WFLHD Sampling and Testing Methods

Western Federal Lands
Highway Division
Materials Laboratory

Standard Method of Test for

Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens

WFL Designation: W 166-19

1. SCOPE

1.1. This method of test covers the determination of bulk specific gravity (G_{mb}) of specimens of compacted hot mix asphalt (HMA).

1.2. This method should not be used with samples that contain open or interconnecting voids or absorb more than 6.0 percent of water by volume, as determined by this procedure. If the sample contains open or interconnecting voids or absorbs more than 6.0 percent of water by volume, then T 275 or T 331 should be used.

1.3. The bulk specific gravity (G_{mb}) of the compacted asphalt mixtures may be used in calculating the unit mass of the mixture.

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards:*

- M 231, Weighing Devices Used in the Testing of Materials
- T 275, Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt (HMA) Using Paraffin-Coated Specimens
- T 331, Bulk Specific Gravity (G_{mb}) and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method

2.2. *ASTM Standards:*

- C670, Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials
- D7227/D7227M, Standard Practice for Rapid Drying of Compacted Asphalt Specimens Using Vacuum Drying Apparatus

3. TEST SPECIMENS

3.1. Test specimens may be either laboratory-compacted HMA or sampled from HMA pavements.

3.2. *Size of Specimens*—It is recommended that: (1) the diameter of cylindrically compacted or cored specimens, or the length of the sides of sawed specimens, be at least equal to four times the maximum size of the aggregate; and (2) the thickness of specimens be at least one and one-half times the maximum size of the aggregate.

3.3. Specimens shall be taken from pavements with a core drill, diamond or carborundum saw, or by other suitable means.

3.4. Care shall be taken to avoid distortion, bending, or cracking of specimens during and after the removal from the pavement or mold. Specimens shall be stored in a safe, cool place.

3.5. Specimens shall be free from foreign materials such as seal coat, tack coat, foundation material, soil, paper, or foil.

3.6. If desired, specimens may be separated from other pavement layers by sawing or other suitable means. Care should be exercised to ensure sawing does not damage the specimens.

METHOD A

4. APPARATUS

4.1. *Weighing Device*—The weighing device shall have sufficient capacity, be readable to 0.1 percent of the sample mass or better, and conform to the requirements of M 231. The weighing device shall be equipped with a suitable suspension apparatus and holder to permit weighing the specimen while suspended from the center of the scale pan of the weighing device.

4.2. *Suspension Apparatus*—The wire suspending the container shall be the smallest practical size to minimize any possible effects of a variable immersed length. The suspension apparatus shall be constructed to enable the container to be immersed to a depth sufficient to cover it and the test sample during weighing. Care should be exercised to ensure no trapped air bubbles exist under the specimen.

4.3. *Water Bath*—For immersing the specimen in water while suspended under the weighing device, equipped with an overflow outlet for maintaining a constant water level.

5. PROCEDURE

5.1. Dry the specimen to a constant mass (Note 1) at a temperature of 52 ± 3˚C (125 ± 5˚F). Samples saturated with water shall initially be dried overnight and then weighed at 2-h drying intervals. Recently compacted laboratory samples, which have not been exposed to moisture, do not require drying. As an alternative to oven drying to constant mass, drying the sample according to ASTM D7227/D7227M may be used. When using ASTM D7227/D7227M to achieve constant mass (Note 1), perform the drying procedure at least twice, with a mass determination after each drying cycle.

Note 1– Constant mass shall be defined as the mass at which further drying at 52 ± 3˚C (125 ± 5˚F) does not alter the mass by more than 0.05 percent when weighed at 2-h drying intervals when using oven drying, or by more than 0.05 percent when weighed after at least two drying cycles of the vacuum-drying apparatus required in ASTM D7227/D7227M.

5.2. Cool the specimen to room temperature at 25 ± 5˚C (77 ± 9˚F), and record the dry mass as *A* (Note 2). Immerse each specimen in the water bath at 25 ± 1˚C (77 ± 1.8˚F) for 4 ± 1 min, and record the immersed mass as *C*. Remove the specimen from the water bath; damp-dry the specimen by blotting it with a damp (Note 3) towel, and determine the surface-dry mass as *B*. The elapsed time from when the specimen is removed from the water bath until it is placed on the balance shall not exceed 5 seconds. Any water that seeps from the specimen during the weighing operation is considered part of the saturated specimen. Each specimen shall be immersed and weighed individually.

Note 2– The sequence of testing operations may not be changed.

Note 3– Damp is considered to be when no water can be wrung from the towel.

6. CALCULATION

6.1. Calculate the bulk specific gravity of the specimen as follows:

$$\text{bulk specific gravity} = \frac{A}{B - C}$$

where:
A = mass of the specimen in air, g;
B = mass of the surface-dry specimen in air, g; and
C = mass of the specimen in water, g.

6.2. Calculate the percent of water absorbed by the specimen (on a volume basis) as follows:

$$\text{percent of water absorbed by volume} = \frac{B - A}{B - C} \text{ x } 100$$

6.3. If the percent of water absorbed by the specimen as calculated in Section 5.2 exceeds 6.0 percent, use AASHTO T 275 or T 331 to determine the bulk specific gravity.

METHOD C (RAPID TEST)

7. PROCEDURE

7.1. This procedure can be used for testing specimens that are not required to be saved and that contain a substantial amount of moisture. Specimens obtained by coring or sawing can be tested the same day by this method.

7.2. The testing procedure shall be the same as given in Section 4 except for the sequence of operations. The dry mass *A* of the specimen is determined last as follows:

7.2.1. Place the specimen in a large, flat-bottom drying pan of known mass. Place the pan and specimen in an oven at 110 ± 5˚C (230 ± 9˚F). Leave the specimen in the oven until it can be easily separated to the point where the particles of the fine aggregate-asphalt portion are not larger than 6.3 mm (¼ in.). Place the separated specimen in an oven at 110 ± 5˚C (230 ± 9˚F), and dry to a constant mass (Note 1).

7.2.2. Cool the pan and specimen to room temperature at 25 ± 5˚C (77 ± 9˚F). Determine the mass of the pan and specimen, subtract the mass of the pan, and record the dry mass, *A*.

8. CALCULATIONS

8.1. Calculate the bulk specific gravity as given in Section 5.1.

9. REPORT

9.1. *The report shall include the following*:

9.1.1. The method used (A or C).

9.1.2. Bulk specific gravity reported to the nearest thousandth.

9.1.3. Absorption reported to the nearest hundredth.

Standard Method of Test for

Accelerated Weathering of Aggregate by use of Dimethyl Sulfoxide

WFL Designation: W DMSO-19

1. SCOPE

1.1. This method covers the determination of aggregate resistance to disintegration when immersed in a solution of dimethyl sulfoxide (DMSO). This test method furnishes information helpful in judging the durability of aggregates subject to weathering action, particularly when adequate information is not available from service records of the material exposed to actual weathering conditions.

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards:*

- M 92, Wire-Cloth Sieves for Testing Purposes
- M 231, Weighing Devices Used in the Testing of Materials

3. APPARATUS

3.1. The apparatus shall consist of the following:

3.1.1. *Sieves* — With square openings of the following sizes conforming to AASHTO M 92, for sieving the samples in accordance with Sections 4 and 5:

4.75 mm	(No. 4)
8.0 mm	(5/16 inch)
9.5 mm	(3/8 inch)
12.5 mm	(1/2 inch)
16.0 mm	(5/8 inch)
19.0 mm	(3/4 inch)
25.0 mm	(1 inch)
31.5 mm	(1-1/4 inch)
37.5 mm	(1-1/2 inch)
50 mm	(2 inch)
63 mm	(2-1/2 inch)

3.1.2. *Containers for Samples* — Containers for immersing the samples of aggregate in the solution, in accordance with the procedures described in this method, shall be prepared of materials not attacked by the solution used (Note 1).

Note 1– Baskets of suitable wire mesh or sieves with suitable openings are satisfactory containers for the samples. Pans or other containers without perforations may be used.

3.1.3. *Thermometer* — A thermometer covering the recommended temperature range for solutions during test and readable to 0.1˚C (0.2˚F).

3.1.4. *Temperature Regulation* — Suitable means for regulating the temperature of the samples during immersion in the dimethyl sulfoxide solution shall be provided.

3.1.5. *Balance* — The balance shall have sufficient capacity, be readable to 0.1 percent of the sample mass, or better, and conform to the requirements of AASHTO M 231.

3.1.6. *Drying Oven* — The oven shall be capable of being heated continuously at 110 ± 5˚C (230 ± 9˚F).

4. SPECIAL SOLUTION REQUIRED

4.1. Prepare the solution for immersion of test samples in dimethyl sulfoxide in accordance with Section 4.1.1.

4.1.1. *Dimethyl Sulfoxide* – Dimethyl sulfoxide shall be an industrial chemical, marketed under the name DMSO. Discolored solution shall be discarded, or filtered before reuse (Note 2). The volume of the solution in which samples are immersed shall be at least five times the volume of the sample immersed at one time.

Note 2–. To reduce evaporation and prevent contamination, keep the solution covered at all times when access is not needed.

5. SAMPLES

5.1. *Coarse Aggregate* — Coarse aggregate for the test shall consist of material from which the sizes finer than the 4.75 mm (No. 4) sieve have been removed. The sample obtained shall be of such a size that it will yield the amounts indicated in Table 1.

Table 1— Coarse Aggregate Sample

Sieve Size	Mass, g
63 mm to 37.5 mm (2-1/2 inch to 1-1/2 inch)	5000 ± 300
Consisting of:	
50-mm to 37.5-mm (2 inch to 1-1/2 inch) material	2000 ± 200
63-mm to 50-mm (2-1/2 inch to 2 inch) material	3000 ± 300
37.5 mm to 19.0 mm (1-1/2 inch to ¾ inch)	1500 ± 50
Consisting of:	
25.0-mm to 19.0-mm (1 inch to ¾ inch) material	500 ± 30
37.5-mm to 25.0-mm (1-1/2 inch to 1 inch) material	1000 ± 50
19.0 mm to 9.5 mm (3/4 inch to 3/8 inch)	1000 ± 10
Consisting of:	
12.5-mm to 9.5-mm (1/2 inch to 3/8 inch) material	330 ± 5
19.0-mm to 12.5-mm (3/4 inch to ½ inch) material	670 ± 10
9.5 mm to 4.75 mm (3/8 inch to No. 4)	300 ± 5

5.1.1. Should the samples contain less than 5 percent of any of the sizes specified in Section 5.1, that size shall not be tested, but, for the purpose of calculating the test results, it shall be considered to have the same loss as the average of the next smaller and the next larger size, or if one of these sizes is absent, it shall be considered to have the same loss as the next larger or next smaller size, whichever is present. When the 63 to 37.5 mm (2-1/2 to 1-1/2 inch), 37.5 to 19.0 mm (1-1/2 to 3/4 inch), or 19.0 to 9.5 mm (3/4 to 3/8 inch), test samples specified in Section 5.1 cannot be prepared due to absence of one of the two sizes of aggregate shown for each, the size available shall be used to prepare the sample tested.

6. PREPARATION OF TEST SAMPLE

6.1. *Coarse Aggregate* — Thoroughly wash and dry the sample of coarse aggregate to constant mass (Note 3) at 110 ± 5˚C (230 ± 9˚F) and separate into the different sizes in Section 5.1 by hand sieving to refusal until none of the particles being sieved are passed in one minute's time (Note 4). Weigh quantities of the different sizes within the tolerances of Section 5.1 and place them in separate containers. Record the masses of the test samples and their fractional components. In the case of sizes larger than 19.0 mm (3/4 inch), record the number of particles in the test samples.

Note 3–Constant mass shall be defined as the mass at which further drying at 110 ± 5˚C (230 ± 9˚F) does not alter the mass by more than 0.1 percent.

Note 4– Finger manipulation of the particles may be used to determine refusal.

6.2. Test samples of coarse aggregate shall be weighed to the nearest 1 g.

7. PROCEDURE

7.1. *Storage of Samples in Solution* — Immerse the samples in the solution for not less than 112 hours nor more than 120 hours in such a manner that the solution covers them to a depth of at least 12.5 mm (1/2 inch). Cover the containers to reduce evaporation and prevent the accidental addition of extraneous substances. Maintain the samples immersed in the solution at a temperature of 21 ± 3˚C (70 ± 5˚F) for the immersion period.

7.2. *Drying Samples after Immersion* — After the immersion period, remove the aggregate sample from the solution, permit it to drain for 15 ± 5 minutes and wash with tap water.

8. QUANTITATIVE EXAMINATION

8.1. After the solution has been removed, each fraction of the sample shall be dried to constant mass (Note 4) at 110 ± 5˚C (230 ± 9˚F), and weighed. Hand-sieve the coarse aggregate over the sieve shown below for the appropriate size of particle.

Size of Aggregate	Sieve Used to Determine Loss
63 mm to 37.5 mm (2-1/2 to 1-1/2 inch)	31.5 mm (1-1/4 inch)
37.5 mm to 19.0 mm (1-1/2 to 3/4 inch)	16.0 mm (5/8 inch)
19.0 mm to 9.5 mm (3/4 to 3/8 inch)	8.0 mm (5/16 inch)
9.5 mm to 4.75 mm (3/8 inch to No. 4)	4.00 mm (No. 5)

9. REPORT

9.1. The report shall include the following data:

9.1.1. Mass of each fraction of each sample before and after testing.

9.1.2. The material from each fraction of the sample passing the sieve used to determine the loss expressed as a mass percent of the fraction as shown in Table 2.

Table 2— Suggested Form for Recording Test Data (with Illustrative Test Values)

Sieve Size		Grading of Original Sample, percent	Mass of Test Fractions before Test, g	Percent Passing Sieve Used to Determine Loss	Weighted Average (Corrected Percent Loss)
Passing	Retained on				
63 mm (2-1/2 inch)	3.75 mm (1-1/2 inch)	20.0	3000	4.8	1.0
3.75 mm (1-1/2 inch)	19.0 mm (3/4 inch)	45.0	1500	8.0	3.6
19.0 mm (3/4 inch)	9.5 mm (3/8 inch)	23.0	1000	9.6	2.2
9.5 mm (3/8 inch)	4.75 mm (No. 4)	12.0	300	11.2	1.3
Totals		100.0	5800		8.1

9.1.3. Weighted average calculated from the percentage of loss for each fraction, based on the grading of the sample as received for examination or, preferably, on the average grading of the material from that portion of the supply of which the sample is representative.

9.1.4. The weighted average loss shall be computed to the nearest 0.1 percent.

HIGHWAY RESEARCH BOARD

Bulletin 319

Factors Influencing Compaction Test Results

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Highway Research Board

and

J.R. SALLBERG, Highway Research Engineer
Division of Physical Research
Bureau of Public Roads

National Academy of Sciences—
National Research Council
Washington, D.C.
1962

Start →

THE HUMPHRES METHOD FOR GRANULAR SOILS

The Humphres method (102) consists of establishing the maximum obtainable (that is, with current construction equipment) unit weight of a granular material for different percentages of fine aggregate (portion passing the No. 4 sieve). The method is intended for use with ballast, base course, and surfacing materials with specified gradations. The maximum unit weight curve developed, which relates maximum unit weight and percentage of fine aggregate, can be used by the compaction inspector to determine the proper "control" unit weight of material whose gradation fluctuates between fairly wide specification limits. To determine the proper "control" value, the inspector need only determine the percentage of fine aggregate in his sample and refer to the maximum unit weight curve for the material sampled.

To establish the maximum unit weight curve, for one material, the following 12 steps are necessary:

1. Oven-dry a representative sample of the granular material at 110 to 120 F.
2. Divide a sample into two parts: coarse aggregate, retained on No. 4 sieve; fine aggregate, passing No. 4 sieve.
3. Determine the maximum compacted dry unit weight of each part by using a combination of vibratory and static loading. (The vibratory spring load compactor unit is described in detail in HRB Bull. 159 (1957). Other methods of vibratory compaction (120) that yield comparable unit weights can also be used in determining maximum unit weight.) The maximum compacted dry unit weight of the fine aggregate is represented by γ_f^c ($\gamma_{fine}^{compacted}$) and the maximum compacted dry unit weight of the coarse aggregate by γ_c^c ($\gamma_{coarse}^{compacted}$).
4. Determine the loose dry unit weight of each part (γ_f^l; γ_c^l) by gently pouring each through an appropriately-sized funnel into a container of known volume, weighing, and calculating dry unit weight. The size of sample, pouring device, and volume of measure based on maximum particle size given in Table 27 may be used (121).
5. Determine the solid unit weight of each part (γ_f^s; γ_c^s). First determine the specific gravity of each (for fine aggregate, test ASTM D 854-52 or AASHO T 100-54; for coarse aggregate, apparent specific gravity ASTM C 124-42 or AASHO T 85-45), then multiply each specific gravity by 62.4.

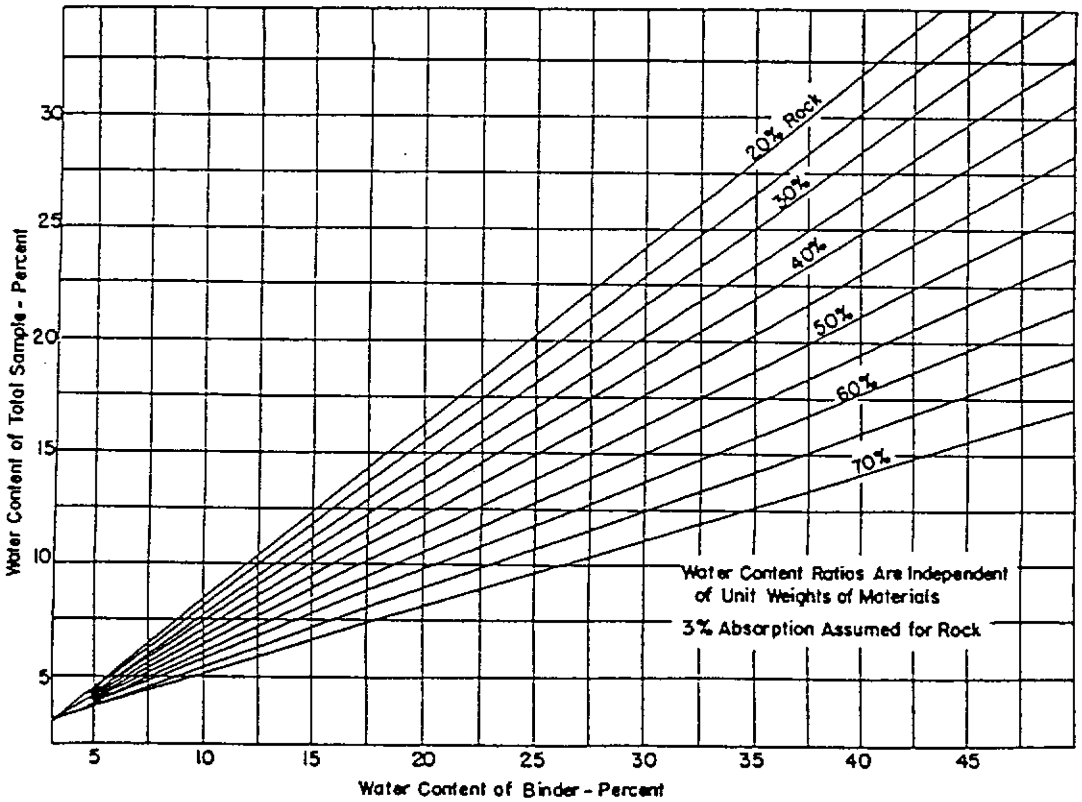


Figure 82. Chart for determining relation between water content of portion passing ¼-in. sieve and total sample (26).

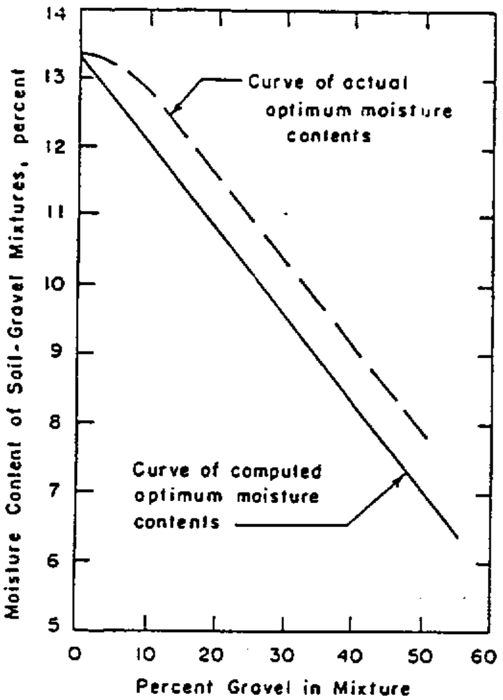


Figure 83. Effect of coarse aggregate (gravel) content on optimum moisture content (28).

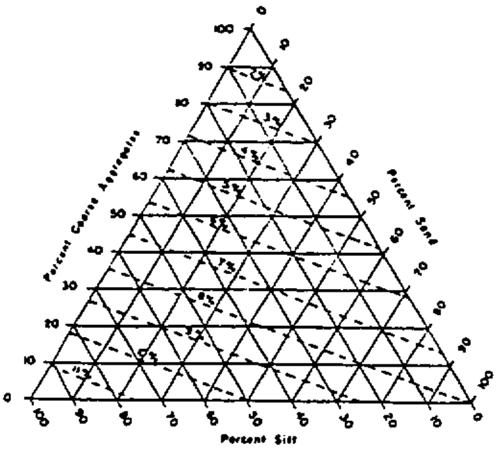


Figure 84. Triangular chart showing optimum moisture content of total material for various proportions of coarse aggregate, sand, and silt (58).

TABLE 27

Max. Size of Soil Particle (in.)	Size of Sample (lb)	Pouring Device	Volume of Measure (cu ft)
3	150	Shovel	1.0
1½	150	Scoop	0.5
¾	100	1½-in. spout	0.5
⅜	25	1-in. spout	0.1
¼	25	½-in. spout	0.1

6. Plot the three unit weights (loose, compacted, and solid) for the coarse aggregate and the fine aggregate on a chart (as in Fig. 85) relating unit weight to percentage of fine aggregate. The three unit weights for coarse aggregate are plotted on the left side of the chart on the zero percent vertical line. The three unit weights for the fine aggregate are plotted on the right side, on the 100 percent vertical line.

The data used in the example in Figure 85 are, as follows:

Coarse aggregate:

$\gamma_c{}^s = (2.73)(62.4) = 170.3$ pcf

$\gamma_c{}^c = 107$ pcf

$\gamma_c{}^1 = 89$ pcf

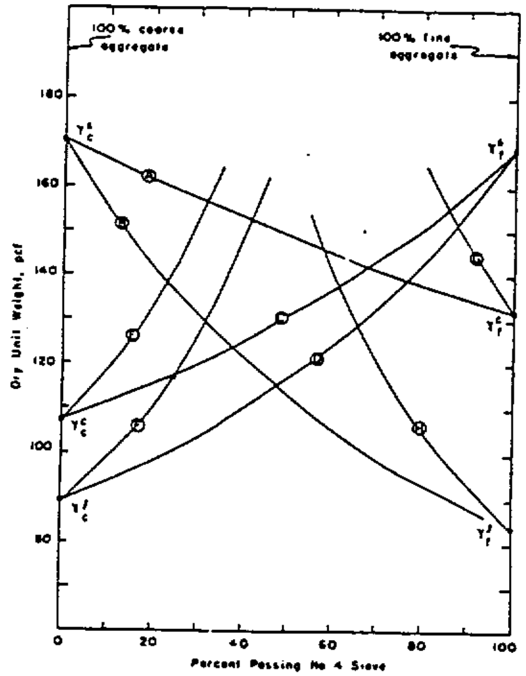


Figure 85. Sample theoretical curves for various combinations of coarse and fine aggregate and for solid, compacted, and loose unit weights (102).

Fine aggregate:

γ_f^s = (2.71) (62.4) = 169.0 pcf

γ_f^c = 132 pcf

γ_f^l = 84 pcf

7. Determine sufficient points to plot each of the curves A, B, C, ...H, as shown in Figure 85, with the aid of the nomographs in Figures 86 and 87 or by using the following equations, and plot the curves. These curves will be used as guides in establishing the maximum unit weight curve. The equations for each curve, A through H, are as follows:

Curve A (theoretical unit weight formula)

$$\gamma_p = \frac{\gamma_c^s \ \gamma_f^s}{\left(\frac{p}{100}\right) \gamma_c^s + \left(\frac{1-p}{100}\right) \gamma_f^c}$$

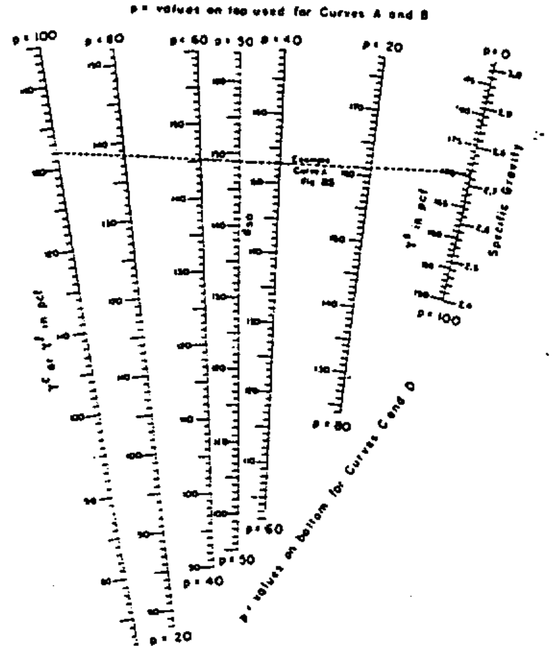


Figure 86. Nomograph for determining unit weight values (γ_p) for curve A, B, C, or D for different values of p, the percentage passing the No. 4 sieve (102).

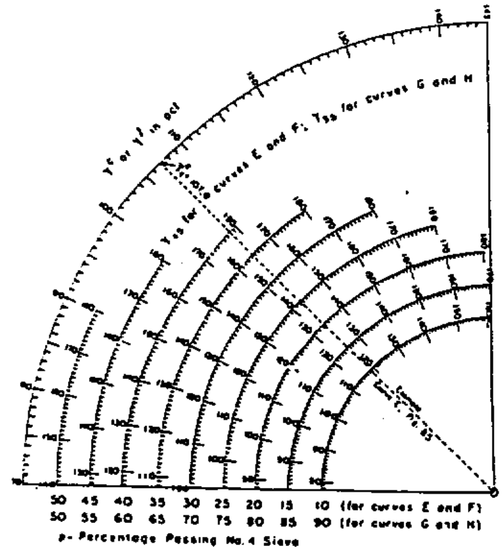


Figure 87. Nomograph for determining unit weight values (γ_p) for curve E, F, G, or H for different values of p, the percentage passing the No. 4 sieve (102).

in which

p = percentage of fine aggregate;
γ_p = unit weight of combination with p percent fine aggregate, pcf;
γ_c^s = solid unit weight of coarse aggregate, pcf; and
γ_f^c = compacted unit weight of fine aggregate, pcf.

For example, the ordinate (γ_p) on curve A (Fig. 85) for a given mixture (with 20 percent fine aggregate, $\gamma_c^s = 170$ pcf and $\gamma_f^c = 132$ pcf) is

$$\gamma_{20} = \frac{(170)\ (132)}{\left(\frac{20}{100}\right)(170) + \left(1 - \frac{20}{100}\right)(132)} = \frac{(170)\ (132)}{(0.2)\ (170) + (0.8)\ (132)}$$

$$\gamma_{20} = 160.8 \text{ pcf}$$

Curve B:

$$\gamma_p = \frac{\gamma_c^s\ \gamma_f^l}{\left(\frac{p}{100}\right)(\gamma_c^s) + \left(1 - \frac{p}{100}\right)\gamma_f^l}$$

Curve C:

$$\gamma_p = \frac{\gamma_c^c\ \gamma_f^s}{\left(\frac{p}{100}\right)\left(\gamma_c^c\right) + \left(1 - \frac{p}{100}\right)\left(\gamma_f^s\right)}$$

Curve D:

$$\gamma_p = \frac{\gamma_c^l\ \gamma_f^s}{\left(\frac{p}{100}\right)\left(\gamma_c^l\right) + \left(1 - \frac{p}{100}\right)\left(\gamma_f^s\right)}$$

Curve E:

$$\gamma_p = \frac{\gamma_c^c}{1 - \frac{p}{100}}$$

Curve F:

$$\gamma_p = \frac{\gamma_c^l}{1 - \frac{p}{100}}$$

Curve G:

$$\gamma_p = \frac{\gamma_f^c}{\frac{p}{100}}$$

Curve H:

$$\gamma_p = \frac{\gamma_f^l}{\frac{p}{100}}$$

8. Label intersections of the curves (as shown in Figure 88) as follows: Curves B and E intersect at point a, G and D at b, A and D at c, B and D at d, A and F at e, and C and H at f.

9. Calculate the coordinates of point r (Fig. 88) between points γ_c^c and e as shown in the following equation and plot point r.

$$p_r = 0.5\ p_e$$

$$\gamma_r = \frac{\gamma_c^c\ \gamma_e}{0.5\gamma_c^c + 0.5\gamma_e}$$

in which

p_r = percentage of fine aggregate in mixture represented by point r;
p_e = percentage of fine aggregate in mixture represented by point e;
γ_r = unit weight of mixture represented by point r, pcf;
γ_e = unit weight of mixture represented by point e, pcf; and
$\gamma_c{}^c$ = compacted unit weight of coarse aggregate, pcf.

If, for example, p_e = 41.5 percent γ_e = 152.0 pcf, and $\gamma_c{}^c$ = 107.0 pcf,

$$p_r = -(0.5)(41.5) = 20.75 \text{ percent}$$

$$\gamma_r = \frac{(107)(152)}{(0.5)(107) + (0.5)(152)} = \frac{16270}{53.7 + 76} = 125.6 \text{ pcf}$$

10. Draw a smooth curve from $\gamma_c{}^c$ through point r to e; label intersection with curve B, point o.

11. Draw straight lines ab and de and label their intersection point m; draw straight lines ac and df and label their intersection n.

12. Draw the maximum unit weight curve through $\gamma_c{}^c$, r, o, m, n, and $\gamma_f{}^c$ as shown in Figure 89.

This maximum unit weight curve shows how the maximum obtainable dry unit weight of a particular material varies with the percentage of fine aggregate in the mixture. In Figure 89 it can be seen that for the sample material, the maximum unit weight increases rapidly as the fine aggregate content increases from 0 to about 35

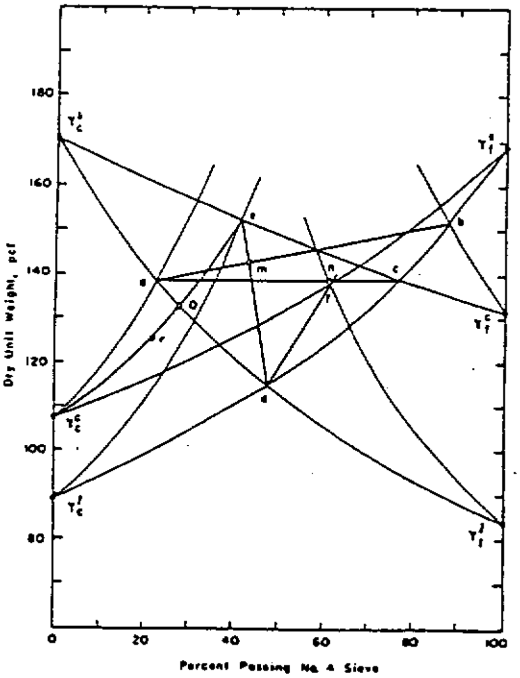


Figure 88. Determination of points (r, o, m, n) for maximum unit weight curve for mixtures of sample materials (102).

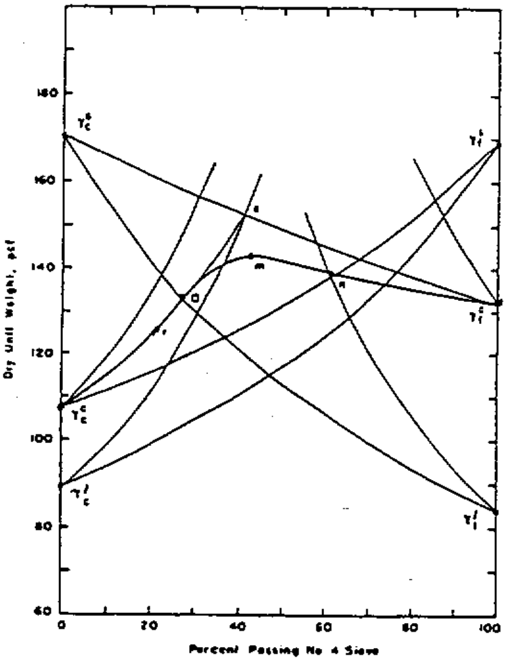


Figure 89. Derived maximum unit weight curve for mixtures of sample materials (102).

percent of the mixture. For the higher percentages of fine aggregate, fluctuations in gradation would have less effect on maximum unit weight.

The Humphres method is complex and lengthy, but has proved very useful in the State of Washington.

If several points on the Humphres maximum dry unit weight curve could be obtained by simply compacting several mixtures of coarse and fine aggregate, much time could be saved. James and Larew (133) investigated this possibility. They performed a series of impact compaction tests on two materials: a crushed limestone and a natural gravel. For each material, they first established the Humphres maximum unit weight curve. Then, they determined the compaction effort required to compact the fine aggregate (100 percent passing the No. 4 sieve) to the same unit weight as obtained in the Humphres method. Finally, they determined the maximum unit weight for each of several mixtures. The resulting maximum unit weight curve for the crushed limestone matched the Humphres curve very closely; the curve for the natural gravel generally fell below the Humphres curve. James and Larew concluded that the Humphres maximum unit weight curve represents a single level of compaction effort for some soil materials. It was also evident that a simple impact compaction test could not be used to duplicate the Humphres method for all soil-aggregate mixtures.

Highway Research Board Bulletin No. 159, "A Method of Controlling Compaction of Granular Materials", dated 1957

A Method for Controlling Compaction Of Granular Materials

HERBERT W. HUMPHRES, Senior Materials Engineer
Washington State Highway Commission

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 deterent 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 incompatability with field results has caused the field

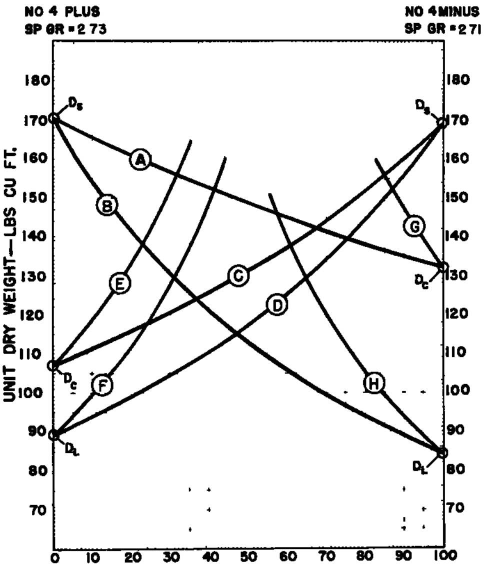


Figure 1. Theoretical curves.

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 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

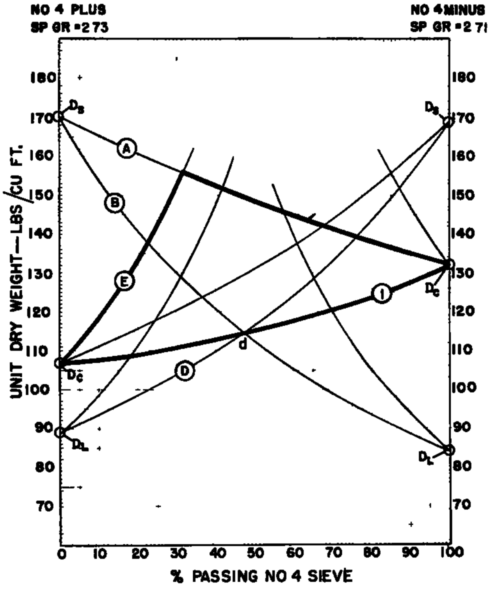


Figure 2. Theoretical limits of maximum density.

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 compatable 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.

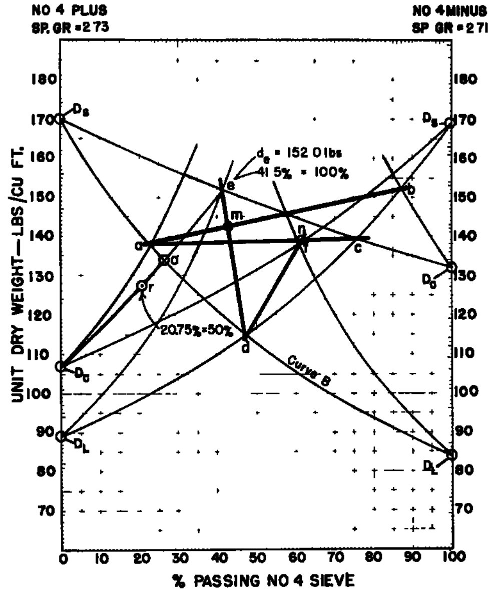


Figure 3. Points for maximum density curve.

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.

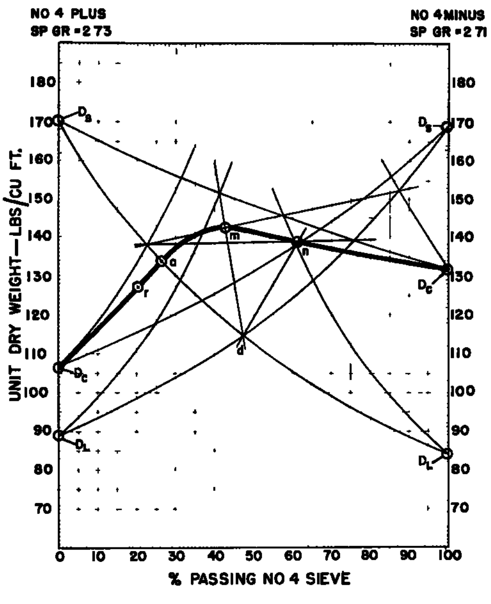
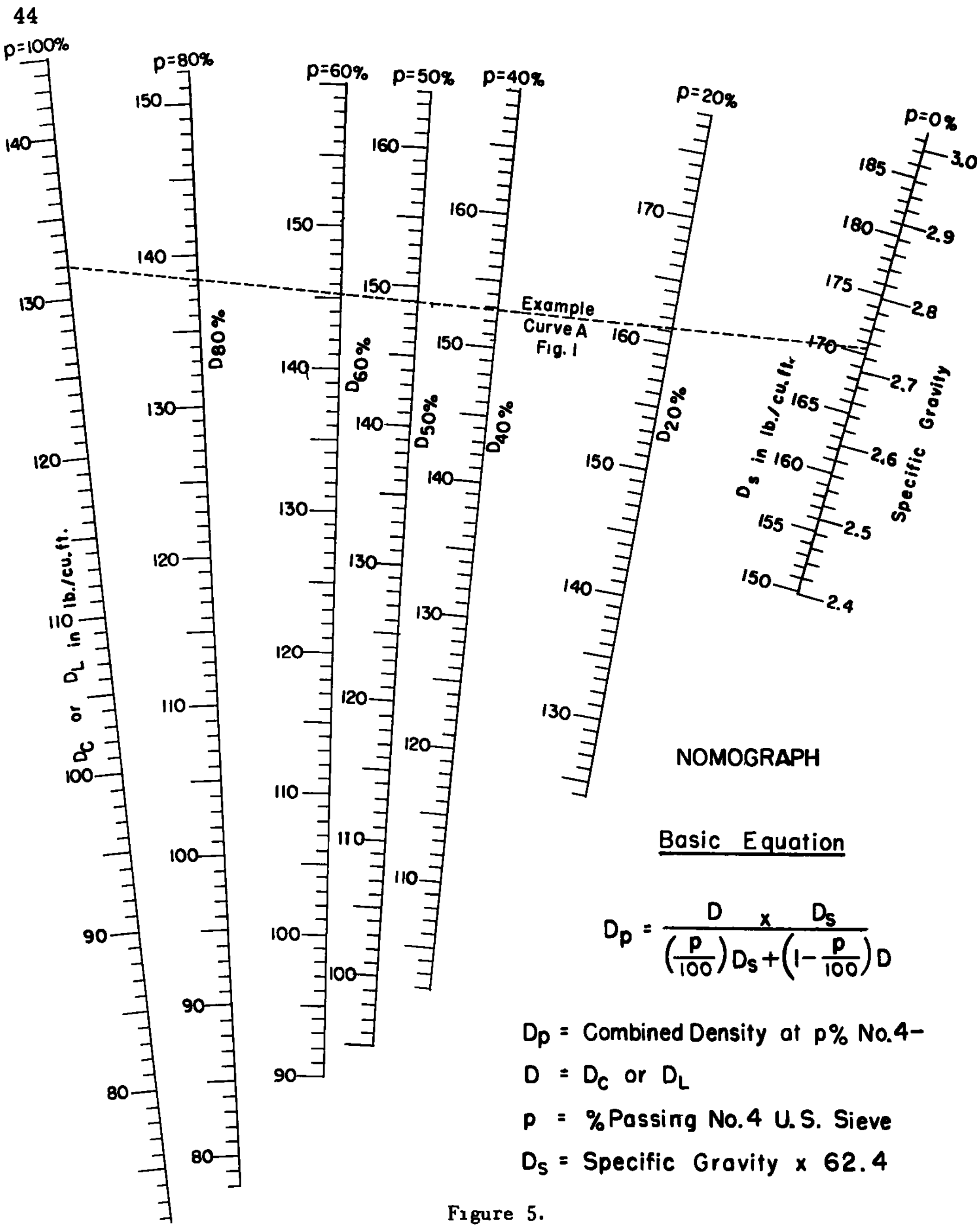


Figure 4. Derived maximum density curve.

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



NOMOGRAPH

Basic Equation

$$D_p = \frac{D \times D_s}{\left(\frac{p}{100}\right) D_s + \left(1 - \frac{p}{100}\right) D}$$

D_p = Combined Density at p% No.4-

D = D_C or D_L

p = %Passing No.4 U.S. Sieve

D_S = Specific Gravity x 62.4

Figure 5.

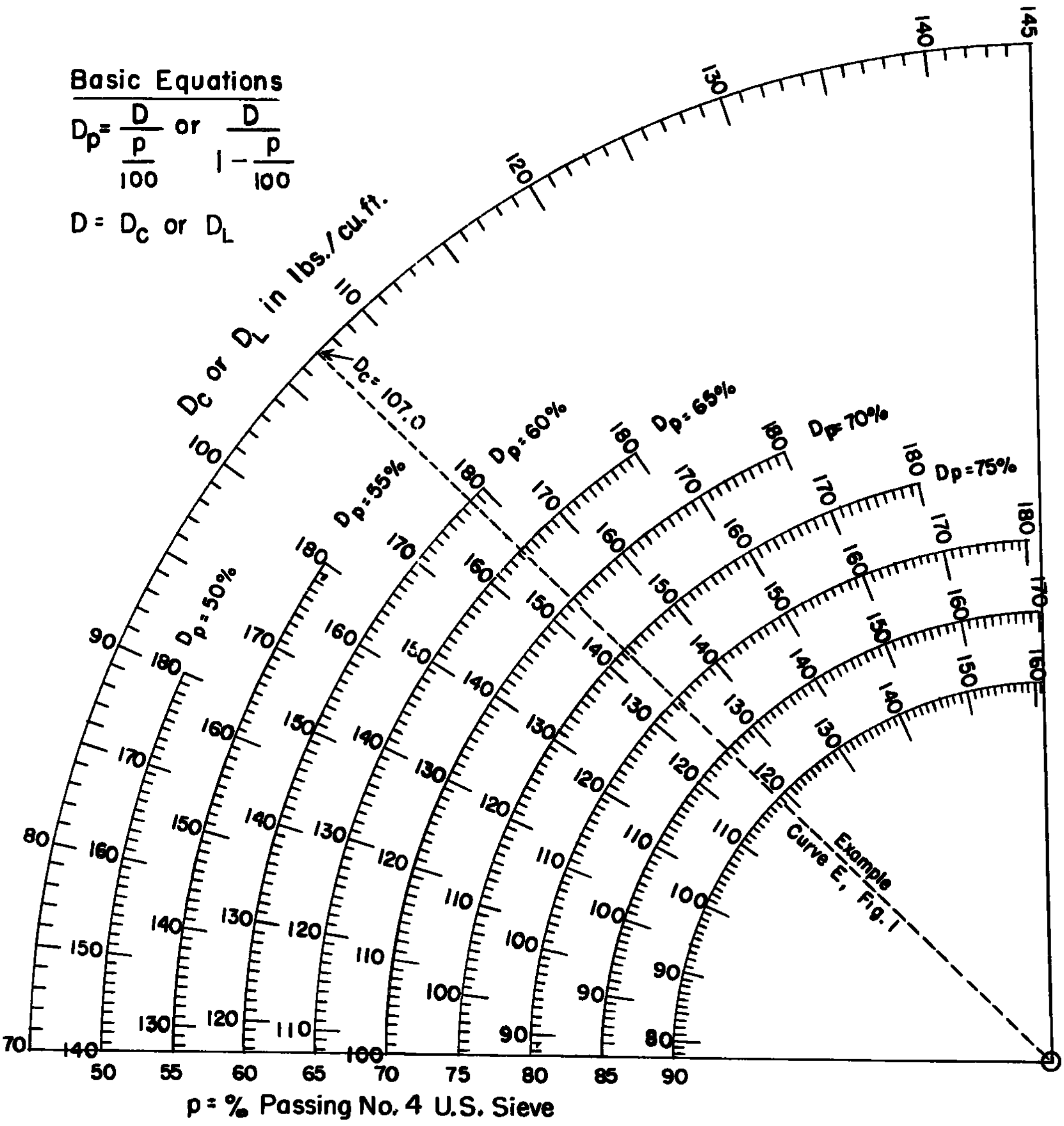
that each of the relationships shown by the theoretical curves derived from limited assumptions and conditions hold true to a certain extent, and that the inter-relationship of these curves establishes the correct position of the true maximum density curve.

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



$$D_p = \frac{D}{\frac{p}{100}} \text{ or } \frac{D}{1 - \frac{p}{100}}$$

$$D = D_c \text{ or } D_L$$

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:

$$d_p = \frac{(D_s \text{ No. 4-plus}) \quad (D_c \text{ No. 4-minus})}{\frac{p}{100} \; D_s \text{ No. 4-plus} + \left(1 - \frac{p}{100}\right) D_c \text{ No. 4-minus}} \qquad (1)$$

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.

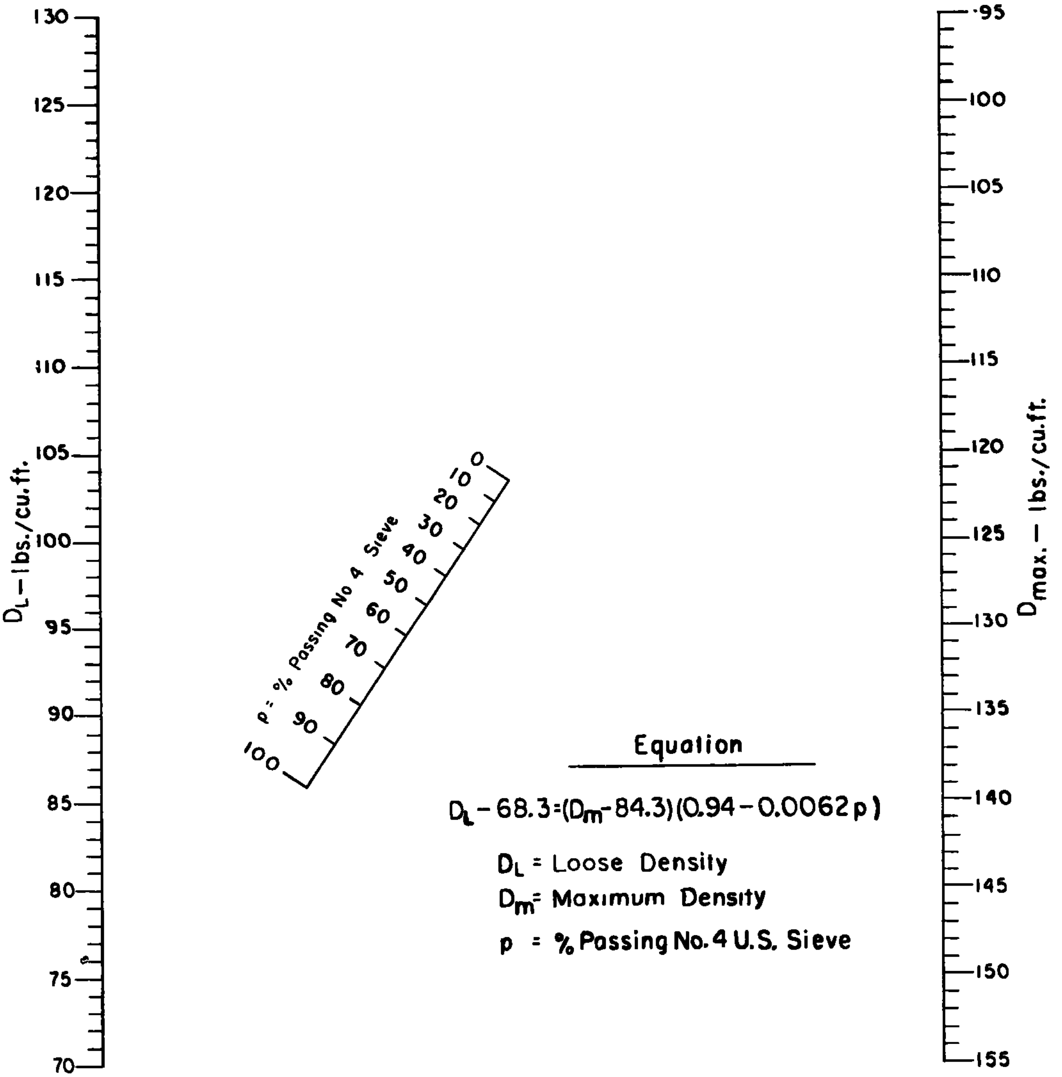


Figure 7. Nomograph for relationship of maximum density and loose density.

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:

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

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

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

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

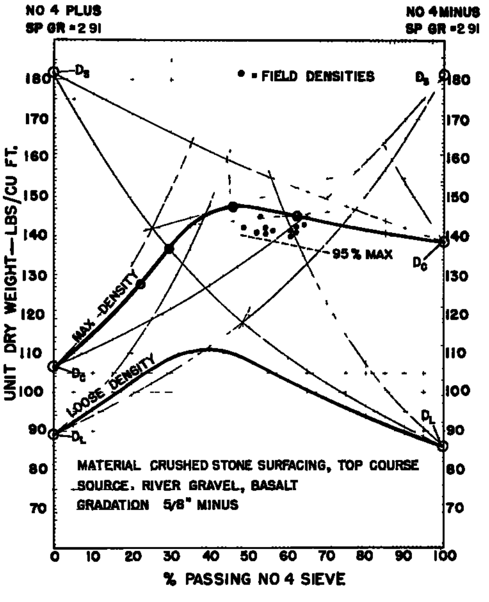


Figure 8.

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.

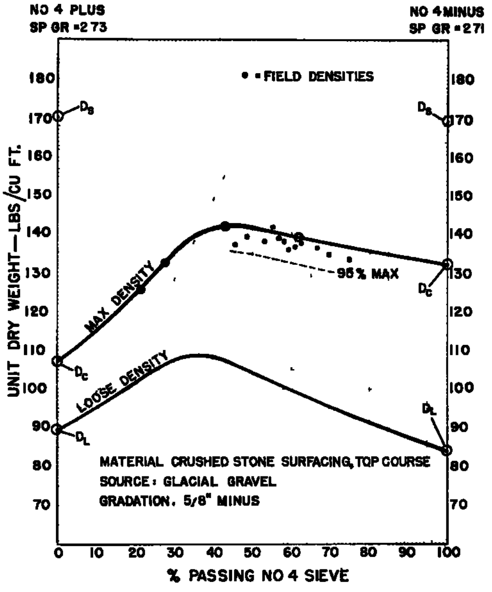


Figure 9.

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

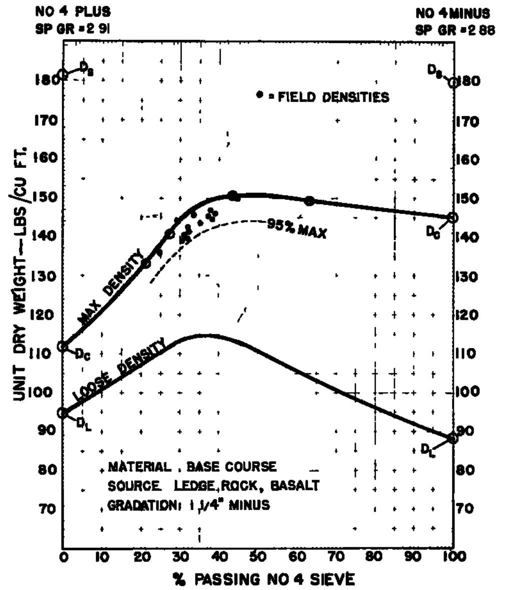


Figure 10.

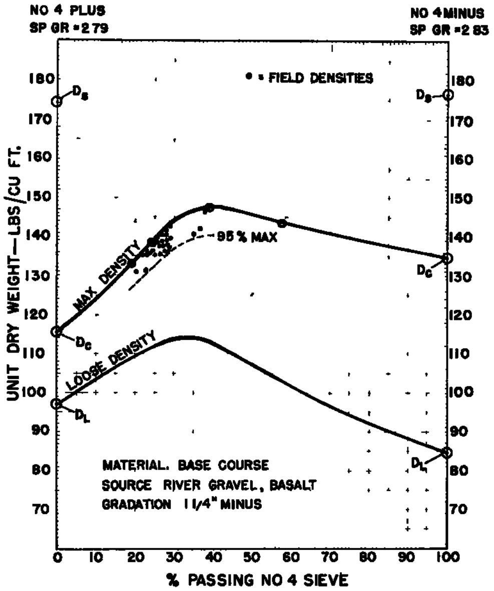


Figure 11.

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

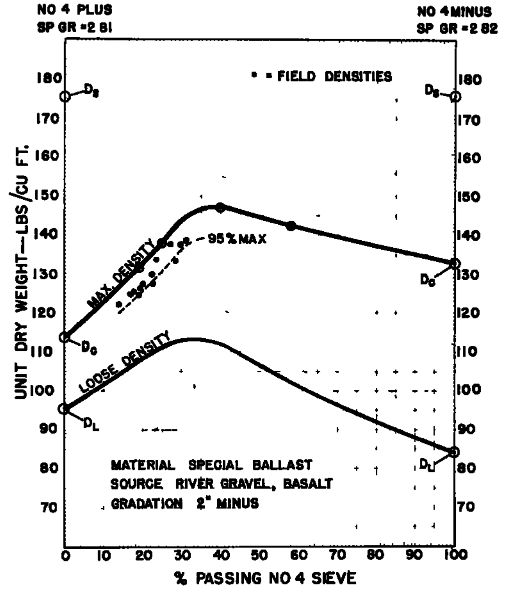


Figure 12.

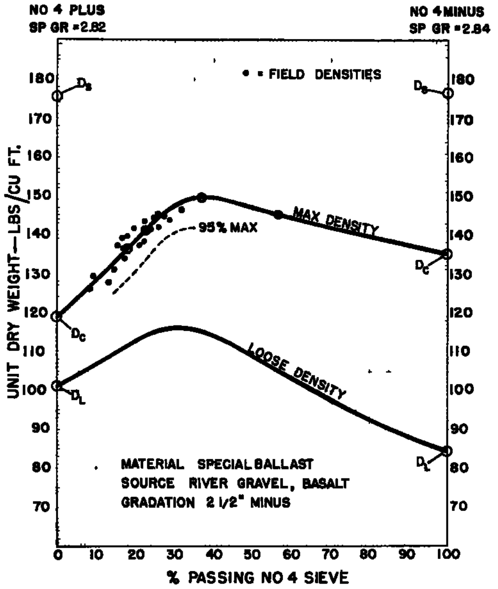


Figure 13.

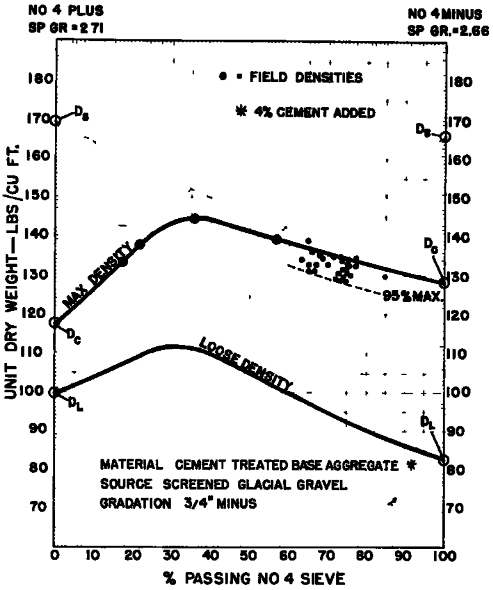


Figure 14.

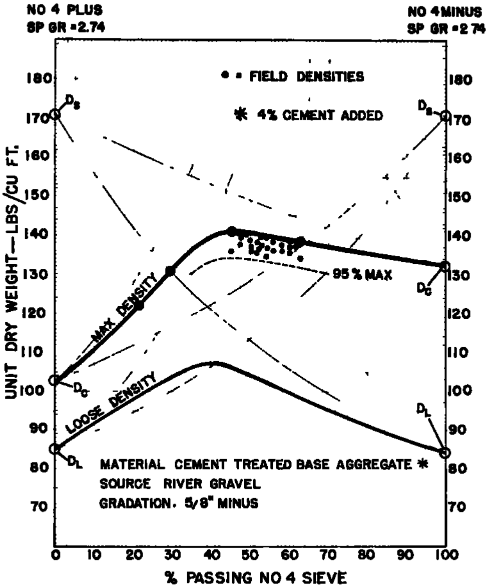


Figure 15.

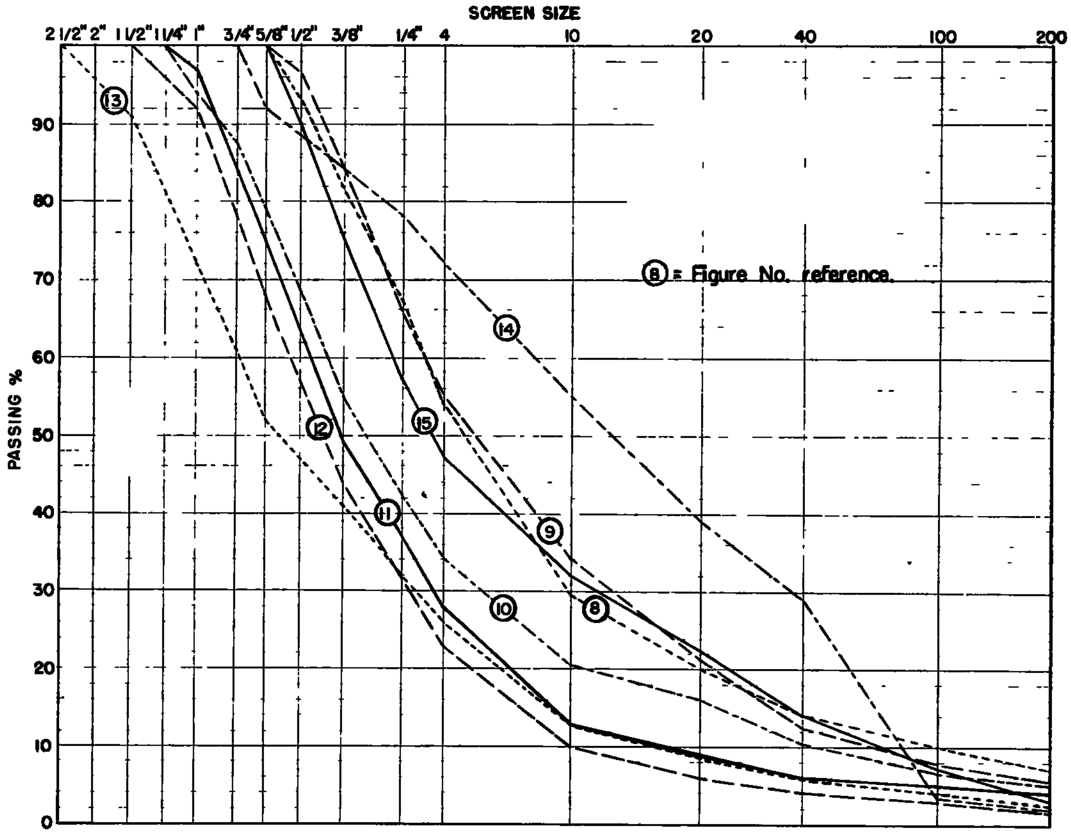


Figure 16. Gradation curves for aggregates illustrated by Figures 8 through 15.

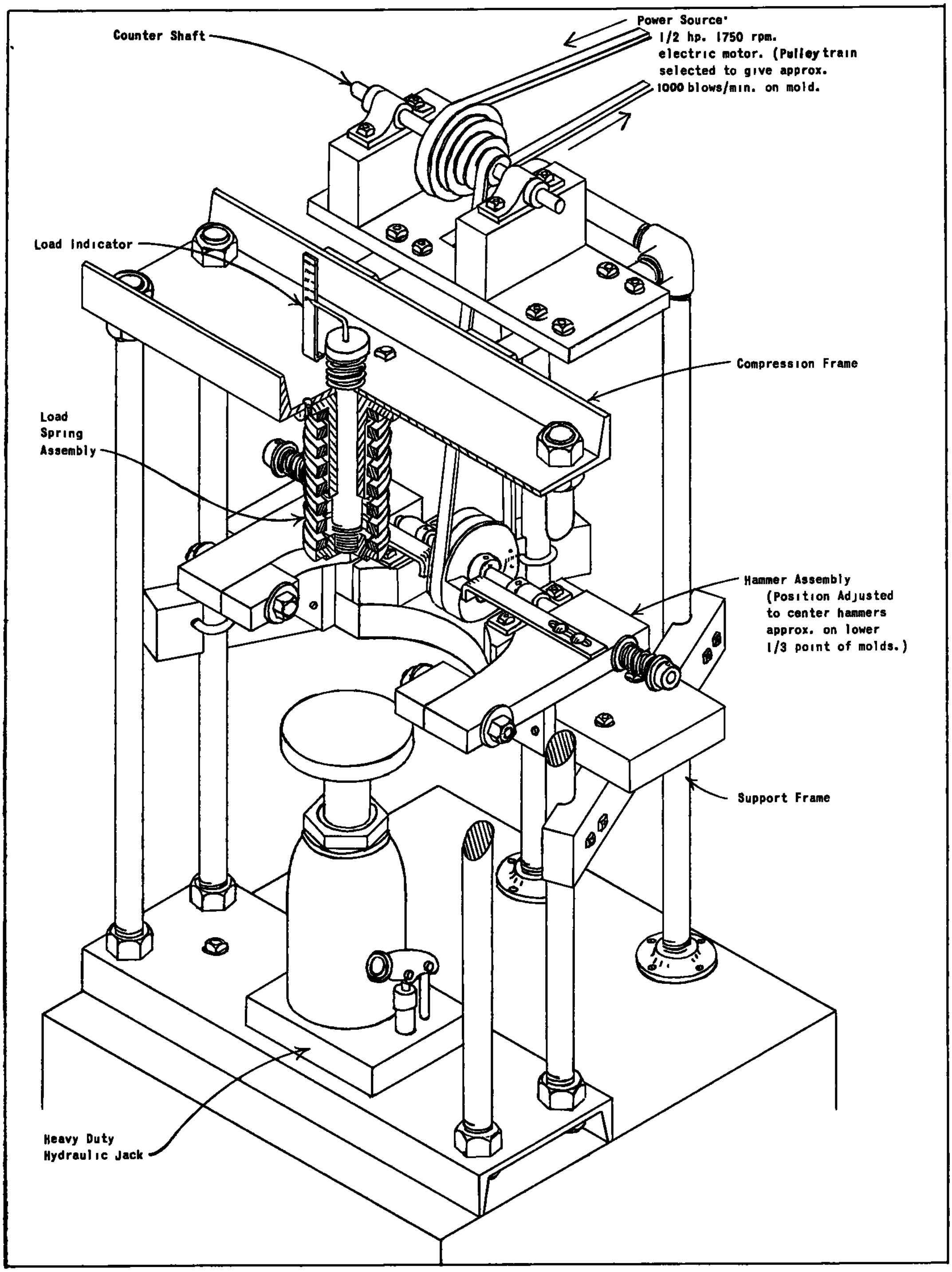


Figure 17. Pilot model -- vibratory spring-load compactor.

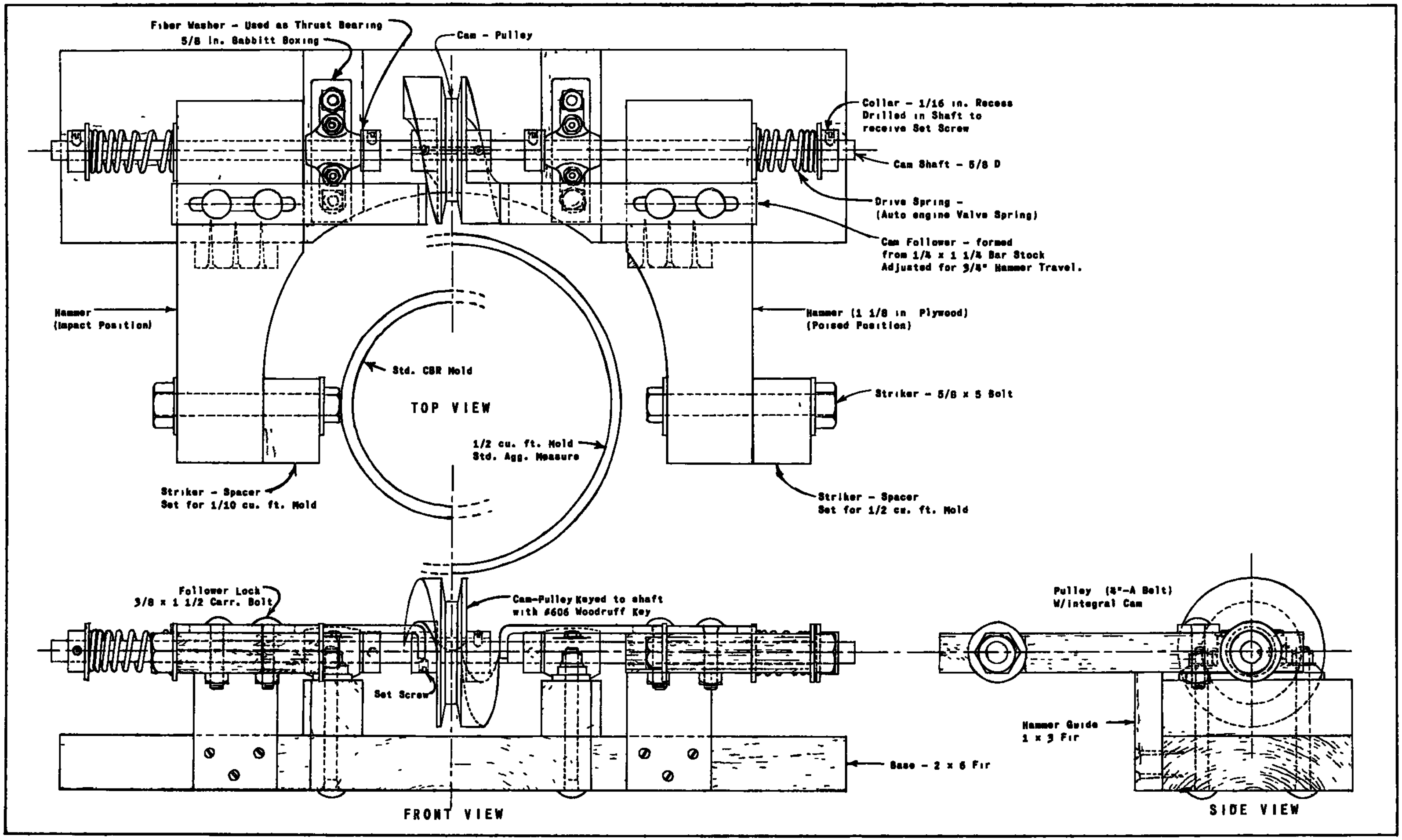


Figure 18. Hammer assembly. Pilot model -- vibratory spring-load compactor.

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

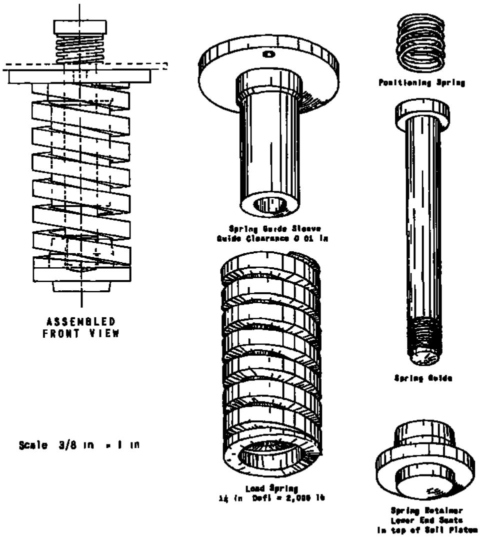


Figure 19. Load spring assembly. Pilot model -- vibratory spring-load compactor.

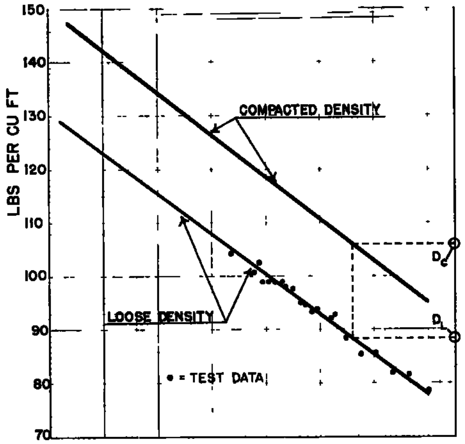


Figure 20. No. 4 plus fraction compacted density (D_c) vs. loose density (D_L).

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

The author is indebted to Laurence J. Gadbois, Junior Materials Engineer, for his critical assistance in developing the new test procedures described, and to both him

and Kenneth Gaw, Engineering Aide, for obtaining and compiling the large volume of field and laboratory test data necessary to the development of this report. Appreciation is expressed to Roger V. LeClerc, Senior Materials Engineer, for his contribution of the nomographs in Figures 5 and 7.

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Appendix A

TEST PROCEDURES

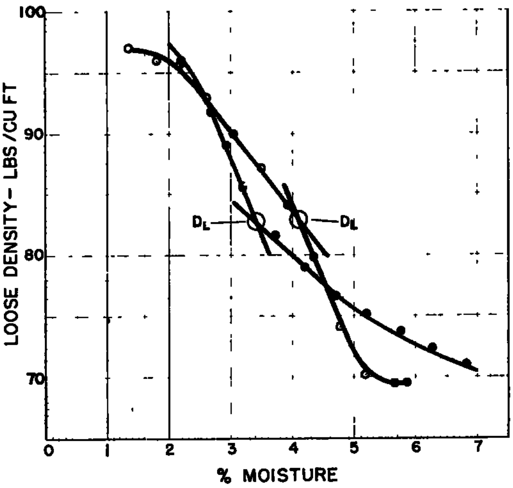

Figure 21. Percent moisture vs. loose density for No. 4 minus fraction.

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, AASHO 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 (1/16-in. clearance); height-measuring device accurate to 0.001 in.; and 5-lb tamping hammer with 3-sq. in. face area and 5/8-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.[1]

---

[1] 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	-	½ min
1,000 to 2,000 lb	-	½ 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.[1] 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 ¾ 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 ½ cu ft for accuracy.

A. Test for Coarse Aggregate having a maximum size of ¾ 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 2½ percent moisture[2] 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 ¾ in.

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

---

[1] (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.

[2] It was found through experiment that moisture in excess of 2½ percent has no effect on the final density obtained with these coarse, open-graded aggregates. For very coarse aggregate requiring the use of the ½-cu ft mold, moisture has no effect on density and can be omitted.

½-cu ft standard aggregate measure
¾-in. piston, plywood with bottom face covered with 16-gage sheet steel and diameter ⅛ in. less than I.D. of ½-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 [3] 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

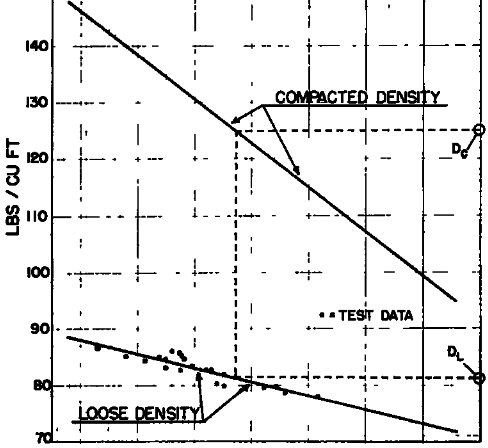

Figure 22. No. 4 minus fraction. Compacted density (D_c) vs. loose density (D_l).

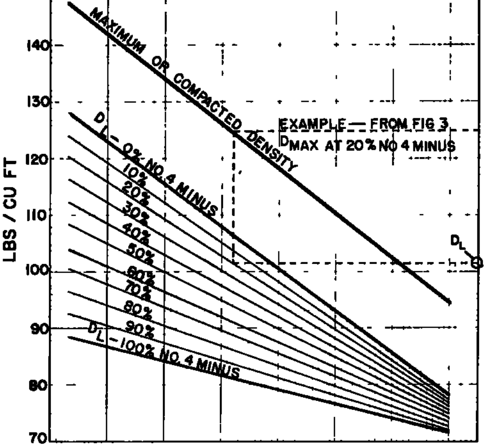

Figure 23. Relationship of maximum density and loose density.

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[3] 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 ⅜ 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.