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Land Locomotion Laboratory
Research Division
Research and Engineering Directorate

PRESSURE SINKAGE TESTS ON SYNTHETIC AND NATURAL CLAY SOILS

By

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ABSTRACT

The general purpose of the present investigation has been to study some of the physical factors that influence the strength of soil as measured by Bekker's (1955) parameters. The results of the investigation for all soils tested show fairly definite relationships between the two moduli of deformation, k_ϕ and k_c, and the four fundamental variables studied; namely, water content, clay type, clay-clastic ratio, and median diameter. However, the relationship for the exponent, n, are less clearly indicated.

Comparison of test results from synthetic soils of different basic clay mineralogy shows that the clay type is probably more important than any other variable in determining the strength. In the prediction of the strength of unknown soils, the clay type and its chemical environment may well be the most important variable, followed in order of relative importance by the water content, the proportion of admixed clastic material and the grain size.

The prediction of the strength of a natural, remolded soil, based on relationships between k_ϕ, water content, grain size and clay-clastic ratio failed to agree. Tests of the one prototype soil show that mineralogically identical soils are apt to differ in strength, presumably because the surface chemistry differs, owing to the particular type or types of clays present.

FOREWARD

SUMMARY

An investigation of the pressure-sinkage relationship of various clays and mixtures of clay with clastic silt and sand has been conducted in the laboratory. Bekker's soil parameters were used to describe the strength of the soils. Both commercially available clays and a natural clay soil and mixtures of these soils with clastic materials of varying grain size were investigated. The investigation also included the effects of two other variables on the strength of the soil, water content and clay-clastic ratio.

The pressure sinkage tests on the soil samples consisted of forcing circular or rectangular footings into the sample at a constant rate of strain and measuring the resisting force as a function of the sinkage. Bekker's strength parameters are derived from the resulting curves.

FINDINGS

The moduli of deformation, k_ϕ and k_c, decrease in magnitude as the water content increased. This general relationship has been found to hold for the natural soil and all mixtures, as well as for synthetic soils.

The moduli of deformation to grain size of admixed sand for the natural soil indicate that for a given k_ϕ or k_c, the water content increases regularly as the grain size decreases logarithmically. This inverse relationship of water content to grain sizes also was found for the synthetic soils.

The exponent, n, has been found to be essentially constant for all water contents and grain sizes for given clays and given clay-sand ratios. The exponent, n, does vary from one clay to another. In the natural soils, the exponent, n, was found to be neither constant nor systematically dependent on water content.

The prediction of the remolded strength of an untested soil of known clay mineral type and proportion and grain size of clastic material based on relationships between k_ϕ, water content, grain size and clay-clastic ratio or a mineralogically similar but synthetic laboratory soil fail to agree.

CONCLUSIONS

The general purpose of the investigation has been to study some of the physical factors that influence the strength of soils as measured by Bekker's parameters. The results of the investigation for all soils tested show fairly definite relationships between the two moduli of deformation k_ϕ and k_c and the four fundamental variables studied, namely, water content, clay-type, clay-clastic ratio, and median diameter. However, the relationships for the exponent, n, are less clearly indicated.

Comparison of test results from synthetic soils of different basic clay mineralogy shows that the clay type is probably more important than any other variable in determining the strength. Tests of the one prototype soil show that mineralogically identical soils are apt to differ in strength, presumably because the surface chemistry differs, owing to the particular type or types of clays present.

RECOMMENDATIONS

An environmental classification of clay type perhaps would serve as an appropriate basis for further tests. The functional relations of water content, clay-sand ratio and grain size reported in the present study should prove helpful in such investigations.

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INTRODUCTION

The fundamental factors that affect the behavior of soils under bearing stresses are matters of concern to the Land Locomotion Laboratory of the Detroit Arsenal, U. S. Army Ordnance Tank-Automotive Command, Ordnance Corps, in its efforts to design more efficient tracks and wheels for vehicles. In his recent publications, Col. M. G. Bekker (1955, 1956) of the Land Locomotion Laboratory discusses pressure-sinkage relationships in soils, and describes various parameters related to the strength of soils that are used in the laboratory and in the field.

The University of California, in a cooperative project with the Land Locomotion Laboratory, has undertaken a laboratory investigation of the relationships of Bekker's parameters to various clays and to mixtures of clay with clastic silt and sand. The present report is the sixth and final of a series of papers on pressure-sinkage phenomena of these different soils. It presents new data on a natural clay soil and on mixtures of this soil with clastic materials of varying grain size. It also contains a summary of the first five papers. It thus represents a final report of the project.

The first report (Trask and Skjei, 1958a) describes the procedures of investigation and presents data on pressure-sinkage effects on illite and kaolinite clay, on dry sand and on silt composed of crushed beach sand. The second paper (Trask and Skjei, 1958b) gives data for two montmorillonite soils, one a Wyoming Bentonite, and the other a material called "Volclay" which is a montmorillonite from a different source. The third and fourth papers (Trask and Skjei, 1958c; and Trask and Klehn, 1958) give data for synthetic soils of montmorillonite, kaolinite and illite mixed with 16 micron clastic silt. The fifth paper (Trask and Klehn, 1959) gives data on synthetic soils of montmorillonite, kaolinite and illite mixed with sands and silts of different grain size. In these studies, the clayey soils were tested at four or five different water contents, all higher than the plastic limits of soils. The soils were essentially saturated at the time of testing. The pure silt and sand samples were tested at one water content, as they are dilatant and have little or no plasticity. The clastic materials admixed with various commercial clays were well-sorted ground and natural sands. The coefficient of sorting ($\sqrt{Q_3/Q_1}$) ranged between 1.1 and 2.2. The median diameters were 1.2, 16, 74, 120 and microns, respectively. Sands from similar sources and of essentially the same grain size distribution were utilized in the tests reported in this paper.

The data presented in the present report relate to a natural clay soil, called "Sonoma No. 5", an estuarine clay from Sonoma Slough at the north end of San Francisco Bay. Two series of tests were made. The first was conducted by Trask and Klehn on undisturbed and remolded samples of the pure, natural soil. Subsequent tests by Trask and Snow were applied to mixtures of the natural soil with the different clastic materials. The purpose of these latter tests was to provide means of comparison between the strength parameters of natural and synthetic mixtures of clay and sand.

Relatively undisturbed samples were obtained by sinking thin-walled containers into the uniform deposit at low tide. These containers were 5 inches in diameter and 6 inches deep. Pressure-sinkage tests were performed on these samples while still in the container. Some undisturbed samples were tested immediately after collection, so that data could be obtained for their high natural water content. Other samples were allowed to stand for different periods of time while enclosed in polyethylene bags. The water content of each sample tested was measured by coring the top inch, a precaution necessitated by the water content gradient developed by gravity drainage. Other samples were removed from their containers, partially dried and thoroughly reworked to various water contents, to determine the remolded strength of the soil. Pressure-sinkage data from 26 tests of undisturbed samples are recorded in Table 1, together with data from 7 tests of remolded soil.

SOIL-TESTING APPARATUS

The testing apparatus was designed by Trask and Skjei (1958a). This apparatus measures bearing stress on soil samples subjected to a constant rate of strain. Motive power is provided by a constant-speed motor, geared to the upper section of a three-part, vertically-moving plunger. Various bearing plates are attached to the lower section of the plunger, and are driven into the test soil sample. The center section consists of a calibrated, machined aluminum test ring. This test ring joins the upper and lower sections of the plunger, moves with it and transmits the motor-applied force with negligible friction loss to the bearing plate.

Four SR-4 resistance strain gages mounted on the test ring measure its strain. Forces applied are within the elastic range of the test ring, insuring proportionality between measured test ring strains and the stresses that produce them.

Leads from the four strain gages are connected to the input terminals of a Brush Universal Analyzer, Model BL 320.

This is a self-contained AC Wheatstone bridge, voltage amplifier, discriminator and DC power amplifier. It has an attenuation control that provides eight amplification ratios. Use of four strain gages permits maximum utilization of the Wheatstone bridge circuit, resulting in quadrupled sensitivity as well as automatic compensation for temperature variations.

The input signal, after amplification, is transmitted to an adjoining Brush magnetic oscillograph, Model 202 or 902. This recording instrument measures the input signal by the magnetic deflection of a pen arm. This pen arm traces a curve on a moving roll-graph. The roll-graph is driven by a constant-speed motor. Since both the roll-graph and test plunger are driven by constant-speed motors, a proportionality exists between units of graph travel and units of sinkage of the bearing plate into the soil sample.

The relation between pen deflection and the force applied to the bearing plate has been determined by loading the plunger with known weights while the motor is disengaged and the bearing plate rests on a firm surface. A direct proportionality was found to exist throughout a range of applied force extending both above and below the range used in the tests. The useful range in applied force was 0.1 to 30 pounds. Inaccuracies of measurement may result from bearing friction at extremely light loads, and from inadequate compensation for test ring deflection at extremely heavy loads.

The gear ratio between the motor and plunger provides a constant penetration rate of 1.14 inches per minute. This speed was chosen in accordance with principles set forth by Bekker (1955) and Rutledge (1947), in order to produce a rate of strain of less than one percent per minute, above which viscous resistance may be introduced.

The first tests in this program (Trask and Skjei, 1958a) were conducted with various plates of different shapes, including rectangles 1/2, 1, 1-1/2 and 2 inches wide by 2 inches long, and with circles 1, 1-1/2 and 2 inches in diameter. These tests indicated that the rectangular plates gave somewhat anomalous results. Therefore, subsequent tests (Trask and Skjei, 1958b, 1958c and Trask and Klehn, 1958, 1959) were made with circular plates of 1, 1.5 and 2 inch diameters. Tests with circular plates occasionally gave anomalous results, but to a much less extent than with rectangular plates. In the last of these reports, it was stated that the strength parameters computed from the various combinations of circular plate sizes gave such consistent results that it was practicable to report only the findings derived from 1.0 and 2.0 inch plates. The present test series was therefore conducted with the 1.0 and 2.0 inch circular plates.

Other test procedures and equipment have remained unaltered throughout the program.

METHOD OF ANALYSIS

The basic pressure-sinkage relationship is expressed by Bekker in the form

$$p = (k_c/b + k_\phi)z^n$$

in which p is the pressure, b is the breadth of the bearing plate used in the test, k_c is the modulus of deformation, k_ϕ is the modulus of deformation, z is the sinkage, and n is a parameter representing the slope of the curves. The object of the experimental tests is to determine the parameters k_c, k_ϕ and n in the above equation.

Simultaneous values of pressure, p and sinkage, z are taken from the oscillograph record and plotted on logarithmic paper. In plotting these data we have followed Bekker (1955, p. 13), using p as the abscissa, and z as the ordinate. The exponential, n, is obtained directly from the logarithmic plot. This slope, n, represents the cotangent of the angle between the straight-line portion of the graph with the abscissa, when the axes are chosen in the above-mentioned manner. Two successive pressure-sinkage tests, made with two different bearing plates on a sample of known water content provide four quantities, b_1, b_2, a_1 and a_2. The moduli of deformation, k_c and k_ϕ are calculated from Bekker's equations.

These equations are:

$$k_\phi = \frac{a_2\ b_2 - a_1\ b_1}{b_2 - b_1} \quad \text{and} \quad \frac{(a_1 - a_2)\ b_1\ b_2}{b_2 - b_1} = k_c$$

where $a_1 = (k_c/b_1 + k_\phi)$ and $a_2 = (k_c/b_2 + k_\phi)$. b_1 and b_2 are diameters of the bearing plates. The pressure for 1.0 inch sinkage of the 1.0 inch and 2.0 inch plates are a_1 and a_2 respectively.

SUMMARY OF TEST RESULTS

Table 1 summarizes the subject of tests reported in all issues of this series, including the present paper. For details of earlier tests, the reader should refer to the original reports (Trask, et al, Inst. Engr. Research Publ., Series 116, Issues 1 - 5). Hereafter in this report the above five references (Trask et al, etc.) are referred to as Issues 1 to 5, because they represent Issues 1 to 5 of University of California, Institute of Engineering Research, Series 116.

Tests on synthetic soils:

The first 5 reports were concerned with the strength of synthetic laboratory soils. The basic materials used in preparing them have been described by Trask and Close (1958). The clays are (1) Edgar china clay from Georgia, which is a nearly pure kaolinite midway in composition between a hydrogen and sodium clay; (2) Illinois grundite which consists of 80 percent illite and 20 percent of clastic material, mainly quartz; (3) Kentucky Mine Special, a ball clay estimated to contain 80 percent kaolinite and the rest quartz and organic matter; (4) Wyoming bentonite, a clay estimated to contain 97 percent montmorillonite and 3 percent quartz; and (5) vol clay - a nearly pure bentonite. The median particle diameter of the kaolinite is 1.2 microns and of ball clay, 2.3 microns. The other clays presumably have grain sizes of a similar order of magnitude.

The clastic admixtures are processed beach and river sands, largely of quartz with some feldspar. The finest material is called Del Monte DMAF 1.2 micron silica. It is a ground beach sand from Pacific Grove, California. The median grain diameter of different samples that were tested ranged between 1.1 and 1.8 microns. The sorting coefficient ($\sqrt{Q_3/Q_1}$) was about 2.0. The material called 16 micron silt is a ground sand from the same source, with a median grain size of 15.5 to 16.2 microns and sorting from 1.8 to 2.2. The 74 micron sand, from the Russian River at Fernbridge, is quite variable in median diameter; for it was treated by sieving and decantation so that its median grain diameter became about 74-microns with a sorting coefficient of 2. The 120-micron sand is a California beach sand from an unknown source, with rounded grains of 120 micron median diameter and a sorting coefficient of 1.5. The 210 micron processed sand, from Bolinas Bay, California, is composed of rounded grains of 210 micron median diameter and has a sorting coefficient of 1.1.

The salient results of the first five reports (I.E.R. Series 116, Issues 1 to 5) are summarized in figures 1 through 14. These graphs show the interrelationships between the strength parameters k_ϕ and k_c and the four independent variables of clay-mineral type, clay-clastic ratio grain size of admixed clastic material and water content. For each plot, the three variables that describe the solid components of a sample are constant, while one of the strength parameters varies with the water content.

In the original reports, strength and water content were plotted arithmetically. In some tests, however, the strength parameters varied with water content in a manner which is more nearly geometric than arithmetic. Therefore, in the present report these summary graphs of the previous work have been replotted semi-logarithmically. Comparison of the two types of plotting suggests that neither type is particularly more significant than the other, owing to the few number of points and the degree of scatter of the data. Semi-logarithmic plotting is most advantageous in representing variations of cohesive modulus k_c versus water content, because some of the arithmetic plots show marked curvature at high water content. Semi-logarithmic plotting is disadvantageous because it makes no provision for the few negative values of k_c that were found.

Figures 1 and 2 relate k_ϕ and k_c, respectively, to water content, for all the commercial clays tested without clastic admixtures. No further tests were run on either Kentucky Ball Clay (kaolinite) or Wyoming Volclay (montmorillonite). On the other hand the Georgia, Edgar ASP (kaolinite), the Illinois Grundite (illite) and the Wyoming Bentonite (montmorillonite) were studied more extensively. The results of tests on the kaolinite at 50 and 20 percent concentration with admixed clastic materials of 1.2, 16, 74, 120 and 210 micron median size are summarized in figures 3 through 6. Similar results for montmorillonite appear in figures 7 through 10, and for illite in figures 11 through 14.

The data have been replotted in figures 15 through 20 to show the dependence of strength upon the grain size of admixed clastic material. Grain size is expressed geometrically in ϕ units, which are defined as the negative logarithm of the grain size in millimeters to the base 2. (See Issue 5, Page 6). Each curve defines the relationship between ϕ and water content for a fixed value of strength (k_ϕ or k_c), clay-clastic ratio and for a specified clay type. When possible, two values of each strength parameter have been plotted for each mixture. The utility of these plots will be shown later.

A third strength parameter, n, is required to define the pressure-sinkage relation,

$$p = (k_c/b + k_\phi)z^n$$

For any one sample, n is a constant beyond some finite sinkage. Log-log plots of pressure versus sinkage (see examples in Issues 1, 2 or 4) are linear after about 0.6 inch sinkage. Linearity apparently corresponds to soil failure by rupture around the test plate, but does not apply to the initial plastic deformation. The parameter n proved to be essentially independent of water content and the grain size of course clastic material admixed, but to vary with the type of clay and with the clay-clastic ratio. Higher clay-clastic ratios yielded lower n values, and very fine silt yielded higher values.

Average values and the ranges of variability of n are summarized in Table 2.

Tests on Sonoma No. 5 Natural Clay Soil:

Sonoma No. 5 has been taken from the right bank of Sonoma Slough adjacent to California State Route 48 near San Francisco Bay. The soil is a dark gray, moderately fat marine clay, of very uniform nonstratified texture, essentially devoid of macroscopic particles, roots, shells or cavities. This clay is probably in a flocculent state. A thin deposit presumably is added during each high tide. The organic material at depth in the soil evidently is slowly decaying, because of the peculiar odor emitted. The mineralogical composition of the soil, reported in Table 3, is essentially that of a mixture of hydrous mica and silt.

Nine test samples were mixed, using a machine blender to insure uniformity. Admixed to the natural soil were five different clastic materials whose median diameters were 1.78, 15.5, 76.1, 119 and 212 microns. These materials represent the 1.2, 16, 74, 120 and 210 micron sizes, respectively, used in the previous investigations. Five of the samples were mixed to 50 percent clay content, and four to 20 percent clay content. It is not possible to make a satisfactory mixture of the finest silica, 1.78 microns, when the clay-sand ratio is small, for such mixtures are dilatant.

Additional information on the soils from the Sonoma Slough are given in Langston, Trask and Pask (1958), p.226.

Tables 4 and 5 present the basic data for the parameters k_ϕ, k_c and n for the natural soil samples in the undisturbed and remolded soils, respectively. Table 6, shows data for mixtures of the soil with various clastic materials. The relationships of water content to deformation moduli, k_ϕ and k_c for undisturbed and remolded natural clay-soil,and for various mixtures of clay-soil with clastic materials, are shown graphically in figures 21 to 32. The 79 basic pressure-sinkage curves, on which the figures and tables 4, 5 and 6 are based, are not included in this report. These graphs are on file in the Wave Research Laboratory of the University of California at Berkeley and may be consulted on request. The data shown in figures 23 to 32 are replotted in figures 33 to 37, to show the affect of grain size upon water content for given k_{ϕ} and k_c. Grain size is expressed in ϕ units.

The exponent n was found to be neither constant nor systematically dependent on water content. Trial plots of n versus water content, not reproduced here, do show that for a given water content, n increases as the bearing plate breadth increases. There is a suggestion of dependence upon water content, insofar as some samples indicate decreasing n values, or steeper pressure-sinkage curves as water content increases. This same finding was expressed by Trask and Klehn (1958).

The moduli of deformation, k_{ϕ} and k_c, decrease in magnitude as water content increases. This general relationship has been found to hold for the natural soil and all mixtures, as well as for synthetic soils (Trask and Skjei, 1958b, 1958c; Trask and Klehn, 1958, 1959). In report number 5 (Trask and Klehn, 1959), it was indicated that the strength properties of the caly component in a mixture governed this phenomenon, for tests showed a general increase in steepness of the strength-water content curves with increasing clay-sand ratios. Figures 26 to 32 show that this relationship holds for natural soils as well. For a given water content, and a given clay-sand ratio, strength generally increases with decrease in size of the admixed sand (Trask and Close, 1958; Trask and Skjei, 1958c; Trask and Klehn, 1959). With a few exceptions, this relationship also holds true for mixtures of natural clay. The exceptions noted in the present data are shown in figures 24, 25 and 26. The modulus, k_c, for the mixture of clay with 50 percent 1.2 micron silica was lower than expected from coarser mixtures. Both moduli, k_ϕ and k_c, for the 20 percent clay with 16 micron silt were low.

Other measures of strength vary in the same manner as do pressure-sinkage tests, with respect to clay-sand ratio or grain size, as shown by the vane-shear and blow-count tests of Trask and Close (1958) and Trask, (1959). Blow-count data for Sonoma No. 5 soil and mixtures, plotted in figure 38, show the anticipated results of increasing strength with decreasing water content or grain size, and increasing strength with increasing clay-sand ratio.

The effect of clay concentration on strength has been explored to only a limited extent; that is, at 100, 50 and 20 percent concentration. Trend lines can be approximated from these data, facilitating extrapolation beyond the range of tests. Such a plot is figure 30, which shows the probable liquid limit (a measure of water content for a particular strength) for all concentrations of Sonoma No. 5 clay-soil mixed with various clastic materials.

The pressure-sinkage tests have been performed within a range of soil moisture such that the sample is always essentially saturated. No attempt has been made to explore the extremes of the range wherein test results may be possible. Atterburg limit tests were performed on all mixtures of sand and Sonoma No. 5 clay-soil, in order to compare them with the moisture range covered by pressure-sinkage tests. Figure 40 shows the results. Solid vertical lines, whose lengths equal the plastic indices and whose terminals are the plastic and liquid limits, indicate the properties of 50 percent mixtures, and dashed lines, the 20 percent mixtures. Inclined lines bound the pressure-sinkage test ranges. It is seen that all tests were performed above the plastic limit. It is suggested that the plastic limit is near the lower range of applicability of these tests for remolded soils, because the strength of soil samples dryer than the plastic limit may be influenced by air entertainment and the method of compaction. Saturated undisturbed samples might conceivably follow the pressure-sinkage formula below the plastic limit, even approaching the shrinkage limit.

Nothing in these pressure-sinkage tests suggest any definite upper moisture limit with respect to the applicability of the pressure-sinkage formula. Figure 40 shows that tests have been performed at water contents as much as 20 percent above the liquid limit. They might have been conducted on wetter samples had the apparatus been designed to register lesser loads with greater sensitivity.

The relationships of moduli of deformation to grain size of admixed sand are shown by figures 33 to 37. They indicate that for a given k_ϕ or k_c, the water content increases regularly as the grain size decreases logarithmically. The relationship is more clearly defined for the coefficient k_ϕ than for the coefficient k_c.

Trask and Klehn (1959) found similar effects of grain size on strength. Their curves indicate, that as a general rule, water content for any given strength changes less with respect to grain size as the clay-sand ratio increases. Though that result should logically be expected, it is not borne out in figures 33 to 37, because scatter of the data is too great to indicate reliably the slope of a line through the points plotted.

INTERPRETATION OF RESULTS

The needs of the Land Locomotion Laboratory would best be satisfied by testing hundreds of different natural soils for direct determination of their properties. We have attempted to circumvent the practical difficulties of such a program by testing controlled synthetic soils composed of various clay types with admixtures of various clastic materials. Trends of strength variation with changing clay material, clastic size, clay-sand ratio and water content have been determined in the hope that these data on synthetic soils may be correlated with a few natural or prototype soils so that the properties of any natural soil of a given composition might be predicted from the test data. The prediction of the strength of a soil also must include its loss of strength upon remolding, for trafficability of a soil is affected by changes in its strength.

The data of previous reports, summarized herein, pertain to rewetted soils which were made from dried, commercial clays. The data from the new tests, reported in this paper, pertain to a natural clay-soil, Sonoma No. 5. These tests were designed to afford means of comparing the strength of a natural clay-soil with mixtures of different clastic materials with the strength of commercial clay with the same clastic mixtures.

Since Sonoma No. 5 clay soil is essentially a mixture of hydrous mica and silt, it is similar in composition to the mixtures of illite (Illinois Grundite) and clastic silt as reported in previous pressure-sinkage tests (Issues 1 to 5). Thus, the results of the pressure-sinkage tests on the Sonoma No. 5 soil and on its mixtures with clastic material provide a means of interpreting the significance of the pressure-sinkage tests previously reported on synthetic mixtures of illite and clastic material. It is obvious that many additional tests on a variety of soils and mixtures of clastic material are needed before the data obtained in the preliminary tests of mixtures of dried commercial clays with clastic material can be used to predict the strength of soil upon the basis of clay type, clay-sand ratio, and percentage of admixed material of given grain size. In particular, it would be desirable to examine natural soils containing significant amounts of kaolinite and montmorillonite.

The composition of the natural Sonoma No. 5 soil, without any artificial addition of clastic material, is estimated to represent a mixture of 83 percent Illinois Grundite illite and 17 percent clastic material of mean grain size of 7 microns, or 7.1 ϕ units. This estimate is based on the assumption that the composition of the natural

Sonoma No. 5 soil is equivalent to 67 percent pure illite and 33 percent clastic material. In Table 3, showing the composition of Sonoma No. 5 soil, hydrous mica is given as 60 percent, and clastic materials, notably quartz and feldspar, are indicated as composing 30 percent. Thus, on one hundred percent basis for clay plus clastic material, clay is 67 percent and clastic material 33 percent. The Illinois Grundite, which is the source of the "illite" in the first series of tests of the present investigation (Issues 1 to 5), is estimated to have the composition of 80 percent illite and 20 percent clastic material (Trask and Close, 1958, p. 828). Thus, a mixture of 83 percent Illinois Grundite with 17 percent clastic material will contain only 80 percent of 83 percent or 66.4 percent of the mineral illite, and clastic material will be the remainder, or 33.6 percent, which is essentially the same as the estimated composition of the Sonoma No. 5 natural clay soil. The figure of 7 microns for the grain size of the clastic material is based on mechanical analyses of the Sonoma natural soil (Figure 41), and represents the median size of the coarsest 17 percent.

In attempting to compare data from the first series of tests with the second series of tests in figures 42 and 43, we have extrapolated data for mixtures of 50 percent illite and 50 percent clastic material, and 20 percent illite and 80 percent clastic material, as presented by Trask and Klehn (1959). Basic data for such comparisons are presented in figures 19 and 21.

Figure 43 presents an estimate of the remolded strength of an untested soil, based on relationships between k_ϕ, water content, grain size and clay-clastic ratio. In order to make such estimates, one must know the clay mineral type and the proportion and grain size of clastic material. The procedure for making such interpretations is as follows:

(1) On the chart of the appropriate type of synthetic clay-soil, plot new curves of ϕ versus water content for the required clay-clastic ratio. Their positions can be interpolated from the known 20 and 50 percent curves, as shown on figure 42. The example given in this figure is a prediction of properties of Sonoma No. 5 clay-soil. A separate curve is required for each of the fixed strength values, such as $k_\phi = 3$, and $k_\phi = 6$, $k_c = 1$, and $k_c = 3$.

(2) Enter the curves at the appropriate grain size of the unknown soil to find the water content corresponding to the strength those curves represent.

(3) Plot the two points of water content versus strength for k_{ϕ} and for k_c separately, determining thereby, new relations of strength for all water contents. Figure 43 shows the predicted frictional modulus of Sonoma No. 5 clay-soil.

On the same graph is drawn the curve for the natural, remolded soil, which develops the same strength with roughly twice the water content. The predicted values fail to agree with the actual.

The high water content of natural soil, compared with the corresponding synthetic soil, cannot be rationalized on the basis of organic content. It is suspected that the disparity in water content between natural and synthetic soils is due to differences in history of their respective clays. The commercial clays are dried for shipping. Dehydration-rehydration becomes irreversible beyond some temperature of drying. The time required for strong polar water layers to form on dried clay may not have been provided in preparing the synthetic soils. The effects of irreversibility and insufficient time for rehydration are to reduce the water content for a given strength. On the other hand, the history of the natural clay, which has been in a wet, tidal environment for some time, favors the development of strong polar water layers - therefore, high water content for a given strength. The cations present in a clay also govern the water-absorption phenomena, and the clays may differ in this respect. Low electrolyte content in the fresh-water laboratory mix may have led to dispersed structure, while the marine clay is probably flocculent. It is also possible that remolding by hand only partially destroyed the structural strength of the undisturbed soil. The comparison of strength based on predictions from synthetic soils with strength of natural soils shows that the experimental data must be judiciously applied in predicting the strength of untested soils.

A second objective of the new tests was to determine the effect of disturbance of the sample. The relative sensitivity of the natural soil studied in the present investigation is indicated by figures 21 and 22, which show the undisturbed and remolded strengths of Sonoma No. 5 clay-soil. It is convenient to define sensitivity as the ratios of the moduli of the soil in the undisturbed state to the moduli in the remolded state. Three sensitivity indices will define the change in strength properties of a soil, as indicated by its cohesive and frictional moduli, and by its slope factors. At 125 percent water content, these values for Sonoma No. 5 soil are:

$$\text{Sensitivity, } S_c = \frac{k_c \text{ undisturbed}}{k_c \text{ remolded}} = 30.0$$

$$\text{Sensitivity, } S_\phi = \frac{k_\phi \text{ undisturbed}}{h_\phi \text{ remolded}} = 3.2$$

$$\text{Sensitivity, of Exponent n, } S_n = \frac{n \text{ undisturbed}}{n \text{ remolded}} = 0.25$$

One cannot presume that these sensitivity measures apply to any other soil, even though it may be of the same composition. Soil strength is not a simple mechanical interaction between solid and liquid soil components, because clay-water systems involve complex physico-chemical phenomena. Additional factors governing strength include the ion concentration of the fluid, the ions present, the pH, and to a less extent, the temperature and dialectric constant. The exchangeable ion content of a clay is a reflection of its history. The sensitivity of one specific soil, such as the marine soil, Sonoma No. 5, therefore, cannot be expected to apply to a soil of the same composition if it comes from a different environment, such as a fresh-water deposit. Similarly, one should not be surprised to find that the strength of the remolded salt-water soil, Sonoma No. 5, differs markedly from the predicted remolded strength of its fresh-water laboratory counterpart.

Changes in the proportions or grain size of clastic material in a soil are, for any one clay-water system, primarily mechanical variables. Strength variation with clastic content variation has been rather thoroughly investigated in the course of this test program, and the effect of the variable has been found to be predictable. These tests have concerned only three of the many possible clay-water systems. These systems may never be exactly duplicated in nature. The strength of prototype soils must be based on empirical evaluations of the properties of naturally-occurring clay-water systems. Yet, it may be found that the variations of strength with variations of the inert components of a soil can be formulated in such a general way that they can be applied to any other clay-water system. Properties of a new clay-water system would first have to be determined by pressure-sinkage tests, and correlated with its synthetic counterpart. Properties of the array of different soils formed by this new dry-water system with all the possible clastic admixtures may then be found by applying the relations of strength to clastic content that were determined for the synthetic clay-water system.

The methods of soil testing used in this program have demonstrated the dependence of soil strength upon (1) water content, (2) proportion and grain size of clastic material in the soil, and (3) the type of clay present. Empirical relationships between strength, water content, proportion and grain size of clastic material can be derived successfully by these methods. Extensive testing of natural soils is required to determine the effects of clay mineralogy and colloid chemistry; for the clays used in these tests are commercial kaolinite, illite and montmorillonite, which probably have very different basic properties than most natural clays. In the prediction of the strength of unknown soils, the clay type and its chemical environment may well be the most important variable, followed in order of relative importance by the water content, the proportion of admixed clastic material and the grain size. By applying the relationships between strength, water content and clastic content from these completed tests to limited test data on new, natural clay types, it should be possible to expand the variety of soil types whose strength may be predicted.

CONCLUSION

The general purpose of the present investigation has been to study some of the physical factors that influence the strength of soil as measured by Bekker's (1955) parameters. In particular, the study was designed to investigate the effect of water content, clay type, clay-clastic ratio, and grain-size of admixed clastic particles. The investigation was carried on in two phases: (1) A study of synthetic mixtures of dried soils with clastic particles of different grain size and in different proportions (Trask, et. al., Inst. Engr. Research Series 116, Issues 1 to 5); and (2) A study of Bekker's parameters for a prototype soil in its natural condition without any previous drying or desiccation and with mixtures of different clastic materials with this natural soil (present report, Trask and Snow, 1961). The ultimate objective of such studies is to develop criteria for predicting the strength of natural soils from data on water content, clay type, clay-clastic ratio, and grain size distribution of of its contained clastic particles.

Bekker, in his studies of strength of soil, uses three parameters, k_{ϕ}, k_c and the exponent, n, whose mathematical relationships are described above in the first part of the present report. The results of the present investigation for all soils tested show fairly definite relationships between the two moduli of deformation, k_{ϕ} and k_c, and the four fundamental variables studied, namely water content, clay-type, clay-clastic ratio, and median diameter, as shown in the different graphs and tables presented above. However, the relationships for the exponent, n, are less clearly indicated.

Comparison of test results from synthetic soils of different basic clay mineralogy shows that the clay type is probably more important than any other variable in determining the strength. Tests of the one prototype soil, reported in the present report, show that mineralogically identical soils are apt to differ in strength, presumably because the surface chemistry differs, owing to the particular type or types of clays present.

An environmental classification of clay type perhaps would serve as an appropriate basis for further tests. The functional relations of water-content, clay-sand ratio and grain size reported in the present study should prove helpful in such investigations.

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Table 1

Summary of Tests Performed

Publication	Soils Tested	Clay Content Clastic Materials Admixed Bearing Plates Applied
Trask, P. D. and R. E. Skjei, May, 1958, Series 116, Issue 1	Kaolinite (Edgar ASP, Georgia)	100 percent clay 0.5, 1.0, 1.5, 2.0 by 2.0 inch rectangular plates
	Illite (Grundite, Illinois)	100 percent clay 0.5, 1.0, 1.5, 2.0 by 2.0 inch rectangular plates
	Montmorillonite (Volclay, Wyoming, Glycerine Admixed, Identified as A 19 KN)	Percent clay unknown 0.5, 1.0, 1.5, 2.0 by 2.0 inch rectangular plates, 1.0, 1.5, 2.0 inch circular plates
	Sand, loose, 30-mesh beach sand. Water content 12.7 percent	0.5, 1.0, 1.5, 2.0 by 2.0 inch rectangular plates
	Silt, ground beach sand, 16 micron median diameter, water content 12.7 percent	0.5, 1.0, 1.5, 2.0 by 2.0 inch rectangular plates 1.0, 1.5, 2.0 inch circular plates
Trask, P. D. and R. E. Skjei, May, 1958, Series 116, Issue 2	Montmorillonite (Bentonite, Wyoming)	100 percent clay 1.0, 1.5, 2.0 inch circular plates

Table 1 (continued)

Publication	Soils Tested	Clay Content Clastic Materials Admixed Bearing Plates Applied
Trask, P. D. and R. E. Skjei, May, 1958, Series 116, Issue 2	Montmorillonite (Volclay, Wyoming)	100 per cent clay 1.0, 1.5, 2.0 inch circular plates
Trask, P. D. and R. E. Skjei, July, 1958, Series 116, Issue 3	Montmorillonite, (Bentonite, Wyoming)	10, 20, 50 percent clay 16 micron silt 1.0, 1.5, 2.0 inch circular plates
Trask, P. D. and H. Klehn, Sept, 1958, Series 116, Issue 4	Illite (Grundite, Illinois)	20, 50, 100 percent clay 16 micron silt 1,0, 1.5, 2.0 inch circular plates
	Kaolinite, (Edgar ASP, Georgia)	20, 50, 100 percent clay 16 micron silt 1.0, 1.5, 2.0 inch circular plates
	Kaolinite, (Ball Clay, Kentucky Special)	100 percent clay 1.0, 1.5, 2.0 inch circular plates

Table 1 (continued)

Publication	Soils Tested	Clay Content Clastic Materials Admixed Bearing Plates Applied
Trask, P. D. and H. Klehn, Jan. 1959, Series 116, Issue 5	Montmorillonite, (Bentonite, Wyoming)	20, 50 percent clay
		1.2, 74, 130, 210 micron clastic material
		1.0, 1.5, 2.0 inch circular plates
	Illite, (Grundite, Illinois)	20, 50 percent clay
		1.2, 74, 130, 210 micron clastic material
		1.0, 1.5, 2.0 inch circular plates
	Kaolinite (Edgar ASP, Georgia)	20, 50 percent clay
		1.2, 74, 130, 210 micron clastic material
		1.0, 1.5, 2.0 inch circular plates
Trask, P. D. and D. T. Snow	Illite (60 percent) Sonoma No. 5, natural clay-soil	20, 50 percent clay-soil
		1,2, 16, 74, 130, 210 micron clastic material
		1.0, 2.0 inch circular plates
		100 percent clay-soil undisturbed and remolded
		1.0, 2.0 inch circular plates

Table 2

Mean Slope Parameter, n, and Standard Deviation in Synthetic Mixtures of Clay and Clastic Material

Mixture	Parameter n		
	Pure Clay	1.2 Micron Material added	16, 74, 120 and 210 Micron Material added
100% Kaolinite	0.43 ± 0.08		
50% "		0.96 ± 0.19	0.48 ± 0.05
20% "			0.76 ± 0.15
100% Illite	0.23 ± 0.04		
50% "		0.54 ± 0.08	0.32 ± 0.04
20% "			0.76 ± 0.15
100% Bentonite	0.15 ± 0.01		
50% "		0.15 ± 0.02	0.15 ± 0.02
20% "		0.18 ± 0.01	0.21 ± 0.04

Table 3

Composition of Natural Clay Soil Sonoma No. 5

Material	Percent by weight (Dry basis)
Hydrous mica	60
Feldspar	18
Quartz	12
Organic matter	2.5
Kaolinite	present

All analyses except organic content were made by Robert B. Langston of the Ceramics Laboratory of the Department of Mineral Technology of the University of California. Techniques used included X-ray diffraction, differential thermal analysis, cation-exchange, and chemical tests. The data are approximate, but indicate the order of magnitude. The ratio of feldspar to quartz is higher than normally encountered in sediments, but the figures are given as reported. The "hydrous mica" is similar in nature to the "illite" reported in previous work (Trask et. al., Issues 1 to 5).

Organic matter is based on carbon content times 1.7. The organic carbon content, as measured on four samples is 1.50 ± 0.01. The carbon analyses were made by J. V. Kerrigan in the Sanitary Engineering Research Laboratory of the University of California, by standard techniques.

Table 4

Pressure-sinkage Parameters for Natural Clay Soil Sonoma No. 5[1]
Tested in the Undisturbed State

Water Content Percent	Parameters a_1	a_2	k_c	k_ϕ	n_1	n_2
189	0.63	0.50	0.26	0.37	0.35	0.45
188	0.30	0.37	-0.14	0.44	0.42	0.53
181	0.49	0.44	0.10	0.39	0.41	0.55
177	0.51	0.50	0.02	0.49	0.27	0.41
171	0.64	0.61	0.06	0.50	0.40	0.34
165	0.87	0.72	-0.30	0.57	0.29	0.22
160	1.07	1.13	-0.12	1.19	0.19	0.20
159	0.97	1.04	-0.14	1.11	0.11	0.22
157	1.47	1.40	0.14	1.33	0.20	0.18
156	1.23	1.10	0.26	0.97	0.33	0.27
152	1.31	1.35	-0.08	1.49	0.10	0.36
151	1.80	1.72	0.16	1.64	0.05	0.06
150	1.94	1.77	0.34	1.60	0.18	0.32
150	1.53	1.72	-0.38	1.91	0.12	0.32
145	2.07	2.01	0.12	1.95	0.06	0.15
145	2.07	1.49	1.16	0.91	0.27	0.29
143	1.82	1.64	0.36	1.42	0.15	0.29
141	2.60	2.08	1.04	1.56	0.10	0.24
139	1.93	1.98	-0.10	2.03	0.21	0.38
126	4.18	3.67	1.02	3.16	0.05	0.10
95	8.41	5.58	2.83	2.75	0.18	0.38

(1) Note: All calculations are based on 1.0 and 2.0-inch plates $a_1 = (k_c/b + k_\phi)$, $a_2 = (k_c/b_2 + k_\phi)$ where $b_1 = 1.0''$ and $b_2 = 2.0''$, n is exponent in pressure-sinkage formula:

$$p = (k_c/b + k_\phi)\, z^n$$

Table 5

Pressure-sinkage Parameters for Natural Clay-Soil Sonoma No. 5
Tested in Remolded State

Water Content Percent	Parameters					
	a_1	a_2	k_c	k_ϕ	n_1	n_2
126	0.98	0.94	0.08	0.90	0.22	0.36
125	1.13	1.14	-0.02	1.15	0.27	0.41
121	1.42	1.36	0.12	1.30	0.32	0.37
119	1.48	1.43	0.10	1.38	0.35	0.48
118	2.61	2.70	-0.18	2.79	0.42	0.40
115	2.26	2.02	0.48	1.78	0.23	0.35
99	2.60	2.45	0.30	2.30	0.21	0.33
71	16.4	16.0	0.80	15.6	0.14	0.32

(1) Note: All calculations are based on 1.0 and 2.0-inch plates.

$a_1 = (k_c/b_1 + k_\phi)$, $a_2 = (k_c/b_2 + k_\phi)$ where $b_1 = 1.0''$ and $b_2 = 2.0''$

n is exponent in pressure-sinkage formula:

$$p = (k_c/b + k_\phi)\, z^n$$

Table 6

Pressure-sinkage Parameters for Mixtures of Clastic Material of Different Grain Size with Natural Clay soil Sonoma No. 5

Percent Clastic Material	Water Content Percent	a_1	a_2	k_c	k_ϕ	n_1	n_2
		1.2 Micron Size					
50 percent	55.8	8.32	7.18	2.28	6.04	0.76	0.34
	58.3	5.52	4.92	1.20	4.32	0.31	0.67
	65.5	2.82	2.54	0.56	2.26	0.32	0.56
	69.3	1.74	1.63	0.22	1.52	0.41	0.54
	75.2	1.10	1.16	-0.12	1.12	0.29	0.48
		16 Micron Size					
50 percent	43.8	9.79	10.03	-0.48	11.27	0.15	0.71
	47.3	5.41	4.24	2.34	6.58	0.26	0.61
	53.8	2.51	2.20	0.62	1.89	0.34	0.26
	60.2	1.52	1.47	0.10	1.42	0.33	0.35
	68.0	0.94	0.88	0.12	0.82	0.40	0.50
80 percent	28.9	7.18	5.81	2.74	4.44	0.54	0.79
	31.4	4.55	3.83	1.44	3.11	0.30	0.62
	34.0	2.57	2.36	0.42	2.15	0.37	0.49
	36.8	1.73	1.56	0.34	1.38	0.32	0.52
		74 Micron Sand Size					
50 percent	47.0	6.14	5.72	0.84	5.30	0.18	0.64
	50.9	3.45	3.18	0.54	2.91	0.20	0.45
	53.8	1.76	1.72	0.08	1.68	0.14	0.32
	61.4	1.10	1.11	-0.02	1.12	0.10	0.35
	65.7	0.82	0.76	0.12	0.70	0.22	0.46
80 percent	27.7	10.03	8.91	2.24	7.79	0.37	0.58
	28.9	7.90	6.59	2.62	5.29	0.29	0.35
	29.6	6.46	5.89	1.14	5.32	0.35	0.46
	30.5	5.47	5.05	0.84	4.63	0.15	0.43
	32.4	5.39	3.54	3.70	1.79	0.15	0.43
	33.7	2.97	2.65	0.64	1.33	0.22	0.44
	36.1	2.00	1.90	0.20	0.80	0.31	0.36

Table 6 (contd)

Pressure-sinkage Parameters for Mixtures of Clastic Material of Different Grain Size with Natural Clay-soil Sonoma No. 5

Percent Clastic Material	Water Content Percent	a_1	a_2	k_c	k_ϕ	n_1	n_2
				Parameters			
			120 Micron Sand Size				
50 percent	41.2	8.08	9.10	-2.04	10.12	0.16	0.69
	45.8	3.93	3.61	0.64	3.29	0.34	0.55
	51.9	1.62	1.73	-0.22	1.84	0.22	0.55
	55.6	1.32	1.17	0.30	1.02	0.30	0.46
	61.1	0.86	0.81	0.10	0.86	0.46	0.53
80 percent	24.5	9.04	7.51	3.06	5.98	0.49	0.86
	25.3	7.23	5.69	3.08	4.15	0.44	0.71
	26.5	5.30	4.26	2.08	3.22	0.47	0.77
	27.2	4.35	3.72	1.26	3.09	0.44	0.54
	28.3	3.81	3.16	1.30	2.51	0.16	0.30
	28.0	3.11	2.96	0.30	2.81	0.23	0.51
	30.6	2.15	0.56	0.86	1.29	0.21	0.56
	33.2	1.33	1.25	0.16	1.27	0.32	0.65
			210 Micron Sand Size				
50 percent	30.1	15.1	11.1	8.00	7.10	0.26	0.58
	40.6	6.18	5.37	1.62	4.56	0.20	0.70
	45.8	2.46	2.41	0.10	2.36	0.30	0.42
	58.6	1.31	1.29	0.04	1.07	0.40	0.49
80 percent	22.8	8.54	7.48	2.12	6.42	0.46	0.75
	23.6	7.02	5.87	1.15	4.72	0.61	0.75
	24.1	5.47	5.02	0.90	4.57	0.28	0.63
	24.9	4.71	4.33	0.76	3.95	0.29	0.63
	25.3	3.12	3.19	-0.14	3.46	0.40	0.70
	26.5	2.62	2.53	0.18	2.42	0.31	0.60
	29.3	1.72	1.58	0.28	1.44	0.28	0.71

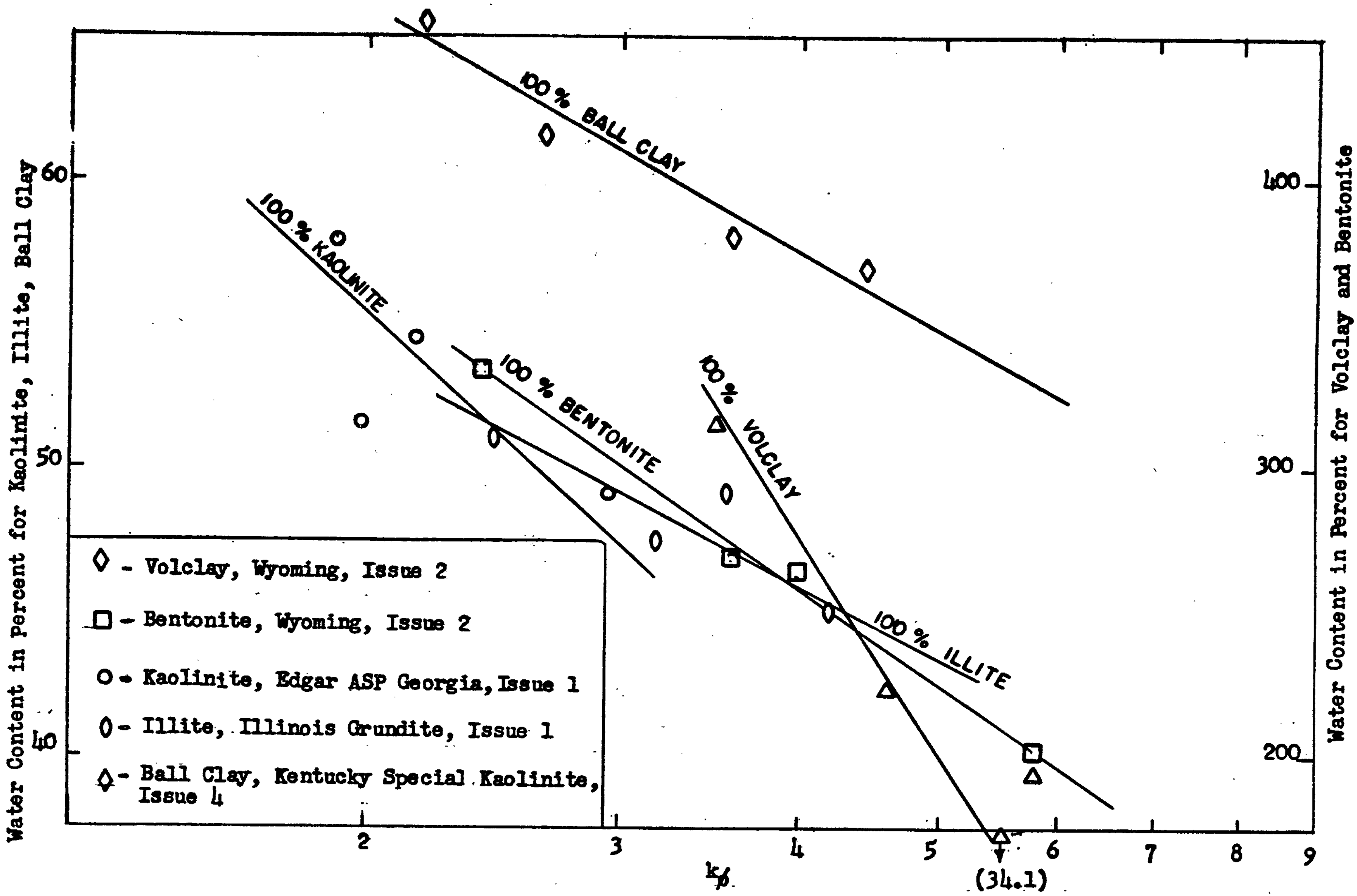


Figure 1. Relationship between Water Content and Modulus of Deformation k_{ϕ} for 100 Percent Wyoming Volcay, Wyoming Bentonite, Edgar ASP Georgia Kaolinite, Illinois Grundite Illite, Kentucky Special Ball Clay Kaolinite.

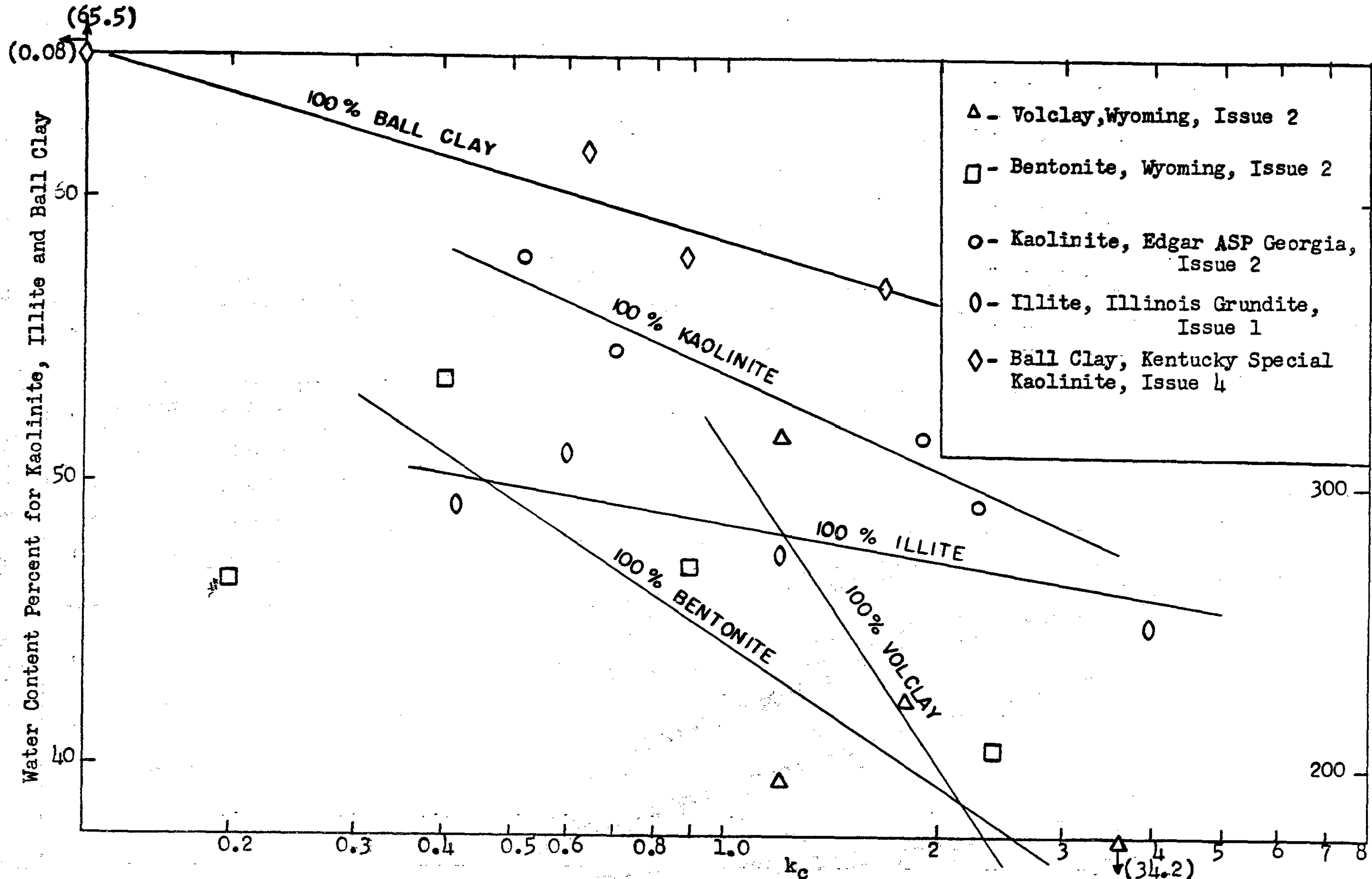


Figure 2. Relationship between Water Content and Modulus of Deformation k_c for 100 Percent Wyoming Volclay, Wymoning Bentonite, ~~Edgar ASP Georgia~~ Kaolinite, Illinois Grundite Illite, Kentucky Special Ball Clay Kaolinite.

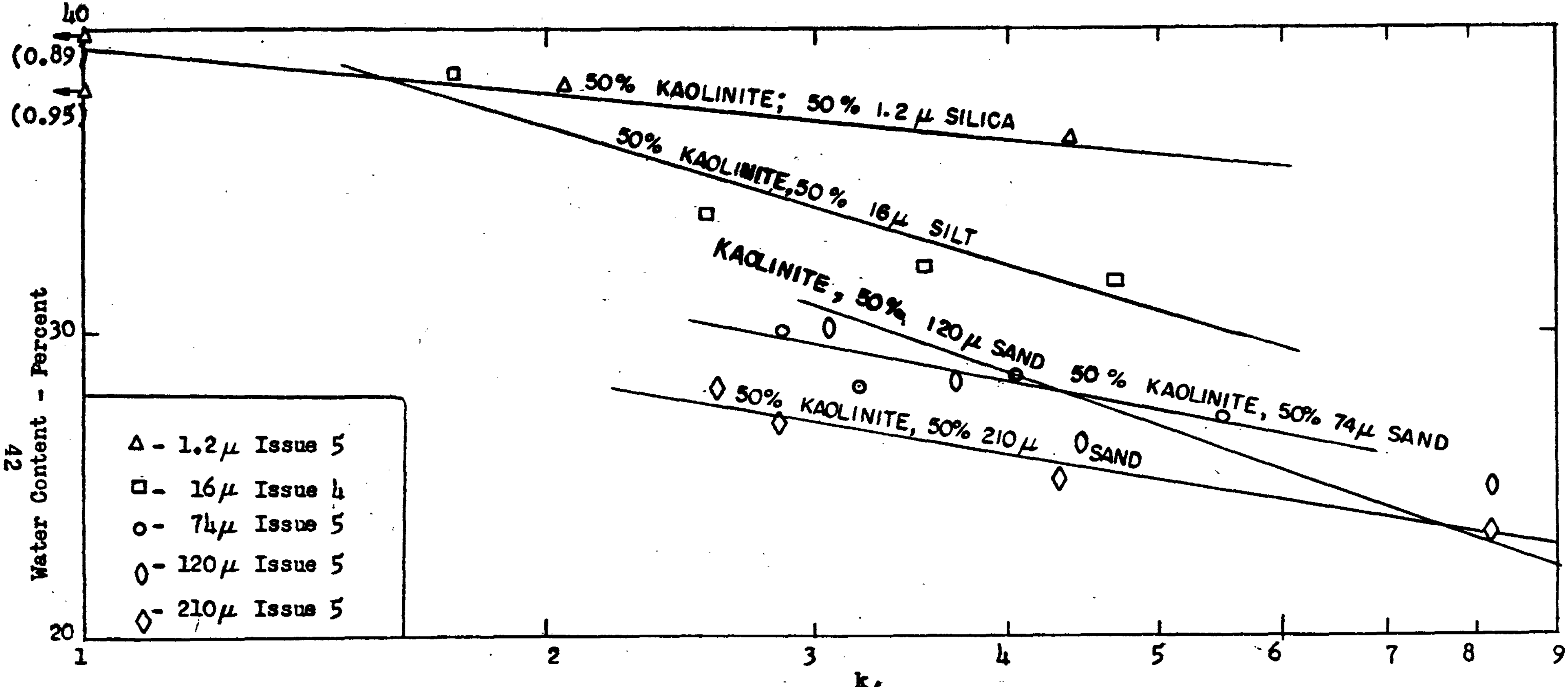


Figure 3. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of 50 Percent Edgar ASP Georgia Kaolin Clay and 50 Percent Clastic Material.

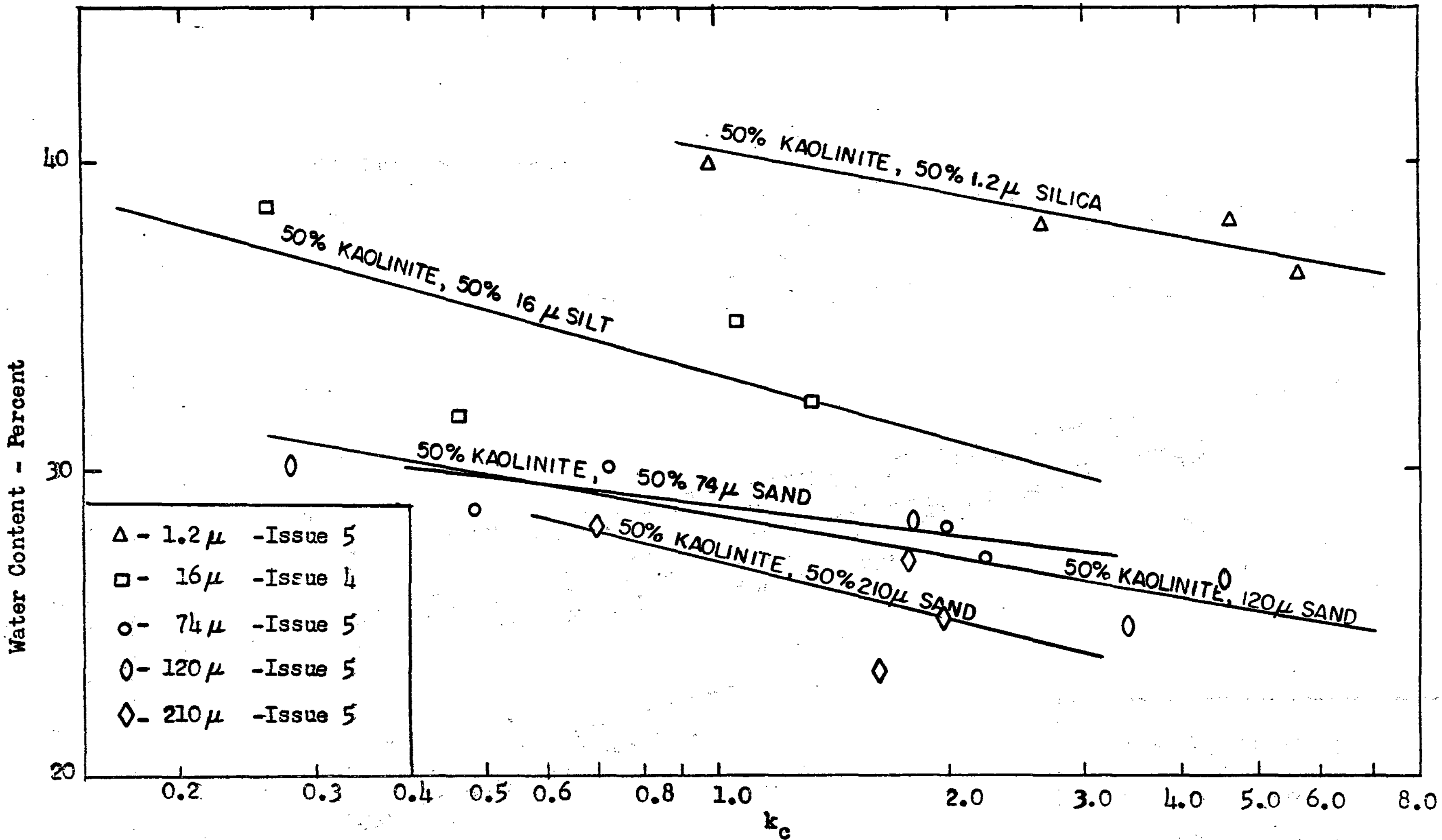


Figure 4. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of 50 Percent Edgar ASP Georgia Kaolinite Clay and 50 Percent Clastic Material.

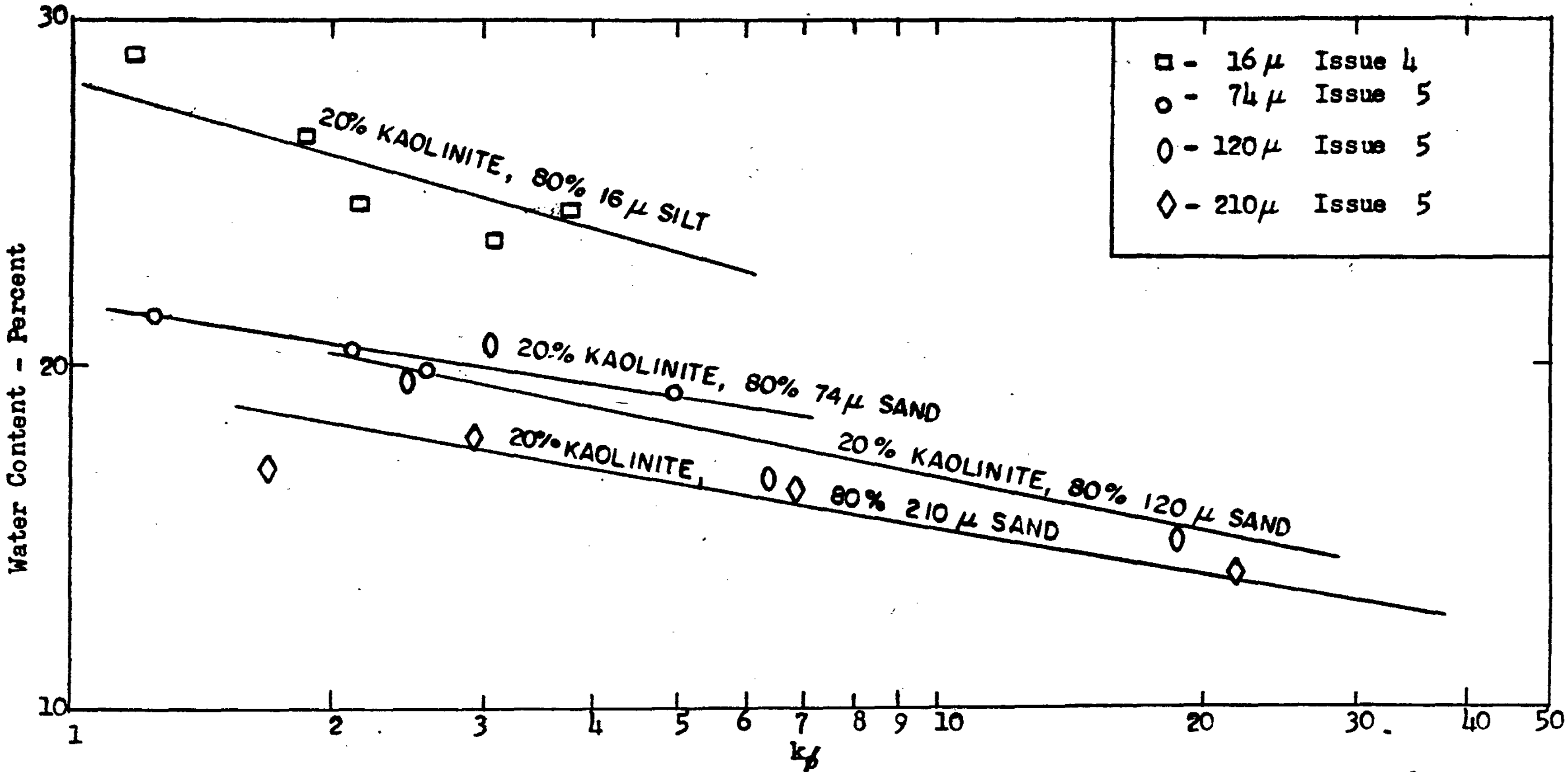


Figure 5. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of 20 Percent Edgar ASP Georgia Kaolin Clay and 80 Percent Clastic Material.

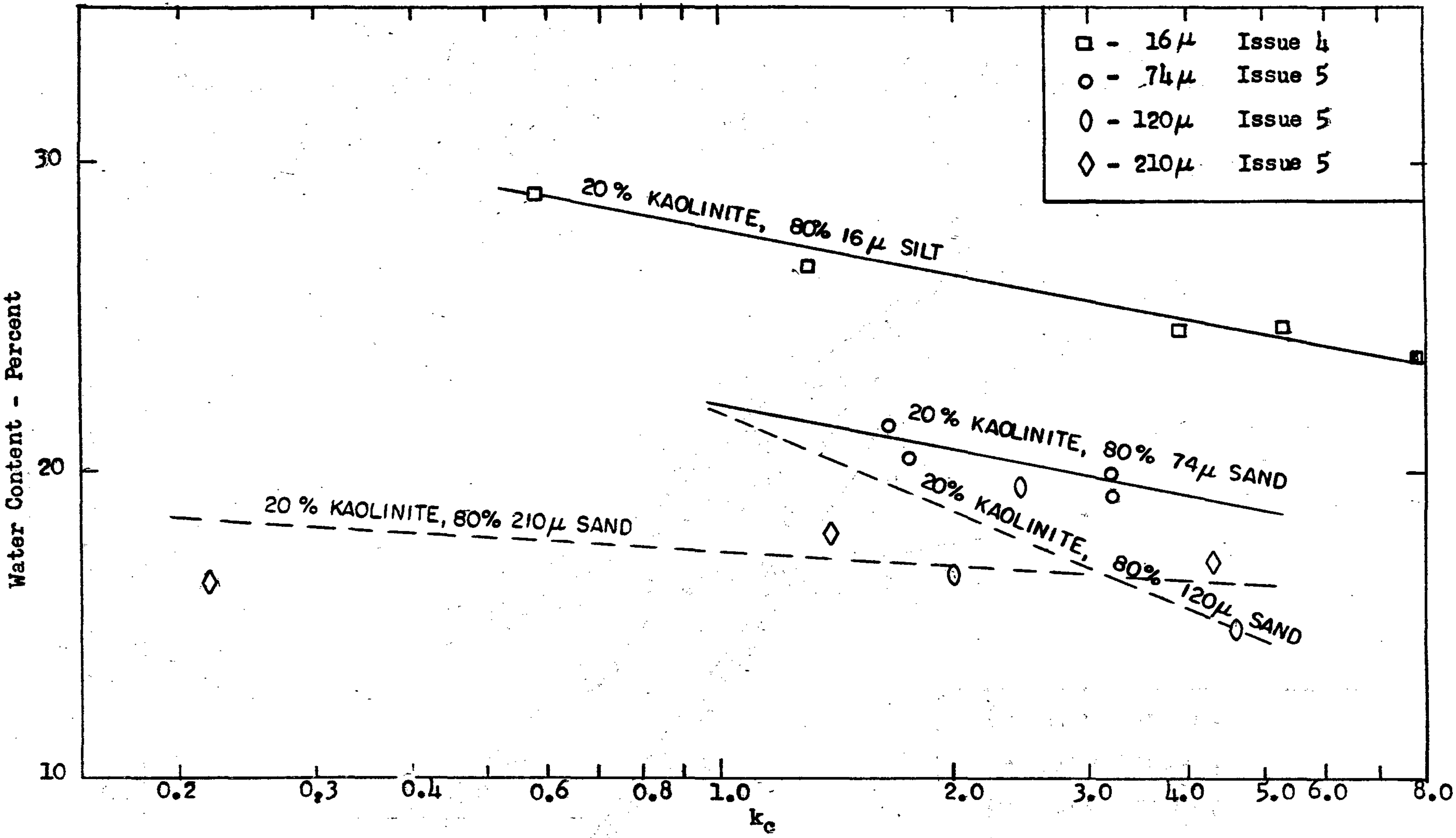


Figure 6. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of 20 Percent Edgar ASP Georgia Kaolin Clay and 80 Percent Clastic Material.

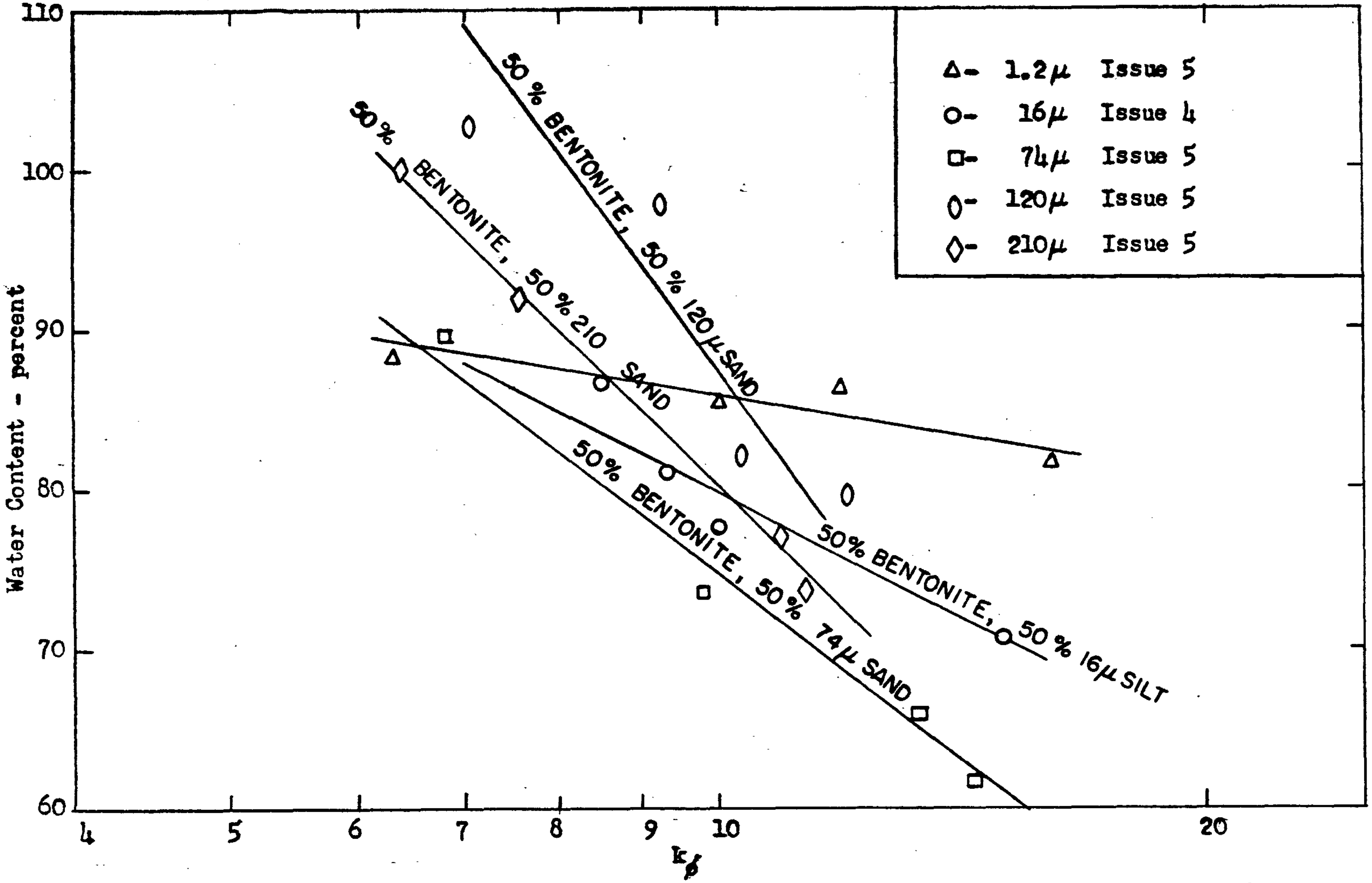


Figure 7. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of 50 Percent Wyoming Bentonite and 50 Percent Clastic Material.

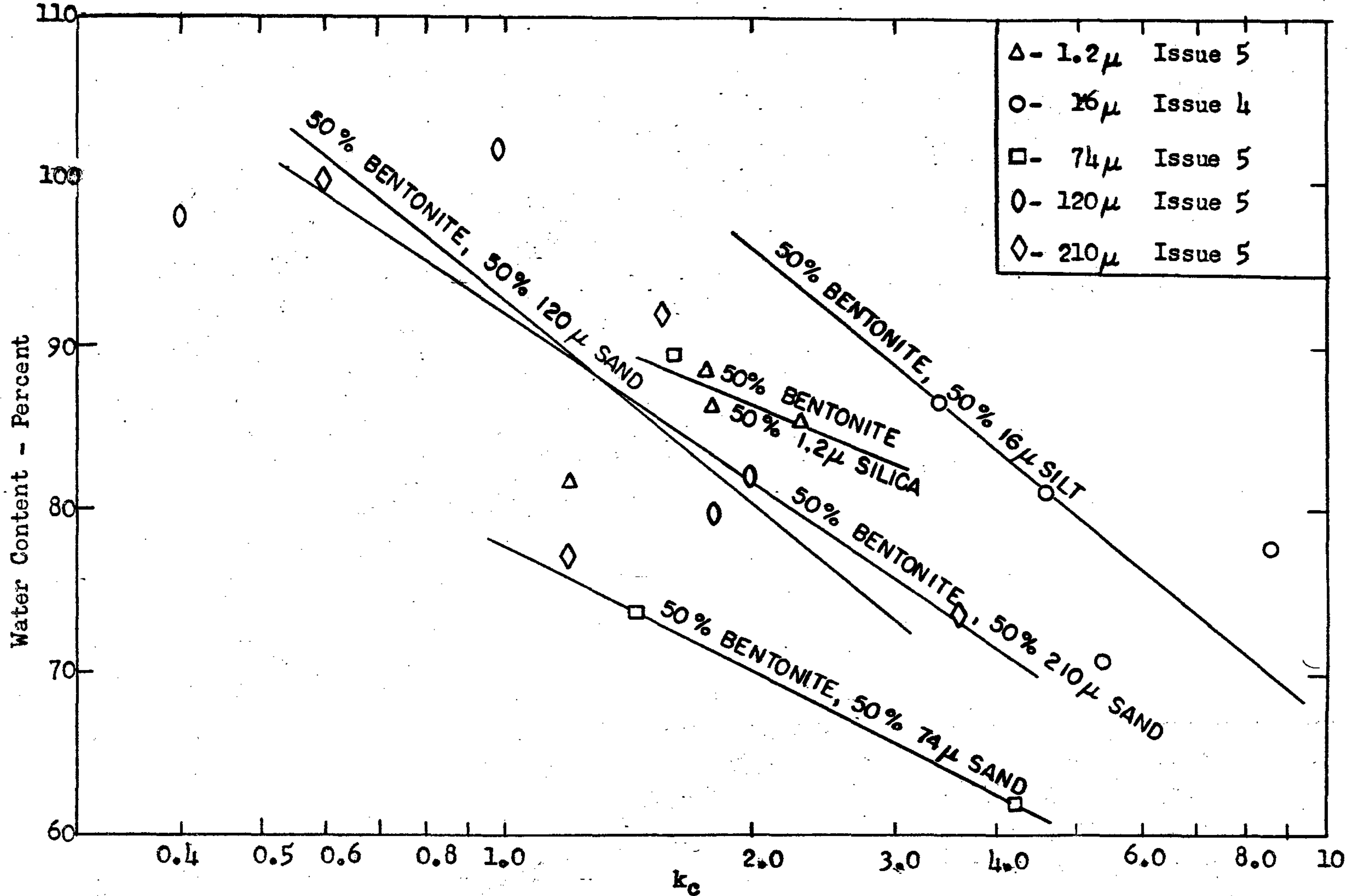


Figure 8. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of 50 Percent Wyoming Bentonite and 50 Percent Clastic Material.

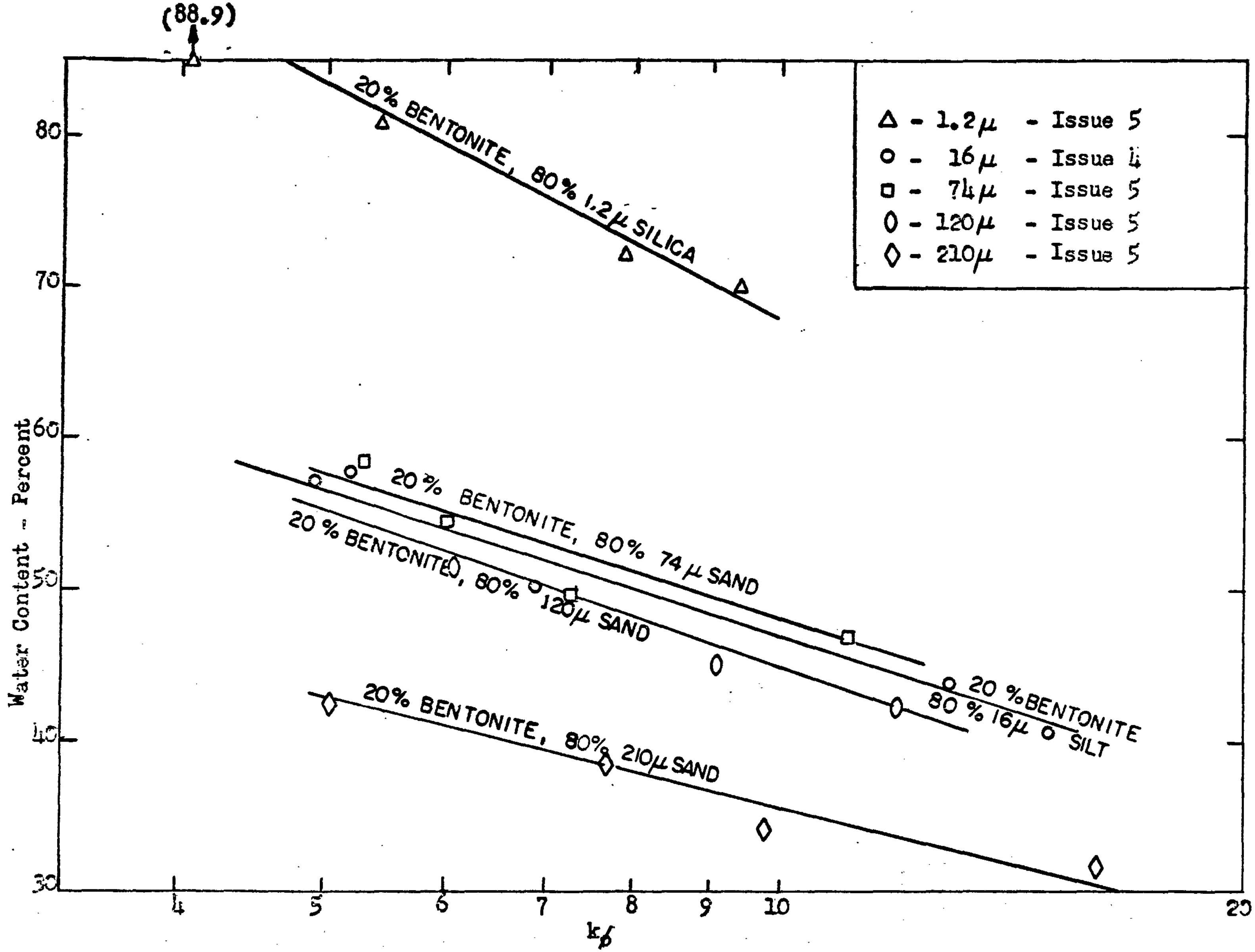


Figure 9. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of 20 Percent Wyoming Bentonite and 80 Percent Clastic Material.

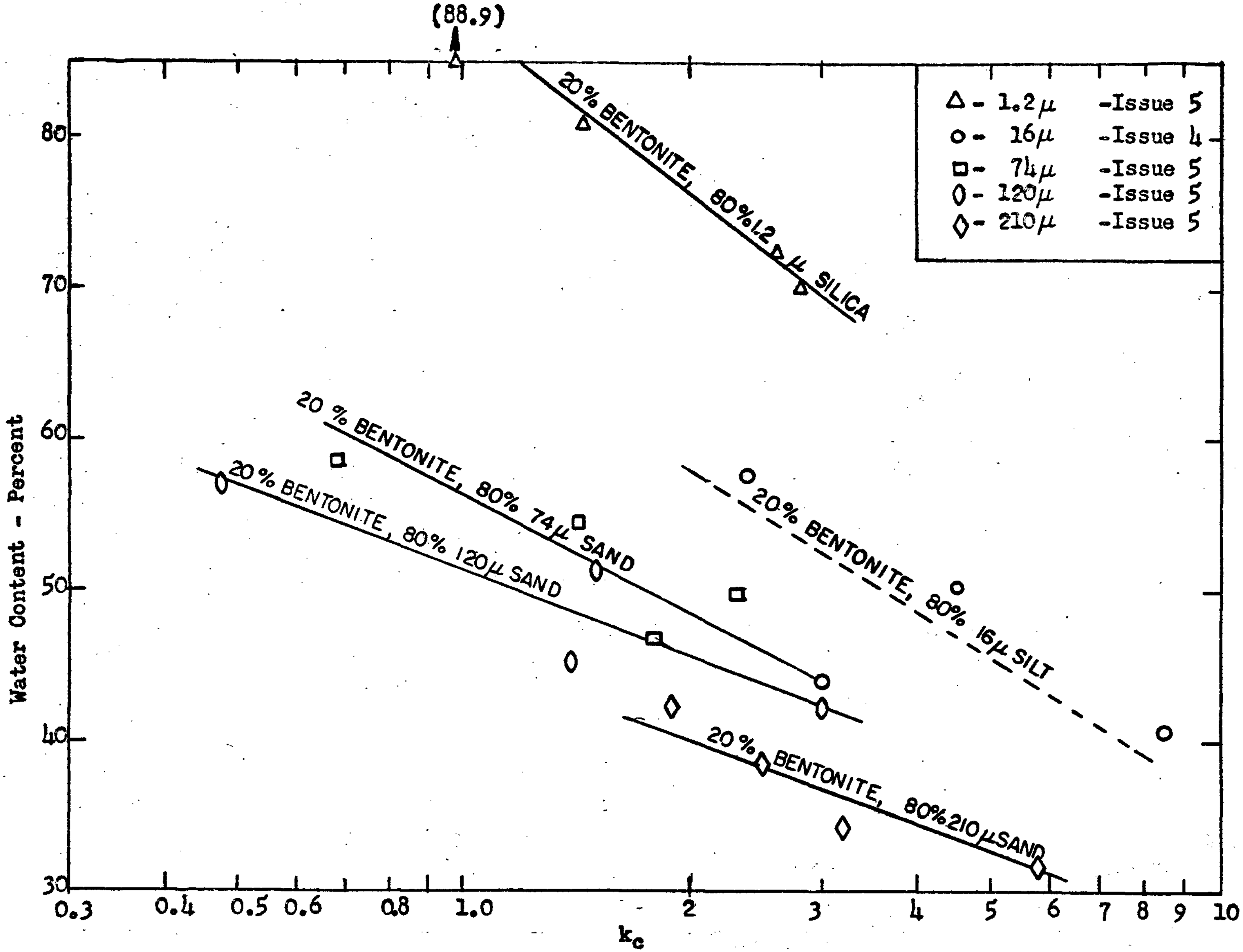


Figure 10. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of 20 Percent Wyoming Bentonite and 80 Percent Clastic Material.

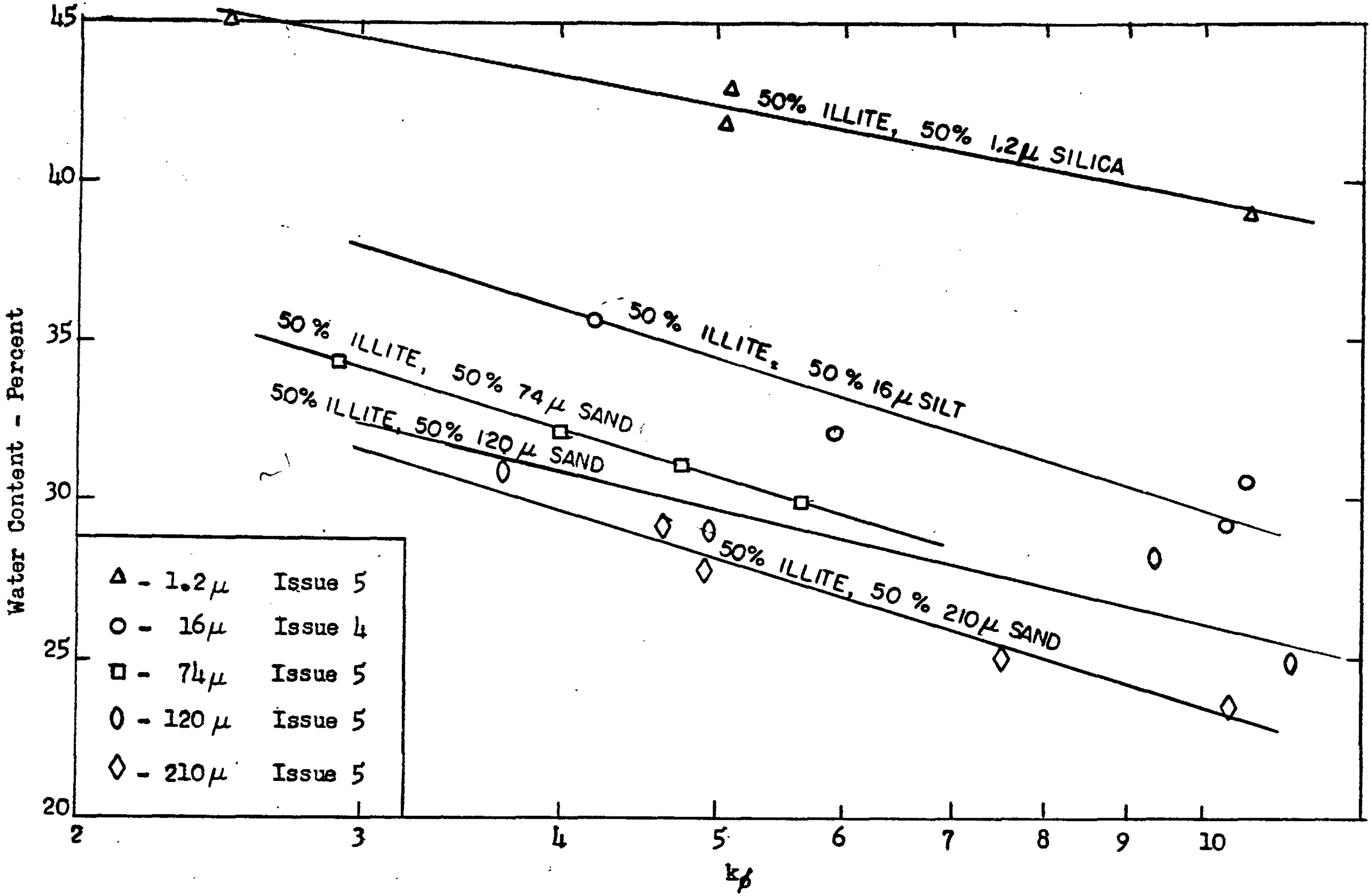


Figure 11. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of 50 Percent Illinois Grundite Illite and 50 Percent Clastic Material.

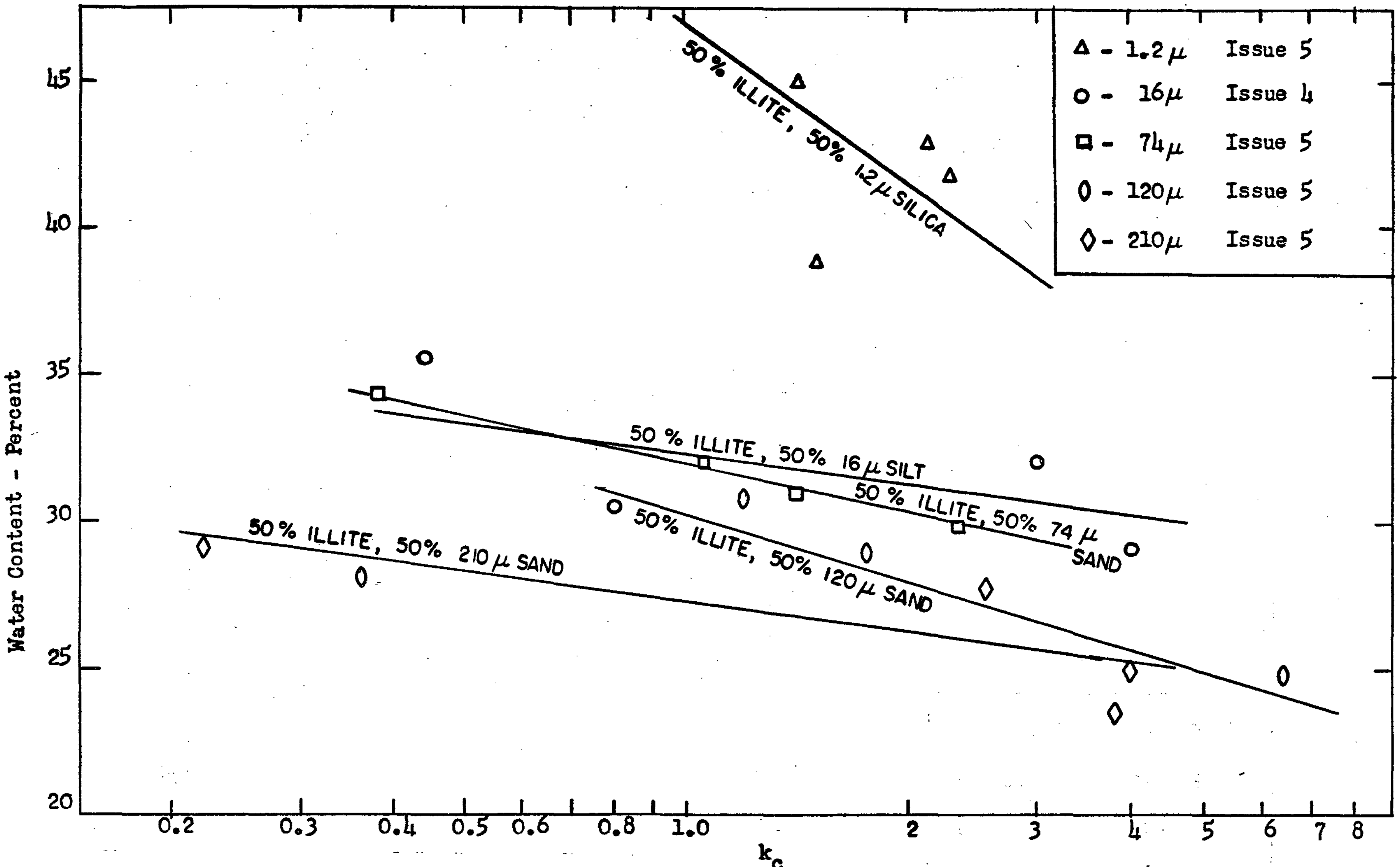


Figure 12. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of 50 Percent Illinois Grundite Illite and 50 Percent Clastic Material.

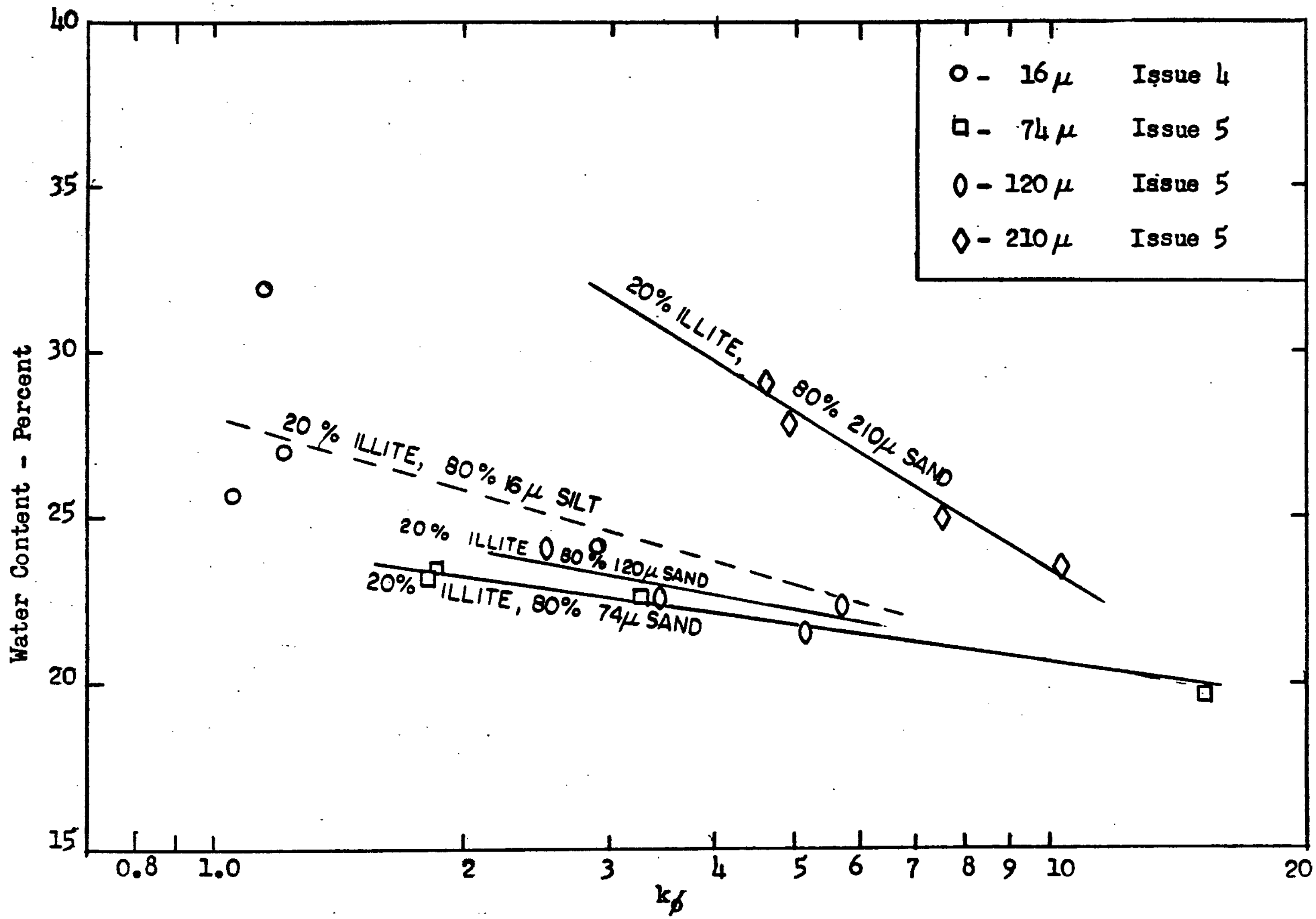


Figure 13. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of 20 Percent Illinois Grundite Illite and 80 Percent Clastic Material.

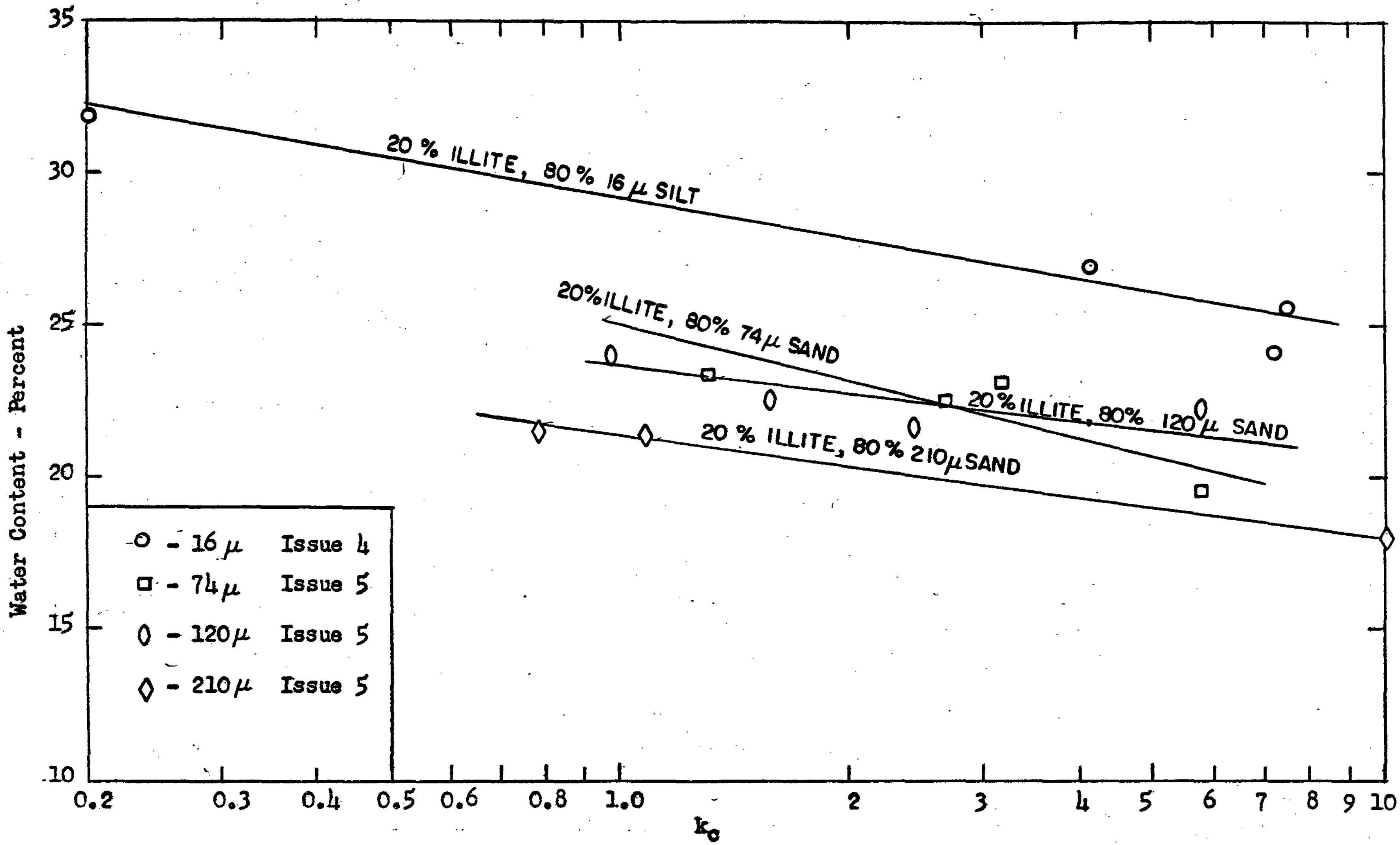


Figure 14. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of 20 Percent Illinois Grundite Illite and 80 Percent Clastic Material.

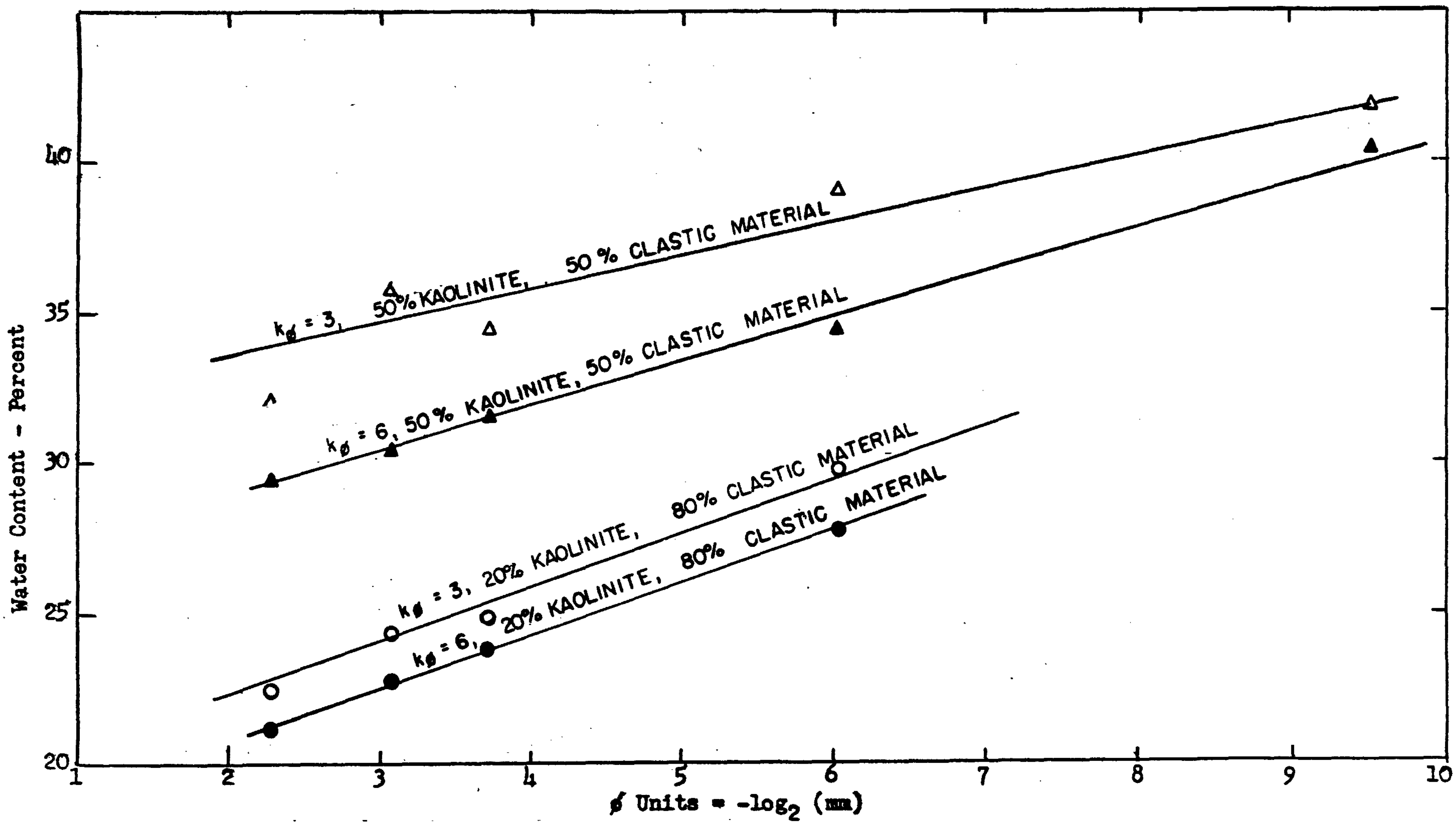


Figure 15. Relationship between Water Content and Grain Size for Mixtures of Edgar ASP Georgia Kaolin Clay and Clastic Material at Constant Values of the Modulus of Deformation k_ϕ.

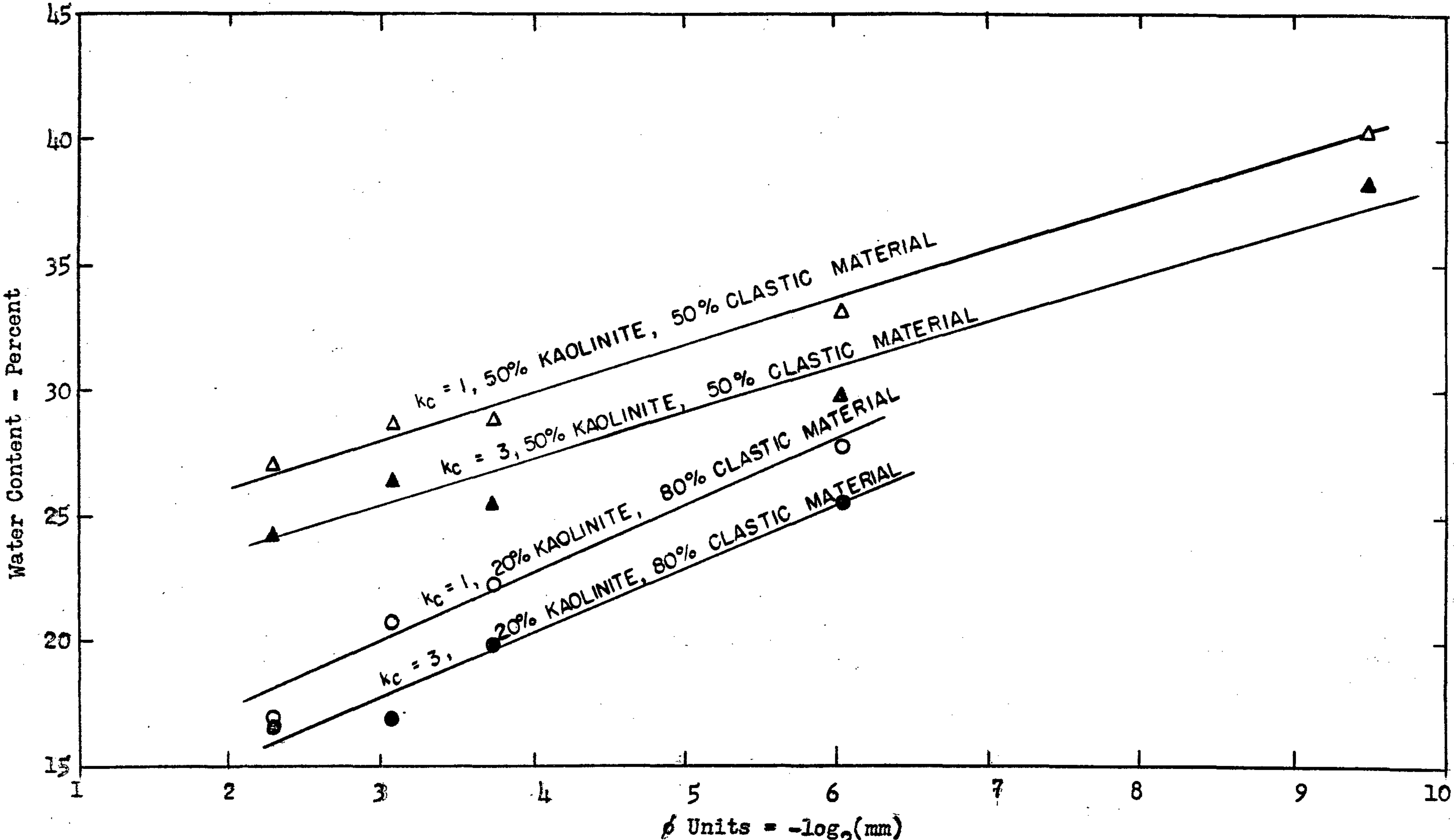


Figure 16. Relationship between Water Content and Grain Size for Mixtures of Edgar ASP Georgia Kaolin Clay and Clastic Material at Constant Values of the Modulus of Deformation k_c.

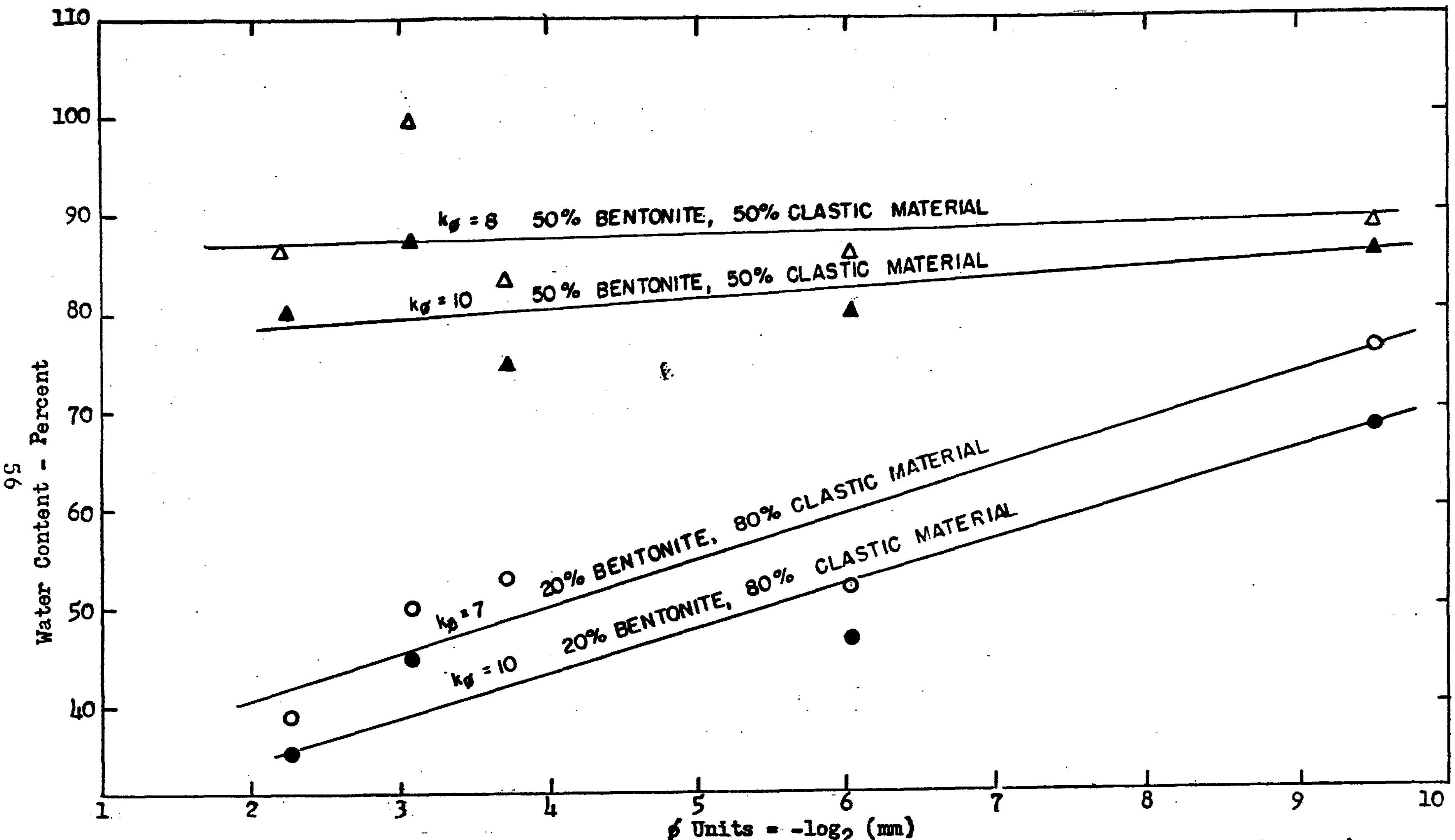


Figure 17. Relationship between Water Content and Grain Size for Mixtures of Wyoming Bentonite and Clastic Material at Constant Values of the Modulus of Deformation k_ϕ.

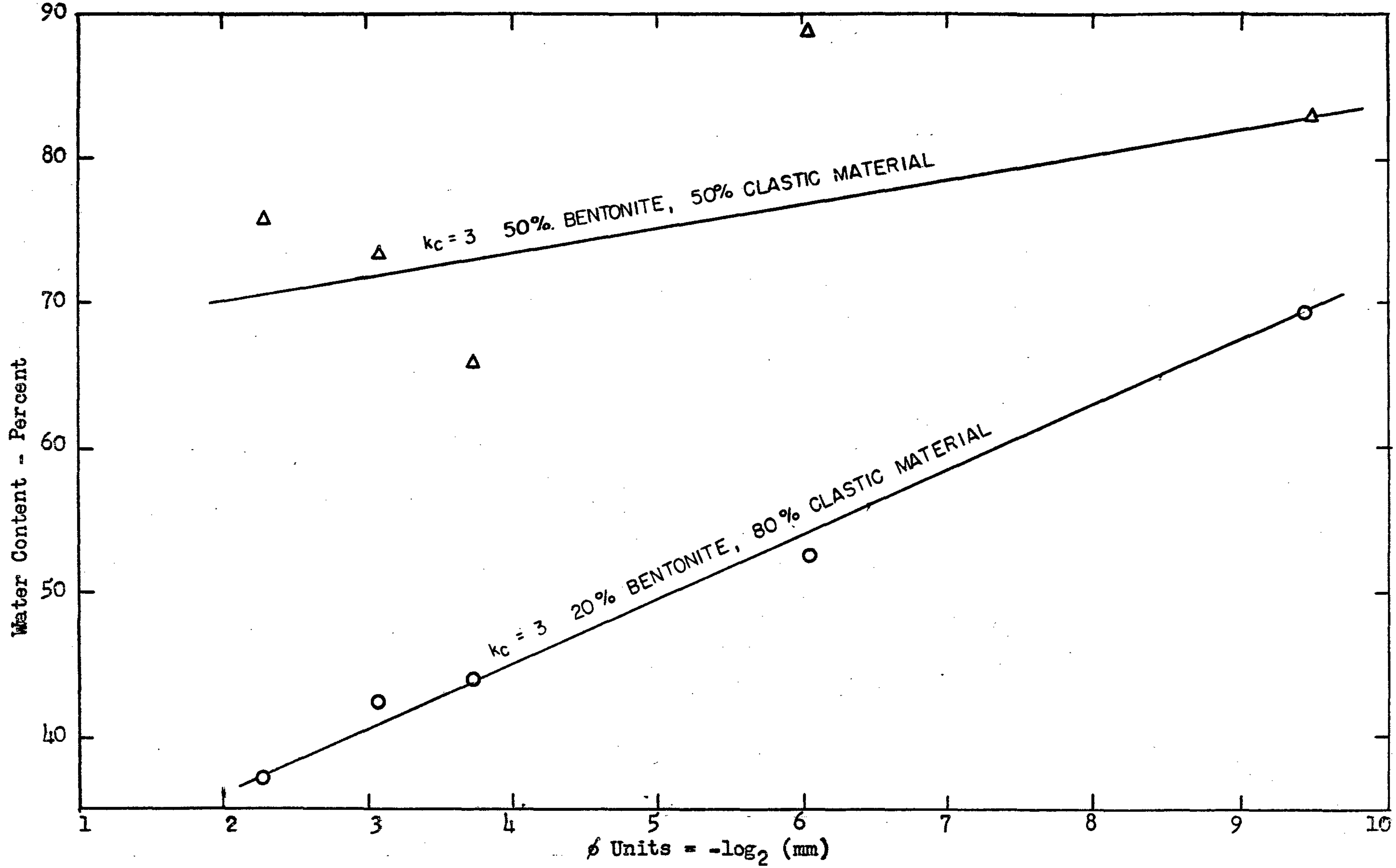


Figure 18. Relationship between Water Content and Grain Size for Mixtures of Wyoming Bentonite and Clastic Material at a Constant Value of the Modulus of Deformation k_c.

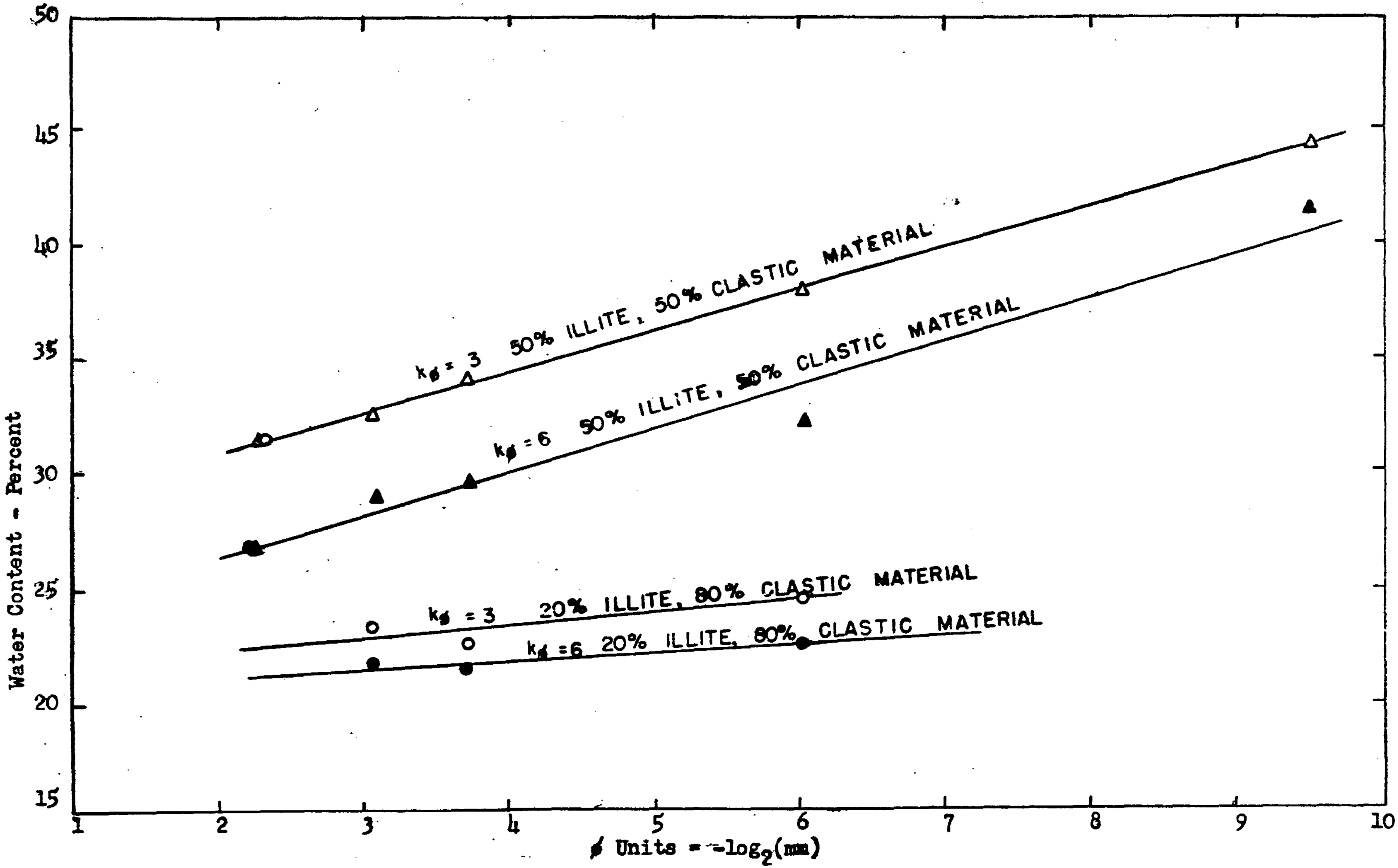


Figure 19. Relationship between Water Content and Grain Size for Mixtures of Illinois Grundite Illite and Clastic Material at Constant Values of the Modulus of Deformation k_ϕ.

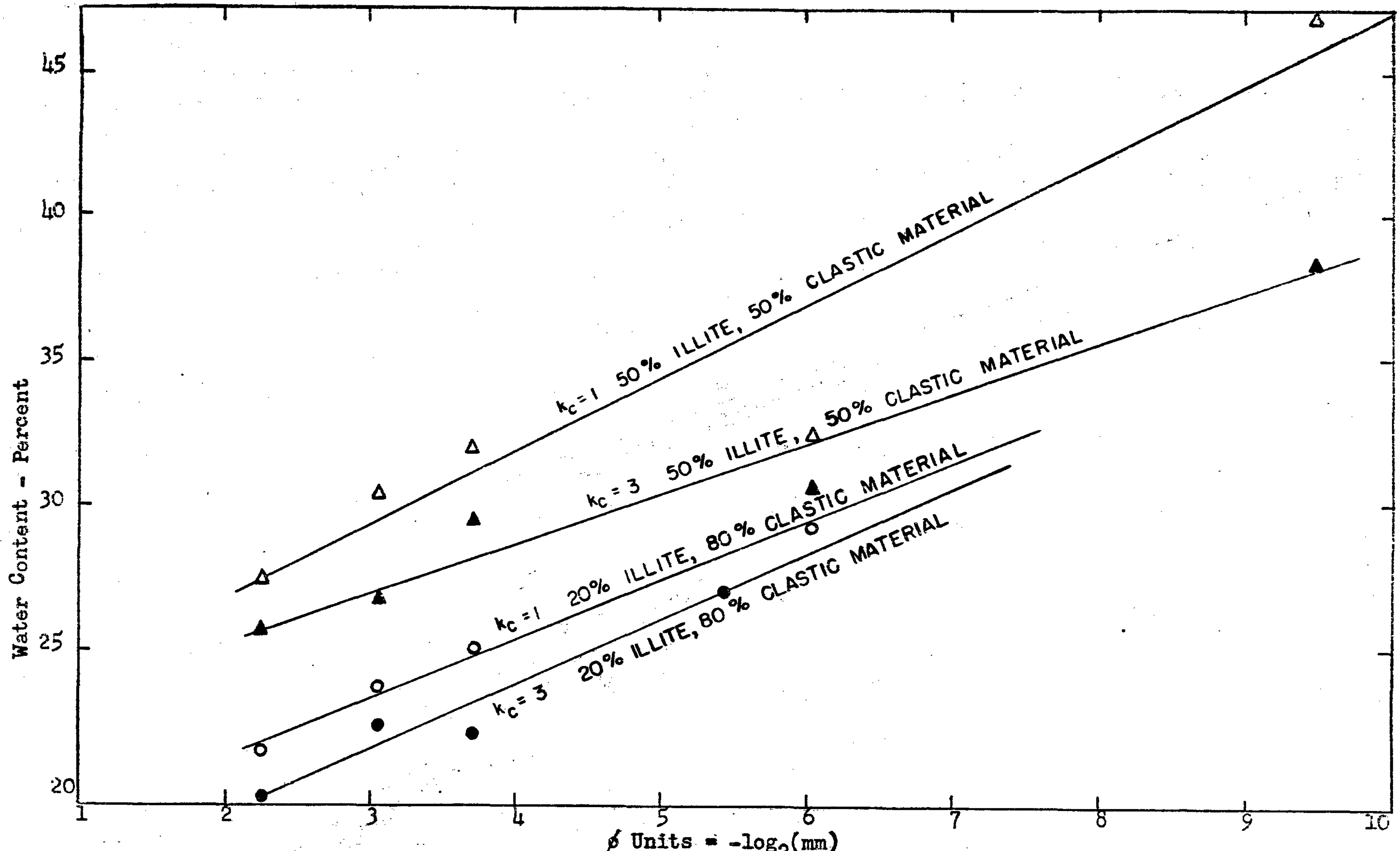


Figure 20. Relationship between Water Content and Grain Size for Mixtures of Illinois Grundite Illite and Clastic Material at Constant Values of the Modulus of Deformation k_c.

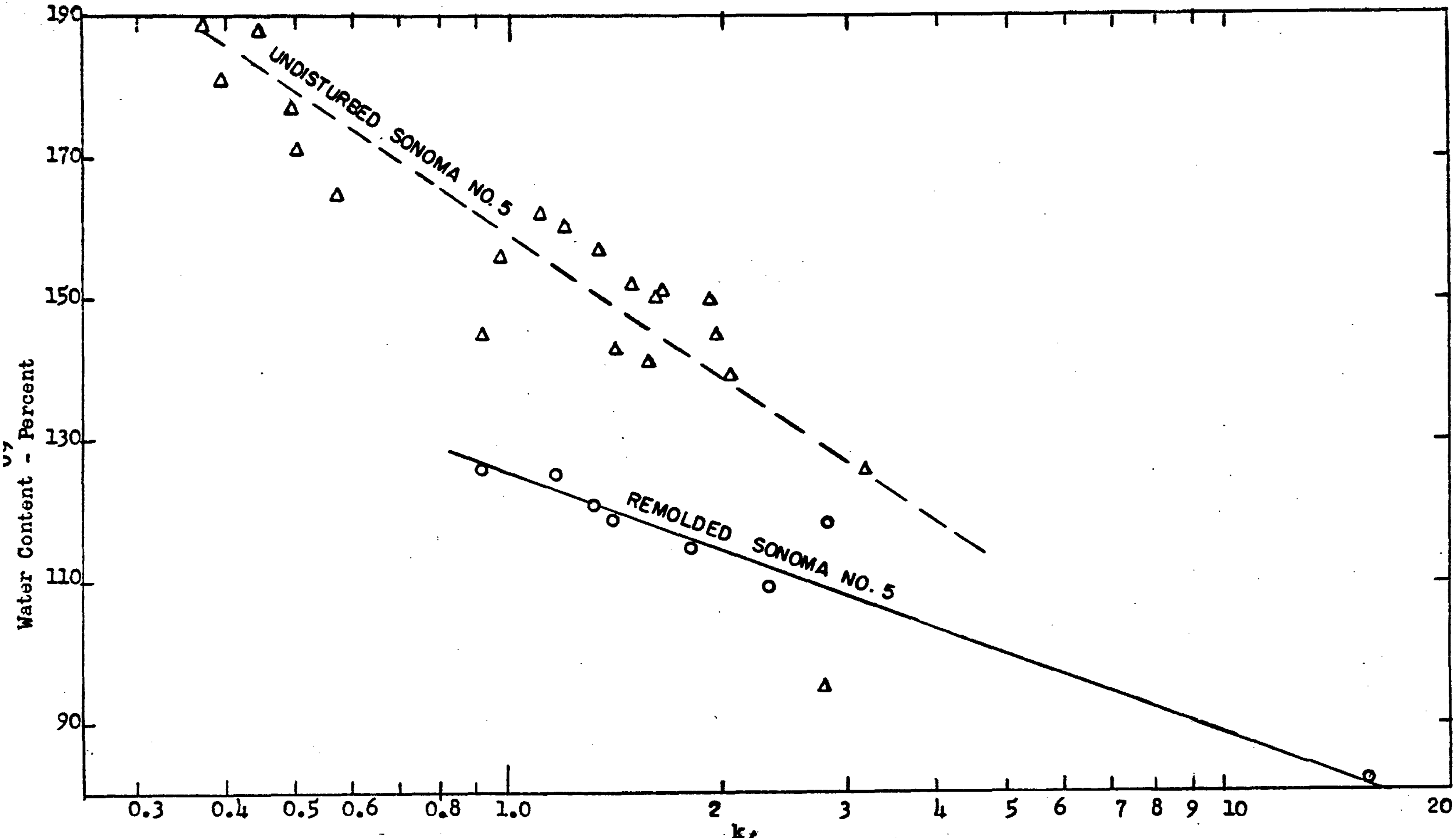


Figure 21. Relationship between Water Content and Modulus of Deformation k_ϕ for Undisturbed and Remolded Natural Clay Soil Sonoma No. 5.

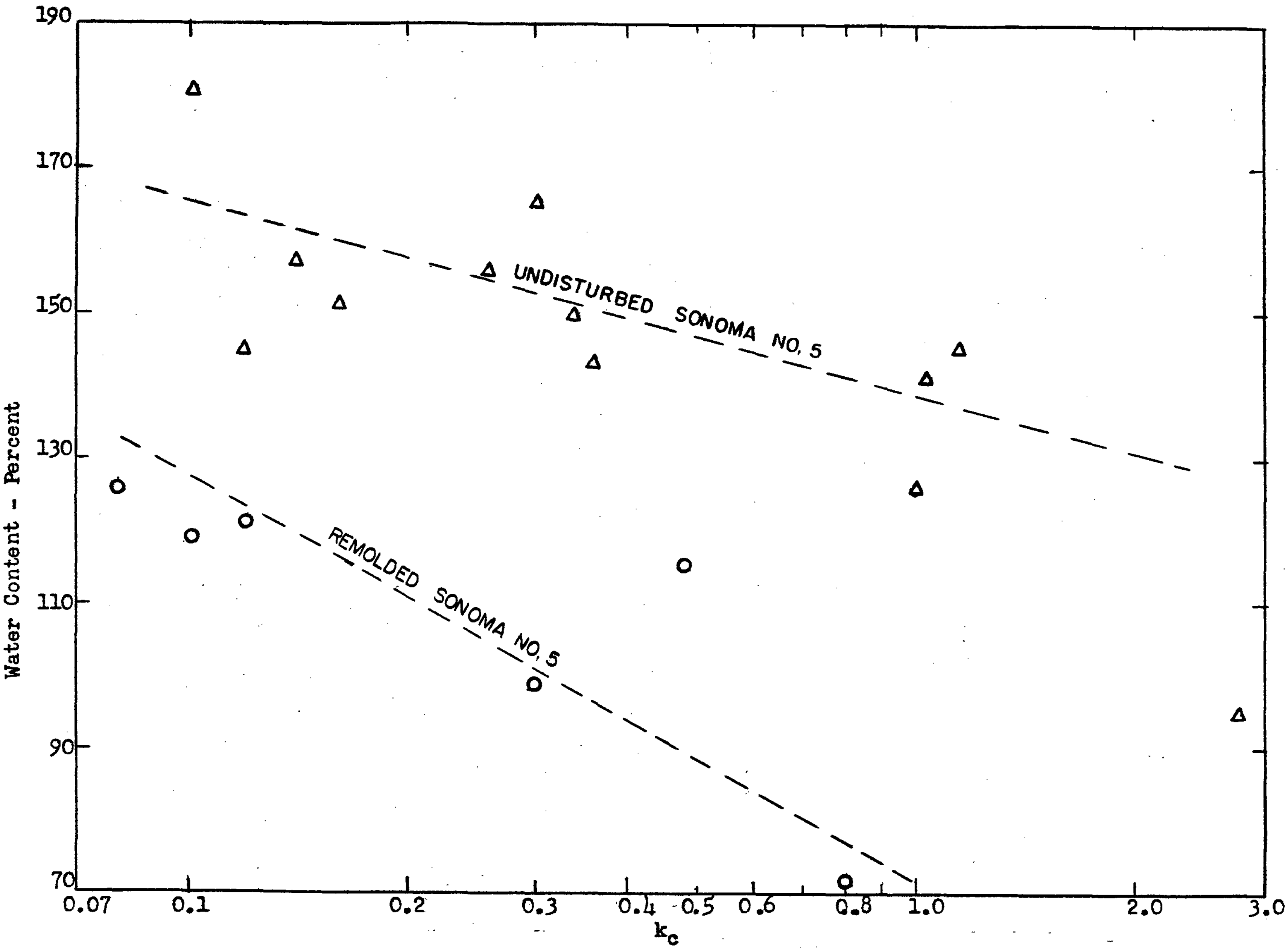


Figure 22. Relationship between Water Content and Modulus of Deformation k_c for Undisturbed and Remolded Natural Clay Soil Sonoma No. 5.

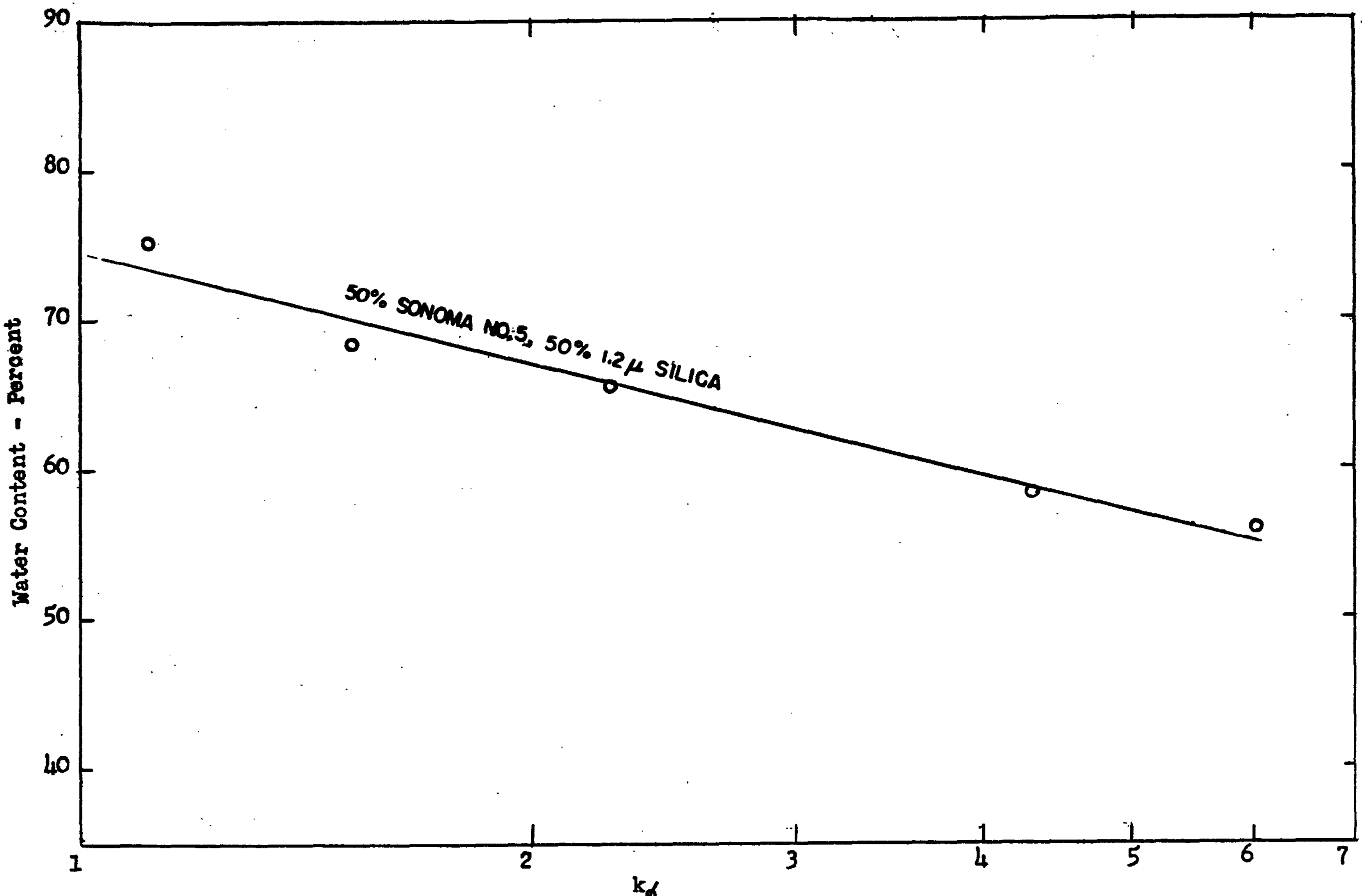


Figure 23. Relationship between Water Content and Modulus of Deformation k_ϕ for a Mixture of Sonoma No. 5 Clay Soil with 50 Percent 1.2 Micron Silica.

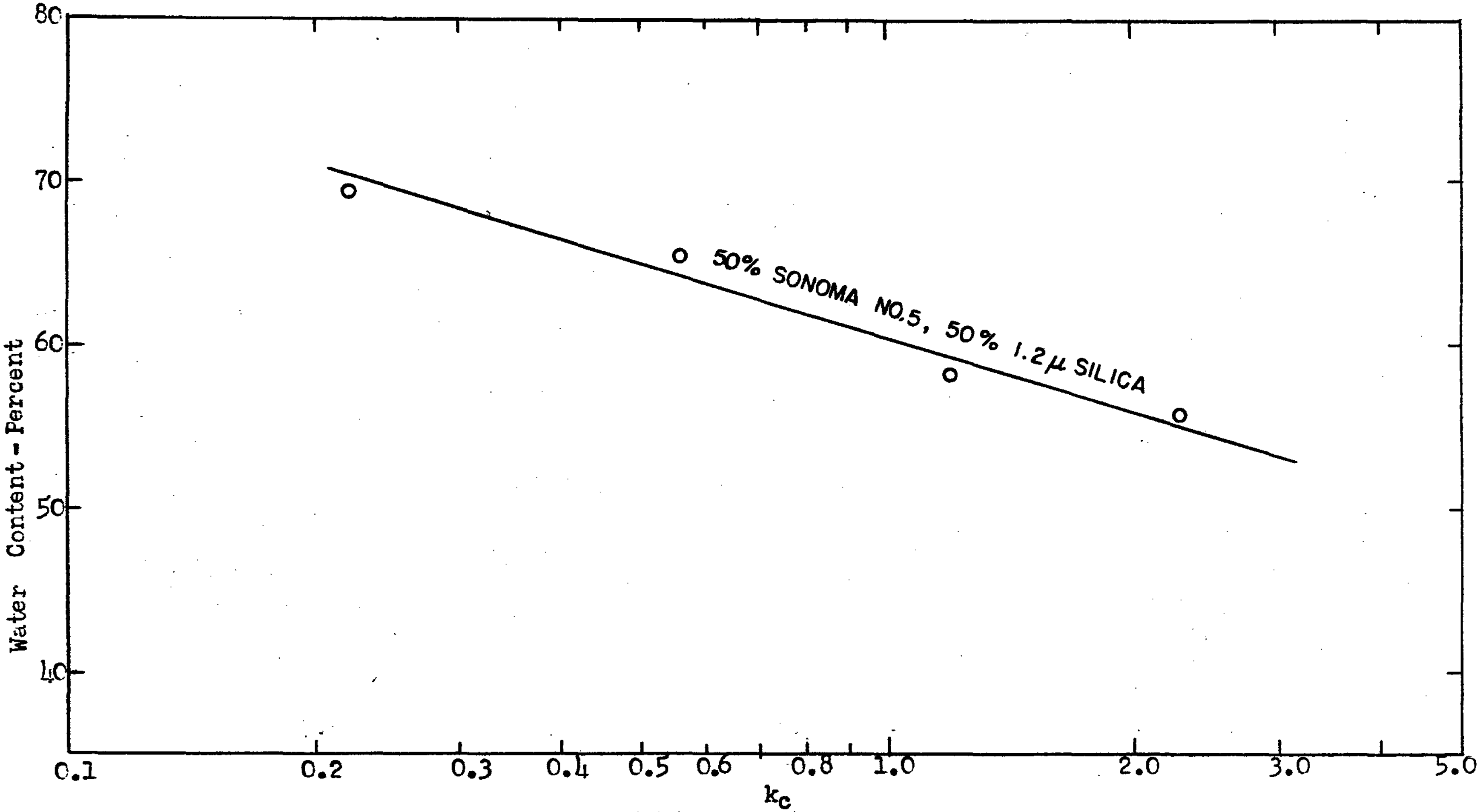


Figure 24. Relationship between Water Content and Modulus of Deformation k_c for a Mixture of Sonoma No. 5 Clay Soil with 50 Percent 1.2 Micron Silica.

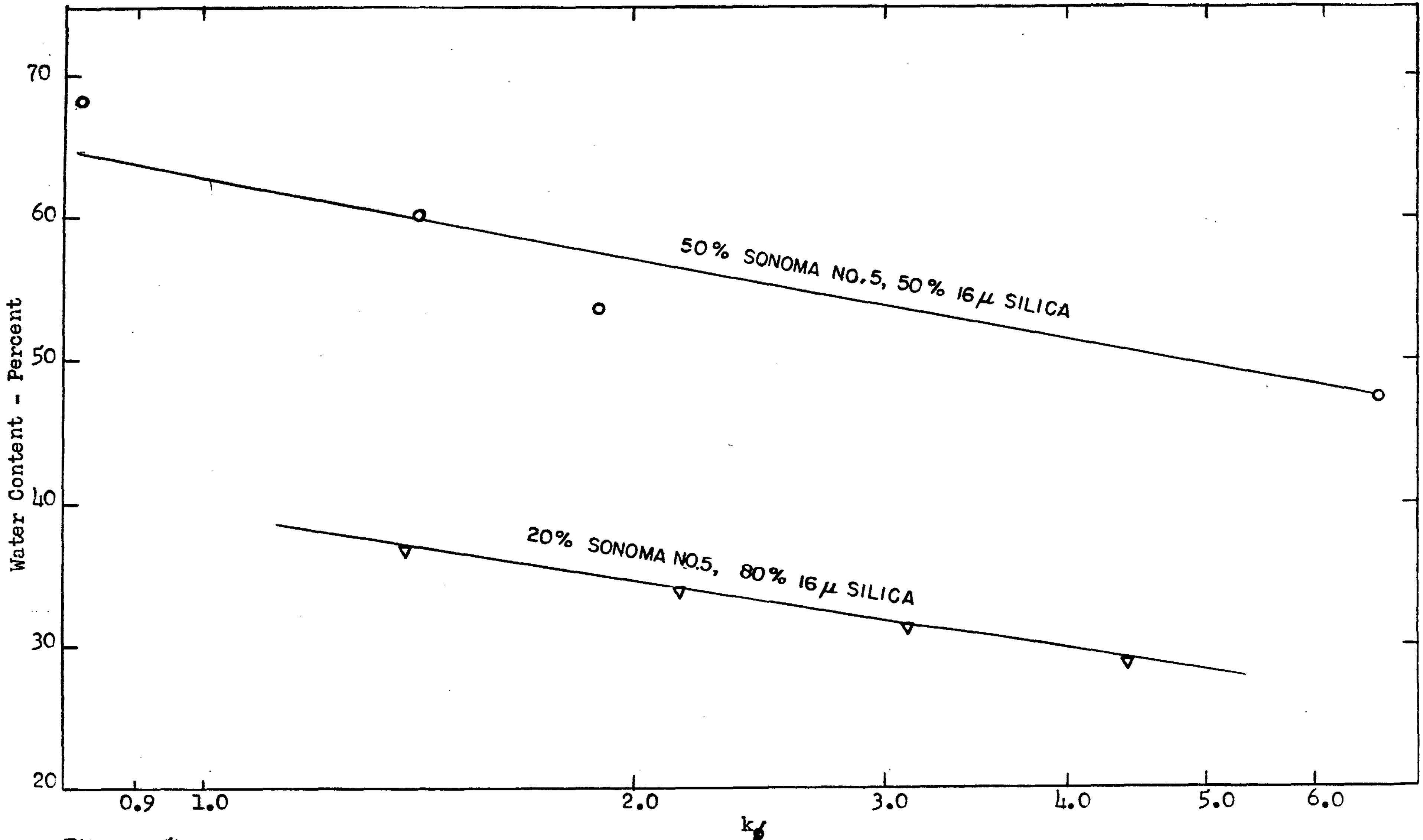


Figure 25. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of Sonoma No. 5 Clay Soil with 16 Micron Silica.

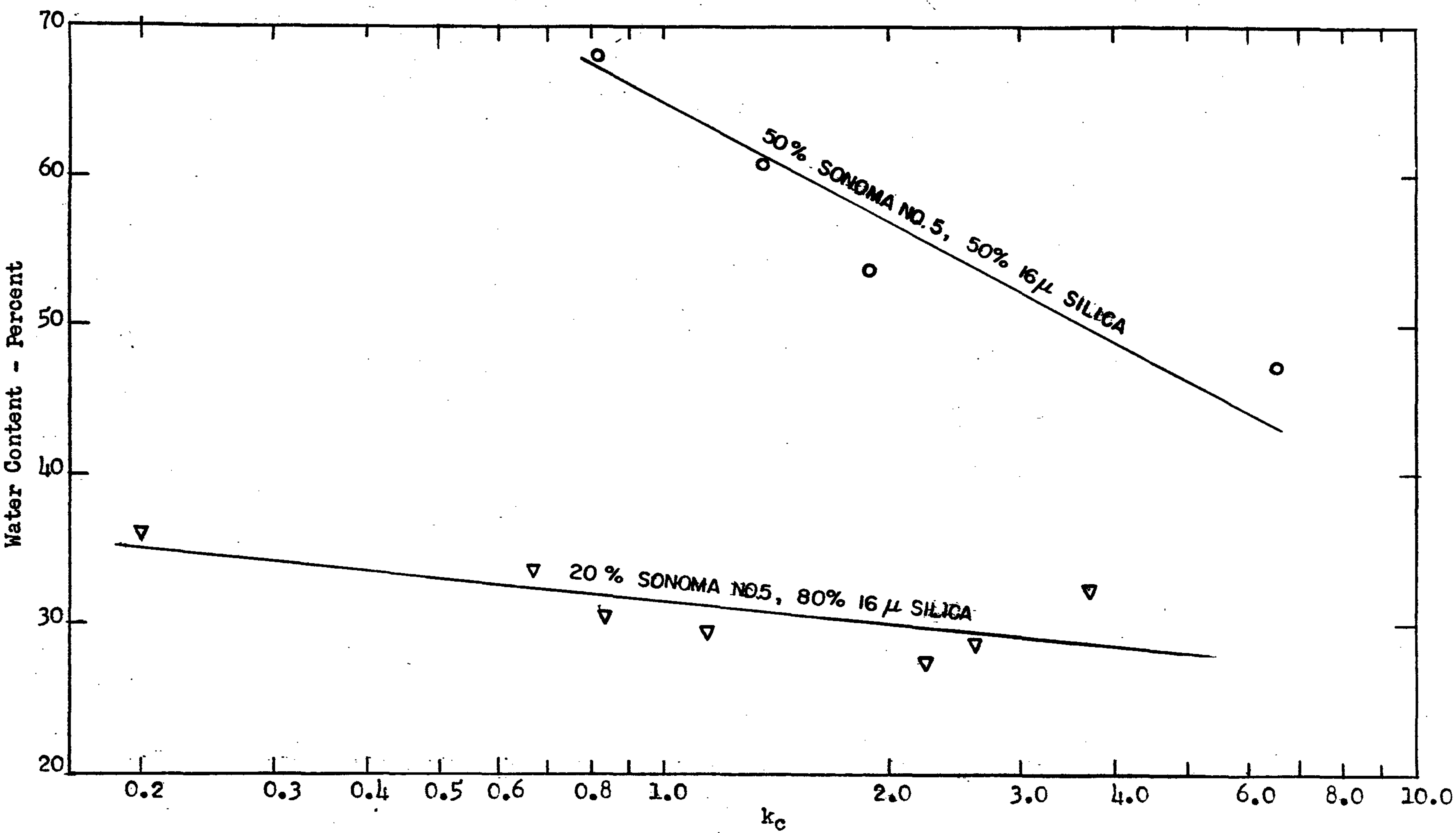


Figure 26. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of Sonoma No. 5 Clay Soil with 16 Micron Silica.

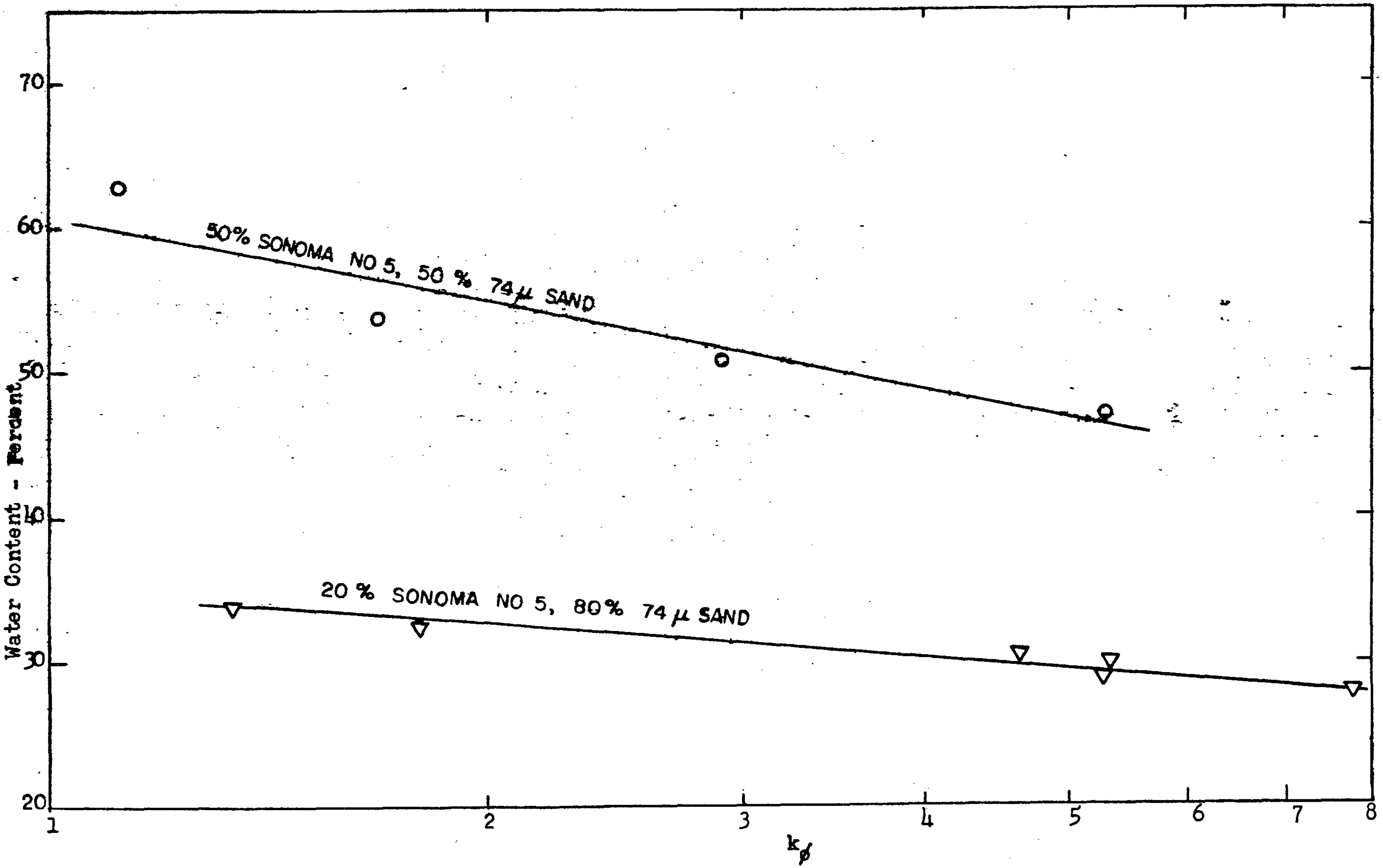


Figure 27. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of Sonoma No. 5 Clay Woil and 74 Micron Silt.

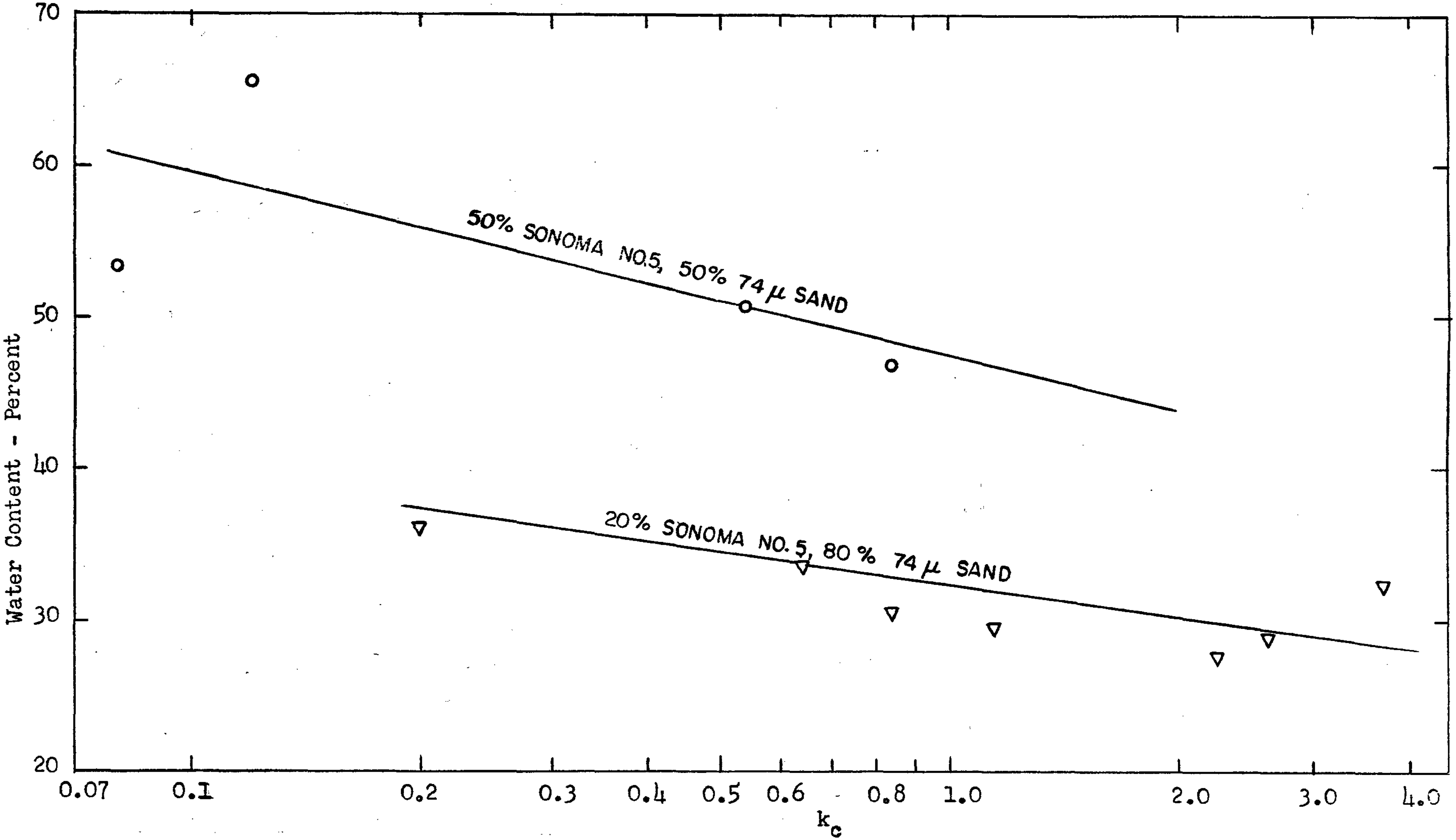


Figure 28. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of Sonoma No. 5 Clay Soil and 74 Micron Silt.

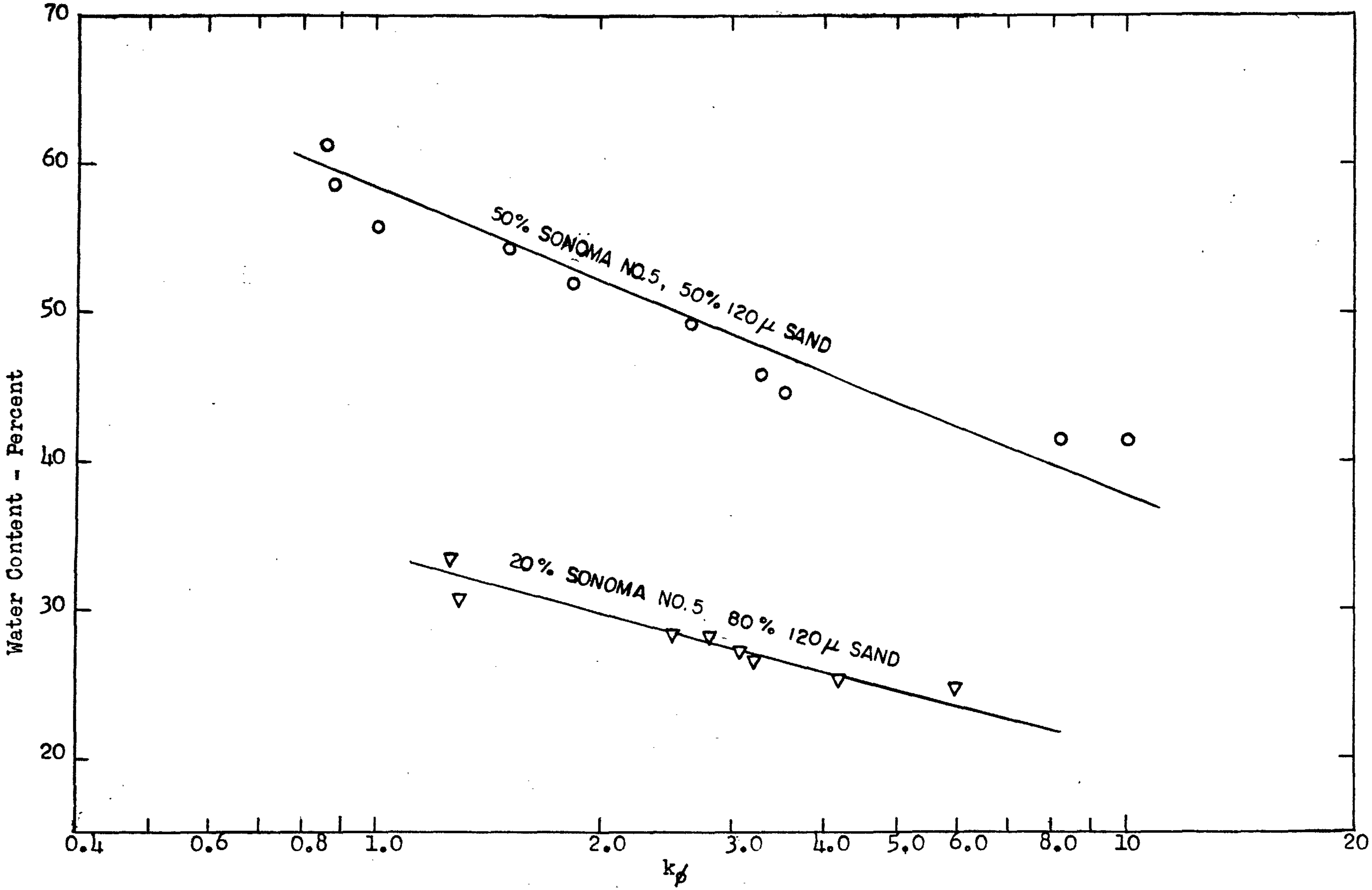


Figure 29. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of Sonoma No. 5 Clay Soil and 120 Micron Sand.

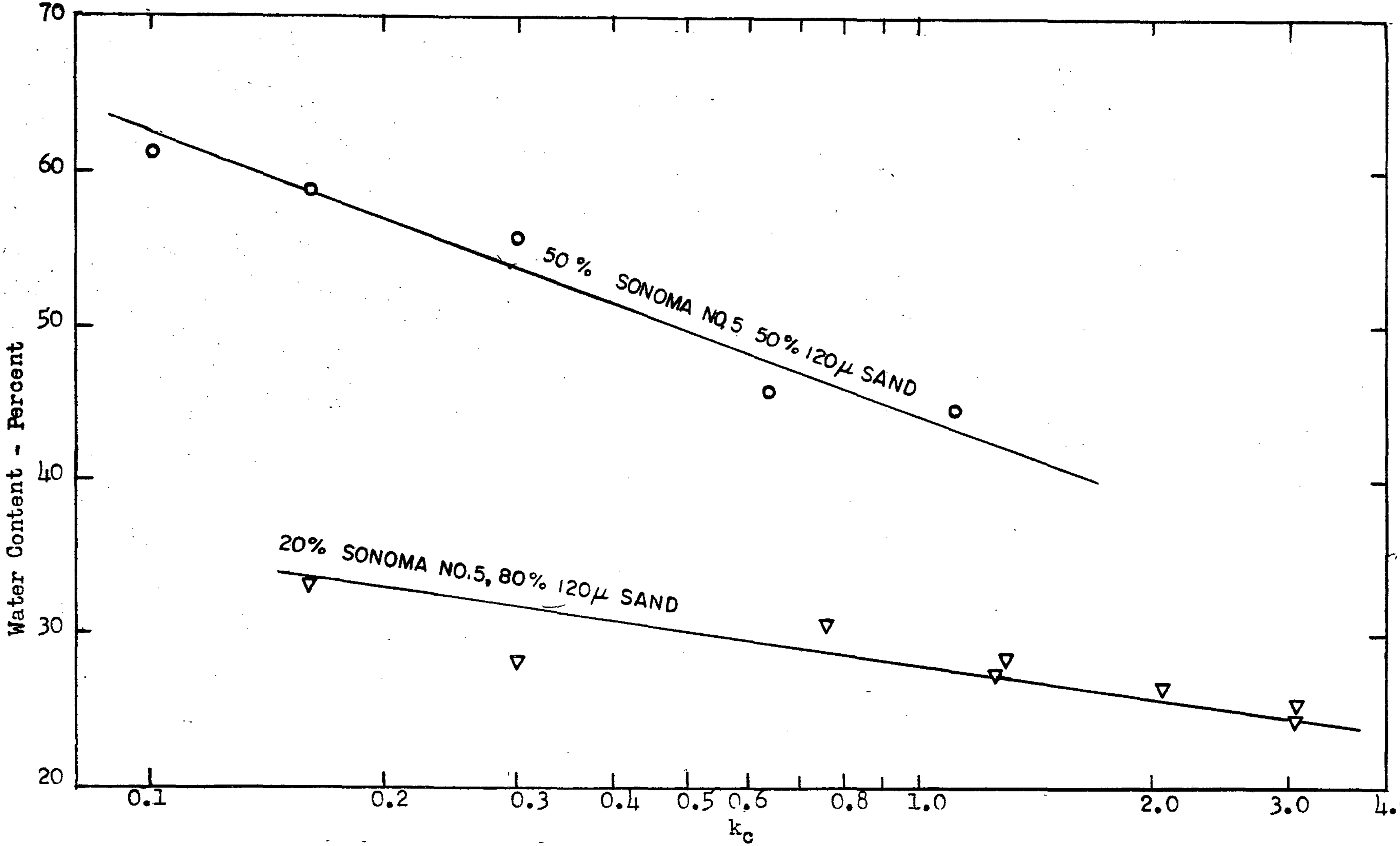


Figure 30. Relationship between Water Content and Modulus of Deformation k_c for Mixtures of Sonoma No. 5 Clay and 120 Micron Sand.

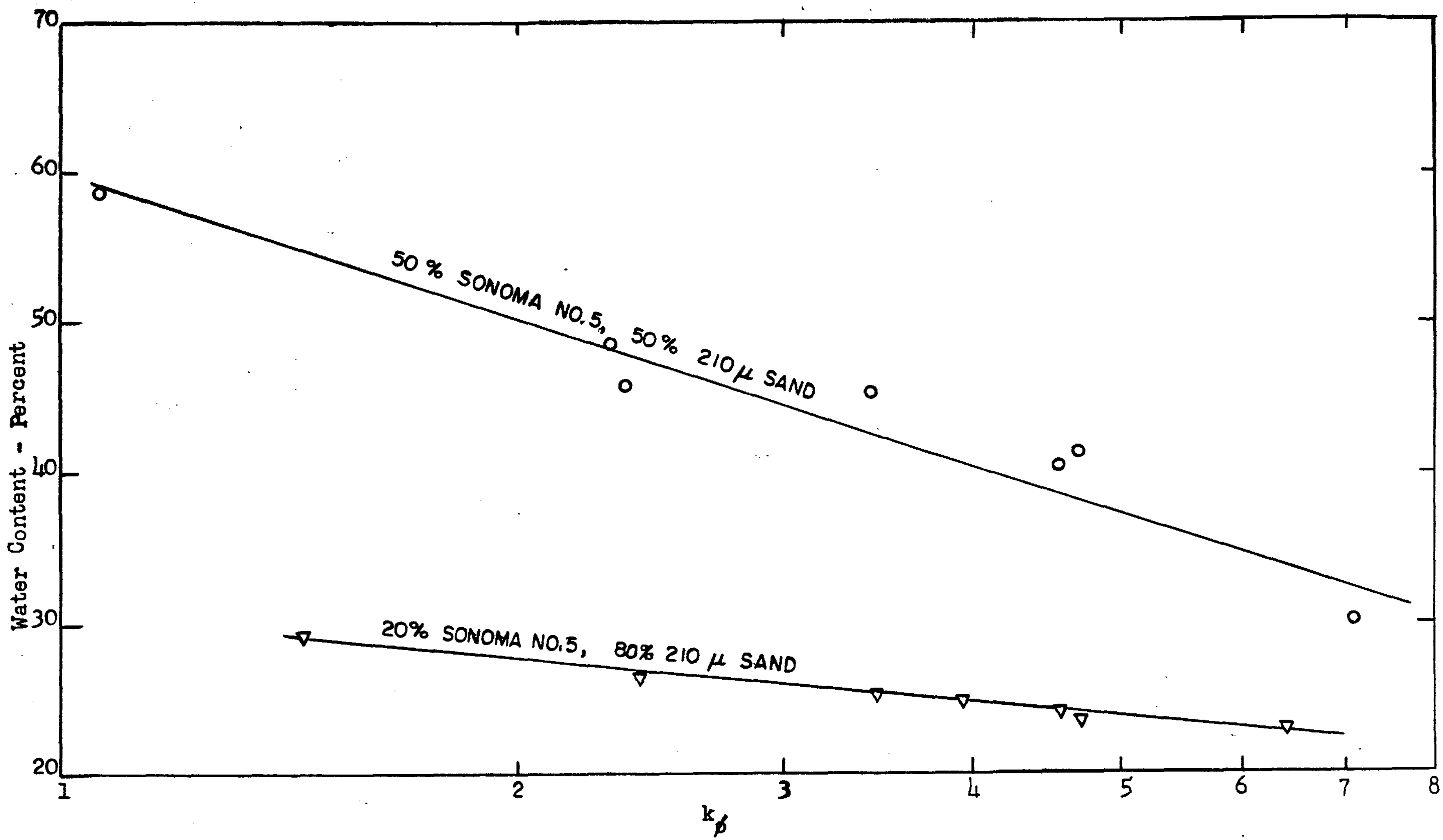


Figure 31. Relationship between Water Content and Modulus of Deformation k_ϕ for Mixtures of Sonoma No. 5 Clay Soil and 210 Micron Sand.

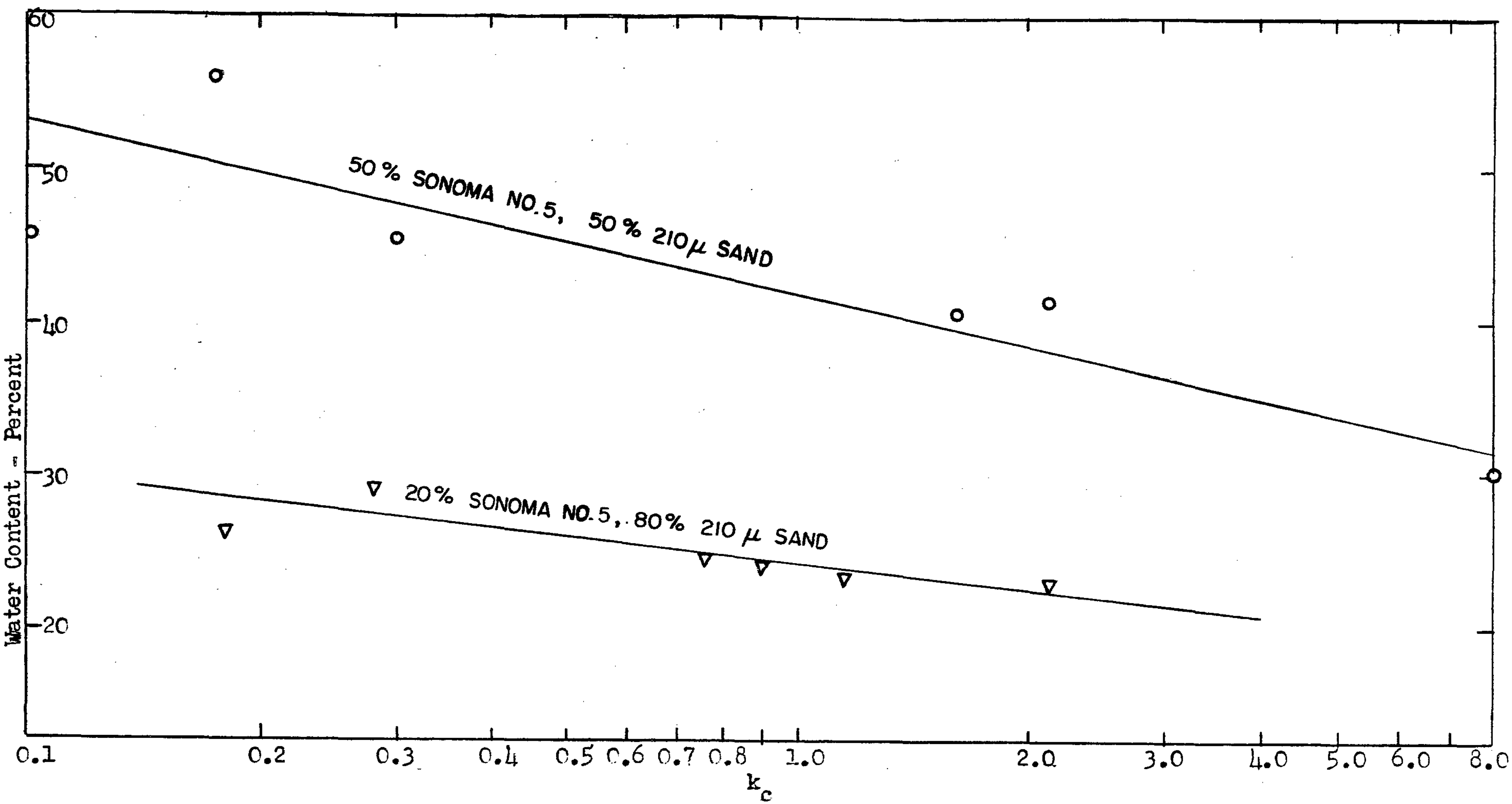


Figure 32. **Relationship between Water Content and Modulus of Deformation k_c for Mixtures of Sonoma No. 5 Clay Soil and 210 Micron Sand.**

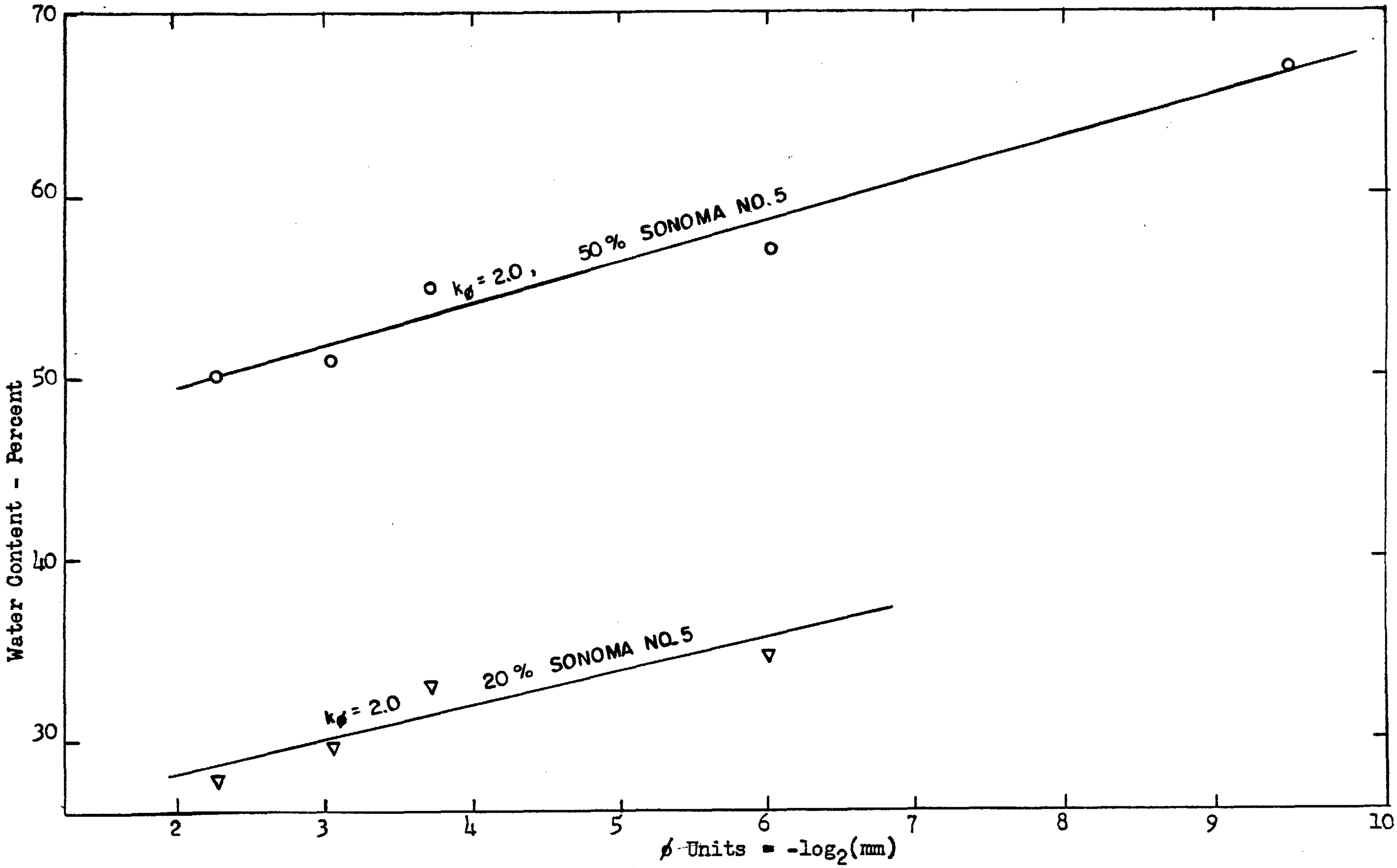


Figure 33. Relationship between Water Content and Grain Size, with $k_\phi = 2.0$ for Mixtures of Sonoma No. 5 Clay Soil and Clastic Material.

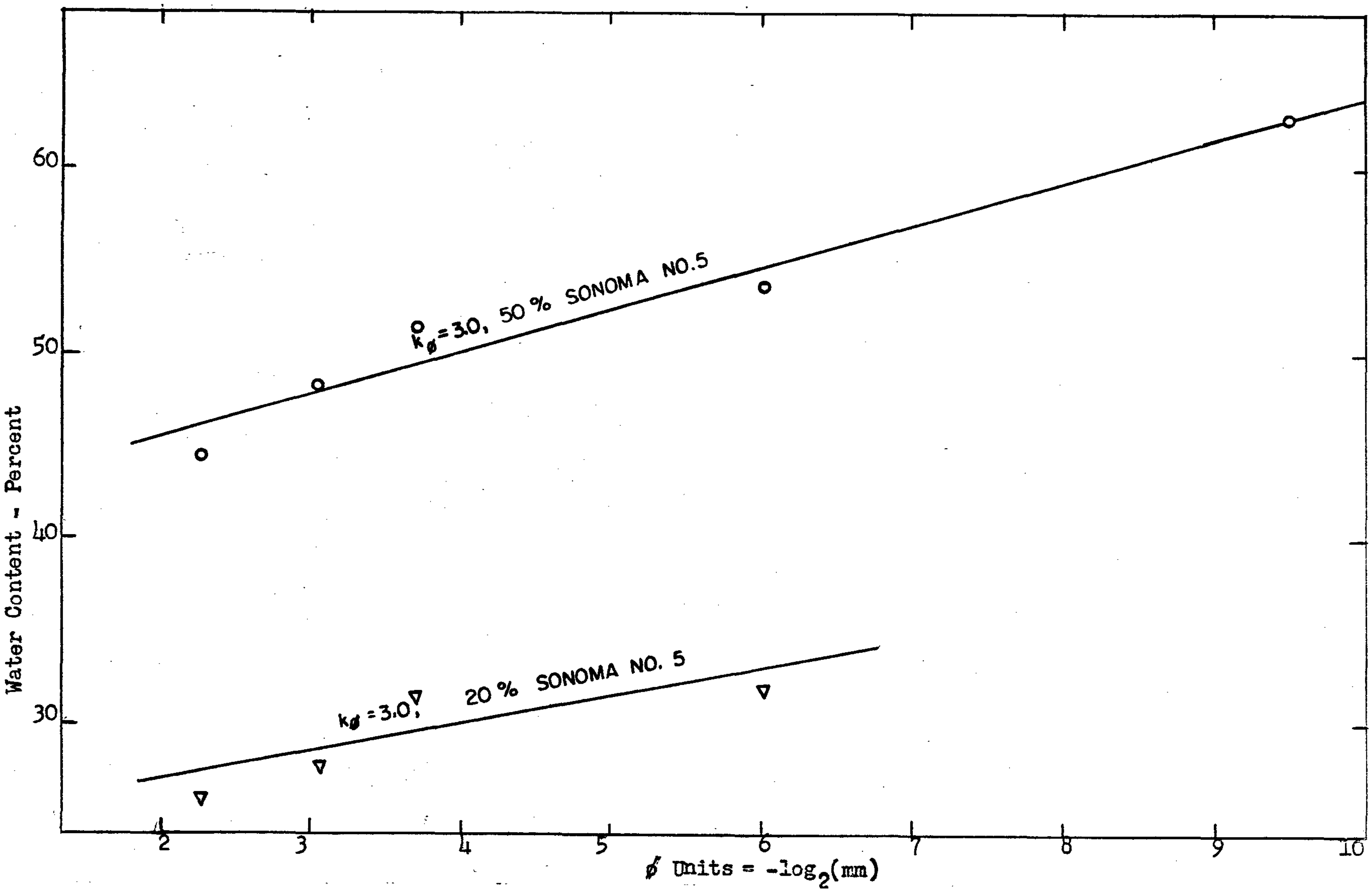
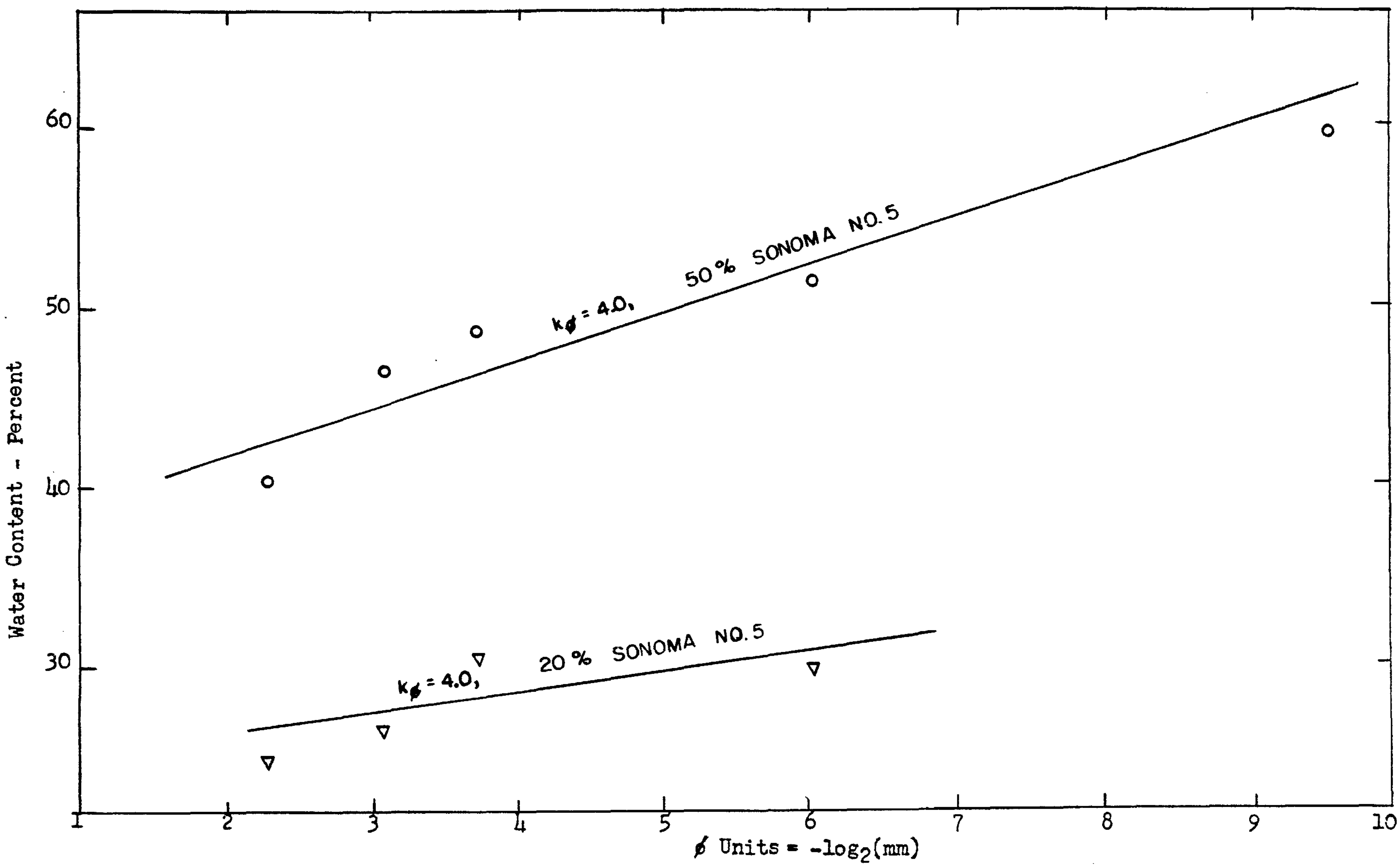


Figure 34. Relationship between Water Content and Grain Size with $k_\phi = 3.0$ for Mixtures of Sonoma No. 5 Clay Soil and Clastic Material.



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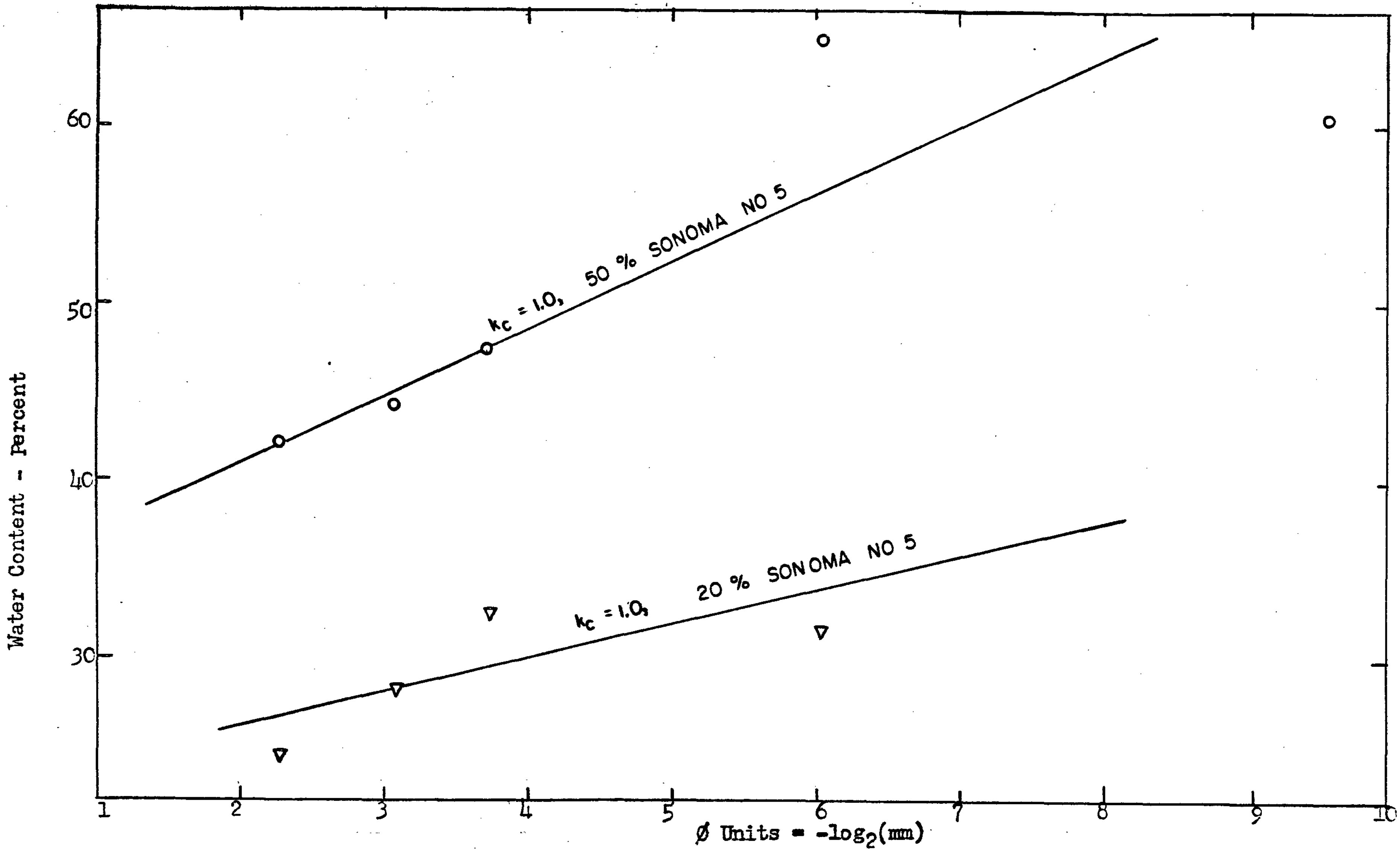


Figure 36. Relationship between Water Content and Grain Size with $k_c = 1.0$ for Mixtures of Sonoma No.5 Clay Soil and Clastic Material.

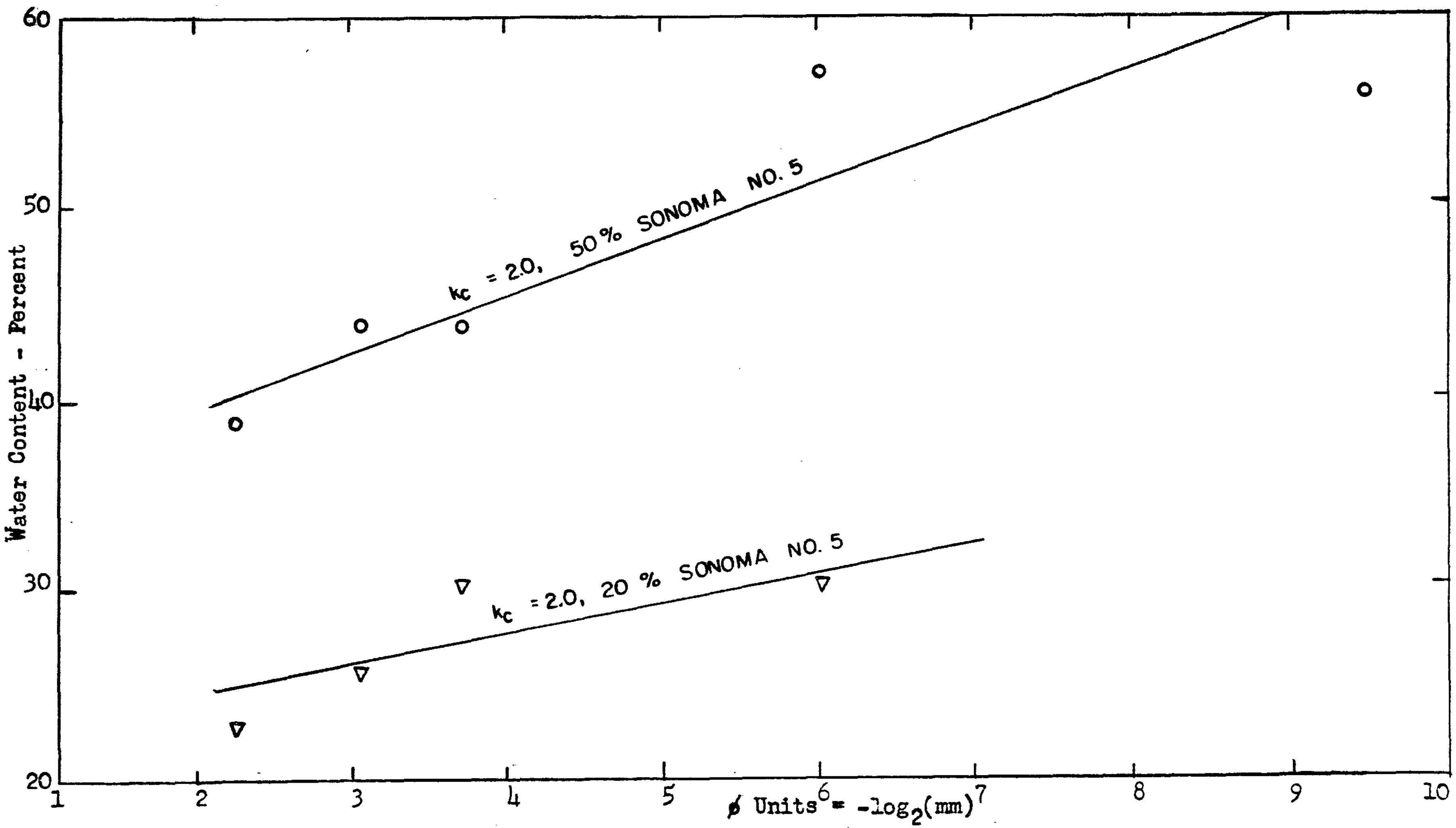


Figure 37. Relationship between Water Content and Grain Size, with k_c=2.0 For Mixtures of Sonoma No. 5 Clay Soil and Clastic Material.

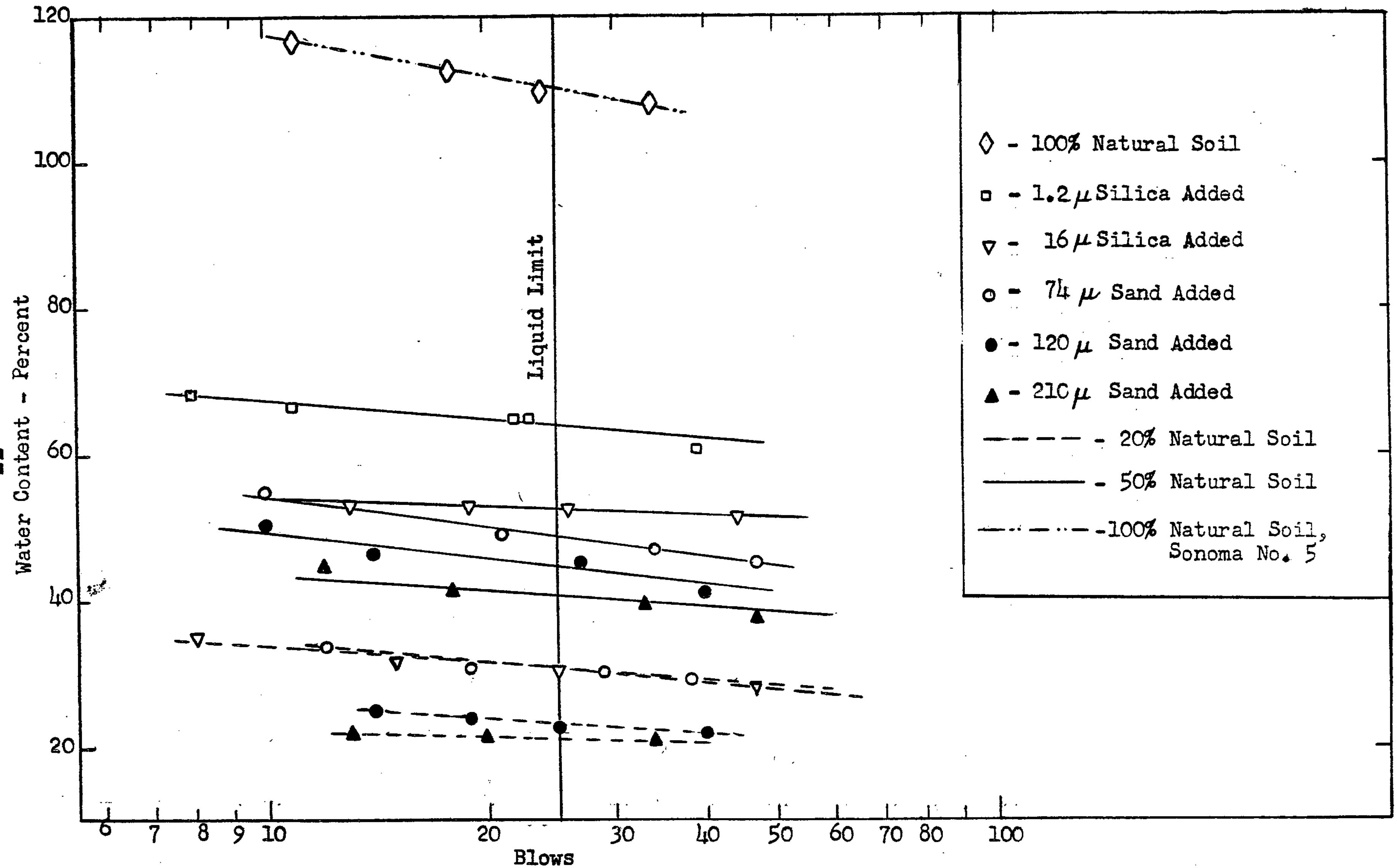
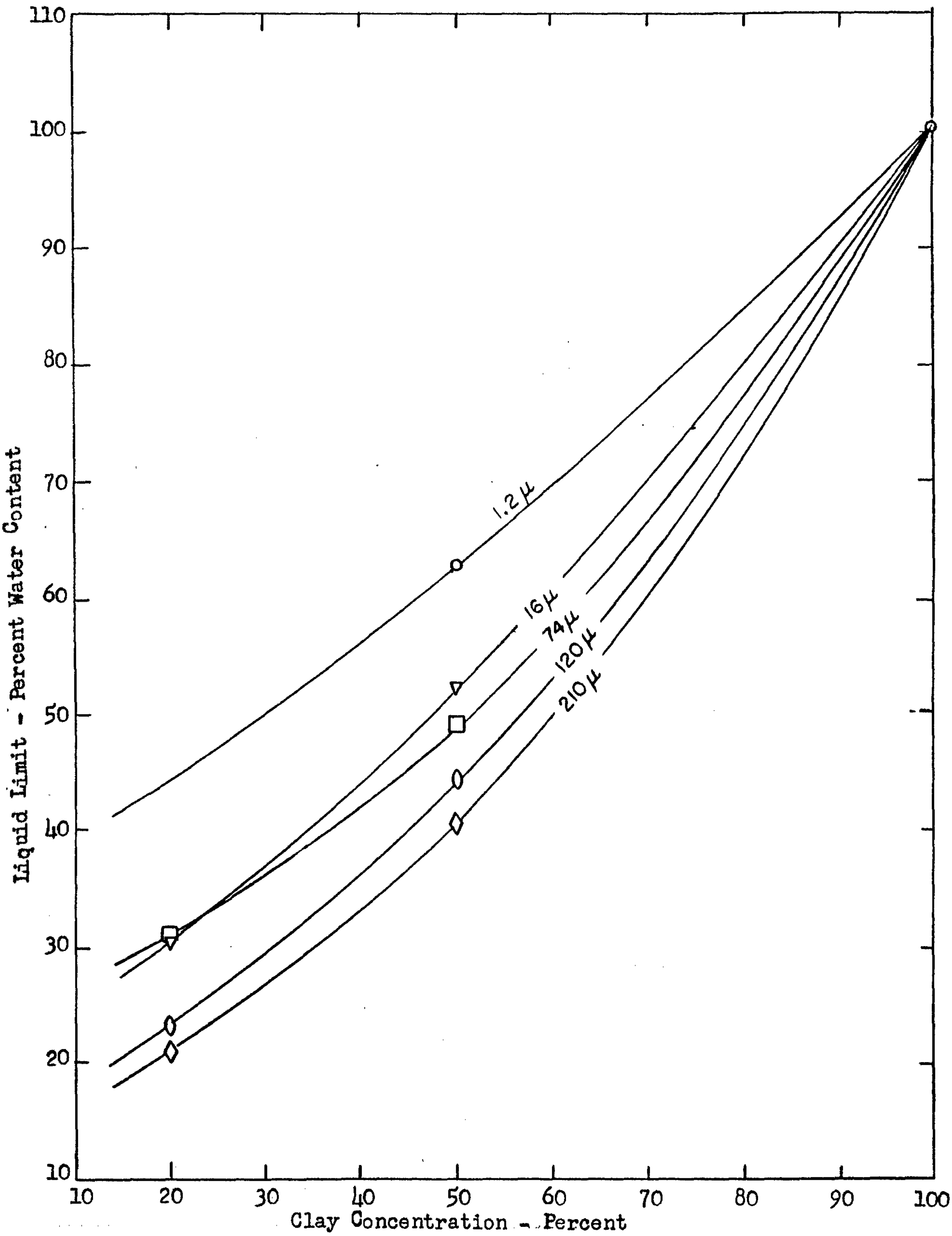


Figure 38. Relationship of Strength to Water Content, as Measured by the Count of Blows with a Standard Casagrande Liquid Limit Device, Varying with Concentration of Sonoma No. 5 Clay Soil Admixed Clastic Materials.



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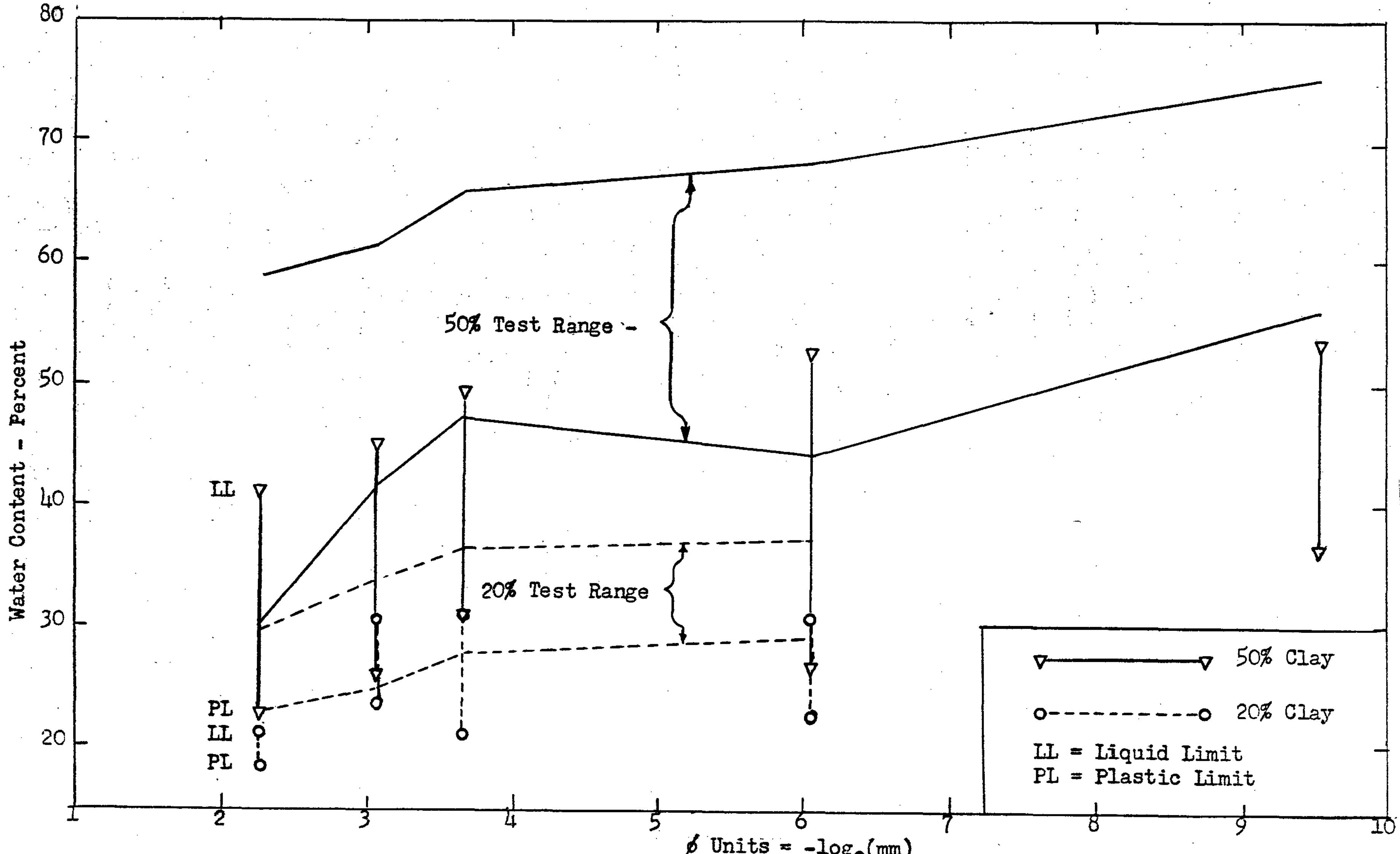
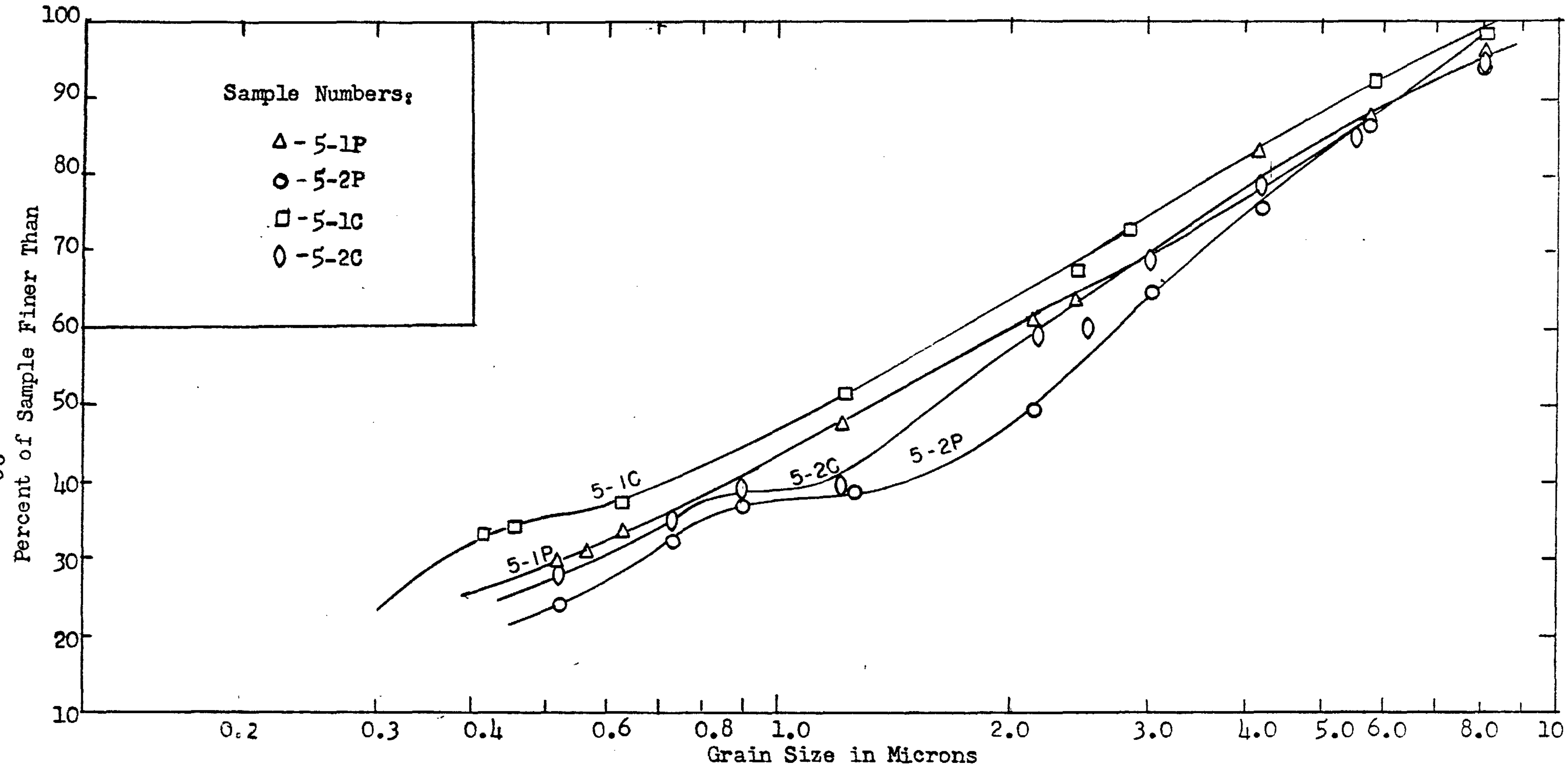


Figure 40. Atterberg Limits and Range of Water Content of Pressure-Sinkage Tests Performed on Mixtures of Sonoma No. 5 Clay Soil with Clastic Admixtures of the Grain Size Indicated.



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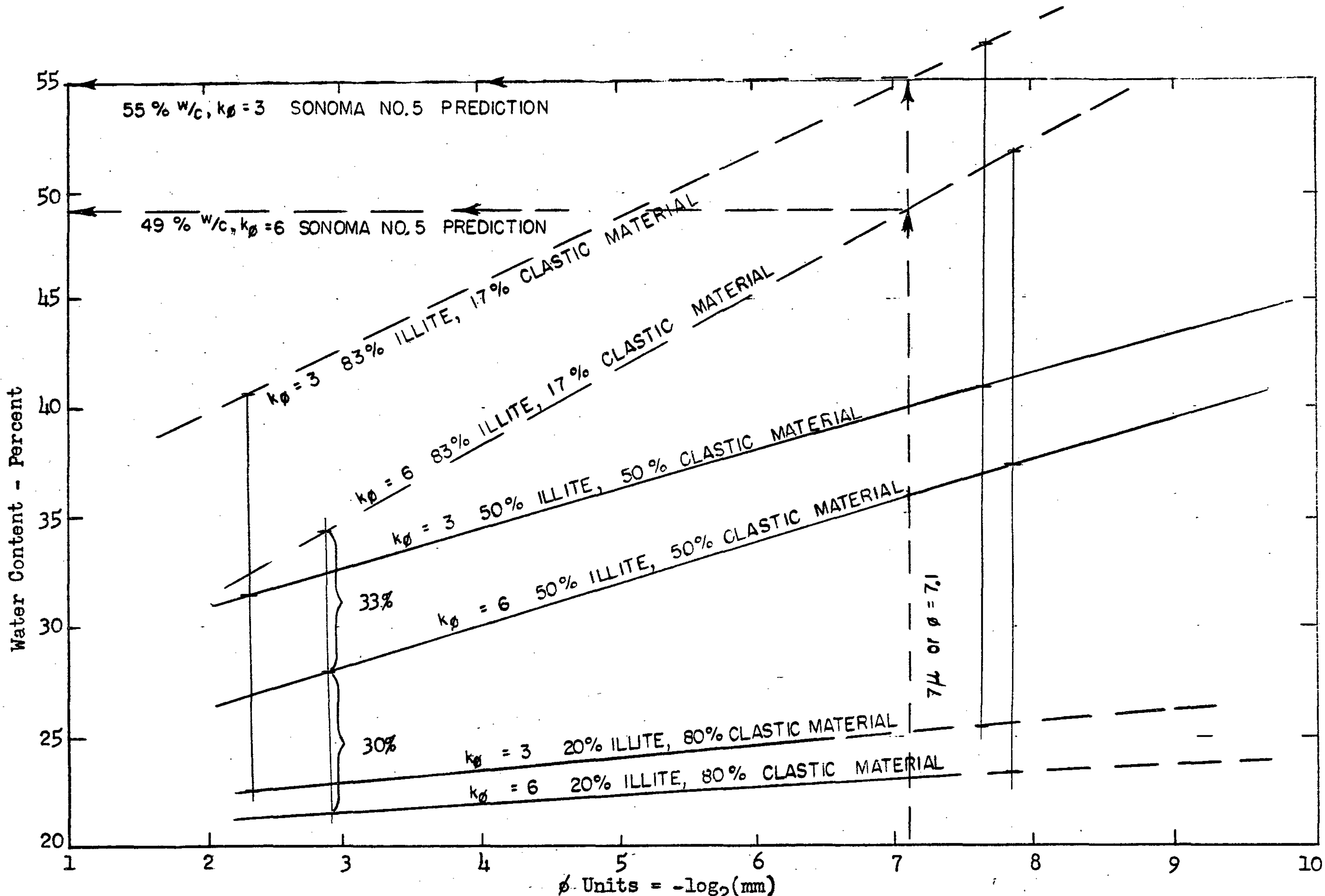

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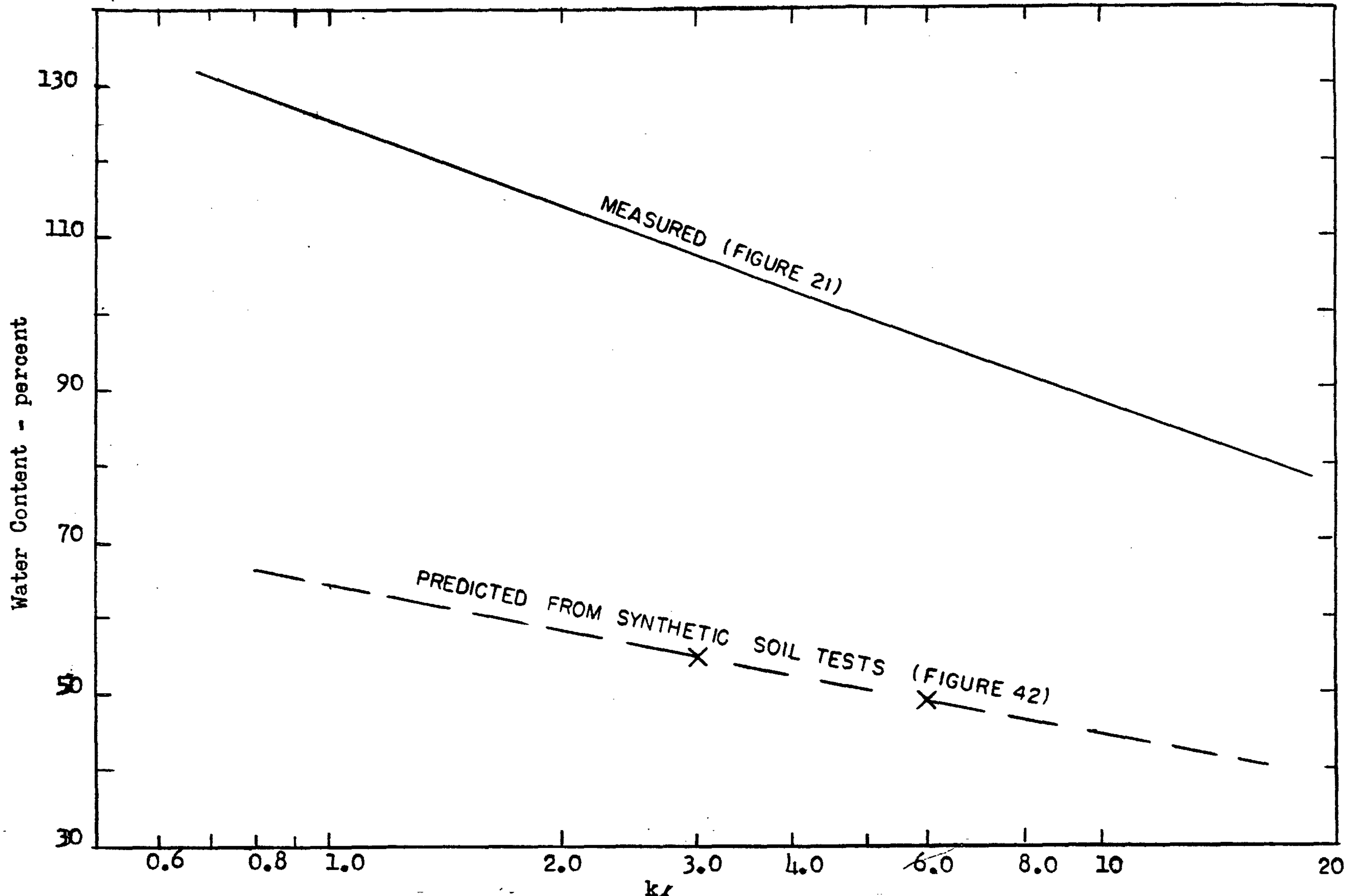

Figure 43. Comparison of Predicted and Measured Relationships between Modulus of Deformation, k_ϕ and Water Content for Remolded Sonoma No. 5 Clay Soil.

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