Technical Report Documentation Page

1. REPORT No.

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE

Statistical Quality Control In Highway Construction

5. REPORT DATE

January 1968

6. PERFORMING ORGANIZATION

7. AUTHOR(S)

John L. Beaton

8. PERFORMING ORGANIZATION REPORT No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

10. WORK UNIT No.

11. CONTRACT OR GRANT No.

13. TYPE OF REPORT & PERIOD COVERED

12. SPONSORING AGENCY NAME AND ADDRESS

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

California's experience in making a statistical study of its quality specifications for highway and bridge construction materials is described. Four years of research on sampling and testing of materials such as compacted embankment, plastic concrete, cement treated base, structural concrete aggregate, untreated base material and aggregate subbase material is beginning to provide information concerning variations due to sampling, testing, and those inherent in the material itself. Suggested in place of traditional methods is Statistical Quality Control (SQC). The use of SQC could shift the quality control responsibility to the contractor with the buyer basing his purchase on a statistically sound end point evaluation. Problems arising in the use of SQC may be met by training in the technology of statistical control, recognition of the fact that there is no need to supply statistical specifications to every construction item, the establishment of new specification limits, and a revision of testing procedures.

17. KEYWORDS

aggregates; cements; concretes; construction; control charts; highways; quality control; sampling; statistical analysis; tests

18. No. OF PAGES:

20

19. DRI WEBSITE LINK

http://www.dot.ca.gov/hq/research/researchreports/1968/68-67.pdf

20. FILE NAME

68-67.pdf

68-67

5708 January, 1968 CO 1

Journal of the
CONSTRUCTION DIVISION
Proceedings of the American Society of Civil Engineers

STATISTICAL QUALITY CONTROL IN HIGHWAY CONSTRUCTION[a]

By John L. Beaton,[1] F. ASCE

INTRODUCTION

Control of the quality of construction materials used in modern highway and bridge construction is undergoing a revolution. The first step in this revolution occurred in the late 1950's as the result of a multitude of investigations of interstate highway construction. The effect of these investigations was to show a need to upgrade highway construction practices throughout the United States.

To implement this program, check samples are taken during the progress of the work and from the completed structure. This record sampling is in addition to regular control sampling. A statistical analysis of California's final record samples indicates that the highway industry has met this challenge successfully and, in general, is now producing construction that is uniformly as near to perfection as is economically practical. Fig. 1 shows a typical example of this improvement in the quality of subbase material. This success was achieved with little change in the basic quality controls of highway materials and with little or no application of the statistical concept to the enforcement of specifications.

Now that we have achieved a uniform product, the United States Bureau of Public Roads and several of the various State highway agencies have initiated statistical studies of their quality specifications. These studies have been under way since 1963 and are now beginning to provide objective information concerning sampling error, testing error, and variations inherent in the material itself. Many highway administrators felt that the extensive investigations into highway practices during the late 1950's and early 1960's substantiated the adoption of statistical specifications with particular emphasis on random sampling in lieu of representative sampling. However, the practical

Note.—Discussion open until June 1, 1968. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Construction Division, Proceedings of the American Society of Civil Engineers, Vol. 94, No. CO1, January, 1968. Manuscript was submitted for review for possible publication on June 13, 1967.

[a]Presented at the May 8-12, 1967, ASCE Structural Engineering Conference held at Seattle, Wash., where it was available as Preprint 513.

[1]Materials and Research Engr., California Div. of Highways, Sacramento, Calif.

engineer, well aware of the increased cost that this might entail, pointed out that the desired results were achieved without radical innovations; and they were therefore reluctant to change unless a more efficient procedure could be developed. At the present, however, there are more compelling reasons for changing current control procedures: namely, the trend towards end point specifications and the increasing speed of construction.

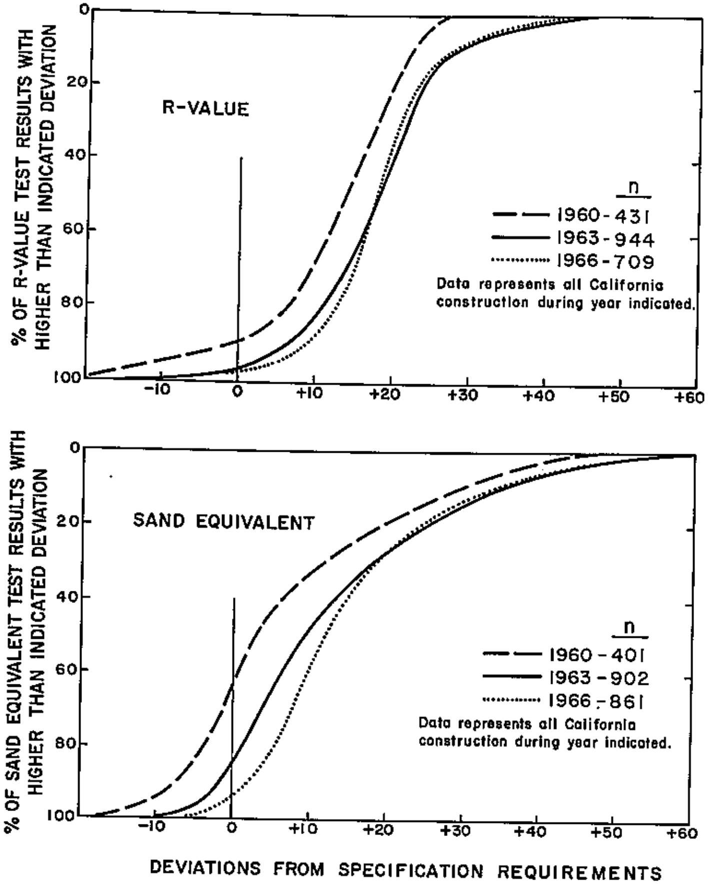

FIG. 1.—OGIVE CURVES FOR DEVIATIONS FROM THE SPECIFICATION R-VALUE AND SAND EQUIVALENT REQUIREMENTS FOR AGGREGATE SUBBASE

Most of our present quality tests are based on a tempo much slower than today's fast moving construction industry. Innovation in future construction work will hasten the obsolescence of today's testing methods.

A promising method that might be used to meet these demands of tomorrow is the utilization of the statistical quality control (SQC) procedures employed by other industries. To do this, however, will require complete changes in philosophy, several years of training, and specification revisions. Traditionally, highway and bridge construction have been controlled by methods or prescription type specifications combined with some end point controls. This has irritated some of the more competent contractors, who say, "Tell us what you want and we will give it to you, but don't interfere with the method we plan to use." As a matter of fact, by using a method specification as Foster and Stander[2] imply, the engineer finds himself in the position of being a party to the control and is in a difficult position when rejection of the final product is needed. Probably the engineer's biggest concern over abandoning method specifications is that there are certain qualities of materials which do not lend themselves to an end point specification. At present (1967), end point tests are not available to measure many of the particular qualities needed. Quality measurement is further complicated because the level of quality

TABLE 1.—CALIFORNIA'S STATISTICAL SURVEY PROGRAM

Construction Items	Tests of Properties
Roadway Embankment	Relative Compaction Test
Untreated Base Material	Sieve Analysis Sand Equivalent R-Value
Subbase Material	Sieve Analysis Sand Equivalent R-Value
Cement Treated Base	Determination of Cement Content
Structural Concrete Aggregate	Sieve Analysis Sand Equivalent Cleanness
Plastic Concrete	Slump of PCC (Kelly Ball Method)
Corrugated Metal Pipe	Thickness of Galvanizing
Paving Asphalt	Penetration Test

required for a specific material varies with use. For example, an aggregate satisfactory as a subbase might be totally inadequate for use as a base or in a structure.

In attempting to control the quality of concrete, the only reasonable rapid end point controls we have at present are tests of strength either in compression or flexure. However, the qualities of durability, low shrinkage, sulfate resistance, etc., are more important, especially insofar as a highway pavement is concerned. At present, these latter qualities can only be controlled by regulating the aggregate characteristics, cement chemistry, percentage of entrained air, and other related factors. If such a material is to be accepted on end results alone, enforcement procedures and measurements must be devised. There are some who advocate an adjusted price scale for a less than desirable quality. This is a questionable practice in that the original

[2] Foster, C. R., and Stander, R. R., "Implications of Statistical Quality Control From the Contractors' Viewpoint," Proceedings, May 3-5, 1966, National Conference on Statistical Control Methodology in Highway and Airfield Construction, University of Virginia, Charlottesville, Va., p. 629.

design concept was based on a service life established by experience. Presently there is little background available to determine the degree of effect of a lesser quality in one of the items. In fact, it seems right to presume that had the designer known that a lesser product were to be furnished, he might well have designed a completely different project.

Most industries using SQC at the present time (1967) have shifted the control responsibility to the producer, with the buyer basing his purchase on a statistically sound end point specification. The important part of this process is that the producer maintains quality control records that are always available to the buyer. Using this approach, the control of most of the factors could be achieved and the responsibility would be where it probably belongs—with the contractor. Procedural checks would, of course, be necessary so that the owner could be assured that the contractor's operation is actually under control at all times. However, one governmental agency which uses statistical quality control for road construction performs its own control work. After five years of experience, the engineers of the City of Montreal have found that the advantages of SQC outweigh the disadvantages. The contractors also favor these procedures.[3]

As stated previously, much of the information necessary to write objective statistical specifications for existing tests is now available. (Most of this information is on file with the United States Bureau of Public Roads.) Table 1, for instance, lists the items in California's contribution to this program.

SAMPLING AND TESTING PLAN

The object of the California study was to determine the variance due to sampling and testing as well as the variance inherent in the material being studied. This was accomplished independently for each item studied by randomly selecting 50 sampling locations on each of three separate construction projects. At each sampling location, duplicate samples were taken side by side and later split, thus allowing four independent test results for each location. There were 200 test results from each project and a total of 600 test results for each item tested.

The duplicate sampling provided a measure of the sampling error. Duplicate tests on split samples provided a measure of the variance introduced by the splitting and testing process. The 50 test locations on each project provided a measure of the basic variance in the process or material.

All field sampling and testing for this research was done in addition to the normal job control testing (representative sampling). Only material which had been accepted by construction forces was sampled in this random survey.

In addition, an evaluation of the control test records on hand was conducted for both asphalt and zinc coating of corrugated metal pipe. No further special tests were conducted. Even though random sampling procedures were not

[3] Keyser, J. Hode, "Experience in the Application of Statistical Methods in Road Construction and Materials," Proceedings, May 3-5, 1966, National Conference on Statistical Quality Control Methodology in Highway and Airfield Construction, University of Virginia, Charlottesville, Va., p. 117.

employed, these results are still considered valid since in both cases every lot of material was tested for quality.

ANALYSIS OF FINDINGS

A summary of the results for the construction items included in this survey is presented in Fig. 2 and Table 2.

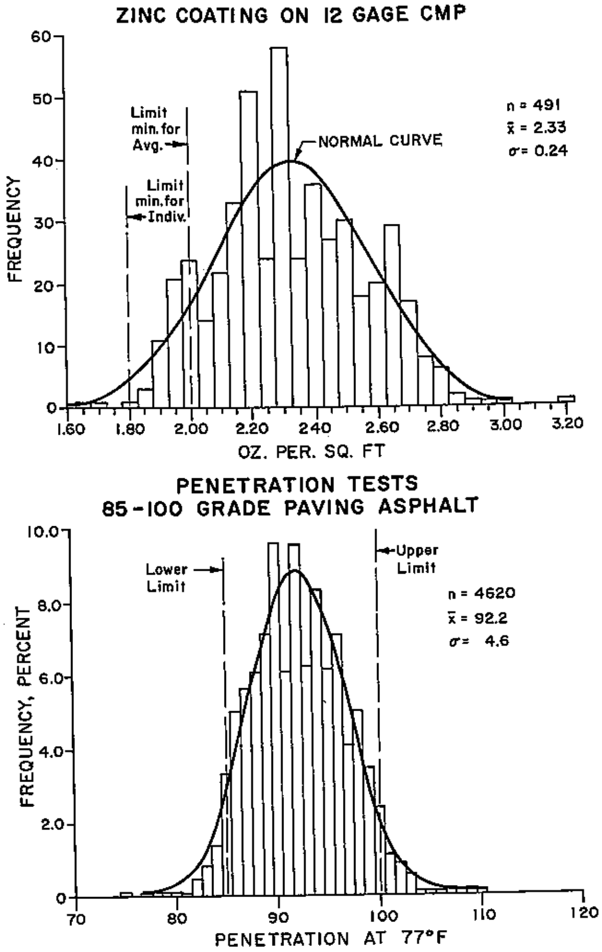

FIG. 2.—DISTRIBUTION CURVES

An important over-all finding of this research work is that present specifications, in many instances, are too restrictive and consequently are not being met, statistically speaking. Present specifications make no provisions

TABLE 2.—SUMMARY OF RESULTS FOR VARIOUS CONSTRUCTION ITEMS

Project (1)	Number of Obser-vations, n (2)	Arith-metic Mean, $\bar{x}$ (3)	Specifi-cations (4)	Material Variance, σ_A^2 (5)	Sampling Variance, σ_S^2 (6)	Testing Variance, σ_T^2 (7)	Overall Variance, σ^2 (8)	Overall Standard Deviation, σ (9)
(*a*) Plastic Concrete								
Test: Slump of PCC (Kelly Ball Method)—Test Method No. Calif. 520								
			Intended Slump, in inches					
K-1	200	3.7	4.0	0.6	0.0	0.1	0.8	0.9
K-2	196	4.0	Varied from 3 to 4.5	0.6	0.0	0.2	0.8	0.9
K-3	199	4.0	4.5	1.4	0.1	0.1	1.6	1.3
K-4	200	1.7	1.5	0.1	0.0^c	0.3	0.4	0.6
(*b*) Cement Treated Base								
Test: Percentage of Cement in CTB—Test Method No. Calif. 338								
			Intended Cement Content					
1	184	2.5	Varies Usually 2.4%	0.07	0.07	0.02	0.16	0.40
2 (Adjusted)	100	3.8	4.0%	0.22	0.08	0.03	0.33	0.57
3	200	3.0	3.0%	0.06	0.01	0.01	0.08	0.28
(*c*) Compacted Embankment								
Test: Relative Compaction (Sand Volume)—Test Method No. Calif. 216								
E-1	200	92.9	90 min	3.7	2.2	0.2	6.1	2.4
E-2	200	90.5	90 min	5.4	4.2	0.0	9.6	3.1
E-3	176	93.6	90 min	15.1	15.1	0.7	30.9	5.5
(*d*) Structural Concrete Aggregate—Sand								
Test: Sand Equivalent—Test Method No. Calif. 217								
C-1	200	77.0	75 min	12.8	0.2	5.5	18.5	4.3
C-2	200	86.0	75 min	3.5	0.0^c	3.2	6.7	2.6
C-3	200	82.2	75 min	2.7	1.0	3.9	7.6	2.8
Test: Sieve Analysis—Percentage Passing No. 4 Sieve—Test Method No. Calif. 202								
C-1	196	96.4	90—100	1.1	0.0	0.4	1.5	1.2
C-2	200	96.3	90—100	0.2	0.0^c	0.3	0.5	0.7
C-3	200	99.9	90—100	0.0	0.0	0.1	0.1	0.3
Test: Sieve Analysis—Percentage Passing No. 8 Sieve—Test Method No. Calif. 202								
C-1	200	74.3	65—95	6.0	0.6	7.3	13.9	3.7
C-2	200	80.5	65—95	0.8	0.3	0.5	1.6	1.3
C-3	200	83.9	65—95	0.5	0.0^c	1.5	2.0	1.4
Test: Sieve Analysis—Percentage Passing No. 16 Sieve—Test Method No. Calif. 202								
C-1	200	51.2	45—70	15.8	2.6	15.3	33.7	5.8
C-2	200	64.7	45—70	1.4	0.4	0.6	2.4	1.5
C-3	200	61.9	45—70	1.7	0.0	2.4	4.1	2.0
Test: Sieve Analysis—Percentage Passing No. 30 Sieve—Test Method No. Calif. 202								
C-1	200	34.2	25—45	23.3	2.2	7.2	32.7	5.7
C-2	200	42.2	25—45	2.6	0.2	0.8	3.6	1.9
C-3	200	39.1	25—45	2.3	0.0	2.9	5.2	2.3

TABLE 2.—*CONTINUED*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Test: Sieve Analysis—Percentage Passing No. 50 Sieve—Test Method No. Calif. 202								
C-1	200	15.0	10—20	9.0	0.4	2.0	11.4	3.4
C-2	200	16.9	10—20	2.4	0.3	0.6	3.3	1.8
C-3	200	18.0	10—20	1.0	0.0[c]	1.3	2.3	1.5
Test: Sieve Analysis—Percentage Passing No. 100 Sieve—Test Method No. Calif. 202								
C-1	200	3.5	2—8	0.5	0.0	0.3	0.8	0.9
C-2	200	4.3	2—8	0.5	0.0	0.3	0.8	0.9
C-3	200	4.9	2—8	0.1	0.0[c]	0.3	0.4	0.6
Test: Sieve Analysis—Percentage Passing No. 200 Sieve—Test Method No. Calif. 202								
C-1	196	1.7	0—4	0.0[c]	0.1	0.1	0.2	0.4
C-2	200	1.6	0—4	0.5	0.0[c]	0.4	0.9	0.9
C-3	200	1.7	0—4	0.1	0.0	0.2	0.3	0.5
(*e*) Structural Concrete Aggregate—1-1/2 in. × 3/4 in. Test: Cleanness Value—Sediment Height, in inches—Test Method No. Calif. 227								
C-1	200	0.5	1.0 max	0.02	0.0[c]	0.01	0.03	0.17
C-2	188	1.4	1.0 max	0.58	0.07	0.06	0.71	0.84
C-3	184	1.1	1.0 max	0.62	0.04	0.15	0.81	0.90
Test: Sieve Analysis—Percentage Passing 1-1/2 in. Sieve—Test Method No. Calif. 202								
C-1	200	94.7	90—100	4.4	0.0[c]	8.8	13.2	3.6
C-2	200	98.3	90—100	2.4	0.0[c]	3.4	5.8	2.4
C-3	200	88.8	90—100	16.0	1.5	9.6	27.1	5.2
Test: Sieve Analysis—Percentage Passing 1 in. Sieve—Test Method No. Calif. 202								
C-1	200	25.5	20—55	39.4	3.4	44.3	87.1	9.3
C-2	200	19.3	5—40	67.3	0.6	7.7	75.5	8.7
C-3	200	23.1	5—40	45.8	1.2	19.3	66.3	8.1
Test: Sieve Analysis—Percentage Passing 3/4 in. Sieve—Test Method No. Calif. 202								
C-1	200	6.4	0—15	2.2	0.3	2.2	4.7	2.2
C-2	200	6.9	0—15	16.3	1.0	1.0	18.3	4.3
C-3	200	7.4	0—15	11.8	1.0	4.2	17.0	4.2
Test: Sieve Analysis—Percentage Passing 3/8 in. Sieve—Test Method No. Calif. 202								
C-1	200	1.7	0—5	0.3	0.1	0.4	0.8	0.9
C-2	200	2.9	0—5	4.2	0.5	0.3	5.0	2.2
C-3	200	3.4	0—5	4.5	0.7	1.3	6.5	2.5
(*f*) Structural Concrete Aggregate—1 in. × No. 4 (Project C-1 is 3/4 in. × No. 4) Test: Cleanness Value—Sediment Height, in inches—Test Method No. Calif. 227								
C-1	200	0.26	1.0 max	0.01	0.0	0.0	0.01	0.10
C-2	200	0.69	1.0 max	0.04	0.0	0.01	0.05	0.22
C-3	200	0.58	1.0 max	0.02	0.0	0.0	0.02	0.14
Test: Sieve Analysis—Percentage Passing 3/4 in. Sieve—Test Method No. Calif. 202								
C-1	200	92.6	90—100	4.3	0.0[c]	8.1	12.4	3.5
C-2	200	69.1	60—85	122.9	5.6	4.5	133.0	11.5
C-3	200	75.5	60—85	124.0	9.3	24.5	157.8	12.5
Test: Sieve Analysis—Percentage Passing 3/8 in. Sieve—Test Method No. Calif. 202								
C-1	200	40.9	20—55	34.4	0.0[c]	30.4	64.8	8.0
C-2	200	18.6	15—40	71.8	1.2	6.0	79.0	8.9
C-3	200	17.0	15—40	39.1	4.9	3.7	47.7	6.9
Test: Sieve Analysis—Percentage Passing No. 4 Sieve—Test Method No. Calif. 202								
C-1	200	3.5	0—15	1.6	0.0[c]	1.0	2.6	1.6
C-2	200	2.1	0—15	0.9	0.1	0.2	1.2	1.1
C-3	200	3.3	0—15	1.5	0.4	0.3	2.2	1.5

TABLE 2.—*CONTINUED*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Test: Sieve Analysis—Percentage Passing No. 8 Sieve—Test Method No. Calif. 202								
C-1	200	1.1	0—5	0.1	0.0[c]	0.3	0.4	0.6
C-2	—	—	0—5	—	—	—	—	—
C-3	200	2.5	0—5	0.5	0.2	0.3	1.0	1.0
(*g*) Untreated Aggregate Base Material Test: R-value—Test Method No. Calif. 301								
B-1	200	81.9	78 min	0.1	0.2	1.5	1.8	1.3
B-2	200	79.9	75 min	1.1	0.0[c]	4.7	5.8	2.4
B-3	200	79.7	78 min	0.2	0.2	1.8	2.2	1.5
Test: Sand Equivalent—Test Method No. Calif. 217								
B-1	200	42.9	30 min	10.7	0.9	4.2	15.8	4.0
B-2	200	30.6	30 min	35.2	0.5	1.3	37.0	6.1
B-3	200	59.2	30 min	11.1	0.0[c]	4.7	15.8	4.0
Test: Sieve Analysis—Percentage Passing No. 4 Sieve—Test Method Calif. 202								
B-1	200	50.9	35—55	9.2	0.3	0.3	9.8	3.1
B-2	200	58.1	35—55	5.6	0.7	1.7	8.0	2.8
B-3	200	52.7	35—55	21.4	6.9	4.0	32.3	5.7
Test: Sieve Analysis—Percentage Passing No. 30 Sieve—Test Method No. Calif. 202								
B-1	200	23.8	10—30	4.5	0.2	1.5	6.2	2.5
B-2	200	27.3	none	4.4	0.4	0.6	5.4	2.3
B-3	200	23.4	10—30	5.2	1.6	1.7	8.5	2.9
Test: Sieve Analysis—Percentage Passing No. 200 Sieve—Test Method No. Calif. 202								
B-1	200	6.0	3—9	0.2	0.0	0.2	0.4	0.6
B-2	200	7.9	3—12	1.0	0.1	0.2	1.3	1.1
B-3	200	4.6	3—9	0.4	0.0[c]	0.5	0.9	0.9
(*h*) Aggregate Subbase Material Test: R-value—Test Method No. Calif. 301								
S-1	200	68.8	60 min	14.6	0.0[c]	25.9	40.5	6.4
S-2	188	77.2	60 min	4.5	0.1	5.3	9.9	3.1
S-3	200	70.9	55 min	54.0	0.0[c]	25.3	79.3	8.9
Test: Sand Equivalent—Test Method No. Calif. 217								
S-1	200	30.2	25 min	3.5	0.0[c]	12.8	16.3	4.0
S-2	188	36.2	25 min	60.6	2.4	9.4	72.4	8.5
S-3	200	29.2	25 min	5.5	0.0[c]	1.9	7.4	2.7
Test: Sieve Analysis—Percentage Passing No. 4 Sieve—Test Method No. Calif. 202								
S-1	200	49.5	35—65	14.4	0.3	3.7	18.4	4.3
S-2	188	72.6	30—100	36.7	0.1	5.9	42.7	6.5
S-3	200	45.0	35—80	34.3	3.3	6.0	43.6	6.6
Test: Sieve Analysis—Percentage Passing No. 200 Sieve—Test Method No. Calif. 202								
S-1	200	7.8	3—11	0.5	0.2	1.1	1.8	1.3
S-2	188	10.0	0—20	2.5	0.0[c]	0.8	3.3	1.8
S-3	200	8.6	5—35	2.3	0.1	0.5	2.9	1.7

[c] Slight negative variance set equal to zero.

for other than 100% compliance, although 100% is not always practical or even attainable.

Even though these restrictive specifications provide a satisfactory working document for construction, there is still a recognized need—indeed pressure—to improve specifications in order to have more uniform interpretation on all construction projects. It is in this area that statistical control procedures may prove to be advantageous to all concerned, no matter what management of control is used.

Statistical specifications are based on certain theoretical assumptions and, before attempting to find practical applications for these procedures, it should first be established that statistical procedures can be theoretically applied to construction control. Usually statistical control procedures are based on the assumption that the samples are drawn from a normal population. This does not mean that a few results will plot in the familiar bell-shaped pattern. However, a histogram of 3,000 or 4,000 results can be expected to approach normality. As seen in Fig. 2, the results of penetration tests for asphalts closely approach a normal distribution. Results from many control tests, strength of concrete, consistency of fresh concrete, and others, approach normality. It can therefore be concluded that it is theoretically possible to use established statistical control procedures for the control of many construction items.

Before concluding, however, that statistical control procedures will be adopted without any difficulties, it would be well to review some problems which could retard the adoption of such specifications.

PROBLEMS

1. Most construction engineers and inspectors are unfamiliar with the technology and terminology of statistical quality control.
2. In highway work where most of the construction involves local native materials, it is often necessary to make immediate decisions regarding variations from specifications. Such decisions must be made by experienced engineers and based on the knowledge of the effect of the varying factors on the over-all structure.
3. Most of the present specifications and test methods are not written with the intent of using random or statistical sampling.
4. There is serious concern that the cost of construction control will increase with the adoption of statistical control procedures.

The first problem denotes a need for training in the technology of statistical control. To exemplify this need, reference is made to Fig. 3 which provides an insight into the difference between statistical control methods and present construction control procedures. The curve of random tests represents the results acquired for this research study, while the final control tests are plotted from "representative" samples chosen in the presently accepted manner and used for actual acceptance of the work. Thus, we have two representations of the same material which do not indicate the same results. The experienced engineer, who is used to thinking in terms of the final control tests, could draw erroneous conclusions if presented with random results. For instance, during discussions of the histogram in Fig. 3

with groups of experienced engineers, even though it was clearly stated that all random results were from material that had been previously and independently accepted and that the work was, in fact, fully acceptable, some members of each group would invariably conclude that the material needed additional processing or that someone was lax. It usually took a full review to convince the engineers that the random samples were taken from acceptable construction.

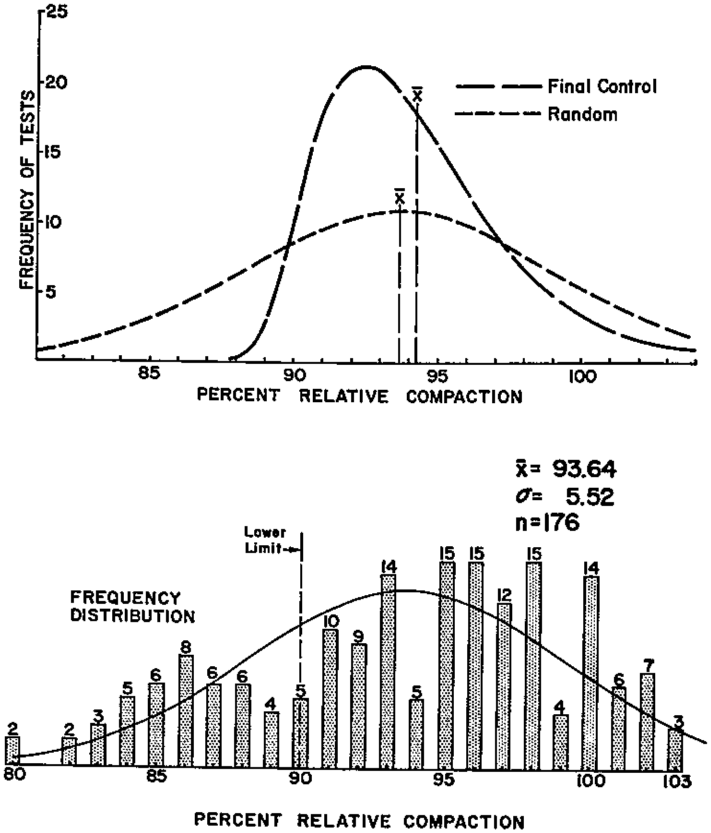

FIG. 3.—DISTRIBUTION CURVES, FREQUENCY VERSUS PERCENTAGE RELATIVE COMPACTION FOR ROADWAY EMBANKMENT

The problem of training is not limited to engineers. Recently Ted Busch, Vice President of the Dundick Corporation, stated[4]:

> We lack a language for communication with other disciplines. We lack technicians who can reliably provide data. We are subject to fatuous

[4]Busch, Ted, "Industrial Quality Control," Journal of the American Society for Quality Control, Vol. 23, No. 1, July, 1966, p. 7.

instrumentation claims. And we have allowed the American love of novelty and fad to becloud measurement practices.

If this problem is still to be found in the precise tool manufacturing industry, it can only be expected to be magnified in construction.

The development of a new group of engineers, technicians, and contractors who are oriented toward statistical procedures will be a slow, tedious process. The development of personnel needed to make this necessary change will take planning, training and, most importantly, experience.

The second problem regarding the adoption of statistical procedures in areas where engineering judgment now prevails is complicated, to say the least. For example, in California the experienced engineer would be concerned about obtaining the highest possible density of asphalt concrete when it is placed late in the fall just before the winter rains begin. The same pavement, if it were placed in the spring, would be further consolidated and sealed by traffic during the warm, dry California summer. The experienced engineer is aware of many factors which contribute to the final density of asphalt concrete, and to commit all these factors to formal statistical control procedures appears almost impossible at this time. There seems to be no need to substitute this experience and concern with a voluminous document which could not possibly cover all situations.

The solution to this problem is to recognize that there is no great need to apply statistical specifications to every construction item. We should proceed only in those areas where it appears that these control procedures could be used to the greatest advantage.

The third problem has to do with the necessary changes in specifications and test methods before statistical control procedures can be adopted. As mentioned earlier, there is a basic difference in the test results from random and nonrandom samples. Since it has been well established that statistical control procedures should not be applied unless samples are drawn in a random manner,[5] it directly follows that new specification limits would have to be established. Ideally, these specifications should be based on engineering design criteria. However, the present state of the art of highway engineering is such that we need further information concerning many of the relationships between the destructive forces of traffic, environment, time, etc., and those material properties which resist these forces. Materials engineering knowledge has not yet reached the level of sophistication to statistically specify many of these characteristics.

In addition to changes in the specification limits, it will also be necessary to revise most current test methods. For example, one proposed statistical specification requires that all aggregates shall be sampled using random sampling procedures.[6] In another section of this specification is found the following: "Insofar as applicable, AASHO T-2 makes no reference to random sampling, but rather makes several references to representative sampling. In fact, the following quotation from T-2 would be incompatible with random sampling: "Samples from railroad cars should be taken from three or more

---

[5] "Probability Sampling of Materials," American Society for Testing and Materials, ASTM Designation E105-58, ASTM Standards, Part 30, 1967.

[6] Miller-Warden and Associates, "Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (Futurized Revision)," FP-61, U.S. Dept. of Commerce, Bureau of Public Roads, Washington, D.C., December, 1965, pp. 22, 43.

trenches dug across the car at points that appear on the surface to be representative of the material." Such examples of conflict are found throughout specification sampling procedures. Consequently, the adoption of random sampling will require modification of many existing sampling plans.

In modifying these test methods, it will be necessary to change more than just the sampling procedures. There will be an increased concern in the precision and reproducibility of the test methods and it will be advantageous to clearly define procedures and frequency for calibrating a laboratory. A daily procedure has been proposed for assuring that an asphalt laboratory is in operational control.[7] No doubt, in the future, it will be necessary to develop others.

The fourth problem being considered is the often expressed concern of many engineers that the adoption of statistical controls will result in considerably increased construction control costs. Presently, the field engineer makes a decision to accept or reject material on relatively few test results. This low sampling and testing frequency is practical because the engineer has close knowledge of construction under way and can recognize efficient operation of a plant, proper handling of materials, etc. Therefore, he can increase or decrease testing frequency according to the circumstances. In other words, the actual control is based on a much broader knowledge of the product than that obtained from a few test results. This method presumes individual experience and competence.

After studying the various established statistical sampling procedures available, such as Military Standards 105 and 414,[8,9] it is often concluded that the adoption of an established sampling plan would result in considerably more sampling and testing than is presently required. Obviously, if the present control procedure has been even remotely successful, a significant increase in the present sampling frequency would be hard to justify. In one recently proposed statistical specification for gradation of aggregate base material, a sample size of "five random samples of in-place material" was required from each day's construction.[10] While five gradation tests per day may be tolerable under some conditions, it would in general result in increased control costs. If the same principles were to be applied to all control tests, the cost of construction control would significantly increase.

In presenting these problems, it is not the intent to convey the thought that statistical quality procedures cannot be extremely valuable in construction work. On the contrary, these procedures have proved of great value in the manufacturing industries and there is no reason to believe that there are not many applications where they would be of significant value in construction work. While considerable work and effort would be required to solve the problem considered above, the only basic problem is economics. Are statistical specifications economically justified?

---

[7] "A Statistical Analysis of Penetration Test Results," Research Report #210338-1, California Div. of Highways, Materials and Research Dept., Sacramento, Calif., May, 1965, p. 5.

[8] "Sampling Procedures and Tables for Inspection by Attributes," Mil-Std-105D, U.S. Dept. of Defense, Washington, D.C., April 29, 1963.

[9] "Sampling Procedures and Tables for Inspection by Variables for Percent Defective," Mil-Std-414, U.S. Dept. of Defense, Washington, D.C., June 11, 1957.

[10] Miller-Warden and Associates, Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (Futurized Revision)," FP-61, op. cit., p. 90.

A good example of the use of statistical specifications with no increase in cost can be illustrated by California's recent shift from the sand volume method to the nuclear gage for relative compaction determination. The sand volume method is so slow that only a few tests can be made without delaying construction. Now sufficient readings can be made to apply a modified statistical method. This has been done with no change in over-all control costs and has provided the contractors with faster results. This combination of speedier tests with statistical sampling is one answer.

In addition, it should be possible to develop a systematic program with the manufacturers of cement, asphalt, steel, etc., so that inspectors could make a periodic surveillance of a plant's control procedures, chart and records. There seems to be little need for a contracting agency to duplicate the quality assurance measures performed daily by the producers. Programs of this type are in constant use and are a regular part of the military quality control program.[11] When such a program is in effect, use of the material may be based on a certification by the producer. Audit sampling and inspections could be made at the job site to assure that contamination or other damage had not occurred.

Although the refineries and mills have not statistically formalized their testing procedures, such a certification program is used successfully by the California Division of Highways for cement and asphalt. The certification is the responsibility of the contractor who must accept final responsibility. There are, no doubt, other construction items that could be controlled in this manner.

While we are waiting for statistical specifications to be developed, there are tools of the statistical procedure that probably could increase the management efficiency of our current methods. In order to hold down the cost of sampling and testing, it is proposed that chain sampling procedures be used. Chain sampling and the use of a moving average are not new and have been reported by others.[12,13,14]

It is proposed that the moving average be used to allow the engineer to make a decision to accept or reject the material based on the accumulative information from four or five of the most recent test results. The specifications could also include a procedure which would allow the engineer to make a judgment decision when an occasional test result is out of specification limits, if the moving average indicates that the particular procedure is in operational control.

In addition to using this chain sampling procedure, it is further proposed that control charts be considered. A properly maintained control chart can provide an immediate review of the quality of the material being used on

[11] "Quality Control Inspection of Purchases Manufactured by Sub-Contractors and Vendors," AFR 74-9, Dept. of Defense, U.S. Air Force, Washington, D.C., 1963.

[12] "Recommended Practice for Evaluation of Compression Test Results of Field Concrete," ACI Standards, American Concrete Institute, 1964, pp. 214.8-214.9.

[13] Wade, P. F., Kushner, M., and Keyser, J. H., "Applications of Control Charts," Proceedings, May 3-5, 1966, National Conference on Statistical Quality Control Methodology in Highway and Air Field Construction, University of Virginia, Charlottesville, Va., p. 472.

[14] Brown, H. E., "Applications of Statistical Evaluation Techniques for Quality Control of Steam Cured Concrete," Proceedings, May 3-5, 1966, National Conference on Statistical Quality Control Methodology in Highway and Air Field Construction, University of Virginia, Charlottesville, Va., p. 343.

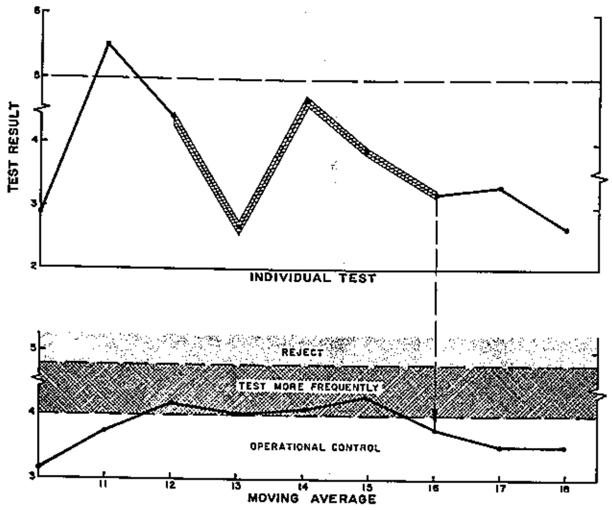

FIG. 4.—CONTROL CHARTS, INDIVIDUAL AND MOVING AVERAGE

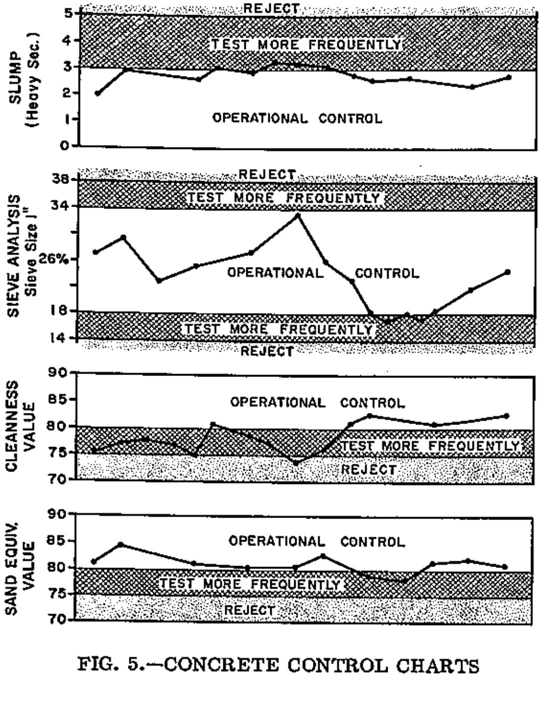

FIG. 5.—CONCRETE CONTROL CHARTS

construction and can be easily understood. These control charts could be expanded to record not only the quality of the material being used, but also pay quantities, work schedules, and other pertinent information. While control charts are not new to highway construction, it is suggested that they be formalized and accepted as contract documents in lieu of the great volume of test reports and other records which now must be maintained on all large construction projects. Samples of proposed control charts are shown in Figs. 4 and 5. (In Fig. 4, the decision to accept lot 16 is based on the average of test results 12 through 16. For lot 17 the average of 13 through 17 would be used, etc.).

If the highway industry adopts the use of SQC, it is probable that the statistical concept first would be developed and applied with no transfer of the control responsibility. After SQC proves itself, the transfer of the control responsibility to the contractor can take place. If we are to arrive at the Utopia where quality could be in the hands of the contractor, then he must be willing to accept full responsibility. For instance, take the situation where an aggregate supplier is producing from a quarry where rock tends to produce clay-like particles with handling. The engineer is interested only in the quality of the rock in place. Therefore, the contractor cannot be satisfied with a rock that just meets the cleanness specification at the plant. The rock he obtains at the plant must be of high enough quality to enable it to meet the specifications after placement has been completed. The engineer will no longer share the responsibility of progress control.

CONCLUSIONS

It is the opinion of the writer that full use of statistical quality control of highway and bridge construction is somewhat in the future. However, due to the trend towards end point specifications and the rapid acceleration of the rate of construction, some form of statistical discipline is becoming a necessity. It behooves the engineering and contracting fraternities, therefore, to join hands in sponsoring education, research, and specification preparation towards the use of SQC.

ACKNOWLEDGMENTS

This paper is based in part on data collected during a research project financed jointly by the California Division of Highways and the United States Bureau of Public Roads. The opinions, conclusions, and findings of this report are those of the writer and not necessarily those of the California Division of Highways or the Bureau of Public Roads; however, their contribution is acknowledged.

The writer especially wishes to express his appreciation to George B. Sherman and Robert O. Watkins for their help in preparation of the paper, and also to the many materials and construction engineers of the California Division of Highways for their technical contributions.

5708 QUALITY CONTROL IN HIGHWAY CONSTRUCTION

KEY WORDS: aggregates; cements; concretes; construction; control charts; highways; quality control; sampling; statistical analysis; tests

ABSTRACT: California's experience in making a statistical study of its quality specifications for highway and bridge construction materials is described. Four years of research on sampling and testing of materials such as compacted embankment, plastic concrete, cement treated base, structural concrete aggregate, untreated base material and aggregate subbase material is beginning to provide information concerning variations due to sampling, testing, and those inherent in the material itself. Suggested in place of traditional methods is Statistical Quality Control (SQC). The use of SQC could shift the quality control responsibility to the contractor with the buyer basing his purchase on a statistically sound end point evaluation. Problems arising in the use of SQC may be met by training in the technology of statistical control, recognition of the fact that there is no need to supply statistical specifications to every construction item, the establishment of new specification limits, and a revision of testing procedures.

REFERENCE: Beaton, John L., "Statistical Quality Control in Highway Construction," Journal of the Construction Division, ASCE, Vol. 94, No. CO1, Proc. Paper 5708, January, 1968, pp. 1-15.