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The purpose of this study was to investigate an application of statistical concepts to quality control of highway construction. The application was presented qualitatively and demonstrated quantitatively by an investigation of asphalt content in asphalt concrete.

For the example, an Oregon State Highway Project was sampled and tested. The average asphalt content, the standard deviation and the contribution of variation due to production, sampling and testing were evaluated. These results were compared with plant records and with the results of Oregon State Highway Department tests. Also, the example results were used to assign specification limits, demonstrate the significance of the limits, and to describe producer and purchaser risks. Comparison of results showed that present construction was good, and comparable to that of other states.

While the results of this investigation are of insufficient scope

to provide the foundation for statistical specifications, they substantially indicate the procedure for, and the value of, applying statistical quality control to highway construction and to highway specifications.

Statistical Quality Control Applied to Asphalt Concrete

by

Gerald Thomas Coghlan

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SYMBOLS AND NOTATION

LL	Lower specification limit.
n	Numbers of measurements.
P_g	Probability of rejecting acceptable material having a mean of $\overline{X}_g$.
P_p	Probability of accepting unacceptable material having a mean of $\overline{X}_p$.
t	Distance from mean to a point on the base of a normal distribution curve expressed in standard deviation units.
T_a	Allowable tolerance, difference between desirable and undesirable means.
UL	Upper specification limit.
X_i	An individual value from a series of values.
$\overline{X}$	Mean, or average, of a characteristic.
$\overline{X}_g$	Desirable, or good, mean.
$\overline{X}_p$	Undesirable, or poor, mean.
σ	Standard deviation.
$\sigma_{\overline{X}}$	Standard deviation of sample averages.
σ^2	Total variance.
σ_p^2	Variance due to production.
σ_s^2	Variance due to sampling.
σ_t^2	Variance due to testing.

STATISTICAL QUALITY CONTROL APPLIED TO ASPHALT CONCRETE

INTRODUCTION

Purpose

This study investigates an application of statistical concepts to quality control of highway construction. To provide an example of this application, the variation in asphalt content was examined as a measure of the quality of asphalt concrete.

Background

In 1969, the United States will invest just over $17 billion in highway construction (1). The highway engineer shoulders the responsibility of insuring the quality of this construction.

The construction specifications are the basis for quality and quality control. To provide this basis, the specifications must state:

1. The quality controlling characteristics
2. The acceptable limits of variation
3. The procedure for determining compliance
4. The criteria for accepting or rejecting the product.

The quality controlling characteristics have been determined by experience and research. Table 1 presents an example of some of the characteristics for asphalt concrete (2, p. 7). Generally,

Table 1. Characteristics of asphalt concrete (2, p. 7).[a]

Characteristics	General Significance[b] Major	Minor
Asphaltic Pavement:		
Density	x	
Temperature and Compaction	x	
Thickness		x
Surface Tolerance		x
Roughness		x
Asphaltic Base:		
Density	x	
Thickness		x
Asphaltic Mix:		
Gradation of Aggregate	x	
Dust Ratio	x	
Asphalt Content	x	
Stability and Flow	x	
Asphalt Cement:		
Penetration or Viscosity	x	
Retained Penetration of Thin Residue	x	
Thin Film Test Loss		x
Aggregate:		
Los Angeles Loss	x	
Gradation	x	
Liquid Limit and Plastic Index	x	
Durability		x
Deleterious Material		x
Flat and Elongated Particles		x

[a] Prepared by the Task Force on Statistical Quality Control, Office of Research and Development, U. S. Bureau of Public Roads.

[b] Major: a small degree of deviation acceptable.
Minor: a relatively larger degree of deviation acceptable.

the more significant, measureable characteristics have been incorporated in the specifications. However, the actual effect of minor variations of the controlling characteristics on the end product is not fully understood, much less evaluated.

In the past, the desired value for each characteristic was determined by design and definite limits of variation were set. For the most part, these limits were set from experience and from what the producer could meet. How the variation would affect the performance of the end product was not really known. Also, the definite limits made no allowance for normal variation outside the specified limits.

Similarly, procedures for measuring compliance were established without knowing how realistically the test results evaluated the actual characteristic, or the variation of that characteristic. "Representative" samples taken by the inspector, with no effort to randomize, could not be expected to represent the actual product without bias. Because of the delay in testing and the limited validity of results, these methods are of little help for process control or for acceptance criteria.

The fact that variation limits are exceeded and that compliance procedures do not truly represent the product is amply shown in the construction and performance of our modern, high quality roads. This was dramatically demonstrated on the AASHO Road Test and reported by Carey and Shook (3). On the Road Test, more inspectors were used than would be economical in normal construction, a large-scale materials lab was located on the project site, construction was done by a highly competent and cooperative contractor whose procedures were under complete control of the engineer, and the attention of the entire highway industry was focused on the project. Still, specifications were not always met! However, there was no evidence that the failure to meet specifications had any significant effect on the performance of the road.

Acceptance or rejection of material with variation outside the fixed limits was often decided solely by engineering judgement. This provided no rational and legally defensible basis for evaluating quality. Thus, the contractors had no clear, consistent understanding of quality requirements upon which to base their bids, and the engineers and the auditors had no numerical measure of substantial compliance or basis for adjusting payment.

Therefore, despite the many miles of high quality road being built every year, there is logically room for, and need for, improvement in the present quality control procedure. Incorporation of statistical concepts into quality control will contribute to this improvement.

APPLICATION OF STATISTICAL CONCEPTS

General

The application of statistical concepts to quality control was introduced by staff members of Bell Telephone Laboratories in the 1920's (4). The concept flourished during World War II, and is now used extensively throughout industry.

The application of statistical concepts is based on the fact that variation obeys fundamental laws. Through statistics, these laws may be expressed in mathematical terms, and inferences may be made in terms of probability. Thus, for a given situation, both the producer and the purchaser risks can be evaluated.

To the engineer, the mention of statistics implies overwhelming quantities of tests and numbers, unfamiliar mathematics, and large expenditures of time. This may be true in obtaining the data and developing the statistical quality control system, but it is not necessarily true in employing the system. In the development phase, laboratories and specialists would gather and analyze the data. The actual application would simply involve taking random samples, averaging the results, and checking the values against a table or chart. Additional procedures required by random sampling would be minimal.

The use of statistics does not control the engineer, nor does it relieve him of responsibility. Rather, it provides a tool to aid him in evaluating production and substantiating his decisions. The engineer and inspector must still watch for trouble from obviously defective material which must be rejected even though not indicated by random sampling.

The application of statistics begins with obtaining and understanding the statistical parameters--mean and standard deviation--of the product or characteristic. With these parameters, specification limits are chosen, acceptance plans are developed, and control procedures are implemented.

Determining Parameters

The basic statistical parameters used to describe a product or characteristic are the mean, or average, $\overline{X}$, and the standard deviation, or measure of the spread of values, σ. Mathematically, the standard deviation equals the square root of the total variance, σ^2. This in turn equals the sum of the sources of variance as shown in Equation 1.

$$\sigma^2 = \sigma_t^2 + \sigma_s^2 + \sigma_p^2 \qquad \text{Eq. 1}$$

in which σ = standard deviation

σ^2 = total variance

σ_t^2 = variance due to testing

σ_s^2 = variance due to sampling

σ_p^2 = variance due to production

To be of value, the parameters must be determined in accordance with statistical concepts, and must represent the desirable and attainable characteristic.

Assuming that present construction is good construction, the level of present construction and control represents desirable and attainable characteristics. Therefore, statistically satisfactory parameters obtained from present construction will insure that new construction approximates the good quality of present construction.

The measurements made to determine the parameters must be based on a sampling plan that insures randomness. Also, the project being studied must represent the desired quality and must be sampled in sufficient number to obtain a reliable measure of the parameters. The tests should be made by routine, standard methods.

Such a sampling and testing program has been outlined in considerable detail by the BPR's research guide: The Statistical Approach to Quality Control in Highway Construction (5). Figure 1 shows the basic plan outlined for asphalt concrete construction. Samples are taken from trucks, or pavement areas, randomly chosen at the rate of about one sample per 100 tons. Similarly, the

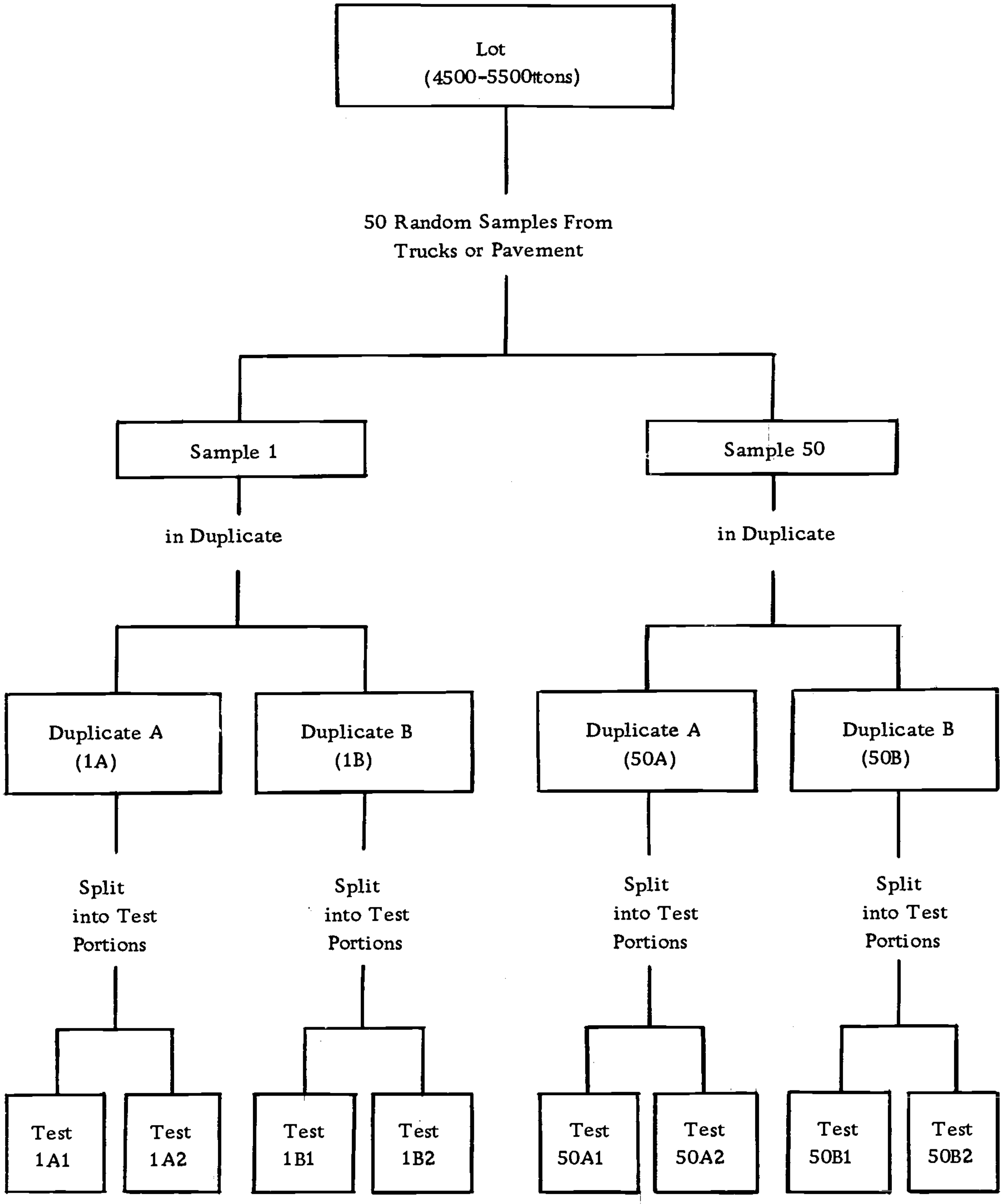


Figure 1. Sampling plan for basic parameters of asphalt concrete (5, p. 7).

location for two duplicate portions from the sample truck, or pavement area, is randomly chosen. Each duplicate portion is then split into two test portions and reduced to test size. Thus, four tests are performed for each sample truck or sample pavement area. Similar plans are outlined for portland cement concrete, pavement thickness, aggregates and embankments.

The analysis of test results, as outlined by the BPR's research guide, gives the variance due to testing (between test portions), due to sampling (between duplicates), and due to production (between truck or pavement samples). The sum of the contributing sources of variance gives the total variance according to Equation 1, and thus the standard deviation. For one or two sets of data, this analysis of variance can be most expeditiously performed manually (6, p. 12). Appendix B presents an example of the manual procedure for the analysis of variance. However, for continued use or for several sets of data, the BPR's research guide includes a FORTRAN program with a sample input and output for analyzing variance.

Setting Limits

Appropriate specification limits must balance costs against insuring adequate performance. Costs include those of testing and those associated with the contractor's risk. Adequate performance is a design quality including the intended use and life of the road.

Weighing these factors requires a basic understanding of distributions and risks.

When deciding to accept or reject a material on the basis of sampling, there is the possibility of making an error. This error may be one of two types. A type I error occurs when acceptable material is rejected. This is a producer risk. A type II error is the accepting of material which actually is unacceptable. This is a purchaser risk. The evaluation of risk depends on the distribution of variation.

The measured results of a normally distributed variable plot in the form of a histogram. Take, for example, the pavement core thickness data shown in Figure 2 with mean $\overline{X} = 2.016$ and standard deviation $\sigma = 0.11725$ (7, p. 13). These data fit a normal, bell-shaped curve with parameters $\overline{X} = 2.016$ and σ 0.11725 quite well. Statistical inferences are made from the theoretical normal curve.

The normal distribution curve can be converted from a scale of inches to a scale of σ units by

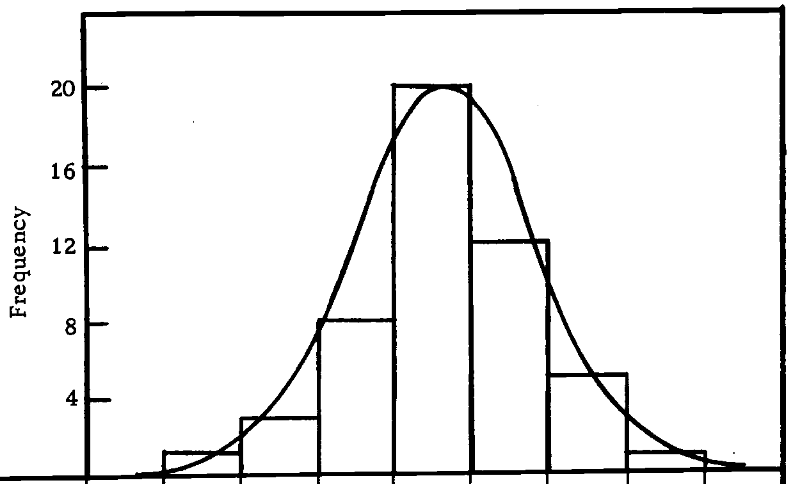
$$t = \frac{X_i - \overline{X}}{\sigma} \qquad \text{Eq. 2}$$

in which t = standard deviation in σ units

X_i = an individual value

$\overline{X}$ = average

The advantage of this conversion is that the areas under the curve,



Pavement Thickness (in.)		1.7	1.8	1.9	2.0	2.1	2.2	2.3	
Frequency		1	3	8	20	12	5	1	

Average = $\bar{X}$ = 2.016 inches
Standard Deviation = σ = 0.11725 inches

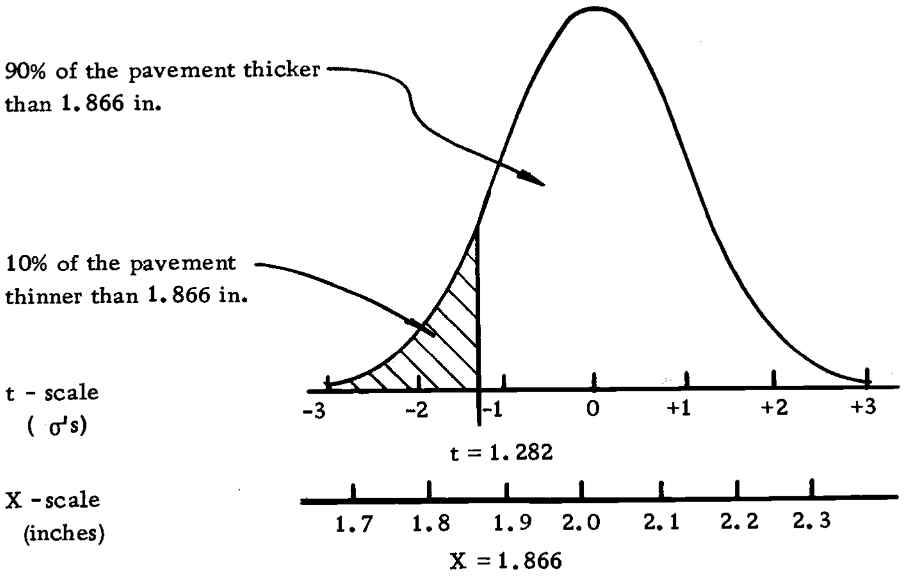


Figure 2. Example of statistical analysis of pavement core thickness data (7, p. 13).

expressed as a percent of the total area, have been tabulated for all values of t (8, p. 625). Thus, for the example in Figure 2, 90% of the cores could be expected to have a thickness greater than X_i. Obtaining t from the tables for 90%,

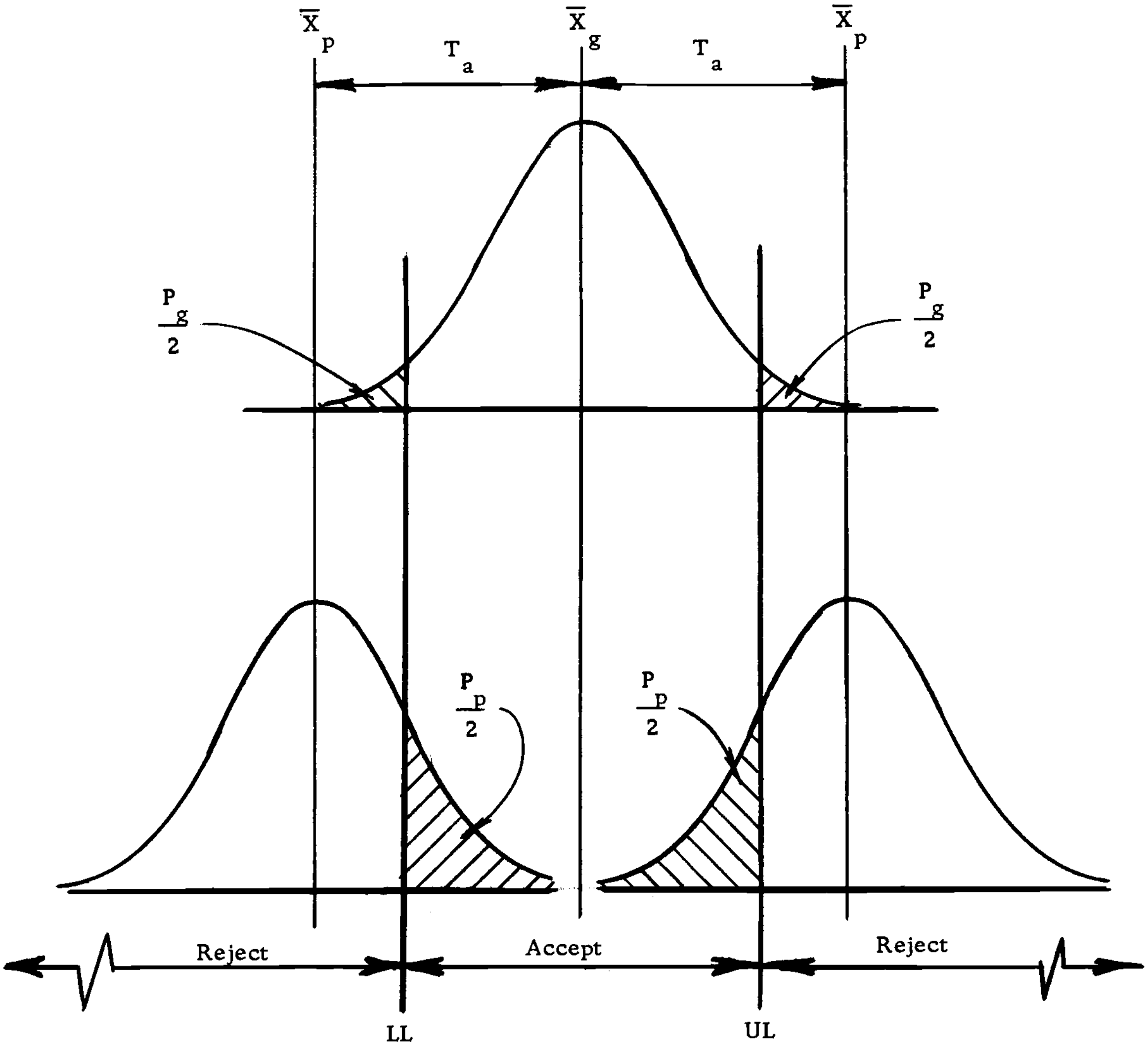
$$\begin{aligned} X_i &= \sigma t + \overline{X} \\ &= 0.11725(-1.282) + 2.016 \\ &= 1.866 \text{ inches.} \end{aligned}$$

Or, 90% of the pavement would probably have a thickness greater than 1.866 inches.

The normal curve is similarly employed to estimate risk, set limits, and determine acceptance criteria. When the development phase of the investigation has been completed, the standard deviation is known for the characteristic to be considered.

Figure 3 illustrates the relationship between limits, risks and the number of samples for a characteristic having an upper and a lower limit. Let $\overline{X}_g$ be the desired mean of good material and P_g the probability of rejecting that good material. Similarly, let $\overline{X}_p$ be the mean of poor material for which the probability of acceptance is P_p. If σ is the known standard deviation of the characteristic being investigated, then the standard deviation of the average of n samples is given by

$$\sigma_{\overline{X}} = \frac{\sigma}{\sqrt{n}} \qquad \text{Eq. 3}$$



$\overline{X}_p$	Mean of undesired, poor material.
$\overline{X}_g$	Mean of desired, good material.
T_a	Allowable tolerance between good and poor material.
P_g	Probability of rejecting good material (producer risk).
P_p	Probability of accepting poor material (purchaser risk).
LL	Lower specification limit.
UL	Upper specification limit.

Figure 3. Relationship between limits, risks and the number of samples (7, p. 37).

in which n = number of samples

$\sigma_{\overline{X}}$ = standard deviation of the average of n samples

Thus, by knowing σ, and by setting n, P_g and P_p, the limiting average of the poor material and the specification limits can be calculated.

Miller-Warden Associates (7, p. 34) have suggested a balance of these factors based on the criticality of the characteristic as shown in Table 2. For a very critical characteristic, only a very slight chance of accepting poor material, P_p, can be permitted and a greater chance of rejecting good material, P_g, must be taken. Conversly, for a characteristic of only slight importance, a greater chance of accepting poor material can be permitted, and a lesser chance of rejecting good material need be taken. For any given set of risks, more samples increases the reliability of the results and therefore would decrease the size of the limits.

Table 2. Suggested balance of acceptance specification factors (7, p. 34).

Criticality of Characteristic	Probability of Rejecting Good Material P_g	Probability of Accepting Poor Material P_p	Number of Measurements n
Critical	0.100	0.010	6
Major	0.020	0.100	5
Minor	0.010	0.200	4
Contractual	0.002	0.400	3

The rationale for the limit is that if the measured average of the samples is at the limit there is only a set chance or probability (P_p) that the true average is as low, or high, as $\overline{X}p$, and that this low or high value will be accepted. The procedure for setting limits for a characteristic with only one limit would be analogous.

Sampling and Testing

There are two different situations involving sampling and testing. The first is the evaluation of the basic parameters. This was shown in Figure 1 and discussed in the section on determining parameters.

The second application is the day to day sampling and testing for process control and acceptance. The daily sampling plan must insure randomness and the tests should be made by the same routine, standard methods used to evaluate the basic parameters.

To prepare a random sampling plan, the scope of construction, or lot, to be represented by the samples must be defined. This lot might be any well defined quantity such as a certain number of cubic yards of portland cement concrete, so many lineal feet of one lift of base course, or one days production of asphalt concrete. The lot is then divided into identifiable segments such as truck loads or square yards, and in turn the segments are subdivided into increments. For the sampling of each lot, the increments of the segments to be sampled are predetermined using random numbers. This procedure insures that sampling is not haphazardly done, but rather it is done without bias. Actual sampling should be done in accordance with procedures recommended by ASTM to avoid bias due to localized or temporary segregation.

Performing tests by standard and routine procedures promotes the consistency of results between different operators and between the day to day testing, and that used to obtain the basic parameters. Also, standard methods are understood and accepted by common usage.

Process Control

Many individual elements and processes combine to produce an end product. Variation in one of these could result in rejection of the end product. Therefore, to insure continuing conformance, testing for control is as important as that for acceptance.

The statistical control chart (9) provides one tool for process control. The control chart is a continuing plot of the daily tests of each measured characteristic. As these continuous plots trend toward or away from the limits established by statistical evaluation of risk, they indicate the trend in variation of the process, and the cause for the trend can be identified and corrected.

Another value of the control chart is that it provides a comparison of the parameters of the process with the basic parameters used to prepare the specified limits. Significant variation in the project results from the predicted parameters would call attention to the need for further investigation.

Advantages and Dangers

In the development of the application of statistical concepts to quality control, many advantages and many areas for caution are indicated. It is well to summarize some of these.

A partial list of the advantages obtained with statistical quality control are:

1. Sampling can be done without bias, and the uniformity of test results between people and between projects will increase.
2. Sources of variation are isolated, identified and measured. Steps can then be taken to reduce the variation.
3. The true quality of the product will be evaluated in mathematical terms, providing a common denominator for the contractor, the engineer and the auditor.
4. Both the producer and the purchaser risks can be evaluated and assigned.
5. Specification limits can be assigned in terms of risk, cost and desired quality.
6. The contractor can prepare a better bid price since his risk,

and the basis for acceptance or rejection is clearly known before bidding.

7. The engineer gains a tool for evaluating products and for making decisions.
8. Contractor-Engineer relations are improved since decisions are based on logical, impersonal procedures.
9. Since the true nature of the product is understood and mathematically evaluated, there is a basis for evaluating the loss in service of the product due to poor quality. Thus, there could be an appropriate reduction in payment, rather than rejection of the product.

Potential areas for caution in applying statistical quality control include:

1. The program must be introduced slowly and in conjunction with a training and familiarization program because the concepts are new and foreign.
2. The application must be a serious effort or any advantages are lost.
3. The initial cost, time and effort to develop this concept are considerable.
4. The distribution of variation of a characteristic must be checked to insure valid assumptions.
5. Characteristics distributed in some pattern other than

normal involve considerable more knowledge and effort for application. Generally the help of an applied statistician would be desirable.

6. The contribution to variation due to sampling and testing is appreciable and must be considered in setting product limits.
7. The basis for employing sampling and testing characteristics on a project must be analogous to those used in developing the parameters used in setting the specification limits.
8. Finally, statistics can not be expected to relieve the engineer of the responsibility for the quality of the product and the project.

SAMPLE APPLICATION

Project Description

The Burlington-Portland widening and repaving of highway U. S. 30, designated as Project No. 26-1080 by the Oregon State Highway Department, provided a good project for this study. The advantages of this project were the reliability of the paving contractor and the convenience for sampling. The prime contractor was Slate-Hall and Babler Brothers, Inc. was the paving sub-contractor.

The asphalt concrete sampled was an Oregon State Highway Department (OSHD) "B"-mix, surface coarse with a nominal 5.7% asphalt. The asphalt used during sampling, and during most of the project, was a 60-70 penetration, paving grade asphalt produced by Shell Oil Company. An 85-100 Chevron Asphalt Company asphalt was used for patching and minor finishing during the winter months. The aggregate used was a good quality basalt excavated as part of the required widening and crushed at the plant site.

The asphalt mix plant was a 1964 model Pioneer Continuflo Bituminous Plant. This electronically automated plant had a cost of $400,000 and a peak capacity of 400 tons per hour. The actual plant output on this project was held at 250 tons per hour because of the limited dust control capacity. Mix was carried by convenyor from the plant to a storage silo and was loaded from the silo directly into the trucks.

Paving was done using two paving machines in adjacent lanes, and about two hundred feet apart. Breakdown rolling was done with a three-wheel roller, followed by secondary rolling with a pneumatic-tired roller. A two-wheel tandem roller finished the pavement.

Sampling

The sampling plan was based on the BPR research guide (5) as outlined in Figure 1. Sampling was planned over approximately 5000 tons at the rate of one truck per 100 tons, or a total of 50 trucks. Assuming 12.5 tons per truck average, 50 random samples were required from 400 trucks.

Arbitrarily choosing a beginning point, the next 50 numbers were chosen from the Table of Random Numbers (5, p. 28). Each selected number times the total number of trucks (400), and rounded to the nearest whole number, assigned a truck to be sampled. The trucks to be sampled were arranged in ascending order and entered on a sampling log, Appendix A.

Sampling points in the trucks were established by dividing the rear half of the bed into eight segments and, again using random numbers, choosing two segments--one for each duplicate portion. Within a segment, a duplicate portion was taken one-third each from the top, middle and bottom. Figure 4 shows the truck sampling scheme.

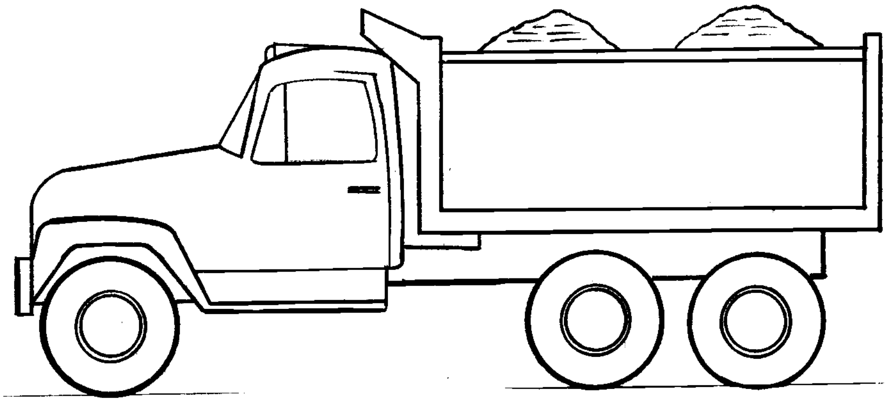
All sample planning and scheduling was done prior to arriving on the project. Only the first 25 of the scheduled 50 sample trucks were sampled and tested.

Sampling was done with a square tipped, short handled shovel. A two inch surface layer was scraped off the top, middle, and bottom of the segment to be sampled. Then, in each cleared area, the shovel was inserted about 3 inches, and that amount of asphalt mix was removed and placed in a cardboard box. The sampling boxes were 8'' × 6'' × 4'' deep and held 4500 to 5000 grams.

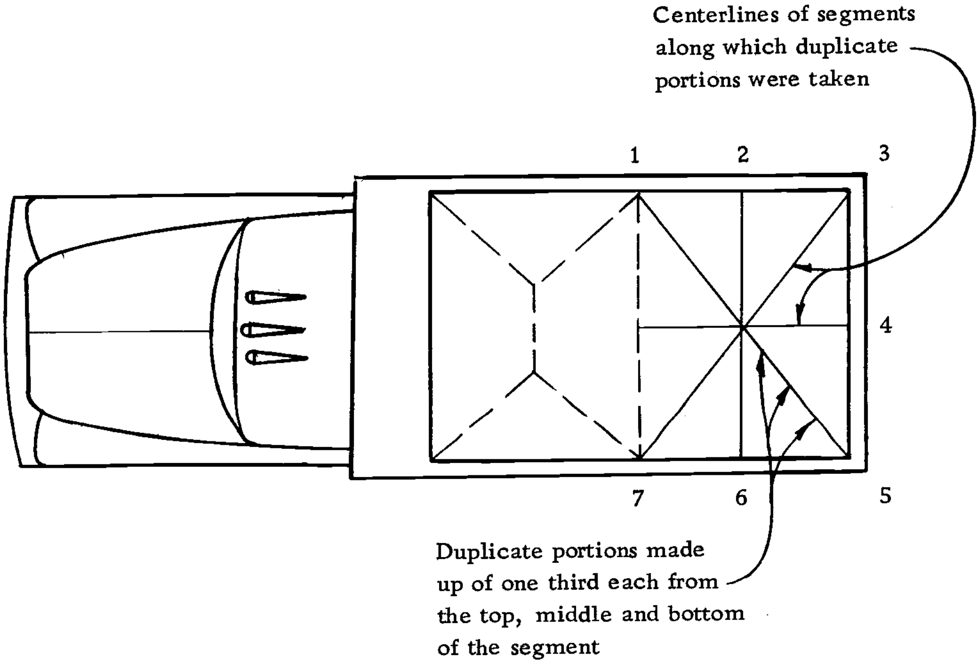
Testing

Test portions were prepared for extraction by first heating the boxed duplicate portion in the oven at 200 to 250° F for two to three hours. The box was then dumped on a stainless steel surfaced workbench, mixed and quartered with a metal straight edge. Diagonal quarters were returned to the box and set aside. After mixing and quartering the remaining material, diagonal quarters were combined for test specimens.

The test procedures followed were those used by the OSHD. These included centrifuge extraction, using toluene solvent, as outlined by ASTM D2172-63T except as noted below. No test was



(a) Elevation



Centerlines of segments along which duplicate portions were taken

Duplicate portions made up of one third each from the top, middle and bottom of the segment

(b) Plan

Figure 4. Truck sampling scheme.

made for mineral fines in the extract, the filters were burned rather than dried and weighed, and moisture tests were not made according to ASTM D95. Moisture corrections were made by drying 100 to 150 gram portions of the test specimens before extraction and of the remaining aggregate after extraction. The difference in moisture content between these was taken as a correction to the measured asphalt content. Moisture samples were dried for 24 hours rather than for 48 hours as is done by the OSHD.

Results and Sample Calculations

The asphalt contents obtained by the research sampling and testing plan are summarized in Table 3. The table identifies the test results by sample, duplicate portion and test portion. The values range from 5.19 to 6.25% and have an average asphalt content of 5.759%. Twenty percent of the individual test results were outside the project specification limits of 5.40 to 6.00%.

Table 4 presents the total asphalt cement used and the total asphalt concrete produced during the two days of sampling. These plant measures gave an average asphalt content of 5.773%.

The OSHD continued their normal sampling and testing throughout the project. Their test results for asphalt content for the surface coarse are summarized in Table 5. The field testing and laboratory testing results both yielded an average asphalt content of 5.53%.

Table 3. Asphalt content from research plan.

	Asphalt Contents, %			
Sample	A1	A2	B1	B2
1	5.84	5.94	6.01	5.77
2	5.66	5.72	5.92	5.64
3	5.85	5.77	6.01	5.97
4	6.07	5.99	5.73	6.21
5	5.81	5.70	5.90	6.25
6	5.79	5.72	5.77	5.70
7	5.26	5.52	5.26	5.22
8	5.56	5.86	5.81	5.84
9	5.60	5.29	5.70	5.82
10	5.50	5.66	5.58	5.68
11	5.59	5.68	5.97	5.93
12	5.49	5.47	5.89	6.24
13	5.38	5.69	5.60	5.50
14	5.76	5.58	5.67	5.97
15	5.97	5.48	5.69	5.77
16	5.50	5.52	5.79	5.80
17	5.62	5.77	5.93	5.64
18	5.89	6.05	6.02	6.03
19	5.69	5.86	5.86	6.07
20	5.69	5.85	6.07	5.68
21	5.85	5.93	5.68	5.82
22	5.90	5.78	5.59	5.57
23	5.77	5.57	5.97	6.19
24	6.09	5.94	6.04	5.87
25	5.41	5.19	5.62	5.47

Table 4. Asphalt content by plant measurement.

Date	Asphalt, tons	Mix, tons	Asphalt Content, %
1 Aug	125.61	2173.80	5.778
2 Aug	101.76	1764.85	5.766
Totals	227.37	3938.65	5.773

Table 5. Asphalt content for OSHD testing.

	60-70 Shell		"B"-Top	
	Date	No. Averaged	% Asphalt	No. × %
Field				
	6-25	3	6.0	18.0
	6-26	1	5.6	5.6
	7-25	2	5.5	11.0
	7-26	2	5.7	11.4
	7-29	2	5.5	11.0
	8-1	3	5.4	16.2
	8-2	4	5.3	21.2
	8-8	2	5.2	10.4
	8-9	2	5.1	10.2
	8-15	2	5.5	11.0
	8-16	3	5.8	17.4
	8-2	2	5.3	10.6
	9-6	2	5.6	11.2
	9-9	2	5.8	11.6
	9-10	2	5.5	11.0
	Totals	34		187.8
			Average = 5.53	
Lab				
	7-29	1	5.6	
	8-1	1	5.7	
	8-1	1	5.3	
	8-1	1	5.3	
	8-2	1	5.3	
	8-2	1	5.5	
	8-16	1	5.4	
	8-16	1	5.6	
	8-20	1	5.5	
	9-6	1	5.9	
	9-9	1	5.7	
	Totals	11	60.8	
			Average = 5.53	

Table 6 summarizes the average asphalt contents as obtained by research sampling and testing, by plant measurement and by the OSHD field and laboratory testing. The research and plant results are very similar, and the OSHD field and laboratory results are the same.

Table 6. Summary of measured asphalt contents.

Source	Asphalt Content %
Research Plan	5.759
Plant Measurement	5.773
State: Field	5.53
Lab	5.53

The results of the analysis of variance are presented in Table 7. Approximately two-thirds of the variance was due to sampling and testing, and only one-third was due to the actual variance of the asphalt content.

Table 7. Results of analysis of variance.

Testing Variance σ_t^2	Sampling Variance σ_s^2	Product Variance σ_p^2	Total Variance σ^2	Standard Deviation σ
0.0204	0.0142	0.0163	0.0509	0.2255

Figure 5 demonstrates the evaluation of limits for asphalt content. The assumed risks and numbers of samples were those recommended by Miller-Warden Associates (7, p. 34) and summarized in Table 2. The limits obtained for Case b, 5.41 to 5.99%, are very similar to the project specification limits, 5.40 to 6.00%.

Sample calculations for Case a, Figure 5, are given below.

Case a, Figure 5:

$$n = 5, \quad P_g = 0.020, \quad P_p = 0.100$$

$$\sigma_{\overline{X}} = \frac{\sigma}{\sqrt{n}} = \frac{0.2255}{\sqrt{5}} = 0.10085$$

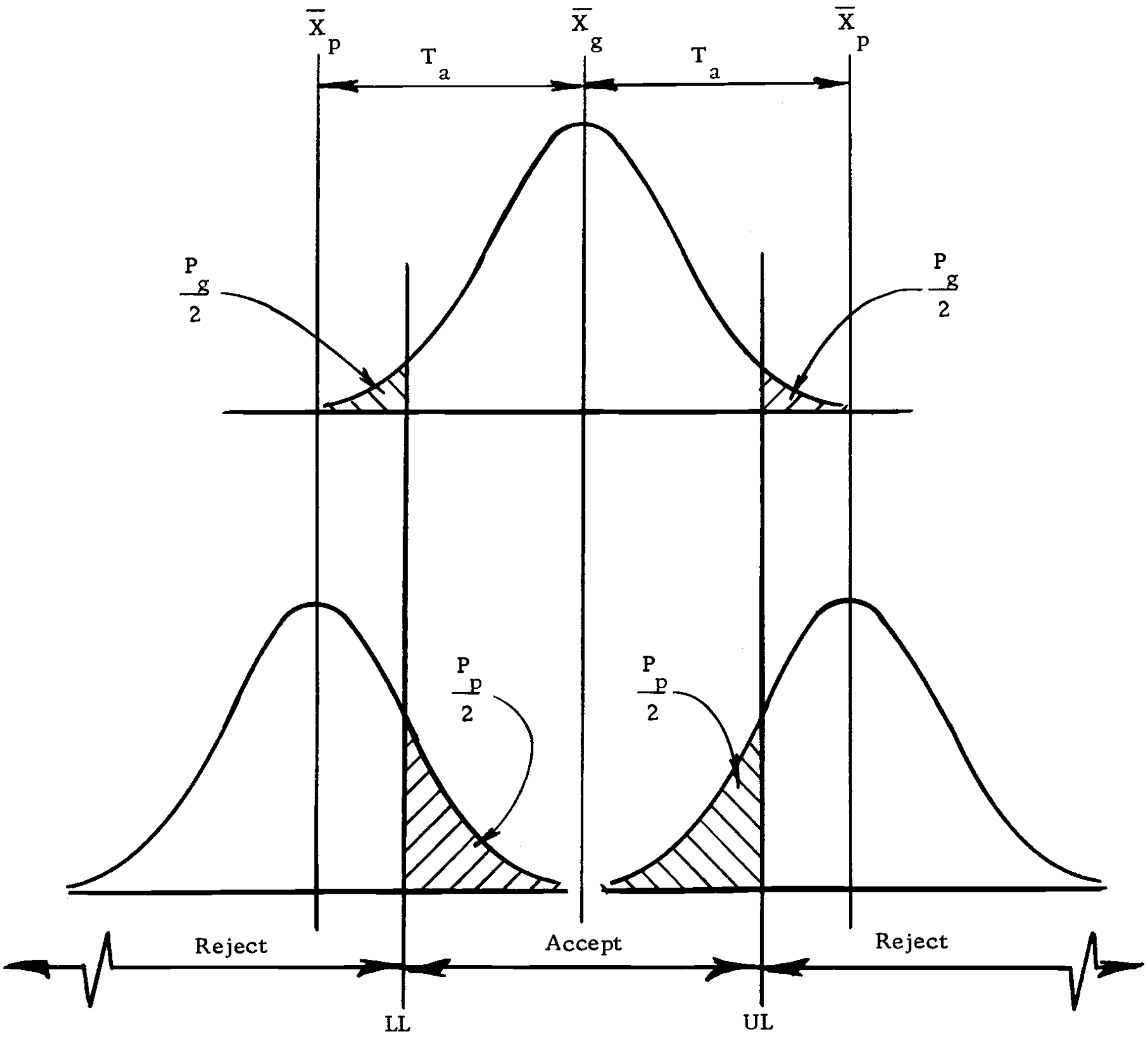
$$(X_i - \overline{X}_g) = \pm \sigma_{\overline{X}} t_{.99} = 0.10085\ (2.327) = 0.2347$$

$$(X_i - \overline{X}_p) = \pm \sigma_{\overline{X}} t_{.95} = 0.10085\ (1.645) = 0.1659$$

$$T_a = (X_i - \overline{X}_g) + (X_i - \overline{X}_p) = 0.4006$$

In the calculations, the value of t was taken from a table (8, p. 625) for the total area under the curve minus the error at one limit, $\frac{P_p}{2}$ or $\frac{P_g}{2}$. In the sample calculation

$$t_{(1.00 - \frac{P_g}{2})} = t_{(100 - 0.01)} = t_{(.99)} = 2.327 \ .$$



Case	Assumed Factors				T_a	% Asphalt	
	$\bar{X}_g$	P_g	P_p	n		LL	UL
a	5.70	0.020	0.100	5	0.40	5.46	5.94
b	5.70	0.010	0.200	4	0.43	5.41	5.99
c	5.70	0.002	0.400	3	0.51	5.30	6.10

Figure 5. Limits based on three sets of assumed factors.

DISCUSSION

Sampling and Testing

Samples for research testing were taken from the trucks, whereas the OSHD samples were taken directly behind the asphalt paver. Difference between the two methods should be negligible. However, sampling behind the paver is statistically preferable because the total product is available to be sampled. In sampling from a truck, or any stock pile, the deeply buried material is not available for sampling. Truck sampling was convenient because it interfered the least with the contractor.

The South Carolina State Highway Department (10) compared sampling from the truck, from behind the spreader, and after compaction for both surface and binder mixes. The results of this comparison are shown in Table 8. The variation in these results makes it inconclusive as to which sampling point is preferable. It should be noted that the South Carolina investigation used a grid for choosing duplicate sampling points in the truck. This means that a duplicate portion could come exclusively from either the edge or the center of the pile, giving a coarser or finer sample respectively. This procedure should indicate a higher variation due to sampling than the procedure presented in this thesis.

Table 8. South Carolina sampling results (10, p. 36).

Place Sampled[a]	No. Tests	Product Variance	Sampling Variance	Testing Variance	Total Variance
Surface					
1	40	0.08	0.00	0.04	0.14
2	24	0.06	0.00	0.05	0.11
3	128	0.00	0.00	0.04	0.08
Base					
1	284	0.04	0.04	0.06	0.15
2	68	0.17	0.05	0.08	0.29
3	380	0.09	0.06	0.06	0.20

[a] 1. Sampled from truck
2. Sampled behind spreader
3. Sampled after compaction

Random numbers were used to choose both segments for taking duplicate portions. This procedure would be necessary when sampling from the pavement. However, when sampling from the truck, one segment could be chosen by random numbers and the duplicate portion could be taken from the opposite segment. This would simplify the sampling plan and make it easier for the sampler to keep track of the areas to be sampled while actually performing the sampling operation.

Prior to sampling, the location of all samples and duplicates were determined and entered on a sampling log, Appendix A. In three cases, the intended truck was not sampled in order to avoid delay at the paver. Rather, the following truck was sampled using the predetermined segments. Logging the truck receipt numbers related the test data to state records. Insufficient test results were obtained to employ the time of day as a basis for evaluating asphalt content variation.

In preparing test specimens, the OSHD does not reduce their field samples by mixing and quartering. However, this was particularly important for the duplicate portions obtained for this research because they were segregated into three parts during sampling. Generally, quartering is a desirable procedure and there appears to be very little loss of asphalt due to sticking to the box or to the working surface. This loss may be slightly higher for the warmer, softer samples, but this type of sample is desirable because considerable heat is lost during mixing and quartering. When placing the test portion into the extractor, it must be soft enough to be completely broken apart.

The centrifugal extractor used for testing was larger than that indicated by ASTM 2172 and used by the OSHD. The extractor used had a bowl top, inside diameter of 9 5/8 inches as compared to that specified by ASTM of 8 inches. The larger extractor permits the testing of larger samples, but should not give significantly different results if run only fast enough to force the solvent through the filter.

Although no specific test was made for fines, the collection bowl was checked periodically for sediment. During experimentation with various filters, sediment was noted after an extraction using a thin filter, but no appreciable error was apparent in the measured asphalt content. Since no sediment was noticeable when using the manufacturers recommended filters, it was concluded that the loss of fines was not significant.

The moisture correction procedure used was that used by the OSHD. Specimens were only dried for 24 hours because this was generally adequate to reach a constant weight. If some slight amount of moisture remained, it would be essentially the same in both the mix and the aggregate, and the ultimate correction would not be affected.

A significant source of testing variation arises from the weighing operation. Generally, balances commonly used, such as the solution balance, are calibrated to read to the nearest gram. When taking the asphalt content as the loss of weight from the original test portion and the remaining aggregate, a one gram error can make a difference of 0.1%. For example:

	(1)	(2)
Total Sample	1160 g.	1160 g.
Remaining Agg.	1094	1093
Diff.	66 g.	67 g.
Asphalt Content	5.70%	5.78%

Further, for the solution balance first tried in this investigation, a two gram error was noted between the upper and lower ends of the

0-100 gram scale, and also between different 100 gram loading increments for some settings. To minimize this error the solution balance was replaced by an even arm balance which could be read to the nearest 0.5 grams. However, this necessitated the inconvenience of using weights.

Results

Figure 6 shows a comparison of all measured asphalt contents. This provides an overview of the test results by sequence, and provides a basis for comparison with the mean, the limits and the standard deviation. It can be seen that in only one case did the average of the test portions for one truck fall outside the project specification limits, whereas individual test results exceeded the limits 20 times.

Table 7 compared different measures of the average asphalt content on the project. Since the asphalt content indicated by plant measurement does not involve sampling and testing errors, it provides a good check on the average. A time recording of the asphalt used, combined with the truck loads of mix weighed, would continually indicate the variation in asphalt content. However, this check on variation was not made. The close agreement between the plant measured asphalt content and the average of the research sampling and testing substantiates the results. The OSHD field and

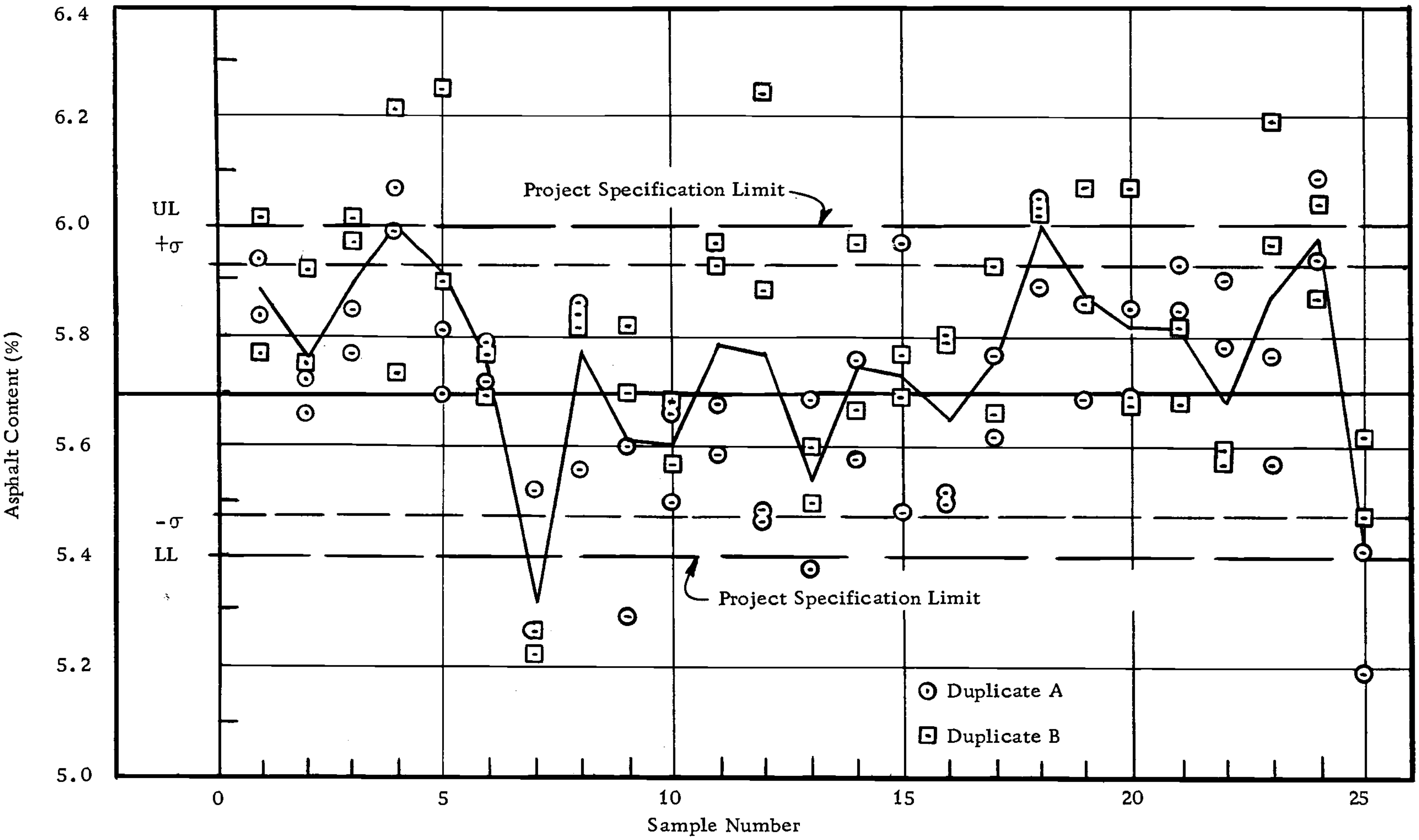
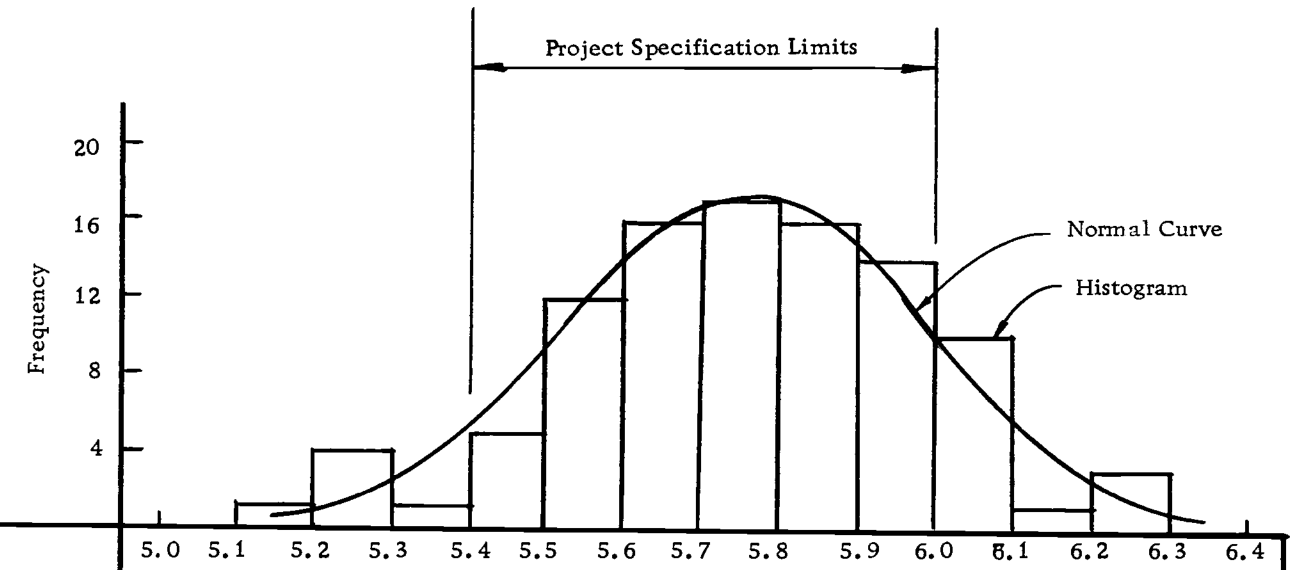


Figure 6. Overall comparison of test data.

laboratory test results agree quite well, but differ from the experimental and plant results. Since both the laboratory and the field samples are taken by one individual, this might indicate that the State's "representative" sampling procedure introduced appreciable bias.

The frequency histogram, Figure 7, and the cumulative frequency curve, Figure 8, provide a good picture for statistically comparing the test results. These figures compare the test data with the theoretical normal distribution. In Figure 7, the normal, bell-shaped curve approximates the histogram quite well. Additional sampling would smooth the histogram, bringing it closer to the ideal curve and increasing the accuracy of the measured parameters.

The sample cumulative frequency also matches the normal cumulative frequency curve, Figure 8. Because the sample data is based on a finite sample and the ideal curve is based on an infinite sample, there is some variation between the upper and lower ends. Normal probability paper has an expanded scale such that the normal cumulative frequency curve such as that in Figure 8 will plot as a straight line. An evaluation of normalcy can be made by fitting a straight line to test data plotted on normal probability paper. Figure 9 shows the straight line fit for the test data. Except for the 5.3% and the 6.1% intervals, the straight line fits the data very well. As mentioned, additional sampling should



Asphalt Content (%)	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.1	6.2	6.3	6.4
Frequency		1	4	1	5	12	16	17	16	14	10	1	3		

Average $\overline{X}$ = 5.759 % asphalt

Total Standard Deviation σ = 0.2255 % asphalt

Figure 7. Test data histogram and normal curve.

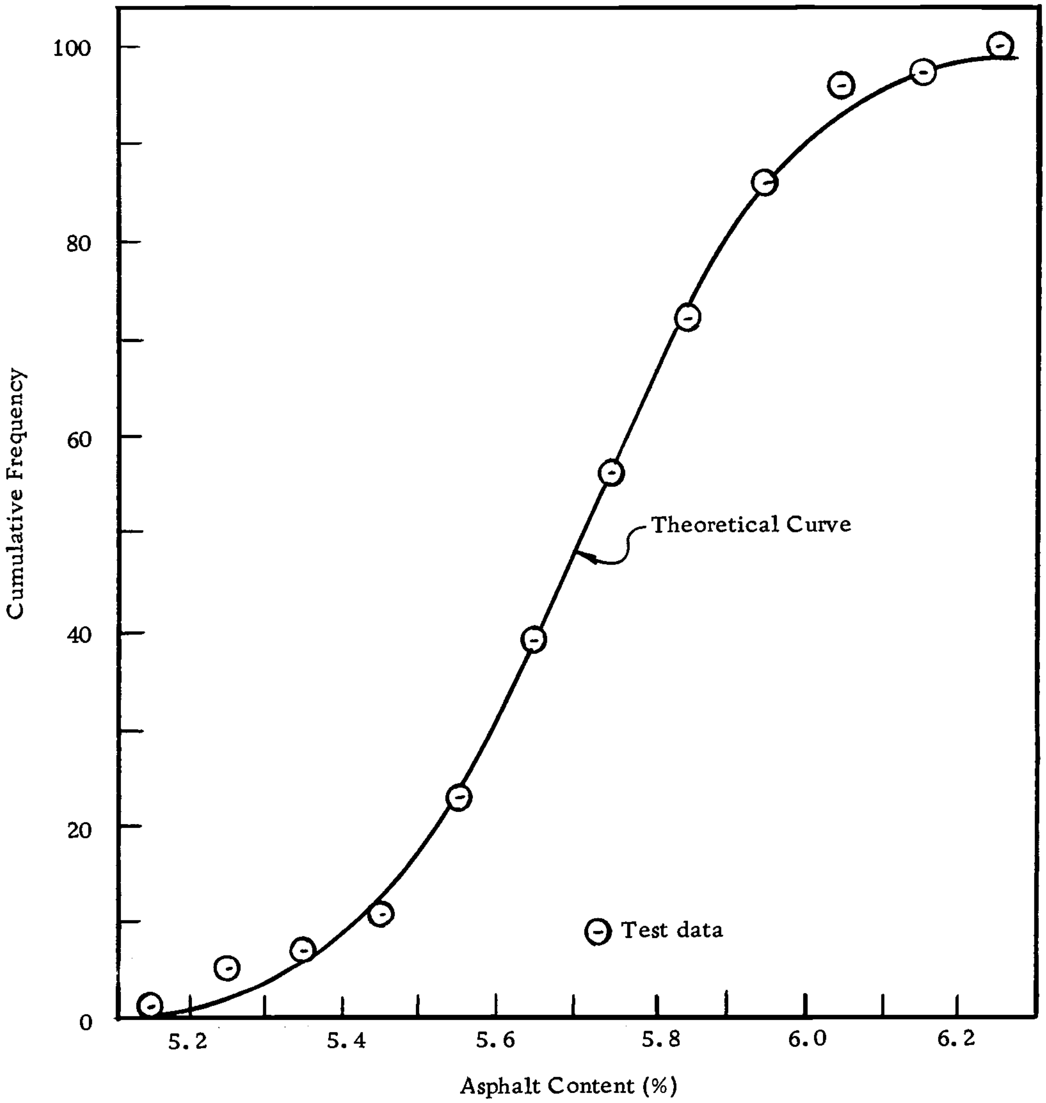


Figure 8. Test data and theoretical cumulative frequency curve.

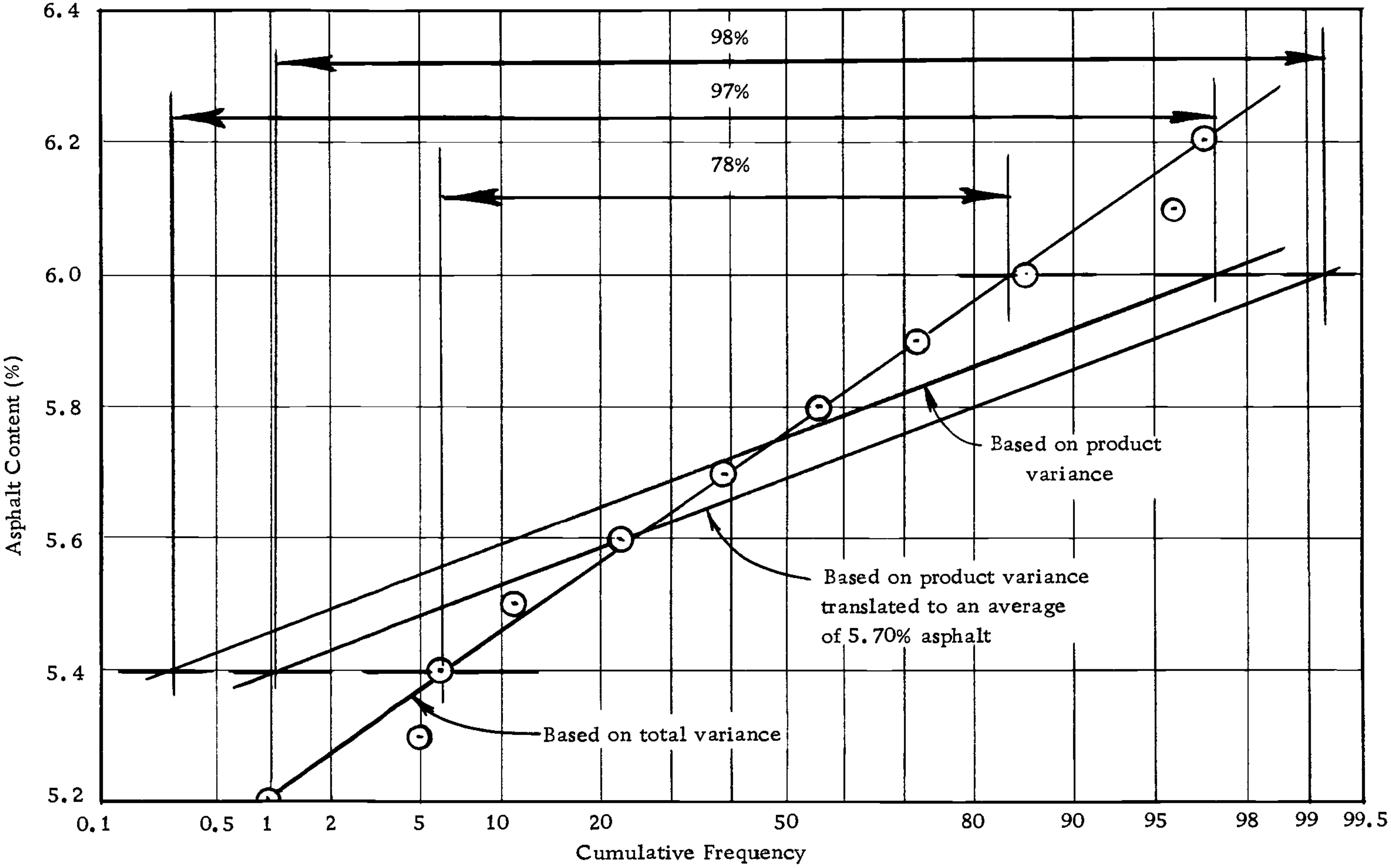


Figure 9. Plot of data on normal probability paper.

improve the fit. Therefore, the assumption that the asphalt content is normally distributed appears justified and the calculation of errors may be made using the theoretical normal distribution based on the measured parameters.

Between any range of asphalt contents, the percent of the total product in that range can be read directly from the plot on normal probability paper, Figure 9. The slope of the line is a function of the standard deviation. As the standard deviation decreases, the slope decreases and the percent of the end product within any range increases. The analysis of variance, Table 6,showed that only one third of the total variance was due to product variance. Based on the total standard deviation, 78% of the pavement on the sample project would appear to have an asphalt content between 5.40 and 6.00%, the project specification limits. However, by the standard deviation based on the product variance alone, 97% of the pavement actually had an asphalt content within the specified limits. Had the asphalt content been ~~at~~ the specified mean of 5.7, 98% of the pavement would have met the specification.

The results of the analysis of variance in asphalt content, Table 6, compared reasonably with results obtained by other agencies, Table 9 (6, 10, 11, 12). Considerable variation exists between different investigations due to normal variation and to different details of sampling, testing and material production. Therefore, for the

Table 9. Summary of analysis of variance investigation results (6, 10, 11, 12).

Study of % Asphalt[a]		No. Samples[b]	Material Variance	Sampling Variance	Testing Variance	Total Variance	Standard Deviation
BPR	(6)	50	0.009	0.002	0.003	0.014	0.120
S. Carolina	(10)	10	0.04	0.00	0.08	0.14	0.37
		8	0.05	0.00	0.06	0.11	0.33
		32	0.04	0.00	0.00	0.08	0.28
		71	0.06	0.04	0.04	0.15	0.38
		17	0.08	0.05	0.17	0.29	0.54
		95	0.06	0.06	0.09	0.20	0.45
New Jersey	(11)	50	0.022	0.000	0.091	0.113	0.335
		50	0.042	0.057	0.089	0.188	0.433
14-1	(11)	50	0.066	0.006	0.002	0.074	0.272
28-1	(12)	50	0.000	0.013	0.015	0.028	0.167
2		50	0.014	0.012	0.016	0.042	0.205
3		22	0.000	0.005	0.016	0.021	0.145
4		28	0.003	0.008	0.010	0.021	0.144
48-1	(12)	50	0.046	0.011	0.018	0.075	0.272
33-1	(12)	50	0.020	0.008	0.004	0.032	0.179
2		50	0.032	0.003	0.003	0.038	0.193
2-1	(12)	56	0.065	0.007	0.013	0.084	0.291
This project		25	0.016	0.014	0.020	0.051	0.226

[a] Code numbers are BPR, State and project designations.

[b] Number of samples represents 4 times that many individual tests.

limited data, a detailed comparison by source of variance is not practical.

A general comparison can be made of the total variance by comparing the standard deviation, Figure 10. The standard deviation obtained from the total variance is about the same as that obtained by the analysis of individual test values. In order to include more data, the overall comparison includes the results of additional investigations, Table 10 (12, p. 255), in which the standard deviation was determined by the analysis of individual test values.

Table 10. Additional asphalt content variation results (12, p. 255).

Study	Tests	Standard Deviation % Asphalt
Hode-Keyser	40	0.33
	40	0.22
Adams and Shah	36	0.16
	48	0.26
	34	0.18
	40	0.38
AASHO Road Test	58	0.13
	43	0.18

In Figure 10, the variation in standard deviations of asphalt content does not appear to be normally distributed. However, the figure provides a picture of the progress of research to date and it provides another check on individual results. No investigation had a

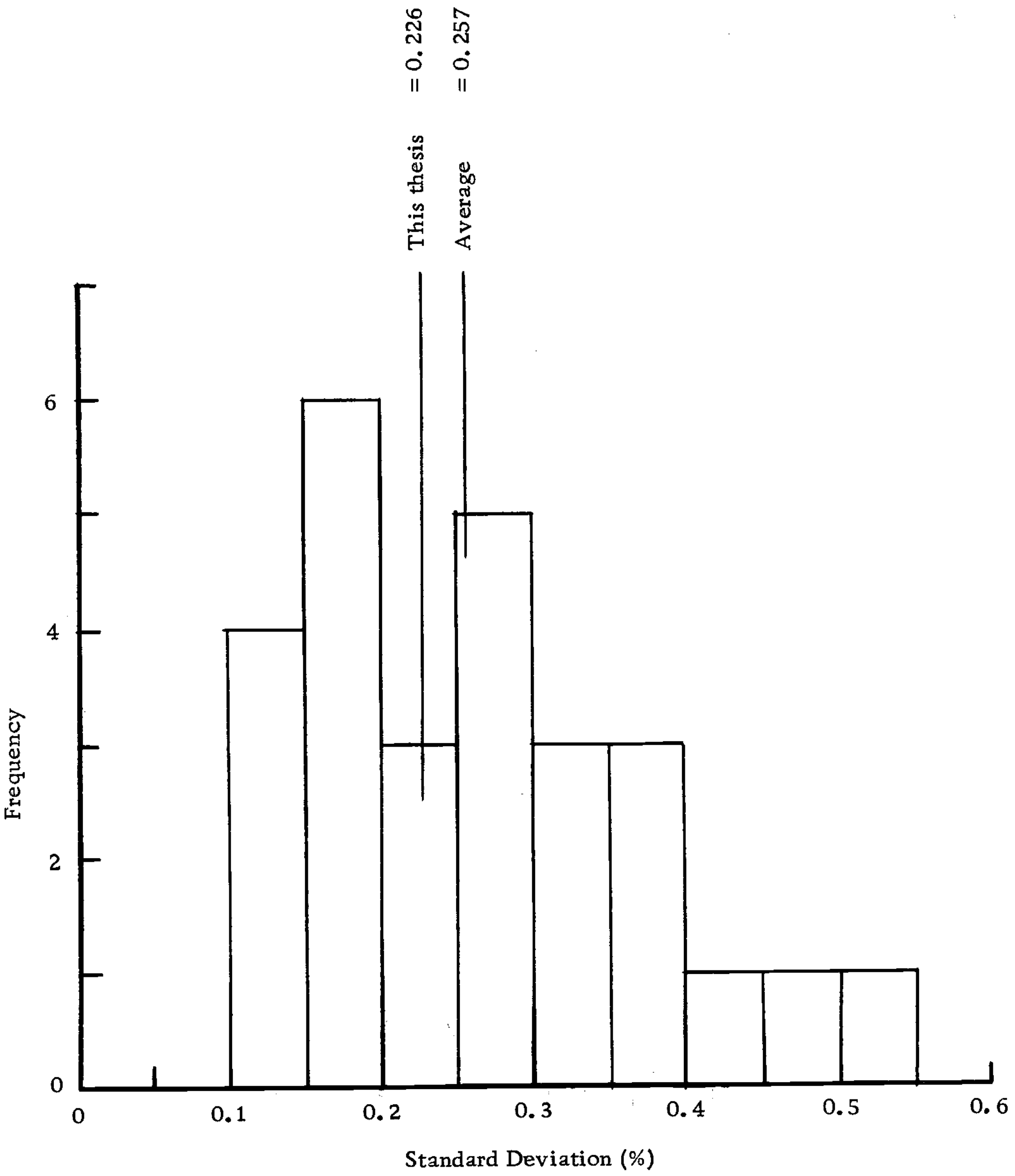


Figure 10. Variation in standard deviation of asphalt content.

standard deviation of less than 0.1%, and 24 out of 27 investigations were between 0.1 and 0.4%. This consistency of results indicates that the average of 0.26% is a reasonable and useful value for comparing the results of variation of asphalt content studies. The standard deviation obtained in this investigation, 0.23%, agrees very well with the average of available data.

Figure 5 compared upper and lower limits for asphalt content based on three sets of assumed data as recommended by Miller-Warden Associates (7, p. 34). As can be seen, the limits become more restrictive as the permissible magnitude of risk becomes less and as the number of samples increases. Case b, Figure 5, gave limits of 5.41 to 5.99% asphalt; very near those actually specified on the project, 5.40 to 6.00% asphalt. Corresponding to these values would be an allowable tolerance between the means of good and poor material, T_a, of ± 0.43. Thus, the existing limits would appear reasonable and based on a mean of 5.7, would indicate the following risks:

1. Probability of accepting material with an average asphalt content of 5.27% = 10%.
2. Probability of accepting material with an average asphalt content of 6.13% = 10%.
3. Probability of rejecting material with an average asphalt content of 5.70% = 1%.

It may appear that the suggested values for the probability of accepting poor material are high. However, P_p is an arbitrary measure that does not contribute to the setting of the limits, but rather provides a measure of $\overline{X}_p$. As P_p gets smaller, the average of the poor material being considered gets further from $\overline{X}_g$ and therefore progressively less desirable.

Assuming the above risks, $P_p = 20\%$ and $P_g = 1\%$, the limits for different numbers of samples could be determined and compared with the OSHD testing results as were shown in Table 5. However, considering the bias indicated by the differences in average asphalt contents, the comparison would not be of any value.

CONCLUSIONS

1. Statistical concepts applied to quality control will provide a more realistic and usable evaluation of highways and highway construction.
2. The application of random sampling is essential to any testing program for quality.
3. Occasionally, individual test results will exceed specification limits. Therefore, the number of tests and the permissible errors must be set in order to employ limits in a rational and meaningful manner.
4. Variance due to sampling and testing contributes appreciably to the total measured variance of the end product.
5. As a general measure of the variation in asphalt content for an automatic, continuous mixing asphalt concrete plant, the standard deviation of 0.13 found on this project for the product variation may be useful. The overall standard deviation (including variance of product, sampling and testing) of 0.23 is nearly the average of a number of studies and is probably typical.
6. Procedures and concepts outlined in this report are by no means exhaustive, but they do provide a workable introduction to the application of statistical quality control.
7. Considerably more research should be done to increase the

application of statistical specifications to highway construction. Further areas for study include:

a. More extensive sampling and testing of characteristics of different types of highway construction.

b. Investigation of variation due to type of plant, and type of construction materials.

c. Investigation to reduce sampling and testing errors.

d. Research to determine the cumulative effect on the end product due to variations in the individual characteristics.

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APPENDICES

APPENDIX A: Sampling Log

Date and Totals	Sample No.	Truck No.	Truck Receipt No.	Segment "A"	Segment "B"	Tons	Time
1 Aug 1968	1	8	044475	5	1	12.15	7:49
	2	28	495	0	7	14.50	8:59
	3	42	044514	6	5	14.80	10:00
Sta 475+00 to	4	60	527	4	3	15.50	10:56
	5	68	535	2	7	15.35	11:20
431+00 Lt.	6	68	535	3	2	15.35	11:20
	7	70	537	1	6	14.75	11:28
	8	75	542	4	0	15.10	11:49
	9	78	545	4	4	13.95	11:59
	10	86	553	5	4	15.05	12:58
Total:	11	96	563	3	2	14.85	1:24
Asph 125.61^{T}	12	105	572	6	4	13.90	1:48
Mix 2173.80^{T}	13	115	582	2	4	13.85	2:25
	14	125	592	7	4	14.65	2:52
	15	133	044600	5	6	14.15	3:15
Last Truck #151	16	* 147	614	6	1	15.50	4:00
2 Aug 1968	17	(4)* 156	622	2	4	12.95	7:35
	18	(8)* 160	626	6	3	15.00	7:48
Sta 431+00 to	19	(20) 171	638	1	2	14.00	8:23
402+00 Lt.	20	(28) 179	646	3	5	14.15	8:47
Total:	21	(31) 182	649	1	6	14.65	9:16
Asph 101.76^{T}	22	(34) 185	652	4	7	14.20	9:25
Mix 1764.85^{T}	23	(45) 196	663	5	2	15.05	10:09
	24	(69) 220	687	2	5	14.25	11:32
	25	(75) 226	044693	3	2	12.95	11:48

*In order to avoid delay at the paver, the anticipated truck was not sampled. The next truck was sampled.

APPENDIX B

Analysis of Variance

Sample No.	Duplicate No.	1	2	Test Diff. $(1 - 2)^2$	Duplicate Diff. $(\Sigma A - \Sigma B)^2$	Duplicate Sum $(\Sigma A + \Sigma B)^2$
1	A	5.84	5.94	0.0100	0.0000	555.0736
	B	6.01	5.77	0.0576		
2	A	5.66	5.72	0.0036	0.0784	530.8416
	B	5.92	5.74	0.0324		
3	A	5.85	5.77	0.0064	0.1296	556.9600
	B	6.01	5.97	0.0016		
4	A	6.07	5.99	0.0064	0.0144	576.0000
	B	5.73	6.21	0.2304		
5	A	5.81	5.70	0.0121	0.4096	559.7956
	B	5.90	6.25	0.1225		
6	A	5.79	5.72	0.0049	0.0016	528.0804
	B	5.77	5.70	0.0049		
7	A	5.26	5.52	0.0676	0.0900	451.9876
	B	5.26	5.22	0.0016		
8	A	5.56	5.86	0.0900	0.0529	532.2249
	B	5.81	5.84	0.0009		
9	A	5.60	5.29	0.0961	0.3969	502.2081
	B	5.70	5.82	0.0144		
10	A	5.50	5.66	0.0256	0.0100	502.6564
	B	5.58	5.68	0.0100		
11	A	5.59	5.68	0.0081	0.3969	637.8489
	B	5.97	5.93	0.0016		
12	A	5.49	5.47	0.0004	1.3689	533.1481
	B	5.89	6.24	0.1225		
13	A	5.38	5.69	0.0961	0.0009	491.5089
	B	5.60	5.50	0.0100		
14	A	5.76	5.58	0.0324	0.0900	528.0804
	B	5.67	5.97	0.0900		
15	A	5.97	5.48	0.2401	0.0001	524.8681
	B	5.69	5.77	0.0064		
16	A	5.50	5.52	0.0004	0.3249	511.2121
	B	5.79	5.80	0.0001		
17	A	5.62	5.77	0.0225	0.0324	527.1616
	B	5.93	5.64	0.0841		
18	A	5.89	6.05	0.0256	0.0121	575.5201
	B	6.02	6.03	0.0001		

Sample No.	Duplicate No.	Test 1	Test 2	Test Diff. $(1-2)^2$	Duplicate Diff. $(\Sigma A-\Sigma B)^2$	Duplicate Sum $(\Sigma A+\Sigma B)^2$
19	A	5.69	5.86	0.0289	0.1444	551.3104
	B	5.86	6.07	0.0441		
20	A	5.69	5.85	0.0256	0.0441	542.4241
	B	6.07	5.68	0.1521		
21	A	5.85	5.93	0.0064	0.0784	541.9584
	B	5.68	5.82	0.0196		
22	A	5.90	5.78	0.0144	0.2704	521.6656
	B	5.59	5.57	0.0004		
23	A	5.77	5.57	0.0400	0.6724	552.2500
	B	5.97	6.19	0.0484		
24	A	6.09	5.94	0.0225	0.0144	573.1236
	B	6.04	5.87	0.0289		
25	A	5.41	5.19	0.0484	0.2401	470.4561
	B	5.62	5.47	0.0225		
Total		575.90				
Sums of Squares				2.0416	4.8738	13,277.3646
		A		B	C	D

$n = 25$

Correction Factor $CF = \frac{A^2}{4n} = 3316.6081$

Degree of Freedom	Sum of Squares		Mean Squares	Variance Component
Samples n - 1 = 24	$\frac{D}{4} - CF = 3316.6081$		$MS_1 =$ 0.11387	$\sigma_p^2 = \frac{MS_1 - MS_2}{4}$ $= 0.016284$
Duplicates n = 25	$\frac{C}{4} =$	1.21845	$MS_2 =$ 0.048738	$\sigma_s^2 = \frac{MS_2 - MS_3}{2}$ $= 0.014161$
Tests 2n = 50	$\frac{B}{2} =$	1.0208	$MS_3 =$ 0.020416	$\sigma_t^2 = MS_3$ $= 0.020416$
Total Variance				$\sigma^2 = 0.050861$
Total Standard Deviation				$\sigma = 0.2255$