SELECTED PHYSICAL PROPERTIES OF VARIOUS SOIL MEDIUMS AS INFLUENCED BY DIFFERENT COMPACTION LEVELS

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN HORTICULTURE

DECEMBER 1972

By

Michael J. Tanabe

Thesis Committee:

C. L. Murdoch, Chairman
R. A. Criley
R. K. Nishimoto
F. D. Rauch

We certify that we have read this thesis and that in our opinion it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Horticulture.

THESIS COMMITTEE

Charles L. Murdoch
Chairman

Richard A. Criley

Roy K. Nishimoto

Fred D. Rauch

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Dr. G. Uehara and Mr. R. Watanabe for their helpful assistance. Appreciation is also extended to the Hawaii Turfgrass Association and the Agriculture Engineering Department for their valuable assistance with the construction of the hydraulic press. Special thanks are extended to Mr. Glenn Morimoto and Miss Marsha Fujii for their helpful assistance. Finally the author wishes to express his sincere appreciation to Mr. George Tai See for his unselfish time and valuable assistance.

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS ii

LIST OF TABLES iv

LIST OF ILLUSTRATIONS v

INTRODUCTION 1

REVIEW OF LITERATURE 3

MATERIALS AND METHODS 15

- Mediums 15
- Compaction 19
- Hydraulic Conductivity 23
- Soil Bulk Density 27
- Total Porosity 30
- Soil Moisture Content 30
- Analysis of Data 30

RESULTS AND DISCUSSION 32

SUMMARY 60

APPENDIX 62

BIBLIOGRAPHY 64

LIST OF TABLES

Table Page

1 PARTICLE SIZE DISTRIBUTION OF UNSIEVED VOLCANITE 17

2 PARTICLE SIZE DISTRIBUTION OF BEACH SAND 17

3 PARTICLE SIZE DISTRIBUTION OF LOAMITE 18

4 PERCENT MOISTURE CONTENT BY WEIGHT OF THE SOIL MIXES WHEN SATURATED AND DURING COMPACTION 31

5 BULK DENSITY AND HYDRAULIC CONDUCTIVITY OF VARIOUS SOIL MIXTURES AS INFLUENCED BY COMPACTION LEVEL AND PERCENT OF SOIL AMENDMENTS INCLUDED IN THE MIXTURE (AVERAGE OF 3 REPLICATIONS). 41

6 BULK DENSITY AND HYDRAULIC CONDUCTIVITY VALUES AS AFFECTED BY DIFFERENT PERCENTAGES OF AMENDMENTS FOR DIFFERENT MEDIUMS. DATA ARE AVERAGES OVER ALL COMPACTION LEVELS 44

7 BULK DENSITY AND HYDRAULIC CONDUCTIVITY VALUES AS AFFECTED BY COMPACTION FOR DIFFERENT AMENDMENTS. DATA ARE AVERAGES OVER ALL PERCENT AMENDMENTS 46

8 BULK DENSITY AND HYDRAULIC CONDUCTIVITY VALUES AS AFFECTED BY COMPACTION WITH DIFFERENT PERCENTAGES OF AMENDMENTS. DATA ARE AVERAGES OVER ALL MEDIUMS 47

Appendix Table

1 ANALYSIS OF VARIANCE FOR EFFECTS OF COMPACTION ON BULK DENSITY AND HYDRAULIC CONDUCTIVITY OF VARIOUS SOIL MIXTURES 62

2 TOTAL POROSITY FOR VARIOUS MEDIUMS AS INFLUENCED BY DIFFERENT COMPACTION LEVELS 63

LIST OF ILLUSTRATIONS

Figure Page

1 MODIFIED HYDRAULIC PRESS USED TO COMPACT THE MEDIUMS . . . 21

2 SCHEMATIC DIAGRAM OF APPARATUS USED AS A PERMEAMETER . . . 25

3 DIAGRAM OF THE CONSTANT-HEAD SYSTEM USED TO DETERMINE HYDRAULIC CONDUCTIVITY 29

4 RELATION BETWEEN COMPACTION AND BULK DENSITY FOR BEACH SAND, VOLCANITE AND WAHIAWA SOIL 35

5 RELATION BETWEEN COMPACTION AND HYDRAULIC CONDUCTIVITY FOR BEACH SAND, VOLCANITE AND WAHIAWA SOIL 37

6 RELATION BETWEEN COMPACTION AND BULK DENSITY FOR MEDIUMS CONSISTING OF WAHIAWA SOIL AND A PERCENTAGE OF EITHER BEACH SAND, VOLCANITE, OR LOAMITE. FIGURES 6A, 6B, AND 6C CONSIST OF RESPECTIVELY 25%, 50% AND 75% AMENDMENTS 50

7 RELATION BETWEEN PERCENT AMENDMENTS BY VOLUME AND HYDRAULIC CONDUCTIVITY AT 44 PSI FOR MEDIUMS CONTAINING DIFFERENT PERCENTAGES OF EITHER BEACH SAND, VOLCANITE, OR LOAMITE 52

8 RELATION BETWEEN PERCENT AMENDMENTS BY VOLUME AND BULK DENSITY AT 44 PSI FOR MEDIUMS CONTAINING DIFFERENT PERCENTAGES OF EITHER BEACH SAND, VOLCANITE, OR LOAMITE 55

9 RELATION BETWEEN COMPACTION AND HYDRAULIC CONDUCTIVITY FOR MEDIUMS CONSISTING OF WAHIAWA SOIL AND A PERCENTAGE OF EITHER BEACH SAND, VOLCANITE, OR LOAMITE 58

INTRODUCTION

Soil compaction is a very serious problem encountered on golf course putting greens, tees, and fairways. Alderfer (1951) describes compacted soil as follows: "It is a soil whose particles have been fitted together so closely that the openings or pores which remain between them are of such a size, shape, and arrangement that the plumbing, ventilation, and heating system within the soil are out of order."

A major influence of soil compaction on golf courses is vehicular or human traffic on the surface of the soil (Ferguson, 1950). This phenomenon, when present, will usually decrease the quality of the affected area and increase the cost of maintenance. Attempts to curb soil compaction would include: decreasing the flow of traffic on the course, cultivating compacted areas, and constructing critical areas of the course with compaction tolerant mediums. The most economical and practical route would be the preparation of soil mixes with compaction resisting properties.

Studies by Morgan (1966) and Smalley (1962) partially substantiate the possibilities of using various soil amendments to decrease the detrimental effects of soil compaction. Uehara (1970) also did some work concerning the use of amendments readily available in Hawaii.

Although this field of study is not a new one, Hawaii has many problems limiting the use of amendments proven acceptable in the mainland states. The foremost problem is an economical one involving the shipping of silica sand from the mainland U.S. to Hawaii. Silica sand is used as a major component for mixes by most of the mainland U.S. golf courses.

Since there are no deposits of silica sand in the state, Hawaii has been substituting beach sand (90+% $CaCO_3$) for silica sand with mediocre results. Since it is not an inert material, undesirable characteristics limit its potential as an equivalent to silica sand. The dredging of beach sand may also be forbidden by late 1973. This mandates the study of a possible replacement or replacements for beach sand. Therefore, the objective of this work is to evaluate some potential soil amendments that are economically available in Hawaii for golf courses.

REVIEW OF LITERATURE

Soil Compaction

Soil compaction results when an external pressure or environmental condition causes a unit area of soil to decrease in volume. This decrease in volume may be due to the closer packing or rearrangement of the soil particles.

On golf courses, external pressures would include traffic over the surface of the soil by humans, golf carts, and maintenance equipment. The impact of golf balls and golf clubs on the surface of a given area of soil also results in some compaction.

The force of raindrops on the aggregates of certain soils may cause these aggregates to break down into smaller structures. This allows for a closer packing of the particles and essentially influences soil compaction. The movement of water through the soil may destroy aggregates and initiate the rearrangement of the soil particles. The particles of some soils may also assume a flat, platy shape, and may become layered as with a brick wall (Alderfer, 1951).

Soil moisture content also plays a significant role in soil compaction. Gerard (1965) found that the strength of briquets[1] was increased as moisture content was decreased to an optimum level. This optimum level was found to be at a moisture content consisting of 2 to 3 monomolecular layers of water. Lotspeich (1964) observed that a moisture content between 1 and 5 bars tension was optimum for maximum soil

---

[1] Brick-shaped piece of artificial stone.

strength and compaction. Less water resulted in insufficient lubrication for particle movement and more water interfered with the packing arrangements of the soil particles. Gerard and others (1962) also indicated that a slow rate of soil drying was an important factor in causing closer packing of soil particles. They suggested that the cohesive force of water molecules may have played a role in the closer packing or bonding of the soil particles.

Lotspeich (1964) determined conditions that were conducive to maximum soil strength and compaction. He found that certain species of clays, when present at an optimum level, increased compaction. He also stated that two multicomponent mediums composed of several sized fractions were more susceptible to compaction. His reasoning for this phenomenon was that a multicomponent medium with secondary, tertiary, and quaternary grains permits tetrahedral packing with mutual contact of all grains.

The effects of compaction are usually detrimental to the quality of the turf in the affected area. Gill (1959) associated compaction with a decrease in the percentage of non-capillary pores, increased mechanical strength of the soil mass, poor plant growth, and under severe conditions, the deformation of the soil.

Ferguson (1950) cited other adverse effects from soil compaction: the need for green-keepers to overwater the green in an effort to soften it, alteration of the soil structure such that air and water movement is impeded, and sometimes layering of the soil due to top dressing. Ferguson (1959) also noticed that foot traffic on a given area of turf resulted in loss of vigor to the turf, an encroachment of weeds, infections by diseases, and infestation of algae.

Johnson and Henry (1964) experimented with the effect of soil compaction on corn seedling emergence. They noticed that unless the compacted zone was maintained at a relatively high moisture content, the soil strength was high enough to delay or prevent the sprout emergence. A study to determine the association between soil compaction and plant growth was pursued by Hopkins and Patrick (1969). Their work involved the combined effect of oxygen content and soil compaction on root penetration. Their experiment results indicated that root penetration was apparently more restricted by mechanical impedance due to compaction than by poor aeration.

Several techniques can be used to determine soil compaction. Alderfer (1951) discussed the use of a probing instrument called a penetrometer, and a technique for the determination of permeability of soil to water and air. Terry and Wilson (1953) described the use of a penetrometer in their soil compaction studies. Their instrument had the advantage of being a self-recording unit. The determination of soil bulk density also provides both laboratory and field estimations of soil compaction.

The use of compacting devices has aided studies concerned with soil compaction. Felt (1965) used an impact type of compactor considered to be the standard method of the American Society for Testing and Materials. Richards, Warneke and Weeks (1965) explained the use of their motor-driven, spring loaded compactor and the procedure used in preparing soil cores for measuring physical properties. Another impact type of compactor was studied by Bruce (1955). His unit could be used satisfactorily for small quantities of soil with the flexibility to produce a wide range of compaction energies. A modified aerifier specially designed with legs and shoes to simulate human compaction was developed by Goss and Roberts (1964). This unit was able to exert a maximum of 17 psi on the surface of the soil (a 180 pound man would exert a pressure of about 6.7 psi when standing on one foot).

Cooper and Nichols (1959) reviewed observations of: compaction as related to soil physical properties affecting plant growth, types of forces applied to the soil, measurement of pressure distribution in the soil, effect of pressure on change in bulk density, and the breaking up of compacted layers.

Control or prevention of further soil compaction after the construction of the turf area is usually difficult. Economics and practicality usually discourage correction of this adverse condition. Therefore, the problem should be foreseen and preventative measures undertaken.

Various approaches to this problem have been studied. Kunze and others (1957); Smalley and others (1962); Morgan and others (1966) approached this problem by working with various soil mixes possessing compaction tolerant properties. McLeod and others (1966) concluded that the use of wider tires on tractors with air pressure as low as 4 psi decreased soil compaction and increased traction. Additional studies done by Wong (1967) involved the use of different wheels as they affect the movement of soil particles.

Soil-Water Movement

Klute (1965) stated that the rate of movement of water through the soil is of considerable importance for agricultural and urban life. He claimed that the rate of water movement through the soil may affect the movement of water to the plant roots, the entry of water into the soil, the flow of water to drains and wells, and the evaporation of water from the soil surface.

Several terms have been used to describe the movement of water through the soil. Lewis and Powers (1938) defined water infiltration as "the rate of water entrance at the soil surface." Richards (1952) defined percolation as "a qualitative term applying to the downward movement of water through the soil." He also defined permeability qualitatively as "the quality or state of a porous medium relating to the readiness with which such a medium conducts or transmits fluids. Quantitatively, permeability is the specific property designating the rate or readiness with which a porous medium transmits fluids under standard conditions."

Richards (1952) defined hydraulic conductivity as "the ratio of the flow velocity to the driving force for the viscous flow under saturated conditions of a specified liquid in a porous medium."

"Physical dimensions will depend on the equation selected to express the flow. The ratio $v/i=k$, where v is the flow velocity of a specified liquid under saturated conditions, and i is the hydraulic gradient in the Darcy equation, $v=ki$."

The movement of water through the soil may be influenced by various forces. Klute (1952) mentioned possible such forces as pressure gradient, and gravitational, adsorptive, and osmotic. He also mentioned the possibility of electrical and thermal gradients which may affect the movement of water through the soil. The most significant change in water movement through the soil is probably caused by soil compaction.

Fireman and Bodman (1939) reported that applications of saline irrigation water produced an almost immediate increase in soil water permeability. Fireman (1944) extended his research in this area and found that great decreases in saturated water permeability of soils examined may have been attributed to the early removal of electrolytes. This phenomenon was possibly the result of the gradual dispersion and rearrangement of the clay particles and also a reduction in size of water conducting pores. In general, he found that the lower the salt concentration, the lower the soil permeability. Decreasing the electrolyte content of the percolating water from 10,000 ppm to 40 ppm decreased the permeability of a clay loam from 10.2 cm/hr to 7.3 cm/hr and a Yolo fine sandy loam from 2.8 cm/hr to .3 cm/hr. Fireman also observed that some soils were hundreds of times more permeable to tap water than they were to distilled water. His tap water contained approximately 280 ppm of mixed salts of which 90% were sodium salts.

Calcium is the principal adsorbed cation of the colloidal complex of most agricultural soils. The addition of sodium salts to tap water causes a base exchange to take place and thereby initiate an exchange of sodium ions for calcium ions with a resultant dispersion of the soil particles. The presence of high salt content in the tap water tends to keep the soil flocculated and moderately permeable even with a high sodium content in the water (Fireman, 1944).

Further work was done by Reeve and Tamaddoni (1965) concerning hydaulic conductivity as affected by electrolyte concentration. They stated that the soil-water-movement could be increased in salt-affected soils by increasing the electrolyte concentration of the applied water. To facilitate the removal of excess salts or harmful exchangeable sodium, it was suggested that the water must move into and pass through the soil. This caused the soil-clay packets to contract, and thereby increased the permeability of the soil to water.

Waldron and Constantin (1968) noticed that saturating the soil with sodium chloride solution followed by decreasing concentrations of the same salt resulted in a marked decrease of hydraulic conductivity. They explained that the treatment may have caused an increase in net repulsion or swelling pressures between the clay platelets to influence the weakening, swelling, or dispersion of the soil aggregates. Therefore, the aggregate failure may be influenced by internal swelling pressures, from local shearing stresses deforming the weakened aggregates, or a combination of both.

Gardner, Mayhugh, Goertzer, and Bower (1959) claimed that permeability of a soil is directly related to pore-size distribution, which in turn depends upon the texture of the soil and the extent of swelling of the clay fraction. They further stated that the effect of a given amount of swelling upon permeability or difusity should depend to some extent upon the amount and kind of clay minerals in the soil and particle size distribution of the non-swelling particles.

Nelson and Baver (1940) discussed the movement of water through the soil in relation to the nature of the pores. They mentioned the significance of the continuity of pores as it affects permeability. Laliberte and Brooks (1967) worked with the determination of saturated permeability of soils using a bubbling pressure technique.

Other factors affecting the movement of water through the soil were discussed by Wischmeier and Mannering (1965). Their data showed that increasing the content of decomposed and partially decomposed organic residues substantially increased infiltration of water into most soils.

DeJong (1966) found that the moisture content of the soil did not significantly affect the hydraulic conductivity of shrinking soils. However, hydraulic conductivity rapidly approached zero for non-shrinking soils with decreasing moisture content. DeJong discussed four stages associated with the shrinkage of natural clods and aggregates of high clay content.

Although all the factors discussed are important, compaction may be considered one of the most influential factors governing the vertical movement of water through the soil. Swartz and Kardos (1963) mentioned the detrimental effects of compaction on the physical properties of various soil mixtures at different moisture contents. Their data indicated inadequate percolation rates after their mixture containing 50% sand was compacted. Mixtures containing 70% sand were able to maintain adequate percolation rates after compaction. However, these mixtures were prone to excessively high percolation rates or insufficient available moisture status.

Porosity

Buckman and Brady (1967) defined pore space of a soil as, "that portion occupied by air and water." The amount of pore space is strictly dependent on the arrangement of the solid particles. If the particles are arranged close to each other, as with most sand and compacted soils, the total porosity is low. However, if a soil is not compacted and well aggregated, total porosity will be high.

Vomocil (1965) stated that the geometry of the pore system of the soil is just as complex as the solid phase. The pores may differ from one another in shape, lateral dimensions, length, tortuosity, and continuity. This system of pores may be described as total porosity, volume percentage of large pores, or pore size distribution.

There are essentially two types of pore spaces found in most soils. The large non-capillary pore spaces are called macropore spaces, whereas the smaller capillary pore spaces are called micropore spaces. The macropores are mainly instrumental in permitting the ready movement of air and percolating water. In contrast, the micropores greatly impede the movement of air and allow for only a slow movement of water.

Lutz and Leamer (1939) found that permeability of the separate soil fractions increased exponentially with the size of the particles, and therefore, with the size of the pore spaces. They also observed that swelling of the soil caused a decrease in its permeability to water due to the clogging of the pore spaces for subsoils or finer fractions. Browning (1939) noticed that the volume of the soil increased when the soil was wetted. This caused a decrease in volume of micropore spaces and likewise in infiltration rates.

Nelson and Baver (1940) claimed that low porosity soils, such as sandy soils, may have larger pore spaces with few small pore spaces distributed between the large ones. This arrangement, which is usually present in soils with a high volume of pores, rendered the macropores less continuous.

Soil compaction plays a very important role associated with the porosity of the soil. Davis (1952), in a study of golf course greens, found that there was a strikingly smaller quantity of non-capillary pores in the upper part of the greens than the lower portions of the greens, probably due to soil compaction. Voorhees and others (1966) stated that the average apparent pore diameter decreased with a decrease in aggregate diameter. Therefore, the reduction of non-capillary pore spaces in the compacted zone may be a result of aggregates that have lost their structure and were reduced to a smaller diameter.

Particle-size Distribution

Day (1965) stated that "the particle-size distribution of a soil expresses the proportions of the various sizes of particles which it contains. The proportions are commonly represented by the relative numbers of particles within stated size classes, or by the relative weight of such classes."

The solid soil phase is constituted of individual particles or aggregates. The strength of these aggregates usually determines the ability of that particular soil medium to tolerate severe soil compaction.

Meredith and Kohnke (1965) discussed microbial activity as it affected the strength of the soil aggregates. They found that microbial activity associated with the decomposition of organic matter in the soil encouraged greater strength of the soil aggregates. These aggregates became more tolerant to the destructive forces of water accompanied by poor wettability. Slow rates of wettability were associated with greater stability of the soil aggregates.

Amemiya (1965) associated soil aggregate size with moisture retention. He observed an increase in moisture retention of the Nicollet silt loam medium as the aggregate size increased and concluded that the moisture retention for that particular medium was a result of a difference in the relative pore size distribution between the within the aggregates.

Soil compaction greatly influences the rearrangement of the soil particles and, consequently, the amount of macropores and micropores. These pore spaces are essential for the mobility of air and water in the soil. Bodman and Constantin (1965) studied the influence of particle size distribution in soil compaction. They claimed that the greater the difference in individual particle size of the mixes, the less will be the bulk volume of that particle mix. This would probably allow for greater soil compaction and a reduction in macropore spaces.

Soil Moisture Content

Water or moisture content of the soil may be expressed as the ratio of the mass of water present in a sample to the mass of the sample after it has been dried to a constant weight, or as the volume of water present in a unit volume of the sample (Gardner, 1965).

The factors that influence the capacity of soils to retain available water are: 1) soil texture, 2) soil structure, 3) particle-size distribution, and 4) organic matter content (Salter and Williams, 1965). They found that soil texture was the basic factor determining the moisture characteristics of the soils. The moisture contents at field capacity and permanent wilting point increased as the soils became finer in texture. However, the medium textured soils held the greatest volume of available water.

Amemiya (1965) attributed compaction, organic matter content, aggregate stability, and type of clay mineral as factors influencing soil moisture retention. He also mentioned that soil capillary conductivity appeared to be a function of moisture content.

Soil bulk density changes have been shown to produce marked changes in moisture characteristics of many soils. Hill and Sumner (1967) observed that moderate soil compaction resulted in an increase in moisture content of the soil at a constant matric suction. However, severe soil compaction initiated a decrease in soil moisture content at a constant matric suction.

Uehara (1970) found a definite correlation between compactability of a kaolinitic clay and moisture content of that particular medium. Maximum compaction expressed as bulk density occurred at approximately 36% moisture content by weight of the clay soil. A possible explanation for this phenomenon is that an optimum moisture content is necessary to lubricate the soil particles and induce closer packing of these particles. Moisture content above this optimum level would not increase the compactability of the soil medium because of the incompressability of water.

MATERIALS AND METHODS

Four different mediums and several soil mixtures were used in this study to determine their ability to tolerate surface applied soil compaction. Tolerance to soil compaction was based on the results of various measurements made after the medium was exposed to compactive forces. These measurements included soil bulk density and soil hydraulic conductivity. A soil mix was considered tolerant to soil compaction if the hydraulic conductivity values were within the limits specified by the United States Golf Association (inch to inch and a half per hour). Soil bulk density was used as a measurement of the degree of soil alteration caused by compactive forces. Other measurements made were total porosity and particle size distribution.

Wahiawa soil, Loamite, and beach sand were selected for this study because of their present availability and usage on most golf courses and turfgrass areas. Volcanite is being used in limited quantities by a few golf courses and may be acceptable in the future when the dredging of beach sand is prohibited.

Medium combinations have great potential for usage on turfgrass areas exposed to a high degree of human and vehicular traffic. They have the advantage of possessing several desirable properties contributed by each medium component. In contrast, individual mediums are limited to the properties they possess.

Mediums

The mixtures used in this study contained different percentages by volume of the Wahiawa soil. This kaolinitic clay was used as a component for all mixtures because of its availability and desirable properties. The mixtures used were as follows: soil:Volcanite; soil:sand; and soil:Loamite.

The Wahiawa soil is a clay soil containing kaolinite as its dominant mineral. This soil, if not compacted, has good structure and is very permeable to water. Compaction at an optimum moisture content will alter the soil's structure sufficiently to severely impede the movement of water. It is resistant to erosion and will not crack when dried as with the Dark Magnesium clays. Water retention is good. It is usually moderately acid with a pH of approximately 4.0-5.5 and low in fertility.

The soil used in this study was obtained from a private home located in Wahiawa, Hawaii. Most of the soil was taken from the upper twelve inches of the soil profile. The organic matter content was relatively high due to prior addition of foliage into the soil.

Volcanite is a commercial product obtained from the Puu Waa Waa cinder cone on the island of Hawaii. It is composed mainly of Trachyte minerals. Salinity is negligible and its cation exchange capacity is approximately 6 meq./100 gm. Silica content is approximately 62% and pH is about 8.0. Physically, its structure is weak and fertility level is low. Presently it is receiving attention as a component of a synthetic soil for nursery crops and as a possible substitute for beach sand on golf courses.

The Volcanite used for this study was tested both in the sieved and unsieved state. It was obtained from the Kunia Golf Course in Wahiawa. The sieved state consisted of particle sizes between .0331-.0098 inches or .850-.250 millimeters. The unsieved Volcanite consisted of a diverse distribution of particle sizes (Table 1). The bulk of the particles were greater than .850 mm and less than .106 mm.

Table 1. Particle size distribution of unsieved Volcanite

Inches	mm	% by wt.	Cumulative % by wt.
.0787	2.000	54.6	54.6
.0787-.0331	2.000-.850	18.0	72.6
.0331-.0165	.850-.425	6.0	78.6
.0165-.0098	.425-.250	3.4	82.0
.0098-.0041	.250-.106	5.5	87.5
.0041	.106	12.5	100.0

Beach sand is presently Hawaii's substitute for silica sand. It is a coarse textured medium with no structure and has a very low water holding capacity. Fertility level is low, and the dominant mineral is calcium carbonate.

The beach sand used for this study was obtained from the Kunia Golf Course in Wahiawa. It was alkaline and had a pH of 8.1. The particle size distribution was as shown in Table 2.

Table 2. Particle size distribution of beach sand

Inches	mm	% by wt.	Cumulative % by wt.
>.0787	>2.000	0.8	0.8
.0787-.0331	2.000-.850	8.9	9.7
.0331-.0165	.850-.425	57.2	66.9
.0165-.0098	.425-.250	31.7	98.6
.0098-.0041	.250-.106	1.4	100.0

Loamite is an organic amendment manufactured by Loamite Corporation, San Francisco, California, that is widely accepted for use on turfgrass areas. It is a product of redwood and fir shavings which have been specially processed. This special processing involves the treatment of the shavings with sulfuric acid and heat to remove the cellulose and hemi-celluloses. The end product of this treatment is essentially lignin which does not decompose readily.

Water holding capacity and water permeability of Loamite is good. Its fertility level is low, but adsorption of nutrients is relatively high. Table 3 shows the particle size distribution of the Loamite used in this study.

Table 3. Particle size distribution of Loamite

Inches	mm	% by wt.	Cumulative % by wt.
>.0787	>2.000	6.7	6.7
.0787-.0331	2.000-.850	42.0	48.7
.0331-.0165	.850-.425	40.4	89.1
.0165-.0098	.425-.250	10.0	99.1
.0098-.0041	.250-.106	0.7	99.8
<.0041	<.106	0.2	100.0

Several different soil mixtures were used in this study. These mixtures consisted of an amendment and Wahiawa soil which had been passed through a sieve with 2 mm openings. The soil was sieved because of the presence of large aggregates. This high degree of aggregation was probably influenced by the high organic matter content of the soil.

The various mixtures were prepared on a volume basis and expressed as a percentage. Each component of the soil mix was placed into a plastic bag after measurement to a specific quantity with a graduated cylinder. Then the soil medium was thoroughly mixed in a plastic bag by shaking vigorously for a minimum of one minute.

The mixes developed and used for this study were: 75% soil:25% Volcanite; 50% soil:50% Volcanite; 25% soil:75% Volcanite; 75% soil:25% beach sand; 50% soil:50% beach sand; 25% soil:75% beach sand; 75% soil: 25% Loamite; 50% soil:50% Loamite; and 25% soil:75% Loamite. The Volcanite used in the mixtures was of particle size between .850-.250 millimeters.

Compaction

A modified hydraulic press was used to provide the compactive force on the various soil mediums used in this study (fig. 1). This compactor system was selected because of its versatility to provide a specific amount of pressure. It was also capable of sustaining a given compactive force for an indefinite period of time. A gauge calibrated in pounds per square inch enabled the duplication of different pressures within the limits of the gauge.

In contrast to the impact type of compactor (Ferguson, Howard and Bloodworth, 1960), this unit is relatively expensive. Portability may also be a problem because of its three component construction. Comparison of data obtained from this system with the impact type of compactor may be difficult. This system expresses compactive force in pounds per square inch, whereas, the compactive force of the impact type of compactor is expressed in number of blows or foot pounds.

Figure 1. Modified hydraulic press used to apply compaction on mediums.


HYDRAULIC SHOP PRESS
10
TON CAPACITY
OWATONNA
TOOL COMPANY

The compacting unit is called a hydraulic shop press with a 10 ton capacity and is manufactured by the Owattonna Tool Company, Owattonna, Minnesota, 55060. It consists of a press frame, a hydraulic ram (number YS-106A, Model B), a hydraulic pump (number Y2-1, Model B), and a rubber steel banded hose which connects the hydraulic pump and hydraulic ram.

The maximum extension of the hydraulic ram piston is 6 1/2 inches. Operation of the piston is by a hydraulic pump which is connected to the hydraulic ram. A pressure gauge calibrated in pounds per square inch indicated the amount of force being exerted.

Soil, Volcanite (unsieved), and beach sand were exposed to compaction as individual mediums. Compaction was applied by tapping the permeameter containing the soil medium, and also by the use of a hydraulic press. Loamite was not subjected to compaction because it is rarely used as an individual medium for turfgrass areas.

Preparation of the soil medium for the compaction treatments involved the placement of a quantity of medium into a permeameter. This quantity was expressed in grams of the soil medium required to occupy between two-thirds and four-fifths of the volume of the permeameter. The side of the permeameter was tapped for one minute in an effort to reduce variation of the soil particle arrangement between replications. Each compaction treatment was replicated three times.

The piston of the hydraulic ram was designed to fit the permeameter with less than 1/32 of an inch clearance. A special stand was made to secure the permeameter below the hydraulic ram. The permeameter containing the soil medium was placed in the stand. Compaction was applied by pumping the hydraulic ram onto the surface of the medium.

The compaction placed on each medium was cumulative. Successive compactive treatments were applied to the same medium depending on the ability of the medium to tolerate compaction.

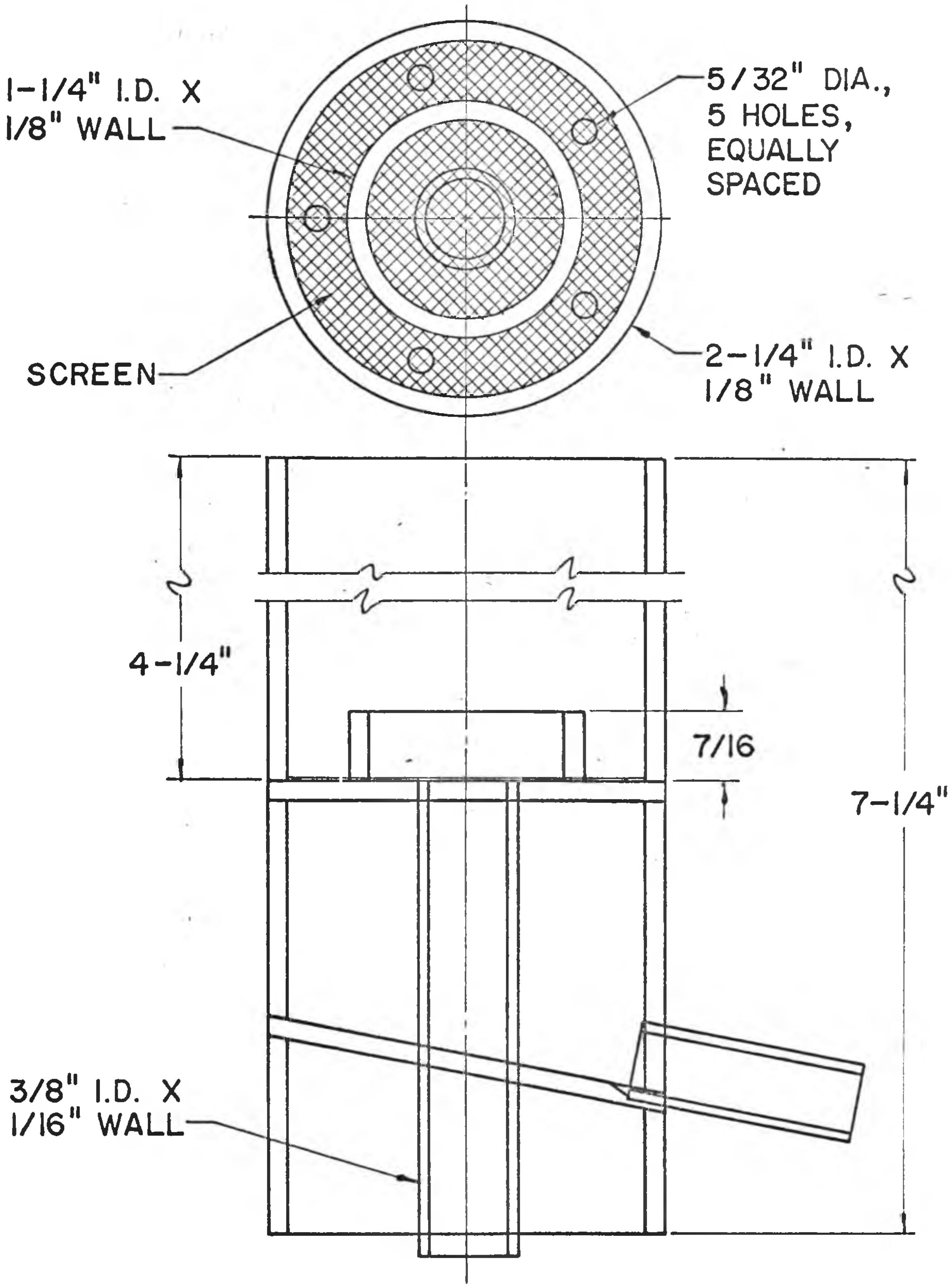
Unsieved Volcanite and sand were compacted at 5, 10, 15, 20, 25, 30, 35, and 40 psi. Soil was compacted at 5, 10, 15, 20, and 25 psi. The soil mixtures were exposed to 22 and 44 psi. All individual mediums and soil mixtures were exposed to the shaking treatment prior to compaction with the hydraulic press.

Hydraulic Conductivity

Hydraulic conductivity was determined in this study by using the constant-head method. Fireman (1944) discussed the advantages and disadvantages of this system. Some advantages are: the soil is not disturbed except by the movement of water; the effluent is quickly and accurately measured; and the equipment is economically feasible and accessible. Problems include difficulty in maintaining a constant head and the low frequency at which a constant head would be encountered under natural conditions.

A modified plexiglass cylinder was utilized as a permeameter in this study (fig. 2). This unit permitted the measurement of the water movement through the center of the cylinder. Measurement of liquid through this central column decreased the possibility of obtaining invalid data resulting from cylinder wall to water movement interaction. The water that passed along the inner walls of the permeameter was disregarded.

Figure 2. Schematic diagram of apparatus used as a permeameter.


1-1/4" I.D. X
1/8" WALL
5/32" DIA.,
5 HOLES,
EQUALLY
SPACED
SCREEN
2-1/4" I.D. X
1/8" WALL
4-1/4"
7/16
7-1/4"
3/8" I.D. X
1/16" WALL

A 500 ml. separatory funnel with a stopcock was used as the reservoir for the effluent. A length of plexiglass tubing was inserted into the separatory funnel to allow for the displacement of water by air. This gas and liquid exchange maintained a constant supply of water from the reservoir to the permeameter.

Mediums that conducted water in excess of 50 in/hr required the use of a larger reservoir. To cope with this problem, a rubber hose was connected to a water faucet and the separatory funnel reservoir. The reservoirs supply of water was maintained by the flow of water from the water faucet.

The compacted soil medium was saturated in a tank of water before being exposed to the hydraulic conductivity test. The period of soaking to assure complete water saturation was dependent on the type of medium and the amount of compaction it had been subjected to. Beach sand for all compactive treatments was soaked in the water for a minimum of 8 hours. Volcanite was soaked for a minimum of 10 hours. Wahiawa soil and all compacted soil mixtures were submerged in the water for a minimum of 16 hours.

The medium was immediately exposed to water from the reservoir after the water saturation treatment. The rate of water flow into the permeameter was determined by adjusting the stopcock of the separatory funnel or by regulating the height of the reservoir at a constant stopcock setting. The constant head of water above the soil medium was maintained at .25 inches.

Soil mediums that conducted water in excess of one inch per hour were subjected to a constant head of water for a minimum of one hour.

Less permeable soil mediums were exposed to the constant head of water for a minimum of three hours.

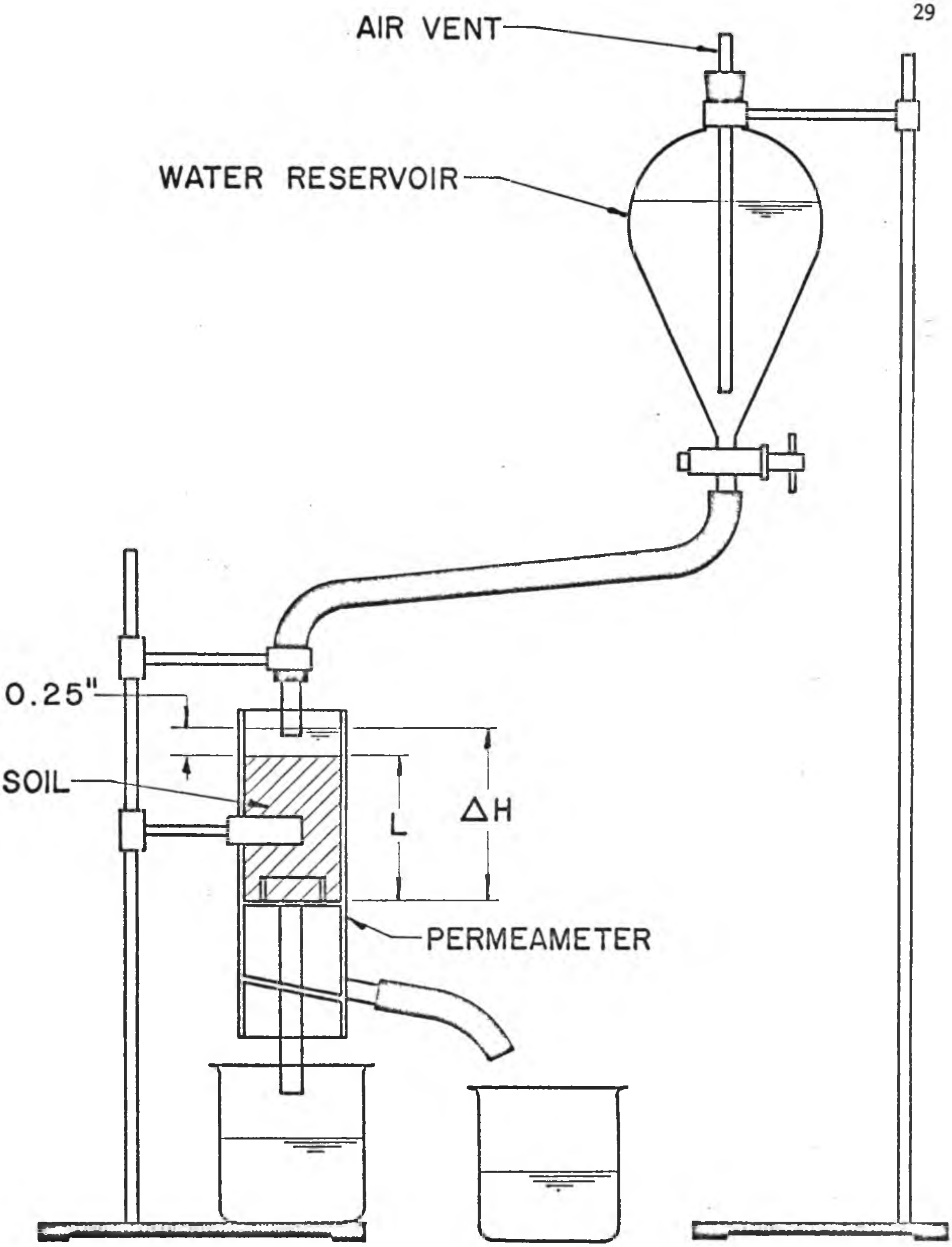
The water that passed through the central column of soil medium was collected and measured. Collection of the effluent was made for a given duration of time dependent on the ability of the medium to conduct water.

The equation $K=(Q/At)(L/\Delta H)$ was used to calculate hydraulic conductivity. In this equation, K is the conductivity of the soil to water, Q is the volume of water that passes through the sample in a known time (t), A is the cross sectional area of the sample, L is the length of the sample, and ΔH is the hydraulic head difference. A schematic diagram of the apparatus is shown in fig. 3.

Soil Bulk Density

Blake (1965) described soil bulk density as, "the ratio of the mass to the bulk or macroscopic volume of soil particles plus pore spaces in a sample." In this study, the mass was determined after drying the soil medium to a constant weight at 105°C. The samples were left in a forced air dryer for a minimum of 10 hours and a maximum of 12 hours. The volume was calculated after the oven-dried soil medium was placed in the permeameter. These measurements were expressed as gms/cm^3. Subsequent determinations of soil bulk densities at different compactive treatments were also made as an aid in evaluating the mediums tolerance to compaction.

Figure 3. Diagram of the constant-head system used to determine hydraulic conductivity.


AIR VENT
WATER RESERVOIR
0.25"
SOIL
L
ΔH
PERMEAMETER

Total Porosity

The formula $S_t = 100[(P_p - D_b)/P_p]$ was used to calculate total porosity. S_t is defined as the percentage of the bulk volume not occupied by solids. P_p values, or particle densities, were obtained from the University of Hawaii's Soils Department. The values used were: Wahiawa soil - 3.0 gm/cm^3, Volcanite - 2.7 gm/cm^3, and beach sand - 2.65 gm/cm^3. The values for D_b, or bulk density, were obtained from calculations previously performed.

Moisture Content

Each medium was adjusted to a specific moisture content prior to compaction in an attempt to influence maximum soil compaction.

After saturation, the column of medium was subjected to a vacuum which adjusted the moisture content to a specific value. Determination of the amount of moisture present in the medium was accomplished by weighing the saturated medium and subtracting its dry weight from this figure. The amount of moisture present in the medium was reported as a percent by weight of the oven-dried weight.

Table 4 shows the moisture content of the mediums immediately after the water saturation treatment and during compaction.

Analysis of Data

The data obtained from the hydraulic conductivity and bulk density measurements were subjected to analysis of variance as a 3^3 factorial, randomized complete block design. Each treatment was replicated three times with three permeameters. The treatment sums of squares were

Table 4. Percent moisture content by weight of the soil mixes when saturated and during compaction

Mediums	Compaction level	% moisture content when saturated	% moisture content during compaction
75% soil:	0	57	36
25% Volcanite	22	52	36
	44	45	36
50% soil:	0	47	36
50% Volcanite	22	46	36
	44	44	36
25% soil:	0	41	36
75% Volcanite	22	42	36
	44	43	36
75% soil:25% sand	0	43	25
	22	34	25
	44	31	25
50% soil:50% sand	0	35	25
	22	31	25
	44	29	25
25% soil:75% sand	0	31	20
	22	26	20
	44	25	20
75% soil:	0	71	54
25% Loamite	22	62	54
	44	57	54
50% soil:	0	91	61
50% Loamite	22	88	61
	44	83	61
25% soil:	0	150	100
75% Loamite	22	146	100
	44	146	100

partitioned utilizing one degree of freedom for each comparison.

The three factors comprising the 3^3 factorial experiment were as follows:

Amendments: sieved Volcanite, beach sand, and Loamite

Percent of amendments: 25%, 50%, and 75%

Compaction: shake, 22 psi, and 44 psi.

RESULTS AND DISCUSSION

The degree of compaction of the various mixtures was represented by bulk density measurements. Large increases in bulk density with increased compaction levels indicated that the particular medium was susceptible to compaction. Mediums which showed no increase or only slight increase in bulk density with increased compaction levels were considered resistant to compaction.

Hydraulic conductivity measurements were expressed in inches per hour. A water flow rate of an inch to an inch and a half per hour was considered ideal (Ferguson, Howard, and Bloodworth, 1960).

Wahiawa Soil

Wahiawa soil was considered susceptible to compaction. Bulk density increased from .84 gms/cm^3 to 1.04 gms/cm^3 after compaction (fig. 4). This increase in bulk density indicated that the soil particles were probably deformed and rearranged.

Hydraulic conductivity for the Wahiawa soil decreased with compaction (fig. 5). The flow rate of water was 10.15 in/hr at shake compaction, 16.60 in/hr at 5 psi, and .70 in/hr at 25 psi. The increased flow rate at 5 psi was probably due to the removal of entrapped air (Christiansen, 1944). Whereas, the decrease in hydraulic conductivity was due to compaction.

Total porosity of Wahiawa soil varied between 72% at shake compaction and 65.3% at 25 psi (Appendix Table 2). These figures were high in comparison to the total porosity figures of the other mediums.

Figure 4. Relation between compaction and bulk density for beach sand, Volcanite and Wahiawa soil.

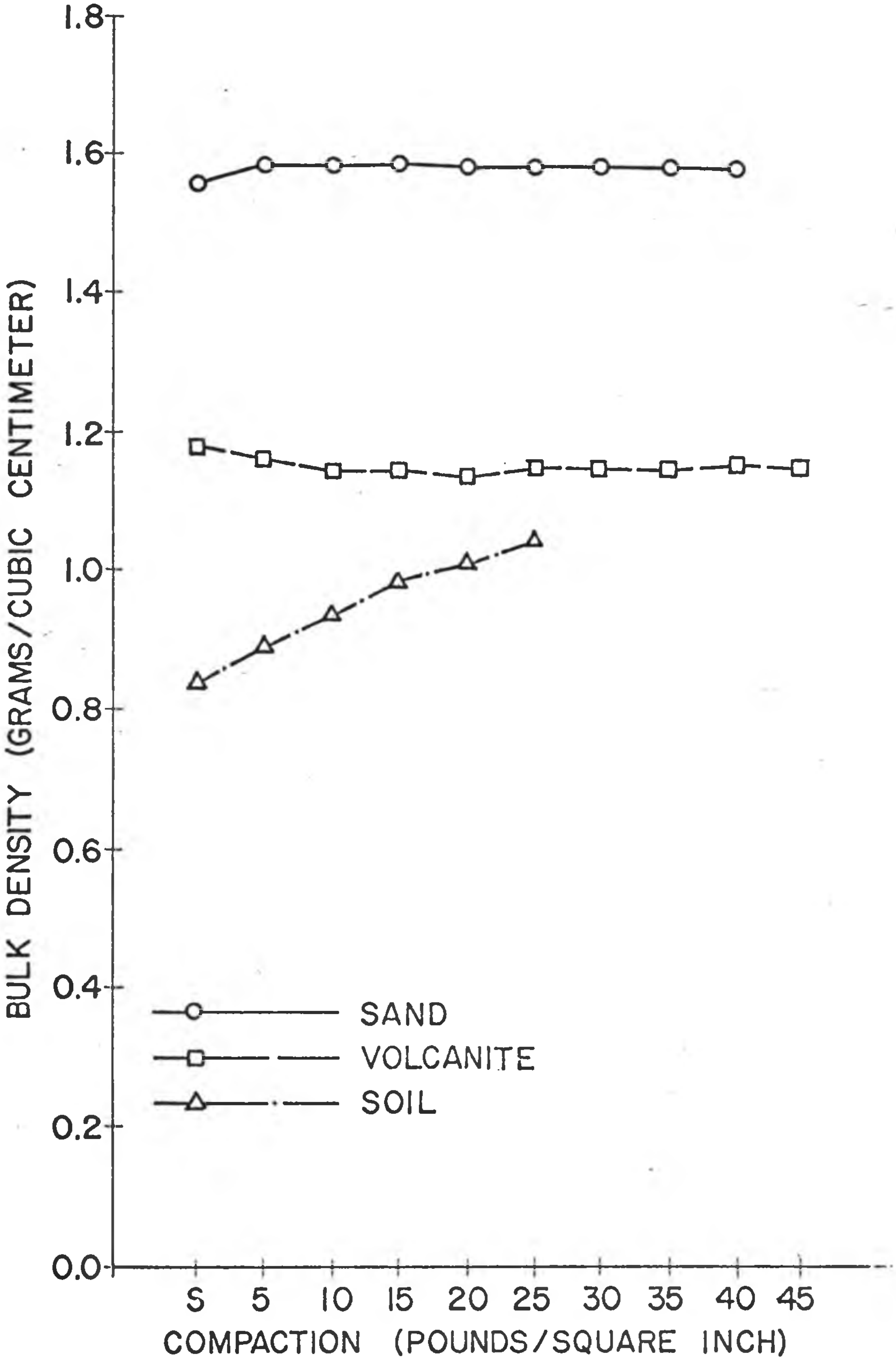
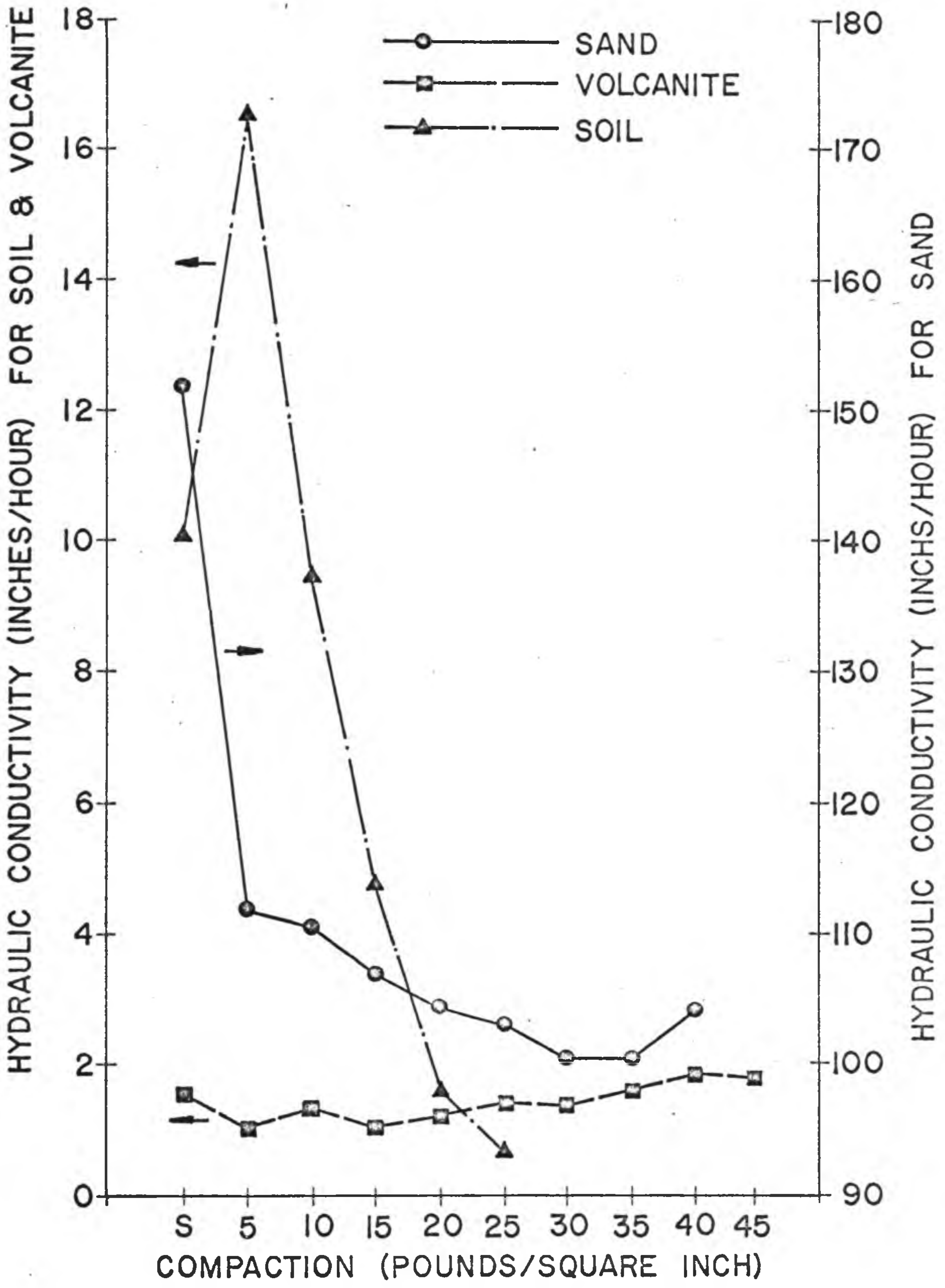

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
BULK DENSITY (GRAMS/CUBIC CENTIMETER)
S
5
10
15
20
25
30
35
40
45
COMPACTION (POUNDS/SQUARE INCH)
SAND
VOLCANITE
SOIL

Figure 5. Relation between compaction and hydraulic conductivity for beach sand, Volcanite and Wahiawa soil.


SAND
VOLCANITE
SOIL
HYDRAULIC CONDUCTIVITY (INCHES/HOUR) FOR SOIL & VOLCANITE
HYDRAULIC CONDUCTIVITY (INCHS/HOUR) FOR SAND
COMPACTION (POUNDS/SQUARE INCH)
0
2
4
6
8
10
12
14
16
18
90
100
110
120
130
140
150
160
170
180
S
5
10
15
20
25
30
35
40
45

The high values may be attributed to a greater quantity of micropore spaces. Total porosity decreased in a linear fashion with compaction due to a linear increase in bulk density. Therefore, hydraulic conductivity also decreased as illustrated in figure 5.

Volcanite

Figure 4 shows that unsieved Volcanite was tolerant to compaction. Its bulk density varied only .04 gms/cm^3 from lowest to highest compaction level. The particles seemed to crush rather than become deformed during compaction. This crushing action may have been the reason that closer packing of the particles was not as pronounced as with the Wahiawa soil.

Hydraulic conductivity for unsieved Volcanite remained relatively constant when compaction was applied (fig. 5). The values ranged from 1.52 in/hr to 1.82 in/hr. Improved continuity of the macropore spaces may have caused the increased water movement at the higher compaction levels. Rearrangement of the Volcanite particles also could have influenced the flow of water.

Total porosity values for Volcanite were between 57.3% at shake compaction and 58.7% at 20 psi (Appendix Table 2). The difference between these two values was considered negligible. Thus the amount of pore spaces and hydraulic conductivity were not affected by compaction.

Beach Sand

The bulk density of beach sand varied only .02 gms/cm^3 from lowest to highest compaction levels (fig. 4). Therefore, this medium was also considered tolerant to compaction. Its bulk density was highest of the three mediums. This indicated that the beach sand particles were in close contact with each other which was expected since beach sand usually has a low organic matter content. The initial close packing of the particles was probably the reason compaction had little effect on bulk density. The high density and greater weight of the beach sand particles probably also contributed to the high bulk density figures.

Figure 5 shows a great decrease in hydraulic conductivity for beach sand from shake compaction to five psi. Closer packing of the particles, as indicated by an increase in bulk density, may have decreased the size of the macropore spaces. The particles also may have shifted, resulting in less continuity of the macropore spaces. Although there was a decrease in hydraulic conductivity, the rate of water movement was still high at all compaction levels which indicated that beach sand had a high percentage of macropore spaces.

Total porosity for beach sand was the lowest for all mediums tested (Appendix Table 2). This was probably due to a low percentage of micropore spaces. Essentially no change in total porosity was observed with compaction except for a decrease at five psi.

Mixtures of Mediums

Appendix Table 1 shows the results of the analysis of variance for mixtures. The degrees of freedom were partitioned into main effects and interactions. The main effects were inorganic amendments versus organic amendment, between inorganic amendments, percent amendments linear, percent amendments quadratic, compaction linear, and compaction quadratic.

The interactions were amendments x percent, amendments x compaction, percent x compaction, and amendments x compaction x percent.

Bulk density and hydraulic conductivity values for organic amendment versus inorganic amendments when averaged over all compaction levels and percent amendments were highly significant.

Table 5A shows that the average bulk density and hydraulic conductivity values were greater for the inorganic amendments than the organic amendment. Loamite probably had lower hydraulic conductivity values because of its compressibility. This may have caused the deformation of the particles and decrease of macropore spaces. The light weight of the Loamite particles greatly contributed to the lower bulk density.

Bulk density values were significantly greater for mediums containing beach sand than for mediums containing Volcanite. The mixes containing beach sand probably had higher bulk densities because of its greater particle weights. In contrast, the lower bulk densities of mediums amended with Volcanite were probably due to the highly porous characteristics of the Volcanite particles (Hagan and Stockton, 1952).

Hydraulic conductivity values were significantly greater for mediums containing Volcanite than for those containing beach sand (Table 5A). The higher total porosity for mediums containing Volcanite probably influenced hydraulic conductivity (Appendix Table 2). The beach sand particles also may have packed closer to each other and caused a reduction of water flow.

The addition of different percentages of amendments, when averaged over all compaction levels and amendments, affected bulk density and

Table 5. Bulk density and hydraulic conductivity of various soil mixtures as influenced by compaction level and percent of soil amendments included in the mixture (average of 3 replications)

Table 5A

		Compaction Level							
Amendment	percent amendment	0		22		44			
		B.D. (gm/cm^3)	H.C. (in/hr)	B.D. (gm/cm^3)	H.C. (in/hr)	B.D. (gm/cm^3)	H.C. (in/hr	B.D.Ave. (gm/cm^3)	H.C.Ave. (in/hr)
Beach sand	25	1.00	19.34	1.21	1.28	1.28	0.19	1.16	6.93
	50	1.15	59.30	1.27	16.42	1.33	10.40	1.25	28.70
	75	1.29	109.48	1.32	63.87	1.34	51.09	1.31	74.81
	Ave.	1.14	62.70	1.26	27.19	1.31	20.56	1.24	36.81
Volcanite	25	0.82	59.30	0.87	4.87	0.93	0.38	0.87	21.51
	50	0.83	112.22	0.96	22.08	1.11	8.85	0.96	47.71
	75	0.81	275.53	0.87	190.68	0.89	152.36	0.85	206.19
	Ave.	0.82	149.01	0.90	72.54	0.97	53.86	0.89	91.80
Loamite	25	0.65	45.07	0.80	1.70	0.87	0.18	0.77	15.65
	50	0.51	70.25	0.60	14.23	0.65	4.93	0.58	29.80
	75	0.30	134.12	0.34	78.46	0.37	38.96	0.33	83.84
	Ave.	0.48	83.14	0.58	31.46	0.63	14.69	0.56	43.09

Table 5B

	25%		50%		75%	
Ave. for percent	B.D. (gm/cm^3)	H.C. (in/hr)	B.D. (gm/cm^3)	H.C. (in/hr)	B.D. (gm/cm^3)	H.C. (in/hr)
amendments	0.93	14.69	0.93	35.40	0.83	121.61

Table 5C

	Shake		22 psi		44 psi	
Ave. for	B.D. (gm/cm^3)	H.C. (in/hr)	B.D. (gm/cm^3)	H.C. (in/hr)	B.D. (gm/cm^3)	H.C. (in/hr)
compaction	0.81	98.28	0.91	43.73	0.97	29.70

hydraulic conductivity in a linear and quadratic fashion.

Loamite amended mediums probably caused the significant linear decrease in bulk density. Mediums containing 75% Loamite had very low bulk densities. This was probably due to the low particle weights of this medium.

A larger decrease in bulk density due to the addition of 75% amendments over that of adding 50% amendment was responsible for the quadratic effect. The reason for this decrease was as explained earlier for the linear effect.

Table 5B shows the dramatic increase in hydraulic conductivity with the addition of amendments. The addition of greater percentages of amendments to the Wahiawa soil resulted in a higher percentage of macropore spaces. Thus, the flow of water increased due to less resistance.

The difference in magnitude of the hydraulic conductivity values was probably a cause of the quadratic effect. Hydraulic conductivity for mediums containing 25% and 50% amendments differed by approximately 16 in/hr. However, mediums containing 75% amendments had hydraulic conductivity values that averaged 86 in/hr more than mediums containing 50% amendments.

The following discussion (of the main effect of compaction) will involve values that were averages over all amendments and percent of amendments (Table 5C).

Compaction caused a highly significant linear increase in bulk density (Appendix Table 1). Higher compaction levels resulted in closer packing of the particles and therefore higher bulk densities.

In contrast, compaction caused a highly significant linear decrease in hydraulic conductivity. This can be explained on the basis that higher compaction levels caused a reduction in pore spaces and consequently a reduction in hydraulic conductivity.

The significance of the significant quadratic effect of compaction for bulk density is difficult to see from the data in Table 5C. A probable cause for this effect is the different rate of change of the bulk density values between compaction levels. Bulk density varied .10 gm/cm^3 between shake compaction and 22 psi, but varied .06 gm/cm^3 between 22 psi and 44 psi compaction.

Hydraulic conductivity decreased approximately 55 in/hr from shake compaction to 22 psi and approximately 14 in/hr from 22 psi to 44 psi compaction. This variation in rate of change in hydraulic conductivity probably was responsible for the significant quadratic effect.

The interaction of amendments x percent amendments was highly significant for bulk density and hydraulic conductivity (Appendix Table 1).

The mediums responded in various ways to the addition of different percentages of amendments and therefore caused a significant interaction (Table 6). Bulk density for mediums containing beach sand increased with higher percentages of amendments. However, Volcanite amended-mediums responded with an increase in bulk density followed by a decrease when larger amounts of Volcanite were added. Bulk density for mediums containing Loamite decreased with an increase in percent amendments.

Table 6. Bulk density and hydraulic conductivity values as affected by different percentages of amendments for different mediums. Data are averages over all compaction levels.

	Sand		Volcanite		Loamite	
Percent Amendments	Bulk Density (gm/cm^3)	Hydraulic conductivity (in/hr)	Bulk Density (gm/cm^3)	Hydraulic conductivity (in/hr)	Bulk Density (gm/cm^3)	Hydraulic conductivity (in/hr)
25	1.16	6.93	0.87	21.51	0.77	15.65
50	1.25	28.70	0.96	47.71	0.58	29.80
75	1.31	74.81	0.85	206.19	0.33	83.84

The significant interaction for hydraulic conductivity was probably due to the great difference in hydraulic conductivity between mediums at the 75% amendment level. The hydraulic conductivity values for all mediums at the 25% and 50% amendment levels were similar. However the value for Volcanite at the 75% amendment level was at least twice as great as the values for beach sand or Loamite amended mixes.

The interaction of amendments x compaction was significant for bulk density (Appendix Table 1). Bulk density increased for all mediums with added increments of amendments after exposure to compaction (Table 7). As expected, the bulk density values for mediums containing inorganic amendments were much greater than for mediums containing Loamite.

Hydraulic conductivity values showed a significant amendments x compaction interaction. An increase in compaction for all amendments caused a decrease in hydraulic conductivity. However, Volcanite amended mediums had hydraulic conductivity values that were at least twice as great as the values for mediums containing beach sand or Loamite (Table 7).

Percent amendments x compaction was significant for bulk density and hydraulic conductivity (Appendix Table 1). This may be accounted for by the fact that bulk density varied differently with the addition of different percentages of amendments at a given compaction level (Table 8). At shake compaction bulk density increased, then decreased with the incorporation of more amendment. However, bulk density continued to decrease with the addition of higher percentages of amendments at 22 psi. Bulk densities were identical with 25% and 50% amendments at 44 psi, but decreased with 75% amendments.

Table 7. Bulk density and hydraulic conductivity values as affected by compaction for different amendments. Data are averages over all percent amendments.

	Sand		Volcanite		Loamite	
Compaction	Bulk density (gm/cm^3)	Hydraulic conductivity (in/hr)	Bulk density (gm/cm^3)	Hydraulic conductivity (in/hr)	Bulk density (gm/cm^3)	Hydraulic conductivity (in/hr)
Shake	1.14	62.70	0.82	149.01	0.48	83.14
22	1.26	27.19	0.90	72.54	0.58	31.46
44	1.31	20.56	0.97	53.86	0.63	14.69

Table 8. Bulk density and hydraulic conductivity values as affected by compaction with different percentages of amendments. Data are averages over all mediums.

	Shake		22 psi		44 psi	
Percent amendment	Bulk density (gm/cm^3)	Hydraulic conductivity (in/hr)	Bulk density (gm/cm^3)	Hydraulic conductivity (in/hr)	Bulk density (gm/cm^3)	Hydraulic conductivity (in/hr)
25	0.82	41.24	0.96	2.62	1.03	0.25
50	0.83	80.59	0.94	17.58	1.03	8.06
75	0.80	173.04	0.84	111.00	0.87	80.80

Hydraulic conductivity did not increase in similar intervals for the three compaction levels with the addition of different percent amendments (Table 8). There was a two-fold increase in hydraulic conductivity with the addition of different percentages of amendments at shake compaction. Whereas, the increases were six times and a minimum of ten times at respectively 22 psi and 44 psi compaction.

The interaction of amendments x compaction x percent was significant for bulk density and not for hydraulic conductivity (Appendix Table 1). The significance was probably due to beach sand and Loamite. The difference in weights of the beach sand and Loamite particles probably were responsible for the contrasting bulk density values. The addition of beach sand to the Wahiawa soil increased bulk density for all compaction levels. In contrast, greater percentages of Loamite decreased bulk density.

Beach Sand Mix

Mediums containing beach sand had higher bulk density values for all compaction levels than those containing other amendments (fig. 6). This was probably due to the greater weight and packing characteristics of the beach sand particles. Compaction affected bulk density less for mediums containing higher percentages of beach sand (fig. 6C). This shows that the addition of beach sand increased the medium's tolerance to compaction.

Hydraulic conductivity values for mediums containing beach sand ranged from low to excessively high after exposure to 44 psi compaction (fig. 7). Mediums amended with 25% beach sand at 44 psi had hydraulic

Figure 6. Relation between compaction and bulk density for mediums consisting of Wahiawa soil and a percentage of either beach sand, Volcanite, or Loamite. Figures 6A, 6B, and 6C consist of respectively 25%, 50%, and 75% amendments.

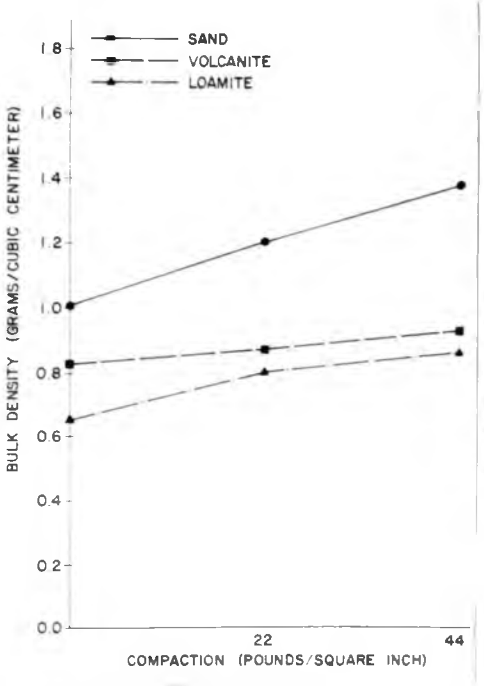


Figure 6A

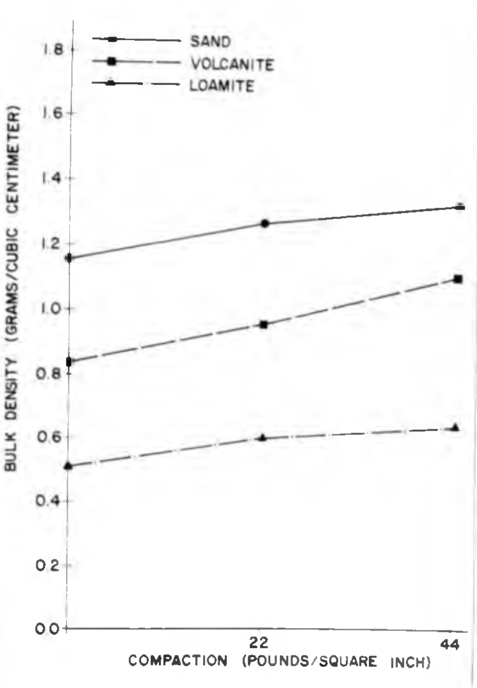


Figure 6B

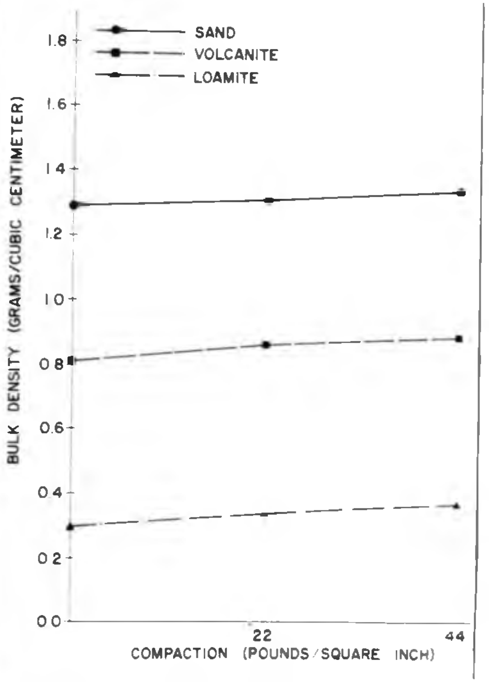
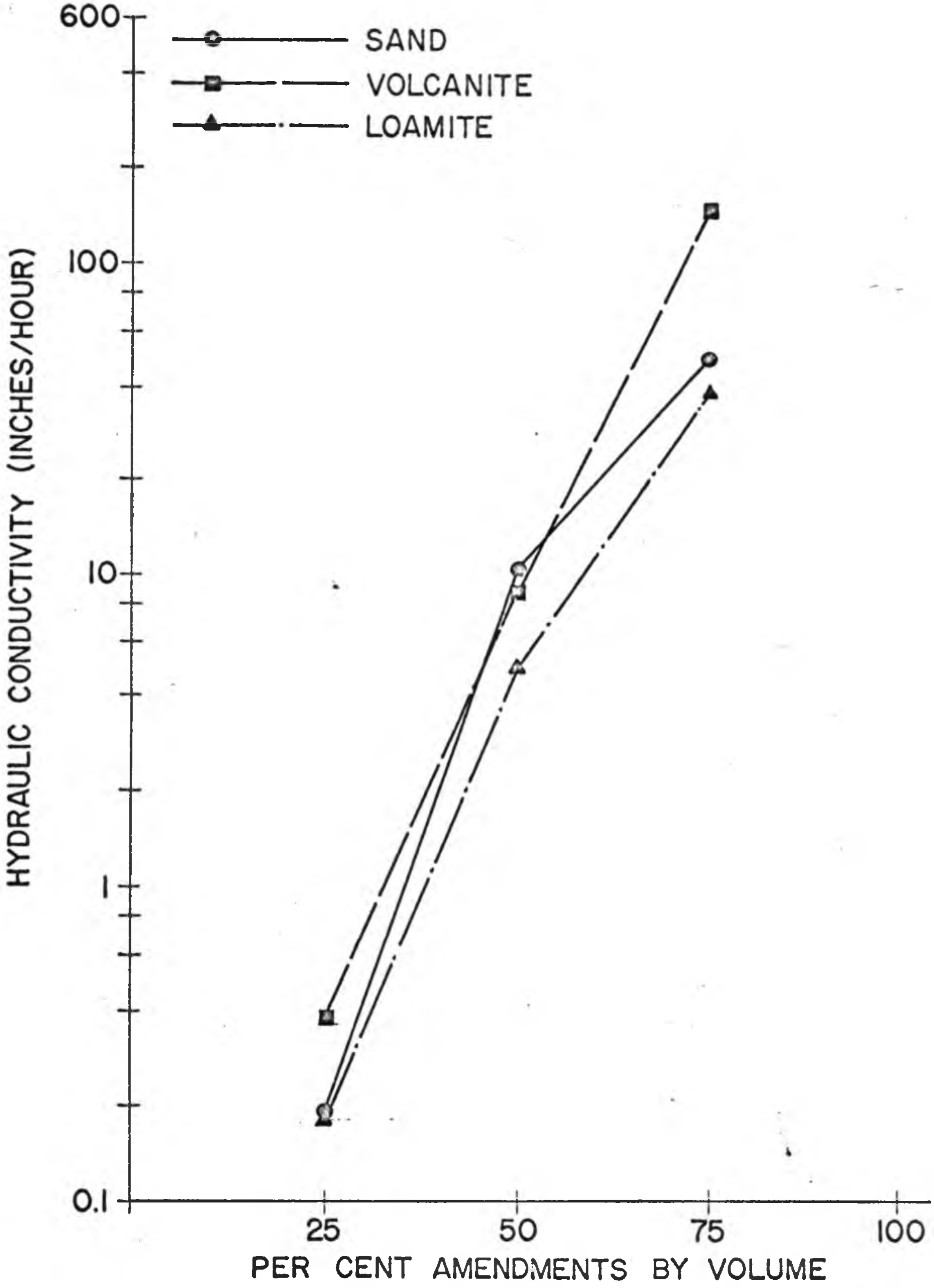


Figure 6C

Figure 7. Relation between percent amendments by volume and hydraulic conductivity at 44 psi for mediums containing different percentages of either beach sand, Volcanite, or Loamite.


SAND
VOLCANITE
LOAMITE
600
100
10
1
0.1
HYDRAULIC CONDUCTIVITY (INCHES/HOUR)
25
50
75
100
PER CENT AMENDMENTS BY VOLUME

conductivity values below the acceptable range. The high percentage of soil was probably responsible for the compactibility and low hydraulic conductivity values of this medium. Mediums containing 50% beach sand were able to conduct water in excess of the acceptable range. Whereas, mediums containing 75% beach sand had hydraulic conductivity values that were excessively high. The high percentage of beach sand probably increased the quantity of macropore spaces which influenced the flow of water.

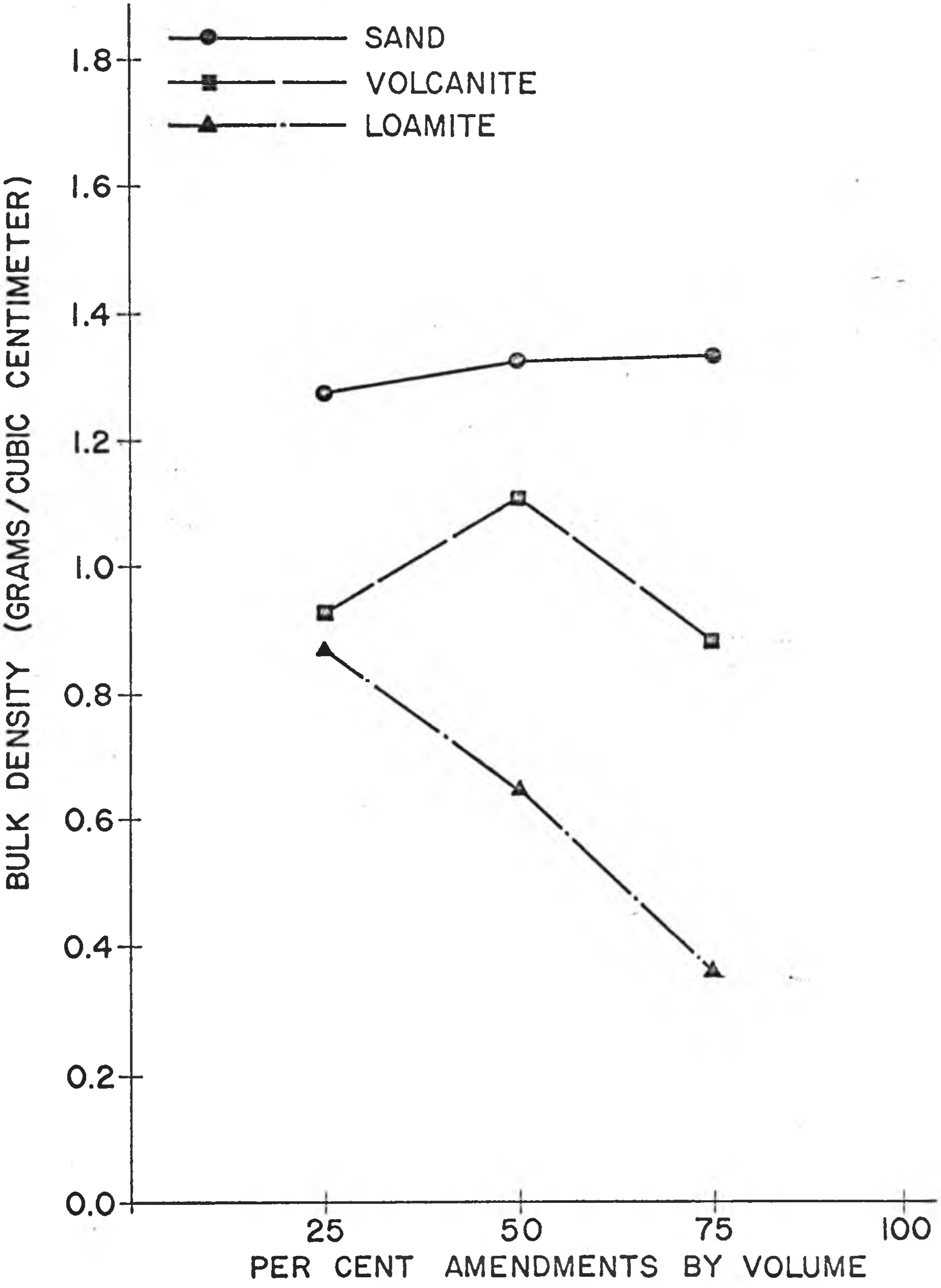
The addition of higher percentages of beach sand to Wahiawa soil decreased total porosity (Appendix Table 2). This was probably due to the replacement of soil containing a high percentage of micropore and macropore spaces with beach sand containing a low percentage of micropores. Although total porosity decreased, hydraulic conductivity increased. This increase was probably due to an increase in quantity and size of macropore spaces.

Volcanite Mix

Figure 6 shows that mediums containing sieved Volcanite had bulk density values intermediate to mediums containing beach sand or Loamite.

Compaction had little effect on mediums containing 25% and 75% Volcanite. But figures 6B and 8 show that mediums amended with 50% Volcanite used for this treatment may have had a higher percentage of particles within the range .425 mm-.250 mm than in the range .850 mm-.425 mm. The presence of a high percentage of smaller fraction particles could have increased bulk density. A moisture content conducive to compaction may also have been prevalent.

Figure 8. Relation between percent amendments by volume and bulk density at 44 psi for mediums containing different percentages of either beach sand, Volcanite or Loamite.


SAND
VOLCANITE
LOAMITE
BULK DENSITY (GRAMS/CUBIC CENTIMETER)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
25
50
75
100
PER CENT AMENDMENTS BY VOLUME

Mediums amended with Volcanite had higher hydraulic conductivity values than mediums containing other amendments (fig. 9). This indicated that Volcanite-amended mediums probably were more tolerant to compaction. Figure 9A shows that hydraulic conductivity was low for mediums containing 25% Volcanite, high for mediums containing 50% Volcanite (fig. 9B), and excessively high for mediums containing 75% Volcanite (fig. 9C).

Mediums containing Volcanite had total porosity values that were higher than mediums containing beach sand (Appendix Table 2). This was expected since Volcanite particles are more porous than beach sand particles.

Higher percentages of Volcanite did not decrease total porosity appreciably and thus was partially responsible for the higher hydraulic conductivity values.

Loamite Mix

Loamite was the only amendment that decreased bulk density of the mediums. Figure 6 shows that the addition of Loamite to Wahiawa soil at all compaction levels resulted in lower bulk density values. As discussed earlier, the light weight of the Loamite particles caused the reduction in bulk density and contributed to the interaction.

For mediums containing Loamite, bulk density fluctuated very little at all compaction levels. This was due to the ability of the Loamite particles to re-bound like sponges after being compressed. This characteristic became less pronounced with continued compaction. Repeated compaction would probably cause Loamite to compact more than the other amendments.

Figure 9. Relation between compaction and hydraulic conductivity for mediums consisting of Wahiawa soil and a percentage of either beach sand, Volcanite, or Loamite. Figures 9A, 9B and 9C consist of respectively 25%, 50% and 75% amendments.

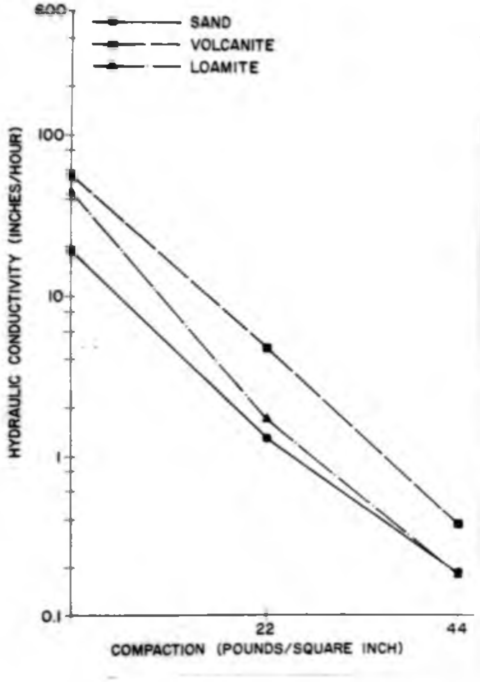


Figure 9A

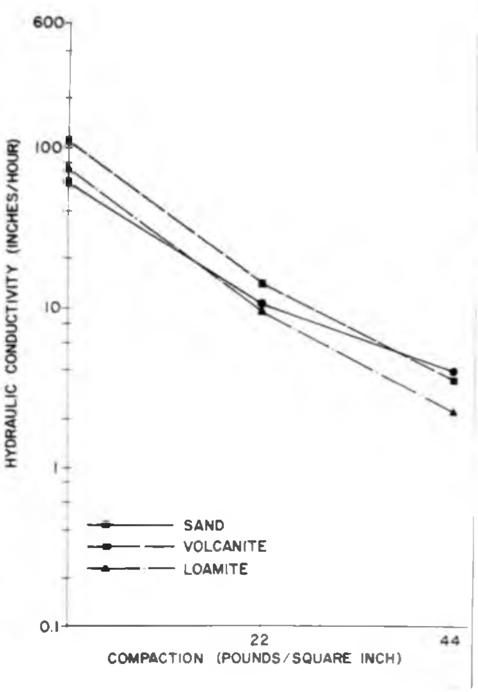


Figure 9B

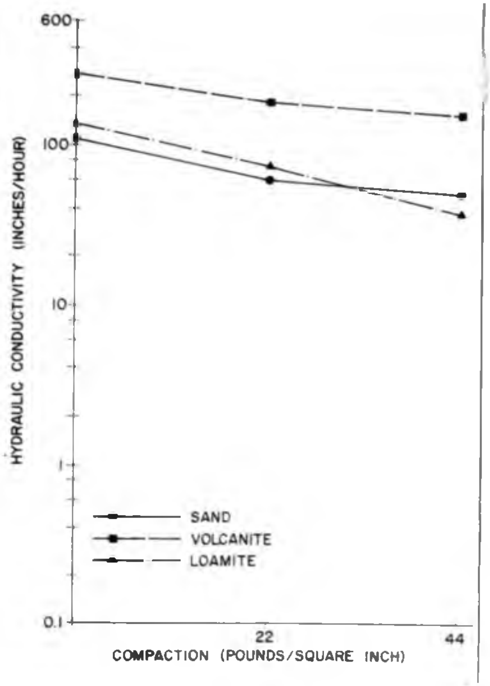


Figure 9C

Figure 8 shows that hydraulic conductivity at 44 psi for mediums amended with Loamite was low with 25% Loamite, moderately high with 50% Loamite, and excessively high with 75% Loamite. Loamite's characteristic of compression was probably the reason mediums containing this amendment did not have the highest hydraulic conductivity values. Unlike the other amendments, the Loamite particles were compressed when exposed to compactive forces. This caused the soil mixed with Loamite to become compacted to a higher degree than the soil mixed with Volcanite.

Total porosity was not calculated for Loamite and mediums containing Loamite due to no information relating to its particle density.

SUMMARY

Physical properties of various soil amendments were studied in an attempt to produce a soil mix that would be able to tolerate soil compaction.

The mediums used for the mixes were Wahiawa soil, beach sand, Loamite, and sieved Volcanite. A mix consisted of Wahiawa soil and a percentage of an organic or inorganic amendment -- Loamite being the organic amendment, and sieved Volcanite and beach sand being the inorganic amendments. These mixes were exposed to compaction with a modified hydraulic press. Hydraulic conductivity, bulk density, and total porosity measurements were conducted to determine the affects of compaction.

The data obtained indicated that all mixes were able to conduct water in excess of an inch and a half per hour with 50% or more amendments after compaction. Whereas unamended soil conducted water at a rate less than an inch per hour after compaction. Mixes containing 75% amendments had hydraulic conductivity values that exceeded 50 in/hr and would be considered too well drained. In general, amendments of the soil improved its capacity to withstand compaction.

Mediums amended with sieved Volcanite seemed least susceptible to compaction. Bulk density, hydraulic conductivity, and total porosity values were highest for these mediums. The relatively incompressible and porous characteristics of the Volcanite particles were probably responsible for the high values.

Beach sand-amended mediums were also tolerant of compaction. Bulk

density was not affected by compaction because of the incompressible nature of the particles. Hydraulic conductivity remained very high after compaction due to a high percentage of macropore spaces. But addition of beach sand did tend to reduce total porosity of a soil-sand mix.

Mediums containing Loamite may be considered compaction tolerant under the conditions of this study. But under field conditions, Loamite amended mediums may become susceptible to compaction because of its particles' compressible nature.

This study confirmed previous reports that the use of an inorganic or organic amendment will improve certain physical properties of a medium. The most acceptable combination was a medium containing approximately 50% amendments and 50% soil.

The data may not be representative of conditions prevalent in the field. Therefore, a detailed study encompassing soil moisture content, higher levels of compaction, and cumulative compaction should be conducted. The study would also be more valuable if it were conducted in the field.

Appendix Table 1. Analysis of Variance for effects of compaction on bulk density and hydraulic conductivity of various soil mixtures

Source of variance	Degrees of freedom	Mean square		*F*	
		Bulk density	Hydraulic conductivity	Bulk density	Hydraulic conductivity
Replications	2	0.0008	167.91	4.0*	0.3256
Amendments					
1. Inorganics versus organics	1	4.6	.003	23002.5**	15.710**
2. Between inorganics	1	1.6	.016	8008.0**	79.16**
Per cent Amendments					
1. Linear	1	.135	.060	675.0**	299.67**
2. Quadratic	1	.041	.007	205.0**	37.44**
Compaction					
1. Linear	1	.331	.025	1656.5**	123.15**
2. Quadratic	1	.007	.003	34.0**	14.34**
Amendments x per cent	4	.858	.020	4287.5**	98.95**
Amendments x compaction	4	.005	.003	24.5**	13.62**
Per cent x compaction	4	.057	.003	283.5**	12.42**
Amendments x compaction x per cent	8	.041	.0002	205.0**	1.3
Error	52	.0002	515.6513	-	-

Appendix Table 2. Total porosity for various mediums as influenced by different compaction levels

Medium	Compaction level (psi)	Replications			Average
		1	2	3	
Wahiawa soil	Shake	72.0	73.0	71.0	72.0
	5	70.0	72.0	69.0	70.3
	10	69.0	70.0	68.0	69.0
	15	68.0	67.0	66.0	67.0
	20	66.0	66.0	65.0	65.7
	25	66.0	65.0	65.0	65.3
Volcanite (unsieved)	Shake	57.0	58.0	57.0	57.3
	5	58.0	58.0	57.0	57.7
	10	58.0	58.0	59.0	58.3
	15	58.0	58.0	59.0	58.3
	20	59.0	59.0	58.0	58.7
	25	58.0	59.0	58.0	58.3
	30	58.0	59.0	58.0	58.3
	35	58.0	59.0	58.0	58.3
	40	58.0	58.0	58.0	58.0
Beach sand	Shake	42.0	41.0	41.0	41.3
	5	41.0	40.0	41.0	40.7
	10	41.0	40.0	41.0	40.7
	15	41.0	40.0	41.0	40.7
	20	41.0	40.0	41.0	40.7
	25	41.0	40.0	41.0	40.7
	30	41.0	40.0	41.0	40.7
	35	41.0	40.0	41.0	40.7
	40	41.0	40.0	41.0	40.7
75% Wahiawa soil: 25% Volcanite (sieved)	Shake	72.0	73.0	72.0	72.3
	22	70.0	70.0	71.0	70.3
	44	68.0	68.0	68.0	68.0
50% Wahiawa soil: 50% Volcanite (sieved)	Shake	72.0	71.0	71.0	71.3
	22	67.0	67.0	67.0	67.0
	44	62.0	61.0	62.0	61.7
25% Wahiawa soil: 75% Volcanite (sieved)	Shake	71.0	72.0	70.0	71.0
	22	69.0	69.0	69.0	69.0
	44	68.0	69.0	68.0	68.3
75% Wahiawa soil: 25% Beach sand	Shake	66.0	65.0	66.0	65.7
	22	58.0	58.0	59.0	58.3
	44	56.0	56.0	56.0	56.0
50% Wahiawa soil: 50% Beach sand	Shake	60.0	59.0	59.0	59.3
	22	56.0	55.0	55.0	55.3
	44	54.0	53.0	53.0	53.3
25% Wahiawa soil: 75% Beach sand	Shake	53.0	53.0	53.0	53.0
	22	51.0	51.0	51.0	51.3
	44	51.0	51.0	51.0	51.0

LITERATURE CITED

1. Alderfer, R. B. 1951. Compaction of Turf Soils - some causes and effects. U.S.G.A. Green Sect. J. and Turf Management 4(2):25-28.
2. Amemiya, M. 1965. Influence of aggregate size on soil moisture content - capillary conductivity relations. Soil Sci. Soc. Am. Proc. 29:744-748.
3. Blake, G. R. 1965. Bulk density. _Methods of Soil Analysis_. pg. 374-390.
4. Bodman, G. B. and G. K. Constantin. 1965. Influence of particle size distribution in soil compaction. Hilgardia. 36:567-591.
5. Browning, G. M. 1939. Volume change of soils. Soil Sci. Soc. Am. Proc. 4:23-27.
6. Bruce, R. R. 1955. An instrument for the determination of soil compactibility. Soil Sci. Soc. Am. Proc. 19:253-257.
7. Buckman, H. O. and N. C. Brady. 1967. Pore space of mineral soils. _The Nature and Properties of Soils_.
8. Christiansen, J. E. 1944. Effect of entrapped air upon the permeability of soils. Soil Sci. 58:355-365.
9. Cooper, A. W. and M. L. Nichols. 1959. Some observations on soil compaction tests. Ag. Eng. 40:264-267.
10. Davis, R. R. 1952. Physical condition of putting-green soils and other environmental factors affecting quality of greens. U.S.G.A. J. Vol. V, no. 1, pg. 25.
11. Day, P. R. 1965. Particle fractionation and particle size analysis. _Methods of Soil Analysis_.

12. DeJong, E. 1966. Hydraulic conductivity of clays during shrinkage. Soil Sci. Soc. Am. Proc. 30:289-292.

13. Felt, E. J. 1965. Compactibility. Methods of Soil Analysis. Part 1:400-412.

14. Ferguson, M. 1950. Compaction, aeration, and drainage. U.S.G.A. Green Sect. J. and Turf Management 3:32-33.

15. Ferguson, M. 1959. Turf damage from foot traffic. U.S.G.A. Green Sect. J. and Turf Management 12:29-32.

16. Ferguson, M., L. Howard, and M. E. Bloodworth. 1960. Laboratory methods for evaluation of putting green soil mixtures. U.S.G.A. J. 13:5-8.

17. Fireman, M. 1944. Permeability measurements on disturbed soil samples. Soil Sci. 58:337-353.

18. Fireman, M. and G. B. Bodman. 1939. The effect of saline irrigation water upon the permeability and base status of soils. Soil Sci. Soc. Am. Proc. 4:71-77.

19. Gardner, W. H. 1965. Water content. Methods of Soil Analysis.

20. Gardner, W. R., M. S. Mayhugh, J. O. Goertzen, and C. A. Bower. 1959. Effect of electrolyte concentration and exchangeable-sodium percentage on difusivity of water in soils. Soil Sci. 88:270-274.

21. Gerard, C. J. 1965. Influence of soil moisture, soil texture, drying conditions, and exchangeable cations on soil strength. Soil Sci. Soc. Am. Proc. 29:641-645.

22. Gerard, C. J., W. R. Cowley, C. A. Burleson, and M. E. Bloodworth. 1962. Soil hardpan formation as affected by rate of moisture loss, cyclic wetting and drying and surface-applied forces. Soil Sci. Soc. Am. Proc. 26:601-605.

23. Gill, W. R. 1959. Soil compaction by traffic. Ag. Eng. 40:392-394.

24. Goss, R. L. and J. Roberts. 1964. A compaction machine for turfgrass areas. Agron. J. 56:522.

25. Hagan, R. M. and J. R. Stockton. 1952. Effect of porous soil amendments on water retention characteristics. U.S.G.A. J. Vol. V., no. 1, pg. 29.

26. Hill, J.N.S. and M. E. Sumner. 1967. Effect of bulk density on moisture characteristics of soils. Soil Sci. 103:234-238.

27. Hopkins, R. M. and W. H. Patrick. 1969. Combined effect of oxygen content and soil compaction on root penetration. Soil Sci. 108: 408-413.

28. Johnson, W. H. and J. E. Henry. 1964. Influence of simulated row compaction on seedling emergence and soil drying rates. Am. Soc. Ag. Eng. Trans. 3:252-255.

29. Klute, A. 1965. Laboratory measurement of hydraulic conductivity of saturated soil. Methods of Soil Analysis.

30. Kunze, R. J., M. H. Ferguson, and J. B. Page. 1957. The effects of compaction on golf green mixtures. U.S.G.A. J. Vol. X, no. 6, pg. 24.

31. Laliberte, G. E. and R. H. Brooks. 1967. Hydraulic properties of disturbed soil materials affected by porosity. Soil Sci. Soc. Am. Proc. 31:451-454.

32. Lewis, M. R. and W. L. Powers. 1938. A study of factors affecting infiltration. Soil Sci. Soc. Am. Proc. 3:334-339.

33. Lotspeich, F. B. 1964. Strength and bulk density of compacted mixtures of kaolinite and glass beads. Soil Sci. Soc. Am. Proc. 28:737-740.

34. Lutz, J. F. and R. W. Leamer. 1939. Pore-size distribution as related to the permeability of soils. Soil Sci. Soc. Am. Proc. 4:28-31.

35. McLeod, H. E., I. F. Reed, W. H. Johnson, and W. R. Gill. 1966. Draft, power efficiency, and soil-compaction characteristics of single, dual, and low pressure tires. Am. Soc. Ag. Eng. Trans. 9, no. 1:41-44.

36. Meredith, H. L. and H. Kohnke. 1965. Significance of the rate of organic matter decomposition the aggregation of soil. Soil Sci. Soc. Am. Proc. 29:547-550.

37. Morgan. 1966. Turfgrass management. Agronomy Journal. 58:527.

38. Morgan, W. C., J. Letey, S. J. Richards, and N. Valoras. 1966. Physical soil amendments, soil compaction, irrigation, and wetting agents in turfgrass management; effects on compactibility, water infiltration rates, evapotranspiration, and number of irrigations. Agron. J. 58:525-528.

39. Nelson, W. R. and L. D. Baver. 1940. Movement of water through soils in relation to the nature of the pores. Soil Sci. Soc. Am. Proc. 5:69-76.

40. Reeve, R. C. and G. H. Tammaddoni. 1965. Effect of electrolyte concentration on laboratory permeability and field intake of a sodic soil. Soil Sci. 99:261-266.

41. Richards, L. A. 1952. Report of the subcommittee on permeability and infiltration. Soil Sci. Soc. Am. Proc. 16:85-88.

42. Richards, S. J., J. E. Warneke, and L. V. Weeks. 1965. A soil compactor and procedure used in preparing soil cores for measuring physical properties. Soil Sci. Soc. Am. Proc. 29:637-639.

43. Salter, P. J. and J. B. Williams. 1965. Influence of texture on the moisture characteristics of soils; available-water capacity and moisture release characteristics. J. Soil Sci. 16:310-317.

44. Smalley, R. R., W. L. Pritchett, and L. C. Hammond. 1962. Effects of four amendments on soil physical properties and on yield and quality of putting greens. Agron. J. 54:393-395.

45. Swartz, W. E. and L. T. Kardos. 1963. Effects of compaction on physical properties of sand-soil-peat mixtures at various moisture contents. Agron. J. 55:7-10.

46. Terry, C. W. and H. M. Wilson. 1953. The soil penetrometer in soil compaction studies. Agr. Eng. 34:831-834.

47. Uehara, G. 1970. Unpublished.

48. Vomocil, J. 1965. Porosity. Methods of Soil Analysis.

49. Voorhees, W. B., R. R. Allmaras, and W. E. Larson. 1966. Porosity of surface soil aggregates at various moisture contents. Soil Sci. Soc. Am. Proc. 30:163-167.

50. Waldron, L. J. and C. K. Constantin. 1968. Bulk volume and hydraulic conductivity changes during saturation tests. Soil Sci. Soc. Am. Proc. 32:175-179.

51. Wischmeier, W. H. and J. V. Mannering. 1965. Effect of organic matter content of the soil on infiltration. J. Soil and Water Conserv. 20:150-152.

52. Wong, J. 1967. Behaviour of soil beneath rigid wheels. J. Ag. Eng. Res. 12:257-269.