

Maximum Density and Optimum Moisture of Soils

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The present prospect that many states and public agencies will be making use of data from the AASHO test road means that there will be need to relate the evidence from tests on the Illinois material to similar tests on local soils.

Many engineers seem to believe that the term "maximum compaction" is the ultimate state of compaction obtainable and that each soil has a single definite "optimum moisture" content. Data are offered to show that there are several standards in use throughout the United States, each of which will produce a different maximum compaction and indicate a different optimum moisture for a given soil. The purpose of this paper is to point out some of the relationships that exist and call attention to the fact that increased compaction effort may or may not produce high density and that increased density may or may not be beneficial, depending upon the materials and circumstances.

It is concluded that the terms "maximum compaction" and "optimum moisture" are purely relative and have a definite meaning only when all conditions are described.

●THE practice of transporting and placing earth materials to form fills or embankments for highway construction is older than the term "highway" itself. In fact, the very name was adopted in ancient times to describe the more ambitious roads that had been built up above the surrounding terrain and hence were called "high" ways to distinguish them from the casual paths or byways. It is fairly well known that the construction of a modern highway or airport generally involves the moving of a considerable amount of dirt followed by the shaping and compacting of large areas to receive and support a pavement. Such a shaped and compacted area is called a subgrade. With higher standards of alignment and expansion of multilane freeways, the quantities of earth that must be moved often become tremendous, usually measured and paid for in the form of excavation.

For centuries, embankments were constructed by the most simple and direct methods, using hand-barrows or horse-drawn scrapers operating from side borrow pits. With the development of motorized equipment, longitudinal haul became more prevalent, moving material from the cuts and dumping it into the appropriate low areas that need to be brought up to grade. The construction of fills by end dumping methods continued into comparatively modern times and in certain cases is still the only feasible method. However, with improved standards of alignment and the necessity for constructing higher fills, resulting settlements and subsidence became serious and these settlements were especially undesirable and troublesome when more or less permanent and expensive pavements were placed over the newly constructed embankments. It became evident that if a highway on new alignment was to be paved and opened to traffic immediately, fills or embankments would have to be consolidated or compacted if the pavement was to remain anywhere near the planned grade line.

Attempts were made in California and elsewhere about 1925 to meet this problem by overloading the deeper fills; that is, by building the fills temporarily above profile grade in an amount proportional to the depth of the fill. These "hump-backed" or "camel-backed" fills presented a rather novel appearance in an otherwise conventional grade line but, with the well-known perversity of inanimate things, most of the fills refused to settle where the greatest surcharge had been applied and all too often the greatest subsidence occurred at the ends of the fill near the point of junction with the existing ground. This effect accentuated the hump in the center so this expedient was soon discarded.

The California Division of Highways' Standard Specifications for 1927 included the requirement that all embankments be constructed in layers and much argument and controversy developed because the specifications also required contractors to distribute

haul equipment over the entire surface. About 1929, the Division adopted the practice of requiring that the layers be thoroughly rolled in order to forestall settlements. This requirement immediately raised the question of control and demanded a means for checking the contractors' operations. The following is quoted from a paper written by T. E. Stanton in 1938 (1).

"The first work along this line was done by the California Division of Highways in 1929 when an extensive series of tests was conducted from which was developed field equipment and methods of consolidating soil samples to determine optimum moisture requirements before construction and subsequently the relative compaction of the completed embankment. This procedure and equipment was adopted as standard in August, 1929, and has been in use without substantial change to the present date.

"About 1933 the engineers of the Bureau of Water Works and Supply of the city of Los Angeles conducted a similar study, the results of which were described in a series of articles by R. R. Proctor, field engineer of the bureau, published in several issues of Engineering News-Record, beginning August 31, 1933.

"Proctor describes a field consolidation outfit somewhat different from the California Division of Highways equipment but using similar consolidation procedure."

The Proctor method (2) of compaction control became widely known, and led to the widespread adoption of similar control test procedures such as the Standard AASHTO method. With the tremendous expansion of military construction, particularly of airfields during the war years, the Corps of Engineers stepped up the compaction requirements by adopting a compaction procedure known as the Modified AASHTO which sets a much higher standard of density and, as will be shown later, produces results closely comparable to those obtained by the long established California Impact Method. The army engineers had concluded that if embankments were to withstand the increasingly heavy loads and propeller vibration of military planes a higher standard of construction compaction would have to be established. Thus, some 27 years ago engineers began to talk about maximum density and optimum moisture of soils and today many seem to believe that these terms express fundamental basic constants like the gravity constant or the boiling point of water.

Table 1 lists the essential details of certain compaction test procedures used by various agencies under the designation shown. It will be noted that while these various procedures have general similarities and that all accomplish compaction by the impact of a rammer there are differences in the weight of the ram and in the drop as well as the depth and number of layers of soil. The diameter of the ram and the area of the face are the same, however, for all of those listed. It is also pertinent to note that the California Impact and Mechanical Compactor methods are the only ones permitting coarse stone up to $\frac{3}{4}$ -in. in size. All others exclude coarse particles above No. 4.

Charts, Figures 1 through 8 represent typical curves showing moisture-density relationships for a series of soils selected to provide a range of types and on each chart the moisture-density curve as determined by the various methods is shown. It is clearly evident that there are marked differences in the maximum dry weight per cubic foot obtained by these different "standard" laboratory procedures. It is also evident that the devices giving the higher density generally indicate a lower percentage of moisture as "optimum." These charts then demonstrate a fact that is well known to many engineers; namely, that as the compactive force is increased the moisture content needed to produce maximum density is generally reduced. An examination of these charts leads also to the strong presumption that if the so-called optimum moisture is a variable depending upon the force and the efficiency of effort exerted in a laboratory test, it is also a variable depending upon the type or weight of rollers used during actual construction. Table 2 lists the maximum density and optimum moisture for ready comparison. By referring to this table or to Figures 1 through 8, it will be noted that there is a fairly consistent order in the maximum density values produced in a soil by the several compaction methods under consideration. First, it is evident that in all cases the Standard AASHTO produces the lowest dry weight per cubic foot and the optimum moisture content is higher than for the other methods. On the same relative scale, the Proctor method produces the next higher "maximum" density with a corresponding reduction in optimum moisture, but the California Impact Method and the Modified AASHTO are con-

TABLE 1
RELATIVE COMPACTION TEST METHODS IN USE BY VARIOUS AGENCIES
Summary of Laboratory Apparatus and Procedure

Test Identification	Std. AASHO	Bureau Rec.	Std. Proctor	Calif. Impact	Mod. AASHO
MOLD:					
Diameter, in.	4"	4"	4"	3"	4"
Height, in.	4 $\frac{5}{8}$ "	6"	4 $\frac{5}{8}$ "	10-12"	4 $\frac{5}{8}$ "
Volume, cu.ft.	$\frac{1}{30}$	$\frac{1}{20}$	$\frac{1}{30}$	Var.	$\frac{1}{30}$
TAMPER:					
Weight, lbs.	5.5	5.5	5.5	10.0	10.0
Free drop, in.	12"	18"	Struck ^a	18"	18"
Face diam., in.	2"	2"	2"	2"	2"
Face area, in.	3.1"	3.1"	3.1"	3.1"	3.1"
LAYERS:					
Number, total	3	3	3	5	5
Surface area, each, sq. in.	12.6	12.6	12.6	7.1	12.6
Compacted thickness, each	1 $\frac{5}{8}$	2 $\frac{1}{8}$	1 $\frac{5}{8}$	2 $\frac{1}{4}$	1
EFFORT:					
Tamper blows per layer	25	25	25	20	25
Ft.-lbs. per cu. ft.	12,375	12,375		33,000	56,250
MATERIAL:					
Max. size (passing)	#4	#4	#4	$\frac{3}{4}$ "	#4
Correction for oversize	No	Yes	No	Yes	No

NOTES: All dimensions shown above are close, but not necessarily exact.

Layer thickness in all above except California Impact allow for $\frac{1}{4}$ " - $\frac{3}{8}$ " trim off of last layer.

^aProctor test employs a firmly rammed, or struck, blow from a 12" height instead of free drop.

While the basic procedures for AASHO and Proctor do not provide for compensation for rejected oversize aggregate, some agencies employing these tests do specify a correction method.

sistently higher and about at a standoff as they produce nearly identical weights on certain soils while they tend to alternate for top position on others. As mentioned before, with the exception of the California method these test procedures establish the density for the material passing a No. 4 sieve and this practice leads to difficulties and uncertainties in check tests and interpretation when the material placed on the road contains particles coarser than No. 4.

An examination of the curves, Figures 1 through 8, show that for many soils a difference in weight of ten pounds per cubic foot may exist between the maximum density established by the Standard AASHO as compared with the Modified AASHO or with the California Impact. Viewed as a percentage, the data show a 10 percent range for a clean sand and less than 5 percent difference for a silty sand. One question naturally arises after an examination of these data—Which one most nearly simulates the density to be expected on the road with modern rollers and construction equipment? Or, which "standard" laboratory procedure shows the best parallelism with the density to be expected on the job? This problem has confronted all engineering organizations dealing with the compaction of earth whether they were aware of it or not. For example, it has been noted many times in California that granular sandy gravels will

TABLE 2
COMPARISON OF COMPACTION TEST PROCEDURES

Maximum Density

Data from Figures 1 to 8								
Figure No.	1	2	3	4	5	6	7	8
Calif. Impact	111	118	103	129	115	105	128	144 ^a
Mod. AASHO	110	116	105	128	118	105	126	139
Proctor	108	111	98	124	112	98	122	133
Std. AASHO	103	107	95	121	98	95	119	130
Mech. Compactor	109			125	117	98	128	134

^aTen layer specimen.

Optimum Moisture Content

Data from Figures 1 to 8								
Figure No.	1	2	3	4	5	6	7	8
Calif. Impact	17	14	15	10	15	21	12	7
Mod. AASHO	18	14	17	10	12	19	12	8
Proctor	18	16	19	11	17	22	14	10
Std. AASHO	21	18	20	12	23	23	14	11
Mech. Compactor	19			9	15	21	13	10

Column 1. Sandstone and sand (40% coarse sandstone of Sp. Gr. 191 added to specimen for California impact test).

Column 2. Sandy, silty clay.

Column 3. Clean sand.

Column 4. Silty sand.

Column 5. Silty clay.

Column 6. Silty clay loam.

Column 7. Sandy, silty clay (from AASHO test road in Illinois).

Column 8. Crushed stone base (retained No. 4 eliminated).

compact quite readily and probably achieve the specified density with only a few passes of the roller or simply under the contractor's hauling equipment. On the other hand, clay soils and certain clay silts may be subjected to a tremendous amount of rolling and still fail to meet the specified density. It seems quite evident, based both on observation of results obtained on actual construction and upon theoretical considerations, that the arrangement of soil particles produced by impact within the confining space of a steel mold is not necessarily the same as that produced by steel or pneumatic tired rollers operating over large areas. It would not matter particularly whether the density obtained in the test method was consistently higher or lower than that which could be developed by construction equipment on the road. It is highly desirable, however, that the results with all types of soil should be reasonably parallel with those obtainable with construction equipment. While some of these devices may produce densities closer to the average densities obtained with certain soils on the road all fail to parallel construction compaction on all types of materials.

As part of a study seeking to improve the correlation between laboratory compaction and that obtained in the field, a series of samples were compacted in the California Impact test apparatus and the densities determined after differing numbers of blows per layer. The standard test procedure established in 1929 for this device has called for 20 blows of the hammer falling a distance of 18-in. on each of five layers approximately 2¼-in. deep, Figure 14. Figures 9 and 10 illustrate the smooth straight line curves obtained when the number of blows per layer is plotted on a semi-log scale against the density in pounds per cubic foot. This indicates an orderly increase in

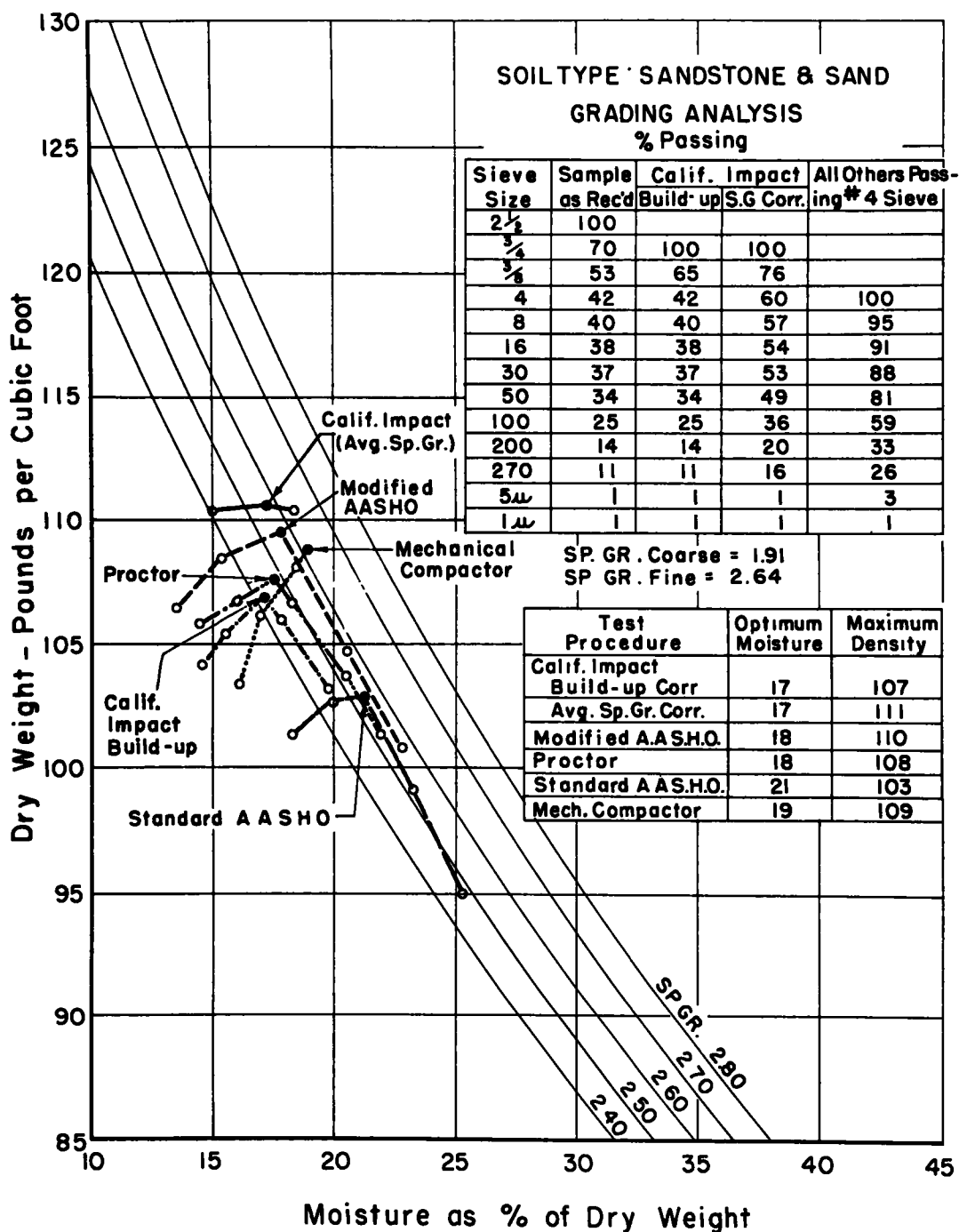


Figure 1. Comparison of various laboratory compacting procedures.

density that varies directly as the log of the number of blows per layer. Figures 9 and 10 therefore show a consistent increase in density for all materials when subjected to an increasing number of blows per layer of soil. As the density obtained under

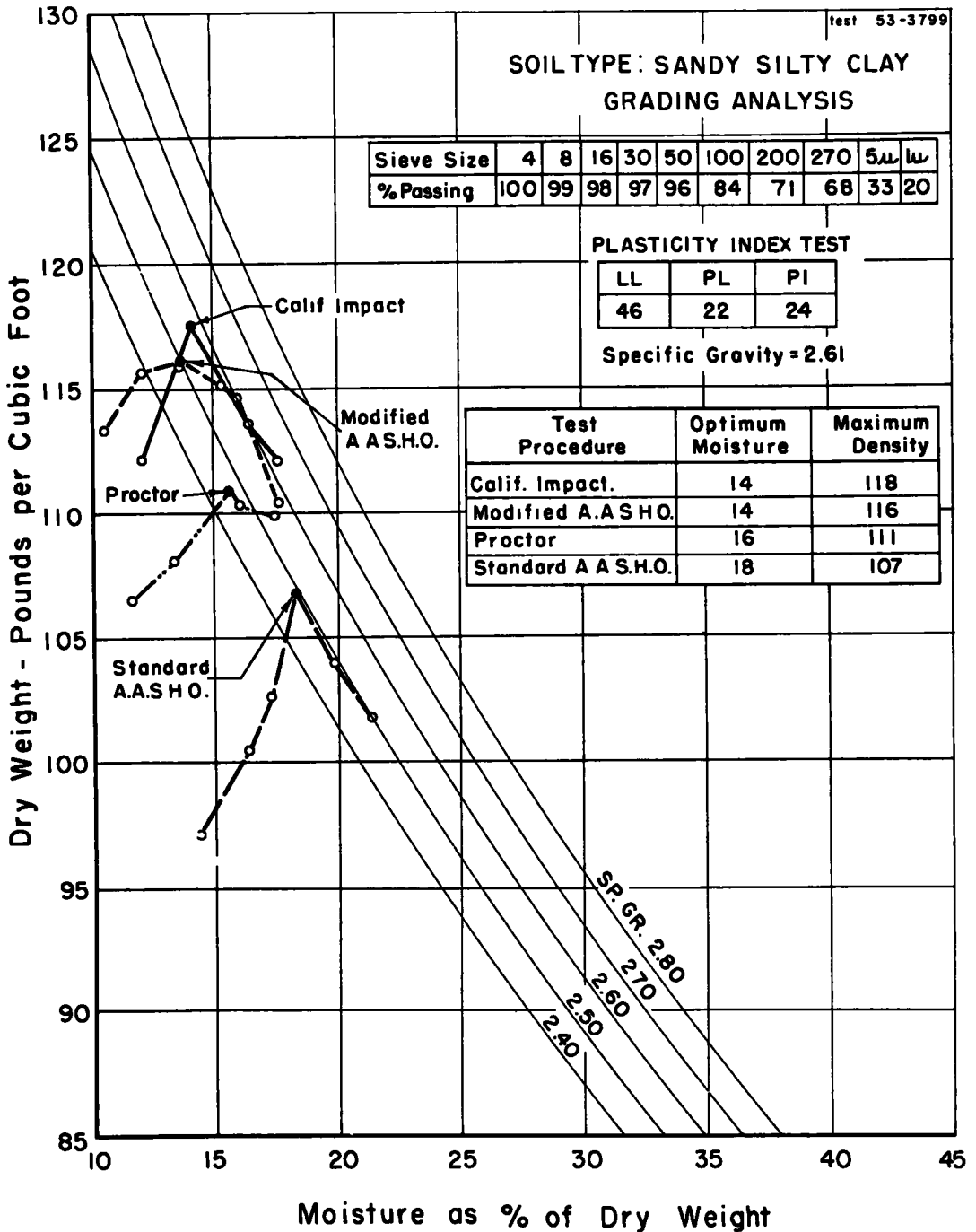


Figure 2. Comparison of various laboratory compacting procedures.

20 blows was in general about equal to that obtained with the Modified AASHO and the density at five blows somewhat less than the Standard AASHO method, it seemed that we might superimpose the densities characteristic of the other methods upon this straight line plot developed in the California Impact equipment. Chart, Figure 11,

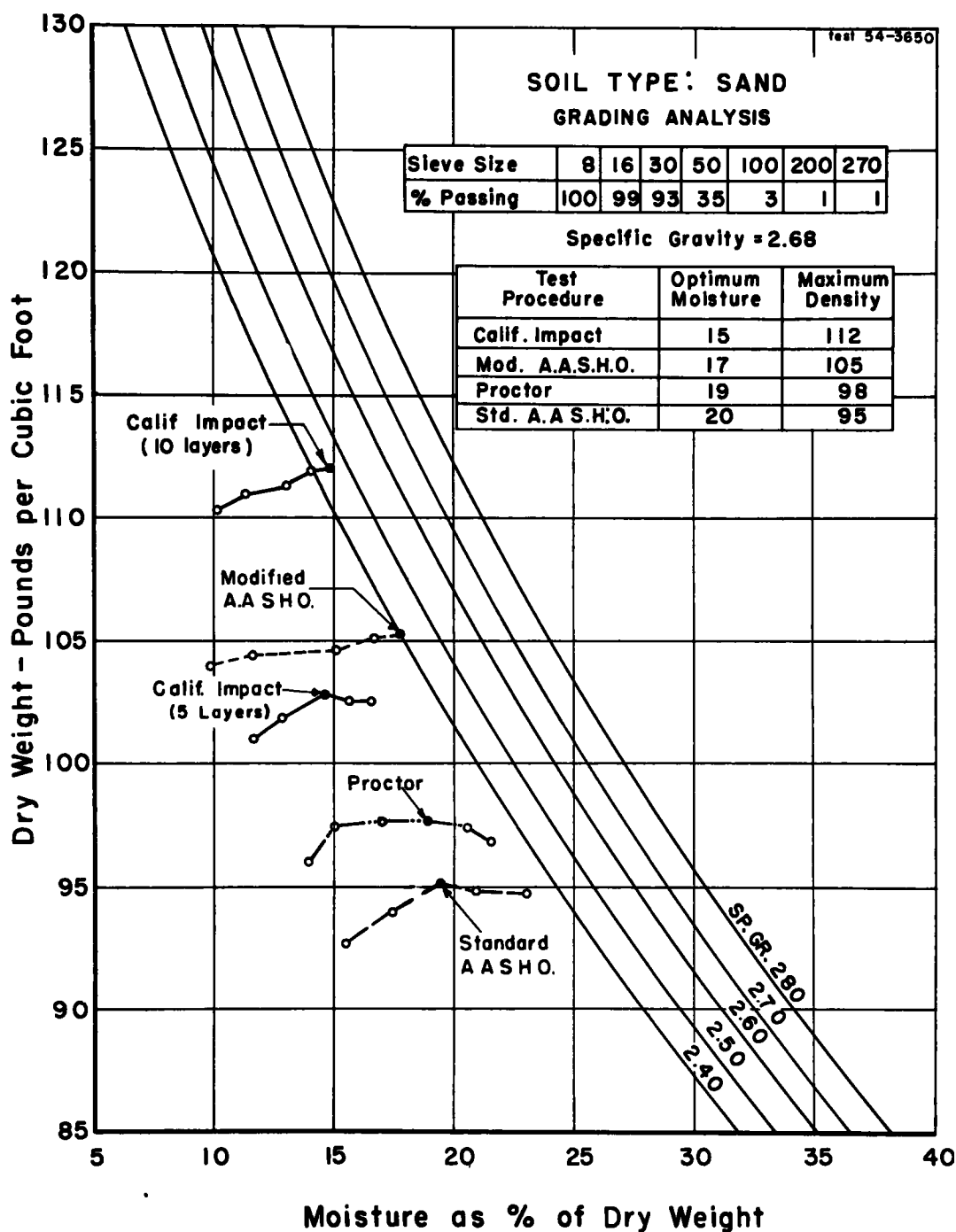


Figure 3. Comparison of various laboratory compacting procedures.

represents an attempt to establish a comparison. In other words, we are trying to determine whether the density obtained in the other methods would be consistently duplicated by some given number of blows in the California Impact method. By selecting the data for certain soils, it is possible to demonstrate a rather satisfactory con-

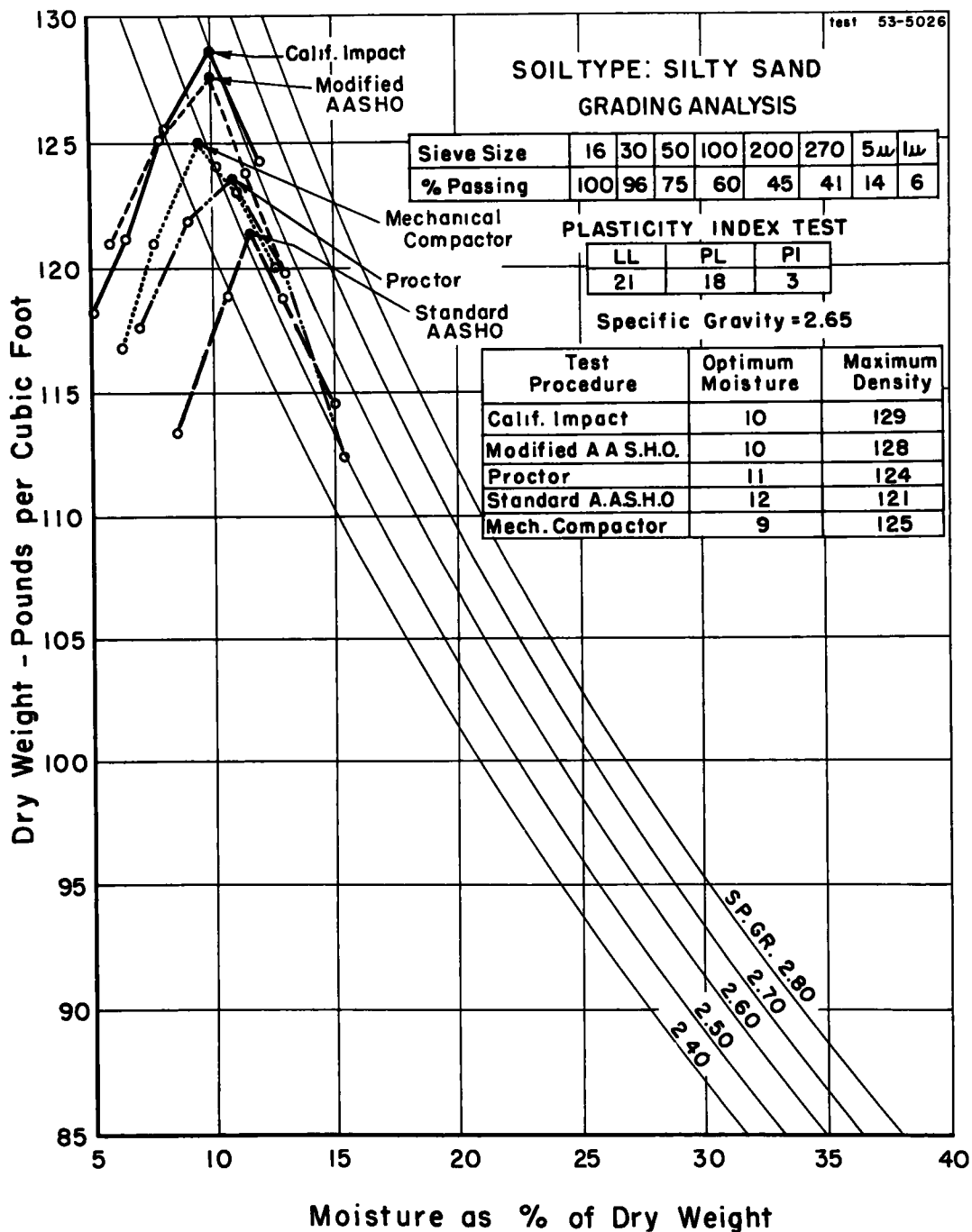


Figure 4. Comparison of various laboratory compacting procedures.

sistency of behavior and from this selected and limited number of comparisons it appears that the densities obtained in the Standard AASHO method will be duplicated by the density in the California Impact equipment using only seven blows per layer. In a similar manner an equivalent number of blows in the California Impact method may be

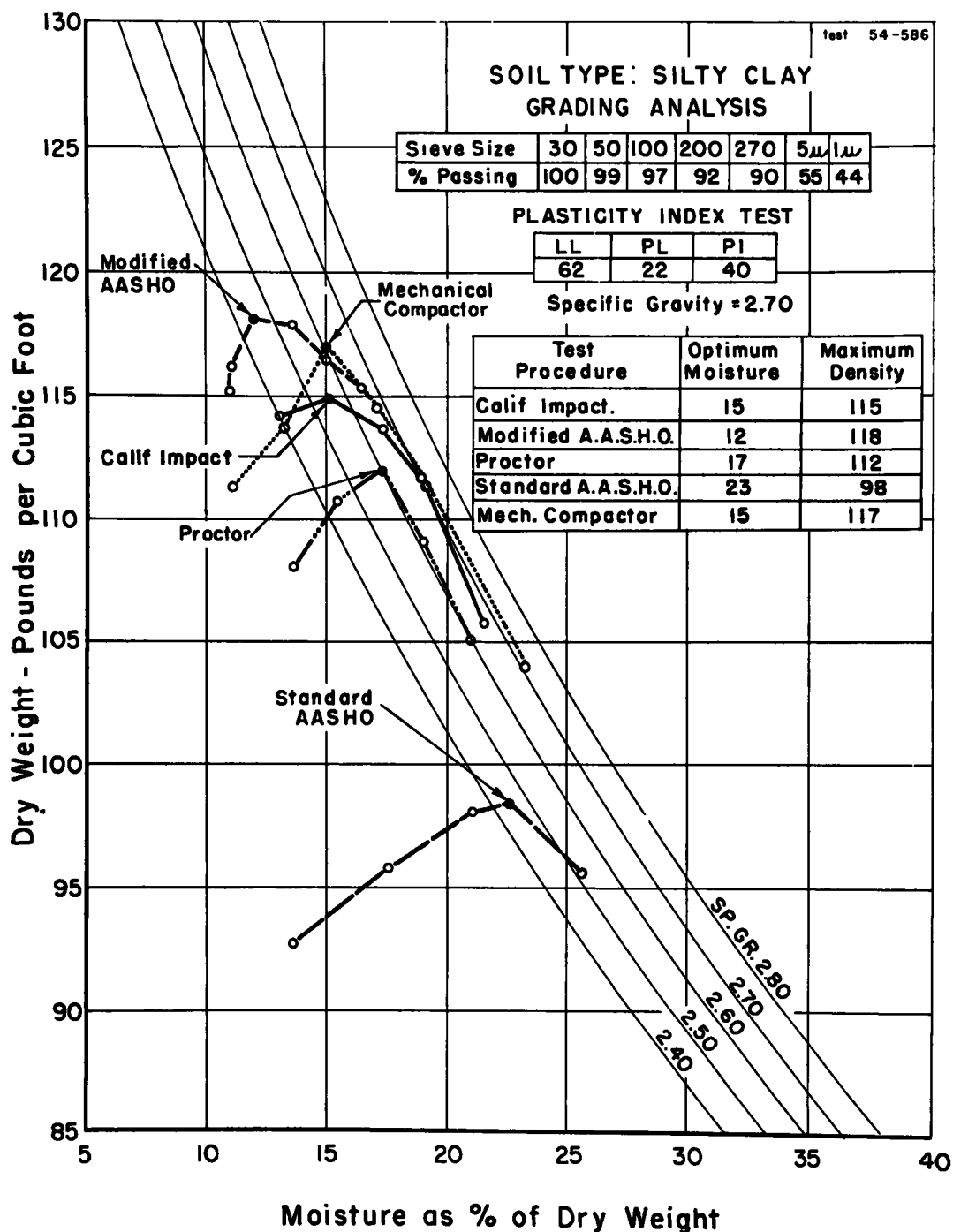


Figure 5. Comparison of various laboratory compacting procedures.

assigned to the other devices. This tentative relationship is shown in Table 3. It is evident, however, that when compacted in these various devices the densities obtained with all materials do not follow a straight line on a semi-log plot ranging from the Standard AASHO to the California Impact if we apply the relationship indicated in

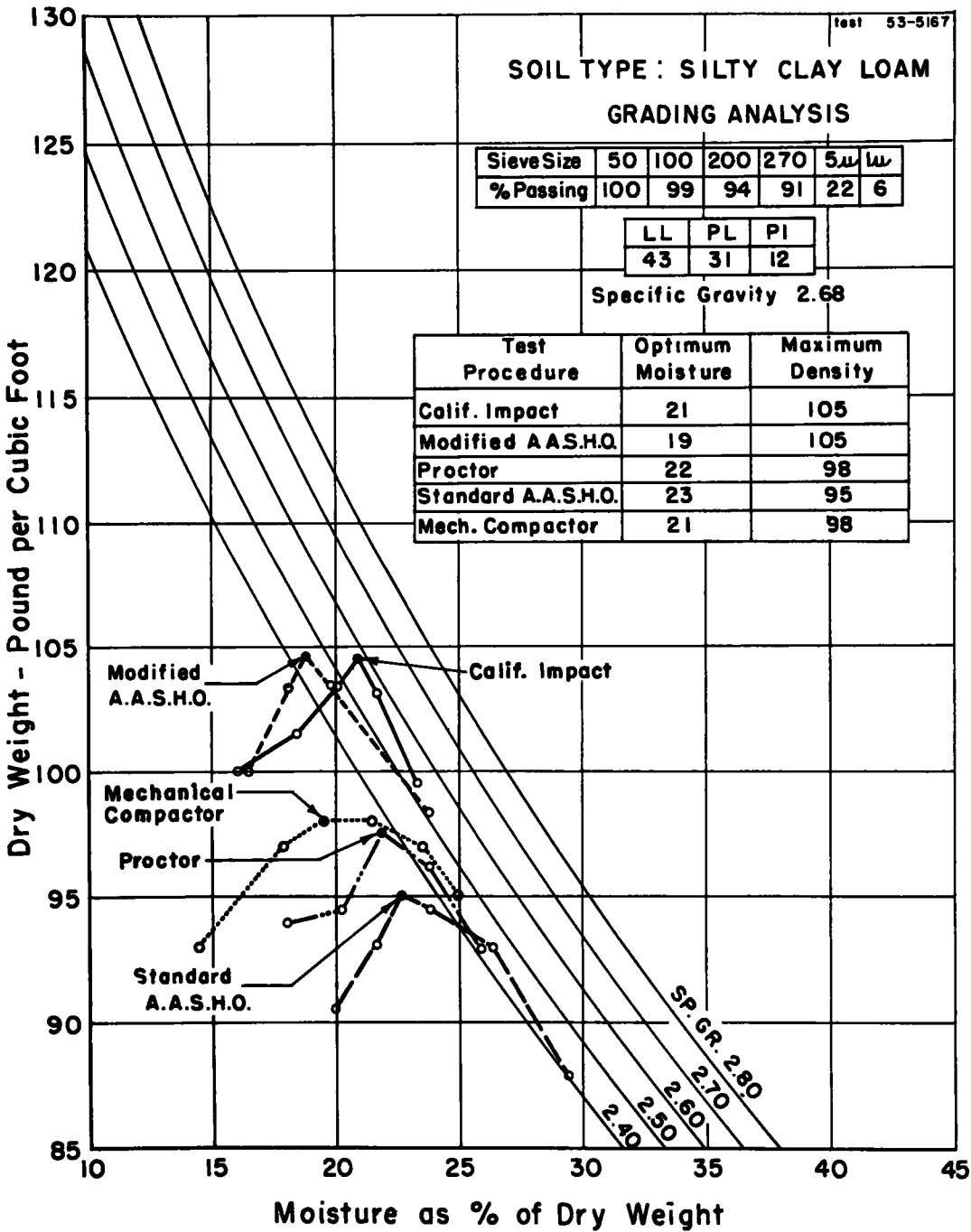


Figure 6. Comparison of various laboratory compacting procedures.

Table 3. Some of the exceptions are shown in Figure 12 in which the densities obtained are plotted according to the above relationship. In order to connect the points curved lines are necessary indicating a departure or deviation from the relationship shown on Figure 11.

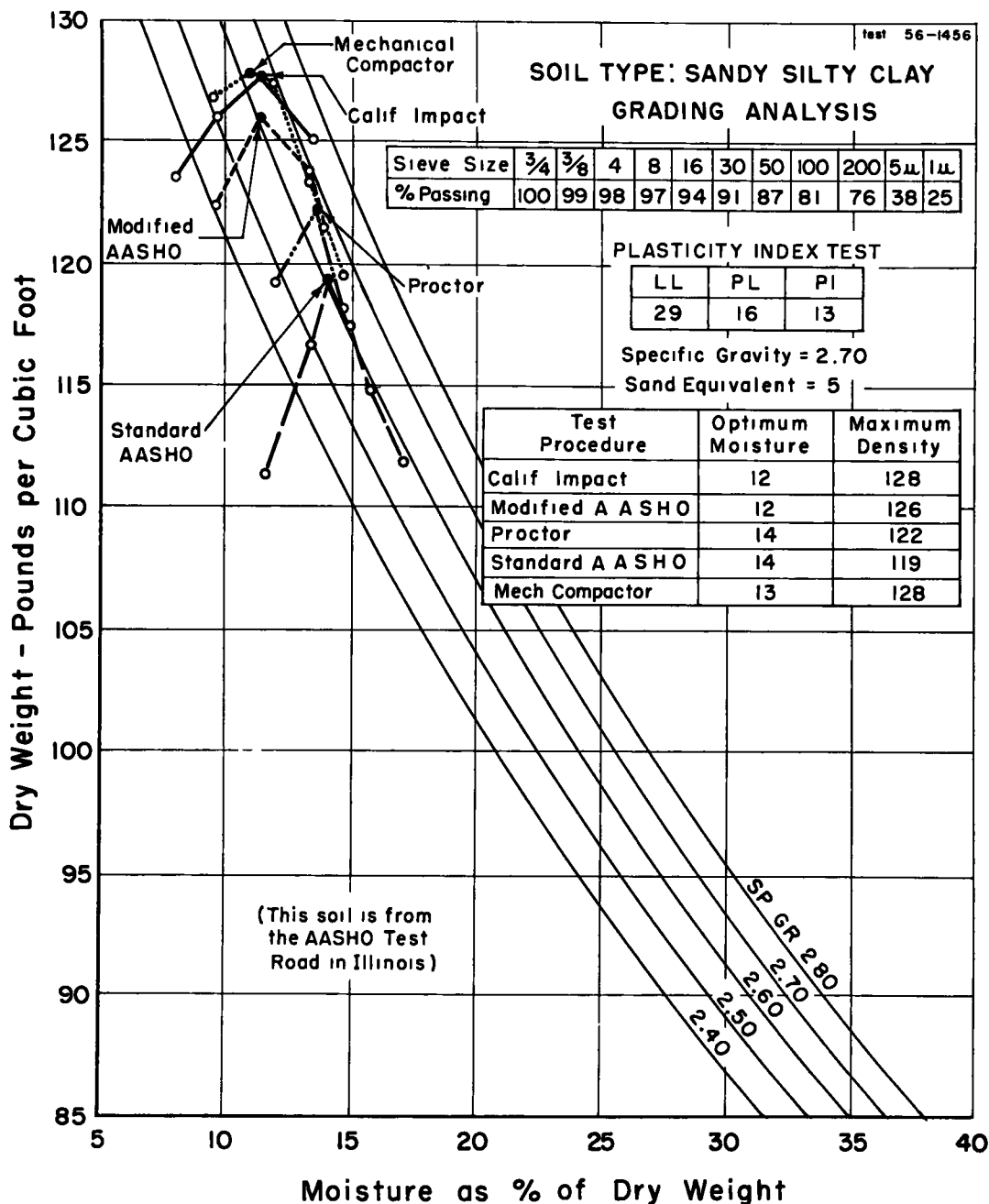


Figure 7. Comparison of various laboratory compacting procedures.

All of these procedures have several characteristics in common; namely, density is developed in a confining steel cylinder three or four inches in diameter and force is delivered by means of a hammer or ram having about three square inches area. An important point is that all use a ram smaller than the surface of the specimen, and all except the Kneading Compactor employ sharp impact.

Leaving aside for the moment consideration of those materials that show an unusual pattern of response to the various methods, Figure 11, one might speculate upon the

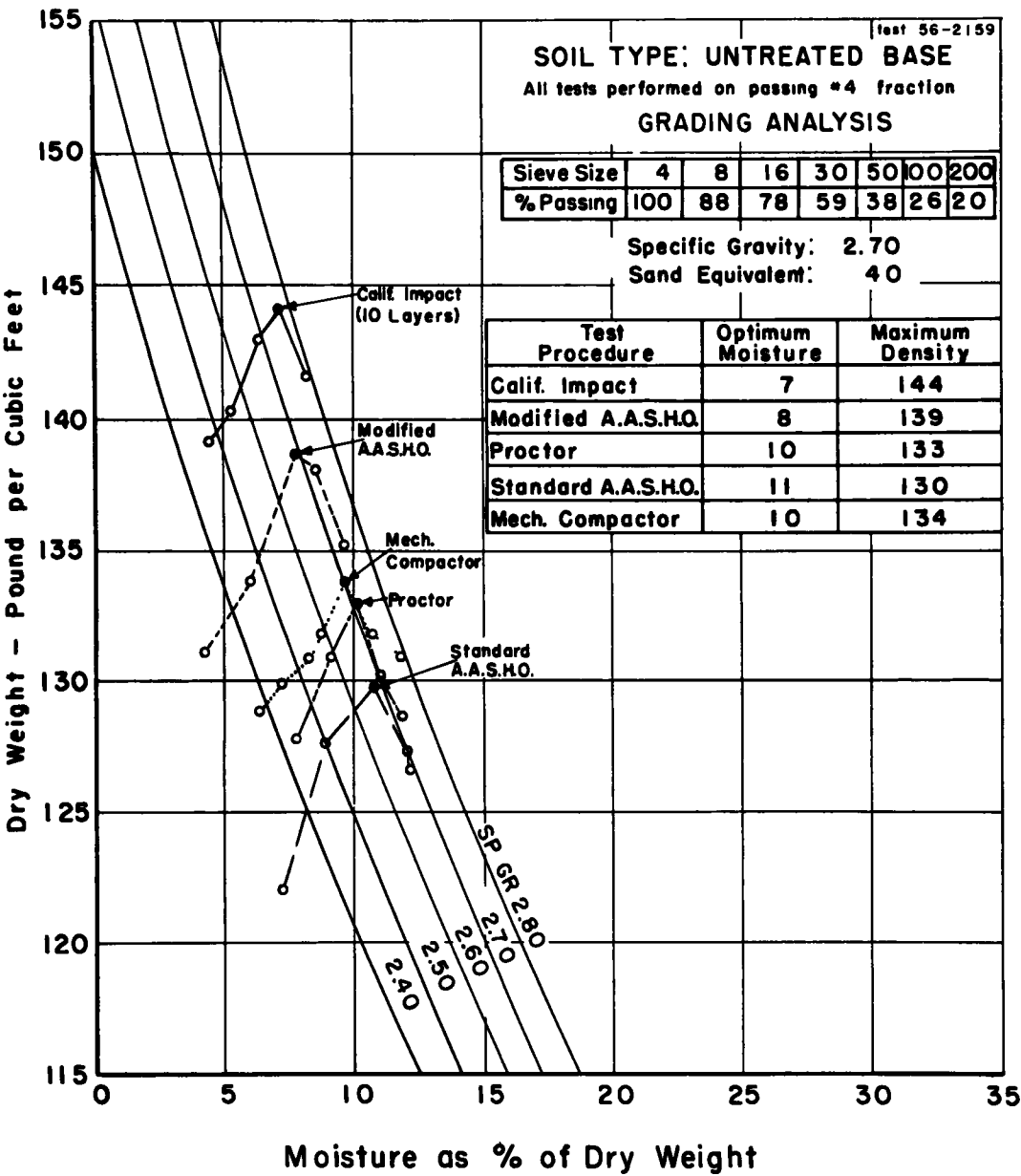


Figure 8. Comparison of various laboratory compacting procedures.

relationship between these various test results and the degree of compaction normally achievable on the road. In California practice, it is usual to require 90 percent of the "standard." Thus a test maximum weight of 128 pounds would mean about 115 pounds on the grade. In order to produce the same degree of compaction on the road one would have to specify over 95 percent compaction with

TABLE 3

Compaction Method	Equivalent Number of Blows per layer in Calif Impact Method
Standard AASHO	7 blows
Proctor	11 "
Kneading Compactor	13 "
Modified AASHO	18 "
California Impact	20 "

the Standard AASHO. In another case, a 90 percent requirement for soils developing 110 pounds in the California Impact method would be equal to requiring about 100 percent of the Standard AASHO for the same soil.

In describing the discrepancies or differences between these existing test methods I am not ready to propose a better technique or procedure. It is obvious that any device used to establish the attainable density of a soil during construction must be reasonably simple, rugged and portable in order to be practicable for field control. It is the primary purpose here to point out the relationships that do exist as it seems that all engineers engaged in the design, preparation or enforcement of specifications for highway or airport construction should be aware of these differences. Figures 13, 14 and 15 show the equipment and typical test specimens for the laboratory compaction methods discussed. The test specimens were made with alternate layers of different colored soil to permit ready visual comparison and the specified height of drop on each layer is illustrated by the position of the ram. With the exception of the Proctor the force exerted on the specimen is the result of a free fall of the rammer. In the case of the Proctor method the operator is expected to exert additional force by hand, therefore, the force of the blow must vary somewhat depending upon the strength and enthusiasm of the operator. It may be pertinent to point out that two

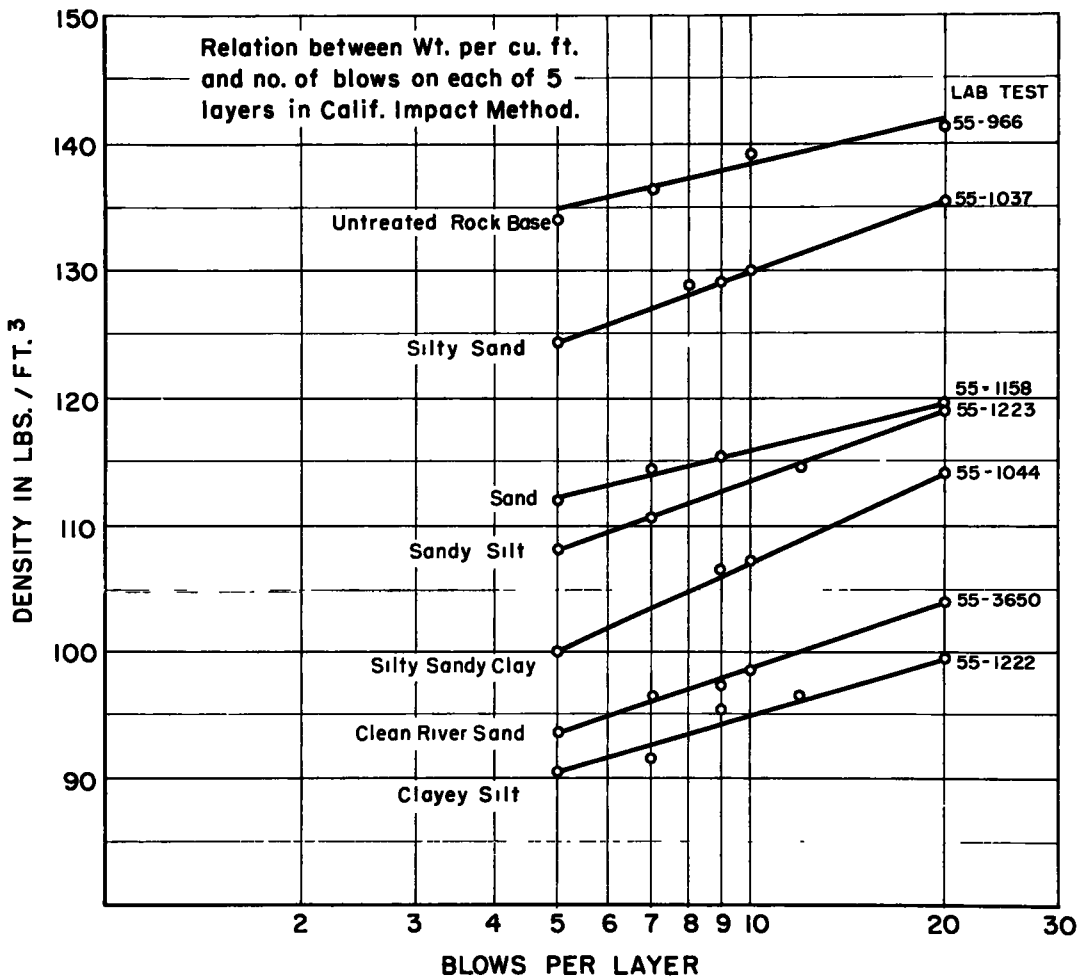


Figure 9.

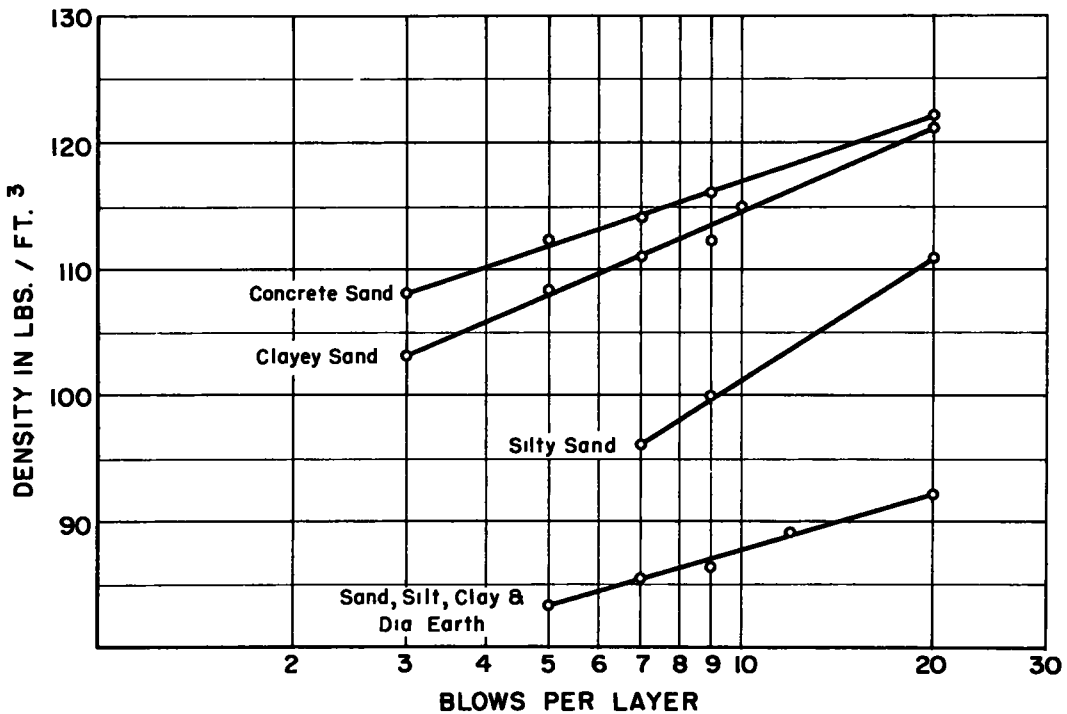


Figure 10. Relation between weight per cubic feet and number of blows on each of 5 layers in California impact method.

states are using the California Impact method and present day construction equipment is able to meet the densities called for in the specifications which refer to this method. It is equally pertinent to note that the Corps of Engineers who developed the Modified AASHTO have used this method which sets a standard very close to that provided by the California Impact method, and presumably they have also found that specifications based on this test can be met by modern construction equipment.

In view of widespread interest in the AASHTO test road project, and the necessity of sooner or later trying to apply to the construction problem in each state, any new lessons learned these differences in compaction standards should be fully realized by all. Furthermore, the influence of the federal aid standards on the inter-state system points to the need for consideration of the compaction standards to be followed if anything like uniform construction is to be achieved. While the standard reference method for compaction is of concern to those who plan the projects, write specifications and inspect the work, the construction engineers and the contractors are equally interested in the ability of present day compaction equipment to achieve the density specified. The last 15 years have seen many advances and new developments in compaction equipment. These include heavier steel tired rollers, tremendous pneumatic tired "Super Compactors," as well as improvements in the time-honored sheep'sfoot or tamping rollers. Two new devices are of considerable interest, one the segmental type of roller and the other, the vibration principle being embodied in several new rollers or compaction devices.

It has been the practice for some years in the California Division of Highways to make comparative field tests whenever a new roller is introduced by the contractor on a construction project. Thus far, however, these full scale field trials have failed to bring forth convincing evidence that one type of roller is vastly superior to another. At least, the densities obtained when expressed as a percentage of the standard show surprisingly little variation. Here again, however, percentage figures can be somewhat misleading. For example, a soil that registers 130 pounds per cubic foot in the

laboratory compaction test would meet the specification of 90 percent if compacted to 117 pounds on the road. However, a silty sand giving 100 pounds per cubic foot in the test would, of course, show a variation of only 10 pounds for the same percentage difference.

The view has long been held that we should achieve all the compaction that is feasible or which can be reasonably obtained without exorbitant construction cost, but there is ample evidence to show that it requires a much greater amount of work to achieve the specified density with one type of soil than it may with another. There is a feeling among some engineers that a contractor should expect to do a certain minimum or standard amount of work in order that the specifying agency might have the benefit of whatever degree of compaction can be reasonably developed. Noting this difference, however, is only another way of saying that the densities and optimum moisture contents indicated by the laboratory devices do not always duplicate and, in fact, do not parallel the densities and optimum moisture contents that are characteristic of the various construction procedures on the same soils.

Some engineers have expressed the opinion that the amount of compaction produced in a soil material is directly proportional to the energy or force used in performing the compaction. This is not inevitably true as it is necessary to take into account the particular method or efficiency of compaction. The same amount of energy may produce different degrees of compaction, depending upon the method used. For example, the Modified AASHO develops about 56,250 ft-lb per cu-ft of soil and the California Impact develops 33,000, yet the latter produces the greater density on many soils.

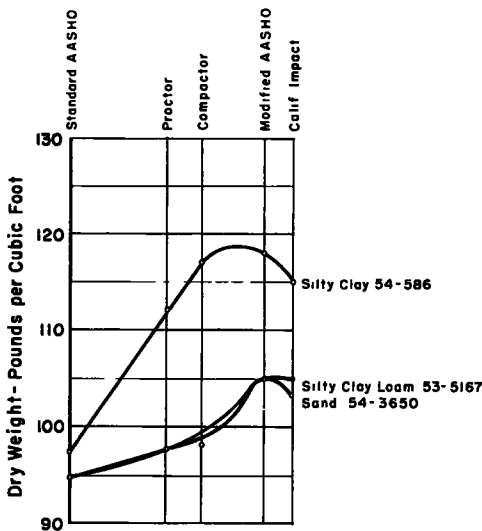


Figure 12. Comparison between different laboratory methods used to establish maximum density for compaction control.

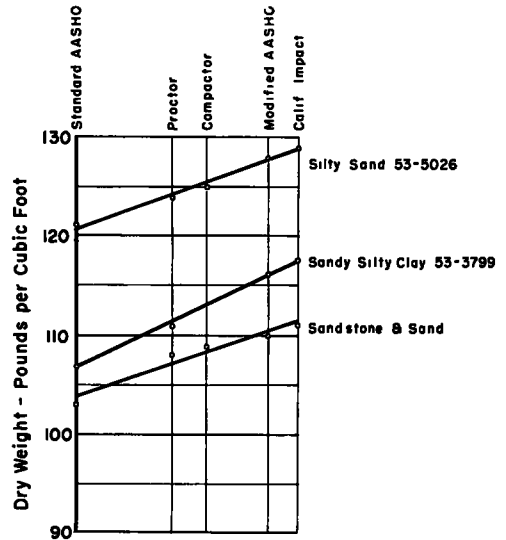


Figure 11. Comparison between different laboratory methods used to establish maximum density for compaction control.

It might be well to point out at this juncture that some misunderstanding arises because of the lack of distinction between the terms "density" and "compaction." The term "density" for all materials means, of course, the weight per unit volume, and for metals or solids is often used as more or less synonymous with specific gravity. When used in relation to soils, the term in effect reflects the ratio between the absolute or solid volume of the particles as compared to the total space occupied by the granular mass. The noun "compaction" is generally considered to be synonymous with density but the verb form "compacted" conveys the idea that materials have been subjected to tamping or pressure, and that the particles have been driven into close contact by forces exceeding the force of gravity. However, even after a great deal of com-

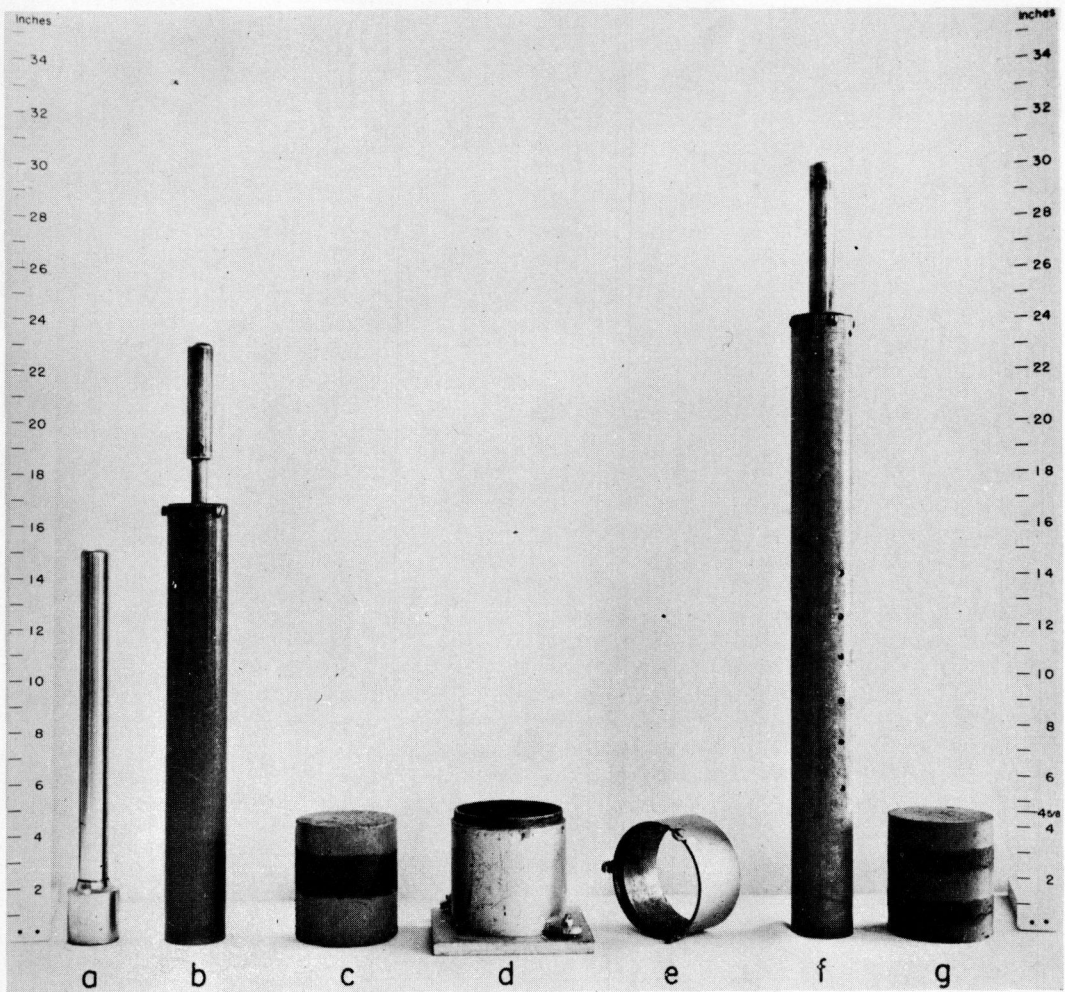


Figure 13. Proctor and AASHTO compaction test apparatus.

active effort has been exerted, a mass of particles may still retain a considerable percentage of void space and hence may not be particularly "dense." By careful manipulation, often with the expenditure of but little energy, particles can be caused to fit closely together and develop low void spaces or high density without having been highly "compacted." Present day engineering terminology does not recognize the need of clear-cut distinction between these two states. In other words, density developed by compactive effort is one thing. Density resulting from an efficient arrangement of particle sizes can be something else. Distinction is important because a well rammed or compressed soil or granular mass may develop high resistance to displacement; in other words, produce an engineering structure of considerable stability. However, a dense mass of low void volume may or may not have comparable structural properties. This, of course, brings up the question of whether one is interested in controlling density as such during construction operations, or whether a more direct focus of attention should not be placed on the compaction and the generally improved structural stability. After the foregoing was written a paper by W. J. Turnbull and Charles R. Foster of the Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, came to my attention (3). The discussion and conclusions in that paper are all very informative and pertinent to this subject. The data included therein confirm our own findings (4) that increasing either the compaction or

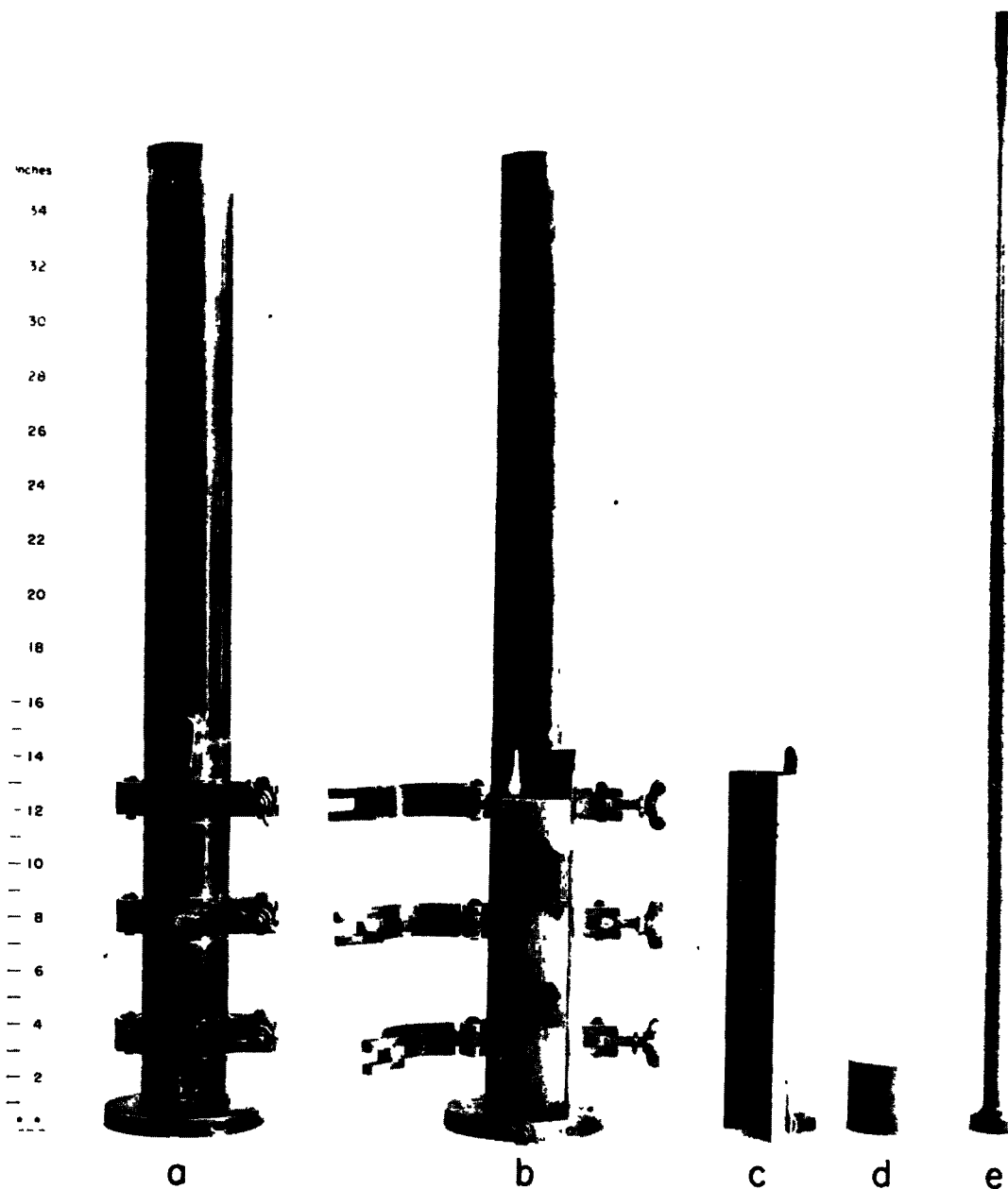


Figure 14. California impact compaction test apparatus.

density or both may or may not be beneficial depending upon the particular soil, the degree of compaction and the moisture content.

While the answer may seem more or less obvious to all, it may be pertinent to consider the question—Why do we require compaction of soils? First, as stressed in the introduction, it is necessary if embankments are to maintain the planned grade line; in other words, to avoid settlements due to consolidation within the embankment material itself. Secondly, many materials do have improved bearing values or supporting power when thoroughly compacted, although the amount of liquid present is usually more significant. Compaction also tends to reduce the size of the void spaces; in

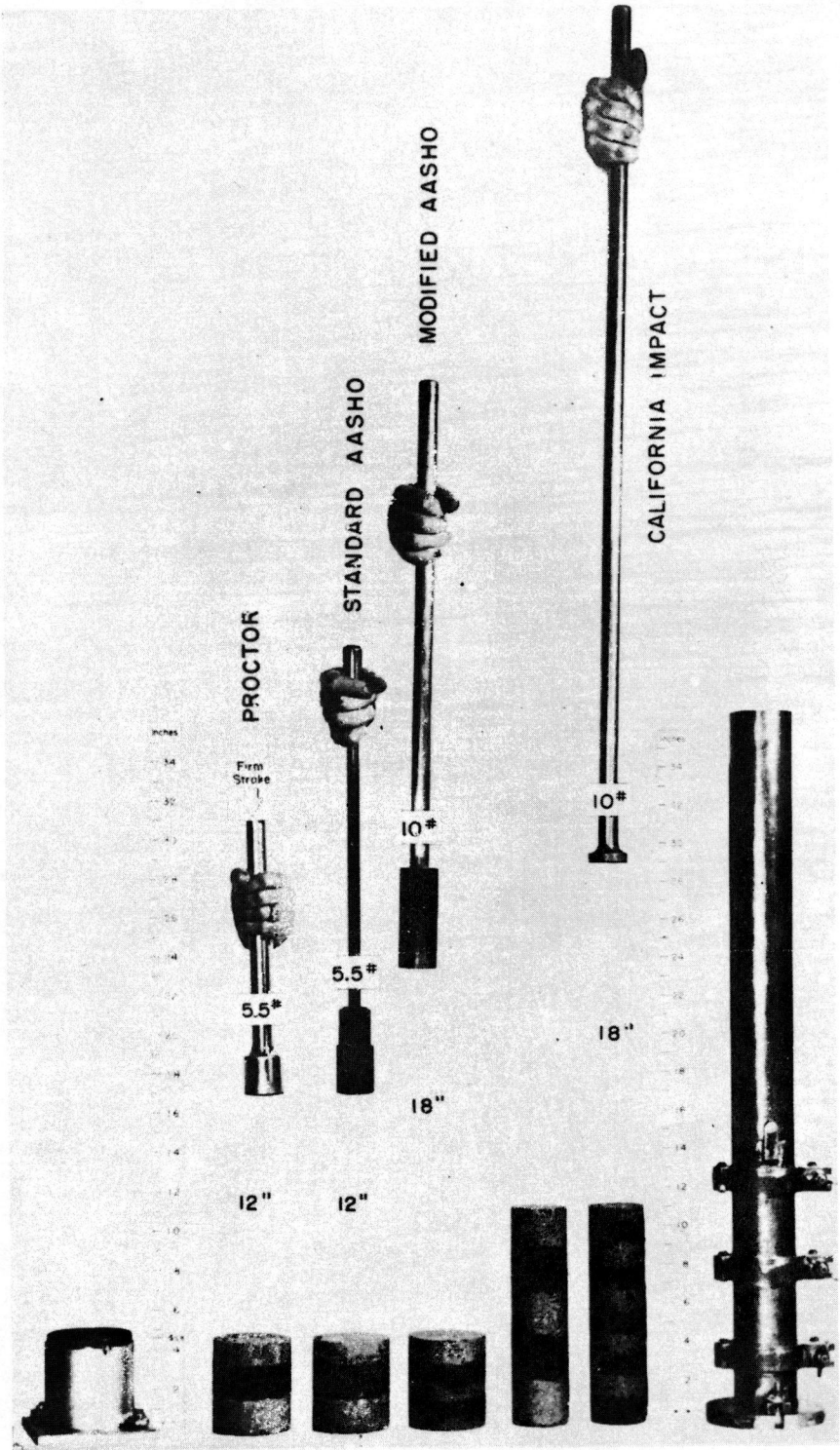


Figure 15.

other words, reduce porosity and thus to some extent limit the absorption of moisture. Again we must scrutinize the terminology because porosity does not necessarily correlate with permeability. This fact is readily perceived if we consider a well graded sand or gravel containing less than 30 percent voids which may be quite permeable offering little resistance to the passage of water. On the other hand, clay may be virtually impervious with void space or "porosity" approaching 50 percent. Like most similar questions, the problem will not be resolved until engineers visualize clearly just what it is they are interested in accomplishing. In other words, sooner or later we must separate the essential from the less essential and make sure that the terminology used is not misleading or diverting from the main purpose.

The expressions Maximum Density and Optimum Moisture are purely relative terms and mean nothing tangible unless all conditions and circumstances are clearly defined.

I wish to acknowledge the assistance of A. W. Root and W. S. Maxwell of the Materials and Research Department of California Division of Highways for data and suggestions used in preparing this paper.

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Discussion

W. N. CAREY, JR., Chief Engineer for Research AASHO Road Test, Highway Research Board—Mr. Hveem's interesting and provocative paper serves as an excellent starting point for some comments dealing with the reliability of optimum moisture-maximum density information regardless of the method used to obtain it.

For this discussion, let us assume that the engineer responsible for compaction control is serious in wanting to know what the optimum moisture content and maximum density of his soils are and what the field conditions are in relation to these optimum values. Let us make the further assumption that the laboratory technique he has chosen will produce the same optimum values as those that would be developed by running a field moisture-density test on the material placed under the compactive effort furnished by the construction equipment. That is, the best laboratory technique for this particular soil and construction was chosen, whether it be California, AASHO, standard Proctor or some other.

With these assumptions, the engineer is then in an excellent position to control his embankment—or is he? How is he going to make decisions based upon the amount of information he may be expected to get from a testing program that is normal or even ten times normal for highway construction work? Unfortunately, the answer is probably something like this—he will have a few tests run, look at the results, discard those values that are "obviously" out-of-line, and then make his decision on the basis of past experience and engineering judgment. It is fortunate that we have engineers with experience, because the engineer in our example may just as well not have taken the tests at all.

During the past construction season at the AASHO Road Test we had an unique opportunity to take a close look at moisture-density tests, compaction specifications and their meaning. Since in a road test it is essential that the character and condition of the various components of the pavement be as nearly uniform as possible, a great many tests of the embankment material were made. Analyses of the data from these tests brought out some rather startling facts about the particular soil that comprises the embankment of the AASHO test pavement and led us to question seriously the

efficacy of presently used specifications.

As compared to most normal highway jobs, we had ideal conditions for control. The soil used in the construction of the three foot soil embankment was obtained from nearby borrow pits, transported to the grade, mixed with rotary speed mixers and compacted in 4-in. lifts. The material was a silty clay classified on the borderline between A-6 and A-4. In the opinion of our Advisory Panel on Soils (comprised of some of the country's top soils men), the material was considerably more uniform than would normally be found in glacial fill soil borrow pits; obviously soils encountered along the right-of-way of a typical pavement project would be extremely variable in comparison.

Let us consider then, just how variable is a "highly uniform" borrow pit, and what is meant in terms of compaction attained in the field by a specification requiring, say 95 percent of maximum density attained in some stated test.

We are all aware that there is no such thing as a truly homogenous or uniform material. If one has instruments sensitive enough, he can find variability in successive measurements of any phenomena or material characteristic. Consequently, no real knowledge of the characteristics of a material is gained unless it is possible to estimate the degree of variability that exists.

In the determination of percentage compaction of soil there are many principal sources of variability. The soil is variable—the maximum densities at any two points are truly different. The field densities at any two points are different even if the laboratory determined maximums are the same because of variability in field moisture content, field compactive effort, etc. There exists considerable experimental error in both the tests for maximum density and for field density. Replicate tests are unlikely to give identical results.

The usual field technique in which the inspector selects what appears to him to be a "good" spot for his sample may reduce variability, but, of course, introduces a bias indicating higher than average compaction.

It is the purpose of this discussion to demonstrate that the variability in what is reported to be percent compaction of a soil considered to be uniform is greater than is generally recognized and to urge that specifications take the distribution of test results into account.

Figures quoted here relate to the selected embankment soil from one of the AASHO soil borrow pits. Maximum density figures were obtained in the standard Proctor test (ASTM T-99) which was specified for the project.

Prior to construction, some 300 samples were taken at various depths from borings on a grid-like pattern covering the area of the pit. The standard Proctor test was run on each of these samples. Based on these tests, the mean maximum dry density of the pit material was estimated to be 117.2 lbs per cu ft at an optimum moisture content of 14.1 percent.

It is interesting to note, however, that even in this supposedly highly uniform material, the reported maximum density varied from about 110 to 126 lbs per cu ft. About 5 samples were taken at different depths in each of the 59 borings. Maximum densities of samples from one of the holes varied by as much as 11 lbs per cu ft, and the range in 8 of the 59 holes was over 8 lbs per cu ft. The mean range with depth of all holes was 4 lbs per cu ft. This variation was not systematic, i. e., the higher maximum densities in any hole were found just as frequently near the surface as near the middle or bottom of the hole.

Further tests of maximum dry density were made after the material was placed on the grade. These determinations were made by means of one-point wet Proctor tests utilizing a series of standardized moisture-density curves that were developed from the data taken in the preconstruction borrow pit studies. On the basis of about 1,500 such determinations on soil from the same pit, the mean maximum density was 116.7 lbs per cu ft and the standard deviation 2.0 lbs per cu ft. This means that practically all (99 percent) of the material placed from this pit may be estimated to fall between 110.7 and 122.7 lbs per cu ft in maximum density, or that about two-thirds of it would fall between 114.7 and 118.7 lbs per cu ft.

The foregoing serves to demonstrate that even in a soil considered to be highly

uniform, the denominator of the percent compaction expression is anything but a constant. Thus, it appears essential that a separate determination of maximum density be made at each sampling point. If the specific gravity of the material is reasonably constant, it may be appropriate to use one-point wet density tests to determine maximum density and optimum moisture provided that an appropriate series of curves is available.

In the construction and testing of the embankment material, it was found that field density varied even more than the maximum density and in much the same way. The practice at the road test was to make two determinations within a few inches of each other at every sampling point. The values obtained were generally about 2 or 3 lbs per cu ft apart. Variability between more widely separated points was greater of course. Within construction blocks (600 ft long) the mean standard deviation of field densities was about 3 lbs per cu ft. About half of this can be attributed to variability in Proctor maximum densities. Thus, one can assume that the remaining half was due to lack of uniformity in compaction or moisture content or to unexplained error in the field density determination.

Now consider a typical specification requiring a minimum of 95 percent of maximum density with no allowance for normal distribution. Using figures from the AASHO test, in which compaction was without doubt controlled more carefully than it ordinarily is (the peak laboratory and construction control forces included over 100 engineers and technicians), it is possible by standard statistical techniques to make a very good estimate of the distribution curve for percent compaction. This estimate shows that if an infinite number of tests had been taken in each 600 foot construction block, about 8 percent of the results (nearly 1 in 12) would have fallen below the 95 percent level when the mean of all tests was 98 percent. Incidentally, these estimates can be made only if the locations of points to be sampled are selected at random. It is obvious that if our hypothetical engineer based his opinion on whether or not the contractor was meeting specification on as few tests as are normally made, the odds are better than 12 to 1 that he would accept an area 8 percent of which is outside of specifications. Based on the AASHO conditions again (relatively high uniformity), if the designer wanted to insure that practically no part of the embankment be placed at less than 95 percent compaction, he should specify that the mean percent compaction of some small stated number and frequency of tests located at random be not less than 101 percent (101 less three standard deviations equals about 95.7).

Obviously, the foregoing is not the basis for a complete specification. Before one is written a comprehensive study of the variability attained by normal construction methods must be made.

In this discussion we have tried to emphasize these points:

1. There is a great deal of variability in percent compaction within an embankment even under ideal conditions and provision should be made to measure it.
 2. Every phenomenon and every material characteristic has a distribution which must be recognized. In some cases it can be determined rather precisely; in most others it can be estimated from a small number of tests.
 3. Specifications should take distribution into account. A specification requiring an absolute minimum of, say, 95 percent compaction is unrealistic. Who can say that in a mile of embankment, no soil exists of less than 95 percent, even if the mean of all tests made in that mile was 105 percent and no test result was under 100 percent.
 4. Test methods should be devised to measure whatever phenomenon they are intended to measure (no test for maximum density is truly repeatable for example).
- Mr. Hveem's paper illustrates this point very well.

In closing we would like to ask the soils engineers for a step-up in efforts towards the ideal, on which, I am aware, they have been working for years. This is the development of a field test that measures some basic property of a compacted soil mass that can be correlated with pavement behavior considering environment, climate and the other related variables. Only then can we do away with the cumbersome, unreliable and unrealistic percent compaction specifications.

W. H. CAMPEN, Manager, Omaha Testing Lab., Omaha, Nebraska—At the 1945 meeting I presented a paper in which I suggested that the quality of compacted soils be specified on the basis of strength rather than density. The suggestion was prompted by the fact that the strength of soils compacted to standard density at optimum moisture varies over a wide range.

In order to substantiate the suggestion, a number of soils and soil-aggregate mixtures were compacted by three methods in which the compactive effort varied over a wide range. Stability tests were then made at maximum density and optimum moisture conditions. Finally, a relationship was established between stability and density. This relationship can be used to select desired strength which can be controlled by density.

In connection with the tests, we also showed that with fine grained plastic soils, the energy required to obtain a given density increases as the plasticity of the soils increases. The density of plastic soils can be varied over a wide range of varying the compactive effort. Soil-aggregate mixtures of low plasticity require comparatively low energy and for that reason the effect of compactive effort is not so pronounced.

This brief synopsis indicates that Mr. Hveem has worked on the same basic problem. Mr. Hveem is certainly correct in point out that the attainment of maximum density, by a given method, in itself does not imply that the pinnacle of perfection has been obtained in regard to the strength and other properties of the mixture.

F. N. HVEEM, Closure—Mr. Carey has presented a discussion which is for the most part not a comment upon the subject matter or scope of the paper.

Mr. Carey points out an important and pertinent fact; namely, that both the density and the moisture content of soils usually varies from point to point in the roadbed. He further indicates that this fluctuation or variation is not systematic and apparently is more or less a matter of pure chance. In other words, the evidence cited by Mr. Carey from the unusually well controlled conditions of the AASHO test road confirms the experience from many existing highway projects; namely, that there is rarely any such thing as uniform moisture or density except perhaps in the case of a saturated beach sand.

In summing up, Mr. Carey emphasizes certain points:

- "1. That there is a great deal of variability in percent of compaction. . . .
2. Every phenomenon and every material characteristic has a distribution which must be recognized.
3. Specifications should take distribution into account.
4. Test methods should be devised to measure whatever phenomenon they are intended to measure."

I am not inclined to disagree with the first two points, but anyone seeking to apply the idea expressed in Mr. Carey's third point may soon find that there are difficulties. A specification covering contract work departs somewhat from the realm of engineering and mathematics and becomes a legal document. In order to determine a standard deviation, it is necessary to have a large amount of data, and the large amount of data are only available after a number of tests have been performed. Therefore, in the beginning the engineer would be forced to accept the materials even though some tests were below the desirable minimum and in effect he would be hoping that in the long run the average values would be acceptable. In actual practice, any tolerance or allowance for variation in materials or test reproducibility becomes in effect the specification. Mr. Carey's statement under No. 4 that no test for maximum density is true or repeatable is true for all tests. Few of the current tests on any material are exactly and precisely repeatable.

In the final paragraph, Mr. Carey asks for a step-up in efforts toward the "development of a field test that measures some basic property of a compacted soil mass that can be correlated with pavement behavior considering environment, climate and the other related variables." I feel that we do have such a test but it must be performed on laboratory specimens, and while it is dangerous today to state that something or other will never be done, I think that it will prove to be practically impossible to devise

a field test for newly constructed embankments that will predict ultimate behavior. It seems very improbable that there will be any way of producing in the field the state of moisture and density that will develop in the soil with the passage of time and after the soil has been covered by a more or less impervious pavement and subjected to alternations in temperature and traffic loads over a period of years.

Mr. Campen has made some interesting comments and in his opening paragraph he expresses the same thought as Mr. Carey and which has occurred to many engineers; namely, "that the quality of compacted soils be specified on the basis of strength rather than density." I have already commented on the similar suggestion by Mr. Carey and few will question that such a goal is attractive. However, we must continue to keep in mind the relationship between the specifying agency and the contractor. It is a difficult matter to make a contractor wholly responsible for quality, especially when it involves the selection of native materials. In the final analysis, only the engineer is in a position to know what soils are acceptable or satisfactory for his particular purpose. The only thing that the contractor is required to do is to transport these soils into place and then compact them. The engineer is supposed to know whether or not the soils will be satisfactory when properly compacted. Therefore, the general practice of requiring the contractor to develop some specified density is based upon widespread recognition of these different fields of responsibility.

In some cases the source from which the soils are obtained is designated by the engineer and in some cases the contractor is free to select a source for imported borrow. In either case the soil is supposed to meet some quality specification as established and supervised by the engineer. The contractor is expected to place it and compact it properly and if he does so he can hardly be held responsible for the final performance or quality.

As stated above, it also seems very unlikely that characteristic field conditions can be produced during construction that will permit the engineers to test the materials in place and determine what the load carrying capacity will be several years ahead. It seems very likely that such forecasting and prediction will have to be based on laboratory specimens deliberately prepared and modified to simulate the most adverse future conditions which will develop in the soil.