Control and Acceptance of Aggregate Gradation by Statistical Methods

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The purpose of this investigation was to develop a procedure for control and acceptance of gradations of aggregates by statistical methods. Because the South Carolina State Highway Department is most interested in gradation of aggregates when they are used, a procedure for control and acceptance was developed for "as-used" samples. This procedure was tested on 14 projects. As refined, the system provides that the size of a lot shall be the quantity required for 1 mile of 24-ft wide roadway or 100 cu yd of structural concrete. Five random samples per lot are specified. For analysis of the data, the "standards given" control chart technique is used. The central value is the desired average of the gradation specified. Upper and lower control limits are established using standard deviations previously determined. When test values exceed control limits, the delivered price for the lot will be adjusted.

In this study, analysis of variance showed variance resulting from the testing process significant in 98.8 percent of results analyzed, variance between batches in 30 percent, and variance within batches in 56 percent. A study of the testing process was recommended with a goal of reducing this variance. A limited series to explore the effect of the size of sample on gradation test results showed no definite preference for a certain size sample.

•IN HIGHWAY CONSTRUCTION, aggregates composed of rock fragments form the bulk of the materials in cement concrete, bituminous concrete, base mixtures, and subbase mixtures. The properties of these mixtures are directly influenced by the aggregates used in them. Durability may be greatly affected by the chemical and mineral composition. Workability and strength are affected by the shape, size, and gradation of the particles.

The chemical and mineral composition and shape of aggregate particles are usually fairly constant at any one source. The size of particles and gradation (proportions of different sizes) can be and are varied by crushing and screening to obtain properties of workability and strength desired for a certain mixture. Ideally, the gradation should be constant, but variations are always encountered in any mixture containing particles of different sizes. When aggregate consisting of different sizes of particles is handled or moved, segregation or separation of the sizes occurs. The tendency to segregate increases when the size of particles is large or when the range in sizes is large.

The gradation of a certain lot of aggregate is usually determined by obtaining a sample from the lot and separating the particles on appropriate sieves. The problem of obtaining this sample has always caused testing engineers much concern. Traditionally, the attempt has been to select a "representative" sample, one that will indicate the

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average gradation of the particles in the lot. How closely this goal is attained depends on several factors, such as the experience of the one who obtains the sample, the maximum size of the particles, the different sizes of particles present, the segregation of the sizes, and the quantity of material included in the sample. Because of the many possibilities for variations in a representative sample, there is often controversy regarding the accuracy of the results.

It is the practice of the South Carolina State Highway Department to base acceptance of aggregate gradation on samples obtained from stockpiles because there is usually no other feasible sampling point. Such samples often fail to meet gradation requirements. When a sample does not conform to specification limits, the usual policy is to select two check samples and base acceptance on the results of the three samples.

The difficulties in obtaining a representative sample from a stockpile, the emphasis on no-deviation compliance with specifications, and the desire to develop a more practical and realistic procedure for control and acceptance of aggregate gradation were factors that influenced the South Carolina State Highway Department to undertake this research project. The Bureau of Public Roads agreed to cooperate in this project and to defray part of the cost with H. P. R. funds.

The State Highway Department did the sampling and testing with a crew of two men. Sampling was done at production sources and at projects. All testing was done at the central laboratory at Columbia, South Carolina.

The firm of William H. Mills and Associates was retained to do the detailed planning for this work, to maintain coordination with Highway Department personnel in performing field sampling and testing, to tabulate and analyze data, to prepare the sampling plan and the procedure for obtaining random samples, to prepare a tentative system for control and acceptance based on statistical concepts, to continue coordination with field forces during the testing of the tentative procedure, to review and refine the procedure, and to prepare model requirements for specifications to use the system.

The research project was conducted in four parts as follows:

Phase I — Determination of statistical parameters for gradations of typical aggregates used by the department;
Phase II — Preparation of tentative procedures for random sampling and acceptance of gradation of aggregates;
Phase III — Field testing and refining the tentative procedures; and
Phase IV — Preparation of models for specifications to utilize the system.

PHASE I—DETERMINING STATISTICAL PARAMETERS

Survey of Plants and Stockpiling

For background material and in order to become familiar with the methods of handling, loading, and sampling aggregates at the various sources, a survey was made of commercial plants supplying aggregate to the department. Particular attention was given to the methods of combining different sizes to obtain a specified gradation and to the methods of loading trucks and railroad cars, especially in regard to segregation of different sizes. The locations and procedures for obtaining and testing control samples were noted. Methods for stockpiling aggregate at project sites were observed.

Following this survey, two short pilot studies were conducted to investigate procedures for obtaining random samples and to develop initial information in the variations in gradation that could be expected.

Pilot Studies

The first study was conducted on crushed stone, $1\frac{1}{2}$ in. to No. 8, used in class B concrete for curb and gutter work. Samples were obtained at the source by passing a metal box through the stream of aggregate as it flowed from the loading bin to a railroad car below the loading platform. Samples were obtained during unloading from the discharge of a belt by passing a 5-gallon bucket through the stream of material as it dropped to the stockpile. The aggregate as used (actually incorporated into the concrete) was also

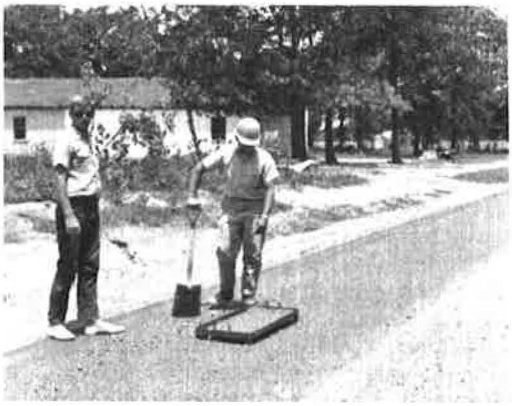

Figure 1. Tray for sampling surface treatment aggregate as used.

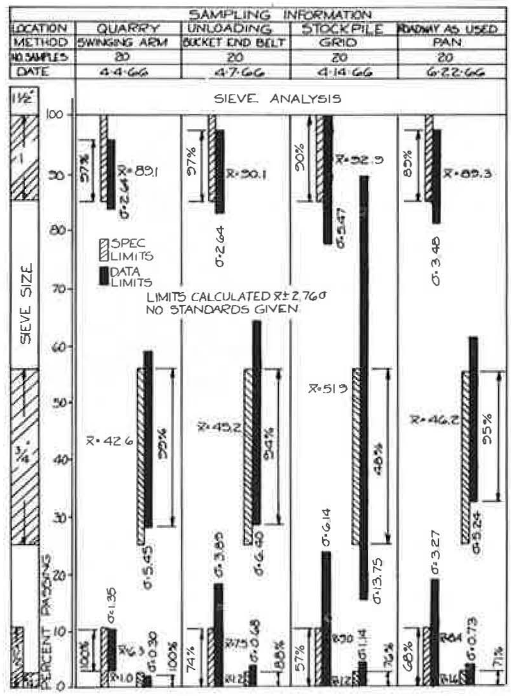

Figure 2. Aggregate No. 3, Weston and Brooker Co., Cayce, S.C., sampling information.

sampled in a similar manner as it was being delivered by chute from the mixer truck into the forms. Randomization in the selection of samples was attained by using random numbers to determine the ton or time at which the sample would be drawn. Twenty random samples were obtained at each location from this shipment of approximately 800 tons.

The second study was on 3,000 tons of crushed stone, $1\frac{1}{2}$ to $\frac{1}{2}$ in., used in surface treatment. Twenty random samples each were obtained at the source, during unloading, from the stockpile, and as the material was being placed on the roadway. Randomization was attained by using random numbers to determine the ton or time at which the sample would be drawn.

Samples at the source were obtained with a removable box mounted on a swinging arm that was passed through the stream of material as it was discharged into a railroad car. This material was unloaded by discharging it through gates onto a conveyor belt. Samples were obtained from the end of this belt by passing a bucket through the stream of aggregate.

The aggregate was deposited in the stockpile by truckloads in such a way that a succeeding load would overlap the previous load by about one half and leave a well-defined small cone from each dump. The cone to be sampled was determined by random numbers. The exact location from which the sample was drawn was then determined by random numbers.

The device developed for sampling the aggregate as used consisted of a heavy metal pan, 18 by 36 by 2 in. (0.5 sq yd in area), mounted on short supports to hold the pan above the surface of the asphalt. This pan was placed on the roadway ahead of the spreader truck at a randomly preselected location (Fig. 1). The data for these samples are shown in Figure 2.

Aggregates for Concrete Pavement

The study was continued at a concrete paving project. At this plant, aggregate in three separate sizes was fed to the weighing bin by separate belts operating from under small bins that were filled by a front end loader. The conveyor belts from these loadings bins to the weighing bin were stopped each time the hopper above the weighing bin was full. Thus, it was practical to obtain samples of the separate sizes of aggregate from stopped loaded belts (Fig. 3).

Figure 3. Sampling from a stopped belt.

Randomization for the five samples per lot (quantity used in a day) was attained by using random numbers to select the exact time to draw the sample.

Sampling of the concrete from the roadway was done by placing a container at a randomly preselected location on the subbase and having this container filled as the spreader passed over the area.

Samples were obtained from the outer layer of the large stockpiles by dividing the outer surface of the stockpile into areas approximately 10 by 10 ft and subdividing these 1-ft squares. The exact squares for sampling were determined by random numbers.

Aggregate at another concrete paving project was sampled later in the year. At this plant, sizes of aggregates were weighed in individual hoppers and fed by belts to a common bin from which they were moved to the mixers. By switching the plant to manual operation, it was possible to obtain samples from the individual loaded belts after the aggregate had been weighed.

Aggregates for Concrete for Structures

A series of tests was made on aggregate, 1½ in. to No. 8, used on a bridge project. The size of the lot to be sampled was chosen as the quantity used in a normal day's placement of concrete on the bridge deck (about 100 cu yd). Samples of aggregate were obtained at the source from a stopped loaded belt, and as-used samples from a stopped loaded belt at the batch plant. Samples of concrete were obtained from the chute as concrete was delivered to the forms. Randomization for the five samples was based on the time required for the day's production of concrete. The data are shown in Figure 4.

Aggregates for Surface Treatment

The original sampling plan for surface treatment aggregates, 1½ to ½ in. and ⅜ in. to No. 16, was to obtain five random samples from a shipment, considered as one lot, at the source, at the stockpile, and as the material was being used. This program could not be followed, however, because most of the aggregates for the current construction season had already been stockpiled at project sites. The procedure followed in most instances was to sample the aggregate in the stockpile considered as a lot, and then sample that material as it was being placed on the roadway. Later, samples were obtained at the source by the method used by the producer. Such samples give typical results for the source, but they are not comparable directly to the material sampled in the stockpile or as used.

The procedure described in the pilot study was followed to obtain the stockpile and the as-used random samples.

Replicate Sampling

To obtain data for the analysis of variance, replicate samples were obtained from two lots of each aggregate size at each sampling point. Replication requires taking two samples at essentially the same time. Where samples were taken from a stockpile or from a stopped conveyor belt, the replicate samples were taken adjacent to each other. Where the material was being discharged from a bin or from a conveyor belt, the two samples were obtained within the shortest time practicable. For roadway samples, two devices were placed side by side.

Testing

All tests (sieve analysis) were performed at the central laboratory in Columbia, S.C. A Gilson shaker and one set of sieves were used throughout. A Gilson aggregate splitter was used to reduce samples to test portions when the sample size was greater than the normal capacity of the shaker, as was usually the case.

The actual performance of the sieve test was routine. The duration of the shaking varied somewhat with the quantity of fine material in the sample. Shaking was continued until there was no visible evidence of material passing the two smallest screens. Smaller size aggregates, such as ⅜ in. to No. 16, were reduced to test size in a sand splitter and sieving was performed in a Rotap.

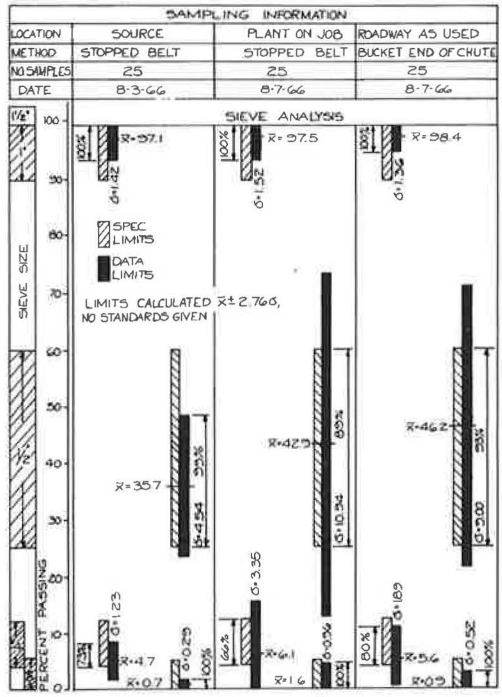

Figure 4. Aggregate No. 4, Becker County Sand and Gravel Co., Marlboro, S.C., sampling information.

Analysis of Data

Data in Phase I included gradation test results of 175 samples obtained at the source, 120 samples obtained during unloading on the project, 320 samples from stockpiles, and 400 samples taken as the material was being used. Coarse, intermediate, and fine gradation of aggregates were included, as well as crushed aggregate produced at five sources and gravel produced at two sources.

The data for the samples from each location were analyzed to obtain mean values ($\overline{X}$) and standard deviations (σ) for each sieve in the gradation series. These data were used in calculating upper and lower control limits on the basis of no standards given ($\overline{X} \pm 2.76\ \sigma$) for each sieve. Typical results are summarized and compared graphically with specification limits in Figures 2 and 4. In each case the percentage conforming with specifications is shown. The statistical values for samples in Phase I are summarized in Tables 1 and 2.

Conclusions

Based on experience and analysis of the data in Phase I, the following conclusions were derived:

1. In most cases, samples obtained at the source conform to specifications.
2. Samples obtained from stockpiles on the project show wide variations and frequently do not meet specifications.
3. Samples obtained as the aggregate is used show less variation than the stockpile samples but somewhat larger variation than the source samples.
4. Source samples show less variation than others because they are obtained from the stream of aggregate after the several sizes have been measured in proportions to give the gradation desired and before discharge or handling that would cause segregation. At some producers, source samples are obtained from a stopped loaded belt; at others, by cutting through the stream of material as it is discharged from the loading belt.
5. Sampling from a stockpile always involves difficulties because of the segregation of different-sized particles. Also, in most cases, only the material near the surface of the pile can be included in the sample.

TABLE 1

SUMMARY OF STATISTICAL VALUES OF AGGREGATES FOR CONCRETE—PHASE I

Sample	σ	X̄	%	σ	X̄	%	σ	X̄	%	σ	X̄	%
Aggregate No. 4, Crushed Stone, Columbia												
Sieve size		1 in.			½ in.			No. 4			No. 8	
Source	1.11	97.8	100	2.95	30.3	96	1.44	7.8	100	0.46	1.6	100
Unloading	1.80	97.6	100	6.95	36.0	94	3.78	8.4	71	0.95	2.1	100
Concrete	4.72	95.6	88	11.80	32.9	74	2.67	4.7	61	0.35	0.2	100
Aggregate No. 4, Gravel, Marboro												
Sieve size		1 in.			½ in.			No. 4			No. 8	
Source	1.42	97.1	100	4.54	35.7	99	1.23	4.7	73	0.29	0.7	100
Belt (as used)	1.52	97.5	100	10.94	42.9	89	3.35	6.1	66	0.96	1.6	100
Concrete	1.36	98.4	100	9.00	46.2	93	1.89	5.6	80	0.52	0.9	100
Aggregate 1A, Crushed Stone, Columbia and Cayce												
Sieve size		2 in.			1½ in.			1 in.			½ in.	
Stockpile	7.80	91.9	56	15.77	43.9	66	5.57	4.8	97	1.84	0.6	99
Belt (as used)	3.31	94.6	92	6.03	58.3	97	4.75	13.7	61	2.29	3.9	69
Aggregate 4M, Crushed Stone, Columbia and Cayce												
Sieve size		1 in.			½ in.			No. 4			No. 8	
Stockpile	3.60	94.4	89	14.27	39.3	78	5.49	8.5	54	2.02	2.6	100
Belt (as used)	1.56	95.5	100	7.06	46.7	97	3.15	13.1	95	1.35	5.0	100
Aggregate No. 20, Sand, Two Sources Mixed												
Sieve size		No. 4			No. 16			No. 50			No. 100	
Belt (as used)	0.03	99.9	100	6.46	76.4	100	2.32	16.7	100	0.68	3.8	100
Aggregate No. 20, Sand, One Source												
Sieve size		No. 4			No. 16			No. 50			No. 100	
Belt (as used)	0.00	100	100	0.86	94.2	100	1.44	9.1	100	0.68	2.4	100
Mixed Aggregates from Concrete												
Sieve size		2 in.			1 in.			½ in.			No. 4	
Concrete	1.91	98.4	100	3.55	54.5	100	4.23	23.6	100	2.23	6.7	97
Belt (calculated)			96			84			98			88
Aggregate No. 1B, Crushed Stone, Augusta												
Sieve size		1½ in.			1 in.			¾ in.			⅜ in.	
Belt (as used)	3.24	90.5	54	5.02	33.8	100	2.17	9.7	98	1.07	1.1	99
Routine	1.71	92.3	91	1.55	37.5	100	1.29	10.8	100	0.28	1.6	100
Aggregate No. 6M, Crushed Stone, Augusta												
Sieve size		¾ in.			⅜ in.			No. 4			No. 8	
Belt (as used)	1.76	91.6	82	2.54	24.4	96	0.84	7.0	100	0.40	2.3	100
Routine	0.92	91.5	95	3.81	29.9	100	0.70	5.7	100	0.24	1.2	100
Aggregate No. 20, Sand												
Sieve size		No. 4			No. 16			No. 50			No. 100	
Belt (as used)	0.0	100	100	3.18	78.4	100	1.42	14.0	100	0.41	2.5	100

Note: X̄ = mean of data percentage passing; σ = standard deviation; % = percentage of results within specification limits.

6. For sampling at concrete plants, it is often practical to obtain as-used samples from a stopped loaded belt en route to the weighing bin or mixer. In cases where belts are not used for transporting the aggregate, as-used samples can be obtained by dropping the material for the sample from the storage or weighing bin into a suitable container.

7. A suitable device for sampling surface treatment aggregate as used consists of a tray 0.5 sq yd in area. This tray is placed on the roadway at preselected random locations.

8. It is interesting to note that for all sizes and gradations of aggregates included in this study, the largest variations (sigmas) occur at the third sieve smaller than the maximum size. In the summaries, data for the maximum size (100 percent passing) are not shown; therefore, the second size shown is actually the third size in the gradation series.

Analysis of Variance

To obtain data for the analysis of variance, the following plan for replicate sampling was adopted:

1. The location for sampling was selected, i.e., stockpile or as used.
2. For a certain lot of aggregate, five units or batches were selected by random numbers for sampling. Thus, between-batch variance, σ_b^2, could be evaluated.

TABLE 2

SUMMARY OF STATISTICAL VALUES OF AGGREGATES FOR SURFACE TREATMENT—PHASE I

Sample	σ	X̄	%	σ	X̄	%	σ	X̄	%	σ	X̄	%
Aggregate No. 3, Crushed Stone, Cayce												
Sieve size	1 in.			¾ in.			½ in.			No. 4		
Source	2.15	89.1	97	5.45	42.6	99	1.35	6.3	100	0.30	1.0	100
Unloading	2.64	90.1	97	6.40	45.2	94	3.89	7.5	74	0.68	1.2	88
Stockpile	5.47	92.9	90	13.75	51.9	48	6.14	9.0	57	1.14	1.2	76
As used	3.48	89.3	89	5.24	46.2	95	3.27	8.4	68	0.73	1.6	71
Aggregate No. 3, Crushed Stone, Rion												
Sieve size	1 in.			¾ in.			½ in.			No. 4		
Source	2.60	91.6	99	8.50	42.7	91	2.18	5.4	98	0.36	1.36	96
Unloading	1.62	93.1	100	5.81	40.5	99	2.18	6.2	96	0.65	1.6	75
Stockpile	3.81	92.2	88	13.58	51.6	45	9.75	13.9	34	2.06	2.4	28
As used	3.98	92.0	96	7.99	41.7	93	2.88	6.2	91	0.63	1.5	81
Aggregate No. 3, Crushed Stone, Stoney Point												
Sieve size	1 in.			¾ in.			½ in.			No. 4		
Source	2.25	86.5	75	6.34	31.0	83	2.26	3.9	99	0.51	1.5	84
Stockpile	2.92	90.8	98	8.14	39.0	93	5.12	8.7	60	1.98	3.4	34
As used	3.05	88.0	83	5.64	30.9	85	3.53	6.8	82	1.89	3.1	36
Aggregate No. 3, Crushed Stone, Augusta												
Sieve size	1 in.			¾ in.			½ in.			No. 4		
Source	1.61	92.3	100	5.93	29.2	76	1.95	4.5	100	0.67	1.0	94
Unloading	3.60	92.8	92	8.70	39.4	91	4.01	8.3	67	0.38	1.2	98
Stockpile	4.58	89.0	81	7.25	32.6	85	3.26	5.9	89	0.84	1.2	82
As used	4.23	91.3	93	12.78	41.8	76	6.11	10.0	50	0.76	1.6	71
Aggregate No. 3, Gravel, Hagood												
Sieve size	1 in.			¾ in.			½ in.			No. 4		
Source	2.34	93.2	100	5.14	40.5	100	2.29	4.7	99	0.45	0.6	100
Stockpile	2.23	95.4	100	9.78	46.6	79	5.36	6.3	75	1.04	1.2	77
As used	3.53	92.6	98	6.63	39.6	98	3.92	6.7	80	1.95	1.8	52
Aggregate No. 9, Crushed Stone, Rion												
Sieve size	⅜ in.			No. 4			No. 16			No. 100		
Source	4.79	85.0	85	7.16	39.6	92	0.94	3.2	100	0.13	0.5	100
Unloading	4.20	90.2	99	7.92	40.2	89	2.54	3.9	79	0.39	0.8	100
Stockpile	5.57	89.6	96	9.58	40.9	81	1.80	3.7	90	0.34	0.7	100
As used	4.42	89.3	98	5.99	40.1	95	1.78	3.9	88	0.37	0.7	100
Aggregate No. 9, Crushed Stone, Stoney Point												
Sieve size	⅜ in.			No. 4			No. 16			No. 100		
Source	7.84	78.8	44	7.54	29.0	88	1.62	4.3	86	0.90	1.3	79
Stockpile	5.18	85.4	85	7.45	34.1	97	2.78	6.6	41	0.75	2.1	46
As used	3.68	82.8	83	7.22	31.4	94	1.89	5.0	70	0.52	1.2	93

σ = standard deviation. X̄ = mean of data, percentage passing. % = percentage of results within specification limits.

3. At each of these batches or units, two separate samples were drawn: adjacent to each other if sampling a stopped belt or stockpile; within the shortest time practical if sampling a discharge stream; or with trays or containers side-by-side if sampling the roadway. This sampling procedure provided data for the determination of within-batch variance, σ_w^2.

4. Each of these samples was reduced by splitting into two test portions. This procedure provided data for the determination of variance due to testing, σ_t^2.

This study included 84 individual results. The variance of testing was significant in all except one instance or in 98.8 percent of the results. The variance between batches was significant in 30 percent of the results, and the variance within batches was significant in 56 percent of the results.

Investigation of Sample Size

Investigation of the effect of the size or quantity of material in the sample on the result of the gradation test was not contemplated in the outline for this research project. It was undertaken because at one plant standard deviations in the results from a few samples consisting of approximately 20 lb, compared with those of samples of approximately 40 lb, showed much smaller variations in the 40-lb samples.

The quantity of aggregate to be included in a sample for a gradation test has been a concern of testing engineers for many years. Standard test procedures of the American Association of State Highway Officials and the American Society for Testing and

Materials specify the size or quantity for a sample varying with the maximum-size particles in the mixture of aggregate. These requirements have not been changed in many years. It is logical that the quantity for a sample should vary with the size of particles because the inclusion or loss of one large particle in a small sample could change the percentage values. However, there is a natural and practical tendency for a sampler to take as small a quantity of aggregate as he can justify because of the work involved in the sampling and handling processes.

Arrangements were made with a gravel producer to stop the belt during the loading of a railroad car and to allow time for taking the samples desired. Five replicate series of samples were obtained. Each series had samples of approximately 200, 100, 50, 25, and 12.5 lb. The loading belt at this plant was 125 ft in length. Each series of samples required material from about 16 ft. The five sections to be sampled were determined by random numbers.

Several sets of tests were performed on these samples as follows:

1. Routine Test, Mechanical Splitter—The larger samples were reduced to test size in a Gilson mechanical splitter in the standard manner. The first test thus obtained is the one normally used in routine testing. However, each large sample was reduced to separate test portions. Thus, eight results were obtained for each 200-lb sample, four for each 100-lb sample, two for each 50-lb sample, one for each 25-lb sample, and one for each 12.5-lb sample.
2. Quartering—To compare results obtained by splitting samples in the mechanical device with those obtained by reducing samples to test size by the quartering method, the larger samples (200 lb, 100 lb) were re-mixed and then quartered by the standard method to test size. Thus, eight results were obtained for the 200-lb samples and four results for the 100-lb samples.
3. Layer Samples—To compare size of samples from aggregate spread in a relatively thin layer, such as in an ideally formed stockpile, the material in all these samples was spread into a layer approximately 6 by 6 ft by 6 in. thick. The surface of this layer was divided into 36 one-ft squares. Five 12.5-lb samples were obtained from the central portion of 5 randomly selected squares. A cylinder or ring having a diameter large enough to yield the quantity desired was pushed into the layer and the material inside was withdrawn as the sample. After testing, the material was returned to the square from which it was taken. Next, five 25-lb samples were obtained from 5 randomly selected squares using a similar procedure. Similarly, five 50-lb, five 100-lb, and five 200-lb samples were obtained and tested. For the large samples, the randomly selected square was used as the central portion for the sample with the remainder coming from adjacent squares.

The test data were transferred to punch cards that were put through a computer programmed according to statistical methods to determine mean values and components of variance, with the following results:

1. Mean testing—There is no significant difference in means (5 percent level) for the different size samples from 12.5 to 200 lb. There is more variation within large samples than between samples of different sizes. This conclusion is true no matter if the sample is split using quartering or the splitting method. This conclusion is subject to some controversy, however, because one of the basic assumptions of analysis of variance may have been violated, i. e., the assumption that the variances are equal.
2. Variance testing—Quartering produces significantly greater variability than splitting on the 100- and 200-lb samples. Based on Cochran's test and the F ratio test, the proper choice of sample size is not clear; i. e., it is not clear if one obtains less variability by testing 200 lb or 12.5 lb of material. Based on the results of the computer output of variances and Cochran's test and the F ratio test at the 5 percent level, and the practicality of testing, the 25-lb sample seems to be appropriate. There is some indication, however, that the 50-lb sample may produce a more acceptable variability when one considers sample size. In no case, however, should a sample be reduced by using the quartering method.

3. Ranges in test results of the following magnitude were found in the results for the five sizes of samples.

Sieve Size	Percent
1 in.	1.1 to 3.3
½ in.	1.8 to 7.4
No. 4	1.9 to 3.3
No. 8	0.6 to 1.4

4. Samples from the stopped loaded belt show less variation than do samples from the layer.

PHASE II—TENTATIVE PROCEDURES FOR GRADATION ACCEPTANCE

The field experience and data in Phase I of this research project led to the following statements as guidelines for a system of control and acceptance of aggregate gradations:

1. The gradation of any given lot of aggregate must be controlled initially at the source. The sampling and testing can be done by the producer or by the State Highway Department. However, acceptance at the source is impractical because of the possibilities of segregation during subsequent handling before the aggregate is used. The producer should test each lot or shipment to determine conformity with specifications.
2. The chances for variations in stockpile samples are so great that such samples are entirely undependable for control or acceptance purposes.
3. Even though a lot of aggregate may be graded within specifications as it is loaded, segregation may occur during subsequent handling, and samples obtained from the lot as the material is used will fail to meet specifications.
4. The State Highway Department wants and expects aggregate to meet gradation requirements when it is used. Therefore, as-used samples of the aggregate are most pertinent to a realistic acceptance plan.

From this background, tentative procedures for random sampling and tentative procedures for acceptance of gradations of aggregates were developed. The details are not given here because of revisions later.

PHASE III—FIELD TESTING OF TENTATIVE PROCEDURES

The tentative procedures for obtaining random as-used samples and the tentative method for determining acceptance of gradation test results were tested under regular field conditions to determine the applicability of these procedures to routine operations.

The field work was planned to include various sizes and types of aggregate most commonly used. All samples were obtained by the same team of two men in order to remove the variable resulting from different operators. Samples were obtained as the aggregate was being used from loaded belts, where possible, or from the roadway. Sixty lots of aggregate were sampled on projects. Five random as-used samples were obtained from each lot. Twenty-three lots were replicated to develop data on the sources of variations in the test results. The size of the lot was considered as the quantity of aggregate used during the day on which the samples were obtained. The time or batch or station at which the samples were obtained was determined by random numbers.

Analysis of Data

Many of the results did not conform to the requirements of present specifications. The variations from specification limits were very large in some instances, and they indicate that some lots of material did not conform to specification requirements.

Study of the test data compared with the tentative procedure for acceptance disclosed that the procedure was workable but somewhat complicated. The incidence of failure to conform with control limits was somewhat higher than the failures to conform to existing specifications. The tentative tables of percentages for payment gave drastically reduced prices for payment in some instances. Thus, it became evident that revisions in the procedure were needed.

The analysis of variances showed definite indications that variance resulting from testing is the major source of variation. The variance between batches and within batches is very large in a few instances, but the data indicate that these variations are random in nature and can be expected on that basis. The constant appearance of high values for testing variance indicates that a study to try to reduce testing variance is needed.

Revised System

Based on the foregoing analysis, sone details of the system were revised. The system as revised specifies that a lot of aggregate will be considered for acceptance on the basis of the results from five random samples obtained from the lot as the aggregate is being used. The quantity of aggregate that will constitute a lot will be the quantity of aggregate used in 1 mile of 24-ft wide concrete pavement, surface treatment, or base course. For structures, the quantity of aggregate used in 100 cu yd of concrete or equivalent volume will constitute a lot. These assumptions would give a lot size of approximately 2,000 tons of each coarse aggregate for concrete pavement, 350 tons of coarse aggregate and 150 tons of fine aggregate for surface treatment, and 4,500 tons for macadam or stabilizer aggregate.

The gradation results for the five random samples from the lot will be compared with standards-given control charts for which the engineer has previously established central values and standard deviations. Upper and lower control limits for the individual samples will be determined by the formula $\overline{X}' \pm 2.33\sigma$, and for grouped data, average of five results, by the formula $(N = 5) = \overline{X}'' \pm 1.04\sigma$.

The lot of aggregate will be considered for acceptance according to the following criteria:

Case I—All results are within control limits. When, for all sieves, individual results and the average of the five results are within the respective tolerances of the upper and lower control limits, the lot will be accepted.

Case II—Individual results are out of control. When, for a certain sieve, one or more individual results exceed the tolerances of the upper or lower control limit and the average of the five results is within the respective tolerances, the payment for the lot will be adjusted according to the following procedure:

1. The percentage of excess for each individual deviation will be determined by the following formula:

$$\text{Percentage of Excess} = \frac{X - (\overline{X}' \pm 2.33\sigma)}{2.33\sigma} \cdot 100$$

Where

X = individual test result,
$\overline{X}'$ = desired average, and
σ = standard deviation.

2. The percentage for payment for each deviation will be determined according to the following schedule:

Percentage of Excess	Percentage for Payment	Percentage of Excess	Percentage for Payment
0	100	30 to 60	98
0 to 15	99.5	60 to 100	95
15 to 30	99	100 and over	90*

*The engineer will direct whether to adjust at this figure and leave in place or remove and replace.

3. The payment for the lot will be the delivered price of the aggregate multiplied in series by the percentage for payment for each deviation.

Case III—Individual results are within tolerances but the average of the five results is out of control. When, for a certain sieve, the individual results are within the tolerances of the upper and lower control limits but the average of the five results exceeds the tolerances of the upper and lower control limits for grouped data, the price for payment for the lot will be adjusted according to the following procedure:

1. The percentage of excess will be determined by the formula:

$$\text{Percentage of Excess} = \frac{\overline{X}\ (N = 5) - (\overline{X}' \pm 1.04\sigma)}{1.04\sigma} \cdot 100$$

where

$\overline{X}$ = average of five results,
$\overline{X}'$ = desired average, and
σ = standard deviation.

2. The percentage for paymant will be determined according to the following schedule:

Percentage of Excess	Percentage for Payment
0	100
0 to 15	99
15 to 30	98
30 to 60	95
60 to 100	90
100 ±	80*

*The engineer will direct whether to adjust at this figure and leave in place or remove and replace.

3. The payment price for the lot will be the delivered price of the aggregate multiplied by the percentage for payment.

Case IV—Individual results and average of five results are out of control on one sieve. When, for a certain sieve, one or more individual results exceed the tolerances of the upper and lower control limits for individual results and the average of the five results also exceeds the tolerances for grouped data, the payment for the lot will be adjusted according to the following procedures:

1. The percentage for payment for the deviations of individual results will be determined by the method given for Case II.
2. The percentage for payment for the average of the five results will be determined by the method given for Case III.
3. The percentage for payment for the lot will be the smaller of the percentages for payment as determined in 1 and 2 immediately preceding. The payment price for the lot will be the delivered price of the aggregate multiplied by the percentage for payment.

Case V—Individual results and/or average of five results exceed tolerances on two or more sieves. When, for two or more sieves of a gradation, the individual results or the average of the five results exceed the respective tolerances of the upper or lower control limits, the payment for the lot will be adjusted according to the following procedure:

1. The payment price for the deviations on each sieve will be determined by the methods prescribed for Case II, III, or IV.
2. The payment price for the lot will be the delivered price of the aggregate multiplied in series by the payment price for each sieve on which there are deviations.

Conclusions

The test results for the samples obtained in Phase III were compared with present specifications and with the system as revised. Conclusions are as follows:

1. Random as-used samples—The procedures for obtaining random samples of aggregate as the material is being used are practical for routine operations. Usually, a technician and a helper are needed for this sampling. Because plant layouts and procedures are not standardized, the exact sampling procedure at a plant must be established by an engineer who is familiar with the theoretical background of random sampling.

The lot sizes for different aggregates as recommended herein are a compromise between the desire for accuracy, the cost of the material, and the cost of inspection. For concrete pavement and structures, the frequency of sampling is about the same as now practiced. For stabilizer and macadam aggregate, the frequency is much less than now practiced because gradation of this aggregate is not critical. For surface treatment, the frequency recommended is more than now practiced, but may be justified because gradation of this aggregate is critical to the quality of the construction.

2. Present specifications—Conformity with present specifications varied from complete conformity in a few lots to a complete failure in others. The incidence of failure to conform is considered very high—20 percent of the individual results exceed limits and 33 percent of the samples fail to meet these requirements. However, there is no background of test data on as-used random samples and more variation would be expected in random samples than in representative samples. Considering that all material had been accepted, the data show that present control procedures do not ensure that the aggregates as used will conform to present gradation requirements.

3. Acceptance criteria—The revised system for control and acceptance is developed around the assumption that the aggregates sampled in Phase I and Phase III did produce acceptable results in pavement and structure. The standard deviations shown in Table 3 (Phase IV) were established from the test data on as-used samples.

Even with standard deviations established from the test data, there were many deviations outside of the control limits. These deviations are indications of large variations (nonuniformity) in the product, and show a need for effort to improve the uniformity.

4. Price adjustment—Sixty lots were sampled in Phase III; eight of these could not be analyzed because of large variations from specifications. According to criteria, adjustment in price would be due on 40 lots.

The number of these lots on which adjustments would be made according to the revised criteria is much larger than would be the case in actual practice. On a regular construction project when results of samples from a lot exceeded control limits, the contractor would be expected to make corrections so that succeeding lots would be acceptable. However, in this research work, the samples for each lot were obtained from the aggregate currently being used without regard to the results for a lot sampled previously. Therefore, no corrections were made. Typical of this difficulty were results on one project where 22 of the 24 samples contained excess fine material and on another where 19 of the 25 samples were deficient in fine material.

Also, in specifications to utilize this system, requirements can be established so that fewer instances of adjustments in price will be needed. In order to conform to present practice, the desired averages for the several gradations were set initially at the mean of present specifications. By modifying these values, slightly in most cases, the incidence of failure to conform to control limits can be greatly reduced. For example, for Aggregate No. 4 a change in the desired average for passing a 1-in. sieve from 95 to 97 percent would eliminate deviation on this sieve in 7 of the 10 lots tested. Such data were considered in preparing the drafts of models for specifications (Phase IV).

5. System for control and acceptance—The system for random sampling and control and acceptance of aggregate gradation as presented herein is practical. It will give much more accurate data on the gradation of the aggregate being used than the present method, which is based on samples from stockpiles. This system requires random samples obtained at a location as near as practical to where the aggregate is being used and where the gradation of the aggregate is the same as it is when the aggregate is incorporated into the work. This system provides a definite procedure for dealing

with lots of aggregate when test results do not conform to specification limits. The method of determining the adjustment in price is simple and easy to operate. The details of the system can be modified readily to fit new conditions and new materials without altering the basic procedures. Lot size can be changed and standard deviations can be altered with additional experience. The schedules for percentages for payment should be modified if experience indicates that the present figures do not coincide with judgment as to the effect of the deviation on the severiceability of the finished product

PHASE IV —SUGGESTED MODELS FOR SPECIFICATIONS

Models for specifications to utilize the results of this research project in regular construction are included in the unabridged final report. These specifications are based on control and acceptance of gradation determined from test results on random samples obtained as the aggregate is used or placed in the work. Generally, the gradation requirements contain a desired average value for each sieve size with tolerances or control limits for individual test results and for the average of the five results from a lot. The desired average is based on the mean of the present specifications. In a few instances, modifications have been made in order to define more exactly the gradation desired for a definite purpose or to eliminate a technical limit that would not improve the usefulness of the product. The tolerances or control limits are established by standard statistical formulas using values for variation (standard deviations) found in this research work. The desired average ($\bar{X}'$) and the standard deviations (σ) used in preparing the suggested models of specifications for each aggregate are given in Table 3.

The suggested specifications include a schedule for making an adjustment in the delivered price for a lot of aggregate when test results do not conform to the tolerances of the control limits. This schedule provides for an adjustment in the delivered price

TABLE 3

VALUES USED IN PREPARING MODELS OF SPECIFICATIONS

Sieve Size	$\bar{X}'$	σ	$\bar{X}'$	σ	$\bar{X}'$	σ	$\bar{X}'$	σ	$\bar{X}'$	σ	$\bar{X}'$	σ	$\bar{X}'$	σ
	Aggregate Number													
	1		1A		1B		2		2A		4		4M	
2½ in.	100	0.50	100	0.50			100	0.50						
2 in.	97	3.00	97	3.00	100	0.50	97	3.00						
1½ in.			52	8.00	97	3.50			100	0.50	100	0.50	100	0.50
1 in.	52	8.00	7	5.00	37	6.50	67	8.00	85	8.00	97	2.00	95	2.50
¾ in.					7	4.00								
½ in.	20	6.00	2	2.00			35	11.00	47	11.00	42	8.00	42	8.00
⅜ in.					2	2.00								
No. 4							22	9.00	22	9.00				
No. 8	1	2.00									1	2.00	5	2.00
	Aggregate Number													
	3		4X		5		6		6M		9		9M	
1½ in.	100	0.50												
1 in.	95	4.00	100	0.50	100	0.50	100	0.50	100	0.50				
¾ in.	40	8.00			97	3.00	95	3.00	95	3.00				
½ in.	4	3.50	42	8.00							100	0.50	100	0.50
⅜ in.					17	6.00	37	8.00	37	8.00	90	5.00	100	1.00
No. 4	0	1.50			1	1.00					35	6.00	55	7.00
No. 8			1	2.00			5	2.00	2	2.00				
No. 16					0	1.00								
No. 100											0	1.00	0	1.00
	Aggregate Number													
	20		21		22		23		24					
½ in.										0.50				
⅜ in.		0.50				0.50	100			2.00				
No. 4		1.00		0.50		2.00	95	2.00						
No. 8		2.50		2.50						6.00				
No. 16		6.00		6.00		6.00	60	6.00						
No. 30		4.00		4.00						6.00				
No. 50		2.50		2.50		2.50								
No. 100		1.00		1.00		1.00	0	1.00						
No. 200										2.00				

Note: $\bar{X}'$ = desired average, σ = standard deviation.

TABLE 4

TYPICAL MODEL SPECIFICATION
(Gradation Only)

61B6 Aggregates: Aggregate No. 3

Gradation: Each lot of aggregate shall be graded to conform to the requirements given hereafter. The size of a lot will be the quantity required for 1 mile of pavement 24 ft wide, or the quantity required for a project, whichever is smaller. Five random samples will be obtained from each lot as the aggregate is being used. The method of sampling will be established by the engineer.

Sieve Size	Percentage by Weight Passing (control limits)		
	Desired Average	Individual Results	Average of Five Results
½ in.	100	98.8 to 100	99.5 to 100
1 in.	95	85.7 to 100	90.8 to 100
¾ in.	40	21.4 to 58.6	31.7 to 48.3
½ in.	4	0.0 to 12.2	0.0 to 7.6
No. 4	0	0.0 to 3.5	0.0 to 1.6

When test results exceed these control limits, the lot of aggregate may be accepted subject to an adjustment in the delivered price that will be determined according to the following schedule:

Sieve Size	Percentage by Weight Passing									
	Individual Results					Average of Five Results				
1½ in.	98.8	98.6	98.4	98.1	97.6	99.5	99.4	99.3	99.2	99.0
	100.0					100.0				
1 in.	85.7	84.3	82.9	80.1	76.4	90.8	90.2	89.6	88.4	86.6
	100.0					100.0				
¾ in.	21.4	18.6	15.8	10.6	2.8	31.7	30.4	29.2	26.7	23.4
	58.6	61.4	64.2	69.8	77.2	48.3	49.5	50.8	53.3	56.6
½ in.	0.0					0.0				
	12.2	13.4	14.6	17.1	20.4	7.6	8.1	8.7	9.8	11.2
No. 4	0.0					0.0				
	3.5	4.0	4.6	5.6	7.0	1.6	1.8	2.1	2.5	3.2
Percent Excess	0+	-15+	-30+	-60+	-100+	0+	-15+	-30+	-60+	-100+

Percentage for Payment											
100	99.5	99	98	95	90*	100	99	98	95	90	80*

*The engineer will direct whether to adjust at this figure and leave in place or remove and replace.

The percentage for payment will be determined for each deviation in individual results and in the average of five results from the lot. For each sieve size only the smaller of the values thus obtained will be applied in adjusting the price. The adjusted price for the lot will be the delivered price of the aggregate multiplied in series by the percentage for payment for each sieve size.

TABLE 5

EXAMPLES OF PRICE ADJUSTMENTS

Sample No.	Sieve Size			
	1 in.	¾ in.	½ in.	No. 4
1. Test Results: Five random samples from lot No. 4; variations from control limits are underlined				
16	89.9	50.6	8.5	1.5
17	91.3	60.8	19.8	5.3
18	88.5	36.1	6.4	2.0
19	85.4	45.3	11.3	4.3
20	80.8	48.1	6.5	1.6
Average 5 results	87.2	48.2	10.5	2.9
Percentages for payment (from schedule in model for specification):				
Individual results	99.5			98
	98.0	99.5	95	99
Average 5 results	90	100	90	90

Price adjustment: Assume delivered price $2.85 per ton
Price for payment = $2.85 × 0.90 × 0.995 × 0.90 × 0.90 = $2.07

Sample No.	1 in.	¾ in.	½ in.	No. 4
2. Test Results: Five random samples from lot No. 5; variations from control limits are underlined				
21A1	96.8	45.2	10.0	1.3
22A1	89.9	39.2	3.6	0.5
23A1	85.7	24.8	1.5	0.4
24A1	92.8	20.4	1.2	0.1
25A1	84.2	23.1	0.8	0.2
Average 5 results	89.9	30.5	3.4	0.5
Percentages for payment (from schedule in model for specification):				
Individual results	99	99.5	100	100
Average 5 results	98	99	100	100

Price adjustment: Assume delivered price $2.85 per ton
Price for payment = $2.85 × 0.98 × 0.99 = $2.76

for the lot of aggregate on a percentage basis that decreases as the magnitude of the deviation increases.

Each suggested specification is complete within itself except that the engineer or someone familiar with the theoretical considerations involved should select the location from which the random samples will be drawn. The guiding principle for this selection is that the samples will be drawn at a place as near as possible to where the aggregate is used in the work, and where the gradation of the aggregate is the same as it is when the aggregate is incorporated into the work. For concrete aggregate, sampling from a stopped loaded belt between the storage and the weighing bins is preferred. For surface treatment aggregate, sampling with special trays placed on the roadway is expected. For macadam or stabilizer aggregate, the sampling will be done at a randomly selected point after the aggregate has been spread and processed.

A typical model for a specification is given in Table 4. The method for determining the adjustment in price for actual test results is given in Table 5.

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