STUDIES OF SHEARING RESISTANCE BETWEEN CEMENT MORTAR AND SOIL

by

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Soil Properties as Related to Load
Transfer Characteristics of Drilled Shafts

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PREFACE

This is one of a series of reports from Research Project 3-5-65-89 of the Cooperative Highway Research Program. This report, entitled "Studies of Shearing Resistance Between Cement Mortar and Soil," is the third in the series. The first report in this series, "Field Testing of Drilled Shafts to Develop Design Methods," described the overall approach to the design of drilled shafts based on field and laboratory investigations. Readers are referred to that report for a presentation of the overall problem.

This report involved the efforts of a number of people on the staff of the Center for Highway Research. Technical contributions were made by Harold H. Dalrymple, James N. Anagnos, Michael O'Neill, W. R. Hudson, and V. N. Vijayvergiya. Preparation and editing of the manuscript were done by Joyce Yonker, Eddie B. Hudepohl, and Art Frakes.

The Texas Highway Department Project Contact Representatives Messrs. Horace Hoy and H. D. Butler and District No. 14 personnel have been most helpful and cooperative in the development of this work. We wish to thank them as well as the U. S. Bureau of Public Roads who jointly sponsored the research program.

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LIST OF REPORTS

Report No. 89-1, "Field Testing of Drilled Shafts to Develop Design Methods," by Lymon C. Reese and W. Ronald Hudson, describes the overall approach to the design of drilled shafts based on a series of field and laboratory investigations.

Report No. 89-2, "Instrumentation for Measurements of Lateral Earth Pressure in Drilled Shafts," by Lymon C. Reese, J. Crozier Brown, and H. H. Dalrymple, describes the development and evaluation of pressure gages to measure lateral-earth pressures on the drilled shaft.

Report No. 89-3, "Studies of Shearing Resistance Between Cement Mortar and Soil," by John W. Chuang and Lymon C. Reese, describes the overall approach to the design of drilled shafts based on field and laboratory investigations.

Report No. 89-4, "The Nuclear Method of Soil-Moisture Determination at Depth," by Clarence J. Ehlers, Lymon C. Reese, and James N. Anagnos, describes the use of nuclear equipment for measuring the variations of moisture content at the drilled shaft test sites.

Report No. 89-5, "Load Distribution for a Drilled Shaft in Clay Shale," by Vasant N. Vijayvergiya, W. Ronald Hudson, and Lymon C. Reese, describes the development of instrumentation capable of measuring axial load distribution along a drilled shaft, the development, with the aid of full-scale load testing, of a technique of analysis of observed data, and the correlation of observed data with the Texas Highway Department cone penetration test.

ABSTRACT

This report presents the results of an investigation performed to study the nature of moisture migration from unset cement mortar to soil and the interactions between the cement mortar and soil.

More than 200 cement mortar-soil samples were tested to determine the factors that affect the moisture migration, and more than 70 cement mortar-soil sample tests were performed to investigate the shear-strength modification factor α .

The laboratory-test results on moisture migration and the shear-strength modification factor α have been used to estimate the wall friction resistance of a drilled and cast-in-place shaft. The accuracy of the estimated wall friction resistance is found to be satisfactory when compared to the actual test load results. The moisture migration and shear-strength modification factor α are recommended for studies concerned with the estimation of wall friction resistance of a drilled shaft in homogeneous clay or sandy clay.

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NOMENCLATURE

Symbol	Typical Units	Definition
c	lb/sq ft	Apparent cohesion of soil
c_a	lb/sq ft	Modified shearing resistance of soil
c_i	lb/sq ft	Shearing resistance of undisturbed soil at i^{th} increment
e	ft	Void ratio of soil
H_m	ft	Distance from top of fresh concrete below which lateral pressure on formwork does not increase
h_f	ft	Maximum height of concrete in form
i	--	When used as subscript, denotes station number, increment or point
k	ft/sec	Coefficient of permeability
M	lb/sq ft	Number of increments in a shaft
P	lb/sq ft	Maximum lateral pressure of fresh concrete activity against formwork
P^F	--	Logarithm of height of a water column in centimeters which would be caused by a given pressure
R_p	ft/hr	Rate of placement of concrete
s_z	lb/sq ft	Load transfer at a point z below top of shaft
T	degrees F	Temperature
w	percent	Moisture content
α	--	Shearing resistance modification factor

Symbol	Typical Units	Definition
γ	lb/cu ft	Unit weight of material (general)
γ_w	lb/cu ft	Unit weight of water
ΔA_i	sq ft	Peripheral area of shaft at i^{th} increment
ΔR_i	lb	Frictional resistance at i^{th} increment
Δw	percent	Moisture content increase
σ^1	lb/sq ft	Effective normal stress
τ	lb/sq ft	Shear stress
τ_f	lb/sq ft	Shear strength of soil or limiting shear of a viscous fluid
ϕ	degrees	Apparent angle of internal friction of soil

CHAPTER 1. INTRODUCTION

Drilled shaft foundations have been widely used in the United States. In the last decade the improvement of drilling augers and drilling machines has made it possible to drill economically a shaft up to 5 feet in diameter and 90 feet deep (Ref 1). There are two types of drilled shafts, the straight shaft and the belled shaft. For a belled shaft, the base resistance and uplift resistance are increased. The load on a drilled shaft is transferred to the surrounding soil, as in a driven pile, by shaft side resistance and bottom resistance (Refs 2 and 3). The amount of load carried by shaft side resistance and bottom resistance is dependent on the size of the shaft and on the shear strength of the supporting soil.

Since a drilled shaft is made of cast-in-place concrete, a certain amount of water will migrate into the surrounding soil from the fresh concrete. The amount of water that migrates between concrete and soil is not well known. Meyerhof and Murdock (Ref 4) and Skempton (Ref 5), who studied bored piles in London Clay, concluded that the water migrated from fresh concrete into the surrounding soil to a distance of 2-1/2 to 3 inches. Meyerhof found that the water migration caused the clay next to the pile wall to have a moisture content from 6 to 7 percent higher than the original moisture content for London Clay.

Skempton found further that the increase of water content in the soil surrounding the shaft caused a decrease in the soil strength along the shaft surface. Since the soil strength along the shaft surface decreases due to moisture migration, a modification of the shear strength of the soil is necessary. Meyerhof concluded that the average adhesion between clay and shaft c_a along the shaft could be obtained by multiplying the average undisturbed soil shear strength c by a factor α :

$$c_a = \alpha c$$

The value of α for London Clay was found to be between 0.3 and 0.6 (Ref 4).

Generally, the shaft side resistance will start to develop soon after the concrete is poured into the drilled excavation. Field tests in London Clay prior to loading show that the integral of the shaft side resistance will equal a force with a magnitude of one-half to two-thirds the weight of the concrete in the shaft. In order for adhesion to develop, there must be lateral pressures between the soil and the concrete of the drilled shaft. Lateral pressure-cell measurements taken before the test loading of a drilled shaft in Austin, Texas, show that there is indeed a sizable lateral earth pressure along a cast-in-place shaft (Ref 6).

The behavior of a drilled shaft is fully dependent on the shear strength of the supporting soil. The aim of this report is to study the interaction of wet concrete with soil.

The soil properties along the shaft surface are changed by water migration from the fresh concrete; therefore, it is important to acquire basic knowledge about the water migration between fresh concrete and soil. It is also important to study any other interactions between soil and concrete. Laboratory studies of moisture migration between cement mortar and soil and of shearing resistance between cement mortar and soil were conducted. Details of the laboratory studies will be explained in the following chapters. The possible interaction between fresh concrete and soil was studied for full-scale drilled shafts constructed in Austin and San Antonio, Texas.

CHAPTER 2. MOISTURE MIGRATION BETWEEN CEMENT MORTAR AND SOIL

INTRODUCTION

Soil-water relations have been of interest since the earliest times of the human race. Agriculturists and agronomists have been studying soil-water-plant relations since the first days of agriculture. The soil-water relation has been considered the most important factor affecting the behavior of soil, especially its mechanical properties.

The water content of native soil varies with both location and time. It is rarely static. The distribution and migration of water in soil are a function of many known and unknown factors, such as gravitational, osmotic, and ionic gradients (Ref 7).

In soil, moisture transfer can be divided into saturated and unsaturated flow. Water movement under the ground water level is classified as saturated flow; water movement above the ground water level is classified as unsaturated flow. In general, most of the water movement in soil is classified as unsaturated flow.

Phenomena associated with migration of water from cement mortar into the soil are not very well understood. The degree and amount of cement water that migrate from unset cement mortar or fresh concrete are dependent on many factors. The pressure head that might be built up from unset cement mortar or fresh concrete, soil properties, water-cement ratio, and underground temperature all affect the water migration between concrete or cement mortar and soil.

The pressure head that might be built up from fresh concrete during placing is influenced by several factors, including the following (Ref 8):

(1) water-cement ratio,
(2) velocity of concrete placing,
(3) properties of the fresh concrete,
(4) temperature of the concrete,
(5) total depth of placement, and
(6) rate of hardening.

The study of pressure from fresh concrete or unset cement mortar is a very complicated and difficult problem. If one considers a certain depth near the bottom of a drilled excavation, the pressure of fresh concrete against the soil will increase as the fresh concrete continues to be poured into the excavation. Meanwhile, the concrete starts to set after a certain period of time, and the pressure of the concrete will reach a maximum and will then drop. Concrete usually takes an initial set in less than 60 minutes and a final set in less than ten hours; therefore, the pressure gradients causing the water flow into the surrounding soil last only a short time.

LABORATORY TESTS ON MOISTURE MIGRATION BETWEEN CEMENT MORTAR AND SOIL

Introduction

A series of tests on remolded samples and undisturbed samples was performed to investigate the water movement from cement mortar to soil and the shearing resistance between cement mortar and soil. Information from the literature, some of which is reviewed briefly below, served as a guide for the experiments.

In 1953, G. G. Meyerhof and L. J. Murdock described soil investigations and loading tests which were made on bored and driven concrete piles in London Clay (Ref 4). They found that the water migrated from the fresh concrete into the soil, thus causing a decrease of the shearing strength of the soil surrounding the drilled shaft. Meyerhof and Murdock suggested that since the water of the fresh concrete is greater than the amount theoretically required for hydration of the cement, the water will migrate from the fresh concrete into the surrounding soil. From their test results, they found that the water content in the soil increased the most at the soil-shaft interface and that changes in water content were observed to about 2 inches from the shaft.

Later, in 1956, the Texas Highway Department, in cooperation with the Agricultural and Mechanical College of Texas (Ref 13), carried out a series of drilled shaft tests; they suggested that water had migrated from the fresh concrete into the surrounding soil and caused a decrease of the shear strength of the soil. After carrying out several tests in the laboratory by drilling borings (2-1/2 inches in diameter by 18 inches deep) into compacted clay, they found that the soil samples taken adjacent to the pile surface (in the 0 to 1/2-cm range) were wetter than those taken at a greater distance from the pile surface. The influence of a 5-foot pressure head on the fresh concrete on water migration was considered negligible.

It is very clear that there is a migration of water and cement particles from fresh concrete into the soil surrounding a drilled shaft, and that the migration is a complicated function of water-cement ratio, grain-size distribution of soil, time, temperature, and many other factors. Since water has a great influence on soil properties, such as strength, the study of moisture migration between fresh concrete or cement mortar and soil is important in developing an understanding of the behavior of a drilled shaft. It is important to know how water migrates into soil and how it influences the soil properties. Laboratory tests were planned to evaluate the influence of water-cement ratio, grain-size distribution, pressure head on unset cement mortar, type of cement, time, void ratio, and initial moisture content of the soil on the migration of water or cement from the fresh mortar into the soil.

Meyerhof and Murdock (Ref 4) quoted Dr. L. F. Cooling of the Building Research Station (United Kingdom) as suggesting that since the water in fresh concrete or in cement mortar is more than is required for the hydration of cement, the excess water will migrate into soil. However, the water required for hydration is dependent on the amount and type of cement and is assumed to be homogeneously distributed throughout the concrete. The water that is available for migration is only a certain part of the unset concrete near the interface.

Material Used

Soil. The soil used in all tests was taken from Montopolis, a community east of Austin. Two borings were made in May 1966, for this study. The soil contains inclusions of calcareous material up to 1/4-inch in diameter. The physical and mechanical properties of the soil are listed in Appendix 1. Most of the soil is classified as inorganic clay of high plasticity and inorganic clay of medium plasticity.

Cement. Two types of cement were used for making cement mortar. Type I, normal portland cement, was used for basic water migration studies between cement mortar and soil. Type III, high early strength portland cement, was used to investigate how the rate of hydration of cement affects the moisture migration.

Sand. The sand used for cement mortar was Colorado River sand. The gradation of the sand is listed in Appendix 2. The sand was treated so that it was saturated surface dry when it was used.

Idea of Test

Soil constituents exist in three physical states: solid (grain), liquid (water or solution of salts), gas (air in pores). The existence of these three phases makes the behavior of soil very difficult to deal with. The movement of water in soil is very complicated. However, the assumption that water movement in soil is a function of potential gradient is a very reasonable approach.

A small element taken from the wall of the shaft is considered. From the theory of fluid flow, the direction of flow must be perpendicular to the hydraulic gradient of potential gradient.

The hydraulic gradient build-up from unset concrete can be calculated. From the finite-element concept, when the suction force of the soil is much higher than gravitational force, the effect of gravity can be neglected; therefore, the water from the fresh concrete will move in a direction normal to the wall of the drilled shaft. As described later, the transfer of moisture from fresh concrete into soil was studied in the laboratory by using small specimens to simulate the conditions of an element at the interface of the shaft.

Preparing Samples

Four different types of soil were tested in the remolded condition. Preparation of the material consisted of crushing and grinding all solid clods. The large particles were discarded and only those particles that would pass through a No. 40 sieve were used. The clay was then mixed with well-graded sand to form different gradations. The grain-size distribution curves of each soil are given in Appendix 2. In order to control the void ratio and initial water contents, the amount of water added was carefully controlled and mixed with the soil in a mixer. The prepared soil was then sealed in a container and put in a 100 percent humidity room for at least seven days to allow a more uniform and consistent distribution of moisture.

To make sure of the initial moisture contents, they were remeasured before each test. A steel tamper, 325 grams in weight, 6-1/2 inches in length, with a diameter of 7/8-inch at one end and 5/8-inch at the other end, was used to compact the prepared soil into a steel tube. The steel tube is 2.83 inches in diameter and 5 inches in height. The soil was compacted into the tube up to 3 inches in height in six layers. The soil for each layer was weighed according to the calculated void ratio and was uniformly compacted to a height of 1/2-inch. To provide uniformity in the vertical direction, the surface of each layer was lightly scarified prior to placing the succeeding layer. The top 1/4-inch of the last layer was removed. The volume of the sample was carefully remeasured, and the void ratio was recalculated. It was found that the void ratio was within ± 1 percent with respect to accuracy. The number of blows was varied from 45 for a void ratio of 0.48 to 25 for a void ratio of 1.00. The inner surface of the tube above the soil was lubricated with grease before the cement mortar was poured on the top of the soil sample. Enough unset cement mortar was poured to make a height of about 2 inches. The top of the cement mortar was covered with aluminum paper and grease. The specimen was then put into a triaxial chamber, as shown in Fig 1.

Air pressure was slowly applied to either 5 or 10 psi. This condition was maintained for seven days. The pressure was applied on the specimen two minutes after the cement mortar was poured on top of the soil sample. In each series of tests, a plain soil (no cement mortar) sample was tested to compare with samples that had cement mortar on top of the soil. At the end of seven days, the soil was squeezed out on a sample extruder and sliced into 1/4-inch pieces. The moisture content of each slice was determined. For each condition, at least five samples were tested.

The Determination of Applied Pressure on Specimen

As stated in Chapter I, the pressure head from fresh concrete that acts against soil from continuous pouring into the drilled excavation is influenced by many factors. In 1955, the American Concrete Institute organized a committee to develop a specification for the design and construction of form work. They came out with formulas considering the effect of two variables, the rate of placement, and the temperature. The maximum pressure to be expected on column-type formwork is expressed as

$$P = 150 + \frac{1}{T}\,9{,}000\ R_p \qquad (1)$$

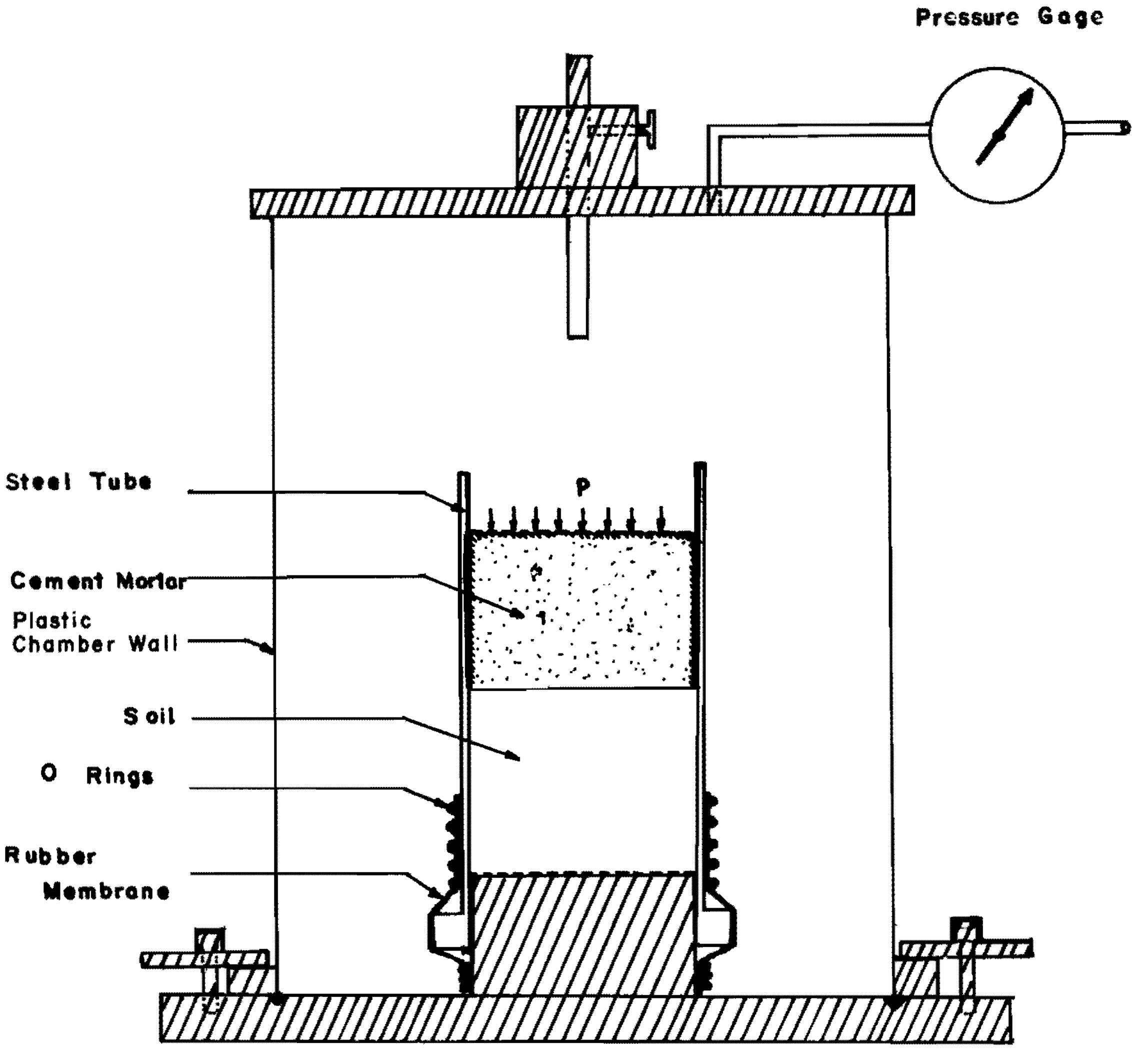


Fig 1. Moisture migration test.

where maximum P is 3,000 psf or 150 h_f, whichever is less, and

P = maximum lateral pressure, psf;

R_p = rate of placement, ft/hr;

T = temperature of concrete in the forms, ^{o} F;

h_f = maximum height of fresh concrete in the form, feet.

In 1965, R. L. Peurifoy (Ref 8) studied the lateral pressure of concrete on formwork under different temperatures and rates of placement. The results show a relatively high degree of agreement with the value calculated from the American Concrete Institute code (Ref 15). According to Peter D. Courtois (Ref 14), Stanley Rodin in 1962 presented his work on lateral pressure of concrete on formwork. He developed a formula for predicting the location of maximum lateral pressure H_m and expressed it as

$$H_m = C_T \sqrt[3]{R_p} \tag{2}$$

where

C_T = a coefficient which varies with temperature,

H_m = the distance from the top of the wet concrete below which lateral pressure does not increase.

The lateral pressure is one of the factors that affect the water migration between unset freshly placed concrete and soil. According to the American Concrete Institute code specifications, for R_p equal to 5 feet per hour at a temperature under 70^{o} F, the maximum lateral pressure is about 5 psi. For R_p equal to 9 feet per hour at a temperature equal to 70^{o} F, the maximum lateral pressure is about 10 psi. Based on the above discussion, pressures of 5 and 10 psi were used in studying moisture migration from fresh concrete into laboratory soil specimens.

TEST RESULTS ON REMOLDED SAMPLES

Influence of Grain-Size Distribution

Particle-size distribution in soils influences strength and compressibility, which are important in the consideration of bearing capacity. Particle-size distribution is also important in water movement and aeration. In order to investigate the relation between the grain-size distribution and moisture migration from fresh cement mortar to soil, four different types of soil, classified as (1) clay (CH), (2) sandy clay (CL), (3) sandy-clay loam (SC), and (4) sandy loam (SC), were tested under controlled conditions.

The increase in pressure from the continuous placement of fresh concrete or cement mortar is a very complicated problem. Usually, the pressure exerted by fresh concrete is influenced by such factors as water-cement ratio, temperature, rate of placement, rate of hardening, and time. The pressure can be computed approximately from the equations for lateral pressure of concrete on formwork as discussed earlier. For each series of tests, the initial moisture content was controlled at 10 percent and void ratio was controlled at approximately 0.48.

Moisture migration tests were performed with the device shown in Fig 1. The results of measuring moisture migration between cement mortar and soil under no overburden pressure are listed in Table 1, and for the case of 5 psi overburden pressure, the results are listed in Table 2. The range of fineness modulus plotted in Fig 2 is only 0.1 to 1.8; it may be desirable to run additional tests to increase fineness modulus range.

During the moisture-content determinations, observations were made as to whether cement had moved into the soil. It was observed that for larger grain-size soil (F.M. = 1.8), the cement penetrated about 1/4 inch into the soil. The penetrated cement formed a layer of cement soil that prevents the further penetration of water into the soil. When the soil particles were very small (F.M. = 0.1), no cement penetration was observed.

In Tables 1 and 2, the term Δw shows the average moisture-content increase in the inch of soil nearest the interface. Fig 2 shows the relation between the moisture-content increase and the fineness modulus of soil, and Fig 3 shows the effect of the overburden pressure and fineness modulus on moisture-content increase Δw . The results shown in Tables 1 and 2 and Figs 2 and 3 may be summarized as follows:

(1) The average moisture-content increase Δw decreases as the grain-size distribution changes from clay to sandy clay.

(2) The average moisture-content increase Δw is higher for an overburden pressure of 5 psi than for a 0 psi overburden pressure.

TABLE 1. INFLUENCE OF GRAIN-SIZE DISTRIBUTION ON MOISTURE MIGRATION BETWEEN CEMENT MORTAR AND SOIL UNDER 0 PSI OVERBURDEN PRESSURE

Type of Soil	Fineness Modulus	Initial Moisture Content	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
			0-1/4	1/4-1/2	1/2-3/4	3/4-1	
Clay (CH)	0.13	10.10	17.55	16.28	15.90	14.60	6.00
Sandy Clay (CL)	0.73	10.50	15.30	13.70	12.50	11.82	2.83
Sandy-Clay Loam (SC)	1.30	10.30	14.58	12.95	12.36	11.74	2.61
Sandy Loam (SC)	1.87	10.60	11.95	11.40	11.18	11.11	0.80

Void Ratio	0.48
*Water-Cement Ratio	0.60
Curing Period	7 days

TABLE 2. INFLUENCE OF GRAIN-SIZE DISTRIBUTION ON MOISTURE MIGRATION BETWEEN CEMENT MORTAR AND SOIL UNDER 5 PSI OVERBURDEN PRESSURE

Type of Soil	Fineness Modulus	Initial Moisture Content	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
			0-1/4	1/4-1/2	1/2-3/4	3/4-1	
Clay (CH)	0.13	10.10	17.62	17.00	16.45	15.50	6.60
Sandy Clay (CL)	0.73	10.50	15.08	14.38	13.25	12.50	3.30
Sandy-Clay Loam (SC)	1.30	10.30	14.92	13.29	12.96	12.20	3.07
Sandy Loam (SC)	1.87	10.60	13.74	12.70	12.38	12.15	2.14

Void Ratio	0.48
*Water-Cement Ratio	0.60
Curing Period	7 days

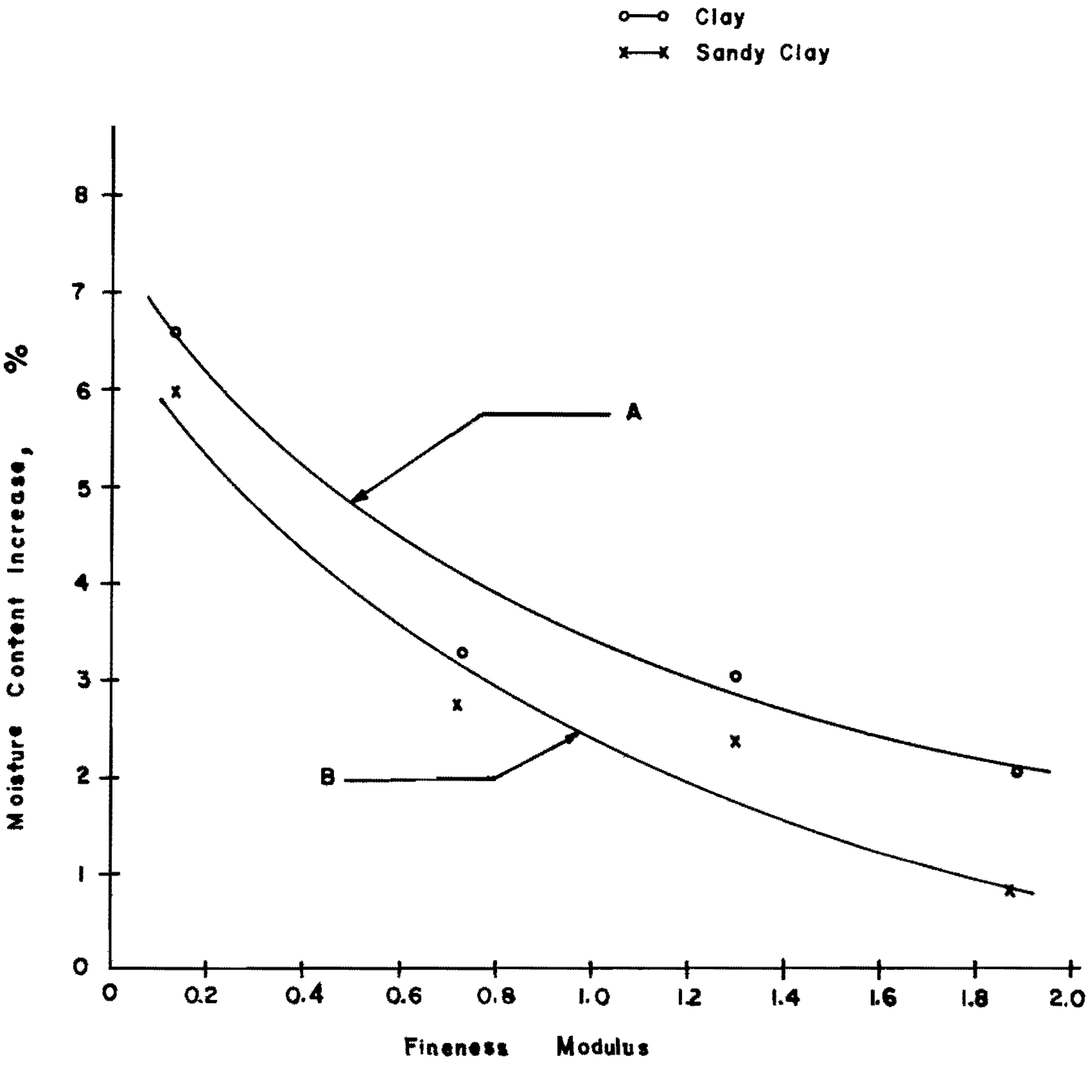


Fig 2. Relation between moisture content increases and fineness modulus of soil.

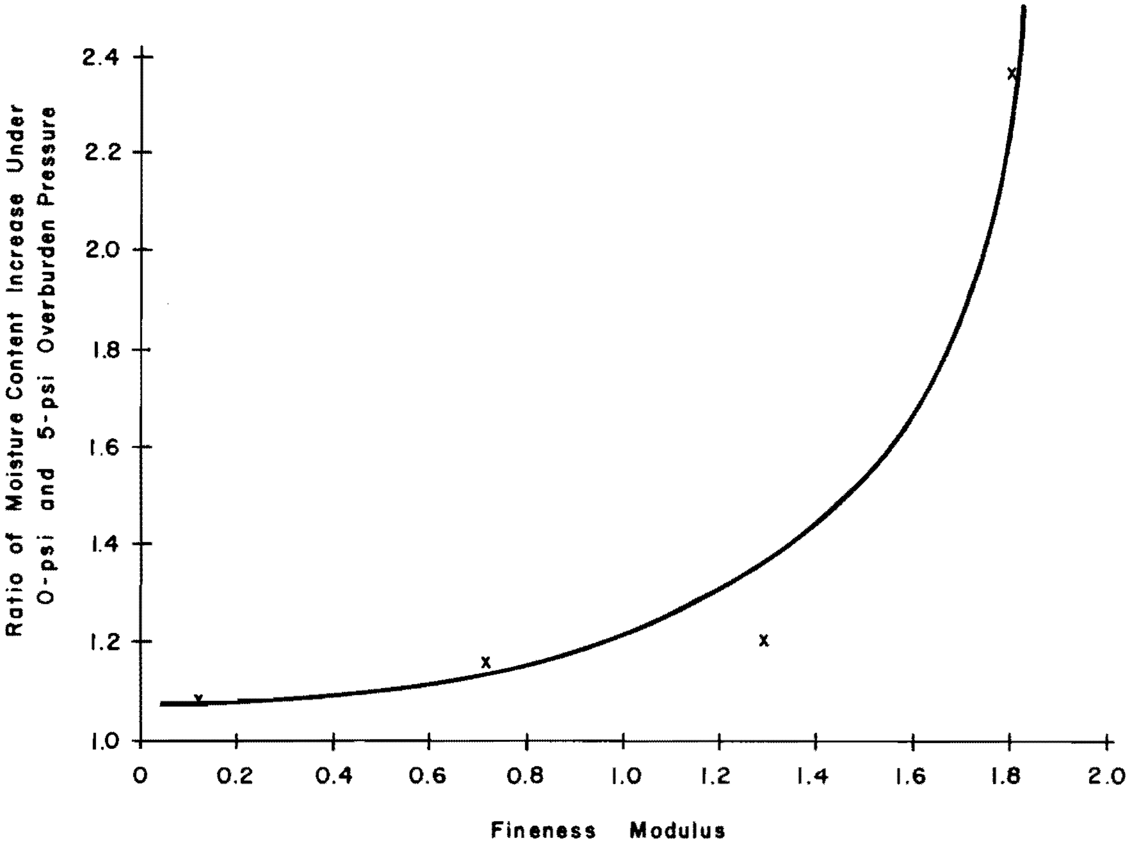


Fig 3. Effect of pressure and fineness modulus on moisture migration.

TABLE 3. INFLUENCE OF INITIAL MOISTURE CONTENT ON MOISTURE MIGRATION BETWEEN CEMENT MORTAR AND SANDY CLAY

Initial Moisture Content	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
	0-1/4	1/4-1/2	1/2-3/4	3/4-1	
10.80	15.30	13.80	12.50	11.82	2.55
17.20	19.75	17.80	17.60	17.40	0.94
20.20	21.50	20.70	20.30	20.10	0.45

Void Ratio	0.48
* Water-Cement Ratio	0.60
Curing Period	7 days

TABLE 4. INFLUENCE OF INITIAL MOISTURE CONTENT ON MOISTURE MIGRATION BETWEEN CEMENT MORTAR AND CLAY

Initial Moisture Content	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
	0-1/4	1/4-1/2	1/2-3/4	3/4-1	
10.30	17.55	16.28	15.90	14.60	6.00
13.20	17.60	16.70	15.47	15.00	3.24
17.40	19.06	18.60	18.10	17.80	1.39
21.70	23.40	22.50	21.80	21.75	0.60

Void Ratio	0.48
* Water-Cement Ratio	0.60
Curing Period	7 days

(3) The average moisture-content increase Δw decreases with distance from the interface.

(4) As the fineness modulus increases, there is an increase in the ratio $(\Delta w)_5/(\Delta w)_0$, showing that the higher overburden pressure is more effective in causing moisture-content change in the larger grained soils.

The Influence of Initial Moisture Content

The concept of the soil-water potential field is very useful in studying moisture migration in unsaturated soil. Quantitative comparisons can be made on the basis of the potential among soil properties which vary with water content. According to Croney and Coleman's test on heavy clay soil (Ref 15), the suction pressure of soil in centimeters of water can be expressed as an exponential function of water content. The suction pressure at a water content of 10 percent is approximately 5.3 P^F, and at 20 percent is approximately 4.3 P^F. The concept of the relation between suction pressure and original water content can be used to determine the degree of moisture migration between unset cement mortar and soil.

Soil samples were prepared with the same void ratio but with various initial moisture contents. Moisture and migration tests were performed with the initial properties of the cement mortar being maintained constant. The results of the moisture migration into sandy clay are shown in Table 3, and Table 4 shows the results of moisture migration into clay. Both tables indicate that the moisture-content increase Δw increases as the initial moisture content of soil decreases. Tables 3 and 4 show that the amount of moisture migration varies with the original moisture content, i.e., varies with soil suction pressure. Two least-square curves in Fig 4 show that:

(1) The amount of moisture migration can be expressed as an exponential function of moisture content.

(2) Soil with fine grains tends to have high Δw values.

(3) When the moisture content becomes very large, the influence of grain size on Δw becomes negligible.

Distance of Moisture Migration into Soil from Cement Mortar

In order to investigate the distance of moisture migration into soil from fresh cement mortar, samples composed of a 3-inch section of soil and a

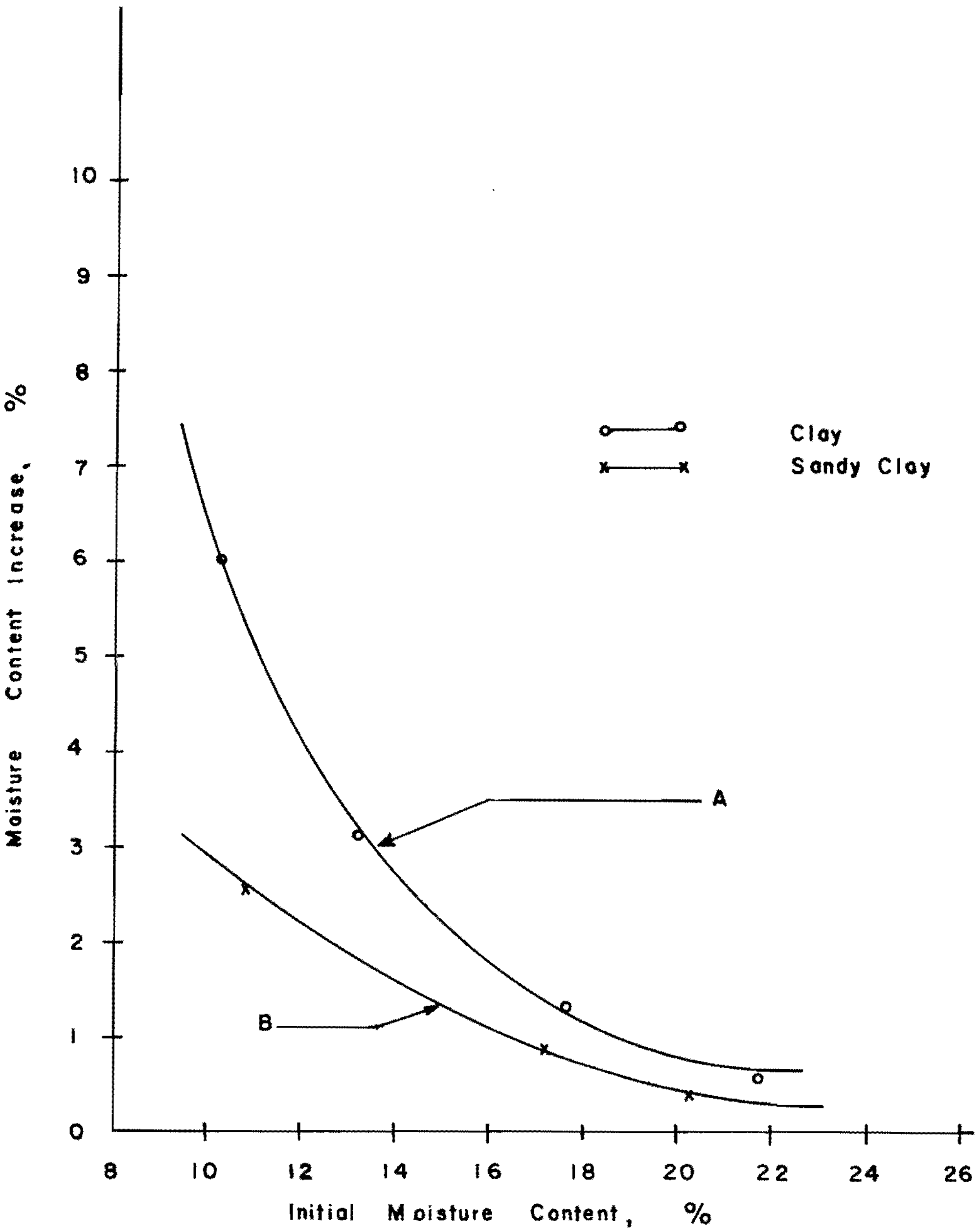


Fig 4. Relation between initial moisture content and the average moisture content increase in the inch of soil nearest the interface between cement mortar and soil due to moisture migration.

1-1/2-inch section of cement mortar were tested. As before, soil samples were prepared with the same initial void ratio but with varying initial water contents. The initial properties of the cement mortar were the same.

The results in Fig 5(a) show that the distance of moisture migration is a function of the water content of soil. In clay soil at a water content equal to 10.30 percent, the deepest moisture migration is about 2-1/2 inches. For sandy clay, it is about 1 to 2 inches. Figure 5(b) shows that when the initial moisture content of the soil increases, the distance of moisture migration into the soil decreases.

To see if the thickness of cement mortar had any effect upon moisture, samples with thickness of cement mortar equal to 1-1/2 inches and 2-1/2 inches were tested. The results show that there are no significant differences and that the water which migrates from the fresh concrete or unset cement mortar into the soil is only a certain portion of the water in the cement mortar near the interface of cement mortar and soil. However, when the void ratio of the soil becomes very large and the water content of soil decreases, there may be some effect of the thickness of cement mortar on moisture migration between cement mortar and soil.

Figure 6 shows the relationship between the moisture-content increase in the soil Δw at each succeeding 1/4-inch interval from the surface of the cement mortar for various initial moisture contents of the soil. The moisture-content increase at each succeeding 1/4-inch interval of soil is not only a function of water content of soil, but also a function of the distance from the surface of the cement mortar.

Influence of Void Ratio

The amount of moisture migration between soil and cement mortar also depends on the void ratio of the soil. The relationship of permeability values of sand under any two conditions of structure and void ratio is (Ref 10)

$$k_1 : k_2 = \frac{\beta_1 e_1^3}{1 + e_1} : \frac{\beta_2 e_2^3}{1 + e_2}$$

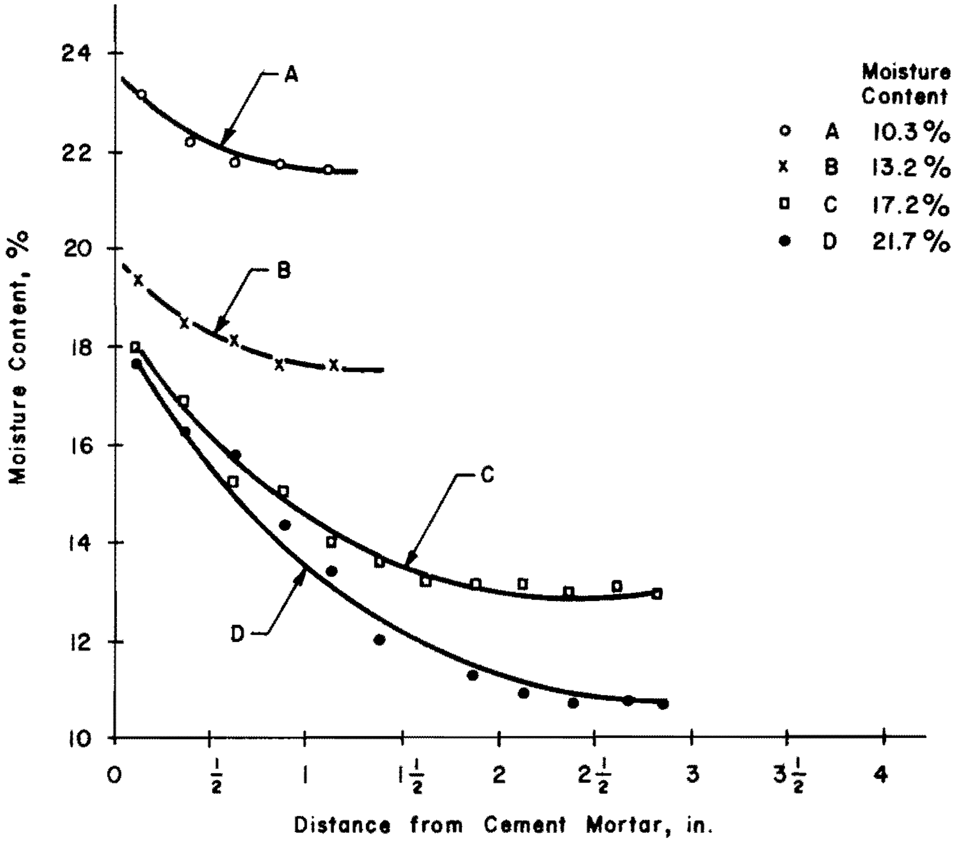


Fig 5(a). Distribution of moisture content in clay at different initial moisture contents.

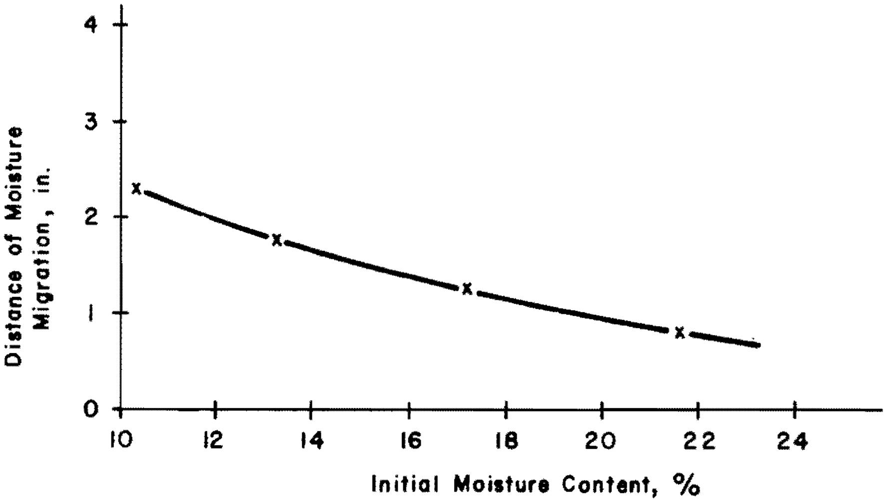
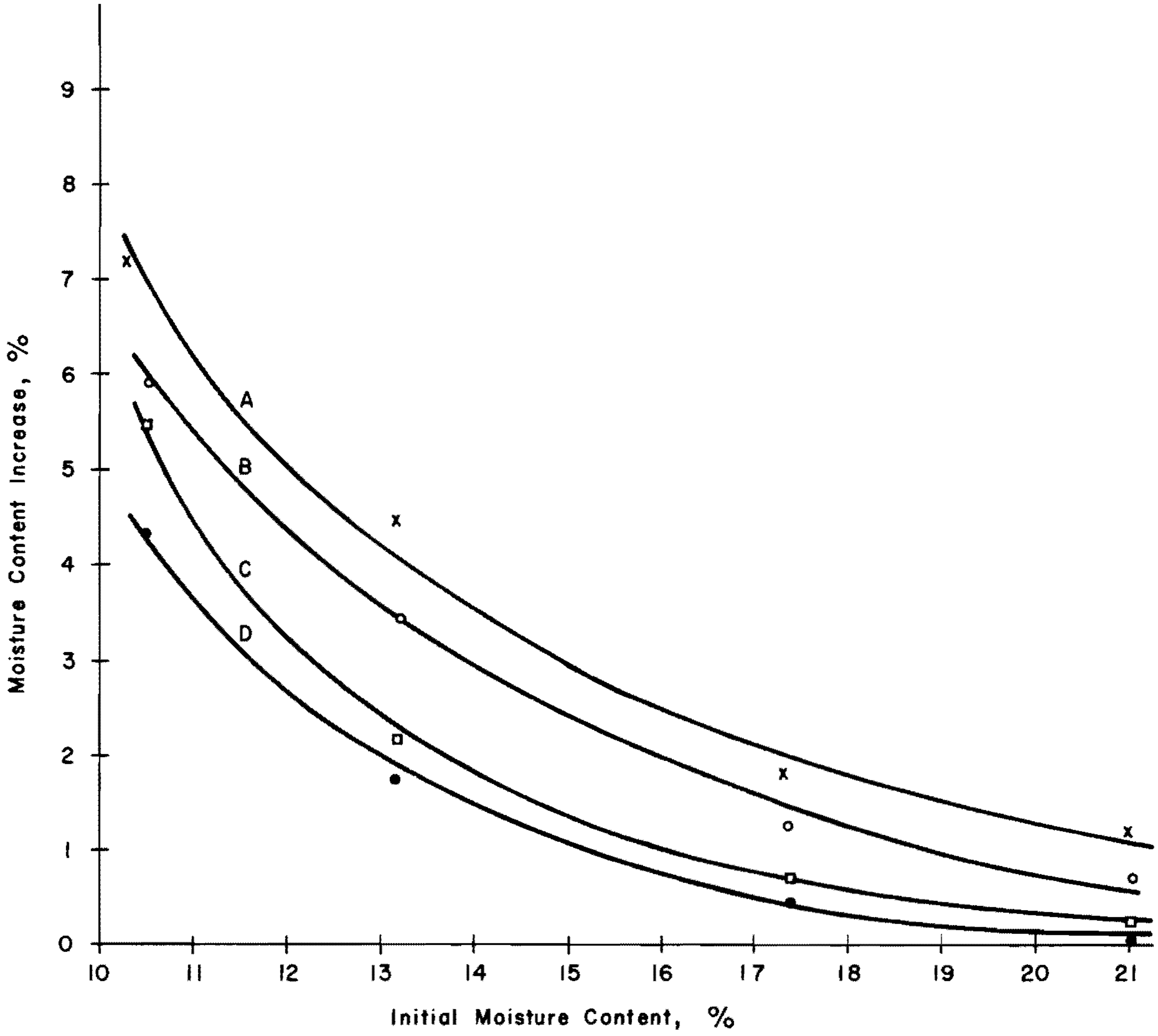


Fig 5(b). Relation between distance of moisture migration and initial moisture content.



A : 0 - 1/4 in.
B : 1/4 - 1/2 in.
C : 1/2 - 3/4 in.
D : 3/4 - 1 in.

Fig 6. Relation between initial moisture content and moisture content increase at each succeeding 1/4-inch interval of clay.

or approximately

$$k_1 : k_2 = \frac{e_1^3}{1 + e_1} : \frac{e_2^3}{1 + e_2}$$

or more approximately

$$k_1 : k_2 = e_1^2 : e_2^2$$

where

k_1 and k_2 are the permeabilities of two different types of sand,

e_1 and e_2 are the void ratios of the two different types of sand,

and

β_1 and β_2 are constants for the different types of sand.

For clay, if the void ratio is plotted using the natural scale, and permeability is plotted using a logarithmic scale, the result is approximately a straight line.

To study the effect of void ratio on moisture migration, samples with various void ratios were tested under different initial moisture-content and water-cement ratios. Results are shown in Tables 5 and 6. The relation between the moisture content increase and void ratio, shown in Tables 5 to 7, is plotted in Fig 7. The results shown in Fig 7 may be summarized as follows:

(1) The degree of moisture migration between cement mortar and soil depends on the void ratio of the soil.

(2) For the same void ratio and water-cement ratio, a lower moisture content tends to cause a higher migration of water from the cement mortar to the soil.

(3) For the same void ratio and moisture content, a higher water-cement ratio leads to more migration of water from the cement mortar to the soil.

TABLE 5. INFLUENCE OF VOID RATIO ON MOISTURE MIGRATION FROM CEMENT MORTAR TO CLAY*

Void Ratio	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
	0-1/4	1/4-1/2	1/2-3/4	3/4-1	
0.38	19.51	18.52	17.60	17.50	1.28
0.48	19.55	18.60	18.00	17.90	1.52
0.68	22.50	21.50	20.30	18.25	3.66
0.84	23.45	22.05	19.22	19.00	3.92
1.02	26.10	25.60	23.70	21.65	7.25

*	
Water-Cement Ratio	0.65
Initial Moisture Content	17 percent
Curing Period	7 days

TABLE 6. INFLUENCE OF VOID RATIO ON MOISTURE MIGRATION FROM CEMENT MORTAR TO CLAY*

Void Ratio	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
	0-1/4	1/4-1/2	1/2-3/4	3/4-1	
0.48	17.65	16.70	15.37	15.00	3.24
0.68	19.60	18.35	17.00	16.80	4.94
0.84	21.10	18.60	17.90	16.90	5.63

*	
Water-Cement Ratio	0.65
Initial Moisture Content	13 percent
Curing Period	7 days

TABLE 7. INFLUENCE OF VOID RATIO ON MOISTURE MIGRATION FROM CEMENT MORTAR TO CLAY*

Void Ratio	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
	0-1/4	1/4-1/2	1/2-3/4	3/4-1	
0.484	18.30	17.25	17.10	17.05	0.43
0.683	20.00	19.00	18.80	18.40	2.03
0.843	22.40	20.00	19.40	18.00	4.05

* Water-Cement Ratio	0.45
Initial Moisture Content	17 percent
Curing Period	7 days

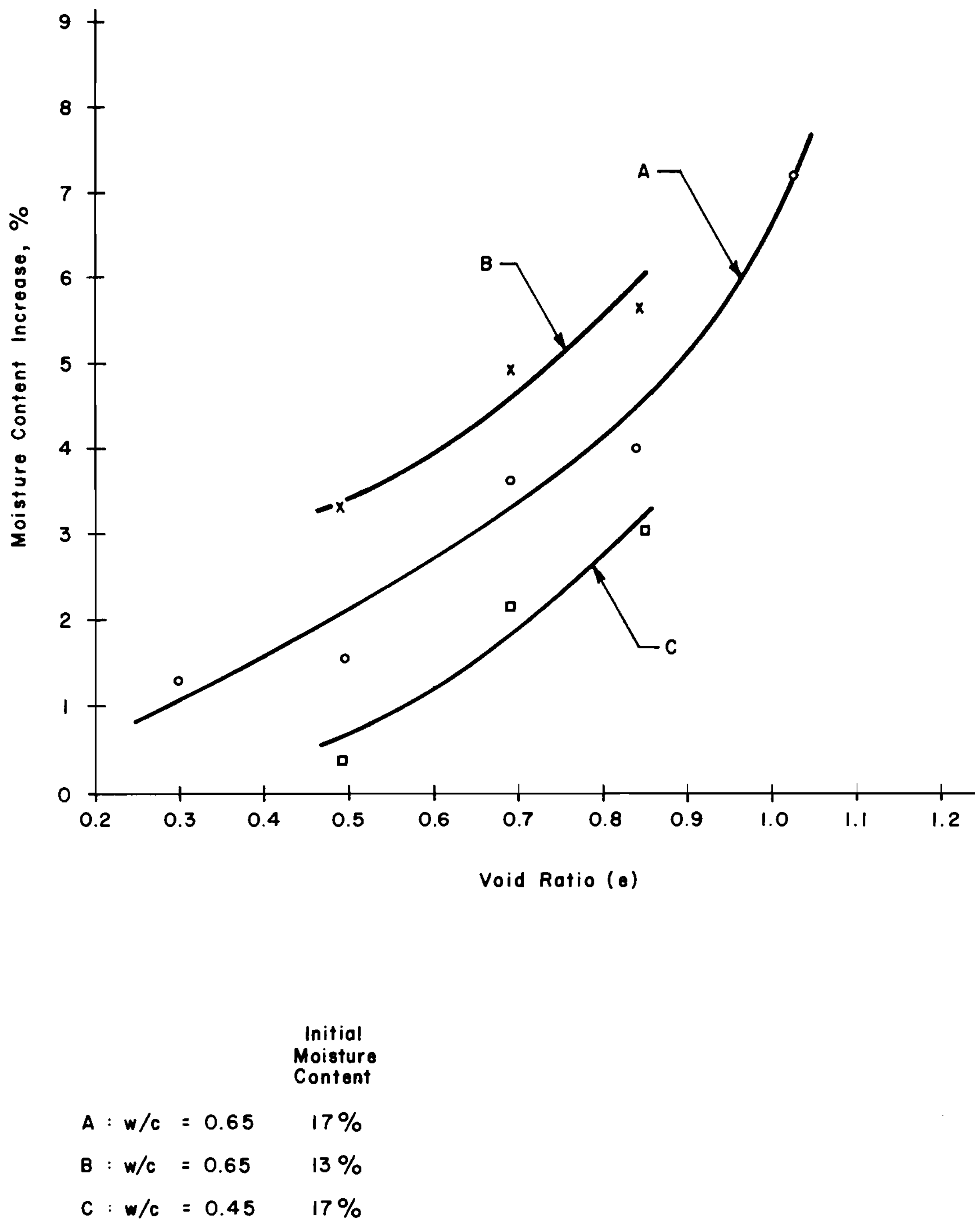


Fig 7. Relation between void ratio and moisture content increase.

Influence of Water-Cement Ratio

The water-cement ratio of cement mortar (for the same cement-sand ratio) is one of the main factors affecting water migration between cement mortar and soil, and it is the most important factor controlling the strength and consistency of concrete. In order to investigate the influence of water-cement ratio on moisture migration, soil with a void ratio equal to 0.68 and cement mortar with water-cement ratios of 0.5, 0.65, 0.8, and 0.9 were used. For water-cement ratios higher than 1.0 and lower than 0.4, the workability of cement mortar is very poor. The results of the tests are listed in Table 8.

The degree of moisture migration with relation to water-cement ratio is controlled by the void ratio and grain size of the soil. The prevention of water migration and consequent softening of the soil might be partly achieved by decreasing the water-cement ratio to a very low value. As can be seen from Table 8, the moisture-content increase of the soil Δw decreases as the water-cement ratio decreases. The value of the water-cement ratio that will cause negligible water migration and, consequently, prevent softening of the soil must be carefully studied.

Skempton (Ref 5), who studied the moisture migration problem on London Clay, using a water-cement ratio of 0.2, found that the water migration problem and local softening of the soil along a drilled and cast-in-place shaft were avoided. A low value of water-cement ratio will produce higher strength concrete, but it might be difficult to place such concrete in a drilled shaft in which there is a cage of reinforcing steel.

Influence of Time

The depth of migration of water from cement mortar into soil is relatively small. However, evaporation, transpiration, and soil-water capillarity will cause the moisture content near the surface of the cement mortar to change with time. The moisture content of the soil near the surface of the cement mortar will increase to a maximum and then decrease to a constant value. The moisture content of the soil at greater distances from the cement mortar will increase to a constant value, and the moisture will be retained by capillary and swelling forces.

The retention of water in the soil varies depending on the type of soil. For cohesionless soil, water is retained by the pressure difference developed

TABLE 8. INFLUENCE OF WATER CEMENT ON MOISTURE MIGRATION BETWEEN CEMENT MORTAR AND CLAY*

Water Cement Ratio	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
	0-1/4	1/4-1/2	1/2-3/4	3/4-1	
0.5	18.80	17.10	15.50	15.70	3.80
0.65	19.38	18.70	17.50	16.40	5.00
0.8	22.80	21.50	19.60	18.20	7.50
0.9	24.50	24.50	22.30	21.00	10.10

* Void Ratio	0.68
Initial Moisture Content	13 percent
Curing Period	7 days

across the air-water interface. For cohesive soil, water is retained by swelling forces. For the soils containing a mixture of particle sizes, the water retention is partly by capillary forces and partly due to swelling forces (Ref 7).

Laboratory tests were performed on remolded samples with an initial moisture content equal to 17.80 percent and a void ratio of 0.68. The water-cement ratio of the cement mortar was 0.65. After curing the samples for periods of 1, 7, 14, and 28 days, the samples were sliced into 1/4-inch pieces and the moisture content of each slice was determined. Undisturbed samples with initial moisture content of 15.0 ± 0.2 percent taken at the test site at Montopolis were also tested. The moisture contents of the undisturbed samples were determined after curing the samples for periods of 7 and 66 days. The results, given in Table 9, show that there is a decrease of water content when the curing period becomes longer.

The decrease of moisture content after a long period of curing will cause the soil to regain some of its strength. Whitaker and Cooke (Ref 1), after carrying out large-bored pile tests in London Clay, found that the shear strength increases as the curing period increases.

The Influence of Type of Cement

The rate of hydration of cement is an important factor affecting the moisture migration between cement mortar and soil. To study the effect of rate of hydration on moisture migration, two cements (Type I and Type III) with different rates of hydration were used in preparing test specimens. The rate of hydration for Type I cement is slower than the rate of hydration for Type III cement; therefore, theoretically, the moisture migration from cement mortar made of Type III cement will be smaller than that made from Type I cement. As was predicted, the results in Table 10 show that moisture migration is smaller for Type III cement.

The high early strength cement (Type III), which contains a higher percentage of tricalcium aluminate will hydrate rapidly and gain a high percentage of its potential strength within a few hours after placement. Though the Type III cement will harden more rapidly, it will liberate more heat and will shrink more. The shrinkage of concrete will decrease the normal pressure acting against the soil; therefore, the shearing resistance of the soil may be

TABLE 9. INFLUENCE OF TIME ON MOISTURE MIGRATION FROM CEMENT MORTAR TO SOIL

Curing Period	Average Moisture Content in Percent at Various Distances from Interface in Inches					
(Days)	0-1/4	1/4-1/2	1/2-3/4	3/4-1	1-1 1/4	1 1/4-1 1/2
	Remolded Samples					
1	23.50	20.30	19.20	17.90	17.80	17.85
7	22.50	21.50	20.30	18.35	18.00	17.70
14	22.85	21.50	20.00	19.42	18.28	17.84
28	22.36	20.15	19.94	18.70	18.00	18.00
	Undisturbed Samples					
7	17.82	16.84	16.28	15.80	15.03	14.95
66	17.50	16.75	16.30	15.86	15.20	15.00

TABLE 10. MOISTURE MIGRATION FROM CEMENT MORTAR MADE OF DIFFERENT TYPES OF CEMENT*

Type of Cement	Average Moisture Content in Percent at Various Distances from Interface in Inches				Δw Average Increase in First Inch
	0-1/4	1/4-1/2	1/2-3/4	3/4-1	
I	25.50	22.60	21.40	20.90	2.6
III	23.80	21.90	20.50	20.10	1.6

* Water-Cement Ratio 0.60
Initial Moisture Content 20.10 percent

TABLE 11. MOISTURE MIGRATION ON UNDISTURBED SAMPLES

Depth, ft.	Water-Cement Ratio = 0.6		Water-Cement Ratio = 0.7		Water-Cement Ratio = 0.8	
	Initial Moisture Content	Δw Average Increase in First Inch	Initial Moisture Content	Δw Average Increase in First Inch	Initial Moisture Content	Δw Average Increase in First Inch
3	27.10	-	23.15	0.44	21.60	1.30
6	18.00	0.37	17.28	2.23	18.35	2.60
8	16.00	1.61	16.10	2.24	16.00	3.28
9	13.70	3.19	13.10	3.42	13.70	4.88
11	13.82	2.08	13.82	2.04	13.80	2.33
13	15.00	1.99	14.30	2.38	14.95	3.24
15	-	-	-	-	12.70	-

reduced. To reduce the shrinkage of the concrete, the addition of a high percentage of tricalcium silicate and a low percentage of dicalcium silicate is necessary in the high early strength cement.

Influence of Water-Cement Ratio on Moisture Migration Into Undisturbed Samples

The migration of water between cement mortar and undisturbed samples from the Montopolis test site was studied using water-cement ratios of 0.6, 0.7, and 0.8. Samples were cured under an overburden pressure of 10 psi. Results are shown in Table 11 and are plotted in Fig 8. The results show that the moisture-content increase Δw changed as the water-cement ratio increased. Also, Δw varies with initial moisture content such that if the initial moisture content increases, the Δw value decreases and vice versa. The results are also shown in Fig 8, which depicts moisture-content increase in the inch nearest the interface between cement mortar and soil versus the initial moisture content of the soil samples. In addition to the above results, it was noted that the deepest moisture penetration was about 2-1/2 inches.

SUMMATION OF RESULTS OF LABORATORY STUDIES ON MOISTURE MIGRATION

The nature of moisture migration from cement mortar to soil is a complex problem. The influence of factors which affect moisture migration can be studied separately, but the analysis of the relationship of multiple factors to moisture migration is still an intricate problem. However, it can be concluded that the degree of moisture migration between cement mortar and soil is greatly affected by (1) void ratio, (2) initial moisture content, (3) water-cement ratio, and (4) other variables such as temperature, type of cement, hydraulic pressure, and time.

The relationship between water migration, as represented by Δw , and independent factors has been treated separately as discussed. The numerical results, shown in Points 2 through 4 below, were obtained by making least-squares fittings of the data points. For the soils and cements used in these tests, the results are as follows:

(1) The overburden pressure on unset cement mortar will increase the moisture migration. However, the influence of 5 psi overburden pressure on moisture migration is insignificant.

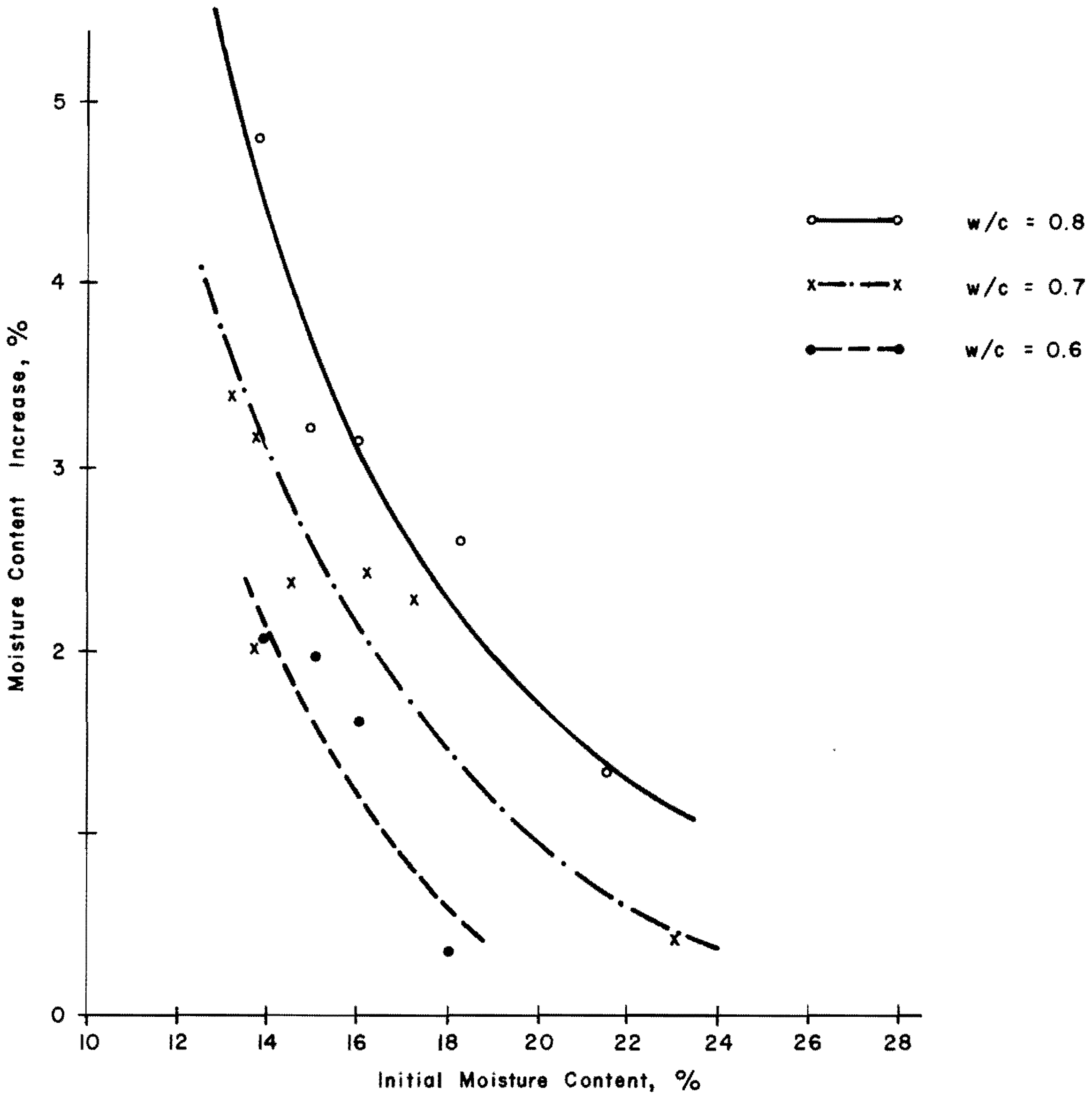


Fig 8. Relationship between initial moisture content and moisture content increase migrated from fresh cement mortar to undisturbed soil.

(2) There is a definite relationship between moisture migration and water-cement ratio. For a water-cement ratio in the range of 0.4 to 1.1, an increase of 0.1 in water-cement ratio will cause approximately a 1.42 percent increase in moisture migration.

(3) The relationship between moisture migration and void ratio is such that for a void ratio in the range of 0.4 to 1.2, an increase of 0.1 in void ratio causes a 0.685 percent increase in soil moisture.

(4) The suction of water from unset cement mortar into soil will decrease as the initial moisture content of the soil increases.

The numerical results shown in Fig 8 are obviously related to the type of soil employed in the testing; however, it is felt that the general relationships which were developed are valid for clay or sandy clay.

CHAPTER 3. LABORATORY STUDIES ON SHEAR STRENGTH BETWEEN CEMENT MORTAR AND SOIL

INTRODUCTION

For a drilled shaft, the applied load is transferred into the surrounding soil by base bearing and wall friction. The maximum load that can be transferred to the soil (Refs 2, 3, and 4), or the bearing capacity of a drilled shaft, depends on the size of the shaft and the shear strength of the supporting soil. If the shear strength of soil is represented by Coulomb's equation, which states that

$$\tau_f = c + \sigma' \tan \phi$$

there are three factors which determine the shear strength of a soil. As illustrated in Fig 9, they are cohesion c, effective normal stress σ', and the angle of internal friction ϕ (Refs 9, 10, and 11).

A complete discussion of the shear strength of soil is not appropriate to this report. For the purposes of this discussion, it will be assumed that c and ϕ are soil properties at a given soil water content and void ratio, and that these properties can be obtained from appropriate laboratory or field tests.

Problem

Water is an important factor in determining the mechanical properties of a soil. For an unsaturated clay, the addition of water not only decreases the cohesion of clay but also decreases the effective stress. Since the moisture content of unsaturated soil at the drilled shaft will increase after concrete is poured, a certain change of the soil properties, especially the mechanical properties of the clay, is expected. For a soil with pores larger than cement particles, both cement and water will penetrate into the soil. The cement that penetrates into the soil will form a layer of cement soil at

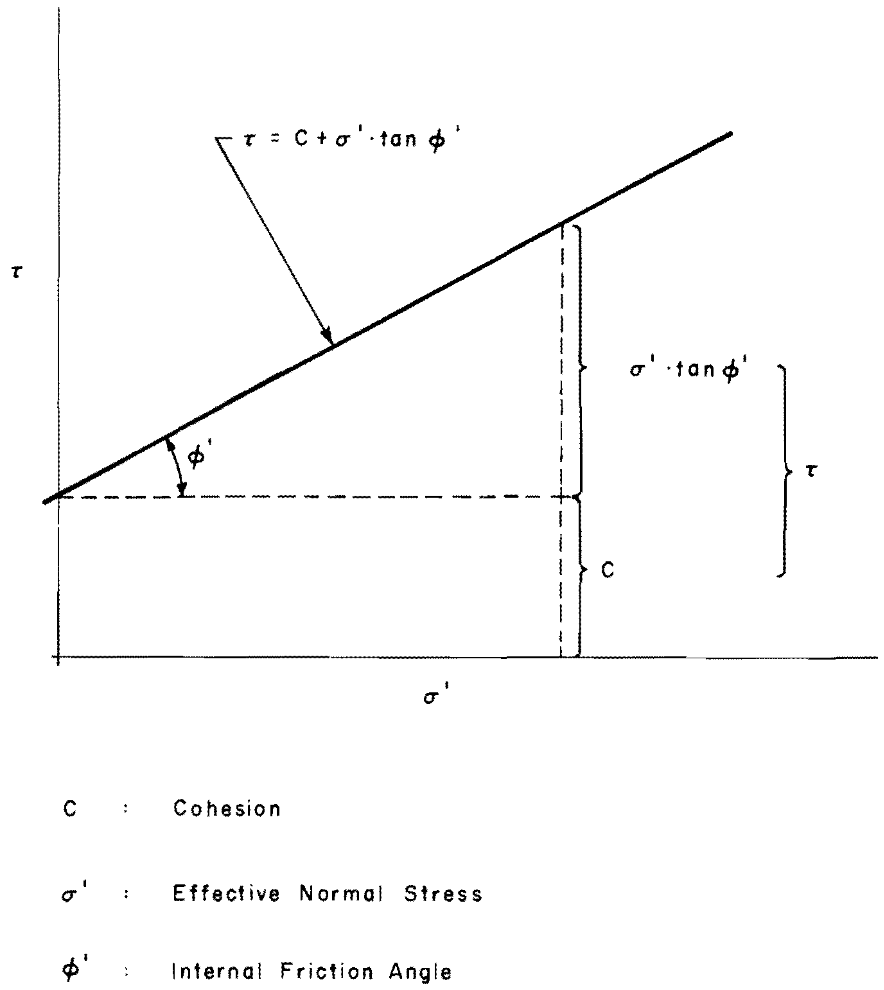


Fig 9. Shear strength factor shown graphically.

the interface, which will increase the shearing strength of the soil. For soil such as clay, with pores smaller than the cement particles, there will be only water migration (no cement penetration) with a consequent decrease in shear strength.

Scope of the Investigation

The objectives of the investigation of shear strength between cement mortar and soil are

(1) to determine the consequence of wetting of the soil after the cement mortar is poured,

(2) to determine the weakest zone which might be formed between cement mortar and soil after cement mortar is poured, and

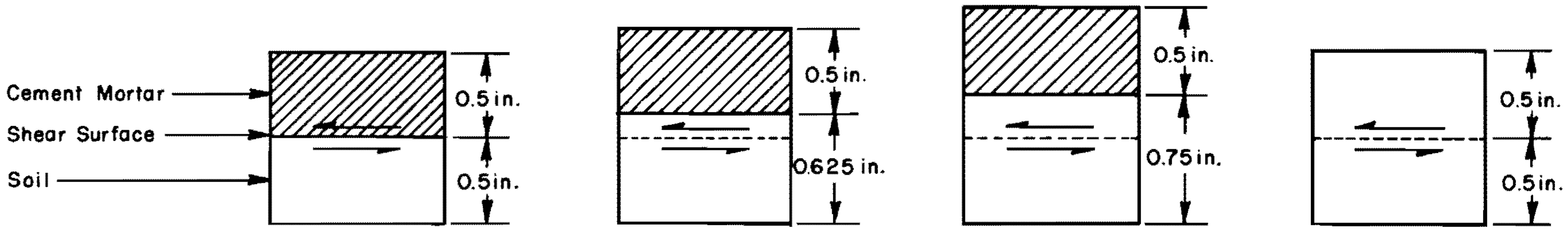
(3) to determine the effect of water-cement ratio on the interaction between cement mortar and soil.

Testing Program

To obtain better understanding of the interaction between cement mortar and soil, a series of direct shear tests on cement mortar-soil specimens was performed in such a way that the shear surfaces were arranged at the contact surface, at 1/8 and 1/4 inch from the cement mortar surface. It was desired to establish the effect of the added moisture from cement mortar on the shear strength of clay. The four different shear surfaces tested are shown in Fig 10.

Preparation of Samples

The materials (soil and cement mortar) used in this series of tests were the same as those used in the moisture migration tests. Soils with various moisture contents were compacted in the shear box according to the calculated void ratio, to a height of 1/4 inch above the desired height. The excess 1/4 inch of soil was trimmed off so that the shear surface was located as desired (see Fig 10). For shear tests which required undisturbed soil, the soil specimen was trimmed to the desired dimensions and placed in the shear box. With the soil in place, the upper frame of the shear box was greased and cement mortar, with a mixing ratio of sand to cement of 3 to 1 and a water-cement ratio of 0.6, was poured on the soil. The box was then sealed with grease and placed in the direct shear machine for a curing period of seven days.



Shearing at interface

Shearing 1/8 in. from interface

Shearing 1/4 in. from interface

Shearing of soil alone

Fig 10. Section through test specimens used in direct shear machine.

Description of Direct-Shear Test

In order to investigate the shear strength of soil-cement mortar samples, an MIT direct-shear-test machine with a variable-speed-control motor was used for testing the remolded and undisturbed samples (Refs 16 and 17). The direct-shear-test machine is illustrated in Fig 11. The shear box which holds the sample, half of which is within either frame, consists of two parts, the upper frame and lower frame. The lower frame is fixed on a movable platform, and by moving the platform in a direction parallel to the plane of separation, a shear force is applied at the plane of separation of the sample between upper frame and lower frame. The magnitude of the shear force is measured by a proving ring which is connected to the upper frame by a connecting bar. The shearing displacement is given by readings of a horizontal extensometer dial.

The influence of water-cement ratio, moisture content of the soil, and grain sizes on shear strength of the cement mortar-soil sample was investigated. In each series of tests, every effort was made to keep all variables constant except for ones being studied. The following is a list of these constant conditions:

(1) The soils, clay and sandy clay, were prepared in the same manner.

(2) The initial void ratio of all specimens was approximately equal to 0.48.

(3) The shearing box was 2.83 inches in diameter.

(4) The normal load was 10 psi during the curing period and during testing.

(5) The speed of the tests was controlled by moving the platform at 0.05 inch of horizontal displacement per minute.

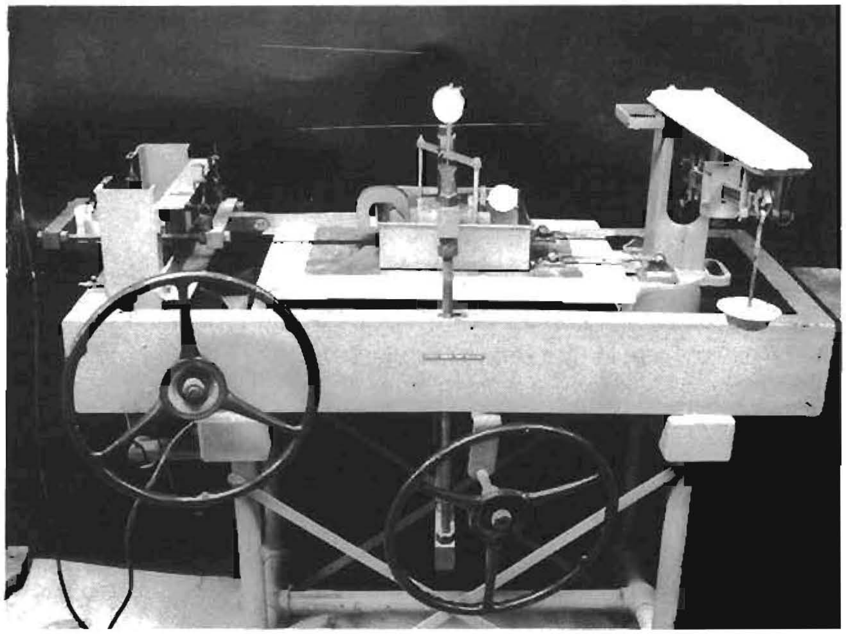
(6) Tests were continued until the shearing resistance of the specimen decreased.

After each test, the specimen was cut into 1/4-inch slices, and the moisture content of each slice and the increase in moisture content were determined.

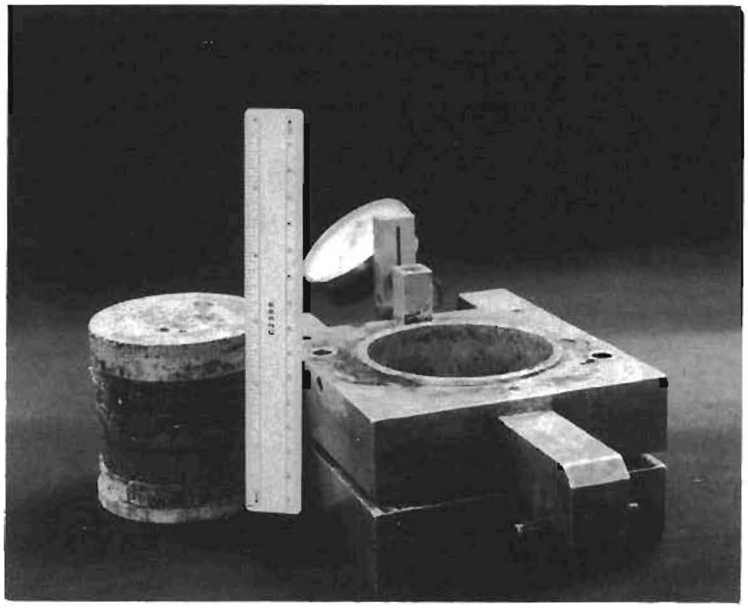
TEST RESULTS ON REMOLDED SAMPLES

Shear-Test Results of Sandy Clay and Sandy-Clay Loam Samples

For samples made of sandy-clay loam and sandy clay, cement is drawn into the soil and forms a layer of soil cement about 1/8-inch thick at the surface



Direct Shear Machine



Direct Shear Box

Fig 11. Direct shear test machine.

of the cement mortar; therefore, the shear strength at the contact surface of cement mortar is found to be higher than the shear strength of samples prepared entirely from soil. The increase of shear strength depends on the penetration of cement into the soil, i.e., it depends on the void ratio of soil and water-cement ratio of the cement mortar. Also, when the grain size of the soil increases, more soil-cement forms at the surface of the cement mortar, and the shear strength at the contact surface is increased.

The shear strengths of sandy clay on the different shear planes are listed in Table 12. The results show that the shear strength at the contact surface is larger than the shear strength of the soil. The weakest zone occurs at a distance of about 1/4 inch from the surface of the cement mortar. For those tests where the shearing surface was arranged at the interface, the actual rupture surface for most of the specimens developed at about 1/8 inch into the soil.

Typical curves of the ratio of shear stress to normal stress τ/σ versus the horizontal displacement, in Figs 12 and 13, show the following:

(1) When the shearing surface was arranged at the interface, brittle behavior was observed (see Curves B in Figs 12 and 13).

(2) The shearing resistance of soil-cement-mortar samples develops at less horizontal displacement than the shearing resistance of samples composed entirely of soil.

(3) At maximum shearing resistance, the horizontal displacement of the soil with cement mortar is smaller than that of plain soil.

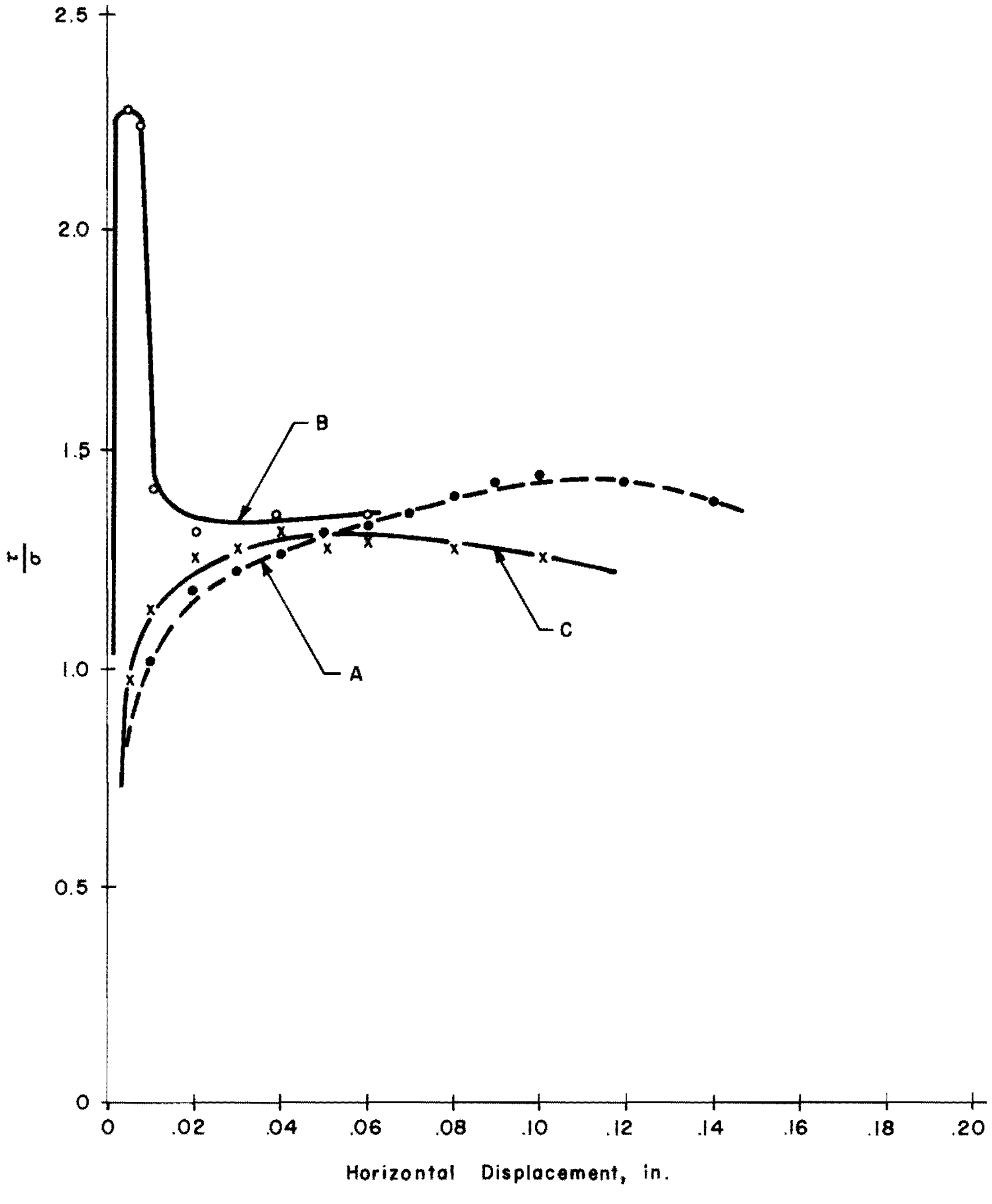
Shear-Test Results of Clay Samples

The ratio of the shear strength of soil-cement-mortar samples to the shear strength of the soil before the placement of cement mortar is defined as α . It was found that α is greatly affected by the moisture change. The more water drawn into the soil, the lower the α value. The shear strength of the soil after the placement of the cement mortar was found to be smaller than the shear strength of the soil before the placement of the cement mortar; this fact was indicated by α values less than 1.0. As with sandy clay, most of the samples which were shear tested at the contact surface of the soil and cement mortar did not fail at the contact surface but somewhere at about 1/8 inch from the cement-mortar surface, because the shear strength of soil within 1/8 inch of the cement-mortar surface is higher than the shear strength of the

TABLE 12. SHEAR STRENGTH OF SANDY CLAY AND SANDY-CLAY LOAM AT DIFFERENT SHEAR PLANES AFTER CEMENT MORTAR IS POURED

Grain-Size Distribution	Initial Moisture Content	Shear Strength Tested at a Distance from Interface (0-1/4 inch) α Value in Parentheses			
		0*	1/8	1/4	Soil
Sandy Clay	10	3560 (1.09)	2700 (0.88)	2020 (0.62)	3260
Sandy Clay	13.8	2740 (1.01)	2120 (0.785)	1630 (0.604)	2700
Sandy-Clay Loam	10.5	3480 (1.17)	3280 (1.10)	1980 (0.67)	2960

* Shear failure planes occurred at about 1/8 inch from cement mortar.

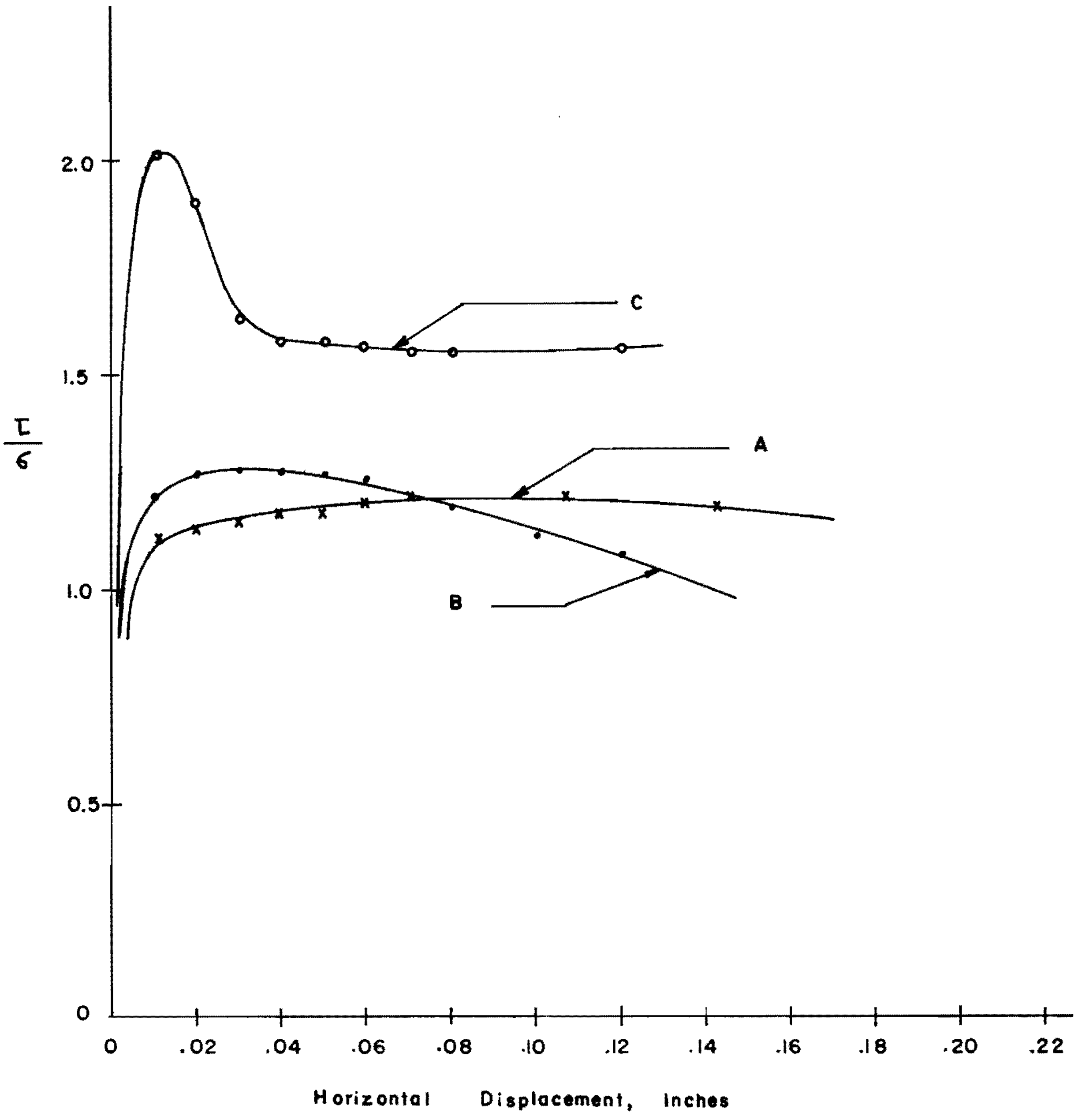


A = Plain Soil

B = Shear Surface at 1/8 in. from Cement Mortar

C = Shear Surface at 1/4 in. from Cement Mortar

Fig 12. τ/σ versus horizontal displacement (sandy-clay loam).



A : Plain Soil
B : Shear Surface at 1/4 Inch from Cement Mortar
C : Shear Surface at 1/8 Inch from Cement Mortar

Fig 13. τ/σ versus horizontal displacement (sandy clay moisture content 13%).

soil at a distance greater than 1/8 inch. As shown in Table 13, the weakest zone is located about 1/4 inch from the cement-mortar surface, and the α value for the weakest zone lies between 0.4 and 0.6. Typical curves of τ/σ versus horizontal displacement, shown in Fig 14, show that the maximum τ/σ appears at about 0.01 inch, and the maximum τ/σ value is decreased by the placement of mortar.

Influence of Moisture Content

The α values obtained from the test results indicate that when the initial moisture content is low (see Tables 12 and 13), the α value is low, and when the initial moisture content becomes high, the α value becomes high. The values of α from Tables 12 and 13 are plotted in Fig 15 versus moisture content of the soil. The results show appreciable scatter, but a pattern of curve trend can be estimated. The scattered values of α are probably caused by the fact that the weakest shearing resistance plane changes with varying moisture content of the soil. They also might be caused by the temperature and sample size.

The results shown in Fig 15 also show a change in the value of α from about 0.4 at a moisture content of 10 percent to about 0.68 at a moisture content of 20 percent. The effect of initial moisture content on the shearing resistance of soil becomes negligible when the initial moisture content is very high. It can be concluded that when a drilled shaft is founded in a soil of high moisture content, the shearing strength modification factor α is higher than that used when the soil is dry.

A study of all the data shows that a difference in the initial moisture contents of the samples caused a change in the shape of the plot of τ/σ versus horizontal displacement. The peak of τ/σ will occur at a large horizontal displacement.

Influence of Water-Cement Ratio

The water-cement ratio of cement mortar is one of the main factors that determine the moisture migration between cement mortar and soil and, thus, affect the shearing resistance of the soil. The prevention of moisture migration from fresh concrete to soil and the softening of soil surrounding a

TABLE 13. SHEAR STRENGTH OF CLAY AT DIFFERENT SHEAR PLANES AFTER CEMENT MORTAR IS POURED

Initial Moisture Content	Shear Strength Tested at a Distance from Cement Mortar Surface (0-1/4 inch) α Value in Parentheses			
	0	1/8	1/4	Soil
13	4040 (0.903)	3250 (0.726)	2575 (0.576)	4470
17	2373 (0.649)	2575 (0.704)	1786 (0.488)	3660
20	*1940 (0.670)	1980 (0.683)	2090 (0.715)	2900

* Shear failure plane occurred at a distance of 1/8 inch from the cement mortar surface.

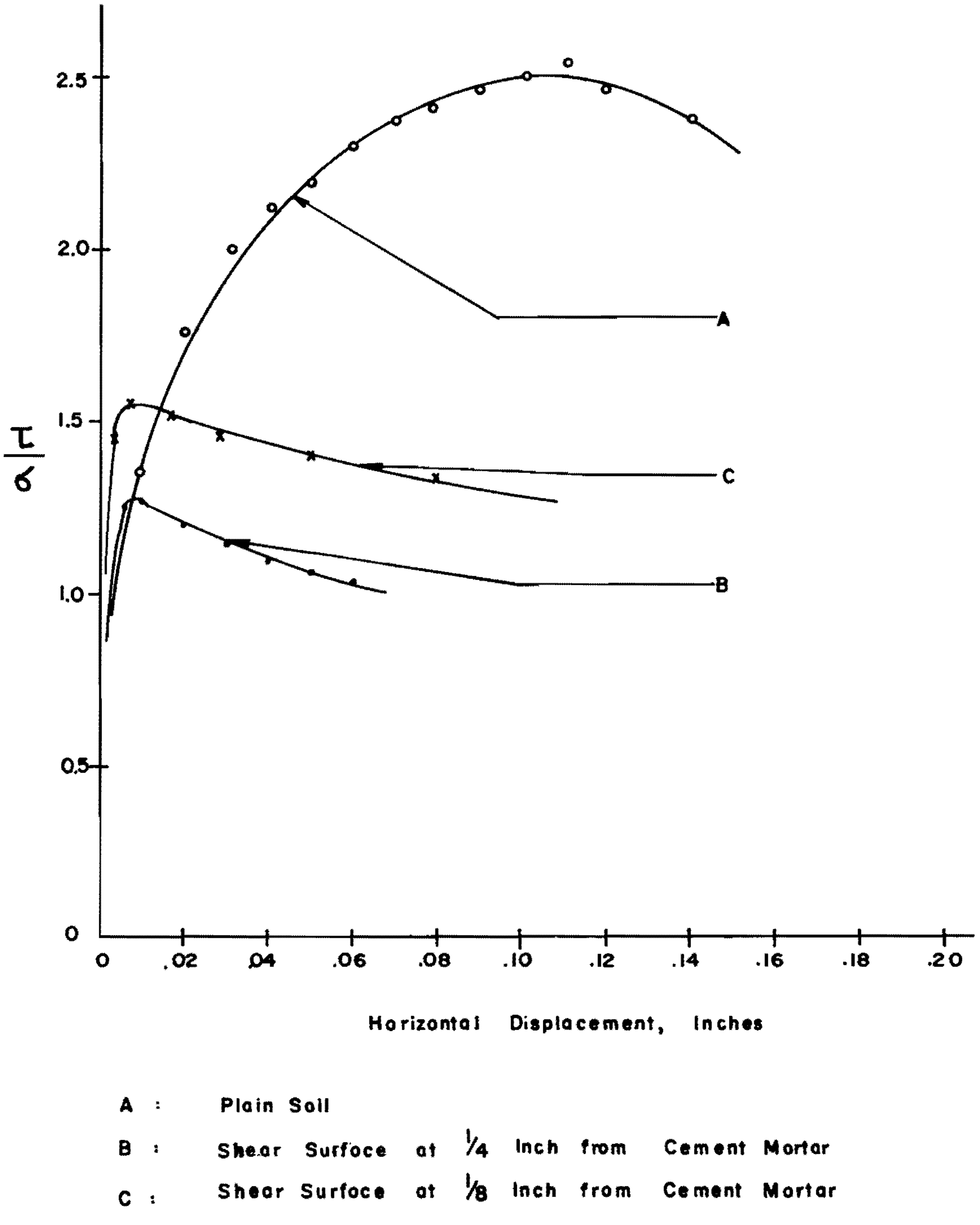


Fig 14. τ/σ versus horizontal displacement (clay moisture content 17.0%, normal pressure 10 psi).

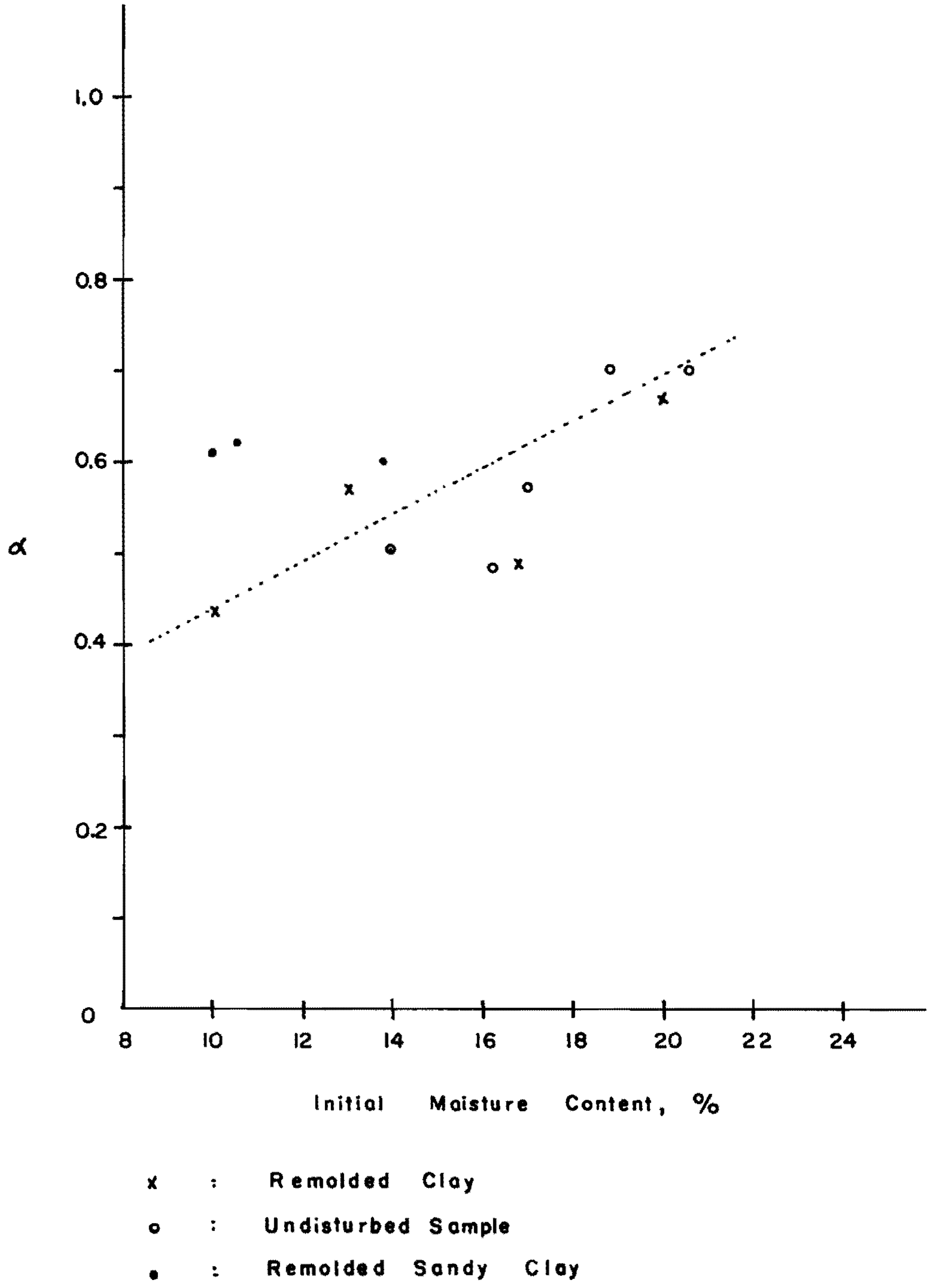


Fig 15. α value versus moisture content of soil.

drilled shaft can be partly achieved by decreasing the water-cement ratio. This concept was first studied by Meyerhof in London Clay, where he, in an attempt to avoid the local softening of the soil, constructed some bored piles with a water-cement ratio of only 0.2. He found that the local softening of the soil had been avoided.

In order to investigate the effect of the water-cement ratio on the shearing resistance of soil, specimens with various water-cement ratios were made and tested at the same shear plane under the same conditions. Samples of clay with an initial moisture content of 20 percent and a void ratio equal to 0.48 were tested at 1/8 inch from the cement-mortar surface. The results show that the shearing resistance of the soil increased as the water-cement ratio decreased.

The results, shown in Table 14, show that the value α increases from 0.48 at a water-cement ratio of 0.9 to 0.79 at a water-cement ratio of 0.5. Thus, the local softening of the soil obviously has been partly avoided.

Tests on Undisturbed Samples

Table 15 shows results from shear tests of undisturbed samples. For various depths, the table shows shearing resistance and moisture content for two locations of the shearing surface, one at the interface and another at 1/4 inch from the interface. The table shows that the moisture content at the contact surface of the cement mortar and soil is higher than at a distance of 1/4 inch from the cement mortar except for the test at a depth of 13 feet. However, the shearing resistance developed at the contact surface is higher than the shearing resistance at a distance of 1/4 inch from the cement mortar. The reason for this increase is the adhesion and binding forces that developed between the cement mortar and soil after the fresh cement mortar was poured. The weakest zone of most samples tested was located 1/4 inch from the cement mortar.

The higher the moisture content, the lower the shear strength of the soil-mortar samples, except that the shearing strength of soil cement samples recorded at 6 feet is higher than that at 8 feet. These contradictions are probably caused by the change of soil properties between 6 feet and 8 feet. (see Appendix 1).

TABLE 14. SHEARING RESISTANCE AT 1/8 INCH FROM CEMENT MORTAR SURFACE UNDER VARIOUS WATER-CEMENT RATIOS

Water-Cement Ratio by weight	Shear Strength, tsf	α
0.9	1400	0.48
0.8	1700	0.58
0.7	1720	0.59
0.6	1980	0.68
0.5	2300	0.79
Soil	2900	1.00

TABLE 15. SHEAR TESTS RESULTS (UNDISTURBED SAMPLES)

Depth, ft	U C Test, tsf	Direct Shear Test, tsf	Shearing Resistance Tested at a Distance from Interface, tsf			
			0 inch	α	1/4 inch	α
6	3.84(17.8)*	1.70	1.59(20.1)*	0.93	1.34(18.8)	0.79
8	4.50(14.4)	2.10	1.36(19.6)	0.65	1.09(16.1)	0.52
9	5.30(14.0)	2.55	2.10(16.1)	0.83	1.35(15.5)	0.53
11	-	3.48	3.05(14.7)	0.87	1.73(14.5)	0.50
13	-	2.50	1.75(16.3)	0.70	1.28(17.1)	0.51

* Water content at failure surface.

SUMMATION OF RESULTS OF LABORATORY STUDIES ON SHEARING RESISTANCE

The results of the change of shearing resistance of the unsaturated soil tested may be summarized as follows:

(1) For sandy loam and sandy clay, the shearing resistance at the interface is slightly increased above undisturbed strength, but slightly decreased for clay.

(2) The weakest zone observed from most samples is located 1/4 inch from interface.

(3) The α values can be expressed as a function of the water-cement ratio (with the same cement-sand ratio) and moisture content of soil.

CHAPTER 4. CHANGE OF SOIL PROPERTIES AROUND A DRILLED SHAFT DUE TO THE MOISTURE MIGRATION FROM THE FRESH CONCRETE

The change of soil properties around a drilled shaft due to the moisture migration from fresh concrete is determined by properties of the soil such as water content, particle-size distribution, and void ratio, and properties of concrete such as water-cement ratio, sizes of aggregates, and type of cement. When the fresh concrete is poured in the drilled excavation, water will migrate into the surrounding soil in a horizontal direction due to the suction pressure of the soil. The increase of moisture content of the soil, however, decreases the suction pressure of the soil, that is, the retention force of the soil. As a consequence, the water will flow downward (due to gravity) until the retention force and gravity are balanced. Moisture migration between concrete and soil on bored piles in London Clay was studied by G. G. Meyerhof (Ref 4). He found that the amount of moisture migration along a drilled shaft increases as the depth increases.

Two methods can be used to determine the shearing resistance of the soil around a drilled shaft after the concrete is poured, and from this the load carried by the side of the drilled shaft can be computed. These procedures may be described as follows:

(1) Determine the shearing resistance directly in the laboratory by testing specimens composed of cement mortar in contact with undisturbed soil.

(2) Compute the shearing resistance by finding the initial moisture content of the undisturbed soil and obtaining the modification factor for the appropriate water-cement ratio based upon the studies reported in Chapters 2 and 3.

These methods are discussed in detail below, and examples involving the use of each method are presented.

METHOD I: DETERMINATION OF SOIL PROPERTIES AROUND A DRILLED SHAFT BASED ON TESTS OF CEMENT-MORTAR-SOIL SPECIMENS

Laboratory studies concerned with moisture migration from wet concrete to soil and the shearing resistance of the soil, as discussed in previous chapters, can be performed. These tests can be used to determine the change of soil properties around a drilled shaft, and also can be used to estimate the total friction resistance along the surface of the shaft.

The procedure for obtaining shearing resistance from laboratory studies of cement-mortar-soil samples is as follows:

(1) Use thin-walled sampling tubes, and obtain undisturbed samples down to the desired depth (some distance below the shaft tip).

(2) Consider the shaft to be composed of finite increments. Determine the shearing resistance and moisture content of the undisturbed soil at the level of each increment.

(3) Conduct tests to obtain the moisture migration from mortar to soil as a function of the overburden, using the undisturbed samples. The overburden pressure to be applied to the mortar-soil specimens is determined from Eq 2.1. Other details of the test are described in Chapter 2.

(4) Using undisturbed soils, with mortar-soil specimens prepared as for Step 3, perform direct shear tests to determine shearing resistance. The shearing surface is forced to occur at the interface and in the soil at various distances from the interface. The details of these shearing tests are described in Chapter 3.

(5) From the results of Step 3 plot soil-moisture content versus distance from interface for the various depths for which the tests in Step 3 were conducted.

(6) From Step 4 plot α versus distance from interface for the various depths described above. From this relationship determine the minimum value of α and the distance from the interface at which it occurs and thereby obtain the position of the weakest zone at each increment along the drilled shaft. The soil will fail along this zone.

(7) The modified shearing resistance of the soil after the concrete is poured can be obtained by multiplying the value of shearing resistance of the undisturbed soil by the factor α .

METHOD II: SHEARING RESISTANCE ESTIMATED BY ASSUMING α AS A FUNCTION OF MOISTURE CONTENT

After analyzing the results in Chapters 2 and 3, it can be concluded that the amount of moisture migration from fresh concrete into medium stiff clay and the interaction between soil and concrete is a function of the water-cement ratio of the concrete and the original moisture content of the soil. Interaction between concrete and the soil can also be estimated approximately by using the results of laboratory tests on undisturbed and remolded samples.

In other words, the results expressed in Figs 8 and 15 are taken to be valid for the range of water-cement ratios shown and for any medium stiff clay.

The procedure for estimating the shearing resistance of the soil along a drilled shaft by assuming α as a function of moisture content is

(1) follow Step 1 in Method I,

(2) follow Step 2 in Method I,

(3) find the minimum value of α from Fig 15 as a function of original moisture contents for various depths, and

(4) obtain the modified shearing resistance of the soil after the concrete is poured by multiplying the value of the shearing resistance of the undisturbed soil by the factor α .

In addition to finding the shearing resistance, the increase in moisture content can be determined using Fig 8. Thus, the average moisture content of the soil 1 inch from the interface can be obtained by adding the moisture increase to the original moisture content of the soil.

Computing Load Carried by Side of a Drilled Shaft

The load carried by the side of the drilled shaft can be estimated by using the modified shearing resistance of the soil. The procedure for obtaining the load is as follows:

(1) Using the modified shearing resistance of the soil obtained from Method I or Method II, compute the load carried by each increment along the drilled shaft:

$$\Delta R_i = \Delta A_i c_i \alpha_i$$

where

ΔR_i = frictional resistance at the i^{th} increment,

ΔA_i = area of side of drilled shaft in contact with soil at the i^{th} increment,

α_i = the minimum value of α at the i^{th} increment,

c_i = shearing resistance of undisturbed sample at the i^{th} increment.

(2) The estimated load carried by the side of the drilled shaft is equal to the sum of the frictional resistance at each increment. Thus

$$R = \sum_{i=1}^{M} \Delta R_i = \sum_{i=1}^{M} \Delta A_i c_i \alpha_i$$

where M is the total number of increments.

EXAMPLE OF THE USE OF METHOD I

A drilled shaft 2 feet in diameter and 12 feet long was constructed in Austin, Texas, in August, 1966. The moisture content and unconfined compression strength variations are shown in Fig 16. Curve A in Fig 16 is the best fit for moisture content, and Curve B is the best fit for unconfined compression strength. The water-cement ratio of the concrete was 0.6.

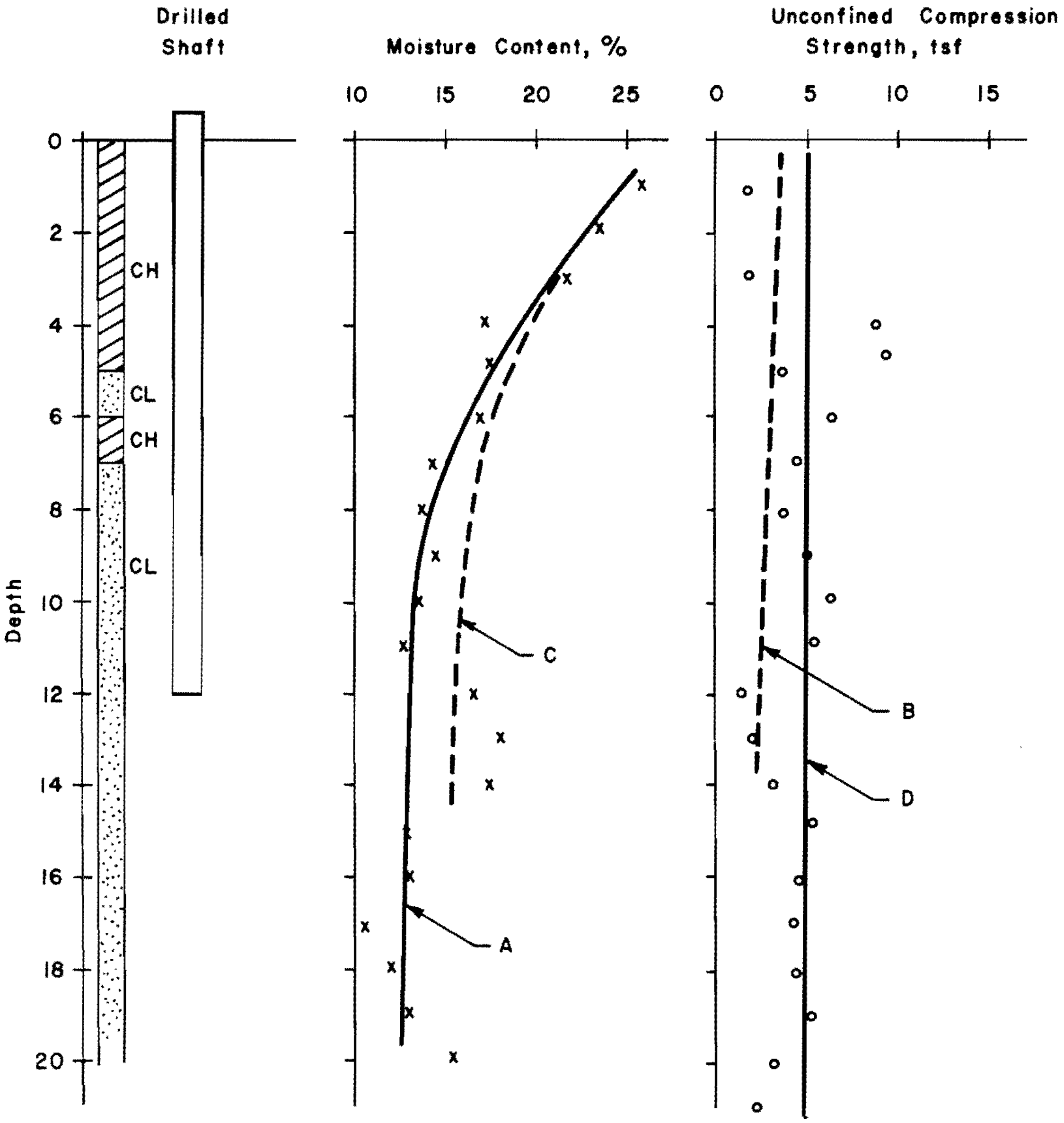
Undisturbed samples were tested for moisture migration at depths of 3, 6, 8, 9, 11, and 13 feet. The overburden pressure applied during the curing periods for samples at 8, 9, 11, and 13 feet was 10 psi, while an overburden pressure of 5 psi was used for the samples taken at 3 and 6 feet. The moisture content versus distance from interface at each depth obtained from these tests is shown in Fig 17, and the average moisture-content increase in the first inch is given in Table 10. Moisture migrated up to 1-1/2 inches into the soil, thus decreasing the shear strength in that region near the interface.

Direct-shear tests which forced the shearing plane to develop at various distances from the interface were conducted on mortar-soil samples. The samples used in the direct-shear tests were taken from the same depths and tested at the same overburden pressures, except that the 3-foot sample was omitted. The results of these tests are plotted in Fig 18.

Figure 18 clearly indicates that the zone of weakest soil occurs at about 1/4 inch from the interface. Hence, the soil in this zone will have its maximum shearing resistance mobilized first, and failure will occur at approximately 1/4 inch from the interface.

Assume that the shearing resistance of the soil is fully developed along the drilled shaft; the total load on the side of the drilled shaft is equal to R. The computation of the load is shown in Table 16.

The actual side load obtained from analyzing the results of a load was 106 tons. The side load was separated from the total load applied at the top



A = Original Moisture Content
B = Unconfined Compression Strength
C = Estimated Moisture Content After Fresh Concrete Is Poured
D = Estimated Unconfined Compression Strength After Fresh Concrete Is Poured

Fig 16. Estimated moisture and shearing resistance of soil at various depths.

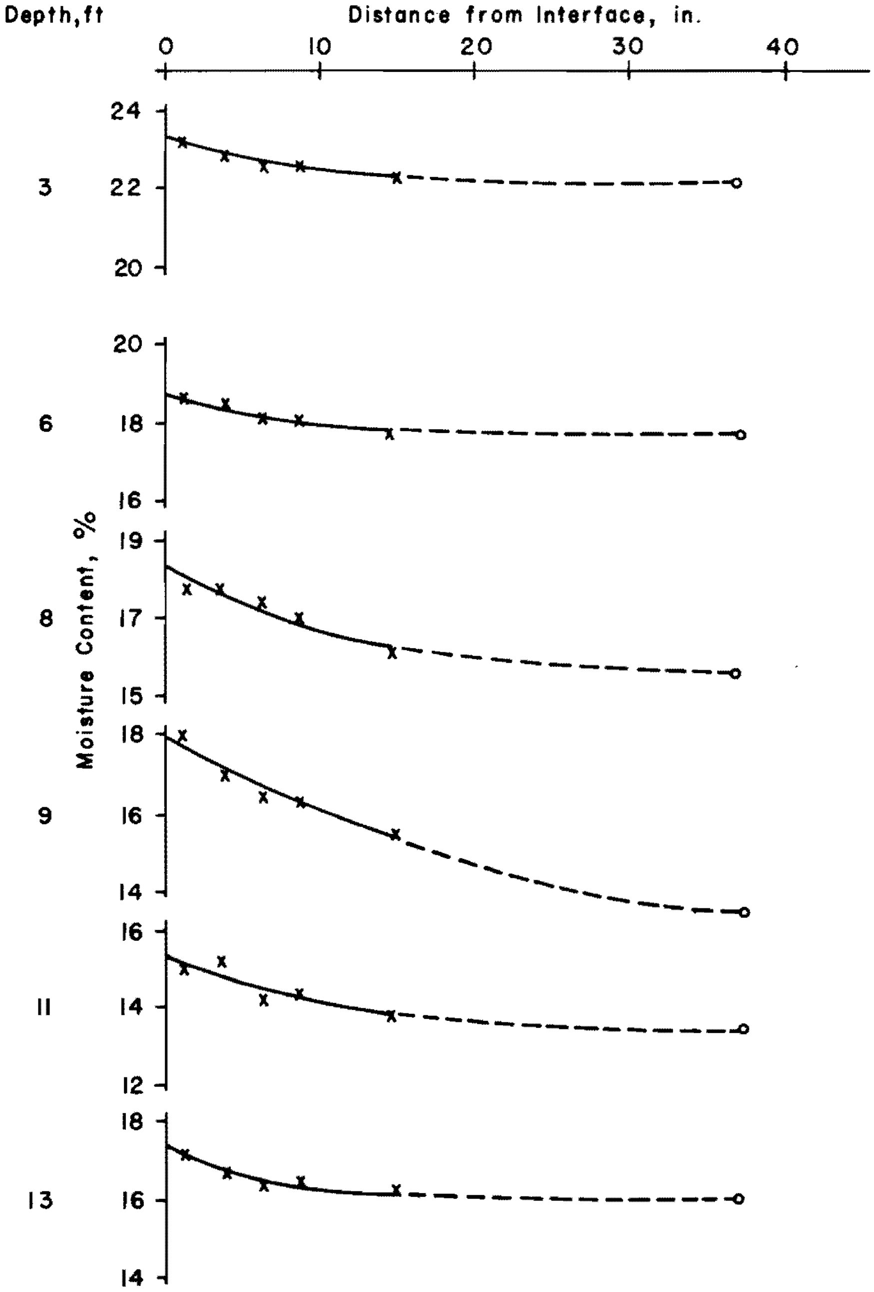


Fig 17. Distribution of moisture contents of soil at cement mortar-soil samples.

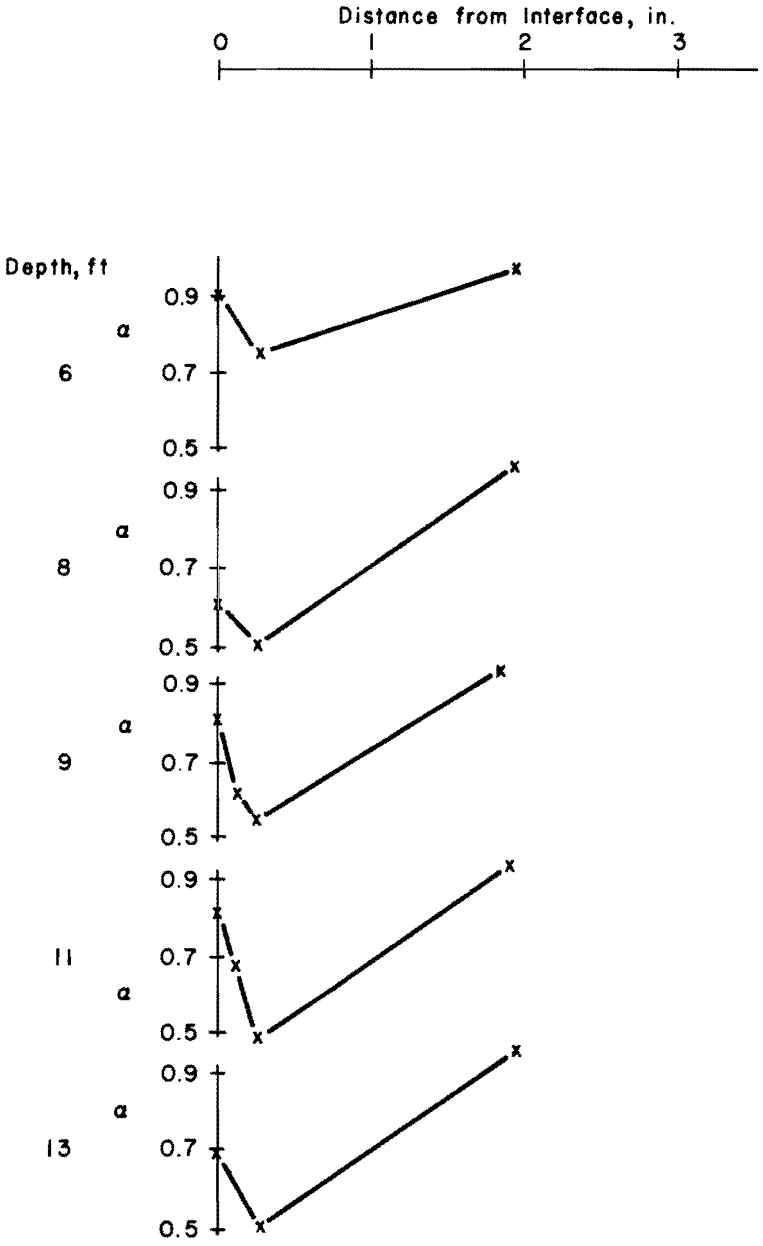


Fig 18. α values with relation to the distance from interface along the drilled shaft.

TABLE 16. LOAD COMPUTATION

Depth, ft	c_i , tsf	α_i	$c_i\alpha_i$, tsf	ΔA_i , ft^2	ΔR_i , tons
0-6	1.70	0.79	1.34	38.46	51.5
6-8	2.10	0.52	1.09	12.82	15.6
8-9	2.55	0.53	1.35	6.44	7.8
9-11	3.48	0.50	1.74	12.82	19.9
11-12	2.50	0.51	1.28	6.44	9.7
Total load carried by side of the drilled shaft					104.5

of the shaft by the use of instrumentation along the shaft. For this test, the agreement between computed and experimental values of side load was very good.

USE OF METHOD II

The use of Method II for the example in this paper would produce results identical with those for Method I since the basic data are the same. In general, Method II would produce results with some indeterminate error since one could not be certain that results of moisture migration and strength studies reported in Chapters 2 and 3 would be valid for the soil at the site in question.

However, in the absence of results from a comprehensive test series on undisturbed samples, Method II could be applied to obtain at least a first approximation of the load capacity of the side of a drilled shaft.

SUMMARY

The shearing resistance of soil surrounding a drilled shaft will change after concrete is poured. This change depends upon the properties of the soil and concrete. The change in shearing resistance can be expressed approximately as a function of only concrete-water cement ratio and initial soil-moisture content in medium stiff clays.

The computed load capacity of the side of the drilled shaft investigated in the example described was 104.5 tons while the load capacity measured in a field experiment was 106 tons. This is excellent agreement. If no reduction had been made for loss in shear strength due to moisture migration, the computed capacity of the side of the drilled shaft would have been 189 tons.

In the absence of experimental data on moisture migration and shearing strength as described in Chapters 2 and 3, Method II for computing load capacity of the side of a drilled shaft could be used as a first approximation. The use of Method II should be restricted to soils similar to those investigated in this report.

Actually, the moisture content of the soil around the drilled shaft changes with time. Periods of heavy and prolonged rainfall or periods of severe drought will change the moisture content of the soil. As a consequence, there will be changes in the soil properties and in the load-transfer characteristics.

Therefore, the computations shown are valid only for a certain period of time after the shaft has been constructed because of possible environmental effects. Some adjustments will have to be made in computation procedures to account for further wetting and drying. The nature of these adjustments is at present unknown.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this project is to investigate the moisture migration and shearing strength between cement mortar and soil. Laboratory studies on clay, sandy clay, and sandy-clay loam with grain-size distributions as shown in Appendix 2 were performed, and the results analyzed. Several conclusions and recommendations based on the experimental results can be summarized as follows:

CONCLUSIONS

(1) The amount of moisture migration is not only a function of grain-size distribution, void ratio, and original moisture content of the soil, but is also a function of the water-cement ratio of cement mortar.

(2) Pressure on unset cement mortar will cause more moisture migration into large-grained soil than into fine-grained soil.

(3) Under the same void ratio, moisture content, and water-cement ratio, more water will migrate into clay than into sandy clay.

(4) For clay, the moisture content increase Δw shows a rapid decrease with distance from the surface of the cement mortar. A maximum moisture content increase of 10 percent was observed at the surface of the cement mortar during this investigation.

(5) The degree of moisture migration can be reduced somewhat by decreasing the water-cement ratio of cement mortar. The reduced moisture migration will mean less decrease in shear strength.

(6) The moisture content of soil surrounding the cement mortar changes rapidly after contact with mortar and does not decrease significantly with increasing time.

(7) The shearing strength of soil is decreased due to local softening after the cement mortar is poured. The value of α mainly depends on the original moisture content of the soil and the water-cement ratio of the cement mortar. For the soils tested, the value of α lies between 0.40 and 0.68, with the smaller values occurring with the greater depths.

(8) The real shear failure plane occurs at least 1/8 inch from the cement mortar. The weakest zone of the soils tested is located approximately 1/4 inch from the cement mortar.

(9) For sandy clay and sandy-clay loam, 1/8 inch of soil cement will be formed near the surface of the cement mortar.

(10) Under the same testing conditions, cement mortar made with Type III cement will cause less moisture migration into soil than cement mortar made with Type I.

RECOMMENDATIONS

(1) Additional testing of the type described in Chapters 2 and 3, using different types of soil, is needed in order to develop additional knowledge concerning moisture migration and shearing resistance of soil after the placement of cement mortar.

(2) The value of water-cement ratio, which will minimize moisture migration and consequent softening of the soil, should be carefully studied.

(3) Field tests are needed to correlate with the results obtained from laboratory tests.

(4) The expansion of concrete will increase the force acting against the surrounding soil and a study of the effect of expansive cement on moisture migration and shear strength between cement mortar and soil is worthy of consideration.

(5) The relation between moisture content and shear strength after periodic wetting and drying over an extended period of time needs study.

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APPENDIX 1

SOIL BORINGS AT MONTOPOLIS SITE

BORING NO. 1: MONTOPOLIS

Sampling Device: 4" Shelby Tube

Depth, ft	Water Content, percent	Liquid Limit	Plastic Limit	Unconfined Compression Test			Description of Materials
				Water Content, percent	Failure Strength, tsf	Strain at Failure	
1	24.70	54.30	26.00	25.80	1.7	4.0	Dark Gray Clay with Calcareous Material.
2	23.20	51.80	23.83	-	-	-	
3	24.50	57.00	26.00	21.90	2.0	1.6	
4	23.35	53.00	23.90	17.00	8.34	2.0	
4.5	-	51.60	25.30	15.36	9.74	2.0	
5	22.35	45.70	24.62	19.70	3.84	1.5	Dark Gray Clay.
6	-	53.26	18.35	17.80	6.85	1.4	
7	-	39.90	19.40	14.40	4.50	1.0	Gray Tan Clay with Calcareous Material.
8	-	44.40	18.00	14.00	3.08	1.6	
9	13.00	44.30	19.45	14.40	5.30	0.8	Tan Clay with Calcareous Material.
10	13.80	43.40	15.20	13.45	6.00	1.3	
11	11.70	42.40	14.95	13.00	5.30	1.1	
12	-	-	-	-	-	-	
13	-	-	-	-	-	-	
14	-	-	-	-	-	-	
15	13.94	41.00	17.80	13.30	5.20	1.0	
16	13.86	44.40	13.86	13.70	4.50	1.2	
17	10.50	34.20	16.80	10.46	4.10	1.1	Sandy Tan Clay.
18	11.86	34.40	17.21	12.1	4.60	1.2	
19	11.60	35.40	15.60	13.0	5.30	1.7	
20	15.30	43.00	18.30	15.70	3.26	1.2	
21	12.65	29.30	15.30	13.80	2.30	1.0	

BORING NO. 2: MONTOPOLIS

Sampling Device: 4" Shelby Tube

Depth, ft	Water Content, percent	Liquid Limit	Plastic Limit	Unconfined Compression Test			Description of Soil
				Water Content, percent	Failure Strength, tsf	Strain at Failure	
1	26.67	52.00	23.70	-	-	-	Top Soil Fill Material Disturbed.
2	26.30	51.90	18.00	-	-	-	Dark Gray Clay With Calcareous Material Disturbed.
3	27.41	54.60	25.22	-	-	-	
4	28.41	59.40	26.38	-	-	-	
5	-	-	-	-	-	-	
6	16.75	50.50	24.60	19.50	2.40	2.90	Gray and Tan Clay.
7	-	-	-	-	-	-	
8	19.55	39.10	19.20	18.35	1.10	0.70	
9	20.60	39.80	18.15	-	-	-	
10	-	-	-	-	-	-	
11	-	-	-	17.05	1.40	1.45	Tan Clay.
12	-	-	-	17.10	1.47	1.60	
13	-	-	-	18.20	2.70	2.10	
14	16.60	43.30	17.60	17.60	3.20	3.50	
15	15.40	43.60	18.50	16.30	4.80	2.75	

BORING NO. 4: MONTOPOLIS

Texas Highway Department Penetrometer Test

Depth ft	No. of Blows		Description of Soil
	1st 6"	2nd 6"	
0			Tan Sandy Loam Fill Material.
1			Dark Gray Clay With Calcareous Material.
2			
3			
4			
5	14	16	
6			Stiff Tan Clay With Some Calcareous Material.
7			
8			
9	21	21	
10			
11			
12			
13	20	22	
14			
15			
16			
17	14	15	
18			
19			
20			
21	15	18	
22			
23			Stiff Tan Clay With Light Gray Sand Streaks.
24			
25	50 at 5"	50 at 7"	
26			
27			
28			Light Gray and Tan Clayey Sand.
29	44	50	
30			

APPENDIX 2

GRAIN SIZE ACCUMULATION CURVES

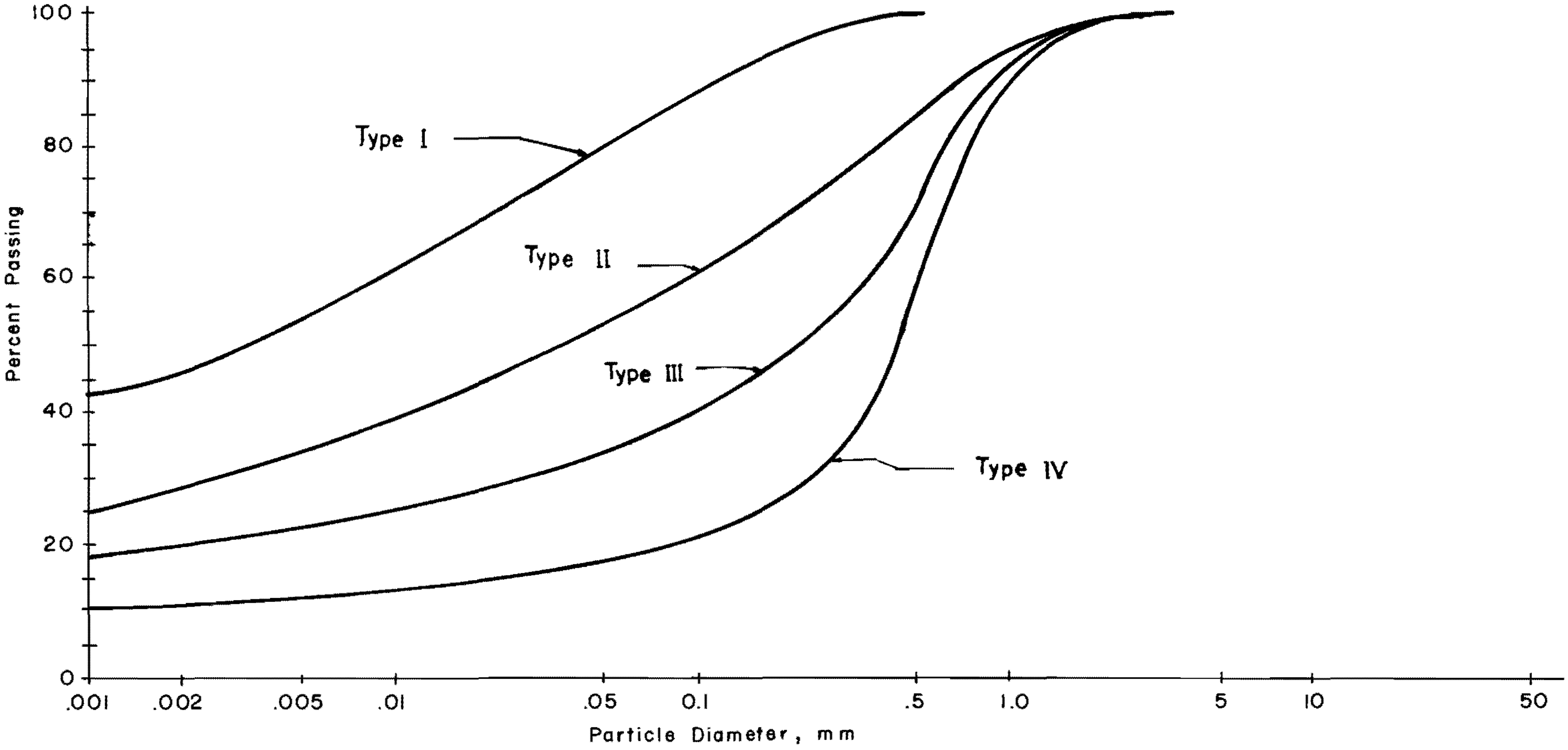

Fig A2.1. Grain size accumulation curve of soils.

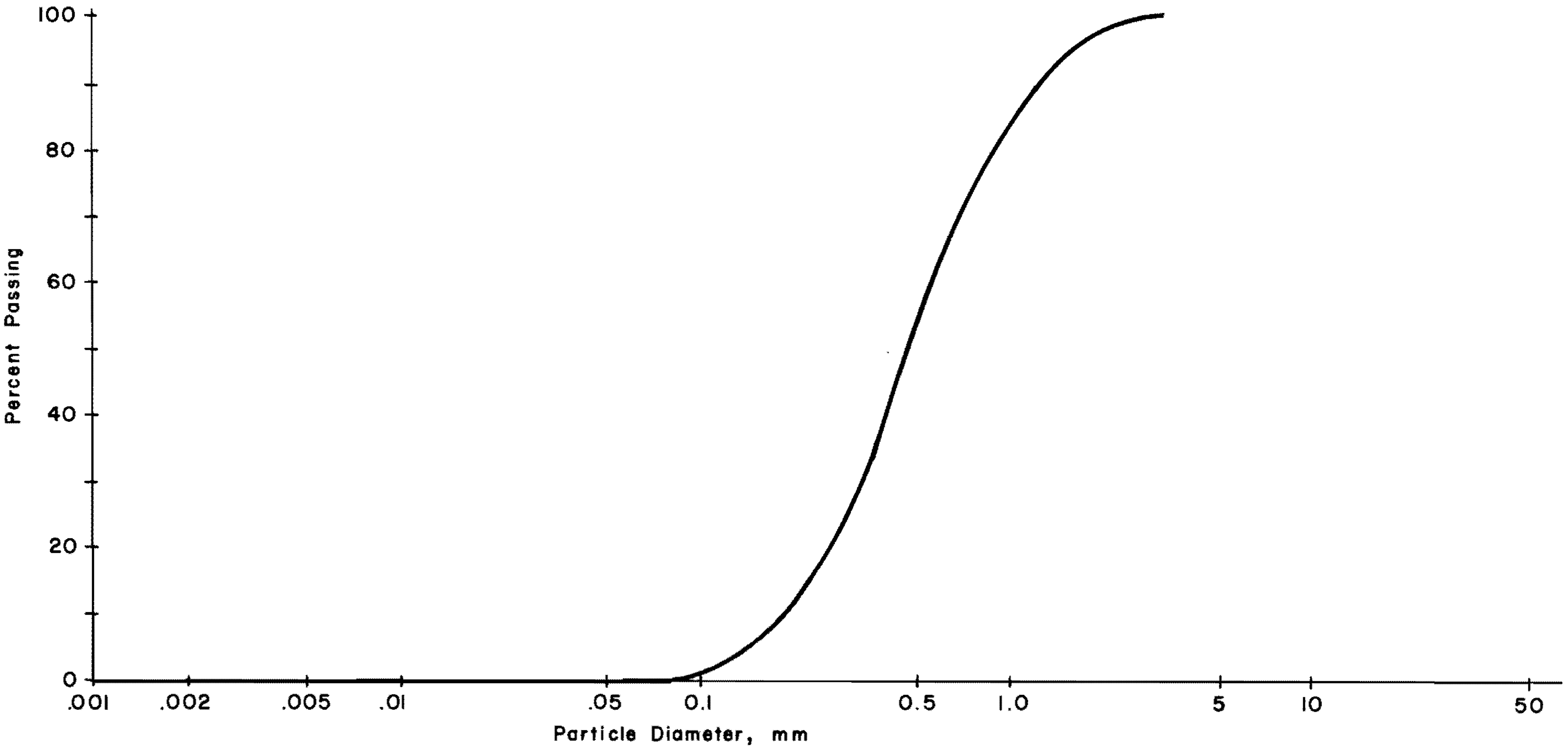

Fig A2.2. Grain size accumulation curve of sand.