# HIGHWAY RESEARCH RECORD

## Number 184

# Quality Control

## 4 Reports

Subject Area

31 Bituminous Materials and Mixes
32 Cement and Concrete
33 Construction


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Washington, D.C., 1967 Publication 1515

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# Foreword

The papers in this RECORD were presented in one technical session of the annual meeting which was dedicated to the theme, "Statistical Quality Control of Construction." Three of the papers cover the controls involved in the construction of bituminous pavements and one, concrete pavement.

One of the easiest and still most important uses of statistical methods is toward uniformity in plant mixes for asphalt paving. It has long been recognized that such mixes are highly sensitive to pronounced variability in both aggregate gradation and asphalt content. Based on technical experience and preliminary laboratory investigations, a definite job mix is selected for the exact set of materials proposed for use. Once selected it is recognized that there will be variability due to sampling and testing as well as the inherent variability of the job mix materials themselves. Traditionally, specifications have provided standard construction tolerances for each major aggregate fraction. These standard allowances are the same for materials of all types, for all acceptable equipment and all working conditions. Historically, all that is known is that they have been considered reasonable and generally attainable with appraisal generally on a single sample. The application of statistical procedures removes the magnitude of these allowances from the area of arbitrary values to tolerances directly related to a specific set of materials and construction conditions. As expressed in one of the papers, they become realistic, not for a single sample but for a whole operation.

The application of these data should and does influence acceptability of a type and combination of aggregates as well as the practicability of the job mix. Since uniformity is the target, the system is a must for high-tonnage works supplied from automatically controlled plants. The research reported in these papers more firmly supports such a practice.

The study of Statistical Quality Control for concrete pavement shows the vastly involved set of circumstances in application of statistical variability to components, the concrete furnished and the end product—the completed pavement. With all specified components complying within an acceptable confidence level of variability, strict mixing and transportation control to produce a pavement within tolerances for thickness and surface, who is to designate the feature needing adjustment to insure less variance in cylinder strength or, to carry it further, in strength of pavement cores? Perhaps the SQC system cannot successfully reconcile such a great variety of construction stages into one result. This is a major challenge.

— J. F. Tribble

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# Statistical Quality Control in Portland Cement Concrete Pavements

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Respectively, Graduate Student and Associate Professor of Civil Engineering, University of Oklahoma

Quality control for portland cement concrete (PCC) pavements and their component parts was statistically studied in a field project approximately 8 mi long. Standard field tests on fresh concrete and standard laboratory tests on hardened concrete, coarse and fine aggregate, and cement were run on an adequate number of samples. Ninety-five pavement thickness measurements were taken, and 400 concrete cylinders were tested. For all the other characteristics, such as slump, air content, gradation, durability, Los Angeles loss, sand equivalent, fineness, and percent passing No. 200 sieve, 200 observations were made. The typical statistical parameters, i.e., testing, sampling and material variances, standard deviation, and arithmetic mean, were calculated, and frequency distribution curves were drawn.

In nearly all cases, the arithmetic mean of the measured characteristic complied well with the specifications. However, the relatively high values of standard deviation and of the testing variance should raise serious questions about the philosophy underlying the existing acceptance-rejection procedures in PCC pavements. Upper and lower control limits, especially those based on average values, show conclusively that unfit material is sometimes accepted. Also, large values of the testing variance $\sigma_t$ suggest that standard tests need some refinement, if not a complete modification, to reduce their inherent variance.

•THE application of statistical quality control procedures to the production of portland cement concrete (PCC) pavements has been the subject of recent studies (1, 2, 4, 5). The ultimate goal in these studies is to review critically specification writing in this area and to determine modifications, if any, which should be introduced in the acceptance-rejection procedure in the field.

The present paper is a part of this investigation undertaken by the School of Civil Engineering at the University of Oklahoma. It is being funded jointly by the Oklahoma Department of Highways and the U. S. Bureau of Public Roads. The opinions, findings, and conclusions expressed are those of the authors and not necessarily those of the funding agencies.

## METHOD OF INVESTIGATION

### Theoretical Considerations

The expansion of the highway industry has been massive; the manufactured product—the highway—has assumed an unparalleled growth; yet, testing and control methods

Paper sponsored by Committee on Construction Practices—Rigid Pavement and presented at the 46th Annual Meeting.

TABLE 1

PROPERTIES OF PCC PAVEMENT TESTED[a]

| Pavement | Plastic Concrete | Coarse Aggregate | Fine Aggregate |
|---|---|---|---|
| Thickness[b] | Slump[b]<br>Air content[b]<br>Cylinder compressive strength | Grading<br>Durability<br>Passing No. 200<br>Deleterious materials<br>Los Angeles loss | Grading<br>Fineness modulus<br>Passing No. 200<br>Sand equivalent |

[a]ASTM (3) or the equivalent AASHO (8) procedures used for testing.
[b]On-site testing; the rest laboratory tests.

for accepting this product have remained relatively static. The application of statistical concepts to the highway industry will enable the engineer to produce an economically feasible, better quality material and to evaluate more reliably the finished product. This new approach may possibly lead to a revision of specifications and to a better understanding of the variability in construction materials which, in turn, will render possible the correlation of expected performance and actual behavior.

To arrive at a stage in which application of statistical concepts is effective, it is imperative to draw on information relating to the distribution characteristics of the materials involved. More specifically, for PCC pavements the following must be studied:

1. The overall variance in the various components of concrete and the type of distributions;
2. The components of the overall variance, $\sigma_T$, attributed to testing, $\sigma_t$, sampling, $\sigma_s$, and inherent variability resulting from the process capability of the producer, $\sigma_a$, such that $\sigma_T^2 = \sigma_a^2 + \sigma_t^2 + \sigma_s^2$;

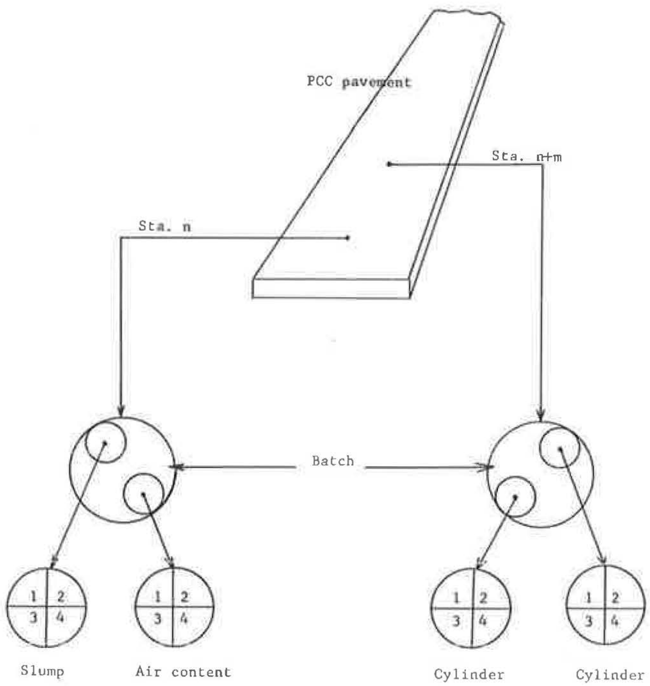


Figure 1. Random sampling of fresh concrete.

TABLE 2

STATISTICAL PARAMETERS FOR THE PCC PAVEMENT

| Characteristics | Number of Observations (n) | Testing Variance ($\sigma_t^2$) | Sampling Variance ($\sigma_s^2$) | Material Variance ($\sigma_a^2$) | Overall Variance ($\sigma_T^2$) | Overall Standard Deviation ($\sigma_T$) | Arithmetic Mean ($\bar{x}$) | Specification Provision |
|---|---|---|---|---|---|---|---|---|
| (a) Pavement | | | | | | | | |
| Thickness (in.) | 95 | | | | | 0.1 | 8.9 | 9.0 in. |
| (b) Plastic Concrete | | | | | | | | |
| Slump (in.) | 200 | 0.13 | 0.02 | 0.45 | 0.60 | 0.8 | 1.5 | 0.5-3.5 in. |
| Air content (%) | 200 | 0.08 | 0.12 | 0.46 | 0.67 | 0.8 | 4.6 | 3-6% |
| (c) Cured Concrete | | | | | | | | |
| Cylinder strength (psi) | 400 | 264,694 | 0.0 | 254,848 | 519,543 | 721 | 3803 | — |
| (d) Coarse Aggregate | | | | | | | | |
| Grading (% passing) | | | | | | | | |
| 2½ in. | 200 | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | 100% |
| 2 in. | 200 | 2.6 | 0.3 | 0.0 | 3.0 | 1.7 | 97.9 | 95-100% |
| 1½ in. | 200 | 26.4 | 17.9 | 29.4 | 73.7 | 8.6 | 84.2 | 70-95% |
| 1 in. | 200 | 69.2 | 50.4 | 68.7 | 188.3 | 13.7 | 62.1 | 50-85% |
| ¾ in. | 200 | 64.5 | 44.8 | 47.3 | 155.9 | 12.5 | 45.4 | — |
| ½ in. | 200 | 33.5 | 20.5 | 19.6 | 73.6 | 8.6 | 20.8 | 15-40% |
| ⅜ in. | 200 | 14.0 | 6.7 | 12.4 | 33.1 | 5.8 | 9.3 | — |
| No. 4 | 200 | 1.1 | 0.4 | 1.6 | 3.1 | 1.8 | 2.2 | 0-5% |
| No. 8 | 200 | 0.5 | 0.0 | 1.0 | 1.5 | 1.2 | 1.8 | — |
| Durability | 200 | 37.5 | 3.0 | 21.9 | 62.4 | 8.0 | 63.0 | — |
| Percent Passing No. 200 | 200 | 1.9 | 0.4 | 0.2 | 2.5 | 1.6 | 1.7 | 2% max. |
| Los Angeles loss | 200 | 12.2 | 0.1 | 5.4 | 17.6 | 4.2 | 29.2 | 40% max. |
| Deleterious material | 200 | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| (e) Fine Aggregate | | | | | | | | |
| Grading (% passing) | | | | | | | | |
| ⅜ in. | 200 | —[c] | —[c] | —[c] | —[c] | —[c] | —[c] | 100% |
| No. 4 | 200 | 0.1 | 0.0 | 0.1 | 0.2 | 0.5 | 98.7 | 95-100% |
| No. 8 | 200 | 0.3 | 0.3 | 0.5 | 1.7 | 1.3 | 93.6 | — |
| No. 16 | 200 | 1.4 | 0.7 | 2.8 | 4.9 | 2.2 | 80.2 | 45-85% |
| No. 30 | 200 | 6.7 | 0.9 | 19.0 | 26.4 | 5.1 | 54.6 | — |
| No. 50 | 200 | 4.0 | 0.0 | 10.9 | 14.9 | 3.9 | 12.3 | 5-30% |
| No. 100 | 200 | 0.1 | 0.0 | 0.2 | 0.4 | 0.6 | 1.2 | 0-7% |
| Fineness modulus | 200 | 0.01 | 0.00 | 0.01 | 0.02 | 0.15 | 2.60 | — |
| Percent Passing No. 200 | 200 | 0.2 | 0.1 | 0.2 | 0.5 | 0.7 | 1.1 | 3.0% max. |
| Sand equivalent | 200 | 0.7 | 0.0 | 0.1 | 0.8 | 0.9 | 97.6 | — |

[a] Samples finer than 2½ in.
[b] Visual observation indicated complete absence of deleterious materials.
[c] Samples finer than ⅜ in.

3. The present sampling and testing procedures; and
4. The practicality of present specifications and any possible changes.

## Field Problem

To test the applicability of the statistical concepts, a PCC pavement project in Oklahoma was selected. It was 7.9 mi in length; the contractor used two slip-form pavers and the same source of materials throughout. To keep the operator effect constant, both field and laboratory crews were kept the same throughout the entire project. The properties tested are indicated in Table 1. Where testing of the finished product (concrete) was involved, a set of 50 stations was selected to sample for slump and air content and another set to sample for concrete cylinder preparation. No two stations coincided (Fig. 1); their selection was based on the standard random table.

Aggregate materials were sampled from the stockpiles and bins at the central plant. After the dry aggregate was weighed at the bin site and the cement added, it was hauled by trucks to the roadside where the concrete was prepared and laid. As random stations could not be set at the plant, it was assumed that the aggregate materials were being processed from the stockpile into the bins at a continuous and uniform rate. At specified intervals of time, samples were taken at a point in the stockpile nearest the bins. This, in effect, means that, with regard to time, random stations were used.

| No. | Thickness, in. | f | % | Cum % |
|---|---|---|---|---|
| 1 | 8.8 | 7 | 7.4 | 7.4 |
| 2 | 8.9 | 30 | 31.6 | 39.0 |
| 3 | 9.0 | 33 | 34.8 | 73.8 |
| 4 | 9.1 | 10 | 10.5 | 84.3 |
| 5 | 9.2 | 13 | 13.7 | 98.0 |
| 6 | 9.3 | 1 | 1.0 | 99.0 |
| 7 | 9.4 | 1 | 1.0 | 100.0 |

| | |
|---|---|
| n | 95 |
| specs | 9.0 |
| $\bar{x}$ | 8.9 |
| $\sigma_T$ | 0.1 |
| v | 2.2% |

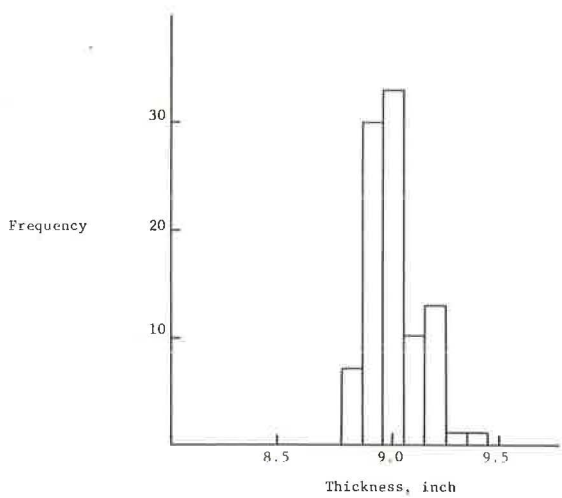


Figure 2. Thickness distribution.

| No. | Slump Range | f | % | Cum % |
|---|---|---|---|---|
| 1 | 0-0.5 | 16 | 8.0 | 8.0 |
| 2 | 0.6-1.0 | 43 | 21.5 | 29.5 |
| 3 | 1.1-1.5 | 52 | 26.0 | 55.5 |
| 4 | 1.6-2.0 | 54 | 27.0 | 82.5 |
| 5 | 2.1-2.5 | 16 | 8.0 | 90.5 |
| 6 | 2.6-3.0 | 9 | 4.5 | 95.0 |
| 7 | 3.1-3.5 | 3 | 1.5 | 96.5 |
| 8 | 3.6-4.0 | 7 | | 100.0 |
| | | 200 | 100.0 | |

| | |
|---|---|
| n | 200 |
| spec. | 0.5-3.5 |
| $\bar{x}$ | 1.5 |
| $\sigma_T$ | 0.8 |
| $\sigma_t$ | 0.4 |
| $\sigma_s$ | 0.1 |
| $\sigma_a$ | 0.7 |
| v | 53.3% |

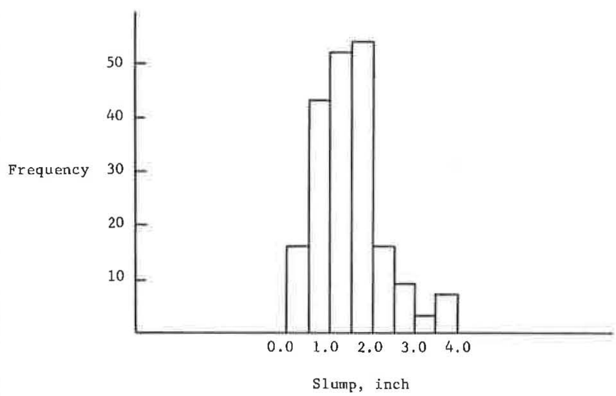


Figure 3. Statistical properties for slump.

The cement was sampled from the cement truck before being added to the mixer at intervals of time following the procedure outlined for the aggregates.

## DISCUSSION OF DATA

The accumulated data from each observation were tabulated and run on the OSAGE computer for the determination of the various statistical parameters as given in Table 2.

### Pavement Thickness

The thickness of the pavement was measured behind the paver immediately after placement. Ninety-five random observations yielded results similar to truncated normal distribution with an average of 8.9 in. and a standard deviation of 0.1 in. (Fig. 2). The tolerance permitted in pavement thickness is within ¼ in. This is based on average values, and it constitutes a weak point of the specifications because the extent of variability is not specified.

### Slump Test

The analysis of the data obtained from 50 randomly selected stations indicates that the results fit the log normal distribution better than the normal distribution (Fig 3.). At each station 4 observations were made, and each point in Figure 4 represents the average of these 4 observations, thus giving a total of 200. Furthermore, this figure depicts the upper control limit (UCL) and the lower control limit (LCL) based on both single and average values (observations). Those based on average observations gave numerical values equal to the arithmetic mean, $\bar{x}$, ± the standard deviation, $\sigma$. This was obtained from $\bar{x} \pm 2\sigma/\sqrt{n}$ where the number of observations n equals 4. Unless the batch was very wet, the reproducibility was fairly good.

The test is quick, and requires a small amount of concrete. However, immediate identification of the factors conducive to an off-specification slump are not possible because of their variety. Gradation, surface area, and cement content are only a few of the factors which, in addition to water, are accepted as influencing the variability of slump. If this project is an indication of the capabilities of good contractors, it is expected that 90 to 95 percent of the time the slump will be $\bar{x} \pm 1.6$ in., and therefore the possible adjustment of specifications should be considered.

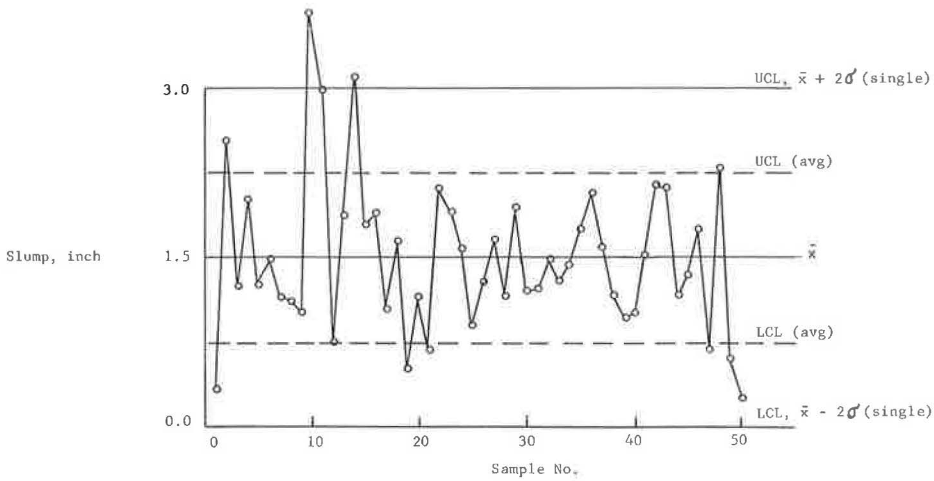


Figure 4. Slump distribution quality control chart.

| No. | Air Cont. Range (%) | f | % | Cum % |
|---|---|---|---|---|
| 1 | -3.0 | 4 | 2.0 | 2.0 |
| 2 | 3.0-3.5 | 3 | 1.5 | 3.5 |
| 3 | 3.5-4.0 | 27 | 13.5 | 17.0 |
| 4 | 4.0-4.5 | 76 | 38.0 | 55.0 |
| 5 | 4.5-5.0 | 54 | 27.0 | 82.0 |
| 6 | 5.0-5.5 | 21 | 10.5 | 92.5 |
| 7 | 5.5-6.0 | 6 | 3.0 | 95.5 |
| 8 | 6.0-6.5 | 4 | 2.0 | 97.5 |
| 9 | 6.5- | 5 | 2.5 | 100.0 |
| | | 200 | 100.0 | |

| | |
|---|---|
| n | 200 |
| specs | 3-6% |
| $\bar{x}$ | 4.6 |
| $\sigma'_T$ | 0.8 |
| $\sigma'_t$ | 0.2 |
| $\sigma_s$ | 0.1 |
| $\sigma_a$ | 0.7 |
| v | 17.6% |

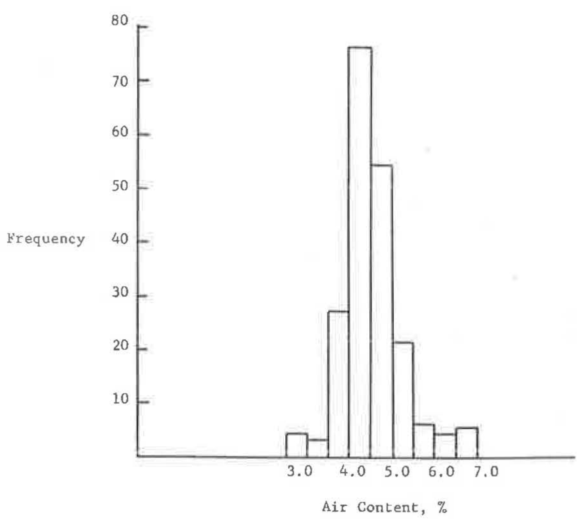


Figure 5. Statistical properties for air content.

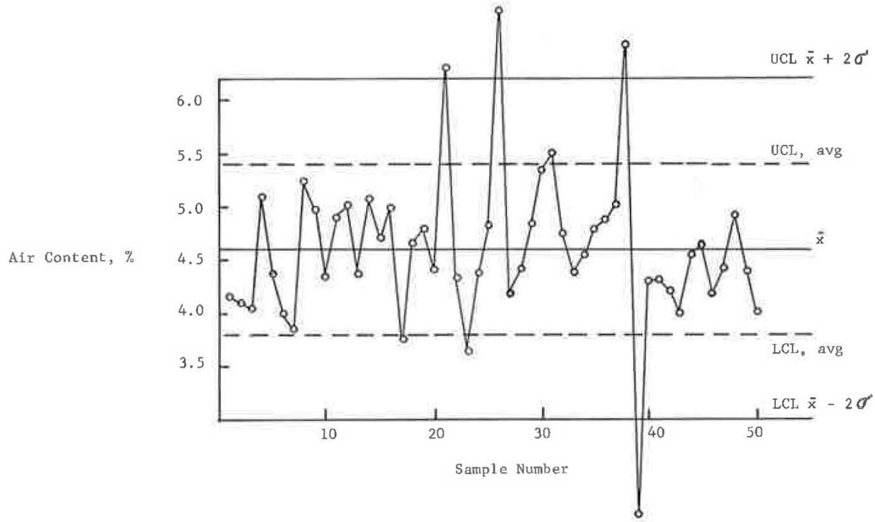


Figure 6. Air content distribution quality control chart.

| | |
|---|---|
| n | 400 |
| specs | none |
| $\bar{\bar{x}}$ | 3803 |
| $\sigma'_T$ | 721 |
| $\sigma'_t$ | 514 |
| $\sigma'_s$ | 0 |
| $\sigma'_a$ | 504 |
| v | 18.7% |

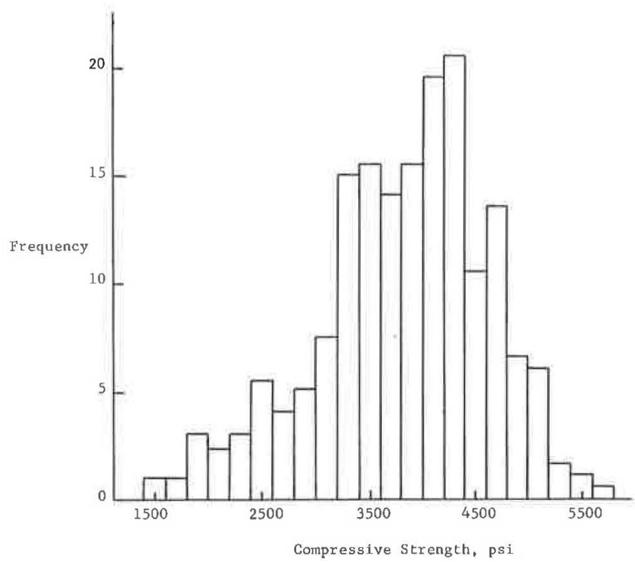


Figure 7. Distribution of the 28-day cured cylinder compressive strength.

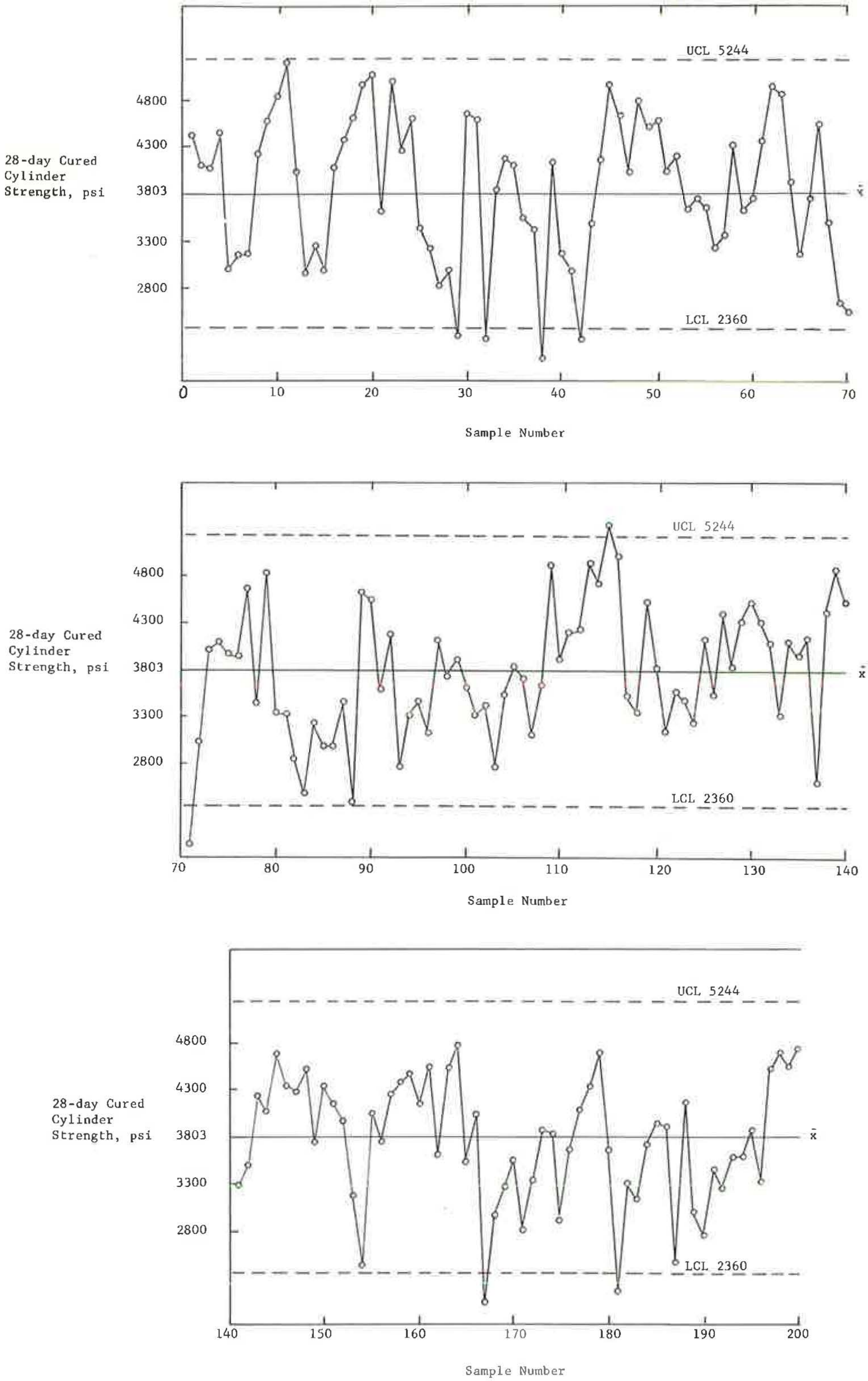


Figure 8. Quality control chart cylinder strength.

## Air Content

The air content of plastic concrete was measured, employing a ¼-cu ft standard air meter. Using 50 stations and 4 measurements per station, a total of 200 observations were made. The results (Fig. 5), indicate that variations within the batch, $\sigma s_1$, are by far less than those between batches. Thus, it appears that there is a variance inherent in the operation of the air compound mechanism rather than in the mixing process. Also, the data $\bar{x} \pm 1.6$ percent indicate that it is possible to conform to current specifications, 3 to 6 percent. Each of the 50 points in Figure 6 represents the average of 4 observations, as is the case with the slump, and the UCL and LCL based on average values, although numerically equal to $\bar{x} \pm \sigma$, are actually $\bar{x} \pm 2\sigma/\sqrt{n}$, where $n = 4$.

The Chase air meter was used sparingly as a secondary control. The limited observations which are not reported herein showed tendencies for good correlation between the two methods; however, the chance of hitting a high or low air concentration spot with the Chase air meter is always high. Therefore, this particular limitation should be considered whenever the Chase air meter is used.

## Cylinder Compressive Strength

The data in Figure 7 relate to the compressive strength of 200 duplicate cylinders (400 total) which were sampled over a period of two weeks and cured for 28 days at 95 percent relative humidity. A very popular test, the 28-day compressive strength, is believed to reflect the quality of concrete; however, insofar as quality control practice is concerned, it is ineffective because the results are available at a time when immediate corrective measures, if required, cannot be taken and rejections, if necessary, are impractical.

A skewed normal frequency distribution with a coefficient of skewness of 0.42 was obtained. Tests for normality showed good fit of the population; however, some difficulties were experienced with the extreme values.

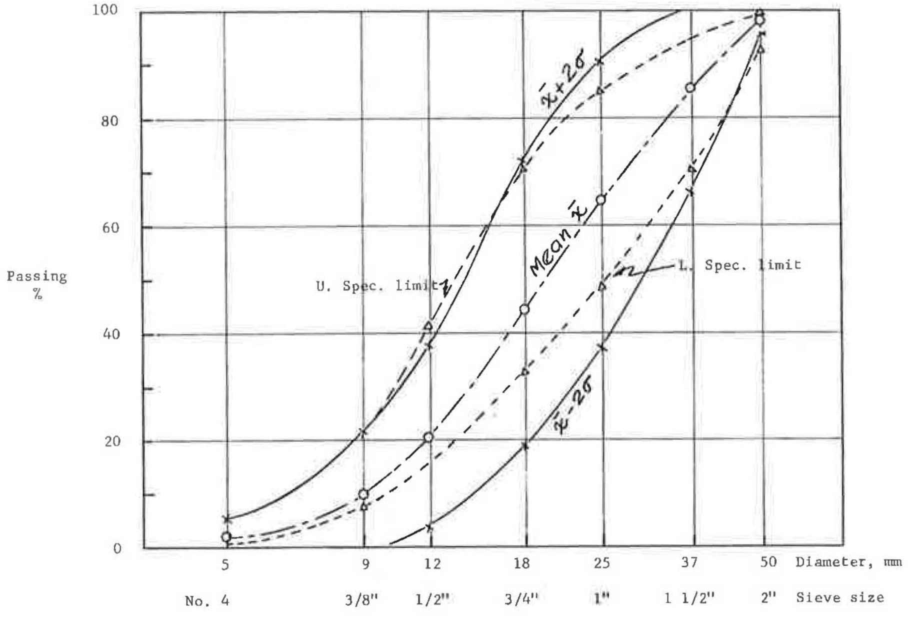


Figure 9. Gradation analysis of coarse aggregate.

A large part of the total variation seemed to result from the handling, curing, and testing methods. This is evident when the testing standard deviation, $\sigma_t$ = 514 psi, is compared with the inherent standard deviation, $\sigma_a$ = 504 psi. To reduce $\sigma_t$, it is necessary to modify the foregoing testing time.

Figure 8 shows that the mean value $\bar{x}$ = 3803 psi and the UCL and LCL were calculated from $\bar{x} \pm 2\sigma/\sqrt{n}$ where n = 1, as each point represents the average of 2 readings.

## Coarse Aggregate

The coarse aggregate, which consisted of crushed limestone, was tested for grain size distribution, including percent passing U. S. standard sieve No. 200, durability, Los Angeles loss, and presence of deleterious materials. The latter was effected by visual examination of the samples and was found satisfactory. Although the mean of the percent passing No. 200 was 1.7 and seemed satisfactory because it was below the maximum permissible limit of 2, the overall standard deviation, $\sigma_T$, of 1.6 indicates that there are cases where the specification has been violated.

The gradation analysis (Fig. 9) indicates that the mean values $\bar{x}$ fell within the specification limits. However, the UCL and the LCL which represent the $\bar{x} \pm 2\sigma_T$ values at 95 percent confidence level fall outside the specification limits. The results of the Los Angeles abrasion test are satisfactory, primarily because a rather high value of 40 percent is specified as the limit. In this case the inherent variability depends entirely on the quaility of raw material and its location in the quarry.

The durability of the coarse aggregate, as indicated by the data obtained from the California test (7), gave a mean of 63 and a $\sigma_T$ = 8. Visual examination of the samples revealed no presence of deleterious material.

## Fine Aggregate

River sand, washed and screened, was used as fine aggregate in this project. Gradation specification provisions, including UCL and LCL and passing No. 200 sieve, were satisfactorily met (Fig. 10) mainly because of the control exercised during the initial production stage. Although this project did not include provisions for fineness modulus and sand equivalent, the values obtained (Table 2) seem logical and satisfactory.

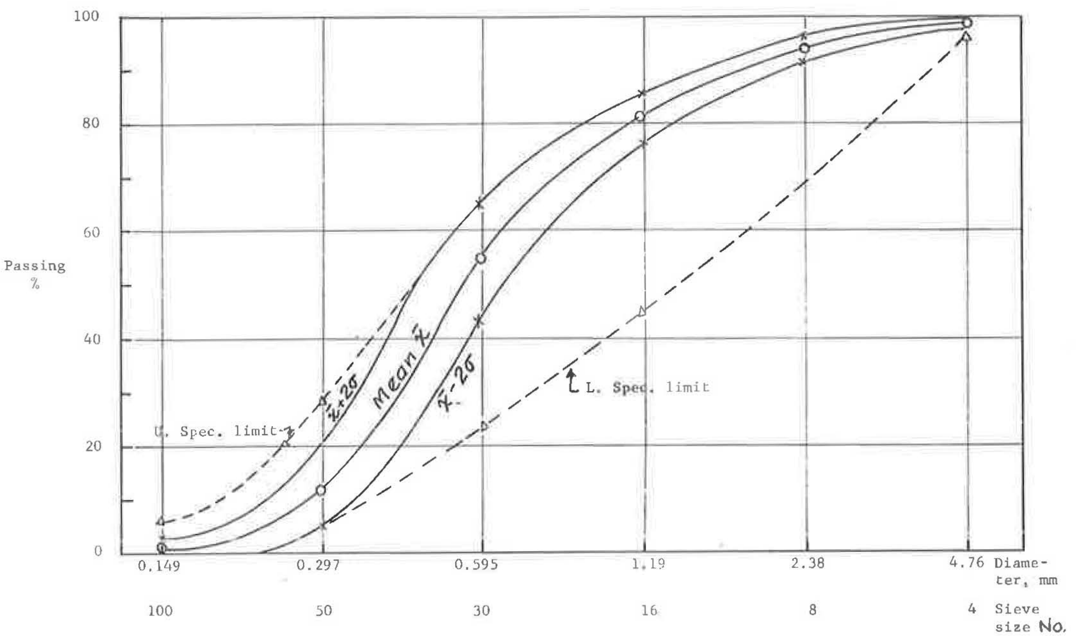


Figure 10. Gradation analysis of fine aggregate.

Assuming that this may be the case always, it is conceivable that the fineness modulus test may suffice as a single control as long as the same source of fine aggregate is used.

Cement

Tests on cement (air content, strength, alkali content) are incomplete and therefore statistical parameters could not yet be evaluated. However, from the data obtained it may be tentatively concluded that specifications will be met. Improved manufacturing methods have given cement uniformity and a quality which can be closely controlled during its manufacture.

## GENERAL OBSERVATIONS

During this study a considerable amount of field and laboratory data have been obtained. Using the information developed, it is possible to approach the problem of quality control in PCC pavements from a general point of view, although the study, with the exception of the standard tests, was limited to localized conditions.

The basic problem of quality control is whether the test methods employed actually do reflect the quality of the product involved. In many instances it was felt that the tests used in this study are somewhat irrelevant although they have become standard, and it may be argued that they are service related. However, what cannot be argued and questioned is the variability involved in standard testing procedures as measured by the testing variance $\sigma_t$. A prime example of this is the cylinder strength where $\sigma_t$ was large enough to be significant. The possibility of reducing large values of $\sigma_t$ should be investigated before any application is made to quality control methods. Relevant to this is the exploration of new testing methods such as the employment of nondestructive tests in the area of quality control.

One of the problems involved in the acceptance or rejection of aggregates, both coarse and fine, is the complication which arises in a situation where only one of the sieves is out of specification. Another problem arises in the case where an average point falls within, but very close to, the specification limit. This means that the variability reflected by the standard deviation, $\sigma_T$, is such that some observations (more than the ones predicted by the confidence level) may have to fall outside the specification limits. Likewise, a zigzagging curve within the specification limits is not qualitatively the same as a smooth curve which is coincident with the average specification line. Thus, it appears that specifying the upper and lower limits of the gradation curve is not adequate to produce uniform results. Tighter specifications do not seem to be the plausible answer. Therefore, some thought should be given to the possibility of incorporating in the specifications some realistic maximum deviation from the mean of the upper and lower limits. This is of great significance because the design of satisfactory concrete mixes is partly based on the gradation of the aggregate (6).

Currently, specifications are based on average (mean) values, and rejection-acceptance methods follow this philosophy without any consideration of variance. This possibly leads to gross errors between actual quality and presumptive quality. Also, it may pave the way for uneconomical designs if complaince of simple observations and measurements with safest limits are strictly enforced.

Finally, it is gratifying to see that people in the highway industry are deeply concerned with quality control which utilizes statistical tools to evaluate both the product and its components.

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# A Statistical Study of Asphaltic-Concrete

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A typical New Jersey State Department of Transportation construction project was selected to establish average values and variability parameters for asphaltic pavement material characteristics, such as asphalt content and gradation, presently used as measures of quality. The effect of variations in material or the material production process, sampling, and field and laboratory testing on the measured variability parameters are discussed. A comparison is made between present field and laboratory testing to determine the possibility of reducing the number of tests normally run on a construction project. The validity of the Department's present sampling and testing processes, and the adequacy of its present asphaltic-concrete specifications are studied.

A FORTRAN computer program was used to perform the analysis.

Findings indicate that for New Jersey, field testing alone cannot as yet supplant laboratory testing as the basis for final judgment on material compliance. For the asphaltic content determination, it was established that the Department's present sampling and laboratory testing processes are as valid (in uniformity) as those typical of the highway field today. It was found that in general the asphaltic-concrete specifications, for the construction project studied, dealt fairly with the material supplier allowing sufficiently for the natural variabilities encountered. However, a few important exceptions were noted which occurred in the critical areas of the asphaltic-concrete test. In these instances the specifications were found to be overly restrictive for the present capabilities of the production, sampling, and testing processes.

•THE NEW JERSEY State Department of Transportation has recently completed its initial research project in the area of statistical quality control. One phase of this project dealt with a statistical investigation of asphaltic paving materials. The purposes of this investigation were as follows.

1. To establish, for the asphaltic paving materials of a normal construction job, average values and variability parameters for the material characteristics currently used as measures of quality (asphalt content, gradation, etc.).
2. To determine, through analysis of variance, the effect on measured variability parameters of variations in the material, the material production processes, sampling, and testing.
3. To compare, through the use of the specialized sampling and testing plan required for the analysis of variance, the present field and laboratory testing processes.
4. To use the statistical data from this and similar studies to determine the validity of the Department's present sampling and laboratory testing processes and to provide information on the adequacy of its present specifications.

This project was performed in conjunction with the quality control research program established by the U. S. Bureau of Public Roads. The purpose is essentially to gather,

Paper sponsored by Committee on Construction Practices—Flexible Pavement and presented at the 46th Annual Meeting.

from the various state highway agencies, statistical parameters that can be used to establish statistical quality control procedures for highway construction. It was intended that the statistical data established in New Jersey's investigation be provided to the Bureau to augment its information on asphaltic-concrete.

The procedure used in the Department's investigation was outlined in the Bureau of Public Roads' research guide, The Statistical Approach to Quality Control in Highway Construction (1). Random sampling and testing plans were employed which provided test data in an appropriate form for the desired statistical analysis. The actual analysis was done with a FORTRAN computer program given in the Bureau's research guide.

A comparison of field, or at-the-plant testing, with laboratory testing was made to determine the possibility of reducing the number of tests now being performed on any one job. At the present time, daily production control is handled through mixture samples taken and tested by Department inspectors at the asphaltic or bituminous concrete plant. Duplicates of the plant-tested samples are also sent to the Department's main laboratory in Trenton to verify the field results. In addition, for the wearing course and the stabilized base components of a pavement, samples of the actual pavement are obtained for laboratory testing, to establish a final record of material compliance. This testing program results in the same material being tested two or occasionally three times.

For obvious economic reasons, the Department wishes to eliminate laboratory testing, either totally or in part, and to rely primarily on field test results to establish material compliance. It is willing to make this change, however, only if field testing can be shown to measure compliance, throughout the state, in as nearly uniform a manner as that currently provided by the main laboratory. In the investigation described, a within-laboratory testing variance was first established for the main laboratory. This was then compared to a combined within-and-between-plant testing variance for the field, to ascertain the practicability of making the desired testing changes.

## SCOPE

The construction job selected called for the resurfacing of a previously constructed route. Two types of bituminous materials were specified: FABC-top (wearing course), and FABC-bottom (binder course). On mixture samples from each of these materials, determinations of asphalt content and aggregate gradation were made. The statistical parameters evaluated for each of the foregoing characteristics were the mean ($\bar{x}$), the overall variance, standard deviation (square root of overall variance), and the components of variance for testing, for sampling, and for the material production process.

## MATERIALS AND BATCHING EQUIPMENT

The construction job studied used some 26,000 tons of FABC-top and approximately 27,000 tons of FABC-bottom. A 5,450-ton portion of each material was selected for the in-depth sampling. The "lot volume" was in accordance with the 50 sampling units suggested by the Bureau of Public Roads, at a ratio of one sample unit per each 90 to 110 tons of mix.

In both materials, crushed trap rock and bituminous sand were combined with a 60 to 70 asphalt-cement to achieve the desired mixtures. For the top or wearing course material, a filler of dolomite dust was also used. The two types of mixtures were required to meet the specifications given in Table 1.

The binder course material sampled was mixed in 4-ton batches at a Batch-O-Matic plant having a twin shaft pugmill mixer. Five hot bins were used for aggregate storage with their batch quantities and the amount of asphalt all being controlled automatically. The mixing time employed for each batch was 5 sec dry and 30 sec wet. The specified mixture temperature was 300±15 F.

A continuous-mix plant with an output of 200 tons/hr was used for production of the FABC-top material. Aggregate storage was accommodated in 4 hot bins, with mixing

TABLE 1

SPECIFICATIONS FOR TOP AND BOTTOM COURSE ASPHALTIC-CONCRETE[a]

| Item | Top Course | Bottom Course |
|---|---|---|
| Percent asphalt content | 6.2±0.3 | 4.7±0.3 |
| Percent stone content (retained on No. 10) | 40±4 | 70±5 |
| Percent pass. 1½ in. and retained on 1 in. | — | 0-35 |
| Percent pass. 1 in. and retained on ½ in. | 0-10 | 25-70 |
| Percent pass. ½ in. and retained on ¼ in. | 12-40 | 0-20 |
| Percent pass. ¼ in. and retained on No. 10 | 8-30 | 0-15 |
| Percent pass. No. 10 and retained on No. 30 | 2-17 | 1-11 |
| Percent pass. No. 30 and retained on No. 50 | 4-24 | 2-15 |
| Percent pass. No. 50 and retained on No. 80 | 6-22 | 2-14 |
| Percent pass. No. 80 and retained on No. 200 | 3-20 | 2-13 |
| Percent pass. No. 200 | 4-8 | 0-5 |

[a]The New Jersey Department of Transportation utilizes target values only for asphalt and stone contents. The Department's present method of test for sieve analysis specifies the use of both perforated plate screens and wire cloth sieves. The screen sizes employed are 1½, 1, ½ and ¼ in.; the sieve sizes are numbers 10, 30, 50, 80, and 200.

performed by a twin shaft pugmill. All processed material was subjected to a mixing time of 47.5 sec. The mixing time was given by the following formula:

$$\text{Mixing time (sec)} = \frac{\text{pugmill dead capacity (lb)}}{\text{pugmill output (lb/sec)}}$$

The mixture temperature specified for the binder course material was the same as that of the top: 300±15 F.

## SAMPLING

At each plant 227 trucks were required to achieve a material lot volume of 5450 tons. Only 50 were subjected to sampling. The trucks sampled were chosen with a

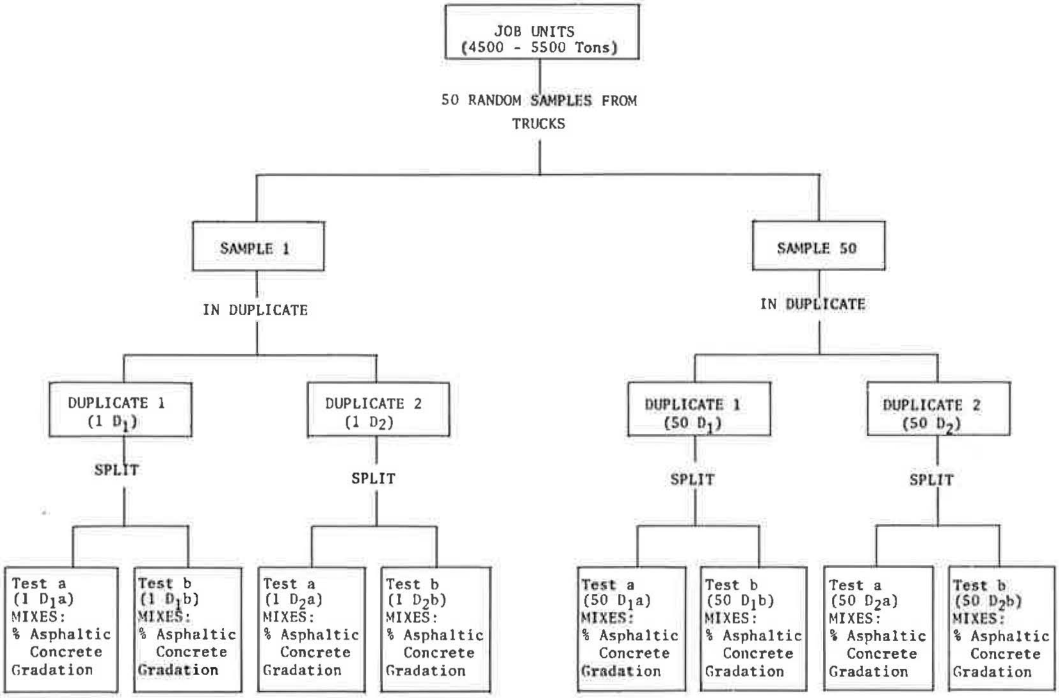


Figure 1. Sampling plan.

table of random numbers. For each truck, two 1-ft deep furrows were dug in the conical pile of asphaltic material extending from apex to base. One furrow was in the rear of the truck; the other in the front. In each furrow, three approximately equal-volumed scoops of material were taken—one at the apex, one at center, and one at the base of the pile. The three scoops were thoroughly mixed together to form one sample volume of approximately 11 lb. The sample volume from one furrow was labeled duplicate sample no. 1 and that from the other, duplicate sample no. 2.

When all sampling was completed, duplicates were sent to the Department's Trenton laboratory to be divided into test portions. Each duplicate was cut into quarters, and the diagonally opposite quarters were combined to form two test portions per duplicate sample.

The samples taken in accordance with this plan (Fig. 1) were in addition to those obtained by the plant inspectors for their normal plant control work.

It was originally intended to take temperature measurements in each of the furrows of a sampled truck. But the time required for the thermometers to reach a temperature equilibrium with the bituminous concrete was so long that the special sampling operation began to interfere with the flow of material out of the plants. To avoid excessive disruptions in normal plant activities, the temperature measurements were discontinued.

## TESTING

To obtain variability values for both field and laboratory testing processes, testing was divided equally between the two testing areas: for each of the two material types (top and bottom) 25 of the 50 lot samples (including four test portions per sample) were tested in the main laboratory and 25 in the field.

The field testing was performed at five different bituminous-concrete plants, using available plant testing equipment. At each plant, only one set of testing apparatus was used. Thirteen experienced Departmental plant inspectors performed the actual testing. The bituminous material for field analysis was distributed so that the four test portions of any one sample were each analyzed at a different plant. This mode of distribution was selected so that a measure of the total testing variability, both within and between typical field testing plants, could be obtained.

Laboratory testing was performed by five experienced technicians utilizing all the normally employed equipment which included: four different sets of sieves, two shakers, three balances, and two centrifuges. ASTM Method D 2172-63T Method A(2) was used for asphalt content determinations in both the laboratory and the field. Sieve analysis of extracted aggregate was performed in accordance with AASHO Method T 30 (3). These methods are currently standard testing methods for the Department.

## DATA ANALYSIS

As samples were obtained in a manner conforming to the experimental design suggested by the U.S. Bureau of Public Roads (BPR), test results were suitable for analysis with the computer program provided in the BPR's research guide.* This program was used to determine all the statistical parameters desired in the study. The procedure of the program for analysis of variance is based on the assumption that the variances considered are additive and that overall variance is the sum of three components: process variance, sampling variance, and testing variance. This assumption is given by

$$\sigma'^2 = \sigma_p^2 + \sigma_s^2 + \sigma_t^2$$

where

$\sigma'^2$ = overall variance of measurements,

$\sigma_p^2$ = process or material variance,

*Copies of the program are available from the author upon request.

$\sigma_s^2$ = variance due to random errors of sampling, and

$\sigma_t^2$ = variance due to random errors of testing.

The initial step in the analysis was to determine the separate variability values for the two types of testing used. For each material, the laboratory testing variability was evaluated by first analyzing, with the BPR program, only the laboratory data (100 test results per material, 25 samples at four tests per sample). The testing variances calculated were then taken as measures of the variability of testing within the main laboratory. The same approach was used with the field data, analyzing them separately to establish a set of testing variances for the field testing process. These latter variances, however, had a different meaning from those for the main laboratory. The field testing variances, in reality, were measures of the combined testing variability within and between the plants (field testing laboratories) used.

The remaining statistical parameters required were determined by combining the field and laboratory results for each material and running the combined data a second time through the Bureau's program.

## DISCUSSION OF FINDINGS

### Normality Check

For the purpose of determining the adaptability of the test data to standard statistical treatment, several checks were made to ascertain how well the data distribution for each test characteristic agreed with the theoretical normal distribution. The first approach consisted of plotting frequency histograms and looking for signs of pronounced skewness or multimodal tendencies. Plots of cumulative frequencies were made on normal probability paper, and the resulting curves were compared to the diagonal straight line of the normal curve. The last technique employed consisted of comparing areas under the normal curve within specified limits of the mean with those areas under the test distribution defined by the same limits (Table 2).

The use of the foregoing techniques revealed only one excessive deviation from the normal curve. Test data for the 1-in. screen on the top material had an extremely skewed distribution. Figure 2 shows the frequency histogram and cumulative frequency plot of the 1-in. screen data. The skewness is to be expected and is caused by the material having an average passing percentage very close to the zero percent limit.

Except for a few instances of slight peakedness, the remainder of the data conformed fairly well to the theoretical normal curve and appeared suitable for use with standard statistical methods.

TABLE 2

COMPARISON OF AREAS OF TEST DISTRIBUTIONS WITHIN SPECIFIED LIMITS WITH THOSE OF THEORETICAL NORMAL CURVE

| Test Property | Percentages Within Given Limits | | | | | |
|---|---|---|---|---|---|---|
| | Top Material | | | Bottom Material | | |
| | $\bar{x} \pm 0.675\sigma$ | $\bar{x} \pm \sigma$ | $\bar{x} \pm 2\sigma$ | $\bar{x} \pm 0.675\sigma$ | $\bar{x} \pm \sigma$ | $\bar{x} \pm 2\sigma$ |
| Normal curve | 50.0 | 68.3 | 95.5 | 50.0 | 68.3 | 95.5 |
| AC | 53.0 | 72.5 | 97.0 | 53.0 | 67.5 | 95.0 |
| SC | 51.0 | 75.5 | 95.5 | 55.0 | 70.5 | 94.5 |
| Passing 1½ in. and retained on 1 in. | — | — | — | 57.0 | 75.5 | 97.0 |
| Passing 1 in. and retained on ½ in. | 61.0 | 82.5 | 96.1 | 52.0 | 74.0 | 96.0 |
| Passing ½ in. and retained on ¼ in. | 47.5 | 70.5 | 95.5 | 52.5 | 67.5 | 94.5 |
| Passing ¼ in. and retained on No. 10 | 56.0 | 70.5 | 95.0 | 58.0 | 76.0 | 92.0 |
| Passing No. 10 and retained on No. 30 | 53.5 | 72.5 | 96.5 | 49.0 | 69.0 | 91.0 |
| Passing No. 30 and retained on No. 50 | 53.0 | 72.5 | 98.5 | 50.5 | 68.0 | 95.0 |
| Passing No. 50 and retained on No. 80 | 48.0 | 63.0 | 97.0 | 50.0 | 67.5 | 95.0 |
| Passing No. 80 and retained on No. 200 | 50.5 | 70.5 | 96.0 | 46.0 | 66.5 | 95.0 |
| Passing No. 200 | 63.0 | 80.5 | 93.0 | 46.0 | 65.0 | 94.5 |

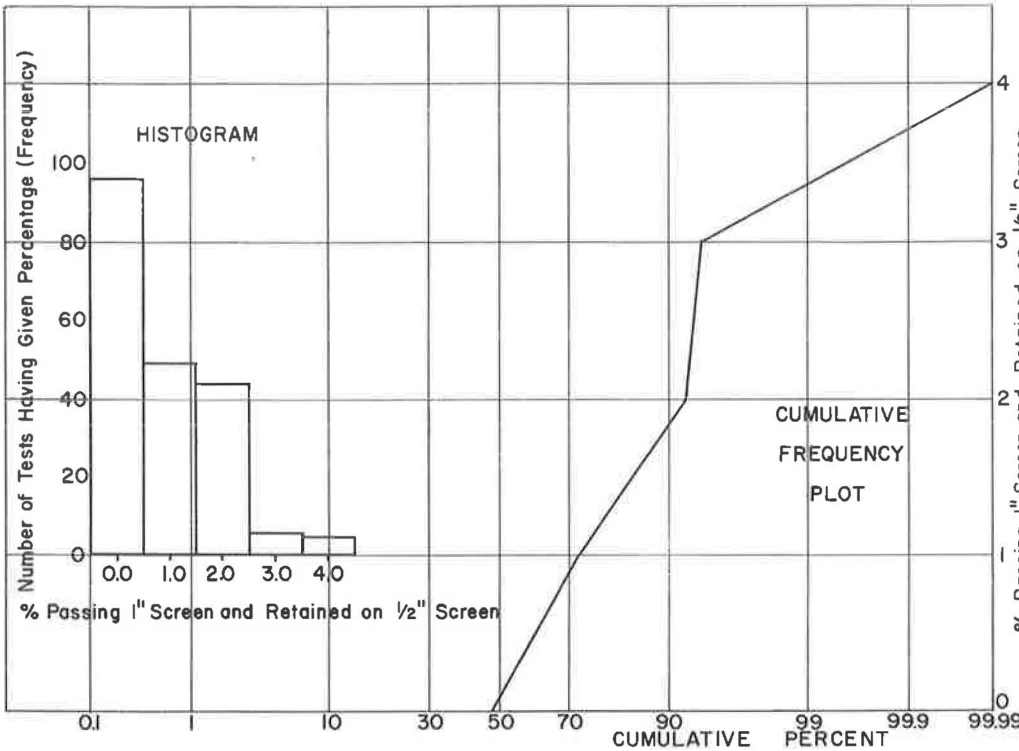


Figure 2. Normality checks of test data on percent passing 1-in. screen and retained on ½-in. screen for top material.

## Differences in Laboratory and Field Testing

The results of the separate analysis of testing variabilities are given in Table 3. For each test property, a testing variance for both the laboratory and the field is provided. In a majority of the cases the field testing variance (within and between field laboratory testing variance) exceeds the laboratory value (within main laboratory testing variance); for 15 out of the 21 test properties the field variance is largest.

A statistical F test at the 5 percent level was made to determine how many of the observed variance differences were actually significant. The results (Table 3) showed that only 10 of the 21 was significantly different. However, in 7 significant cases the field variance was the largest. Of greater importance, 5 of the 7 occurred in the critical areas of the bituminous test: the determinations of asphalt content, stone content, and passing the No. 200 sieve.

Field testing variance was significantly larger for all 3 critical properties on the top material and for 2 of the 3 on the bottom material. The excessiveness of the field variability was particularly striking for the asphalt content determination. With variabilities expressed as variances, field testing for asphalt content was nearly 20 times more variable than laboratory testing on top material, and 15 times more variable on bottom material.

The large field testing variances appear to be primarily due to differences between testing plants. If no difference in test method existed between field testing locations, the mean of the test results for each field testing plant should have been approximately the same. In the instances of large field testing variance, these means were strikingly

TABLE 3

TESTS FOR SIGNIFICANCE OF VARIANCE DIFFERENCE BETWEEN FIELD AND LABORATORY TESTING (5% Level)

| Test Property | Testing Variance: Laboratory Value | Testing Variance: Field Value | Largest Variance | Computed F Ratio | Critical F Ratio | Significant Difference |
|---|---|---|---|---|---|---|
| (a) Top | | | | | | |
| Percent asphalt content | 0.0088 | 0.1734 | Field | 19.70 | 1.75 | Yes |
| Percent stone content | 1.5500 | 2.9040 | Field | 1.87 | 1.75 | Yes |
| Sieve analysis | | | | | | |
| Percent passing 1 in. and retained on ½ in. | 0.7200 | 1.0358 | Field | 1.44 | 1.75 | No |
| Percent passing ½ in. and retained on ¼ in. | 2.6100 | 6.2827 | Field | 2.41 | 1.75 | Yes |
| Percent passing ¼ in. and retained on No. 10 | 0.9200 | 0.7246 | Lab | 1.27 | 1.75 | No |
| Percent passing No. 10 and retained on No. 30 | 0.9000 | 0.3591 | Lab | 2.51 | 1.75 | Yes |
| Percent passing No. 30 and retained on No. 50 | 1.6400 | 1.8232 | Field | 1.11 | 1.75 | No |
| Percent passing No. 50 and retained on No. 80 | 1.1700 | 0.9429 | Lab | 1.24 | 1.75 | No |
| Percent passing No. 80 and retained on No. 200 | 0.7600 | 3.0043 | Field | 3.95 | 1.75 | Yes |
| Percent passing No. 200 | 0.2900 | 0.5121 | Field | 1.76 | 1.75 | Yes |
| (b) Bottom | | | | | | |
| Percent asphalt content | 0.0111 | 0.1658 | Field | 14.94 | 1.75 | Yes |
| Percent stone content | 2.9700 | 7.9839 | Field | 2.69 | 1.75 | Yes |
| Sieve analysis | | | | | | |
| Percent passing 1½ in. and retained on 1 in. | 13.8400 | 19.7247 | Field | 1.42 | 1.75 | No |
| Percent passing 1 in. and retained on ½ in. | 17.1100 | 23.1702 | Field | 1.35 | 1.75 | No |
| Percent passing ½ in. and retained on ¼ in. | 8.0100 | 9.3947 | Field | 1.17 | 1.75 | No |
| Percent passing ¼ in. and retained on No. 10 | 3.0000 | 1.4930 | Lab | 2.01 | 1.75 | Yes |
| Percent passing No. 10 and retained on No. 30 | 0.6200 | 0.3234 | Lab | 1.92 | 1.75 | Yes |
| Percent passing No. 30 and retained on No. 50 | 0.5400 | 0.8708 | Field | 1.61 | 1.75 | No |
| Percent passing No. 50 and retained on No. 80 | 0.4600 | 0.4776 | Field | 1.04 | 1.75 | No |
| Percent passing No. 80 and retained on No. 200 | 0.8700 | 0.9584 | Field | 1.10 | 1.75 | No |
| Percent passing No. 200 | 0.3000 | 0.2867 | Lab | 1.05 | 1.75 | No |

different. With the asphalt content determination, mean differences were almost as large as the entire specification range. This suggests that an extremely significant disparity existed in either equipment, procedure, or testing technique from one plant to another during this study.

These findings indicate that in the more important areas of the bituminous concrete test, for top and bottom material, there is a lack of uniformity in the field in relation to the laboratory. This discrepancy appears to be the result of a deficiency in the standardization of the field testing method.

## Individual Test Results

Table 4 summarizes all test results and includes the mean and standard deviations for each tested property. It also indicates the percentage of tests that fell within and outside the specification limits. For more than half of the test characteristics or properties, all samples tested were within the desired limits. Furthermore, for the passing 1½ in., 1 in., ½ in., ¼ in., and No. 200 properties on bottom material, failures were recorded on only one end of the specification. For the ½-in. data, a comparison of the mean and standard deviation with the specification center value and tolerance (in parentheses above the mix specification Table 4b) shows that the failures resulted primarily because the material's average was too far above the middle of the specification range. For the other four sieves this same effect, combined with the occurrence of a few extreme values, seems to account for the small failing percentages reported.

The remaining failures occur in the three critical areas of the bituminous test (asphalt content, stone content), and passing No. 200 for top course and asphalt content and stone content for bottom course. These properties have failures at both ends of the specification. The failure of material at both the upper and lower limits is an in-

TABLE 4

SUMMARY OF EXTRACTION TEST RESULTS

| Test Property | Mix Specification | No. of Tests | Mean | Std. Dev. | Percent of Tests | | |
|---|---|---|---|---|---|---|---|
| | | | | | Within Spec. | Below Spec. | Above Spec. |
| **(a) Top Mixture** | | | | | | | |
| Percent asphalt content | 6.2±0.3 | 200 | 6.40 | 0.335 | 64.0 | 4.0 | 32.0 |
| Percent stone content (retained on No. 10) | 40±4 | 200 | 41.51 | 2.904 | 83.0 | 1.0 | 16.0 |
| Percent passing 1 in. and retained on ½ in. | (5±5) 0-10 | 200 | 0.875 | 1.019 | 100.0 | 0.0 | 0.0 |
| Percent passing ½ in. and retained on ¼ in. | (21±9) 12-40 | 200 | 26.35 | 2.980 | 100.0 | 0.0 | 0.0 |
| Percent passing ¼ in. and retained on No. 10 | (19±11) 8-30 | 200 | 14.27 | 1.987 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 10 and retained on No. 30 | (9.5±7.5) 2-17 | 200 | 9.07 | 1.623 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 30 and retained on No. 50 | (14±10) 4-24 | 200 | 12.32 | 1.520 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 50 and retained on No. 80 | (14±8) 6-22 | 200 | 12.68 | 1.516 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 80 and retained on No. 200 | (11.5±8.5) 3-20 | 200 | 12.22 | 1.637 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 200 | (6±2) 4-8 | 200 | 5.49 | 1.141 | 92.5 | 5.0 | 2.5 |
| **(b) Bottom Mixture** | | | | | | | |
| Percent asphalt content | 4.7±0.3 | 200 | 4.83 | 0.433 | 58.5 | 13.5 | 28.0 |
| Percent stone (retained on No. 10) | 70±5 | 200 | 68.38 | 3.169 | 87.0 | 10.5 | 2.5 |
| Percent passing 1½ in. and retained on 1 in. | (17.5±17.5) 0-35 | 200 | 9.57 | 5.313 | 99.5 | 0.0 | 0.5 |
| Percent passing 1 in. and retained on ½ in. | (47.5±22.5) 25-70 | 200 | 34.84 | 5.136 | 97.5 | 2.5 | 0.0 |
| Percent passing ½ in. and retained on ¼ in. | (10±10) 0-20 | 200 | 16.56 | 4.596 | 82.0 | 0.0 | 18.0 |
| Percent passing ¼ in. and retained on No. 10 | (7.5±7.5) 0-15 | 200 | 7.37 | 2.638 | 99.0 | 0.0 | 1.0 |
| Percent passing No. 10 and retained on No. 30 | (6±5) 1-11 | 200 | 4.39 | 0.941 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 30 and retained on No. 50 | (8.5±6.5) 2-15 | 200 | 6.20 | 1.011 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 50 and retained on No. 80 | (8±6) 2-14 | 200 | 6.60 | 1.029 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 80 and retained on No. 200 | (7.5±5.5) 2-13 | 200 | 6.93 | 1.340 | 100.0 | 0.0 | 0.0 |
| Percent passing No. 200 | (2.5±2.5) 0-5 | 200 | 2.54 | 0.653 | 99.5 | 0.0 | 0.5 |

dication that the variability of test data is in excess of that allowed by the specification. This is confirmed by the fact that, in all five cases cited, four times the standard deviation (for data normally distributed this would encompass 95.5% of the test results around their mean) is in excess of the specification range. This excessive variability of the data does not necessarily indicate that the material itself is too variable; it may be the result of undue testing or sampling variability. The exact cause of the excessive overall variations can be ascertained from the analysis of variance.

## Analysis of Variance

Table 5 gives the results of the analysis of variance performed on the test data from the two plants. For each property tested, the table gives the overall variance of the data, the standard deviation, and the three components of the total variance: the process, sampling, and testing variances. Inasmuch as the laboratory and the field test

TABLE 5

ANALYSIS OF VARIANCE—EXTRACTION TEST RESULTS

| Test Property | Variance | | | | Std. Dev. |
|---|---|---|---|---|---|
| | Process | Sampling | Testing | Total | |
| **(a) Top Mixture** | | | | | |
| Percent asphalt content | 0.0216 | 0.000 | (0.0088) 0.0911 | 0.1127 | 0.335 |
| Percent stone content (retained on No. 10) | 5.0439 | 1.1623 | (1.5500) 2.2270 | 8.4331 | 2.904 |
| Percent passing 1 in. and retained on ½ in. | 0.1405 | 0.0000 | (0.7200) 0.8779 | 1.0384 | 1.019 |
| Percent passing ½ in. and retained on ¼ in. | 3.3819 | 1.0503 | (2.6100) 4.4463 | 8.8785 | 2.980 |
| Percent passing ¼ in. and retained on No. 10 | 2.8679 | 0.2586 | (0.9200) 0.8223 | 3.9488 | 1.987 |
| Percent passing No. 10 and retained on No. 30 | 1.7195 | 0.2837 | (0.9000) 0.6295 | 2.6328 | 1.623 |
| Percent passing No. 30 and retained on No. 50 | 0.5774 | 0.0000 | (1.6400) 1.7316 | 2.3090 | 1.520 |
| Percent passing No. 50 and retained on No. 80 | 0.8620 | 0.3803 | (1.1700) 1.0565 | 2.2993 | 1.516 |
| Percent passing No. 80 and retained on No. 200 | 0.0000 | 0.7961 | (0.7600) 1.8821 | 2.6782 | 1.637 |
| Percent passing No. 200 | 0.4927 | 0.4085 | (0.2900) 0.4011 | 1.3022 | 1.637 |
| **(b) Bottom Mixture** | | | | | |
| Percent asphalt content | 0.0421 | 0.0573 | (0.0111) 0.0885 | 0.1878 | 0.433 |
| Percent stone content (retained on No. 10) | 2.4201 | 2.1425 | (2.9700) 5.4770 | 10.0395 | 3.169 |
| Percent passing 1½ in. and retained on 1 in. | 5.1919 | 6.2548 | (13.8400) 16.7823 | 28.2291 | 5.313 |
| Percent passing 1 in. and retained on ½ in. | 0.8170 | 5.4197 | (17.1100) 20.1401 | 26.3768 | 5.136 |
| Percent passing ½ in. and retained on ¼ in. | 10.8057 | 1.6141 | (8.0100) 8.7023 | 21.1221 | 4.596 |
| Percent passing ¼ in. and retained on No. 10 | 3.2970 | 1.4145 | (3.0000) 2.2465 | 6.9580 | 2.638 |
| Percent passing No. 10 and retained on No. 30 | 0.2597 | 0.1541 | (0.6200) 0.4717 | 0.8855 | 0.941 |
| Percent passing No. 30 and retained on No. 50 | 0.1062 | 0.2097 | (0.5400) 0.7054 | 1.0212 | 1.011 |
| Percent passing No. 50 and retained on No. 80 | 0.1637 | 0.4267 | (0.4600) 0.4688 | 1.0592 | 1.029 |
| Percent passing No. 80 and retained on No. 200 | 0.3408 | 0.5396 | (0.8700) 0.9142 | 1.7946 | 1.340 |
| Percent passing No. 200 | 0.1327 | 0.0000 | (0.3000) 0.2933 | 0.4260 | 0.653 |

results were combined for this portion of the analysis, the testing variances are actually averages of the individual variances for the two testing processes. The mathematics of the analysis of variance are such that these are straight arithmetic averages. For purposes of comparison, the laboratory testing variances are included (in parentheses above the averaged testing variance values).

To determine the cause of the excessive variability of test results in the five instances previously cited, a comparison was made of the variance components for the test properties involved. Examination of the components of the asphalt content determination for top material clearly shows that the testing variance is by far the largest factor indicating that most of the recorded variability was caused by testing. This averaged testing variance compared with that of the laboratory alone reveals that laboratory testing could not have been responsible for the excessive testing variability. The laboratory value is less than one-tenth of the averaged figure. The field testing,

TABLE 6

COMPARISON OF SPECIFICATION TOLERANCES WITH OVERALL VARIABILITIES ASSUMING LABORATORY TESTING

| Test Property | Top Material | | | | Bottom Material | | | |
|---|---|---|---|---|---|---|---|---|
| | Spec. Tolerance | $\sigma'$[a] | $2\sigma'$ | $3\sigma'$ | Spec. Tolerance | $\sigma'$[a] | $2\sigma'$ | $3\sigma'$ |
| Asphalt content | ±0.30 | 0.174 | 0.35 | 0.52 | ±0.30 | 0.332 | 0.66 | 1.00 |
| Stone content | ±4.0 | 2.78 | 5.6 | 8.3 | ±5.0 | 2.74 | 5.5 | 8.2 |
| Passing 1½ in. and retained on 1 in. | — | — | — | — | ±17.5 | 5.04 | 10.1 | 15.1 |
| Passing 1 in. and retained on ½ in. | ±5.0 | 0.93 | 1.9 | 2.8 | ±22.5 | 4.84 | 9.7 | 14.5 |
| Passing ½ in. and retained on ¼ in. | ±9.0 | 2.65 | 5.3 | 8.0 | ±10.0 | 4.51 | 9.0 | 13.5 |
| Passing ¼ in. and retained on No. 10 | ±11.0 | 2.01 | 4.0 | 6.0 | ±7.5 | 2.78 | 5.6 | 8.3 |
| Passing No. 10 and retained on No. 30 | ±7.5 | 1.70 | 3.4 | 5.1 | ±5.0 | 1.02 | 2.0 | 3.1 |
| Passing No. 30 and retained on No. 50 | ±10.0 | 1.49 | 3.0 | 4.5 | ±6.5 | 0.93 | 1.9 | 2.8 |
| Passing No. 50 and retained on No. 80 | ±8.0 | 1.55 | 3.1 | 4.[illegible] | ±6.0 | 1.02 | 2.0 | 3.1 |
| Passing No. 80 and retained on No. 200 | ±8.5 | 1.16 | 2.3 | 3.5 | ±5.5 | 1.32 | 2.6 | 4.0 |
| Passing No. 200 | ±2.0 | 1.06 | 2.1 | 3.2 | ±2.5 | 0.66 | 1.3 | 2.0 |

[a] $\sigma' = \sqrt{\sigma_p^2 + \sigma_s^2 + \sigma_t^2}$ laboratory

therefore, had to be the primary causal factor for the high combined or averaged testing variance recorded. This same effect, to a lesser extent, also occurred in the other four cases of concern.

The influence of field testing, although significant, does not explain all the excessiveness in the questionable overall variabilities. After adjusting these parameters to account for the field testing effect, they still fail to be compatible with the governing specification limits. With an equitable specification and well-controlled production, sampling, and testing processes, the plus-or-minus tolerance should probably fall between $\pm 2\sigma$ and $\pm 3\sigma$. The $\pm 2\sigma$ allowance would provide for the acceptance of 95.5 percent of the production output; $\pm 3\sigma$ would result in an output acceptance of 99.7 percent. Table 6 compares overall variabilities, assuming the use of only laboratory testing, with specification tolerances. There is an obvious inconsistency with this approach for the five test properties of concern. With these properties (asphalt content, stone content, and passing No. 200 sieve—top material, asphalt content and stone content—bottom material), the tolerances correspond to something less than $\pm 2\sigma$. This means that either a lack of control existed in the contributing variability factors (the production process, sampling, and laboratory testing) or that the specifications cannot be satisfied under existing standard controls. The actual situation can be established by comparing the variability parameters recorded here with those typical of the bituminous concrete field in general.

For the test properties shown previously to have no failing results, or failures at only one end of the specification (passing 1½-in. screen through No. 80 sieve on both materials, and passing the No. 200 sieve on bottom material), Table 6 indicates a different type of disparity with the $\pm 2\sigma$ to $\pm 3\sigma$ approach. For these properties, with the exception of the items passing ½ and ¼-in. screens on bottom material, the specification tolerances exceed $\pm 3\sigma$. In this instance, the specifications seem to have provided more allowance than was actually required for the existing variation. It appears that a target value approach, similar to that used with asphalt content and stone content properties, employing tolerance limits smaller than the present specification ranges, could have been used without additional burden on the supplier.

## Comparison of Present Variability Parameters with Bureau of Public Roads Data

To check the validity of the Department's present sampling and laboratory testing processes, and to determine a reason for the five instances of inordinate overall variability, a comparison was made of the variability parameters of this study with those established by other state highway agencies. The data were extracted from a compilation of statistical parameters provided by the quality control task force of the Bureau of Public Roads (4) as a summary of its research findings to date. The sampling and testing variabilities for the asphalt content determination obtained by other states and those in this study are given in Table 7 in the form of variances. The corresponding

TABLE 7

COMPARISON OF VARIANCE COMPONENTS FOR ASPHALT CONTENT DETERMINATION

| Data Source | Number of Tests | Variance Components | | |
|---|---|---|---|---|
| | | Process | Sampling | Testing |
| (a) Top Material | | | | |
| Present study | 200 | 0.0216 | 0.0000 | 0.0088 |
| U.S. Bureau of Public Roads | | | | |
| State | | | | |
| No. 14 | 200 | 0.066 | 0.006 | 0.002 |
| No. 17 | — | — | — | 0.256 |
| No. 17 | — | — | — | 0.256 |
| No. 21 | 40 | 0.084 | 0.000 | 0.043 |
| No. 21 | 24 | 0.06 | 0.00 | 0.05 |
| No. 21 | 128 | 0.04 | 0.00 | 0.04 |
| (b) Bottom Material | | | | |
| Present study | 200 | 0.0421 | 0.0573 | 0.0111 |
| U.S. Bureau of Public Roads | | | | |
| State | | | | |
| No. 17 | — | — | — | 0.0961 |
| No. 17 | — | — | — | 0.0729 |
| No. 21 | 284 | 0.04 | 0.04 | 0.06 |
| No. 21 | 68 | 0.17 | 0.05 | 0.08 |
| No. 21 | 380 | 0.09 | 0.06 | 0.06 |

process variances in each case are also included. Variability of our laboratory testing compares favorably with that of other states; most of the sources reporting have higher variability for both top and binder materials. The same is true of our sampling variability, except that for binder material ours is among the highest values reported. The process variances for this particular study are the lowest of all sources reporting. This may reflect the fact that the two plants involved in this investigation were automatically controlled systems reputed to have a high degree of uniformity in production.

Analysis of variance data was not available in the Bureau's tabulations for the other asphaltic-concrete test properties included in this study. However, data were provided on overall variability for the No. 10 (stone content) and No. 200 sieve characteristics. This information is given in Table 8 along with the overall variability values (standard deviations assuming the use of only laboratory testing) determined in the present study. Our measured variabilities, again, compare favorably, being below the weighted average of other states in all instances, with the exception of the No. 200 sieve property for top material. For this characteristic, however, the overall standard deviation is still within the range of values recorded by other states.

It can be inferred from the latter comparisons that our sampling and laboratory testing processes for the No. 10 and No. 200 sieves are also on a par with those typical of the highway field today. This is only an inference, however. The overall variabilities compared are a function of material variability, in addition to the sampling and testing factors. It is possible that small material variances produced the small overall variabilities obtained. A more comprehensive check of the validity of sampling and testing for these and the remaining properties of the asphaltic-concrete test cannot be accomplished until additional variance component data are provided by the Bureau of Public Roads.

From the preceding discussion it is evident that in the five instances of indicated excessive overall variability, the variability parameters were actually not inordinate by present standards. Therefore, the specification limits for these test properties (asphalt content, stone content, No. 200—top material; asphalt content, stone content—bottom material) were unrealistically restrictive in the control of materials at the two plants studied. Their narrow allowance for variations was incompatible with the present capabilities of asphaltic-concrete production, sampling, and testing. Whether or not this is the case on other construction projects for the state can only be conjectured. Further investigation is obviously necessary.

TABLE 8

COMPARISON OF OVERALL STANDARD DEVIATIONS ON PASSING NO. 10 AND NO. 200 SIEVES

| Sieve | Present Study | Range of BPR Report | Weighted Average |
|---|---|---|---|
| (a) Top | | | |
| No. 10 | 2.78 | 2.0-5.0 | 3.14 |
| No. 200 | 1.06 | 0.27-1.27 | 0.86 |
| (b) Bottom | | | |
| No. 10 | 2.74 | 2.67-3.9 | 3.67 |
| No. 200 | 0.66 | 0.55-1.5 | 0.67 |

## SUMMARY AND CONCLUSIONS

For FABC top and bottom in the critical areas of the asphaltic-concrete test, field testing is significantly more variable than main laboratory testing; this difference was extremely pronounced in the case of the asphalt content determination. The discrepancy appears to be primarily due to differences in field test method from one plant to another.

Testing variances were found in the variance analysis to contribute substantially to the overall variability of test results. This fact, combined with the observation that significant differences in test method exist between field testing locations, indicates that the replacement of laboratory testing by field testing, as the final means for measuring material compliance, would result in a marked decrease in the uniformity of the compliance-measuring process. Therefore, for FABC-top and FABC-bottom, it is concluded that field testing cannot as yet replace laboratory testing as the basis for final judgment of material compliance. A greater standardization of the field method (equipment, procedure, testing technique) is required before this change would be practicable.

For the two asphaltic-concrete plants included in this study, present specifications on top and binder asphaltic-concrete generally dealt fairly with the materials supplier. As specifications on individual test results, for the most part they made sufficient allowance for the natural variabilities encountered. There was also an indication that in the less critical areas of asphaltic testing a decrease in the specification ranges was possible if a target value approach were used. However, there were several important exceptions to these general observations. In the three critical areas of the asphaltic-concrete test, five of the six governing specifications were overly restrictive for the present capabilities of the production, sampling, and testing processes. In these instances a loosening of the limits appears required to provide an equitable specification.

A comparison with data supplied by the U. S. Bureau of Public Roads showed that the uniformity of the sampling procedures and laboratory testing process for the asphalt content determination is on a par with and, perhaps, even superior to that of other highway agencies. For this test property, therefore, the Department's present sampling and laboratory testing processes are at least as valid (in uniformity) as those typical of the highway field today.

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# A System for Control and Acceptance of Bituminous Mixtures by Statistical Methods

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Problems caused by enforcement of strict compliance with specifications and failure to consider the inherent variations in materials, construction, sampling, and testing motivated the South Carolina State Highway Department to conduct the research project which this paper describes.

The work was done in four parts. Phase I included the development of random sampling procedures and statistical parameters for hot asphaltic mixtures. These data and experience led to the preparation of the elements of a procedure for process control and acceptance of such mixtures. In Phase II the mixtures as placed on the roadway were investigated by sample survey techniques to verify the control procedures. A tentative system for process control and acceptance of bituminous mixtures was developed from the data and experience in Phase I and Phase II, and this system was tested at four locations in Phase III. The tentative system was further refined as a result of this experience. Phase IV gives the details of the system as developed and a procedure for adjusting the unit price for lots of .mixture which do not conform to the criteria.

•IN recent years there has been great emphasis in most highway departments on literal interpretation of specifications requirements and strict "no deviation" compliance with them. This approach to construction has caused much concern among highway engineers. Everyone familiar with materials and materials testing knows that materials and test results vary. They know, also, that regardless of the control exercised, there is a strong probability that some results may not conform to the exact limits specified even though the average of all the results may be well within the prescribed limits. The fact that results do vary is so well established that if normal variations are not found, penciled or spurious data are suspected.

There are many reasons for such variations. Some are assignable, such as those due to changes in the gradation of aggregate, changes in proportions of components, or lack of control in a manufacturing process. Others are random and may develop from chance causes in a production process, in selecting samples, in preparing the sample for testing, or in performing the test itself. Any one or a combination of assignable or random causes occurring in manufacturing and handling of raw materials or in mixing, placing, sampling and testing the product will affect individual test results.

These problems motivated the South Carolina Highway Department to undertake this research. Hot bituminous mixtures were selected for study because of extensive use throughout the State.

The Department requested cooperation and financial assistance from the U. S. Bureau of Public Roads. After a review of the proposed program, approval was given for the use of Highway Planning Survey funds in defraying part of the cost of the work.

Paper sponsored by Committee on Construction Practices—Flexible Pavement and presented at the 46th Annual Meeting.

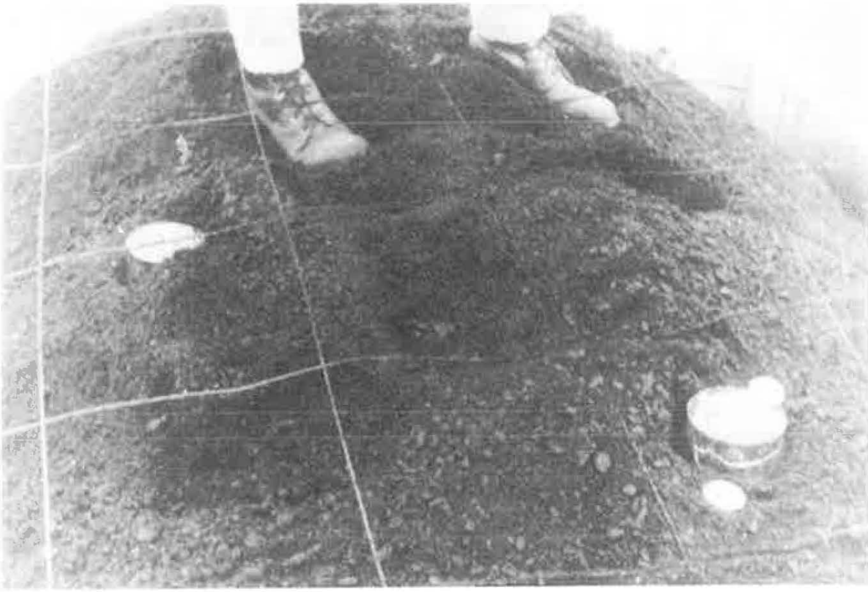

Figure 1. Sampling mix from batch truck, showing grid, sampling cans, and thermometers.

The specific aims of this investigation were as follows.

1. Phase I. Develop statistical quality control procedures for process control and acceptability for hot-mix components on a project under construction.
2. Phase II. Investigate the completed components, using sample survey techniques to verify the quality control procedures used during the construction of the project.

Figure 2. Sampling mix from batch truck, showing grid, sampling device, and thermometers.

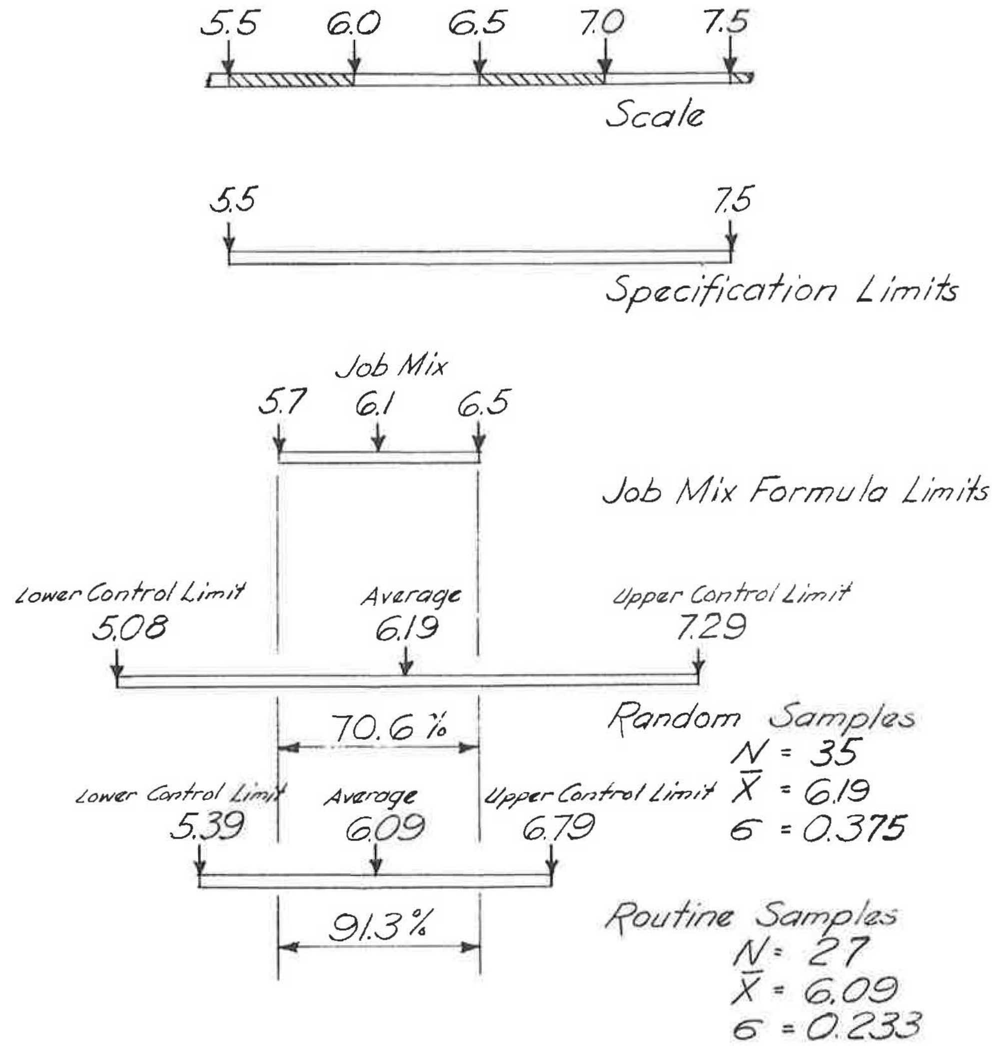


Figure 3. Comparison of limits: asphalt content, surface mix.

3. **Phase III.** Develop a statistical quality control program for process control and acceptability for regular construction of asphaltic components and test these requirements on at least three projects in different sections of the State.

4. **Phase IV.** Develop model requirements for specifications, using statistical concepts based on the results of studies performed on the construction components considered in this research.

Field work for Phase I and Phase II was done concurrently during the fall of 1964 on a project near Greenville.

Field work for Phase III was started during the spring of 1965 and was completed in October 1965. Four plants located in different sections of the State were included.

## PHASE I AND PHASE II

### General

The work plant for Phase I and Phase II made the following provisions.

1. Sampling and testing would be entirely separate from job control. The results would not be used for control of current operations.

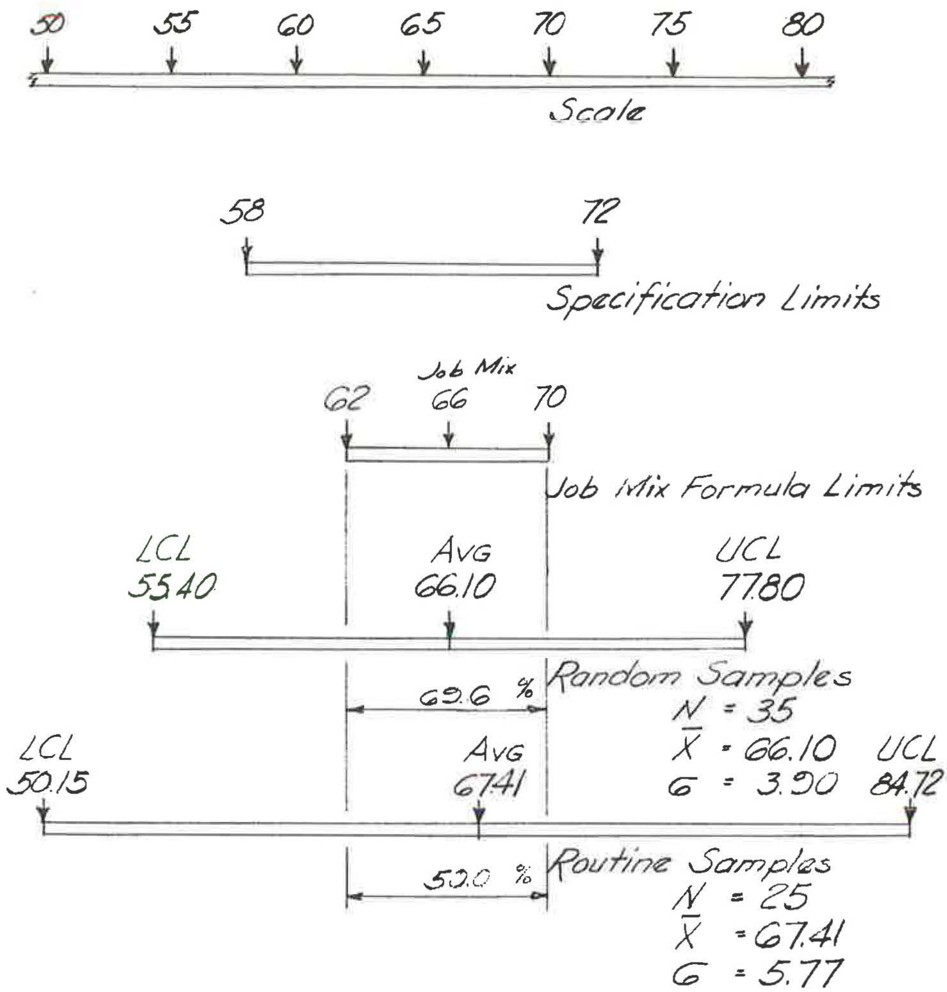


Figure 4. Comparison of limits: percent passing No. 4 sieve, surface mix.

2. All sampling would be on a random basis using random numbers to select the unit for sampling. Two separate samples would be obtained from each unit at locations predetermined by random numbers. Each sample would be reduced to two test portions which would be analyzed separately. Thus, four test results would be obtained for each unit sampled.

3. Samples would be obtained from the mixture in trucks at the plant, from the mix immediately behind the spreader, and from the finished roadway.

4. Regular procedures used by the Department for routine job control would be followed in all testing.

Randomization of Sampling

Probably the most important single feature of this study was the development of procedures to eliminate bias in obtaining the samples. This idea was paramount in the planning for sampling and in actually obtaining the samples. All sampling was done on a random basis. The procedures used gave no opportunity for the sampler to discriminate as to when or where the sample would be drawn. The unit and/or batch to be

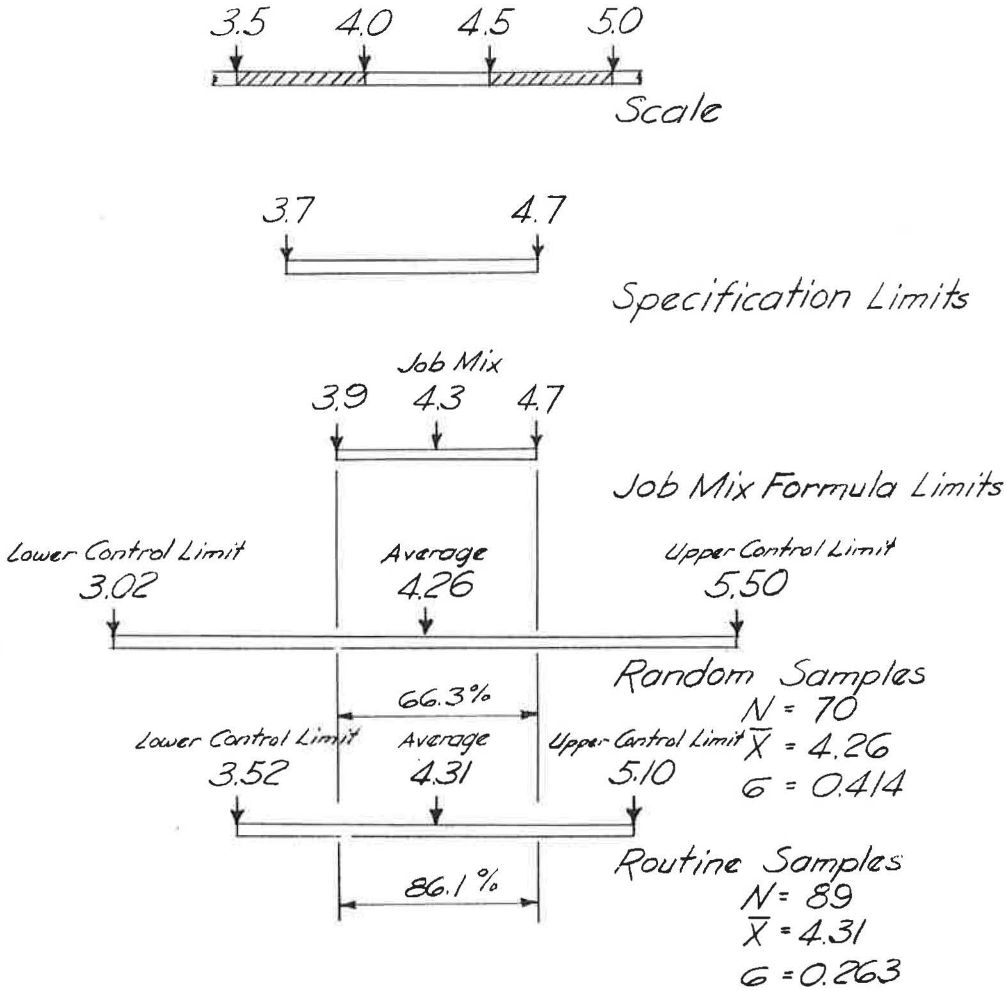


Figure 5. Comparison of limits: asphalt content, binder mix.

sampled and the location within the unit or batch were predetermined (by random numbers) before the operator went to get the sample. Every effort was made to make the actual drawing of the samples as mechanical as possible to eliminate, or at least to minimize, personal bias.

Logic indicates that samples obtained under the traditional approach—a representative sample—usually introduce bias because the sampler can accept or reject material according to his judgment. This judgment depends on the training and experience of the sampler. Too often he is not well trained and his judgment may be affected by prejudice, a headache, weather, etc. However, random samples provide data for obtaining reliable estimates of the variations in the product. Only with random samples can the laws of probability and statistics be applied realistically in analyzing test data.

## Sampling Procedures

Mixture from Trucks—The truckload of mix to be sampled was determined by random numbers. A grid made from paving mesh was used on the surface of the mix to define the small area from which the sample was to be drawn. This grid had 30 openings, each approximately 12 in. square. The position of this grid on the truck body (front, middle or rear) was determined by random numbers, and the opening in the grid

TABLE 1
UPPER AND LOWER LIMITS

| Item | Job-Mix Tolerance | 99.7 Percent of the Time (3 σ) | | 95 Percent of the Time (2 σ) | |
|---|---|---|---|---|---|
| | | Routine | Random | Routine | Random |
| (a) Surface Mix | | | | | |
| Pass ½ in. | ± 7 | ± 11.0 | ± 8.6 | ± 7.3 | ± 5.7 |
| Pass No. 4 | ± 4 | ± 17.3 | ± 11.7 | ± 11.5 | ± 7.8 |
| Pass No. 10 | ± 4 | ± 14.8 | ± 10.3 | ± 9.8 | ± 6.9 |
| Pass No. 40 | ± 4 | ± 9.3 | ± 5.1 | ± 6.2 | ± 3.4 |
| Pass No. 200 | ± 2 | ± 4.4 | ± 3.2 | ± 2.9 | ± 2.1 |
| Asphalt content | ± 0.4 | ± 0.70 | ± 1.11 | ± 0.46 | ± 0.74 |
| (b) Binder Mix | | | | | |
| Pass 1 in. | ± 7 | ± 7.6 | ± 11.8 | ± 5.1 | ± 7.9 |
| Pass No. 4 | ± 4 | ± 10.8 | ± 14.2 | ± 7.2 | ± 9.5 |
| Pass No. 10 | ± 4 | ± 9.9 | ± 12.0 | ± 6.6 | ± 8.1 |
| Asphalt content | ± 0.4 | ± 0.79 | ± 1.24 | ± 0.52 | ± 0.82 |

from which samples were drawn was determined by random numbers. At first, 48-oz cans were pushed into the mix to obtain the sample (Fig. 1). This procedure worked well in surface mix containing small size aggregate. The cans were too fragile and did not take out sufficient material when the mix contained large size aggregates. A larger and more rugged sampling device was developed from a standard 6-in. steel concrete cylinder mold. This device served equally well for all mixes. To obtain the sample, the operator boarded the truck containing the preselected batch, placed the grid in the preselected position (front, middle, or rear of the truck body), then inserted the sampling device (cylinder mold) into the mix in the preselected grid openings (Fig. 2). After the mold was pushed into the mixture the operator removed the material surrounding the mold, slipped a shovel underneath it, and slid the mold containing the sample from the shovel onto an aluminum pie plate. To obtain the larger sample needed to perform Marshall tests and the Department's "basket test" for gradations of binder and macadam mixes, additional material was obtained from the same grid opening. The temperature of the batch was measured by inserting thermometers in the mixture immediately adjacent to the sampling device.

Mixture Directly Behind Spreader—The samples were obtained on the arrival of the operator at the site, and were taken from the roadway directly behind the spreader, before rolling. An effort was made to follow trucks from which samples had been drawn at the plant, but there was no practical way of determining that the mix sampled behind the spreader was from the specific batch sampled at the plant. Positions for sampling, in terms of width of spread, were selected by random numbers.

Compacted Mix—The length of pavement to be sampled was divided into 300-ft sections and 100-ft subsections. Selection of the subsection to be sampled was by random numbers. Exact locations for sampling within the 100-ft subsections were determined by random numbers.

## Analysis of Data, Phase I

Individual Test Results—Typical results on random samples are compared with those obtained in routine plant control and with the requirements of the specifications and the job-mix formula in Figures 3, 4, and 5. During this study, routine plant control was carried out in the usual manner.

Figure 3 shows the asphalt content of the surface mix within the limits permitted by the job-mix formula 91 percent of the time by routine control samples and 70 percent by random samples.

Figure 4 shows the percentage passing the No. 4 sieve in the surface mix within the limits permitted by the job-mix formula 50 percent of the time by routine control samples and 70 percent by random samples. The extreme limits of the specifications are exceeded by both types of samples.

Figure 5 shows the asphalt content of the binder mix within the limits permitted by the job-mix formula 86 percent of the time by routine control samples and 66 percent by random samples.

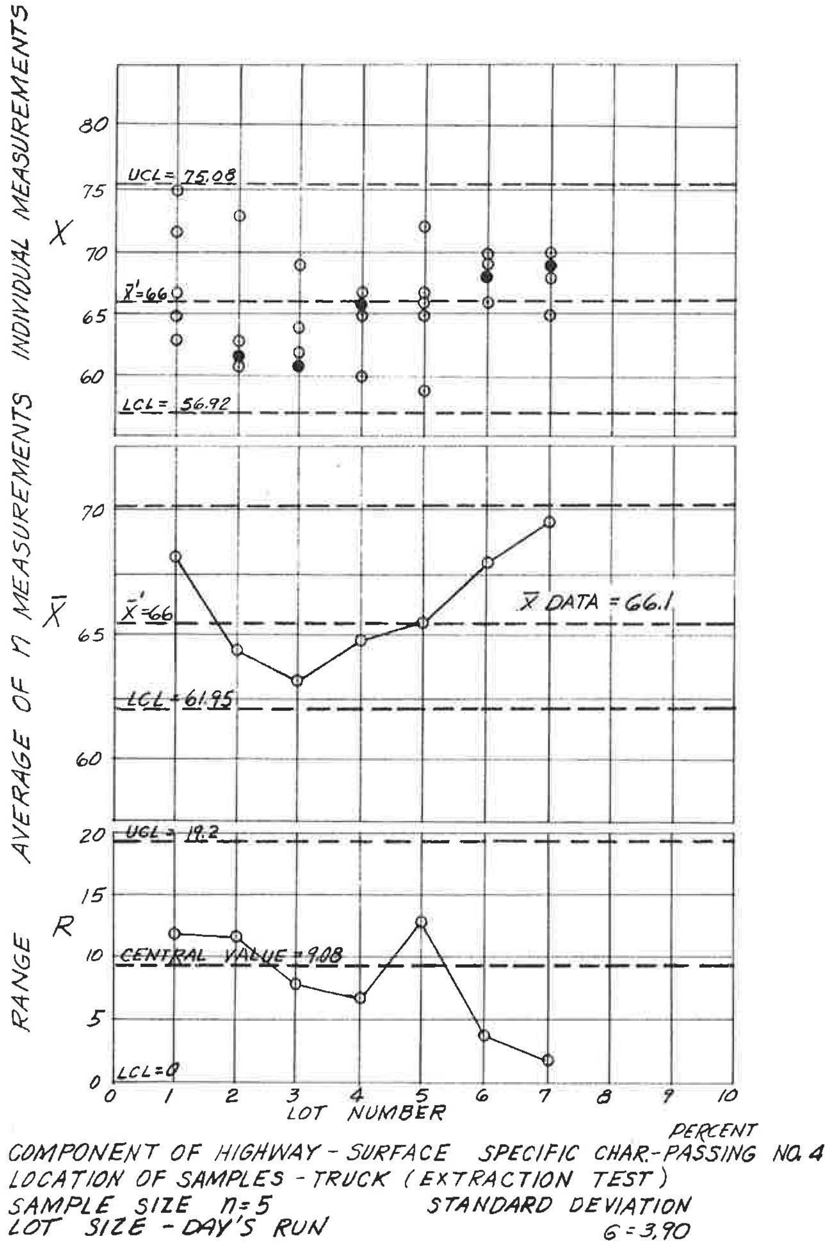


Figure 6. Standards given control chart: percent passing No. 4 sieve.

Tolerances—Table 1 gives tolerances from a mean value that would be necessary to include all these test results [based on individual results (n = 1) for both routine control and random samples].

The impracticality of expecting all samples to conform with tolerances permitted by present job-mix allowances is clearly demonstrated by these figures.

Control Charts—The control chart technique is the core of the system of control of a manufacturing process by statistical methods. With "standards given" control charts the central value ($\bar{x}'$) is a specified standard of production. For bituminous mixes this would be the value stated in the job-mix formula for asphalt content or a given sieve

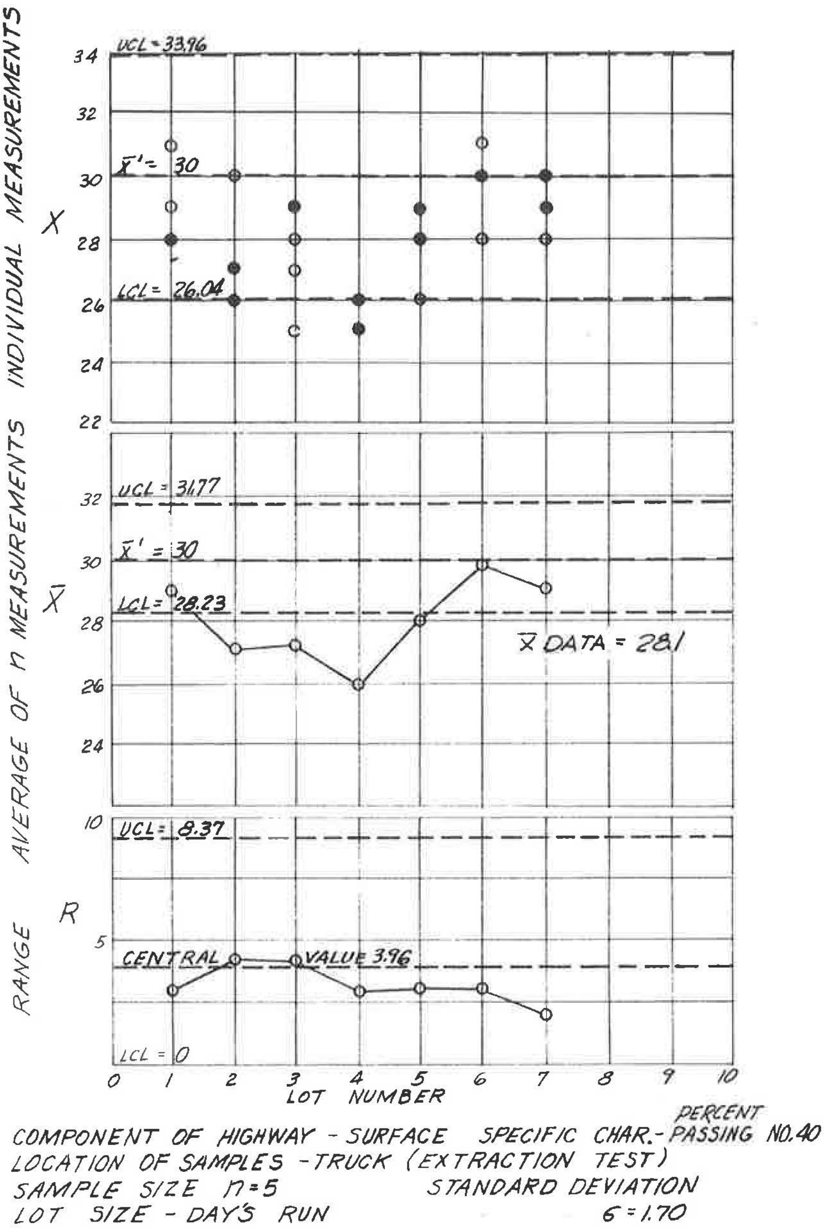


Figure 7. Standards given control chart: percent passing No. 40 sieve.

size. Control limits are established from this mean or standard value using standard formulas in which the Department's risk of accepting poor material and contractor's risk of having good materials rejected are predetermined, and the maximum allowable difference in the mean value for acceptable material and the mean value for unacceptable material are specified.

Standards given control charts were prepared from these data, using the results from five samples for a lot, with a lot equal to approximately a day's production.

Surface mix—Control charts were prepared for 7 lots for the ½ in., No. 4, No. 10, No. 40, No. 200 sieves and for asphalt content (Figs. 6, 7, and 8).

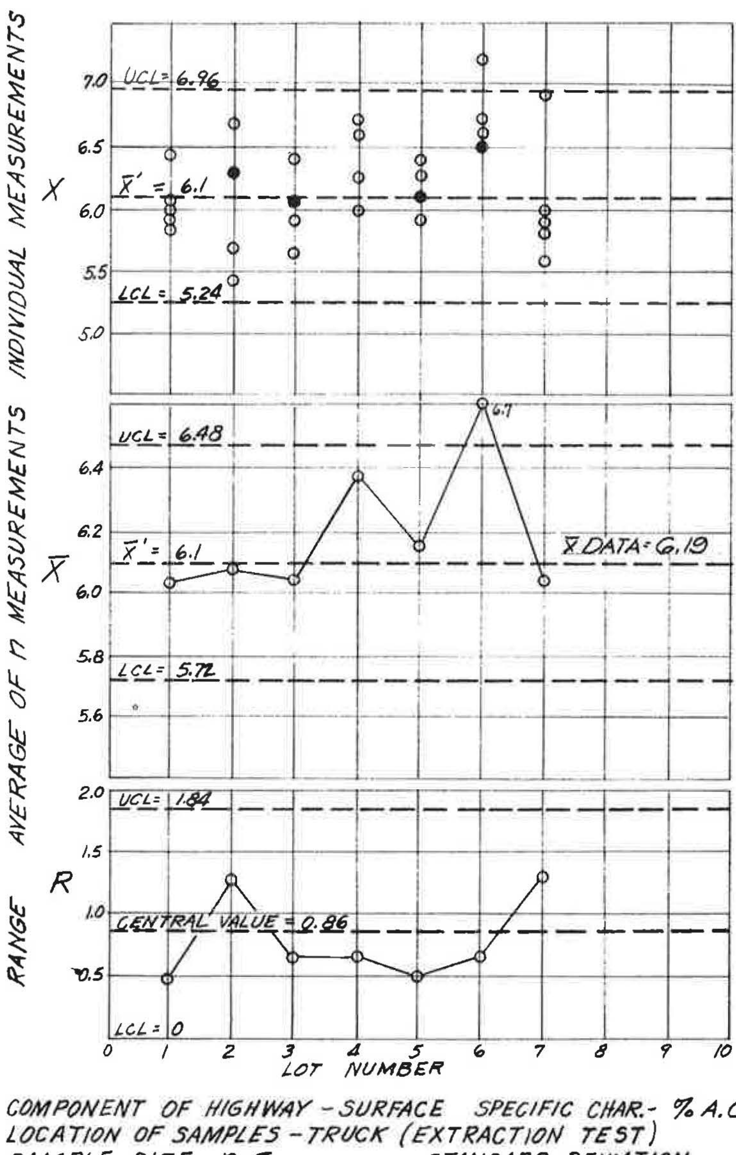


Figure 8. Standards given control chart: asphalt content.

Figure 6, passing No. 4 sieve, shows individual results and the values for lots within control limits.

Figure 7, passing No. 40 sieve, shows several individual results outside of control limits and the values for four of the seven lots below the control limit. The indication is that the mix was not controlled to the job-mix value on this sieve.

Figure 8, asphalt content, shows that the asphalt content is out of control in only one lot. The mean value for the test results is very close to the job-mix value.

Binder mix—Control charts were prepared for 14 lots for the 1 in., No. 4, No. 10 and asphalt content. Typical results are given in Figures 9 and 10 for ten lots only.

Figure 9, passing 1-in. sieve, shows three individual results out of control, but the values for lots exceed the control limits in four of the ten lots. Also, the mean for the

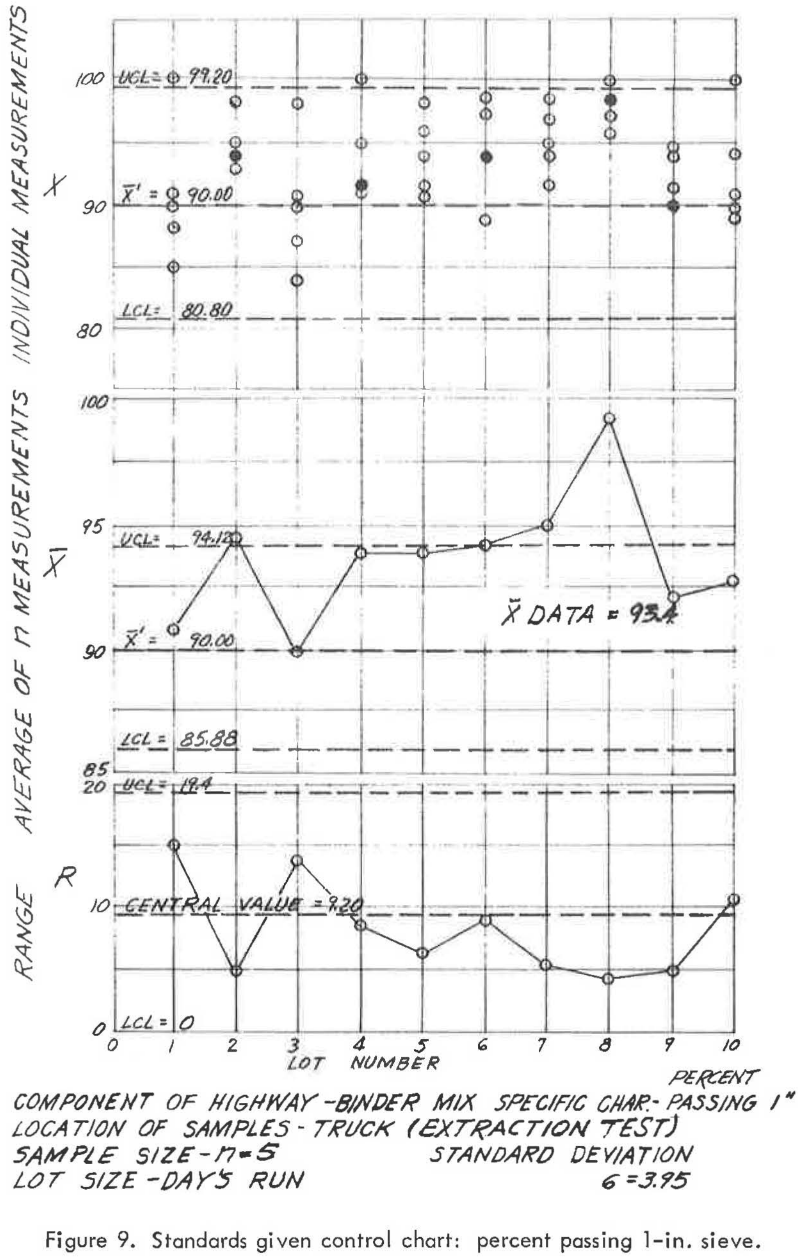


Figure 9. Standards given control chart: percent passing 1-in. sieve.

data is above the value of the job-mix, which indicates that the mix was not controlled to the job-mix value.

Figure 10, asphalt content, shows results that vary widely but are within control limits.

## Analysis of Data, Phase II

Comparison of Plant and Roadway Results—Results from samples obtained at the plant from batch trucks, from the roadway immediately behind the spreader, and from the roadway after compaction are given in Tables 2 and 3.

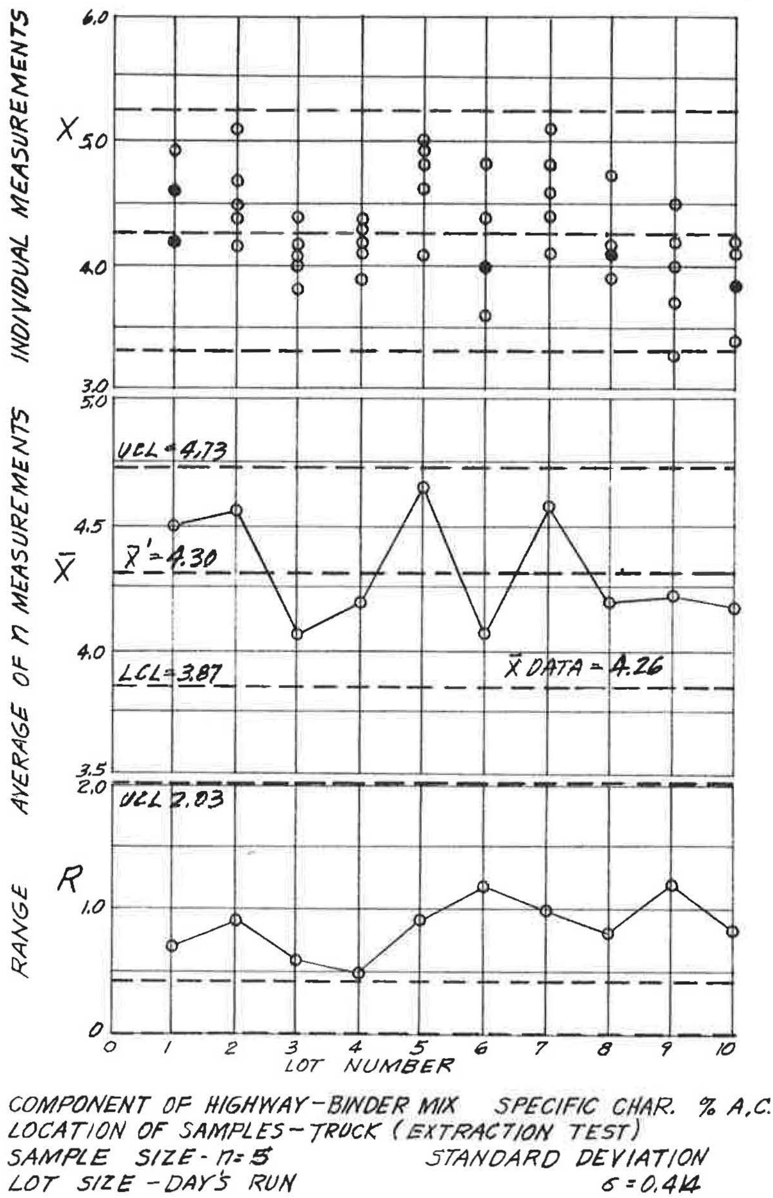


Figure 10. Standards given control chart: asphalt content.

These data show reasonably close agreement in the mean values for the samples obtained at the plant from batch trucks, those from the roadway immediately behind the spreader, and those from the compacted roadway. These results indicate that the methods used for sampling give realistic representations of the mixture.

In several instances, mean values for the samples from the roadway after compaction show more fine material than those from other sources. In the binder mixture, the percentages passing No. 4, No. 10, and No. 200 on the compacted samples are higher in all instances than those on samples from the plant or at the spreader, indicating that some degradation has occurred.

The standard deviations (sigmas) for results from the three sources are not greatly different, generally, for a particular measurement such as asphalt content and each sieve size. Inadequate data exist to make meaningful tests for significant differences.

TABLE 2

COMPARISON OF RESULTS FOR SURFACE MIXTURE SAMPLES OBTAINED FROM PLANT, SPREADER AND COMPACTED ROADWAY—GREENVILLE, S. C.

| Place Sampled | Extraction Test Gradation | Spec. Limits (%) | Control Chart | | Analysis of Variance[a] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma_t$ | $\sigma_t^2$ | $\sigma_b^2$ | $\sigma_w^2$ | $\sigma_e^2$ |
| Plant | Percent pass ½ in. | 87-97 | 92.0 | 2.88 | 91.8 | 3.10 | 9.62 | 2.45 | 0 | 7.60 |
| Spreader | | | 90.0 | 4.00 | 90.7 | 3.52 | 12.41 | 8.74 | 0 | 3.50 |
| Compacted | | | 92.2 | 3.30 | 92.1 | 3.16 | 10.02 | 0 | 2.18 | 6.19 |
| Plant | Percent pass No. 4 | 58-72 | 66.1 | 3.90 | 66.8 | 3.92 | 15.37 | 9.70 | 0 | 5.15 |
| Spreader | | | 65.2 | 5.71 | 65.7 | 5.84 | 34.06 | 30.9 | 0 | 4.75 |
| Compacted | | | 65.0 | 4.32 | 65.2 | 4.28 | 18.34 | 0 | 10.18 | 8.11 |
| Plant | Percent pass No. 10 | 42-58 | 52.0 | 3.45 | 52.6 | 3.69 | 13.59 | 8.33 | 1.76 | 3.69 |
| Spreader | | | 53.0 | 4.98 | 52.7 | 5.60 | 31.35 | 28.15 | 0 | 5.04 |
| Compacted | | | 54.3 | 3.92 | 54.5 | 4.01 | 16.11 | 0 | 11.36 | 7.39 |
| Plant | Percent pass No. 10 | 21-35 | 28.1 | 1.70 | 28.3 | 1.91 | 3.64 | 2.28 | 0 | 1.40 |
| Spreader | | | 28.0 | 1.41 | 28.5 | 2.34 | 5.48 | 4.92 | 0 | 1.00 |
| Compacted | | | 28.7 | 1.85 | 28.8 | 2.08 | 4.31 | 0 | 2.51 | 2.09 |
| Plant | Percent pass No. 200 | 4-10 | 5.7 | 1.06 | 5.8 | 1.15 | 1.32 | 1.15 | 0 | 0.18 |
| Spreader | | | 5.7 | 1.20 | 6.34 | 1.38 | 1.91 | 0 | 0 | 1.44 |
| Compacted | | | 6.5 | 1.04 | 6.4 | 1.03 | 1.05 | 0.30 | 0.48 | 0.20 |
| Plant | Bitumen | 5.5-7.5 | 6.19 | 0.37 | 6.23 | 0.37 | 0.14 | 0.08 | 0 | 0.04 |
| Spreader | | | 6.00 | 0.43 | 6.02 | 0.33 | 0.11 | 0.06 | 0 | 0.05 |
| Compacted | | | 6.15 | 0.32 | 6.12 | 0.28 | 0.08 | 0 | 0 | 0.04 |
| No. of tests performed | | | | | | | | | | |
| Plant (truck) | | | | | | | | | 40 | |
| Spreader (roadway behind spreader) | | | | | | | | | 24 | |
| Compacted (roadway compacted) | | | | | | | | | 128 | |

[a]Analysis of variance data were based on four times as many tests as control chart data.

TABLE 3

COMPARISON OF RESULTS FOR BINDER MIXTURE SAMPLES OBTAINED FROM PLANT, SPREADER AND COMPACTED ROADWAY—GREENVILLE, S. C.

| Place Sampled | Extraction Test Gradation | Spec. Limits (%) | Control Chart | | Analysis of Variance[a] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma_t$ | $\sigma_t^2$ | $\sigma_b^2$ | $\sigma_w^2$ | $\sigma_e^2$ |
| Plant | Percent pass 1 in. | 80-97 | 93.4 | 3.95 | 93.9 | 4.13 | 17.09 | 0 | 2.60 | 13.04 |
| Spreader | | | 93.8 | 5.19 | 93.3 | 4.07 | 16.56 | 3.35 | 0 | 12.25 |
| Compacted | | | 93.4 | 4.70 | 93.7 | 4.48 | 20.07 | 4.59 | 0 | 15.43 |
| Plant | Percent pass No. 4 | 35-50 | 40.6 | 4.76 | 40.8 | 4.61 | 21.25 | 8.47 | 5.37 | 7.52 |
| Spreader | | | 40.1 | 6.79 | 41.3 | 6.01 | 36.14 | 21.20 | 0 | 12.87 |
| Compacted | | | 43.1 | 4.42 | 42.9 | 4.54 | 20.60 | 4.23 | 7.36 | 8.67 |
| Plant | Percent pass No. 10 | 25-35 | 32.2 | 4.06 | 32.2 | 3.90 | 15.24 | 7.22 | 3.68 | 4.43 |
| Spreader | | | 32.2 | 5.46 | 32.9 | 4.83 | 23.3 | 14.03 | 0 | 8.38 |
| Compacted | | | 34.8 | 3.51 | 34.6 | 3.74 | 13.96 | 0 | 5.86 | 5.91 |
| Plant | Percent pass No. 40 | None | 18.0 | 2.09 | 18.1 | 2.18 | 4.74 | 2.17 | 1.14 | 1.46 |
| Spreader | | | 18.3 | 2.66 | 18.5 | 2.34 | 5.48 | 3.18 | 0 | 2.37 |
| Compacted | | | 19.7 | 2.00 | 19.9 | 3.62 | 13.15 | 2.24 | 0 | 10.87 |
| Plant | Percent pass No. 200 | None | 4.1 | 0.53 | 4.1 | 0.54 | 0.30 | 0.17 | 0.05 | 0.09 |
| Spreader | | | 4.0 | 0.49 | 4.1 | 0.58 | 0.33 | 0.18 | 0 | 0.18 |
| Compacted | | | 4.3 | 0.67 | 4.3 | 0.67 | 0.44 | 0.11 | 0.18 | 0.15 |
| Plant | Bitumen | 3.7-4.7 | 4.26 | 0.41 | 4.26 | 0.38 | 0.15 | 0.04 | 0.04 | 0.06 |
| Spreader | | | 4.18 | 0.59 | 4.26 | 0.54 | 0.29 | 0.17 | 0.05 | 0.08 |
| Compacted | | | 4.32 | 0.47 | 4.30 | 0.45 | 0.20 | 0.09 | 0.06 | 0.06 |
| No. of tests performed | | | | | | | | | | |
| Plant (truck) | | | | | | | | | 284 | |
| Spreader (roadway behind spreader) | | | | | | | | | 68 | |
| Compacted (roadway compacted) | | | | | | | | | 380 | |

[a]Analysis of variance data were based on four times as many tests as control chart data.

TABLE 4
PLANT DATA, PHASE III

| | | | | |
|---|---|---|---|---|
| Local designation | Allendale | Walterboro | Pacolet | Darlington |
| Docket no. | 3.330 and 25.382 | 15.355 | 11.1046 and 44.1040 | 17.1018 and 34.1031 |
| Contractor | J. F. Cleckley and Co. | Same as Allendale | Sloan Constr. Co. | R. B. Pond |
| Sampling started | March 26 | May 11 | July 12 | August 26 |
| Sampling completed | April 30 | May 25 | Oct. 8 | Sept. 15 |
| Plant | Barber Greene | Barber Greene | Barber Greene | Hetherington Burner |
| Type | Volumetric continuous | Volumetric continuous | Batch-O-Matic (manually operated) | Batch fully automatic |
| Nominal capacity | 250 tons/hr | 300 tons/hr | 6000 lb batch | 6000 lb |
| Type of mix | Binder type 2 | Sand asphalt | Sand asphalt | Not included |
| Aggregates | Crushed stone, local sand | Local sand, fly ash | Screenings, local sand | Not included |
| No. samples | 40 cold feed<br>40 mix from trucks | 55 mix from trucks | 45 mix from trucks | Not included<br>Not included |
| Type of mix | Surface type 2 | Not included | Surface type 3 | Surface type 3 |
| Aggregates | Crushed stone, screenings, local sand | Not included | Crushed stone, screenings | Gravel, local sand |
| No. samples | 55 mix from trucks | Not included | 96 mix from trucks | 45 mix from trucks |
| Location of testing | Central laboratory | Central laboratory | Field laboratory | Central laboratory |

Comparisons with Specifications—The data in Tables 2 and 3 indicate, in many instances, that the mean value of the test results is considerably different from the mean of the specification limits. Such variation places the center of the normal curve either to the right or left of the center of the specifications. In such instances a higher proportion of the test results fall outside the limits than would be the case if the mean value coincided with the mean of the specification limits.

## Analysis of Variance, Phase I and Phase II

In this particular study the total variance ($\sigma_t^2$) for either asphalt content or for the percentage passing a certain sieve is composed of the variation from batch to batch or unit to unit ($\sigma_b^2$) plus the variation within a batch or unit ($\sigma_w^2$) plus the variation due to the testing operations ($\sigma_e^2$).

To provide data for this analysis, the sampling plan provided for obtaining separate samples from two randomly selected locations from each randomly selected unit and reducing each such sample to two test portions.

The data for surface mix are given in Table 2 and for binder mix in Table 3. The computed values for the components of total variance do not give conclusive indications. Generally, the effect of batch-to-batch variation is the greatest. The variation due to testing is next in order. The within-batch variation is least and frequently not significant.

Batch-to-batch variations are essentially problems of manufacturing. Variations due to testing are problems of inspection. The many instances of a high ratio of testing variance to total variance indicates a need for careful study to reduce variations due to testing.

# PHASE III

## General

This part of the research included the preparation of a tentative system for process control and acceptability based on the experience in Phase I and Phase II and the field operations for testing this system at four plants.

## Field Operations

The work plan for this phase provided for testing the tentative system for process control and acceptance at several plants. To broaden the base of experience, this series was planned to include different producers, different aggregates, and different types of plant equipment. Details concerning plant locations, projects, contractor's

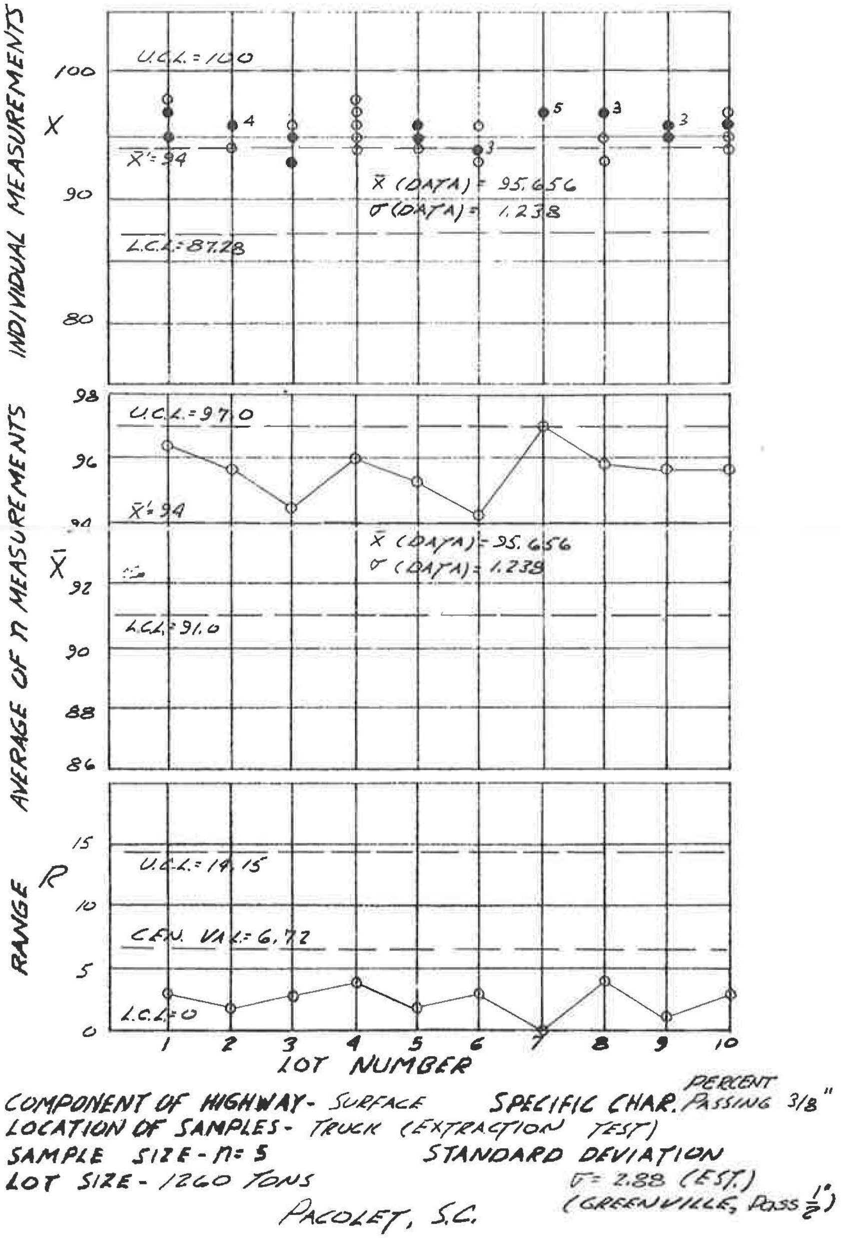


Figure 11. Standards given control chart: typical results.

equipment, aggregates, number of samples, etc., are given in Table 4. Sampling was done from loaded trucks using the grid method developed for the Greenville project. The time or batch to be sampled, the position of the grid in the truck body, and the opening from which the sample was drawn were all predetermined by random numbers.

It was expected that extraction tests would be made on the project using facilities separate from those used for job control. However, for three of the projects, samples had to be tested in the central laboratory because equipment for performing the tests on the project was not available. Arrangements were made with the contractor operating the plant at Pacolet to produce mix under the proposed system of control. At this plant, the samples were tested in the job laboratory by project personnel.

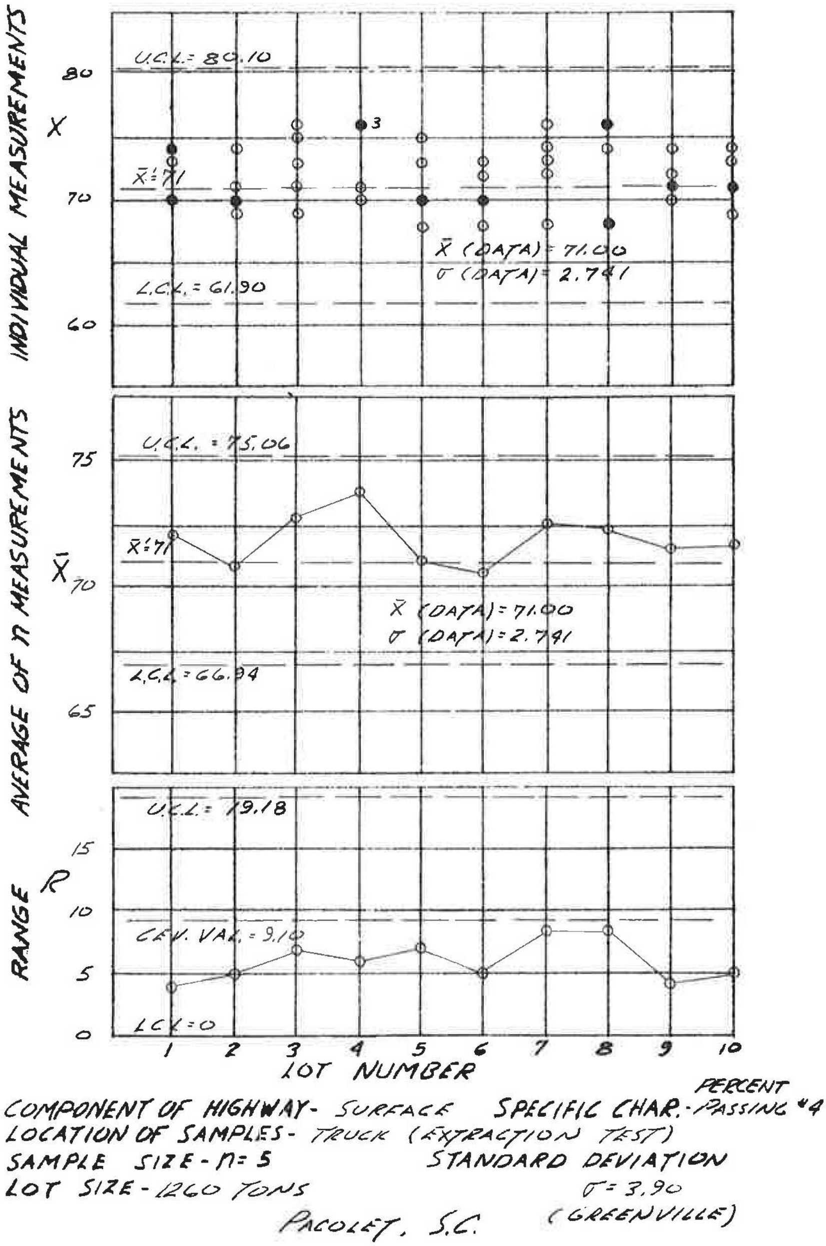


Figure 12. Standards given control chart: typical results.

## Standards Given Control Charts

The data for gradation of aggregate and for asphalt content for each plant were plotted on control charts. The mean or central value for each chart was the value of the approved job-mix formula. Control limits were calculated by standard formula using standard deviations developed from the data obtained on the project at Greenville. In a few instances, sigmas for a certain sieve size were estimated.

Control charts for 10 of the 19 lots tested at the plant at Pacolet are typical of the results obtained (Figs. 11-15).

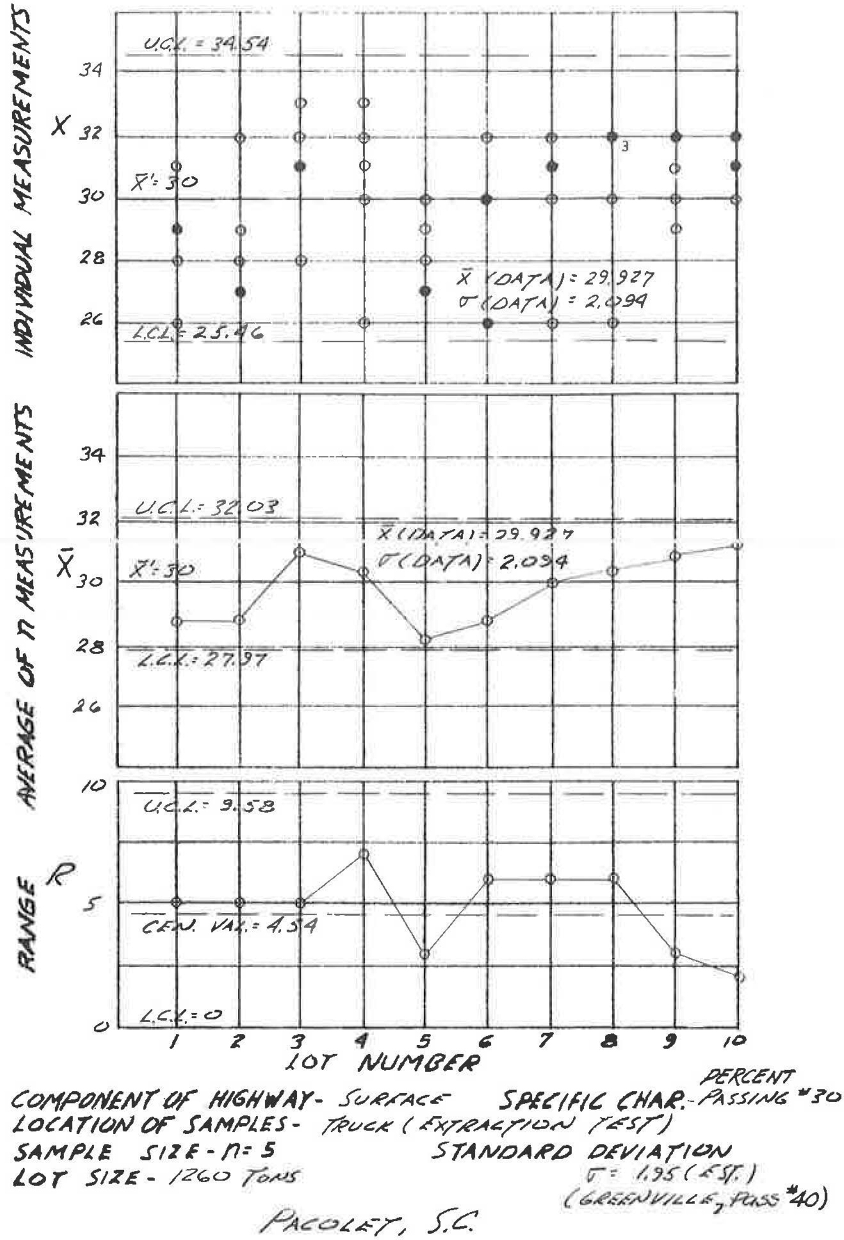


Figure 13. Standards given control chart: typical results.

Detailed analysis of the 35 charts showing the data for the four plants led to some revisions in the tentative system and to the following conclusions.

1. The procedure for obtaining random samples, both as to predetermining the location and actually drawing the material for the sample, is practical for operation by regular job inspectors.
2. The system for control and acceptance of bituminous mixtures is practical, both from the standpoint of the Department and the contractor.
3. Standards given control charts using the values of the job-mix formula for the mean or central value and calculating upper and lower control limits using standard

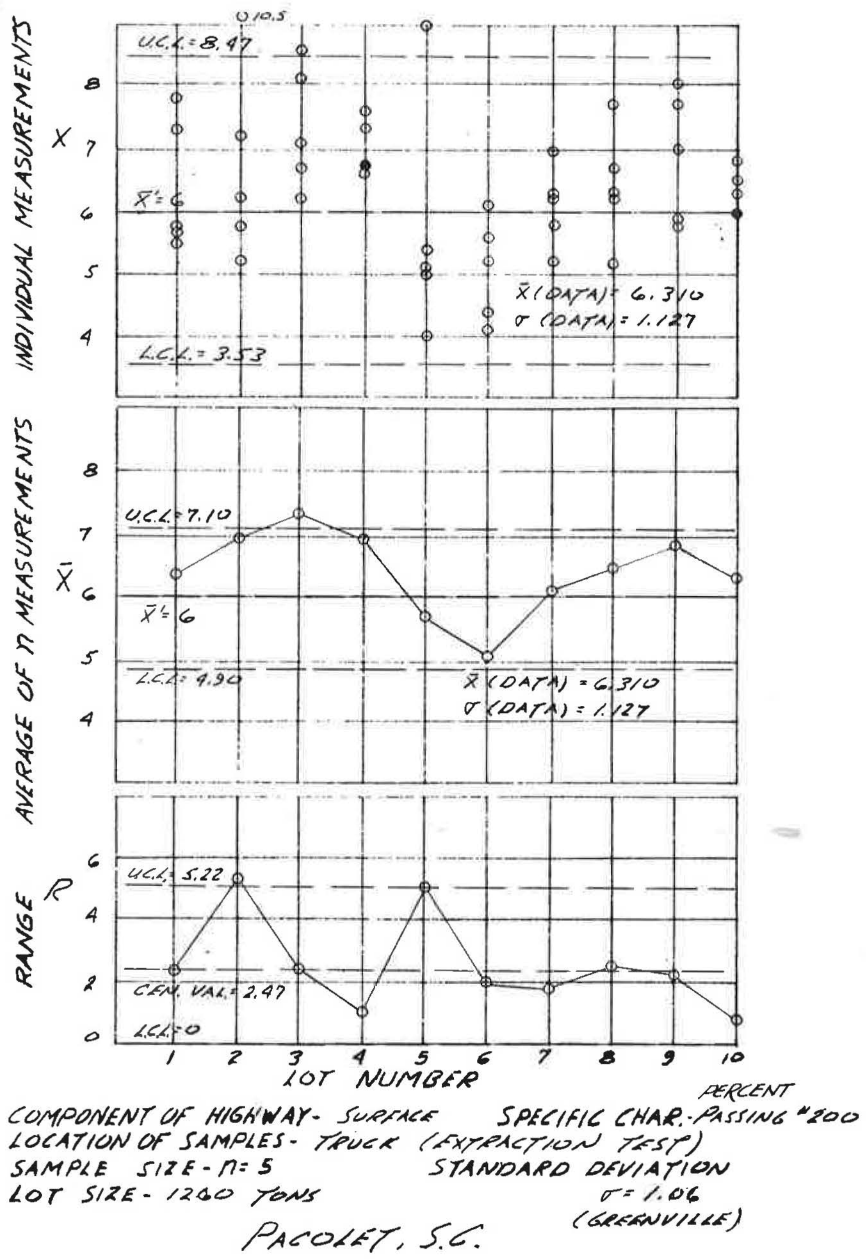


Figure 14. Standards given control chart: typical results.

deviations developed on other projects in this research can be developed initially for each project by the testing division.

4. For the production to stay in control, it is necessary that the mean value for the mixture produced be as near as practicable to the value of the job-mix. When adjustments are made, the change should be aimed at attaining the job-mix value, not to get results barely within the limits of tolerance.

5. Once the control charts are established by the testing division, they can be used for routine control by district inspectors after a short training period.

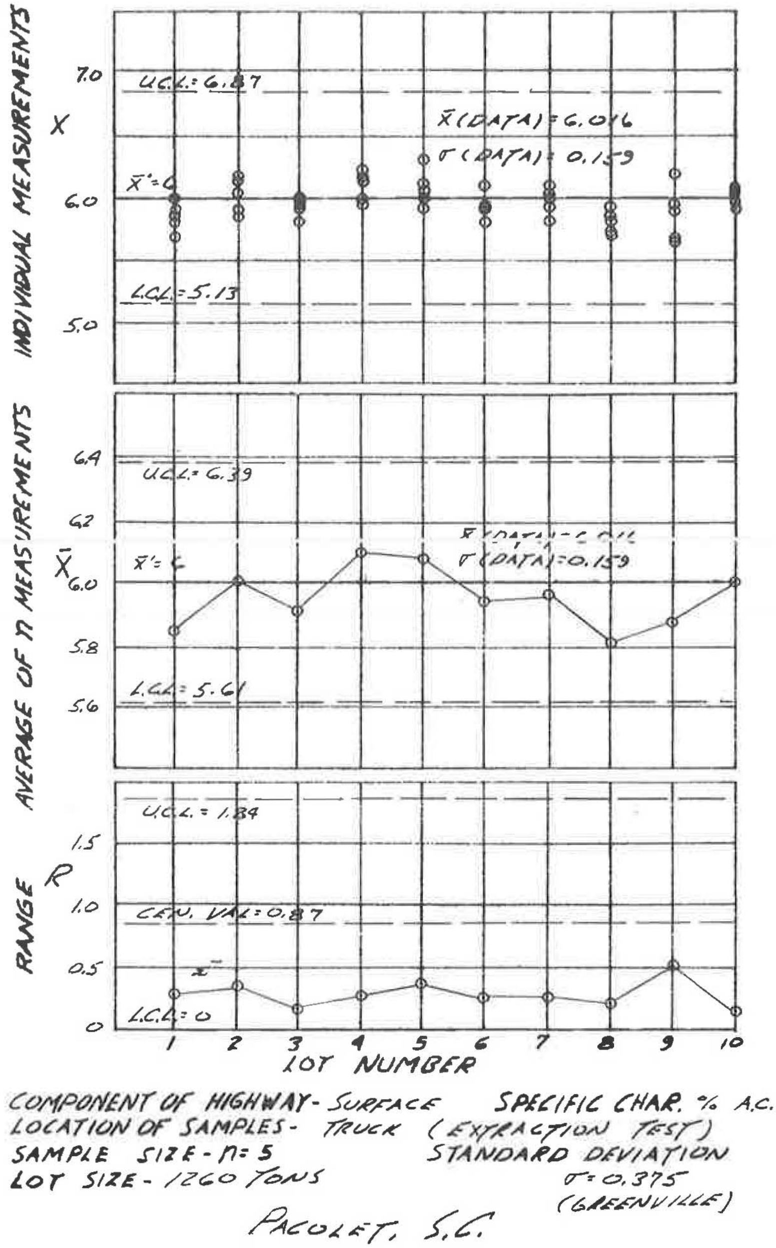


Figure 15. Standards given control chart: typical results.

6. The standard deviations used to establish the limits for the control charts in routine work should be examined at intervals to determine the advisability of revising values for any certain measurement. As more data become available, it is probable that revisions of the values will be needed.

7. The data on variations available so far are not sufficient to indicate the effect of differences in the types of aggregates or in the types of proportioning or mixing plants on values of standard deviations.

8. This system of control and acceptance must be supplemented by visual inspection of the operations and the mix produced to eliminate batches in which an obvious error has been made.

TABLE 5

TABULATIONS OF STANDARD DEVIATIONS EXTRACTION TESTS ON RANDOM SAMPLES

| Test Property | Greenville | | | | Allendale | | Walterboro | Pacolet | | | Darlington |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Binder Mix[a] | Binder Mix[b] | Surf. Mix[a] | Surf. Mix[b] | Binder Mix[a] | Surf. Mix[a] | Sand Asphalt[a] | Sand Asphalt[a] | Surf. Mix[a] | Surface Check[a] | Surface Mix[a] |
| No. of tests | 71 | 234 | 35 | 140 | 40 | 55 | 55 | 85 | 96 | | 45 |
| Pass 1 in. | 3.95 | 4.13 | | | | | | | | | |
| Pass ¾ in. | | | | | 4.044 | | | | | | |
| Pass ½ in. | | | 2.880 | 3.10 | | 2.974 | | | | | |
| Pass ⅜ in. | | | | | | | | | 1.238 | | 1.171 |
| Pass No. 4 | 4.76 | 4.61 | 3.90 | 3.92 | 3.743 | 4.113 | | | 2.741 | | 2.731 |
| Pass No. 8 | | | | | 3.170 | 4.190 | | | 2.932 | | 4.306 |
| Pass No. 10 | 4.06 | 3.90 | 3.45 | 3.69 | | | | | | | |
| Pass No. 30 | | | | | | 2.993 | | | 2.094 | | 2.758 |
| Pass No. 40 | 2.09 | 2.18 | 1.70 | 1.91 | | | | | | | |
| Pass No. 100 | | | | | | | | | 1.417 | | 1.177 |
| Pass No. 200 | 0.53 | 0.548 | 1.060 | 1.147 | | 0.859 | | | 1.127 | | 0.493 |
| Asphalt content | 0.414 | 0.385 | 0.375 | 0.357 | 0.318 | 0.360 | 0.161 | 0.153 | 0.159 | 0.173 | 0.353 |
| Basket tests | 70 | 280 | | | 40 | | | | | | |
| Pass 1 in. | 2.57 | 2.52 | | | | | | | | | |
| Pass ¾ in. | | | | | 2.374 | | | | | | |
| Pass No. 4 | 4.62 | 4.16 | | | 2.781 | | | | | | |
| Pass No. 8 | | | | | 2.561 | | | | | | |
| Pass No. 10 | 4.02 | 3.71 | | | | | | | | | |

[a]Tests on 1 random sample per unit.
[b]Tests on 2 random samples and 2 test portions each unit made for analysis of variance.

## Evaluation of Tentative System for Control and Acceptance of Bituminous Mixtures

Quality and Uniformity of Mix Produced—At Pacolet, when the plant was operated under the proposed system there were only four instances of failure to conform to criteria on gradation and one failure of asphalt content to conform.

At other locations there are many instances where the production is out of control. The fact that the average of the test results did not conform to the value of the job-mix caused most of these problems. When the data are compared with a revised job-mix value equivalent to the mean of the data, the production is generally in control.

No specific checks were made of problems encountered in placing these mixtures; but, as far as known, all the mixtures were placed without difficulty. No complaints of lack of uniformity were received.

Problems Encountered by Contractor—The Pacolet plant was the only one operated under the proposed system. As far as known, no special problem in production of mix was encountered by the contractor. In fact, the data show that the production at this plant was under better control and had fewer variations than at the other plants.

Problems Encountered by the Department—At the Pacolet plant, after a short training period, regular project inspectors did the sampling and testing. The plotting and interpretation of the control charts was done by laboratory inspectors. The project inspectors had no trouble in following the sampling procedure and in keeping up with the testing.

# PHASE IV

## General

The procedures for process control and acceptance of bituminous mixes as developed, refined, and demonstrated to be practical in this research are presented next.

## Standard Deviations for Control Charts

A necessary first step in the development of control charts is to determine the standard deviations which will be used to calculate the limits. Table 5 gives a list of standard deviations developed on the five projects studied in this research. These values reflect the differences in plant operation, plant equipment, raw materials, sampling, and testing. They are the background for establishing the standard deviations to be used for calculating control and acceptance limits for work in the immediate future. As more data become available it is probable that some changes in these values will be advisable.

The standard deviations recommended for use are based on those given in Table 5 plus knowledge of the materials, equipment and personnel involved at the several plants where the tests were made.

| Gradation | Recommended Standard Deviation |
|---|---|
| Pass 1-in. sieve | 4.00 |
| Pass $^3/_4$-in. sieve | 4.00 |
| Pass $^1/_2$-in. sieve | 3.00 |
| Pass $^3/_8$-in. sieve | 3.00 |
| Pass No. 4 screen | 4.00 |
| Pass No. 8 screen | 3.50 |
| Pass No. 30 screen | 2.50 |
| Pass No. 100 screen | 1.25 |
| Pass No. 200 screen | 1.00 |
| **Asphalt Content** | |
| Binder mix | 0.38 |
| Surface mix | 0.35 |
| Sand-asphalt mix | 0.24 |

For passing $^3/_4$-in. sieve, the data indicate a value of about 1.25, but judgment dictates that the value should not be very different from that for passing a $^1/_2$-in. sieve.

The standard deviation for asphalt content of surface mix produced at Pacolet is considerably below the figure 0.35 given in the foregoing table. However, because of values at other plants, the figure of 0.35 is considered representative of average conditions.

The standard deviation for sand-asphalt mix, as previously indicated, is considerably larger than those obtained at the two plants in this research project. However, the use of a low value for standard deviation in preparing standards given control charts for future work would result in very narrow tolerances which might be unnecessarily restrictive for this type of work. The value of 0.24 is suggested for the immediate future. This value should be readjusted as soon as more data justify a change.

## System for Process Control and Acceptance of Bituminous Mixes

This system for process control and acceptance of bituminous mixtures is to be used only after the plant has been adjusted, trial batches have been tested and approved, and the plant is ready for normal operations.

General Requirements—The system as described is predicated on the following.

1. Statistical methods will be used for random sampling, for preparing and maintaining control charts, and for analyzing test data.
2. All samples will be obtained by the random sampling procedure described hereafter.
3. Testing will be done by standard methods used by the Highway Department.
4. Control charts will be prepared for each size sieve specified and for bitumen content. The central value on these charts will be the figure of the approved job-mix formula. Upper and lower control limits will be calculated from previously determined statistical values of variability (sigmas) for each control property.
5. Interpretation of results will follow criteria given hereafter to determine when adjustments in the operations are required and to establish guidelines for acceptance of the product.
6. When an adjustment is made in operations because a property is out of control, the goal shall be the central value for that property. An adjustment merely to attain a result just within the tolerance is unsatisfactory because of normal variations in the process.

Lot Size—Acceptance of the product is based on test results determined on random samples obtained from a certain lot of the material. For bituminous mixtures the size of this lot should be the quantity of production on which control is desired. An average day's run of the plant has been considered a normal lot. However, due to the intermittent operations of most plants, a certain tonnage figure approaching that of a normal day's production is considered more practical. Lot sizes of 1, 260, 1, 500, and 1, 800 tons have been used. The lot size for a specific plant should be established by the engineer.

Number of Samples—The number of samples required for acceptance of a lot varies with the degree of importance of the property being measured, the variability of the product, and the risks assumed by the Department and the contractor of accepting or rejecting material outside of limits within which a satisfactory product is obtained. Asphalt content, as determined by the extraction test, is of major importance in judging a bituminous mixture, and according to criteria, five samples per lot are required. As five samples are obtained for determination of asphalt content, gradations tests are made also on all five samples.

Random Sampling Procedure—Details for the procedure for obtaining random samples of mixture are given in the Appendix.

Preparing Control Charts—A control chart for each sieve size and for asphalt content will be prepared. Values for the standard deviation will be furnished by the engineer. In each case the central value for individual results and grouped data ($n = 5$) shall be the figure of the job-mix formula. The upper and lower control limits (tolerances) for individual results will be calculated by the formula $\bar{x}' \pm 2.33\,\sigma$. For grouped data, $n = 5$, upper and lower control limits (tolerances) will be determined by the formula $\bar{x}' \pm 1.04\,\sigma$. For range the upper control limit will be established by the formula $4.92\,\sigma$.

Interpretation of Results on Control Charts—The criteria for determining when adjustment in the operations should be made are prepared on the assumption of close cooperation between the plant inspector and the contractor's plant superintendent. For the first few projects in which this system of control is used, the criteria are prepared so that the decision as to when an adjustment should be made is the plant inspector's. How to attain the adjustment is, of course, the responsibility of the contractor. As experience is gained in using this system and personnel become familiar with the details of its operation, it is expected that the contractor can assume the responsibility for detailed control of the production.

Test data will be plotted on the appropriate control chart as soon as they become available. The following criteria will be applied.

1. Individual Test Results. When a result is outside of the control limits the indication is that this property is out of control. An adjustment should be made to bring the property to the central value—the figure of the job-mix formula. If the divergence beyond the control limit is small, then it may not be necessary to stop the plant to make the adjustment. If the divergence beyond the control limit is large or if the result is markedly different from previous results, the plant should be stopped until the adjustment is made. In either case, a new sample should be obtained and tested as soon as the adjustment is made. This sample should be obtained from the same grid opening and with the grid in the same position as the former sample. However, the results on this new sample are to confirm the adjustment and they should not be included in the average for the lot.

If the average of the first three individual results indicates that the average for the lot will be outside of the control limit for grouped data $n = 5$, an adjustment should be made to avoid producing an unacceptable lot.

2. Grouped Data $n = 5$. This figure is the average of the results on the five random samples from a lot.

When this value exceeds a control limit, the whole lot is unacceptable from a statistical standpoint. A lot which is found unacceptable according to this criteria may be permitted to remain in place on the road subject to an adjustment in the unit price based on the amount of the excess and the probable effect of this excess on the serviceability of the product.

When the average value for a lot is outside of control limit, the adjustment necessary to bring the property to the value of the job-mix must be made before more mix is produced.

If two (or three) consecutive lots have average values which vary from the central value in the same direction by more than 75 percent of the tolerance permitted, then an adjustment to bring the property to the value of the job-mix will be required.

3. Range. Range is the difference between the maximum and minimum values in a lot. It is a measure of variability of test results.

When the range in results in a lot exceeds the control limit, the lot is unacceptable from a statistical standpoint. However, in this research the range has exceeded the control limit in only a few instances. In each case the result was outside of the control limit for individual results. Adjustment in the operation would be required as given previously for individual results. Acceptance would be based on the results and analysis of grouped data n = 5 as previously described.

## Adjusting the Unit Price for an Unacceptable Lot of Mixture

Background—When the average of the five random samples from a lot exceeds a control limit, the whole lot is unacceptable from a statistical standpoint.

Based on the experience in this research project, there should be no occasion of having a lot of mix outside of control and acceptance limits if the system of process control is observed with due diligence. However, such an occasion is a possibility due to assignable causes, and a procedure for making a decision on unacceptable lots of mixture is a necessary supplement to the system for process control and acceptance.

In practice, bituminous mixture is placed on the road and compacted at approximately the rate of production from the plant. The result is that by the time the test data on the five samples from the lot are complete, the mixture is in place on the road. At this stage of construction, adjustment to correct the deficiency cannot be made. The practical solution is to permit the mix to remain on the road and make an adjustment in the unit price to be paid for it. The excess outside of control and acceptance limits may be very small and relatively unimportant from the standpoint of the serviceability of the mixture. An example would be a divergence beyond the control limit of a percentage point on the No. 4 sieve. However, the excess may be relatively large and of great importance to the serviceability of the mixture. An example would be very high (or low) asphalt content. These factors are considered in the procedure for adjusting the unit price described below.

Magnitude of the Excess—Determination of the amount of the excess is a first step in estimating the effect of the divergence on the serviceability of the mix. The larger the excess the greater the probability of detrimental effect. However, excesses in some properties are more important in their effect on the serviceability of the mix than others.

To calculate the magnitude of the excess, the amount outside of the control limit is determined, and this quantity is expressed as a percentage of the tolerance permitted ($1.04 \times \sigma$). For example, assume the following:

| | | |
|---|---|---|
| Passing ¾-in. sieve, lot 8 | | |
| Average value for 5 results for the lot | = | 87.8 percent |
| Control limit job-mix value (93%) - tolerance (4.1%) | = | 88.89 percent |
| Amount outside of control limit | = | 1.09 percent |
| Percentage of excess (outside of control limit) | = | $\frac{1.09}{4.1} \times 100 = 26.6\,\%$ |

Adjusting the Unit Price—The effect of an excess beyond the control limits (tolerances) on the serviceability of a mix is a matter of engineering judgment. It would perhaps be agreed that a divergence of a percentage point on one sieve is not as detrimental as excesses of several percentage points on several sieves. Also, it would probably be agreed that a divergence of one-half of a percentage point on asphalt content is not as detrimental as an excess of one percentage point. Such factors are

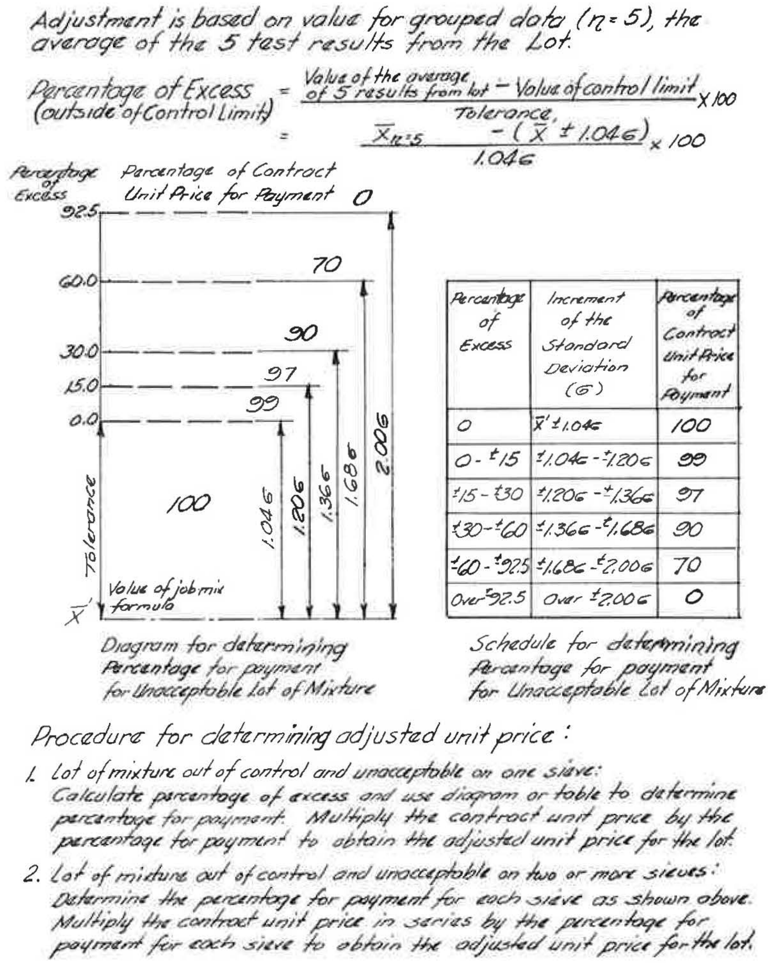


Figure 16. Adjusting contract unit price for unacceptable lot of mixture out of control on gradation.

background. Suggested percentages of the contract unit price for payment for lots failing to conform to criteria are given in the following tables. The percentages were chosen with the intent of adjusting the unit price downward in steps from almost no reduction when the divergence outside of control limits is small to no payment when the excess is large and there is little doubt that it will impair the serviceability of the mix.

These percentages are graduated in increments to a value approximately equal to two sigmas (Figs. 16 and 17). This value has been arbitrarily selected as the boundary for rejection. It is highly improbable that an average of five test results will reach this value except when the mix is completely out of control due to assignable causes. When such a condition occurs, operations of the plant should be stopped until the proper adjustments are made.

When a lot of mix is out of control and does not conform to acceptance limits on one size sieve, the unit price for payment will be adjusted as follows.

| Percent of Excess | Percent of Contract Price Per Ton of Mixture |
|---|---|
| 0. 1 to 15 | 99 for payment |
| 15 to 30 | 97 for payment |
| 30 to 60 | 90 for payment |
| 60 to 92. 5 | 70 for payment |
| Over 92. 5 | No payment. Engineer will direct whether to leave in place or remove. |

*Adjustment is based on value for grouped data (n=5), the average of the 5 test results from the Lot.*

$$\text{Percentage of Excess (outside of control limit)} = \frac{\text{Value of the average of 5 results from lot} - \text{Value of control limit}}{\text{Tolerance}} \times 100$$

$$= \frac{\bar{X}_{n=5} - (\bar{X}' \pm 1.04\sigma)}{1.04\sigma} \times 100$$

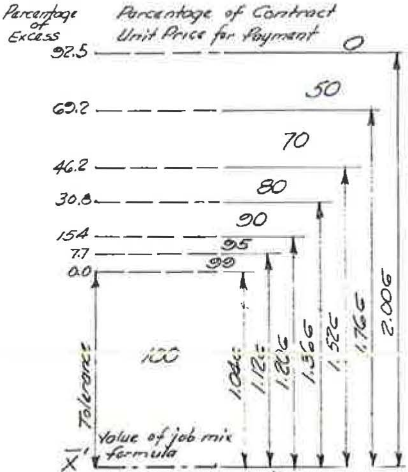


*Diagram for determining Percentage for payment for Unacceptable Lot of Mixture*

| Percentage of Excess | Increment of the Standard Deviation (σ) | Percentage of Contract Unit Price for Payment |
|---|---|---|
| 0 | $\bar{X}' \pm 1.04\sigma$ | 100 |
| 0 - ±7.7 | ±1.04σ - ±1.12σ | 99 |
| ±7.7 - ±15.4 | ±1.12σ - ±1.20σ | 95 |
| ±15.4 - ±30.8 | ±1.20σ - ±1.36σ | 90 |
| ±30.8 - ±46.2 | ±1.36σ - ±1.52σ | 80 |
| ±46.2 - ±69.2 | ±1.52σ - ±1.76σ | 70 |
| ±69.2 - ±92.5 | ±1.76σ - ±2.00σ | 50 |
| Over ±92.5 | Over ±2.00σ | 0 |

*Schedule for determining Percentage for payment for Unacceptable Lot of Mixture*

*Procedure for determining adjusted unit price:*

*1. Lot of mixture out of control and unacceptable on asphalt content. Calculate percentage of excess and use diagram or table to determine percentage for payment. Multiply the contract unit price per ton of mixture by the percentage for payment to obtain the adjusted unit price for the lot.*

Figure 17. Adjusting contract unit price for unacceptable lot of mixture out of control on asphalt content.

TABLE 6

APPLICATIONS OF PROCEDURE FOR ADJUSTING UNIT PRICE
(Test Data, Phase III)

| Test Property | Lot | Average of the 5 Results | Control Limit | Excess Beyond Control Limit | Tolerance | Percentage of Excess | Percentage of the Contract Unit Price for Payment |
|---|---|---|---|---|---|---|---|
| Pass ¾ in. | 8 | 87.8 | 88.89 | -1.09 | 4.11 | 26.6 | 97 |
| Pass No. 4 | 8 | 34.4 | 35.05 | -0.65 | 4.95 | 13.1 | 99 |
| Asphalt content | 5 | 4.22 | 4.27 | -0.05 | 0.43 | 11.6 | 95 |
| | 8 | 4.17 | 4.27 | -0.10 | 0.43 | 23.2 | 90 |
| Pass ¾ in. | 4 | 89.8 | 90.22 | -0.42 | 2.78 | 15.1 | 97 |
| Pass No. 4 | 7 | 34.2 | 35.20 | -1.00 | 4.80 | 20.8 | 97 |
| Pass ½ in. | 6 | 95.3 | 92.99 | +2.31 | 2.99 | 77.5 | 70 |
| Pass No. 4 | 6 | 72.8 | 69.05 | +3.75 | 4.05 | 92.5 | 70 |
| Pass No. 8 | 3 | 59.7 | 58.59 | +1.11 | 3.59 | 31.1 | 90 |
| | 6 | 64.1 | 58.59 | +5.51 | 3.59 | 154.0 | No payment |
| Pass No. 30 | 1 | 35.6 | 35.03 | +0.57 | 2.03 | 28.2 | 97 |
| | 6 | 38.9 | 35.03 | +3.87 | 2.03 | 191.0 | No payment |
| Asphalt content | 2 | 5.41 | 5.61 | -0.20 | 0.39 | 51.2 | 70 |
| | 1 | 5.58 | 5.61 | -0.03 | 0.39 | 7.7 | 99 |
| Asphalt content[a] | 6 | 5.99 | 5.97 | +0.02 | 0.17 | 11.8 | 95 |
| Pass No. 8[a] | 15 | 56.00 | 55.59 | +0.41 | 3.59 | 11.4 | 99 |
| Pass No. 100[a] | 5 | 10.58 | 10.65 | -0.07 | 1.35 | 5.2 | 99 |
| —[a] | 6 | 9.8 | 10.65 | -0.85 | 1.35 | 63.1 | 70 |
| Pass No. 200[a] | 3 | 7.4 | 7.1 | +0.30 | 1.10 | 27.3 | 97 |
| Pass No. 30 | 5 | 30.3 | 30.97 | -0.67 | 2.03 | 33.1 | 90 |
| Pass No. 200 | 2 | 2.7 | 2.90 | -0.20 | 1.10 | 18.2 | 97 |
| | 5 | 1.5 | 2.90 | -1.40 | 1.10 | 127.0 | No payment |
| Asphalt content | 4 | 4.88 | 4.91 | -0.03 | 0.39 | 7.7 | 99 |

[a]Data from plant being operated under proposed system of control; other data from plants not adjusted to produce mix conforming to the mean of the data.

When a lot of mix is out of control and does not conform to acceptance limits on two or more sieves: the percentage payment for each sieve will be determined by the foregoing method. The contract price will be multiplied in series by the percentage for payment for each sieve to obtain the adjusted unit price. For example, assume values out of control on the following:

Passing ½-in. sieve - 99 percent for payment
Passing No. 100 sieve - 97 percent for payment
Contract price per ton - $4.50

Then, $4.50 × 99 percent × 97 percent = $4.321, adjusted unit price.

When a lot of mix is out of control and does not conform to acceptance limits on bitumen content, the unit price for payment for the mixture will be adjusted as follows.

| Percent of Excess | Percent of Contract Price Per Ton of Mixture |
|---|---|
| 0.1 to 7.7 | 99 for payment |
| 7.7 to 15.4 | 95 for payment |
| 15.4 to 30.8 | 90 for payment |
| 30.8 to 46.2 | 80 for payment |
| 46.2 to 69.2 | 70 for payment |
| 69.2 to 92.5 | 50 for payment |
| Over 92.5 | No payment. Engineer will direct whether to leave in place or remove. |

Application of Procedure for Adjusting Contract Price—In Table 6 the procedure outlined in the foregoing paragraphs is applied to test data in the standards given control charts of Phase III. Twenty-three instances of excesses outside of control limits, and therefore unacceptable from a statistical standpoint, are indicated. These figures are to demonstrate the procedure. Except for the five cases marked, the plants at which the data were obtained were not adjusted to produce mix conforming to the mean of the data.

The percentages for adjusting payment for unacceptable lots of mixture need very careful review and consideration before being adopted. As far as can be determined, there is no background or precedent for the procedure outlined herein. The procedure is practical, but the percentages for payment may require adjustment to be more lenient. The work in Phase III demonstrated conclusively that with reasonable care there should be no difficulty in producing mixtures conforming to the calculated control and acceptance limits.

The full report contains drafts of special provisions to be used with the Standard Specifications of the South Carolina State Highway Department to utilize the procedure for control and acceptance, including price adjustment as described herein. It is expected that bids will be received in the near future on the first projects containing these special provisions.

## CONCLUSIONS

### Field Procedures and Testing

The successful application of statistical methods to materials control and specifications presupposes that unbiased samples will be obtained and that the testing will be performed correctly.

Practical procedures for obtaining unbiased (random) samples were developed. These procedures depend on predetermination, by means of random numbers, of the exact locations from which the samples will be drawn.

In particular, the method devised for sampling trucks at the plant, using the grid and sampling device, shows promise for development as a standard. It comes nearer to removing the personal element for sampling than any procedure known to the consultant.

Large variations in asphalt content (in the extraction test) occurred in many cases between the two tests on the same sample. These were apparently random variations and may be inherent in the test method. A study of this test procedure is needed.

## Phase I

The present methods of routine job control do not insure that all mixtures accepted and placed on the road are in conformity with specifications. The tolerances of the job-mix formula were exceeded frequently on asphalt content and on gradation by both random and routine samples.

Random samples show greater variations in asphalt content than are shown by routine job control samples. Usually, random samples show greater variations in gradation than are shown by routine job samples. In a few instances, smaller variations are shown by the random samples. The average or mean values for random samples differ considerably in some cases from those for routine samples.

Standards given control charts can be prepared using as the mean or central values the figures of the approved job-mix formula and calculating upper and lower limits with standard deviations previously determined. The data from random samples so plotted can be used for process control and acceptance of mixtures. The data from the random samples as plotted on the charts show many instances in which the process was out of control.

The analysis of variance shows the effect of several factors that contribute to overall variance. Generally, the variations from batch-to-batch or unit-to-unit are greatest. The variations within batches or units are smaller and frequently not significant. The variations due to the testing operations are quite large in many cases. They indicate need for a study of test procedures with the goal of reducing the variability in testing operations.

## Phase II

The mean values for randomly selected samples from the trucks at the plant and from the roadway directly behind the spreader agree quite well. The standard deviations for samples obtained from directly behind the spreader are larger than those from the truck samples. However, four times as many samples were obtained from trucks as from behind the spreader. These results show that the random method of sampling trucks gives realistic information on the mix placed on the roadway.

The mean values for the samples obtained from the roadway after compaction show that some degradation occurs during compaction. This effect is more pronounced in the binder mix than in the surface mix.

Because of degradation, it is unrealistic to expect samples obtained from the roadway after compaction to conform to the same specification limits that are used for plant control of the mix.

Comparison of the data with specifications shows a considerable number of results outside of limits. Samples obtained at the plant show fewer such variations than samples from behind the spreader, and samples from behind the spreader show fewer than samples from the compacted mix. The differences are more pronounced in binder than in surface mix.

## Phase III

The procedure for obtaining random samples, both with regard to predetermining the location and actually drawing the material composing the sample, is practical for operation by regular job inspectors.

The variations in the mixtures produced under the proposed system for process control are lower than those obtained on mix produced at other locations where plants were operated under routine control procedures.

The system for control and acceptance of bituminous mixtures is practical, both from the standpoint of the department and the contractor.

Standards given control charts using the values of the job-mix formula as the mean or central value and calculating upper and lower control limits with standard deviations developed on other projects in this research can be used in the operation of this system. These charts should be developed initially for each project by the testing division.

For the production to stay in control, the mean value for the mix actually being produced should be maintained as nearly as practicable to the value of the job-mix formula. When adjustments are made to conform with criteria, the change should be aimed to attain the job-mix value and not to get results just within the limits of tolerance.

Control charts prepared by the testing division can be used for routine control by district inspectors after a short period of training. The standard deviations used to establish the limits for the control charts in routine work should be examined at intervals to determine the advisability of revising values for any particular measurement. As more data become available it is probable that revisions will be needed.

The data on standard deviations available so far are not sufficient to indicate the effect of differences in types of aggregate, or in types of proportioning or mixing plants.

This system of control and acceptance does not take the place of plant inspection. Visual inspection of the operations and the mix produced are needed, in addition to the sampling and testing, to eliminate batches in which an obvious error has been made.

Phase IV

The work in Phases I, II and III provides the background and experience for the system for process control and acceptance of bituminous mixes. The lot or quantity to be controlled and accepted as a unit can be the tonnage in a normal day's run.

Five random samples per lot are required because asphalt content is of major importance in controlling and accepting bituminous mixes. Control and acceptance of lots of mixture will involve obtaining random samples, testing tham as prescribed, plotting the test data on standards given control charts, and analyzing these charts according to the prescribed criteria.

The central value for the standards given control chart should be the value of the approved job-mix formula. Upper and lower control limits for these charts can be calculated using standard deviations determined in this research project.

Interpretation of the data on these control charts according to the criteria will show when adjustments in the mix are needed and when the mix is out of control and unacceptable.

A necessary supplement to the system for process control and acceptance of bituminous mixes is a procedure for making a decision regarding lots of mixture that are found unacceptable according to the statistical criteria. The limits are suggestions and should be revised as experience and judgment indicate. Once the limits are established, adjustments in the unit price for an unacceptable lot can be calculated by the simple procedure given herein.

## RECOMMENDATIONS FOR FUTURE RESEARCH

The following recommendations are made for future research.

1. The testing procedures used for asphalt mixtures should be studied to determine the factors contributing to variations in test results and to refine these procedures where feasible. The variations inherent in the procedures due to chance causes should be determined so that the test results can be used with greater confidence.
2. Looking toward more extensive use of statistical methods, a field study should be made of completed pavement to determine the limits within which satisfactory work is obtained. This study should be a comprehensive investigation of all elements: subgrade, subbase, base, and surface courses. The mean values and variations of the properties by which each element is controlled should be determined by statistical methods. To attain sound specifications from the standpoint of lowest initial cost, the scope of this research should include investigation of work that is rendering satisfactory service and work whose serviceability is questionable.
3. The system for control and acceptance of bituminous mixes as outlined in Phase IV should be utilized on a trial basis on two or three projects before being incorporated into a standard specification. It is probable that refinement will be needed.
4. Studies should be continued to develop the data needed to prepare standards given control charts for temperature and stability of the mix. The system for control and acceptance is also applicable to these measurements.

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# *Appendix*

## RANDOM SAMPLING PROCEDURE

For statistical laws to operate effectively, it is necessary that the test data be based on random samples. Therefore, all samples must be obtained in accordance with the following procedure.

### Equipment Required

Grid—The grid should have openings approximately 1 ft square, and it should be approximately one-third the length of, and about 6 in. narrower than, the body of trucks hauling mixture from the plant. This grid can be made with steel rods approximately ⅛ in. in diameter welded together. Wire mesh reinforcing of the types used in concrete pavement is suitable. The openings are numbered consecutively, beginning with the upper left-hand square as 1 and continuing horizontally for that row, returning to the left-hand square in the second row, etc., continuing to the lower right-hand square.

Sampling Tube—This tube should be approximately 6 in. in diameter and 12 in. high with a strap or handle welded across the top. A steel concrete cylinder mold makes a convenient device.

Miscellaneous—In addition to a grid and a sampling tube, the following items are required: a round point shovel, thermometer, pans or buckets, wood planks 8 in. wide and longer than the width of the truck body, and a table of random numbers.

Safety—The procedure requires that samples be obtained from the surface of piles of hot asphalt mix (about 300 F) after it is dumped into a truck. The operator is urged to observe the greatest caution at all times.

Predetermining Location to Sample

This sampling data must be determined for an entire lot before sampling begins.

Select a series of random numbers from the table, for example, 0.509, 0.025, 0.794.

Use a set of three numbers as follows:

First number × tons in lot = ton to be sampled
0.509 × 1,500 (assumed) = 764 ton

Second number = position of grid in truck body
0.00 to 0.33 = front position
0.34 to 0.66 = middle position
0.67 to 1.00 = rear position
0.025 = front position

Third number × No. openings in grid = opening from which sample drawn
0.794 × 40 (assumed) = 32

Similar calculations are made for each set of random numbers. The first sample is drawn from the smallest ton figure obtained by these calculations. The second sample is obtained from the next smallest, etc. Samples can only be drawn from the top of the mix in a truck, so it will not be possible to sample the exact batch. The sampler should keep a close check on the accumulated total production and should draw the sample from the truckload which contains the ton indicated by the random number.

It may be advisable to sample on a time basis rather than on a tonnage basis. If so, the ton to be sampled can be converted to a time basis as follows:

Assume that the plant produces the 1,500 ton lot in 10 hours.
Convert the ton to sample to a fraction of the tons in the lot as 764/1,500 = 0.509.

The time to obtain the sample would be 10 hr × 0.509 = 5.09 hr after production of this lot started, if the plant operated continuously. If the plant started at 7:00 a.m., the time to obtain this sample would then be 12:05 p.m.

Drawing the Sample—When the indicated ton has been produced, the hauling truck is stopped at the sampling platform. The sampler places the grid in the predetermined position and locates the preselected opening. The sampling cylinder is pushed down into the mix for a distance of 4 to 6 in. The mix is removed from around the cylinder, and a shovel or trowel is slipped under the bottom of the cylinder so that the bottom is entirely closed. The apparatus and contents are then removed, and the sample is deposited in a suitable container. If a larger sample is needed for stability or other tests, the additional material is obtained from the same opening.

## *Discussion*

KALANKAMARY P. GEORGE, Associate Professor of Civil Engineering, University of Mississippi—This report represents a valiant effort to introduce a procedure, based on statistical methods, for control and acceptance of bituminous mixtures.

The authors conclude that the average or mean values for random samples differ considerably in some cases from those for routine samples. The writer assumes that the conclusion was based on the data shown in Figures 3, 4 and 5, respectively, for asphalt content, percent passing No. 4 sieve, and asphalt content of the binder mix. In Figure 3, for example, the characteristic values of the distribution for random samples are $\overline{X}_1 = 6.19$, $\sigma_1 = 0.370$ and $N_1 = 35$; corresponding values for routine samples are $\overline{X}_2 = 6.09$, $\sigma_2 = 0.233$, and $N_2 = 27$. Is the difference, $\overline{X}_1 - \overline{X}_2 = 0.10$, attributable to sampling procedures or may it be inherent random variation? To answer this question, we set up the null hypothesis that the population difference is equal to zero. Table 7 summarizes the calculations to test the foregoing hypothesis according to the procedures

TABLE 7

SUMMARY OF STATISTICS FOR COMPARISON OF TWO GROUPS[a]

| Sampling | Number of Samples | Degrees of Freedom | Mean (%) | Sample Standard Deviation (%) | Sum of Squares |
|---|---|---|---|---|---|
| Random | ($N_1$) 35 | 34 | 6. 19 | 0. 370 | 4. 6546 |
| Routine | ($N_2$) 27 | 26 | 6. 09 | 0. 233 | 1. 4118 |
| | | Sum = 60 | Diff. = $\bar{X}_1 - \bar{X}_2$ = 0. 10 | | Sum = 6. 0664 |

[a]Pooled mean square = $S^2 = \frac{6.0664}{60} = 0.1011$

$$S_{\bar{x}_1 - \bar{x}_2} = \sqrt{S^2 \frac{N_1 + N_2}{N_1 \, N_2}} = \sqrt{\frac{(0.1101)(62)}{945}} = 0.084$$

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{\bar{x}_1 - \bar{x}_2}} = \frac{0.10}{0.084} = 1.19, \text{ d.f.} = 60$$

TABLE 8

CONCLUSIONS FROM "STUDENT'S" t-TEST

| Property in Question | P | Conclusion |
|---|---|---|
| Asphalt content, surface mix | 0. 25 | Not significant |
| Passing No. 4 sieve, surface mix | 0. 32 | Not significant |
| Asphalt content, binder mix | 0. 35 | Not significant |

suggested by Snedecor (11). It is assumed that the population is the same as that from which all the samples come, and that the difference is primarily due to sampling procedures.

The corresponding probability is about P = 0. 25 (11, p. 46), so the null hypothesis would presumably not be rejected. In other words, the difference in the two mean values of asphalt content from the two sampling procedures does not appear to be statistically significant.

Table 8 summarizes the results of this statistical test on the data that appear in Figures 3, 4, and 5.

The writer concludes, therefore, that whereas the two sampling procedures are capable of producing data that conform to distributions of different standard deviations, the means of those distributions are not significantly different.

## Reference

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WILLIAM H. MILLS, Closure—The discussion submitted by Professor George is very interesting. The mathematics used in his analysis is apparently correct. However, the statement in the paper that "the average or mean values for random samples differ considerably in some cases from those routine samples" was intended as a simple statement of fact and it was not based on the application of statistical methods of analysis.

Furthermore, the routine samples were obtained under the traditional approach of representative sampling. This approach involves the use of judgment by the person obtaining the sample in which he undertakes to obtain a sample which will be the average of the product being produced at that time. However, the plan under which the random samples were obtained provided for the use of random numbers to determine when and exactly where the sample would be drawn. The operator was given no discretion to include or exclude material.

Although in our paper some statistical parameters were calculated on data from the routine sample, we believe that these values are of academic interest only and that methods of statistical analysis cannot be applied realistically to data from these routine samples because they were not randomly selected. Therefore, even though the mathematics is correct, the comparisons are invalid.

# Realistic Job-Mix Formula Tolerances for Asphalt-Concrete

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New York State Department of Public Works

In 1960, the Department initiated a study to determine the uniformity of asphalt-concrete top course mix to establish realistic gradation control specifications. During the years between 1961 and 1964 research crews visited 55 asphalt plants where they obtained 868 hot-bin samples and 682 mix samples. Data were processed and analyzed by electronic computer and from the results it is concluded that the mix gradation ($\bar{x}$, $\sigma$) depends on the method of testing (i.e., hot-bin analysis or extraction test). Neither method is totally superior to the other, but each complements the other. The hot-bin method is more meaningful when related to coarse aggregate than when related to fine aggregate, whereas the reverse is true with the extraction test.

Job-mix formula tolerances developed from this study are realistic and fair to both the producer and to the Department, and are now being used on a statewide basis.

•IN 1960 the New York State Department of Public Works, in cooperation with the U.S. Bureau of Public Roads, started a research project to determine those asphalt plant and construction procedures which produce the most serviceable asphalt-concrete pavement. The first characteristic studied was the uniformity of asphalt-concrete mixes being supplied to state projects.

Once a satisfactory asphalt-concrete mix design is selected, there should be as little deviation as possible from this aggregate gradation and asphalt content, to minimize the necessity for making adjustments in the placement and compaction operations. In addition, a well-graded and uniform pavement surface mix develops fewer distressed areas and thereby increases pavement service life. However, some variation is unavoidable because of the nature of the product. Thus, the question arises as to how much inherent variation is associated with the production, sampling, and testing of asphalt-concrete mixes. If this can be established, it is then possible to identify variations which exceed this amount as a change in product which is unacceptable.

When the investigation began, the Department specifications for asphalt-concrete required aggregate gradation and asphalt content to fall within rather wide specification limits. These requirements did not prevent a plant from supplying a mix which constantly varied from one side of the specification band to the other. Understandably, much interest was shown in a specification which would establish tolerance limits around a job-mix formula and thereby reduce the allowable variation in aggregate gradation.

Therefore, the purpose of this uniformity study was to gather information on product variation to permit the establishment of specification tolerances which would minimize the acceptance of poor material and the rejection of good material. Further, it would permit the development of a practical control procedure for asphalt-concrete plant production.

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Paper sponsored by Committee on Construction Practices—Flexible Pavement and presented at the 46th Annual Meeting.

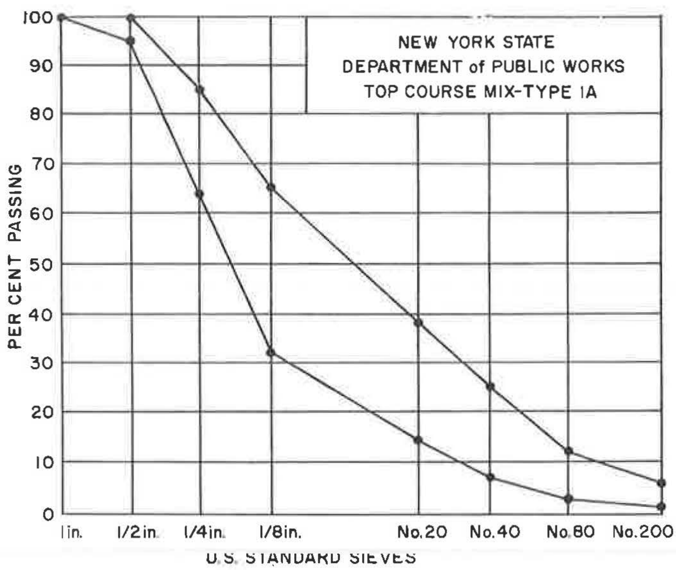



Figure 1. Asphalt-concrete specification limits.

## SCOPE

### Mixes

Six types of top course, one binder, and one base course mix are used by the New York State Department of Public Works. In general, traffic character and volume govern the selection of the top course mix. Type 1A is most commonly used on primary and interstate highways. Therefore, this report is concerned only with the type 1A mix. The current (1) aggregate specification limits for type 1A top course are shown in Figure 1.

### Sampling

To obtain a realistic measure of product variation, it was important that a sufficient number of samples be obtained daily from each plant over a reasonable period of time and that a wide variety of plants be included in the program. A total of 55 plants in New York State producing top course mix were visited during this four-year uniformity study. Of these plants, 51 were batch type and 4 were continuous. In 16 of the plants, batching was performed manually, whereas in 32 plants batching was semiautomatic (i.e., hand levers had power assists). The remaining three batch plants were operated automatically, as were the four continuous mixing plants.

Ten or more batches were sampled in 80 percent of the plants visited, while 15 or more batches were sampled in half of the plants visited. A total of 868 hot-bin samples and 682 mix samples were gathered. A year-by-year listing of plants visited and samples taken is given in Table 1. This sampling covered the entire state, and the large number of samples obtained provided a reliable measure of the uniformity of asphalt-concrete being produced for Department projects.

TABLE 1

TOP COURSE SAMPLES

| Year | No. of Plants | No. of Samples | |
|---|---|---|---|
| | | Hot-Bin | Mix |
| 1961 | 22 | 297 | 118 |
| 1962 | 19 | 282 | 275 |
| 1963 | 9 | 223 | 223 |
| 1964 | 5 | 66 | 66 |
| Total | 55 | 868 | 682 |

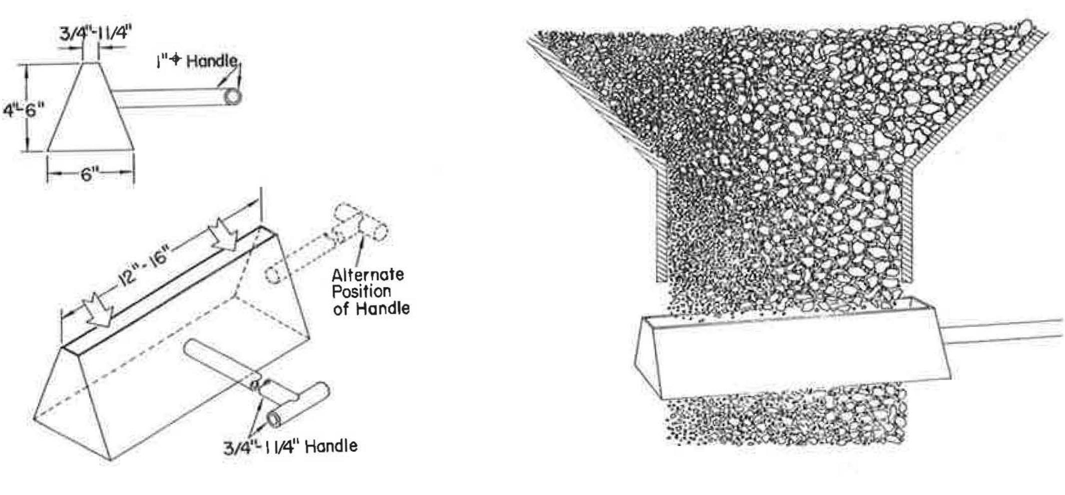
## SAMPLING PROCEDURE

To produce type 1A top course, the majority of plants use three hot bins. The usual hot-bin designations are: No. 1 (predominantly $\frac{1}{2}$ to $\frac{1}{4}$-in. stone); No. 1A (predominantly $\frac{1}{4}$ to $\frac{1}{8}$-in. stone); and the fines or sand bin (all passing the $\frac{1}{8}$-in. sieve). A few plants insert a No. 1B bin between the No. 1A and fines bin, and a very few plants use a mineral filler bin.

All hot-bin samples were obtained as the aggregate was dropping from the hot bin into the weigh hopper. However, the method of obtaining the sample varied, depending on the type of plant. Newer plants had built-in devices which facilitated sampling the hot bins. In older plants, samples were obtained whenever possible with an aggregate sampling device similar to that shown in Figure 2. This device was placed across the aggregate flow and is designed to reduce sample bias caused by aggregate segregation in the hot bins.

Approximately 15 lb of aggregate were obtained from each hot bin. The material was then passed several times through a sample splitter to produce $2\frac{1}{2}$ to $3\frac{1}{2}$ lb (i.e., 1,000 to 1,500 gm) of aggregate for final sieve analysis. One-half to $1\frac{1}{2}$ hours elapsed between batches that were sampled for hot-bin analysis. The time range was caused by fluctuations in contractor paving demands, and by the general layout of the asphalt plant facilities. However, the randomness of sampling was statistically beneficial, because it precluded the possible introduction of bias due to a constant time interval between truckloads.

In 1961, hot-bin samples were taken whenever convenient, and consideration was not given as to which particular batch was being loaded into a truck. The same random procedure was followed in obtaining mix samples from the trucks, and only one mix sample was obtained for every three hot-bin samples. However, in 1962, 1963, and 1964 the hot-bin samples were obtained from the last batch of a truckload, and the mix samples were taken from that same batch after it was deposited in the truck. Therefore, during these latter three years of the study, for every hot-bin analysis there was a "companion" sample of mix. With regard to extractions, there was a possibility that an operator bias might have been introduced in the manual or semiautomatic plants because the plant operator shortened the mixing time of the last batch to get started sooner on the next truckload. However, a comparison of plant uniformity with method of production (i.e., automatic or manual) did not reveal such a trend.




*Sampling Device* — *Correct Use of Sampling Device*

Figure 2. Hot-bin aggregate sampler.

In 1961, 1962, and 1963, samples of mix were obtained from the trucks in such a way as to minimize sample bias. The portion of the truck bed covered by the last batch was divided longitudinally and laterally into four equal areas. The average batch covered between 40 to 50 sq ft. A 1 to 2-qt sample was taken from the midpoint of each of these four sections. The four samples were combined, mixed and quartered to provide a 1-qt sample for extraction. In 1964, larger size, but single, samples were removed from the left and right side of the batch in the truck and were processed separately. The 1964 extraction data represent the average of the left and right side samples.

## TESTS AND COMPUTATIONS

Hot-bin samples were sieved either at the plant or at the main office laboratory. Location was determined by operating circumstances and not by any predetermined design. All sieving was performed dry, but representative samples were set aside for washed sieve analyses. About 95 percent of the extraction tests were performed at the main office laboratory by the reflux process. The remainder were extracted at the plants by the centrifuge method. Sieve analysis of extracted samples was performed at the place of extraction.

The sample from each hot bin was individually sieved, and its gradation was computed. The gradation percentages from each bin were multiplied by the proportion of the total batch weight theoretically drawn from that bin. The adjusted percentages were then totaled for each sieve size to obtain the mix gradation. The combined computed gradation is based on the assumption that the correct weights were drawn from each bin.

Basic computations and statistical analyses were performed by an electronic data processing system because of the volume of data collected. Computer programs were developed which, in addition to performing the basic computations of transforming weights into percents, performed statistical analyses by computing for each sieve size: a plant average (the arithmetic mean), standard deviation (a measure of how the individual test results are distributed about the plant average), and a coefficient of variation (a ratio of the standard deviation to the arithmetic mean, expressed as a percent). The Department's Bureau of Electronic Data Processing has published a detailed explanation of these hot-bin analysis and extraction computer programs (2).

## RESULTS AND DISCUSSION

This study was undertaken to determine the variability of top course mix as measured by dry sieved hot-bin samples. The information would then be used to arrive at realistic gradation tolerance limits about a job-mix formula. Dry sieving of hot-bin samples is the most desirable method of measuring aggregate gradation of asphalt-concrete because it is a simple, rapid test. This advantage is essential if expedient corrective action is to be taken when the product does not meet specifications. In addition, the average gradation result of the dry sieved hot-bin test were compared with those of the wash sieved hot bins and extractions.

The gradation results from the large number of samples provided a reliable base for a statistical analysis of the uniformity of asphalt-concrete. A common basis had to be selected for computing the scatter or spread of values typical of bituminous plant production in the state. The plant average for each sieve was established as a datum, from which the deviation (difference) of individual sample results was computed. These deviations were then used to compute a standard deviation, indicating the variability of the product. This was accomplished using the formula:

$$\sigma = \left[\frac{\Sigma(\bar{x} - x)^2}{n - 1}\right]^{1/2}$$

where

$\sigma$ = standard deviation,
$\bar{x}$ = average (arithmetic mean),

x = individual values,
$(\bar{x} - x)$ = individual deviation from the average, and
n = number of values.

Gradation Tolerances

From statistics it is known that in a normal distribution approximately 95 percent of the samples fall within $\pm 2\sigma$ of the average. Considering the job-mix formula to be the average, which indeed it should be, establishing tolerance limits at $\pm 2\sigma$ should result in only 5 percent of the samples falling outside this limit unless production has shifted away from the job-mix formula or unless test results are not normally distributed. It is believed that 95 percent is a reasonable requirement, and that percentage was selected as the confidence level for providing realistic tolerances about a job-mix formula.

The statewide uniformity of the material passing the ¼ and ⅛-in. sieves improved appreciably after 1961. Consequently, 1961 data were not included in the summation of standard deviations because this would have resulted in unnecessarily broad tolerances for material passing the ¼ and ⅛-in. sieves. The fact that this uniformity study was initiated on a statewide basis in 1961 probably focused the producers' attention on their general quality control methods and, as a result, they began improving them.

In addition to the data omitted from the 1961 plants, data were omitted from 4 of the 33 plants visited between 1962 and 1964. The number of samples obtained from two of the plants was less than five, and this was considered insufficient to be statistically significant. At the conclusion of sampling in the third plant it was discovered that one of the hot-bin screens had torn, and the data collected were therefore considered unreliable. The fourth plant omitted from consideration had been newly erected, and the data taken from it were not considered representative of a typical plant. Therefore, 29 asphalt plants, from which 491 combined hot-bin analyses had been obtained, were used as the basis from which to develop realistic job-mix formula tolerances for top course mix. For tolerances to be applied in practice, they must include variability due to sampling and testing as well as variability inherent in the material. Therefore, it was not considered necessary, or even desirable, to determine how much each of these three factors contributed to overall variability.

The standard deviation for overall production during the period from 1962 to 1964 was determined by two procedures. First, a pooled standard deviation was computed by combining the individual sample deviations; this might be thought of as a weighted average value. Second, a median standard deviation was determined; i.e., the value at which 50 percent of the plants had a greater variability or a higher standard deviation and 50 percent of the plants had less variability or a smaller standard deviation. There is relatively little difference between the standard deviations determined by each method (Table 2). Either of these standard deviation values could be considered as

TABLE 2

GRADATION TOLERANCES
(Total Percent Passing)

| Sieve Size | Standard Deviations[a] | | Tolerances Around the Job-Mix Formula |
|---|---|---|---|
| | Pooled | Median | |
| ½ In. | 0.3 | 0.2 | 5 |
| ¼ In. | 2.5 | 1.9 | 5 |
| ⅛ In. | 3.0 | 2.6 | 6 |
| No. 20 | 3.7 | 3.8 | 7 |
| No. 40 | 3.3 | 3.4 | 6 |
| No. 80 | 1.9 | 1.7 | 3 |
| No. 200 | 1.0 | 0.8 | 2 |

[a]Data based on 491 combined hot-bin analyses from 29 asphalt plants during 1962, 1963, and 1964.

representing the variation in a typical asphalt-concrete plant producing for a Department project. Tolerances for 1A top course (Table 2) were established by doubling the larger measured standard deviation and rounding down to the nearest percent. The only exception is on the ½-in. sieve where the standard deviation was only 0.3. The ±5 percent tolerance is not related to the σ actually determined and is unnecessarily large, but for convenience was made equal to the tolerance on the ¼-in. sieve. The standard deviation is very low because so little material is retained on the ½-in. screen in our 1A top mix.

The tolerances given in Table 2 were adopted by the Department in 1965 for top course bituminous mix gradation. It is believed that these tolerances, in whole percentages, are the most realistic possible, because they are based on three years of intensive hot-bin sampling and testing. It is anticipated that uniformity will increase due to better control procedures and the continual modernization that is taking place in plant equipment. Consequently, it does not appear that producers will have any difficulty meeting these tolerances even though they are slightly less than 2σ on some sieves.

The assumption was made at the beginning of this study that the test results would be normally distributed. A control level was selected at ±2σ, because 95 percent of the samples should fall within this range. To check data normality, the percentage of samples that fell outside of each plant average ±2 pooled standard deviations was computed for each sieve. The ½ in., ¼ in., ⅛ in., and No. 200 sieve had 5 percent outside these limits. The Nos. 20, 40 and 80 sieves had, respectively, 6, 6 and 7 percent outside. This rather rudimentary check indicates that the test results were very close to being normally distributed, and justifies the use of standard deviations to establish tolerances.

## Plant Operation and Uniformity

These pooled standard deviations were compared with the standard deviations computed at the AASHO Road Test (3) for surface course mix. This was done to compare the uniformity of the "typical" plant in New York State with a plant operated under almost optimum conditions for quality control. Conditions, as they existed, were as follows:

1. At the Road Test, the mix was produced from two sizes of coarse aggregate, two sizes of fine aggregate, and mineral filler. Material sources were kept constant. The typical New York State plant also uses two sizes of coarse aggregate, but only one size of fine aggregate and no separate mineral filler bin. Material sources are usually constant.
2. Road Test aggregates were stockpiled separately and prevented from mixing by wooden barriers; the storage area was paved with bituminous stabilized gravel. The typical plant in New York State separates the stockpiles by distance, but not barriers. The storage area surfaces are not paved.
3. At the Road Test four cold-feed bins were used in conjunction with four hot bins, a mineral filler bin and a dust recovery system. In the New York plants, a cold bin fed each of the three hot bins. A mineral filler bin was not used, but dust collectors were standard equipment.
4. The amount of oversize and undersize material in any one hot bin at the Road Test could not exceed 5 and 10 percent, respectively. Therefore, the minimum amount of primary size material in any one hot bin was 85 percent. The typical New York State plant had a minimum primary size requirement of 75 percent and this applied only to the coarse aggregate bins.
5. At the Road Test a continuous type of plant was employed, and this facilitated hot-bin sampling which may have minimized sampling bias. In New York State, the typical plant was a semiautomatic batch type, with hand-held sampling devices.
6. At the Road Test three or more samples were obtained and combined to provide a hot-bin analysis during each hour of production, and results were used for quality control. Stockpile gradations and cold-feed analyses were also performed to assist in control. In the typical New York State plant, hot-bin samples were obtained every hour

for the purposes of this study. However, normal quality control was based on a hot-bin analysis and an extraction test performed for each day of production.

Table 3 gives the average total percent passing each sieve and the standard deviation on that sieve. All of the Road Test sieve sizes did not correspond with those used by the Department. Consequently, the Road Test values for the ¼ and ⅛-in. sieves were obtained by graphical interpolation from the values of the adjacent sieves (⅜ in., No. 4, and No. 10). The average gradation of the Road Test mix was reasonably similar to the average mix gradation produced in the 29 plants from which the pooled standard deviations were computed. Consequently, a direct comparison of standard deviations was possible without introducing an undue bias. However, each Road Test hot-bin analysis was performed on a composite of at least three separate samples, whereas the gradation of each sample obtained at the New York State plants was determined separately. Because the physical combining of subsamples before sieving should give nearly the same answer as averaging the results of three separate sieve analyses, the standard deviation of the results is smaller for the combined samples than for individual samples. The principle involved here is that the scatter of sample averages is less than the dispersion of individual values and is reduced in proportion to the square root of the number of samples making up each average ($\sigma_{\bar{x}} = \sigma/n^{1/2}$). Therefore, the Road Test standard deviations were each multiplied by $\sqrt{3}$ to place them on a reasonably comparable basis with the standard deviations computed for individual samples, and these modified values are given in Table 3 for comparison purposes.

The pooled standard deviations are about the same as those computed at the Road Test (Table 3). What this might mean is that the production uniformity of the typical New York State plant and the optimum plant at the Road Test are not too far apart. It is probable that the method used to convert Road Test standard deviations so that they could be compared with those measured in New York State slightly distorted the Road Test results. However, there is an independent basis here for roughly evaluating the level of quality control achieved throughout the state and it appears that this control is reasonable. Therefore, the development of job-mix formula tolerances based on the standard deviations of the typical plant has resulted in tolerances that apparently represent good quality control practice, and which can probably be adhered to by the implementation of simple, common-sense quality control procedures.

TABLE 3

COMPARISON OF NEW YORK STATE AND AASHO ROAD TEST STANDARD DEVIATIONS

| Sieve Size | Average Gradation[a] | | Standard Deviation | |
|---|---|---|---|---|
| | NYS DPW | Road Test | DPW Pooled[b] | Road Test[c] |
| 1 In. | 100.0 | 100.0 | — | — |
| ½ In. | 99.6 | 91.5 | 0.3 | 1.9 |
| ¼ In. | 78.6 | 73.0 | 2.5 | 2.4 |
| ⅛ In. | 47.5 | 57.0 | 3.0 | 3.5 |
| No. 20 | 21.0 | 33.3 | 3.7 | 4.0 |
| No. 40 | 13.3 | 19.8 | 3.3 | 3.8 |
| No. 80 | 6.3 | 10.7 | 1.9 | 1.6 |
| No. 200 | 2.8 | 4.8 | 1.0 | 0.5 |

[a]Cumulative percent passing, total aggregate.
[b]Based on 491 combined hot-bin analyses from 29 plants.
[c]Based on 130 composite hot-bin combined analyses (3 or more subsamples per composite sample).

## Washed vs Dry Sieving of Hot-Bin Samples

To determine if serious inaccuracies were introduced by dry sieving the hot-bin samples, a portion of the material retained on each sieve was held and later washed on a No. 200 sieve. This operation was performed on about 150 samples collected during 1962, 1963, and 1964. The results showed a general increase in the average percent of total material passing the No. 200 sieve. In some plants no increase was measured and in one plant the increase was 1.8 percent. For the asphalt plants included in this study, the average increase was 0.5 percent. About 0.2 percent of the passing No. 200 material washed off the stone and about 0.3 percent washed off the fines (passing 1/8 in.).

This slight increase in the total percent of material passing the No. 200 sieve does not significantly influence the amount passing the larger sieves. Within the tolerance limits established, variations up to 0.1 percent on an individual sieve should not be a cause for concern. Therefore, the inability of the dry sieved hot bin to detect all of the fine material does not affect its applicability in controlling gradation.

## Extraction vs Dry Sieving of Hot-Bin Samples

Because gradation determined by dry sieved hot-bin samples is a rapid and simple test to perform, it was selected as the primary plant control procedure. Tolerances around a job-mix formula were developed from the variability measured with this test and are therefore applicable when the test is used. However, as a matter of policy, the extraction test is currently used for determining the passing No. 80 and No. 200 material.

The question arose as to how much the gradation of companion samples would differ when tested by these two methods, and also what average difference might be expected and how the variability of the two tests compared. Table 4 gives the average percent passing measured by each method and the average difference. Also listed are the pooled standard deviations for each method.

In regard to uniformity, the pooled standard deviations for each test method are significantly different (99 percent level) for all sieves except the No. 200. Gradation determined by dry sieving the hot-bin samples is more uniform on the 1/2 and 1/4-in. sieves while extraction results are more consistent for all sieves below that size except the No. 200.

The difference in average results is what would be expected on the No. 200 sieve. The extraction test indicates an average of 1.7 percent more than the hot-bin tests. An unexpected result was the lower percent of material passing the 1/2, 1/4, and 1/8-in.

TABLE 4

COMPARISON OF DRY HOT-BIN AND EXTRACTION RESULTS[a]

| Sieve Size | Total Percent Passing | | | Standard Deviation | |
|---|---|---|---|---|---|
| | Avg. Hot Bin | Avg. Extraction | Avg.[b] Difference | Pooled Hot Bin | Pooled Extraction |
| 1/2 In. | 99.6 | 99.6 | 0.0 | 0.3 | 0.5 |
| 1/4 In. | 78.6 | 77.8 | 0.8 | 2.5 | 3.7 |
| 1/8 In. | 47.5 | 46.2 | 1.3 | 3.0 | 2.3 |
| No. 20 | 21.0 | 21.4 | -0.4 | 3.7 | 2.3 |
| No. 40 | 13.3 | 14.7 | -1.4 | 3.3 | 1.3 |
| No. 80 | 6.3 | 7.8 | -1.5 | 1.9 | 1.3 |
| No. 200 | 2.8 | 4.5 | -1.7 | 1.0 | 1.0 |
| Percent AC | — | 6.3 | — | — | 0.3 |

[a]Data based on 491 combined hot-bin analyses and 491 extraction tests from 29 mix plants during 1962, 1963, and 1964.

[b]Difference is significant at 99 percent confidence level for all sieves excepting No. 20, which is significant at 95 percent confidence level.

sieves in the extraction test as compared to the hot-bin test. When the same data were analyzed in percent passing-retained form, this trend was even more evident. The extraction samples apparently contained a proportionately larger amount of coarse material than the hot-bin samples, possibly because the extraction samples were taken from the sides of a truckload where the coarser aggregate migrate. High-speed movies of a pug mill discharging into a truck were taken and appear to substantiate this theory.

The data in Table 4 indicate that extraction test results, with the exception of the ¼-in. sieve, would fall within tolerances developed on the basis of dry sieved hot-bin samples. Therefore, this allows the substitution of the extraction test when determining the quantities passing the No. 80 and No. 200 sieves without penalizing the producer.

## Difference Between Plant Average and Job-Mix Formula

The tolerances established are based on deviations measured from the plant average. No additional allowance is made for any difference between a plant average and job-mix formula. During 1963 and 1964, the eleven plants visited had selected a job-mix formula. The median differences between job-mix formula and average gradation were 3.0, 2.7, 1.7, 2.8, 1.0 and 0.9 percent on the ¼ in., ⅛ in., and Nos. 20, 40, and 80 and 200 sieves, respectively. The typical plant average gradation was 2¼ percent different than the job-mix formula. Such occurrences increase the probability of samples being outside the tolerance limits on the side toward which the average shifts. However, assuming the selection of a job-mix formula is based on the past gradation records of the plant, there should be little difference between the two unless some change takes place in the source of aggregate. If the average gradation being produced shifts away from the job-mix formula, positive corrective action is indicated.

## Plant Control Procedure

While the Bureau of Physical Research was measuring asphalt-concrete uniformity to establish realistic job-mix formula tolerances, the Bureau of Materials was developing a method of quality control in which the tolerances would be employed. This control method is included in a comprehensive manual entitled, Materials Method 5—Plant Inspection of Bituminous Concrete. The manual covers all phases of asphalt plant inspection, from the acceptance and handling of raw materials to the inspection of the automation and recordation equipment which is now a prerequisite to plant acceptance by the Department. As it pertains to quality control, the manual states:

> In general, production is accepted by obtaining gradation test results within the limits of a job-mix formula. Hot-bin analyses and uniformity tests determine the gradation of material larger than the No. 80 sieve. The extraction test is used to determine gradation of material smaller than the No. 80 sieve and also indicates the approximate bitumen content. Actual bitumen content is determined by verifying batch quantities.

A uniformity test is run for every 100 batches and a hot-bin analysis is performed after every four uniformity tests. If the specified mix gradation includes material below the No. 80 and No. 200 sieves, one extraction test is performed each day.

The dry sieved hot-bin gradation test and the extraction test are similar to those employed by most highway departments. The uniformity test was developed by the Bureau of Materials as a rapid test which would give the plant inspector a general indication of how mix gradation was deviating from tolerance limits. The test is based on the fact that in each hot bin there is usually a predominant, or "primary size" material. If the percentage of primary size material remains reasonably constant and material is weighed properly, the resulting mix will be uniform. During the uniformity study it was determined that when the amount of primary size material in the coarse aggregate hot bins (i.e., No. 1 and No. 1A) fell below 70 percent, the mix generally became nonuniform. Consequently, the uniformity test consists of determining just the percentage of primary size material in a hot bin (i.e., ½ to ¼ in. in No. 1 bin; ¼ to ⅛ in. in No. 1A bin) and only two sieves are needed per hot-bin uniformity test. The fines hot bin does not always contain a primary size aggregate as do the No. 1 and 1A hot bins. Usually a maximum of half of the fine aggregate is retained on the No. 20 sieve, and the remainder is distributed among the smaller sieve sizes. Thus, there is no primary size fraction requirement (70% of the material) as in the coarse aggregate bins.

Fluctuations in the percentage of primary size coarse aggregate above the 70 percent minimum requirement also influence plant uniformity. Consequently, a ±12 percent tolerance is specified, measured from the primary size percentage determined in the last hot-bin analysis. The same tolerance is specified for the No. 20 sieve material, although a minimum primary size percentage is not specified. The 12 percent tolerance was selected by comparing the primary size fluctuations with the fluctuations in the total mix. Total mix fluctuations as allowed within the gradation tolerances were mathematically converted to obtain maximum anticipated fluctuations in the primary sizes. A trial and error analysis was then performed using 8, 12 and 15 percent. It was found that 12 percent was a practical limit because it provides advance warning when production is approaching the job-mix formula limits.

To determine how well the Materials Method 5.0 quality control procedure worked, it was applied to the results of hot-bin tests performed in 24 plants during 1962 and 1963. The tolerances were first applied about the plant averages using all data. They were then applied about the individual job-mix formula being used by each plant visited during 1963. Applying a quality control procedure to data already collected introduces a bias against the producer, because he has no opportunity to make adjustments, and rejections will be disproportionately high. However, the results are of value because they make it possible to compare the ability of the method to differentiate between uniform and nonuniform plants.

If the quality control procedure performed its task properly, the following would occur.

1. The simple and fast uniformity test would be performed more often than the hot-bin analysis.
2. Any samples out of tolerance would be detected.
3. Mix rejection would be evenly distributed among the sieves used for gradation control.
4. More mix would be unacceptable in the plants having poor uniformity than in the plants having good uniformity.

In general, Materials Method 5.0 met the foregoing criteria. Approximately half of the tests that theoretically would have been performed were uniformity tests, whereas the other half were hot-bin analyses. As a result of this ratio of 1:1, the plant inspector would have had available for other uses about one-third of the testing time that would normally have been spent performing complete hot-bin analyses. This saving is based on an estimate that a hot-bin analysis takes about one hour, while a uniformity test takes only about 20 minutes.

The second requirement for an adequate quality control procedure is detection of any samples that are out of tolerance. Of the uniformity tests performed, less than 5 percent were unsuccessful in indicating that the hot bins contained gradations which would produce an out-of-tolerance mix. About 20 percent of the uniformity tests helped detect out-of-tolerance mix, whereas approximately 25 percent of the uniformity tests initiated the running of a complete hot-bin analyses on the next sample which proved unnecessary, because the mix gradation was within tolerances. The remaining 50 percent of the uniformity tests indicated the hot-bin gradations were within tolerances, and this was substantiated by the actual hot-bin analysis results.

Approximately 20 percent of the samples analyzed showed one or more sieves were out of tolerance. The occurrences were fairly evenly divided among the ¼ in., ⅛ in., No. 20, and No. 40 sieves. The ½-in. sieve was not included because very little material is retained above it and material passing the No. 80 sieve was not included because Materials Method 5.0 specifies it be controlled by extractions. The relatively even distribution of "outside-of-tolerance" by sieve size indicates each individual sieve tolerance is in balance with the others.

The 24 plants to which Materials Method 5.0 was applied were classified into three uniformity groups: good, fair and poor, based on the average standard deviation of hot-bin gradations. The quality control procedure detected more out-of-tolerance mix in the poor uniformity group than in the good uniformity group. Of the production not considered acceptable about 5 percent was from the plants in the good uniformity group, 35 percent from the fair group and 60 percent from the poor groups.

In the foregoing analysis, gradation tolerances were applied about the plant averages. When the procedure was applied about the job-mix formulas the results were modified to the extent that each plant average deviated from its job-mix formula gradation. The more uniform plants were in better accord with their job-mix formula than the less uniform plants. Accordingly, the plants in the poor uniformity classification required almost continuous theoretical checking by hot-bin analyses, and in some cases entire production runs would have been out of specification because one or two sieves deviated widely from their job-mix formula. The plants in 1963 were producing for the first time under a job-mix formula requirement. Therefore, as they gain experience in selecting more realistic job-mix formulas their noncompliance should decrease accordingly.

## CONCLUSIONS

1. This study has resulted in job-mix formula tolerances for asphalt-concrete top course mix which have been incorporated into New York State Department of Public Works specifications. These tolerances are based on actual variations measured among 491 hot-bin samples obtained from 29 asphalt-concrete plants. They are set at approximately two standard deviations as computed by pooling test results. Variability due to sampling and testing, as well as the inherent variability in the material itself, are included in the tolerances selected.
2. A control procedure was developed for asphalt-concrete plants taking into account statistical data accumulated in this study. It is based on sequential sampling of hot bins and has proven an effective quality control procedure.
3. There is a significant difference between the results of dry sieved hot-bin analyses and extraction tests. Further, the hot-bin test is more uniform in the coarse sizes, whereas the extraction test shows greater uniformity in the finer sizes.

## ACKNOWLEDGMENTS

This study was suggested by George W. McAlpin, Deputy Chief Engineer, Technical Services Subdivision, New York State Department of Public Works, and was conducted by the Bureau of Physical Research under the administrative supervision of Malcolm D. Graham, Director.

Personnel of the Bureau of Physical Research performed the study, processed part of the samples, and wrote the report. The Bureau of Materials processed the remainder of the samples and the Bureau of Electronic Data Processing performed data reduction and statistical computations.

The assistance of District Materials Engineers, the asphalt plant inspectors, and the asphalt plant producers is gratefully acknowledged.

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