



112
253
THS

A STUDY OF EVAPORATION LOSSES FROM SANDY
LOAM AND SANDY CLAY LOAM SOILS

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY

You-tsai Hung

1964

THESIS

27



LIBRARY
Michigan State
University



RETURNING MATERIALS:

Place in book drop to
remove this checkout from
your record. FINES will
be charged if book is
returned after the date
stamped below.

13 MAY 1964

ROOM USE ONLY

A STUDY OF EVAPORATION LOSSES
FROM SANDY LOAM AND SANDY CLAY LOAM SOILS

by

You-tsai Hung

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1964

ABSTRACT

The objective of this preliminary study using a closed chamber to control temperature, relative humidity, wind velocity and using a tension table to control soil moisture to determine evaporation losses from sandy clay loam and sandy loam soil was intended to find the effects of soil moisture and soil type on evaporation. The equations derived from this laboratory test chamber study were fairly adaptable to the physical characteristics of the variables. The formulas were not assumed to be used in practical problems. However, they showed that both soil moisture factor and soil type factor would exert significant effects on evaporation and play an important role in the process of evaporation.

Two equations of evaporation from soil in terms of air temperature, wind velocity vapor pressure deficit and soil moisture and two equations of evaporation from soil in terms of air temperature, wind velocity, vapor pressure deficit and soil tension for sandy clay loam and sandy loam soil were derived from the results of this experiment.

The equations based on soil moisture for sandy clay loam and sandy loam soil were:

(1). For sandy clay loam soil;

$$E = C_{tc} C_{wc} C_{hc} C_{sc} \dots \dots \dots (1)$$

where

E is the evaporation from the soil in inches per day

$C_{tc} = 0.209 - 0.004 T + 0.000033 T^2$; C_{tc} is the subcoefficient of air temperature, T is the temperature of the overrunning air in $^{\circ}\text{F}$

$C_{wc} = 0.559 + 0.443 W + 0.000805 W^2$; C_{wc} is the subcoefficient of wind, W is the velocity of overrunning air in feet per second

$C_{hc} = 0.8233 - 0.1029(e_s - e) + 1.706(e_s - e)^2$; C_{hc} is the subcoefficient of vapor pressure deficit, $(e_s - e)^2$; C_{hc} is the vapor pressure deficit at a given overrunning air temperature in pound per square inch

$C_{sc} = 2.2791 - 0.2395 S + 0.00666 S^2$; C_{sc} is the subcoefficient of soil moisture, S is moisture in the soil expressed by percentage of moisture on oven-dry basis.

(2). For sandy loam soil;

$$E = C_{ts} C_{ws} C_{hs} C_{ss} \dots \dots \dots (2)$$

where

E is the evaporation from the soil in inches per day

$$C_{ts} = 0.133 - 0.00226 T + 0.0000349 T^2$$

$$C_{ws} = 0.599 + 0.0809 W - 0.00297 W^2$$

$$C_{hs} = 0.726 + 1.3401(e_s - e) + 0.4706(e_s - e)^2$$

$$C_{ss} = 1.013 - 0.0647 S + 0.00371 S^2$$

Except the second subscript "s" of the subcoefficient was used to distinguish sandy loam from sandy clay loam, the other symbols had the same explanation as used in equation(1).

The equations based on soil tension for sandy clay loam and sandy

loam soils were;

(3). For sandy clay loam soil;

$$E = C_{tc} C_{wc} C_{hc} C_{Tc} \dots \dots \dots (3)$$

where

E is the evaporation from the soil in inches per day

C_{tc} , C_{wc} and C_{hc} are equivalent to the values of C_{tc} , C_{wc} and C_{hc} in equation(1)

$C_{Tc} = 2.281 - 0.0803 T_{en} + 0.000225 T_{en}^2$; C_{Tc} is the subcoefficient of tension, T_{en} is tension in centimeters.

(4). For sandy loam soil;

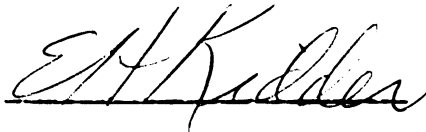
$$E = C_{ts} C_{ws} C_{hs} C_{Ts} \dots \dots \dots (4)$$

where

E is the evaporation from the soil in inches per day

C_{ts} , C_{ws} and C_{hs} are equivalent to the values of C_{ts} , C_{ws} and C_{hs} in equation(2)

$C_{Ts} = 1.515 - 0.02658 T_{en} + 0.000225 T_{en}^2$; C_{Ts} is tension in centimeters.

Approved by 

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Professor Ernest H. Kidder of the Agricultural Engineering Department under whose guidance, supervision, and unfailing interest this work was done.

The author is especially indebted to the Agency For International Development for the graduate research and financial aid that made this research possible.

The author also wishes to express his sincere gratitude to Dr. Frederick H. Buelow, Mr. Clarence M. Hansen and Mr. R. Z. Wheaton of the Agricultural Engineering Department for their criticisms and comments.

Grateful acknowledgement is also extended to Dr. A. Earl Erickson and Mr. Curtis D. Piper of the Soil Science Department for their frequent assistance.

Appreciation is extended to Messrs. James B. Cawood and all other friends who provided valuable aid during the investigation.

The author also is indebted to his wife, Yueh-chin who has been taking care of their two children in Taiwan and encouraged him to establish his research work.

TABLE OF CONTENTS

Section	Page
INTRODUCTION	1
REVIEW OF LITERATURE	3
DESIGN OF EXPERIMENT	10
APPARATUS	13
EXPERIMENTAL PROCEDURE	21
DISCUSSION OF RESULTS	23
CONCLUSIONS	35
LITERATURE CITED	37
APPENDIX	39

LIST OF FIGURES

Figure	Page
1. Schematic diagram of test apparatus	14
2. Soil samples	16
3. Soil moisture control system	16
4. Humidity control system	17
5. Air speed control system	19
6. Temperature control system	19
7. Temperature vs. evaporation	25
8. The ratios of E_c/C_{tc} and E_s/C_{ts} vs. wind velocity	26
9. The ratios of $E_c/C_{tc}C_{wc}$ and $E_s/C_{ts}C_{ws}$ vs. vapor pressure deficit	28
10. The ratios of $E_c/C_{tc}C_{wc}C_{hc}$ and $E_s/C_{ts}C_{ws}C_{hs}$ vs. soil moisture.	30
11. The ratios of $E_c/C_{tc}C_{wc}C_{hc}$ and $E_s/C_{ts}C_{ws}C_{hs}$ vs. tension	32

INTRODUCTION

The consumption of heat from the sun in the evaporation of moisture from land and water surfaces and in the transpiration of soil moisture by vegetation is the process by which precipitated water is returned again to the earth's atmosphere as vapor to perpetuate the hydrologic cycle.

Evaporation is the process by which water is changed from the liquid or the solid state into the gaseous state through the transfer of heat energy.

The study of evaporation from soil has important applications in the field of irrigation. The complex nature of the relating factors of temperature, vapor pressure deficit, wind velocity, solar radiation, type of soil and soil moisture produces a very difficult problem. In particular the variation of soil moisture and the soil type are phases of this study which seems to have been wholly neglected by previous researchers. Most researchers are concerned with the evaporation from the free water surface. Therefore it was not possible to find a formula which included soil moisture and soil type factors which must be taken into consideration.

Since it was apparent that work had not been done on the effects of soil moisture and type of soil on soil moisture loss, a study to investigate these factors was proposed. This study had the following objectives:

1. Construct a suitable test chamber which would enable control of air temperature, relative humidity and wind velocity.
2. Construct two tension tables for maintenance of tensions which would make possible the control of the moisture content in soil samples.
3. Determine suitable equations from experimental results to predict evaporation from soil on the basis of soil moisture, soil tension and soil type in addition to the factors previously studied.

It was known from previous studies that the factors affecting evaporation had linear combination, therefore the expected equations based on soil moisture and soil tension for these factors were assumed to be:

$$E = C_t C_w C_h C_s \dots \dots \dots (1)$$

$$E = C_t C_w C_h C_T \dots \dots \dots (2)$$

where

E is evaporation in inches per day

C_t is the subcoefficient of air temperature

C_w is the subcoefficient of wind velocity

C_h is the subcoefficient of vapor pressure deficit, which is expressed by $(e_s - e)$

e_s is the saturated vapor pressure at a given temperature

e is the actual vapor pressure at the given temperature

C_s is the subcoefficient of soil moisture

C_T is the subcoefficient of soil tension.

REVIEW OF LITERATURE

Reports on evaporation and evapotranspiration in the literature are extensive. Robinson and Johnson's compilation of the literature for the period 1800 to 1958 was published by U.S. Geological Survey in 1961. Christiansen and Lauritzen(1963) compiled a bibliography of 225 publications with emphasis on recent publications.

The methods used in investigating evaporation from lakes or reservoirs fall into four categories: 1. The "water budget determinations of evaporation". This approach is simple in theory, but application rarely produces reliable results since all errors in measuring outflow, inflow, and change in storage are reflected directly in the computed evaporation. 2. The "energy-budget determination of evaporation". This approach like the water budget, employs a continuity equation and solves for evaporation as the residual required to maintain a balance. Application of the energy budget has been attempted by numerous investigators, with cases selected so as to minimize the effect of terms that could not be evaluated. The principal limitation of this approach is the lack of sufficient climatological measurements in most localities. Only a few climatological stations record the needed solar energy data. The formula, even though quite reliable, has serious practical limitations. 3. The "mass-transfer determinations of evaporation"; The theoretical development of turbulent-transport equations has followed two basic approaches, the discontinuous, or mixing length and continuous mixing concepts. The

derived formulas are according to the differences of wind and vapor pressure at two levels near the surface. This method is simpler and can utilize readily available climatological data. Thornthwaite(1955) theorized that temperature was a good index to energy in a zone of essential equilibrium. In essence, the procedure developed by Thornthwaite has the same limitations regarding areas of application as energy budget, It applies quite well to humid, well-vegetated areas. Increased errors are observed in arid, low-humidity regions. 4. The "estimation of evaporation from pan evaporation and related meteorological data"; The pan is the most widely used evaporation instrument today. Its application in hydrologic design and operation is of long standing. Several authors have developed pan coefficients to transform pan evaporation to lake evaporation.

Mann(1871) concluded that evaporation from a free water surface depends almost wholly on three factors; 1. The area of the water surface, 2. The temperature of the water at its surface, 3. Vapor pressure of water in the air above the water. Fortier(1907) stated that the factors having the greatest influence on evaporation from soils are the quantity of water in the top soil, the temperature of the soil and air movement. Fukuda(1955, 1956) studied the effect of wind on soil. He reported that the soil depth to which air can penetrate as a result of wind gustiness is very slight. Even in sandy soils the particles of which have a mean diameter of 0.5 - 0.25 mm, the wind penetrates only about 5 mm below the surface. Staple(1956) suggested that computation of evaporation must be stepwise process involving the calculation, in short time intervals, of

both the changing moisture profiles in the drying soil and the resulting evaporation at the surface. Onchukov(1957) concluded that evaporation should not occur below 25 cm but that extensive evaporation occurs within 5 cm of the soil surface. Richards et al.(1956) reported that vapor transfer was agriculturally insignificant below the 15 cm depth. Peterson(1959) found that maximal evaporation occurred at a depth 1/2 to 1 inch below the soil surface.

Evaporation formulas

The fundamental law of evaporation from a free water surface was enunciated by Dalton in 1882. He stated that if the actual vapor pressure of the air above the water is less than that at the water surface, then evaporation will occur. Several empirical equations to estimate evaporation are based on Dalton's law. It may be written as:

$$E = (e_0 - e_a) f(U)$$

where

E is the evaporation in a unit of time

e_0 is the vapor pressure of the evaporating surface

e_a is the vapor pressure in the atmosphere

$f(U)$ is a function of the wind velocity that can be of the

form $-a + b u$, or $c u^n$ where a , b , c and n are constants.

Meyer(1942) suggested a formula for estimating evaporation from a lake which can be expressed by the equation:

$$E = c(e_s - e_a)(1 + \frac{V}{10})$$

where

E is evaporation in inches per day

e_s is the vapor pressure of the water surface(in. of Hg)
 e_a is the vapor pressure of the overrunning air(in. of Hg)
 v is the wind speed (mph) about 25 ft above the surface
 c is the coefficient (about 0.36 when the formula is applied to daily data for an ordinary lake).

Edney(1957) expressed it as:

$$E = K(P_o - P_a)$$

where

E is the rate of evaporation

K is a proportionality "constant"

P_o is the partial pressure of water vapor in air saturated at temperature of the surface

P_a is the partial pressure of water vapor in air a short distance away from the surface.

Rohwer(1931) working at Fort Collins, Colorado, proposed an equation of the form:

$$E = (1.465 - 0.0186 B)(0.44 + 0.118 W)(e_o - e_a)$$

where

B is the barometric pressure in inches of mercury at 32°F

W is the wind velocity near the ground in miles per hour.

Perran(1948) proposed a formula in England:

$$E_o = 0.35(1 + 9.8 \times 10^{-3} U_2)(e_o - e_a)$$

where

E_o is the evaporation in millimeters per day

U_2 is the wind velocity in miles per day measured 2 meters

above the surface.

In investigating evaporation from shallow lakes near Ogden, Utah, Christiansen(1960) derived a formula, which can be expressed by the equation:

$$E = K C R$$

where

E is the evaporation (or evapotranspiration)

K is the dimensionless constant

R is the extraterrestrial radiation that is received at the outer surface of the atmosphere expressed as an equivalent depth of evaporation in the same units of E

C is a dimensionless coefficient that is the product of several subcoefficients, each one a function of climatic and related factors that affect evaporation.

The value of the coefficient C in the above equation is:

$$C = C_T C_W C_S C_H C_E C_L C_M$$

where

C_T is the subcoefficient of temperature

C_W is the subcoefficient of wind

C_S is the subcoefficient of sunshine percentage

C_H is the subcoefficient of humidity

C_E is the subcoefficient of elevation

C_L is the subcoefficient of latitude

C_M is the subcoefficient of month

Linear equations were found for the subcoefficients C_T , C_W , C_S ,

C_M and mean values were found for the monthly coefficient C_M .

A further study in determining the subcoefficients was conducted by Mathison(1963) in Utah. He used data from 40 weather stations scattered throughout the western United States and proposed a formula for computing evaporation from a Standard Weather Bureau Class A pan:

$$E = C_C C_T C_W C_{\Delta T} C_S C_E$$

where

E is the evaporation in inches per month

$$C_C = C_R C_{\cos(L - D)} C_M$$

C_R is the coefficient of radiation, where $C_R = 0.20 R + 0.015 R^2$;

R is radiation in inches water

$C_{\cos(L - D)}$ is the cosine of the latitude minus the declination coefficient, where $C_{\cos(L - D)} = 1.16 + 0.42 \cos(L - D) - 0.7 \cos^2(L - D)$ in which L and D are the latitude and the declination

C_M is the monthly coefficient, where $C_M = 1 + 0.00155(L - D) \cos(N + 1)$ in which N is the number of month

$C_T = -0.26 + 0.03425 T - 0.000075 T^2$, where T is air temperature

$C_W = 0.8 + 0.0035 W - 0.0000027 W^2$, where W is wind velocity in miles per day

$C_{\Delta T} = 0.45 + 9.6 \times 10^{-4} \Delta T^2 - 2.76 \times 10^{-7} \Delta T^4$, where ΔT is the difference in average maximum and minimum temperature for the month

$C_S = 0.622 + 0.005875 S - 0.000011 S^2$, where S is the sunshine

percentage

$C_E = 0.967 + 0.35 E - 0.00156 E^2$, where E is the elevation in thousands of feet.

Pan evaporation

The U.S. Weather Bureau Class A evaporation pan is widely used in the United States. Records were published for 350 stations in 1956. Pan coefficient is defined as a ratio of lake evaporation to pan evaporation. Mean annual USWB Class A pan coefficients range from 0.81 at Lake Okeechobee to 0.60 at Lake Mead(Linsley, Ray K. Jr. and Max A. Kohler and Joseph L. H. Paulhus, 1958). The subcommittee on evaporation of the special committee on Irrigation Hydraulics of the American Society of Civil Engineers, adopted 0.70 as a ratio of the annual evaporation from a USWB Class A pan to that from a reservoir. This value would result in a maximum difference of 12 percent from 0.81 at Lake Okeechobee. Young(1942) reported that Lake Elsinore has an average annual coefficient of 0.77 for the Class A pan, but the monthly coefficient varied from 0.63 in February to 0.97 in November. A summary of pan coefficients (Lake-to-pan ratios) has been published(Linsley, Ray K. Jr. and Max A. Kohler and Joseph L. H. Paulhus, 1958).

DESIGN OF EXPERIMENT

In order to meet the objectives of this study, it was necessary to evaluate the factors of temperature, relative humidity, wind velocity and soil moisture in a closed chamber. The factors of elevation and latitude were kept constant since all tests were conducted in the same place. Since the test chamber was closed, the factors of radiation or sunshine and monthly variations were eliminated.

From the literature survey it was concluded that the factors influencing evaporation from soil, except soil moisture, were limiting only within a thin top soil layer. In order to eliminate the nonuniform vertical distribution of soil moisture it was decided to use a thin layer of soil and conduct an experiment in which the soil moisture and soil type factors were taken into consideration. The only factors considered in this experiment were temperature, relative humidity, wind velocity, soil moisture and soil type. Each of the variables was controlled separately in order to obtain various combinations of treatments.

Environmental variables

The temperature levels consisted of three average values of 60°F, 75°F and 95°F. The relative humidity ranged from about 20 to 95 percent. Three wind velocities of 0, 8 and 16 feet per second were used. Soil moisture was varied to three levels by soil tensions of 0, 27.5 and 45 cm. Two soil types were used.

The treatments of these variables were arranged so as to have all possible combinations of factors. The combinations of the treatments are listed in Table 1.

Table 1. Combinations of treatments

Temperature (° F)	Relative humidity (%)	Wind velocity (ft/sec)	Soil moisture (Expressed by tension in cm)	Types of soil
60	20	0	0	Sandy clay loam
75	60	8	27.5	
95	95	16	45	
				Sandy loam

From Table 1, it was apparent that 162 combinations of the treatments must be evaluated. Each combination had three replications. A total of 486 observations were made.

Soil samples

In order to compare the effects of two soil types and to eliminate the errors due to the effects of different operating conditions, it was decided to run the two soil types at the same operating conditions during the test. The moisture content of the two soil types was controlled by tension tables.

The soils were taken from locations on the Michigan State University farm. Mechanical composition was determined by the hydrometer method. Mechanical composition, bulk densities and saturated moisture are listed in Table 2.

Table 2. Properties of two soil samples

	Mechanical composition			Bulk density	Saturated moisture (%)
	Sand (%)	Silt (%)	Clay (%)		
Sandy loam	66	19	15	1.412	23.27
Sandy clay loam	48	28	24	1.314	35.87

APPARATUS

Test chamber

In order to control the factors affecting evaporation from soils, a closed test chamber was constructed in the Land Development Laboratory in the Department of the Agricultural Engineering, Michigan State University. The chamber was 8 feet high, 8 feet wide and 3 feet deep (Fig. 1). The walls of chamber consisted of $1/4$ inch plywood inside and outside with 2 inches of glass wool insulation in between. Four doors were set in the front face of the chamber to handle and check the salt solution, heat exchanger and soil samples.

Soil samples

Two sample boxes 1 foot long, 6 inches wide and 2 inches deep were constructed of $3/8$ inch plastic. Two samples were placed side by side with the greatest dimension parallel to the direction of air flow at the top portion of the chamber (Fig. 1 and Fig. 2). The required tension was established prior to filling the sample box. The box had a $1/4$ inch hole in the middle of the bottom and was connected by a $1/4$ inch tube to a glass bottle (Fig. 3). The box was cleaned with soap and distilled water. The next step was to fill the box and the plastic tube with distilled water. The tube was clamped. A mesh screen 4 inches long, 2 inches wide was put in the middle bottom of the box, then three layers of blotting paper were placed on the screen. In order to prevent air from

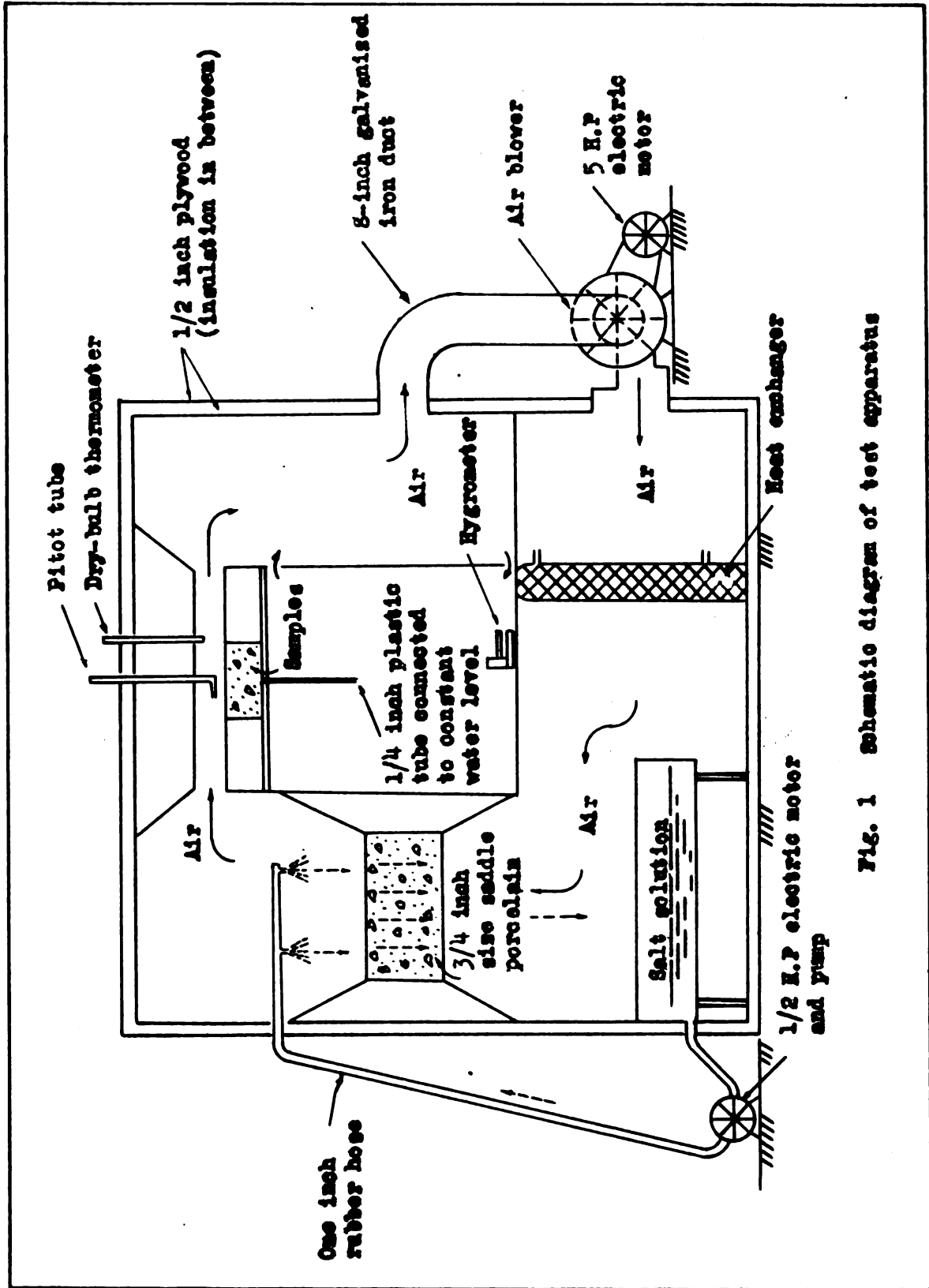


Fig. 1 Schematic diagram of test apparatus

coming in at the edges of the paper, four plastic strips were used to press down these edges. The box was raised above the glass bottle about one foot, then the clamp was loosened to drain the water until it reached one foot of tension. This unit was observed for at least 6 hours to determine whether the tension would hold. The disturbed soil sample was uniformly placed on the blotting paper up to the top of the box.

Soil moisture control

The moisture content of the soil samples was controlled by different tensions. The tensions were measured by the difference of water heads between the soil and the free water surfaces which were controlled by a glass bottle mounted on the front face of the chamber(Fig. 3). The bottle was filled with distilled water and a $1/4$ inch diameter tube was connected to the bottom of the sample. In order to maintain constant water level in the bottle it was necessary to have an automatic water surface control device. A one foot long, one inch diameter cylinder with its top sealed with a rubber plug was used for this function. A $1/4$ inch diameter glass tube with both ends open was inserted from the rubber plug to one inch from the bottom of the cylinder. The top end was exposed to atmosphere and the lower end was immersed in the water in the cylinder. A second $1/4$ inch plastic tube was connected from the bottom of the cylinder to the glass bottle in order to keep water supply continuous. The cylinder was movable so that the lower end of the glass tube could be adjusted at the same level as the water surface in the glass bottle. Since there were two soil samples, two sets of the above equipment were prepared.

Graduations of $1/5$ c.c. were placed on the side of the cylinder.

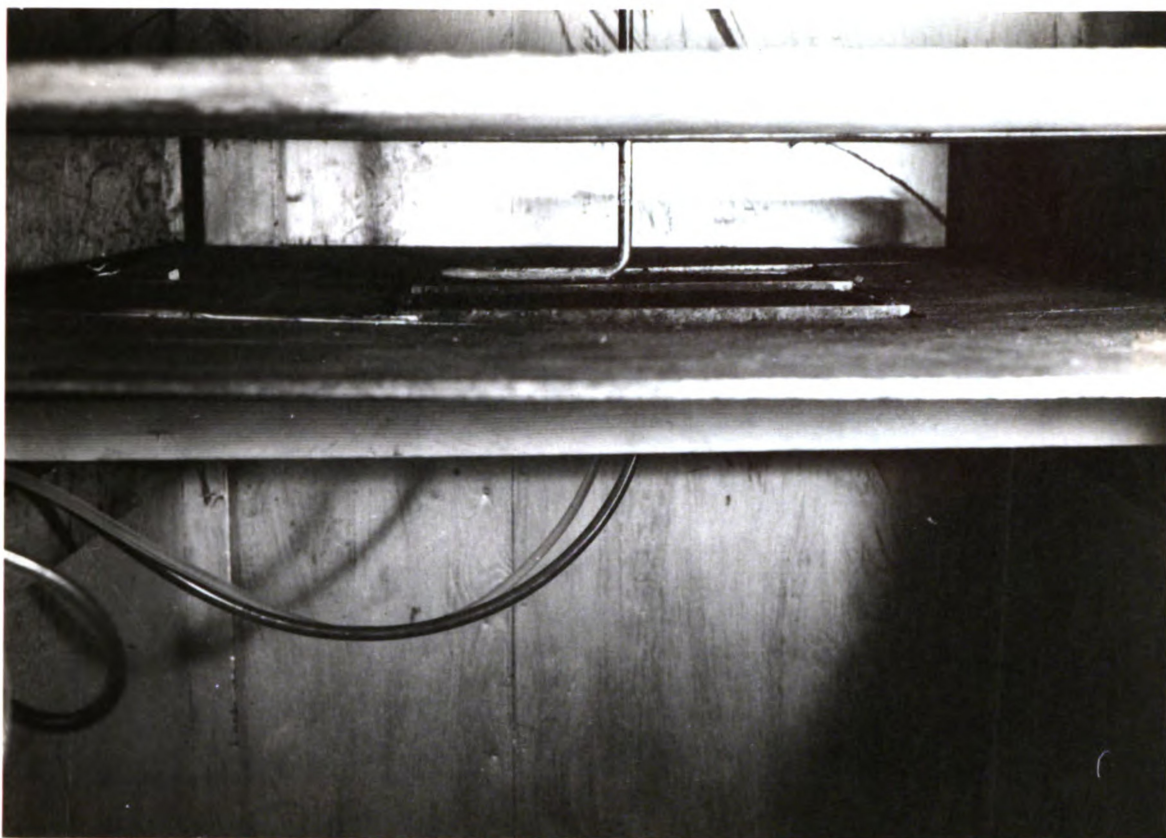


Fig. 2 Soil samples



Fig. 3 Soil moisture control system

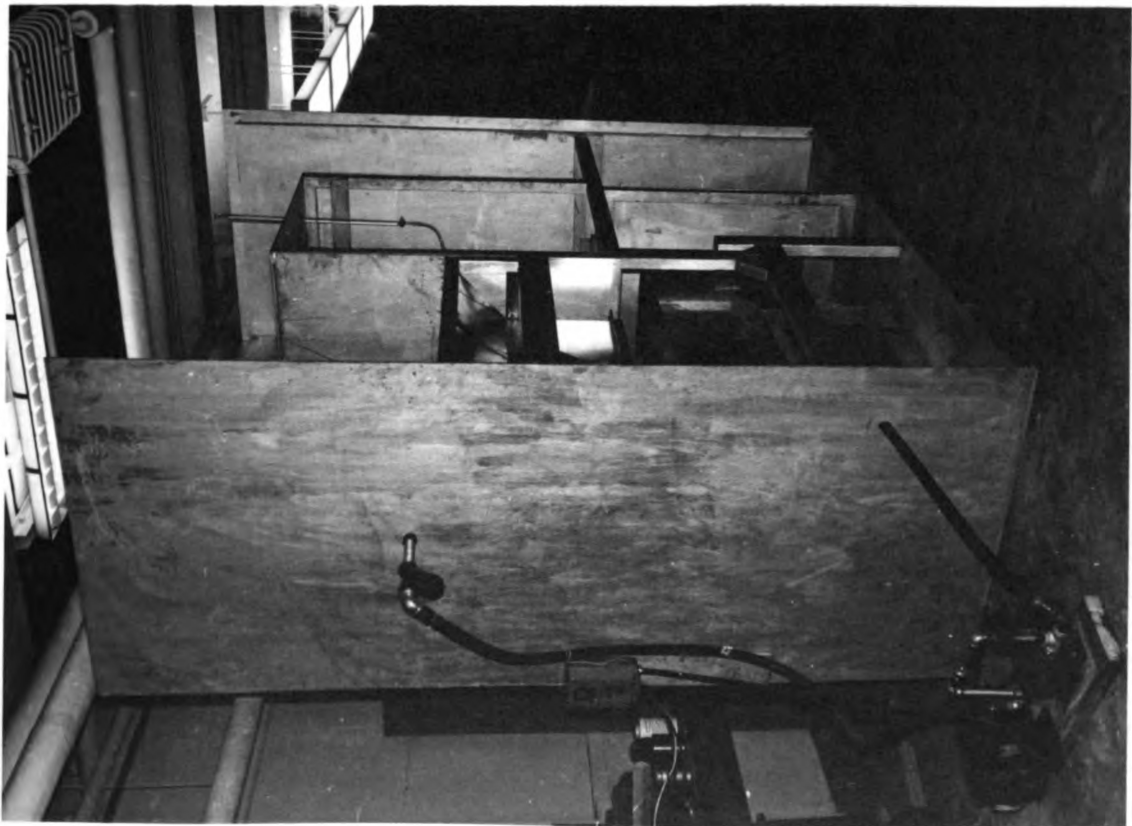
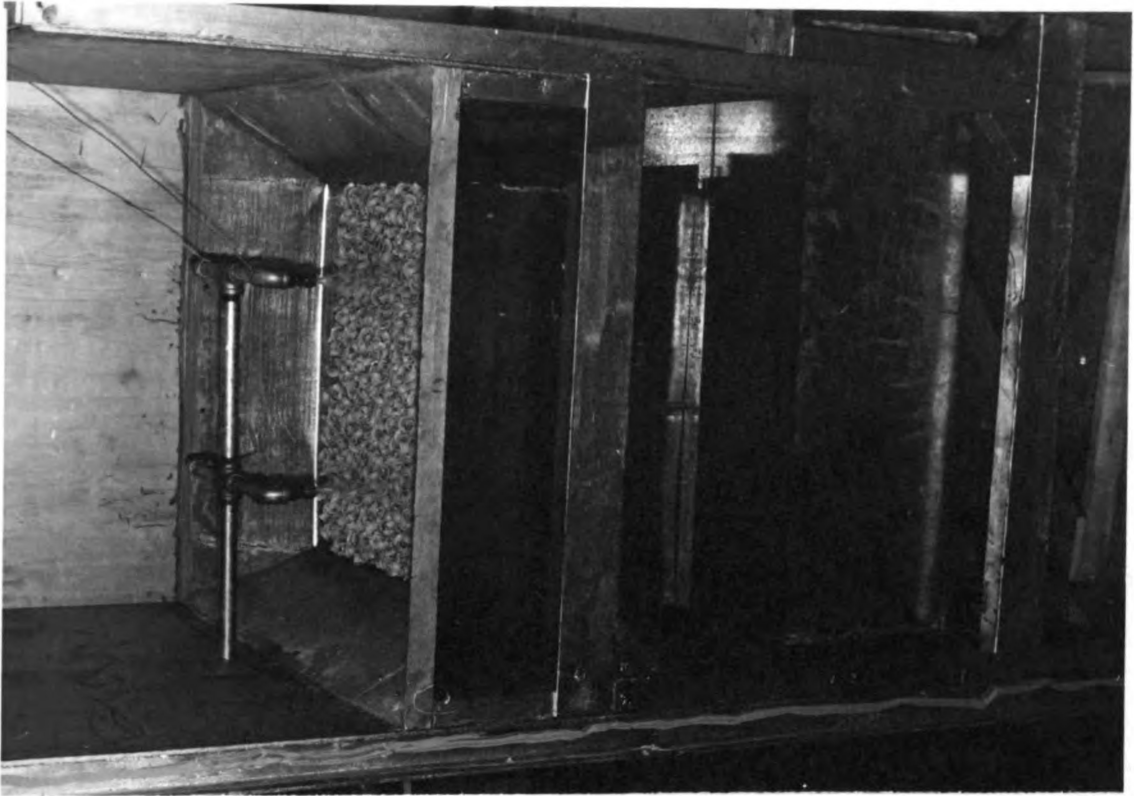


Fig. 4 Humidity control system

The water lost from two samples was measured here.

The moisture contents in the soil samples for various tension levels were measured by taking small samples from the soils.

Humidity control

Three saturated salt solutions were prepared to control the humidity in the chamber. Lithium chloride, magnesium nitrate and potassium nitrate were used to supply low, medium and high humidity respectively. Saddle porcelain of 3/4 inch size was used for a contact area between the salt solution and the air coming in from the air blower in order to obtain the desired humidity.

A container 2 feet long, 2 feet wide and 1 foot deep having a screen at its bottom was placed in the left central side of the chamber. This container was filled with saddle porcelain(Fig. 1). A tank 3 feet long, 2.5 feet wide and 6 inches deep was placed under the container to catch the salt solution. The solution was circulated by a pump equipped with a 1/2 hp electric motor through a one inch rubber hose and sprayed by four nozzles onto the saddle porcelain(Fig. 1 and Fig. 4).

An automatic recording hygrometer was placed below the soil samples.

Air speed control

The air flow passing over the soil samples was controlled by an air blower. It was placed at the right hand side of the chamber. An 8 inch diameter pipe covered with glass wool insulation connected the blower to the top and to the bottom of the chamber to circulate the air(Fig. 1 and Fig. 5). The blower speed was regulated to control the air

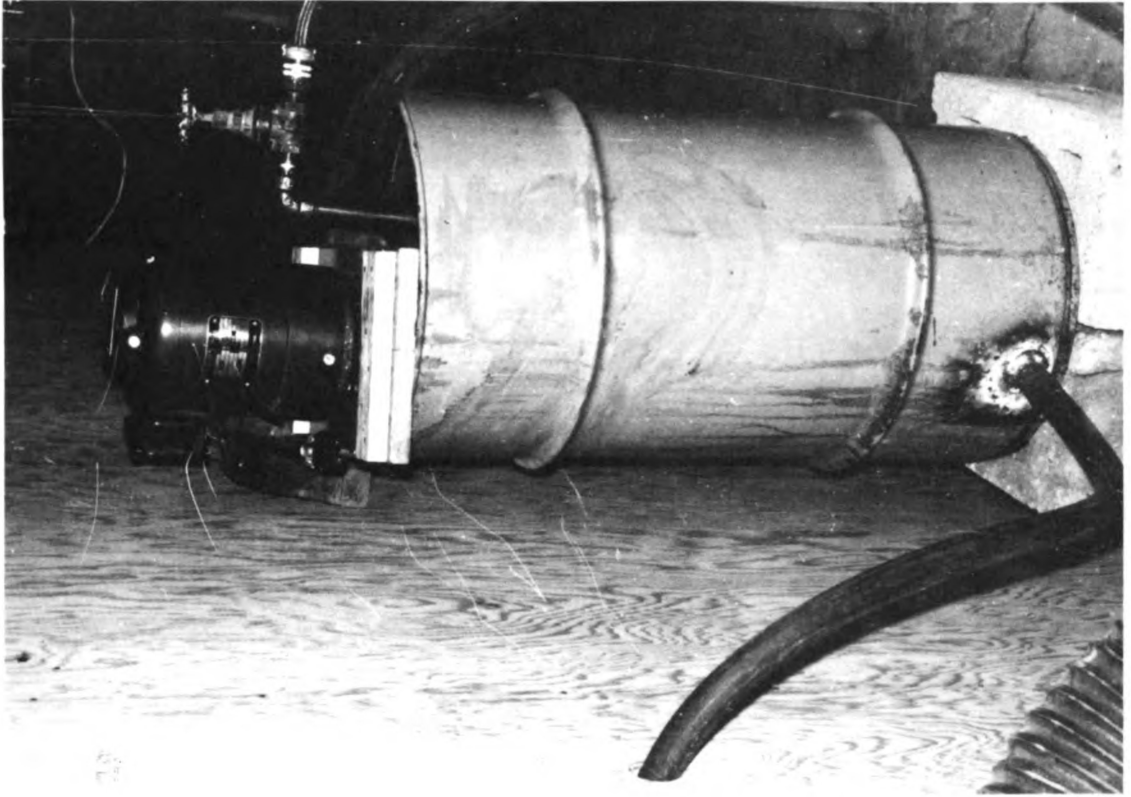


Fig. 6 Temperature control system

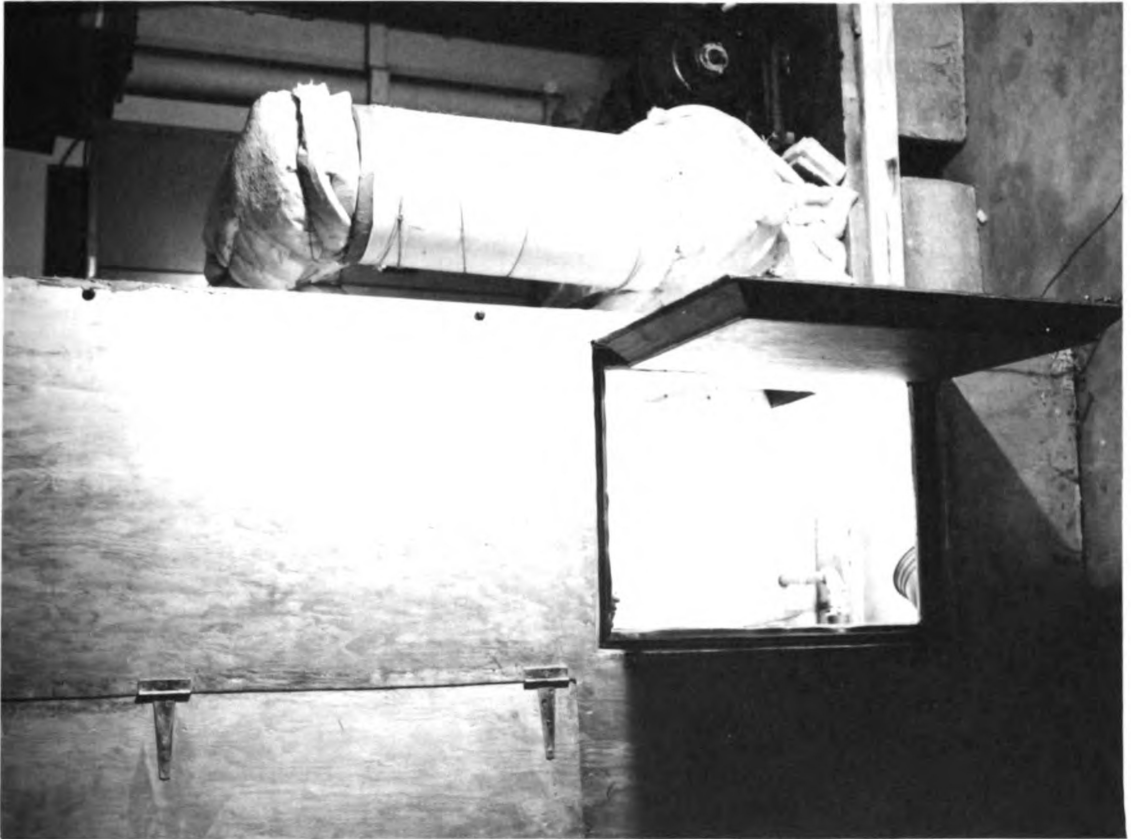


Fig. 5 Air speed control system

speed.

A pitot tube was inserted from the top center of the chamber near the surface of the samples to measure air velocity over the soil samples (Fig. 1).

Temperature control

A tank filled with water and a heat exchanger were prepared to control the temperature in the chamber. The temperature in the tank was adjusted by putting ice, running cool or hot water through the water in the tank. The heat exchanger was placed 2 feet away from the outlet of the air blower. It was connected to the pump and tank by a one inch pipe (Fig. 6).

The air temperature in the chamber was measured with a glass bulb thermometer inserted from the top of the chamber and close to the surface of the two soil samples (Fig. 1). It was checked by the above mentioned recording hygrometer. The soil samples were so small that the temperature of the soil was essentially controlled by the temperature of the chamber.

EXPERIMENTAL PROCEDURE

The first variable to be controlled in the chamber was humidity. Three levels of soil tensions were set to correspond to the controlled humidity. Temperatures and air velocities were changed and set so as to meet the required combinations of the treatments. While humidity was changed, the same procedure for tension, temperature and air velocity was repeated.

During the test, while tension was changed, the time needed for the tension to reach equilibrium was about 24 hours. It was also necessary to run the whole system of the chamber for two hours to obtain the desired conditions for each day's test. All test runs were for 30 minutes. The readings for 3 replications were taken when each combination of the treatments was being conducted.

Evaporation losses from the two soil samples were measured by the water lost in cubic centimeters from the cylinders which were mounted on the front face of the chamber(Fig. 3). The loss readings were converted into inches per day. The correction of the error of the lost water volume due to the glass tube in the cylinder was also made.

The temperatures of the air overrunning the samples were measured by the glass bulb thermometer. The temperatures in the samples were also measured at the end of every treatment. It was found that the temperatures in the soils were the same as in the air.

Wind velocities passing over the samples were measured by the pitot

tube in feet per second. Three wind velocities of 0, 8 and 16 feet per second were controlled by the air blower.

Relative humidities were measured by hygrometer and were converted into vapor pressure deficit in pound per square inch by using Psychrometric Charts prepared by the American Society of Agricultural Engineers. Since there was some chamber leakage, it was difficult to control the low and the high humidities. The saturated lithium chloride solution only brought the humidity down to 27 percent of relative humidity. The highest relative humidity varied a small amount during the test. The saturated lithium chloride solution lost its ability to control the humidity while the tests at zero tension were being conducted. The relative humidity for the experiment on zero tension controlled by the saturated lithium chloride solution was found to be around 40 - 50 percent.

The moisture content of the soil samples was controlled by various tensions. The soil moisture for each tension was determined by taking small soil samples from the soils. It was expressed by percentage on oven-dry basis.

DISCUSSION OF RESULTS

Presentation of data

Each value of evaporation for 81 combinations was obtained by taking the average value of three replications. The mean low, medium and high temperatures of 61.9°F, 76.0°F and 95.8°F of over all observations were found. Three values of wind velocities(0, 8 and 16 feet per second) were obtained. Since the humidities found from the experiment were so scattered, it was almost impossible to get three average values close to the designed values. Five average values of 0.638, 0.154, 0.252, 0.342 and 0.408 pound per square inch of vapor pressure deficit for the ranges 0.035 - 0.09, 0.10 - 0.19, 0.20 - 0.29, 0.30 - 0.39 and 0.40 - 0.57 were found and the method of least squares was used to find the best-fit curves and the equations of the subcoefficient of vapor pressure deficit. Soil moistures obtained from three tensions were fairly stable. The average values of moisture content for 0, 27.5 and 45 cm of tension were 35.87, 27.22 and 11.61 percent for sandy clay loam and 23.27, 16.49 and 9.71 percent for sandy loam soil respectively.

Procedure to find the coefficients

For determination of the formula presented here, 81 average values of evaporation for both sandy clay loam and sandy loam soils, three average values of temperature, three average values of wind velocity, five average values of vapor pressure deficit, three average values of moisture for both sandy clay loam and sandy loam soil and three tensions

were used to plot the curves and to find the equations of the subcoefficient.

1. Temperature coefficient:

The first coefficient found was C_{tc} and C_{ts} . All data of evaporation were grouped in 3 lots of 27 according to low, medium and high temperatures (61.9°F, 76.0°F and 95.8°F) to find average values. The equations for the curves were found to be (Fig. 7):

$$C_{tc} = 0.209 - 0.004 T + 0.000033 T^2$$

$$C_{ts} = 0.133 - 0.00226 T + 0.0000349 T^2$$

where

C_{tc} is the subcoefficient of air temperature for sandy clay
loam soil

C_{ts} is the subcoefficient of air temperature for sandy loam
soil

T is the temperature of overrunning air in °F.

From Fig. 7, it was obvious that the effect of air temperature on evaporation for the sandy loam soil was greater than that for the sandy clay loam soil. As the temperature of the air increased, more rapid increase of evaporation occurred in the sandy loam soil. It was also found that the effect of temperature on evaporation from the sandy clay loam soil was less if the temperature of air was less than 75°F.

The next step was to divide values of E (evaporation) of each of 81 average values by calculated values of C_{tc} and C_{ts} respectively to eliminate the effect of air temperature.

2. Wind velocity coefficient:

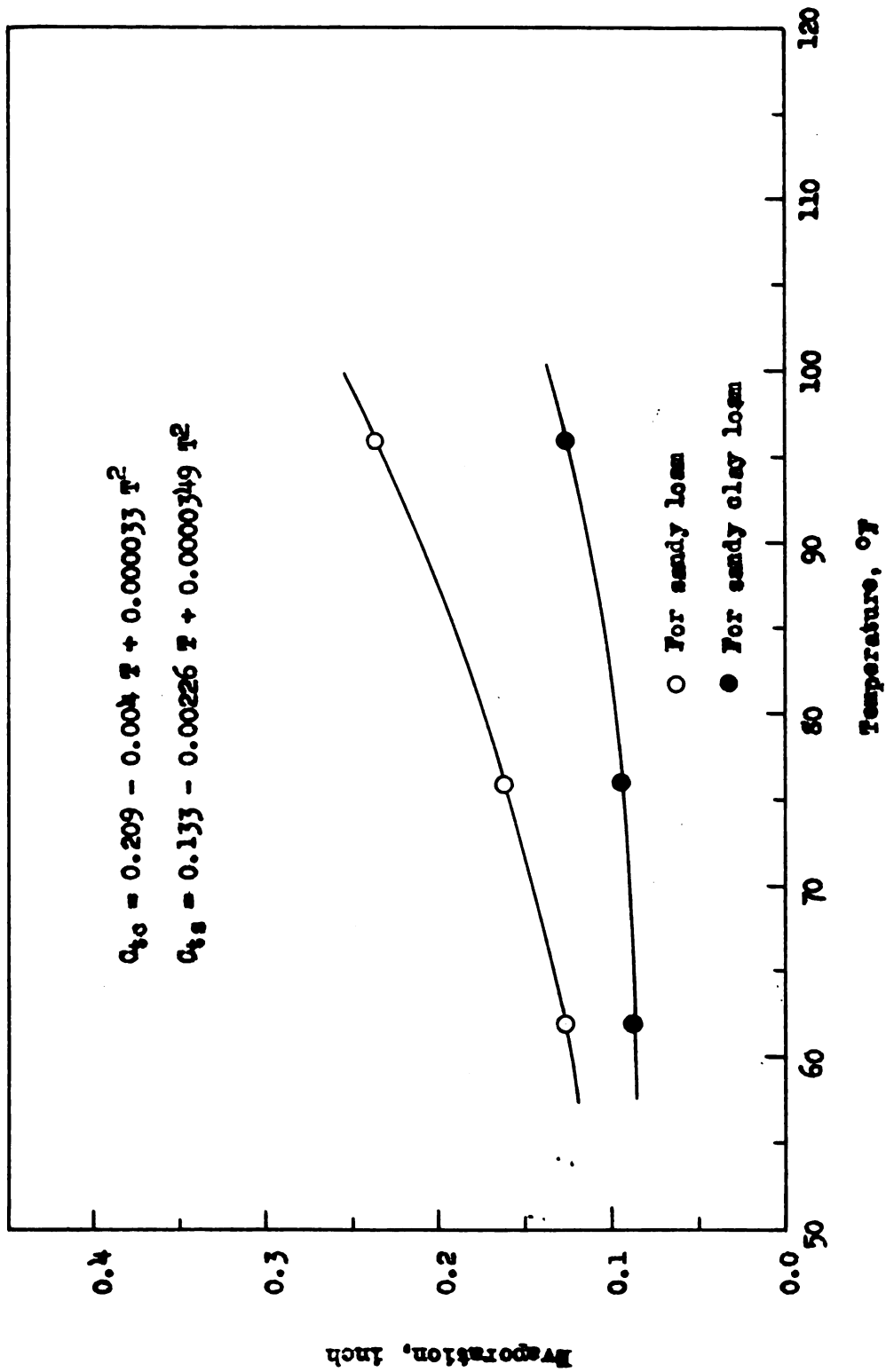


Fig. 7 Temperature vs. evaporation

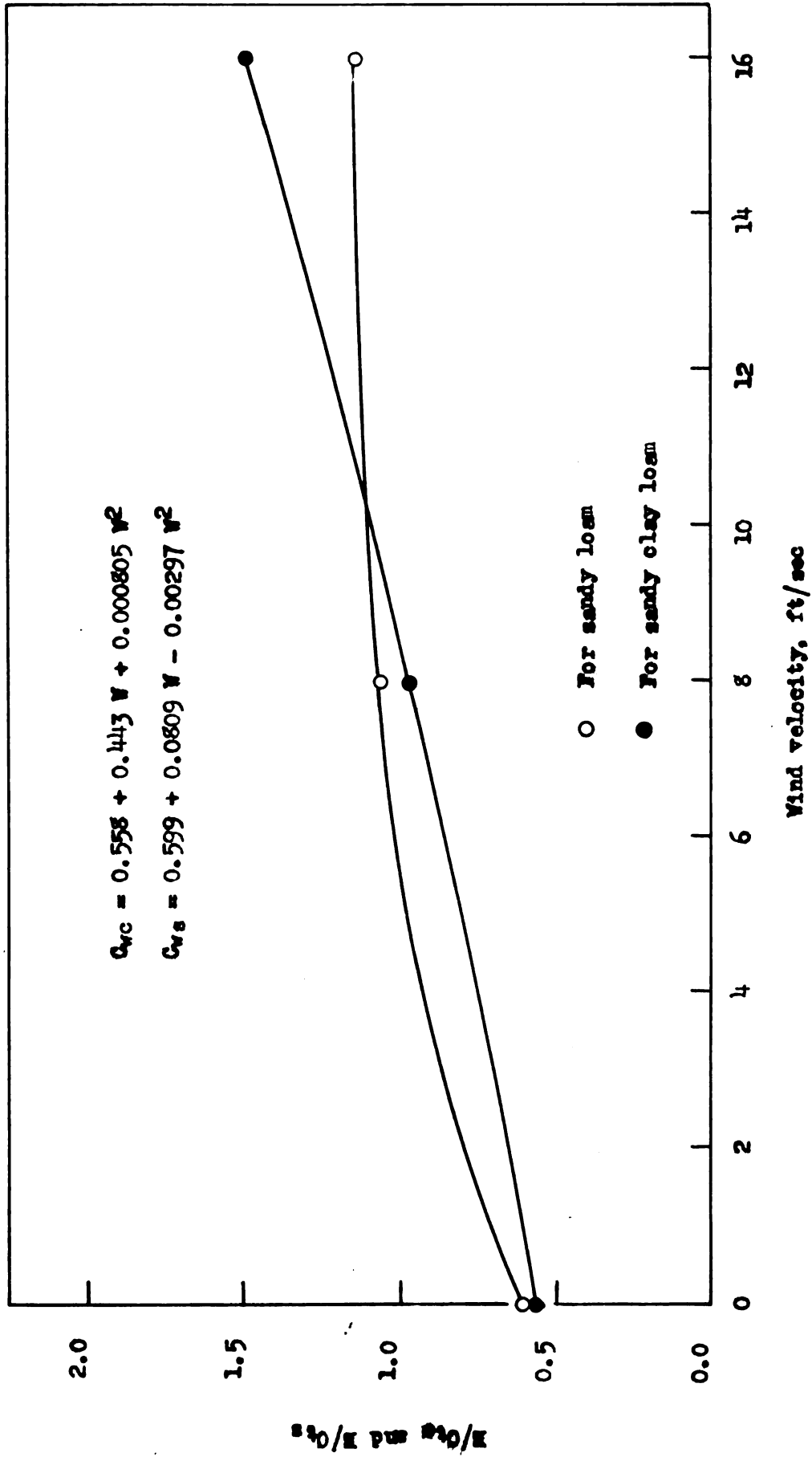


Fig. 8 The ratios of H/C_{t0} and H/C_{ts} vs. wind velocity

The second step was to arrange all data according to wind velocities (0, 8 and 16 feet per second) into 3 lots of 27 to find average values of E_c/C_{tc} and E_s/C_{ts} for each lot. The values of 3 points for sandy clay loam and sandy loam soils were plotted and equations for the curves were found (Fig. 8):

$$C_{wc} = E_c/C_{tc} = 0.558 + 0.443 W + 0.000805 W^2$$

$$C_{ws} = E_s/C_{ts} = 0.599 + 0.0809 W + 0.00297 W^2$$

where

C_{wc} is the subcoefficient of wind for sandy clay loam soil

C_{ws} is the subcoefficient of wind for sandy loam soil

W is the wind velocity near the surface of the soil

Fig. 8 showed that the effect of wind on evaporation for the sandy loam was greater than that for the sandy clay loam when the wind velocity was less than 10 feet per second, but the reverse phenomenon was found when the wind velocity was greater than 10 feet per second.

Values of E_c/C_{tc} and E_s/C_{ts} were divided by C_{wc} and C_{ws} respectively in order to take out the effect of wind.

3. Vapor pressure deficit coefficient:

The third step was to arrange all data of vapor pressure deficit in increasing order and to group the data in 5 lots according to 5 intervals of vapor pressure deficit. The average value of vapor pressure deficit and the corresponding average value of $E_c/C_{tc}C_{wc}$ and $E_s/C_{ts}C_{ws}$ for each lot was found. The values of these 5 points for each soil sample were plotted and equations for the best-fit curves found by the method of least squares were (Fig. 9):

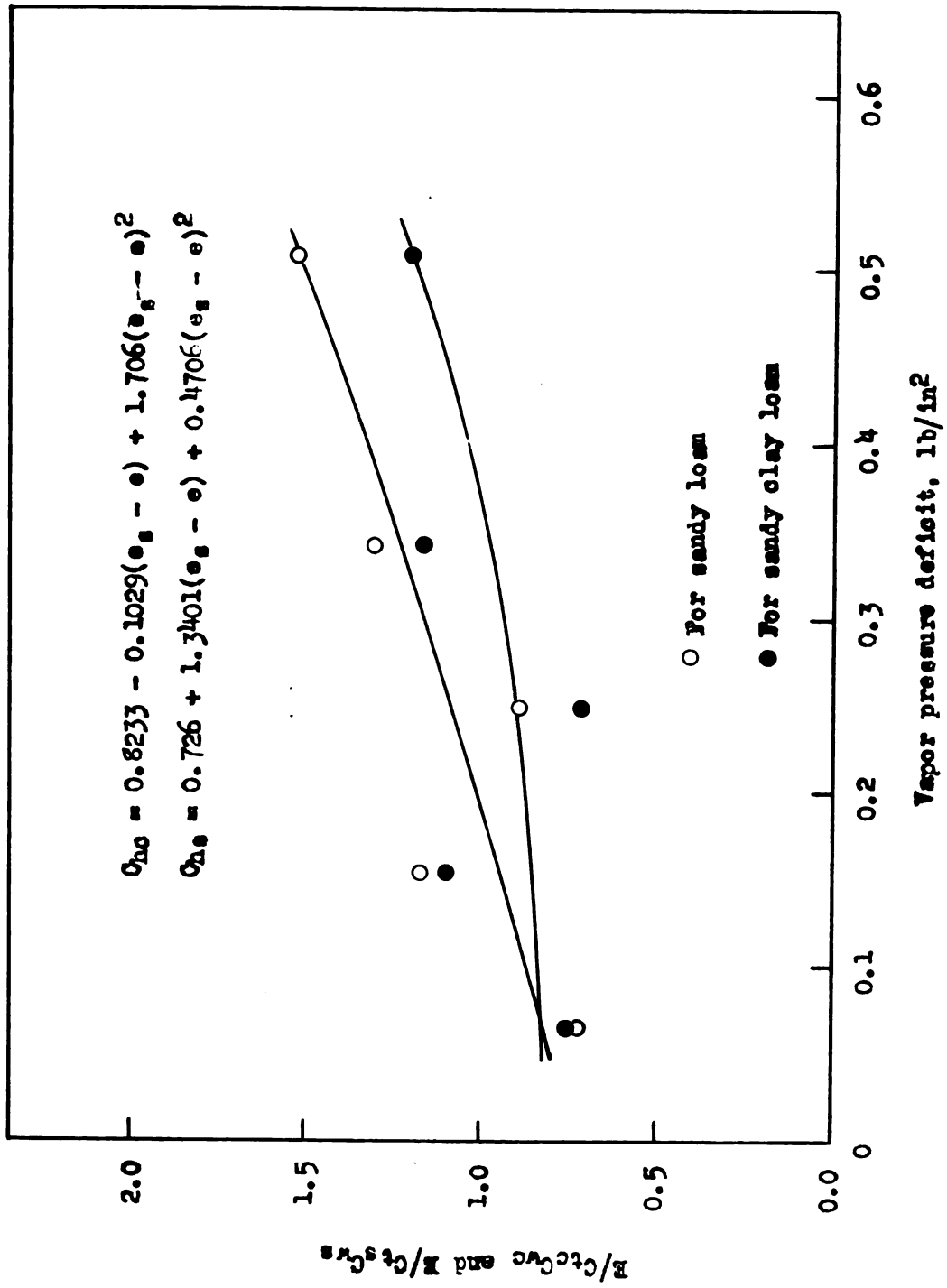


Fig. 9 The ratio $H/CtCv$ and $H/CtCs$ vs. vapor pressure deficit

$$C_{hc} = 0.8233 - 0.1029(e_s - e) + 1.706(e_s - e)^2$$

$$C_{hs} = 0.726 + 1.3401(e_s - e) + 0.4706(e_s - e)^2$$

where

C_{hc} is the subcoefficient of vapor pressure deficit for sandy

C_{hs} is the subcoefficient of vapor pressure deficit for sandy
loam soil

$(e_s - e)$ is vapor pressure deficit; where e_s is the saturated
vapor pressure at a given temperature, e is the actual vapor
pressure at the given temperature.

Fig. 9 showed that when vapor pressure deficit was greater than 0.060 pound per square inch, the effect of vapor pressure deficit on evaporation for sandy loam seemed greater than that for sandy clay loam. When vapor pressure deficit was less than 0.06, the effects of vapor pressure on evaporation for both sandy clay loam soil and sandy loam soil seemed similar.

Values of $E_c/C_{tc}C_{wc}$ and $E_s/C_{ts}C_{ws}$ were divided by C_{hc} and C_{hs} respectively to take out the effect of vapor pressure deficit.

4. Soil moisture coefficient:

The final step was to determine the average value of $E_c/C_{tc}C_{wc}C_{hc}$ and $E_s/C_{ts}C_{ws}C_{hs}$ for the lot corresponding to each of three various tensions (0, 27.5 and 45 cm). Each tension had its average value of moisture content for each soil sample. The values of these 3 points for each sample were plotted and equations for the curves were (Fig. 10):

$$C_{sc} = 2.2791 - 0.2395 S + 0.00666 S^2$$

$$C_{ss} = 1.013 - 0.0647 S + 0.00371 S^2$$

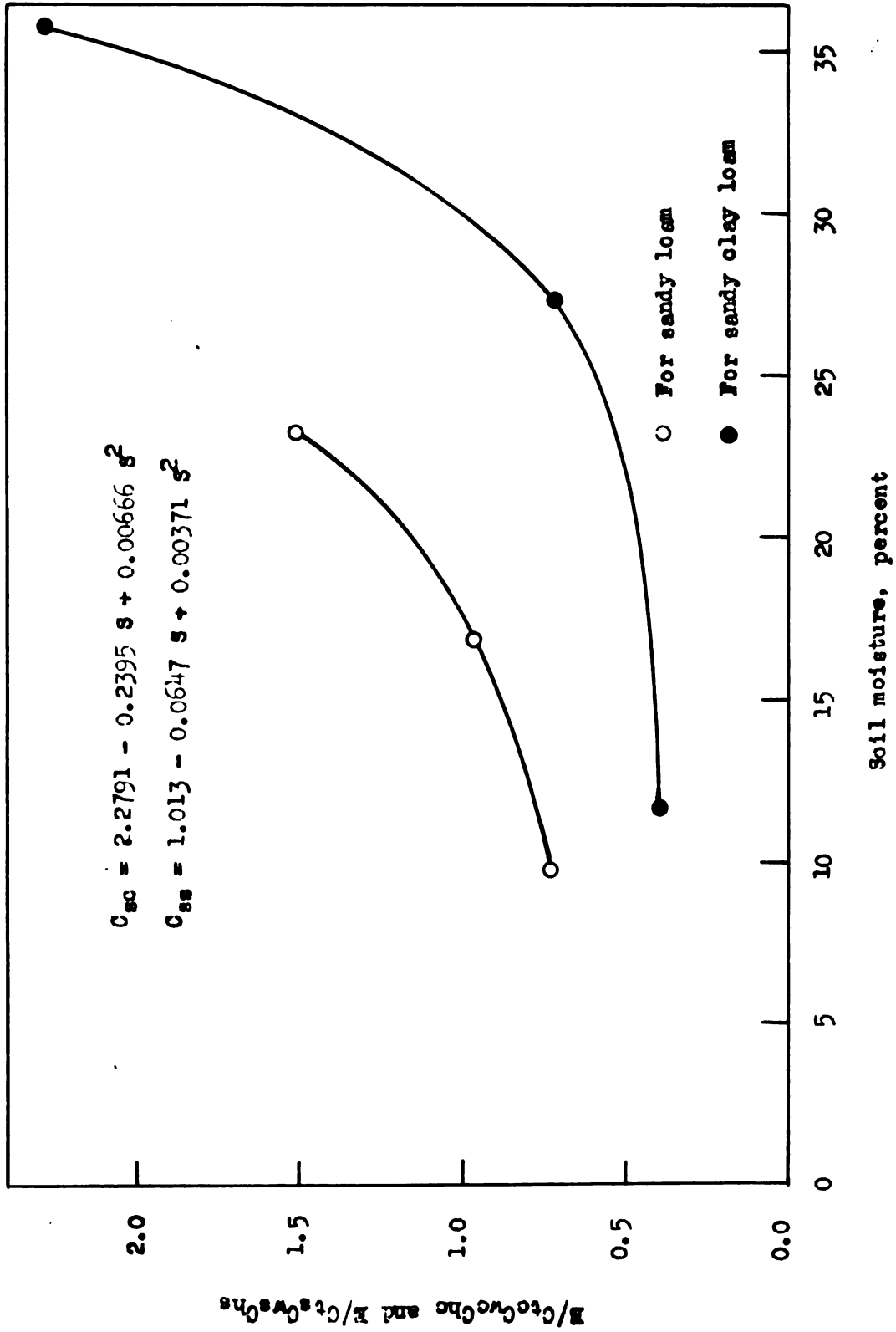


Fig. 10 The ratios of $E/C_{tc}C_{vc}C_{hc}$ and $E/C_{ts}C_{vs}C_{hs}$ vs. soil moisture

where

C_{sc} is the subcoefficient of soil moisture for sandy clay loam soil

C_{ss} is the subcoefficient of soil moisture for sandy loam soil

Another relations were found by expressing soil tension vs. $E_c/C_{tc}C_{wc}C_{hc}$ and $E_s/C_{ts}C_{ws}C_{hs}$. The data used for finding C_{sc} and C_{ss} were used here, and were plotted vs. tensions. The equations for the curves were found(Fig. 11):

$$C_{Tc} = 2.281 - 0.0603 T_{en} + 0.000854 T_{en}^2$$

$$C_{Ts} = 1.515 - 0.02658 T_{en} + 0.000225 T_{en}^2$$

where

C_{Tc} is the subcoefficient of tension for sandy clay loam soil

C_{Ts} is the subcoefficient of tension for sandy loam soil

T_{en} is the soil tension in cm.

Two interesting results from Fig. 10 were found. At the same soil moisture percentage, evaporation from the sandy loam was greater than that from the sandy clay loam. The other fact showed that the higher saturated soil moisture resulted in higher evaporation. It was apparent that the sandy loam had lower saturated soil moisture and the sandy clay had a higher saturated soil moisture.

From the aspect of tension, higher tension applied to sandy clay loam resulted in less effect on evaporation. When tension was reduced to 18 cm or less, the effect of tension in the sandy loam on evaporation was less than the sandy clay loam.

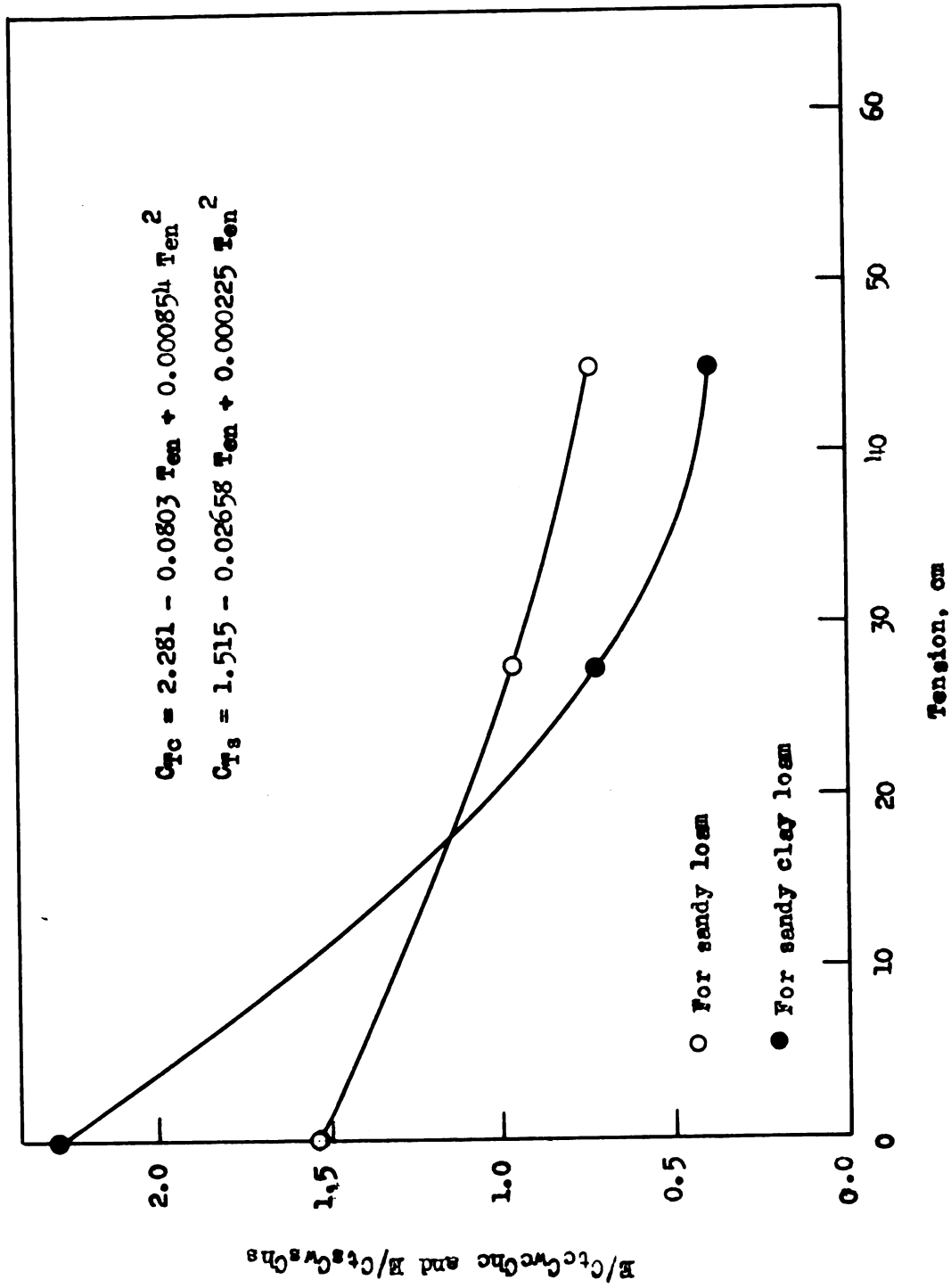


Fig. 11 The ratios of $H/C_{tc}C_{wc}C_{hc}$ and $H/C_{ts}C_{ws}C_{hs}$ vs. tension

Final equations

The formulas derived for sandy clay loam and sandy loam soils from the experimental results are:

(1). For sandy clay loam based on soil moisture;

$$E = C_{tc} C_{wc} C_{hc} C_{sc} \dots \dots \dots (1)$$

where

E is the evaporation from the soil in inches per day

$C_{tc} = 0.209 - 0.004 T + 0.000033 T^2$; C_{tc} is the subcoefficient of overrunning air temperature, T is the temperature of overrunning air in °F

$C_{wc} = 0.558 + 0.443 W + 0.000805 W^2$; C_{wc} is the subcoefficient of wind, W is the velocity of overrunning air in feet per second.

$C_{hc} = 0.8233 - 0.1029(e_s - e) + 1.706(e_s - e)^2$; C_{hc} is the subcoefficient of vapor pressure deficit, $(e_s - e)$ is the vapor pressure deficit at a given overrunning air temperature in pound per square inch

$C_{sc} = 2.2791 - 0.2395 S + 0.00666 S^2$; C_{sc} is the subcoefficient of soil moisture, S is moisture in the soil expressed by percentage of moisture on oven-dry basis.

(2). For sandy loam soil based on soil moisture:

$$E = C_{ts} C_{ws} C_{hs} C_{ss} \dots \dots \dots (2)$$

where

E is the evaporation from the soil in inches per day

$$C_{ts} = 0.133 - 0.00226 T + 0.0000349 T^2$$

$$C_{ws} = 0.599 + 0.0809 W - 0.00297 W^2$$

$$C_{hs} = 0.726 + 1.3401(e_s - e) + 0.4706(e_s - e)^2$$

$$C_{ss} = 1.013 - 0.0647 S + 0.00371 S^2$$

Except the second subscript "s" of the subcoefficient was used to distinguish sandy clay loam soil, the other symbols had the same notation as used in equation(1).

(3). For sandy clay loam soil based on moisture tension:

$$E = C_{tc} C_{wc} C_{hc} C_{Tc} \dots \dots \dots (3)$$

where

E is the evaporation from the soil in inches per day

C_{tc} , C_{wc} and C_{hc} were equivalent to the values of C_{tc} , C_{wc} and C_{hc} in equation(1)

$C_{Tc} = 2.261 - 0.0803 T_{en} + 0.000225 T_{en}^2$; C_{Tc} is the subcoefficient of tension, T_{en} is tension in centimeters.

(4). For sandy loam soil based on moisture tension:

$$E = C_{ts} C_{ws} C_{hs} C_{Ts} \dots \dots \dots (4)$$

where

E is the evaporation from the soil in inches per day

C_{ts} , C_{ws} and C_{hs} were equivalent to the values of C_{ts} , C_{ws} and C_{hs} in equation(2)

$C_{Ts} = 1.515 - 0.02658 T_{en} + 0.000225 T_{en}^2$; C_{Ts} is the subcoefficient of tension, T_{en} is tension in centimeters.

CONCLUSIONS

1. The use of the tension table to control soil moisture in the thin layer of soil gave a very stable moisture content and uniform moisture distribution.
2. Soil tension was a good index of soil moisture. The moisture content of the soil depended on the tension applied. The moisture in the soil was inversely proportional to the soil tension.
3. Increasing air temperature produced more evaporation in the soil of coarser particles than in the soil of finer particles.
4. The effect of wind on evaporation in the soil depended on wind velocity and the particle size of the soil. More evaporation occurred in the soil of coarser particles when the wind velocity was low, but the reverse phenomenon was observed when the wind velocity was higher.
5. Maximum constant wind effect on evaporation was observed from the sandy loam soil.
6. Evaporation does not depend on the moisture content of the different soils, however it does depend on the moisture content of the particular soil. More evaporation occurs in a specified soil when its moisture content is higher. In comparing the evaporation from different soils, the type of soil as well as the moisture content of soil has to be taken into account.
7. Maximum evaporation occurring in the saturated soil depends on the maximum capillary capacity of the soil. The soil of the finer par-

ticles has more capillary capacity than that of the coarser particles. Therefore in the close saturated conditions, the evaporation occurring in the soil of the finer particles is greater than that of the coarser particles.

8. When soil is unsaturated, the rate of evaporation depends on the size of the particles in the soil. The soil of the coarser particles has more evaporation than that of the finer particles although the moisture contents are the same in these different soils.

LITERATURE CITED

- Christiansen, J. E. and Nella W. Lauritzen(1963), A bibliography on evaporation and evapotranspiration. Utah State University, Logan, Utah. March 1, 1963.
- Christiansen, J. E.(1960), Water requirement for waterfowl areas near the Great Salt Lake. Progress Rpt. Utah State Univ. Jan 1960.
- Edney, E.(1957), The water relations of terrestrial Arthropods. Cambridge Eng., Cambridge Univ. Press, 1957.
- Fortier, S.(1907), Evaporation losses in irrigation and water requirement of crops. U.S. Dept. Agr. Bul. 177. 1907.
- Fukuda, H.(1955), Air and vapor movement in soil due to wind gustiness. Soil Sci. 79: 249 - 256. 1955.
- Fukuda, H.(1956), Diffusion of water vapor and its exchange between condensation and evaporation in soil. Soil Sci. 81 - 95. 1956.
- Kenneth Jose Mathison(1963). The use of climatological and related factors for estimating evaporation. Utah State Univ. M.S. thesis. 1963.
- Linsley, Ray K. Jr. and Max A. Kohler and Joseph L. H. Paulhus.(1958), Hydrology for engineers. McGRAW-HILL BOOK COMPANY, INC., New York Toronto London 1958.
- Mann, R. J.(1871), On evaporation, rainfall, and elastic force of vapor. Brit. Met. Soc. Proc. 5: 285-297. 1871.
- Meyer, Adolph F.(1942), Evaporation from lakes and reservoirs. Minn. Resources Comm. St. Paul, Minn. June 1942.

- Onchukov, D. N.(1957), The phenomenon of heat and moisture transmission in soils and subsoils. Moskov. Technol. Inst. Pishch. Promush. Trudy, p. 55 - 63. 1957.
- Penman, H. L.(1948), Natural evaporation from open water, bare soil and grass. Proc. of the Royal Society, Series A. 1948.
- Perterson, H. B.(1959). Personal communication. 1959.
- Richards, et al.(1956), Physical processes determining water loss from soil. Soil Sci. Soc. Amer. Proc. 20: 310 - 314. 1956.
- Rohwer, Carl. (1931), Evaporation from free water surfaces. USDA and Colo. Agr. Exp. Sta. Tech. Bul. 271: 1 - 97. Dec. 1931.
- Spiegel, Murray R.(1961), The theory and problems of STATISTICS. Schaum Publishing Co. New York. 1961.
- Staple, W. J.(1956), Evaporation from soil and vegetation. Netherlands Jour. Agr. Sci. 4: 39 - 42. 1956.
- Thornthwaite, C. W. and J. R. Mather(1955), The water balance. Publ. in Climatology, Vol. VIII, No. 1, Drexel Institute Laboratory of Climatology, Centerton, N. J., 1955.
- Young, A. A. and H. F. Blaner.(1942), Use of water by native vegetation. Calif. Div. of Water Resources Bull. 50. 1942.

APPENDIX

Procedure for finding the constants of the best-fit parabola equation may be stated as follows:

1. For determining the constants of the parabola equation of the coefficients C_t , C_w , C_s and C_T ;

Three points on the curve were given by the results of the experiment. The assumed parabola equation was

$$Y = a_0 + a_1 X + a_2 X^2$$

where

a_0 , a_1 and a_2 were three constants to be determined.

Three sets of (X, Y) were substituted in the equation and three simultaneous equations were obtained;

$$Y_1 = a_0 + a_1 X_1 + a_2 X_1^2$$

$$Y_2 = a_0 + a_1 X_2 + a_2 X_2^2$$

$$Y_3 = a_0 + a_1 X_3 + a_2 X_3^2$$

Then, solved the equations to obtain a_0 , a_1 and a_2 .

2. For determining the constants of the parabola equation of the coefficient C_h ;

It was necessary to use the least square method to obtain the best-fit equation for the coefficient of C_h . The least square parabola approximating the set of 5 points (X_1, Y_1) , (X_2, Y_2) , (X_3, Y_3) , (X_4, Y_4) and (X_5, Y_5) obtained from the results of the experiment had the equation

(Spiegel, Murray R, 1961);

$$Y = a_0 + a_1 X + a_2 X^2$$

where

a_0 , a_1 and a_2 were determined by solving simultaneously equations:

$$\sum Y = a_0 N + a_1 \sum X + a_2 \sum X^2$$

$$\sum XY = a_0 \sum X + a_1 \sum X^2 + a_2 \sum X^3$$

$$\sum X^2 Y = a_0 \sum X^2 + a_1 \sum X^3 + a_2 \sum X^4$$

where

N is number of set. In this experiment, N equals 5.

MICHIGAN STATE UNIV. LIBRARIES



31293201018136