

# A Method for Controlling Compaction Of Granular Materials

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This paper presents a method for establishing the proper maximum density values to be used for controlling the compaction of granular materials which eliminates the inconsistencies frequently encountered with methods now in use. The proposed method accounts for variations of the maximum obtainable density of a given material, for a given compactive effort, due to fluctuations in gradation.

It is proposed that by splitting the material on the No. 4 U.S. standard sieve and determining the specific gravity, the compacted density and the loose density of each of the two fractions, a curve of maximum density versus percent passing No. 4 sieve curve can be plotted, which curve values will correlate closely with the densities obtainable in the field; using modern compaction equipment.

As the density curve can be established in the laboratory prior to construction, the actual field control phase is reduced to performing field density tests only, freeing the field inspector from performing time-consuming standard maximum density tests.

Data accumulated while applying the method to more than 30 highway projects have been summarized and typical results are presented. The method is applicable either to specifications requiring compacting to a given percent of maximum density or to specifications requiring compaction to a given compaction ratio.

Use of this method eliminates the danger of applying the wrong "standard" to compaction control of gravelly soils.

● THE problem of exercising realistic field control over the compaction of granular base course and surfacing materials has perplexed both laboratory and field engineers for many years. The importance of such control becomes more apparent with each passing construction season. With the continued improvement of construction practices and control methods applied to the foundation and subgrade soils has come recognition of the fact that many roadway failures heretofore attributed to failure in the subgrade soils must be attributed to the granular base course and surfacing materials not fulfilling their structural assignment.

As density greatly affects the stability and strength properties of granular materials, and as density can be determined easily and rapidly in the field by improved methods developed for that purpose (1), it follows that, as with fine-grained soils, adequate field compaction control of the granular soils should be of considerable value to the engineer in determining that full structural value is built into the base and surfacing courses.

The primary deterrent to such control in the past has been the lack of a reliable standard with which to compare field results. A number of different procedures for establishing "maximum density" values for gravels have been applied and found inadequate. Those procedures using laboratory test results from tests performed on the fine fraction of the granular soil and applying a correction formula for the percent gravel content of the whole material are often in serious error when the gravel content exceeds 25 to 30 percent (2). Those procedures using the whole material compacted by a specific procedure are cumbersome and slow and require an excessive number of repeat tests on very large samples because minor variations in gradation often have a large effect upon obtainable density.

As a result, the wrong "standard" or "maximum density" value often has been applied, and the resulting frequent incompatibility with field results has caused the field



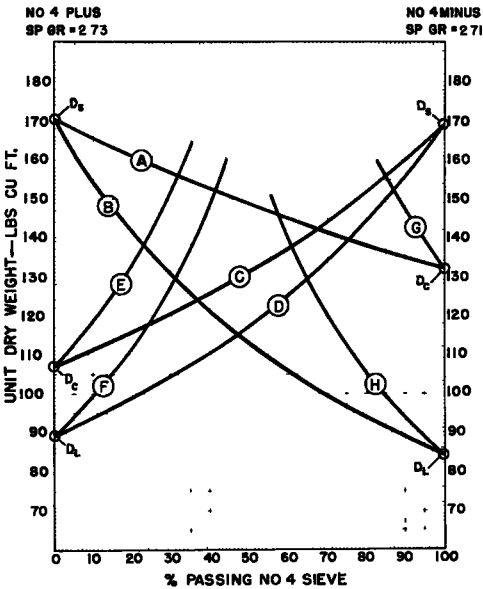


Figure 1. Theoretical curves.

experimental basis to more than thirty projects. The range of granular materials to which it has been applied covers the entire group of specification ballast, base course, and surfacing materials described in the Washington Department of Highways Standard Specifications. In addition, the method has been applied to a number of special ballast, cement-treated base, and selected roadway borrow materials. Special field correlation studies were conducted on most projects to insure complete and adequate data, and normal field control practices were used on other projects to evaluate the practicality of this method of compaction control.

The excellent results achieved with the method during the past three years has led to its adoption as a standard control method by the Washington Department of Highways. Acceptance by field personnel has been excellent.

A theoretical concept of the effects that gradation, grain size and shape, fracture and hardness have upon the maximum density obtainable from a given aggregate is undoubtedly very complex. One approach to analysis of these effects is to attempt to determine the extreme limits of possible results and then to determine if actual results follow a definable pattern in relation to these limits.

By splitting a granular material into a fine fraction and a coarse fraction, we obtain two distinctly different materials whose characteristics can be assumed to represent extremes which will encompass the characteristics of any combination of the two fractions.

In relation to unit weight characteristics

engineer to view with suspicion and distrust any attempts to apply compaction control to the base course and surfacing materials on his job.

The need exists, then, for a reliable method for determining the proper maximum density value for granular materials. As the gradation of a given granular material, such as a base course gravel, may fluctuate between rather wide specification limits, and, as gradation seriously affects the density obtainable with any given compaction procedure, the maximum density values must be correlated to gradation.

To be of practical value the maximum density-vs-gradation relationships should be established prior to construction so that the field inspector can devote his time during construction to the performance of field density tests and to giving adequate attention to the actual compaction process on the job.

The purpose of this paper is to present a method developed to fulfill the above requirements. During the past three years, this method has been applied on an experi-

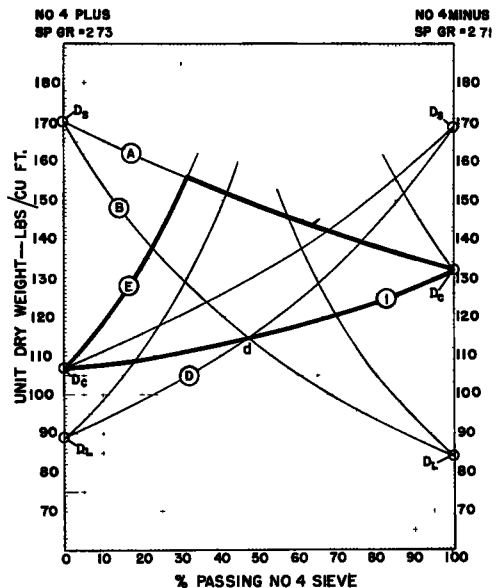


Figure 2. Theoretical limits of maximum density.



of a granular material, there are three values of density which can be determined by tests, as follows:

1. Solid density,  $D_s$ ; the density of a given material considered as a solid having zero void content. This value is determined by multiplying the specific gravity of the material by the unit weight of water.

2. Compacted density,  $D_c$ ; the density obtained by compacting the material by a specified method to the highest unit weight possible using that method of compaction. This value varies, depending on the type of test selected. The test selected should give results compatible with actual field results with modern compaction procedures.

3. Loose density,  $D_L$ ; the loosest condition possible for a material to exist unaffected by "bulking" influences of moisture. This value can be obtained from Figure 22 in Appendix B, or from the nomograph of Figure 7, both of which show the correlation between  $D_c$  (or  $D_{max}$ ) and  $D_L$  as determined by the procedure described in Appendix B. The procedure represents a new approach to the matter of loose density determination which should eliminate much of the present confusion about what loose density value should be used for a given material.

The effects of gradation are reflected in the  $D_c$  and  $D_L$  values. Specific gravity is reflected in the  $D_s$  value. Particle size and shape, texture, and fracture are reflected in the  $D_c$  and  $D_L$  values. By using these three values of density, all characteristics of a material that affect the actual obtainable density are accounted for. In this report unit weight and density shall mean pcf dry weight.

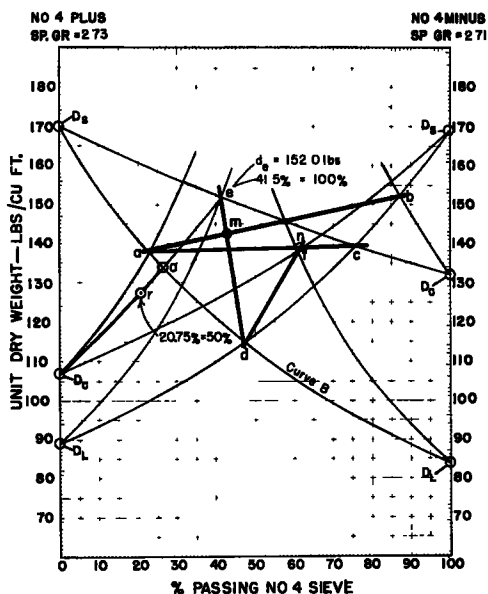


Figure 3. Points for maximum density curve.

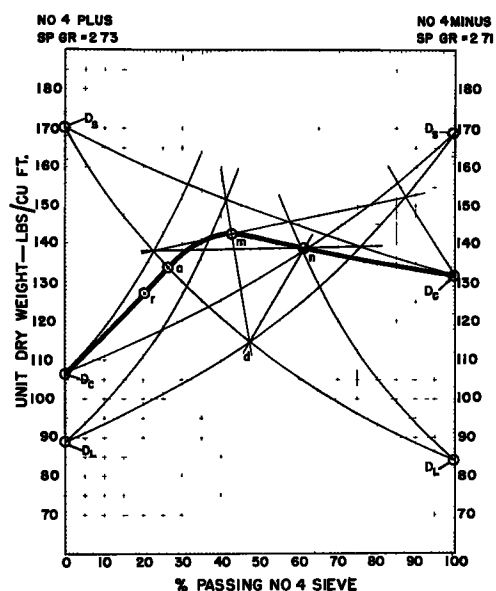


Figure 4. Derived maximum density curve.

#### DERIVATION OF THEORETICAL CURVES FOR DENSITY VERSUS PERCENT PASSING NO. 4 SIEVE

As the gradation of a given specified surfacing or base course material will vary significantly on a given project, and as the actual obtainable density will vary with the gradation, a plotted curve showing the relationship of the density and the gradation is required for realistic control of compaction in the field. Such a curve can be established. The values of loose density,  $D_L$ , compacted density,  $D_c$ , and solid density,  $D_s$ , for each of the two fractions are determined and are plotted on the respective left and right ordinates, as shown in Figure 1.

By establishing certain assumptions and imposing certain conditions, several theoretical curves can be established which describe the gradation-density relationship that would occur should those assumptions and conditions hold true. To establish the true relationship curve, it has been reasoned



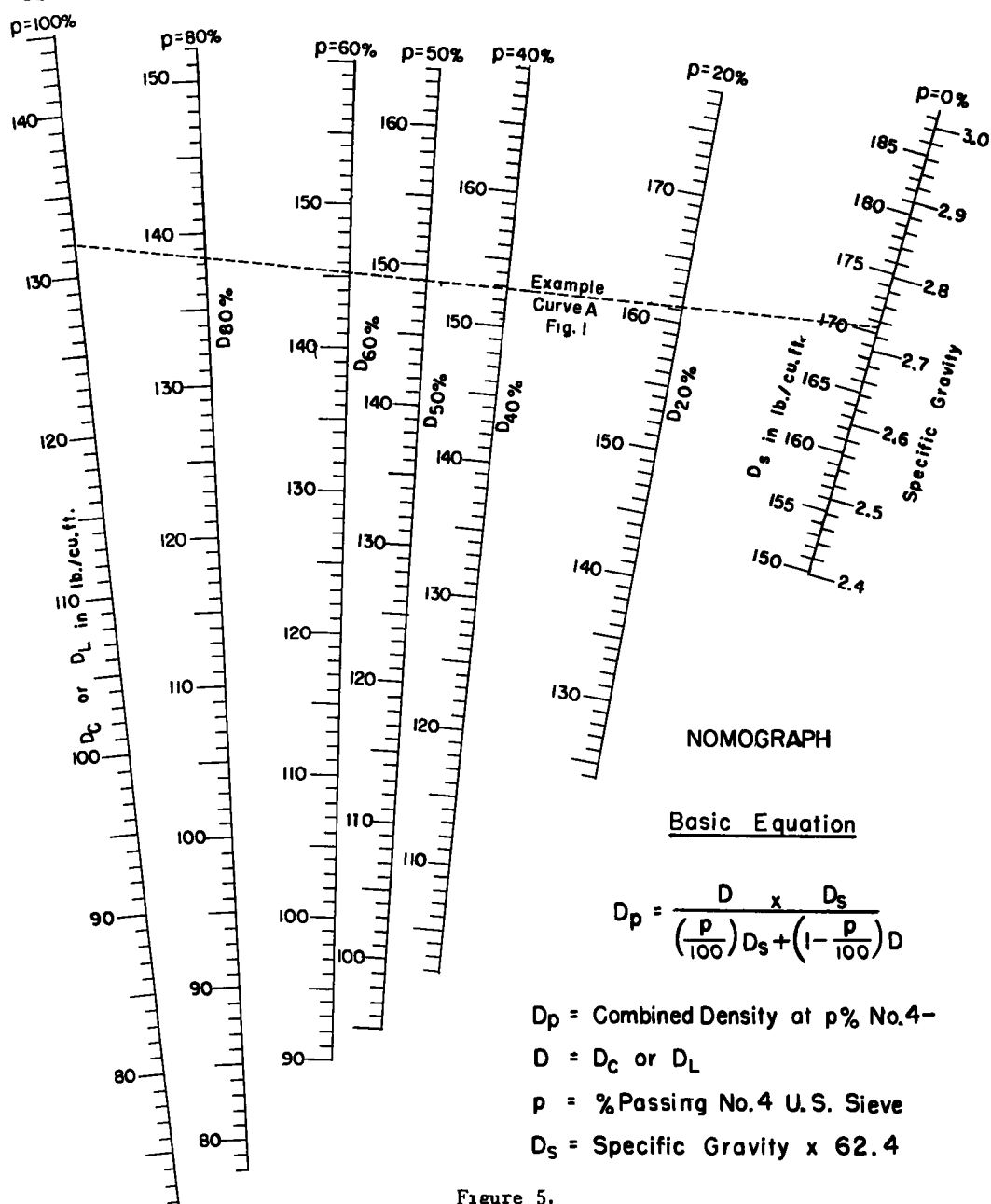


Figure 5.

that each of the relationships shown by the theoretical curves derived from limited assumptions and conditions hold true to a certain extent, and that the inter-relationship of these curves establishes the correct position of the true maximum density curve.

These theoretical curves are shown in Figure 1, and are derived under the following conditions and assumptions.

#### Curve A

1. The No. 4-minus material is compacted to its dense condition,  $D_c$ , and remains in that state.

2. Increasing amounts of solid No. 4-plus material replace part of the No. 4-minus material, until the final product is 0 percent No. 4-minus and 100 percent No. 4-plus



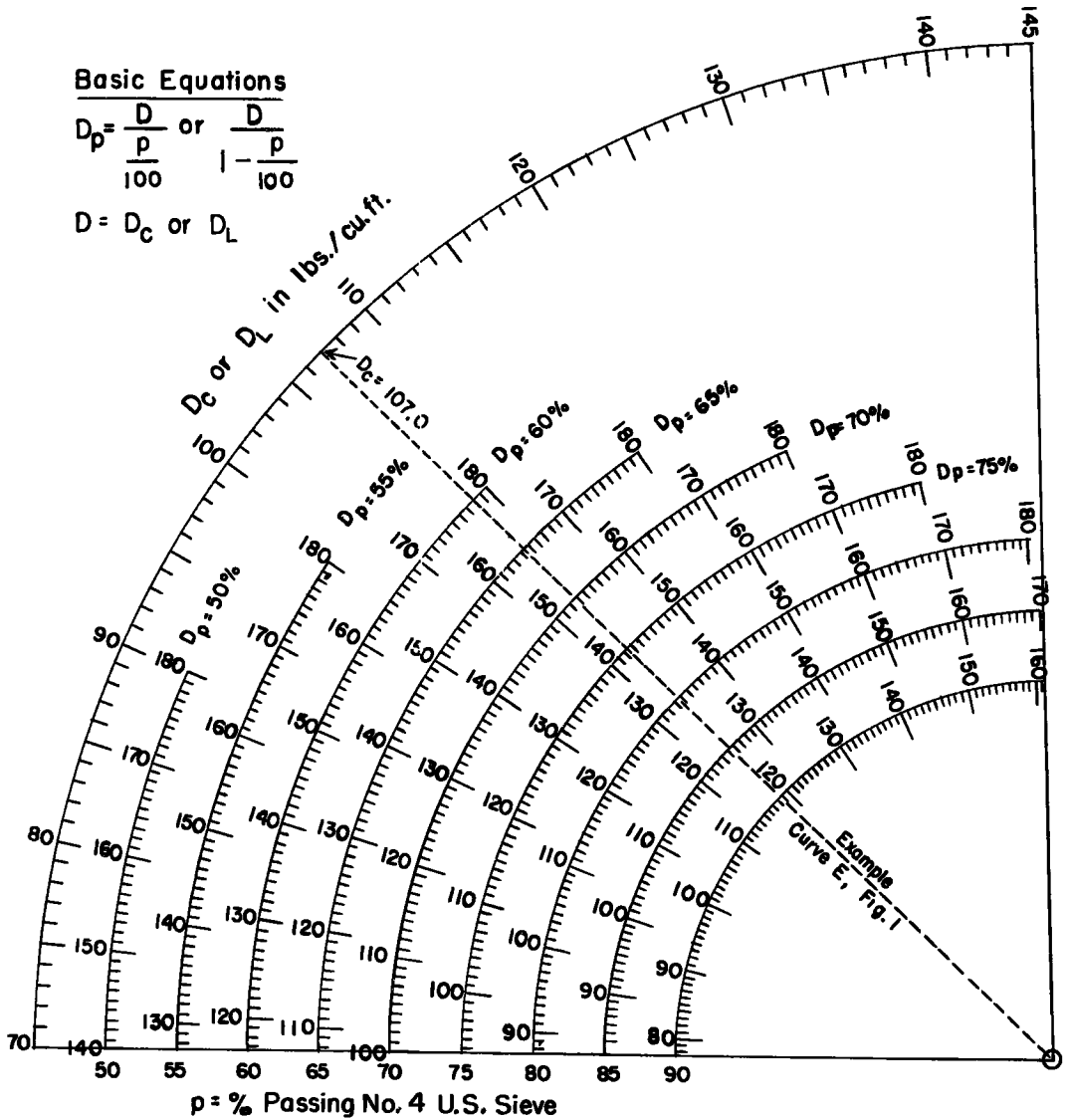


Figure 6. Nomograph for points on curves E F G and H.

in its solid condition,  $D_S$ . As percentages are based on dry weight of total sample, the density at any specific percent content of No. 4-minus can be calculated by:

$$d_p = \frac{(D_S \text{ No. 4-plus}) (D_C \text{ No. 4-minus})}{\frac{p}{100} D_S \text{ No. 4-plus} + \left(1 - \frac{p}{100}\right) D_C \text{ No. 4-minus}} \quad (1)$$

in which  $p$  = percent of No. 4-minus.

To simplify the work involved in solving this equation for a sufficient number of points to establish the curve, the nomograph shown in Figure 5 may be used. From this nomograph,  $d_p$  for  $p = 20, 40, 50, 60$ , and  $80$  percent may be found for any combination of  $D_S$  and  $D_C$  or  $D_L$ .



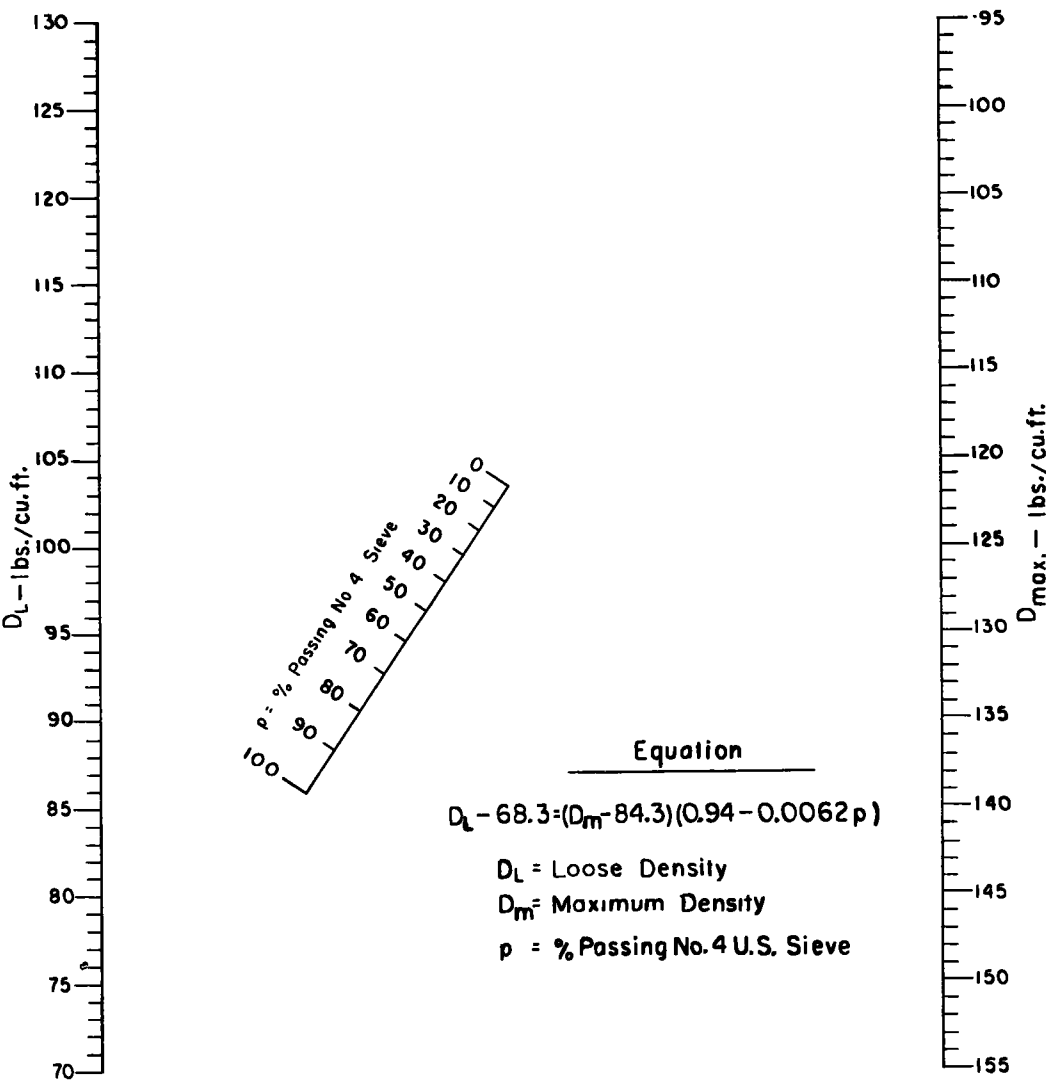


Figure 7. Nomograph for relationship of maximum density and loose density.

Curves B, C, and D

These curves are established in the same manner as Curve A, substituting the proper values in Eq. 1 or using the nomograph (Figure 5). For curves B and D,  $D_L$  is substituted for  $D_c$ . For Curves C and D, the percentage values  $p$  are reversed; that is, 80 percent = 20 percent, etc.

Curve E

1. The No. 4-plus material is compacted to its dense state,  $D_c$  (minimum void content), and remains in that condition.
2. The voids of the No. 4-plus aggregate are gradually filled with No. 4-minus material. Because the unit volume remains constant, the combined unit weight for increasing percentages by weight of No. 4-minus material can be calculated by:

$$\frac{d_p = D_c \text{ No. 4-plus}}{1 - \frac{p}{100}} \tag{2}$$



The nomograph (Figure 6) can be used to solve Eq. 2 for sufficient points to permit plotting the curve.

### Curve F

This curve is established in the same manner, substituting  $D_L$  for  $D_C$  in Eq. 2. The No. 4-plus material is assumed to remain in its loose state while the voids are filled with No. 4-minus material.

### Curves G, H

These curves are established in the same manner, except that the formula is changed to

$$d_p = \frac{D \text{ No. 4-minus}}{\frac{p}{100}} \quad (3)$$

and

$D = D_C$  or  $D_L$ . The nomograph (Figure 6) can be used to solve this equation, also.

The theoretical curves derived as stated and plotted as in Figure 1 form the basis for establishing theoretical extreme limits of maximum density.

If one starts with No. 4-minus material compacted to its dense condition,  $D_C$ , and add increasing amounts of No. 4-plus material, the maximum theoretical density will be that shown by Curve A. This relationship will hold until Curve A intersects Curve E. At this point the coarse fraction is compacted to its densest condition, and the voids are just filled with dense No. 4-minus material. Further increase in the proportion of No. 4-plus material will create more voids than the fines can fill, and the theoretical maximum density will follow Curve E (3). This is illustrated in Figure 2 by the heavy black lines on Curve A and Curve E.

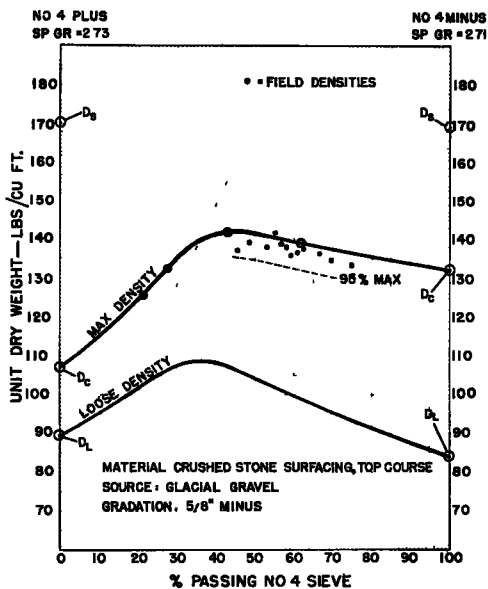


Figure 9.

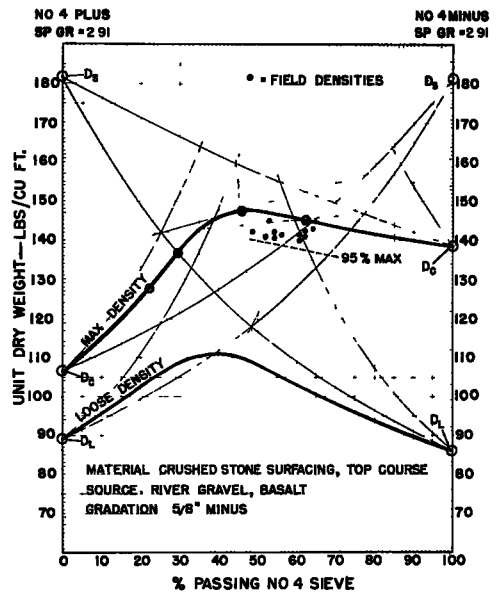


Figure 8.

Curves D and B represent theoretical density curves based on the loose, or minimum densities of the two fractions. The intercept of these curves at point d, therefore, can be said to be a point common to both fractions on the theoretical lower limiting density curve, which starts at  $D_C$  No. 4-plus and terminates at  $D_C$  No. 4-minus. The curve is shown in Figure 2 as Curve I. (The exact shape of Curve I is not important.)

The true maximum density curve must lie within the boundaries of Curves A, E, and I, and its location and shape should be determined by the inter-relationships of the theoretical curves. The following method is used to locate the maximum density curve.

It has been reasoned that when increasing amounts of No. 4-minus material are added to compacted No. 4-plus material, particle interference will cause the void content of the No. 4-plus material to progressively change from minimum to maximum. Therefore, the maximum density curve will tend to follow a curve from  $D_C$  No. 4-plus



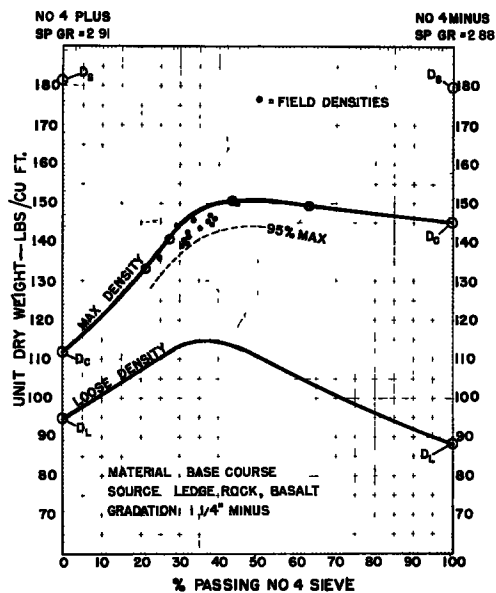


Figure 10.

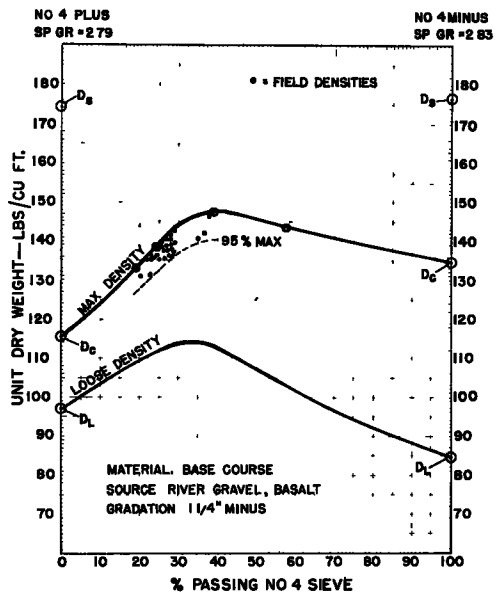


Figure 11.

toward point e (see Figure 3) until other factors divert it at or slightly past its intercept with Curve B (point o). The shape of this curve is determined by the basic equation in Figure 5 by substituting the unit weight of point e for  $D_s$ , and  $D_c$  No.4-plus for  $D$ . The percent passing No.4 sieve at point e is equated to 100 percent, and calculation of the mid-point (50 percent) value ( $r$ ) is sufficient to permit drawing the curve. The unit weight at point  $r$  can be obtained either from the equation or from the nomograph.

Other points on the maximum density curve are located by establishing relationships between critical intercepts of the theoretical curves. Points  $a$  and  $b$  are graphically opposite intercepts. Points  $a$  and  $c$  are similar points on opposing boundary

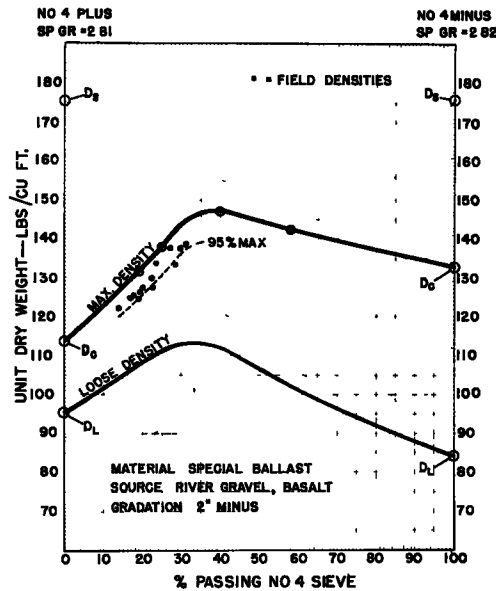


Figure 12.

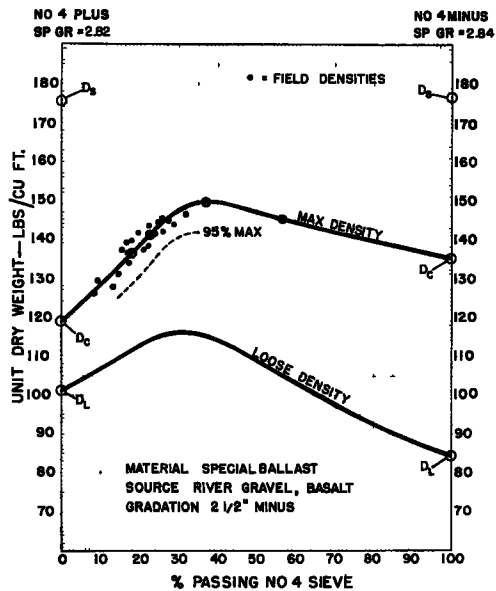


Figure 13.



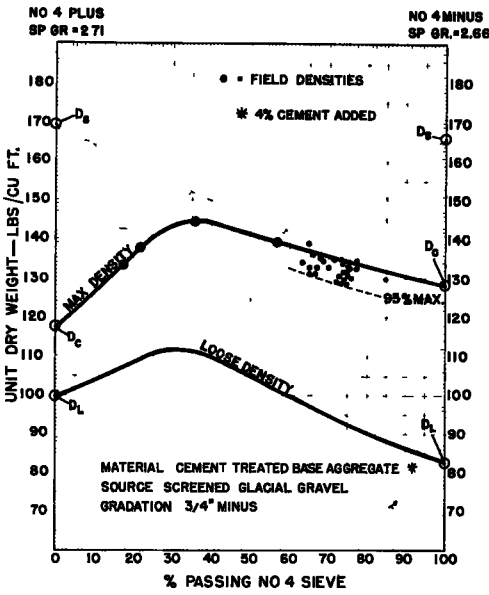


Figure 14.

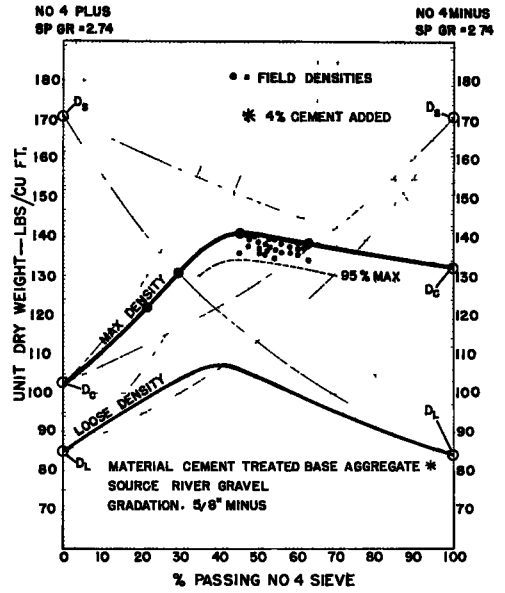


Figure 15.

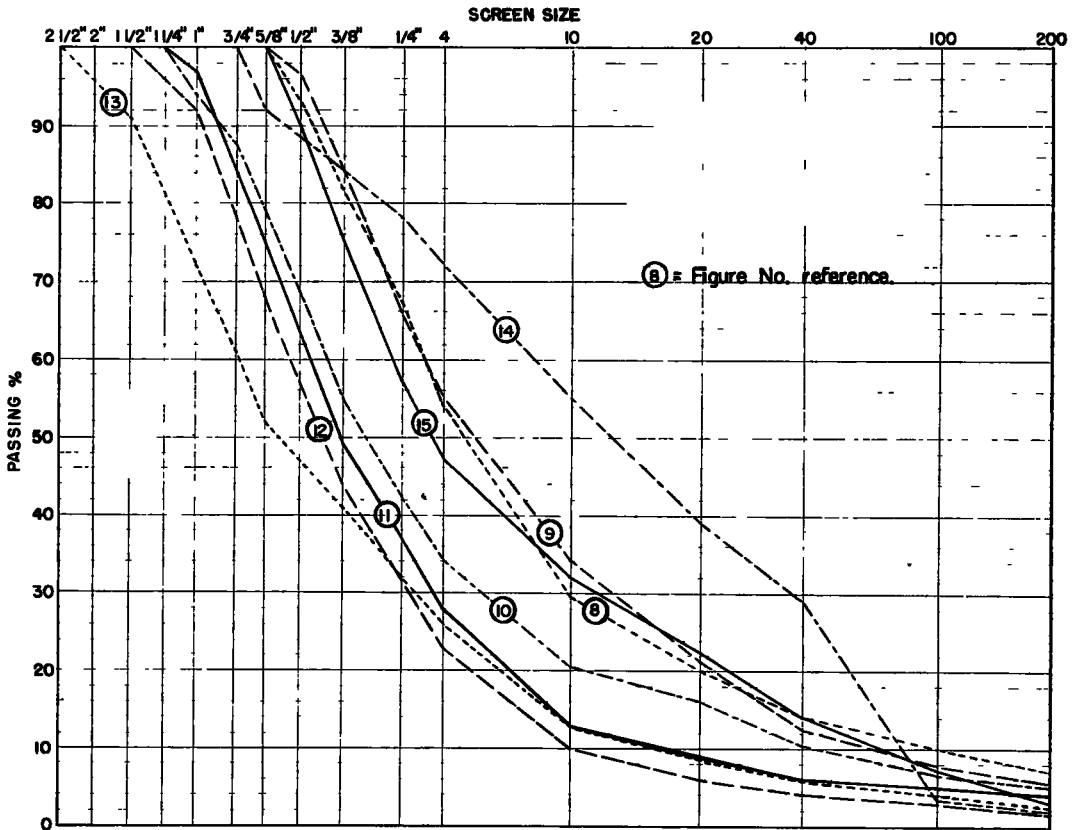


Figure 16. Gradation curves for aggregates illustrated by Figures 8 through 15.



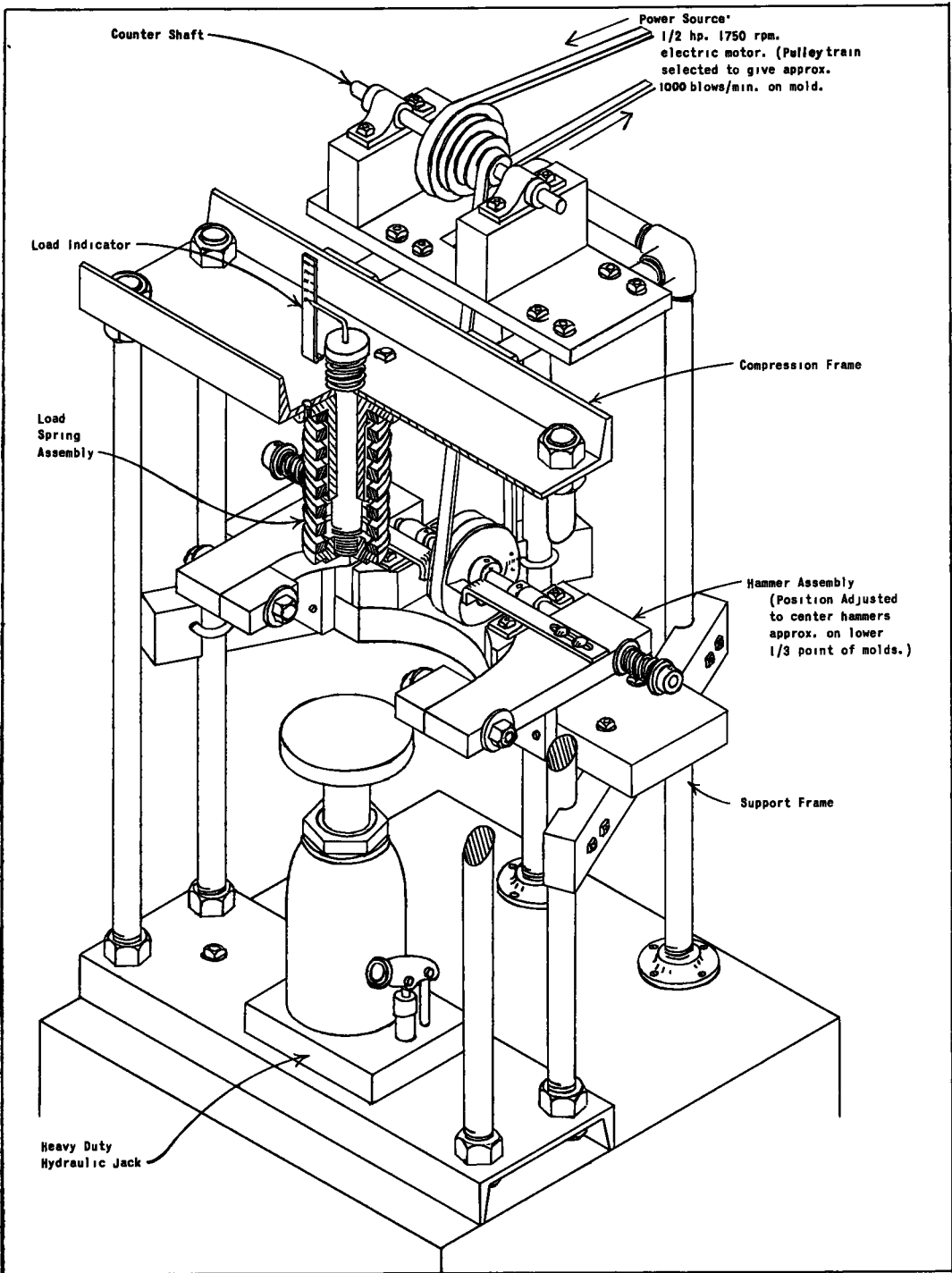


Figure 17. Pilot model -- vibratory spring-load compactor.



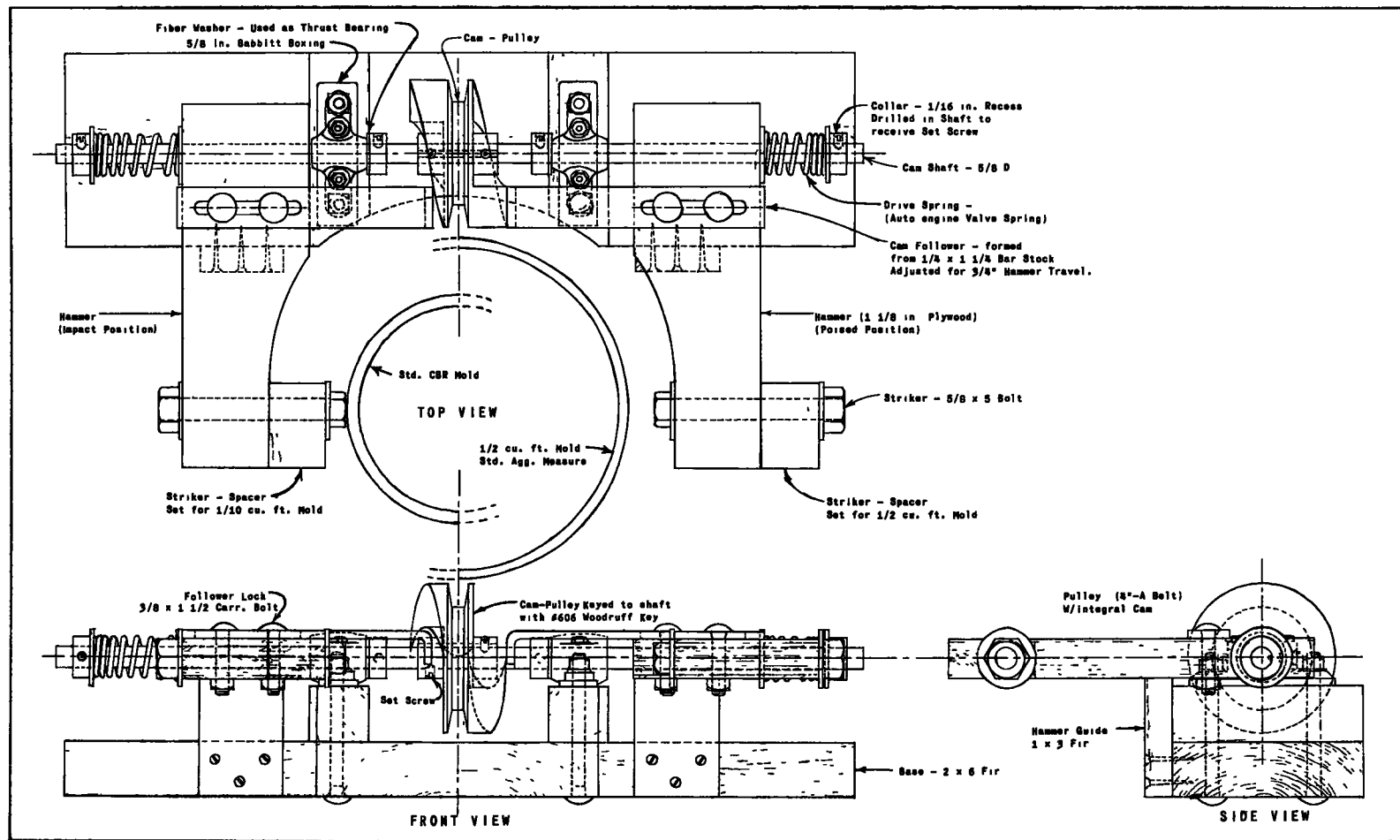


Figure 18. Hammer assembly. Pilot model -- vibratory spring-load compactor.



curves. Points e and f have opposing graphical position, and point d has a neutral position in relation to the two gravel fractions. From these critical points the locations of points m and n on the maximum density curve are determined. Point m is the intercept of  $\overline{ab}$  and  $\overline{de}$ , and point n is the intercept of  $\overline{ac}$  and  $\overline{df}$  or its extension. The maximum density curve is a smooth curve starting at  $D_c$  No. 4-plus, passing through points r, o, m, and n and terminating at  $D_c$  No. 4-minus as shown in Figure 4.

### PRACTICAL APPLICATION

On first reading, the foregoing procedure may appear somewhat involved. However, in actual practice the process is quite simple and direct. The nomographs furnished eliminate the mathematical work involved in locating the curves. The laboratory tests required consume a minimum of time. The over-all economy of time inherent to this method is obvious when one considers that the maximum density curve established for a given material eliminates the need of performing any further standard density tests with which to compare field densities obtained with that material.

A representative sample of the material to be used on a given project is submitted to the laboratory prior to the time of actual use in construction. The sample is graded and divided into two fractions separated on the No. 4 U.S. standard sieve. The specific gravity and the compacted density  $D_c$  are determined for each of the two fractions as described in Appendix A. The loose density  $D_L$  for each fraction is obtained by using the relationships established for  $D_c$  and  $D_L$  in Appendix B. The nomograph (Figure 7) was derived from Figure 23, Appendix B, and may be used for obtaining the  $D_L$  values.

The respective values for  $D_s$ ,  $D_c$ , and  $D_L$  are used as described heretofore to determine the maximum density vs percent passing No. 4 U.S. sieve curve, and this curve is submitted to the field inspector for

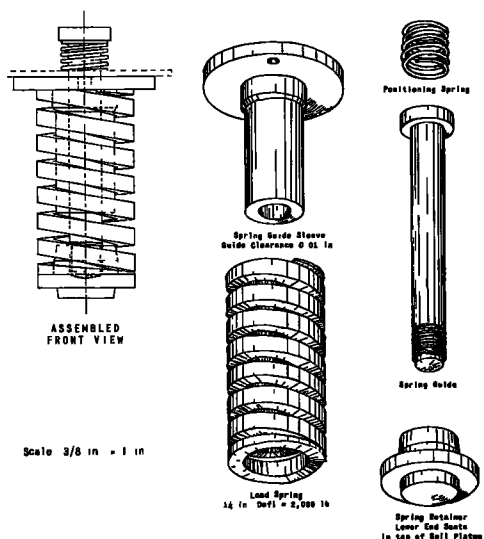


Figure 19. Load spring assembly. Pilot model -- vibratory spring-load compactor.

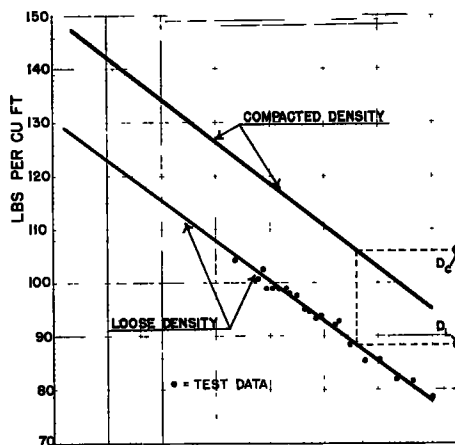


Figure 20. No. 4 plus fraction compacted density ( $D_c$ ) vs. loose density ( $D_L$ ).



use in controlling compaction of the subject material.

When a field density test is made, a representative sample is separated from the total sample excavated from the test hole for moisture determination. After drying and weighing, this portion is screened through a No. 4-sieve and the percent passing the No. 4-sieve is calculated. The calculated value is used to obtain the proper maximum density value for that particular sample from the maximum density curve. The field density value is compared to the maximum density value and the degree of compaction is evaluated.

Some agencies prefer to use compaction ratio as a control standard rather than percent maximum density. Those agencies will find further use of Figure 7 or Figure 23, Appendix B. From either of these graphs, the loose density corresponding to the maximum density for each successive 10 percent increase of percent passing No. 4-minus can be determined, and the loose density curve corresponding to the maximum density curve can be drawn. From these curves, the  $D_{max}$  and  $D_L$  values can be determined for any specific sample gradation.

Typical actual field results are illustrated by Figures 8 through 15. The material is described, the maximum density and loose density curves are plotted, and actual field density test values obtained during construction are plotted in relation to the curves. The gradation curves of the samples used to establish the maximum density curves are shown in Figure 16. As the compaction effort was regulated to yield 95 percent of maximum density or more, the 95 percent curve is drawn also. The Washington Dens-O-Meter, as described in HRB Bulletin No. 93, was used for obtaining field densities.

The range of gradations found in the field tests should be noted. All of these materials were manufactured to meet specifications, and control samples during production verified that specifications were satisfied. These data indicate that segregation during construction is a problem and that the gradation as finally found in the roadbed may sometimes exceed specification limits. From the standpoint of compaction control, the variation in gradation is not extremely serious for the finer materials (such as shown in Figure 8 and 9), because the maximum density does not change excessively for minor changes in gradation. However, radical changes in maximum density occur for minor variations of gradation for the coarse materials illustrated in Figures 10 through 13. For these materials, it is obvious that an "average maximum density" value would be useless for realistic control.

The method has been applied to a number of cement-treated base courses. In Washington, this is a high-quality base constructed by adding cement and water to a graded gravel meeting relatively high standards of quality and gradation. As compaction is rigorously controlled to yield better than 95 percent compaction, these projects serve as excellent measures of the suitability of the compaction control method. Typical results are illustrated in Figures 14 and 15. When performing the basic tests to establish the specific gravity and compacted density values, the proper proportion of cement must be added to the fine fraction.

### CONCLUSIONS

1. Maximum density values obtained in the manner described correlate well with maximum densities obtainable in the field and furnish a satisfactory standard for controlling compaction of granular materials.
2. Elimination of the need to perform continual maximum density tests on the aggregates during construction is of particular advantage and improves the quality of inspection and the efficiency of the inspector.
3. The method is applicable to a wide range of granular soils, ranging from fine aggregates having up to 80 percent passing the No. 4 sieve to coarse aggregates having a maximum size of about 3 in. and as little as 10 percent passing the No. 4 sieve.

### ACKNOWLEDGMENTS

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3. C.H. Turner, "Chart Method Gives Unit Weight of Crushed Base Stone." Roads and Streets, 97: No. 12 (Dec. 1954).

# Appendix A

## TEST PROCEDURES

The following are descriptions of test procedures developed for use in evaluating compaction characteristics of granular materials. For illustrations of the vibratory, spring load compactor unit specified, see Figures 17, 18 and 19.

**TEST NO. 1: Compaction Test for Granular Material, Fine Fraction (100 percent passing No. 4 U.S. standard sieve).**

This test was developed for the sandy, non-plastic, highly permeable soils which normally occur as the fine fraction of granular base course and surfacing materials. When the fine fraction is primarily a soil having some plasticity and low permeability, AASHTO T99-38 (Standard Proctor Test) may be used. With borderline soils, both tests should be applied, and the one yielding the highest density value should be used. Applying shock vibrations to the sides of the mold while using a light vertical compression load has the primary effect of reducing wall friction and thus increasing the efficiency of the vertical compression load. This greater efficiency allows use of the moderate compression load, which reduces sample degradation and particle distortion and closely duplicates actual field compaction.

**Equipment:** Vibratory, spring load compactor; standard CBR mold; piston to fit inside mold ( $\frac{1}{16}$ -in. clearance); height-measuring device accurate to 0.001 in.; and 5-lb tamping hammer with 3-sq. in. face area and  $\frac{1}{8}$ -in. diameter rod handle.

### Procedure:

1. Oven-dry (110 to 120 F) total original sample.
2. Separate sample, by screening, into two fractions divided on the No. 4 U.S. standard sieve. The coarse fraction shall be used in Test No. 2.
3. From the fine fraction (No. 4-minus) split or otherwise obtain a representative sample of approximately 13 lb. (This weight can be adjusted after the first compaction run to yield a final compacted sample approximately 6 in. high.)
4. Add amount of water estimated to produce a saturated sample when compacted.<sup>1</sup>

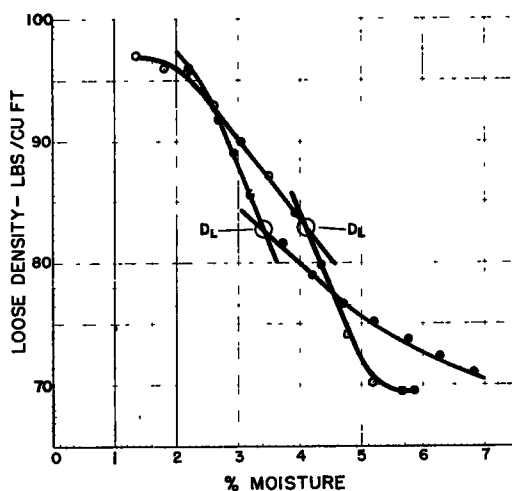


Figure 21. Percent moisture vs. loose density for No. 4 minus fraction.

<sup>1</sup> The moisture content should be adjusted so that free water will show at the base of the mold at about the 500-lb pressure point of the first compression run (step 7). Most



5. Place sample in mold in three layers. Rod each layer 25 times (use handle of tamping hammer) and tamp with 25 blows of the tamping hammer. The blows of the hammer should approximate that produced by a 12-in. free fall provided severe displacement of sample does not occur. In such cases adjust blow strength to produce maximum compaction. The surface of the top layer should be finished as level as possible.

6. Place piston on top of sample in mold and mount mold on jack in compactor. Elevate mold with jack until load-spring retainer seats on top of piston. Apply initial seating load of about 100 lb on sample.

7. Start compactor hammers and at same time gradually increase spring load on sample to 2,000-lb total pressure by elevating jack. The rate of load application is as follows:

0 to 500 lb	-	1 min
500 to 1,000 lb	-	$\frac{1}{2}$ min
1,000 to 2,000 lb	-	$\frac{1}{2}$ min

After reaching 2,000-lb pressure, stop hammer, release jack, and return to zero pressure.

8. Repeat step 7 four additional times. After last run, remove mold from compactor.

9. Determine height of compacted sample to nearest 0.001 in. and calculate volume.

10. Remove specimen from mold, determine weight accurately to nearest 0.01 lb and calculate wet density.

11. Determine moisture content of sample and calculate the dry density.

12. Repeat steps 3 through 11 at higher or lower moisture contents on fresh samples to obtain the maximum density value for material.<sup>1</sup> Three tests are usually sufficient.

**TEST NO. 2: Compaction Test for Granular Material, Coarse Fraction (0 percent passing No. 4 U.S. standard sieve).**

This test involves two separate procedures based on the maximum size aggregate being tested. When the maximum size is  $\frac{3}{4}$  in. or less, a 0.1-cu ft sample size is satisfactory. For material having a maximum size of 1 to 3 in., the sample size should be increased to about  $\frac{1}{2}$  cu ft for accuracy.

**A. Test for Coarse Aggregate having a maximum size of  $\frac{3}{4}$  in. or less.**

Equipment: See list for Test No. 1.

Procedure:

1. From the coarse fraction obtained in step 2, Test No. 1, separate a representative sample of 10 to 11 lb and weigh accurate to 0.01 lb.

2. Dampen sample with  $2\frac{1}{2}$  percent moisture<sup>2</sup> and place in 0.1-cu ft mold in three lifts. Tamp each lift lightly with 25 blows of the tamping hammer (omit rodding). Avoid loss of material during placement.

3. Place piston on sample in mold and follow procedure outlined in steps 6, 7, 8 and 9 of Test No. 1.

4. Using original dry weight value, calculate dry density in pcf.

**B. Test for Coarse Aggregate having a maximum size greater than  $\frac{3}{4}$  in.**

Equipment: See list for Test No. 1 and add the following:

<sup>1</sup> (continued) materials will yield highest density at that moisture content. Some materials may continue to gain density on increasing the moisture above that specified; however, severe washing out of fines will occur, which will alter the character of the sample and void the results.

<sup>2</sup> It was found through experiment that moisture in excess of  $2\frac{1}{2}$  percent has no effect on the final density obtained with these coarse, open-graded aggregates. For very coarse aggregate requiring the use of the  $\frac{1}{2}$ -cu ft mold, moisture has no effect on density and can be omitted.



$\frac{1}{2}$ -cu ft standard aggregate measure  
 $\frac{3}{4}$ -in. piston, plywood with bottom face covered  
 with 16-gage sheet steel and diameter  $\frac{1}{8}$  in.  
 less than I. D. of  $\frac{1}{2}$ -cu ft measure.

#### Procedure:

1. From the coarse fraction obtained in step 2, Test No. 1, separate a representative sample of about 45 lb and weigh accurately to 0.1 lb.
  2. Divide the sample into five representative and approximately equal parts.
  3. Place the sample in the mold in five lifts. After each lift is placed in the mold, position piston on sample, mount mold in compactor, and compact as described in step 7, Test No. 1. Spacers between the load spring and piston must be used to adjust the elevation of the mold so the hammers strike the mold in the vicinity of the lift being compacted.
  4. After the final lift is compacted, remove the mold from the compactor, determine the height<sup>3</sup> of the compacted sample, and calculate the volume.
  5. Calculate the dry density value in pcf.
- TEST NO. 3. Specific Gravity Determination for Fine Fraction (100 percent No. 4-minus). Use ASTM Designation: D 854-52.
- TEST NO. 4. Specific Gravity Determination for Coarse Fraction (0 percent No. 4-minus). Use ASTM Designation: C 127-42 for Apparent Specific Gravity.

## Appendix B

### DETERMINATION OF COMPACTED DENSITY VS LOOSE DENSITY RELATIONSHIPS FOR GRANULAR SOILS

Extensive experimental work with the separate coarse and fine fractions (separated by No. 4 U.S. standard sieve) of granular base and surfacing materials has revealed that a definable relationship exists between the loose density,  $D_L$ , and the compacted

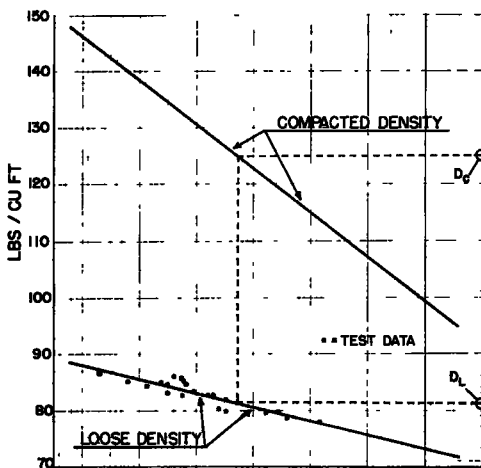


Figure 22. No. 4 minus fraction. Compacted density ( $D_C$ ) vs. loose density ( $D_L$ ).

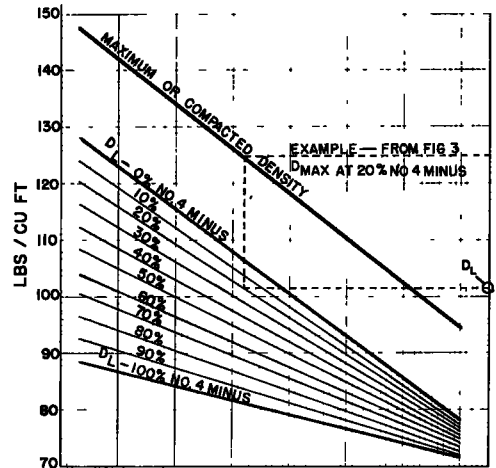


Figure 23. Relationship of maximum density and loose density.

<sup>3</sup>The procedure of measuring the average height of sample to the top surface of the piston, and then correcting for the piston is satisfactory for 1-in. maximum size aggregate. For larger material it is necessary to minimize the error introduced by the excessive void ratio obtained at the surface contact with the piston. By determining the total volume of the mold and using the Washington Dens-O-Meter to measure the unused volume above the sample, a more correct volume of sample can be obtained.



density  $D_c$ , inherent to these materials. For the range of materials examined, this relationship can be shown as a straight line.

The physical procedure used to determine the loose density was very similar to that proposed by Burmister. Appropriately sized funnels were used to place the aggregate in known-volume containers by gently pouring the aggregate through the funnel into the container. With No. 4-minus aggregate, the container was filled over-full and struck off level. With large, coarse aggregates, a funnel could not be used satisfactorily, and the material was placed from a scoop. The surface of these materials was leveled by hand-picking.

With the No. 4-plus fraction, it was found that moisture has no effect on the loose density obtainable, and oven-dried samples were used. When correlated with the compacted density ( $D_c$ ) obtained with Test No. 2 (Appendix A), Figure 20 was obtained. Data are shown for 21 different aggregates ranging from  $\frac{3}{8}$  to 3-in. max. sizes and varying in shape, fracture, and specific gravity.

With the No. 4-minus fraction, no rational correlation could be found with loose densities obtained with the dry aggregate. On adding moisture, the loose density generally followed one of two typical curves (Figure 21) to a minimum value, which also showed no correlation with the compacted density. It was found, however, that the loose density value located at the point of deviation from the upper tangent (point  $D_L$ , Figure 21) yielded the correlation shown in Figure 22, when plotted against the compacted density  $D_c$  obtained from Test No. 1 (Appendix A). Figure 22 shows the results obtained with 21 samples representing a wide range of aggregate types. Deviations from a straight line are within the accuracy limits of the test. It has been reasoned that low moisture contents assist in preventing sample segregation and stabilize the particle orientation during placement, and high moisture contents introduce bulking forces. Point  $D_L$  (Figure 21) is defined as the minimum loose density obtainable without bulking. The excellent correlation obtained indicates that this value should be the significant loose density value related to compactability.

As the relationship of  $D_c$  and  $D_L$  for both fractions is a straight line, it can be assumed that similar straightline relationships exist for all combinations of the two fractions. If a uniform rate of change of slope is established between the two limiting curves, Figure 22 can be produced, and from this the  $D_c$  vs  $D_L$  relationships for all combinations of No. 4-plus and No. 4-minus fractions can be determined. These data permit the application of "compaction ratio" as a method of field density control, and will eliminate the wide divergence of loose density values obtained by different agencies.