Degradation Control of Crushed Stone Base Course Mixes During Laboratory Compaction

J. M. HOOVER, Engineering Research Institute, Iowa State University;
SUBODH KUMAR, Iowa State Highway Commission; and
T. W. BEST, U. S. Army Corps of Engineers

Laboratory compaction of crushed stone base course mixes often results in a degradation of the larger particle sizes and a consequent change in sample gradation. The purpose of this study was to determine a laboratory compaction procedure producing uniform densification at optimum moisture content, while eliminating degradation and segregation of three crushed stone base mixes, each mix being representative of poor to good field service records.

Laboratory procedures analyzed were (a) standard AASHO-ASTM compaction, (b) static compaction, (c) drop hammer compaction, (d) vibratory compaction, and (e) modified AASHO-ASTM compaction. Results indicated that vibratory compaction reproduced standard AASHO-ASTM density and optimum moisture content of the stones while eliminating degradation and segregation. Compaction by vibration reduced degradation, with little or no visual segregation, at modified AASHO-ASTM density and moisture content. Vibratory compaction, however, was found to require a particular combination of frequency, amplitude, surcharge weight, and duration of vibration time. With the poor service record stone, gravel size content was reduced by an average of nearly 7 percent under standard compaction, over 13 percent under static compaction, and intermediate reductions by the two other procedures. With other than vibratory compaction, the good service record stones also showed significant gradation changes.

•LABORATORY COMPACTION of granular base course mixes frequently produces a change in gradation of particle sizes resulting from degradation or crushing of the larger particles during the compaction process. The purpose of this study was to ascertain a laboratory compaction procedure that would produce uniform, controllable density at optimum moisture content, while eliminating or at least minimizing degradation and segregation of compacted crushed stone base course mixes. Laboratory procedures analyzed were as follows:

1. Standard AASHO-ASTM compaction;
2. Static compaction;
3. Drop hammer compaction (i.e., molding a whole, unlayered specimen by drop-hammering on both top and bottom);
4. Vibratory compaction; and
5. Modified AASHO-ASTM compaction.

Paper sponsored by Committee on Compaction.

TABLE 1

MINERAL CONSTITUENTS OF CRUSHED STONE BY X-RAY DIFFRACTION

Stone	Calcite	Dolomite	Quartz	Feldspars	Calcite/Dolomite Ratio
Bedford	1	3	T	0	25.00
Garner	1	2	T	0	1.16
Gilmore	1	0	T	0	

Note: 1, predominant; 2, major amounts; 3, small amounts; T, trace; 0, not identified.

TABLE 2

NON-HCl SOLUBLE MINERALS BY X-RAY DIFFRACTION

Stone	Montmorillonite	Vermiculitechlorite	Micaceous Material	Kaolinite	Quartz
Bedford	0	0	1	2	2
Garner	0	3	1	2	2
Gilmore	0	0	0	1	3

Note: 1, predominant; 2, major amounts; 3, small amounts; 0, not identified.

MATERIALS

Three crushed stone materials were used in this study, each crushed stone being approved by the Iowa State Highway Commission for rolled stone bases and being representative of poor to good field service records. The three stones tested included Bedford quarry stone, a weathered, moderately hard limestone; Gilmore quarry stone, a hard limestone; and Garner quarry stone, a hard dolomite. Mineralogical and chemical tests of the three stones are given in Tables 1, 2, and 3. Engineering properties of each material are given in Table 4. Standard and modified AASHO-ASTM moisture-density curves are shown in Figure 1.

In addition to the physical property tests noted in Table 4, porosities (i.e., percentage relationship of void volume to total volume) of duplicate ½-in. diameter by 1½-in. high cylindrical cores and ¾-in. crusher-run particles were determined by the gas pycnometer method. Quantitatively, the porosity of the Bedford stone was slightly over 32 percent, whereas the Garner and Gilmore stones were about 10 and 12 percent respectively. The difference in porosities between the Bedford sample and the Garner and Gilmore samples is considered significant. Because the Bedford quarry stone was the least hard of the three materials and had been shown in the field to be representative of the least stability, it was used as the major sample in this study.

TABLE 3

QUANTITATIVE CHEMICAL ANALYSIS OF WHOLE MATERIAL

Stone	pH	Cation Exchange Capacity (meq/100 grams)	Non-HCl Soluble Minerals (percent)
Bedford	9.40	10.88	10.92
Garner	9.25	10.60	6.73
Gilmore	8.99	5.86	<1.66

TABLE 4

ENGINEERING PROPERTIES OF CRUSHED STONES

Category	Bedford	Garner	Gilmore
Textural composition, percent			
Gravel, >2.00 mm[a]	73.2	61.6	66.8
Sand, 2.00 to 0.074 mm	12.9	26.0	23.3
Silt, 0.074 to 0.005 mm	8.4	10.2	5.9
Clay, <0.005 mm	5.5	2.2	4.0
Colloids, <0.0001 mm	1.7	1.4	0.9
Atterberg limits, percent			
Liquid limit	20.0	Non-plastic	Non-plastic
Plastic limit	18.0		
Plasticity index	2.0		
Standard AASHO-ASTM			
Optimum moisture content, percent dry soil weight	10.9	7.6	9.4
Dry density, pcf	127.4	140.5	130.8
Modified AASHO-ASTM			
Optimum moisture content, percent dry soil weight	8.0	5.4	5.7
Dry density, pcf	133.5	147.6	140.8
Specific gravity of minus-No. 10 sieve fraction	2.73	2.83	2.76
Textural classification	— Gravelly, sandy loam —		
AASHO classification	A-1-b	A-1-a	A-1-a

[a]Each stone was of ¾-in. maximum particle size.

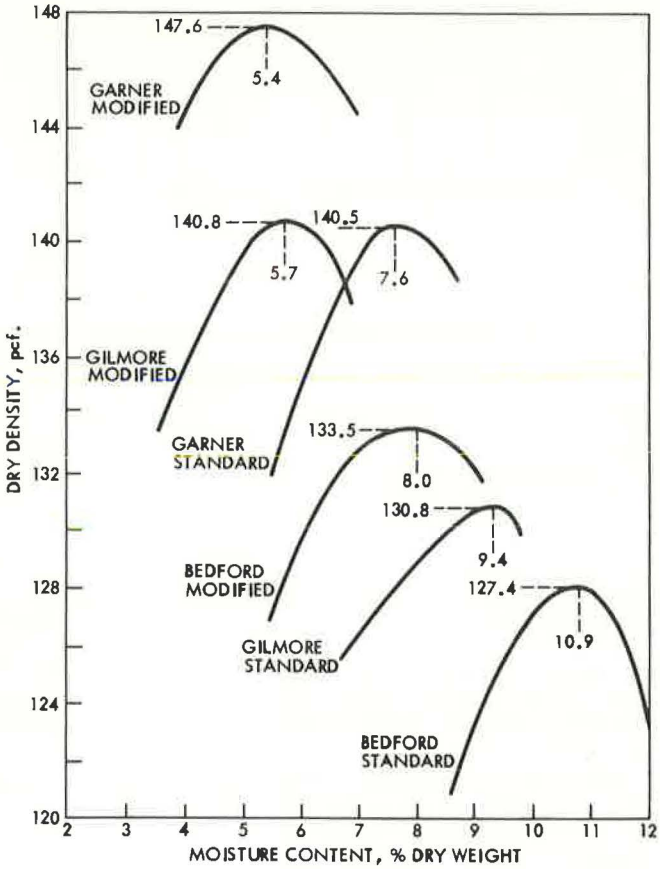

Figure 1. Standard and modified AASHO-ASTM moisture-density relationships of crushed stones.

RESULTS OF TESTING

Standard AASHO-ASTM Compaction

Triplicate representative samples of the Bedford material were divided into six equal portions, each portion being large enough to produce one standard density specimen. The first portion was set aside, uncompacted, to be used as the control sample for comparison by mechanical analysis. Increasing increments of distilled water were added to each of the remaining portions to produce one point on the moisture-density

TABLE 5

SUMMARY OF STANDARD AASHO-ASTM MOISTURE-DENSITY STUDIES

Sample	Optimum Moisture Content, Percent Dry Soil Weight	Dry Density (pcf)
A	10.4	126.9
B	10.8	128.2
C	11.5	127.1
Average	10.9	127.4

TABLE 6

COMPARISON OF AVERAGE PERCENTAGE OF PARTICLE SIZE FRACTIONS BEFORE AND AFTER AASHO-ASTM STANDARD COMPACTION

AASHO-ASTM Particle Size	Percent of Total Dry Sample	
	Control	Compacted
Gravel	73.2	66.3
Sand	12.9	14.6
Silt	8.4	12.2
Clay	5.5	6.9
Colloids	1.7	1.8

curve. Mixing was accomplished by hand to minimize degradation during mixing. Following compaction, each specimen was weighed, extruded, and examined for visual segregation. Duplicate moisture samples were then removed from each specimen and the remainder was retained for mechanical analysis.

Results of standard AASHO-ASTM moisture-density studies, Method C of ASTM Designation D 698-64T and AASHO Designation T99-61 (1), are given in Table 5. Little visual segregation was noted in the specimens. Density and moisture content variation was within normally accepted limits for each sample.

Table 6 gives a comparison of the average percentage of particle size classifications before and after the standard moisture-density test. The control values are the average of triplicate specimens. The compacted values are the average of all compacted specimens. The gravel portion is reduced nearly 7 percent while the fines content (i.e., minus-No. 200 sieve fraction) is increased more than 5 percent following compaction by this method.

In the three replications of the procedure, for the specimens compacted at less than standard optimum moisture content, the data indicated additional decreases in the percentage of gravel and a corresponding increase in fines from the average values given in Table 6. Above standard optimum moisture content, the samples showed little additional change in degradation from the averages given in Table 6, thus indicating the lubricative effect of the water.

Static Compaction

In this procedure, compaction of the Bedford material was accomplished by application of a load to the top of the sample in a $\frac{1}{30}$ cu ft standard AASHO-ASTM mold. The procedure was as follows:

1. Sufficient material, hand-mixed to optimum moisture content (10.9 percent) for maximum standard density (127.4 pcf) in the $\frac{1}{30}$ cu ft mold, was weighed, placed in the mold, and rodded full depth 25 times with a 0.5-in. diameter rod tapered to a dull, rounded point.
2. A 2,000-lb load was transmitted to the top of the specimen through a steel piston, with an outside diameter slightly under the 4-in. inside diameter of the mold, until the height of the sample was 4.56 in.
3. Triplicate specimens were produced for rates of loading of 0.064, 0.208, and 0.304 in./min until the 2,000-lb maximum load was reached.
4. Triplicate specimens were also produced for times of maximum load-holding of 1, 2, and 5 min.

TABLE 7

EFFECT OF STATIC COMPACTION VARIABLES ON PARTICLE SIZE DEGRADATION

Compaction Condition	Average Dry Density (pcf)	Average Moisture Content, Percent Dry Soil Weight	Average AASHO-ASTM Particle Size, Percent of Total Dry Sample				
			Gravel	Sand	Silt	Clay	Colloids
None-uncompacted (control)	—	—	75.7	9.7	9.6	5.0	1.1
0.064 in./min rate, 1 min holding time	129.0	8.9	62.5	17.7	13.3	6.5	2.9
0.064 in./min rate, 2 min holding time	129.0	8.9	63.5	17.7	12.2	6.6	2.4
0.064 in./min rate, 5 min holding time	129.1	8.6	60.7	18.2	13.8	7.3	2.7
0.208 in./min rate, 1 min holding time	128.0	9.6	61.3	18.2	13.4	7.1	2.4
0.208 in./min rate, 2 min holding time	128.2	9.5	60.7	19.5	12.3	7.5	2.6
0.208 in./min rate, 5 min holding time	128.1	9.8	63.2	16.4	12.8	7.6	2.4
0.304 in./min rate, 1 min holding time	128.4	9.6	62.9	18.4	11.2	8.0	2.2
0.304 in./min rate, 2 min holding time	128.4	9.7	62.5	16.9	13.6	7.0	2.5
0.304 in./min rate, 5 min holding time	128.5	9.4	62.2	17.8	13.2	6.8	2.5

TABLE 8

EFFECT OF STATIC COMPACTION ON DEGRADATION

Compaction Condition	Average AASHO-ASTM Particle Size, Percent of Total Dry Sample				
	Gravel	Sand	Silt	Clay	Colloids
None-uncompacted (control)	75.7	9.7	9.6	5.0	1.1
Static load of one ton on 1/30 cu ft sample	62.1	17.9	12.9	7.1	2.5
Average[a]	-13.6	+8.2	+3.3	+2.1	+1.4

[a]Variation of compaction from control.

Following compaction, each specimen was weighed, extruded, and examined for visual segregation. Duplicate moisture samples were then removed from each specimen and the remainder of the specimen was retained for mechanical analysis.

Segregation of particles was visually obvious in almost all of the statically compacted specimens. No correlation of segregation could be related to the compaction variables because of considerable variation of segregation of the samples within any one compaction condition. In each specimen, water and some fines tended to ooze from around the piston and the bottom of the mold, thus reducing the moisture content from an initial average of 10.9 percent to as low as 8.6 percent (Table 7). Average dry density increased from 0.6 to 1.7 pcf above that obtained by standard AASHO-ASTM compaction. However, the general variation of obtained density and moisture content by this procedure was within acceptable limits. (Acceptable limits were assumed to be about ± 1.0 percent moisture and ± 3.0 pcf density, similar to that discussed in ASTM Designation D 560-57.

As noted in Table 7, no major effect on degradation was attributable to the variation in loading rates or load-holding times. It is obvious, however, that sizeable reduction occurred in the percentage of gravel, and sizeable increases occurred in all other particle size classes. Table 8 gives the effects of static compaction on degradation.

Drop Hammer Compaction

Some laboratory strength tests utilize specimens having a height to diameter ratio of 2 to 1. It was therefore considered advisable to ascertain the segregation and degradation effects on 4-in. diameter by 8-in. high, cylindrical Bedford samples compacted similarly to that shown in ASTM Method D 1632-63, Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory. The procedure adopted was as follows:

1. Sufficient material, hand-mixed to optimum moisture content (10.9 percent) for maximum standard density (127.4 pcf) in the 4-in. diameter by 8-in. high mold, was weighed, placed in the mold, and rodded down from the top until it was refused.

2. A separating disk was placed on top of the specimen, and compaction was accomplished by dropping a 15-lb hammer (shown in ASTM Method D 1632-63) a height of 12 in.

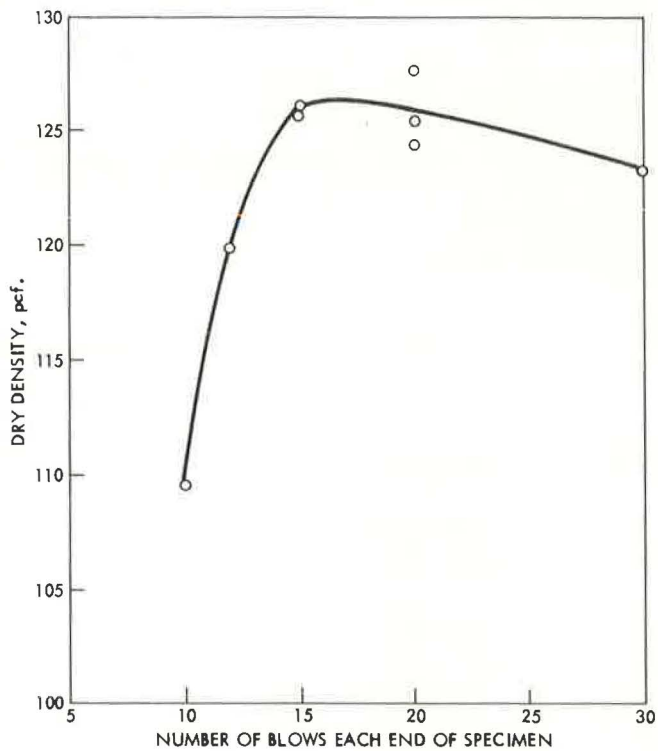

Figure 2. Relationship between dry density and number of blows on each end of specimen—drop hammer compaction.

3. The mold was then inverted and the drop hammer was again used.
4. To obtain the proper relationship between standard density and the number of blows of the hammer, a series of cylinders were molded using 10, 12, 15, 20, and 30 hammer blows on each end of the specimen.

Following compaction, each specimen was measured for height, weighed, extruded, and examined for visual segregation. Slight segregation of the fines was noticeable at each end of the specimens. Duplicate moisture samples were then removed from each specimen and the remainder was retained for mechanical analysis.

Figure 2 shows the relationship between dry density and the number of blows on each end of the specimen. Data shown in the figure represent a minimum of three specimens at each of the designated number of blows. The standard dry density could be reasonably reproduced using 15 blows of the hammer on each end of the specimen. At 20 blows the density was much less reproducible. Variation of moisture content following compaction from the initial mix content of 10.9 percent was very slight with all specimens.

Figure 3 shows the average variation of percentage of particle size in relationship to the number of blows on each end of the specimen. Maximum degradation occurred at 15 blows of the hammer; there was almost 12 percent reduction in amount of gravel with distributed increases in the other size fractions between 10 and 15 blows on each end of the specimen.

The moisture content of each specimen point in Figures 2 and 3, both before and after molding, showed very little variation. There appears to be no reasonable correlation between amount of degradation and number of blows because of lack of variation in moisture content. Because the degradation is shown to be less at 20 and 30 blows than at 15 blows, but still greater than at 10 blows, it may be that the higher numbers of blows cause a state of packing of particles that tends to inhibit increased degradation. Such might be further assumed because of the slight reduction of density from 15 to 20 to 30 blows as shown in Figure 2. Thus, there appears to be only a sketchy correlation between degradation, number of blows, and density—a correlation that countermands logical inter-

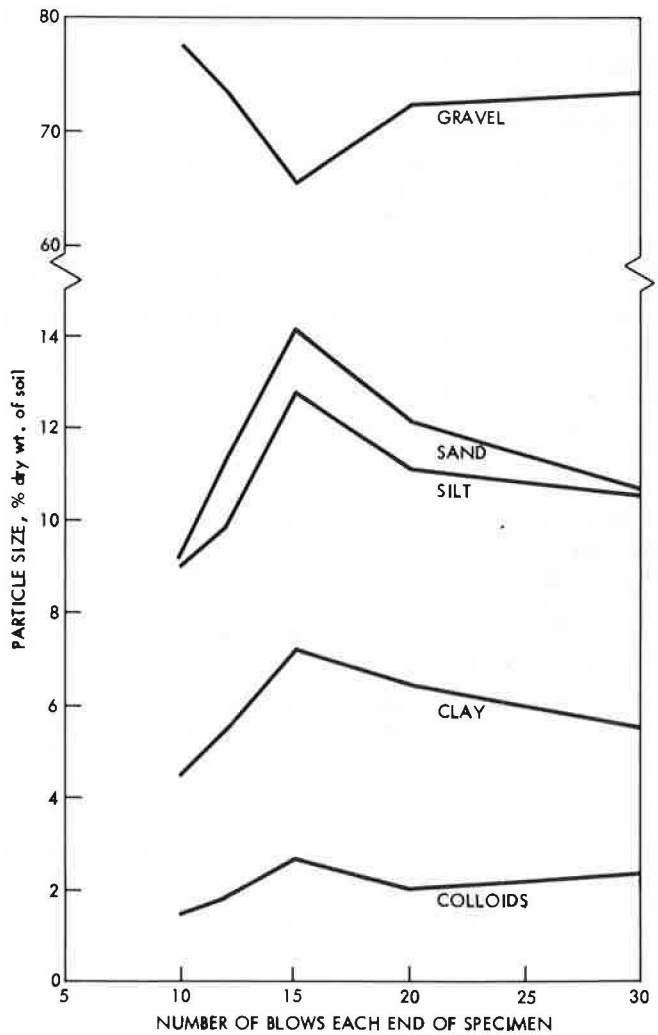

Figure 3. Particle size variation with number of blows on each end of specimen—drop hammer compaction.

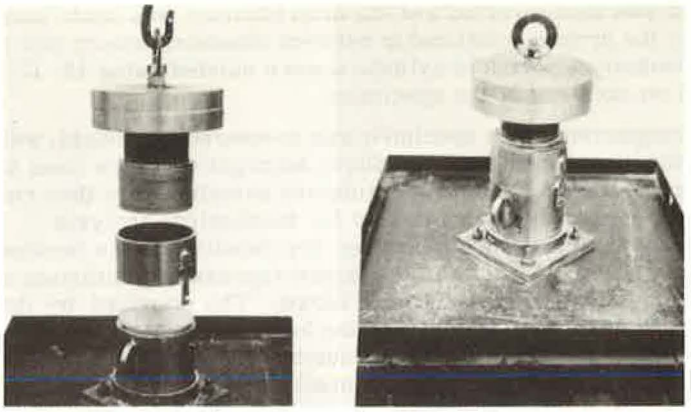

Figure 4. Vibratory compaction apparatus.

pretations that degradation should increase with increasing number of blows.

Vibration Compaction

In the three preceding sections, state of compaction relies on either pounding or pushing the particles into an intimate arrangement. Vibratory compaction relies heavily on the proper combinations of frequency, amplitude, amount of time of vibration, and amount of surcharge weight on top of the specimen to produce the desired state of densification. In this phase of compaction, the following procedure was used:

1. Sufficient Bedford material, hand-mixed to optimum moisture content (10.9 percent) for maximum standard density (127.4 pcf) in a specially built $\frac{1}{30}$ cu ft Proctor mold for attachment to the vibratory table (Fig. 4), was weighed, placed in the mold, and rodded until it was refused.
2. A weight was placed on top of the specimen and vibrated under the conditions noted in the following.
3. The weight was then removed and the specimen was measured for height.

After the mold was removed from the table, each specimen was weighed, extruded, and examined for visual segregation. Duplicate moisture content samples were removed from each specimen and the remainder was retained for mechanical analysis.

Frequency of vibration of each specimen was held constant at 3,600 cpm (cycles per minute) on the electric vibrator table. Duplicate specimens were produced for each of the following variables:

1. Vibration periods of $\frac{1}{2}$, 1, and 2 min;
2. Surcharge weights of 15, 25, and 35 lb; and
3. Three settings of the amplitude dial, each causing a charge of amplitude under the three weights as given in Table 9.

TABLE 9

RELATIONSHIP BETWEEN MEASURED AMPLITUDE AND SURCHARGE WEIGHT—VIBRATORY COMPACTOR

Surcharge Weight (lb)	Amplitude Control Dial Setting	Measured Amplitude of Vibration (mm)
15	10	0.764
	50	0.863
	90	0.915
25	10	0.332
	50	0.705
	90	0.551
35	10	0.330
	50	0.320
	90	0.368

Amplitudes were measured by gluing a fine thread to the edge of the vibrator table, stopping the visible motion of the thread with a stroboscope light beam, and measuring the vertical displacement of the thread with a cathetometer. A minimum of three such readings yielded the average values given in Table 9. An appreciable increase amplitude was noted for dial setting of 50, surcharge weight being 25 lb. This occurrance remained unexplained following additional measurements.

Table 10 gives the effect of the vibratory compaction variables on particle size degradation. The major vibratory compaction variable was the surcharge weight on top of the specimen, the greatest amount of degradation occurring with the 15-lb weight. Little or no degradation appeared with the combination of 35 lb of surcharge weight, amplitude control dial setting of 90 (0.368 mm of amplitude), and 2 min vibration time.

TABLE 10

EFFECT OF VIBRATORY COMPACTION VARIABLES ON PARTICLE SIZE DEGRADATION

Vibratory Compaction Variable	Average AASHO-ASTM Particle Size, Percent of Dry Sample				
	Gravel	Sand	Silt	Clay	Colloids
Surcharge weight (lb)					
15	66.4	16.2	11.4	6.0	1.8
25	70.0	14.6	10.1	5.3	1.6
35	73.2	12.2	9.5	5.1	1.6
Amplitude control dial setting					
10	69.1	14.8	10.5	5.6	1.7
50	69.1	14.4	10.6	5.9	1.7
90	71.5	13.4	10.0	5.1	1.6
Time (min)					
½	70.3	13.9	10.2	5.6	1.7
1	68.9	14.9	10.6	5.6	1.6
2	70.4	14.2	10.1	5.3	1.6
None-uncompacted (control)	73.2	12.9	8.4	5.5	1.7

Segregation was visually noted to vary primarily in relationship to surcharge weight. The 15-lb surcharge specimens were segregated throughout, but segregation became slightly more pronounced at the top of the specimen immediately under the weight. A thick slurry of water and fines oozed out of the specimen around the 15-lb surcharge and apparently caused the more pronounced effect of segregation of the larger particles at the top of the specimen. At the opposite extreme, the 35-lb surcharged specimens were quite uniform in their appearance with no visual segregation.

Following compaction, moisture content and density also appeared to vary in relation to surcharge weight. The 15-lb surcharged specimens varied from near 100 percent to as low as 87.7 percent of the average initial mixing moisture content. Density of these specimens also varied from 88.9 percent to almost 100 percent of the average AASHO-ASTM standard previously noted. The 35-lb surcharged specimens produced much more controllable density, averaging 97.3 percent of the standard. Likewise, the moisture content, following compaction, averaged 96.8 percent of the initial mixing moisture.

The optimum combination of variables of a surcharge weight of 35 lb, a dial setting of 90, and a vibration time of 2 min was also applied to a special mold for vibratory compaction of 4-in. diameter by 8-in. high cylinders. Degradation was again found to range from none to minimal. Visual segregation was found to be nonexistent, with a few exceptions where the samples had not been properly obtained from the bins and quartered. Moisture content following molding was consistently 97 percent of the standard 10.9 percent initial mixing moisture content. Density was consistently reproducible within less than 1.0 pcf but averaged about 2.0 pcf below standard.

Garner and Gilmore Samples

As previously noted, the Bedford sample was the least hard of the three materials and has been shown in the field to be representative of the least stability. It was used as the major sample of the compaction study. Only standard AASHO-ASTM and vibratory compaction procedures were compared using the Garner and Gilmore samples.

The results followed the same general trends as with the Bedford sample with the following exceptions:

1. Degradation of the Garner and Gilmore materials under standard AASHO-ASTM compaction was not as pronounced as with the Bedford sample; i.e., a maximum of about 4 percent decrease by dry soil weight in the gravel fraction with almost double this amount in the Bedford.
2. Little or no visual segregation occurred in any of the vibrated Garner samples.
3. Some slight segregation was noticeable in the 51-lb surcharged Gilmore samples.
4. Because of the lower quantity of fines and lack of plasticity (Table 4) in the Gilmore sample, it was difficult to handle the extruded specimens, several of them falling apart when handled.

TABLE 11

MECHANICAL ANALYSIS OF COMPACTED CRUSHED STONE SPECIMENS

Stone	Percent of Total				
	Gravel	Sand	Silt	Clay	Colloids
Bedford					
Uncompacted	73.2	12.9	8.4	5.5	1.7
Modified AASHO-ASTM	65.8	15.0	11.8	7.4	1.9
Modified vibratory	68.8	14.6	10.2	6.4	2.0
Garner					
Uncompacted	61.6	26.0	10.2	2.2	1.4
Modified AASHO-ASTM	55.7	29.8	11.4	3.1	1.8
Modified vibratory	58.3	28.0	11.0	3.0	1.5
Gilmore					
Uncompacted	66.8	23.3	5.9	4.0	0.9
Modified AASHO-ASTM	62.0	26.2	7.4	4.6	1.6
Modified vibratory	64.3	24.8	6.9	4.0	1.4

5. With each vibratory compaction variable, the density of the Garner and Gilmore specimens were near or above standard AASHO-ASTM values (Table 4). The 35-lb surcharged samples showed more uniform, controllable densities and were consistently 3 to 4 pcf above the standard. Moisture content following compaction was consistently lower than mix content, as with the Bedford sample, even though the moisture content was still within the acceptable limits previously noted.

Modified AASHO-ASTM Compaction

Modified Proctor density for each of the three crushed limestones was first determined in accordance with ASTM Designation D 1557-64 and AASHO Designation T180-61, Method C (1). Following compaction, each specimen was weighed, extruded by hydraulic jack, and visually examined for segregation. After moisture content samples were removed, the remainder of each specimen was retained for mechanical analysis in order to determine the amount of degradation occurring during compaction. Results of the moisture-density relationships are shown in Figure 1.

To determine the combination of factors necessary for vibratory compaction to modified Proctor density, with as little degradation and segregation as possible, the relationship between density and surcharge weight was investigated in a manner similar to that noted previously for 4-in. diameter by 8-in. high cylinders.

Average results of the mechanical analyses performed on specimens uncompacted, modified AASHO-ASTM compacted, and modified vibratory compacted are given in Table 11. A surcharge weight of 105 lb (8.35 psi), an amplitude control dial setting of 90, and a vibration time of 2 min produced modified Proctor density while achieving the most desirable degradation-segregation results. Because of the increased surcharge weight, slight degradation was noticeable with vibratory compaction, but was not as pronounced as with the modified AASHO-ASTM compaction process. Initial moisture content greater than modified optimum was required for two of the materials; i.e., 1.1 percent moisture for Bedford, 0.3 percent for Garner, no additional for Gilmore. This increase may be caused, in part, by the relative porosities of the materials.

Little or no visible segregation was evident in the vibratory compacted specimens undergoing up to 2 min of vibration. Beyond this period, a thick slurry of fines and water oozed from both top and bottom of each specimen.

SUMMARY

The purpose of this study was to ascertain a laboratory compaction procedure that would produce uniform, controllable densities at optimum moisture contents, while eliminating or at least minimizing degradation and segregation of compacted crushed stone base course mixes, each being representative of poor to good field service records. The vibratory compaction procedure met the above criteria in the following manner:

1. Standard AASHO-ASTM compacted densities and optimum moisture contents were achieved within reasonable limits, regardless of the type of crushed stone.
2. Modified AASHO-ASTM compacted densities were achieved by vibration with each stone. Optimum moisture contents by vibration ranged from 1.1 percent above the optimum to equal or modified optimum for the softer to harder stones respectively. Because of the heavy surcharge weight, degradation was evident, but less than that of the conventional modified compaction process.

Vibratory compaction, however, was found to require a particular combination of frequency, amplitude, surcharge weight, and duration of vibration time for prevention of

both degradation and segregation. Segregation essentially varied inversely to surcharge weight.

With the poorer service record stone, gravel size content was reduced by an average of nearly 7 percent under standard compaction, over 13 percent under static compaction, and intermediate reduction by both drop-hammering each end of the specimen and the modified compaction. Segregation during compaction, other than vibratory, ranged from none to visually obvious. With other than vibratory compaction, the better service record stones also showed significant gradation changes, with segregation ranging from none to slight.

ACKNOWLEDGMENTS

This research is part of a study of the factors influencing stability of granular base course mixes conducted by the Engineering Research Institute, Iowa State University (2), under the sponsorship of the Iowa Highway Research Board, Iowa State Highway Commission, and the Bureau of Public Roads, U. S. Department of Transportation. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the sponsors of this project.

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