RELATION OF VARIOUS PARTICLE SIZE LIMITS IN THE SILT SIZE RANGE TO SELECTED PHYSICAL PROPERTIES

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ABSTRACT

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By Gary Carl Steinhardt

Various size limits were correlated with selected physical properties.

Little relation was found between silt fraction and the liquid limit, plasticity index, shrinkage limit, shrinkage ratio, optimum moisture, maximum density, shear stress, 1/2 compressive strength, natural density and dry density. A close relationship, however, was found between the $<$.002mm and $<$.005mm content and the liquid limit and plasticity index.

The highest correlations between size fractions and various measures of available water were found with coarser silt fractions. For .06 to 6 atmospheres as a measure of available water, the .125-.020mm size fraction was best correlated. When .06 to 15 atmospheres was used as a measure of available water, the .100-.020mm fraction was best correlated. The .33 to 15 atmospheres measure of available water was best correlated with .100-.010mm size fraction.

Both capillary rise and hydraulic conductivity were found to be more dependent on the selection of a lower size limit than of an upper size limit.

It was concluded on the basis of results that separations should be made at these particle size limits in the silt to fine sand range:

.002mm

.020mm

.062mm or .074mm

.105mm or .125mm

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I. INTRODUCTION

This study is an attempt to evaluate various lower and upper size limits which have been suggested as silt separations in particle size classifications of earthy materials.

Particle size has long been recognized as a factor in determining physical properties of earthy materials. The exact nature of these relationships has not always been clear. This study will attempt to show quantitative relationships between physical properties and various lower and upper particle size limits of fractions in the .002-.125mm particle size range. The properties studied include Atterberg limits, maximum density, optimum moisture, shear stress, 1/2 compressive strength, natural density, dry density, moisture retention, capillary rise and hydraulic conductivity.

II. LITERATURE REVIEW

Soil scientists, engineers and geologists are using particle size distribution information in their work. These professional groups, however, use different size limits in the classification of particles, particularly in the silt size class. By examining the development of the classification and the means of measuring particle sizes of each discipline, significant decisions and reasons for given size limits can be shown more clearly. Properties related to the size distribution will be examined particularly.

A. PARTICLE SIZE CLASSIFICATION

1. Agricultural Particle Size Classification and Particle Size Analysis

Physical properties of soils which are a direct result of or closely correlated with particle size distribution in the soil materials were noted by early workers in agriculture. The first attempt at a quantitative approach to particle size and physical property relationships was by Houghton. His experiments including procedures and results were published in 1681 in "A Collection of Letters for the Improvement of Husbandry and Trade." The experiments were later cited in Mortimer's "The Whole Art of Husbandry" published in 1706 from which the section quoted below was taken and cited by Keen (1931):

> An Experiment of Mr. Houghton, to know what quantity of Sand any Earth or Marle is mixed with, which may

> be of use to try the nature of several sorts of Land by: He took a piece of Clay such as the Brewers stop their Cash with which is commonly a sort of yellow Tyle-clay, which weighed 4 Ounces ½ Averdupois, which he dissolved in Water, and poured off the thick into another Bason till all was gone but the Sand; which stuck together, but lay loose in the Water, and when it was dry would run like Hour-glass-sand, of which he had about the quantity of an Ounce, being of a yellow colour and something glistening, and some little Stones and other foul matter was with it; and when the Clay was settled he poured off the Water, and left the rest to dry in a Pewter-bason, which hung together, only 'twas full of Cracks.
>
> He tryed likewise Fullers-earth which left a thick settlement, which when dry would easily break to powder, but he could find no Sand in it; neither by the Microscope, nor any Grittiness by rubing of it between his Fingers.

This experiment was the first recorded particle size analysis and was the basis for many others that followed. More importantly, Houghton attempted to establish relations between his results from particle size analysis and physical properties which he could observe. He was particularly interested in the relation of particle size and moisture content. He attempted to explain soil moisture content not only on the basis of sand and earth in the soil, but also plant roots and the globular nature of water. His concepts are not in all cases correct by our explanations today, but they represent a **crucial** first step.

Little use was made of this finding until Sir Humphrey Davy included an improved version of Houghton's system of particle size analysis in his Royal Institution Lectures to the Board of Agriculture, published as Elements of Agriculture in 1813. Davy, who was one of the first agricultural chemists, was quick to realize the importance of particle size to the chemical aspects of soils.

A German named Wanschaffe prepared the following system of particle size limits in 1814 (Roderick 1963).

	Size, mm
fine gravel	>2
very coarse sand	2-1
coarse sand	1-0.5
medium sand	0.5-0.2
fine sand	0.2-0.1
very fine sand	0.1-0.05
silt	0.05-0.01
fine clayey portion	<0.01

It is significant to note that studies in soil physics were then being organized for the first time into a single body of information and pursued by another German named Schubler (Keen 1931). His studies in the physical properties of soils went far beyond the English work at the time which was being done by Davy. It was at this same time that Liebig in Germany, Boussingault in France, and Louis and Gilbert in England were making great strides in soil chemistry. As a result, much of the work on the physical properties of soils including particle size was neglected.

Sieves are commonly used for particle size analysis of soil materials at the present time, but early work in agriculture did not make extensive use of them. Davy included them in his early procedure, but relied on sedimentation for separation of sand fractions (Keen 1931). Sieves, however, have been used for particle size separations far back into antiquity. The first written record of the use of sieves is found in Greek and Roman accounts of mining operations about 150 B.C. These writings describe sieves made out of planks or hides punched full of holes or woven from horse hair, reeds or even human hair. The first woven wire sieves were developed by Germans in the 15th century. Other improvements were made to use machines rather than hand shaking. The principal use for these sieves initially was for mining and other extractive industries (Tyler 1967).

The idea of elutriation as a means of separating particle size fractions was originated by Schulze in 1839 according to Krumbein (1932). Schulze's apparatus consisted of a "champagne glass" with a long thistle tube extending from a water source to the bottom of the glass. The top was sealed with a tube leading out into a beaker. The procedure was to sieve out the pebbles and boil the remaining finer fraction for 10 minutes. The soil was then poured into the glass, and water run into the thistle tube until the water in the glass was clear. Schulze noted the effect of the current and the size of particles which remained in the glass. Prior to his initial work all particle size analysis had been based on the principle of sedimentation in still water. The first mention of the term elutriation came in 1843 in a paper by Fownes. As it was used by Fownes it referred to Davy's sedimentation procedure and not the technique with which the term is associated today.

Ten years later, Schulze published a paper on particle size analysis which included refinements in his elutriation method as well as a grade size classification (Krumbein 1932). He was not satisfied with the sedimentation techniques that were being used for particle size analysis at the time. He was particularly disappointed with the reproducibility of some of the methods, particularly that of Schubler which was impossible to duplicate within 4 percent in the fine fraction. His grade size classification made these separations:

Dimension	Name
>1 Zoll	stone
1 - 1/2 Zoll	gravel
1/8 Zoll - 1/3 lime	coarse sand
1/3 lime - 1/12 lime	strewsand
<1/12 lime	staubsand

Through this procedure he felt he could make these fine separations. First he sieved out the coarse materials using one sieve for stones and another sieve for gravel. Next he boiled the fine material to get dispersion as he had in his previous work. He ran that material through the elutriator first at the faster velocity to carry off the "staubsand" and finer material. The material remaining in the elutriator was "strewsand." The finer sediments were settled for six hours and elutriated again with a lower velocity current. The material remaining in the elutriator was staubsand, and the material which was washed away he referred to as clay. He obtained the amount of clay by substraction rather than by direct measurement. This method was a real advancement at the time and provided a basis for much of the later work.

Several workers made improvements on Schulze's elutriation procedures, both from the standpoint of precision and number of separations. In 1857, Bernnigson-Forden suggested a cylinder with four openings along the side. These could be tapped from top to bottom during the elutriation to give five grade size separations and two more from the initial sieving to make seven separations. Later he developed a graduated flask which could be read directly during the elutriation. Muller in 1862 called for a different design in the Schulze cylinder replacing the conical glass with a retort-shaped container. He also suggested more separations in pretreatment sieving. He suggested three sieve sizes -- 2mm, 1mm and .5mm to be used (Krumbein 1932).

Nobel in 1864, Wolff in 1864 and Dietrich in 1866 suggested changes in design for the elutriator, but added nothing to the basic concept. Up to this point, particle size analysis had been based to a great extent on empirical and qualitative results. A few men such as Schulze and Schubler attempted to make it a quantitative study, but had not really been successful. The qualitative approach was brought to an end with the publication of papers on particle size analysis by Schone in 1867. Schone applied an equation he had formulated relating the diameter of the particle and settling velocity.

$$d = \frac{3\zeta V^2}{4g(S-1)}$$

Where d is the particle diameter, V is the settling velocity, S is the specific gravity of the particle, g is the acceleration of gravity, and ζ is a coefficient. Prior to this, sedimentation in tubes had never been explained quantitatively. Schone said that the diameter of particles measured by a particular current of water could be calculated from his equation. He, of course, realized that complete separation of any given size was impossible because of the different shapes of the particles. Schone's equation has been replaced by one developed in 1850 by Stokes (Baver 1956) for spherical particles. Stokes' Law as it is referred to was first presented before the Cambridge Philosophical Society as a curiosity and was not immediately applied. Stokes' original proposal as cited by Baver (1956) included these elements:

$$V = \frac{(dp-d)\ gr^2}{\eta}$$

where V = velocity of fall in cm/sec

g = acceleration of gravity

dp = density of the particle

d = density of the liquid

r = radius of the particle

η = viscosity of the liquid

In 1868, Muller showed in a paper on particle size analysis that both sedimentation and elutriation were needed for complete analysis. He felt elutriation gave the better result with coarse particles and that sedimentation was the better method to measure fine particles. Both were, of course, based on Stokes' Law. For his work, Muller had designed two new pieces of apparatus. His elutriator was a conical-shaped glass vessel which was smaller at the bottom than at the top. The new feature was a control for the input which allowed separation of fractions with different velocities (Krumbein 1932).

The most significant element in Muller's work, however, was not the refinements in elutriation. He suggested in his paper a technique for use with sedimentation which was the forerunner of the pipette method of particle size analysis. He placed the sample in a glass cylinder. The sample was well mixed and allowed to settle. He then fitted a wooden cover over the cylinder which had glass tubes of various lengths placed in holes in the cover. With these glass tubes, he was able to draw out samples at various depths in the cylinder, and by application of Stokes' Law, he was able to calculate the amount of material present in a given grain size. The basis for his work was an earlier paper that he had written on the nature of milk and cream separation.

Knop suggested a refinement in the apparatus used for the sedimentation procedure. His sedimentation cylinder had four openings on the side. From these at intervals of 10 minutes, he took samples until the water was clear. He could then calculate several fractions. He also followed a sieving procedure before the sedimentation which is notable in grain size classification, because he calibrated his sieves in terms of peas, coriander seeds and turnip seeds.

In 1873 Hilgard, based on the work of Schone, published a method of particle size analysis by elutriation that included a more effective dispersion technique. In the process he also developed a means of classifying grain size based on the velocity of water in the elutriator. Hilgard prepared his samples by first boiling in water for 24 hours and then allowing them to settle for 24 hours. The supernatant was cleared with brine. The material which had settled was then sieved to separate the sand from the fine material. The fine material was placed in the elutriator which Hilgard had modified from Schone's initial design. Hilgard had attempted to work with Schone's apparatus, but he had noticed flocculation of the sediments which, of course, led to inaccurate results. He first attempted to solve the problem of flocculated sediments in the bottom of the vessel with a relay reservoir. This was not successful, and he installed a churn to keep the particles dispersed. Hilgard set up a grain size classification. The classification was based on the hydraulic value or velocity of the current in the elutriator. The sizes from Stokes' Law were a result rather than a starting point (Hilgard 1873, 1890, 1903).

	Size, mm	Hydraulic value, mm/sec
coarse grits	1-3	?
fine grits	0.5-1	?
coarse sand	(80-90) x 1/180	64
medium sand	(50-55) "	32

fine sand	(25-30)	x 1/180	16
finest sand	(20-22)	"	8
dust	(12-14)	"	4
coarsest silt	(8-9)	"	2
coarse silt	(6-7)	"	1
medium silt	(4-5)	"	0.5
fine silt	(2.5-3)	"	0.25
finest silt	(0.1-2.0)	"	0.25
clay	?		0.25

The limits with one exception are selections based on a geometric progression of the hydraulic value. The one value that Hilgard cited as having physical significance was at .5mm/sec hydraulic value of 1/36mm diameter. Hilgard felt this was a neutral value. Any material coarser than this size tended to increase porosity and "lightness" to the soil, and any particles finer tended to modify the plastic properties and make soil "heavier" in tillage.

In 1876 Deetz (Krumbein 1932) attempted an improvement of sedimentation techniques through a specially designed cylinder. The cylinder was 1m tall and 5cm in diameter. Inside the cylinder were brass disks which could be opened and closed as a valve. Deetz would introduce the sample from the top, and by calculation from Stokes' Law he found the size of particle that would be contained inside a section of the cylinder when it was closed off. He found that while the theoretical aspects of the method were good, the practical problems limited the effectiveness of the method. There was apparently a disruption when the valve was closed, and the pressure of the valve may have had an effect on the sedimentation.

From that point to 1887, the development of particle size studies was limited to refinements of existing techniques. However, Osborne (1887) published a paper which was to have a great significance on future work in the agricultural aspects of particle size limits and analysis. To begin with, he did not agree with the pretreatment procedure of boiling the sample. He felt this reduced the size of coarse particles from tumbling and collision. This was also detrimental in his view to the finer particles, because it caused dehydration and coagulation of clays. His method of particle separation was the method he referred to as beaker elutriation. By this method he would pour out liquid from the sedimentation cylinder which had particles lower than a certain size. By a series of such decantations, several size classes could be separated. In addition to his decantation, he also separated three grades by sieve. Perhaps the most significant feature of Osborne's paper was his suggestion of particle size limits. According to Osborne, grain size could be divided into the following system:

	Size, mm
sand	0.25-0.05
silt	0.05-0.01
dust and clay	<0.01

He also examined these separations: 1mm, 1-0.5mm, 0.5-0.25mm, 0.05-0.02mm, 0.02-0.01mm, 0.01-0.005mm, and <0.005mm.

Osborne chose this system arbitrarily with no thought to the physical significance of the limits which he chose. He stated in correspondence with Hopkins (1899) that he had simply used these limits because they corresponded to calibrations on the eyepiece micrometer he was using. In and of itself, this arbitrary approach is not much different from those used previously, except that this particular system was adopted by the U.S. Department of Agriculture. Initial studies in the Bureau of Soils and the Division of Agricultural Soils were based on Osborne's work, although no firm basis was established for reliance on these limits.

A publication by Whitney is of particular note because in this paper he discussed the relation between moisture and soils. This is also the first reference made by anyone to the centrifuge technique to speed up sedimentation. For this he used the Babcock hand separator in connection with the beaker method. It was also in this publication that Whitney suggested the particle size limits which are the basis for the U.S. Department of Agriculture system today. He used these classes: (Whitney 1892)

	Size, mm
fine gravel	2-1
coarse sand	1-0.5
medium sand	0.5-0.25
fine sand	0.25-0.10
very fine sand	0.10-0.05

silt	0.05-0.01
fine silt	0.01-0.005
clay	0.005-0.001
colloid	<.001

Whitney had set up the colloidal size because of his microscopic studies of suspensions that were several weeks old. Later the Bureau of Soils, for its particle size limits, grouped the silt sizes together and considered anything below .005mm as clay.

The next agricultural classification of particle size was suggested by Wolff, a German, in 1891 (Roderick 1963). His was somewhat different from Wanschaffe's in the sense that he did not include a clay texture and was the first to base the classification on sieve standards.

	Sieve
stone	3-2mm
coarse gravel	2-1mm
fine gravel	1mm-No. 50 (0.35-0.39mm)
coarse sand	No. 50-No. 100 (0.14-0.17mm)
fine sand	No. 100-No. 16 (0.09mm)
silt	<0.09mm

Shortly after Wolff, Kuhn and a permanent committee for soil investigation set forth two more systems for classification of particle size.

	Size, mm
stone	>5
coarse gravel	5-3

fine gravel	3-2
very coarse sand	2-1
coarse sand	1-0.5
fine sand	0.5-0.25
very fine sand	<0.25

At this time in Russia, significant progress was being made on a grain size classification. Fadejeff developed a system which was presented by Williams in 1895 to the Agricultural Academie Petroffskaja (Roderick 1963). The system suggested by Fadejeff made these separations:

	Size, mm	Group
stones & pebbles	>10	stony
coarse gravel & grits	10-7	gravelly
medium gravel & grits	7-5	
fine gravel & grits	5-3	
coarse sand	3-1	sandy
medium sand	1-0.5	
fine sand	0.5-0.25	
dust	0.25-0.01	earthy
coarse silt	0.01-0.005	
medium silt	0.005-0.0015	
fine silt	<0.0015	

Williams considered this a good system, but changes were needed based on the physical properties which he found characteristic of certain size particles. His suggested changes resulted in this substitution in the names of the earthy group:

	Size, mm
coarse silt	0.25-0.01
medium silt	0.01-0.005
fine silt	0.005-0.0015
clay	<0.0015

The change in the system was the removal of the dust category on the upper part of the silt range and the addition of clay as the smallest particle size. Williams was not arbitrary in his approach to the classification of particle size. His classification was based more than any other before him on physical properties which were observed related to a given grain size. He suggested the clay designation for particles less than .0015mm. His observations had shown that it was this fraction that was responsible for the cohesive properties of the soil. Particles .0015mm and smaller increased the cohesiveness of the soil, while larger particles tended to decrease it. This is more specific than any previous statement on particle size. Cohesive properties were by no means the only consideration that Williams made in setting his criteria for the particle size limits. He also noted a difference in specific gravity between the clay size and other sizes. Specific gravity of clay particles is less than the others. Total water content at saturation is also different for particles less than .0015mm and the silt size, just as the silt particles **differ** from the sand particles. The clay, of course, holds more total water than the silt and a great deal more than the sand. From a permeability standpoint, he noted that sand was very permeable, silt less so and clay much less permeable. He also noted differences in the mineralogy. The sand and silt fractions were made up of primary minerals while that less than .0015mm which he called clay was made up of secondary minerals as a result of weathering.

Despite the overwhelming acceptance of the Osborne system by government agencies in the United States, there were those who felt the limits were not selected with sufficient study of the implication of particle size limits to the usefulness of the classification. One of those who spoke against the arbitrary nature of the Osborne system was Hopkins of the U.S. Department of Agriculture, Bureau of Chemistry (1899). He was concerned that the comparison between particle size in the Osborne system would not be meaningful because the ratio between sizes was not constant. His approach to particle size classification was not based on a desire to match physical properties with the particle size. Rather his intent was to provide a suitable theoretical framework in which to fit the classification. He evaluated the Osborne classification with an assumed soil of uniform gradation. The comparisons which he made are cited in the following tabulation:

Div. No.	Size, mm	Ratio of diameters	Ratio of surfaces	Ratio of volumes	Theoretical % composition
1	>1	-	-	-	12.50
2	1 -0.5	2	4	8	9.68
3	0.5 -0.25	2	4	8	9.68
4	0.25-0.10	2.5	6.25	15.6	12.10
5	0.10-0.05	2	4	8	9.68
6	0.05-0.01	5	25	125	24.20
7	0.01-0.005	2	4	8	9.68
8	<0.005	-	-	-	12.50

It is obvious from the study that consistent or significant relationships from the mathematical point of view are not readily available in this system. Osborne stated in correspondence with Hopkins the arbitrariness of his particle size limits and his surprise that they had been adopted by so many people (Truog et al. 1936).

> In working out the beaker method of soil analysis I employed the limits of the various grades with reference simply to convenience in using my eyepiece micrometer. I have always thought that the limits of the various grades should be determined by a careful consideration of the various conditions involved in the problem of proper mechanical analysis of a soil, and have been surprised to see that the arbitrarily chosen limits of the various grades employed by me have been followed by others in applying the method in practice.

Hopkins' solution to the difficulties was to devise a system which provided for a constant ratio of diameters, surfaces and volumes between particles and a constant theoretical percentage of composition from an assumed uniform grade. This in Hopkins' view would allow significant features of the particle size distribution to be more easily seen.

For his classification, Hopkins chose the square root of 10 as the factor on which the increments were based. This value is approximately 3.2. His classification and the relationship between the groups are shown in the table below.

Div. No.	Name	Size, mm	Ratio of diameters	Ratio of surfaces	Ratio of volumes	Theoretical percentage of composition
1	gravel	>1	-	-	-	12.5
2	coarse sand	1-0.32	3.2	10	32	12.5
3	medium sand	0.32-0.10	3.2	10	32	12.5
4	fine sand	0.10-0.032	3.2	10	32	12.5
5	coarse silt	0.032-0.010	3.2	10	32	12.5
6	medium silt	0.0100-0.0032	3.2	10	32	12.5
7	fine silt	0.0032-0.001	3.2	10	32	12.5
8	clay	<0.001	-	-	-	12.5

In addition, he also suggested that further subdivisions could be made based on the fourth root of 10. This, in effect, divides each subdivision into two parts which maintain the relationship between classes that Hopkins felt was important.

Although Hopkins had not designed his system as such, the separations which he made were related in many cases to capillarity and porosity of the soil. This classification, while including many of the elements which have been acknowledged as desirable, was never used extensively in soils studies.

In 1904 a paper was written by Briggs, Martin and Pearce which would have great impact on particle size studies for agricultural purposes. In this paper, they compared the grain size classification of Hilgard, Osborne and Hopkins. The conclusion that they reached was that the Osborne scale was best suited to their needs.

In 1905 Atterberg, from Sweden, began publishing his system of particle size classification. Perhaps no other man or system of particle size classification has had such an effect on the particle size work of agricultural soil scientists. The studies of soils by engineers has also been affected by his work on the measurement of physical properties of soils. His system was well received in Europe when first proposed. It was adopted by the International Society of Soil Science in 1913 (Baver 1956) and has been used extensively for soil studies. It should be noted that while the United States and England report data in terms of the International System, they also work in grade scales which have been developed in their own countries.

The Atterberg classification had two features that led to its wide acceptance. First, it was related to physical properties. There might be some question about some of the separations which Atterberg made, but certainly 2.0mm and .002mm are generally accepted today. The second feature is that the divisions are of logarithmic nature and can be better analyzed by statistical means (Krumbein & Pettijohn 1938).

Atterberg's classification was set up in this manner:

		Size
Boulders	Klipp block	> 2m
	Stenblock	20-6dm
	Blocksten	6-2dm
Pebbles	coarse rock	20-6cm
	broken stone	6-2cm
gravel	coarse gravel	20-6mm
	fine gravel	6-2mm
sand	coarse sand	2-0.6mm
	fine sand	0.6-0.2mm
very fine sand	very fine sand	0.2-0.06mm
	rock flour	0.06-0.02mm
silt	silt	0.02-0.006mm
	slime, silt, mud	0.006-0.002mm
clay		<0.002mm

Atterberg made his main separation at 20, 2, .2, .02 and .002mm or two times powers of 10. It was at these that he saw changes in the physical conditions of soil. Further separations were made at six times powers of 10. These are based on the fact that two times $\sqrt{10}$ = 6.32. This was rounded off to 6 and used as an even division in a logarithmic plot. These latter subdivisions were not significant physical separations as originally considered by Atterberg.

Atterberg considered his groupings for these reasons (Krumbein & Pettijohn 1938): The largest category, boulders, included material larger than 200mm or thereabouts was not moved by wave activity on the shore under conditions he observed. Material smaller than this was freely shifted by waves and current. Material between 20 and 200mm was called pebbles. They could be displaced by currents, but their packing properties were not desirable for roads. Material between 2 and 20mm was called gravel. This size was separated from larger material by packing characteristics and from finer material because of water relationships. Sand was defined as particles between 2 and .2mm. This was different from the very fine sand which was between .2mm and .02mm in that the coarser sand was water permeable sand and the finer was a water retaining sand. Atterberg chose .02 as the separation between sand and silt. His observations noted a difference in the rate of capillary movement in materials finer than .02mm. It was not so much the height of capillary rise as it was the speed with which it took place. This size seemed to be an upper limit to aggregates which formed from finer material in the soil. It also appeared that this was the limiting size for penetration of roots into interparticle spaces. As a last point, this is also a limit to observation of the particle with the naked eye. The separation of silt from clay was at .002mm. The reason for this was the effect of Brownian movement on the particles. At this point, the effects can be barely noticed, but in larger particles it is nonexistent and in finer particles it is much more apparent. Other reasons for the significance of this particular separation have been made and will be discussed later.

Atterberg was not totally satisfied that his particle size classification was as good as it could be. He suggested after his initial paper that .3, .03 and .003mm would be better points at which to make the separations (Roderick 1963). He cited the same reason for each division and its physical significance. He was faced with a real problem in his classification. He wished to maintain the even divisions in a logarithmic plot and still make separations which were physically significant. The fact is that rarely do these coincide. Later, further observations had shown him that .2mm was a better measure than .3mm for separating the water retaining and permeable sand. No changes were made in the Atterberg system because of its wide use and the reluctance to change once the system was adopted. Even the argument that less time was required to measure a system of coarser particles failed to convince anyone.

Widespread acceptance of this method of particle size classification in Europe did not stop the search for a better system, especially in the United States and Britian. Atterberg thought that the U.S. Department of Agriculture classification had too many separations in the sands and not enough in the silts and clays. He also felt that the .005mm clay limit was unrelated to physical properties. On the other hand, Hilgard was not in favor of Atterberg's large range for coarse sand. He thought more separations should be made in the sand fraction than Atterberg had allowed.

In 1914, an International Commission from those interested in mechanical and physical investigations of soils met to consider a uniform grade scale to be used by all scientists. They had several scales from which to choose.

One scale which was considered was that used by Frosterus who had done work in the podzol zone. His system as reported by Schucht (Roderick 1963) made these separations:

	Size, mm
gravel	20-2
coarse sand	2-0.2
fine sand	0.2-0.1
very fine sand	0.1-0.02
silt	0.02-0.002
clay	<0.002

The classification was much like that of Atterberg's, except that there was an additional separation in the finer sand fraction.

The American Society of Agronomy also suggested a system and was represented by its chairman, Coffey. Coffey's main interest was in soil classification, and he had worked on a soil map of the United States. The classification suggested set up these limits:

	Size, mm
coarse sand	2-0.7
medium sand	0.7-0.2
fine sand	0.2-0.07
coarse silt	0.07-0.02
medium and fine silt	0.02-0.002
clay	<0.002

The origin of this particular classification is not certain. It has a remarkable similarity to the Atterberg classification with its secondary subdivision inserted in the coarser fractions.

Also available to the commission was the U.S. Department of Agriculture Bureau of Soils Classification which had been in use for several years at this point.

In the end, Atterberg's classification was accepted by the commission and has since been referred to as the International System. The limits which are used in the classification are shown below:

	Size, mm
gravel	> 2
coarse sand	2-0.2
fine sand	0.2-0.02
silt	0.02-0.002
clay	< 0.002

At the same time, developments in the techniques for particle size analysis were also being made by several workers. Decantation, one of the first methods, was shown by Hall (1904) to be effective in clay separations after a 24-hour settling period. Briggs, Martin and Pearce (1904) in the same year showed that a centrifuge could be used to make separations in the fine fraction after the sand had been separated. This resulted in a considerable timesaving step in this method.

Elutriation was also improved and made more precise.

The work of Kopecky in 1901 (Krumbein 1932) stands as the model for further work in rising current elutriators. He arranged in series three conical elutriators, each with a precise diameter. The series was so arranged that water entered the bottom of one, exited at the top and then went to the bottom of another to repeat the process through the final elutriator. For this prototype, he chose diameters of 3.0cm, 5.6cm and 17.8cm. For his particle size analysis, Kopecky recommended an expanded particle size classification similar to Atterberg's. He used these separations:

	Size, mm
gravel	>2
coarse sand	2-0.6
medium sand	0.6-0.2
fine sand	0.2-0.06
coarse sand	0.06-0.02
medium silt	0.02-0.006
fine silt	0.006-0.002
clay	<0.002

Elutriation using water as a medium had become a fairly standard technique. It is not, however, the only application of the rising current separation. Air can also be used as was shown in an apparatus described by Gary in 1906 (Krumbein 1932). This was a cylindrical arrangement with a space at the bottom for an air blast. The force of the blast was sufficient to blow away small sizes while leaving the coarser. This has never been reported in extensive use.

Another more usable air elutriator was developed by Cushman and Hubbard (1907). It was similar in design to the water elutriator developed at approximately the same time. There were five vessels connected together in a series. The first container had a capacity of three gallons; the second two gallons; and the remaining three, one gallon each. The path of the air current was much the same as that of the water in the elutriators that have previously been discussed. The air enters the bottom of the vessel and leaves through the top and on to the next. Care must be exercised just as with water elutriation to avoid loss of particles. To prevent loss of particles and to adjust the current, a suction valve was placed on the last container in the series.

In 1912, a much debated development was made in sedimentation cylinders. Atterberg modified the sedimentation cylinder which had been used up to that point. He added a glass tube near the bottom controlled by a pinchcock that allowed him to remove a sample after a given period of settlement. This was somewhat like a method of analysis proposed by Schubler earlier and had certain features which related it to the pipette method of analysis. The procedure was to take a measured sample and find the amount of particles contained, and the size of the particles could be determined by calculation from Stokes' Law. The method was controversial, and several people particularly in Europe attempted to evaluate the validity of the method, but no consistent conclusion was reached by these workers (Krumbein 1932).

Up to this point, all attempts to evaluate the particle size distribution in soils had involved a physical separation of particles. A new technique involving a continuous sedimentation balance was introduced by Oden in 1915 (Krumbein 1932). The object was to measure the weight of particles, P, sedimented in a given time, t. By plotting P vs. t, a particle size distribution curve results by calculating the size on the curve from the t values. The apparatus for this continuous measurement was by weighing P on a platform balance in the sedimentation cylinder. The other arm of the balance held a weighing pan to which weight could be added to measure the amount of sediment collected on the other pan in a given time. Oden added a feature to this system by putting an electric switch a slight distance above the pan used to balance the sedimented material. This switch was turned on when too little weight was on the pan and it automatically added more weight to the pan. This method proved effective in giving accurate particle size distribution curves. It along with Oden's mathematical analysis of sedimentation did much to advance the study of particle size. Oden also suggested a classification of particle size which is discussed in a later section.

Perhaps the next significant development in particle size measurement came with the development of the continuous sedimentary cylinder by Wiegner in 1918 (Krumbein 1932). In the method the difference between the hydrostatic pressure of the suspension and water was recorded through time. With this a particle size distribution curve could be plotted. The equipment for this determination was quite simple. It consisted of a sedimentation cylinder with a parallel manometer tube attached to the cylinder near the bottom. A stopcock separated the tubes and was opened to record the progress of the sedimentation.

Efforts were made in 1921 by Scales and Marsh (1922) to evaluate the amount of material in a soil suspension from the turbidity of the suspension. Later work by Stemm and Svedberg (1925) showed that particle size distribution could also be measured by this technique. This method was checked by microscopic techniques and similar results were obtained. The principle on which the method was based held that a soil suspension would prevent transmittance of light through it proportional to the content of the suspended material.

The pipette analysis, which is commonly used today for particle size analysis, was introduced in three independent papers during the period 1922 to 1923. Robinson (1922), Krauss (Baver 1956), and Jennings, Thomas and Gardner (1922) all published accounts of a similar method of particle size analysis. The pipette method was an attempt to measure the variation in density of a suspension during the progress of sedimentation. It was dependent on Stokes' Law for the sizes of particles which were being measured. The method consisted of drawing out a known volume of the suspension and drying to find the weight of particles. Calculation of the depth at which the sample was taken and the elapsed time of sedimentation using Stokes' Law will show the size of the material being measured.

The three papers which first developed the pipette method did not differ greatly in theory. There were, however, differences in the techniques employed to take the sample of the suspension. Robinson in his method used a pipette to draw out a sample. This could, of course, be done at various levels in the suspension. Jennings, et al., devised a fixed pipette with several openings inside the sedimentation cylinder which drained out the bottom of the cylinder through a valve. Krauss used three pipettes in his analysis. They were suspended so as to be initially 10cm below the surface.

The Agricultural Education Association of Great Britian (1926) compared several means of particle size analysis. The pipette analysis was selected as the best for routine soil analysis. Up to this point, Great Britian had been using a particle size classification that was developed by Hall and Russell (1911). It was a system based on arbitrary selection of particle size limits but was none the less widely used in Great Britian and was as follows:

	Size, mm
fine gravel	>1
coarse sand	1-0.2
fine sand	0.2-0.04
silt	0.04-0.01
fine silt	0.01-0.002
clay	<0.002

This system was replaced in 1928 with the Atterberg system by the Agricultural Education Association of Great Britian (1928). There was no great attachment to the Hall-Russell classification, and since it was not related to physical properties or a mathematical relationship, it was dropped to foster unity among international workers.

In 1927, Bouyoucos presented the hydrometer method of analysis which measured the density of the soil suspension (1927a, 1927b). It has been criticized for its limitations but with modifications it remains today one of the most used procedures in particle size analysis. Initially, Bouyoucos used a hydrometer calibrated in g/l which had been standardized from previously analyzed soils. Initially, the hydrometer reading was made at the end of 15 minutes' sedimentation time. The value which was obtained at this time was correlated with the heat of wetting. It was the conclusion of Bouyoucos that this 15-minute reading represented the colloidal fraction of the soil, because of its relation to the heat of wetting. He later changed the approach to a measure of the sand silt and clay in the Bureau of Soils particle size classification. In the method that he used, readings were taken at 40 seconds, which was the time for settling of sand grains with .05mm equivalent diameter, and at one hour which was the time for settling material coarser than .005mm. In addition, Bouyoucos also included a third reading at two hours which gave the $<$.002mm material. These values were based on empirical evidence rather than Stokes' Law, although there was a relationship. Later, Bouyoucos applied Stokes' Law to the hydrometer method. In this, he sought to justify his one-hour and two-hour readings by showing that there was a difference in the concentration between the top and bottom of the sedimentation cylinder. The hydrometer measured an average value which approximated the answer by canceling errors as was done with the pipette method.

It was in 1928 when Kohn, as reported by Baver (1956), in studies of solutions of lead iodide found that a spherical sample was withdrawn by the pipette method. Prior to this study, it had been considered that a layer of the suspension was being taken. The spherical sample did not affect the accuracy of the determination because of the canceling effect of larger and smaller particles on each other.

There was considerable criticism of the hydrometer method, particularly from the effect of experimental procedure on the theoretical aspects (Keen 1928, Olmstead, et al. 1931).

In answer to this, Casagrande (Baver 1956) developed a revised theory to explain the action of the hydrometer. Bouyoucos (1937) at this time developed a streamlined hydrometer which was more in harmony with the theoretical considerations.

The significance of the particle size limit between silt and clay was still a problem in the U.S. bureau of Soils particle size classification. It was noted that discrepancies existed between the silt and clay texture classes determined by field parties and those determined by laboratory procedure.

Shaw and Alexander (1936) attempted to resolve this problem by examining material in the following size groups: .05-.005mm, .005-.002mm and <.002mm. They asked field soil scientists to classify these materials. They found that several soil scientists classified the .005-.002mm particles as silt. This showed that these particles acted physically more like silt than clay. Chemical tests to determine the mineralogical content showed that the .005-.002mm fraction was more related to the .05-.005mm size group than the <.002mm fraction because of higher silica-sesquoxide ratio and percent silica. Shaw and Alexander concluded that the limit between silt and clay should be set at .002mm rather than .005mm because of a closer relationship with observed properties.

In that same year, Truog, et al. (1936a, 1936b) also recommended a change in the U.S. Bureau of Soils particle size limits for the clay fraction. The arguments for the change from .005mm to .002mm were based on mineralogical evidence. It was their finding that .002mm represented a significant separation between primary and secondary minerals. Below .002mm, there are very few primary minerals and nearly the entire mass of material is made up of secondary minerals which are resistant to further decomposition and alteration. By setting the size limit of clay at .002mm, much can be inferred about the mineralogy and the state of weathering in the soil which cannot be made with the .005mm limit.

The U.S. Bureau of Soils classification was changed in

1938 so that the clay limit was placed at .002mm instead of .005mm. However, the other agencies using this system in the U.S. Department of Agriculture continued to use the former particle size limits for clay without modification. It was not until 1947 that another change was made in this system of classification. The name of the fine gravel size class which included particles between 1.0mm and 2.0mm was changed to very coarse sand. This was in line with ideas of slightly cohesive properties when referring to sands and noncohesive properties referring to gravel (Soil Survey Staff 1951).

This was the last change to date made in the agricultural classification of particle sizes in the United States. The two major systems in use today are the Atterberg, or International System, and the U.S. Department of Agriculture system.

Recent improvements in particle size analysis have taken the following forms for the major methods of analysis: the pipette method has relied on improvements in dispersion procedures; the hydrometer method has been improved by better design, more detailed study of the theory behind the measurement (Day 1950) and improved dispersion procedures. It is still generally recognized that the hydrometer results are not as precise as the pipette method (Black et al. 1965).

While the foregoing is a survey of particle size classification and particle size analyses from the agricultural viewpoint, it should be noted that developments in the techniques of particle size analyses have been made by individuals in many fields. It is not as may have been implied a result of the efforts of agricultural workers alone.

2. Geological Particle Size Classification

Geologists, particularly those concerned with sedimentation, have an interest in particle size classification. Their classifications have usually tended to emphasize ease in treatment of data rather than relating the classification to physical properties (Krumbein & Pettijohn 1938).

A summation of the geologists' uses of grade scales is found in Krumbein and Pettijohn's Manual of Sedimentary Petrography (1938). They cite two functions of grade scales on page 86: descriptive and analytic. The descriptive function is, in their words:

> Descriptive function. The first and perhaps the most important function of a grade scale is a descriptive function, which serves to place nomenclature and terminology on a uniform basis. If one reads the term coarse sand in a report, he would prefer to understand by the term exactly what the writer intended to convey. As long as there is no uniform terminology, each writer coins his own meanings, which may or may not be precisely defined. If, however, the reader knows that the writer is using the Atterberg classification, he may understand that material having a range of sizes from 2.0mm to 0.6mm diameter is meant. Likewise, if the Wentworth scale is being used, the term refers to material from 1mm to ½mm in diameter.
>
> Obviously, no "justification" whatever is required for the descriptive function of a grade scale. The particular choice of such terms as coarse sand, fine sand, clay, and the like need to be based on no other criterion than mutual agreement. If the limits chosen for each grade are also related to the physical properties of sediments, that fact may be taken as an added advantage.

The analytical function is, in their words:

> Analytical function. In addition to the use of grade scales to establish uniformity of terminology, the classes or grades are used as units in performing various kinds of analyses on the sediment. The classes are used, for example, in determining the mechanical composition of the sediment, and in addition they may be used as units during statistical analysis. It is in connection with these analytic functions of grade scales that most of the confusion arose regarding the merits of one or another of the proposed scales. The recognition of the fact that histograms vary in form according to the grade scale used has led various writers to the conclusion that some single scale should be used for all analyses, so that the unfortunate variation of the histogram could be avoided.

Perhaps the first system devised specifically for geological work was by Orth in 1875, according to Wentworth (1922). His suggested particle size classification included these separations:

	Size, mm
gravel	>3
very coarse sand	3-1
coarse sand	1-0.5
medium sand	0.5-0.25
fine sand	0.25-0.05
dust	0.05-0.01
finest dust	<0.01

It is certain that this classification would not be the most desirable for geologists given the criteria cited previously. This classification, like the early agricultural classifications, was not concerned with the finer fractions.

A somewhat more complete particle size classification was proposed by Diller (1898) in a U.S. Geological Survey Bulletin.

	Size, mm
gravel	< 2
fine gravel	2-1
coarse sand	1-0.5
medium sand	0.5-0.25
fine sand	0.25-0.10
very fine sand	0.10-0.05
silt	0.05-0.01
finest silt	0.01-0.0005
clay	< 0.005

This classification bore a close resemblance to the particle size classification suggested by Whitney in 1892 which became the basis of the U.S. Bureau of Soils system.

In 1898 Udden (Roderick 1963) made perhaps the most important contribution to particle size studies in geology. His was the first classification based on a geometric progression. He had based his particle size classification on earlier work done by agricultural soil scientists. He disagreed, however, with the specific limits set up by the soil scientists, because they did not follow a geometric progression throughout the system. The advantage of this was in the analytical function of a grade scale and not necessarily in the descriptive phase. Udden's initial grade scale made these separations:

	Size, mm
coarse gravel	8-4
gravel	4-2
fine gravel	2-1
coarse sand	1-1/2
medium sand	1/2-1/4
fine sand	1/4-1/8
very fine sand	1/8-1/16
coarse dust	1/16-1/32
medium dust	1/32-1/64
fine dust	1/64-1/128
very fine dust	1/128-1/256

In this geometric progression, each size from top to bottom had to be multiplied by 1/2 and the ratio between each separation and the next higher separation was equal to 2.

It was also apparent in this particle size classification that Udden was interested in getting close to the descriptive classification of the soil scientist, while maintaining the geometric progression that he considered essential to analysis of the distribution curve.

Udden (1914) added to his size limits at the top and the bottom of his classification system. At the top he included:

	Size, mm
very coarse gravel	8-16
very small boulders	16-32
small boulders	32-64
medium boulders	64-128
large boulders	128-256

And in the lower segment of his classification, he added these classes:

	Size, mm
coarse clay	1/256-1/512
medium clay	1/512-1/1024
fine clay	1/1024-1/2048

These additional classes became necessary because of the nature of the material that Udden had begun to study. His initial classification was developed for a study of wind deposits. These later developments were a result of his studies of clastic sediments which afforded a larger range in particle sizes.

It was at this time that the Atterberg classification was gaining popularity among agricultural soil scientists. It also appealed to geologists because: first, it was in the form of a geometric progression, and second, it was in some ways related to descriptive properties. Many geologists at this time used the Atterberg system.

In 1908, Keilhack (Wentworth 1922) suggested a particle size classification for geologists. It was not as complete as the Udden or Atterberg systems and was not extensively used.

	Size, mm
gravel	> 2
very coarse sand	2-1
coarse sand	1-0.5
medium sand	0.5-0.2
fine sand	0.2-0.1
superfine sand	0.1-0.05
dust	0.05-0.01
finest dust	< 0.01

Grabau (1913) reviewed the systems of particle size proposed by Diller, Keilhack and others. As a result of his study, he developed a classification of his own. He included these fractions in his grade scale:

	Size, mm
boulders	> 150
cobbles	150-50
very coarse gravel	50-25
coarse gravel	25-5
fine gravel	5-2.5
very coarse sand	2.5-1.0
coarse sand	1.0-0.5
medium sand	0.5-0.25
fine sand	0.25-0.10
superfine sand	0.10-0.05
rock flour	0.05-0.01
superfine flour	0.01-0.005
clay size	0.005-0.001

This classification is closely related in the finer fractions to the U.S. Bureau of Soils classification.

In 1918, Boswell (Milner 1952) published a study of sands in various industries in Great Britian. For this study, he selected these particle size limits:

	Size, mm
gravel	>2
very coarse sand	2-1
coarse sand	1.0-0.5
medium sand	0.5-0.25
fine sand	0.25-0.10
superfine sand or coarse silt	0.10-0.05
silt	.05-.01
clay or mud	<0.01

Above .05mm this is the same as the U.S. Bureau of Soils classification with some modification in terminology.

The publication of Wentworth's particle size classification in 1922 is commonly hailed as the most important event in geological study of particle size. His classification of grain sizes was in effect a modification of the grade scale originally developed by Udden.

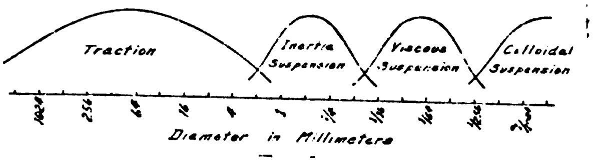
Wentworth made these separations in his size classification:

	Size, mm
boulder gravel	>256
cobble gravel	256-64
pebble gravel	64-4
granule gravel	4-2
very coarse sand	2-1
coarse sand	1-1/2
medium sand	1/2-1/4
fine sand	1/4-1/8
very fine sand	1/8-1/16
silt	1/16-1/256
clay	<1/256

The system was like that of Udden's, based on a geometric progression with a factor of 2 and using 1mm as the base with some intervals left out.

Wentworth felt this system was good for two reasons. First, as a geometric progression, it provided what he considered meaningful comparisons between the size groups. It also was a simple matter to graph and interpret these even units on a logarithmic scale. These were also considerations in the earlier Atterberg system.

Secondly, he felt the separations which he made were as close as possible to those already being made by most workers, while also being, for the most part, a geometric progression. It is significant to note that Wentworth was also concerned to some degree about the relation of physical properties to the size classes which he had determined. In a paper in 1933, he showed how he assumed the sizes were related to mode of transportation of the particles in geologic processes. His conclusion was that even though the separations may have been of an arbitrary nature initially, they were closely related to some critical properties as shown in the following chart.



It seems to assume that there are sizes which are not moved in the same continuum as others. This does not agree with observations of river deposits cited later in this work.

A change was made when Krumbein (1934, 1936) suggested the modification of the Wentworth and Atterberg grade scales to the phi and zeta grade scales, respectively. The modification is nothing more than a logarithmic transformation of these scales using a transformation equation on each size limit diameter. For the transformation of the Wentworth grade scale, this equation is used: $\phi = -\log 2 \zeta$ (when ζ is the diameter of the size limit in millimeters). For the transformation of the Atterberg grade scale, this equation is used: $\zeta = 0.301 - \log_{10} \zeta$ (when ζ is the diameter of the size limit in millimeters on the Atterberg scale). The result of these transformations is shown as follows:

Phi and Zeta Grade Scales

Wentworth Grades	ϕ	Atterberg Grades	ζ
32mm	-5	2000mm	-3
16mm	-4		
8mm	-3	200mm	-2
4mm	-2		
2mm	-1	20mm	-1
1mm	0		
1/2mm	+1	2mm	0
1/4mm	+2		
1/8mm	+3	0.2mm	+1
1/16mm	+4		
1/32mm	+5	0.02mm	+2
1/64mm	+6		
1/128mm	+7	0.002mm	+3
1/256mm	+8		
1/512mm	+9	0.0002mm	+4
1/1024mm	+10		

The theory behind the transformation to these scales is that any geometric scale can be changed to a scale with arithmetic intervals which is equivalent, provided that logarithms of diameter sizes are substituted for diameter sizes.

The intent of these transformations to the ϕ and ζ scales is to provide a better, more easily manipulated framework for the application of statistical methods of analysis.

Hilgard had earlier developed a classification of grain size for agricultural purposes based on the speed of elutriation. Along this same line, Rubey (1930) developed a classification for geologists based on settling times. This was developed in relation to his study of fine grained Upper Cretaceous sedimentary rocks in the Black Hills. His classification made these separations:

Rubey's Size Classification
Based on Settling Velocities

Grade	Settling Velocity (in microns/sec.)
very fine sand	> 3,840
coarse silt	960-3,840
medium silt	240-960
fine silt	60-240
very fine silt	15-60
coarse clay	3.75-15
medium clay	0.9375-3.75
fine clay	< 0.9375

Rubey arrived at these limits by plotting settling velocities vs. diameters of particles on double log paper. He then plotted the size limits of Atterberg, Wentworth and Udden on the graph. The settling velocities cited in the table were obtained from this graph.

It is significant to note at this point that Rubey's classification is a geometric progression. Each settling velocity value is related to the next higher by a factor of 4. The particles themselves are related to the next higher particle by 2 because of the nature of Stokes' Law. This classification has not been used to any great extent and no transformation such as the phi and zeta scale has been worked out, although an equation could be easily developed.

Alling (1943) proposed another classification of particle sizes for geologists. His scale was developed from studies of thin sections and polished blocks. Alling was not considering particle size analysis in the usual sense of sedimentation or sieving. He was interested only in the two dimensional aspects of particle size.

Alling in his article clearly stated four fundamental properties he considered essential to a good particle size grade scale. They are:

1. The grain sizes should constitute a continuous series.
2. Any division of the series will be arbitrary.
3. Convenience of use is a criterion.
4. Statistical analysis requires the use of a constant geometric ratio.

In line with those principles, he proposed this grade scale:

		Size, mm
Boulder	Coarse	560-1000
	medium	320-560
	fine	180-320
	very fine	100-180

Cobble	coarse	56-100
	medium	32-56
	fine	18-32
	very fine	10-18
Gravel	coarse	5.6-10
	medium	3.2-5.6
	fine	1.8-3.2
	very fine	1.0-1.8
Sand	coarse	0.56-1.0
	medium	0.32-0.56
	fine	0.18-0.32
	very fine	0.10-0.18
Silt	coarse	0.056-0.10
	medium	0.032-0.056
	fine	0.018-0.032
	very fine	0.010-0.018
Clay	coarse	0.0056-0.010
	medium	0.0032-0.0056
	fine	0.0018-0.0032
	very fine	0.0010-0.0018
Colloid	coarse	0.00056-0.0010
	medium	0.00032-0.00056
	fine	0.00018-0.00032
	very fine	0.00010-0.00018

It was based on Hopkins' work which was an alternative to the U.S. Bureau of Soils classification proposed in 1899. Hopkins had suggested using a geometric progression with a factor of 10 from one size limit to the next higher size limit. He also made subdivisions based on $\sqrt{10}$ and suggested $\sqrt[4]{10}$ as a possibility for further subdivision. Alling used $\sqrt[4]{10}$ to develop the system which he proposed.

The American Geophysical Union has attempted to get uniform acceptance of a grain size terminology. In 1947, after thorough study of many systems, a subcommittee of the American Geophysical Union recommended this system:

very large boulders	4096-2048mm	or	160-80in
large boulders	2048-1024		80-40
medium boulders	1024-512		40-20
small boulders	512-256		20-10
large cobbles	256-128		10-5
small cobbles	128-64		5-2.5
very coarse gravel	64-32		2.5-1.3
coarse gravel	32-16		1.3-0.6
medium gravel	16-8		0.6-0.3
fine gravel	8-4		0.3-0.16
very fine gravel	4-2		0.16-0.08in
very coarse sand	2-1		
coarse sand	1-1/2		1-0.500mm
medium sand	1/2-1/4		0.500-0.250
fine sand	1/4-1/8		0.250-0.125
very fine sand	1/8-1/16		0.125-0.062
coarse silt	1/16-1/32		0.062-0.031
medium silt	1/32-1/64		0.031-0.016
fine silt	1/64-1/128		0.016-0.008
very fine silt	1/28-1/256		0.008-0.004
coarse clay size	1/256-1/512		0.004-0.0020
medium clay size	1/512-1/1024		0.0020-0.0010
fine clay size	1/1024-1/2048		0.0010-0.0005
very fine clay size	1/2048-1/4096		0.0005-0.00024mm

It is basically the system of Udden with extensions at both ends of the scale.

3. Particle Size Classification in Engineering

Engineers have been concerned with the particle size classification and distribution in earthy materials. Although perhaps beginning the study of particle size later than most groups, they have been keenly interested in the practical aspects of the particle size information.

The first particle size classification specifically suggested for engineers was advanced by Terzaghi in 1925 (Glossop & Skempton 1945). It was a compilation of earlier work done by Romann and Atterberg. He used Atterberg's size limits for the fine fractions and Romann's size limits for the coarse fractions. His size classification made these separations:

	Size, mm
very coarse sand	2-1
coarse sand	1-0.5
medium sand	0.5-0.2
fine sand	0.2-0.1
coarse mo	0.1-0.05
fine mo	0.05-0.02
coarse silt	0.02-0.006
fine silt	0.006-0.002
coarse clay	0.002-0.0006
fine clay	0.0006-0.0002
ultra fine clay	<0.0002

The particle size Mo comes from a Scandinavian word for very fine sand or silt. It not only is used to refer to the particle size, but also the condition of land since it refers to sandy barren heath and a country drill field.

This system became known as the Continental System and an addition was made to Terzaghi's particle size classification to include larger material.

	Size, mm
stone	> 30
coarse gravel	30-15
medium gravel	15-5
fine gravel	5-2

The U.S. Bureau of Public Roads developed guidelines for particle size classes for soils study early in the 1920s. These were based on the work of Boyd (1922) and Goldbeck (1921).

An arbitrary classification was evolved that was referred to as the Bureau of Public Roads system (Hogentogler 1937):

	Size, mm	Sieve
gravel	> 2.0	(No. 10)
coarse sand	2-0.25	(No. 10 - No. 60)
fine sand	0.25-0.05	(No. 60 - No. 270)
silt	0.05-0.005	
clay	< 0.005	
colloids	< 0.001	

Not long afterward the No. 60 sieve in the classification was replaced with the No. 40 sieve or .42mm.

This classification of particle size limits has several limits in common with the U.S. Bureau of Soils classification. The selection of these common size limits was so as to be able to use U.S. Bureau of Soils information. Hogentogler (1937) who had helped to develop the system offered four reasons for modification of the classification:

> 1) Use of the No. 40 sieve to separate coarse sand from fine sand eliminates one determination in the mechanical analysis since tests for properties of the finer portions are performed on the material which passes the No. 40.
>
> 2) With the exception of the division between coarse and fine sands, the limits correspond to those of the U.S. Bureau of Soils system. This facilitates use of information in soil surveys made by that Bureau, in which the mechanical analysis plays an important part.
>
> 3) By using the present methods, the grading by the above sizes is as easily accomplished as were the former sizes by earlier methods.
>
> 4) Each division represents a group of particles having a special significance.

Hogentogler went on to cite these specific properties of the various size classes:

> Gravel - rock fragments which are usually rounded by water action and abrasion. Quartz is the principle constituent. Gravel which is only slightly worn-rough and subangular - commonly includes granite, schist, basalt or limestone.

Coarse sand - is likely to consist of the same minerals as the gravel. It is usually rounded like pebbles.

Fine sand - is usually more angular than coarse sand.

Silt - consists of bulky grains, similar to fine sand except for size, and having the same mineral composition. However, it may be largely a product of chemical decay rather than of rock grinding and so may consist of silicates of aluminum and alkaline earths, and of oxides of iron. In other cases the silt may be composed of foreign materials such as diatoms, pumice, or loess.

Clay - the coarser fractions usually and mainly consist of original fragments such as quartz and feldspar. However, clay consists almost entirely of the secondary products of chemical weathering. It differs from the coarser fractions in that it is the chemically reactive portion of the soil; the coarser fractions are inert.

Colloids - in a strict sense, only those finer clay particles which show pronounced Brownian movement when suspended in water. Some authorities place the upper limit at 0.002mm. In testing soils for highway purposes, colloids are considered as particles 0.001mm in diameter and finer.

This same U.S. Bureau of Public Roads system was adopted in 1935 by American Association of State Highway officials and in 1944 by the American Society for Testing and Materials (Roderick 1963).

In 1930, the system which has come to be known as the MIT system was put forth by Gilboy. This is the same classification which Kopecky suggested in 1914. The MIT system makes these separations (Terzaghi & Peck 1948). The MIT system makes these separations:

	Size, mm
gravel	> 2
coarse sand	2-0.6
medium sand	0.6-0.2
fine sand	0.2-0.06
coarse silt	0.06-0.02
medium silt	0.02-0.006
fine silt	0.006-0.002
clay	< 0.002

This classification also contained the same separations as the expanded Atterberg classification. The relationship between particle size and physical properties will hold for this calssification. Further work by Glossop and Skempton (1945) showed that engineering properties were related to those size separations as well as those advanced by Atterberg and others earlier.

Specifically, Glossop and Skempton said 2.00mm was considered to be the upper size limit of capillary forces.

Below 2.00mm the particles cling together when moist. This is the sand fraction. Above 2.00mm the particles are too large to be held by these capillary forces. The separation between silt and clay was made at .002mm because of the colloidal and base exchange properties cited by Russell. These properties increase below .002mm and are practically nonexistent in coarser fractions. The separation between sand and silt is not nearly as clear as the other breaks but study in three areas shows that .06mm represents a good point to make the separation. From a textural standpoint there appears to be a break in the grittiness of the material at .06 or .07mm. There is also a break in the size of wind-blown sands at approximately .06-.08mm. Frost heaving is another of the properties considered. It was shown that silt was more likely to frost heave than was clay. It was also found that ground water lowering is easily accomplished in material above .06mm and very difficult below .06mm. They also mentioned the increased consolidation and settlement in silts over sands.

Glossop and Skempton found on the basis of natural samples that .06mm was the value which was most closely related to these several properties separating silt and sand.

In 1947, the American Society of Engineering Education through its civil engineering division advanced a size classification (ASCE 1947). They made these separations:

	Size, mm	Sieve
coarse gravel	76.2-25.4	3"-1"
medium gravel	25.4-9.52	1"-3/8"
fine gravel	9.52-2.0	3/8"-No. 10
coarse sand	2.0-0.59	No. 10-No. 30
medium sand	0.59-0.25	No. 30-No. 60
fine sand	0.25-0.074	No. 60-No. 200
coarse silt	0.074-0.02	No. 200
fine silt	<0.02 non-plastic	No Lower Limit
clay	<0.074 plastic	No Lower Limit

This group backed their classification with claims that it is for the most part based on properties of particle size groups which can be recognized either in the field or the laboratory.

In 1947, Casagrande, who had been responsible for the development of the Unified Soil Classification System during World War II, proposed a grain size classification. His grain size classification was based on sieve separations of coarse particles and the fine fraction was classified on the basis of Atterberg constants. He made these separations:

	Size, mm	Sieve
cobbles	>76.2	3"
coarse gravel	76.2-19.5	3"-3/4"
fine gravel	19.5-4.76	3/4"-No. 4
coarse sand	4.76-2.00	No. 4-No. 10
medium sand	2.00-0.42	No. 10-No. 40
fine sand	<0.42-0.074	No. 40-No. 200
fines (silt and clay)	<0.074 (classified as to plasticity and cohesion)	<No. 200

In 1950, American Association of State Highway officials revised their classification of particle size to adopt many of the Casagrande particle size limits (Roderick 1963). Their revised classification makes these separations:

	Size, mm	Sieve
particles larger than	2	
coarse sand	2-0.42	(No. 10 - No. 40)
fine sand	0.42-0.074	(No. 40 - No. 200)
silt	0.074-0.005	
clay	<0.005	
colloids	<0.001	

In 1958, the American Society for Testing and Material also adopted the above classifications. In 1961, further revision of the particle size classification resulted in an expanded system, as follows (Roderick 1963):

	Size, mm	Sieve
gravel	76.2-4.76	3"-No. 4 Sieve
coarse sand	4.76-2.00	No. 4 - No. 10
medium sand	2.00-0.42	No. 10 - No. 40
fine sand	0.42-0.074	No. 40 - No. 200
silt	0.074-0.005	
clay	< 0.005	
colloids	< 0.001	

B. MOISTURE RELATIONSHIPS AND PARTICLE SIZE IN SOILS

Moisture relationships have long been considered important considerations in particle size classification and particle size distributions. Atterberg was perhaps the first to set forth the relatioships of particle size and soil moisture as reviewed above. He discussed elements of fluvial hydraulics as well as water holding properties.

It has been clearly shown that there is a relationship between particle size and a location on a traverse along a river (Leviavsky 1955), as shown in the data presented by Sternberg and the analysis by Schiklitsch. They showed a semilogarithmic relation between distance from source toward the mouth and particle size. Coarser particles are found at or nearer the source and finer at or nearer the mouth. There is still debate as to the cause for this relationship. Leopold, Wolman and Miller (1964) cite a near linear relation between particle size and distance traveled along the Mississippi and Missouri Rivers. Hack (1957) also worked on this subject and attempted to find a relationship to both particle size and lithology.

Water holding capacity has been of real interest in agriculture. It has been particularly critical in relation to droughtiness of soils, irrigation and other water management practices. Several studies have been made of the moisture holding properties and various particle size groupings in an attempt to establish relationships between them. At this point, some of the results appear contradictory but it seems that a definite relationship has been found by several workers.

Initially the work on soil moisture and soil texture stressed measurement of field capacity and moisture equivalent and the relation of each of these to texture and to each other. Perhaps the first study of this type was by Briggs and Shantz in 1912 (Baver 1956). They found a relationship between the moisture equivalent of soils and the percentage of the sand, silt and clay fraction.

Problems with irrigation have created further need for study of available water capacity and readily available water capacity. Wilcox and Spilsbury (1940a, 1940b) observed that available water found by deducting wilting coefficient from field capacity 24 hours after irrigation was related to silt and clay contents. According to them, an increase in clay content up to 60 percent increased the available water in the soil. It appeared too that over 60 percent clay, the water is too firmly bound in surface films to be available.

Peele et al. (1948) found in a study of the irrigation requirements of South Carolina soils that the available water determined as field capacity minus permanent wilt point was primarily dependent on the type of clay and the amount of organic matter content. Briefly stated, three relationships were found. Soils low in both clay and organic matter had lower moisture holding capacities. Soils high in organic matter were high in water holding capacity. Soils high in clay had high and relatively low water holding capacities dependent on the type of clay mineral that was present in the profile. If the clay exhibits low swelling and shrinkage on wetting and drying or has low base exchange capacity, it will also have a low available water capacity.

A study made by Lehane and Staple (1953) on Brown and Dark Brown prairie soils in Canada reports that clay is the dominant controlling factor in water availability. They found that more available water was held by clay textured soils than was stored in silt loams and silty clay loams. Available water in this study was considered as the field capacity 72 hours after saturation minus the wilting coefficient.

In Holland, Ferrari et al. (Hill 1959) showed clay to be the most significant measure of available water holding capacity. It should be noted that his clay determinations included material less than .016mm in diameter.

This view that clay is the particle size in control of available water is no longer held by many workers in the field. In fact, much of the work done in recent years has tended to discount the role of clay in predicting available water capacity. Some results show that increase in clay content actually decreases the available water capacity (Jamison & Kroth 1958). Recent research shows the importance of the silt fraction to the available water capacity.

Perhaps the first publication to cite silt as being more effective than clay in holding available water was by

Jamison (1956). Data in that article showed that silt loam held more water available to plants than did clay soils.

Later, Jamison and Kroth (1958) studied soil profiles from several geographic locations in Missouri. They found that the available water storage capacity of a soil increased with increasing silt content. The coarse silt fraction (.05mm-.02mm) was more effective in increasing the available water capacity than the fine silt (.02mm-.002mm) fraction. In most cases they found higher clay contents actually lowered the available water capacity. In some soils with between 13 and 20 percent clay, however, the available water capacity increased with clay content. Jamison and Kroth suggested that silt size soil aggregates formed with organic matter may have been responsible. This clay relationship reminds one of Peele et al. (1948) and the differences they found in available water capacity associated with clay mineralogy. Jamison and Kroth contend that available water is dependent on particle size and is not affected by organic matter. Others such as Peele et al. (1948) and Jacks (1964) contend that organic matter increases available water holding capacity.

In 1959, Lund (1959) in a study of Alluvial soils in Louisiana found results similar to Jamison and Kroth. He found a direct correlation between available water measured between 1/3 and 15 atmospheres tension and total silt. Lund also found a direct relation between the clay content and the total moisture content at 15 atmospheres tension which was considered by him to be the wilting point of most crops. In addition, he found no correlation between clay and available water capacity and a negative relation between sand and available water. He also reported a positive correlation between pore size and permeability. His conclusion was that total water was related to the clay fraction but available water was related to the silt fraction.

Bartelli and Peters (1959), describing moisture characteristics as unique and of great utilitarian value, sought to relate them to the classification of soils. Their study was made in Illinois on soil types representing Gray Brown Podzolic, Brunizem and Planosol Great Soil Groups. They found that the Gray Brown Podzolic soils averaged more available water regardless of texture than the other Great Soil Groups in the surface horizon. They found, as had Lund, that clay was related to the water content at 15 atmospheres tension but was not related to the available water capacity. They also found that the silt content was related to the available water capacity but not to the water content at 15 atmospheres.

Hill (1959) in a bulletin on the storage of moisture in Connecticut soils used some different measures of soil water. Through these he showed that silt was the most important particle size class in determining the available moisture holding capacity. He also found that moisture release at high tensions was closely related to clay content. He also reported a relation between capillary porosity and the silt content of soils. The correlation coefficient was .73. From his data, organic matter was not highly correlated with available water. He found that cultivated soils had higher available moisture holding capacity than did forested soils. This seems to be in agreement with the finding of Jamison (1953) and with Feustal and Byers (Baver 1956). It is not however in agreement with the findings of all researchers. Millar, Turk and Foth (1965) stated clearly that organic matter increases the available moisture holding capacity. Earlier, Alway and Russell (1916) found organic matter added to moisture holding capacity. Later, Peele et al. found with soils, all of sandy loam texture, that organic matter content and available water was highly correlated. The question of organic matter effect on moisture holding capacity is still not completely clear.

Franzmier et al. (1960) found that soils high in silt and very fine sand in the USDA particle size classification are also high in readily available water. Readily available water was defined in this case as water held between .06 and 6 atmospheres tension. He also found that the clay content was highly correlated with the amount of water present at 6 atmospheres tension. This would indicate two regions of available water; one below 6 atmospheres controlled by silt and very fine sand, and another above 6 atmospheres controlled by the clay content. Previous studies had centered on capacities at 15 atmospheres with no measurement between it and field capacity.

Salter and Williams (1965a, 1965b, 1966) in a study of the influence of soil texture on the moisture characteristics of soils showed clearly the effect of particle size on moisture holding properties. They found that medium textured soils held the most available water. They also found that silt size particles were most effective in holding available water.

C. CAPILLARY RISE AND PARTICLE SIZE IN SOILS

Capillary rise was a property which was recognized early in soil studies (Dougrameji 1965). This has an effect on plant growth (Luthin 1957, Hogen et al. 1967) and on the engineering uses of soils (Terzaghi 1948, Hough 1957, Capper & Cassie 1953). The effect of capillary rise results in questions which have practical as well as theoretical significance.

The first correlation of particle size and capillary rise was found by Schnaskey in 1864 (Dougrameji 1965). It was based on the data collected earlier by Schubler in his studies of soil physics. He is also credited with developing the concept of capillary and noncapillary pores and their effects on moisture retention. He realized the practical aspects of this on plant growth and maintenance of good soil conditions.

Wollney, as reported by Baver (1956), also found a relation between particle size and capillary rise. He found that capillary rise was affected by several factors including particle size. An increase in capillary rise was noted with increases in temperature, looseness of packing and original moisture content of the soil. He found that mixtures of sand sizes were more effective in raising capillary water than were narrow ranges of sand sizes. He also found that the capillary rise was highest with a capillary diameter of .05-.10mm with the lowest limit of capillary rise at 2.0mm. In addition to this, he also established the highest total rise with the finest particle size.

The findings of Wollney were borne out later in experiments by Loughbridge (1894). He too found a relation between coarse silt size particles and higher capillary rise. He went further to say that in the sand fractions, both capillary and noncapillary water is a factor since both kinds of pores are available.

Capillary rise is reduced in dry soil and increased in a moist soil. King (1907) thought that if a thin, dry layer of soil was maintained at the surface, evaporation would be reduced.

It had been recognized earlier by Johnson (Baver 1956) that total capillary rise was not as significant as the rate of capillary rise. In this he of course had reference to plant utilization of the water.

Studies of the rate of capillary rise in relation to particle size were made by Atterberg (1908, from a translation by Dr. R. W. Simonson). He studied the capillary rise of selected size fractions in 24 and 48 hours as well as the time required to reach the maximum capillary rise. He found that the most rapid capillary rise was in the fraction between .02mm and .05mm in both 24 and 48-hour periods. He also found that the days required for maximum capillary rise were greatest in the .05mm to .10mm fractions.

In the study of capillary rise in soils, two explanations of capillary rise have been offered. First was the capillary size hypothesis of Briggs and later the capillary potential hypothesis of Buckingham. Much work has been done to explain these relationships. It seems that most modern work shows the capillary potential to be most useful (Baver 1956).

Regardless of the theoretical approach, it can be seen that different conditions affect the result. Several studies have been conducted on the effects of stratification of soils on capillary rise (Dougrameji 1965). Disruption and variation of capillary rise have been noted in such materials but no specific size differences necessary have been cited. However, general size limits have been set in the sand fraction by Mamanian and later by Felitsiant (1959, 1961). Dougrameji found a 2cm layer of 2.5-1mm diameter particle will stop capillary rise. A similar layer of 1-.5mm particle will not stop capillary rise, relative to adjacent sizes.

Later work on capillary rise in the sand and coarse silt fractions by Dougrameji and Erickson in 1962 showed a similar trend to the results obtained by Atterberg. They showed that the coarse silt fraction gave the highest capillary rise in 48 hours. Earlier work reported by Franzmeier et al. (1960), while choosing different size limits of separations than

Atterberg, showed a similar relation between silt sizes and capillary rise in 48 hours. They were not able to obtain as high a rise in 48 hours as did Atterberg. This variation could be due to a difference in techniques or conditions of the experiments.

D. PERMEABILITY AND PARTICLE SIZE IN SOILS

Permeability measurements in soils with saturated and unsaturated flow of water have been used to help evaluate the physical condition of soils by many authors. Some consider permeability to be the best criterion for measuring soil structure (Fireman 1944). Others approach it from the point of view of measuring capillary and noncapillary pores (Baver 1938). Others propose that permeability in disturbed samples is supplemental to capillary rise measurement, the latter reflecting the amount of capillary pores and the former the noncapillary pores.

Permeability and a closely related property percolation rate are of real interest to sanitarians (US Dept. HEW, PHS 1967, Bender 1961) and to engineers (MSHD 1960). This discussion of permeability will be limited to a study of saturated flow.

Initially, studies of saturated flow were related to the work of Darcy (Baver 1956). The law which he developed, Darcy's Law, can be mathematically stated as follows:

$$v = \frac{kh}{l}$$

Where v is the velocity in cubic centimeters per second, h is the difference in pressure head in centimeters, l is the length of the column in centimeters and k is the proportionality constant. It does not relate permeability to the particle size of the material concerned.

Slichter thought that a more effective formula for saturated flow would include soil properties as well as the external factors; as a result, he arrived at this equation:

$$q = \frac{10.22\ pd^2s}{\mu hk}$$

Where q is the quantity of water in cubic centimeters per second, p is the difference of the pressure head in centimeters, d is the mean diameter of the soil grains in centimeters, s is the cross sectional area in square centimeters, h is the height of the soil column in centimeters, μ is the coefficient of viscosity in poises, and k is a constant.

Later, Zunker (Baver 1956) also found that soil properties were important in calculating permeability. He modified Slichter's equation of expected permeability as follows:

$$Q = \frac{\mu h}{\eta \ell U^2} \cdot \left(\frac{po}{1-p}\right)^2 F$$

When Q refers to amount of transmitted water, h is the pressure difference, η is the coefficient of viscosity, ℓ the length of the column, U the effective specific surface, μ the type and arrangement of particles, p the total pore space, po the tension free pore space, and F the cross sectional area. Zunker placed the values for μ from 2.3 for round particles to .5 for disk-shaped particles. Since most soils are a mixture, 1.0 was the value placed on most soils.

He also developed a formula for finding the tension free pore space, po.

$$po = p - (W/100)\ (1-p)s$$

In the formula, W is twice the hygroscopicity, s is the specific gravity of soil, and p is total pore space.

Because of its relevance for engineers, several studies have been made to show the relationship between particle size and permeability. As Ritter and Paquette (1960) stressed, permeability is a result of void ratio, grain size and structure. The void ratio is defined as the ratio of the volume of voids contained in a soil mass to the volume of solids. Some data specifically relating permeability and grain size of some materials are found in the following table from Terzaghi and Peck (1948).

Formation	Value of k (cm/sec)
River Deposits	
Rhone at Genissiat	Up to 0.40
Small streams, eastern Alps	0.02 to 0.16
Missouri	0.02 to 0.20
Mississippi	0.02 to 0.12
Glacial Deposits	
Outwash plains	0.05 to 2.00
Esker, Westfield, Mass.	0.01 to 0.13
Delta, Chicopee, Mass.	0.0001 to 0.015
Till	Less than 0.0001
Wind Deposits	
Dune sand	0.1 to 0.3
Loess	0.001±
Loess loam	0.0001±
Lacustrine and Marine Offshore Deposits	
Very fine uniform sand,	0.0001 to 0.0064
Bulls's liver, Sixth Ave., N.Y.	0.0000 to 0.0050
Bull's liver, Brooklyn	0.00001 to 0.0001
Clay	Less than 0.0000001

They have also included a classification of soil materials based on permeabilities.

Degree of Permeability	Value of k (cm/sec)
High	Over 10^{-1}
Medium	10^{-1} to 10^{-3}
Low	10^{-3} to 10^{-5}
Very low	10^{-5} to 10^{-7}
Practically impermeable	Less than 10^{-7}

Along with this Terzaghi and Peck included an interpretive table based on work by Casagrande and Fadum.

Permeability and Drainage Characteristics of Soils

Coefficient of permeability k in cm per sec (log scale)

10^{2} 10^{1} 1.0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}

<table>
<tr><td>Drainage</td><td colspan="4">Good</td><td>Poor</td><td colspan="2">Practically Impervious</td></tr>
<tr><td rowspan="2">Soil types</td><td rowspan="2">Clean gravel</td><td colspan="2">Clean sands, clean sand and gravel mixtures</td><td colspan="3">Very fine sands, organic and inorganic silts, mixtures of sand silt and clay, glacial till, stratified clay deposits, etc.</td><td rowspan="2">"Impervious" soils, e.g., homogeneous clays below zone of weathering</td></tr>
<tr><td></td><td colspan="4">"Impervious" soils modified by effects of vegetabion and weathering</td></tr>
<tr><td rowspan="2">Direct determination of k</td><td colspan="4">Direct testing of soil in its original position--pumping tests. Reliable if properly conducted. Considerable experience required</td><td colspan="3"></td></tr>
<tr><td colspan="3">Constant-head permeameter. Little experience required</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Indirect determination of k</td><td></td><td colspan="2">Falling-head permeameter. Reliable. Little experience required</td><td colspan="2">Falling-head permeameter. Unreliable. Much experience required</td><td colspan="2">Falling-head permeameter. Fairly reliable. Considerable experience necessary</td></tr>
<tr><td colspan="3">Computation from grain-size distribution. Applicable only to clean cohesionless sands and gravels</td><td colspan="3"></td><td>Computation based on results of consolidation tests. Considerable experience required</td></tr>
</table>

In England, Capper and Cassie (1953) also cited a relationship between particle size and permeability:

Permeability Ranges

value of k

10^2 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} cm/sec

10^5 10^4 10^3 10^2 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4}ft/day

Gravels	Sands	Silts	Homogeneous Clays
		Fissured & Weathered Clays	
Good drainage		Poor drainage	Impervious

Further, Hough (1957) also discussed permeability and related this to particle size:

Typical Values of Permeability Coefficients

		Particle Size Range Millimeters		Permeability Coefficient-k	
		D_{max}	D_{min}	ft/mo	cm/sec
TURBULENT FLOW	Derrick STONE	--	--	100×10^5	100
	One-man STONE	--	--	30×10^5	30
	Clean, fine to coarse GRAVEL	80	10	10×10^5	10
	Fine, uniform GRAVEL	8	1.5	5×10^5	5
	Very coarse, clean, uniform SAND	3	0.8	3×10^5	3
LAMINAR FLOW	Uniform, coarse SAND	2	0.5	0.4×10^5	0.4
	Uniform, medium SAND	0.5	0.25	0.1×10^5	0.1
	Clean, well-graded SAND & GRAVEL	10	0.05	0.01×10^5	0.01
	Uniform, fine SAND	0.25	0.05	400	40×10^{-4}
	Well-graded, silty SAND & GRAVEL	5	0.01	40	4×10^{-4}
	Silty SAND	2	0.005	10	10^{-4}
	Uniform SILT	0.05	0.005	5	0.5×10^{-4}
	Sandy CLAY	1.0	0.001	0.5	0.05×10^{-4}
	Silty CLAY	0.05	0.001	0.1	0.01×10^{-4}
	CLAY (30 to 50% clay sizes)	0.05	0.0005	0.01	0.001×10^{-4}
	Colloidal CLAY ($-2\mu \eqslantgtr 50\%$)	0.01	10Å	10^{-4}	10^{-9}

Hough also felt that at the 2.00mm limit there was a change in flow within the soil mass. Above 2.00mm size, the flow between particles was turbulent and below 2.00mm, it was laminar.

The Portland Cement Association Soil Primer (1962) also suggests this relation between particle size and permeability:

Size class	k value cm/sec
sands	$1.0 - 10^{-3}$
silty and clayey sand	$10^{-3} - 10^{-7}$
cohesive clays	Less than 10^{-8}

The Asphalt Institute (1966) cites the following figures showing the relation between particle size and permeability:

Material	Approximate coefficient of permeability, feet per day
	0.000001
Silty clay	0.00001
	0.0001
	0.001
Fine sands and silt	0.01
	0.1
	1
Sands	10
	100
	1,000
Gravel	10,000
	100,000

They also showed the relationship of grain size summation curves and permeabilities.

III. METHODS

A. ENGINEERING PROPERTIES OF SOILS AND PARTICLE SIZE LIMITS

In the course of its operations, the Michigan State Highway Department tests for certain soil properties. In addition to materials below a given size from a grain size distribution curve, several other physical properties are evaluated. These tests are run in accordance with various current ASTM and AASHO standards (MSHD 1960). Included in this study are the following properties: liquid limit, plastic index, shrinkage limit, shrinkage ratio, maximum density and optimum moisture.

An attempt is made here to show the relation between these properties and certain portions of the particle size distributions. The techniques used are those of simple correlation and regression analyses.

For purposes of these analyses, samples were selected which were accompanied by particle size distribution curves that were plotted during the particle size analyses. In most cases the <.002mm value was not represented on the curve and it was necessary to extrapolate to get this value.

More data on physical properties and particle size distributions were available in previous Reports on Results of Tests by the Michigan State Highway Department. However, these reports did not include the particle size distribution curves drawn during the particle size analyses in connection with the other tests. Only the percentages of .005, .050, .074 and .105mm, read from the size distribution curves, are reported in the silt size range. To evaluate the accuracy of the values obtained when a particle size distribution curve was replotted from the above mentioned data, 10 samples that represented the approximate range of particle size distributions in the data were selected from among the samples for which the original size distribution curves were still available. In the table below are the results of particle size classes read from the curves redrawn from the data reported together with those read directly from the original graphs.

Comparison of Percentages of Particle Size Classes Read From Curves Constructed During Mechanical Analyses (MSHD), and Those Redrawn (RDC) From<.005, <.050, <.074, <.105 and Sand Sizes Reported:

Sample No.	Maximum Size, mm	% Max. Size MSHD	RDC	Sample No.	Maximum Size, mm	% Max. Size MSHD	RDC
64S1331	.002	1.2	6	66S897	.002	7	4
	.010	16	16		.010	10	10
	.020	20	19		.020	12	13
	.062	25	25		.062	16	16
64S1	.002	66	74	65S1130	.002	2	1
	.010	89	86		.010	4	3
	.020	92	90		.020	5	4
	.062	94	95		.062	9	9
64S242	.002	67	52	67S3148	.002	26	30
	.010	80	78		.010	42	40
	.020	84	87		.020	50	46
	.062	98	97		.062	59	58
65S2917	.002	23	23	67S1773	.002	28	35
	.010	37	37		.010	56	55
	.020	47	48		.020	76	72
	.062	70	70		.062	97	97
64S1334	.002	9	7	66S2659	.002	43	44
	.010	16	15		.010	50	51
	.020	20	18		.020	53	53
	.062	23	23		.062	58	58

Underlined values differ by more than 2%.

It seems clear from this table that a particle size distribution curve drawn from the data usually reported in the silt and sand sizes is not reliable for extrapolating and interpolating all size fractions. Note for example the divergence in the <.002mm values. However, it is good to note too that the .062mm size is easily and with good accuracy available from this data. The intermediate size percentages never differed by more than 4 percent.

As a result of this study, it was decided to avoid use of the data which did not include the original particle size distribution curves. This was done to avoid possible misleading results of comparisons of silt sizes with physical properties because of the inaccuracy in the lower limit, .002mm, of the silt sizes.

In addition to the data from the Michigan State Highway Department, other data from the Federal Housing Agency (1961), with essentially the same properties given, were analyzed. The difference between the two sets of data was in mineralogy. Values reported from the Michigan State Highway Department were of mixed mineralogy. The 124 observations selected from the Federal Housing Agency data were high in kaolinite, a coarse platy clay mineral.

For the Federal Housing Administration data, simple correlation and regression analyses were calculated with only: <.002mm, <.005mm, <.074mm, liquid limit, plastic index and plastic limit.

B. AVAILABLE WATER AND PARTICLE SIZE LIMITS

Soil materials from various parts of Michigan representing several Great Soil Groups and ranging in texture from coarse sand to clay have been sampled by A. E. Erickson et al. The moisture holding capacities at .06, .33, 6 and 15 atmospheres tension were measured for each of the samples. Samples containing more than 1 percent organic matter or containing calcareous material were not considered in these analyses.

Particle size analyses were made on each sample using the pipette method. A particle size distribution curve had been plotted earlier by Dr. D. P. Franzmeier. From this particle size distribution curve, each of the various particle size fractions was available.

The objective of this part of the study was to determine the percentages of various silt size fractions and see which of them is best correlated with water holding capacities. As has been reviewed earlier, current thinking by several workers indicate that silt is the most significant particle size contributing to this property. Simple correlation, regression analysis and plotting of the data were the techniques used. In addition, hydraulic conductivity was also determined by Dr. A. E. Erickson et al. on these samples and these data were analyzed in the same manner as for the moisture holding capacities.

C. PARTICLE SIZE OF SILT FRACTION AND EFFECT ON HYDRAULIC CONDUCTIVITY AND CAPILLARY RISE

A Kibbie silt loam profile was selected to provide material for this experiment. It was located in the lake plain associated with the Erie lobe in Monroe County, Michigan. Only the B horizon was used so as to minimize the influence of organic matter and carbonates.

The material was dispersed according to the procedure outlined in Methods of Soil Analysis, Part 1 (Black et al. 1965). The material was placed in jugs and siphoned off at the prescribed depth and time according to Stokes' Law

to remove all material less than the lower limit of the particular fraction. The material was then wet sieved to remove the material coarser than the selected upper limit.

The size limits selected and the resulting size fractions included were the following:

.002-.105mm
.002-.050mm
.010-.105mm
.010-.050mm
.020-.0625mm

After sieving, the material was dried and thoroughly mixed before proceeding to the study of these size fractions.

1. Hydraulic Conductivity

To determine the hydraulic conductivity of the various fractions, metal cylinders 3 inches in height and diameter were filled with the various fractions. The bottom end of the cylinder was covered with four layers of cheesecloth. The cylinders were then filled with the various fractions and then gently tapped 10 times on the table from a height of 1/2 to 1/4 inch. This lowered the level of material in the cylinder and it was filled again to the top and tapped 10 times as before. A small amount was then added to compensate for the slight lowering of the material in the cylinder, and it was placed in a pan of water to saturate overnight. The fractions with .002mm as the lower limit packed down more than the others when dry.

The saturated samples prepared in duplicate were placed under 1cm constant head and the volume of water going through each was measured over a one-hour period. The rate of this movement calculated in cm/hour or inches/hour was considered the hydraulic conductivity.

2. Capillary Rise

Plastic tubes with 5/8 inch inside diameter and 6 feet in length were covered at the bottom with No. 1 filter paper and held in place by a double layer of cheesecloth. Twelve tubes were filled to the top with the six size fractions.-- .002-.050mm, .010-.050mm, .020-.062mm, .002-.105mm, .010-.105mm and .020-.105mm. The tubes were then tamped by tapping on the floor 10 times from a height of 5cm.

The tubes were then placed in a pan of water, the level of which was held constant by a Mariotte bottle. Readings of the capillary rise in the tubes were made at 15, 30 and 45 minutes and 1, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 16, 20, 24, 28, 36 and 48 hours. The experiment was run in a constant temperature room at 21 $\pm 2^{\circ}$C and 35-40% relative humidity.

IV. RESULTS AND DISCUSSION

A. ENGINEERING PROPERTIES OF SOIL MATERIALS AND SILT PARTICLE SIZE LIMITS

Correlations of various particle size limits and physical properties resulted in the correlation coefficients cited in the following table.

Table 1 -- Correlation coefficients of the relation between various particle size limits and physical properties.

Size Limit	Fed. Housing Adm.		Michigan State Highway Dept.			
	Kaolinitic Clays		Mixed and Illitic Clays			
	Liquid Limit	Plasticity Index	Liquid Limit	Plasticity Index	Shrinkage	
					Limit	Ratio
<.002mm	.78	.79	.92	.95	.57	-.61
<.005mm	.79	.81	.91	.94	.60	-.63
<.010mm			.87	.90	.60	-.63
<.020mm			.81	.83	.57	-.59
<.050mm			.76	.76	.52	-.54
<.062mm			.74	.74	.51	-.53
<.074mm	.70	.72	.73	.73	.51	-.53
<.105mm			.72	.72	.43	-.44
.002-.020mm			.11	.07	.19	-.17
.020-.050mm			-.51	-.56	-.26	.28
.050-.105mm			-.66	-.72	-.45	.46

1. Liquid Limit and Plasticity Index

There is a close relationship as might be expected between the liquid limit and plasticity index and the <.002mm and <.005mm content. It is from the clay fraction that most plastic properties of soil materials are derived. It also seems reasonable that the coarser silt fractions should have a negative correlation because they do not contribute to the plastic properties, and larger amounts in this fraction decrease the amount that is in the clay fraction. This is observed in several of the correlations of size fraction and physical properties.

The relation of the liquid limit to the plasticity index in the material studied from the Michigan State Highway Department is expressed in this equation:

$$\text{plasticity index} = .77\ \text{liquid limit} - 8.24$$

This relation is in agreement with that cited by Casagrande (1947). Using this relationship and the equation found relating clay content to the liquid limit in these samples--

$$\frac{\text{liquid limit} - 6.21}{.77} = \text{clay (Fig. 1)}$$

and that relating clay content to the plasticity index--

$$\frac{\text{plasticity index} + 3.92}{.54} = \text{clay (Fig. 2)}$$

it was found that the separation between CH and CL groups in the Unified Soil Classification should occur at 56.9% clay. Wang (1967) has suggested 50% clay as a separation and Rieger et al. has suggested 43% clay as a separation

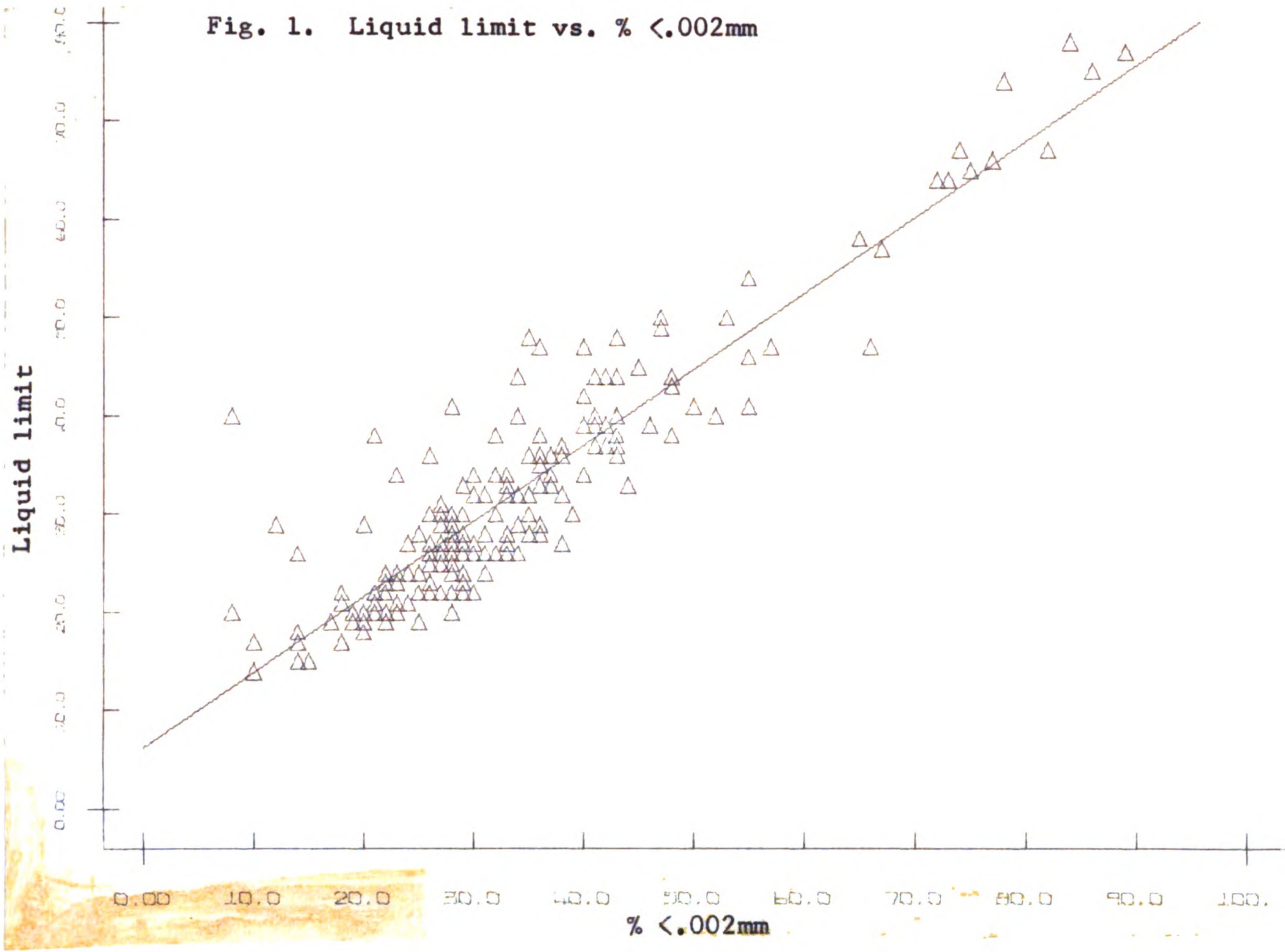


Fig. 1. Liquid limit vs. % <.002mm

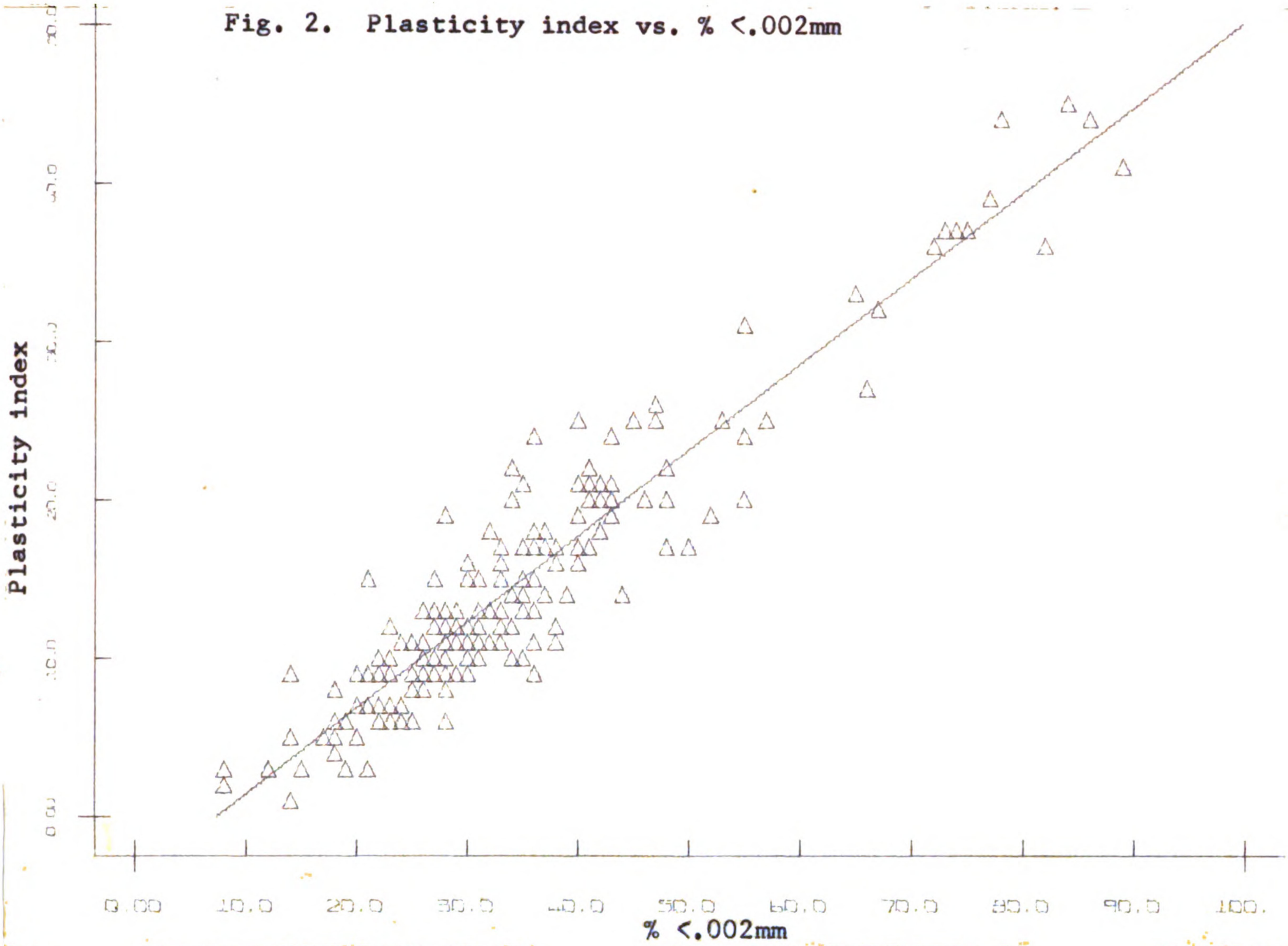


Fig. 2. Plasticity index vs. % <.002mm

between CH and CL groups.

Calculations were also made of the relationships of some properties with the size fractions of some soil series known to be high in kaolinitic clays. These data have been published by the Federal Housing Administration (1961). The correlation coefficients of the clay size fractions with the liquid limit or the plasticity index are somewhat lower on these kaolinitic samples than in the Michigan State Highway Department data for soils of mixed or illitic mineralogy. The correlation coefficients are slightly higher with the <.005mm than with the <.002mm fraction on the kaolinitic soils, and the reverse was true for the mixed and illitic soils.

2. Shrinkage Limit and Shrinkage Ratio

Shrinkage limit and shrinkage ratio were not found to be highly related to any particular fraction. Some higher correlation coefficients were calculated than those cited, but these were a result of a poor distribution of data and were not concluded to be part of a general relationship. Clay has been cited as a major factor affecting these properties (MSHD 1960), and <.005mm and <.010mm are where the best correlations are found. These are still not highly related. Perhaps other factors not studied also affect the shrinkage properties. See Figs. 3 and 4.

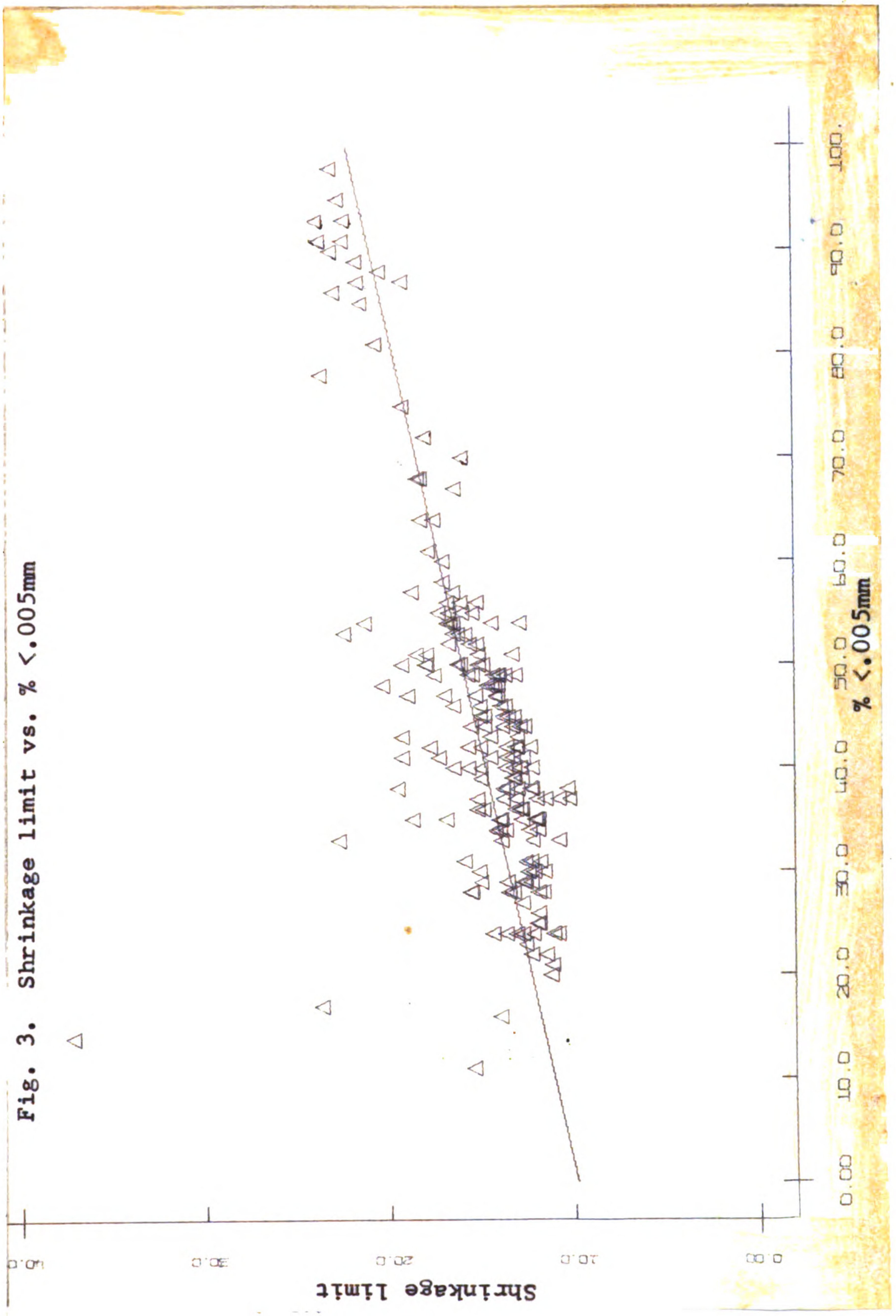


Fig. 3. Shrinkage limit vs. % <.005mm

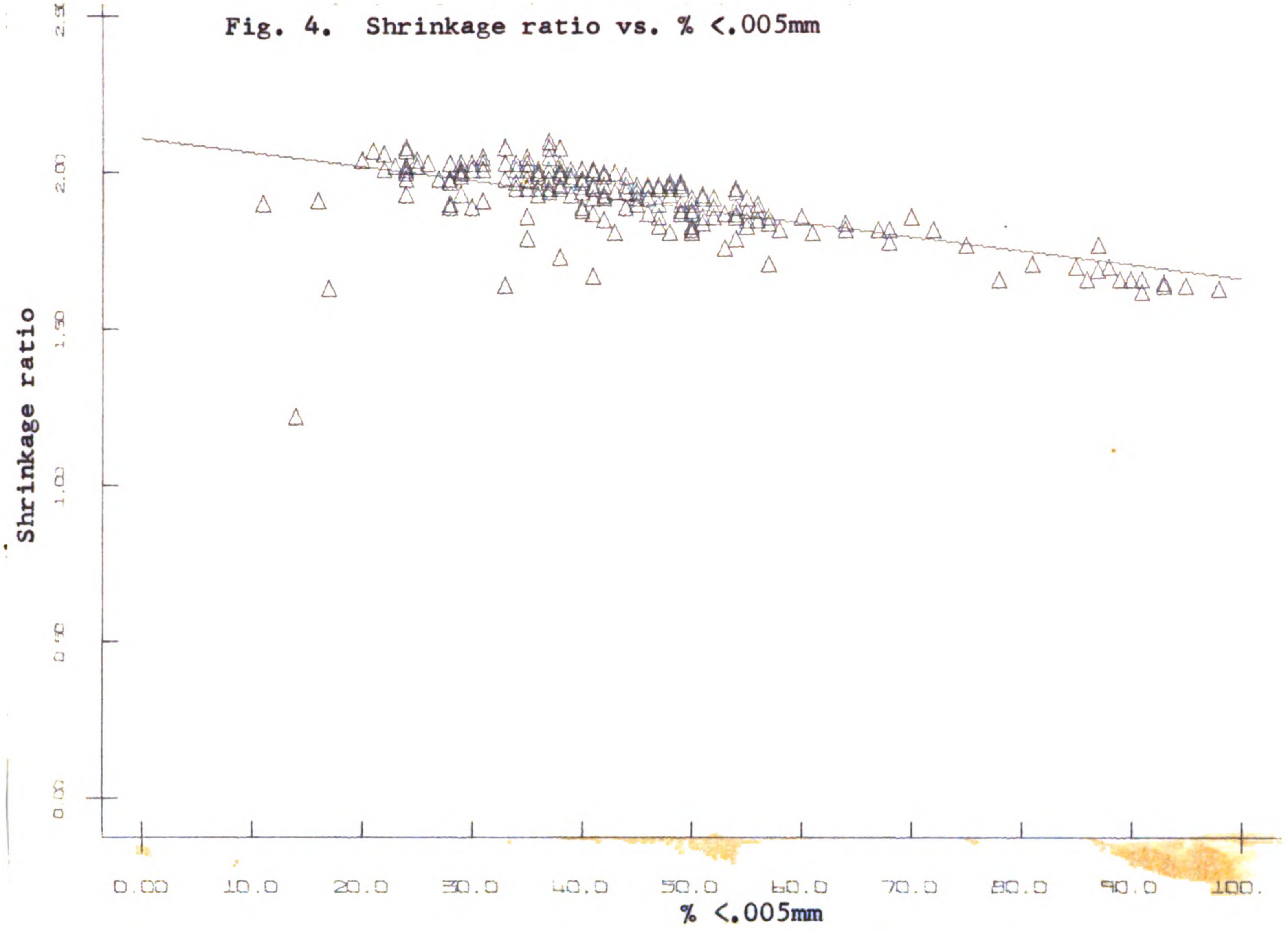


Fig. 4. Shrinkage ratio vs. % <.005mm

Table 2 -- Correlation coefficients of the relation between various particle size limits and physical properties.

Michigan State Highway Department

Mixed and Illitic Clays

Size Limit	Natural Density	Dry Density	Maximum Density	Optimum Moisture	Shear Stress	½ Compressive Strength
<.002mm	.86	-.84	-.43	.66	-.51	-.69
<.005mm	.85	-.89	-.43	.67	-.57	-.74
<.010mm	.79	-.90	-.41	.66	-.63	-.78
<.020mm	.69	-.88	-.38	.65	-.67	-.79
<.050mm	.61	-.86	-.33	.62	-.67	-.74
<.062mm	.60	-.87	-.32	.61	-.68	-.74
<.074mm	.59	-.89	-.31	.60	-.68	-.74
<.105mm	.67	-.86	-.34	.61	-.24	-.04
.002-.020mm	.05	.10	-.26	.50	-.15	.06
.020-.050mm	-.64	.70	.25	-.12	.47	.68
.050-.105mm	-.62	.41	.22	-.48	.28	.46

3. Natural Density and Dry Density

Natural density is highly related with the finest fractions because of their total moisture holding properties and their effect on the natural density. The negative correlation in the coarser fractions is probably due to their reduction of total moisture holding properties. Dry density is negatively related to the fine fractions and positively related to the coarser fractions. This is probably due to a reversal of the moisture relation cited above. The uniformly high correlation for the fractions less than a given size seems to depend on the lack of variation in the measured dry density. See Fig. 5.

4. Optimum Moisture and Maximum Density

The optimum moisture is not highly correlated with the size limits examined in this study. It seems to be slightly better correlated with the finer fractions considered here. Maximum density which is measured at the same time seems to be even less related to particle size than is the optimum moisture. See Figs. 6, 7 and 8.

5. Shear Stress and ½ Compressive Strength

Fewer observations were available for shear stress and ½ compressive strength. These correlation coefficients were not high in either case, but the relationship which does exist seems to be reasonable. Shear stress is related to friction between particles and cohesion, according to the Asphalt Institute (1963). This in turn is related to the moisture content at which the soil was sampled and its relation to optimum moisture. These samples drier than optimum moisture have greater shear stress than those wetter than optimum moisture. Unfortunately, no correlation between optimum moisture and shear stress was found because no observations were made of these properties on the same sample.

The ½ compressive strength is related to the depth from which the sample was taken and the mode of deposition (Asphalt Institute 1963). It appears that to some extent particle

Fig. 5. Dry density vs. % <.005mm

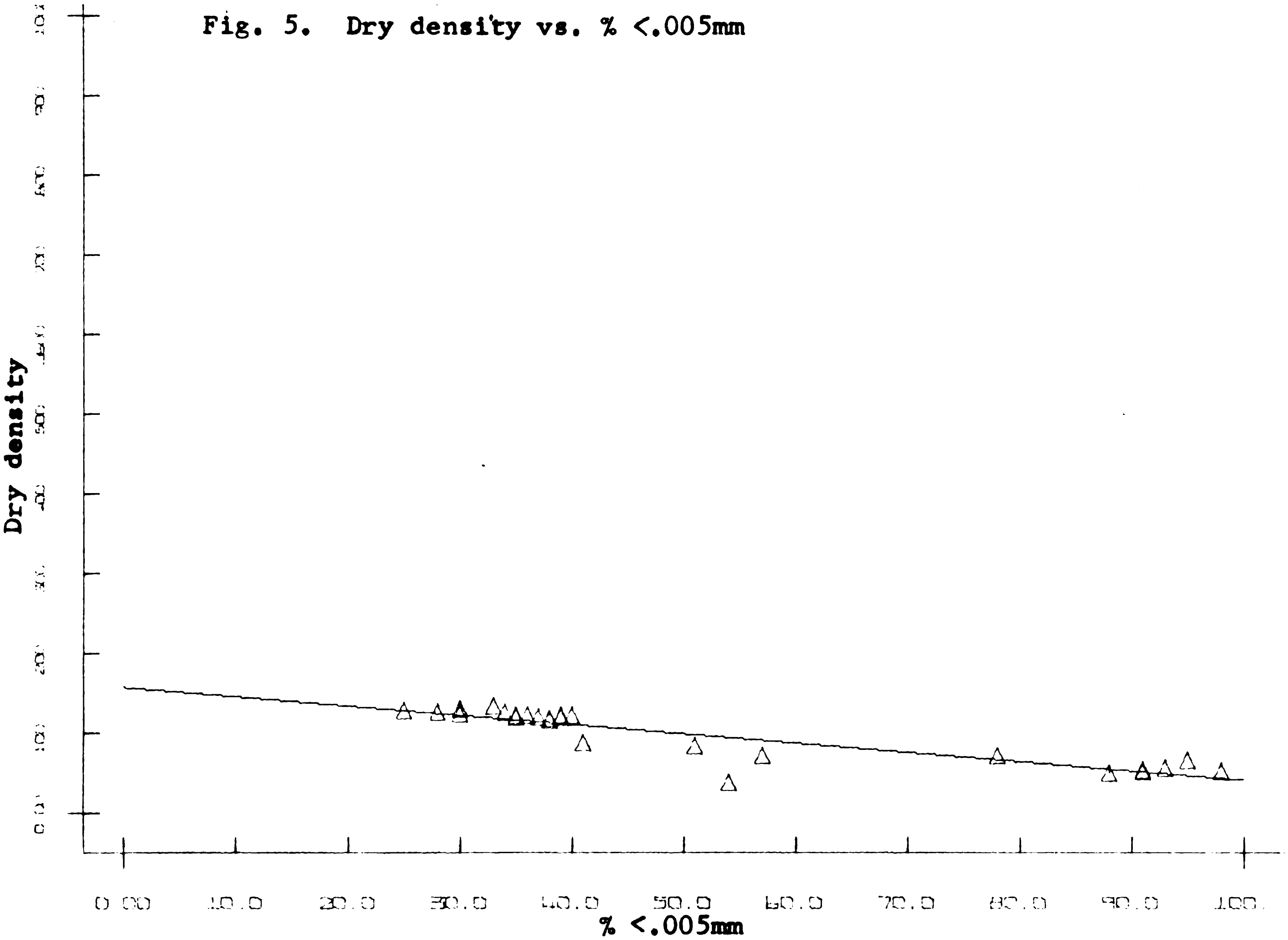


Fig. 6. Optimum moisture vs. % <.005mm

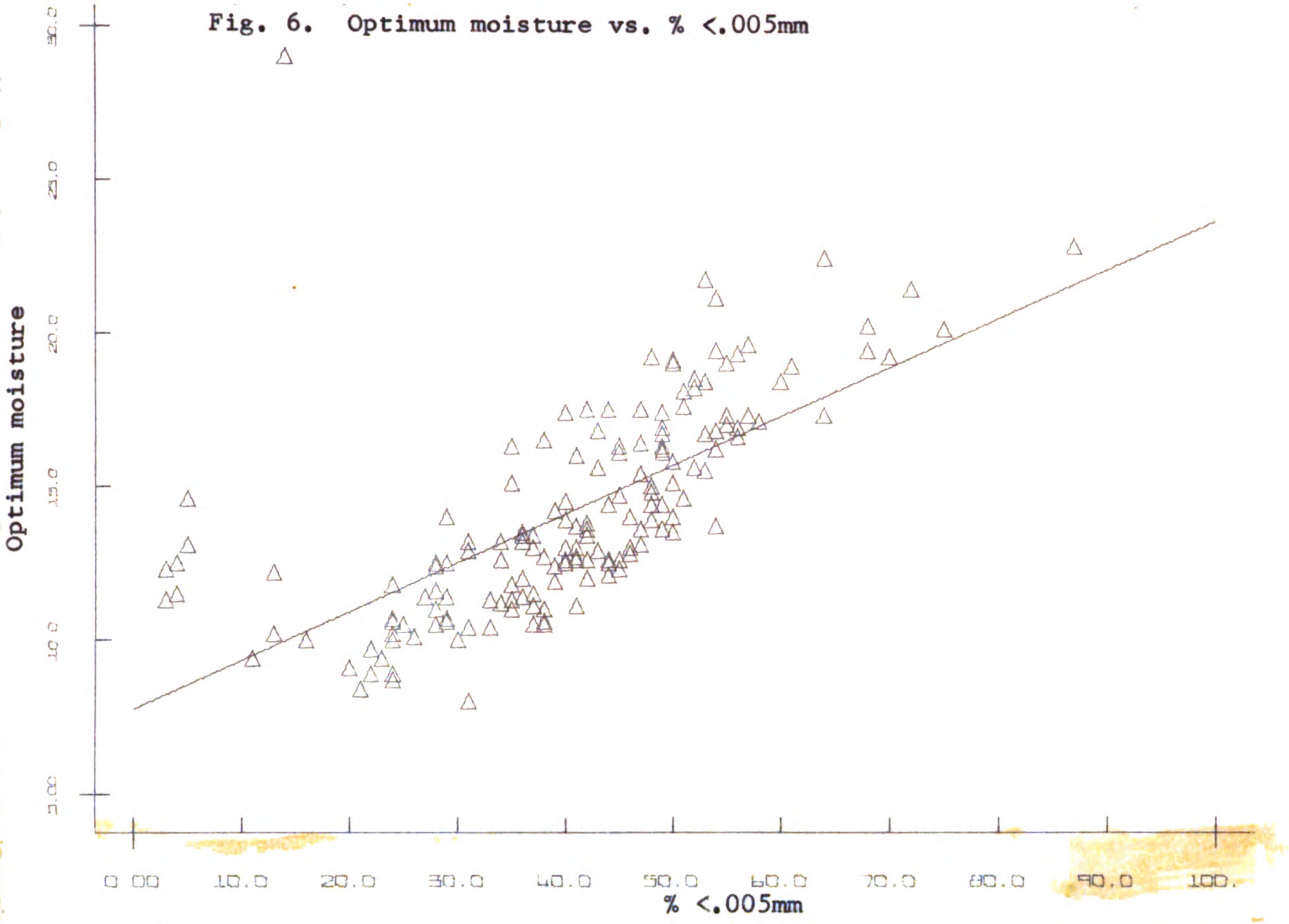


Fig. 7. Optimum moisture vs. % .020-.002mm

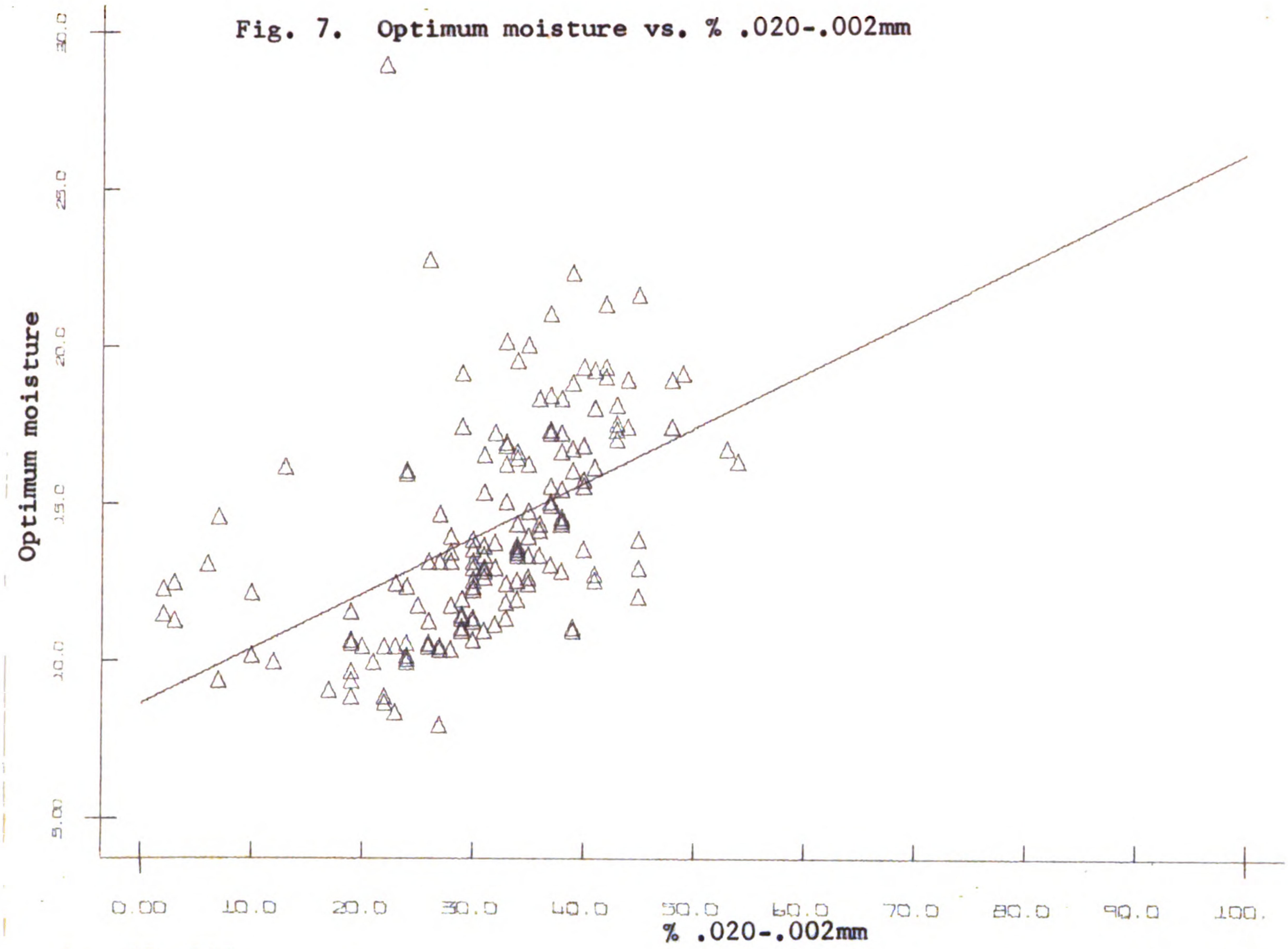
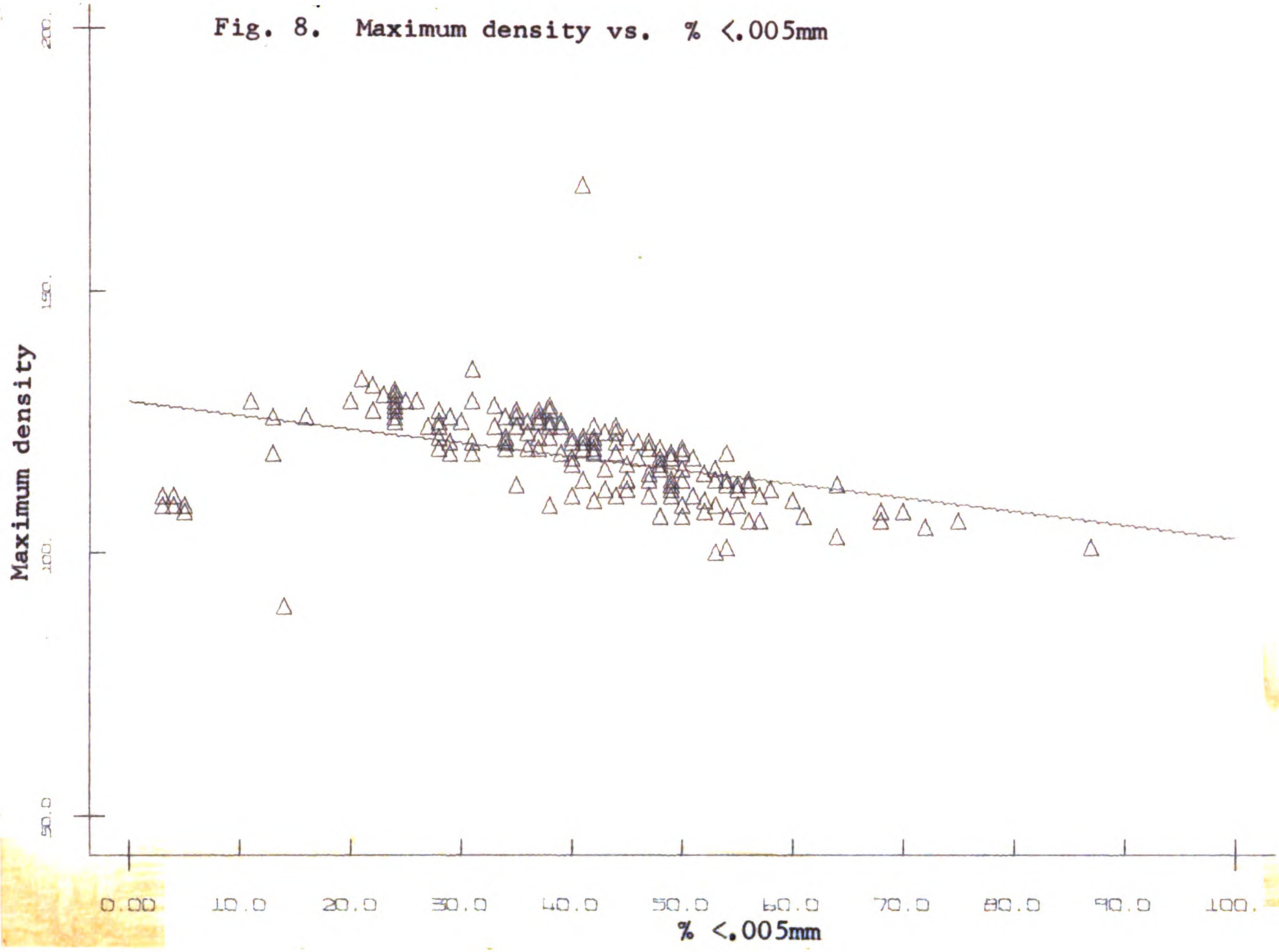


Fig. 8. Maximum density vs. % <.005mm



size may affect the mode of deposition and as a result be related to ½ compressive strength to some extent. For both shear stress and ½ compressive strength, the correlation drops off drastically between <.074mm and <.105mm. The reason for this was not clear. See Figs. 9 and 10.

6. Relation Between Particle Size Limits

For this same set of data, correlation coefficients were calculated for the relation between various particle size limits and other size limits. The results are shown in the following table.

Table 3 -- Correlation coefficients and equations relating various size groupings.

Size Limit	Correlation Coefficient	Equation
<.005mm vs. <.002mm	.97	Y = 1.14X + 6.37
.002-.105mm vs. .002-.050mm	.89	Y = .76X + 17.44
.002-.062mm vs. .002-.050mm	.99	Y = .99X + 2.47
.002-.105mm vs. .005-.074mm	.92	Y = .95X + 16.02
.002-.062mm vs. .005-.074mm	.90	Y = 1.07X + 6.77

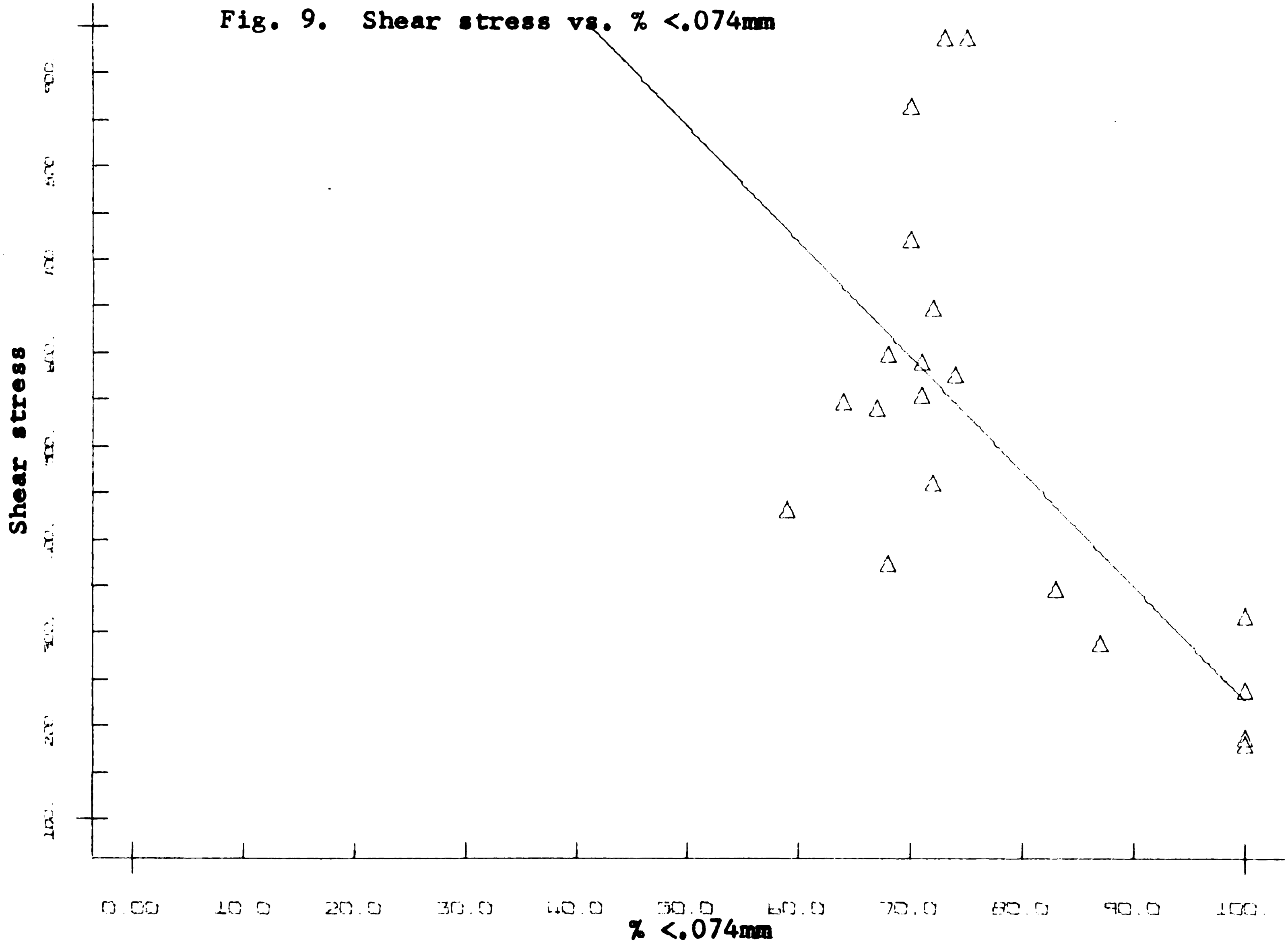


Fig. 9. Shear stress vs. % <.074mm

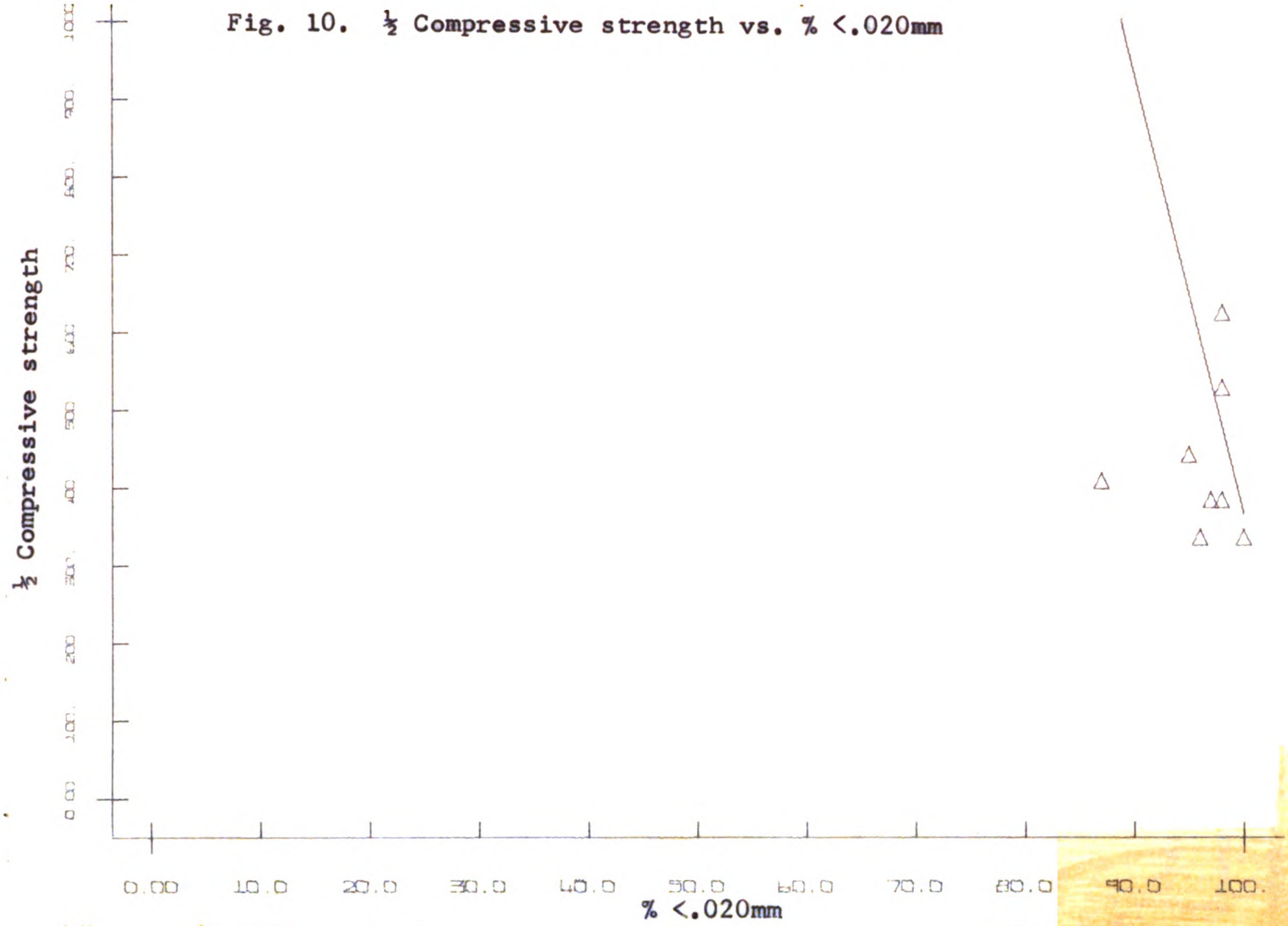


Fig. 10. ½ Compressive strength vs. % <.020mm

The results of three of these relationships are shown graphically in Figs. 11, 12 and 13. These would enable us to predict the amount of material expected in a given size if the amount of another size and the relationship between them is known. Good examples of this that may be useful to soil scientists, geologists and engineers are the relationships cited in Table 3 based on data from the Michigan State Highway Department. The <.002mm vs. <.005mm percentage relationships for the Kaolinitic materials cited by the Federal Housing Administration showed a correlation coefficient of .98 compared to .97 for the Michigan State Highway Department data in Table 3. This indicates a close relation which could be used to transfer data on one clay size into terms of the other clay size limit with the regression equation.

B. AVAILABLE WATER AND SILT PARTICLE SIZE LIMITS

The results of the statistical calculations presented in Tables 4, 5 and 6 and Figs. 14-23 show that a relationship does exist between silt content and available water content. This relation is shown in nearly all cases by the relatively large, >.70, correlation coefficients, and the validity of these relationships is borne out by graphs of available water vs. silt content for various definitions of available water and the various silt size fractions found in these undisturbed, naturally occurring soil materials.

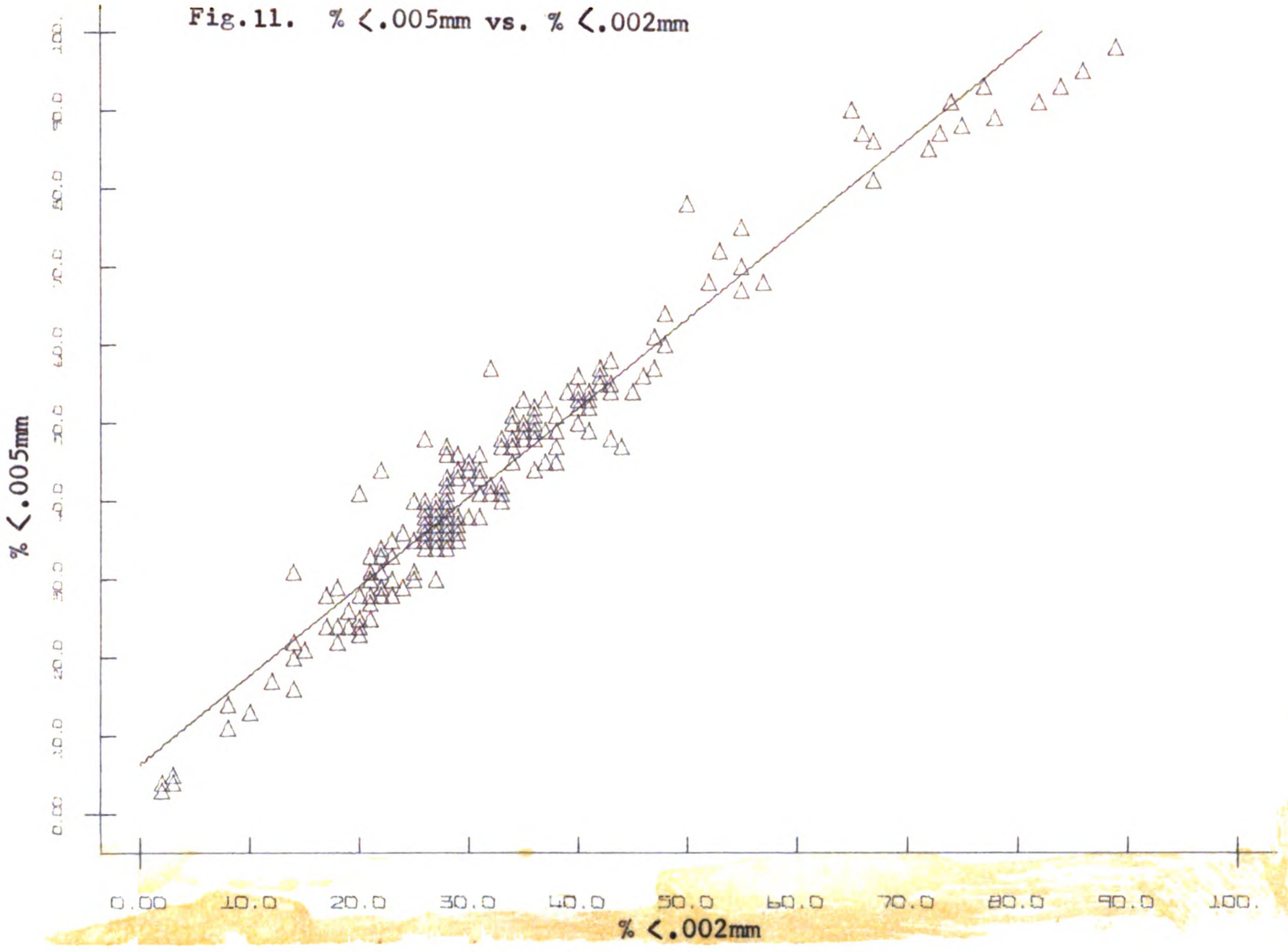


Fig.11. % <.005mm vs. % <.002mm

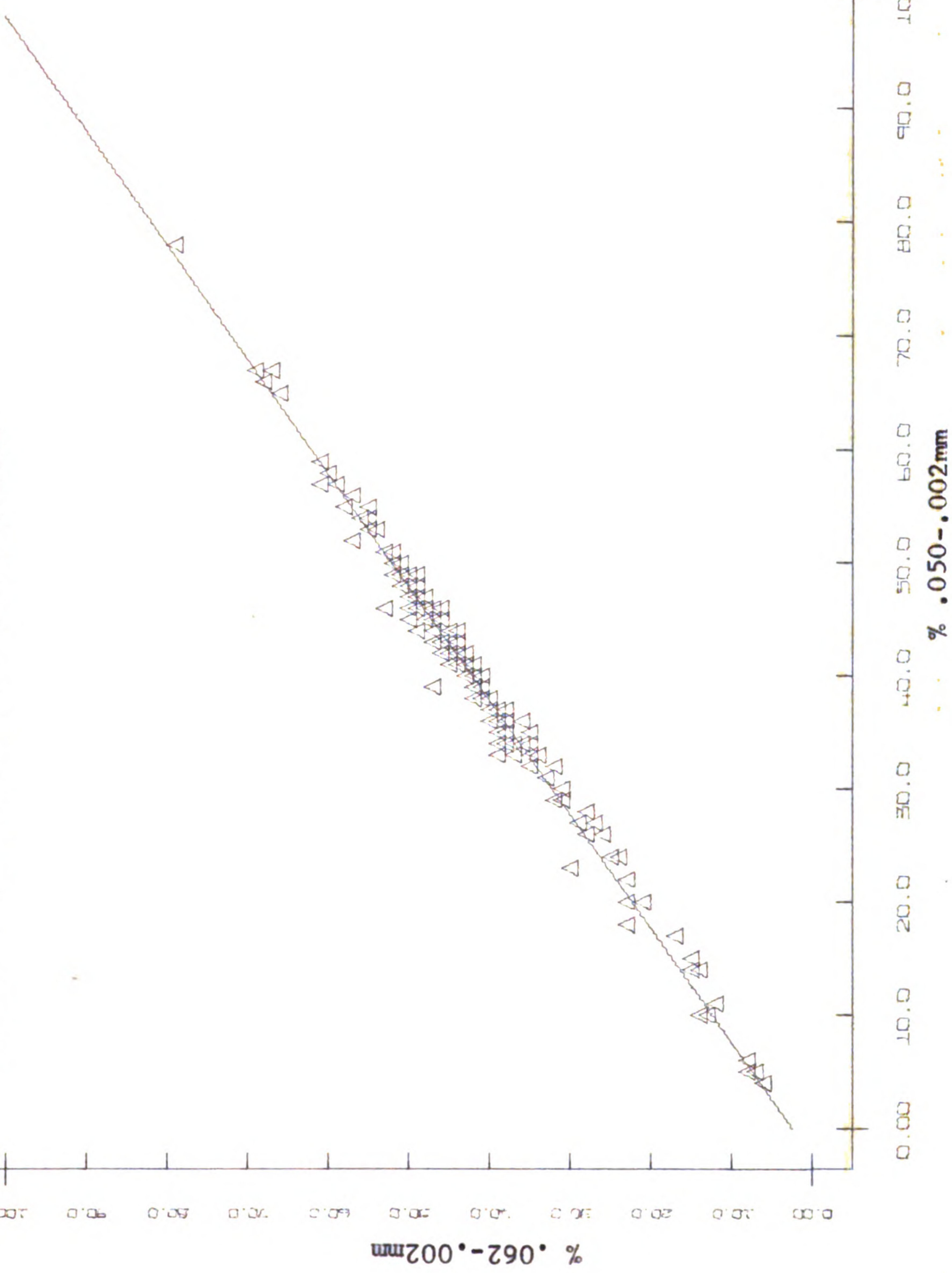


Fig. 12. % .062-.002mm vs. % .050-.002mm

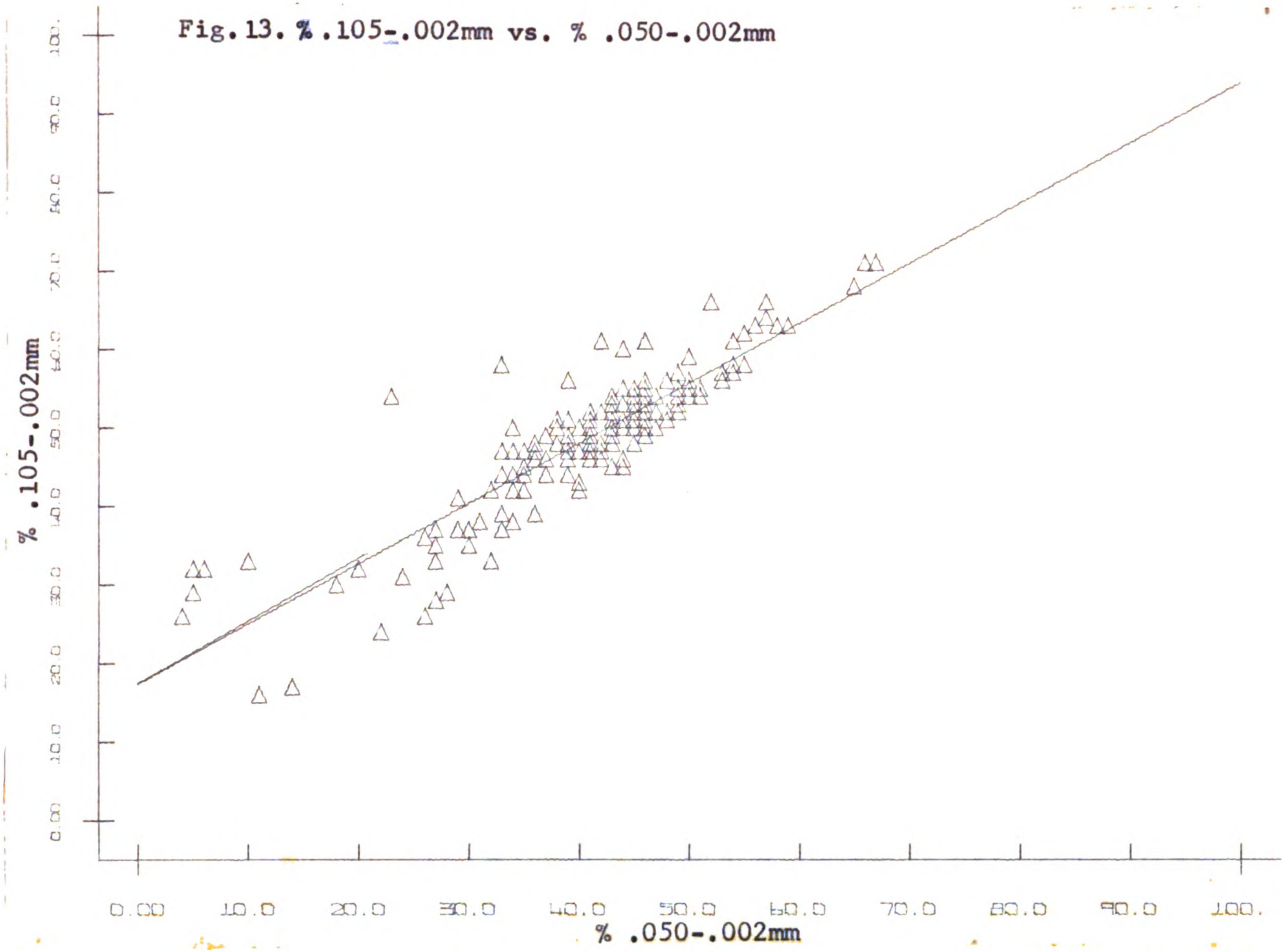


Fig. 13. % .105-.002mm vs. % .050-.002mm

Table 4 -- Correlation of particle size ranges and water released between .06 and 6 atmospheres tension.

Size Range	Correlation Coefficient	Equation*
.125-.020mm	.751	Y = 4.08 + .193X
.125-.010mm	.712	Y = 3.70 + .178X
.125-.002mm	.606	Y = 3.75 + .140X
.100-.020mm	.745	Y = 4.84 + .204X
.100-.010mm	.699	Y = 4.53 + .180X
.100-.002mm	.579	Y = 4.60 + .134X
.074-.020mm	.708	Y = 5.38 + .216X
.074-.010mm	.654	Y = 5.03 + .187X
.074-.002mm	.517	Y = 5.25 + .130X
.050-.020mm	.537	Y = 6.14 + .228X
.050-.010mm	.421	Y = 6.40 + .180X
.050-.002mm	.245	Y = 7.24 + .078X
.020-.002mm	-.123	Y = 9.72 - .064X

* X = % of fraction in size range quoted and Y = % available or readily available water holding capacity.

Table 5 -- Correlation of particle size ranges and water released between .06 and 15 atmospheres tension.

Size Range	Correlation Coefficient	Equation*
.125-.020mm	.760	Y = 5.78 + .190X
.125-.010mm	.755	Y = 5.22 + .182X
.125-.002mm	.711	Y = 4.71 + .158X
.100-.020mm	.777	Y = 6.45 + .204X
.100-.010mm	.756	Y = 5.98 + .187X
.100-.002mm	.696	Y = 5.56 + .155X
.074-.020mm	.737	Y = 7.00 + .216X
.074-.010mm	.714	Y = 6.47 + .196X
.074-.002mm	.640	Y = 6.17 + .154X
.050-.020mm	.587	Y = 7.62 + .302X
.050-.010mm	.507	Y = 7.63 + .208X
.050-.002mm	.398	Y = 7.90 + .122X
.020-.002mm	.078	Y = 10.1 + .039X

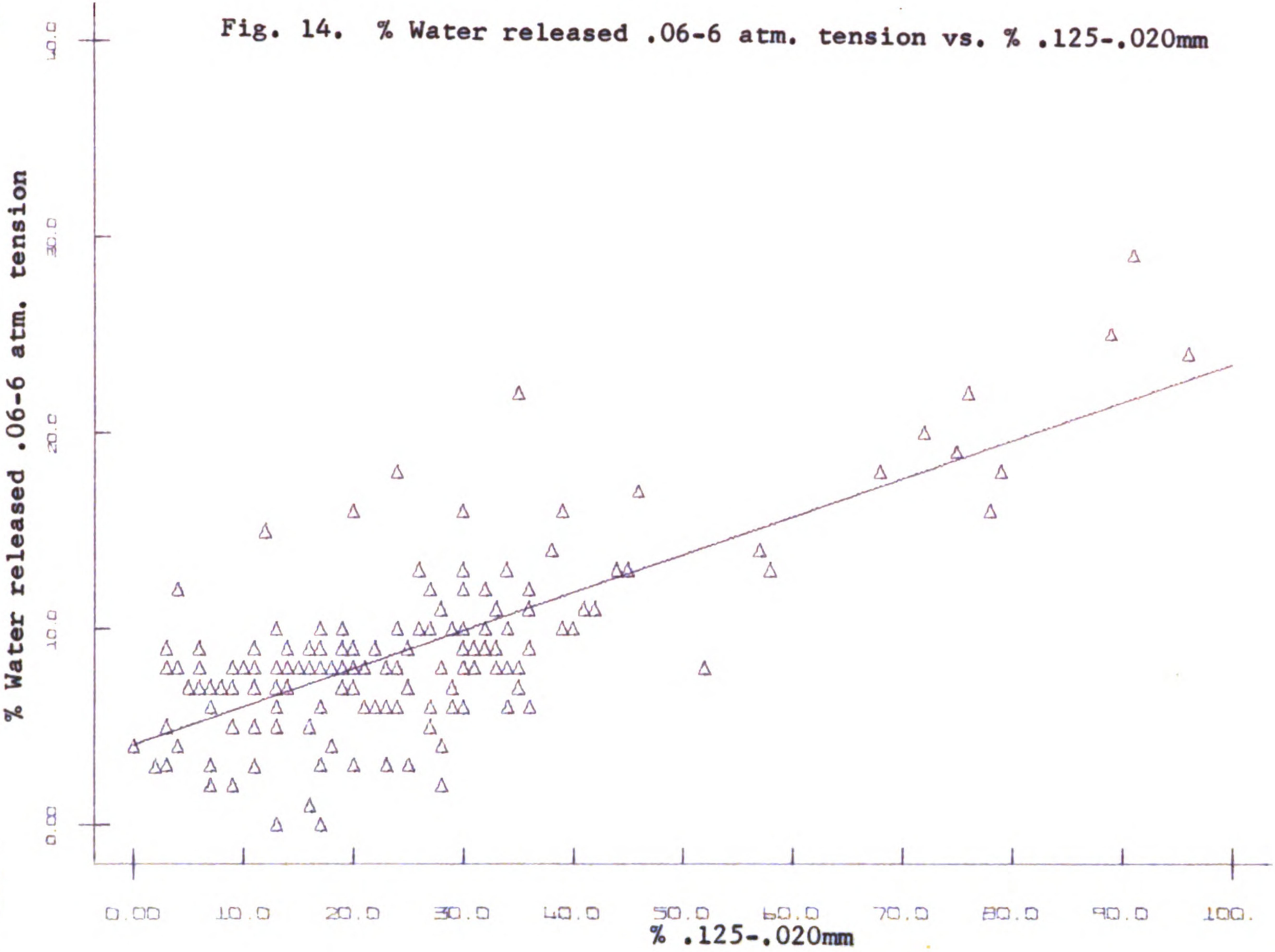
* X = % of fraction in size range quoted and Y = % available or readily available water holding capacity.

Table 6 -- Correlation of particle size ranges and water released between .33 and 15 atmospheres tension.

Size Range	Correlation Coefficient	Equation*
.125-.020mm	.688	Y = 4.30 + .159X
.125-.010mm	.712	Y = 3.58 + .161X
.125-.002mm	.726	Y = 2.70 + .151X
.100-.020mm	.725	Y = 4.71 + .178X
.100-.010mm	.741	Y = 4.09 + .172X
.100-.002mm	.737	Y = 3.35 + .154X
.074-.020mm	.710	Y = 5.09 + .195X
.074-.010mm	.726	Y = 4.40 + .187X
.074-.002mm	.709	Y = 3.74 + .160X
.050-.020mm	.642	Y = 5.29 + .310X
.050-.010mm	.606	Y = 5.01 + .234X
.050-.002mm	.549	Y = 4.86 + .158X
.020-.002mm	.270	Y = 6.78 + .127X

* X = % of fraction in size range quoted and Y = % available or readily available water holding capacity.

Fig. 14. % Water released .06-6 atm. tension vs. % .125-.020mm



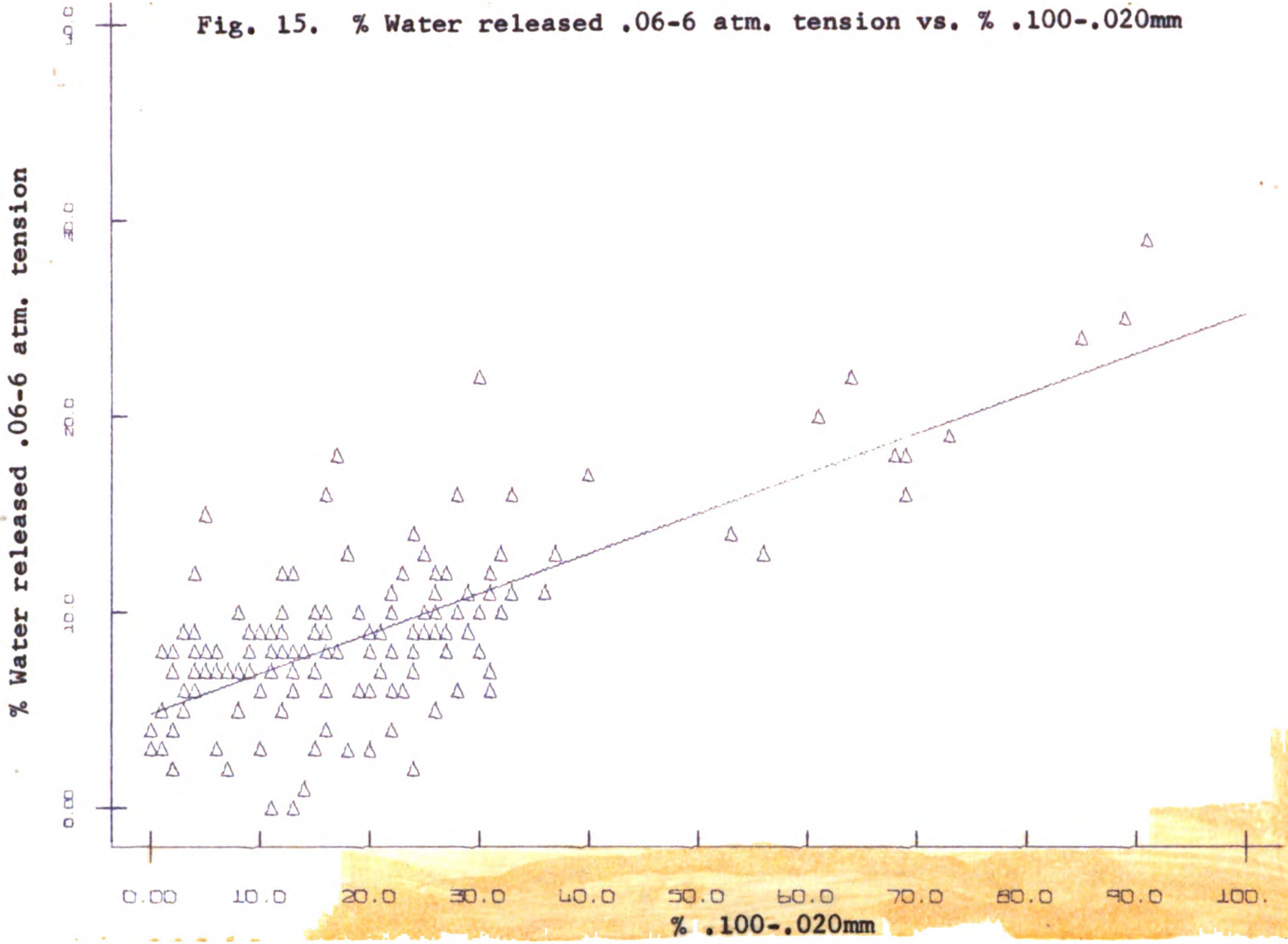
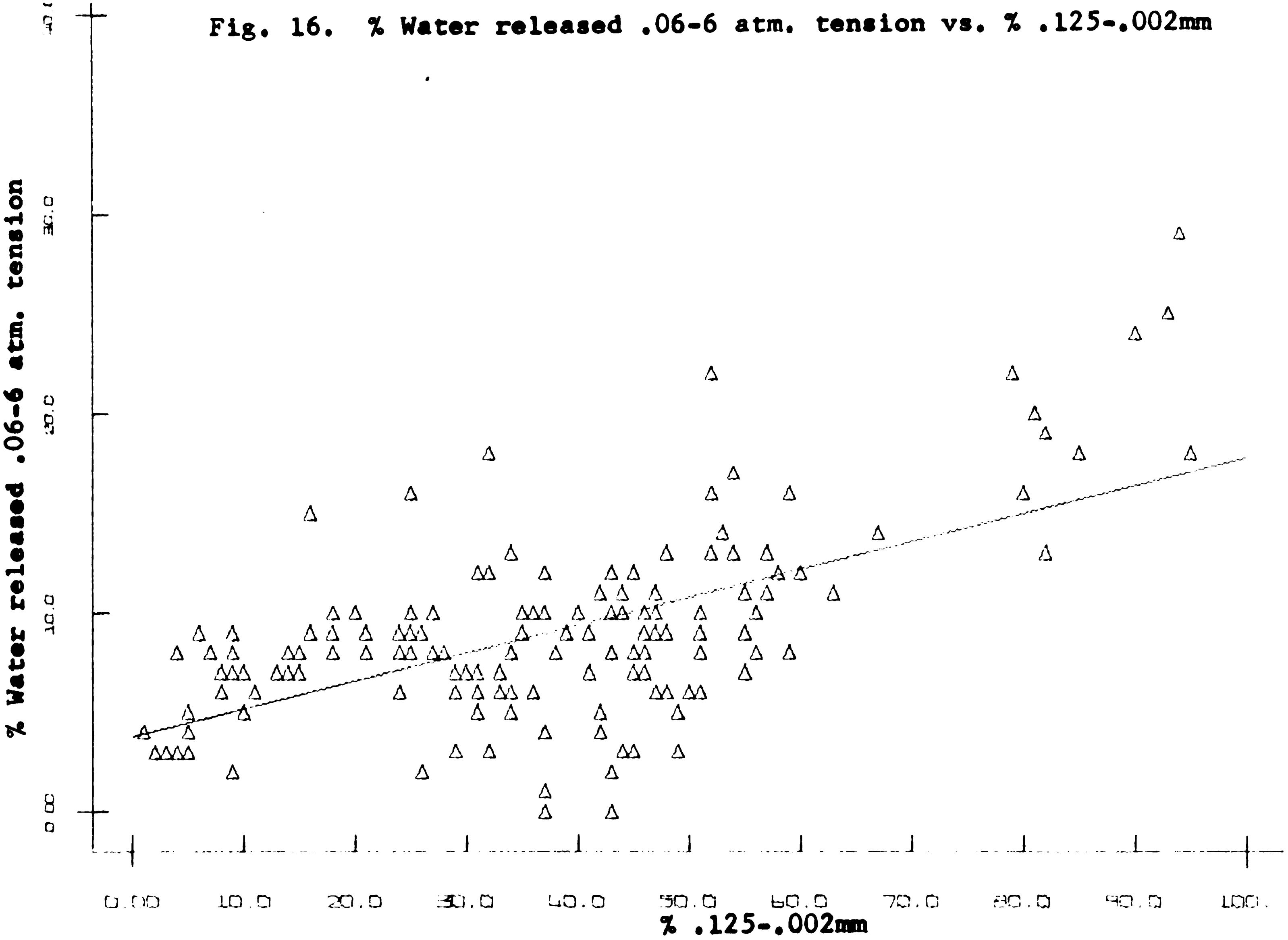


Fig. 15. % Water released .06-6 atm. tension vs. % .100-.020mm

Fig. 16. % Water released .06-6 atm. tension vs. % .125-.002mm



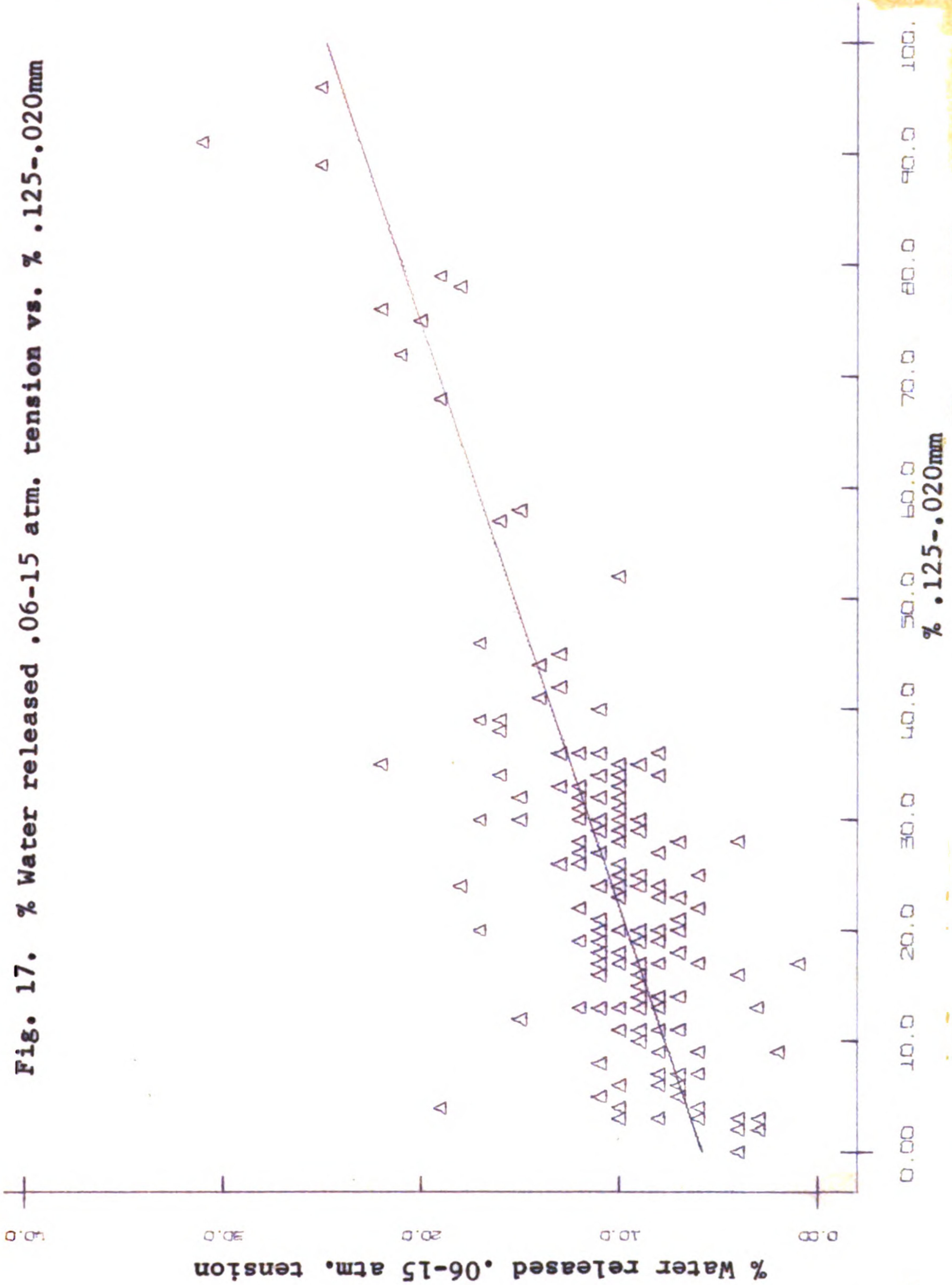
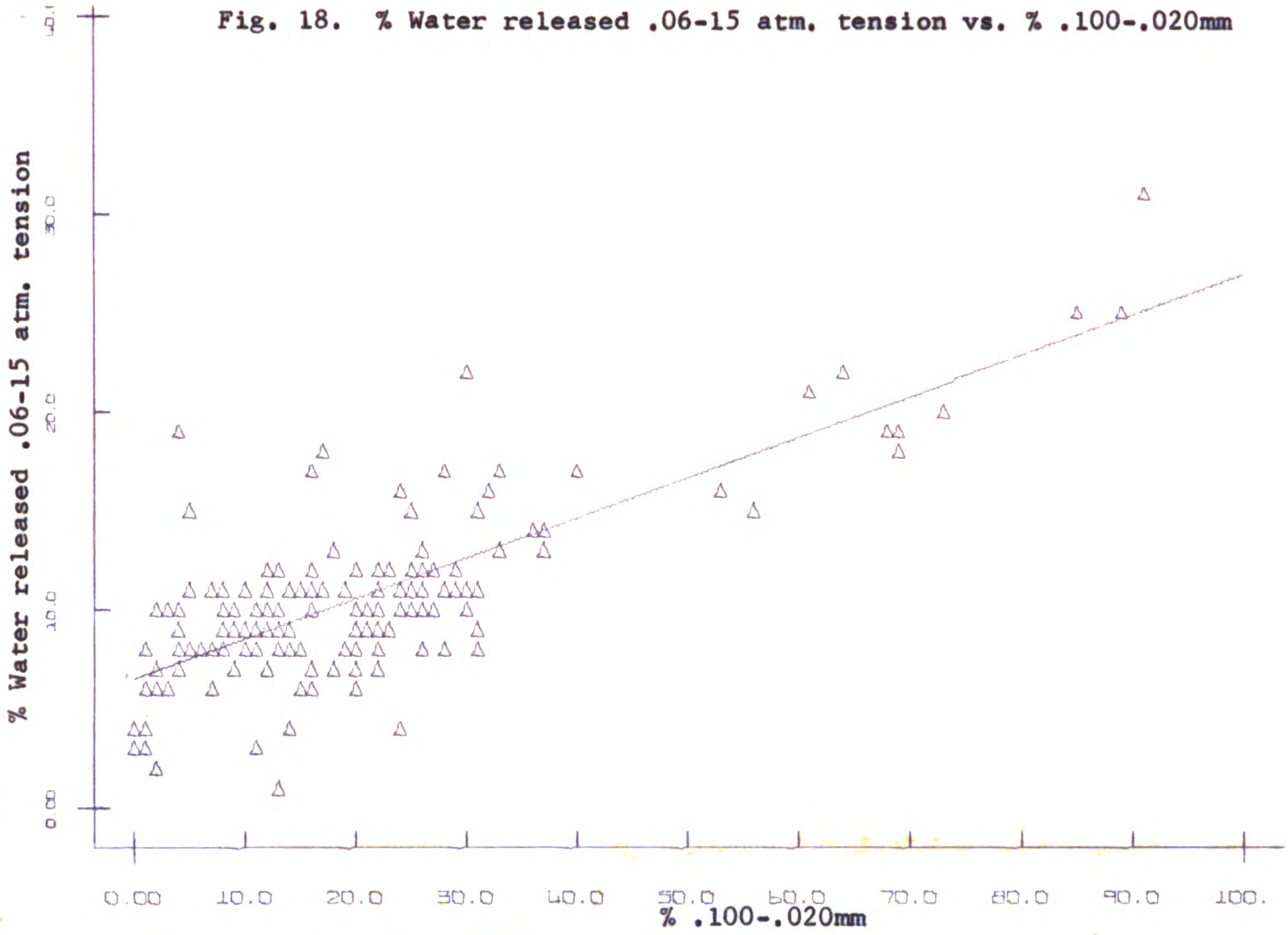


Fig. 17. % Water released .06-15 atm. tension vs. % .125-.020mm

Fig. 18. % Water released .06-15 atm. tension vs. % .100-.020mm



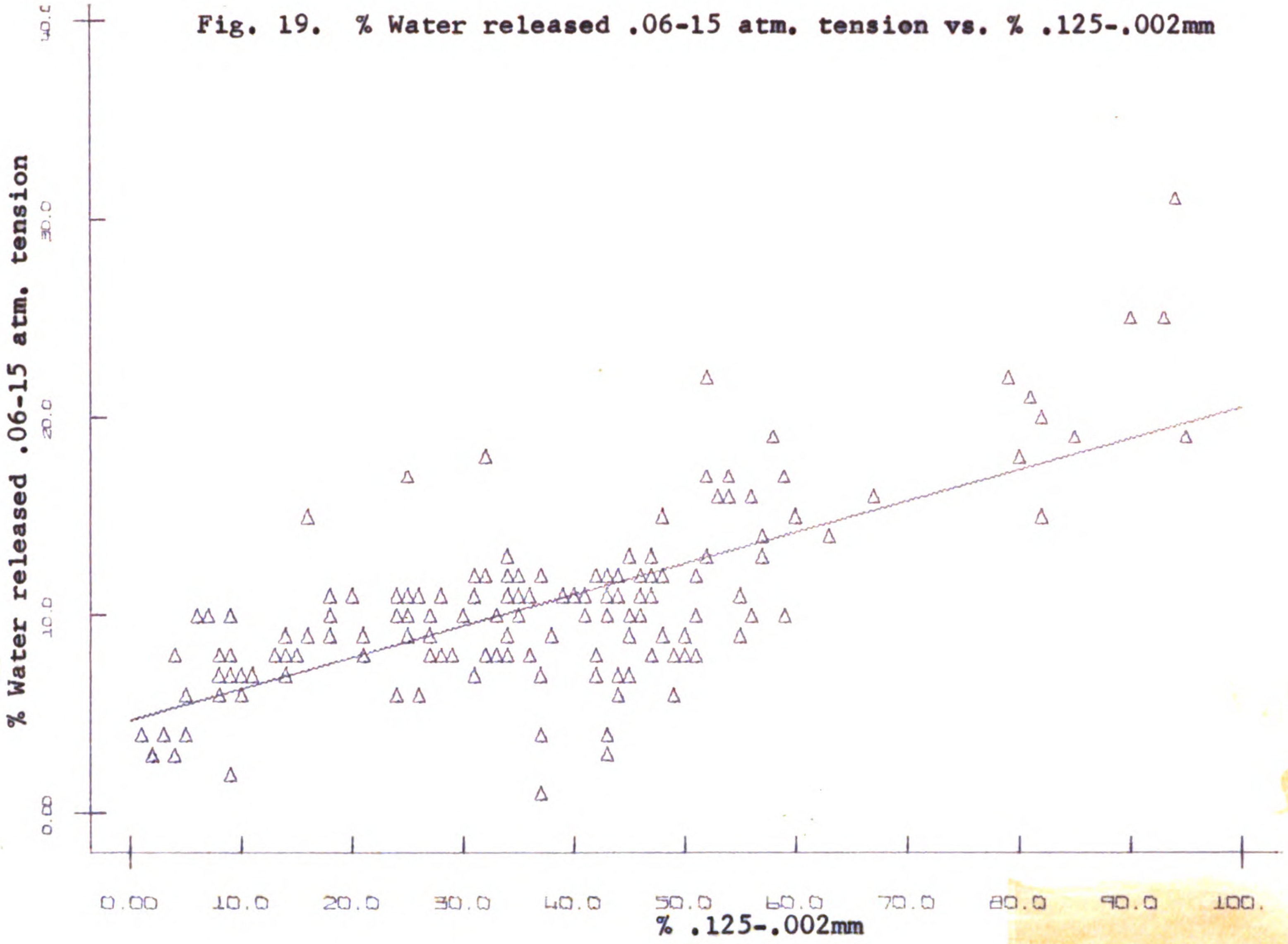


Fig. 19. % Water released .06-15 atm. tension vs. % .125-.002mm

Fig. 20. % Water released .33-15 atm. tension vs. % .020-.002mm

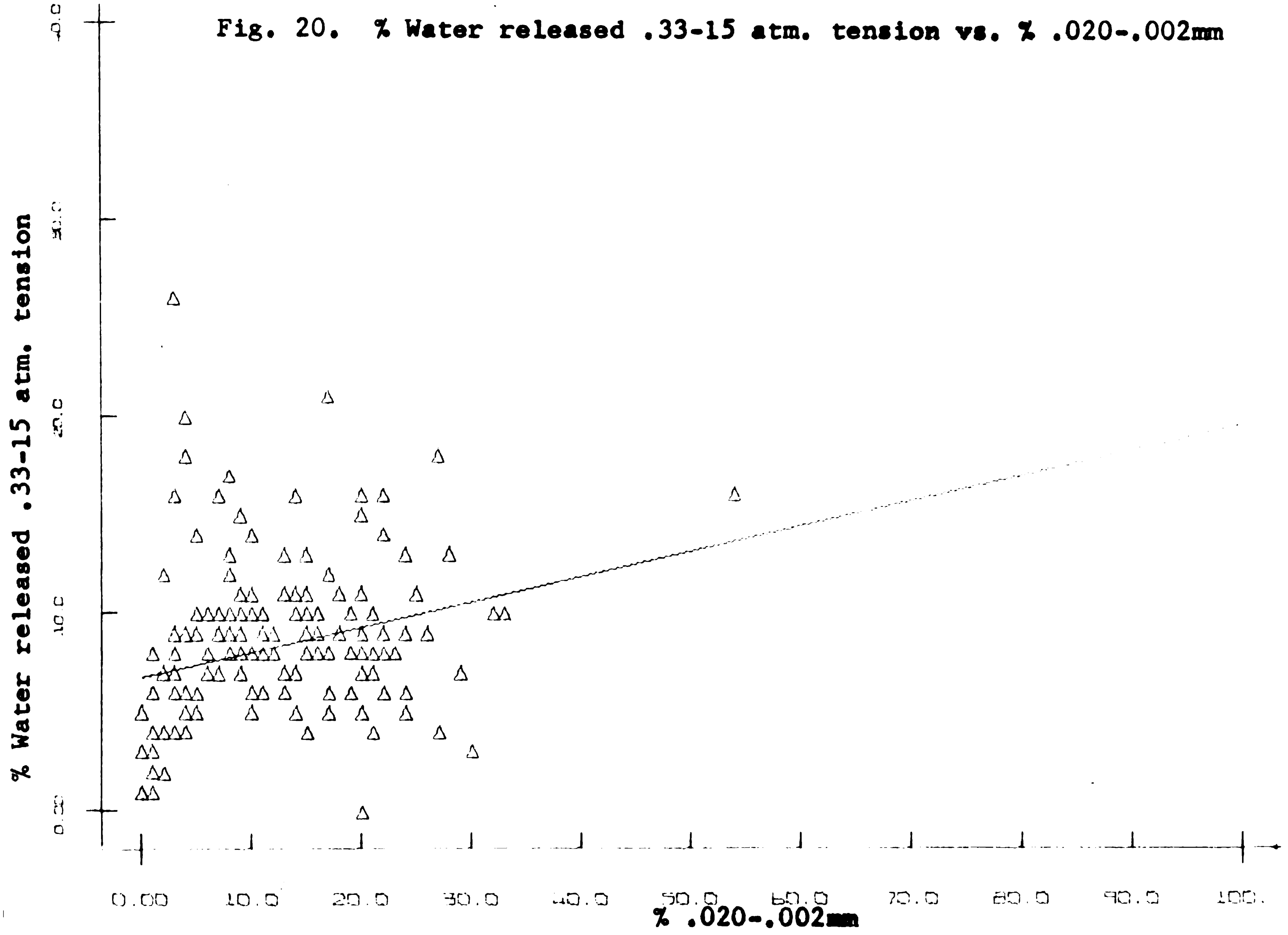


Fig. 21. % Water released .33-15 atm. tension vs. % .050-.002mm

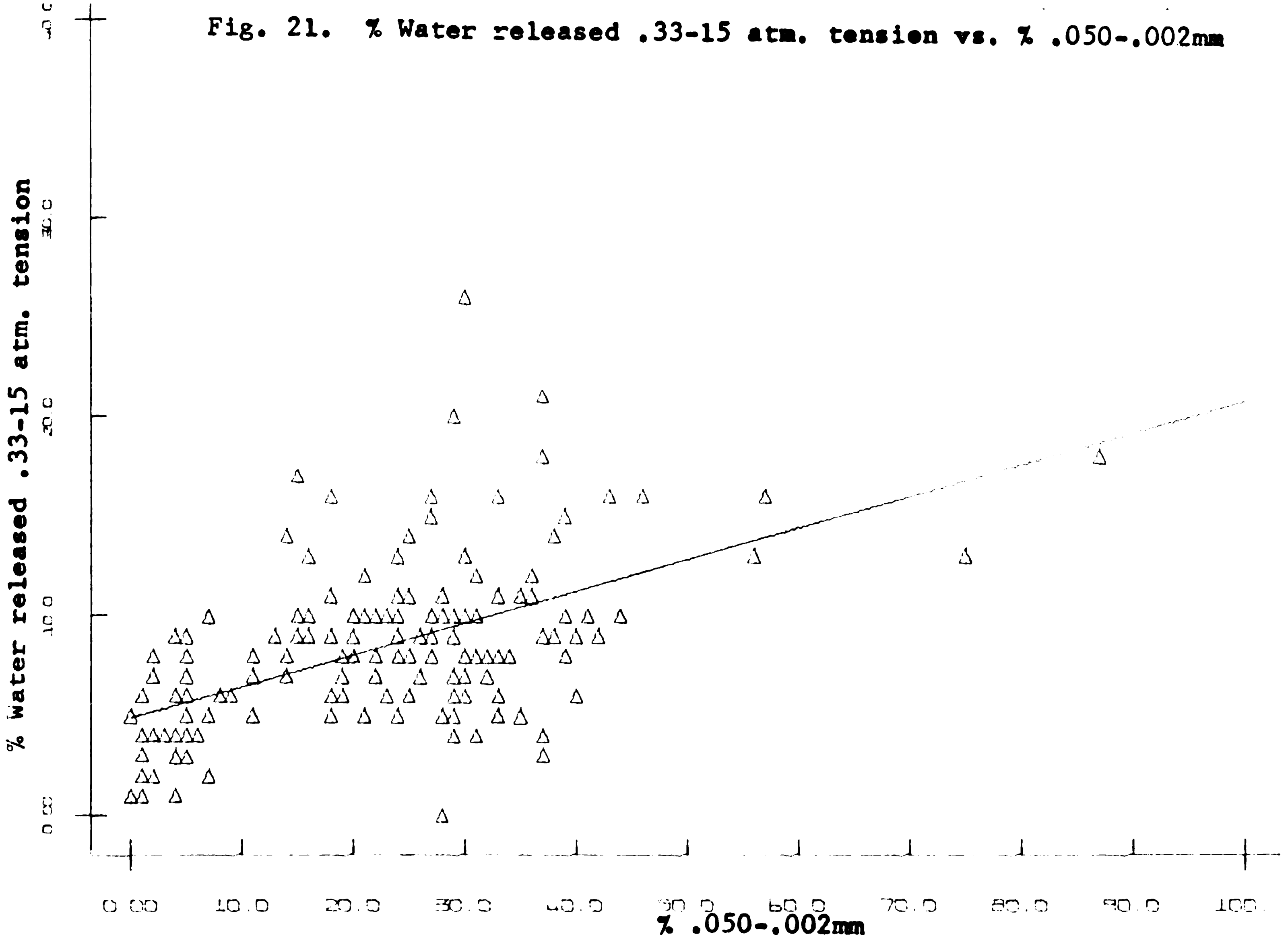
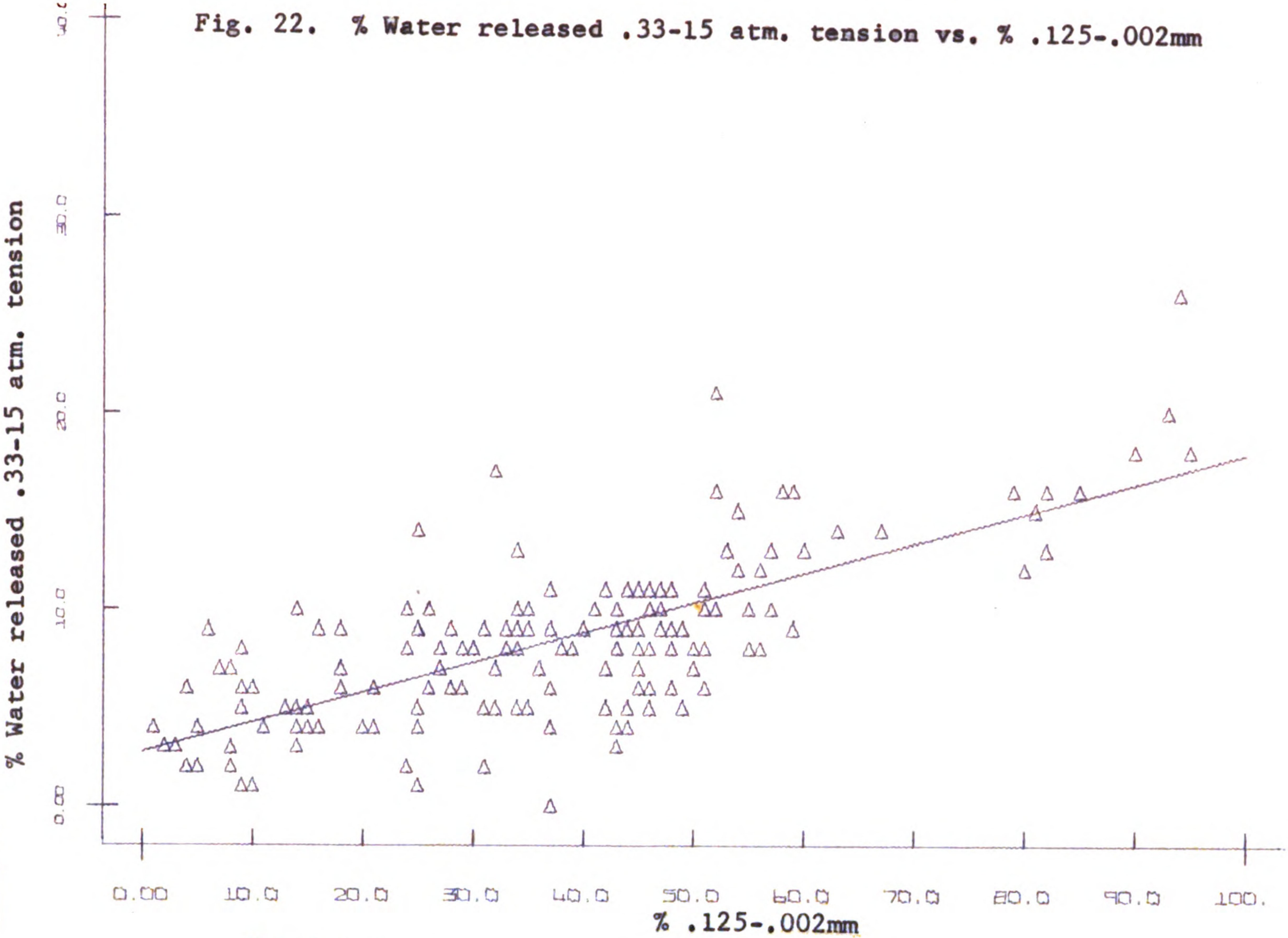


Fig. 22. % Water released .33-15 atm. tension vs. % .125-.002mm



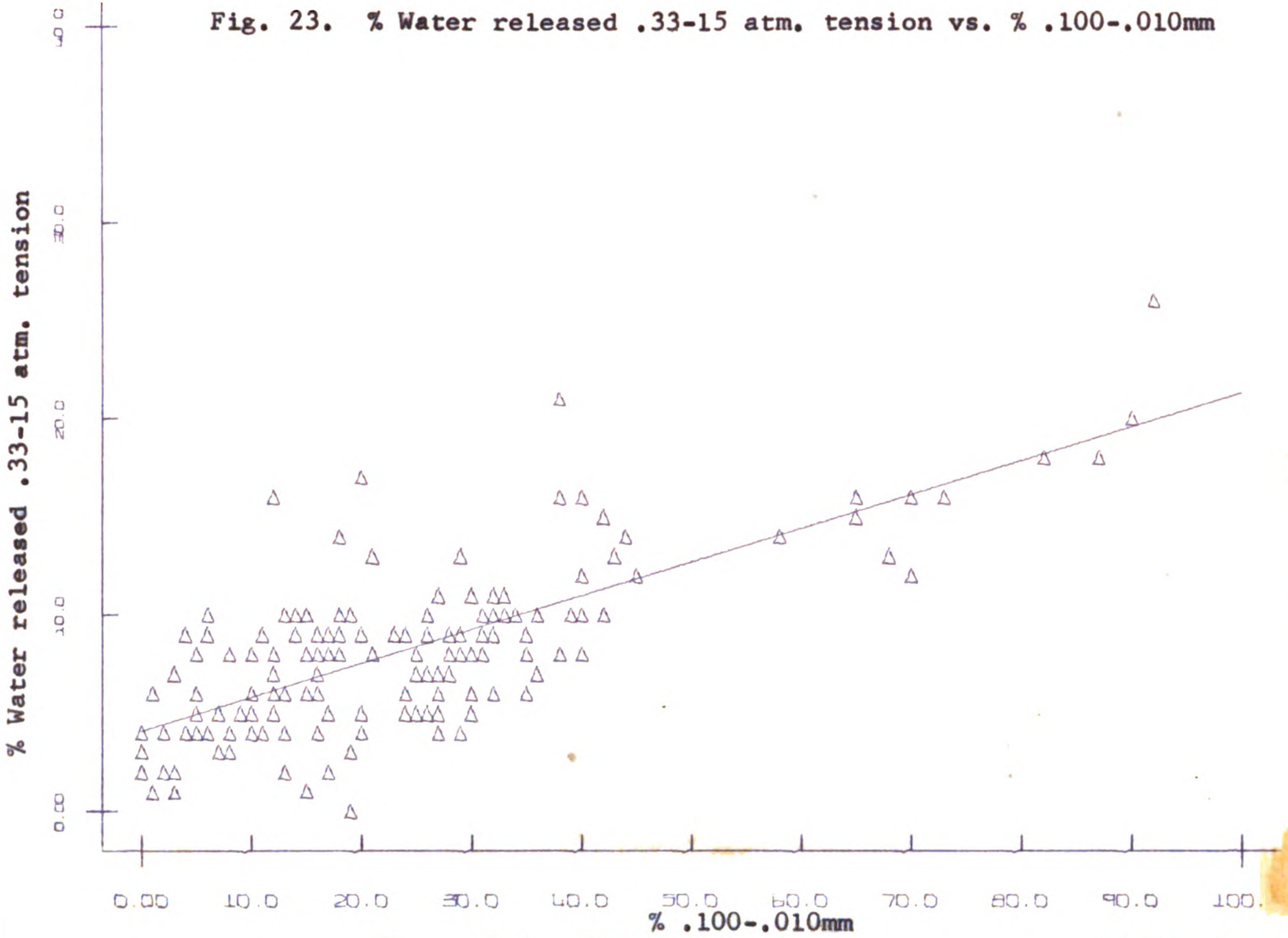


Fig. 23. % Water released .33-15 atm. tension vs. % .100-.010mm

While silt is an important factor in these relationships, it is not the only factor contributing to water retention. Other factors such as aggregation, compaction and distribution of particle sizes in the silt fraction as well as other factors, such as the kind of plant, should be considered to evaluate the total available water holding capacity.

The correlation is greatly affected by the fraction of the particle size distribution which is used. For example, correlations are consistently lower, regardless of the tension values used to measure available water, when .050mm is used as the upper limit of silt as compared to limits up to .100mm or .125mm. The correlation improves as the lower silt size limit used becomes coarser up to .020mm, except when 1/3 to 15 atmospheres is used as the measure of available water. In that case the .010-.100mm fraction gives the best correlation. Correspondingly, the coarser silt fractions are better correlated with available water, particularly when the lower tension, .06 atmospheres, is used as a measure of field capacity. It should be noted that as a group, the correlations with 1/3 to 15 atmospheres tension as the measure of available water are least sensitive to differences in silt size ranges and give better correlations than the other tension limits with the less than .050mm silt fractions. These are not, however, the highest correlations found, nor are they most meaningful expressions of available water.

From these results it seems clear that .050mm does not represent the most significant upper size limit of silt in interpretations involving available water storage capacity. Regardless of the tensions used in evaluating available water, in all cases with .002mm as a lower silt size limit, higher correlations were found with size limits coarser than .050mm. Each definition of available water has a maximum correlation with a different silt size based on these data. For .06 to 6 atmospheres it is with .125-.020mm silt. For .06 to 15 atmospheres tension it is with the .100-.020mm silt fraction, and for .33 to 15 atmospheres it is with the .100-.010mm silt fraction.

For the lower size limit of the silt fraction, correlation with measures of available water show the .020mm limit has the highest correlation coefficients with the .06 to 6 atmospheres and .06 to 15 atmospheres available moisture evaluations. These values seem to show a clearer pattern of relationship to particle size than does .33 to 15 atmospheres available water. In every case, for the former available water values, the highest correlation was obtained using .020mm as the lower limit of the silt size range. This is consistent with the idea that these coarse silt sizes are more significant in determining water availability at lower tensions. This specific result shows the significance of the .020mm size limit used by the International Society of Soil Science. It is thus significant for more than just completing a logarithmic

scale based on 2, or as a limit of vision with the naked eye.

Thus it is clear that an upper size limit greater than .050mm up to .125 or .100mm and a lower size limit of silt up to .010 or .020mm will give better correlations with available water holding capacities. If .002mm is accepted as the lower silt size limit, the best correlation between available water and upper silt size is at .125mm when .06 atmospheres is used as a measure of field capacity, and at .100mm when 1/3 atmospheres is used as a measure of field capacity. An upper silt size limit of .100mm will be near the optimum for any of the lower silt size limits or tensions tested. As suggested by Franzmeier et al. (1960) this seems to be a considerable improvement over the present upper silt size limit for soil scientists.

C. PARTICLE SIZE OF SILT FRACTION AND EFFECT ON HYDRAULIC CONDUCTIVITY AND CAPILLARY RISE

1. Hydraulic Conductivity

Using the .002mm as the lower limit of silt, it appears that in terms of hydraulic conductivity, there is little difference between .050mm and .105mm as an upper size limit, as shown in Table 7.

Table 7 -- Hydraulic conductivity of various size fractions.

Size Limits	1st Reading cm/hr	2nd Reading cm/hr	3rd Reading cm/hr	Average cm/hr	Average in/hr
.002-.050mm	.23	.16	.16	.18	.07
.002-.050mm	.16	.12	.12	.13	.05
.002-.105mm	.16	.14	.09	.13	.05
.002-.105mm	.16	.16	.15	.16	.06
.010-.050mm	1.16	1.14	1.16	1.15	.45
.010-.050mm	1.18	1.18	1.18	1.18	.46
.010-.105mm	1.57	1.59	1.61	1.59	.62
.010-.105mm	1.61	1.59	1.63	1.61	.63
.020-.062mm	2.35	2.29	2.21	2.28	.90
.020-.062mm	2.58	2.39	2.35	2.44	.96
.020-.105mm	4.38	4.38	4.37	4.38	1.76
.020-.105mm	4.64	4.64	4.66	4.65	1.83

The results were obtained on structureless prepared samples of the individual size fractions. There may be a difference between these two limits when considered in the total size distribution with sand and clay of less silty materials or in undisturbed samples where structural development may be present. Certainly there is a marked difference between the fractions when coarser lower limits were used.

There was a marked difference in the turbidity in the water that percolated through the samples with .002mm as the lower limit compared to samples with the coarser lower

size limits. The water from the .002mm samples was consistently muddy, while the others were clean. Also, when removing the material with .002mm as the lower size limit from the metal cylinders, the samples flowed in the saturated condition. The samples with coarser lower size limits had to be dug out. These may be significant in terms of sedimentation and the bearing or plastic properties of similar materials.

On the soil samples studied by Erickson et al. earlier, the hydraulic conductivity in terms of in/hr was also measured on undisturbed and unfractionated samples. Simple correlations with material less than a given size showed these results:

Table 8 -- Correlation of hydraulic conductivity with various fractions.

Fraction	Correlation Coefficient
<.002mm	-.346
<.010mm	-.380
<.020mm	-.406
<.050mm	-.486
<.074mm	-.514
<.100mm	-.522
<.125mm	-.521

The correlations are not high but a definite trend is established in these values. Certainly particle size is not the only factor that determines hydraulic conductivity but these correlations show that some values are more significant than others.

2. Capillary Rise

Results of capillary rise over a 48-hour period are shown in the following table.

Table 9 -- Capillary rise data for various size fractions in cm.

Fractions	15 min	30 min	45 min	1 hr	1.5 hrs	2 hrs	2.5 hrs	3 hrs	3.5 hrs	4 hrs	5 hrs
.002-.050mm #1	3.0	6.5	8.8	10.8	13.2	16.2	18.5	20.4	22.2	24.2	26.9
.002-.050mm #2	2.4	5.3	7.9	9.0	12.0	14.6	15.6	19.0	20.8	22.6	25.6
.002-.105mm #1	1.7	5.9	7.3	9.6	11.9	13.9	15.8	17.8	19.0	20.3	23.4
.002-.105mm #2	3.6	7.0	9.2	10.6	12.2	15.6	17.2	19.1	20.6	21.9	23.8
.010-.050mm #1	13.1	19.9	24.5	28.4	35.7	40.5	43.3	47.2	49.6	52.8	57.3
.010-.050mm #2	11.9	18.1	23.4	27.1	35.5	39.2	43.1	45.9	48.7	50.1	55.4
.010-.105mm #1	13.7	19.0	24.0	27.9	36.2	39.2	43.7	46.8	50.2	53.1	57.9
.010-.105mm #2	13.8	19.6	24.4	28.8	35.0	39.3	42.5	46.0	49.0	51.5	55.9
.020-.062mm #1	12.6	20.3	25.9	30.2	38.2	44.9	50.4	55.2	57.6	59.7	62.9
.020-.062mm #2	16.1	23.5	29.8	33.9	41.9	48.4	53.3	57.6	61.0	64.0	70.4
.020-.105mm #1	17.8	24.9	31.8	36.1	44.3	50.0	54.5	59.1	61.7	64.4	69.2
.020-.105mm #2	19.9	24.1	33.0	38.0	45.3	52.1	56.5	60.4	63.7	66.2	71.9

(continued)

Table 9 (continued)

Fractions	6 hrs	8 hrs	10 hrs	12 hrs	16 hrs	20 hrs	24 hrs	28 hrs	36 hrs	48 hrs
.002-.050mm #1	29.4	34.5	38.4	41.6	45.6	Failure				
.002-.050mm #2	28.4	32.9	36.9	39.8	43.9	Failure				
.002-.105mm #1	26.2	31.0	33.9	37.2	43.2	47.5	52.4	56.2	61.5	75.0
.002-.105mm #2	26.9	30.8	34.8	37.9	43.8	48.4	54.5	58.3	Failure	
.010-.050mm #1	62.3	69.6	74.1	78.3	86.1	93.8	99.2	104.2	108.4	117.0
.010-.050mm #2	59.8	66.8	71.2	75.4	84.4	90.5	96.8	100.4	106.6	115.2
.010-.105mm #1	62.9	68.4	69.9	74.2	87.3	94.0	100.6	105.0	112.2	121.4
.010-.105mm #2	61.8	65.9	71.7	75.8	82.6	88.0	93.2	96.3	101.5	105.2
.020-.062mm #1	63.0	65.3	67.3	69.1	Failure					
.020-.062mm #2	75.5	76.1	88.2	92.1	98.2	103.2	107.0	109.5	110.4	117.0
.020-.105mm #1	69.4	76.8	81.0	83.4	88.2	90.8	94.2	95.8	98.4	102.8
.020-.105mm #2	75.5	79.8	84.3	88.2	92.3	95.0	98.3	101.0	103.0	106.6

Perhaps the most significant relationship found from this data is that the lower size limit of these particular fractions is more important in predicting capillary rise rate than is the upper limit. In the initial 36 hours, the .002mm fractions had the least rise with the .010mm fractions higher and the .020mm fractions the highest. For the 36 hour readings the .010mm fractions equaled the .020mm and in the 48 hour reading the .010mm fractions had the highest rise.

For the .002mm fractions an upper limit of .050mm had consistently higher capillary rise than did those fractions with .105mm as the upper limit. The other fractions showed mixed values for capillary rise between the upper limits.

The differences between results with the same fraction may be due in part to insufficient packing in the tubes. Certainly the packing procedure needs to be more effective. Perhaps complete saturation of the soil in the tubes and drying before testing capillary rise would solve this problem.

V. CONCLUSIONS

The results point to the need to determine certain size limits in particle size analysis because of their relation to physical properties.

Separations at 2.0mm and .002mm are generally regarded as significant as cited previously.

Results in this work note a need for a separation at .020mm to provide a better measure of readily available water. And the amount of this material may affect capillary rise and hydraulic conductivity as well.

A separation at .105mm or .125mm was shown to be important for evaluating readily available water.

It appears, though more work is needed, that a separation is necessary between .020mm and .105mm or .125mm because of shear stress and ½ compressive strength. Some value, either .062mm or .074mm, may be significant for these properties.

LITERATURE CITED

Agricultural Education Association. 1926. The mechanical analysis of soils: a report on the present position and recommendations for a new method. Journal of Agricultural Science, 16:123-144.

Agricultural Education Association. 1928. The revised official method for mechanical analysis. Journal of Agricultural Science, 18:734-737.

Alling, H.L. 1943. A metric grade scale for sedimentary rocks. Journal of Geology, 51:259-269.

American Geophysical Union. 1947. Report of the subcommittee on sediment terminology. Transaction, American Geophysical Union, 28:936-938.

American Society of Civil Engineers. 1947. Report of Committee VII on foundation and soil mechanics. ASCE, Civil Engineering Division, Civil Engineering Bulletin 12.

Asphalt Institute, The. 1963. Soils Manual. College Park, Maryland: The Asphalt Institute.

Asphalt Institute, The. 1966. Drainage of Asphalt Pavement Structures. College Park, Maryland: The Asphalt Institute.

Atterberg, Albert. 1908. Studien auf dem Gebiete der Bodenkunde. Translated by R. W. Simson. Landswirtschaftliche Versuch-Stationen, 69:93-143.

Bartelli, L.J. and Peters, D.B. 1959. Integrating soil moisture characteristics with classification units of some Illinois soils. Proceedings, Soil Science Society of America, 23:145-151.

Baver, L.D. 1938. Soil permeability in relation to non-capillary porosity. Proceedings, Soil Science Society of America, 3:52-56.

Baver, L.D. 1956. Soil Physics. New York, N.Y.: J.W. Wiley and Sons Inc.

Bender, William H. 1961. Soils suitable for septic-tank filter fields. U.S. Department of Agriculture, Soil Conservation Service, Agricultural Information Bulletin No. 243. Washington, D.C.: Government Printing Office.

Black, C.A.; Evans, D.D.; White, J.L.; Ensminger, L.E.; and Clark, F.E. 1965. *Methods of Soil Analysis, Monograph No. 9*. Madison, Wisconsin: American Society of Agronomy.

Bouyoucos, G.J. 1927. The hydrometer as a new method for the mechanical analysis of soils. *Soil Science*, 23:343-353.

Bouyoucos, G.J. 1927. The hydrometer method as a new and rapid method for determining the colloidal content of soils. *Soil Science*, 32:319-330.

Bouyoucos, G.J. 1937. A sensitive hydrometer for determining small amounts of clay or colloids in soils. *Soil Science*, 44:245-246.

Boyd, J.R. 1922. Physical properties of subgrade materials. *Canadian Engineer*, 43:362-364.

Briggs, L.J.; Martin, F.O.; and Pearce, J.R. 1904. The centrifugal method of mechanical soil analysis. U.S.D.A. Bureau of Soils Bulletin 24.

Capper, P. Leonard; and Cassie, W. Fisher. 1953. *The Mechanics of Engineering Soils*. London, England: McGraw-Hill Book Company, Inc.

Casagrande, A. 1942. Classification and identification of soils. *Proceedings, ASCE*, 73:783-810.

Cushman, A.S. and Hubbard, P. 1907. Air elutriation of fine powders. *Journal of the American Chemical Society*, 29:589-596.

Day, Paul R. 1950. Physical basis of particle size analysis by the hydrometer method. *Soil Science*, 70:363-374.

Diller, Joseph Silas. 1898. Educational series of rock specimens. U.S. Geological Survey Bulletin No. 150. Washington, D.C.: Government Printing Office.

Dougrameji, Jamal Sharif. 1965. Soil Water relationships in stratified sands. Unpublished Ph.D. thesis, Michigan State University.

Felitsiant, I.N. 1959. Capillary movement of moisture in stratified soils. *Soviet Soil Science*, 3:282-292.

Felitsiant, I.N. 1961. Capillary movement and accumulation of moisture in stratified soils. *Soviet Soil Science*, 10:1099-1107.

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

Franzmeier, D.P.; Whiteside, E.P.; and Erickson, A.E. 1960. Relationship of texture classes of fine earth to readily available water. 7th International Congress of Soil Science (Madison, Wisconsin), 1:354-363.

Gill, William R. and VandenBerg, Glen E. 1967. Soil dynamics in tillage and fraction. Agricultural Handbook No. 316. Agricultural Research Service. U.S. Department of Agriculture, Washington, D.C.: Government Printing Office.

Glossop, Rudolph; and Skempton, Alex Westley. 1945. Particle-size in silts and sands. Journal of the Institution of Civil Engineers, 2:81-105.

Goldbeck, A.T. 1921. Tests for subgrade soils. Public Roads, 4:15-20.

Grabau, A.W. 1913. Principles of Stratigraphy. New York, N.Y.: A.G. Seiler and Company.

Hack, J.T. 1957. Studies of longitudinal stream profiles in Virginia and Maryland. U.S. Geological Survey Professional Paper 294B. Washington, D.C.: Government Printing Office.

Hall, A.D. 1904. The mechanical analysis of soils and the composition of the fractions resulting therefrom. Journal of Chemical Soceity Transactions, 85:950-963.

Hall, A.D. and Russell, E.J. 1911-1912. Soil surveys and soil analysis. Journal of Agricultural Science, 4:182-223.

Hammitt, G.M. II. 1966. Statistical analysis of data from a comparative laboratory test program sponsored by A.C.I.L. Miscellaneous Paper No. 4-785. U.S. Army Engineer Waterways Experiment Station.

Hilgard, E.W. 1873. On the silt analysis of soils and clays. The American Journal of Science and Arts, 6:288-296.

Hilgard, E.W. 1890. Soil investigation: its methods and results. University of California College of Agriculture, Agricultural Experiment Station Annual Report, 158-159.

Hilgard, E.W. 1903. Methods of physical and chemical soil analysis. University of California Agricultural Experiment Station Circular No. 6.

Hill, David E. 1959. The storage of moisture in Connecticut soils. Connecticut Agricultural Experiment Station Bulletin 627.

Hogan, Robert M.; Haise, Howard R.; and Edminster, Talcott W. ed. 1967. Irrigation of Agricultural Lands. Madison, Wisconsin: American Soceity of Agronomy.

Hogentogler, C.W. 1937. Engineering Properties of Soil. New York, N.Y.: McGraw-Hill Book Company Inc.

Hopkins, C.G. 1899. A plea for a scientific basis for the division of soil particles in mechanical analysis. U.S.D.A. Division of Chemistry Bulletin 56:64-66.

Hough, B.K. 1957. Basic Soil Engineering. New York, N.Y. Ronald Press Company.

Jacks, G.V. 1965. The role of organisms in the early stages of soil formation. Experimental Pedology. London, England: Butterworths.

Jamison, V.C. 1953. Changes in air-water relationships due to structural improvements of soils. Soil Science, 76:143-151.

Jamison, V.C. 1956. Pertinent factors governing the availability of soil moisture to plants. Soil Science, 81:459-471.

Jamison, V.C. and Kroth, E.M. 1958. Available moisture storage capacity in relation to textural composition and organic matter content of several Missouri soils. Proceedings, Soil Science Society of America, 22:189-192.

Jennings, D.S.; Thomas, M.D.; and Gardner, W. 1922. A new method of mechanical analysis of soils. Soil Science, 14:485-499.

Keen, B.A. 1928. Some comments on the hydrometer method for studying soil. Soil Science, 26:261-263.

Keen, Bernard A. 1931. The Physical Properties of the Soil. London, England: Longmens, Green and Co.

King, F.H. 1894. Physics of Agriculture. Madison, Wisconsin: Democratic Printing Company.

Krumbein, W.C. 1934. Size frequency distribution of sediments. Journal of Sedimentary Petrology, 4:65-77.

Krumbein, W.C. 1936. The application of logarithmic moments to size frequency distribution of sediments. Journal of Sedimentary Petrology, 6:35-47.

Krumbein, W.C. and Pettijohn, F.J. 1938. Manual of Sedimentary Petrography. New York, N.Y.: Appleton-Century-Crofts, Inc.

Lehane, J.J. and Staple, W.J. 1953. Water retention and availability in soils related to drought resistance. Canadian Journal of Agricultural Science, 33:265-273.

Leliavsky, Serge. 1966. An Introduction to Fluvial Hydraulics. New York, N.Y.: Dover Publications, Inc.

Leopold, Luna B.; Wolman, M. Gordon; and Miller, John P. 1964. Fluvial Processes in Geomorphology. San Francisco, California. W.H. Freeman and Company.

Loughbridge, R.H. 1894. Investigations in soil physics; the capillary rise of water in soils. California Agricultural Experiment Station Annual Report, 1892-1894, 91-100.

Lund, Z.F. 1959. Available water-holding capacity of alluvial soils in Louisiana. Proceedings, Soil Science Society of America, 23:1-3.

Luthin, James N. ed. 1957. Drainage of Agricultural Lands. Madison, Wisconsin: American Society of Agronomy.

Michigan State Highway Department. 1960. Field Manual of Soil Engineering. Lansing, Michigan: State of Michigan.

Millar, C.E.; Turk, L.M.; and Foth, H.D. 1965. Fundamentals of Soil Science. New York, N.Y.: John Wiley and Sons Inc.

Milner, Henry B. 1952. Sedimentary Petrography. London, England: Thomas Murby and Company.

Olmstead, L.B.; Alexander, L.T.; and Lakin, H.W. 1931. The determination of clay and colloid in soils by means of a specific gravity balance. American Soil Survey Association Bulletin 12: 161-166.

Osborne, T.B. 1887. The methods of mechanical soil analysis. Connecticut Agricultural Experiment Station Annual Report: 141-158.

Peele, T.C.; Beale, O.W.; and Lesene, F.F. 1948. Irrigation requirements of South Carolina soils. Agricultural Engineering, 29:157-159.

Portland Cement Association. 1962. P.C.A. Soil Primer. Chicago, Illinois: Portland Cement Association.

Ritter, Leo J. and Paquette, Radnor J. 1960. *Highway Engineering*. New York, N.Y.: Ronald Press Company.

Robinson, G.W. 1922. A new method for the mechanical analysis of soils and other dispersions. *Journal of Agricultural Science*, 12:306-321.

Roderick, Gilbert L. 1963. A history of particle size limits. Review submitted to Soil Science Society of America Committee on Particle Size Distribution in Soils.

Rubey, W.W. 1930. Lithologic studies of fine-grained upper cretaceous sedimentary rocks of the Black Hills region. U.S. Geological Survey Professional Paper 165A.

Salter, P.J. and Willaism, J.B. 1965. The influence of texture on the moisture characteristics of soils. I. A critical comparison of techniques for determining the available-water capacity and moisture characteristic curve of a soil. *The Journal of Soil Science*, 16:1-15.

Salter, P.J. and Williams, J.B. 1965. The influence of texture on the moisture characteristics of soils. II. Available-water capacity and moisture release characteristics. *The Journal of Soil Science*, 16:310-317.

Salter, P.J.; Berry, G.; and Williams, J.B. 1966. The influence of texture on the moisture characteristics of soils. III. Quantitative relationships between particle size, composition, and available-water capacity. *The Journal of Soil Science*, 17:9398.

Scales, F.M.; and Marsh, F.W. 1922. The tyndellometer reading of soil dispersoids. *Journal of Industrial Engineering and Chemistry*, 14:52-54.

Shaw, T.M. and Alexander, L.T. 1936. A note on mechanical analysis and soils texture. *Proceedings, Soil Science Society of America*, 1:303-304.

Soil Science Society of America. 1967. Considerations relative to a common particle size scale of earthy materials. Committee Report. *Proceedings, Soil Science Society of America*, 31:579-584.

Stemm, A.J. and Svedberg, T. 1925. The use of scattered light in the determination of the distribution of size of particles in emulsions. *Journal of the American Chemical Society*, 47:1582-1596.

Terzaghi, Karl and Peck, Ralph B. 1948. *Soil Mechanics in Engineering Practice*. New York, N.Y.: John Wiley and Sons Inc.

Troug, E.; Taylor, J.R.; Simonson, R.W.; and Weeks, M.E. 1936. Mechanical and mineralogical subdivisions of the clay separate of soils. Proceedings, Soil Science Society of America, 1:175-179.

Troug, E.; Taylor, J.R.; Simonson, R.W.; and Weeks, M.E. 1936. Procedure for special type of mechanical and mineralogical soil analysis. Proceedings, Soil Science Society of America, 1:101-112.

Tyler Sieve Company. 1967. Testing Sieves and Their Uses Handbook 53. Cleveland, Ohio: W.S. Tyler Company.

Udden, J.A. 1914. Mechanical composition of clastic sediments. Bulletin of the Geological Society of America, 25:655-744.

U.S. Federal Housing Administration. 1961. Engineering Soil Classification for Residential Developments. Washington, D.C.: Government Printing Office.

U.S. Public Health Service, Department of Health, Education and Welfare. 1967. Manual of Septic Tank Practice. Washington, D.C.: Government Printing Office.

U.S. Soil Survey Staff. 1951. Soil Survey Manual. Agricultural Research Administration, U.S.D.A., Washington, D.C.: Government Printing Office.

Wang, Chwan-Chan. 1967. Comparisons of texture classification of earthy materials used by engineers and soil scientists in the United States. Unpublished M.S. thesis, Michigan State University.

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. Journal of Geology, 30:377-392.

Wentworth, C.K. 1933. Fundamental limits to the size of clastic grains. Science, 77:633-634.

Whitney, M. 1892. Some physical properties of soils in their relation to moisture and crop distribution. U.S.D.A. Weather Bureau Bulletin 4.

Wilcox, J.C. and Spilsbury, R.H. 1940. Soil moisture studies. II. Some relationships between moisture measurements and mechanical analysis. Scientific Agriculture, 21:459-472.

Wilcox, J.C. and Spilsbury, R.H. 1940. Soil moisture studies. III. An application of soil moisture measurement to soil classification. Scientific Agriculture, 21:473-478.