Suggested Compaction Standards for Crushed Aggregate Materials Based on Experimental Field Rolling

F. P. NICHOLS, Jr. and HAL D. JAMES, respectively, Highway Research Engineer, and Highway Engineer Trainee, Virginia Council of Highway Investigation and Research, Charlottesville

This paper describes field studies undertaken in 1960 and 1961 for the purpose of improving control over the compaction of granular base materials. A conventional vibratory roller was used to compact the base material on a number of construction projects. Short test sections were established and subjected to intensive rolling with up to 50 coverages over each test site. Density tests were made with a water balloon volumeter during various stages of the rolling operation. The data are being used in an attempt to define a mathematical or graphical expression for the maximum field density of the material relative to the percentage of coarse aggregate present.

The results indicate that for mixtures containing coarse aggregate, a number of laboratory test methods, including AASHO Method T-99, Alternates C and D, fail to produce densities nearly as high as the densities readily attainable in the field. Therefore a collateral study, to be reported separately, is under way for the purpose of developing better laboratory methods of establishing a density standard on which to base compaction control specifications.

Observations with respect to the accuracy of various methods of measuring in-place density are also included.

• THERE IS virtually universal agreement that good compaction is essential to good highway construction. Especially in the construction of flexible pavements and in the upper layers that compose the subgrade, subbase, and base courses, inadequate compaction will reduce the load bearing capacity and may lead to serious distress. If an appreciable volume of heavy truck traffic is expected to use the pavement, a definite tendency toward further densification of the layers nearest to the surface may be expected. If further appreciable densification is allowed to occur, it will result in depressions, rutting, and cracking, all of which will impair the riding quality and durability of the surface.

To combat this tendency toward densification under traffic, all layers must be compacted to adequate density during construction. The problem lies in determining what density is adequate for each of the various materials making up the flexible pavement structure. It is with a solution to this problem, particularly as it applies to granular base and subbase materials, that this paper deals.

There exists a wide variety of methods of laboratory tests for maximum density of soils and soil-aggregate materials. The type of test used by the Virginia Department of Highways for years has been the AASHO Standard T-99 test, performed on the minus No. 4 fraction only. Granular base and subbase materials, however, commonly include from 35 to 70 percent plus No. 4 aggregate, which necessitates making a correction to the laboratory density figures to compensate for the effect of the oversize particles. The formula that has been used in Virginia assumes that the minus No. 4 material is able to maintain its maximum laboratory density constant, much as though this material were a fluid, and that coarse aggregate particles merely displace a portion of the fine fraction without introducing any additional air voids. This correction formula is derived from the basic equation (1, p. 127) which states that "the total volume of material equals the sum of the volumes of the fine fraction (including all voids) and coarse fraction (with no voids)":

$$\frac{W}{D} = \frac{P_f W}{D_f} + \frac{P_c W}{D_c} \qquad (1)$$

in which

W = oven-dry weight of whole material;
D = theoretical maximum dry density of whole material;
P_f = percentage by weight of fine fraction (expressed as a decimal);
D_f = maximum dry density of fine fraction;
P_c = percentage by weight of coarse fraction (expressed as a decimal); and
D_c = maximum or solid density of coarse fraction, 62.4 x bulk specific gravity.

If the common factor W is cancelled out, the desired term D may be found:

$$D = \frac{1}{\dfrac{P_f}{D_f} + \dfrac{P_c}{D_c}} \qquad (2)$$

If the cumbersome fraction on the right is multiplied by $\frac{D_f \times D_c}{D_f \times D_c}$, the expression may be made simpler:

$$D = \frac{D_f \times D_c}{P_f D_c + P_c D_f} \qquad (3)$$

It has been the practice in Virginia to use AASHO Standard Method T-99-57 alternate A to determine D_f, the laboratory standard density of the minus No. 4 fraction. Under the same assumptions, however, Eq. 3 may be used to correct for the presence of the oversize particles regardless of what laboratory method is used to determine D_f and regardless of the maximum aggregate size specified in this method. If, for example, the minus No. 4 fraction of a given material is found to have a maximum laboratory density of 135 pcf and the plus No. 4 fraction a bulk specific gravity of 2.64, a plot of the theoretical maximum density "D" of the entire sample for various percentages of plus No. 4 material may be prepared, by substituting the proper values in Eq. 3. This plot is shown as Curve A in Figure 1.

It is apparent, however, that as the percentage of coarse aggregate P_c increases toward 100, the assumptions on which Eq. 3 is based become unrealistic and impractical. At some value of P_c, probably in the neighborhood of 65 percent, the theoretical density "D" shown in the curve would become impossible to attain simply because there is not enough fine material to fill the voids between the coarse particles. This would be true even if the fine fraction were a frictionless fluid offering no resistance to the coarse particles in their attempt to assume an orientation for maximum density.

In a number of test methods an attempt is made to surmount this obstacle by the use of a larger top size for the test sample; alternate procedures C and D to AASHO Standard Methods T-99-57 and T-180-57 are examples in which a top size of ¾ in. is used. But if the percentage of coarse aggregate is appreciable, particle interference restricts the density that can be attained in the mold so that the resulting laboratory density will be significantly lower than that computed from Eq. 3, based on the laboratory value for the minus No. 4 fraction. A study by the Civil Aeronautics Administration (2) showed

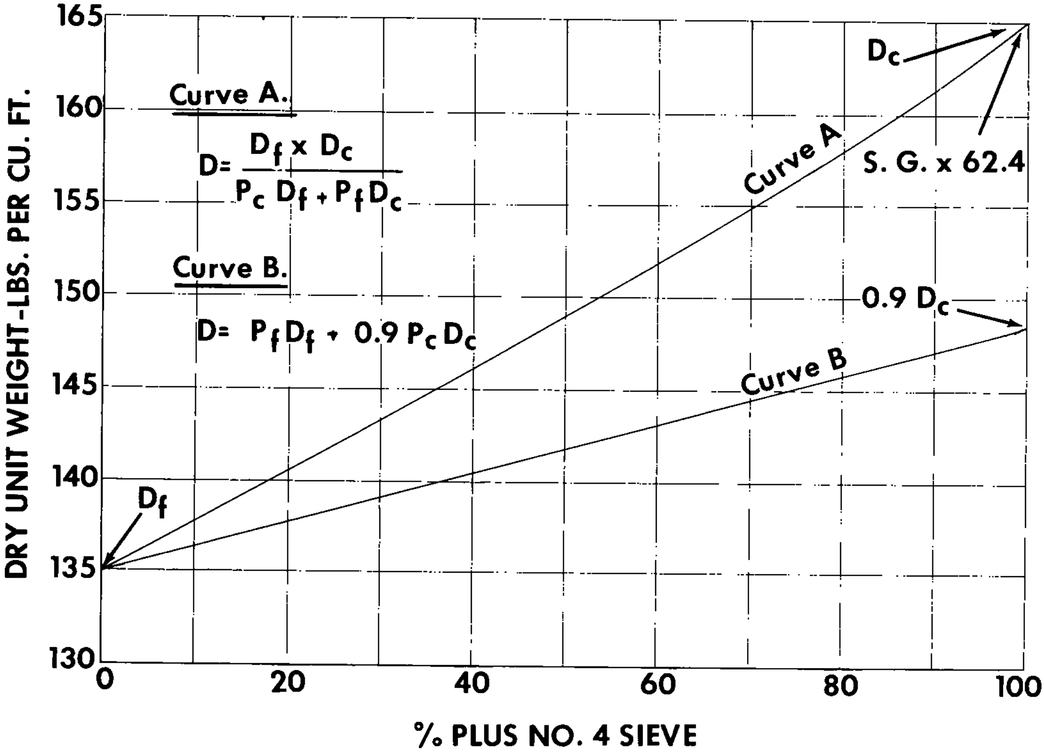


Figure 1. Typical curves for theoretical maximum density "D" in terms of D_f, P_c, and D_c.

that, up to a point, laboratory densities on samples with top size up to 1½ in. could be more closely predicted by the following expression:

$$D = P_f D_f + 0.9 P_c D_c \tag{4}$$

the symbols being the same as those in Eqs. 1, 2, and 3. The compactive effort used in the CAA study was described as "Modified AASHO" with a mold diameter of 6 in. The relationship from Eq. 4, again for a material whose minus No. 4 fraction has a maximum laboratory density of 135 pcf and whose plus No. 4 fraction has a specific gravity of 2.64, is seen graphically as Curve B in Figure 1. It is seen that regardless of how little coarse aggregate is present, its presence has the effect of lowering the molded density below that computed from Eq. 3.

Various other methods have been used by various agencies seeking to establish realistic standard densities for control over the compaction of granular materials. Some are of the impact type with the size of mold and the weight of hammer increased in the attempt to overcome the interference between the larger particles. Some are of distinctly different types; Ohio's Highway Department, for example, requires the contractor to construct a test strip that is rolled with approved equipment until no further increase in density is noted, after which all subsequent sections built of the same material are required to be compacted to at least 98 percent of the density attained in the test strip (3).

A thorough discussion of some of the variety of laboratory methods of determining maximum density and optimum moisture may be found in a paper by Hveem (4). A major point made in this paper is that many engineers have the highly erroneous impression that the terms "maximum density and optimum moisture . . . . express fundamental basic constants like the gravity constant or the boiling point of water" (3, p. 2).

This impression is obviously false; Hveem's data show the wide variety of maximum densities and optimum moisture determined on the same materials by different test methods. Some of these methods produce densities that are probably too low to be used as the basis of proper control specifications; others, perhaps, produce densities that are too high, tending to penalize the contractor unnecessarily. Therefore, in 1960, the Virginia Council of Highway Investigation and Research undertook to determine the maximum field densities attainable on a number of such materials embracing a rather wide range of percentages of coarse aggregate. From the findings of this field study it had been hoped that either a single all-purpose laboratory method or a combination of methods, with or without correction computations, might be shown as most useful in predicting these maximum field densities. One method being investigated involves the use of a vibrating table; the investigation of this method is under the direction of and is being reported separately by Chamblin (5).

It is felt, however, that as a result of the field experiments described herein, a reasonably satisfactory method of specifying density in granular materials, still based on the widely used Standard T-99, Alternate A, has been developed by the authors. The principal purpose of this paper, then, is to describe and report the results of the field experiments and to present the authors' method of specifying density.

FIELD EXPERIMENTS

Arrangements were made with the contractors on a number of field projects to permit State forces, using State-owned or leased equipment, to perform intensive rolling on short sections of the granular base or subbase materials in the attempt to compact these materials to their maximum field densities. In 1960, the experiments were performed on three projects involving four materials, using on separate sections of each a heavy pneumatic-tired roller, a lighter pneumatic-tired roller, and a light tow-type vibrating roller. On the three graded crushed stone materials, somewhat higher densities were obtained with the vibrating roller, while on the fourth, a local pit material containing only about 2 percent plus No. 4 aggregate, the highest densities were obtained with the heavy pneumatic-tired roller. In 1961 the field experiments were continued on three additional projects. Because all materials in the 1961 experiments were graded crushed stone, it was decided that only the vibrating roller would be used.

The following routine procedure was established for the installation of the test sections. Test rolling was begun as soon as possible after the material had been spread and "knocked down" by the contractor. In most cases, little or no compactive effort had been exerted before the test rolling; in some cases, however, the contractor had done some rolling, and additional compaction had been effected by construction traffic. Therefore, the initial density of the test sections was somewhat variable.

A test section, for the purposes of this study, was defined as a section approximately 300 ft long and only as wide as the width of the test roller. Five test sites were established at random locations within the central 200 feet of each test section. Preliminary density tests were made, usually at only two of the five test sites, for the purpose of determining the initial and certain intermediate densities as test rolling progressed.

Final tests to represent the maximum field density were made at each of the five test sites per section after 50 coverages with the test roller. Although this may seem to be an excessive amount of compactive effort (and indeed in 1960 when the experiment began it was not planned that this large a number of coverages would be used) the data show that the density did continue to increase on all materials beyond that attained by 30 coverages. The Appendix gives figures on the progressive densification achieved at various intervals during the rolling process; also shown in the Appendix is the surprisingly insignificant amount of degradation of the aggregate caused by fifty passes of the vibrating roller.

Conceivably, with the great variety of types of compacting equipment available today, it might have been possible to attain these maximum field densities with somewhat less effort by using a different method of compaction. However, in this study there was no intention of attempting to evaluate the relative merits of various types of compacting equipment. The main intent was to produce densities in the field that could not be appreciably exceeded with any reasonable amount of compactive effort.

The reader has probably noted that little mention has been made of the term "optimum moisture." Hveem (4) and many others have shown that optimum moisture is not a fundamental constant but varies, even for the same material, as the amount and type of compactive effort is varied. Therefore, moisture content in the field experiments was not maintained within close limits, but was varied somewhat from section to section in the attempt to find the optimum for the type of compaction actually being used. In the 1960 experiments, some of the sections were compacted on what now appears to have been the dry side. In 1961, an effort was made to put in some of the sections as wet as possible to test the theory that vibratory compaction of granular materials is best accomplished under conditions approaching inundation. In analyzing the results, however, it was found that most consistently high densities were developed in the sections whose moisture content when compacted was not more than 1 percent above or below the mean value for all sections built of that same material. Therefore, only these densities will be included in the final data reported herein. Further information on the effect of moisture content on field density will be presented in a later section.

All field density measurements were made with the aid of a Rainhart volumeter, a rubber balloon device capable of measuring test hole volumes up to 0.10 cu ft. Air pressure of 5 psi was applied to the water cylinder to make sure the balloon conformed as closely as possible to the size and shape of the test hole. This device has been tested thoroughly for accuracy and precision by various methods. Most recently, the volumes of 23 of the actual test holes in this study, which had been measured with the volumeter, were checked by making gypsum plaster casts of them and measuring the cast volumes by the water displacement method. The mean value of all these volumes as measured with the volumeter was only 1.23 percent lower than the mean of the cast volumes; the percentage divergences between the two measurements only ranged from a maximum of 1.67 percent to a minimum of 0.20 percent, the cast volume being slightly greater in all cases. From these figures, it is believed that the volumeter method combines adequate accuracy with considerably greater precision than can be obtained by the use of the conventional sand cone method. A report describing the study from which these data are quoted is available (6).

The volumes of all density test holes were kept quite close to 0.05 cu ft. This was easily accomplished by digging each hole to such a volume that the material removed just filled a ½-gal jar when lightly packed. This procedure aided in the early detection of any major errors in the values of test hole volume or weight of material removed, and is highly recommended for all types of compaction control testing.

The ½-gal jar samples from the field tests were transported to the Council's laboratory at Charlottesville for oven drying, weighing, and separating into plus and minus No. 4 fractions. After this, the materials were combined to form composite samples, coarse and fine, corresponding to each test section. The specific gravities, bulk and apparent, were determined for each composite coarse sample by AASHO Standard Method T-85. For each composite fine sample, the specific gravity was determined by AASHO Standard Method T-100 and the maximum density by AASHO Standard Method T-99, Alternate A.

This paper is based on the field and laboratory test procedures just described. All field density results can be compared with laboratory results on samples of which the field sample itself formed one part and of which all parts were obtained from this same section not over 200 ft long. The laboratory samples thus represent the field samples to a maximum degree.

ANALYSIS OF FIELD DENSITY DATA

A composite sample was made from all the jar samples taken from each group of five test sites. From the specific gravity and minus No. 4 density values obtained on each composite sample, it was possible to plot a separate Curve A (Fig. 1) defining the maximum theoretical density "D" for all variations in plus No. 4 material. The plot of this curve is greatly simplified through the use of a properly designed nomograph (such as in Fig. 2) in which Curve A becomes a straight line connecting points

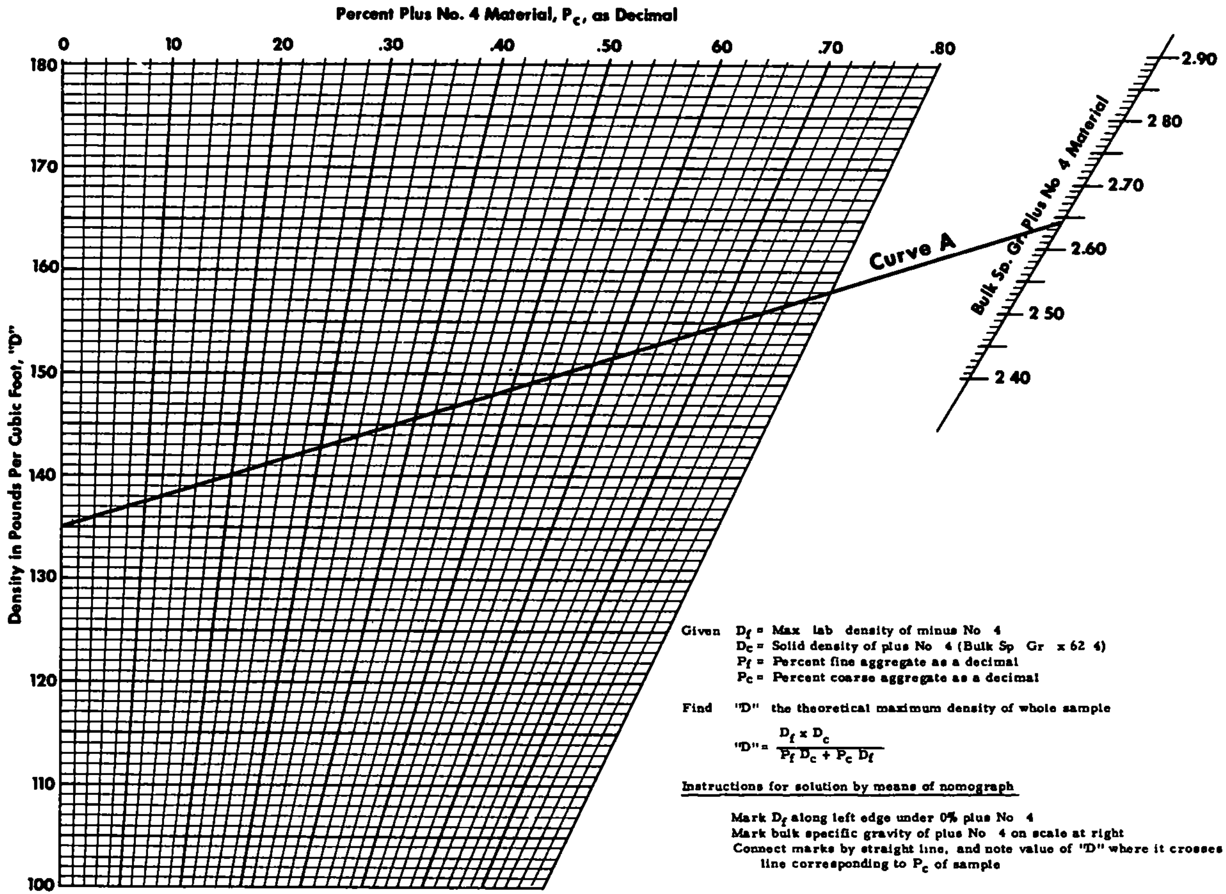


Figure 2. Nomograph for graphical solution of Eq. 3 for "D."

representing D_f on the left and the specific gravity of the coarse fraction on the right. Any point on this straight line represents the solution to Eq. 3 for the applicable percentage of plus No. 4 material. Such a nomograph was prepared for each composite sample, so that each field density determination could be expressed in terms of the same common denominator, the maximum theoretical density "D".

With all maximum field densities for all materials expressed in comparable terminology, it then became possible to prepare a scatter diagram showing the relationship between final percent of "D" and percent plus No. 4. Figure 3 shows all 108 final tests results plotted in this manner.

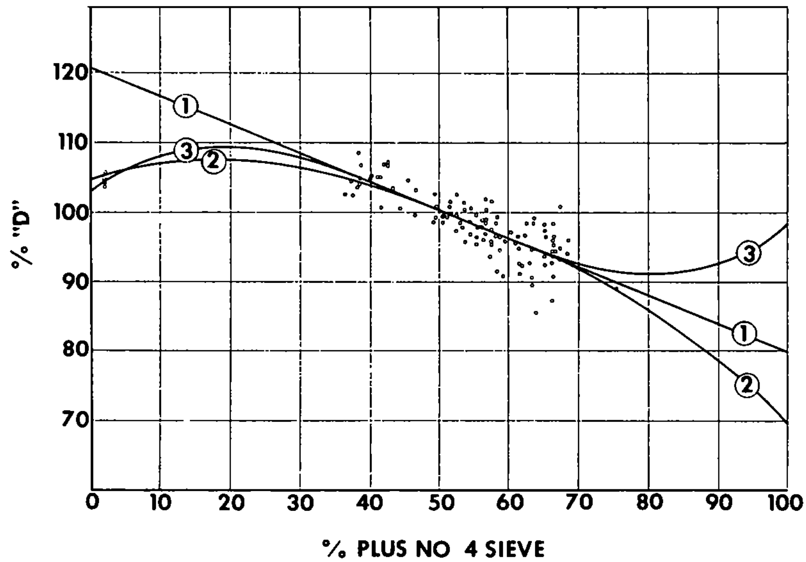


Figure 3. Scatter diagram, final field densities as percent of "D," with 1st, 2nd, and 3rd degree regression lines.

Figure 3 also shows curves of regression plotted from various polynomial equations evolved from analysis of the data by means of the IBM 1620 computer at the Central Highway Office at Richmond. These regression curves were developed in the quest for a simple workable expression for maximum field density on which specifications could be based. Curve 1 represents the best first degree equation (straight line) that could be drawn through the 102 points from the six crushed aggregate materials. Curves 2 and 3 represent the best second and third degree equations that could be drawn through the 108 points representing all the data. There was practically no difference between the standard errors of estimate for the third degree equation, plotted as line 3, and a fourth degree equation that was developed but not plotted.

It is apparent, however, that although line 3 represents a good fit with the data obtained in this limited study it would not fit points that might have been developed had the study included materials with either 10 to 30 percent plus No. 4 or more than 70 percent plus No. 4. However, between about 40 and 60 percent plus No. 4, any one of the three regression lines fits the plotted values about as well as any other, and a straight line is the simplest form to work with.

It was decided therefore to try two straight lines, the first running parallel to the X-axis from 0 percent plus No. 4 to its intersection with line 1 (which occurred at about 40 percent plus No. 4) and the second following the balance of line 1. Figure 4 shows this combination of straight lines superimposed on Figure 3.

As a simple comparative measure of the goodness of fit, or accuracy with which estimates of maximum field density can be made from the various regression lines in

Figure 4, the average absolute value of the deviations of all 108 points from each line was computed. It was found that the average deviation from the pair of straight lines was identical to that from the third degree line, with both values equal to 2.06 percent density.

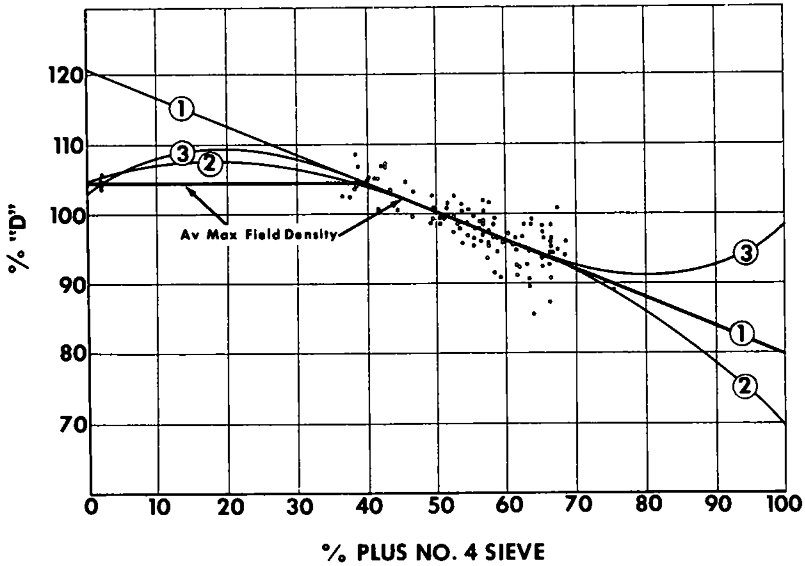


Figure 4. Same scatter diagram as in Figure 3 with straight lines superimposed to represent arbitrarily selected line of regression for average maximum field density.

As mentioned earlier, the points plotted in Figures 3 and 4 represent only those final field density measurements where the moisture content in the sample was within 1 percent of the average moisture content in all samples of the same material. It had been supposed that maximum field density in materials of this sort might be achieved at higher moisture contents, perhaps even approaching saturation. The 1961 test sections were deliberately designed to test this supposition in that each section was built on a solid, cement-treated subgrade so that compaction at high moisture contents could be accomplished without risk of softening the subgrade and producing premature failures.

It has become apparent that the supposition just mentioned is false. Figure 5 shows plots of all the final field density determinations that were not shown in Figures 3 and 4 because of moisture contents more than 1 percent above or below the average. The "average maximum field density" line in Figure 5 is the same as the one shown in Figure 4. Most of the points in Figure 5 fall below this line, indicating that there is an optimum moisture content range outside of which even 50 roller coverages were noticeably less effective in producing density. Moisture contents above the optimum range were even more detrimental than those below; final densities of those samples on the wet side were below the "maximum" line by an average of 3.0 percent, while those on the dry side averaged only 1.4 percent below this line.

RECOMMENDATION OF MODIFIED FIELD DENSITY REQUIREMENTS

The two heavy straight lines in Figure 4, then, indicate quite accurately the probable variation in average maximum density attainable in the field with respect to the percentage of plus No. 4 aggregate present. Because there is, as should be expected, considerable scatter about these lines, the specification used for compaction control should take this scatter into account. Also, it would be neither reasonable nor economical to require a contractor to produce the maximum attainable field density.

A reasonable basis for control specifications would be the requirement that all granular base and subbase materials, and certainly those placed in the top 12 in. of the pavement structure, be compacted to an average field density that is at least 98 percent of the average maximum field density attainable. If the materials used in the field experiments described herein are properly representative, such a requirement can be described in terms of a variable percentage of the maximum theoretical density "D." For a field density sample containing a given percentage of plus No. 4 aggregate, the percentage of "D" which should be specified would be determined from Table 1.

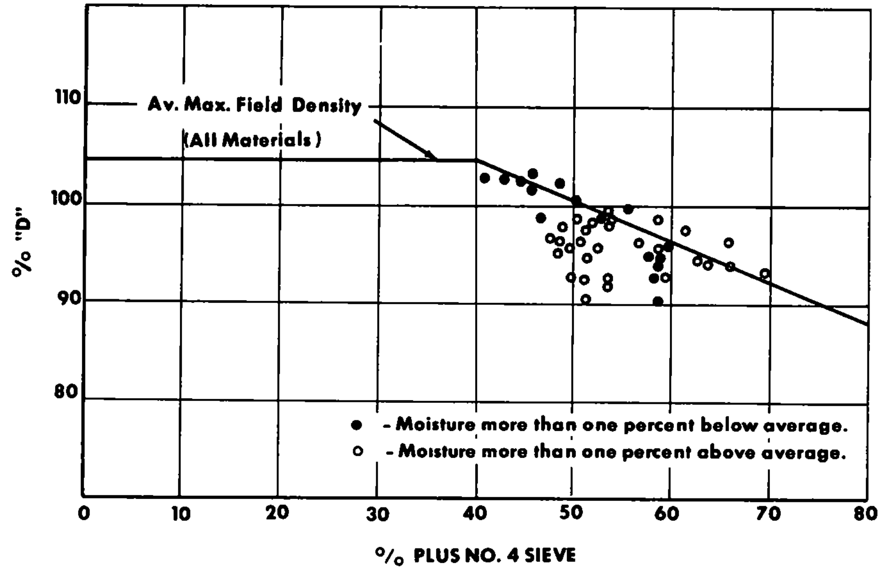


Figure 5. Final field densities on samples more than 1 percent above or below average moisture content of all samples of same material (not shown in Figs. 3 and 4).

TABLE 1

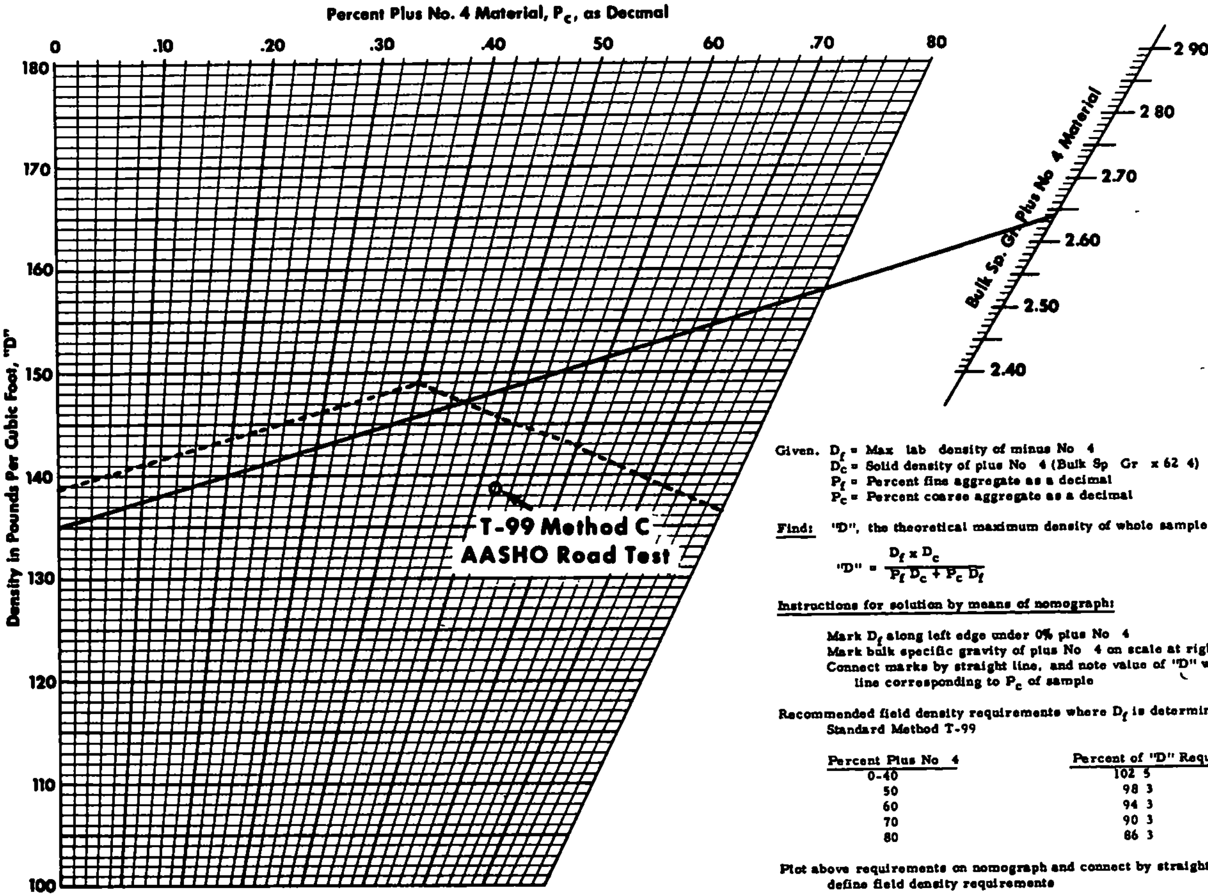
FIELD DENSITY REQUIREMENTS IN TERMS OF THEORETICAL MAXIMUM DENSITY "D"

Percent Plus No. 4	Av. Percent of "D" Required
40 or less	102.5
50	98.3
60	94.3
70	90.3
80	86.3

It may be seen that the percent of "D" required in each instance is 98 percent of the value obtained from the "maximum field density" regression line of Figure 4.

The choice of 98 percent of the average maximum field density was made in a somewhat arbitrary fashion. From the data in Table 3 (in the Appendix) it can be shown that the average density after 30 roller coverages was not always as much as 98 percent of that after 50 coverages. Therefore, if the effort equivalent to 30 roller coverages is considered excessive, this 98 percent figure may be too high. However, if control specifications are not kept high, they may fail to perform their intended function, that of insuring against subsequent densification under traffic.

The practical application of these revised density requirements may be illustrated by a typical example. Figure 6 shows again the nomograph used in Figure 2, where D_f was 135 pcf and the specific gravity of the coarse fraction was 2.64. The solid straight line connecting these points produces the solution of Eq. 3 for the value of "D" for any value of P_c. The values of "D" for 0, 40, 50, 60, 70, and 80 percent



Given. D_f = Max lab density of minus No 4
D_c = Solid density of plus No 4 (Bulk Sp Gr x 62 4)
P_f = Percent fine aggregate as a decimal
P_c = Percent coarse aggregate as a decimal

Find: "D", the theoretical maximum density of whole sample

$$"D" = \frac{D_f \times D_c}{P_f D_c + P_c D_f}$$

Instructions for solution by means of nomograph:

Mark D_f along left edge under 0% plus No 4
Mark bulk specific gravity of plus No 4 on scale at right
Connect marks by straight line, and note value of "D" where it crosses line corresponding to P_c of sample

Recommended field density requirements where D_f is determined by AASHO Standard Method T-99

Percent Plus No 4	Percent of "D" Required
0-40	102 5
50	98 3
60	94 3
70	90 3
80	86 3

Plot above requirements on nomograph and connect by straight lines to define field density requirements

Figure 6. Nomograph from Figure 2 with suggested compaction standards added. Compaction standard used at AASHO Road Test also shown.

plus No. 4 are multiplied by the percentage corrections from Table 1, which are printed in the lower corner. These values are plotted on the nomograph and connected by straight lines. (No great error is made if only the values corresponding to p_c values of 0, 40, and 80 are plotted, because those for 50, 60, and 70 lie very close to this line.) The dotted line now represents the average field density to be required for this material for any reasonable percentage of plus No. 4. The point marked T-99 Method C will be commented on a little later.

The suggestion that compaction control be based on an average rather than an absolute minimum density requirement is made so that the authors may voice agreement with many others who feel that "a specification requiring an absolute minimum . . . . compaction is unrealistic" (7). A reasonable procedure for compaction control on a subbase or base course would seem to be one in which blocks or areas of the course in question would be laid, compacted, and tested as units, with a specified number of field density measurements made at random locations in each unit. If the average of all tests results met the requirements and if not more than one in four, one in five, or even one in ten, fell more than 2 percent below the requirement of the average, the unit as a whole would be accepted. If all these requirements were not met, the entire unit would receive additional compaction and be retested completely.

It is realized that using even the fastest of conventional field density measurement methods, a great deal of manpower is needed to make enough measurements to be sure these requirements are met. The adoption of more effective compaction control procedures will certainly be expedited by the continued development of still faster test methods. It is in the area of compaction control on granular base and subbase materials that the nuclear density measuring devices should stand their best chance of gaining general acceptance; the relative uniformity of these materials should tend to minimize the calibration problem.

PROSPECTS FOR BETTER STANDARD TEST METHODS

The foregoing analysis of field data and suggested modifications to compaction control requirements are all based on the use of a laboratory test that was originally devised for fine-grained cohesive materials, rather than for granular materials. On some granular materials, particularly those with little or no cohesiveness, it is difficult to establish a definite moisture-density relationship with the T-99 test. A more reliable test definitely would be desirable.

One thing in favor of the authors' suggested method is that it involves simple tests with readily available and portable equipment. Thus if a change in the character or gradation of the material being used becomes apparent, which does happen, a new sample can be taken and tested very quickly, even on the job if necessary.

The fact that the properties of maximum T-99 density and specific gravity do change from time to time, even on materials being produced from the same source, can be demonstrated from Table 2, which indicates the variations in materials from the same source between samples taken from different compaction test sections. In this table, the greatest variation is apparent in the results of the T-99 test for maximum density, the range in values running from 4.9 to 6.5 percent of the average values. It is conceded, however, that these variations are not entirely due to changes in the material; human error is known to account for substantial variations, and the impact test itself, as noted already, probably fails to compact some of the least cohesive samples to their true maximum density. But major variations in the material should be detectable from a simple test, and the result should be available quickly and not after the long delay often involved in sending the sample to a distant laboratory for testing by a specialized piece of equipment.

One drawback attached to the authors' method is that it fails to take account of variations in the gradation or particle shape of the coarse fraction, variations that might have a pronounced effect on the compactability of this fraction. If the compactability of the fine fraction varies between samples from the same source, it stands to reason that the compactability of the coarse fraction should vary also. This fact probably accounts for a great deal of the scatter in the data plotted in Figures 3 and 4, which is

TABLE 2

VARIATIONS IN PROPERTIES OF CRUSHED AGGREGATES

Source	Section No.	Max. Density T-99-A (pcf)	Sp. Gr. -#4 T-100	Sp. Gr. +#4 T-85
Winchester	1	139.5	2.75	2.71
	2	137.7	2.75	2.72
	3	135.8	2.74	2.70
	4	135.2	2.75	2.69
	5	135.3	2.72	2.69
	6	135.9	2.74	2.68
	7	130.8	2.76	2.71
	8	133.2	2.76	2.70
	9	134.3	2.75	2.70
	10	132.8	2.73	2.71
	11	131.7	2.74	2.70
	12	133.5	2.71	2.69
	13	134.7	2.71	2.71
	Mean	134.7	2.74	2.70
	Range	8.7	0.05	0.04
	% Range[a]	6.5	1.8	1.5
Danville (13 Sections)	Mean	123.8	2.65	2.59
	Range	7.8	0.07	0.03
	% Range[a]	6.3	2.6	1.2
Gainesville (12 Sections)	Mean	133.8	2.92	2.87
	Range	6.5	0.09	0.06
	% Range[a]	4.9	3.1	2.1

[a]Range expressed as percent of mean value.

noted to be more pronounced at the higher percentages of plus No. 4. A more completely adequate standard test method should take account of variations in compactability of both coarse and fine fractions.

In recognition that the authors' suggested method of establishing density standards in the laboratory is not without drawbacks, consideration has been given to some of the numerous other methods in use. Methods that do take account of the compactability of more than just the minus No. 4 fraction include the Humphres method (8), the alternate procedures C and D in AASHO Standard Methods T-99-57 and T-180-57, and a number of local variations.

An attempt was made to afford a comparison between the maximum field densities and laboratory densities on the same materials by some of these methods. Single composite samples of three of the materials were sent to the Washington State Highway laboratory for test by the Humphres method and for preparation of density curves. Also, tests on composite samples of four of the materials were made by Chamblin on the vibratory table (5). All materials were tested by AASHO Standard T-99 Method C.

Figures 7 through 11 show these comparisons graphically. The captions for these figures are self-explanatory, but it should be emphasized that the Humphres curves, the vibratory table curves, and the T-99-C results are for single samples only. Nevertheless, certain definite indications seem evident from these figures:

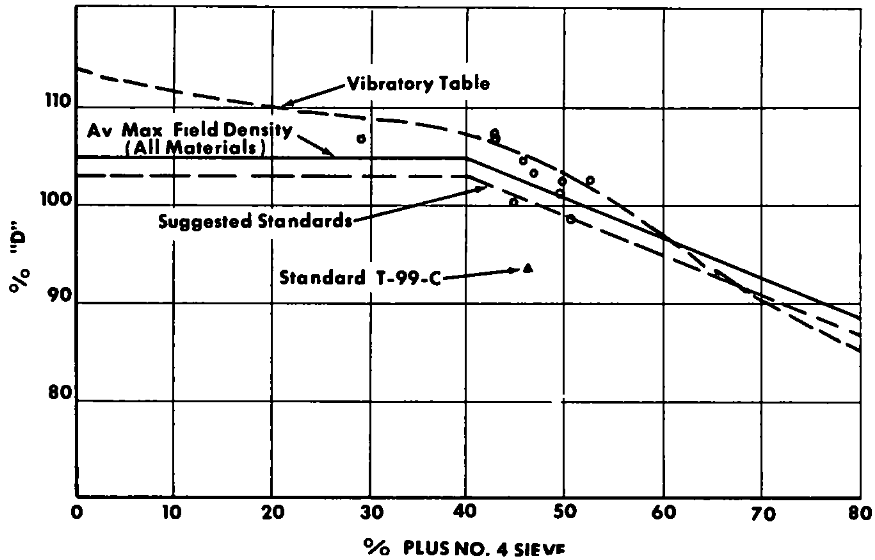


Figure 7. Final field densities, all test sections, limestone material, Madison project.

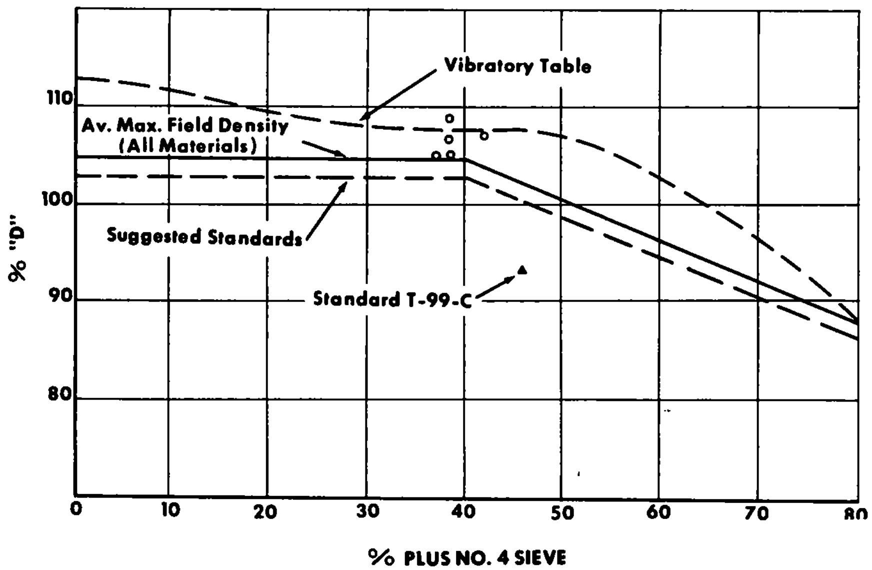


Figure 8. Final field densities, all test sections, siltstone material, Madison project.

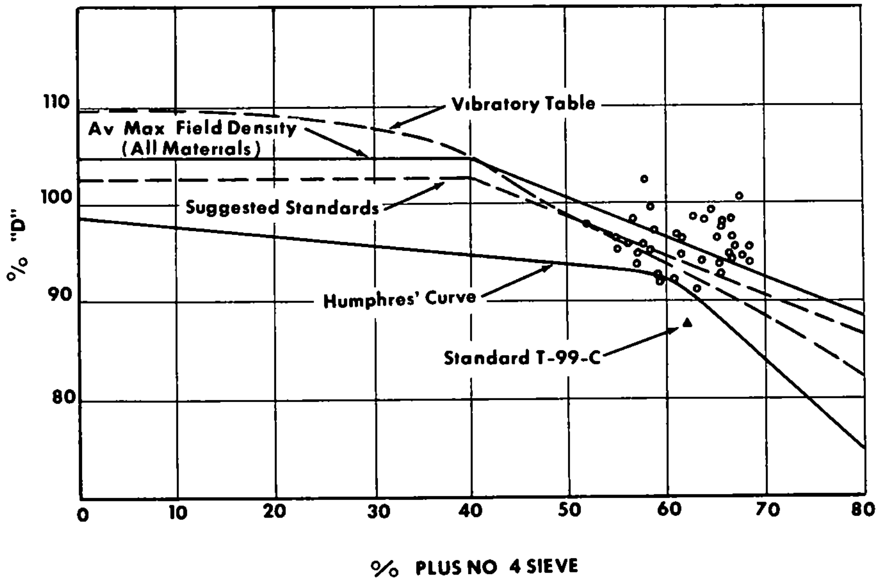


Figure 9. Final field densities, all test sections, limestone material, Winchester project.

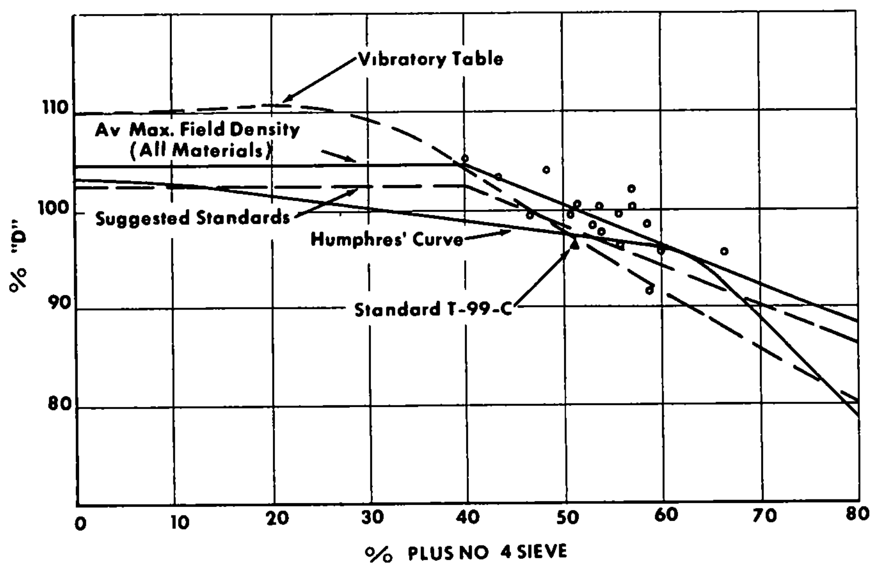


Figure 10. Final field densities, all test sections, granite material, Danville project.

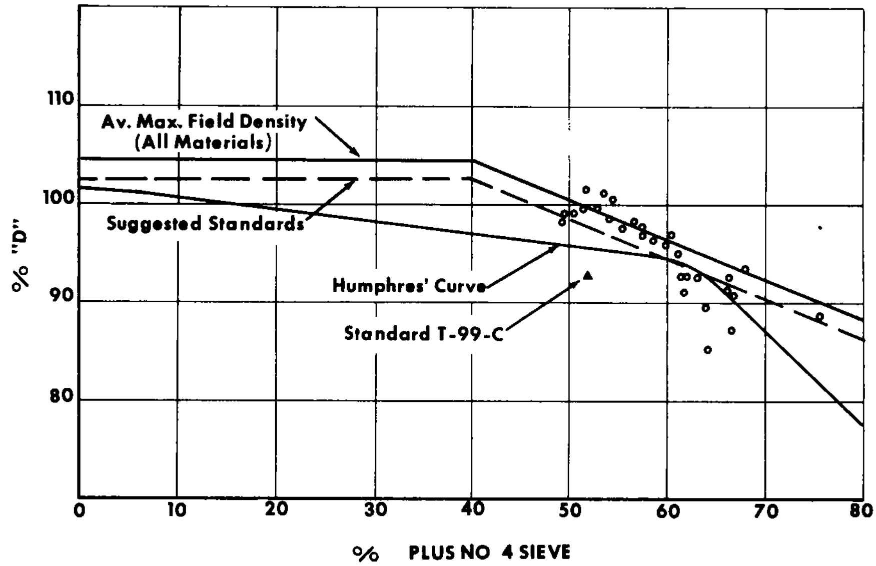


Figure 11. Final field densities, all sections, diabase material, Gainesville project.

1. The average maximum field densities are generally substantially higher than the standard density based on AASHO T-99 Method C. (A striking comparison between the present Virginia requirements, the authors' new suggested standards, and this AASHO standard is also evident from Figure 6. All values in this figure are applicable to the crushed aggregate base material used on the flexible pavement sections of the AASHO Road Test. At the reported average plus No. 4 aggregate content of 52 percent, the standard density of this material by Method T-99-C was 138 pcf. The maximum permissible density in this material at the Test Road, 145 pcf or 105 percent of the standard, approximately equals the authors' recommended requirement for average density and falls 4 pcf below Virginia's present minimum permissible density.)

2. The average maximum field densities also are generally higher than the standard established by the Humphres curve except at plus No. 4 contents in the 60 to 65 percent range. The break in the authors' curve, (based on maximum field density data) falls at a considerably lower plus No. 4 content than does the break in the Humphres curve, which was based on a number of theoretical assumptions. The apparent disagreement between the authors' field density data and the data reported by Humphres (8) is unexplained.

3. The curves produced by the vibrating table method of Chamblin bear no apparent relationship to the field densities. The vibrating table densities at plus No. 4 contents of 0 and 33 percent seem unrealistically high.

Although there are recognized drawbacks to the method of establishing compaction standards suggested by the authors, it is felt that the method provides an acceptable expedient that would result in considerable improvement over the present Virginia method based only on the maximum density computed from Eq. 3. Though the authors' standards are more rigid than those based on AASHO T-99 Method C or the Humphres curve, they would represent a general relaxation from Virginia's current requirements.

Finally in recognition of the logical complaint that the average maximum field densities may have been based on an unrealistically high compactive effort (50 coverages of the test roller), Figure 12 summarizes the results of final field density tests on a number of control sections subjected only to normal rolling by the contractor. Control sections were established on all projects, and tests were made with the Rainhart device only after compaction had been accepted by the project inspector, based on sand-cone density tests. It is noted that at a number of points the density determined by the

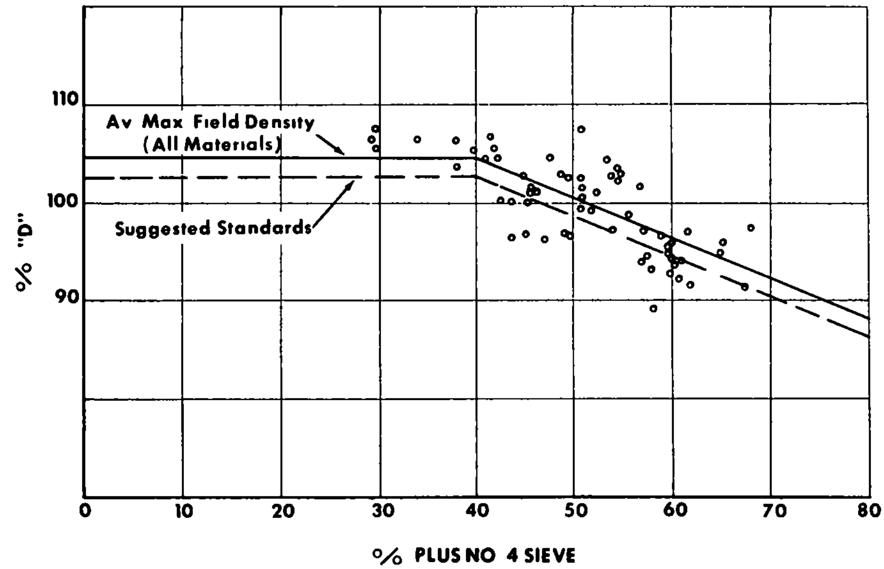


Figure 12. Final field densities, contractor's rolling only, all materials.

Rainhart method failed to meet the current Virginia requirements, but relatively few failed to meet the new standards proposed by the authors.

SUMMARY AND CONCLUSIONS

Two main points form the basis of the foregoing discussion:

1. Base and subbase materials used in flexible pavement construction must be adequately compacted to develop full load-bearing capacity and prevent subsequent further densification under traffic.
2. An essential part of compaction control is the ability to test the material in the laboratory and predict the density that, for any allowable variation in gradation, will be adequate but still attainable with reasonable effort in the field.

In recognition of these facts, the Virginia Council of Highway Investigation and Research embarked in 1960 on a joint field and laboratory study to improve control over compaction of granular materials. Test sections in the field were subjected to intensive vibratory rolling until the materials were believed to have reached their maximum attainable field density. Samples of these materials were then taken to the laboratory to be tested by various methods to see which one method or combination might most accurately predict this maximum field density.

Based on comparisons between the densities attained in the field test sections and the maximum densities achieved by certain types of laboratory test on the same materials, the following conclusions have been drawn:

1. Laboratory tests by AASHO Standard T-99 Method C, on coarse base or subbase materials, generally produce densities that are not as high as those readily attainable in the field. Control specifications based on this standard may not ensure adequate compaction to prevent subsequent densification under traffic.
2. Other nonstandard laboratory procedures, such as the vibratory table method or that developed by Humphres, do not correlate well with maximum field densities attained in this study.

By means of a regression analysis of the maximum field density data, the authors have proposed a method of establishing density standards on materials with a wide range of coarse aggregate content, based on determinations of (a) maximum laboratory density of the minus No. 4 fraction by AASHO Standard Method T-99-A, and (b) bulk specific gravity of the plus No. 4 fraction by AASHO Standard Method T-85. The results of these two determinations may be used to obtain the recommended standard density for any coarse aggregate content, as described in Figure 6.

The suggested method would establish compaction requirements considerably more rigid than those established by a number of agencies, but somewhat less rigid, generally, than those now in force in Virginia. It is felt that compaction requirements on expensive, commercially-produced base materials should be as high as economically feasible in order to develop maximum load bearing capacity. The addition of asphalt or cement to "stabilize" base materials that ought to possess adequate mechanical stability without such additives, if properly compacted, is not favored.

The foregoing density requirements are not suggested as the absolute minimum for any measurement. Such requirements have been shown to be unrealistic. A workable scheme requiring a minimum value for the average of a specific number of measurements covering a specific volume or area has been suggested.

Finally, the importance of competent technicians using reliable methods of measuring field density cannot be overemphasized. After several years of experimenting with various measurement methods, the Research Council has standardized on a method that employs the Rainhart water balloon volumeter for measurement of test hole volumes. This method has been found to possess both accuracy and precision, and is faster than other standard methods in which sand or oil is used. But no method is reliable unless it is used by a reliable technician. Every effort should be made to train these technicians properly and to impress on them the importance of their jobs. There may never be enough trained technicians with enough equipment to make all the density measurements necessary for true control over all layers of embankments, subbases, and bases. This being the case, it is highly recommended that those technicians who are available be instructed to concentrate their efforts on the upper layers composing the subgrade, subbase, and base courses.

It is the firm belief of the authors that adequate compaction control of these upper layers is not an impossible task. It is sincerely hoped that the study reported here will be of material assistance to those agencies interested in improving their compaction control for the construction of better and more economical flexible pavements.

ACKNOWLEDGMENTS

The study reported herein was not accomplished without the cooperation of a large number of individuals, both in the Department of Highways and in the contracting and equipment industries. Though so many were involved that they cannot all be named, it is hoped that all may realize the appreciation felt for their efforts.

Special mention should be made, however, of the work of R. W. Gunn, of the Highway Research Council, who had charge of the field work in 1960 and contributed greatly to the analysis of the data. Richard N. Swift also deserves mention as an able assistant in the field testing phase of the study. Laboratory work was performed by various technicians and student helpers under the supervision of B. B. Chamblin, Jr.

A special note of thanks is also due to Carl Minor, Materials and Research Engineer, Washington State Highway Department, for assistance rendered in testing the samples of crushed stone base material by the Humphres method.

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Appendix

EFFECTS OF EXTENSIVE ROLLING

Densification

The main objective of the study was to record the maximum field density obtained after extensive rolling. The observation of progression of densification was a secondary objective. When the program of research was begun it was believed by the authors that maximum density might be attainable with from 15 to 20 passes, and that little if any significant increase in density would be noted as a result of repeated coverages beyond this range. Unfortunately this was not the case. It soon became apparent that an increase in the number of coverages beyond the 15- to 20-pass range was resulting in increased density. Therefore it became necessary to set a limit as to the maximum practical number of coverages. This limit was set at 50 passes.

Time did not permit the measurement of density at intermediate intervals during the entire rolling operation on each test section. However, density measurements after 30 passes were made on three of the materials at enough locations to afford an evaluation of the effect of the final 20 passes. Table 3 presents these figures as simple averages.

TABLE 3

MEAN INCREASE IN DENSITY FROM 30 TO 50 COVERAGES

Source of Material	No. of Sites	Avg. Density (pcf) 30 Passes	Avg. Density (pcf) 50 Passes	Avg. Increase in Density (pcf)
Winchester	16	144.7	147.8	3.1
Danville	12	134.3	136.6	2.3
Gainesville	12	145.6	150.4	4.8

Because the increase in density caused by the final 20 passes was not at all uniform at different sites, and in fact at a few sites the density appeared to have decreased, it was decided to make standard statistical tests to determine the significance, if any, of the apparent increases. The results of these tests indicated that for each of the three materials, the increases in density due to the final 20 passes were significant. Table 4 and the calculations that follow it show how the t-test was performed on one of the three materials.

TABLE 4

DENSITY INCREASE FROM 30 TO 50 PASSES (WINCHESTER MATERIAL)

Density (pcf)		Difference, d	d^2
50 Passes	30 Passes	(pcf)	
147.4	144.0	+ 3.4	11.56
148.9	144.5	+ 4.4	19.36
142.2	146.2	- 4.0	16.00
145.0	143.8	+ 1.2	1.44
148.5	143.5	+ 5.0	25.00
148.0	149.9	- 1.9	3.61
149.5	149.0	+ 0.5	00.25
145.0	146.0	- 1.0	1.00
145.8	139.8	+ 6.0	36.00
148.8	145.2	+ 3.6	12.96
155.5	148.0	+ 7.5	56.25
149.2	140.2	+ 9.0	81.00
145.3	142.5	+ 2.8	7.84
143.3	140.1	+ 3.2	10.24
151.3	147.7	+ 3.6	12.96
150.8	144.6	+ 6.2	38.44
		49.50	333.91

Sample calculations:

$$s^2 = \frac{\Sigma\, d^2 - n\left(\frac{\Sigma\, d}{n}\right)^2}{n - 1}$$

in which

s = estimated standard deviation;
n = number of pairs of data = 16; and
d = difference in density at 50 and 30 passes shown in third column of Table 3.

$$s^2 = \frac{333.91 - 16\left(\frac{49.51}{16}\right)^2}{15} = 12.05$$

$$s = 3.473$$

$$t = \frac{\bar{d} - m}{s/\sqrt{n}}$$

in which

t = students test constant;

$\bar{d}$ = $\dfrac{\Sigma d}{n}$;

m = specified mean value = 0; and

$$t = \frac{3.09}{3.473/\sqrt{16}} = +3.556.$$

The value of m is 0 because the test is employed to see if $\bar{d}$ is different from zero. From t-test tables, there is a probability of 0.05 that the absolute value of t is accidentally greater than 2.131. The calculated t-value is greater than 2.131. Therefore, a difference in density can be asserted with 95 percent confidence of being correct. The positive sign of t calculated indicates that the difference is an increase.

Degradation

To determine the amount of degradation that occurred during the 50 passes of the test roller, a sieve analysis was made on the composite samples representing the materials in their initial and final conditions (before and after test rolling). Here again it was possible to analyze the material actually used in density determinations.

Table 5 shows the mean percent passing the No. 200, No. 40, No. 10, No. 4, ⅜ in., and 1 in. sieve sizes before and after rolling, and the range of values comprising each mean. The data in this table indicate a slight tendency toward degradation.

TABLE 5

MEAN SAMPLE GRADATION BEFORE AND AFTER 50 COVERAGES

Source	Percent Passing Sieve					
	1-In.	⅜-In.	No. 4	No. 10	No. 40	No. 200
Danville:						
Before:						
Mean	89.9	61.6	45.7	35.6	24.9	12.6
Range	84-94	55-69	31-55	22-42	15-29	7-6
After:						
Mean	92.7	63.6	50.3	38.7	26.7	13.4
Range	88-96	56-72	42.59	31-49	21-35	10-17
Gainesville:						
Before:						
Mean	100	56.7	41.7	30.7	18.2	10.3
Range	100-100	48-68	33-50	24-40	12-26	5-19
After:						
Mean	100	62.4	45.4	35.2	19.7	9.8
Range	100-100	52-69	38.49	29-42	9-25	4-13

Because the increase in percent passing these various sieves was not uniform with different test sections, it was decided to apply the t-test to determine the significance, if any, of the increase in percent passing.

Table 6 and the calculations that follow it are an example of this statistical procedure.

TABLE 6

DEGRADATION ANALYSIS, DANVILLE MATERIAL (GRANITE)
Increase in Percent Passing Sieve[a]

No. 200	No. 40	No. 10	No. 4	3/8-In.	1-In.
+4	+9	+14	+15	+17	+10
-1	+1	+ 7	+ 9	+ 7	+ 8
0	-1	- 2	- 4	- 5	- 4
-1	-1	- 5	+ 1	+ 3	- 1
+1	0	- 1	0	- 4	+ 5
+3	+6	+ 9	+11	- 4	0
0	0	0	0	0	+ 2
Mean +0.9	+2.0	+3.1	+4.6	+2.0	+2.9

[a] From 0 to 50 passes.

Sample calculation t-test on No. 200 sieve:

d	d^2
+4	16
-1	1
0	0
-1	1
+1	1
+3	9
0	0
+6	28

$$s^2 = \frac{\Sigma d^2 \quad -n \left(\frac{\Sigma d}{n}\right)^2}{n-1}$$

$$s^2 = \frac{28 - 7\,(6/7)^2}{6} = 3.81$$

$$s = 1.951$$

$$t = \frac{\bar{d} - m}{s/\sqrt{n}} \quad \frac{0.858}{0.736} = 1.165$$

in which

m = specified mean value = 0;
s = estimated standard deviation;
n = number of data points;
d = difference in percent passing;
t = students "t"; and
$\bar{d}$ = mean difference in percent passing $= \frac{\Sigma d}{n}$.

From t-test tables there is a probability of 0.05 that the absolute value of t is greater than 2.447. Calculated t is less than 2.447; therefore, the mean increase is not significantly different from 0, and there is no significant degradation apparent at the 95 percent confidence level.

Discussion

W.H. CAMPEN, Omaha Testing Laboratories, Omaha, Neb. — The authors cover two main points: (a) it is very difficult to determine maximum laboratory density in mixtures containing plus No. 4 material, and (b) field equipment can produce higher densities than is obtained by standard AASHO methods T99-57 and T180-57.

In regard to the first point, the writer's experience has shown that Eq. 3 in the paper gives high results when any amount of plus No. 4 material is used, and of course the densities are unrealistic when the percentage of minus No. 4 is insufficient to fill the voids in the plus No. 4.

The writer has found the following procedure satisfactory for a 1 ½-in. maximum sized aggregate:

1. Prepare mixtures containing various percentages of +4 aggregate.
2. Replace all + ¾-in. aggregate with plus No. 4 minus ¾-in. aggregate prepared from the material being evaluated.
3. Run a moisture density test with each mixture using method D in AASHO T99-57 or T180-57.

In making field density tests, take samples of at least 0.10 cu ft in volume. Determine the plus No. 4 material in the sample and select the maximum density from the moisture-density curves prepared in advance.

In regard to the second point it is true that field equipment may produce higher densities than AASHO methods; however, it depends on the cohesiveness of the mixture. The field density of cohesive mixtures (even if the plasticity index is very low) can be predicted by the AASHO methods. On the other hand, cohesionless mixtures, if compacted in a wet condition by vibratory methods, can give higher results than AASHO methods. The reason is that impact laboratory methods are not suitable for compacting cohesionless mixtures. There is an urgent need for a standardized laboratory vibratory method for such materials.

Another very important related point should be brought out in this discussion. It pertains to the relationship between specified density and the density that may be produced by traffic. The writer has no specific answer to the problem but it is known that the effect of traffic depends on its weight and frequency. Densities commensurate with traffic of varying intensities will eventually be specified. Right now, the Corps of Engineer require densities of from 100 to 105 percent (AASHO 180T) for airport runways.

F.P. NICHOLS, Jr., and H.D. JAMES, Closure — Mr. Campen's comments are most welcome. With regard to his procedure of determining separate laboratory moisture-density relationships for each of several mixtures containing various percentages of plus No. 4 aggregate, the authors have two comments:

1. The procedure would involve a considerably greater amount of testing to produce a single curve of maximum density vs percent plus No. 4 than does the procedure suggested by the authors.
2. Unpublished data obtained in a Virginia laboratory study indicates that there is usually no significant difference in the maximum densities produced by Methods C and D of the AASHO standard tests. Therefore, as pointed out in the paper, the T-99 test (Method D) on materials containing appreciable plus No. 4 aggregate probably would result in standard densities too low for proper control over compaction. The T-180 test might be more suitable if it does not cause too much degradation during the course of the testing.

The desirability of having a standardized laboratory vibratory test was recognized when the study reported by Chamblin was being planned. So far, as is seen in Figures 7 through 10, the maximum densities obtained by Chamblin's method do not seem to correlate well with maximum field densities.

Finally, the authors feel that regardless of the traffic expected to use a given pavement, the more expensive base and subbase components of that pavement should certainly be given as much compaction as is economically feasible. Even if they do not densify later, the greater void content of poorly compacted mixtures invites the infiltration of water which may lead to disastrous failures, especially under severe climatic conditions. Therefore, the need for compaction standards that closely parallel the maximum densities obtainable seems self-evident.

Stabilization of Beach Sand by Vibrations

LINO GOMES, Engineer, Soil Testing Services, Inc., Chicago, Illinois, and LEROY GRAVES, Associate Professor of Civil Engineering, University of Notre Dame, Notre Dame, Indiana

• STABILIZATION of sands has been achieved by many methods, such as mechanical, chemical, addition of admixtures, grouting, and compaction. Of these methods, the most economical has been compaction, which can be achieved in many ways; for exampled, rollers, vibrotampers, and vibroflotation.

It has been reported that heavy duty pneumatic rollers imposing a pressure of about 150 psi have compacted sand to a depth of 6 ft below the ground surface. Vibrotampers, weighing 435 lb, operating at 2,100 cpm and producing a compacting force of 10,000 lb are reported to cause compaction of over 95 percent of modified AASHO on lifts up to 15 in. in one pass or two. The vibroflotation process, which imparts a centrifugal force of 10 tons at 1,800 rpm, is reported to compact sand up to a radial distance of 5 ft giving densities of 90 percent of optimum to depths in the range of piling.

Much laboratory research has been done on compaction of sands. One project conducted at the California Institute of Technology (1) by placing on the surface of a sand pit 10 ft square and 6 ft deep, an oscillator weighing 61 lb and driven at frequencies from 170 to 3,450 rpm led to the conclusion that the maximum compaction was obtained at resonant frequency involving several variables such as elastic constant of soil, vibrator dimensions, weight of vibrator, dynamic force, and base plate dimensions. Maximum density from 90 to 95 percent of Modified AASHO was obtained in a few seconds to a depth of twice the width of the oscillator.

The authors felt, after reviewing the field practice and laboratory research on the subject, that it would be profitable to investigate the compaction of sand with almost weightless tampers having several base plate dimensions and operated mechanically at the surface of dry sand at varying frequencies including the supersonic range. It was also decided to include some evaluation of the maximum possible laboratory sand density in view of the fact that though several methods have been suggested, none has been accepted so far as a standard.

APPARATUS

The compaction apparatus was constructed by attaching three aluminum plates 3 by 2 ¾ in., 4 by 2 ¾ in., and 5 by 2 ¾ in. of ⅛-in. thickness one at a time to the cone of a heavy duty loud speaker, as seen in Figure 1.

The speaker and plate were made to vibrate by an audio-oscillator augmented by an amplifier. A voltmeter across the supply line controlled the input voltage to prevent overloading the speaker. A cathode-ray oscillograph helped in the calibration of the audio-oscillator and also in the regulation of the precise frequency during the tests.

The sand to be compacted was contained in a glass-sided tank with a grid of 1-in. squares painted on one side. This tank was placed on a three-legged jack to permit raising and lowering of the tank during the compaction process. The complete apparatus is shown in Figure 2.

The dry sand chosen for the investigation has a uniformity coefficient of 4.35 and a grain-size distribution as shown in Figure 3. According to Hough (2), "an ordinary beach sand 'processed' to some extent by wave wash would have a (uniformity) coefficient of about 2 to 6." The selected grading thus has the uniformity coefficient of beach sand and in addition it fits within the grading limits for a well graded sand as specified by AASHO, M6-51, (3) as shown in Figure 3.

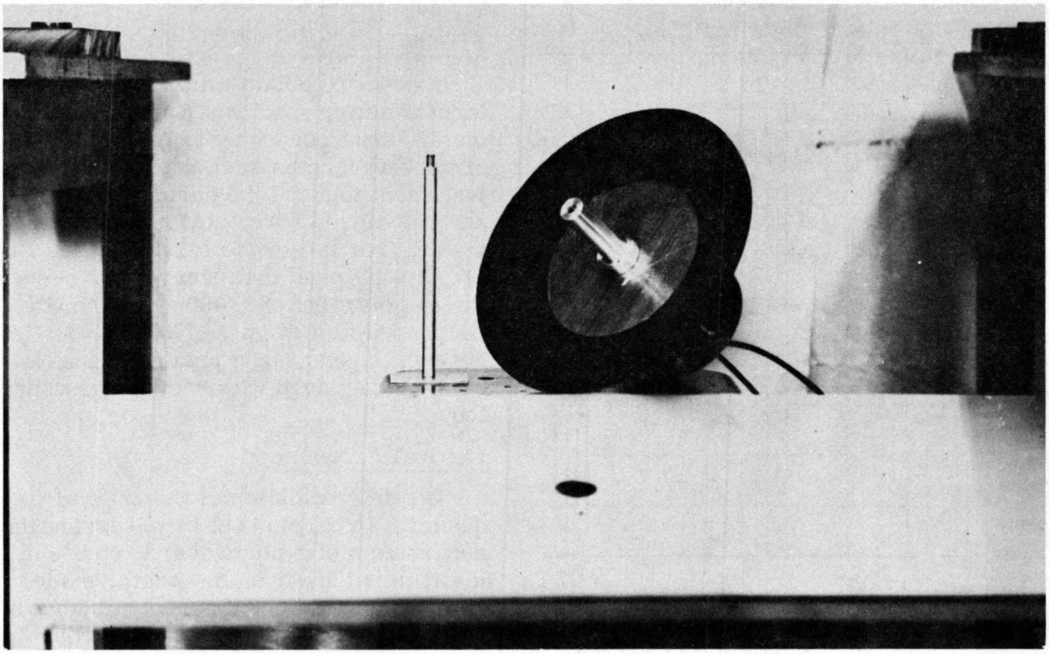

Figure 1. Details of speaker and tamper.

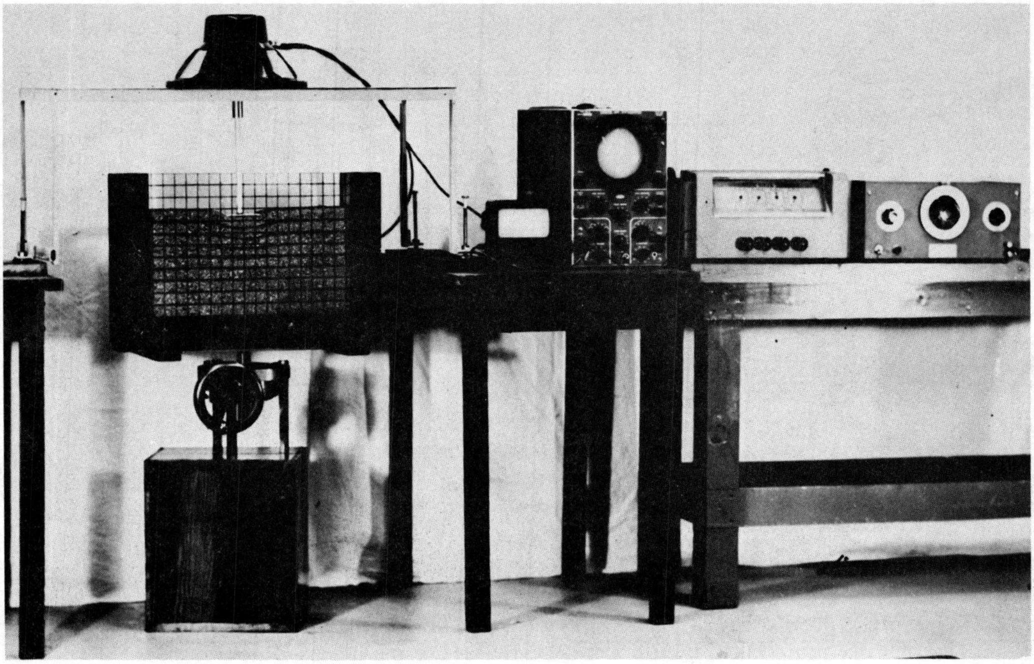

Figure 2. General view of apparatus.

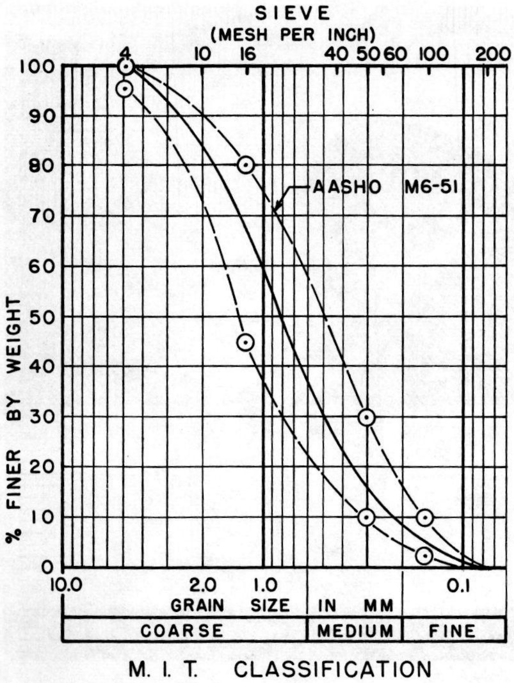

Figure 3. Mechanical analysis of sand.

PROCEDURE

Placing of Sand

In order to obtain minimum and uniform density, sand was poured through a metal funnel connected to extension tubes of varying lengths such that the extension just about touched the surface. The funnel was moved horizontally without giving rise to free fall of the particles (see Fig. 4). It was found that every layer needed the same weight of 1,400 g, which corresponded to a density of 102.5 pcf. In between layers, sand retained on a No. 60 sieve and dyed with red tint was sprinkled.

Critical Frequency

The determination of the critical frequency was carried out by observing the settlements of a piece of iron rod ½ in. in diameter and 7 in. in length, placed vertically on the sand surface as shown in Figure 5. A dial gage measured the settlement. The entire range of frequencies from 18 to 20,000 cps was tried with a duration of ½ min each time, taking care to see that the sand density was 102.5 pcf before each trial. Because the process of placing the oven-dried sand without segregation of sizes and with uniform minimum density was laborous and time consuming the entire range from 18 to 20,000 cps was investigated by using a 3-in. tamper only. However, within the range that gave

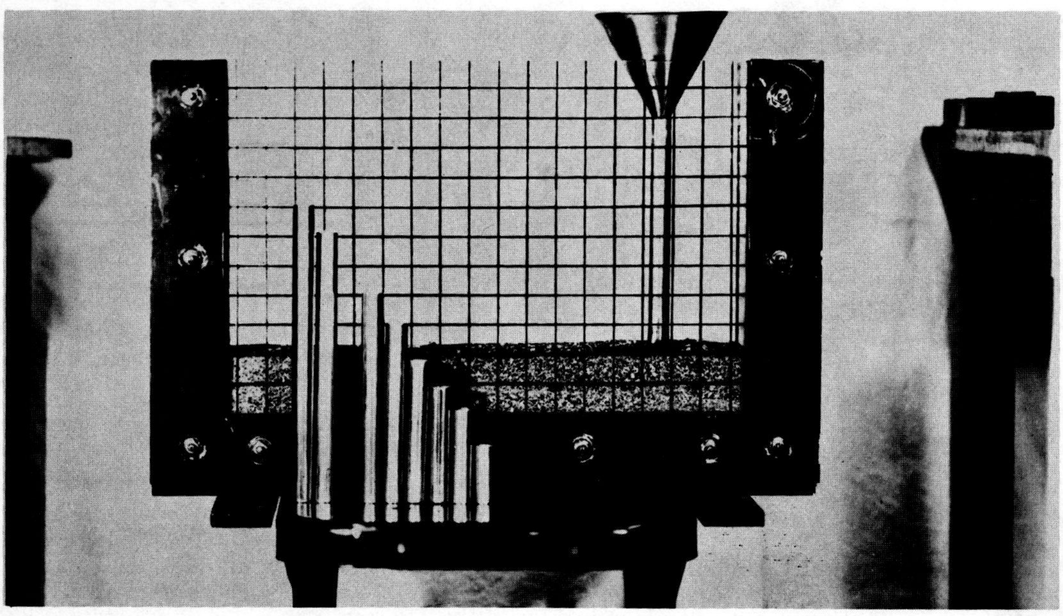

Figure 4. Apparatus for placing sand.

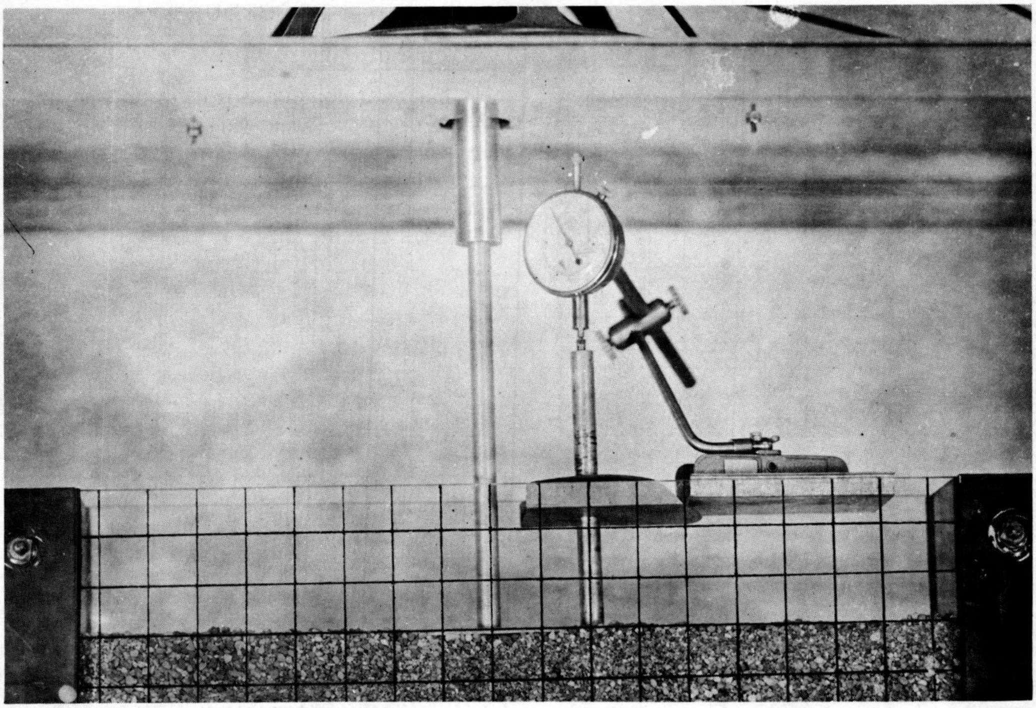

Figure 5. Apparatus for critical frequency.

appreciable settlements (for example, 18 to 30 cps), tests were carried out with all three tampers.

Evaluation of In-Place Density

Each tamper was operated at the critical frequency of 25 cps, during 5 min. Before starting each experiment and at the end of each minute photographs were taken to record the change in the thickness of layers. Examples are shown in Figures 6 through 11.

The reduction in the thickness of the layers is inversely proportional to the increase of the density of sand. Thus the change of the thickness of layers is a measure of their in-place density. On tracing each photograph, the in-place density at every point was calculated and lines drawn connecting equal densities, as shown in Figures 12 through 16.

Evaluation of the Tamping Force

To evaluate the load on the soil from the tamper a proving ring was placed under the tamping rod, as shown in Figure 17. When the tamping rod was vibrated at 25 cps a force of 0.375 lb resulted. Thus the pressures exerted by the 3-, 4-, and 5-in. tampers were 0.045, 0.034, and 0.027 psi respectively.

STANDARD FOR FIELD COMPACTION

Knowing that Proctor curves for sands are erratic and often not sharply defined as to maximum density, relative density was adopted as a standard for the study. The minimum density of the sand was found to be 96.2 pcf by following the funnel method with no circular motion and no free fall, as suggested by D'Appolonia (4). The maximum laboratory density was obtained by the concrete flow table surcharge method of D'Appolonia which resulted in a maximum density of 117 pcf.

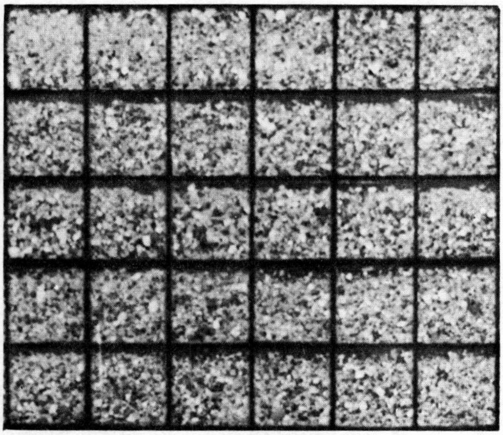

Figure 6. Settlement of 5-in. tamper at 0 min.

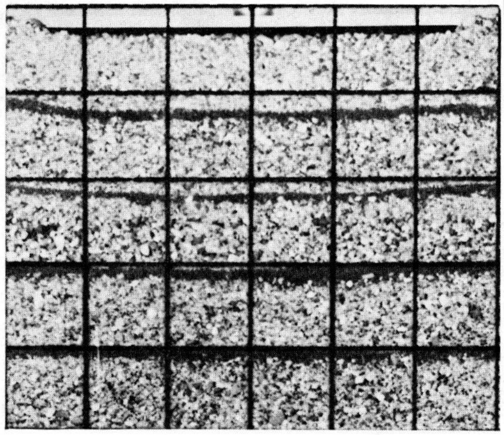

Figure 7. Settlement of 5-in. tamper at 1 min.

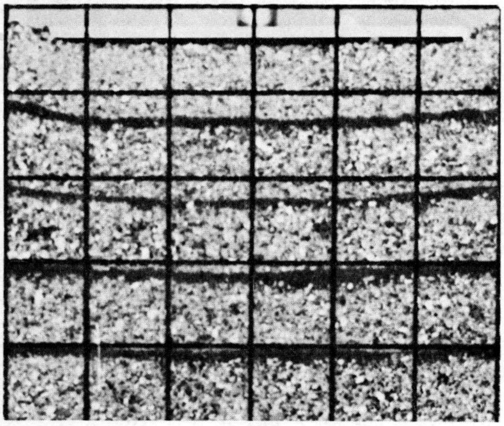

Figure 8. Settlement of 5-in. tamper at 2 min.

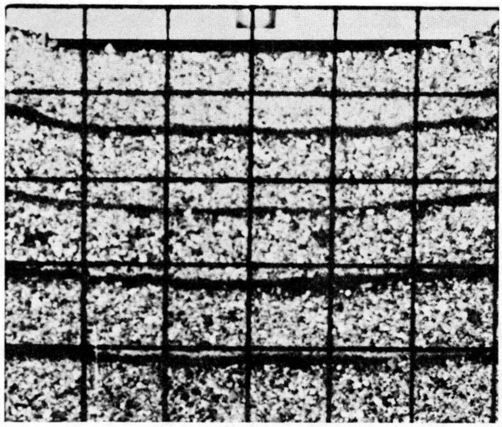

Figure 9. Settlement of 5-in. tamper at 3 min.

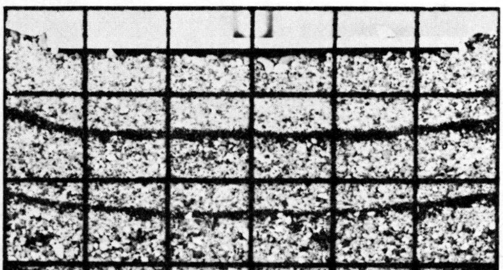

Figure 10. Settlement of 5-in. tamper at 4 min.

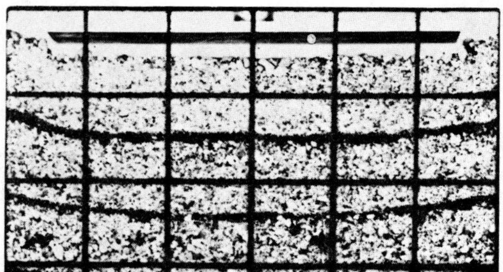

Figure 11. Settlement of 5-in. tamper at 5 min.

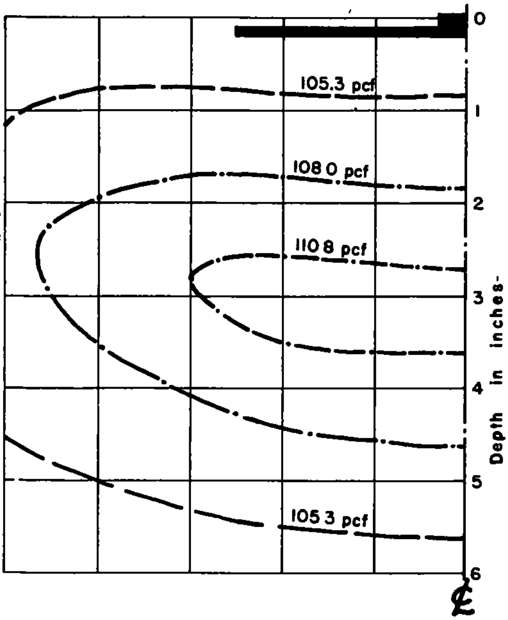

Figure 12. Curves of equal density for 5-in. tamper at 1 min.

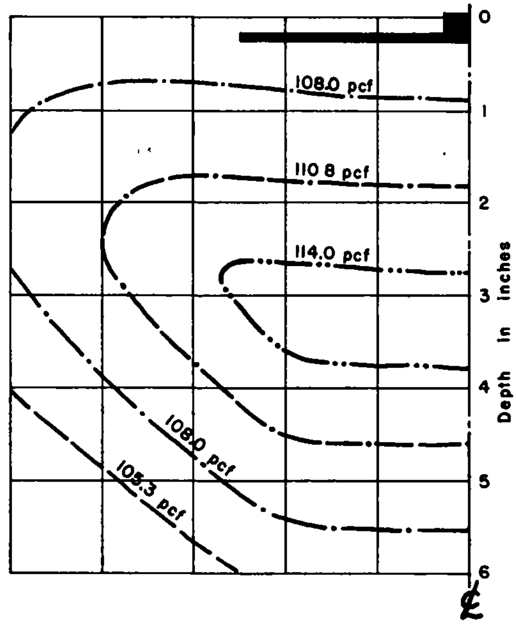

Figure 13. Curves of equal density for 5-in. tamper at 2 min.

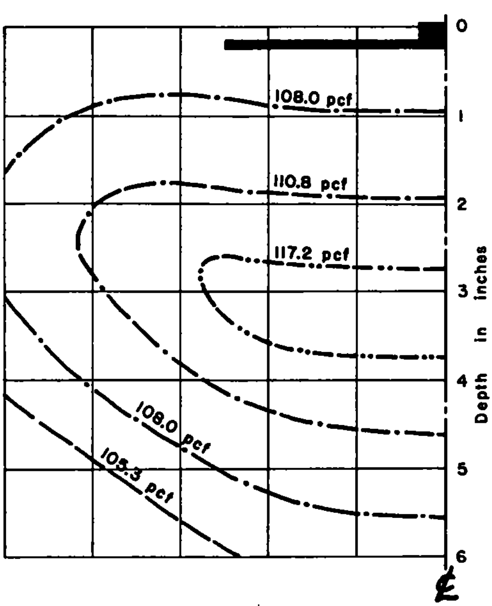

Figure 14. Curves of equal density for 5-in. tamper at 3 min.

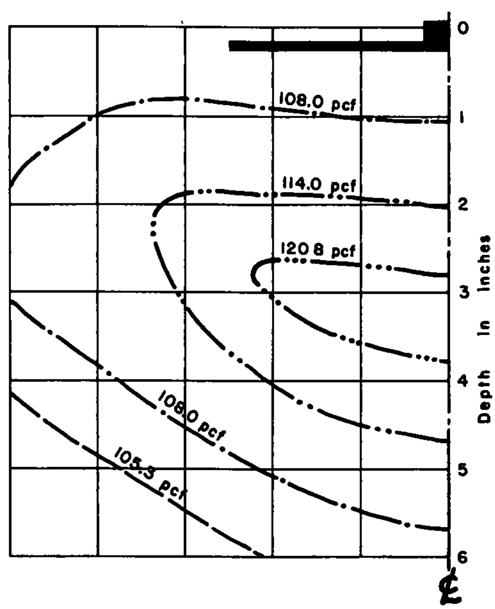

Figure 15. Curves of equal density for 5-in. tamper at 4 min.

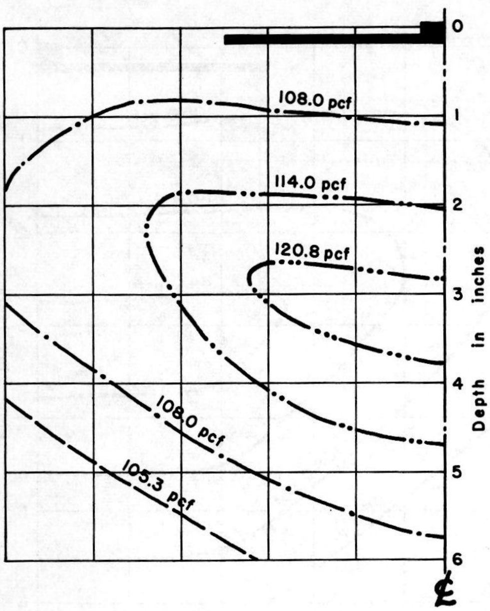

Figure 16. Curves of equal density for 5-in. tamper at 5 min.

RESULTS

The effect on sand settlement and thus density of varying the vibration frequency is shown in Figure 18 and 19. The greatest increase of density was obtained at 25 cps though vibrations above 800 cps did not increase the density at all.

The effect of duration of the vibrations is shown in Figure 20 where it can be seen that 100 percent relative density is reached in 5 or 6 min when the critical frequency of 25 cps is used. The maximum density reached was 120.8 pcf which is larger than the 117 pcf reached by the D'Appolonia method and, therefore, was adopted as the maximum for computing relative density. Also, the area referred to is the region of greatest compaction and not the over-all space beneath the vibrating plates.

Figure 21 shows that this region of greatest compaction moves down from the vibrating plate as the duration increases up to 5 or 6 min but as the plates get larger the ratio of the depth of maximum compaction to the plate width reduces.

The change with time in the depth above which there is 45 or more percent relative

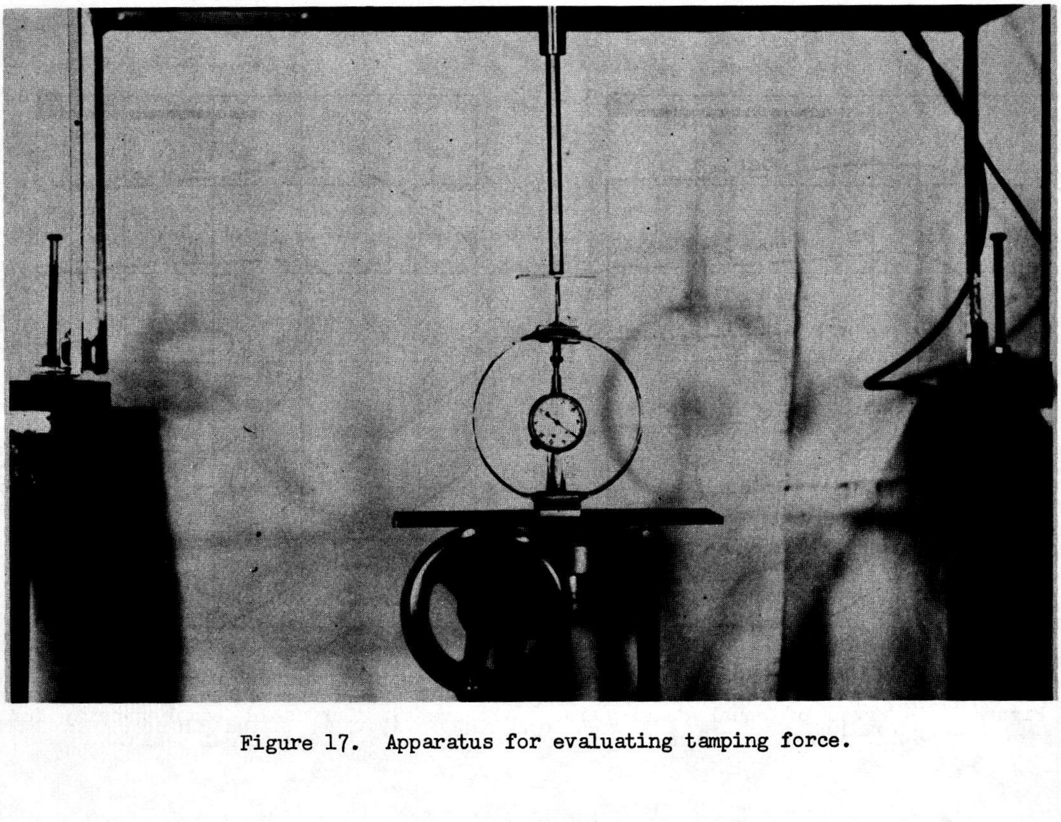

Figure 17. Apparatus for evaluating tamping force.

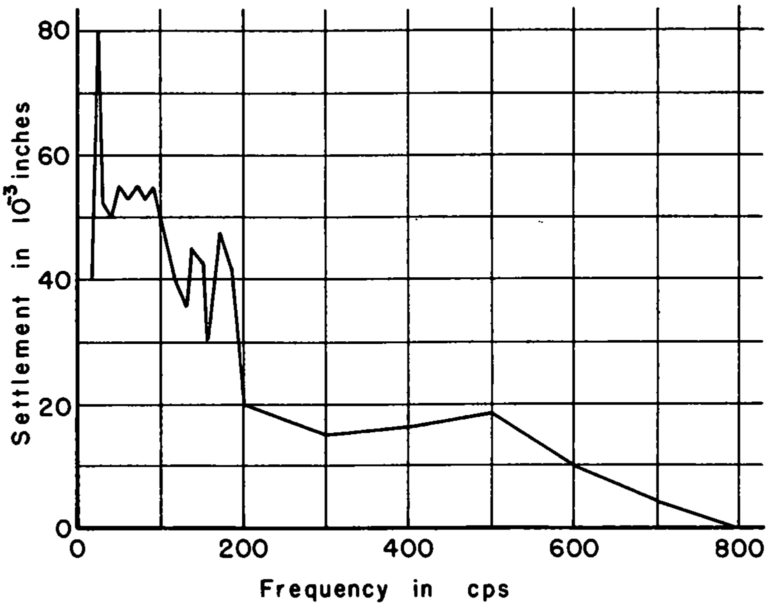

Figure 18. Settlement vs frequency for 3-in. tamper.

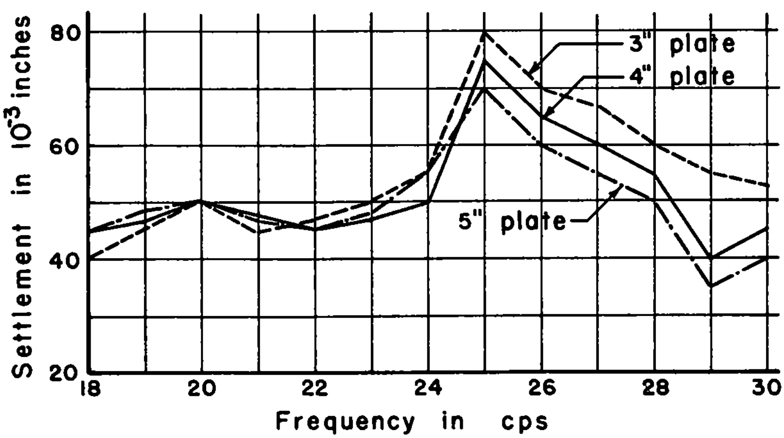

Figure 19. Settlement vs frequency.

density is shown in Figure 22. Here again the ratio of depth of compaction to plate width reduces as the plate size increases.

The change with time in the width within which there is 45 or more percent relative density is shown in Figure 23. Here again the ratio of compacted area to plate width decreases as the plate width increases.

CONCLUSIONS

The results obtained indicate that 25 cps is the most efficient vibration frequency for compacting the dry sand used in the investigation over the tamper-size range used. The efficiency of higher and lower frequencies drops sharply from this optimum indicating that vibrations should not be applied at random frequencies but closely controlled

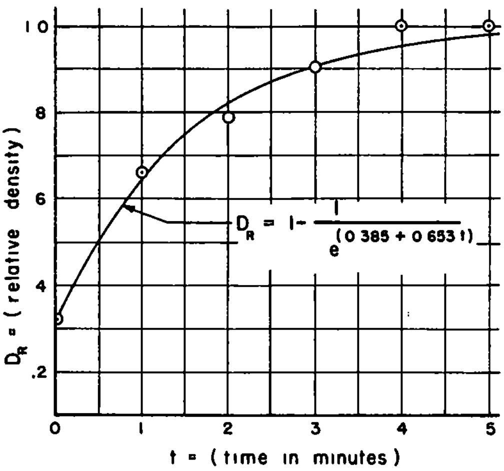

Figure 20. Maximum compaction vs time.

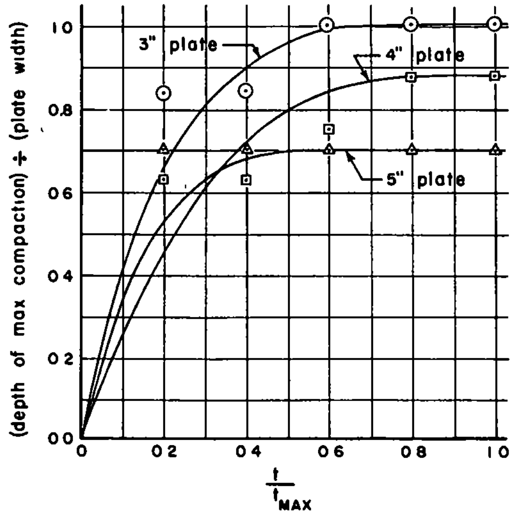

Figure 21. Depth of maximum compaction vs time.

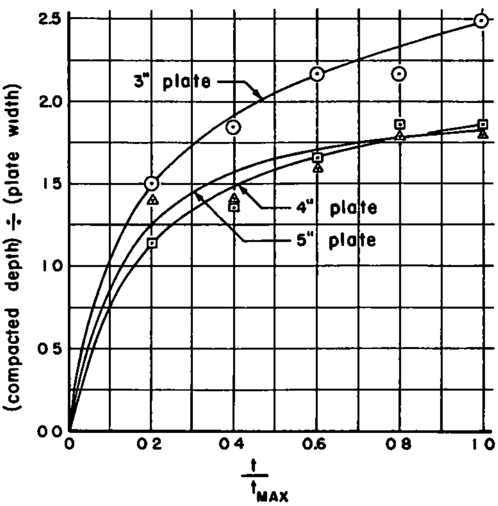

Figure 22. Compacted depth along centerline (D_R = 0.45 or greater) vs time.

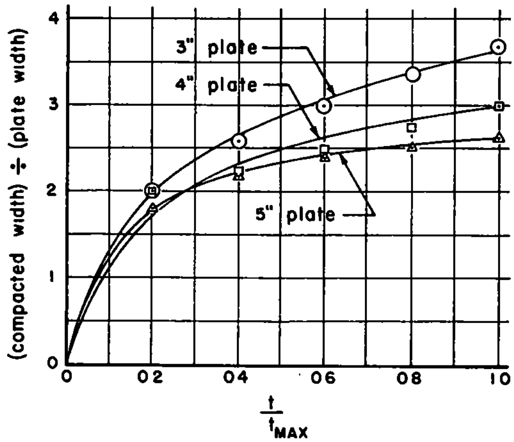

Figure 23. Compacted width at surface (D_R = 0.45 or greater) vs time.

for best results. Comparison of these results with those of other investigators indicates that the optimum frequency may have to be determined for each soil. Even at optimum frequency the vibrations must be applied for an appreciable length of time to obtain reasonable densities.

Maximum compaction is not attained immediately below the tamper but at some distance below the vibrating plate. The ratio of this distance to the plate width decreased as the plate width became larger but not in a straight line variation. There is some evidence that this ratio varied with the tamping force because the tamping force also decreased as the plate size increased.

The following conclusions may be derived from the experiments:

1. Compaction of dry sand by vibration is controlled by the frequency of vibration and is the greatest at the critical frequency.

2. The critical frequency is the one that gives the greatest settlement of surcharge load. For the sand used, the critical frequency was 25 cps.

3. Maximum compaction is not obtained immediately below the tamper but at a certain depth below the surface.

4. No compaction was obtained at supersonic frequencies.

5. The degree of compaction is a function of time and is represented by the equation:

$$D_r = 1 - \frac{1}{e^{(0.358 + 0.653t)}}$$

6. Almost 100 percent compaction is obtained at the end of 6 min at the point of maximum compaction.

7. Surcharge is effective in transmitting the maximum compaction to lower depths.

8. The maximum depth and maximum width to which compaction is effective is an exponential function of tamper dimensions.

9. In evaluating the relative density the minimum laboratory density can be determined by using D'Appolonia's funnel method with no circular motion and no free fall, and the maximum laboratory density can be obtained by vibratory equipment used in this experiment run at critical frequency.

FUTURE SUGGESTED RESEARCH

1. Laboratory maximum density might be determined by using a circular tamper of about a 4-in. diameter with the vibrator used in this experiment. The sand could be continued in a plastic cylinder about 4 in. high with a collar like a Proctor mold. The sand could be placed in four layers. The first layer should be 3 in. thick and the other three layers should be 1 in. thick. Each layer could be compacted at critical frequency for 6 min. The collar could be removed and the excess sand trimmed off as in the Proctor test. The first layer is to permit room for the maximum compaction which would occur in the third inch below the surface with a 4-in. tamper. As the other layers are added, the point of maximum density would move up and the procedure should result in 4 in. of maximum density material.

2. Field compaction by vibrotampers should be run at critical frequencies which could be estimated in situ or determined in the laboratory for each soil.

3. The experiment on dry sand should be repeated with more variety of tamper dimensions to permit correlating the depth of maximum compaction with tamper dimensions.

4. The effect of moisture on the compaction of sand by vibration should be investigated.

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