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Laboratory Compaction Tests of Coarse-Graded Paving and Embankment Materials

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THIS report presents results of a laboratory study of the applicability of the Proctor type of compaction test to the compaction of coarse-graded materials. Three representative granular materials (gravel, limestone, and slag) were tested through a range of carefully controlled artificial gradations in which the ratio of coarse to fine fractions was varied.

These tests indicate that a modified Proctor procedure can be used successfully to compact coarse-graded materials in either a 4- or 6-in. diameter mold. The maximum density of mixtures of coarse and fine materials increased with increasing percentages of coarse material, up to a point of optimum gradation. Beyond this point the further addition of coarse material resulted in lower densities. The optimum gradation for the materials used in this study occurred when the mixtures contained about 40 to 60 percent of material retained on the No. 4 sieve. When the mixture contained more than 80 percent of coarse material, results obtained from the Proctor compaction test were erratic.

Degradation of coarse aggregate during compaction increased with increasing percentages of coarse material. Breakage in the 4-in. mold was negligible when the plus-4 material was less than 30 percent.

The increase in maximum density which is gained by adding coarse materials to fine-graded mixtures can be predicted by a correction formula applied to the density of the finer, or minus-4, portion of the material. Correction formulas were not applicable to mixtures coarser than the optimum gradation.

● IN the standard Proctor soil compaction test (ASTM Designation D698-42T) all of the particles retained on the No. 4 sieve are removed before the sample is compacted. Proctor test results, therefore, cannot be translated directly into specification requirements covering the compaction of coarse-graded materials.

Various expedients have been used in an effort to modify the Proctor test procedure or to evolve a correction factor for extending the test to cover coarsely graded materials. Some specification writers provide for the removal of oversized material but substitute an equal weight of smaller sized granular material. Others modify the procedure and equipment to allow the handling of larger particles. The Civil Aeronautics Administration (*1*) specifies that the compaction test be performed only on material passing the No. 4 sieve and that the following correction formula be used:

$$D = \frac{P_f \times D_f}{100} + \frac{P_c \times 0.90D_t}{100} \quad (1)$$

where

- D = maximum dry density of total sample in pounds per cubic foot.
- D_f = maximum dry density of material passing the No. 4 sieve in pounds per cubic foot.
- D_t = bulk specific gravity of material retained on the No. 4 sieve multiplied by 62.36.
- P_f = percentage of material passing the No. 4 sieve.
- P_c = percentage of material retained on the No. 4 sieve.

Zeigler (*2*), in a study of the compaction characteristics of fine-grained soil and gravel, used another form of correction formula, which when converted to the same terms as used in Equation 1, can be expressed as

$$D = \frac{100}{\frac{P_f}{D_f} + \frac{P_c}{D_t}} \quad (2)$$

From the standpoint of the contractor, the inspector, and the materials testing engineer, it is most desirable that some standard method be developed for conducting compaction tests on materials containing appreciable amounts of plus-4 material. In the present study a series of carefully controlled laboratory tests were performed for the purpose of evaluating the various factors involved in the compaction of coarse-graded material by the Proctor type of compaction test.

DESCRIPTION OF MATERIALS

Three contrasting granular base-course materials were used in the laboratory testing: gravel, crushed limestone, and crushed slag. Each of these materials was separated into three portions: the minus-4, the plus-4 to minus-¾-in., and the plus-¾-in. to the minus-1½-in. Each portion was stored separately and those of the same type were later combined in selected proportions to provide a wide range of gradations. For convenience in reporting, the fine, medium, and coarse fractions have been designated A, B, and C, respectively.

The appearance of each fraction of the three basic materials is shown in Figures 1, 2, and 3. The physical characteristics, obtained by standard ASTM procedures, are summarized in Table 1.

COMPACTION EQUIPMENT

All of the test samples were compacted by means of a Rainhart Automatic Tamper, modified by the addition of a motor drive and a counter for controlling the number of blows applied to each layer of the sample. The equipment was designed for use with either a 4- or 6-in. mold. Interchangeable striking heads, each with an end area of 3.14 sq. in., were provided for use with the different mold sizes. Hammer weight of 10 lb. was used when compacting in the 4-in. mold. This weight was increased to 22.5 lb. for use with the 6-in. mold. The molds were both 4.6 in. high and slightly tapered to permit easy removal of the samples. The tamping equipment, set up for operation with the 6-in. mold, is shown in Fig. 4.

TESTING PROCEDURES

Modified AASHO compaction effort was used in all tests. In order to accommodate the large size aggregate included in some of the tests (1½-in. top size) it was necessary to increase the thickness of the compacted layer to 1½ in. The samples were compacted in three layers at 42 blows per layer rather than the normal five layers at 25 blows. The procedure was the same when using the 6-in. mold except that the hammer weight was increased.

The proper amount of each fraction required to construct the sample was portioned and stored in a separate container. The plus-4 portions were soaked in water for 24 hr. and then allowed to drain on a screen, prior to mixing with the minus-4 fraction. The minus-4 portion was slaked with the mix water for about 1 hr. before mixing with the coarse material. All mixing was performed by hand. Different samples were used to obtain the individual points on a particular compaction curve.

When a large percentage of plus-¾ material was present it was impossible to trim the compacted sample level with the top of the mold in the usual manner. In such cases it was necessary to modify the top portion in order that it be as nearly equivalent to a

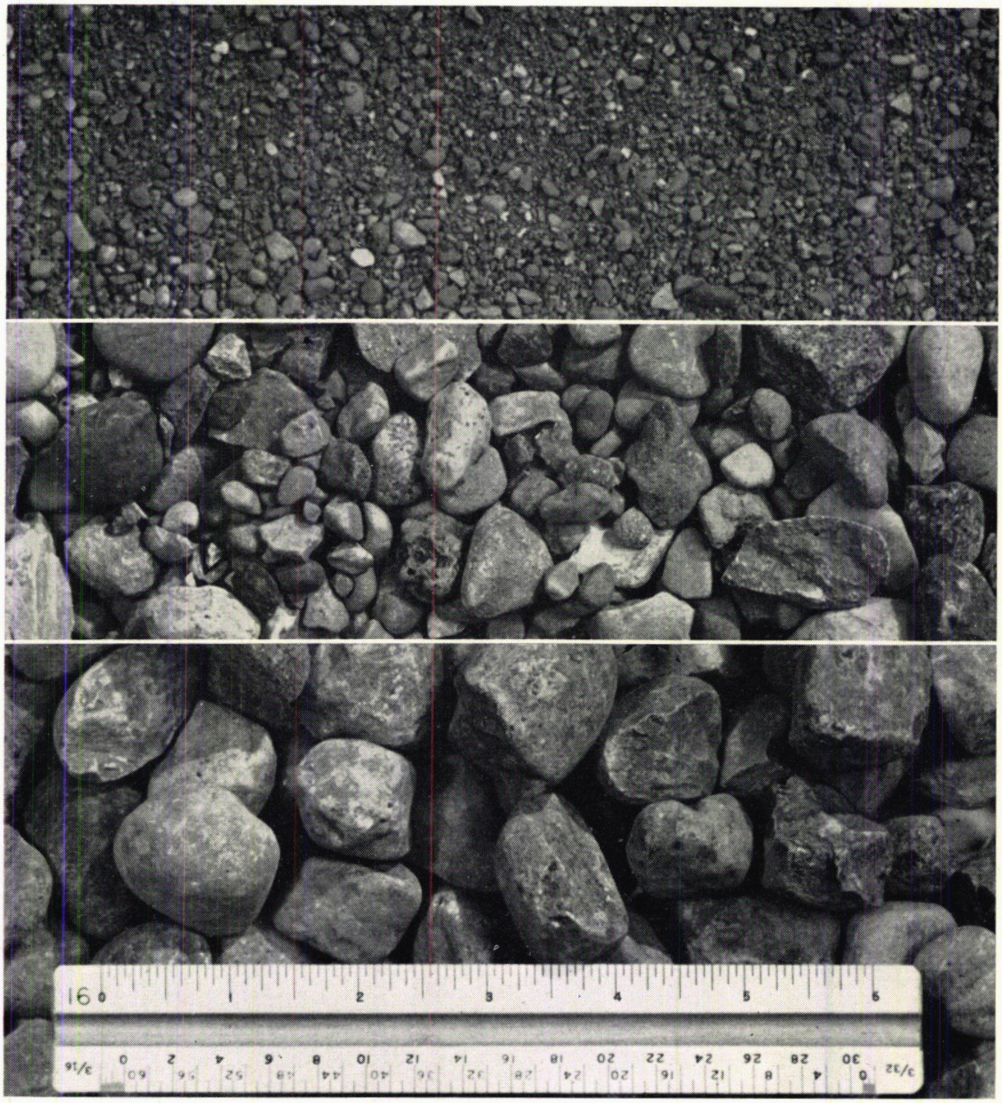

Figure 1. Appearance of the three fractions of gravel. Top, Fraction A; center, Fraction B; bottom, Fraction C.

level sample as possible. Figure 5 shows the condition of a particularly coarse-graded sample during leveling.

Moisture contents were determined by drying the samples in an oven at 105 C. The entire sample contained in the 4-in. mold and reflect the average moisture conditions throughout the whole specimen.

A sieve analysis, using the ¾-in. and the No. 4 sieves, was made after each test in order to determine the amount of degradation of the sample during compaction.

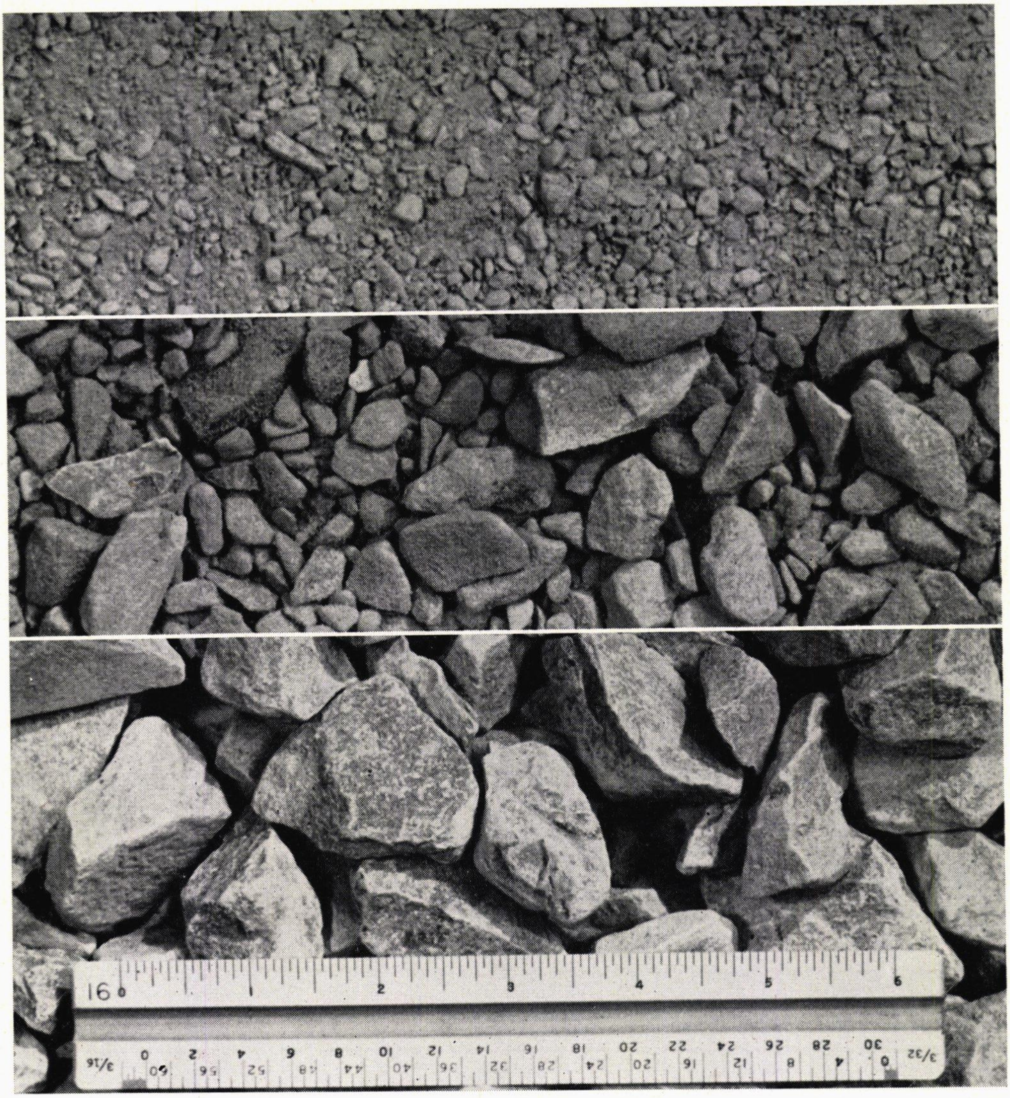

Figure 2. Appearance of the three fractions of limestone. Top, Fraction A; center, Fraction B; bottom, Fraction C.

a 3,000-gram or larger portion of those contained in the 6-in. mold were used for this determination. It was found that the use of smaller moisture samples did not accurately

TEST RESULTS

The compaction-test results can be considered representative for coarsely graded mixtures. It was not always possible, however, to obtain a high degree of accuracy with some of the coarser gradations. As the ratio of coarse to fine material increased the Proctor compaction procedure became more difficult to perform properly. Further, for certain gradations the particles of the mixture tended to segregate during preparation of the samples. Since the mixtures were not homogeneous but consisted of particles of different specific gravity and other physical characteristics, the effect of segregation was significant. With the majority of mixtures, however, the tests could be performed quite satisfactorily, and clearly defined values were obtained. For the less satisfactory samples, the maximum densities represent the best average values that could be interpreted from the data.

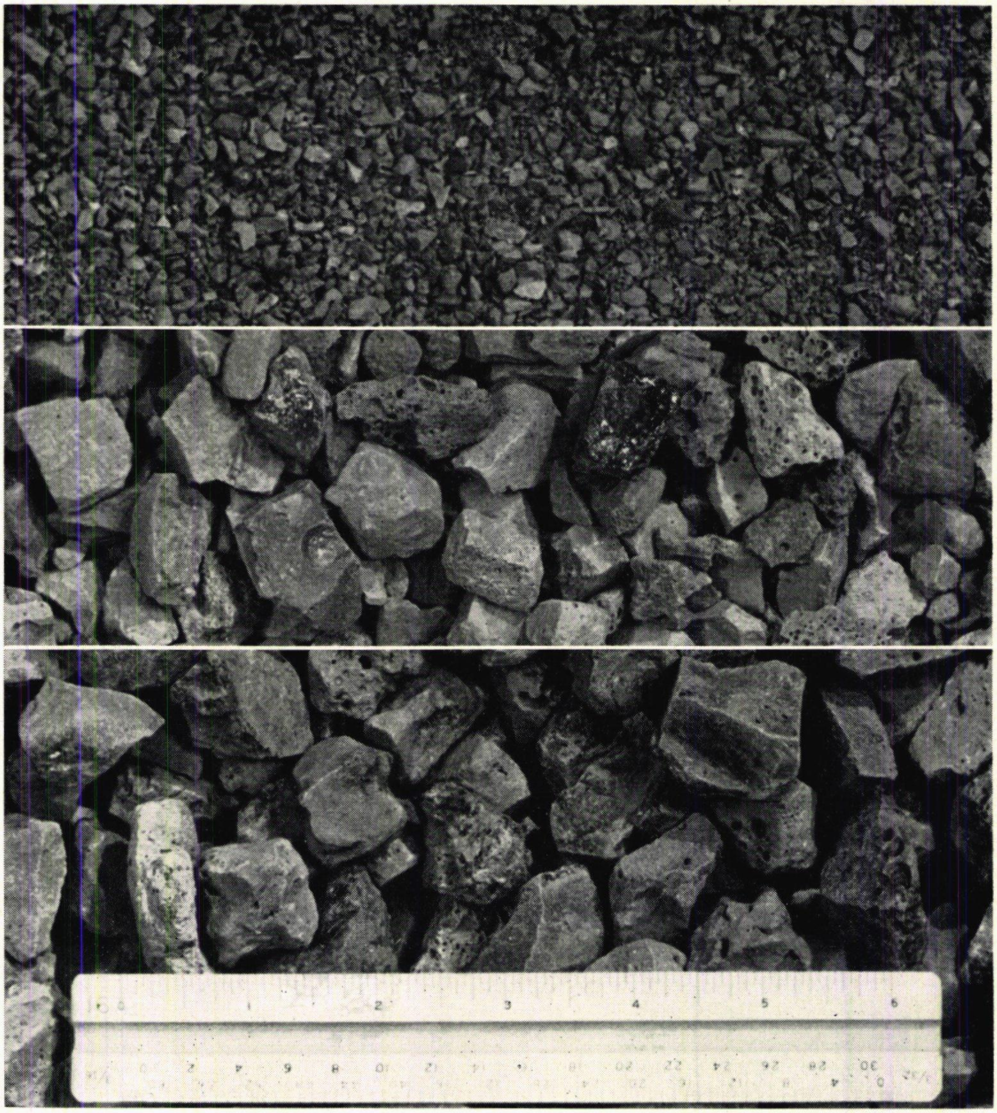

Figure 3. Appearance of the three fractions of slag. Top, Fraction A; center, Fraction B; bottom, Fraction C.

The basic compaction results are shown in

Figures 6 through 16. The curves show the maximum density obtained for a particular gradation plotted against the corresponding gradation. Separate curves are shown for the 4- and 6-in. molds and for gradation before and after compaction. Curves are also included which show the theoretical changes in density due to varying amounts of plus-4 aggregate as computed by Equations 1 and the mixtures yielded a density increase with increasing coarse aggregate content up to an optimum gradation beyond which the densities decreased rapidly with increased amounts of coarse material. The optimum combinations varied for the individual materials and with the particular fractions used to form the sample. In general, however, optimum density was reached when the samples contained

TABLE 1
PHYSICAL CHARACTERISTICS OF DIFFERENT FRACTIONS OF THE TEST MATERIALS

Fraction Identification		Specific Gravity		Percent Absorption	Percentage of Wear, Los Angeles Abrasion Test			Percent Passing Sieve							
		Bulk	Apparent		Whole Sample	¾ Inch to ⅜ Inch	⅜ Inch to No. 4	1½ Inch	1 Inch	¾ Inch	⅜ Inch	No. 4	No. 10	No. 40	No. 200
−4 fraction of a dense-graded gravel	(A)	—	2.76	—	—	—	—	—	—	—	—	100	76	37	12
+4 to −¾ inch fraction of a washed gravel	(B)	2.56	2.74	2.7	33	30	38	—	—	100	31	2	0	0	0
+¾ inch to −1½ inch fraction of a washed gravel	(C)	2.70	2.79	1.3	22	—	—	100	86	2	0	0	0	0	0
−4 fraction of a crushed limestone	(A)	—	2.75	—	—	—	—	—	—	—	—	100	71	42	19
+4 to −¾ inch fraction of a crushed limestone	(B)	2.65	2.69	0.9	38	34	49	—	—	100	26	3	0	0	0
+¾ inch to −1½ inch fraction of a crushed limestone	(C)	2.66	2.69	0.6	22	—	—	100	40	3	0	0	0	0	0
−4 fraction of a crushed slag	(A)	—	2.72	—	—	—	—	—	—	—	—	100	52	13	2
+4 to −¾ inch fraction of a crushed slag	(B)	2.58	2.69	1.2	29	30	25	—	—	100	5	0	0	0	0
+¾ inch to 1½ inch fraction of a crushed slag	(C)	2.58	2.68	0.8	20	—	—	100	80	10	0	0	0	0	0

2. Individual compaction curves from which the points on these gradation-density curves were obtained have not been shown because in most cases they represent typical moisture-density relationships. The optimum moisture contents for each gradation were a function of the minus-4 portion of the samples. These values ranged from about 5 to 8 percent for the different materials compacted at their optimum gradation.

Effect of Gradation

The effect of sample gradation on the maximum density obtainable from a given mixture is clearly shown in the graphs. Except for combinations of very coarse fractions, all of 40 to 60 percent of plus-4 material. The maximum density gradations correspond closely to gradations established by Fuller (*3*) for concrete mixes.

For the materials whose B and C fractions were of the same specific gravity (limestone and slag) maximum densities of the mixtures composed of Fractions A plus B, A plus C, and A plus B plus C were practically the same. For the gravel, in which the specific gravity of the B and C fractions were not the same, the maximum densities of the A-plus-B, A-plus-C, and A-plus-B-plus-C mixtures varied with the specific gravity of the mixture.

These tests show that for normally graded materials the size of the coarsest particle does not significantly affect the maximum density at the optimum gradation. This indicates that, in cases when it is desirable to limit the top size of the coarse fraction, smaller aggregate can be substituted for larger without erroneous results if the difference in their specific gravities is not large.

For the very-coarse-graded samples, containing Fractions B plus C, no optimum gradation was found (see Figs. 12 and 16). Within the range of experimental error, all combinations containing only B-plus-C fractions of a given material reached substantially the same maximum density. These values were considerably lower than corresponding densities obtained with other combinations. Degradation was quite high for the coarse-graded mixtures.

All of the findings showing the effects of gradation on density were consistent. The fact that the optimum point occurs at the same gradation, regardless of mold size, indicates that the decreasing density beyond this point is a function of the gradation and is not due to arching or restriction in the mold.

Effect of Mold Size

The influence of mold size varied with the type and, to less extent, with the gradation of the materials compacted. For the gravel

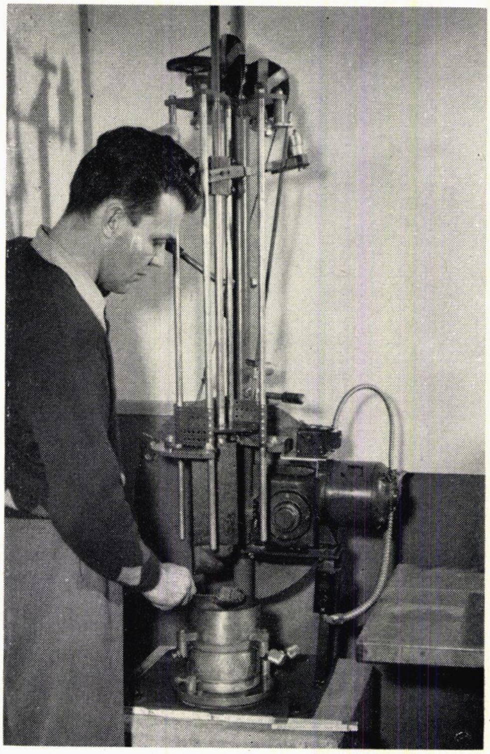

Figure 4. Automatic tamping equipment used to compact samples.

Figure 5. Appearance of the top section of a sample of coarse-graded material after compaction.

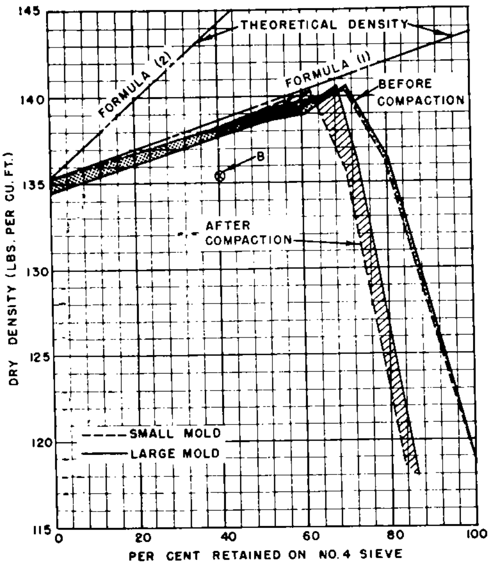

Figure 6. Gradation-density relationship for gravel (Fractions A + B).

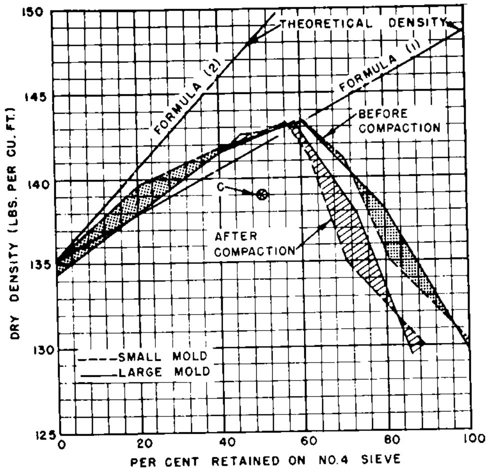

Figure 8. Gradation-density relationship for gravel (Fractions A + B + C).

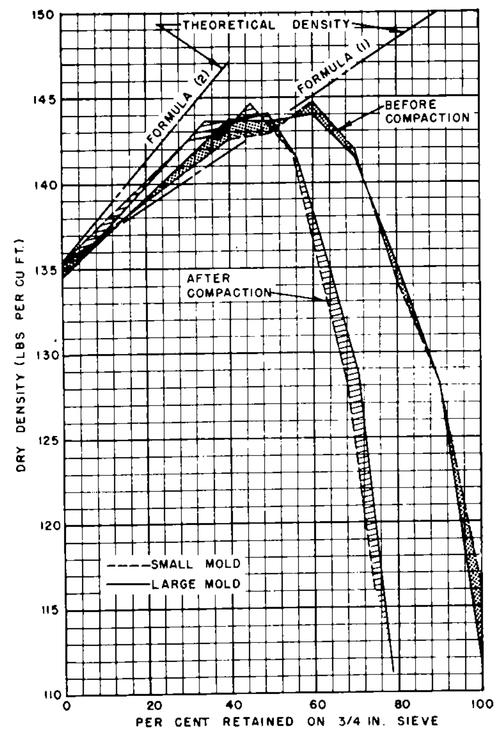

Figure 7. Gradation-density relationship for gravel (Fractions A + C).

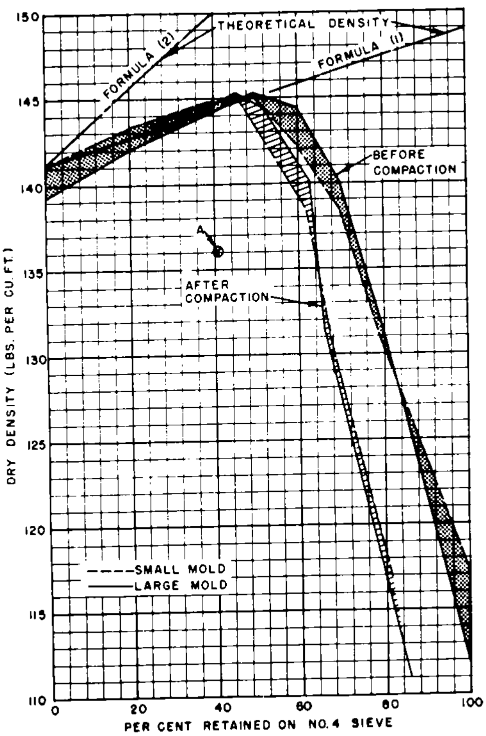

Figure 9. Gradation-density relationship for limestone (Fractions A + B).

and limestone, the effect of mold size was very small. In most of these tests slightly higher densities were obtained in the 4-in. mold for the finely graded mixtures. At or near the optimum point the densities approach equality. Beyond this point, as the mixtures became harsher there was a slight but inconsistent separation. At the point of 100 percent coarse material, equal or higher densities were obtained in the 4-in. mold.

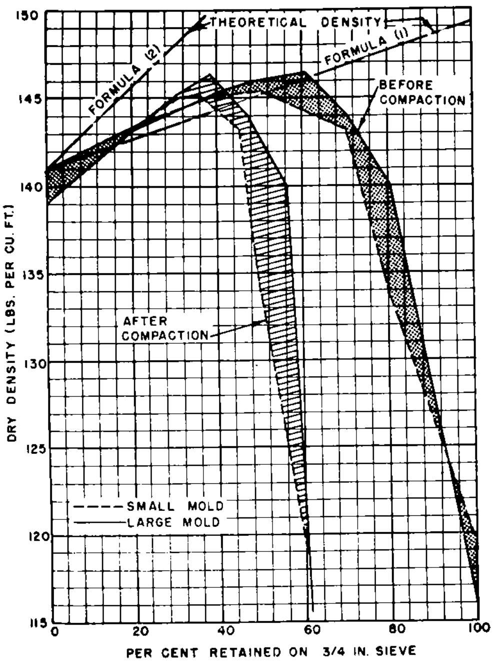

Figure 10. Gradation-density relationship for limestone (Fractions A + C).

With the crushed slag, higher densities were obtained with the smaller mold in all tests. The differences were significant, averaging about 3 or 4 lb. per cu. ft. The slag was the most difficult material to test accurately, but even with possible experimental error the results definitely show that significantly higher densities for this material were obtained in the smaller mold. It should be noted that the slag was inherently harsher than the gravel and limestone used.

In general, these tests indicate that there is no undue particle interference in the 4-in. mold and that this size is satisfactory for tests of coarse mixtures. For such mixtures it produces higher densities than the 6-in. mold because there is less confinement in the latter.

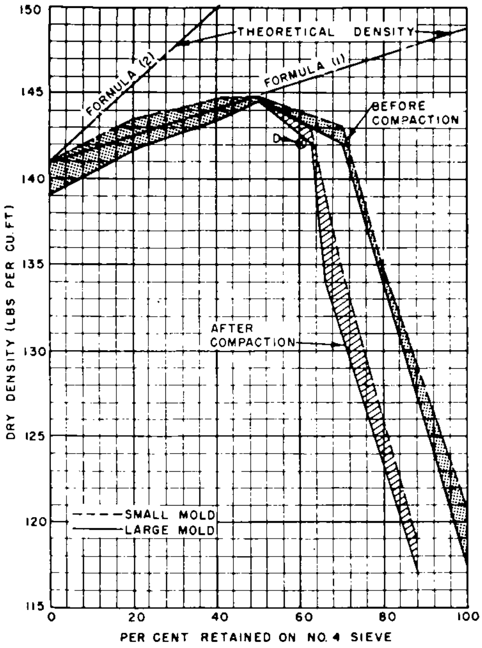

Figure 11. Gradation-density relationship for limestone (Fractions A + B + C).

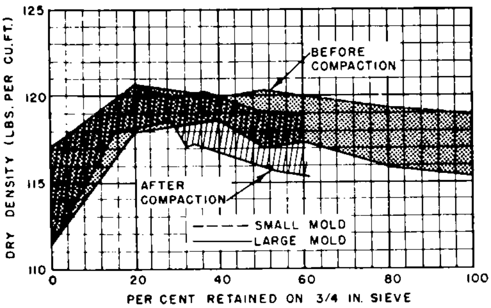

Figure 12. Gradation-density relationship for limestone (Fractions B + C).

Degradation During Compaction

The amount of degradation of the samples due to compaction is indicated in Figures 6 through 16 by the differences in the density-gradation curves before and after compaction.

For most of the samples, only a small

amount of breakage occurred in mixtures finer than those yielding optimum density. Beyond this point the breakage generally increased with increasing percentages of coarse material. An exception to this occurred with the skip-graded samples, composed of Fractions A plus C, where there was considerable degradation when the coarse aggregate exceeded 20 or 30 percent. Degradation was high for the coarse mixtures of Fractions B plus C.

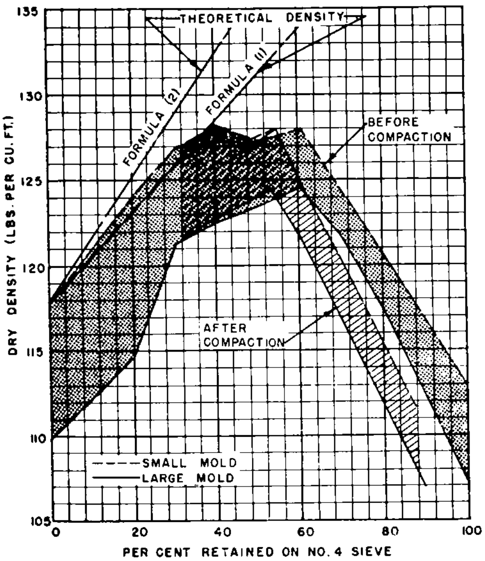

Figure 13. Gradation-density relationship for slag (Fractions A + B).

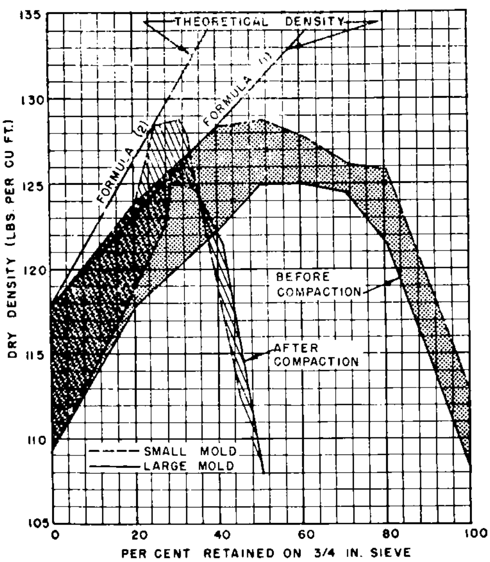

Figure 14. Gradation-density relationship for slag (Fractions A + C).

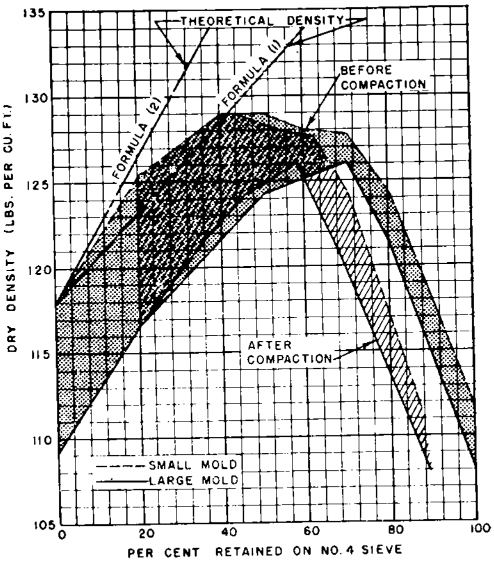

Figure 15. Gradation-density relationship for slag (Fractions A + B + C).

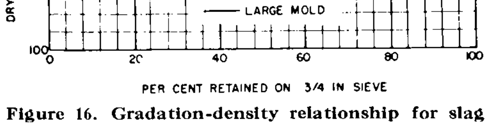

Figure 16. Gradation-density relationship for slag (Fractions B + C).

There was no significant difference in the amount of breakage for gravel, limestone, and slag during compaction, if the samples contained small percentages of plus-¾-in. material. For mixtures containing an appreciable amount of plus-¾-in. material, slag was the most susceptible to breakage. Gravel was the least affected.

In these tests the degradation of the samples was not influenced by variations in their moisture content.

Comparison with Theoretical Densities

Figures 6 through 16 include the theoretical density gradation curves computed from Equations 1 and 2. Equation 1 proved to be quite accurate in predicting the increase in densities resulting from the addition of coarse material to the minus-4 portion, up to the point of maximum density attainable for the particular mixture used. Results obtained by Equation 2 were consistently too high.

Neither formula was applicable beyond the optimum gradation. In using a formula of this type, therefore, it is necessary to know the limit of its applicability or the point of maximum density beyond which the addition of coarse material causes diminishing density.

The information presented in this report and that of other investigations indicates that the Proctor type of test can be used successfully for compacting normally graded materials containing ¾-in. material and larger. With the larger size aggregates, however, the testing operations become increasingly difficult. It appears that a logical compromise would be to limit the top size of coarse aggregate to ¾-in. and correct the density for any plus-¾-in. material contained in the sample. It is believed that Equations 1 or 2 could be modified to serve this purpose.

Comparison of Laboratory and Large-Scale Compaction Data

In order to determine the suitability of the Proctor type test for setting up field compaction requirements for coarse-graded mixtures, the densities obtained in laboratory tests were compared with densities obtained on similar materials under normal construction procedures.

In Figure 9, Point A represents an average density obtained in a highway base course in Indiana. Points B, C, and D in Figures 6, 8, and 11, respectively, represent the field densities obtained on several CAA airport-construction projects using materials and gradations within the range covered by this study. Although exact comparisons between the field data and the laboratory results are not justified, the positions of the points indicate that a specification of 95 percent modified Proctor density would have been a reasonable requirement for field compaction of these materials.

In connection with another experimental project now under way at this center, 10- by 10-ft. experimental base courses using the same materials tested in this study are compacted by means of vibratory equipment. The densities obtained are generally about 5 lb. per cu. ft. less than the maximum for similar gradations obtained by means of the modified Proctor laboratory test. Degradation of materials under the vibratory compaction is small, being about 3 percent based on amounts passing the No. 4 sieve.

The above records indicate the general applicability of the Proctor type of test for field compaction control of coarse-graded materials. They are somewhat sketchy, however, and should be supplemented by extensive experimental correlation of field and laboratory data.

CONCLUSIONS

In this study, a carefully controlled laboratory evaluation has been made of the applicability of the Proctor type compaction test to the compaction of coarse-graded materials. Some of the findings represent definite conclusions, while others require substantiation by field data. Comparative field information concerning certain phases of the study is meager. In these cases the laboratory results can be compared only in a general way to observed field values.

For the range of materials used in this study, the following conclusions appear warranted:

1. The Proctor type of test, using a standard 4-in. mold, was found to be suitable for determining the maximum density and optimum moisture content of coarse materials and mixtures. In testing the harsher mixtures, however, serious operating difficulties were encountered. These were not corrected by the use of a larger mold.

2. For practical purposes it is believed desirable to limit the upper size of the aggregate to ¾-in. When necessary to remove any plus-¾-in. material, the densities can be corrected by means of an equation similar to Equation 1 or Equation 2 or by replacing

plus-$\frac{3}{4}$-in. material with minus-$\frac{3}{4}$-in. coarse material of the same specific gravity.

3. The test results were not appreciably affected by a difference in mold size, except with certain slag gradations for which higher densities were obtained in the 4-in. mold. No significant particle interference was indicated when using the 4-in. mold.

4. Maximum densities of mixtures of graded aggregates increased with increasing percentages of coarse material up to an optimum gradation. Beyond this point the further addition of coarse material resulted in decreasing densities. The optimum gradation occurred when the sample contained 40 to 60 percent of plus-4 material.

5. Maximum densities for well-graded mixtures of a given material were the same regardless of the general gradation of the plus-4 fraction. On this basis smaller aggregate can be substituted for larger, if it is desired to limit the top size of the sample for the purpose of testing.

6. Degradation of samples during compaction increased with increasing percentages of coarse material. No appreciable breakage occurred in the 4-in. mold until the plus-4 material exceeded about 30 percent.

7. Equation 1, used for predicting the increase in maximum density gained by adding coarse-graded material to fine-graded mixtures, was found to be applicable to most of the materials used in this study when the materials were combined in mixtures ranging from fine up to those producing maximum density. Beyond this point the correction formula did not apply.

8. From a limited series of observations, the densities obtained in the laboratory by the Proctor type of compaction test appear to agree with densities obtainable with either vibratory or roller types of field equipment. Further tests conducted for the specific purpose of comparing field and laboratory density values appear desirable.

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DISCUSSION

W. H. Campen, *Manager, Omaha Testing Laboratory*—It is most desirable to include the plus-4 material in determining the moisture-density curve of soil-aggregate mixtures. By so doing both the laboratory and field designing and control work are not only simplified but they are also made more accurate. The existing method of calculating the density of minus and plus mixtures lead to controversies for the reason that correction factors must be applied to the mathematical formulas.

I am gratified with the general conclusion which states that plus-4 material can be used in the standard Proctor method. In our laboratory we have used plus-4 material for a number of years and have been pleased with the results. Our practice has been to substitute the plus-$\frac{3}{4}$-in. material with minus-$\frac{3}{4}$-in. to plus-$\frac{1}{2}$-in. material.

The use of $\frac{3}{4}$-in. maximum-sized aggregate makes it very laborious and difficult to level the mixture at the top of the mold. To eliminate this difficulty we proceed as follows: (1) The sample is compacted in the usual manner, taking special care not to finish too high on the last layer. (2) The surface of the last layer is thoroughly brushed to remove all loose material and mold and material are weighed. (3) The unfilled portion of the mold extension (which is fitted positively and solidly) is then measured either with standardized sand or mercury. (4) From the volume of the mold plus extension and their unfilled volume the volume of the sample is determined.

We are planning on presenting a paper at the next annual meeting of the Highway Research Board in which this method will be described in detail.