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

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Technical Paper

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

TO: J. F. McLaughlin, Director
Joint Highway Research Project

June 13, 1973

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Project: C-36-42J

File: 5-9-10

The attached Technical Paper titled "Effect of Variations in Coarse Aggregate Gradation on Properties of Portland Cement Concrete" has been accepted by the Highway Research Board for publication in its Proceedings of the International Symposium on the Grading of Concrete Aggregates. The paper is a summary of research reported in May, 1973 in a Final Report titled "An Investigation of the Effects of Variations in Coarse Aggregate Gradation on Properties of Portland Cement Concrete".

The paper has been authored by Professor C. F. Scholer of our staff and Mr. Stephen D. Baker, formerly a Graduate Assistant in Research on our staff. The paper is submitted to the Board for approval of publication.

Respectfully submitted,

Harold L. Michael
Associate Director

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PROPERTIES OF PORTLAND CEMENT CONCRETE

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Introduction

Variations in coarse aggregate gradation can be expected to occur on nearly any construction job due to variations in the source material, production, or due to segregation and/or degradation 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.

gradation appear to have: 1) a relatively small effect on slump variability compared to the combined effect of other factors, 2) a surprisingly large effect on compressive strength and 3) little effect on the compactability of a low slump paving mixture.

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Informative Abstract

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 ratio and aggregate-cement ratio were the same for all batches, the only variable being 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 which 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

The variation in coarse aggregate gradation within a given production situation is nothing more than the occurrence of different gradings, within and between 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, 2, 3, 4, 5).

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

Gap gradings have been found to require a lower cement factor for the same workability. Li (7), in a study comparing the workability of mixes with 1 1/2 inch and smaller maximum aggregate size obtained more workable concrete from gap gradings than from continuous gradings, other factors (water-cement ratio, cement content, 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, relatively lower workability resulting from finer gradings (2,3).

2. Variation causes changes in the compressive strength of concrete, gradings with smaller maximum size resulting in higher 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 effects the sensitivity of the mix to changes in grading (4).

An experiment which parallels this investigation was done by Tynes of the U.S. Army Corps of Engineers (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 of a representative South Carolina highway project made by Fletcher and Mills (8) twenty 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.

Plan of The Investigation

The magnitude 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 Indiana State Highway Commission Aggregate Inspectors Test Reports. Batches of concrete which contained gradings having percent 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 Indiana State Highway Commission (ISHC) requirements for slipform pavement. The particular gradings examined were representative of all gradings within a percent passing envelope covering the variation occurring in typical highway concrete aggregate.

The laboratory tests performed on each batch were intended to provide data which could be used to 1) evaluate the effect of gradation on properties used to control and measure the quality and uniformity of field produced concrete and 2) detect changes in workability. Standard slump, compressive strength and unit weight tests were made in order 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 which might not be detected by the slump test. Unit weight or density measurements were also made after vibrating the concrete for ten and twenty seconds. This data combined with that from the standard rodded unit weight and compacting factor unit weight tests allowed evaluation of the effect of grading on compactability. 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 C457.

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 percent passing obtained from statistical analysis of ISHC sieve reports done by the authors. Estimates (Table 1) were established on the basis of the various

studies and used in defining a range of gradings which would be representative of typical gradation variability for natural gravels used in paving concrete. The analysis of ISHC sieve reports also showed the average percent 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 percent passing for each sieve. The estimates listed in Table 1 were applied to the norm to obtain the $3\hat{\sigma}$ limits shown in Figure 1. The envelop outside the $3\hat{\sigma}$ limits 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 which were examined. Figure 3 shows four gradings which typify the variations examined for each sieve. Table 2 lists all thirty-three gradings examined. As a group, the gradings are representative of variations which occur in natural gravel gradation during production of paving concrete.

The inclusion of continuous gradings having $\pm 3\sigma$ variation occurring simultaneously on each sieve is considered conservative. Statistically, the assumption of a normal distribution in regards to the concurrent variation for the series may be extreme, for a binomial distribution might better describe the combinations of individual variation which 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

TABLE 1

ESTIMATES OF STANDARD DEVIATION OF PERCENT PASSING ($\hat{\sigma}_s$)
USED IN THE INVESTIGATION

Sieve Size					
1"	3/4"	1/2"	3/8"	No. 4.	No. 8
3.0	8.0	9.0	8.0	2.0	1.0

FIGURE 1. RANGE OF GRADINGS INVESTIGATED - CUMULATIVE PERCENT PASSING VS. SIEVE SIZE

FIGURE 2. GRADINGS INVESTIGATED - CUMULATIVE
PERCENT PASSING VS. SIEVE SIZE

FIGURE 3. GRADINGS INVESTIGATED - CUMULATIVE
PERCENT PASSING VS. SIEVE SIZE

TABLE 2

CUMULATIVE PERCENT PASSING FOR EACH GRADING INVESTIGATED

Grading No.	Sieve Size						
	1 1/2"	1"	3/4"	1/2"	3/8"	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	01.5	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

pointed out that 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 fifteen percent of sieve analysis test results would be expected to exceed the No. 5 limits, which is comparable to the twenty percent found by Fletcher and Mills (8).

Presentation and Discussion of Results of 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 C125) commonly used to describe the relative fineness of fine aggregate gradings. The fineness index was calculated as $\sum r_i/100$, 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 3 shows the calculation of the fineness index for the norm grading. The terms "fine" and "coarse" in regard to grading are relative classifications on the basis of fineness index, finer gradings having lower indices 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 listed in Table 2 of the section: Selection of Gradings Investigated.

The various components of the variance associated with concrete production are discussed throughout this section. 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.

TABLE 3
CALCULATION OF FINENESS INDEX
FOR THE NORM GRADING

Sieve Size	Percent Passing	Percent Retained	Cumulative Percent Retained
1 1/2 In.	100.00	0.00	0.00
1 In.	91.50	8.50	8.50
3/4 In.	72.50	19.00	27.50
1/2 In.	45.00	27.50	55.00
3/8 In.	22.50	22.50	77.50
No. 4	5.00	17.50	95.00
No. 8	2.50	2.50	97.50

$\Sigma = 361.00$

Fineness Index = $361/100 = 3.61$

Results of Slump Tests

The average result for each grading is listed in Table 4.

Homogeneity of variance among the test results was accepted after evaluating the data by the Foater-Burr test (11). ANOV 1 (Analysis of Variance No. 1), Table 5, showed the variation in slump, which resulted from the entire set of gradings examined, to be significant.

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 from finer to coarser gradings. A simple linear regression of slump on fineness index was found to be significant. This is not to say that the relationship is best defined as simple linear, but rather that, in general, finer gradings 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 1/2 to 2 inch specification requirement.
3. Gap gradings did not seem to affect slump differently than continuous gradings having approximately the same fineness index.

TABLE 4
AVERAGE RESULTS OF SLUMP TESTS

Grading No.	Fineness Index	Number of Tests (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

TABLE 5

ANOV 1 - ANALYSIS OF VARIANCE, SLUMP

Source of Variation	df	SS	MS	EMS	F	F(.05)
Gradation	32	13.7648	0.4301	$\sigma_t^2 + 2.2 \sigma_g^2$	5.62*	1.73
Error	40	3.0640	0.0766	σ_t^2		

$$\sigma_g^2 = 0.16$$

*Significant

FIGURE 4 . AVERAGE SLUMP VS. FINENESS
OF COARSE AGGREGATE GRADING

The variance σ_g^2 from ANOV 1, Table 5, provides a quantitative measure of the effect of gradation which 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 which might occur on typical highway projects, and so σ_g^2 can be considered representative of the variance in slump which results from the variation in gradation in typical highway concrete production. In order 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 which allowed identification of between 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 used. Thus, σ_g^2 was taken as a maximum variance which 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 6 shows 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 which can be attributed to variation in gradation can be

calculated as follows: $(\sigma_g^2 / s_a^2) \times 100$ (13).

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 from Hanna, McLaughlin, and Lott's study of Indiana projects:

$$(\sigma_g^2 / s_a^2) \times 100 = (0.16/0.92) \times 100 = 17\%.$$

Table 7 lists 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 inches as an achievable overall standard deviation and 0.50 as desirable. Using these values to evaluate the importance of gradation variation:

$$\text{Achievable control: } \sigma_g^2 / s_o^2 \times 100 = 33\%$$

$$\text{Desirable control: } \sigma_g^2 / s_o^2 \times 100 = 64\%.$$

TABLE 6

VARIABILITY IN SLUMP FOR FIELD PRODUCED CONCRETE

(After Hanna, McLaughlin and Lott (12))

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

TABLE 7

VARIABILITY IN SLUMP OF PAVEMENT CONCRETE

Cited By	Testing Variance $s_t^2(\text{in.}^2)$	Sampling Variance $s_s^2(\text{in.}^2)$	Material Variance $s_a^2(\text{in.}^2)$	Overall Variance $s_o^2(\text{in.}^2)$
Newlon (14)				0.25
"				0.64
"				0.36
"				0.16
"				0.14
"				0.27
"				0.90
"				0.64
"	0.10			
FHA (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

The results show that gradation significantly affected slump. This is consistent with accepted principles regarding the relationship 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, gradation variability would be of minor importance.

Results of Unit Weight Tests on Specimens Made by Rodding

The average result for each grading is listed in Table 8 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 9 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, σ_b^2 can be used 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

TABLE 8
AVERAGE RESULTS OF UNIT WEIGHT TESTS
ON SPECIMENS MADE BY RODDING

Grading No.	Fineness Index	Number of		Average Unit Weight pcf
		Tests	Batches	
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	148.94
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

TABLE 9

ANOV 2 - ANALYSIS OF VARIANCE, UNIT WEIGHT OF RODDED SPECIMENS

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	70.9835	2.2182	1.09	1.73
Batches	40	81.3452	2.0336	5.21*	1.58
Error	73	28.5000	0.3904		
* Significant					

and σ_b^2 equal to 2.0336 a difference of approximately four pounds per cubic foot can be distinguished at a reasonable level of confidence ($\alpha = 0.05$, $\beta = 0.1$). Thus it can be concluded that the unit weights resulting from all the gradings examined did not differ more than approximately four pounds per cubic foot or three percent. A plot of the average results for each grading is shown in Figure 5 included in the next section.

Hanna, McLaughlin and Lott (12), in a study cited by Newlon (14), obtained a testing variance of 1.15 pounds per cubic foot. 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 x 12 inch paperboard cylinder molds (ASTM C470). 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: 1) the relationship of unit weight or density to air content and strength and 2) the use of unit weight for evaluating uniformity in the yield. The results showed coarse aggregate gradation variability did not substantially affect the unit weight of the concrete as measured by the standard testing procedure. The results, as seen in Figure 5, suggest density if affected at all by gradation, to be less 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 three percent as a result of the maximum variation (four pounds per cubic foot) in unit weight.

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

Results of Unit Weight Tests as a Measure of Compactability

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 effort were: 1) dropping through a compacting factor apparatus in accordance with B.S. 1881, 2) ten seconds of vibration with a poker vibrator, 3) rodding in accordance with ASTM C192 and 4) twenty seconds of vibration with a poker vibrator.

The average unit weight resulting from each compactive effort and grading is listed in Table 10 and plotted in Figure 5 versus the fineness index of each grading. The ANOV's for the results of each compactive effort are shown in Tables 9 and 11-13. The results are discussed in terms of the curves or lines which are defined by the sets of data points shown in Figure 5. (The discussion refers to the

TABLE 10
AVERAGE RESULTS OF UNIT WEIGHT TESTS, PCF

Grading No.	Fine- ness Index	20-Sec. Vibration	Rodded Unit Weight	10-Sec. Vibration	Compact- ing Factor
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

FIGURE 5 . AVERAGE UNIT WEIGHT VS. FINENESS
OF COARSE AGGREGATE GRADING

TABLE 11

ANOV 3 - ANALYSIS OF VARIANCE, UNIT WEIGHT FROM 20-SECONDS OF VIBRATION

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	18.3298	0.5728	0.7553	1.73
Error	40	30.3358	0.7584		

TABLE 12

ANOV 4 - ANALYSIS OF VARIANCE, UNIT WEIGHT FROM 10-SECONDS OF VIBRATION

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	35.5722	1.1126	1.0215	1.73
Error	40	43.5303	1.0883		

TABLE 13

ANOVA 5 - ANALYSIS OF VARIANCE, UNIT WEIGHT FROM COMPACTING FACTOR TEST

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	538.5341	16.8292	4.7447*	1.73
Error	40	141.8792	3.5470		

* Significant

slopes of the curves with the knowledge that they may well be curvilinear.)

ANOV's 2, 3, 4 for the last three compacting efforts listed above show grading to be not significant. This indicates the slopes of the upper three lines shown in Figure 5 are not significantly different from zero (if a linear relationship is assumed) or, as explained for the rodding effort in the section: Results of Unit Weight Tests on Specimens Made by Rodding, 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 compactability 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 compactability is seen to be inconsequential for compacting efforts greater than ten seconds 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 ten seconds of vibration would be expected to transition 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 in regard to compactability 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 ten seconds of vibration applied to the six inch diameter by twelve inch long specimen is a reasonable representation of field vibration. It is observably less than rodding and also substantially less than twenty seconds of vibration. It must be recognized that the above was conducted with a particular electric vibrator (3/4 inch 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 shown in Table 14. 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 with finer gradings rather than coarser ones.

TABLE 14

RESULTS OF MICROSCOPIC AIR CONTENT DETERMINATIONS

Grading No.	Fineness Index	Air Content %
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

Segregation

Several hardened cylinders made of concrete observed to bleed 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 listed in Table 15 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 16, showed the variation in compressive strength, which resulted from the entire set of gradings examined, to be significant.

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 cylinders having finer gradings to have been less dense.

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

TABLE 15

AVERAGE RESULTS OF 7-DAY COMPRESSIVE STRENGTH TESTS
ON SPECIMENS MADE BY RODDING

Grading No.	Fineness Index	Number of		Average Strength psi
		Tests	Batches	
1	3.61	5	3	3780
2	3.09	4	2	4270
3	4.15	4	2	3780
4	3.47	2	1	3950
5	3.72	2	1	3840
6	3.98	2	1	3760
7	3.56	2	1	4140
8	3.69	6	3	4040
9	3.70	2	1	3770
10	3.14	4	2	4200
11	2.45	4	2	4720
12	2.65	2	1	4520
13	2.85	5	3	4730
14	2.96	6	3	4270
15	2.94	6	3	4240
16	2.94	6	3	4390
17	3.42	6	3	4140
18	3.33	4	2	3930
19	3.38	2	1	4170
20	2.94	4	2	4630
21	3.17	2	1	4240
22	3.22	2	1	4280
23	2.55	2	1	4520
24	4.70	4	2	3660
25	4.50	2	1	3700
26	4.30	6	3	3430
27	4.30	5	3	3590
28	4.30	4	2	3620
29	4.25	6	3	3640
30	3.88	4	2	3940
31	3.86	2	1	4080
32	3.91	4	2	3580
33	3.58	2	1	3830

TABLE 16

ANOV 6 - ANALYSIS OF VARIANCE, 7-DAY COMPRESSIVE STRENGTH

Source of Variation	df	SS	MS	EMS	F	F(.05)
Gradation	32	16,197,795	506,181	$\sigma_t^2 + a\sigma_b^2 + 3.7\sigma_g^2$	4.806*	1.83
Batches	30	3,159,877	105,329	$\sigma_t^2 + a\sigma_b^2$	7.337*	1.65
Error	60	861,377	14,356	σ_t^2		
				$\sigma_g^2 = 10.85 \times 10^4$	*Significant

FIGURE 6 . AVERAGE COMPRESSIVE STRENGTH OF RODDED SPECIMENS
VS. FINENESS OF COARSE AGGREGATE GRADING

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 strength of gap gradings were higher than those of continuous gradings with approximately the same fineness index.
3. In 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.

The observation listed as Item 3 is clarified by 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 in the section: Results of Slump Tests, 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. As was also mentioned in the discussion of slump results, 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. Since the data obtained in this investigation was for 7-day strength, it is necessary to assume

7-day and 28-day variations are the same. This assumption has been substantiated by at least one study (15).

Table 17 shows the results of West Virginia research of 28-day compressive strength variations for paving concrete (9). The results agree with Newlon's suggestion of 500-550 psi as an overall standard deviation achievable in normal highway construction. Using the average of the s_o 's from West Virginia's study and σ_g^2 from this investigation: $(\sigma_g^2/s_o^2) \times 100 = (10.85 \times 10^4 / 30.03 \times 10^4) = 36\%$.

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 relationship 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, whereas for less critical work a 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 :

$$\text{Good control: } (\sigma_g^2/s_o^2) \times 100 = 69\%$$

$$\text{Poor control: } (\sigma_g^2/s_o^2) \times 100 = 22\%$$

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

TABLE 17

VARIABILITY OF 28-DAY COMPRESSIVE STRENGTH
FOR PAVING CONCRETE (after FIA (9))

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

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 relationship was seen to be independent of water-cement ratio, density and maximum aggregate size.

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 appear to be surprisingly large and may be a major source of strength variability.

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