

SOIL ANISOTROPY AND ITS RELATION
TO AGGREGATE STABILITY

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ABSTRACT

A study was made to correlate soil anisotropy to aggregate stability. For soils having similar pedality, texture and mineralogy, aggregate stabilities increase with increasing anisotropy. Soil anisotropy in turn is an index of the degree of organization of the primary inorganic constituents.

It was demonstrated that relative measurement of soil anisotropy can be made by the use of a photometer. The anisotropy of a given soil can be evaluated quantitatively if the anisotropic materials are evenly distributed throughout the matrix. Soils which have illuviation cutans or pressure cutans on ped faces but possess isotropic ped interiors cannot be measured in the absence of a suitable sampling technique that will represent an average cross-section of the soil.

A possible mechanism of aggregate formation with plates (kaolinite) and cementing agent (hydrated iron oxide) was elucidated not on the basis of the amount or concentration of each component but on their pedological organization. This mechanism has been shown to hold true for a group of Hawaiian Latosols.

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I. INTRODUCTION

Soil structure has long been recognized as an important soil property. The physical constitution of a soil material as expressed by the size, shape, and arrangement of the soil aggregate has been used by Americans to describe soil structure. Brewer and Sleeman (7) use the term pedality to describe the identical system. The ability of the soil aggregate to resist destruction by mechanical forces or the slaking action of water is an important index to agronomists, soil conservationists and engineers. Often the degradation of soil structure is used synonymously with the deterioration of the soil aggregate. In fact, evaluation of soil structure is based, for the most part, on some measure of aggregate stability.

Soil scientists have described a large number of factors that make for aggregate stability. Some of these factors are free oxide, organic matter, calcium carbonate and clay contents of soils.

Hawaiian Latosols, like their counterparts elsewhere, generally have good soil structure. This excellence in structure has been partly attributed to the high iron oxide content and partly to the predominantly kaolin mineralogy of these soils.

Field examination of these soils in connection with classification studies always reveals a wide range in

structural grade within latosolic soils. Related to this variation in grade is a change in soil anisotropy.

Soils may be anisotropic in many ways to many things. In this report the usage of the term "soil anisotropy" will be restricted to the optical anisotropy of the soil aggregate (ped). Optical soil anisotropy may vary with, among other things, the mineral composition of a soil. However, for a pedological system composed of clay size particles, in this case kaolin and non-crystalline free iron oxide in unvarying amounts, the optical soil anisotropy will depend on the intra-ped organization of these materials.

Since most soils are composed of anisotropic, crystalline components, no soil is completely isotropic. The minute size of the crystallites, however, makes it impossible for them to react to polarized light. For this reason, when the crystallites are arranged in a completely random manner, the system is nearly isotropic. Such a system is also devoid of any pedological organization and might be considered the starting point for the development of soil aggregates. Maximum anisotropy is attained when all the crystallites are oriented in one crystallographic direction. This condition imparts to the mass the characteristic of a single crystal.

Orientation of platy clay particles are best evidenced by illuviation cutans or clay skins on ped faces.

Lineal patterns of illuviation outans following the shape of coated surfaces are easily distinguished when the core of the peds are isotropic. Orientation with reference to anisotropy implies parallel orientation along the 001 face of platy clay particles. This argument does not hold true for the orientation of amorphous clay and tubular halloysite. Clay skins possessing similar physical make-up to that of oriented clay under crossed nicols have been observed under plane light. The difference is one of crystallographic limitation.

One can infer, on the above contentions, that for soils with similar or identical mineralogy, the degree of anisotropy will depend on the amount of orientation of the clay size units. It is obvious that parallel orientation along the 001 face of platy clay particles brings greater surface contact. If bonding occurs between these surfaces, aggregates thus formed may be gauged as more stable than aggregates not similarly endowed. If the degree of anisotropy is related to the degree of clay orientation, one then has the starting point to demonstrate whether a relationship exists between soil anisotropy and aggregate stability.

Since the measured value of soil anisotropy \underline{a} , depends on the mineral orientation \underline{o} , the mineral species \underline{m} , the mineral concentration \underline{c} , and the slide thickness \underline{t} , as well as many other factors as symbolically expressed,

$$a = f(o, m, c, t, \dots) \quad ,$$

the experimenter must control all variables except mineral orientation.

If we express the above equation as a total derivative,

$$d(a) = \left(\frac{\partial a}{\partial o} \right)_{m,c,t,\dots} do + \left(\frac{\partial a}{\partial m} \right)_{o,c,t,\dots} dm + \left(\frac{\partial a}{\partial c} \right)_{o,m,t,\dots} dc \\ + \left(\frac{\partial a}{\partial t} \right)_{o,m,c,\dots} dt + \dots$$

it is readily seen that this study is concerned only with the first partial derivative. In order to evaluate this quantity, such factors as soil mineralogy m , mineral concentration c , and slide thickness t , must remain constant. Much of the work in this study centers around the mathematical ratification of the quantity,

$$\left(\frac{\partial a}{\partial o} \right)_{m,c,t,\dots} do$$

The purpose of this research has been to demonstrate whether there exists a relationship between structural grade, aggregate stability and anisotropy of soils.

II. REVIEW OF LITERATURE

The micromorphological study of Uehara et al. (40) of certain soil structural types in Hawaiian Latosols indicated the possibility of correlating the orientation of clay along ped faces and ped interiors to aggregate stability. This conclusion was reached upon careful observation of structural development of each petrographically described thin section and comparing this to the structure in the field. A two-component system of plates (kaolinite) and cementing agent (hydrated iron oxide) was proposed as the possible mechanism that could explain aggregate formation in these soils. Emphasis was made upon the micromorphological arrangement of these two components as the factor that determines the kind and degree of structural development.

Polar substances produced by the decay of organic matter have been reported as superior aggregating agents (21, 24). A physico-chemical bonding with surface-active clay minerals was used (21) to characterize the action of these substances while iron and aluminum oxides, fats, waxes, and resins were believed to form a continuous matrix which binds the soil particles into aggregates through physical means. McHenry and Russell (24) asserted that the mere presence of organic matter does not promote aggregate formation unless some binding agents such as colloidal material and slimes are produced upon decomposition.

The influence of clay content in promoting stable aggregates has been widely investigated (3, 24, 28, 35). Baver (3) studied different soils throughout the United States, exclusive of lateritic soils, and found a correlation of clay content and organic matter content to aggregation. These two factors were believed to play a major part in soil granulation. In lateritic soils he suggested that colloidal Al_2O_3 and Fe_2O_3 could influence the formation of aggregates. The granulation of semi-lateritic and lateritic soils is believed to be due to free iron. Lutz' data and observations (22) showed the highly significant correlation of free iron oxide to aggregated silt and clay of 10 soil types. Weldon and Hide (43) extracted more sesquioxides from well aggregated soil fractions than from poorly aggregated ones.

McIntyre (25) gave a possible mechanism of the influence of free iron in aggregation: (a) cementation following precipitation and irreversible drying of iron gels, (b) iron in solution preventing deflocculation, and (c) the formation of organic-mineral complexes. Prebble and Stirk (27) speculated that free alumina could also fit in this mechanism inasmuch as aluminum can remain in solution at a higher pH than iron. Another argument in relating aluminum as well as iron in aggregation is the fact that weathering processes retain both free iron oxides and alumina in commensurate amounts. Field observations on

some red Hawaiian soils reported as dominantly kaolinitic, low in bases and rich in oxides of iron and aluminum (37, 40, 41), exhibit significant differences in structural grade and stability of aggregates.

Tropical soils which are generally characterized by a higher proportion of kaolinitic clay have firm aggregates cemented by oxides and hydroxides of iron and aluminum (34). Robinson and Page (31), in running aggregate stability tests on some soils in the continental United States, observed that kaolinite and illite showed no slaking when wetted in a vacuum in contrast with montmorillonite which exhibited gradual disintegration. All the samples slaked readily when wetted at atmospheric pressure. They summarized that slaking is developed by capillary forces of the entering liquid on air entrapped within the aggregate.

Chesters and his colleagues (9), discussing their correlation studies on the factors affecting soil aggregation, generalized that microbial gum is the most important factor in the soils they studied. However, high clay content and iron oxide showed respectively marked effects on some soils where microbial gums failed.

Rogowski and Kirkham (32) studied the effect of moisture and pressure in the formation of water-stable aggregates. Aggregates of 2 to 8 mm size were ground and given moisture and pressure treatments up to 30.5 per cent and 1000 psi respectively, that formed them into cylin-

drical briquettes which were broken into aggregates while moist, air-dried and tested for water-stability. The resulting water-stability values were found to be lower than the untreated water-stability of the 2 to 8 mm aggregates. They concluded that forces such as chemical, biological and other natural factors may be responsible for the formation of stable aggregates.

Reported data (17) on East Bengal soils have shown the highly significant effects of moisture, loss on ignition, clay, Fe_2O_3 and K_2O and significant effects of Al_2O_3 and exchangeable calcium to the structural capacity of these soils.

The use of the petrographic microscope in soil structure studies using thin section technique is gaining wide acceptance. Day (12) discussed his observations on soil structure using a Bausch & Lomb metallurgical microscope employing the fracture surface, debris preparation and polished section techniques. Occurrence of clay movement and clay concentration for the purpose of classifying certain soil horizons can be readily observed by using microscopic methods.

Clay gels upon drying form clearly visible laminar structure observable in natural light as well as under crossed nicols (36). Sideri, in explaining the absence of sharp boundary between the grains of sand and clay substance after mixing, mentioned the "law of mutual orienta-

tion with formation of a laminar system possessing anisotropic properties (35).” Heltzer as cited by Sideri (36) conducted an experiment that followed the formation of structure using serozem as an example of a structureless soil. The soil contained 99.6 per cent of stable macroaggregates after the introduction of an insignificant amount of the autolytic products of the fungus Aspergillus niger. Observations with a polarizing microscope revealed oriented arrangement of particles. The appearance of doubly refractive envelopes was believed as the cause of the abrupt rise in the observed structure.

Brewer (6) published a scheme for classifying and describing soil structure based on observations made on thin sections under polarized light. He suggested cutans be used instead of clay skins and defined them as modifications of texture, structure or fabric at natural surfaces in soil materials due to concentration of particular component or in situ modification of the plasma. The plasma of a soil material is that part capable of being modified by the processes of soil formation. The scheme (6, 7) appears very useful in the micromorphological studies of soils.

Laboratory techniques for determining aggregate stability have been reviewed by Baver (4). The absence of standard procedures for evaluating soil structure leaves the investigator to choose his methods of analysis and ways of expressing his results. The particular technique used

by workers depends on the instrument available, convenience and the purpose of the test. The wet-sieving analysis proposed by Yoder (44) and modified by many workers is gaining wide acceptance. The expression of results from wet-sieving analysis has been the subject of many proposals. The mean weight-diameter of van Bavel (2) gives a statistical index of aggregation. Gardner (13) suggested the use of the logarithmic-normal distribution. Retzer and Russell (30) formulated the coefficient of aggregation to express aggregation status of soils. Many wet-sieving analysis data have been reported as per cent retained on a chosen sieve. Alderfer and Merkle (1) used a stability index which is the sum of the positive differences between the aggregate analysis and the complete mechanical analysis. They claimed that the larger the stability index, the more stable is the structure of the soil. The weighted mean diameter and the Schoklitsch number were suggested by Puri and Puri (29). Conaway and Strickling (11) compared seven methods of expressing aggregate stability and concluded that simple summation fractions of the water-stable aggregates were as sensitive as the other methods. Youker and McGuinness (45) proposed a short method of obtaining mean weight-diameter values of aggregate analyses of soils. They developed a regression equation which could predict the actual mean weight-diameter of most other soil areas.

In general, the merits of each method will depend on the extent of qualitative or quantitative comparisons made.

The necessity of pre-treating the samples before wet-sieving has been recognized. Nijhawan and Olmstead (26) reported that spray wetting, capillary wetting and vacuum wetting gave higher percentage of aggregates in investigating the effect of sample pre-treatment upon soil aggregation in wet-sieve analysis. The length of preliminary soaking of the aggregates has been found to bear no statistical significance (33)

It is safe to state that materials published as regards quantitative correlation of anisotropy to the stability of soil aggregates are inaccessible at this time if any exists.

III. MATERIALS AND METHODS

Soil samples were for the most part collected from the Kipapa Gulch Transect. The Kipapa Gulch Transect is bounded to the west by Kipapa Gulch, to the east by Panukauahi Gulch, to the south by Kamehameha Highway and to the north by the Crosley's Ranch. The soils in this area have been mapped in great detail by the Soil Conservation Service for a special problem it is presently conducting.

Seven soil series have been described in this area. They are the Molokai, Lahaina, Wahiawa, Kipapa, Waipio, Manana and Paaloa series. Elevation in the transect ranges from approximately 350 feet near Kamehameha Highway to 1150 feet at the ranch site. Roughly three quarters of this area, in the central portion of the transect, is occupied by the Wahiawa series. To the south, the Molokai series dominates with a minor strip of Lahaina sandwiched between the Wahiawa and the Molokai series.

The Kipapa series occur near the edge of the gulches in association with the Wahiawa series.

The Waipio series occupies a topographic position just above the Wahiawa series and is followed respectively, by the Manana and Paaloa series.

Three great soil groups, the Low Humic, Humic Ferruginous and Humic Latosols, are recognized in this area. The Molokai, Lahaina and Wahiawa series belong to the Low Humic Latosol, the Manana to the Humic Ferruginous Latosol

and the Paalooa to the Humic Latosol. The Waipio series has been classified as an intergrade between the Low Humic and Humic Ferruginous Latosols.

Two profiles each of the Molokai and Wahiawa series were sampled for this work from the Kipapa Transect. Another Wahiawa profile was sampled in a eucalyptus grove approximately 500 feet north of the Leilehua National Guard building on Kamehameha Highway.

One profile each of the Manana and Paalooa series was collected outside the transect. Since both soils occupy a small area within the transect, it was considered advantageous to seek these soils in areas where they occur in large continuous tracts.

The Paalooa was sampled at a site approximately 1 mile northeast of Helemano Military Camp.

The Manana was sampled at a site located 1/4 mile south of the entrance gate to Kaukonahua Military Camp.

Although the profile descriptions are not of the sampled profile, in each case the morphological data as given were so similar to the published description for each soil series that no revision of the original was considered necessary. The description of these soils were taken from the Soil Survey Legend for the Kipapa Gulch Transect (38).

Samples used in this work represent 22 horizons from 8 profiles. The horizons were selected on the basis of structural difference within the profile and sometimes,

color. Collection of samples within the plow layer was minimized. Samples within the A horizon were collected only if there was no apparent disturbance of structure.

Profile description of the five soil series represented in this study are given in the following pages. At this point it might be well to take note of the structural grade in each horizon. In the case of cultivated fields, the plow layer often reveals a highly altered structure. In the undisturbed subsoil the natural structural grade varies from very weak to strong.

1. Molokai Series

This soil consists of very deep, fine-textured, well-drained Low Humic Latosols developed in residuum from basic igneous rocks. It is located on gently sloping to moderately steep lower upland slopes at a rough altitude of 300 to 400 feet. Apparent texture of the solum is silty clay loam to clay. Rainfall average for 30 years ranges from 20 to 35 inches.

Profile Description

Ap	0-12 inches	Dusky-red (2.5YR 3/3) clay that feels like gritty silty clay loam, very dusky red (2.5YR 2.5/3) when moist; very weak, very fine and fine granular structure; soft, friable, sticky and plastic; many very fine and fine, occasional medium
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pores; some dark-red material from B horizon mixed in by tillage; many very fine iron-black manganese shot; violent reaction with 3 per cent hydrogen peroxide; pH 5.8; abrupt smooth boundary.

- B₁** 12-34 inches Dark-red (2.5YR 3/5) clay that feels like silty clay loam, dark red (2.5YR 2.5/5) when moist; structureless (massive); very friable, slightly sticky and plastic; many very fine, fine and occasional medium pores; occasional very thin patchy coatings; common black iron-manganese shot; moderate reaction with hydrogen peroxide; pH 6.3; gradual boundary.
- B₂₁** 24-36 inches Dark red (10R 3/5) clay that feels like silty clay loam, dark red (10R 2.5/5) when moist; very weak, very fine and fine subangular blocky structure; very friable sticky and plastic; many very fine, fine and occasional medium pores; common thin patchy coatings; slight reaction with hydrogen peroxide; mainly on iron-manganese shot; pH 6.4.
- B₂₂** 36-43 inches Dusky-red (10R 3/4) clay that feels like a clay loam; strong very fine subangular blocky structure; friable, slightly

sticky and plastic; few iron-manganese shot; slight reaction with hydrogen peroxide.

B₃ 43+ inches Dusky-red (10R 3/4) clay that feels like a clay loam; strong very fine subangular blocky structure; friable, slightly sticky and plastic; many patchy coatings; few highly weathered olivine basalt fragments, easily crushed in hands.

2. Wahiawa Series

This soil consists of very deep, fine-textured, well-drained Low Humic Latosols developed from basic igneous rocks located on nearly level to gently sloping medial uplands at an elevation of 500 to 800 feet. Apparent texture of the solum is a silty clay. Annual rainfall ranges from 40 to 60 inches.

Profile Description

Ap 0-10 inches Dusky-red (10R 2.5/2) clay that feels like silty clay, very dusky red (10R 2/2) when moist; weak very fine and fine granular structure; friable, sticky and plastic; many very fine and fine interstitial pores; some dark reddish-brown material from horizon below, many very fine and fine iron-manganese concretions; violent

reaction with hydrogen peroxide; pH 5.4;
abrupt, smooth boundary.

B₂₁ 10-17 inches Dark reddish-brown (2.5YR 3/4) clay that feels like silty clay, dark reddish brown (2.5YR 2/4) when moist; moderate very fine subangular blocky structure; friable, sticky and plastic; many very fine and fine, few medium pores; many patchy coatings on peds and in pores; firm in place; many iron-manganese concretions; violent reaction with hydrogen peroxide; pH 6.4; gradual wavy boundary.

B₂₂ 17-34 inches Dark reddish-brown (2.5YR 3/4) clay that feels like a silty clay, dark reddish brown (2.5YR 2/4) when moist; strong very fine subangular blocky structure; friable, sticky and plastic; common to many very fine and fine tubular pores; continuous coating; compact in place; common fine manganese stains; common iron-manganese concretions, which when checked with auger seemed to increase with depth.

3. Waipio Series

This soil consists of very deep, fine-textured, well-drained intergrade between the Low Humic and Humic Ferruginous Latosols. This was formerly mapped as a Low Humic Latosol. It is developed in residuum from basic igneous rocks and located on nearly level to moderately steep intermediate uplands at an elevation of 500 to 1000 feet. Annual rainfall ranges from 40 to 60 inches.

Profile Description

- | | | |
|-----------------|--------------|--|
| Ap | 0-12 inches | Dark reddish-brown (2.5YR 3/4) clay that feels like silty clay, dark reddish brown (2.5YR 2/4) when moist; mainly structureless (massive) due to recent compaction with heavy equipment, some very fine subangular blocky structure; firm, sticky and plastic; many roots; very few pores due to compaction; some dark reddish-brown material from lower horizon mixed in by cultivation; common iron-manganese concretions; violent reaction with hydrogen peroxide; pH 4.4; abrupt, smooth boundary. |
| B ₂₁ | 12-23 inches | Dark reddish-brown (2.5YR 3/4) clay that feels like silty clay; moderate to strong very fine subangular blocky structure; |

friable, very fine and fine, few medium pores, most of which seem to be between the peds; thin almost continuous coatings; compact in place; many black manganese stains, with some areas within horizon having very few stains; moderate reaction with hydrogen peroxide; pH 5.3; gradual, wavy boundary 6-12 inches thick.

B₂₂ 23-47 inches Dark reddish-brown (2.5YR 3/4) clay that feels like silty clay; strong very fine subangular blocky structure; friable, sticky and plastic; no roots noticed; common very fine, few fine pores; thin continuous coating with some areas that are thick and look like clay films; compact within place; few iron-manganese concretions; very slight reaction with hydrogen peroxide; pH 6.5; diffuse, wavy boundary 21-34 inches thick.

B₂₃ 47-55 inches Dark reddish-brown (2.5YR 3/4) clay that feels like silty clay; strong very fine and fine subangular blocky structure; firm, sticky and plastic; no roots; common very fine and fine pores; almost continuous dark-red coating that looks like clay film; firm in place; no reaction

with hydrogen peroxide; pH 6.5; clear, wavy boundary 5-9 inches thick.

B₃ 55-72+ inches Dark reddish-brown (3.5YR 3/3) clay that
 or feels like silty clay; moderate to strong
 B_{2b} very fine and fine subangular blocky
 structure; friable, sticky and plastic;
 no roots; common very fine and fine
 pores; almost continuous dark-red coating
 that looks like clay film; few highly
 weathered gray pebbles and stones; few
 manganese stains; pH 5.0.

4. Paaloo Series

This soil consists of very deep, fine-textured, well-drained Humic Latosols developed in residuum from basic igneous rocks and located on gently sloping to sloping medial plains at an altitude of 1050 to 1150 feet. Mean annual rainfall ranges from 70 to 80 inches and is fairly distributed throughout the year.

Profile Description

Ap 0-10 inches Dark reddish-brown (4YR 3/3) clay that
 feels like silty clay; moderate very
 fine, fine and medium granular structure,
 firm, sticky and plastic; many roots;
 many very fine and fine pores; some
 dusky-red material from B horizon; bulk

density seems to be high for a Humic Latosol; common glistening specks; no reaction with hydrogen peroxide; abrupt smooth boundary.

- B₁ 10-17 inches Dark reddish-brown (3.5YR 3/4) clay that feels like a light silty clay; weak very fine subangular blocky structure; friable, sticky and plastic; many roots; many very fine and fine pores; few thin patchy coatings; no reaction with hydrogen peroxide; clear wavy boundary.
- B₂ 17-24+ inches Dark reddish-brown (2.5YR 2.5/4) clay that feels like silty clay; moderate very fine subangular blocky structure; common roots; many very fine and fine pores; many thin patchy coatings; no reaction with hydrogen peroxide.

5. Manana Series

This soil consists of very deep, fine-textured, well-drained Humic Ferruginous Latosols developed in volcanic ash located on gently sloping to moderately steep uplands at an elevation of 500 to 1000 feet. Mean annual rainfall ranges from 50 to 80 inches.

Profile Description

- Ap 0-9 inches Reddish-brown (2.5YR 4/4) clay that feels like a light silty clay, dark reddish-brown (2.5YR 3/4) when moist; moderate very fine, fine and medium granular structure, firm, sticky and plastic; many roots; many very fine, fine and medium interstitial pores; common hard earthy lumps, possibly iron oxide aggregation, slight reaction with hydrogen peroxide after short delay; pH 5.3; abrupt slight wavy boundary.
- B₂ 9-15 inches Red (10R 4/6) clay that feels like gritty silty clay loam, dusky red (10R 3/4) when moist; structureless (massive) to very weak, very fine blocky structure; friable, sticky and plastic; many roots; many very fine and fine tubular pores; common patchy coatings on weak structure; root mat at lower boundary; pH 5.1; abrupt lower boundary.
- B_{2b} 15-25 inches Weak red (10R 4/4) clay that feels like a silty clay, dusky red (10R 3/3) when moist; strong very fine subangular blocky structure; firm, sticky and plastic; few

black specks with (10 X) looks like sand grains; no reaction with hydrogen peroxide; pH 5.0.

Methods

Soil Anisotropy

Oven-dried soil fragments were impregnated under vacuum with a laminac-styrene (1:3) mixture and allowed to harden gradually at low oven temperature (40-50°C) for at least 15 hours. Two to three drops of catalyst were added to each 350 cc of mixture to accelerate hardening of the plastic. When the plastic finally set, the impregnated samples were baked for at least 6 hours at a temperature of 80°C. Prolonged baking, too much catalyst and high initial oven temperatures very often resulted in a birefringent plastic. Samples that proved to be of these conditions were eliminated.

The use of the laminac-styrene mixture does not always insure satisfactory impregnation. Poor oven-drying, low vacuum pressure and such characteristics as strong ped development and imperviousness often prevent acceptable impregnation. Impregnation with caedax in thylol is a satisfactory alternative. This kind of impregnation is rapid, sure and eliminates the step of oven-drying the sample and avoids the possibility of "plastic" birefringence in the laminac-styrene method. Caedax is heated with

the sample at 150 to 175°C for 8 hours. A test is made whether it is already satisfactory for grinding by taking out a sample with a stick, cooled and crushed into a powdery material. Malleability after cooling suggests further heating. Subsequent impregnations with the "cooked" caedax will normally take shorter time. However, the decreased fluidity of the plastic upon volatilization of the solvent may retard the flow of the fluid into the soil. This may be compensated by increasing the temperature to 200 to 225°C. The time required for impregnation depends on the permeability of the material.

At least three thin sections were prepared from each sampled horizon. The samples were grouped according to fabric observed under crossed nicols. Relative evaluation of soil anisotropy was made from readings of a photometer attached to a petrographic microscope. Light source intensity and size of objective were the same for all the readings. A medium powered objective (10 X) was used to reduce the area covered and minimize the inclusion of voids. Ten readings each were taken from three slides of each sampled horizon.

Aggregate Analysis

Clods fresh from the field were broken into aggregates and dry-sieved to a size greater than 2 mm but less than 3 mm. Where excessive moisture content prevented sieving, the samples were left in the open air for 12-15

hours until no appreciable aggregates stuck on the sieve. In no case were the samples dried in the technical sense of air-drying. Capillary wetting of the aggregates was made for 30 minutes before wet-sieving. This was done by making the level of water just barely touching the screen of the sieve where the sample was gently poured.

Aggregate stability values were obtained by wet-sieving 20 grams of the aggregates on a series of sieves using a stroke of 2 inches and a frequency of 30 oscillations per minute. Aggregates retained on the >60 -mesh sieves were collected, oven-dried and expressed in an oven-dry basis as per cent of total stable aggregates.

The collected stable aggregates were dispersed by shaking for 1 hour with 50 ml of Na-hexametaphosphate prepared according to Kilmer and Alexander (19). Aggregates remaining on a 60-mesh sieve after shaking for 1 hour were deducted from the computed oven-dry weight of material and from the aggregates retained on the 60-mesh sieves after wet-sieving.

Mineralogical Analysis

Clay samples were separated by sedimentation after the digestion of organic matter with hydrogen peroxide. The soil solution was dispersed by adding increments of sodium hydroxide. Clay suspensions were flocculated with sodium chloride and washed free from salts with ethyl alcohol in a centrifuge. X-ray diffraction patterns and dif-

ferential thermal curves were determined on these samples. The clay was oriented for X-ray analysis. The powdered samples for DTA were passed through a 200-mesh sieve. Identification of the minerals were based on methods suggested by Grim (14).

Chemical Analysis

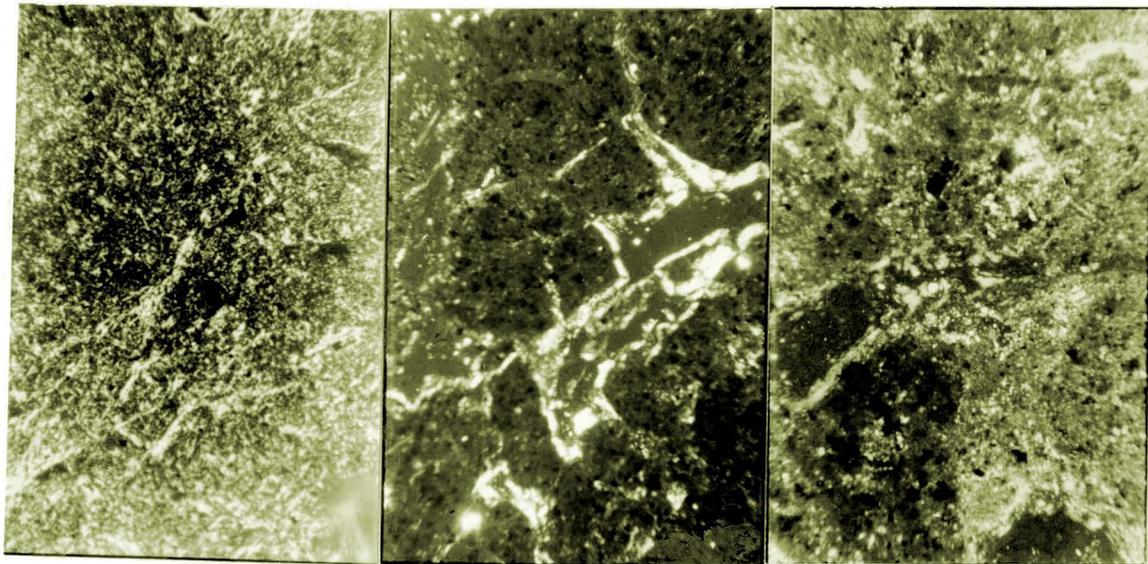
The free iron oxide content was determined by the method of Kilmer (20). Organic matter content was determined using Walkley's method (42).

IV. RESULTS AND DISCUSSIONS

Thin Sections and Evaluation of Soil Anisotropy

Division into fabric types was made on the basis of features observed with a petrographic microscope. Fig. 1 shows photomicrographs of observed fabric types. Fig. 1a shows patches of oriented clay materials that are randomly distributed in the matrix. This fabric is found in all the horizons of Molokai, Wahiawa, upper three of Waipio and Paaloa, and Manana series. The degree of anisotropy varies with different soils. Fig. 1b shows illuviation cutans on ped faces. Notice that the matrix is isotropic. This fabric represents the fourth horizon (44-55 inches) of Waipio series. Fig. 1c is another fabric type which shows oriented clays on ped faces in combination with other anisotropic materials such as gibbsite within or outside the ped. This distinction is easily noticed in actual observation due to the difference in color. In the third type (Fig. 1c), the oriented clays are reddish while the other birefringent mineral (probably gibbsite) is white. This white mineral gives higher photometer readings than the clays. The third fabric is typical of the last two sampled horizons (27-36 and 36-50 inches, respectively) of Paaloa series.

Only the first fabric type (Fig. 1a) was analyzed for anisotropy. The other two were eliminated for two reasons: first, the anisotropic materials are so concentrated that they do not represent a major cross-section of



(a)

(b)

(c)

**Fig. 1. Three fabric types observed under crossed nicols,
size of objective 10X.**

the matrix; second, in trying to get photometer readings on representative slides, the experimenter is beset with the problem of placing his objective in a zone which is representative of the sample.

A question might arise on the validity of anisotropy measurement because anisotropy as measured in this study also depends on the thickness of the slide. This was thought as a major setback at the start of the experiment. However, it was observed from a number of slides made that the color of the soil is an important indicator in getting a fairly uniform thickness if we are to compare the thickness of a set of samples. It is fortunate that the color of the soils studied ranges from red to reddish yellow. In order to get a statistically acceptable figure for anisotropy, 10 readings each of 3 slides for each sample were taken. Each anisotropy value in Figs. 16 to 18 represents a mean of 30 readings. In general, photometer readings were less dependent on thickness than on clay orientation.

Light source intensity, size of objective (in this case 10X) and instrument adjustments were the same for all the readings. It was considered necessary that standards be made in determining a reasonable thickness for anisotropy measurement. This was done by grinding two slides of extreme anisotropies. For this set, the Molokai series having the lowest and the Wahiawa series having the highest anisotropy were selected. The colors were compared both

with plane light of the microscope and by simple visual inspection without the microscope. Inasmuch as the thickness of the matrix was considered more important than the thickness obtained by conventional methods of getting numerical thickness, the visual determination was deemed satisfactory. As a guide, three colors were used as a reference: red, orange, and yellow. Red is too thick, orange is just right; and yellow was considered too thin. To minimize any bias in getting readings, the readings for the whole set in this experiment were taken at one sitting. It was believed that by this technique the variation due to the experimenter's judgment is reduced to a minimum.

The logic in the use of a photometer for evaluating anisotropy can be amply demonstrated. If we consider the matrix of a soil as one unit, the amount of light that is doubly refracted depends on the crystallographic arrangement of its smaller units. It was hinted previously that this is a function of orientation. With increasing orientation, more light is refracted under crossed nicols. The photometer attachment measures light intensity transmitted by the optical system in arbitrary units. If the distribution of birefringent materials is fairly uniform within the matrix, the assumption that a photometer can evaluate the anisotropy of that matrix becomes valid. For this reason, only the first fabric type (Fig. 1a) was selected for this purpose.

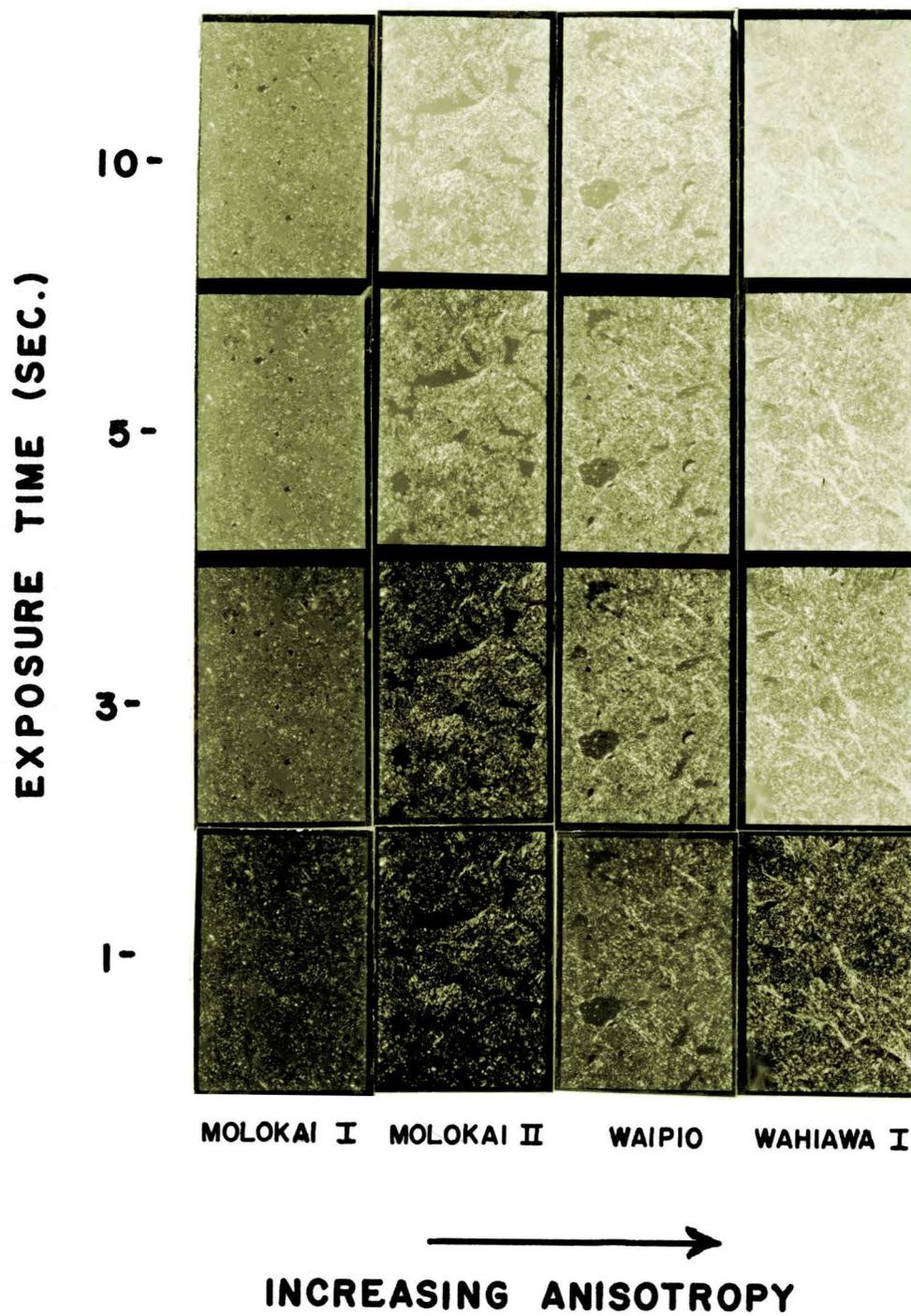
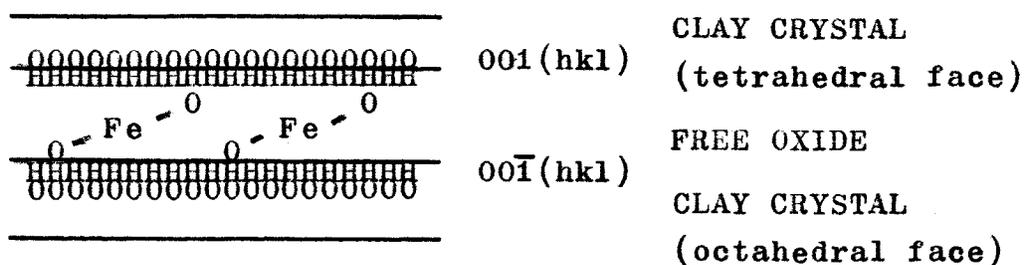


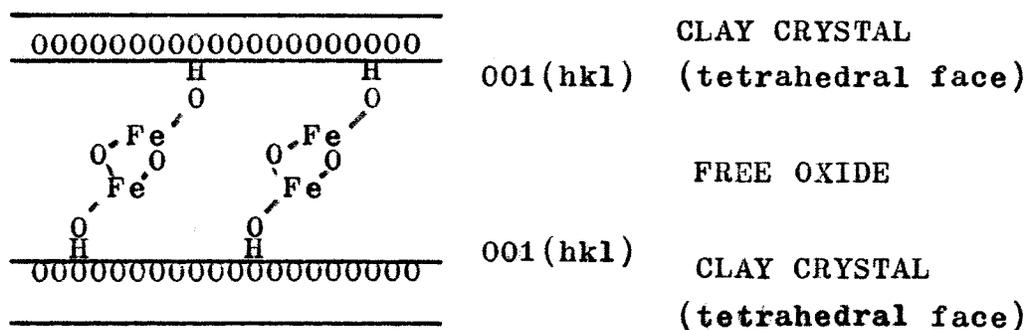
Fig. 2. The relationship of exposure time to anisotropy.

In taking photomicrographs, the degree of anisotropy of each soil affects the kind of picture that can be obtained. Fig. 2 shows the relationship of exposure time to anisotropy. With constant exposure time a gradation of whiteness to darkness of four representative soils is illustrated by the figure. The optimum grade for all the samples seems to fall within a diagonal line drawn from Molokai I at 10 sec. to Wahiawa I at 1 sec. Once this line is drawn, the pictures on the triangle at the upper right-hand corner are overexposed and underexposed for the lower triangle. The time of exposure to light in printing and time of developing are constant for the whole set. Likewise, light source intensity during exposure was maintained constant.

Based on some earlier findings (40) the mechanism on Fig. 3 has been postulated to demonstrate aggregate formation. Aggregates are thus formed if we extend this argument in a three-dimensional system. The arrangement of the plates in a manner by which the cementing agent can form an optimum number of bonds becomes the limiting factor in stable aggregate formation. No attempt shall be made to explain how orientation is brought about. Thoughts on this have been discussed elsewhere (5).



(a)



(b)

Fig. 3. A possible mechanism of aggregate formation in a clay-oxide system.

(a) Tetrahedral-octahedral (001-001̄) contact of two kaolinite particles.

(b) Tetrahedral-tetrahedral (001-001) contact of two kaolinite particles.

Aggregate Stability

The moisture content of the aggregates prior to wet-sieving was deemed important if a relative comparison is to be valid. Table 2 illustrates the change in aggregate stability with varying moisture conditions for Wahiawa series.

The moisture contents of the 22 horizons analyzed without air-drying range from 17 to 43 per cent (oven-dry weight basis). The Molokai series which can be observed very dry in most parts of the year do not seem to be affected in aggregate stability by varying moisture conditions.

TABLE 1. A comparison of the aggregate stability values of two moisture conditions of Wahiawa series expressed in per cent retained on a 60-mesh sieve.

Horizon, Inches	Air dry, 4-6% Moisture	Fresh from the field, 29-30% Moisture
4-10	92	97
17-25	83	94
35-40	81	97

An average of 8 determinations represents each aggregate stability value in Figs. 16 and 18. These have been from samples fresh from the field.

A report from Colorado (10) emphasized the removal of non-dispersible aggregates from aggregates retained on a

60-mesh sieve as these would have not contributed to aggregate stability. It was claimed that a better correlation of aggregate stability with the factors studied was obtained by this method.

The Na-hexametaphosphate dispersion method was adopted in this experiment. Comparison of the aggregate stability values did not show significant difference. All aggregate stability values are herein reported without further treatment after wet-sieving.

The role of free iron oxide and organic matter in aggregate stability

The results of many other investigations (3, 17, 21, 22, 25, 43) urged the author to analyze for free iron oxide and organic matter. Table 2 shows the test of these factors in their role in aggregate stability.

TABLE 2. The effect of three soil factors on aggregate stability irrespective of mineralogy.

Soil factors	Values of r	No. of samples	Degrees of freedom
Free iron oxide	.078 NS	19	17
Organic matter	.384 NS	19	17
Anisotropy	.387 NS	19	17

NS - Not Significant

Clay Content

The Molokai and Wahiawa series have about 80 per cent clay as reported by Kawano (18) and Matsusaka (23). Soils of the Humic Ferruginous Latosols have clay contents ranging from about 40 to 80 per cent. These data suggest that clay content is not limiting and any attempt to correlate aggregate stability to clay content would fail to show any significance.

Clay Mineralogy

The dominant clay mineral as shown by X-ray diffraction analyses is kaolinite. The kaolinite peaks at the 7\AA ($12.3^\circ 2\theta$ for Cu radiation) and 3.5\AA ($24.95^\circ 2\theta$ for Cu radiation) are quite similar in Molokai I and II, Wahiawa I to III and Waipio. The X-ray diagram peaks of the first three horizons of Paalooa and all of the Manana series, are generally smaller than the peaks of the other profiles. (See Figs. 4 to 9.)

The shape and size of the endothermic peaks at 575° to 600°C on the differential thermal curves (Figs. 10 to 13) of the first five profiles mentioned in the X-ray analysis, appear to be similar. In Figs. 14 to 15, one can notice the blunt exothermic peaks of the upper three horizons of the Paalooa and Manana series. This indicates that Paalooa and Manana series have less silicate clays than the first five profiles mentioned.

The small but distinct peaks in the X-ray diffraction diagrams of Wahiawa I, Waipio, Paaloa and Manana at 8.8° and 26.8° are those of illite. Although this mineral occurs in sufficiently large amounts to be of nutritional significance it apparently does not play an important role in aggregate formation.

The endothermic peaks at about 300°C are those of the hydrous oxides. Gibbsite peaks have been identified in the X-ray diagrams. The presence of gibbsite in the clay fraction suggests that this mineral occurs in the finer fraction of these soils (except for Wahiawa II and III). Sodium hydroxide was the only dispersing agent used. Sodium hexametaphosphate has been claimed as a superior dispersing agent for soils that are high in iron. It has been the experience in this laboratory however, that samples dispersed with Na-hexametaphosphate do not show exothermic peaks (Mr. Matsusaka, personal communication). This is perhaps due to the formation of phosphate complexes as reported elsewhere (15).

If the samples are separated on the basis of mineralogy, the Paaloa and Manana series are eliminated from the group. The assumption that the degree of anisotropy for soils with similar or identical mineralogy correlates with aggregate stability can now be tested. Table 3 shows the test of significance for the three soil factors as they

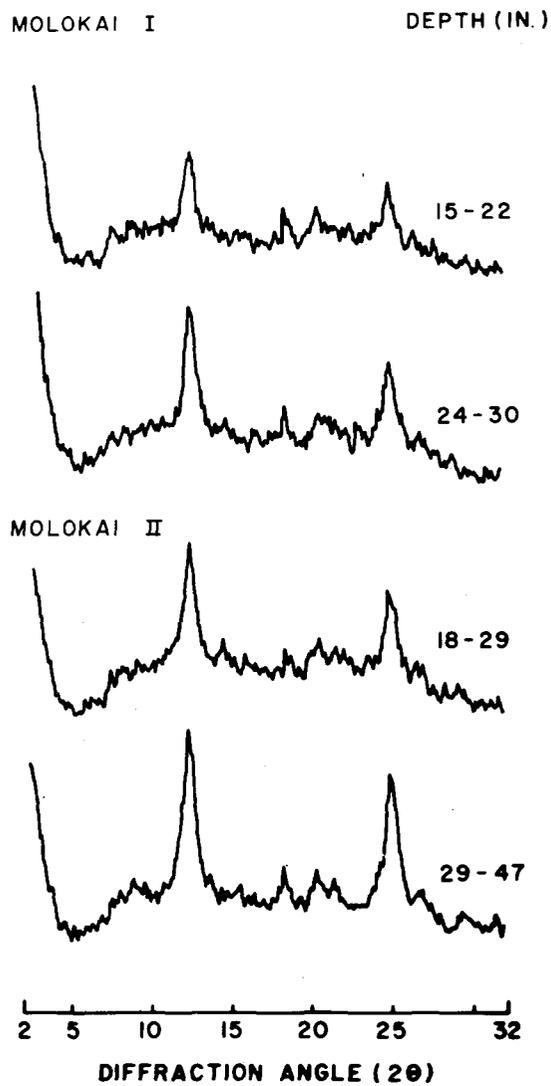


Fig. 4. X-ray diffraction diagrams of oriented clay fractions of Molokai I and II.

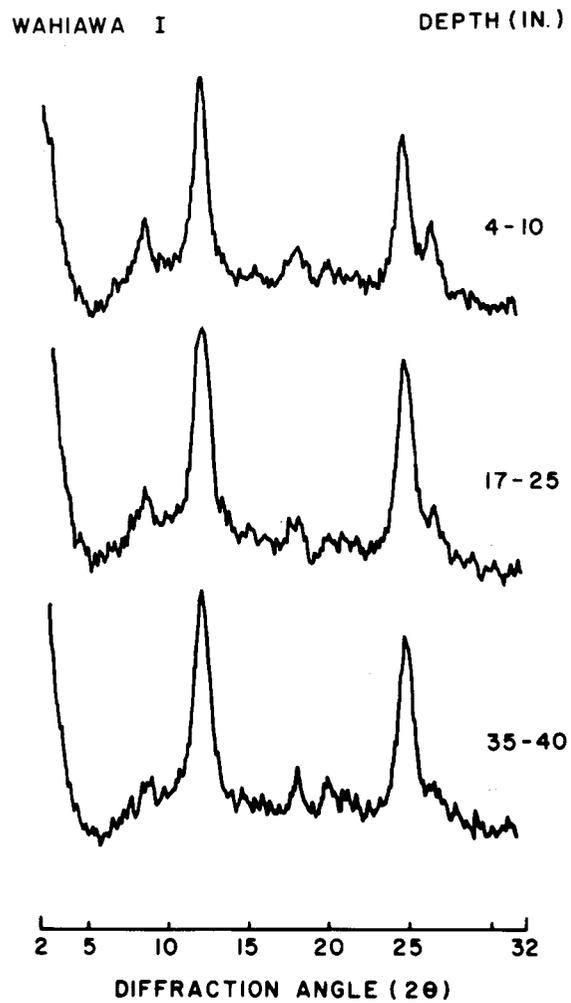


Fig. 5. X-ray diffraction diagrams of oriented clay fraction of Wahiawa I.

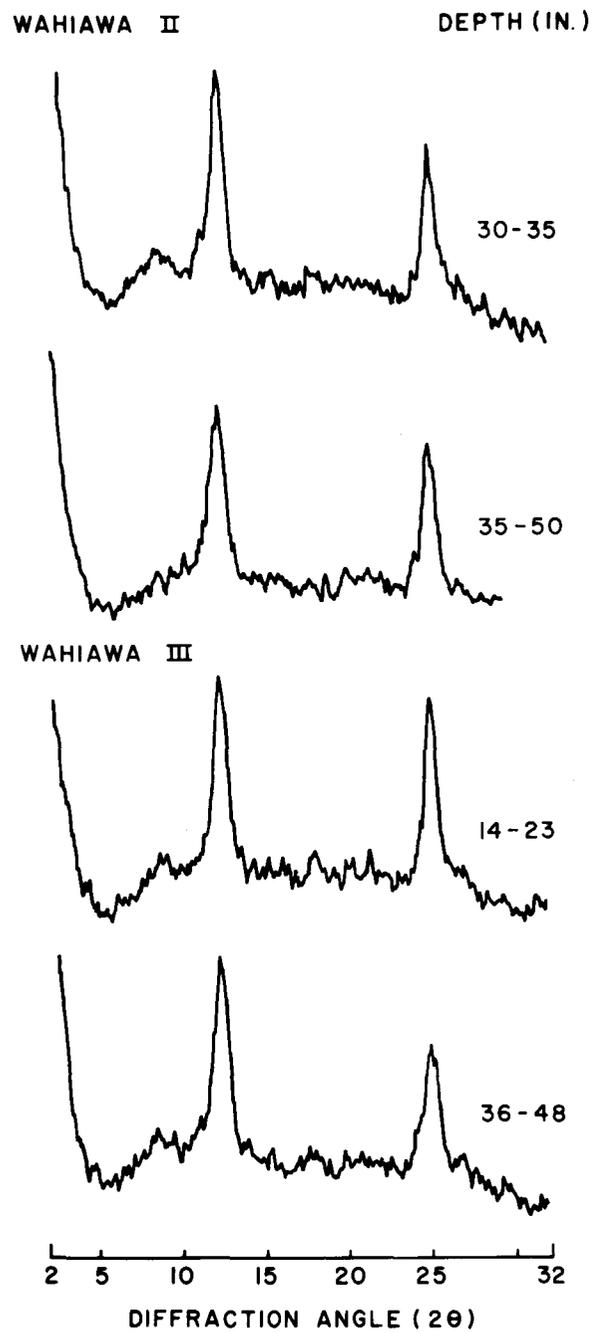


Fig. 6. X-ray diffraction diagrams of oriented clay fractions of Wahiawa II and III.

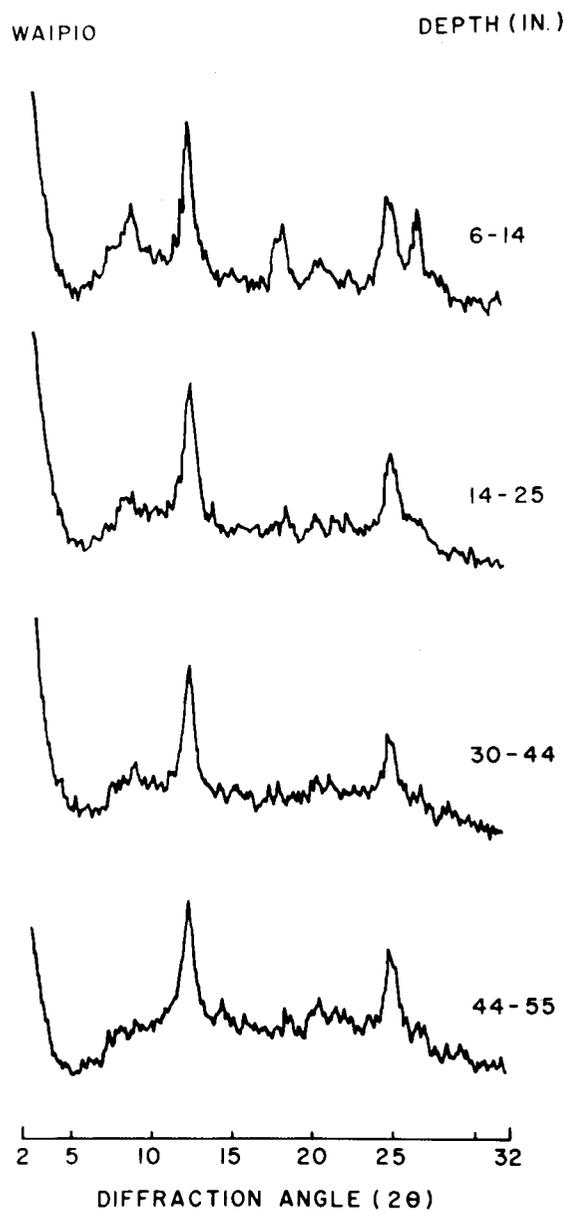


Fig. 7. X-ray diffraction diagrams of oriented clay fraction of Waipio.

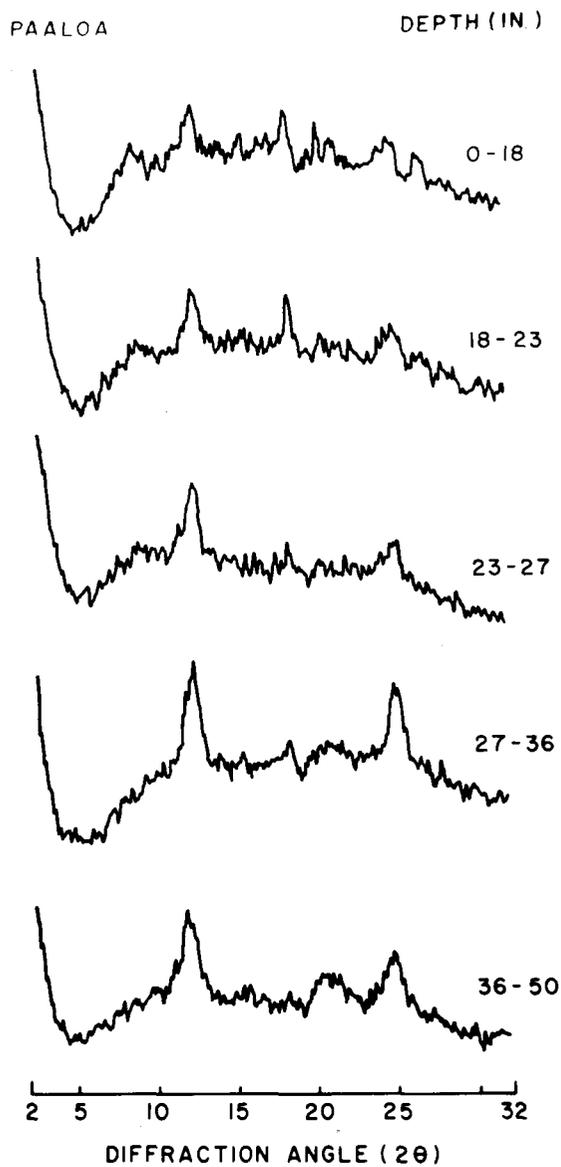


Fig. 8. X-ray diffraction diagrams of oriented clay fraction of Paalooa.

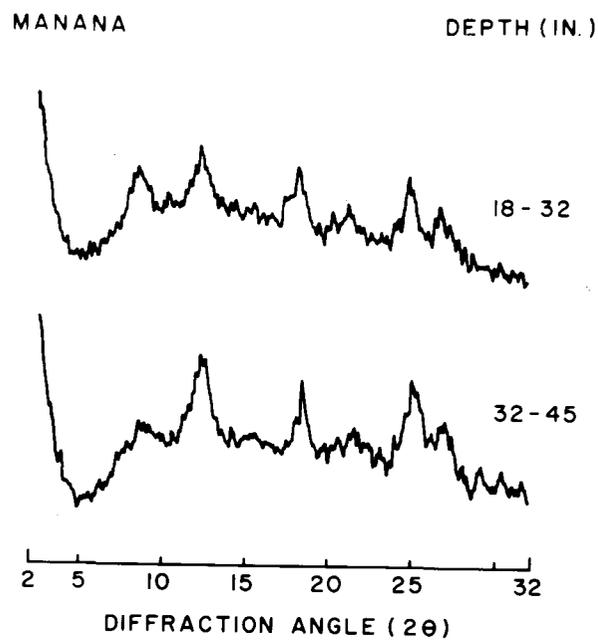


Fig. 9. X-ray diffraction diagrams of oriented clay fraction of Manana.

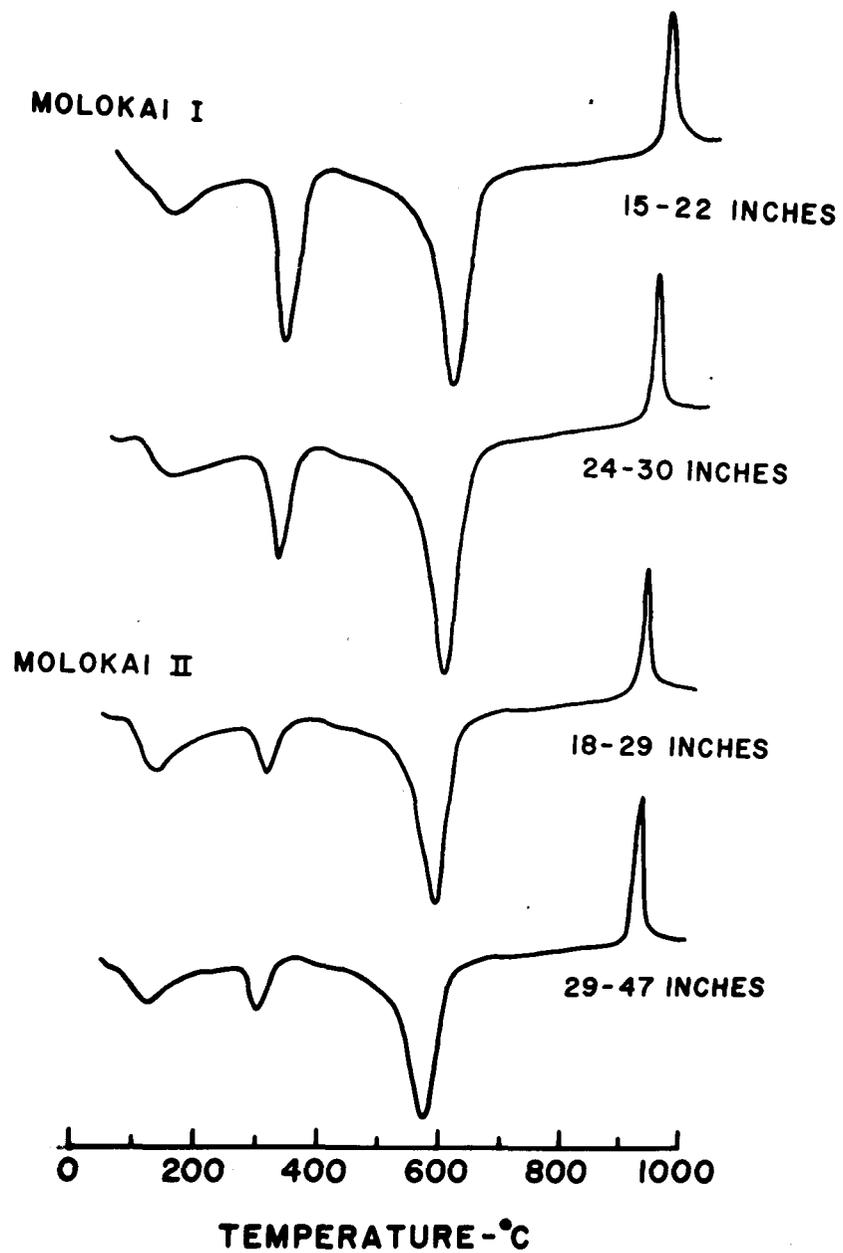


Fig. 10. Differential thermal curves of the clay fractions of Molokai I and II.

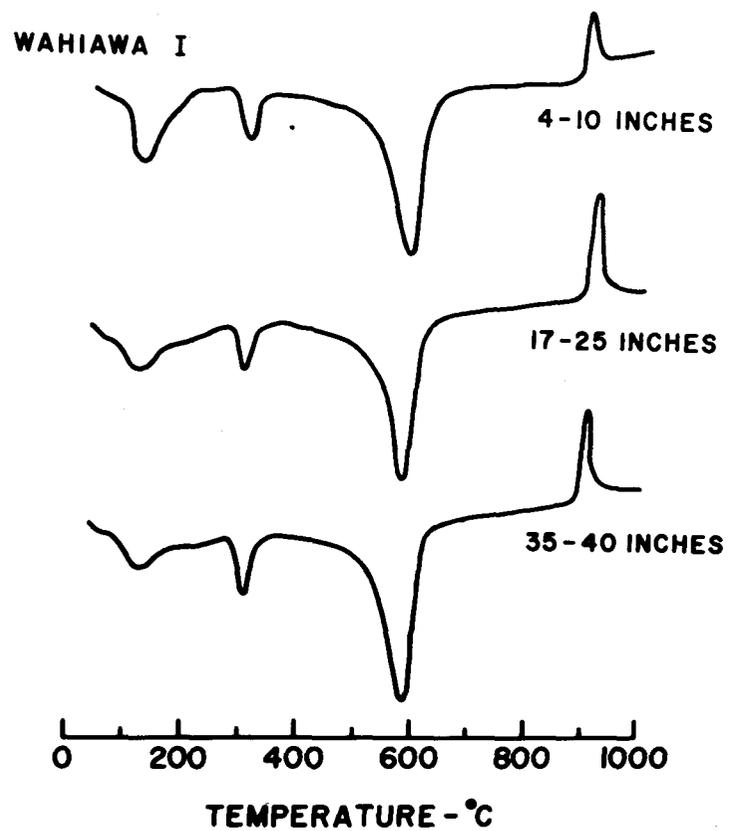


Fig. 11. Differential thermal curves of the clay fraction of Wahiawa I.

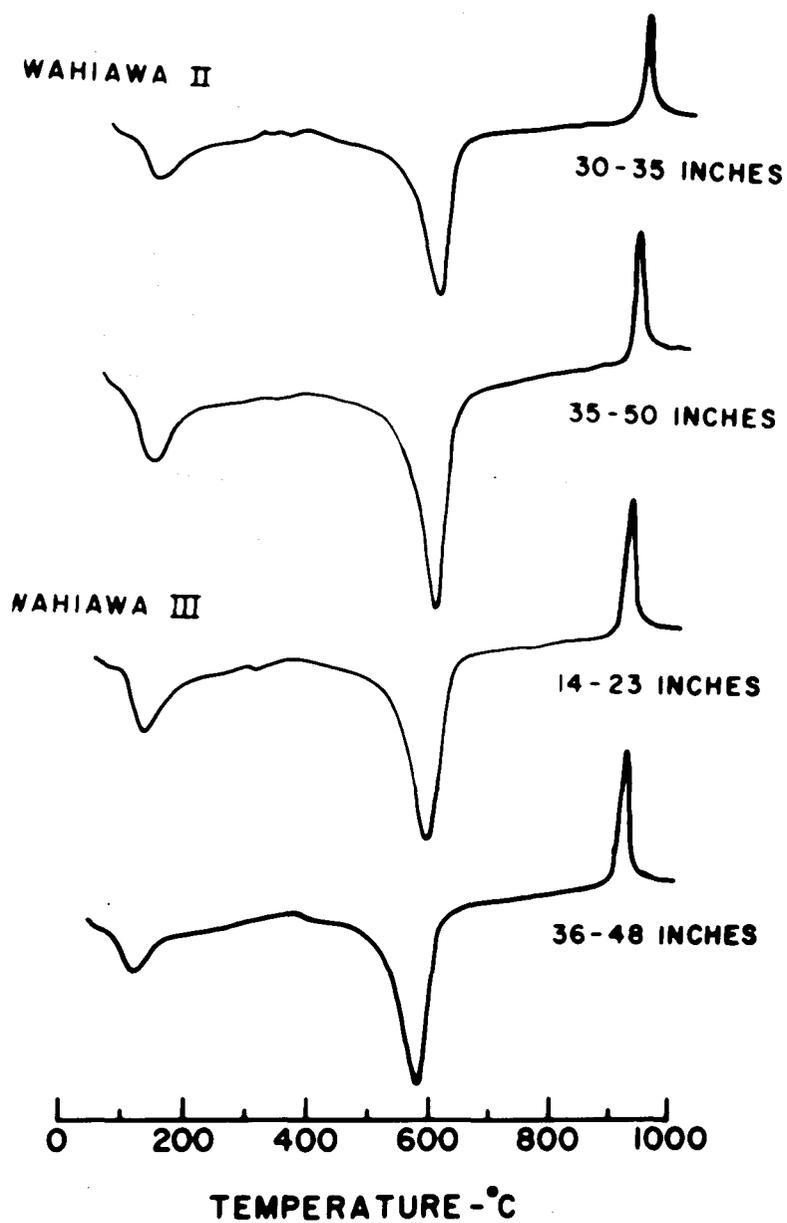


Fig. 12. Differential thermal curves of the clay fractions of Wahiawa II and III.

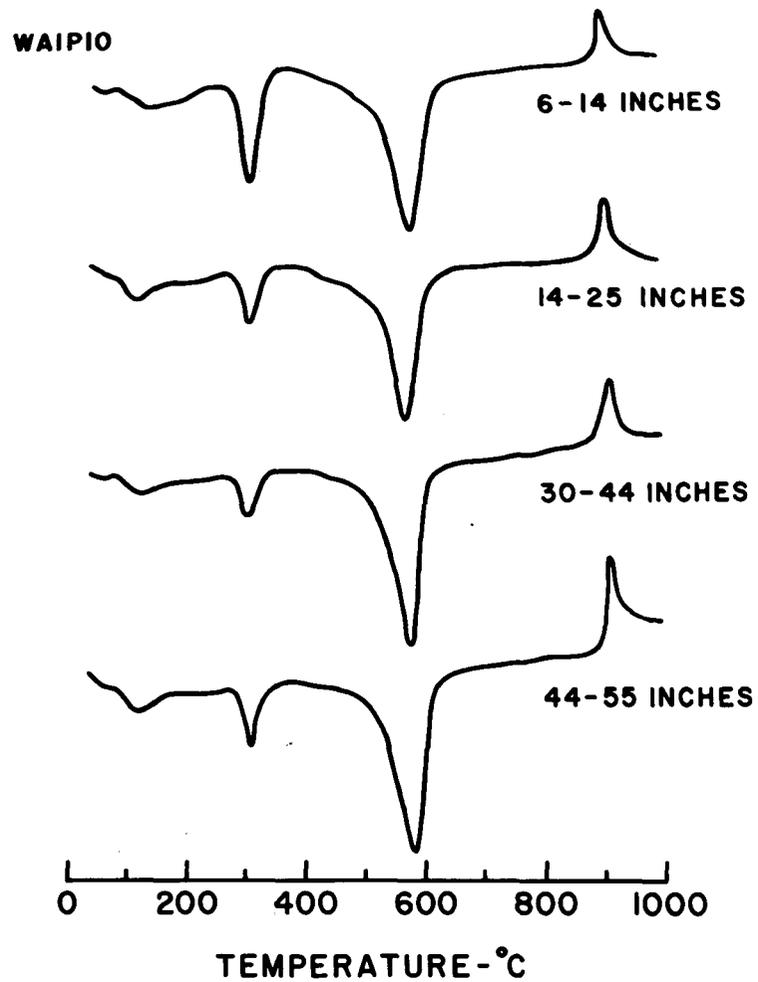


Fig. 13. Differential thermal curves of the clay fraction of Waipio.

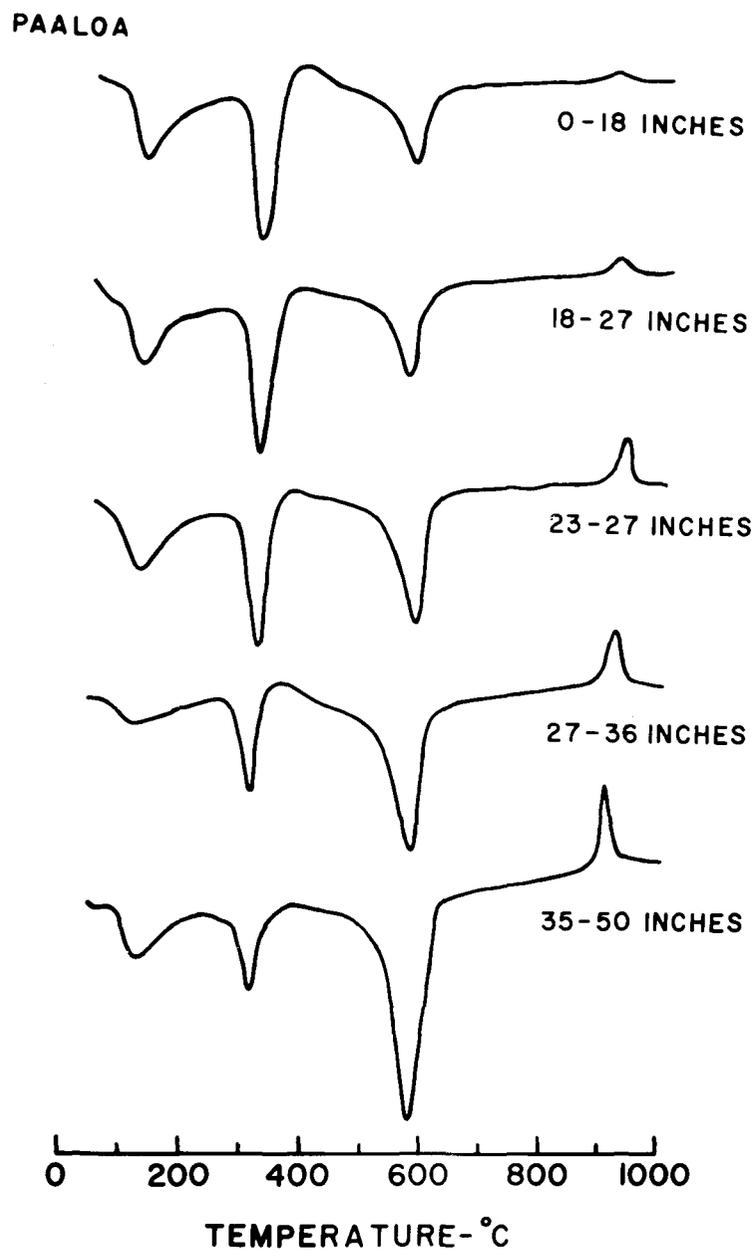


Fig. 14. Differential thermal curves of the clay fraction of Paalooa.

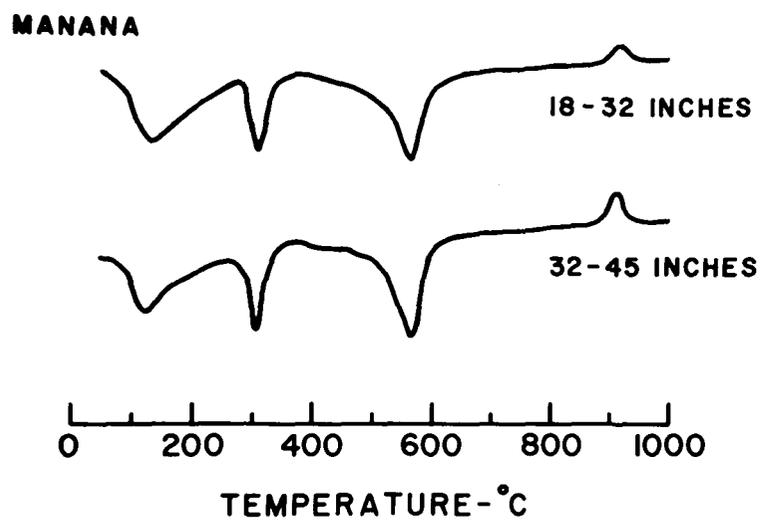


Fig. 15. Differential thermal curves of the clay fraction of Manana.

relate to aggregate stability. The significance of the r value for anisotropy is a linear relationship.

TABLE 3. A comparison of the significance of three soil factors based on similar mineralogy.

Soil factors	Values of r	No. of samples	Degrees of freedom
Free iron oxide	-.490 NS	14	12
Organic matter	.329 NS	14	12
Anisotropy	.621 *	14	12

NS - Not Significant

* Significant at the 5% level

A plot of aggregate stability versus anisotropy shows a strong evidence of curvilinearity. A test was made to confirm this trend. Table 4 illustrates this test. The curvilinearity of regression is highly significant. A suitable equation was found to fit the curve on Fig. 16.

TABLE 4. Test of significance of departure from linear regression of aggregate stability and soil anisotropy.

Source of variation	Degrees of freedom	Sum of Squares	Mean Square
Deviations from linear regression	12	169.18	
Deviations from curved regression	11	73.76	6.71
Curvilinearity of regression	1	96.42	96.42**

$F = 96.42/6.71 = 14.4$

**Significant at the 1% level

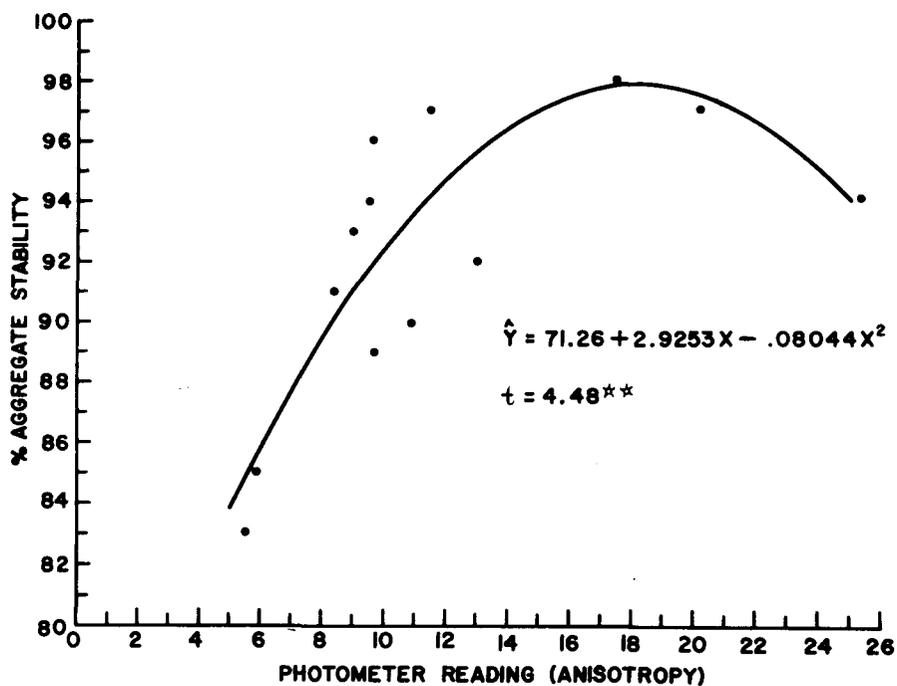


Fig. 16. The regression of aggregate stability on soil anisotropy.

Using the process of multiple regression of Y (aggregate stability) on X (soil anisotropy) and X^2 , the regression of aggregate stability on soil anisotropy (b_{y12}) was tested for its significance. The resulting $t = 4.48$, which is highly significant at a probability, $p = .001$.

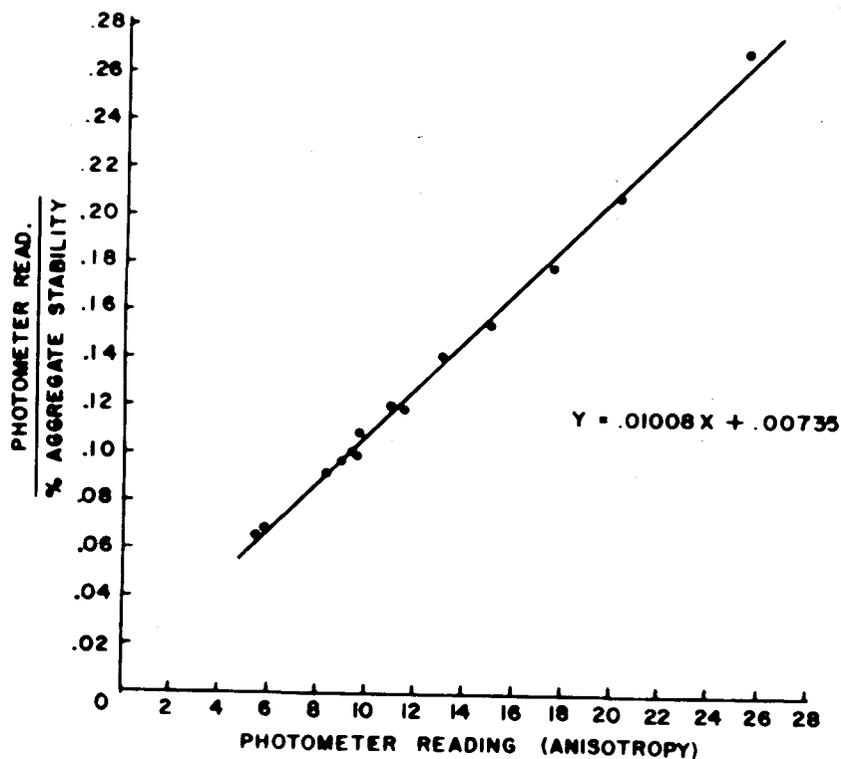


Fig. 17. A plot of anisotropy (X) vs.

$\frac{\text{anisotropy}}{\text{\% aggregate stability}}$ (Y).

The regression has an

$$r = .998.$$

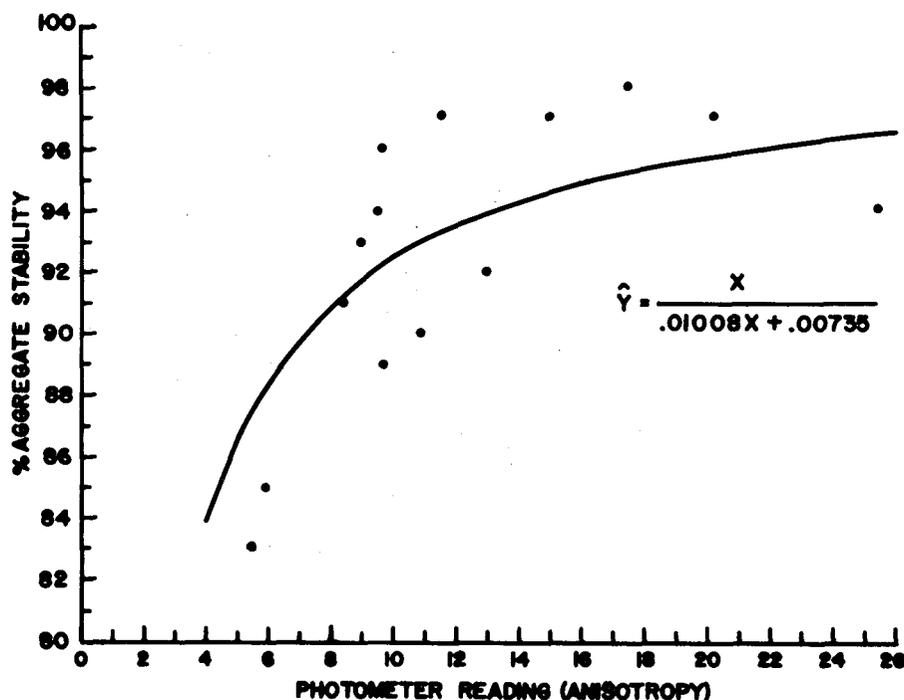


Fig. 18. A plot of the hyperbolic relationship of aggregate stability and soil anisotropy.

If it is assumed that aggregate stability increases but does not exceed 100 per cent as anisotropy increases and that it does not have values lower than zero as anisotropy decreases, the aggregate stability value of 100 per cent and anisotropy value of zero become the asymptotes for the branches of a hyperbola. A test using the hyperbolic law,

$$Y = \frac{X}{aX + b},$$

can be made. A hyperbolic relationship can be shown to

exist if a plot of X versus X/Y follows the linear law,

$$y = ax + b \quad .$$

In this case, $X/Y = y = aX + b$. A plot of X versus X/Y is shown on Fig. 17. The corresponding numerical coefficients of the equation, $Y = .01008X + .00735$, fit the hyperbolic equation,

$$\hat{Y} = \frac{X}{.01008X + .00735} \quad ,$$

on Fig. 18. As X becomes infinite, \hat{Y} tends to approach 100. Conversely, \hat{Y} approaches zero as X recedes to an infinitesimally small value.

V. SUMMARY AND CONCLUSIONS

This study shows that a relationship exists between soil anisotropy and aggregate stability. Soil anisotropy as measured by the method described in this study depends on a number of factors of which soil mineralogy, clay orientation, and the thickness of the slide were considered important. The experiment was conducted in such a manner that only clay orientation was the variable affecting soil anisotropy. This was accomplished by selecting soils of similar pedality, mineralogy and texture. Care was taken to control slide thickness.

A plot of per cent aggregate stability versus soil anisotropy as measured by a photometer showed a highly significant curvilinear relationship.

Aggregate analysis confirmed that with the increase in structural grade from weak to strong, aggregate stability also increases. No correlation between per cent aggregate stability and free iron oxide or organic matter content was shown to exist in the soils studied.

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