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Partial Report on
Synthetically Bonded Steel
Molding Sands

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ABSTRACT

Synthetically bonded steel molding sands were studied to find the effect of changes in sand grain size, size frequency distribution and grain shape on the physical properties of the mixtures. Several clays were tested and their green compressive strengths compared. The clays varied considerably in strength and each clay had a green strength-water content curve which was characteristic of the clay. A widely used cereal binder of the corn flour type was studied in mixes with bentonite and in clay free mixes.

AUTHORIZATION

1. The studies in steel casting research were originally authorized by Bureau of Engineering letter QP/Castings (6-19-Ds) of 13 July 1928. Previous research and development on molding sands used in making steel castings have been presented in reports M-1435 of 25 March 1938, M-1478 of 22 September 1938, and M-1590 of 12 February 1940.

KNOWN FACTS BEARING ON THE PROBLEM

2. Although metal castings have been made for centuries the only method of evaluating the molding sand was by feeling the texture and strength with the hand. It is only recently that methods have been developed to measure accurately the properties of molding sands. Such work has been sponsored in this country since 1918 by the American Foundrymen's Association. In 1923 and '24 the permeability test was developed and adopted as a tentative standard method. In 1925 some of the early compressive strength tests were made and some interesting work on them has been done by Dietert⁽¹⁾, Hansen⁽²⁾ and Adams⁽³⁾. Prior to this time practically all molding sands were naturally bonded. That is, the sand and clay which they contained were combined in the proportions found in nature. Recently, however, synthetically bonded sands have come into widespread use. These consist of a washed and graded silica base sand which is mixed with a suitable clay.

3. The reasons for the use of synthetically bonded sands are many but they all lead to the same end; they reduce the cost of the castings. The materials used are readily available while good natural sands are sometimes hard to obtain. Synthetically bonded sands are easy to control and when properly used they peel well and produce clean, smooth, casting surfaces which reduces cleaning costs. Grain size and fines are very easily controlled. There is little or no spent sand to haul away. The first cost is sometimes higher than that of natural sands but the durability of the synthetically bonded sands is so much greater that the cost per unit of finished castings is less. Synthetic sands are well adapted to use in modern molding machines and continuous production systems. The physical properties can be adjusted to produce all classes of work with one or two base sands whereas it is necessary to maintain large stocks of several natural sands to meet the varied needs of the foundry.

4. In previous reports at this Laboratory the effects of both water and bentonite contents on the physical properties of synthetically bonded steel molding sands were established. The principal facts brought out by this work are summarized in Plates 8, 16 and 18 of NRL Report M-1478 which are reproduced here as Plates 1, 2 and 3. Plate 1 shows the relation between green compressive strength and bentonite content. This graph proved to be of practical value for the control of green sand mixtures.

5. Since sand strength varies rapidly with both bentonite and water content, it is the usual practice to decide on values of green compressive strength and water content which are appropriate for the type of

castings being produced. Plotting these values on the graph locates a point. The position of the point with respect to the bentonite curves indicates how much bentonite is required to produce the desired strength. In heap or used sands where the strength of some of the bentonite is destroyed, it must be replaced if the properties of the sand are to be maintained constant. This is accomplished by making routine tests for green compressive strength and water content. Plotting these values on the graph will indicate how much bentonite is necessary to bring the mixture back to its original strength.

6. Plate 2 shows the dry compressive strengths produced by the same mixes shown in Plate 1. Plate 3 contains the same series of curves as Plate 1 with an additional set superimposed. The additional curves were derived from the dry compressive strength. In this manner it is possible to show the interrelation among the four variables, i.e., water and bentonite contents, and green and dry compressive strengths. When any two of these are known, the other two may be found from the graph.

7. It is clear that these statements apply only to the sand and bentonite used for the tests. Other sands and other clays will give somewhat different results but the general character of the curves would be the same. It is a simple procedure to establish similar curves for any combination of sand and clay and since this work was presented, many foundrymen have stated their need for such information. They wish to know, for example, what changes in the curves would be brought about by variations in sand grain size, size frequency distribution, grain shape and type of clay. Information is needed also on cereal binders and their possible effect in controlling the tendency of bentonite bonded sands to dry out on the surface. Naturally bonded sands or washed sands bonded with fire clay do not exhibit this tendency. It might be possible to reduce surface drying by mixing other clays with bentonite. Grim⁽⁴⁾ has reported that clays such as kaolinite or illite containing small amounts of montmorillonite have a strength out of all proportion to the amount of montmorillonite present. This suggests the possibility of utilizing the high strength of bentonite (composed chiefly of montmorillonite) and at the same time, by the addition of other clays, lessening surface drying.

STATEMENT OF THE PROBLEM

8. Thus, the object of this report is to present information on the effect of grain size, shape, and distribution, type of clay, and cereal content on the physical properties of synthetically bonded steel molding sands.

METHODS USED IN THE INVESTIGATION

9. The sand testing methods used in this investigation are those recommended by the American Foundrymen's Association and given in the 1938 Edition of their handbook "Testing and Grading Foundry Sands and Clays. Standards and Tentative Standards."

10. Test batches were made up so that the total weight of the dry materials was 2000 grams. Clay, cereal binder and sand contents are reported on the basis of this dry weight. The dry materials were placed in a Simpson 18" laboratory muller and mixed dry for one minute. Water was then added and mixing continued for five minutes longer. The batch was dumped into a clean pail and transferred to half-gallon glass jars which were immediately tightly sealed. The sand was allowed to temper in the sealed jars for at least 24 hours. At the end of this time the sand was removed, passed quickly through a 1/4 inch sieve and returned to the jar. 100 grams of sand were then weighed out into a glass crystallizing dish for a moisture test. The sample was dried to constant weight in an oven at 105 to 110°C. cooled to room temperature in a desiccator and reweighed. The loss of weight in grams was taken as the water content. It should be noted that the water content is based on total or wet weight and the percentages of dry materials on the dry weight.

11. In order to avoid variations due to the effects of temperature and humidity, a series of from 6 to 8 batches was made up at one time and allowed to temper. They were then opened, screened and tested one at a time in as rapid succession as possible. This procedure was found to give excellent agreement in test values.

12. The standard green permeability, green compressive strength, dry permeability and dry compressive strength tests were made as well as tests for flowability, deformation and resilience. A careful check was kept on the amount of sand necessary to produce a test specimen exactly two inches long and this was recorded as weight of specimen. Since the volume is constant, this is also a measure of the density of the rammed mixture.

13. Briefly the testing procedure was as follows: A weighed amount of sand was placed in a steel tube with an inside diameter of two inches. This was placed in the usual ramming device consisting of a plunger and a weight. The weight was raised and dropped three times. If the length of the test cylinder was 2 inches + 1/32 inch, it was used, but if it was not within this limit, it was discarded and another specimen was made using an amount of sand corrected to produce a 2 inch long cylinder. The permeability of the rammed specimen was determined by means of a Dietert permeability apparatus. The orifice method was used for all tests after it had been found to be in agreement with the stop watch method. A Dietert hand operated pendulum type testing machine was used for making the green compression, deformation, and resilience tests. Specimens for the dry permeability and compression tests were baked in a Dietert core oven, between 105 and 110°C. for at least two hours. This oven is provided with forced ventilation, a rotating table and thermostatic control. The specimens were kept in a desiccator until they were tested. Dry permeability was measured by means of a special dry permeability tube with a mercury seal around the sides of the specimen which caused the air to travel the full length of the specimen as in the green permeability test. Dry strength was measured on the Dietert machine with the high strength attachment or, for very strong specimens, on a large Southwark-Emery testing machine.

14. Although sand sizes are expressed in A.F.A. fineness numbers throughout this report it is quite instructive to plot and compare them on the basis of their cumulative sieve analyses. Differences in size, distribution, clay and silt content as well as any unusual or abnormal characteristics of the sand are easily seen from the cumulative curve. The Tyler Method⁽⁵⁾ with slight modifications was used for this purpose. First, the sands were sieved thru a set of Tyler 8 inch sieves. The cumulative percentages retained on the various sieves were then plotted as a function of the openings of the sieves in millimeters on a logarithmic scale. The resulting curves are shown in plates 4 to 6. The point where the cumulative curve crosses the 50% retained line was noted and the size at this point is called "Center Grain Size." This may be expressed in millimeters or microns. In the same way the diameters at 25% and 75% retained were found. The larger diameter divided by the smaller is called "Distribution Coefficient."

15. Two-cycle semi-logarithmic graph paper was used although any semi-log paper will be satisfactory if the scales are appropriate. Three-cycle paper is especially suited to the molding gravels and naturally bonded molding sands while the two cycle is usually ample for the synthetically bonded sands. Placing the paper so that the logarithmic scale decreases to the right, the end of the last cycle is given the value of 0.01 mm. The successive cycles to the left will then be 0.1 and 1 mm. respectively. The sizes in millimeters of the openings of the sieves are then marked on this scale and labeled with the mesh numbers of the sieves. The linear scale of per cent retained is made on the left hand margin and the sieve analyses are then plotted as cumulative curves. To illustrate with an example, the 63.7 (A.F.A. fineness) sand was tested for fineness and plotted on Plate 4. The curve was found to cross the 25, 50 and 75 per cent retained line at 0.250, 0.210, and 0.176 millimeters, respectively. The "center grain size" is therefore 0.210 mm. or 210 microns (microns = millimeters x 1000) and the "distribution coefficient" is

$$\frac{0.250}{0.176} = 1.42$$

Krumbein⁽⁶⁾ has discussed the advantages of cumulative curves over size frequency curves. For the foundryman the most important advantages are:

1. Any sieves may be used regardless of the size, interval, or make, so long as the size of the openings is known and is appropriate for the material being tested.
2. As few or as many sieves as desired may be used. Four or five may be ample for routine work while twenty or thirty may be used for extreme accuracy.
3. All sieve analyses plotted in this way are comparable. American sands separated on either Tyler or U. S. Standard sieves may be compared with British or Continental sands.

MATERIALS USED IN THE INVESTIGATION

16. Sieve analyses and cumulative curves of the sands used are shown in Table 1, and plates 4 to 6, inclusive. Sands A to F, inclusive, are washed silica sands with rounded grains all of which have approximately the same distribution but vary in size. These sands were used in the study of the effect of grain size on the physical properties of the mixture.

17. Sands G and H are also washed silica with rounded grains. These are of about the same average size but differ widely in distribution, sand G having grains of a very uniform size and sand H having grains of many sizes.

18. Sand I is a washed silica sand but has sub-angular instead of rounded grains. Sand J is a beach sand from Cape Henry and has angular grains.

19. Sand K is a Downer steel molding sand and L is an Albany sand. A comparison of the test results of these sands with those above serves to bring out the differences between naturally bonded and synthetically bonded sands.

20. The clays used were a Wyoming bentonite composed chiefly of the mineral montmorillonite, an Illinois clay composed chiefly of the mineral illite and a Pennsylvania fire clay. The Downer and Albany sands contained their natural clays. Their mineral composition was not determined.

DATA OBTAINED

The Effect of Grain Size on the Properties of a Synthetically Bonded Sand.

21. Each of the six sands, A to F, inclusive, in Table 1 was used as the base sand for a series of mixtures. Each series contained 5% bentonite with moisture varying between 1 and 10 per cent. The physical properties of each mix were measured as described above and the results are shown on Plates 7 to 12, inclusive. As can be seen from these plates, each property of the sand varies with water content. Because of the similarity of the characteristic curves showing variations in physical property as a function of water content, it is only necessary to discuss one set of curves in detail. Plate 10 was selected for this purpose because these mixes contain sand of a size (A.F.A. fineness 63.7) which is very commonly used. The batch containing 1.17% water was so dry and powdery that it was very difficult to work and was definitely too dry for molding purposes. In this moisture range the sand has a tendency to pack very tightly as shown by the high weight and low permeability values. The green strength was 6.16 lbs. per sq. in. In the next batch the water was increased to 1.70 per cent. The increase in water "opened up" the sand and caused a large increase in permeability with a corresponding decrease in weight. The green strength was also increased from 6.16 to 9.25 lbs. per sq. in. The third batch contained 2.48 per cent water which produced a small increase in permeability and a large decrease in strength, the

weight being slightly reduced. Further increases in water content increased weight and decreased green compressive strength and green permeability. The position of the maximum and minimum points of the various curves change with different sands but their general shape is about the same for all the sands which were studied.

22. Flowability, deformation, and resilience curves also are shown but so far they have been of very little assistance in controlling the sand. A minimum flowability of 82.5 per cent is indicated at 2.5 per cent water. This is well above the amount needed for satisfactory molding⁽⁷⁾. Deformation and resilience values are erratic although in general they increase with increase in water content. Dry permeability for any given mix is always higher than green permeability. At low moisture contents the difference is small and increases in proportion to the increase in moisture. Dry compressive strength increases rapidly with water content up to about 2 or 3 per cent and then increases more gradually as the water is increased to 10 per cent.

23. In order to show the effect of sand grain size on the properties of molding mixtures, certain curves from Plates 7 to 12 have been selected and drawn as composite curves in Plates 13 to 17. Plate 13 shows the effect of sand size on green compressive strength. This set of curves shows clearly the remarkable similarity in the shape of the strength curves for different sands. The maximum strength occurs in each case between the limits of 1.6 and 1.9 per cent water. Since 5 per cent bentonite was used, this gives clay-water ratios from 2.6 to 3.1. In general, the highest strengths were obtained with the very coarse and very fine sands, the 31.0 and 120.3 sands (AFA grain fineness numbers) being the strongest, and the intermediate sizes, 52.4 and 63.7, being the weakest of those tested. This relation is probably influenced by two factors, the surface area and the number of grain contacts. The coarse sands have a relatively small surface area as compared to the fine sands so that for a given percentage of clay, the grains are covered with a thick layer which tends to produce strength. The fine sands with a large surface area have a thin layer of clay but there are a much larger number of grain contacts which contribute to the strength.

24. The green permeability curves are collected in Plate 14. All the curves are similar in shape, increasing rapidly to a maximum and then decreasing approximately as a linear function of the water content. The maxima occur between two and three per cent water regardless of sand size. The magnitude of the maximum naturally varies considerably, being 45 for the fine sand and over 470 for the coarse sand.

25. The dry permeability curves are shown in Plate 15. Here again, increases in grain size produce corresponding increases in dry permeability. In most cases the permeability increases to a maximum with increase in water content and is nearly constant with further additions of water.

26. As stated above, dry strength is very low at low moisture contents. It increases rapidly at first and then more gradually as the water content increases. This is shown by the curves assembled in Plate 16. In general, the fine sands produce higher strengths. The 120.3 sand, for instance, is nearly twice as strong as the 31.0 sand.

27. Plate 17 shows the effect of sand grain size and moisture content on the weight of the specimens which is a measure of the density of the mixture. The coarse sands (31.0 and 40.6) are the most dense while the remaining four are so nearly alike that it is difficult to draw any conclusion regarding them. The shape of the curve is the same for all the sands with the minima occurring in every case between 2.0 and 2.5 per cent water.

The Effect of Grain Shape

28. In an effort to determine the effect of grain shape on the physical properties of molding sands, two sands were tested - one having angular and the other sub-angular grains. Comparison of these two series of tests with each other and with the 63.7 sand (Plate 10) failed to show any differences which could be attributed directly to grain shape. It is planned to study this variable further with suitable sands separated by sieves in order to obtain samples of the same grain size and distribution but having different shapes varying from round to angular.

The Effect of Distribution

29. In order to find the effect of distribution of the base sand on the properties of a synthetic sand mixture, two sands were prepared from samples separated in an AFA sieve series. They were mixed to give one sand very uniform in grain size and one sand widely distributed. (Table 1 and Plate 5) The sieve analyses and cumulative curves of these sands indicate that they are comparable to types normally used in synthetically bonded molding mixes. The slopes of the curves show the difference in the distribution of the two sands. Although the fineness numbers are not the same it may be seen that both sands have approximately 50% of the grain larger and 50% smaller than 190 microns and that they are distributed symmetrically about this point. Six batches of each type were mixed in the usual way and tempered to water contents from 1.2 to 10 per cent. Plates 18 and 19 show the results of the tests on the two series. In Plate 20 the green compressive strengths of the two sands are compared. The distributed sand is stronger over the full range of water contents but distribution has no effect on the shape of the curve or the position of the maximum strength with respect to water content. The two sands were about equally workable but the distributed sand appeared to have more resistance to rubbing off than the uniform sand.

30. Plate 21 compares the green permeabilities. Here again the curves are almost identical in shape and position of the maxima with respect to water but the permeability of the distributed sand is only about 60% of that of the uniform sand.

31. Plate 22 shows a large difference in density between the two sands, the distributed sand being from 6 to 10 per cent more dense than the uniform sand. This is explained by the "fitting in" of small grains between the large ones⁽⁸⁾ which reduces the voids and therefore decreases the permeability. These small grains also increase green strength by increasing the number of grain contacts.

32. From Plate 23 it is seen that uniformity of grain size increases flowability by about 5 per cent. Both sands, however, have ample flowability for all practical purposes.

33. The dry strengths of these sands are shown in Plate 24. Here the distributed sand shows a decided advantage. It is over 50 per cent stronger than the uniform sand at the same water content, or, to produce 180 pounds per square inch dry compressive strength requires 11 per cent water in the uniform sand but only 3.8 per cent in the distributed sand. Baked specimens of the two sands were equally good in surface finish but the distributed sand had more resistance to rubbing off and therefore would be less apt to wash in a mold.

34. In the past a uniform sand has been thought to be the best base for a synthetic molding sand. The curves shown here, however, indicate that a sand which is distributed over several sieves has many points of superiority over the uniform sand.

The Effect of Type of Clay

35. In all the sand mixes tested up to this point bentonite was used as the bonding clay. Many other clays, however, are successfully used in the production of steel castings, fireclay being one of the most common. They must, however, be used in larger percentages than bentonite. Plates 25 and 26 show tests of two series made with the 63.7 sand and 10 and 20% of fireclay respectively. It will be seen that the green compressive strength curves have a shape which is characteristic of fireclay and that it varies somewhat from that produced by similar mixes containing bentonite. The maxima in the permeability curves occur at much higher water contents than is the case with bentonite bonded sands.

36. One of the most interesting differences between the fireclay and the bentonite bonded sands is in their behavior with respect to the ability of moisture to migrate more or less freely from place to place within the mold. In the bentonite sands this migration is very limited; that is, if a completely saturated spot is next to a dry spot the moisture distribution remains practically unchanged. This characteristic can be easily shown by dropping an equal amount of water on the tops of two test specimens, one made with bentonite and the other with fireclay, and, after several minutes, cutting them in half vertically. In the bentonite sand the moisture remains near the top while in the fireclay bonded sand it will be found distributed over a large part of the volume. This property of bentonite leads to rapid surface drying since the surface moisture is evaporated and is not replaced by moisture from the backing sand. Wetting agents have been tried in an effort to modify this characteristic of the bentonite but they have not been found to be very effective. It is possible that clays such as bentonite and fireclay can be blended to produce a mixture having the desirable properties of both clays.

37. In order to show how the properties of naturally bonded sands compare with synthetically bonded sands, a Downer Steel molding sand having a fineness number of 52.1 and 10.7% clay was tested (Plate 27).

38. Plate 28 shows the physical properties of an Illinois clay kindly furnished by Dr. R. E. Grim of the Illinois State Geological Survey. Its principal constituent is the clay mineral illite. A similar series, made with the same sand bonded with bentonite, whose principal constituent is the clay mineral montmorillonite, was shown in Plate 10. A comparison of these series shows that the clays are very similar in effect. The illite gave approximately 40% of the green strength produced by montmorillonite.

39. This is shown more clearly in Plate 29 which gives strength curves produced by several clays all of which are mixed with washed silica sand (AFA fineness 63) except the Downer and Albany. These curves show the large differences which exist between the various clays and such an analysis may provide a means of identification, and evaluation.

40. Plate 31 shows the result of blending two clays in an effort to obtain the most desirable properties of both. The middle curve shows the strength of 10% fireclay in a 63.7 washed silica sand. When two per cent of the fireclay was replaced with two per cent of bentonite the strength shown in the top curve was produced. The strength of the mixed clay is much higher than the sum of the strengths of the two components. The sand with the mixed clay absorbed water somewhat more readily than the straight bentonite mix.

The Effect of Cereals

41. The use of cereal binders in molding sands has been the subject of much discussion. Most steel foundries use them claiming that they produce beneficial results. Usually the effect, however, is not stated in terms of the measurable physical properties of the sand but is described as an improvement in texture or in the behavior of the sand while it is being molded.

42. In order to study this subject six mixes were made up containing 0, 1/2, 1, 2, 3, and 5 per cent of a popular and widely used cereal binder ("Mogul" - Corn Products Refining Company). The remainder consisted of 5 per cent bentonite and enough sand (63.7 AFA fineness) to make up 100 per cent. These materials were mulled dry for one minute, sufficient water was then added to produce 5 per cent moisture, and the mixture was mulled for five more minutes. The six mixes were tested in the usual way and the results are shown on Plate 32. The mix without cereal had good permeability and excellent flowability but felt wet and adhered slightly to the hands. The addition of small percentages of cereal caused the sand to feel much drier. At 1 per cent or more of cereal the sand did not stick to the hands and seemed stronger. At cereal contents of 2 to 3 per cent, a pronounced change in texture was observed. The individual coated grains united to form small pellets from 1/8 to 1/4 inch in diameter. At 5 per cent this was still more pronounced. The sand felt dry although the water content was held approximately constant. The agglomerated grains were quite large and the texture of the sand was so stiff that the sand could not be packed tightly. While the individual pellets were very compact, large interstices remained between them even after the sand was rammed hard.

43. Plate 32 shows the effect of the cereal binder on the physical properties of the sand mixtures. Green compressive strength rises rapidly from 4.4 lbs. per sq. in. without cereal to 8.1 lbs. per sq. in. with 2.5 per cent cereal and then gradually decreases. At first glance it would appear that the cereal binder had approximately doubled the strength. There is another factor which must be considered, however. The strength produced in a sand mixture by bentonite varies rapidly with the water content. When the cereal binder was introduced it absorbed part of the water in the mix and left a smaller amount of water available to the bentonite. With less water, the bentonite will produce a higher strength. This is shown very well in Plate 9. From this it is seen that in a mix containing the same grade of sand and the same amount of bentonite that a strength of 4.1 lbs. per sq. in. was obtained at a water content of 5.0 per cent. When the moisture was reduced, however, the strength increased. This amounts to 8.2 lbs. per sq. in. at 1.85 per cent water. This indicates that the increase in strength is not entirely due to the strength of the cereal binder but partly to its effect on the amount of water available to the bentonite. (Another mix discussed below shows the strength of the same cereal binder used without clay.) It is debatable whether a mix should contain sand and clay with cereal binder and a moderately high moisture or whether the cereal should be omitted and less water used. Each method has its advantages. The omission of the cereal permits the reduction of water but forms a mix which may cause trouble in certain types of work by becoming dry and friable on the surface. Using the cereal forms a mix which does not appear to dry out on the surface so rapidly. This mix will feel about as dry as the one without cereal but will, however, contain more water.

44. Most of the other properties in this series show the effect of the agglomeration of the grains at high cereal contents. Green permeability decreases from 150 to a minimum of 138 at 3 per cent cereal. Further additions of cereal cause a remarkable increase in permeability due to the voids produced between the pellets. Dry permeability was very similar, starting at 179, decreasing to a minimum of 175 at 2 per cent cereal and then increasing very rapidly. At 5 per cent cereal the dry permeability was so high that it could not be measured because the mercury leaked through the voids in the specimen.

45. The dry compressive strength was 210 lbs. per sq. in. without cereal, it increased to about 300 lbs. per sq. in. at 2 per cent cereal and then decreased rapidly with further additions. This corresponds roughly with the maximum in green strength. Unlike green strength, this increase must be attributed solely to the cereal binder.

46. Flowability, which was excellent without cereal (83 per cent) decreased rapidly with the addition of the cereal. At 5 per cent cereal the flowability was reduced to 56 per cent.

47. The weight of the specimen was nearly constant from 0 to 3 per cent cereal and then the weight decreased rapidly. This indicates in another way the formation of voids in the specimen.

48. For the specimens containing cereal binder the fracture in compression in the green state was unusual in that it was very slow. As the load was applied the test cylinder held its cylindrical shape for a time and then began to deform slowly into a barrel shape, indicating a high deformation before the final fracture. The deformation attachment, however, did not show this result as the needle usually started to recede before the final fracture occurred. The specimen was barrel-shaped after fracture with both ends pushed in $1/8$ inch or more. Longitudinal cracks due to circumferential tension developed but the specimen did not break apart as is usually the case.

49. Since the use of cereal binder with clay exhibited such interesting characteristics, it was thought desirable to investigate the effects of the material in mixes without clay to determine the strength which could be attributed directly to the cereal binder. A series of mixes was made up containing the same sand (fineness 63.7) and 2 per cent of the cereal. Water contents were varied from 0.66 per cent to 9.77 per cent and no clay was used. Plate 33 shows the physical properties of the series.

50. The mixture was so weak that it was impossible to measure green compressive strength at water contents below 2 per cent. The sand would not hold together. As the water was increased, the strength increased gradually to 1.47 lbs. per sq. in. at 7 per cent water and then decreased slightly. This strength is small compared with that of most clays. Another interesting point is that the shape of the green compressive strength curve is different from that of all other series discussed in that the high strength which occurs at low moisture contents with clay present is missing when only cereal binder is used. Green permeability rises rapidly with increase in water, reaches a maximum of 245 at about 1 per cent water and decreases rapidly at first and then more gradually. The weight of the specimen, as would be expected, is just the inverse of the permeability curve. Dry permeability is approximately proportional to green permeability in the range tested.

51. The dry compressive strength increases rapidly to a maximum of about 800 lbs. per sq. in. at 6.5 per cent water and then decreases. This is far in excess of the dry strength produced by a comparable mix containing clay. The dry compressive strength curve from Plate 32, for example, shows a dry strength of 298 lbs. per sq. in. for a mix containing 5 per cent bentonite, 5 per cent water, and 2 per cent cereal. From Plate 33 it is seen that the same material without clay has a strength of 700 lbs. per sq. in.

SUMMARY

52. Cumulative curves drawn from sieve analyses are a convenient and effective method of showing the characteristics of molding sands. They show at a glance the size, distribution, clay and silt contents and any unusual characteristics of the sand being studied.

53. Sand grain size changes the green compressive strength-water content curve in magnitude but not in shape. The sands of intermediate sizes (AFA Fineness 50 to 60) are weaker than either the finer or the coarser sands. Dry compressive strength increases as the grain size decreases. The density of the rammed sand is much higher for the very coarse sands (AFA Fineness 30-40) than for the medium and fine sands.

54. Sands of uniform grain size produce higher green and dry permeability and flowability than do non-uniform sands. The non-uniform sand produces higher strength in the green and dry states and higher density in the rammed material.

55. Since each of the clays tested produces a green compressive strength-water content curve which is characteristic of the clay, the shape and magnitude of this curve may provide a method of estimating the mineral constitution of a clay. Each clay would have to be tested at several water contents with a standard sand and compared with curves of relatively pure clay minerals also tested with the standard sand.

56. Small amounts of bentonite added to sands containing other clays give strengths higher than the sum of the strengths of the two clays tested separately.

57. Bentonite sands dry out on the surface more rapidly than fireclay bonded sands because the water from the backing sand does not diffuse into the surface layer as readily as it does in fireclay bonded sands.

58. Cereal binder (corn flour type) increased green and dry strength up to 2.5% cereal, but reduced these values as further cereal was added. The increase in green strength may in part be due to the absorption of water by the cereal, allowing the bentonite to work at a more efficient clay to water ratio, since the cereal produces very little green strength when used alone. The use of over 2% of cereal caused the sand to ball up into small pellets which acted as individual grains. This produced abnormally high permeability, low flowability and soft spots in the sand.

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TABLE I.

Sieve Analyses of Sands Used in the Investigation.

MESH	Percent Retained	Sand A		Sand B		Sand C		Sand D		Sand E		Sand F	
		Indi-vid.	Cumul.	Indi-vid.	Cumul.	Indi-vid.	Cumul.	Indi-vid.	Cumul.	Indi-vid.	Cumul.	Indi-vid.	Cumul.
Retained on 6 mesh		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
" 12 "		0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
" 20 "		14.80	15.00	0.16	0.16	0.40	0.40	0.14	0.14	0.00	0.00	0.02	0.02
" 30 "		20.44	35.44	6.44	6.60	1.34	1.74	0.44	0.58	0.00	0.00	0.02	0.04
" 40 "		28.14	63.58	27.02	33.62	4.64	6.38	1.72	2.30	0.02	0.02	0.02	0.06
" 50 "		20.24	83.82	32.62	66.24	16.76	23.14	7.54	9.84	0.80	0.82	0.02	0.08
" 70 "		13.16	96.98	28.40	94.64	52.34	75.48	41.50	51.34	16.86	17.68	0.28	0.36
" 100 "		2.78	99.76	4.86	99.50	23.18	98.66	36.76	88.10	50.70	68.38	14.80	15.16
" 140 "		0.34	100.10	0.50	100.00	1.48	100.14	9.36	97.46	24.60	92.98	42.12	57.28
" 200 "		0.02	100.12	0.06	100.06	0.10	100.24	2.56	100.02	6.00	98.98	33.62	90.90
" 270 "		0.00	100.12	0.00	100.06	0.02	100.26	0.30	100.32	0.90	99.88	6.56	97.46
Silt		0.00	100.12	0.00	100.06	0.04	100.30	0.12	100.44	0.34	100.22	2.44	99.90
Clay		0.00	100.12	0.00	100.06	0.00	100.30	0.00	100.44	0.00	100.22	0.00	99.90
A.F.A. Fineness		31.0		40.6		52.4		63.7		79.8		120.3	
Center Grain Size		494 microns		350 microns		243 microns		210 microns		167 microns		111 microns	
Distribution Coef.		2.03		1.67		1.40		1.42		1.40		1.45	

TABLE I (Concluded)

MESH	Percent Retained	Sand G		Sand H		Sand I		Sand J		Sand K		Sand L	
		Indi-vid.	Cumul.	Indi-vid.	Cumul.	Indi-vid.	Cumul.	Indi-vid.	Cumul.	Indi-vid.	Cumul.	Indi-vid.	Cumul.
Retained on 6 mesh		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
" 12 "		0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00
" 20 "		0.00	0.00	0.80	0.80	0.16	0.16	0.98	1.00	0.40	0.40	0.58	0.58
" 30 "		0.02	0.02	5.40	6.20	0.38	0.54	6.02	7.02	1.20	1.60	0.58	1.16
" 40 "		0.05	0.07	10.19	16.39	1.30	1.84	24.90	31.92	4.54	6.14	1.86	3.02
" 50 "		1.00	1.07	13.58	29.97	9.64	11.48	30.20	62.12	9.86	16.00	4.20	7.22
" 70 "		33.74	34.81	14.51	44.48	52.00	63.48	26.82	88.94	27.82	43.82	11.58	18.80
" 100 "		51.60	86.41	17.00	61.48	29.94	93.42	10.02	98.96	34.58	78.40	13.64	32.44
" 140 "		12.42	98.83	15.32	76.80	5.20	98.62	0.82	99.78	8.44	86.84	14.66	47.10
" 200 "		1.38	100.21	14.75	91.55	1.30	99.92	0.00	99.78	1.58	88.42	19.82	66.92
" 270 "		0.03	100.24	7.27	98.82	0.18	100.10	0.00	99.78	0.40	88.82	10.40	77.32
Silt		0.01	100.25	1.19	100.01	0.06	100.16	0.00	99.78	0.46	89.38	14.04	91.36
Clay		0.00	100.25	0.00	100.01	0.00	100.16	0.00	99.78	10.72	100.00	8.64	100.00
A.F.A. Fineness No.		67.7		82.9		58.7		42.1		63.3		134.8	
Center Grain Size		192 microns		189 microns		221 microns		335 microns		198 microns		101 microns	
Distribution Coef.		1.36		3.11		1.32		1.75		1.65		3.02	

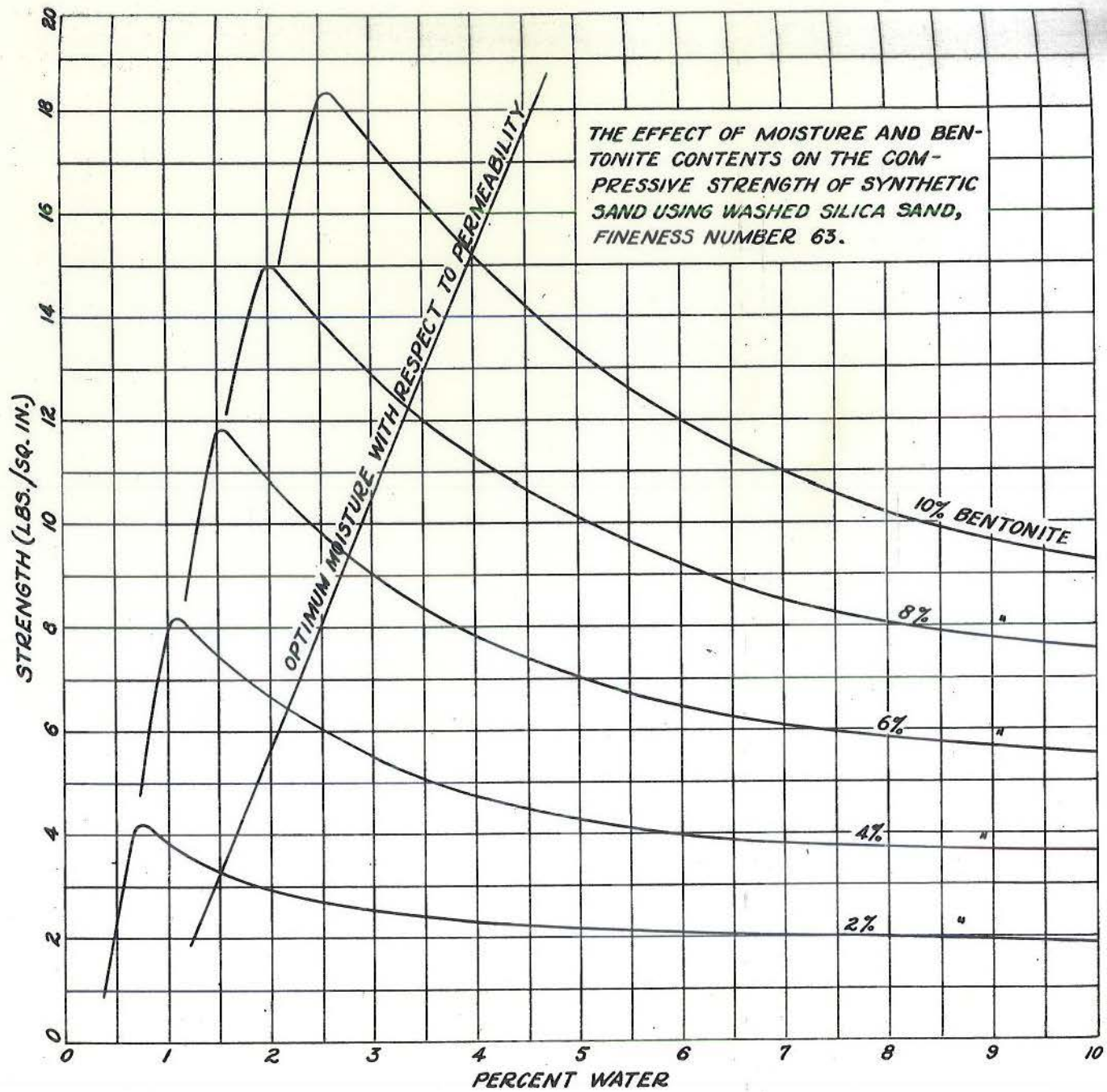
E	"	"	"	"	"	4.44	156.0	186	4.47	0.0314	140.0	85.0	-	-
F	"	"	"	"	"	5.29	157.0	173	3.94	0.0324	127.8	84.2	279	172.9
G	"	"	"	"	"	7.68	161.0	142	3.29	0.0360	118.4	85.3	283	200.2
A	Bentonite	5%	63.7	95%	None	1.38	152.5	120	8.31	0.0116	96.4	87.2	-	-
B	"	"	"	"	"	1.83	149.5	145	8.23	0.0141	117.3	83.1	173	69.5
C	"	"	"	"	"	2.44	149.5	146	6.03	0.0195	117.5	80.6	188	109.4
D	"	"	"	"	"	3.53	151.5	141	4.80	0.0264	126.7	82.0	193	154.8
E	"	"	"	"	"	4.49	153.2	133	4.21	0.0304	128.0	82.4	195	130.7
F	"	"	"	"	"	5.51	155.0	123	3.96	0.0314	124.5	84.0	198	202.6
G	"	"	"	"	"	7.69	159.0	101	3.72	0.0326	121.2	84.2	198	235.9
H	"	"	"	"	"	10.01	163.0	82	3.33	0.0328	109.2	84.8	193	265.1
A	Bentonite	5%	70.8	95%	None	1.46	158.0	81	12.11	0.0111	134.6	89.1	-	-
B	"	"	"	"	"	1.92	153.5	94	11.35	0.0154	174.7	83.6	120	-
C	"	"	"	"	"	2.41	153.5	99	7.90	0.0218	172.3	81.4	129	-
D	"	"	"	"	"	3.63	156.0	90	5.85	0.0293	171.4	82.7	131	-
E	"	"	"	"	"	4.48	157.5	88	5.03	0.0344	173.0	83.5	137	-
F	"	"	"	"	"	5.42	159.5	81	4.64	0.0340	157.7	83.7	134	-
G	"	"	"	"	"	7.99	164.5	61	4.15	0.0409	169.7	85.0	126	-
H	"	"	"	"	"	10.25	169.0	46	3.87	0.0385	149.0	85.6	116	-
A	Bentonite	5%	120.3	95%	None	1.53	156.5	36	12.36	0.0105	129.7	88.3	40	33.8
B	"	"	"	"	"	2.02	153.0	40	13.62	0.0122	166.2	82.9	43	83.7
C	"	"	"	"	"	2.57	151.0	44	10.53	0.0171	180.2	80.5	57	142.6
D	"	"	"	"	"	3.50	153.5	44	7.58	0.0253	192.0	80.3	60	195.9
E	"	"	"	"	"	4.48	155.5	42	6.52	0.0302	137.0	80.1	60	213.9
F	"	"	"	"	"	5.60	157.5	40	5.88	0.0302	178.0	80.6	58	242.7
G	"	"	"	"	"	7.66	162.0	34	5.20	0.0359	186.7	82.6	58	275.1
H	"	"	"	"	"	10.00	166.0	29	4.84	0.0351	170.0	82.8	52	-
9A	Bentonite	5%	67.6	95%	None	1.18	160.5	70	9.20	0.0109	100.3	90.4	-	-
9B	"	"	"	"	"	1.63	154.5	89	11.95	0.0116	133.6	87.0	112	40.9
9C	"	"	"	"	"	2.05	152.0	102	10.33	0.0157	162.3	83.8	126	60.1
9D	"	"	"	"	"	2.96	155.5	91	6.72	0.0231	132.1	82.3	129	108.4
9E	"	"	"	"	"	4.37	159.5	35	4.99	0.0308	153.7	84.2	138	126.8
9F	"	"	"	"	"	9.59	165.0	57	4.23	0.0334	141.2	84.7	139	166.6
9A	Bentonite	5%	82.0	95%	None	1.22	171.0	39	10.65	0.0105	111.8	88.4	-	-
9B	"	"	"	"	"	1.59	166.5	46	14.74	0.0117	172.5	83.7	54	59.9
9C	"	"	"	"	"	2.12	161.0	59	11.64	0.0161	187.5	76.9	80	103.1
9D	"	"	"	"	"	2.94	164.5	55	3.36	0.0222	135.5	78.0	80	160.6
9E	"	"	"	"	"	5.39	170.5	45	6.28	0.0276	173.3	78.7	80	204.7
9F	"	"	"	"	"	10.02	180.5	29	5.93	0.0346	205.1	81.0	67	255.1
25A	Fireclay	10%	63.7	90%	None	0.94	162.0	61	3.09	0.0134	41.4	91.5	-	-
25B	"	"	"	"	"	1.58	161.0	71	5.14	0.0114	58.6	89.7	-	-
25C	"	"	"	"	"	1.90	160.0	88	5.29	0.0118	62.4	87.4	96	13.5
25D	"	"	"	"	"	2.84	159.0	103	4.65	0.0135	62.6	84.5	126	27.5
25E	"	"	"	"	"	3.78	161.0	108	3.29	0.0190	62.5	83.8	139	43.1
25F	"	"	"	"	"	4.56	162.0	108	2.38	0.0233	55.5	85.2	145	47.1
25G	"	"	"	"	"	5.76	164.0	116	1.72	0.0236	40.6	86.7	156	53.5
25H	"	"	"	"	"	8.12	170.0	93	1.64	0.0214	35.5	86.4	122	73.5
26A	Fireclay	20%	63.7	80%	None	2.31	169.5	37	13.58	0.0100	135.8	83.1	44	32.8
26B	"	"	"	"	"	3.29	169.5	50	15.16	0.0138	209.4	79.6	60	47.9
26C	"	"	"	"	"	4.19	170.0	55	13.24	0.0223	295.5	77.8	74	65.8
26D	"	"	"	"	"	5.31	172.0	58	9.75	0.0310	302.0	76.7	81	80.1
26E	"	"	"	"	"	7.43	180.0	62	3.91	0.0384	150.0	81.3	102	90.3
26F	"	"	"	"	"	10.35	189.0	40	2.59	0.0396	100.0	84.6	76	109.0
27A	Downer	10.72%	52.1	89.28%	None	1.54	163.0	44	7.10	0.0123	87.3	89.2	-	-
27B	"	"	"	"	"	2.22	161.5	66	13.05	0.0137	178.8	85.4	-	-
27C	"	"	"	"	"	3.02	158.0	108	13.90	0.0133	185.0	79.4	126	24.8
27D	"	"	"	"	"	4.00	159.0	111	9.07	0.0208	188.5	78.6	133	38.0
27E	"	"	"	"	"	5.00	162.0	108	5.42	0.0261	141.3	79.5	142	43.3
27F	"	"	"	"	"	6.64	168.0	94	3.00	0.0328	98.4	82.5	142	63.9
27G	"	"	"	"	"	8.90	173.0	71	2.45	0.0443	108.3	83.8	128	89.0
28A	Illite	5%	63.7	95%	None	0.98	163.0	89	4.13	0.0112	46.2	91.3	-	-
28B	"	"	"	"	"	1.36	160.0	112	4.97	0.0132	65.6	88.7	-	-
28C	"	"	"	"	"	1.63	159.0	129	3.93	0.0133	52.3	86.3	-	-
28D	"	"	"	"	"	2.47	161.0	126	2.18	0.0220	48.0	86.5	151	42.5
28E	"	"	"	"	"	3.27	162.0	129	1.53	0.0256	39.2	87.0	161	63.7
28F	"	"	"	"	"	4.00	163.7	131	1.22	0.0300	38.1	88.4	167	66.1
28G	"	"	"	"	"	5.67	167.0	114	1.22	0.0341	41.6	93.5	145	93.3
28H	"	"	"	"	"					0.0373	48.5	88.8	94	134.0

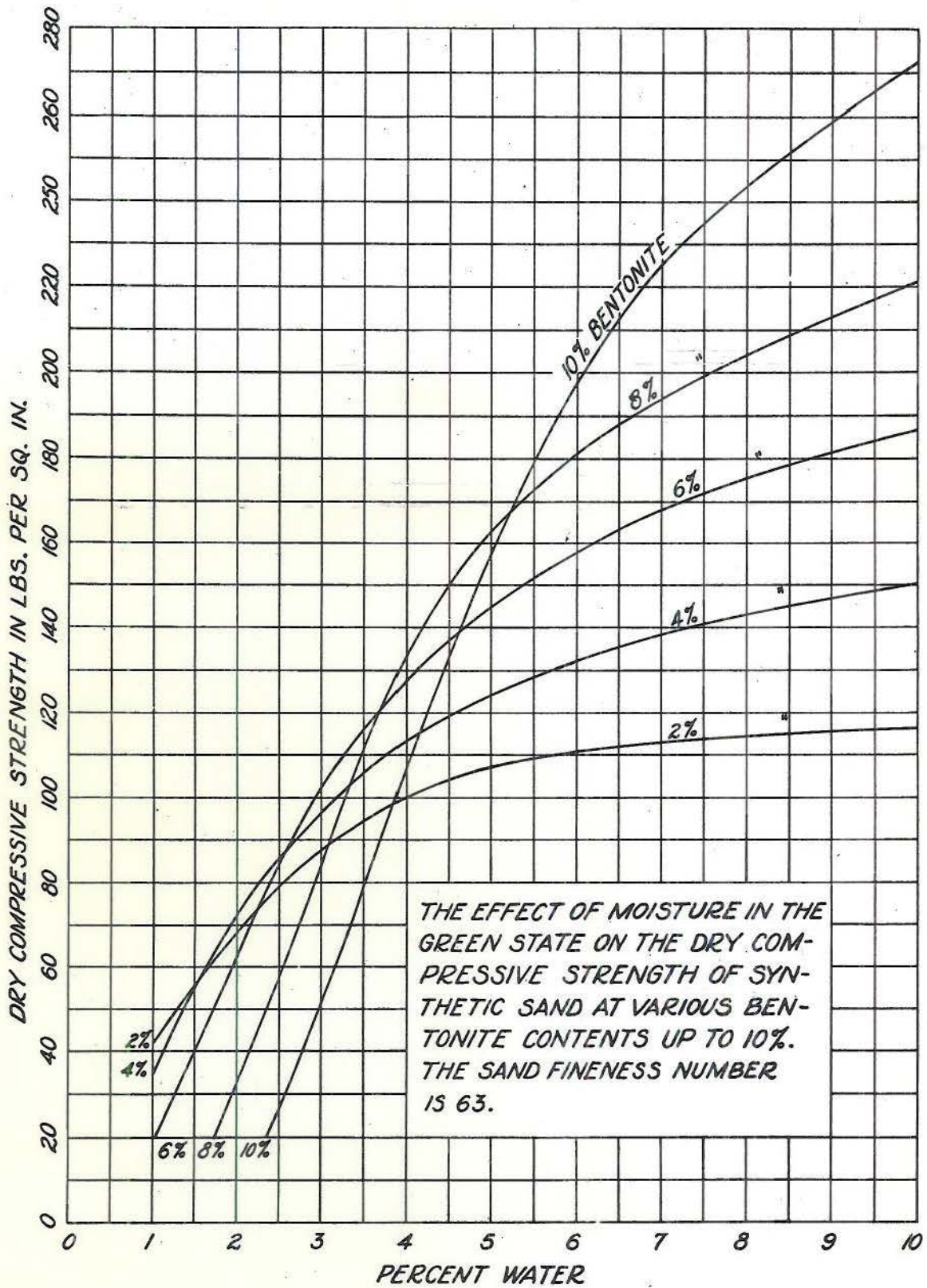
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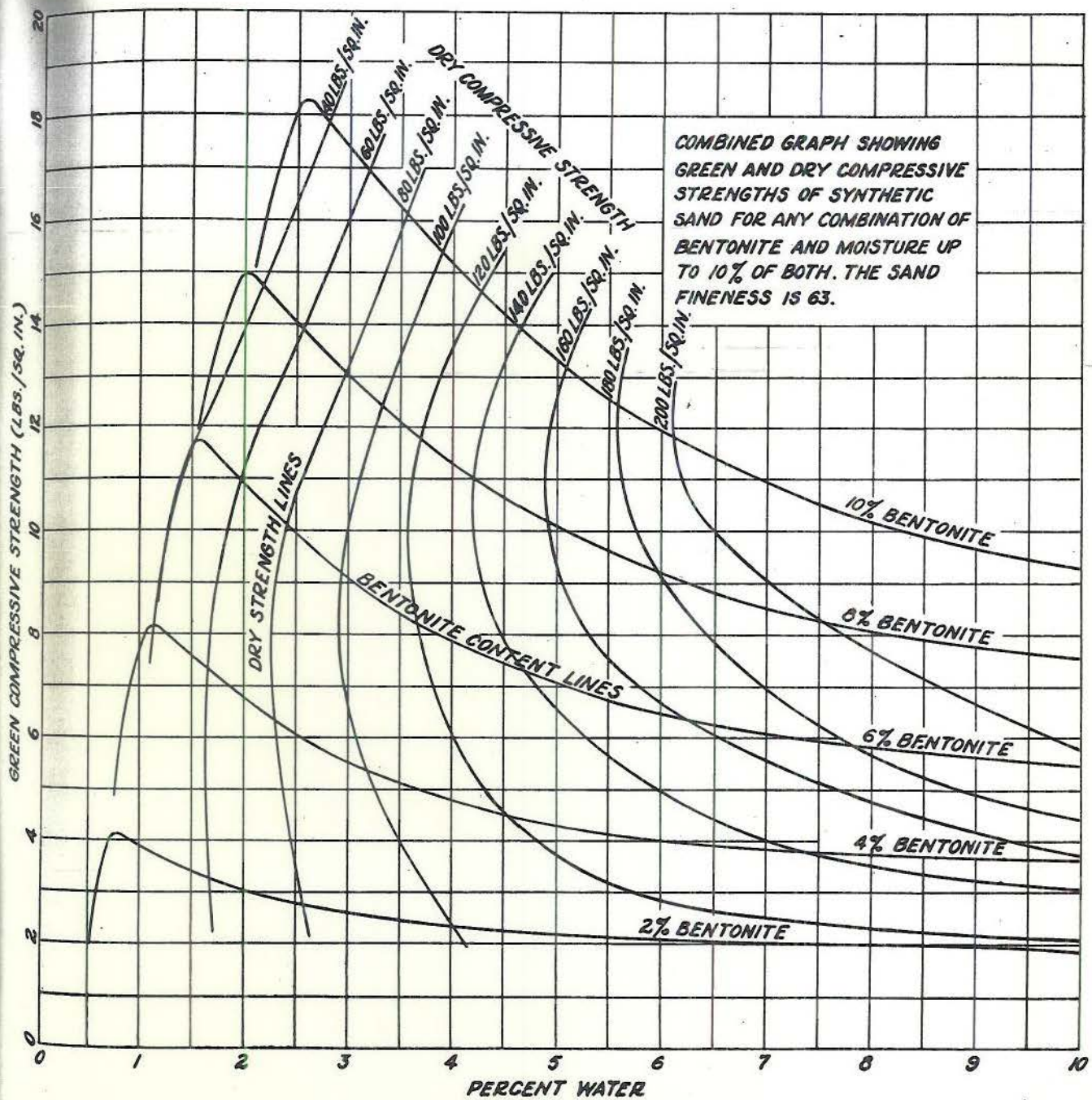
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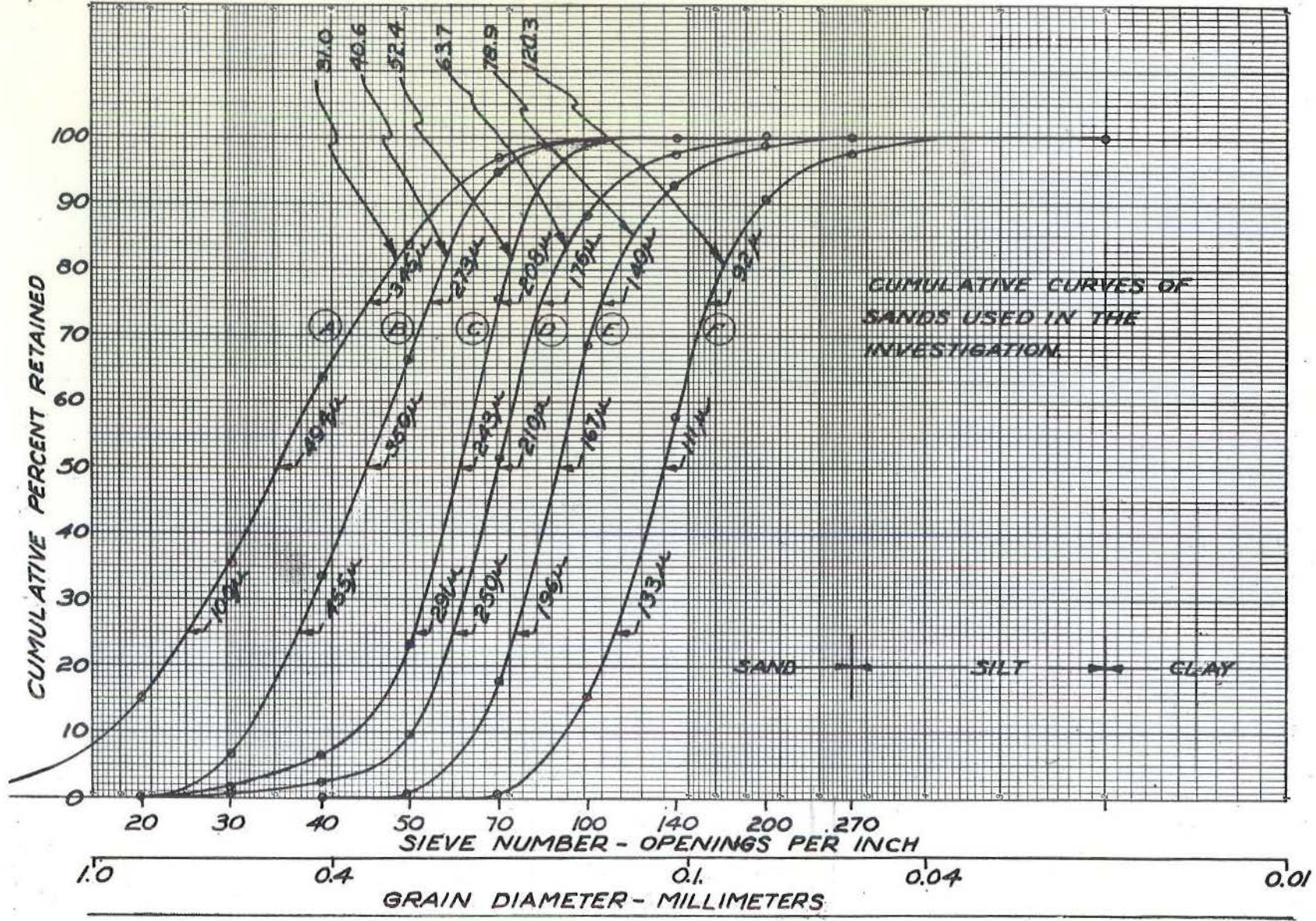
TEST RESULTS

No. of Mix	Type of Clay	Amount of Clay	Size of Sand	Amount of Sand	Other Bonding Material	Water Content	Weight of Specimen	Green Permeability	Green Compressive Strength	Deformation	Resilience	Flowability	Dry Permeability	Dry Compressive Strength
7A	Bentonite	5%	31.0	95%	None	1.35	169.0	417	9.28	0.0107	99.3	87.4	-	-
7B	"	"	"	"	"	1.90	165.0	467	11.31	0.0191	216.0	80.8	550	82.0
7C	"	"	"	"	"	2.53	165.0	440	8.23	0.0265	218.0	80.2	550	111.5
7D	"	"	"	"	"	3.51	168.0	370	6.70	0.0328	220.0	81.8	550	126.1
7E	"	"	"	"	"	4.50	171.0	326	5.90	0.0391	231.0	82.5	550	130.4
7F	"	"	"	"	"	5.55	173.5	287	5.11	0.0398	198.0	84.3	550	135.5
7G	"	"	"	"	"	7.45	177.5	224	4.39	0.0424	186.0	85.9	550	145.1
7H	"	"	"	"	"	10.30	184.5	126	4.00	0.0391	156.0	87.0	525	169.0
8A	Bentonite	5%	40.6	95%	None	1.23	165.0	268	8.59	0.0115	98.8	89.7	-	-
8B	"	"	"	"	"	1.79	161.0	313	12.27	0.0124	152.0	85.7	376	66.1
8C	"	"	"	"	"	2.36	159.0	341	8.37	0.0196	164.0	81.7	467	106.5
8D	"	"	"	"	"	3.45	162.0	317	6.16	0.0285	175.5	83.1	467	127.4
8E	"	"	"	"	"	4.30	164.0	287	5.20	0.0328	170.6	84.0	458	132.6
8F	"	"	"	"	"	5.41	166.5	253	4.54	0.0348	158.0	85.1	467	138.8
8G	"	"	"	"	"	7.41	171.0	190	3.89	0.0367	142.8	86.3	440	168.5
8H	"	"	"	"	"	9.64	175.0	135	3.55	0.0372	132.0	87.0	440	177.5
9A	Bentonite	5%	52.4	95%	None	1.17	156.5	153	6.16	0.0096	59.1	90.9	-	-
9B	"	"	"	"	"	1.70	152.5	203	9.25	0.0138	127.7	86.1	226	51.6
9C	"	"	"	"	"	2.48	151.5	212	6.38	0.0210	134.0	82.5	264	110.2
9D	"	"	"	"	"	3.46	153.5	207	4.92	0.0280	137.8	83.2	275	139.5
9E	"	"	"	"	"	4.44	156.0	186	4.47	0.0314	140.3	83.8	275	152.1
9F	"	"	"	"	"	5.29	157.0	173	3.94	0.0324	127.8	84.2	279	172.9
9G	"	"	"	"	"	7.68	161.0	142	3.29	0.0360	118.4	85.3	283	200.2
10A	Bentonite	5%	63.7	95%	None	1.38	152.5	120	8.31	0.0116	96.4	87.2	-	-
10B	"	"	"	"	"	1.83	149.5	145	8.23	0.0141	117.3	83.1	173	69.5
10C	"	"	"	"	"	2.44	149.5	146	6.03	0.0195	117.5	80.6	188	109.4
10D	"	"	"	"	"	3.53	151.5	141	4.80	0.0264	126.7	82.0	193	154.8
10E	"	"	"	"	"	4.49	153.2	133	4.21	0.0304	128.0	82.4	195	180.7
10F	"	"	"	"	"	5.51	155.0	123	3.96	0.0314	124.3	84.0	198	202.6
10G	"	"	"	"	"	7.69	159.0	101	3.72	0.0326	121.2	84.2	198	235.9
10H	"	"	"	"	"	10.01	163.0	82	3.33	0.0328	109.2	84.8	193	265.1
11A	Bentonite	5%	70.8	95%	None	1.46	158.0	81	12.11	0.0111	134.6	89.1	-	-
11B	"	"	"	"	"	1.92	153.5	94	11.35	0.0154	174.7	83.3	120	-
11C	"	"	"	"	"	2.41	153.5	99	7.90	0.0218	172.3	81.4	129	-
11D	"	"	"	"	"	3.63	156.0	90	5.85	0.0293	171.4	82.7	131	-
11E	"	"	"	"	"	4.48	157.5	88	5.03	0.0344	173.0	83.5	137	-
11F	"	"	"	"	"	5.42	159.5	81	4.64	0.0340	157.7	83.7	134	-
11G	"	"	"	"	"	7.99	164.5	61	4.15	0.0409	169.7	85.0	126	-
11H	"	"	"	"	"	10.25	169.0	46	3.87	0.0385	149.0	85.6	116	-
12A	Bentonite	5%	120.3	95%	None	1.53	156.5	36	12.36	0.0105	129.7	83.3	40	39.8
12B	"	"	"	"	"	2.02	153.0	40	13.62	0.0122	166.2	82.3	48	83.7
12C	"	"	"	"	"	2.57	151.0	44	10.53	0.0171	180.2	80.5	57	142.6
12D	"	"	"	"	"	3.50	153.5	44	7.58	0.0253	192.0	80.3	60	135.3
12E	"	"	"	"	"	4.48	155.5	42	6.52	0.0302	197.0	80.1	60	213.9
12F	"	"	"	"	"	5.60	157.5	40	5.88	0.0302	178.0	80.5	58	242.7
12G	"	"	"	"	"	7.66	162.0	34	5.20	0.0359	186.7	82.6	58	275.1
12H	"	"	"	"	"	10.00	166.0	29	4.84	0.0351	170.0	82.3	52	-

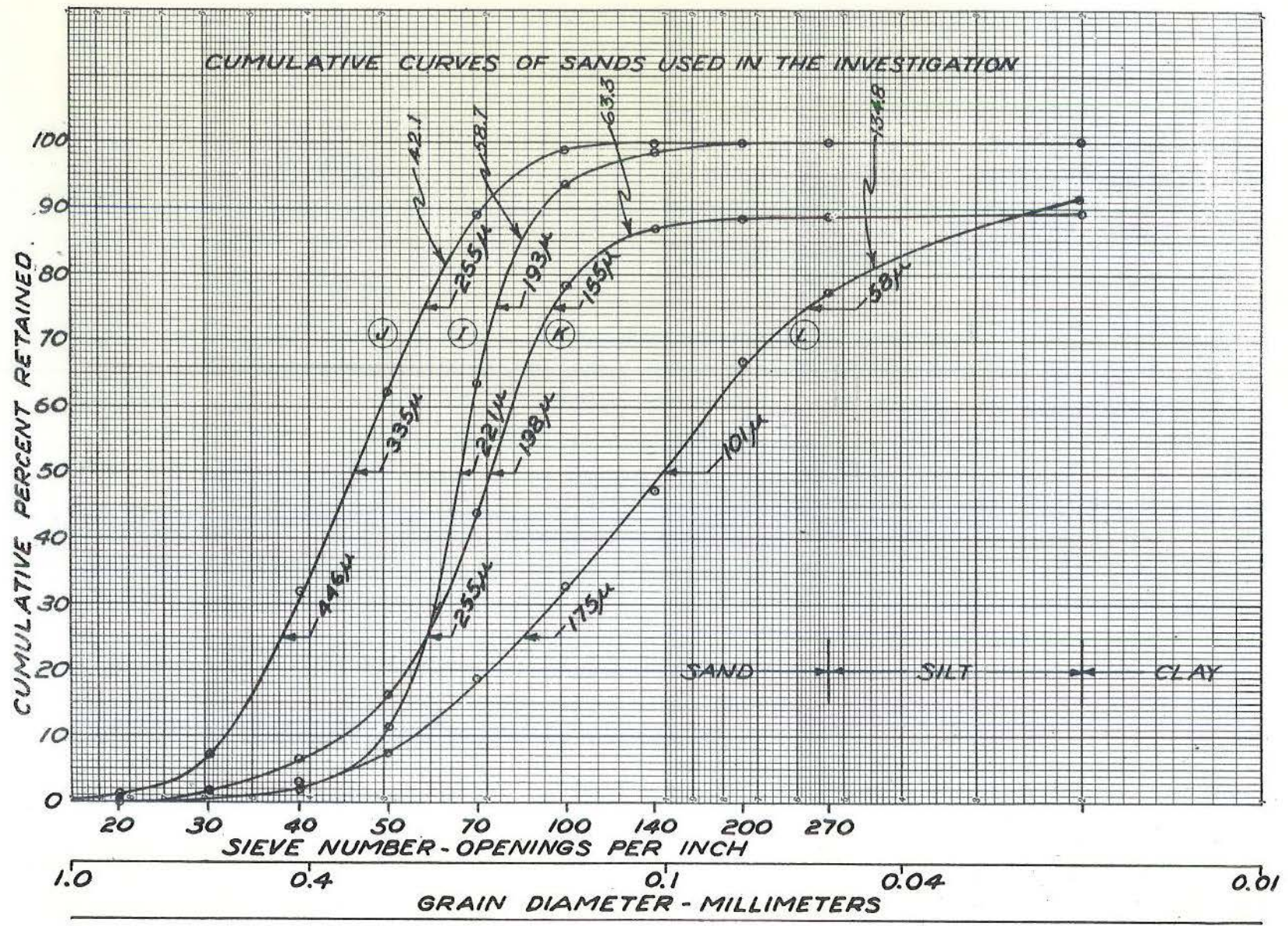








CUMULATIVE CURVES OF SANDS USED IN THE INVESTIGATION



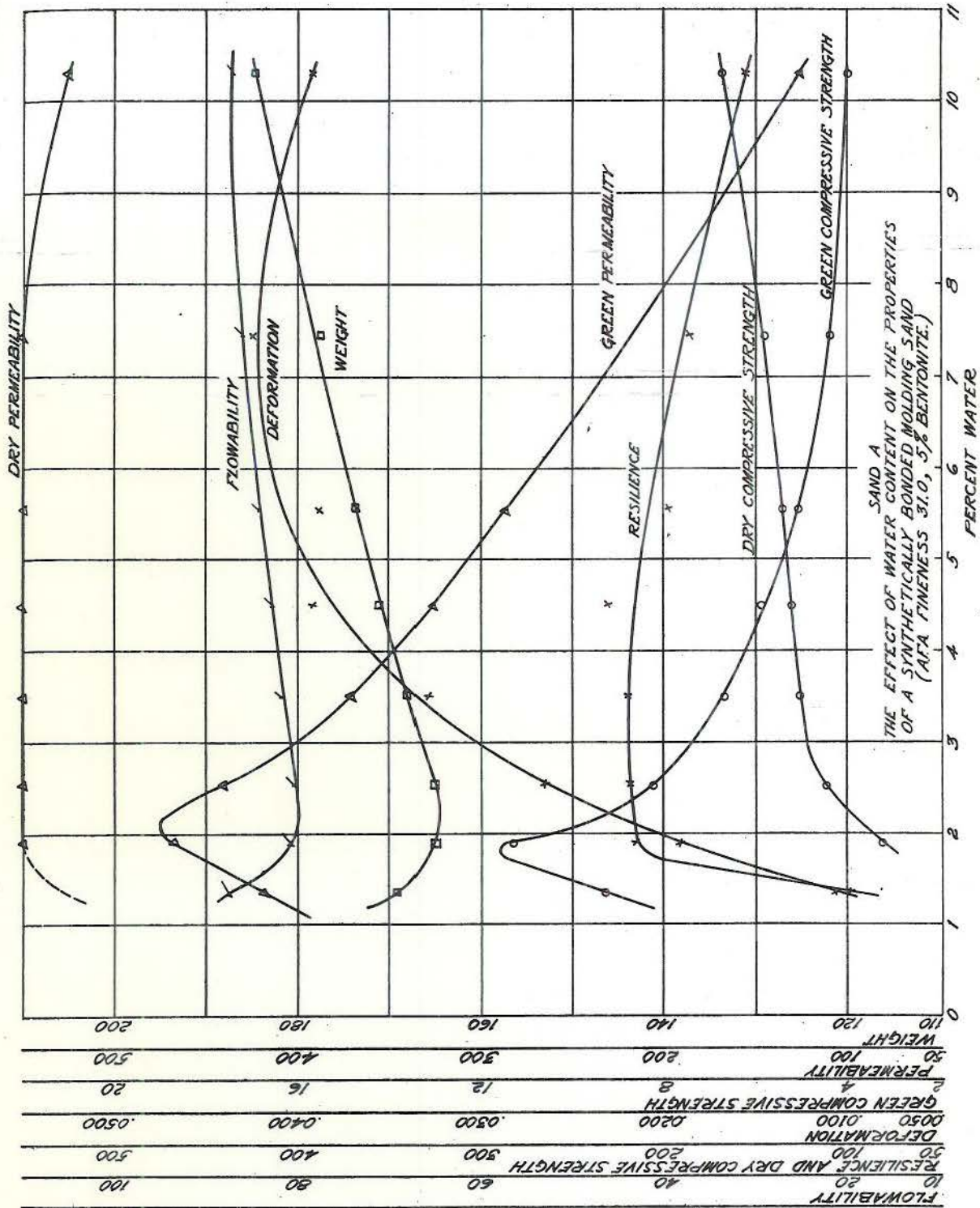
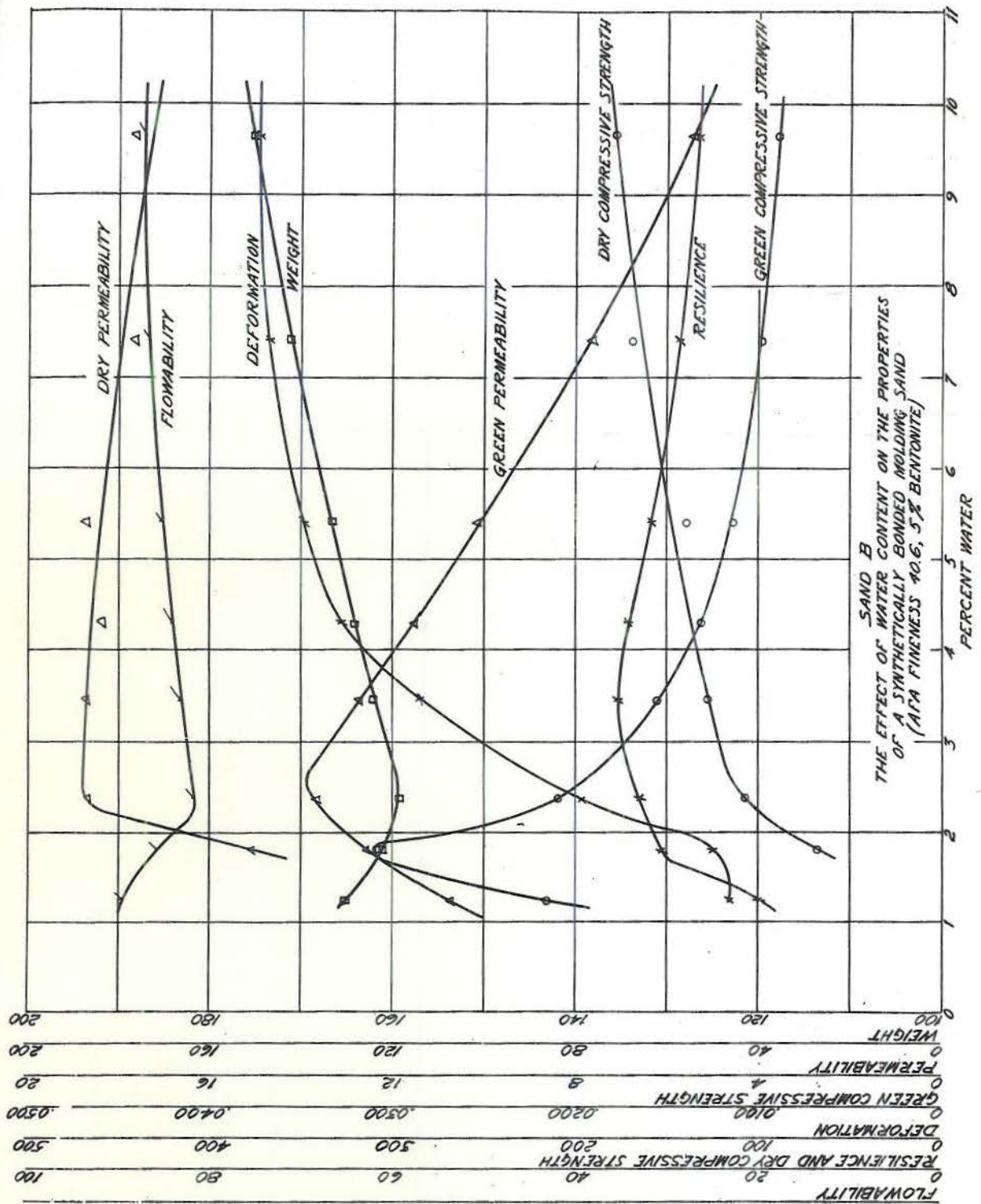
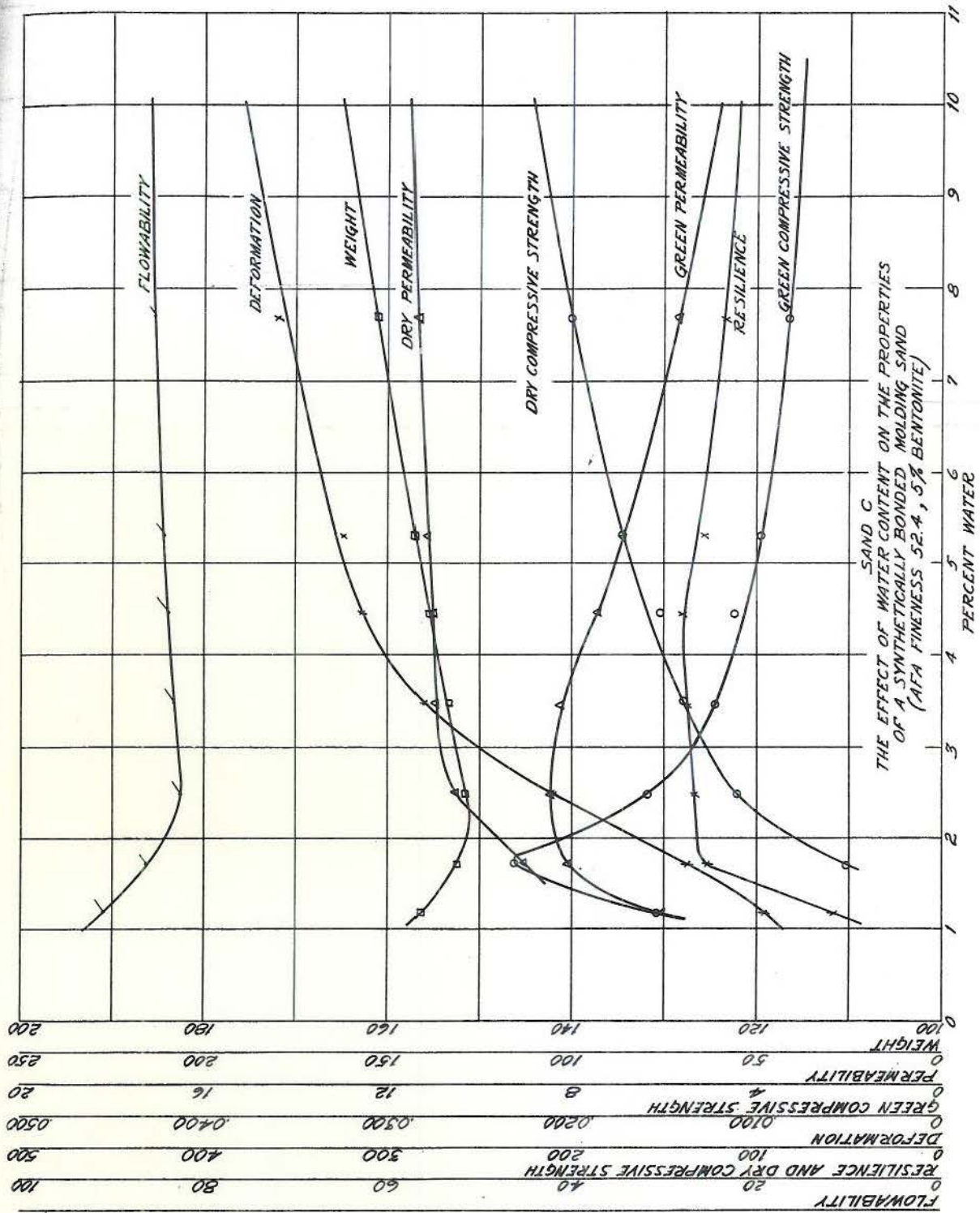
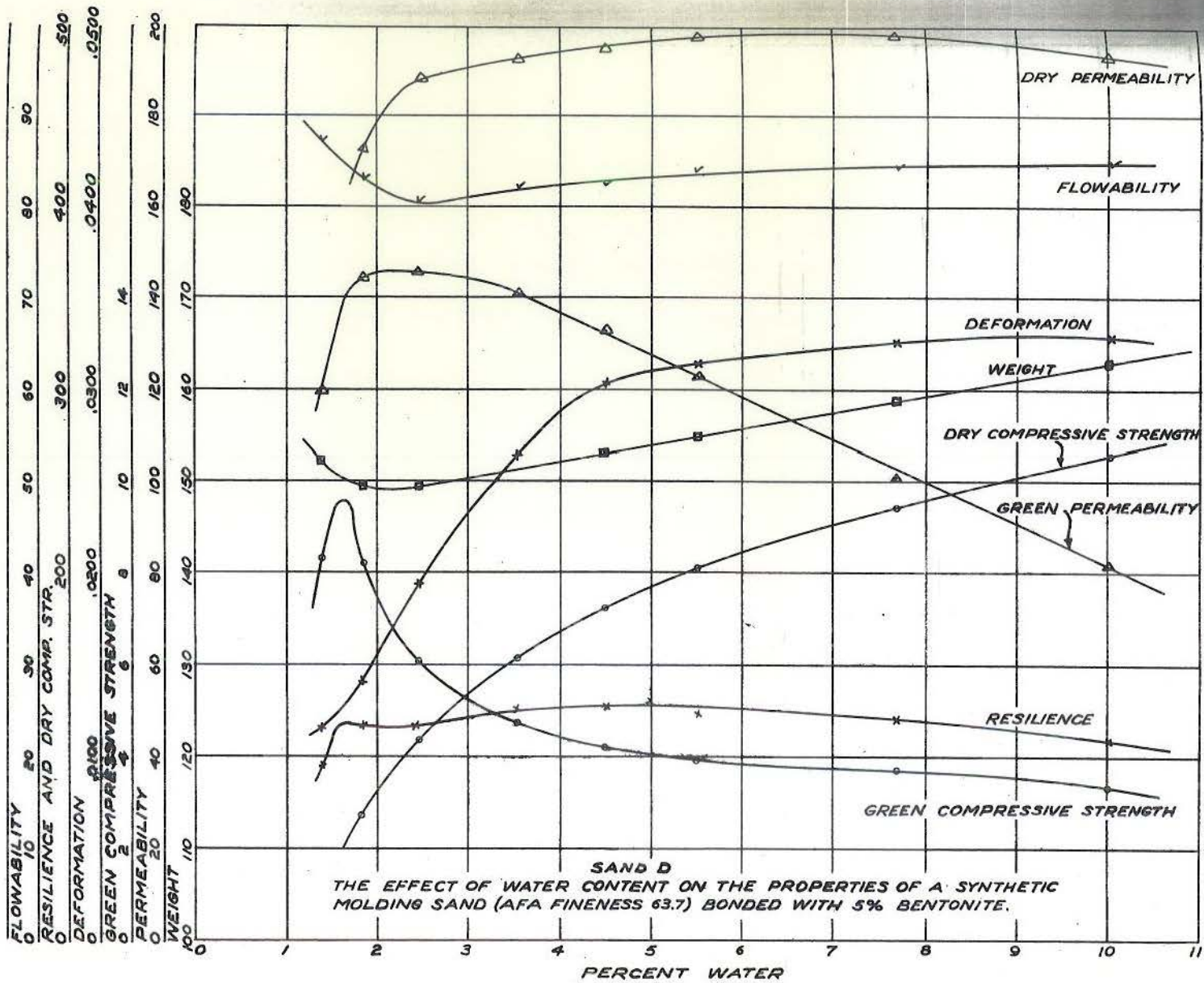


PLATE 7







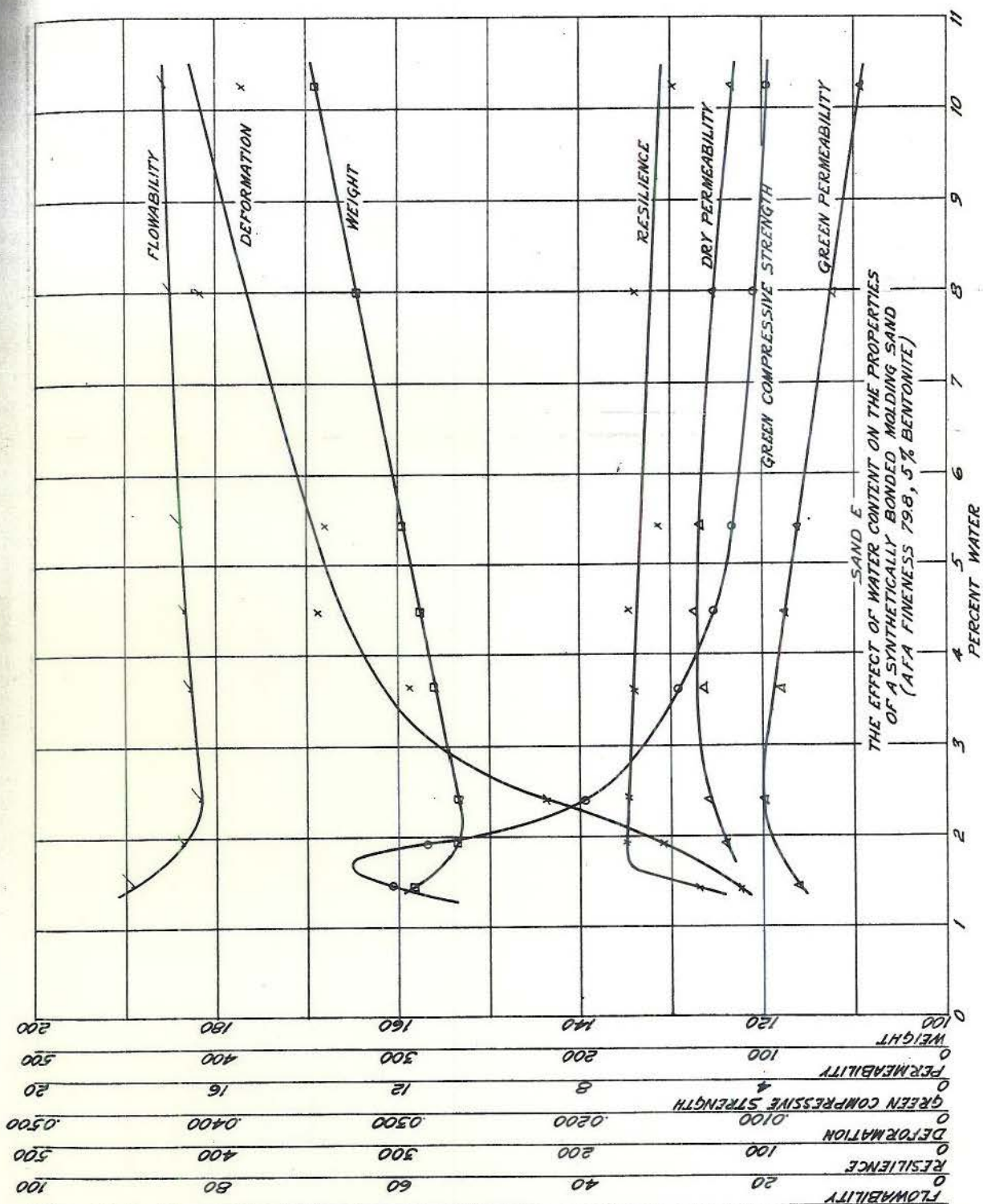
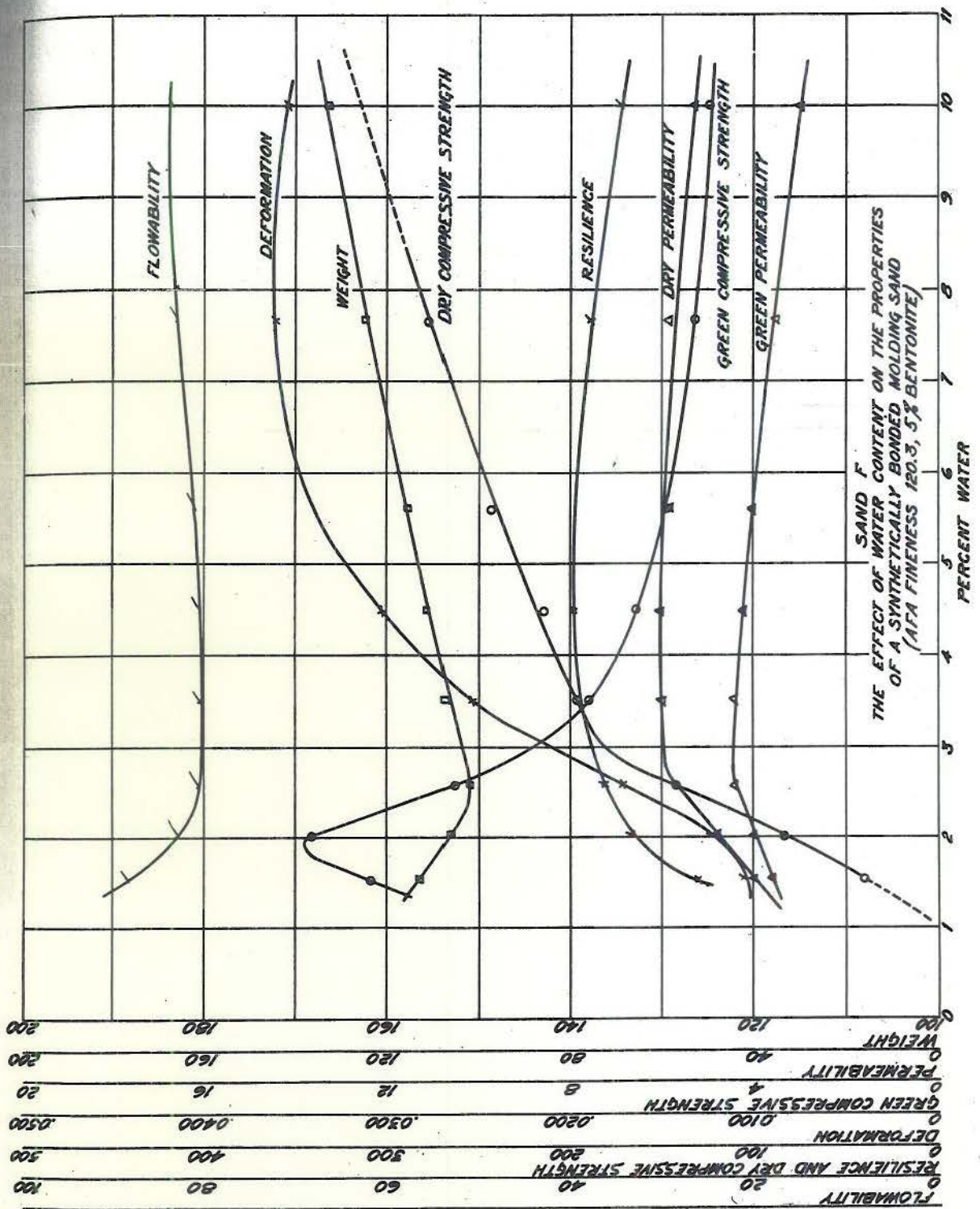
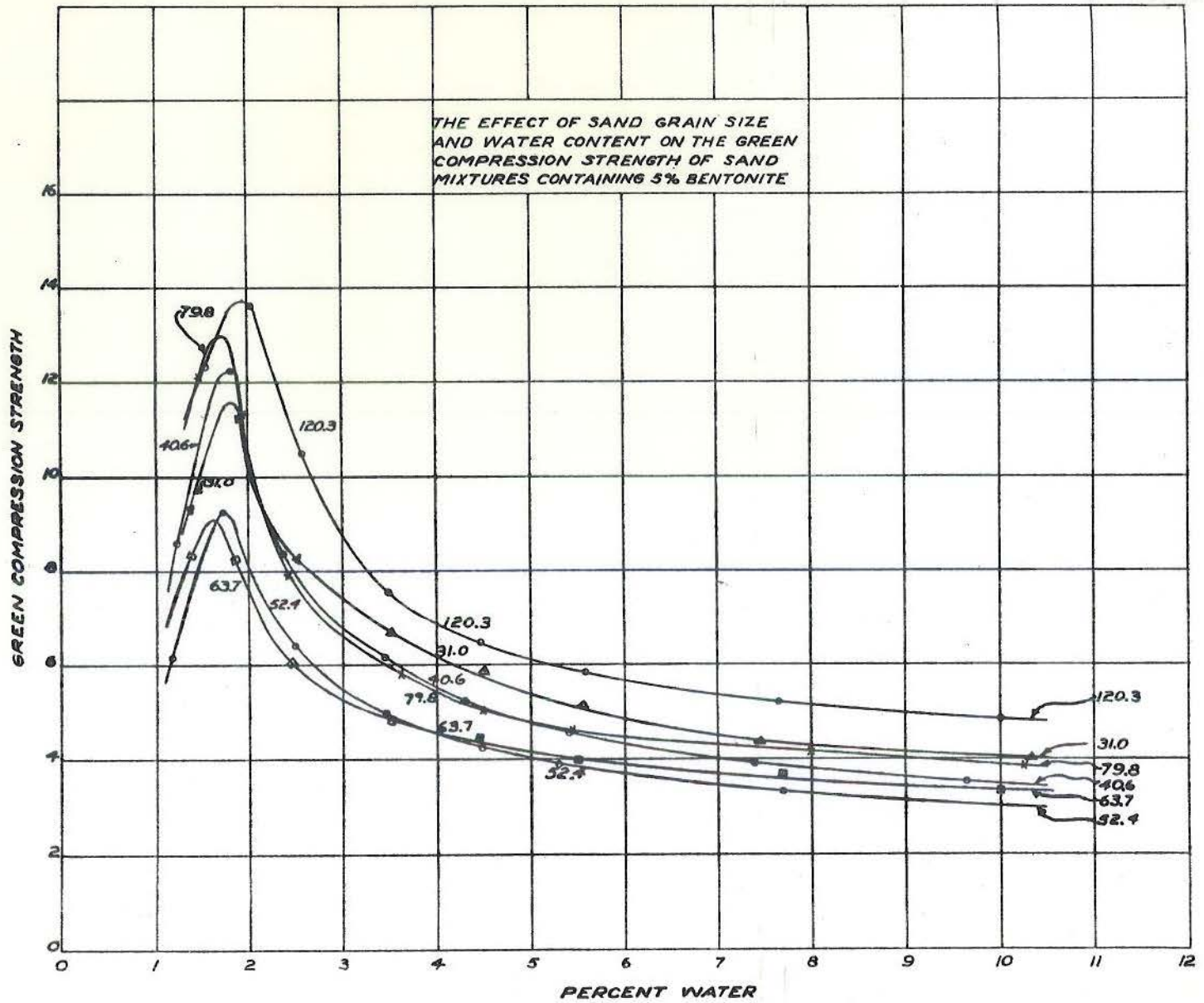


PLATE II



THE EFFECT OF SAND GRAIN SIZE AND WATER CONTENT ON THE GREEN COMPRESSION STRENGTH OF SAND MIXTURES CONTAINING 5% BENTONITE



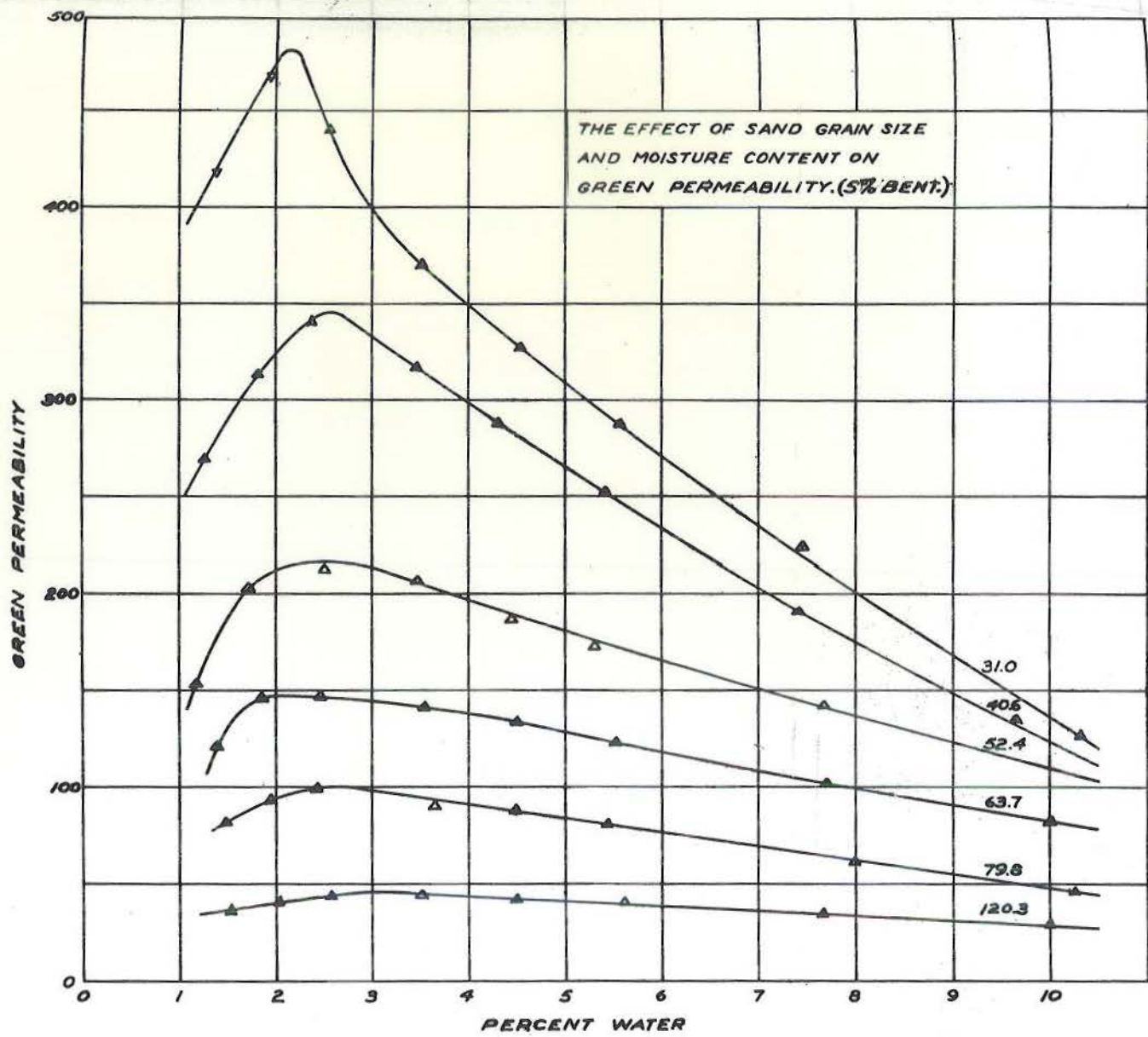
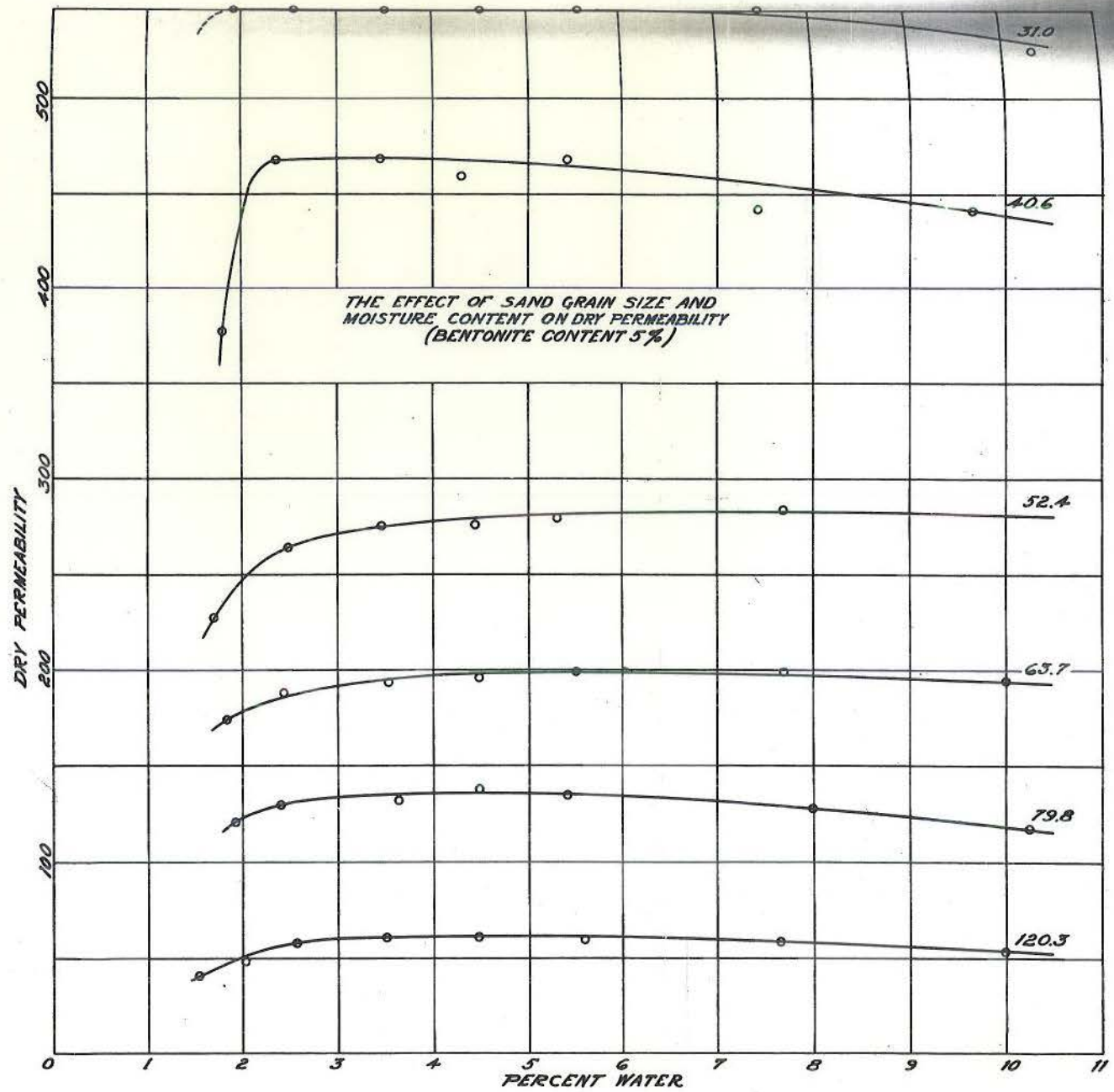


PLATE 14



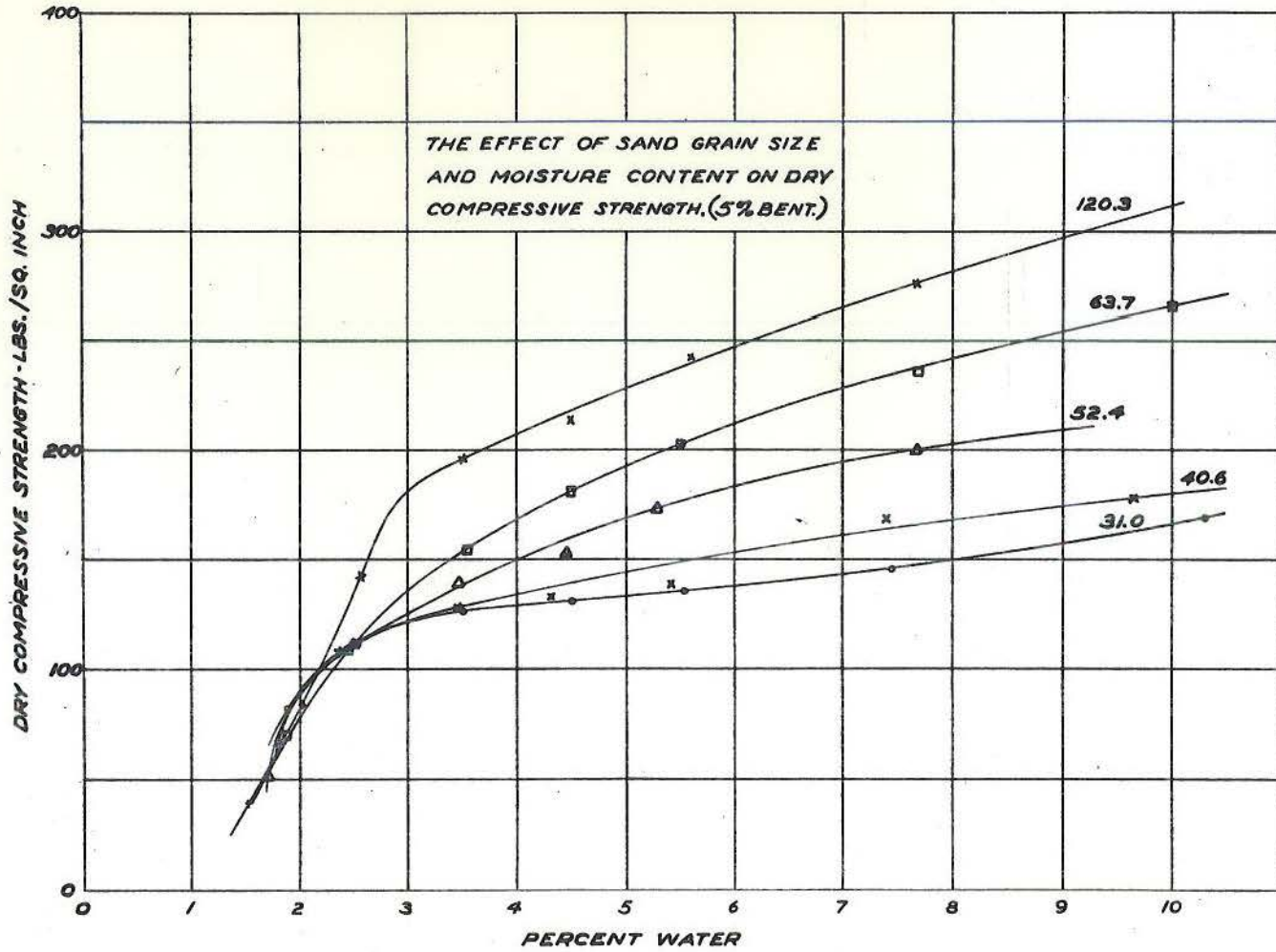
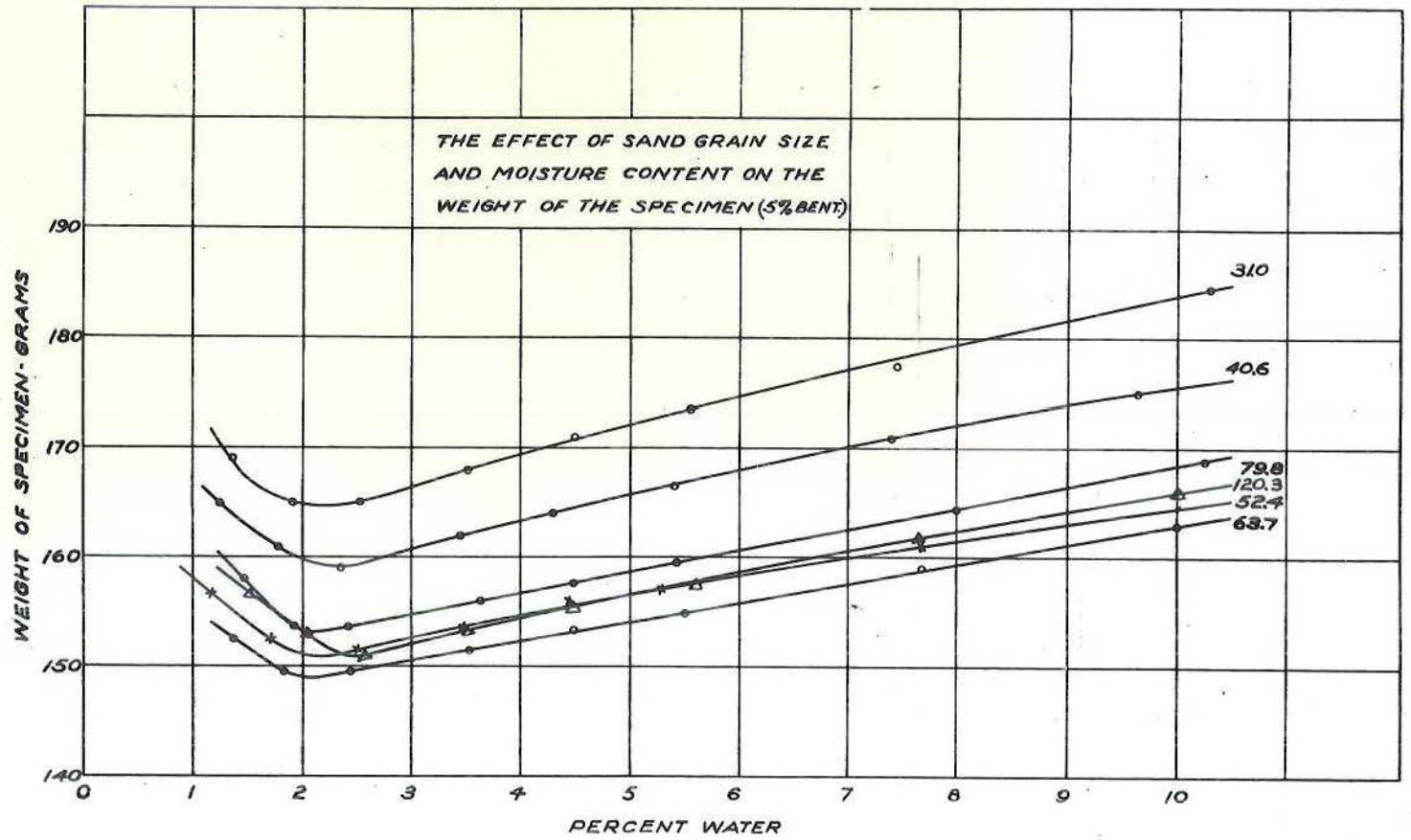
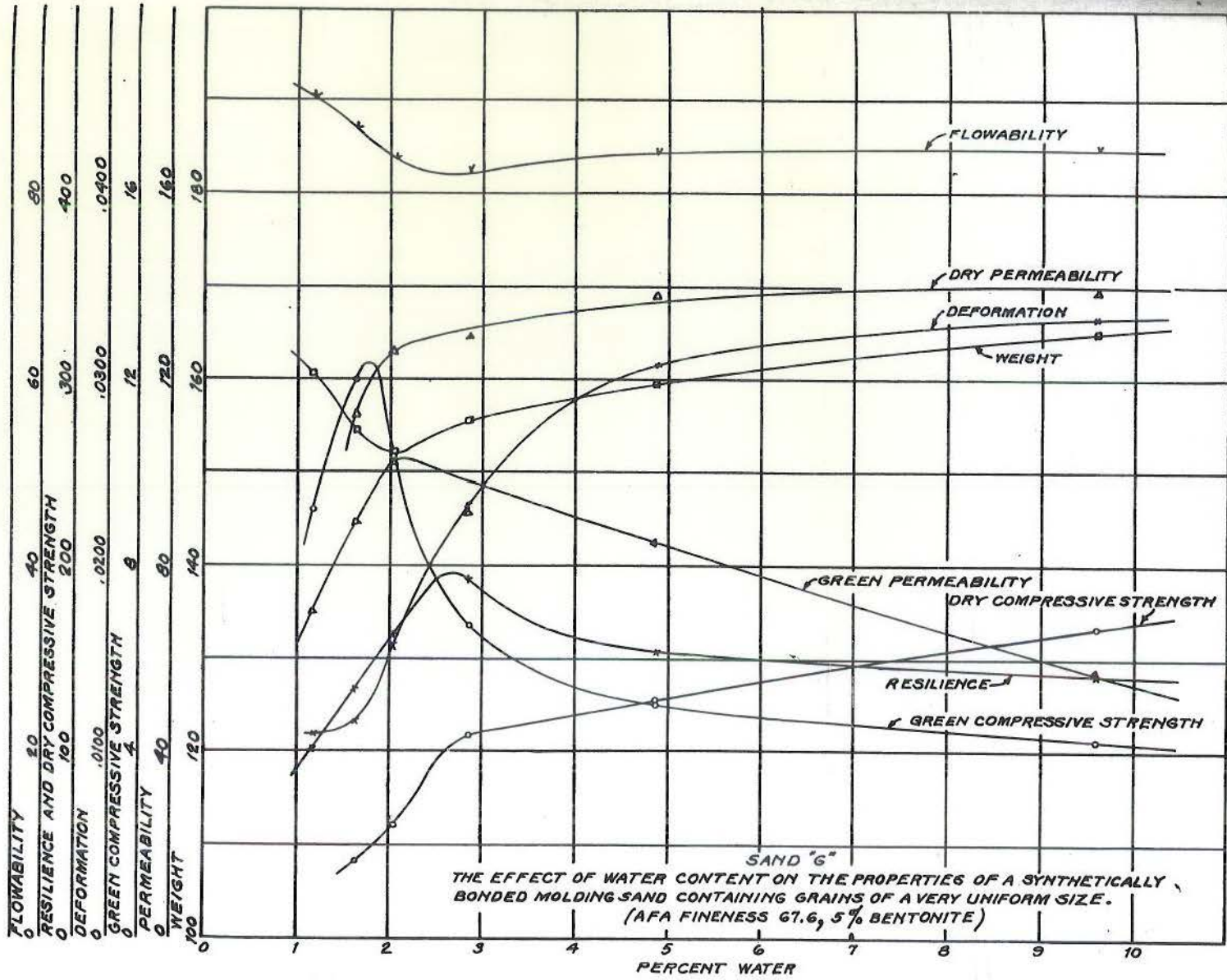
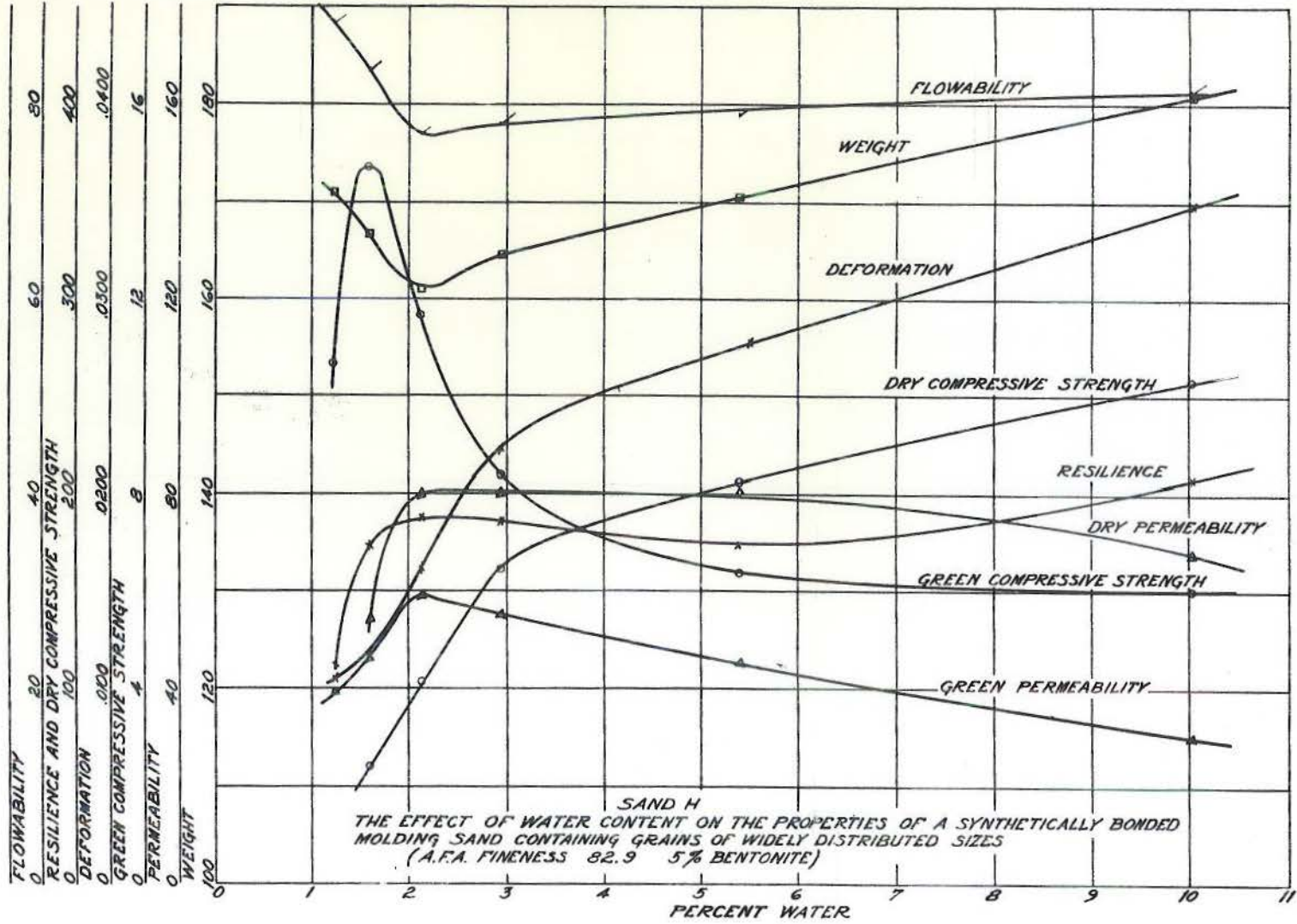
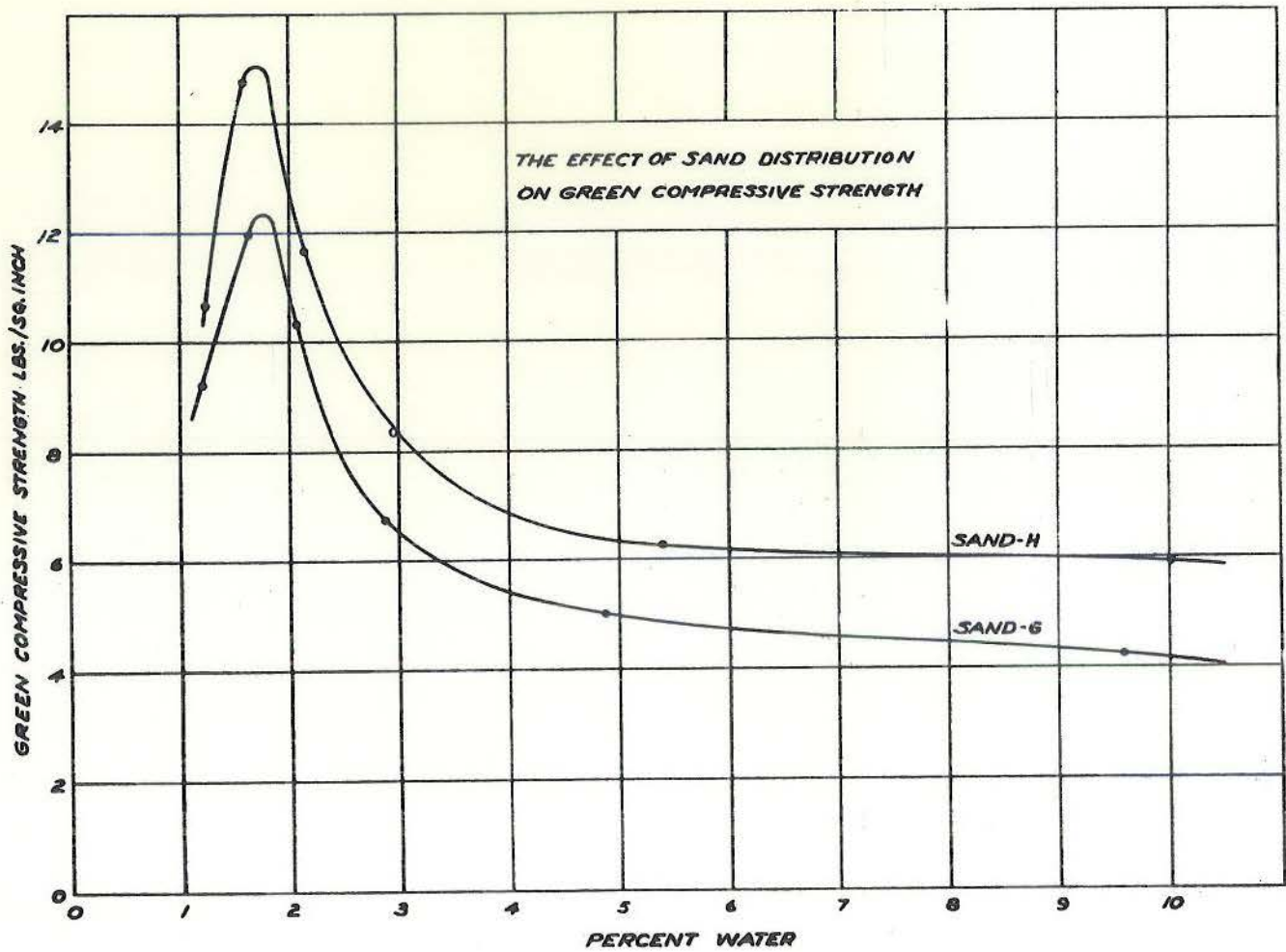


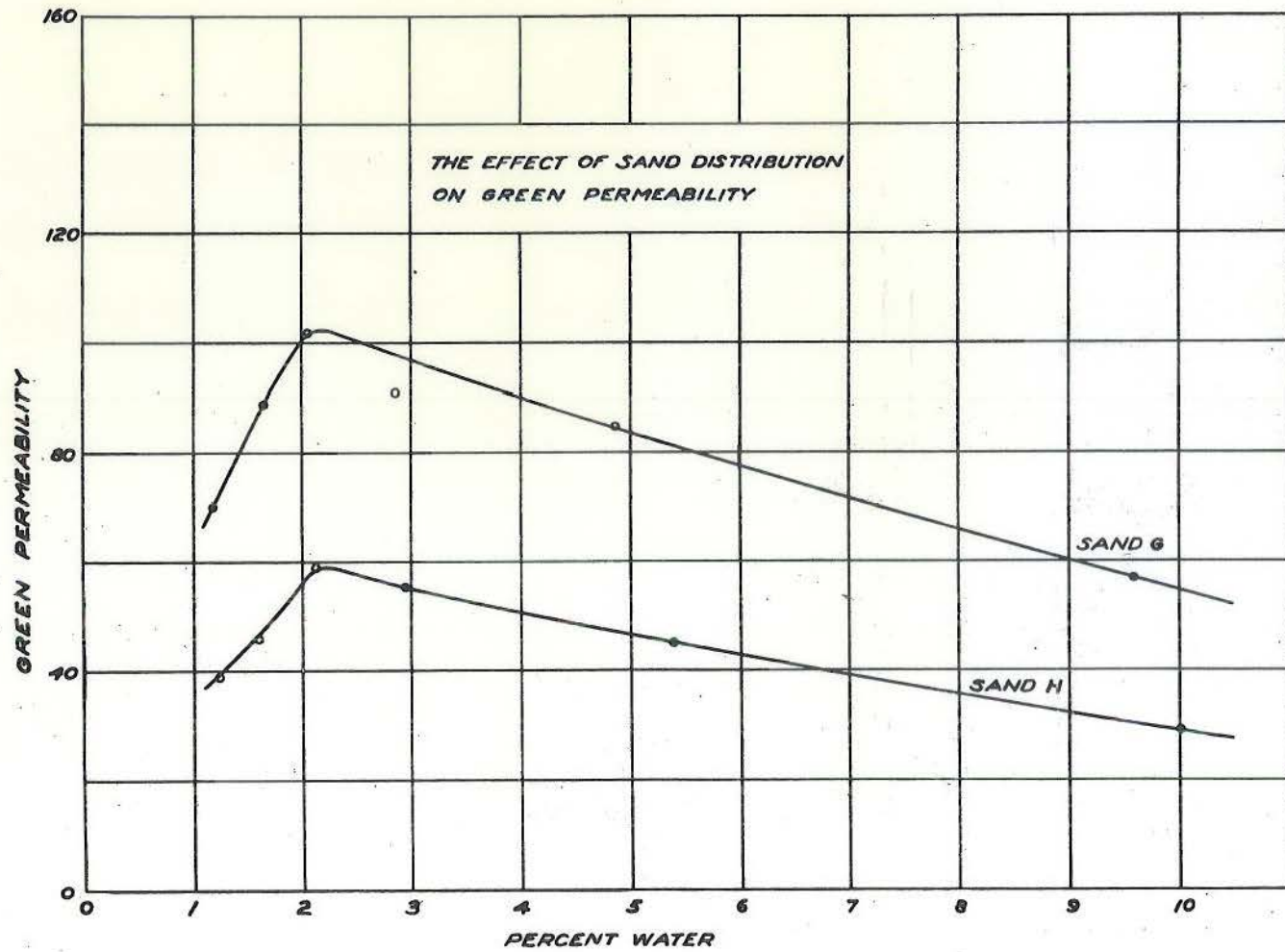
PLATE 16

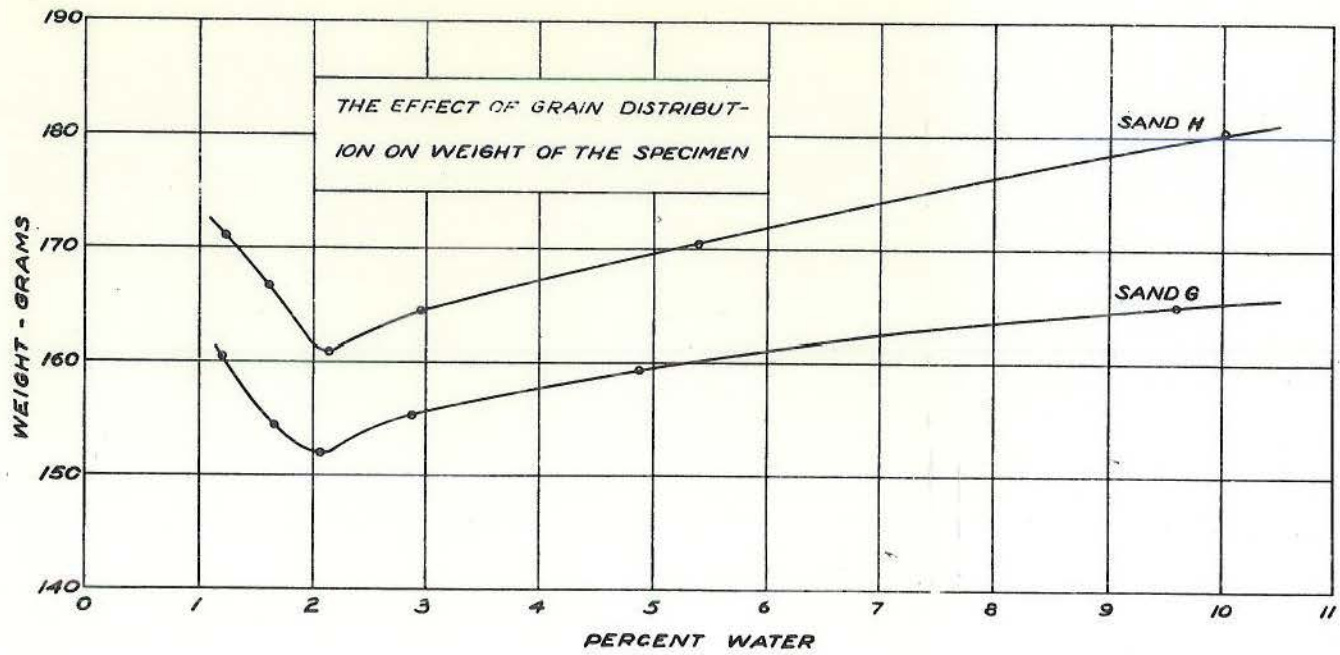


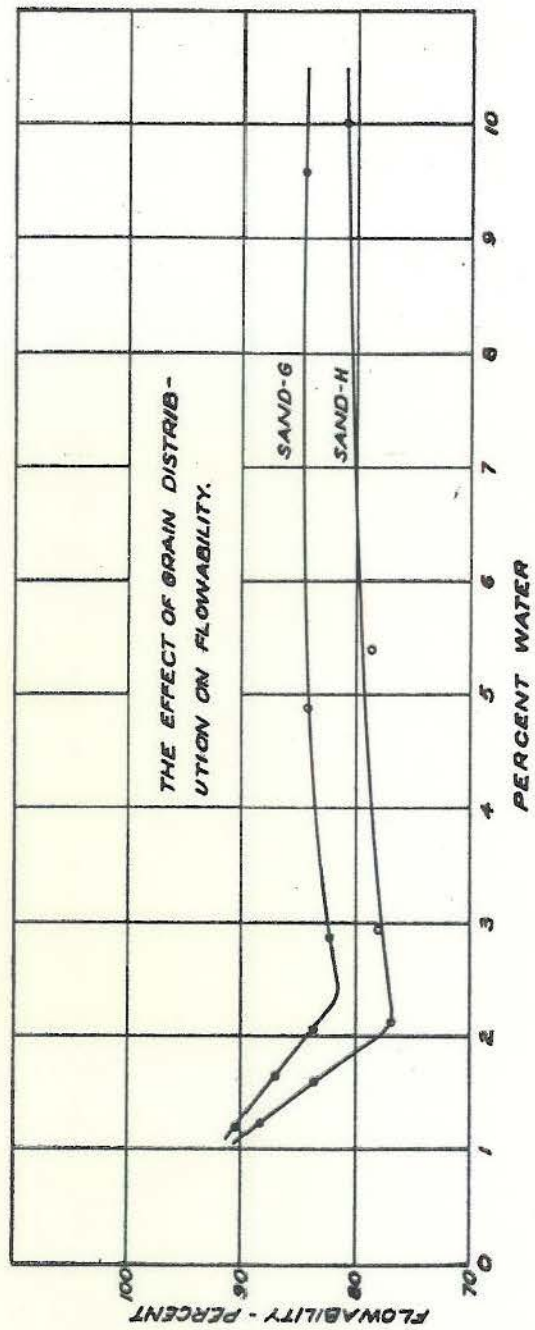


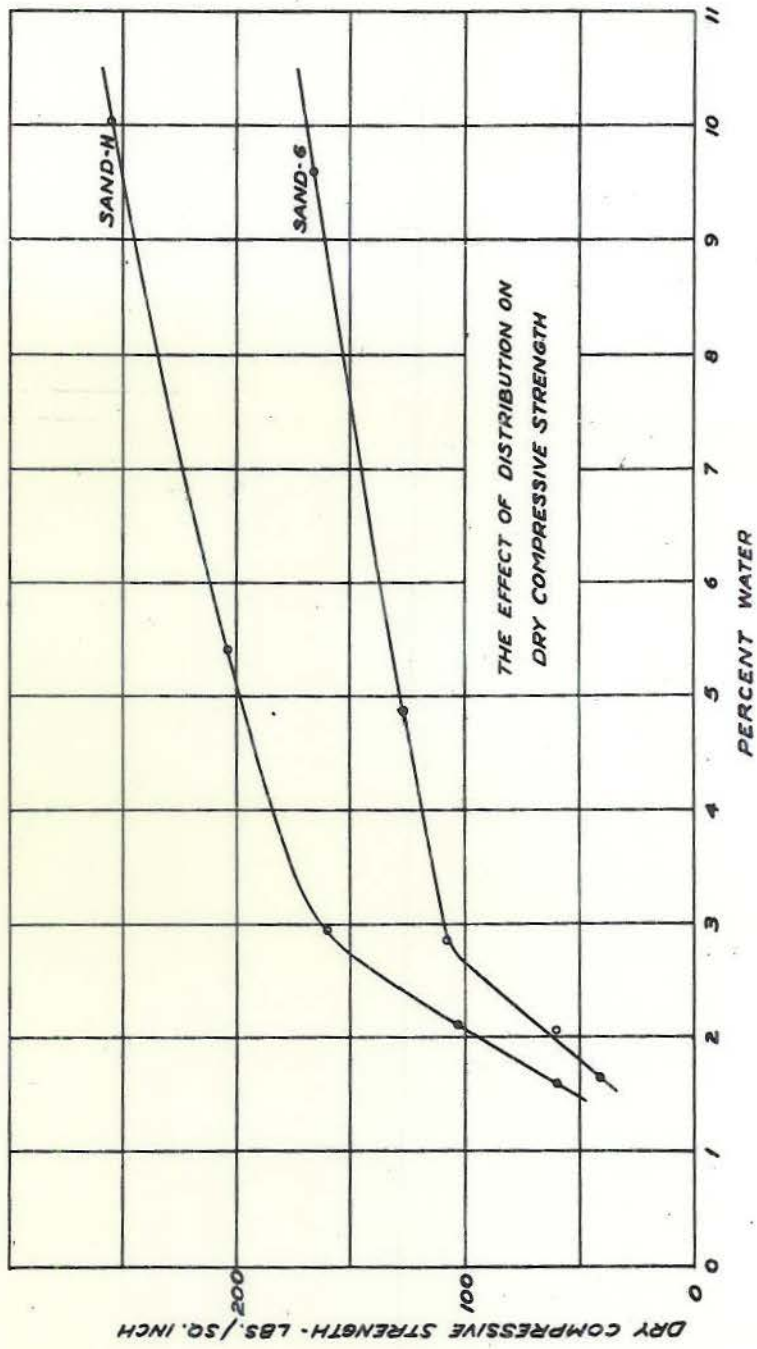


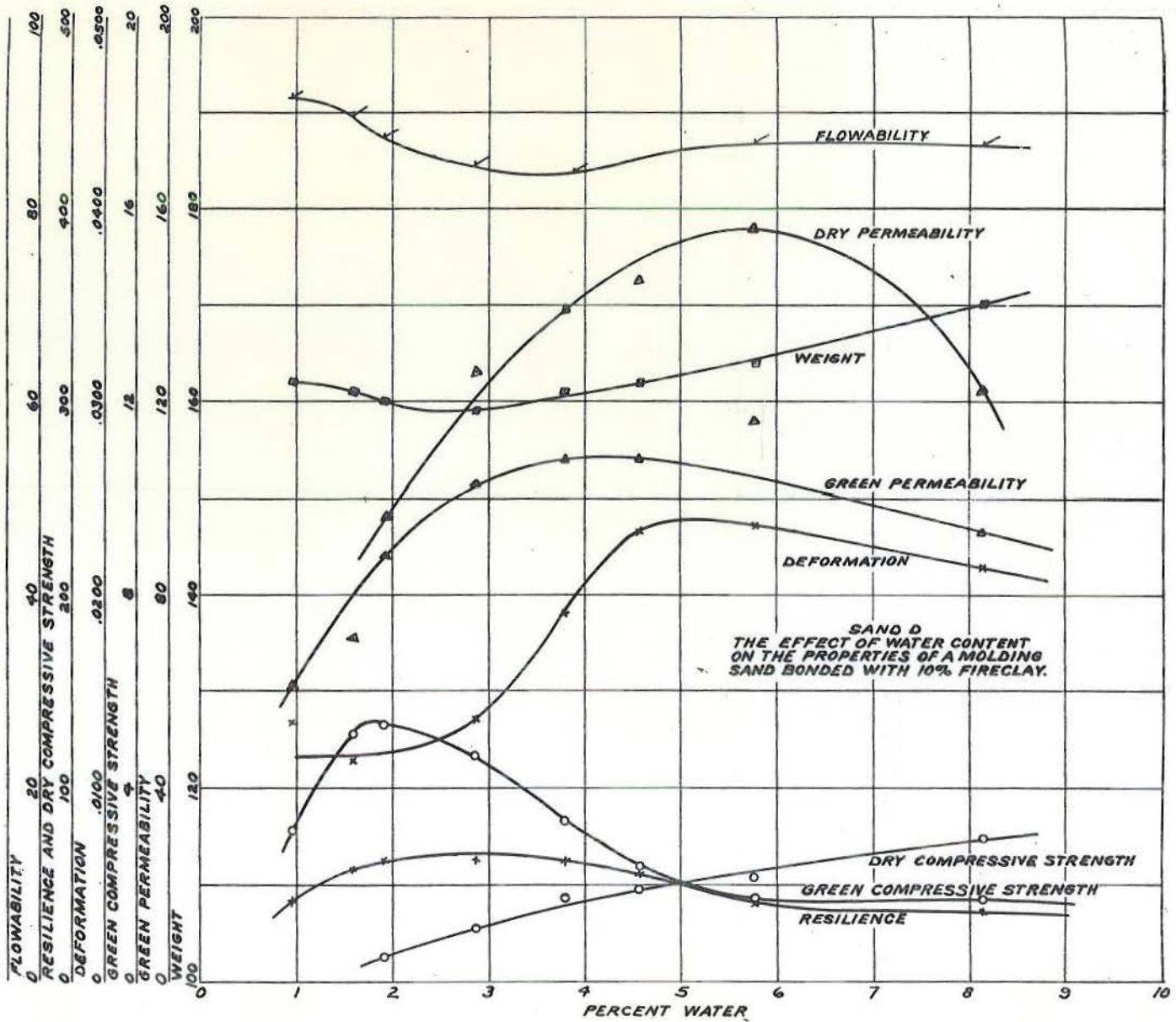


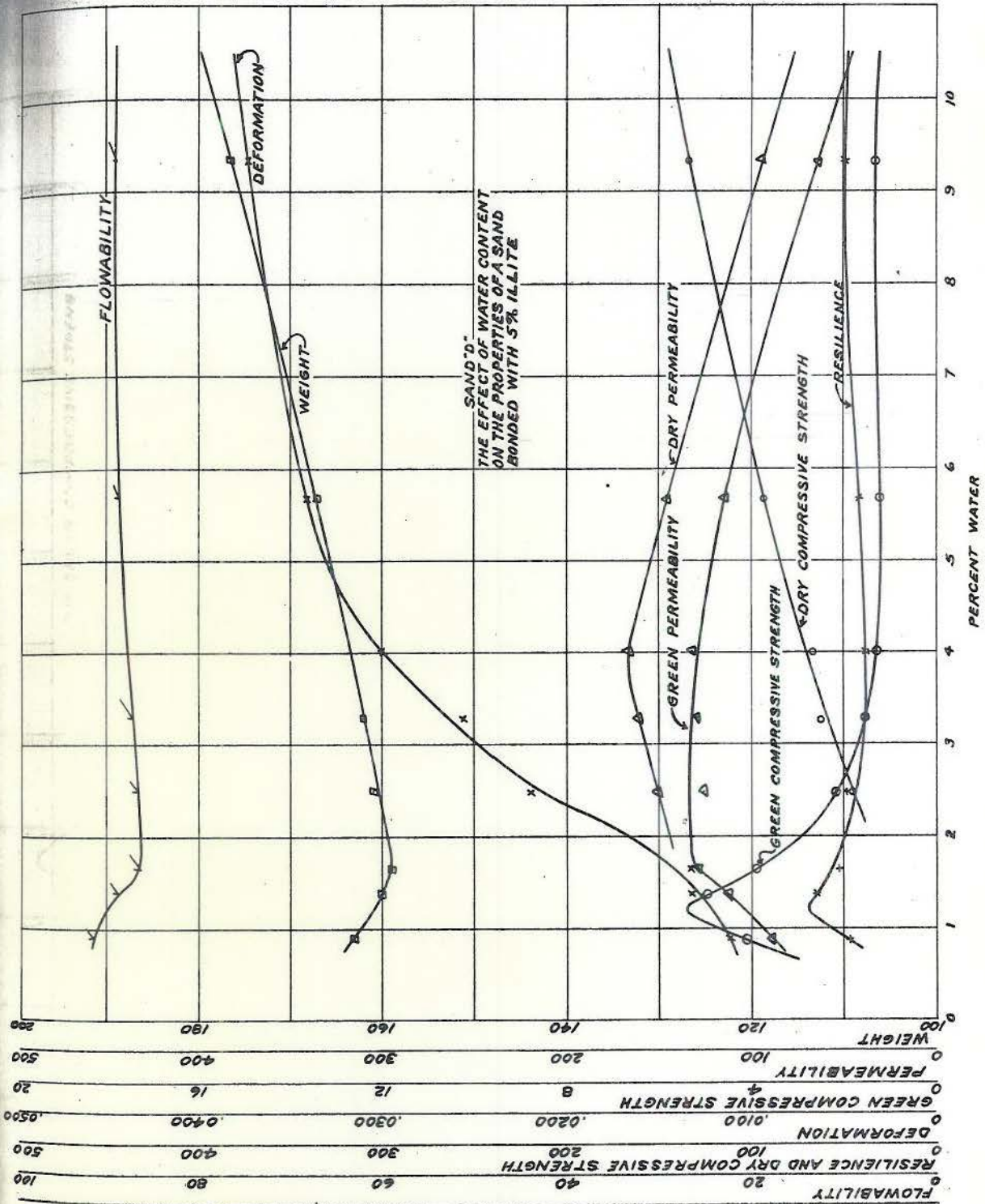


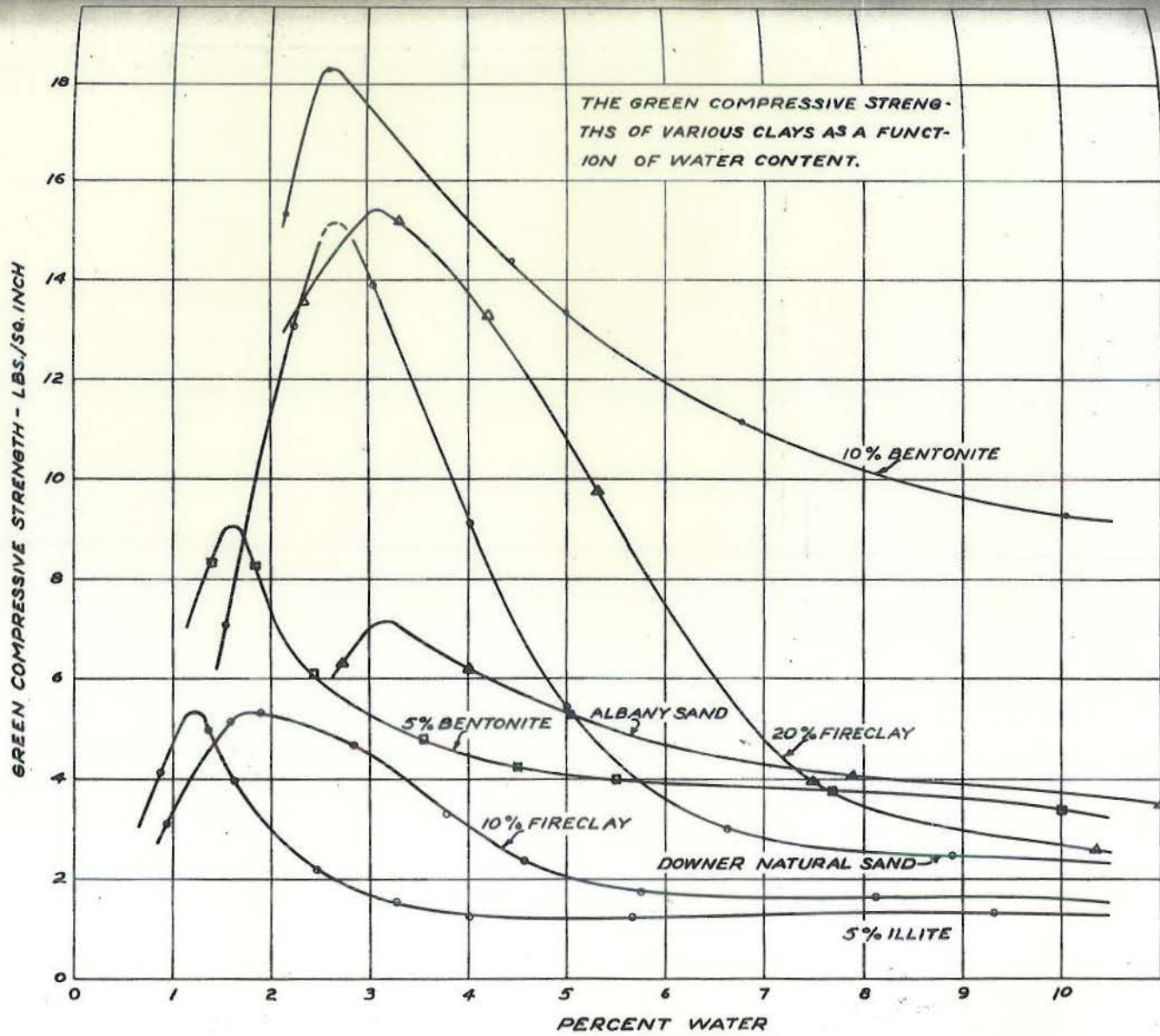












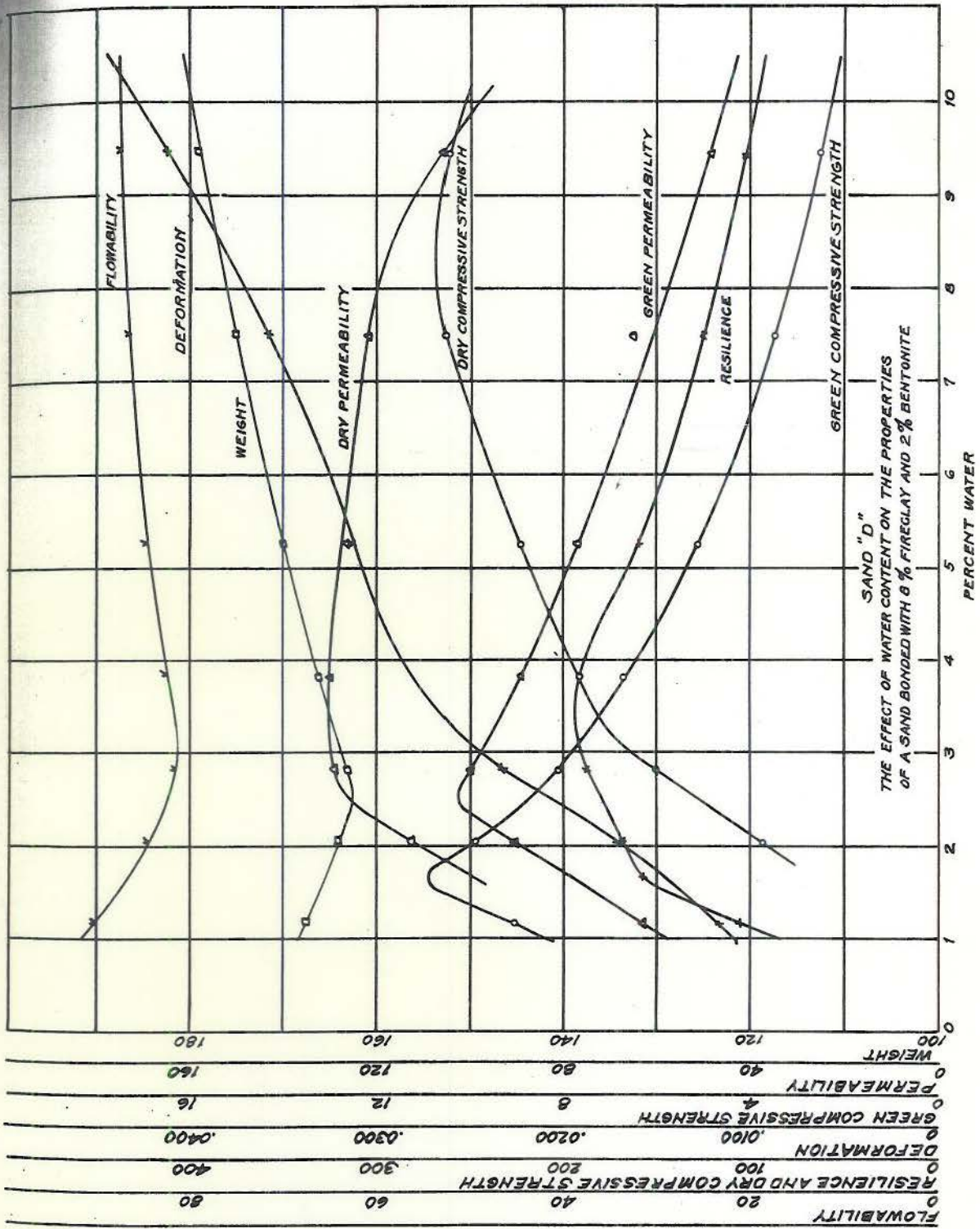


PLATE 30

