2)$$

where

- H = Force
- c = Cohesion
- A = Ground Contact Area
- W = Weight
- ϕ = Angle of Internal Friction

If equation (2) is divided through by the area A, we have the equation as used in the plot of Fig. 1.

$$\frac{H}{A} = c + \frac{W}{A} \tan \phi . \quad \frac{H}{A} = \text{Shearing Strength } (S_s) \text{ and}$$

W/A = Ground Pressure or normal stress. The plot used to determine k_p , k_c , and n is shown on Fig. 2.

RESULTS

A tabulation of the soil values for three types of artsoils is given below:

<u>Artsoil</u>	<u>c</u>	<u>ϕ</u>	<u>k_c</u>	<u>k_p</u>	<u>n</u>
C-32-35	2.05	0°	22.0	17.0	0.16
-40	1.14	0°	18.0	12.1	0.20
-41	0.64	0°	3.6	2.5	0.25
-43	0.25	0°	0.2	0.9	0.40
-50	0.17	0°	0.1	0.3	0.67
CS-33-22	1.06	38°	17.0	9.5	0.15
-23	0.95	38°	11.6	8.3	0.17
-24	0.76	38°	8.9	6.2	0.18
-25	0.38	38°	4.0	1.8	0.20
-26	0.14	38°	3.4	0.4	0.21
S-34-7.5	0.17	22.5°	9.1	20.4	0.42
-10	0.30	14.5°	10.8	18.4	0.46
-12.5	0.35	9.5°	17.0	11.6	0.52
-15	0.44	8.0°	26.5	6.8	0.71

An attempt was made to cover the entire range of soil conditions with these mixtures. The C-32 series (volclay and antifreeze) attempts to cover the cohesive portion of the scale, and the S-34 series (sand and antifreeze) the frictional portion of the scale. The CS-33 series (50-50 sand-volclay

and antifreeze) is midway between the cohesive and frictional mixtures. The numbers following the series designation denote the weight percent antifreeze added. The graphs in Fig. 4-7 shows the changes in soil values as the liquid content changes.

The test results indicate that a wide range of soil value parameters can be obtained. It is highly conceivable that by changing the consistency of the mixture and by changing the proportion of ingredients in the mixtures, the entire range of natural soils could be simulated in the laboratory.

There seems to be no appreciable chemical reaction between the ingredients which would alter the characteristics of the mixture, i.e., the clay mixture retains its cohesive properties and the sand mixture retains its frictional properties.

The ingredients mix well and retain their consistency throughout, except in the very high liquid content mixtures. The high liquid content mixtures appear to be a case of over-saturation where the excess liquid rises to the top. The separation of the excess liquid occurs only after prolonged standing, so a re-mixing arrangement will have to be made if this soft mixture is to be used over a long period of time.

Stability characteristics of the mixtures and the reproducibility of soil values from these mixtures have not been investigated at this time.

CONCLUSION

1. The controllability of the artsoil is superior to that of natural soil over any length of time.
2. The artsoil has a wide range of soil values.
3. There are many different types of soils that can be simulated by the clay, sand, and antifreeze combination. This should cover the entire range from purely frictional to purely cohesive soils. The materials are readily available and no special equipment is necessary for preparation of the soils.
4. To fully explore the potential of the proposed artsoil in laboratory use, it is necessary to explore the characteristics of world soils and see whether they may be simulated by the discussed mixtures.

RECOMMENDATIONS

1. The stability and reproducibility of soil values for the artsoil should be investigated over a long period of time, i.e., three week intervals for a year.

2. An investigation should be made to find the characteristics of soils to be reproduced.

3. A method for preventing solid-liquid separation in saturated art-soil should be explored.

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APPENDIX

1. Antifreeze

The antifreeze is the antic-type Ethylene Glycol used in the cooling systems of internal combustion engines. MIL-C-11755 (Ord), O-E-771A.

2. Sand

Mined and shipped by the Ottawa Silica Co., Ottawa, Illinois. It is marketed as Crystal Silica Sand.

3. Volclay

Volclay, as sold by the American Colloid Co., Chicago, Illinois, is Mississippi Bentonite. Other types of bentonite clays are mined in the Black Hills Region of the United States, and prepared in powdered and granulated forms for commercial use.

Mineralogical Composition

The properties of volclay are those of montmorillonite, a clay mineral of unique characteristics, which constitutes 90% of volclay substance. Montmorillonite has the approximate chemical formula:



The other 10% consists of minute fragments of other minerals, the most abundant being feldspar. There are small fractions of gypsum, calcium carbonate and quartz, and traces of partially altered volcanic glass, biotite mica, magnetite, limonite, hematite, leucosene, apatite and zircon.

AVERAGE CHEMICAL ANALYSIS	Moisture Free
Mechanically-held water	0.00%
Silica (SiO ₂)	64.32
Alumina (Al ₂ O ₃)	20.74
Ferric Oxide (Fe ₂ O ₃)	3.03
Ferrous Oxide (FeO)	.66
Titanium Oxide (TiO ₂)	.4
Phosphoric Acid (P ₂ O ₅)	.01
Lime (CaO)	.52
Magnesia (MgO)	2.30
Soda (Na ₂ O)	2.59

AVERAGE CHEMICAL ANALYSIS (Cont')

	Moisture Free
Potash (K ₂ O)	.39
Sulfur (SO ₃)	.35
Chemically-held H ₂ O	5.15

Particle Size

When dispersed in water, volclay separates into extremely fine particles, as follows:

96 to 97% finer than 44	microns (325 mesh)
93 to 94% finer than 5	microns
87 to 89% finer than 0.5	microns
60 to 65% finer than 0.1	microns

One micron is about 1/25,000 inch. One cubic inch of dry volclay, when disintegrated in water, is estimated to yield 9500 billion individual flakes, and the total surface area of these particles is about one acre in extent.

General

Specific gravity -- 2.75. Actual weight relative to volume depends on the degree of pulverization and the packing and settling.

Index of refraction -- 1.55.

Hardness 1 to 1.5 (Mohr). Slightly harder than talc.

pH of water suspensions about 9.2.

Base Exchange

Volclay has base exchange properties; in water solution it gives up sodium and potassium ions and takes in calcium and magnesium ions, thus softening the water slightly. It also enters strongly into base exchange with organic bases, extracting them from solutions of their salts.

The exchangeable metallic bases of average volclay, determined quantitatively by leaching with ammonium acetate, are:

Sodium	85.5 m/3 per 100 gms.
Potassium	5.0
Calcium	22.0
Magnesium	1.0
Sum -- corrected for Sulphates	89.2

Swelling

The rate of swelling depends on the grade and on how handled; all grades expand very slowly when water is poured on them, much faster when they are poured into water. Finely powdered and coarsely granulated grades soak up water slowly; specially sized KWK volclay much more rapidly.

Volclay absorbs nearly 5 times its weight of water and at full saturation it occupies a volume 12 to 15 times its dry bulk. On drying it shrinks to its original volume. The swelling is reversible -- it can be wetted (swelled) and dried (shrunk) an infinite number of times, if the water used is fairly pure.

It absorbs and swells faster in hot water than cold. Does not swell in alcohol, gasoline and similar liquids; swells only slightly in solutions of strong chemicals, as acids, alkalies or salts.

Water Suspensions

When mixed with 7 to 10 parts water, it makes gelatinous pastes. With 15 to 20 parts water, it forms milky, flowable sols.

Figures are given showing the consistency (viscosity) of two volclay sols compared with clear water:

Determinations By Stomper Viscosimeter At 600 RPM

	Grams	Centipoises
Clear Water	35	0
5% volclay (1 volclay to 19 water)	70-75	6½ - 7
7½% volclay (1 volclay to 13⅓ water)	300-350	55 - 60

The sols were tested immediately after stirring; they would show higher readings after a few hours.

In thinner dilutions -- as 1 volclay to 99 distilled water -- most of the volclay will remain suspended indefinitely. Even in dilutions as low as 1 to 5000, a considerable part will not settle. Distilled water must be used with low volclay concentrations as the electrolytes in tap water might cause partial flocculation.

Dilute suspensions show Brownian movement -- the particles are in motion, colliding and repulsing each other. Heavier slurries exhibit thixotropy, a kind of gelation that occurs when they stand quiescent, but which reverts to fluidity on being shaken or stirred.

Effect of Electrolytes

Particles of volclay in water carry strong negative charges, causing them to attract and cling to positively charged particles of matter. When neutralized by oppositely charged substances, they floc together, forming spongelike aggregates, and if this occurs in dilute dispersions, the flocs will settle. In thicker mixtures, however, as those containing 6% or more of volclay, the effect of added electrolytes is to increase the viscosity.

Suspensions of volclay are ordinarily difficult to filter, forming impenetrable cakes which seal off water. One of the effects of neutralizing or flocculating the particles is to make such suspensions more readily filterable.

It follows that all dispersions of volclay are profoundly affected by electrolytes. The higher the valence of the latter the stronger the effect; mono-valent cations are mildly active in causing flocculation, di-valent ones more so and tri-valent ones much more so.

The order of adding electrolytes is important. If an electrolyte is added to a thick slurry in which the volclay has first been fully hydrated and swelled, the consistency of the slurry will be increased; but if the water is first treated with an electrolyte and the volclay put in later, the dispersion will be thinner than a mixture of volclay and clear water.

Temperature of water and time of standing also are factors. Some electrolytes will stiffen the slurries temporarily, followed by thinning after standing days or weeks; others reverse this action.

Sorption

Montmorillonite molecules, of the particular kind that constitute volclay, have the outstanding peculiarity of expanding accordion-like in water. This enlarges the space between the sheets of atoms which form the molecular structure and permits the free ingress and egress of ions of various kinds.

The mobility of the flakes when in suspension brings them in close contact with other dissolved and suspended substances. Particles of matter are not only absorbed onto the surface of the bentonite molecule, but probably also absorbed within its lattice-like structure. The avid sorption of volclay for other substances -- both organic and inorganic -- is therefore due to one or more of these factors: great surface area; spongy structure; mobility; base-exchange; strong negative polarity.

Bond Strength

The maximum adherent powers of volclay in moistened masses with other minerals is exerted when the volclay has about 50% available moisture.

Effect of Temperature

The properties of volclay are unaltered at temperatures below 400°F. (205°C.). The chemically held water is progressively driven off when exposed to higher heats for any length of time and is completely gone at 1200°F. (650°C.).

However, if heated to 1000°F. (538°C.) and quickly cooled, its properties are unchanged.

Its swelling properties decrease progressively in the same ratio as the loss of chemically held water.

Softening begins about 1900°F. (1040°C.) and complete fusion occurs at 2440°F. (1340°C.).

Volclay imparts to masses of other minerals bonded with it an extraordinary "hot strength", i.e., resistance to load pressure while hot. In the range of temperatures just below the softening point, its "hot strength" far exceeds that of other clays.

Mechanically Held Moisture

Volclay as shipped contains about 7 to 9% moisture. When exposed to the atmosphere, it will slowly gain or lose according to the humidity, within the range between 6% in very dry air to 10% in moist air.

To oven-dry it to constant moisture requires 4 hours at 220 to 230°F.

(1) Miscellaneous Information

<u>Base</u>	<u>Formula</u>	<u>Chem. Character</u>	<u>M.P. in °C</u>
Fire Clay	- - - -	Neutral	Up to 1750° C
Silica	SiO ₂	Acidic	1710
Chromite	FeO.Cr ₂ O ₃	Neutral	About 2000
Magnesia	MgO	Basic	2800
Mullite	3Al ₂ O ₃ . 2SiO ₂	Neutral	1810
Carborundum	SiC	Neutral	Dissoc. 2200
Alumina	Al ₂ O ₃	Neutral	2020
Zirconia	Zr O ₂	Neutral	2700

(2) Some Natural Clay Characteristics

1. Plasticity of clay increases with addition of weak organic acids.
2. A small amount of alkaline solution converts sticky clay to a liquid thin enough to run through a filter cloth.
3. A small amount of acid solution will coagulate clay.
4. Salts may either coagulate a clay or increase the dispersion of the particles.

- 3 -

<u>Soil</u>	<u>% Water</u>	<u>Gal. H₂O/Cu. Ft.</u>
Free flowing sand	0	0
Damp sand	2	1/4
Wet Sand	4	1/2
Very Wet Sand	6	3/4
Very Wet Sand	8	1
Very Wet Sand	10	1-1/4

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<u>Material</u>	<u>Sp. Gr.</u>	<u>Densities in Lbs/Cu. Ft.</u>
Water	1.0	62.428
Clay, dry	1.0	63.
Clay, damp plastic	1.76	110 - 135
Clay & gravel dry	1.6	100
Earth dry loose	1.2	76
Earth dry packed	1.5	95
Earth moist loose	1.3	78
Earth moist packed	1.6	96
Earth mud, flowing	1.7	108 - 120
Earth mud, packed	1.8	100 - 115
Sand, gravel, dry, loose	1.4 - 1.7	90 - 105 (100)
Sand, gravel, dry, packed	1.6 - 1.9	100 - 120
Sand, gravel, wet	1.89 - 2.16	126 - 130
Sand or gravel in water	0.96	60
Sand or gravel & clay in water	1.00	65
Clay in water	1.28	80
River mud	1.44	90
Soil, Wet	1.12	70
Shale		160
Gravel		110
Chalk		170
Diatomite powder		10.6
Kaolinite	2.6 - 2.63	

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<u>Modified Moh</u>	<u>Hardness Scale</u>	<u>Orig. Moh</u>
15	Diamond	10
14	Boron Carbide	9.32
13	Silicon Carbide	
12	Fused alumina	9.03
	Corundum	9
11	Fused zirconia	
10	Garnet	
9	Topaz	8
8	Quartz or stellite	8
7	Vitreous silica	
6	Orthoclase	6
5	Apatite	5
4	Fluorite	4
3	Calcite	3
2	Gypsum	2
1	Talc	1
1-2.5	Kaolinite, pure	

(6) Labeline Penetrometer

40mm = 1.6" penetration
accuracy = 0.25% full scale
needle bar & needle weigh 50 gms.
extra 50 & 100 gm. wts. available.
Operation as grease penetrometer described in
ASTM D5-47T, D217-48, D937-47T and AASHO T49-52

(7) Brookfield Viscometer Model RVF

Full scale torque is 7.187 dyne-centimeters

Max. cp. = 2,000,000 at 2 RPM with Spindle #7.
Min. cp. = 500 at 20 RPM with Spindle #1.

Always state a materials temperature along with its Viscosity.
Viscosity is the measure of fluid friction.
Water at room temperature (68.4°F.) has a viscosity of one centipoise.

<u>Fluid</u>	<u>At Temp °F.</u>	<u>Viscosity (centipoises)</u>
Water	68.4°F	1
Glycerine (100%)	60°F	1400
Lub. oil SAE 10	60°F	100
SAE 30	60°F	400

Viscosities Saybolt Univ., Seconds

<u>SAE</u> <u>Visc. No.</u>	<u>AT 130°F.</u>		<u>AT 210°F.</u>	
	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>
10	90	120		
20	120	185		
30	185	255		
40	255			80
50			80	105
60			105	125
70			125	150

80 100,000 @ 0°F max.
90 800-1500 @ 100° F.
110 120-200 @ 210°F.
250 200 @ 210°F. min.

Light Mineral oil; sp. gr. = 0.83-0.86 Ave 0.845
Heavy Mineral oil; sp. gr. = 0.875-0.905 Ave 0.89

Figure No. 1

Influence of Particle Size Upon Flow Characteristics

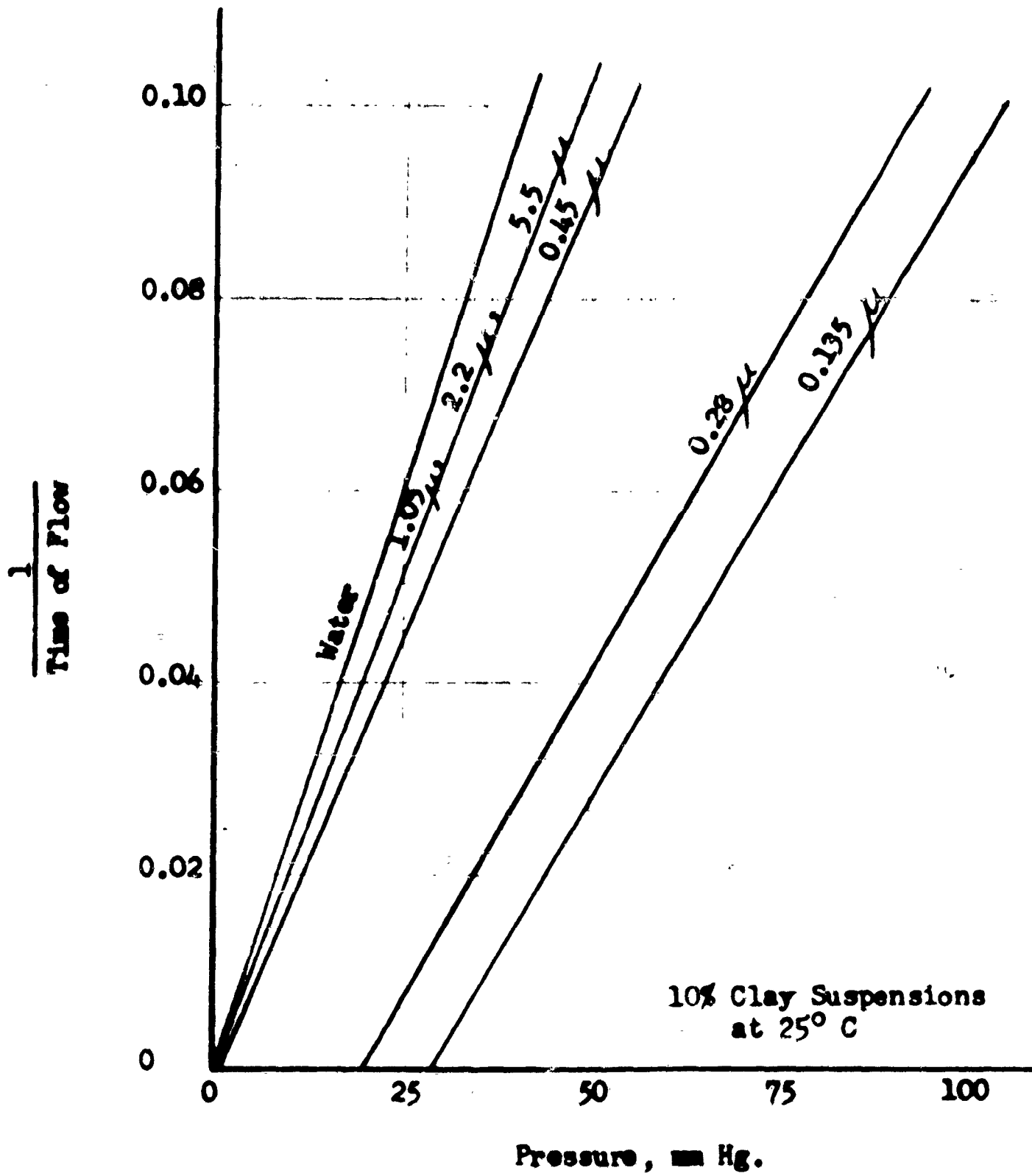


Figure No. 2
Test Data Plot For Determining c and ϕ
Artsoil CS-33-25

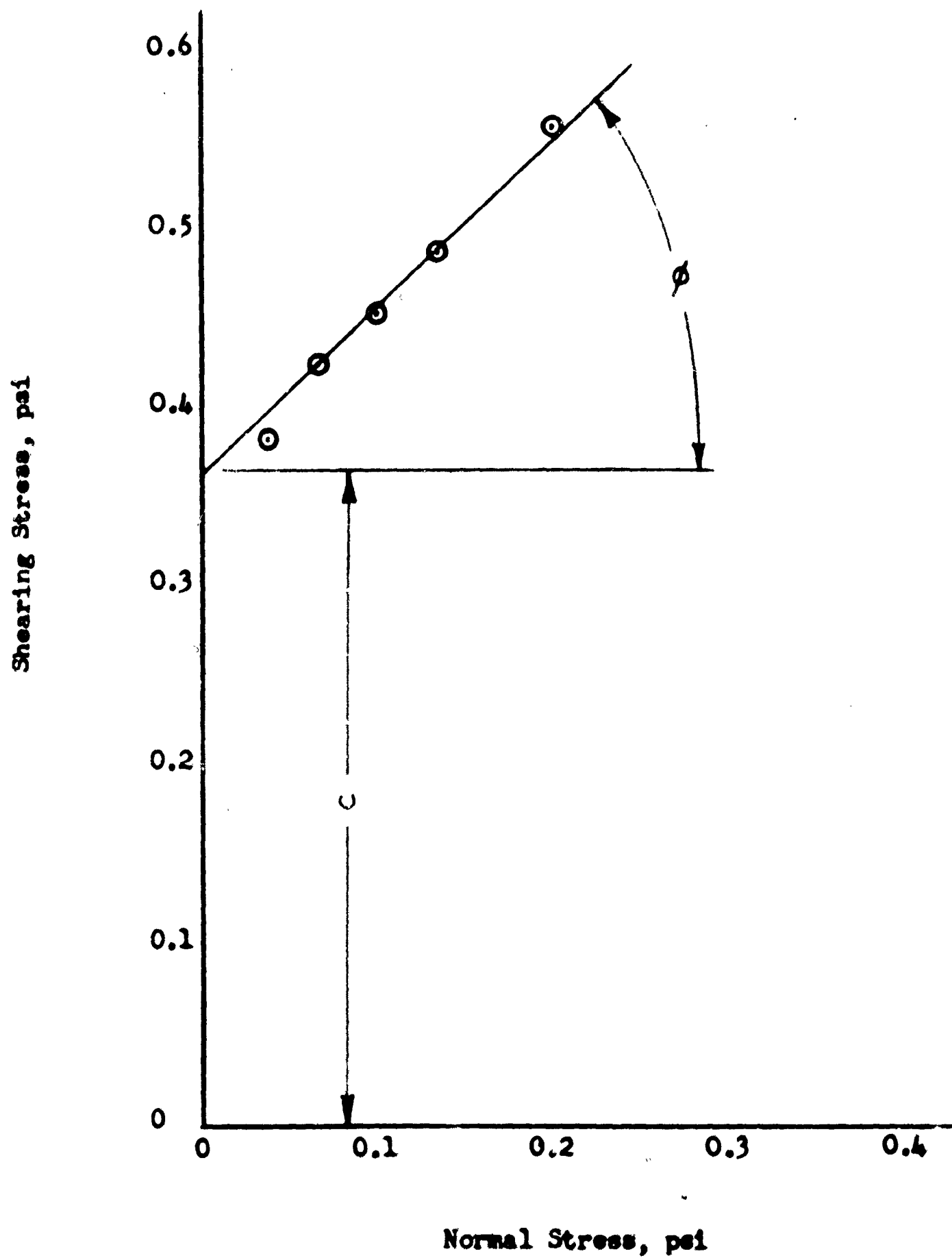
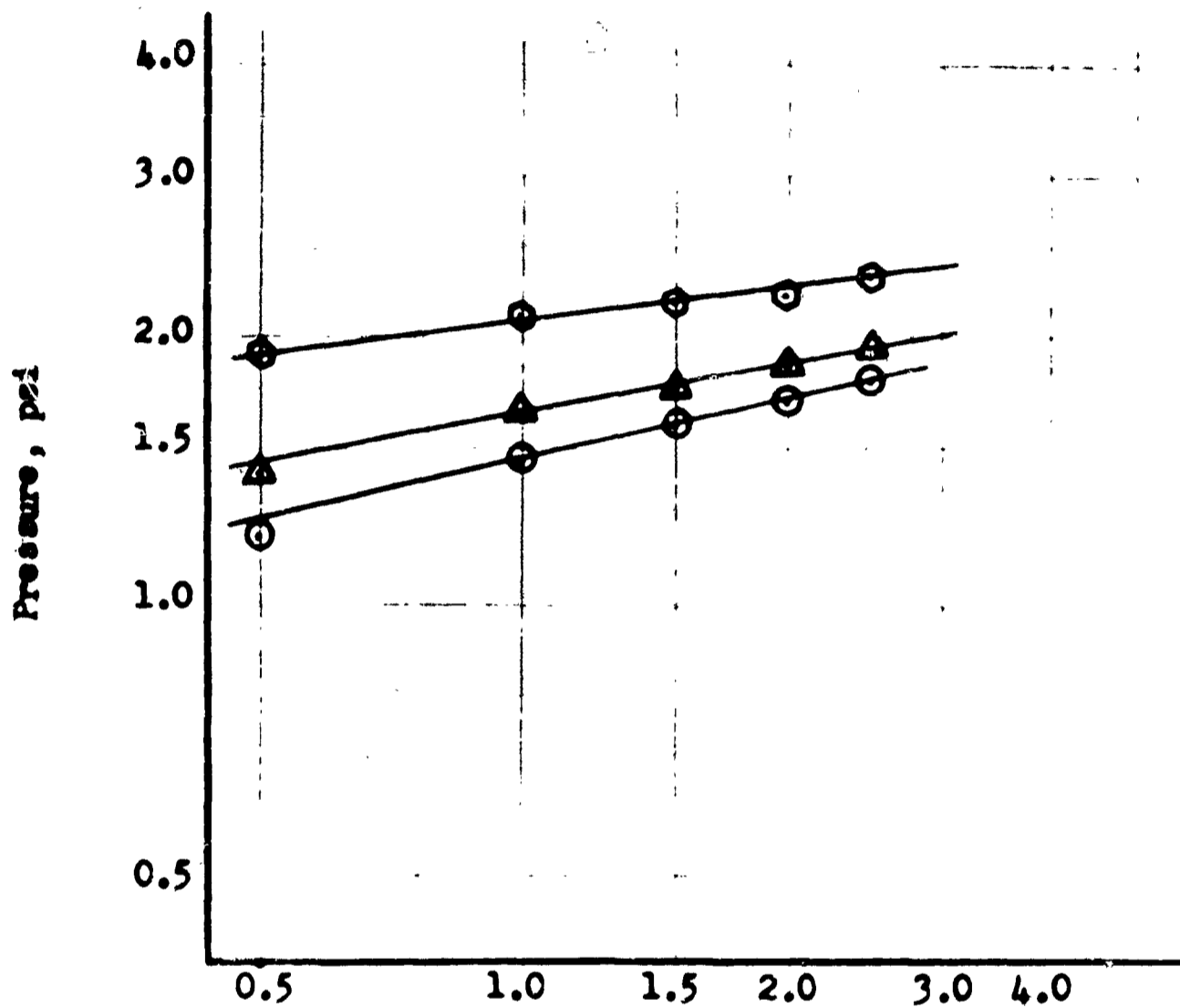


Figure No. 3

Test Data Plot For Determining k_c , k_f , & n

Artsoil CS-33-23



Sinkage, Inches

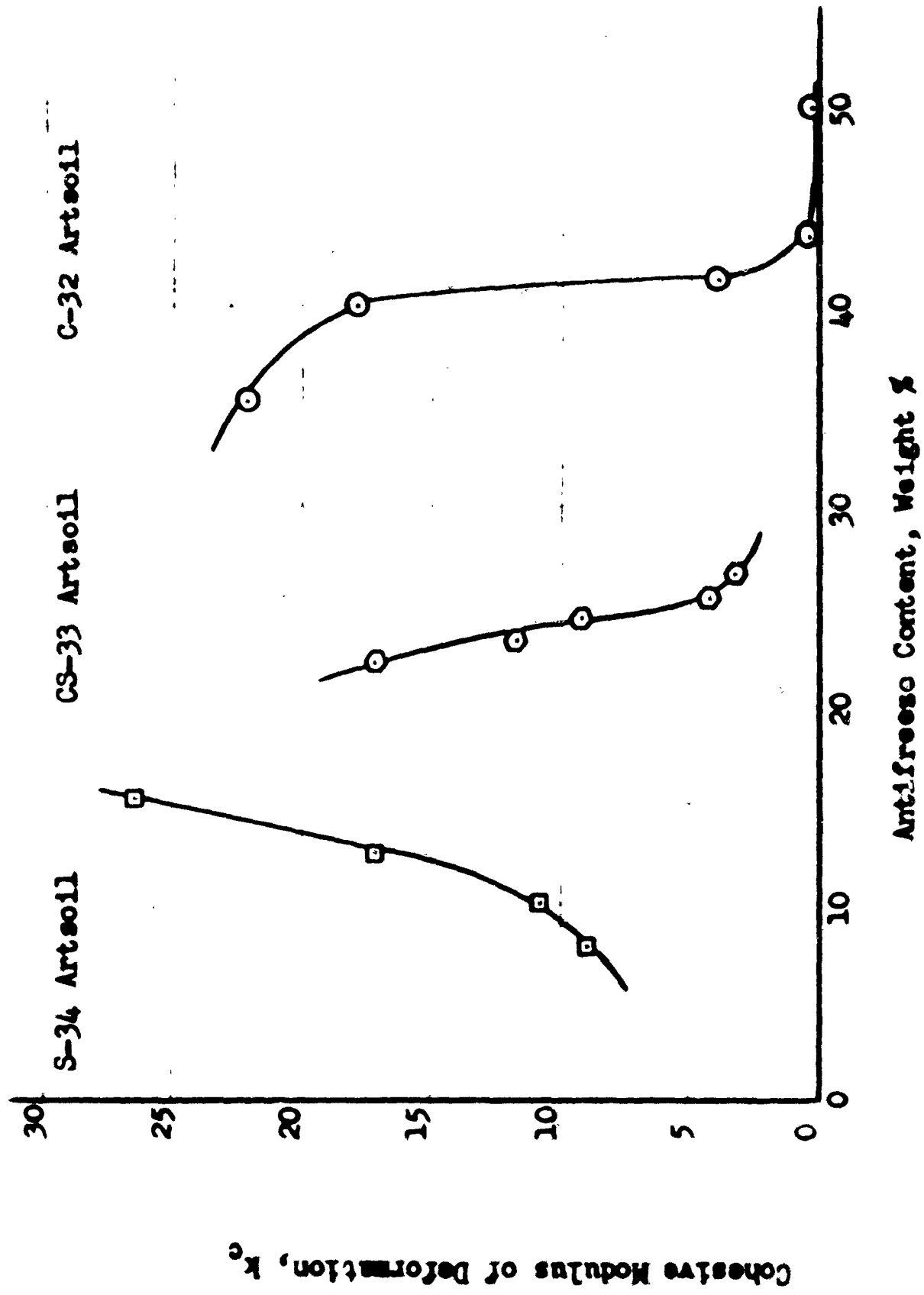
○ $b = 2$ in., $a = 14.7$

△ $b = 1.5$ in., $a = 16.5$

□ $b = 1$ in., $a = 20.7$

Figure No. 4

k_c vs. Antifreeze Content For The Three Artoils



Army - OTAC - Detroit

Figure No. 5

k_d vs. Antifreeze Content For The Three Artoisils

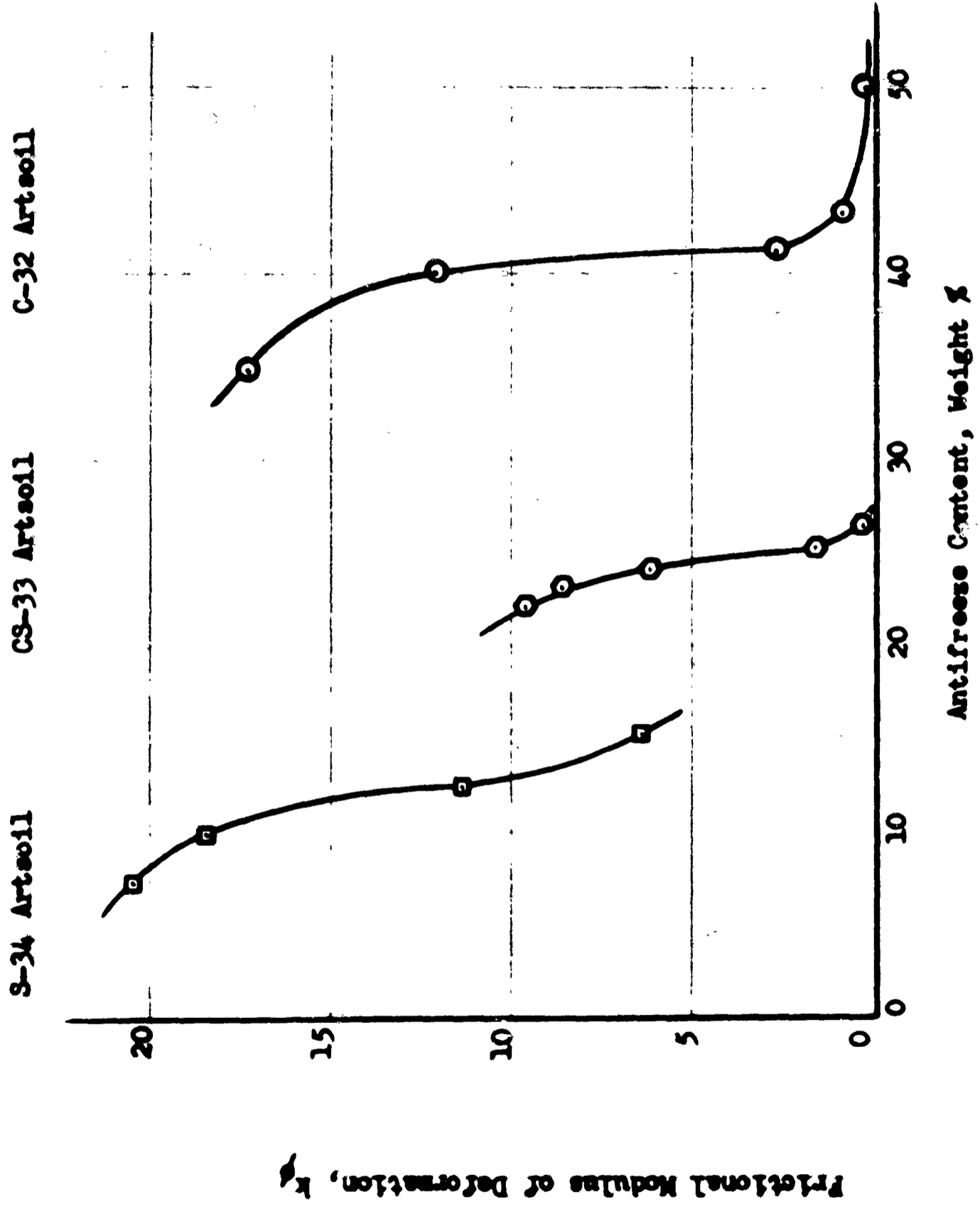
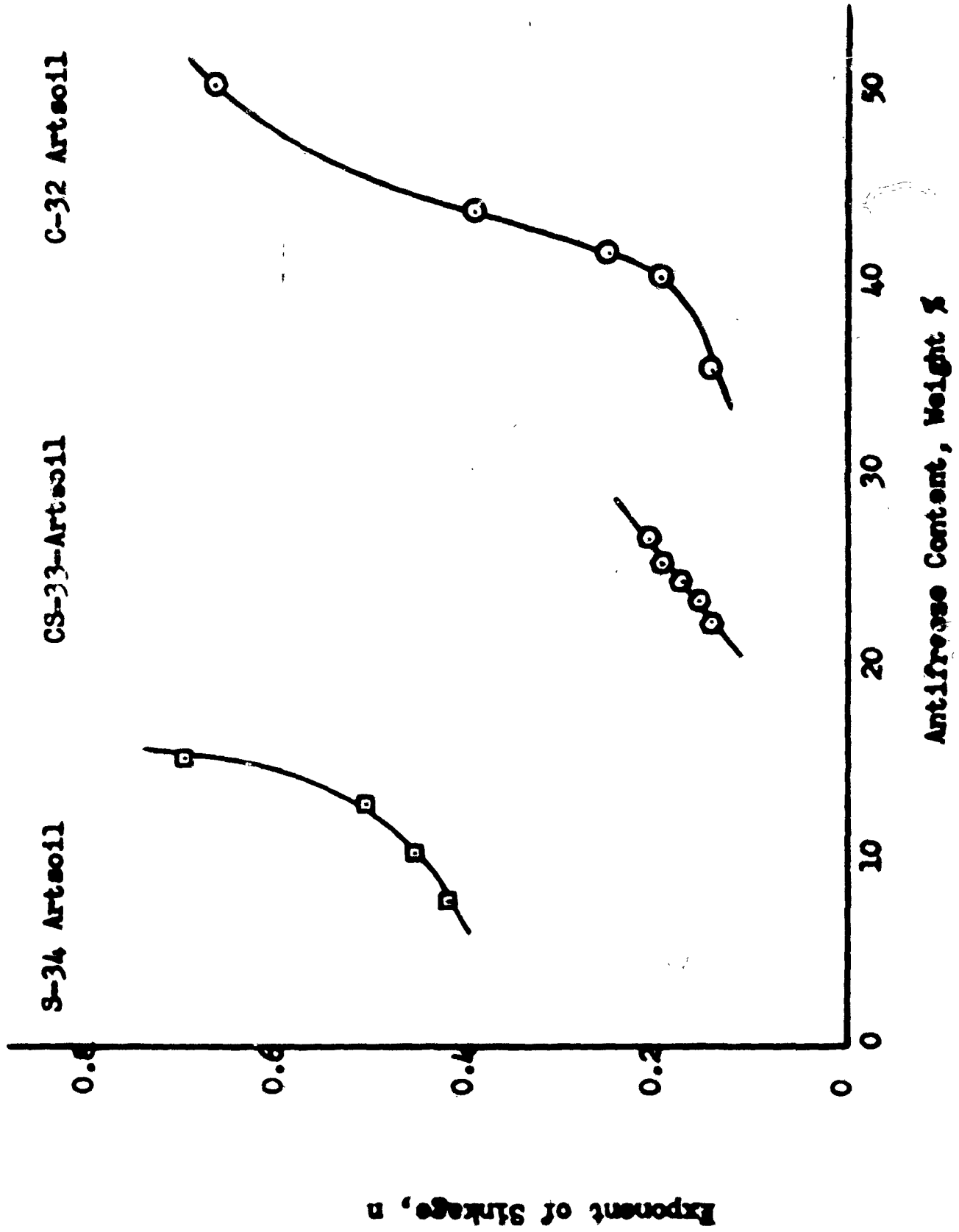


Figure No. 6

n vs. Antifreeze Content For The Three Arto soils



Army - OTAC - Dwell

Figure No. 7

c vs. Antifreeze Content For The Three Artsoils

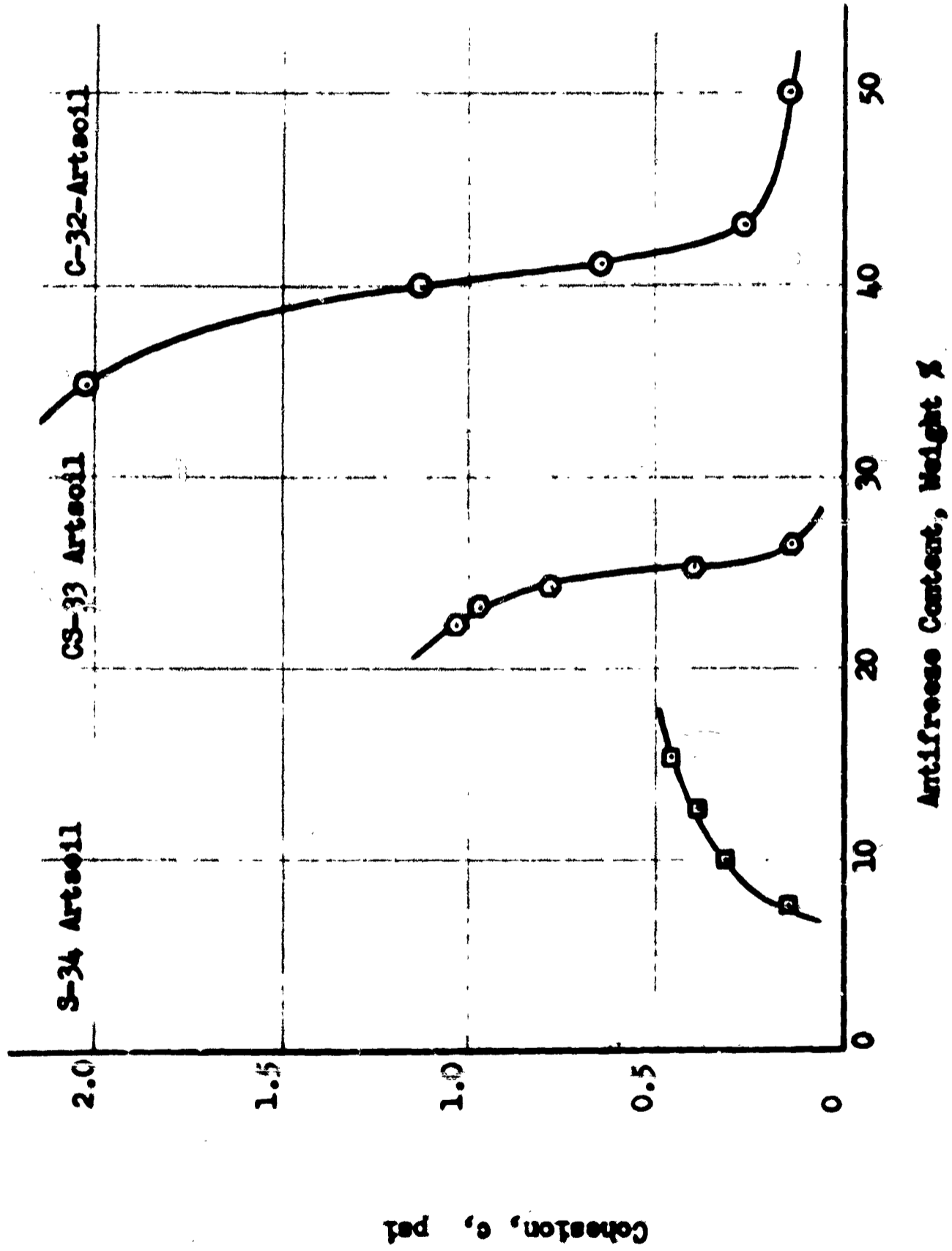




Fig. No. 8
Soil Processing Room

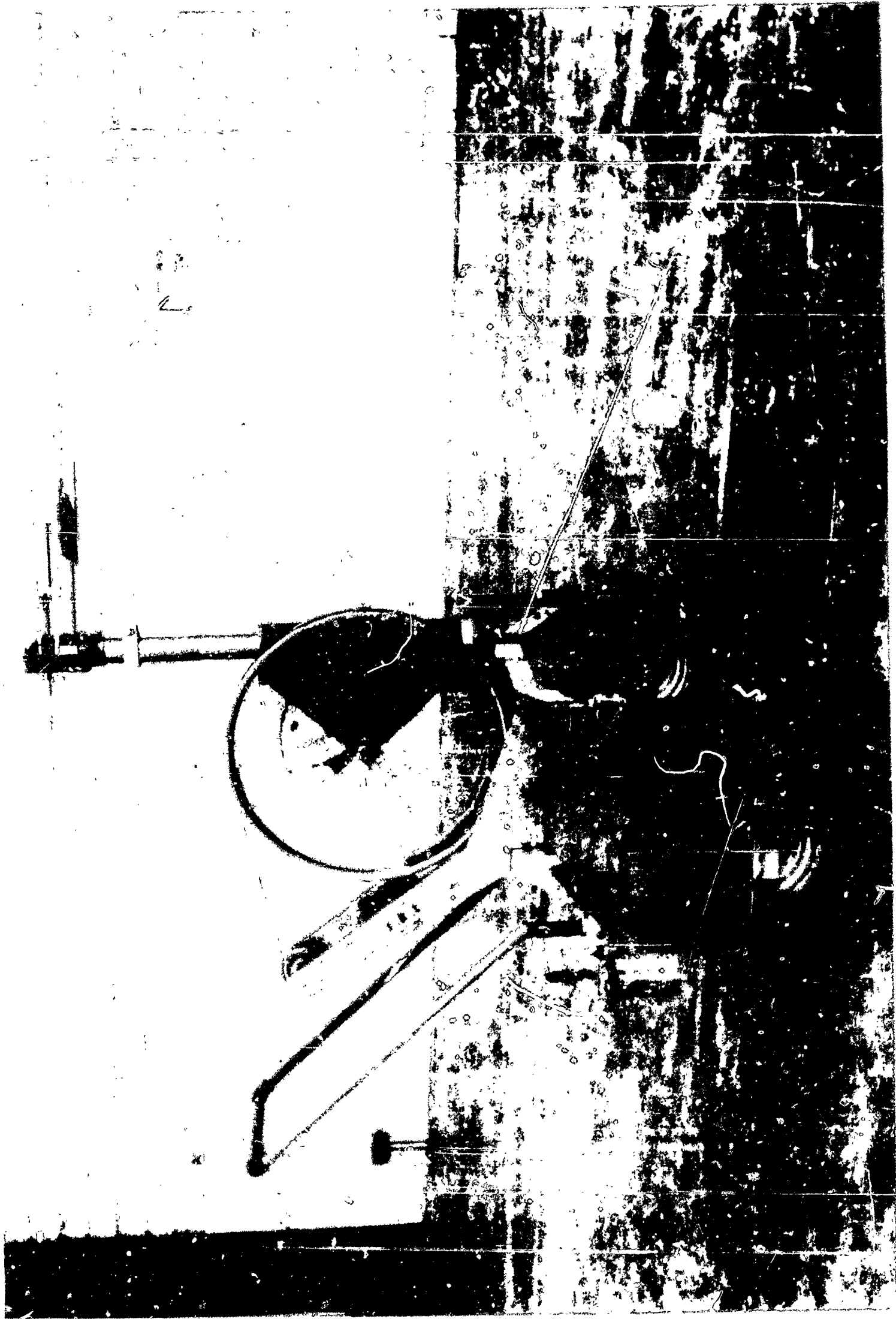


Fig. No. 9
Bevameter Model III, Shear Test Device



Fig. No. 10
Load Sinkage - Shear Test Device