EFFECT OF VARIATIONS IN COARSE-AGGREGATE GRADATION ON PROPERTIES OF PORTLAND CEMENT CONCRETE

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The effect of variations in coarse-aggregate gradation on properties of a highway concrete mixture was studied by testing numerous batches of laboratory-prepared concrete. The water-cement and aggregate-cement ratios were the same for all batches; the only variable was the grading of the natural gravel used as coarse aggregate throughout the investigation. Each batch contained a known coarse-aggregate grading, and the entire group of gradings examined represented the variation determined to occur in typical pavement concrete production. The data were obtained and analyzed in a manner that allowed evaluation of the importance of variations in gradation of natural gravel as a source of variation in slump, compressive strength, and unit weight of field-produced concrete. On the basis of the results obtained in the investigation, typical field variations in coarse-aggregate gradation appear to have a relatively small effect on slump variability compared to the combined effect of other factors, a surprisingly large effect on compressive strength, and little effect on the "compactibility" of a low-slump paving mixture.

•VARIATIONS in coarse-aggregate gradation can be expected to occur on nearly any construction job because of variations in the source material, production, or segregation or degradation or both in the stockpiling operation. The extent of these variations is, of course, partly an economic matter, for close control can be achieved but generally only at greater cost to both the producer and the specifying inspecting agency. Unique gradations are therefore questionable economically and may or may not be better than other gradations.

This paper reports an investigation directed toward determining the quantitative effect of variation in coarse-aggregate gradation on the workability and strength of a highway concrete mixture.

The variation in coarse-aggregate gradation within a given production situation is nothing more than the occurrence of different gradings, within and among batches of concrete, caused by segregation, degradation, or inherent randomness. Though little work has been directed toward the effect of variation specifically, extensive research has been done on the influence of coarse-aggregate gradings on the properties of concrete. These studies provide information from which the qualitative effects of variability can be inferred (1-5).

In 1960 Bloem and Walker (6) dispelled traditional beliefs about strength being unaffected by gradation. They showed that strength is higher for smaller sizes of well-graded aggregates than for larger ones when the cement factor and slump are the same.

Gap gradings have been found to require a lower cement factor for the same workability. Li (5), in a study comparing the workability of mixes with 1½-in. and smaller maximum-sized aggregates, obtained more workable concrete from gap gradings than from continuous gradings, other factors (water-cement ratio, cement content, and maximum size of aggregate) being the same.

The following pertinent deductions can be made from these previous investigations by considering variation as the occurrence of fine, coarse, or gap gradings:

1. Variation in coarse-aggregate gradation causes changes in the workability of concrete, with relatively lower workability resulting from finer gradings (2, 3).
2. Variation causes changes in the compressive strength of concrete, with gradings having smaller maximum sizes increasing in strength (6).
3. Variations in the form of gap gradings may not cause changes in workability if the mix proportions are suitable (5).
4. The cement mortar-coarse aggregate volume ratio affects the sensitivity of the mix to changes in grading (4).

An experiment that parallels this investigation was done by Tynes (7), in which he concluded that mass concrete containing crushed limestone or natural gravel meeting the gradation specification did not show significant differences in compressive strength or workability.

The conclusions made by Tynes were applicable to concrete produced with gradings not exceeding the specification boundaries. The assumption that the extent of gradation variability in highway construction is within typical specification limits has been shown to be invalid by statistical evaluations of concrete aggregates. In a study by Mills and Fletcher (8), 20 percent of the individual sieve analysis results failed to conform to the specification limits.

The variability in some properties of highway concrete, also produced under conditions representative of the highway construction industry, has been measured and is discussed in connection with the results of this investigation.

INVESTIGATION PLAN

The scope of gradation variability investigated was that associated with typical highway concrete production. An estimate of this variability (standard deviation) was obtained from the statistical studies of other investigators and from the authors' statistical analyses of sieve analysis data from the Indiana State Highway Commission (ISHC) aggregate inspectors' test reports. Batches of concrete that contained gradings having percentage passing curves within an envelope representing the estimated gradation variability were mixed in the laboratory and tested for slump, unit weight, compacting factor (3), and compressive strength.

The investigation was limited to a single set of proportions for a six-bag, low-slump mix and to natural gravel from one plant and one pit. Other factors affecting the variability of the concrete were reduced to a practical minimum. Cement from within a continuous run of the source plant and sand from a single stockpile were used throughout the investigation. The aggregates, both fine and coarse, were dried to eliminate the effect of varying moisture content. Though all variation from the many sources could not be totally eliminated, every effort was made to establish coarse-aggregate gradation as the sole variable within a concrete mixture designed to meet the ISHC requirements for slip-form pavement. The particular gradings examined were representative of all gradings within a percentage passing envelope covering the variation occurring in typical highway concrete aggregate.

The laboratory tests performed on each batch were intended to provide data that could be used to evaluate the effect of gradation on properties used to control and measure the quality and uniformity of field-produced concrete and to detect changes in workability. Standard slump, compressive strength, and unit-weight tests were made to evaluate the effect of grading on the commonly measured properties of field-produced concrete. A compacting factor apparatus was used to observe effects of grading on workability that might not be detected by the slump test. Unit-weight or density measurements were also made after vibrating the concrete for 10 and 20 sec. These data, combined with those from the standard rodded unit weight and compacting factor unit-weight tests, permitted evaluation of the effect of grading on compactibility. Those specimens observed to bleed most extremely during vibration were sawed after hardening and visually examined for segregation. The air content of five representative hardened specimens was also determined by microscopic methods in accordance with ASTM Designation C 457.

SELECTION OF THE GRADINGS INVESTIGATED

Statistical evaluations carried out by state highway organizations have identified the magnitude of variation (standard deviation) in coarse-aggregate gradation occurring in paving projects under their jurisdiction (8, 9). The results of such studies were found to be comparable to the standard deviations for percentage passing obtained from statistical analysis of ISHC sieve reports done by the authors. Estimates were established on the basis of the various studies and were used in defining a range of gradings that would be representative of typical gradation variability for natural gravels used in paving concrete. These estimates are as follows:

Sieve Size	Standard Deviation of Percentage Passing
1 in.	3.0
$^3/_4$ in.	8.0
$^1/_2$ in.	9.0
$^3/_8$ in.	8.0
No. 4	2.0
No. 8	1.0

The analysis of ISHC sieve reports also showed the average percentage passing for each sieve to closely approximate the norm of the No. 5 gradation limits specified by the ISHC Standard Specification (10). The term "norm" is used to identify the grading defined by the average percentage passing for each sieve. The estimates were applied to the norm to obtain the $3\hat{\sigma}$ limits shown in Figure 1. The envelope outside the $3\hat{\sigma}$ limits shown in Figure 1 was established as the boundary for the range of gradings to be investigated. Figure 2 shows the continuous gradings of major interest. Figure 3 shows four gradings that typify the variations examined for each sieve. Table 1 gives all 33 gradings examined. As a group, the gradings are representative of variations that occur in natural gravel gradation during production of paving concrete.

The inclusion of continuous gradings having a variation of $\pm 3\sigma$ occurring simultaneously on each sieve is considered conservative. Statistically, the assumption of a normal distribution with regard to the concurrent variation for the series may be extreme, for a binomial distribution might better describe the combinations of individual variation that occur. More practically interpreted, a positive variation on one sieve might more typically be accompanied by negative variation on one or more of the other sieves than by other positive variations. In defense of the possible overestimation, it should be pointed out that a lens of fine or coarse particles within a stockpile could result in the extreme gradings represented by the $\pm 3\sigma$ continuous gradings.

It is noted that the ISHC No. 5 coarse-aggregate gradation envelope is located at approximately the 1.5σ level of the estimated gradation variation. This indicates that approximately 15 percent of sieve analysis test results would be expected to exceed the No. 5 limits, which is comparable to the 20 percent found by Mills and Fletcher (8).

LABORATORY TESTS

The presentation and discussion of results make frequent reference to the fineness index of each coarse-aggregate grading. The index is comparable to the fineness modulus (ASTM Designation C 125) commonly used to describe the relative fineness of fine-aggregate gradings. The fineness index was calculated as $\Sigma r_i/100$, where r_i equals the cumulative percentage retained on the individual sieves in the ISHC No. 5 gradation series, except for the No. 200 sieve. Table 2 gives the calculation of the fineness index for the norm grading. The terms "fine" and "coarse" with regard to grading are relative classifications on the basis of fineness index, finer gradings having lower indexes than coarser gradings. It should also be noted that the surface area of the coarse aggregate is inversely proportional to the fineness index; thus, the finer gradings have more surface area.

The grading numbers used to identify gradings refer to those given in Table 1.

Figure 1. Range of gradings investigated.

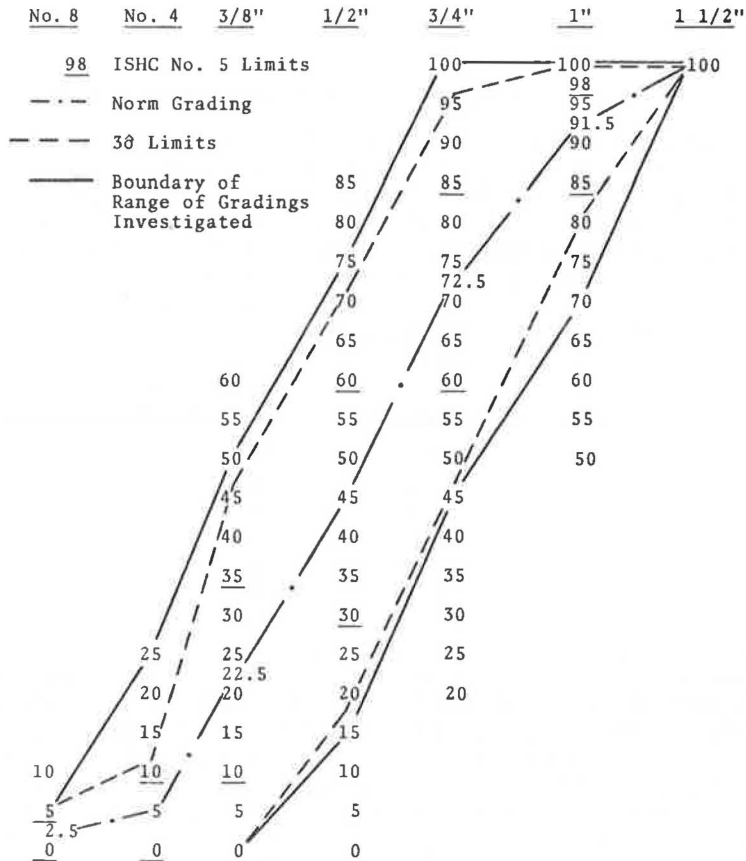

Figure 2. Continuous gradings of major interest.

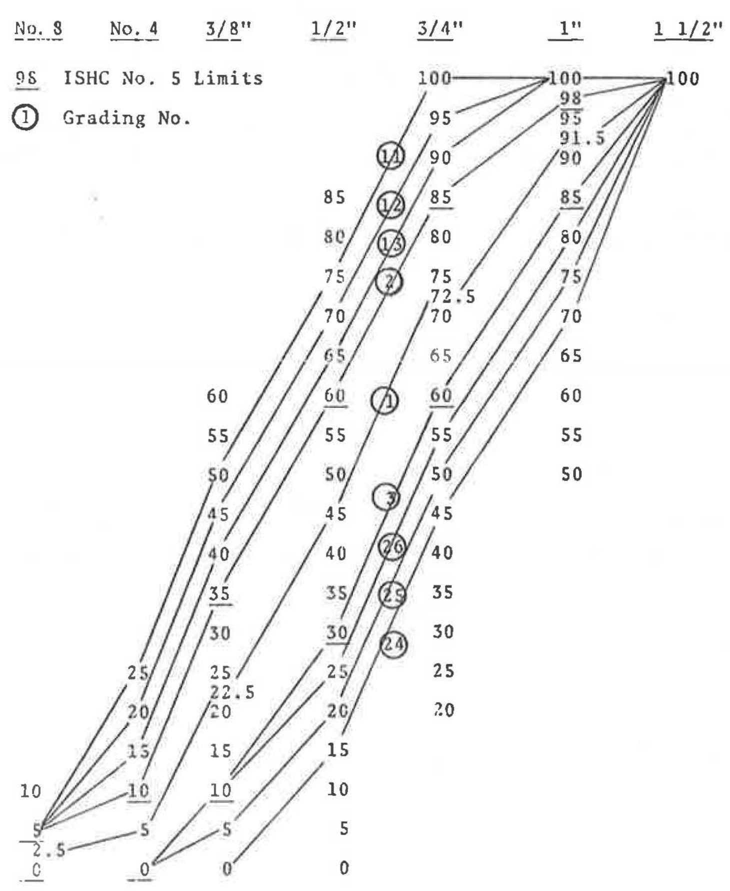

Figure 3. Gradings typifying variations.

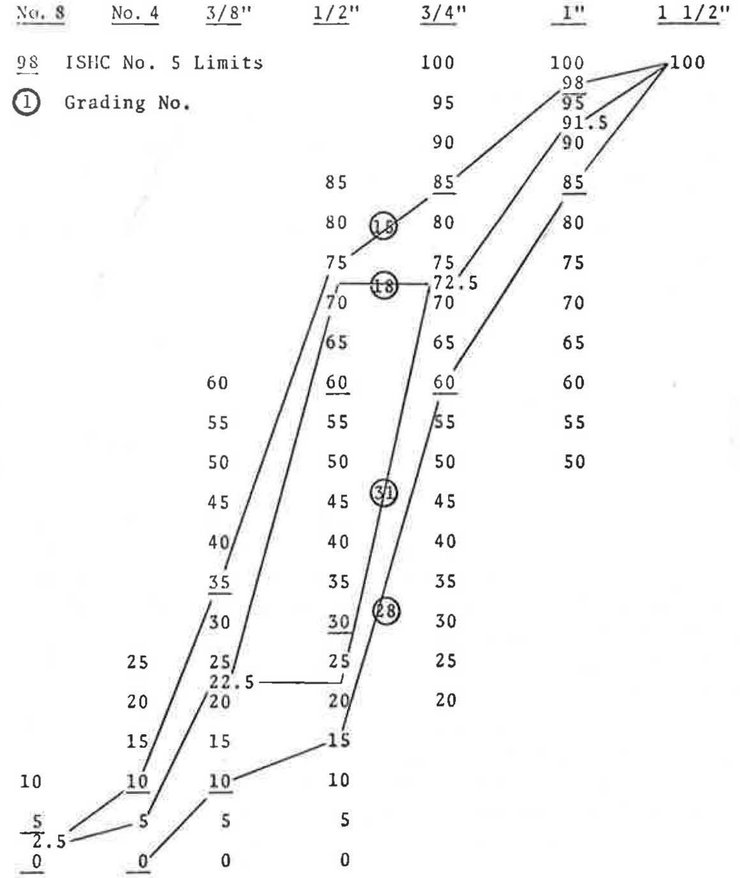

Table 1. Cumulative percentage passing for gradings investigated.

Grading Number	Sieve Size (percent passing)						
	1½ In.	1 In.	¾ In.	½ In.	⅜ In.	No. 4	No. 8
1	100.0	91.5	72.5	45.0	22.5	5.0	2.5
2	100.0	98.0	85.0	60.0	35.0	10.0	2.5
3	100.0	85.0	60.0	30.0	10.0	0.0	0.0
4	100.0	85.0	60.0	60.0	35.0	10.0	2.5
5	100.0	98.0	70.0	30.0	30.0	0.0	0.0
6	100.0	91.5	70.0	30.0	10.0	0.0	0.0
7	100.0	91.5	72.5	45.0	22.5	10.0	2.5
8	100.0	91.5	72.5	45.0	22.5	0.0	0.0
9	100.0	85.0	85.0	30.0	30.0	0.0	0.0
10	100.0	98.0	85.0	60.0	35.0	5.0	2.5
11	100.0	100.0	100.0	75.0	50.0	25.0	5.0
12	100.0	100.0	95.0	70.0	45.0	20.0	5.0
13	100.0	100.0	90.0	65.0	40.0	15.0	5.0
14	100.0	98.0	98.0	60.0	35.0	10.0	2.5
15	100.0	98.0	85.0	75.0	35.0	10.0	2.5
16	100.0	98.0	85.0	60.0	50.0	10.0	2.5
17	100.0	91.5	91.5	45.0	22.5	5.0	2.5
18	100.0	91.5	72.5	72.5	22.5	5.0	2.5
19	100.0	91.5	72.5	45.0	45.0	5.0	2.5
20	100.0	98.0	90.0	70.0	40.0	5.0	2.5
21	100.0	98.0	95.0	60.0	30.0	0.0	0.0
22	100.0	85.0	70.0	70.0	45.0	5.0	2.5
23	100.0	98.0	95.0	85.0	60.0	5.0	2.5
24	100.0	70.0	45.0	15.0	0.0	0.0	0.0
25	100.0	75.0	50.0	20.0	5.0	0.0	0.0
26	100.0	80.0	55.0	25.0	10.0	0.0	0.0
27	100.0	85.0	30.0	30.0	10.0	0.0	0.0
28	100.0	85.0	60.0	15.0	10.0	0.0	0.0
29	100.0	85.0	60.0	30.0	0.0	0.0	0.0
30	100.0	91.5	45.0	45.0	22.5	5.0	2.5
31	100.0	91.5	72.5	22.5	22.5	5.0	0.0
32	100.0	91.5	72.5	45.0	0.0	0.0	0.0
33	100.0	100.0	45.0	45.0	45.0	5.0	2.5

The various components of the variance associated with concrete production are discussed throughout the following sections. The term "overall" as used herein refers to the combination of testing, sampling, and actual variation of the material property being discussed. The term "testing" refers to the combined sampling and testing variation.

The coarse-aggregate gradings taken as a group represent the gradation variability associated with typical paving variations, and the results are often discussed in terms of the effect of gradation variability.

RESULTS OF SLUMP TESTS

The average result for each grading is given in Table 3.

Homogeneity of variance among the test results was accepted after evaluating the data by the Foster-Burr test (11). Analysis of variance No. 1 (ANOV 1) showed the variation in slump, which resulted from the entire set of gradings examined, to be significant (Table 4).

Figure 4 shows the average slump plotted versus the fineness index for each grading examined. The plot suggests a general trend of increased slump over the entire range of gradings. A simple linear regression of slump on fineness index was found to be significant. This is not to say that the relation is best defined as simple linear but rather that finer gradings generally resulted in lower slump.

The following observations were made after examination of the average results for the various gradings:

1. Variation of the smaller sizes of aggregate seemed to have a greater effect on slump than similar variation of larger sizes,
2. The average result for each grading within the ISHC No. 5 limits did not exceed the ½- to 2-in. specification requirement, and
3. Gap gradings did not seem to affect slump differently from continuous gradings having approximately the same fineness index.

The variance σ_g^2 from ANOV 1 (Table 4) provides a quantitative measure of the effect of gradation, a measure that is more meaningful than the individual slump result for each grading. σ_g^2 is the variance in slump caused solely by all gradings examined during the investigation. The entire set of gradings represents the variation in gradation that might occur on typical highway projects, and so σ_g^2 can be considered representative of the variance in slump that results from the variation in gradation in typical highway concrete production. To use σ_g^2 in this manner it is necessary to assume that the batch-to-batch variations were minimized by the laboratory procedures used. ANOV's for other test data that permitted identification of among-batch variation showed batches to be significant, but this should not detract from the understanding that the degree of control maintained on the materials and mixing could not be matched in the field or reduced, to any great extent, by methods other than those used. Thus, σ_g^2 was taken as a maximum variance that could be observed above a practically minimized batch-to-batch variance.

As mentioned previously, the variation in slump for typical highway concrete has been measured. Table 5 gives the standard deviations, s_a, of the slump test results from a study by Hanna, McLaughlin, and Lott (12). The study involved field tests of highway concrete being produced under contract for the ISHC. The testing plan was conducted so as to identify and separate the testing and actual material variation. The portion of the actual material variation that can be attributed to variation in gradation can be calculated (13) as follows: $(\sigma_g^2/s_a^2) \times 100$. In making this calculation the gradation variability represented by the gradings examined in this laboratory investigation is assumed to characterize that same factor in the statistical model for the field studies.

The values of s_a^2 and σ_g^2 are of course estimates, and any comparison of them provides only a means of evaluating the relative importance of coarse-aggregate gradation variability. It should also be reemphasized that σ_g^2 is the result of conservative estimates of the $\pm 3\sigma$ variation in gradation, which would include 99.7 percent of the gradings occurring in typical production. Using the average standard deviation for slump of Indiana projects (12), we derive $(\sigma_g^2/s_a^2) \times 100 = (0.16/0.92) \times 100 = 17$ percent.

Table 2. Calculation of fineness index for norm grading.

Sieve Size	Percentage Passing	Percentage Retained	Cumulative Percentage Retained
1½ in.	100.00	0.00	0.00
1 in.	91.50	8.50	8.50
¾ in.	72.50	19.00	27.50
½ in.	45.00	27.50	55.00
⅜ in.	22.50	22.50	77.50
No. 4	5.00	17.50	95.00
No. 8	2.50	2.50	97.50

Note: Fineness index = 361/100 = 3.61.

Table 3. Average results of slump tests.

Grading Number	Fineness Index	Number of Batches	Average Slump (in.)
1	3.61	7	1.3
2	3.09	2	1.0
3	4.15	2	1.9
4	3.47	1	1.3
5	3.72	1	1.8
6	3.98	1	1.8
7	3.56	1	0.5
8	3.69	3	1.6
9	3.70	1	1.8
10	3.14	2	1.3
11	2.45	3	0.8
12	2.65	1	0.5
13	2.85	3	1.0
14	2.96	3	1.3
15	2.94	3	1.0
16	2.94	3	0.8
17	3.42	3	1.2
18	3.33	3	1.6
19	3.38	1	1.0
20	2.94	2	0.8
21	3.17	1	1.0
22	3.22	1	1.0
23	2.55	1	0.3
24	4.70	3	1.8
25	4.50	1	1.5
26	4.30	3	2.3
27	4.30	3	1.9
28	4.30	3	1.7
29	4.25	3	1.6
30	3.88	2	1.4
31	3.86	2	1.4
32	3.91	3	1.8
33	3.58	1	1.5

Figure 4. Average slump and fineness index for coarse-aggregate grading.

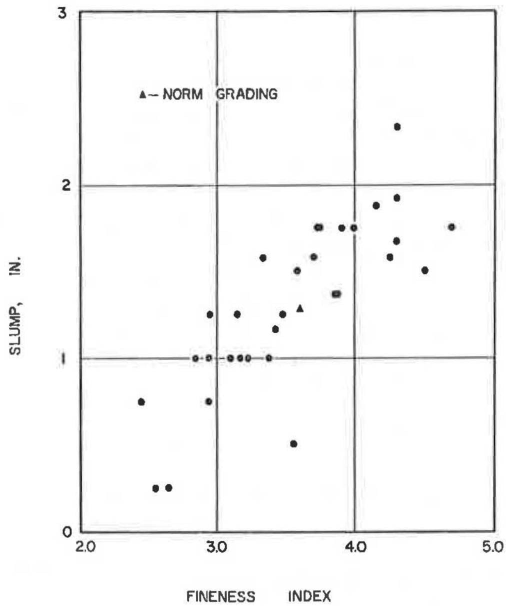

Table 4. ANOV 1 for slump.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	Expected Mean Square	F-Test	F-Test (0.05)
Gradation	32	13.7648	0.4301	$\sigma_t^2 + 2.2\ \sigma_g^2$	5.62[a]	1.73
Error	40	3.0640	0.0766	σ_t^2	—	—

Note: $\sigma_g^2 = 0.16$.

[a]Significant.

Table 6 gives the results of studies by other state agencies, which were reported by Newlon (14) and the Federal Highway Administration (9). The results are for different projects having different types of paving equipment. Though a range in variation would be expected from job to job and state to state, the differences in the reported results are extreme and thus leave in doubt the actual variation one could expect in slump. In a summary statement, Newlon suggested 0.70 in. as an achievable overall standard deviation and 0.50 as desirable. Using these values to evaluate the importance of gradation variation, we derive the following: achievable control, $\sigma_g^2/s_o^2 \times 100 = 33$ percent; and desirable control, $\sigma_g^2/s_o^2 \times 100 = 64$ percent.

The results show that gradation significantly affected slump. This is consistent with accepted principles regarding the relation of gradation and workability. The results further suggest that the combined effect of sources other than coarse-aggregate gradation is the predominate factor in slump variability of paving concrete. For a magnitude of slump variability such as reported by Hanna, McLaughlin, and Lott (12), gradation variability would be of minor importance.

RESULTS OF UNIT-WEIGHT TESTS ON SPECIMENS MADE BY RODDING

The average result for each grading is given in Table 7 along with the fineness index and number of batches.

Homogeneity of variance among the weights for each batch was tested and accepted using the Foster-Burr test. ANOV 2 (Table 8) showed batches to be significant and gradation to be not significant. This indicated either no effect of gradation on unit weight or no identifiable effect because of the significantly high batch-to-batch variance ($\sigma_b^2 = 2.0336$). Relating ANOV 2 to a t-test evaluation, we can use σ_b^2 as an estimate of variance for establishing the observable difference in the mean unit weight of any two gradings. It can be shown that, with three observations (batches) per grading and $\sigma_b^2 = 2.0336$, a difference of approximately 4 lb/ft^3 can be distinguished at a reasonable level of confidence ($\alpha = 0.05$ and $\beta = 0.1$). Thus it can be concluded that the unit weights resulting from all the gradings examined did not differ more than approximately 4 lb/ft^3 or 3 percent. A plot of the average results for each grading is shown in Figure 5.

Hanna, McLaughlin, and Lott (12), in a study cited by Newlon (14), obtained a testing variance of 1.15 lb/ft^3. Comparing this with the testing variance ($\sigma_t^2 = 0.3904$) from ANOV 2, the sampling and testing procedures of this investigation were seen to be relatively good.

The unit weights were determined from weights of fresh concrete compacted in 6- by 12-in. paperboard cylinder molds (ASTM Designation C 470). The size and construction of the container were expected to cause a relatively high testing variance, but the results did not indicate this.

The results are of interest from two aspects: the relation of unit weight or density to air content and strength and the use of unit weight for evaluating uniformity in the yield. The results showed that coarse-aggregate gradation variability did not substantially affect the unit weight of the concrete as measured by the standard testing procedure. The results (Fig. 5) suggest that, if density is affected at all by gradation, it is less so for fine gradings. Thus any effect of density on the strength of the hardened specimens made by rodding should have resulted in lower compressive strength for finer gradings. This result is important to the interpretation of the compressive strengths obtained for these same specimens. The calculated yield of the concrete mix would vary less than 3 percent as a result of the maximum variation (4 lb/ft^3) in unit weight.

The results are discussed further with regard to compactibility in the next section.

RESULTS OF UNIT-WEIGHT TESTS AS A MEASURE OF COMPACTIBILITY

Four different compactive efforts were applied to the concrete for each batch, and unit-weight measurements were made after each effort. The four levels of compactive

Table 5. Variability in slump of field-produced concrete (12).

Site	Material Standard Deviation (in.)	Testing Standard Deviation (in.)
1	1.12	0.48
2	0.75	0.34
3	1.01	0.27
Average	0.96	0.36

Table 6. Variability in slump of pavement concrete.

Cited By	Testing Variance ($in.^2$)	Sampling Variance ($in.^2$)	Material Variance ($in.^2$)	Overall Variance ($in.^2$)
Newlon (14)				0.25
				0.64
				0.36
				0.16
				0.14
				0.27
				0.90
				0.64
	0.10			
FHWA (9)	0.16	0.04	0.26	0.46
	0.13	0.02	0.45	0.64
	0.25	0.09	0.46	0.79
	0.07	0.00	0.15	0.22
	0.08	0.02	0.42	0.53
	0.03	0.03	0.14	0.21
	0.08	0.09	0.20	0.38
	0.16	0.05	0.50	0.71

Figure 5. Average unit weight and fineness index for coarse-aggregate grading.

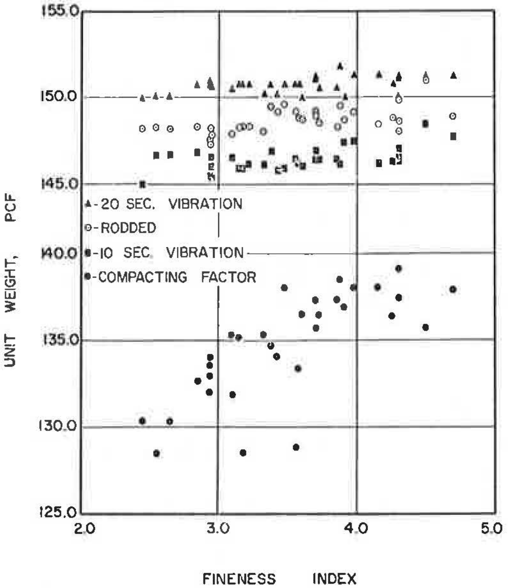

Table 7. Average results of unit-weight tests on rodded specimens.

Grading Number	Fineness Index	Number of Tests	Number of Batches	Average Unit Weight (lb/ft^3)
1	3.61	14	7	148.72
2	3.09	4	2	147.89
3	4.15	4	2	148.47
4	3.47	2	1	149.62
5	3.72	2	1	148.60
6	3.98	2	1	149.23
7	3.56	2	1	148.23
8	3.69	6	3	148.90
9	3.70	2	1	149.24
10	3.14	4	2	148.28
11	2.45	6	3	148.22
12	2.65	2	1	148.21
13	2.86	6	3	148.34
14	2.96	6	3	147.87
15	2.94	6	3	147.36
16	2.94	6	3	147.62
17	3.42	6	3	149.15
18	3.33	6	3	148.05
19	3.38	2	1	149.49
20	2.94	4	2	148.21
21	3.17	2	1	148.34
22	3.22	2	1	148.34
23	2.55	2	1	148.34
24	4.70	6	3	148.04
25	4.50	2	1	150.02
26	4.30	6	3	148.00
27	4.30	6	3	149.87
28	4.30	6	3	148.64
29	4.25	6	3	148.81
30	3.88	4	2	149.55
31	3.86	4	2	148.21
32	3.91	6	3	148.72
33	3.58	2	1	148.85

effort were (a) dropping through a compacting factor apparatus in accordance with British Standard 1881, (b) 10 sec of vibration with a poker vibrator, (c) rodding in accordance with ASTM Designation C 192, and (d) 20 sec of vibration with a poker vibrator.

The average unit weight resulting from each compactive effort and grading is given in Table 9 and shown in Figure 5. The ANOV's for the results of each compactive effort are given in Table 8 and Tables 10 through 12. The results are discussed in terms of the curves or lines that are defined by the sets of data points shown in Figure 5. (The discussion refers to the slopes of the curves with the knowledge that they may well be curvilinear.)

ANOV's 2, 3, and 4 for the last three compacting efforts previously given show grading to be not significant. This indicates that the slopes of the upper three lines shown in Figure 5 are not significantly different from zero (if a linear relation is assumed) or, as explained for the rodding effort, the differences in unit weight are so minimal as to be indistinguishable. The slope of the lower line is seen by ANOV 5 to be significantly greater than zero.

The lower curve shows grading to have affected the workability or compactibility of the mix. The lower unit weights obtained for the finer gradings indicate more difficulty in densifying or compacting the specimens having finer gradings. This may be attributed to the increased water demand imposed by finer gradings, resulting in a harsher mix.

The effect of grading on compactibility is seen to be inconsequential for compacting efforts greater than 10 sec of vibration as indicated by the zero slopes or insignificant differences in unit weights for the upper three curves.

The slopes of the curves for compaction efforts between the compacting factor and 10 sec of vibration would be expected to move from positive to zero. The minimum compactive effort above which the effect of grading is inconsequential is left undefined.

A conclusion as to the importance of gradation variability with regard to compactibility of field-produced concrete rests with one's opinion as to the similarity of field vibration and that used in the laboratory. In the opinion of the authors, the 10 sec of vibration applied to the specimen 6 in. in diameter and 12 in. in length is a reasonable representation of field vibration. It is observably less than rodding and also substantially less than 20 sec of vibration. It must be recognized that the test was conducted with a particular electric vibrator (¾-in. diameter spud) representative of what might be used on small sections in the field. The results would no doubt have different values if another vibrator, differing in size and performance, had been used.

RESULTS OF AIR-CONTENT TESTS

The results of air-content tests on five hardened specimens are given in Table 13. The average for the two finer gradings appears to be higher than for the two coarser gradings, and a trend of increased air content from coarser to finer gradings is seen. Though these observations cannot be statistically substantiated, the results agree in concept with the rodded unit-weight results. The finer gradings appear to have resulted in slightly lower unit weights, which would be indicative of higher air content.

Thus, the results of the air-content tests are taken as further evidence that any reduction in strength from lower density would be expected in specimens having fine gradings rather than those having coarse ones.

Several hardened concrete cylinders, which were observed to have bled during vibration, were sawed longitudinally and examined for segregation, none of which had any extreme settling of coarse particles.

RESULTS OF 7-DAY COMPRESSIVE STRENGTH TESTS ON CYLINDERS COMPACTED BY RODDING

The average result for each grading is given in Table 14 along with the fineness index.

Homogeneity of variance among the test results was accepted after evaluating the data by the Foster-Burr test. ANOV 6 (Table 15) showed the variation in compressive strength, which resulted from the entire set of gradings examined, to be significant.

Table 8. ANOV 2 for unit weight of rodded specimens.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Test	F-Test (0.05)
Gradation	32	70.9835	2.2182	1.09	1.73
Batches	40	81.3452	2.0336	5.21[a]	1.58
Error	73	28.5000	0.3904	—	—

[a]Significant.

Table 9. Average results of unit-weight tests.

Grading Number	Fineness Index	20-Second Vibration (lb/ft^3)	Rodded Unit Weight (lb/ft^3)	10-Second Vibration (lb/ft^3)	Compacting Factor (lb/ft^3)
1	3.61	149.96	148.72	146.03	136.55
2	3.09	150.51	147.89	146.56	135.33
3	4.15	151.28	148.47	146.17	138.01
4	3.47	150.76	149.62	145.92	138.01
5	3.72	150.51	148.60	146.43	136.48
6	3.98	151.28	149.23	147.45	138.01
7	3.56	150.76	149.23	146.43	128.83
8	3.69	151.19	148.89	146.43	137.32
9	3.70	151.02	149.23	146.94	135.71
10	3.14	150.76	148.28	145.92	135.20
11	2.45	149.91	148.21	144.98	130.36
12	2.65	150.00	148.21	146.68	130.36
13	2.85	150.76	148.34	146.85	132.65
14	2.96	150.59	147.87	145.41	134.01
15	2.94	150.68	147.36	146.00	133.67
16	2.94	150.93	147.62	145.58	133.00
17	3.42	150.08	149.15	145.83	134.01
18	3.33	150.17	148.05	145.15	135.37
19	3.38	150.76	149.49	146.94	134.69
20	2.94	150.76	148.21	146.68	132.01
21	3.17	150.76	148.34	145.92	128.57
22	3.22	150.76	148.34	146.17	131.89
23	2.55	150.00	148.34	146.68	128.57
24	4.70	151.19	148.94	147.70	137.92
25	4.50	151.27	151.02	148.47	135.71
26	4.30	150.00	148.00	146.34	139.12
27	4.30	151.19	149.87	147.02	139.11
28	4.30	151.10	148.64	146.51	137.41
29	4.25	150.76	148.81	146.34	136.39
30	3.88	151.78	149.55	146.17	138.52
31	3.86	150.51	148.21	146.43	137.37
32	3.91	149.91	148.72	147.36	136.90
33	3.58	150.76	148.85	146.19	133.42

Table 10. ANOV 3 for unit weight from 20 sec of vibration.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Test	F-Test (0.05)
Gradation	32	18.3298	0.5728	0.7553	1.73
Error	40	30.3358	0.7584	—	—

Table 11. ANOV 4 for unit weight from 10 sec of vibration.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Test	F-Test (0.05)
Gradation	32	35.5722	1.1126	1.0215	1.73
Error	40	43.5303	1.0883	—	—

Figure 6 shows the average strength plotted versus the fineness index for each grading examined. A simple linear regression of strength on fineness index was found to be significant. As explained previously in the discussion of slump results, this analysis provides statistical substantiation of the trend of decreased strength with increased fineness index. Thus, finer gradings resulted in higher strength for the range of gradings investigated. It is noted that the higher strength was not attributable, even partially, to higher density, for both unit-weight and air-content results suggest that cylinders having finer gradings have been less dense.

The following observations were also made after examination of the average results for the various gradings:

1. Variation of the smaller sizes of aggregate seemed to have a greater effect on compressive strength than similar variation of larger sizes,
2. The average compressive strengths of gap gradings were higher than those of continuous gradings with approximately the same fineness index, and
3. With regard to the range in strengths obtained from the various gradings, the decrease in compressive strength, from that associated with the norm grading, was notably less than the increase (Fig. 6).

As shown in Figure 6, even though the range in fineness index (i.e., the variation in grading) is centered on the norm grading, the strength associated with the norm grading is notably lower than the center of the range of strengths.

As discussed previously, σ_g^2 from the ANOV 6 can be used to evaluate the portion of actual variation in the compressive strength of field-produced paving concrete attributable to variation in coarse-aggregate gradation. Also, the significance of batch-to-batch variation does not detract from the analysis if it is realized that the laboratory control was maintained at the lowest level practically possible. Statistical studies of paving concrete, such as those reported by Newlon (14), have analyzed 28-day compressive strength. Because the data obtained in this investigation were for 7-day strength, it is necessary to assume that 7-day and 28-day variations are the same. This assumption has been substantiated by at least one study (15).

Table 16 gives the results of research of 28-day compressive strength variations for paving concrete (9). The results agree with Newlon's suggestion of 500 to 550 psi as an overall standard deviation achievable in normal highway construction. Using the average of the s_o's and σ_g^2 from this investigation (9), we derive $(\sigma_g^2/s_o^2) \times 100 = (10.85 \times 10^4/30.03 \times 10^4) = 36$ percent.

The degree of importance of gradation depends on the level or amount of overall variation occurring. In this regard, it is convenient to evaluate the relation of σ_g^2/s_o^2 for a range of s_o^2. If production is to be tightly controlled, a desirable s_o might be 400 psi; for less critical work, an s_o of 700 psi might be acceptable. The relative importance of variation in gradation for these two cases can be seen by comparing σ_g^2/s_o^2 as follows: good control $(\sigma_g^2/s_o^2) \times 100 = 69$ percent, and poor control $(\sigma_g^2/s_o^2) \times 100 = 22$ percent.

The compressive strength was related to the fineness of the coarse-aggregate grading over the entire range of gradings examined. All gradings, except the finest continuous gradings, are classifiable within a single maximum aggregate size. Thus, it appears that strength is directly influenced not only by water-cement ratio, density, and maximum aggregate size but also by the fineness of coarse-aggregate grading.

SUMMARY

The variations in gradation of natural gravel, typically occurring in paving concrete, were shown to significantly affect workability and compressive strength of a low-slump mixture. Relatively finer gradings resulted in significantly lower slump and compacting factor. However, for a reasonable compaction effort, typical variations in the gradation of natural gravel did not result in any substantial variations in density.

Compressive strength was found to be related to the fineness of the coarse-aggregate grading. Relatively finer gradings resulted in higher strength. This relation was seen to be independent of water-cement ratio, density, and maximum aggregate size.

Table 12. ANOV 5 for unit weight from compacting factor test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Test	F-Test (0.05)
Gradation	32	538.5341	16.8292	4.7447[a]	1.73
Error	40	141.8792	3.5470	—	—

[a]Significant.

Table 13. Results of microscopic air-content determinations.

Grading Number	Fineness Index	Air Content (percent)
11	2.45	6.1
12	2.65	5.9
1	3.61	5.7
32	3.91	4.9
26	4.30	5.1

Table 14. Average results of 7-day compressive strength tests on rodded specimens.

Grading Number	Fineness Index	Number of Tests	Number of Batches	Average Strength (psi)
1	3.61	5	3	3,780
2	3.09	4	2	4,270
3	4.15	4	2	3,780
4	3.47	2	1	3,950
5	3.72	2	1	3,840
6	3.98	2	1	3,760
7	3.56	2	1	4,140
8	3.69	6	3	4,040
9	3.70	2	1	3,770
10	3.14	4	2	4,200
11	2.45	4	2	4,720
12	2.65	2	1	4,520
13	2.85	5	3	4,730
14	2.96	6	3	4,270
15	2.94	6	3	4,240
16	2.94	6	3	4,390
17	3.42	6	3	4,140
18	3.33	4	2	3,930
19	3.38	2	1	4,170
20	2.94	4	2	4,630
21	3.17	2	1	4,240
22	3.22	2	1	4,280
23	2.55	2	1	4,520
24	4.70	4	2	3,660
25	4.50	2	1	3,700
26	4.30	6	3	3,430
27	4.30	5	3	3,590
28	4.30	4	2	3,720
29	4.25	6	3	3,640
30	3.88	4	2	3,940
31	3.86	2	1	4,080
32	3.91	4	2	3,580
33	3.58	2	1	3,830

Figure 6. Average compressive strength and fineness index for coarse-aggregate grading.

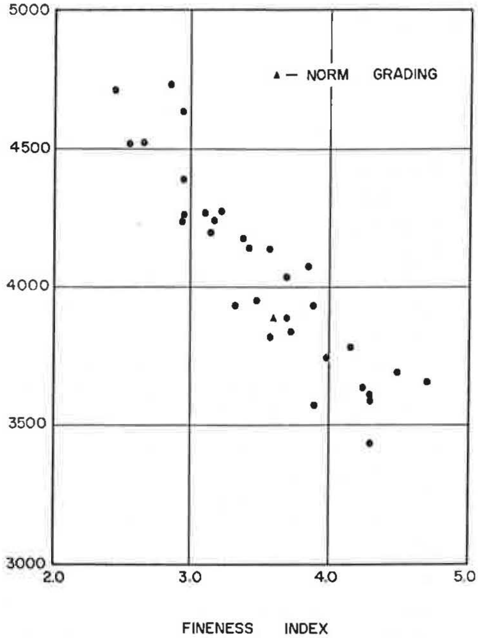

Table 15. ANOV 6 for 7-day compressive strength tests.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	Expected Mean Square	F-Test	F-Test (0.05)
Gradation	32	16,197,795	506,181	$\sigma_t^2 + a\sigma_b^2 + 3.7\ \sigma_g^2$	4.806[a]	1.83
Batches	30	3,159,877	105,329	$\sigma_t^2 + a\sigma_b^2$	7.337[a]	1.65
Error	60	861,377	14,356	σ_t^2	—	—

Note: $\sigma_g^2 = 10.85 \times 10^4$.

[a]Significant.

Table 16. Variability of 28-day compressive strength for paving concrete (9).

Project	Testing Standard Deviation (psi)	Material Standard Deviation (psi)	Overall Standard Deviation (psi)
1	377	386	545
2	322	270	420
3	318	495	575
4	200	420	467
5	585	545	733

On the basis of the results of this investigation, the effect of large variations in the gradation of natural gravel as a source of variability in the slump of paving concrete appears to be smaller than the combined effect of other factors. The effect of variations in gradation on compressive strength appears to be surprisingly large and may be a major source of strength variability.

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