Louisiana Highway Research

QUALITY CONTROL ANALYSIS

PART I
ASPHALTIC CONCRETE

Louisiana Department of Highways - Research Unit

ERRATA

QUALITY CONTROL ANALYSIS
PART I - ASPHALTIC CONCRETE

Page 34, Paragraph 6, Line 2
Should read 1767 lbs. or else instead of 1593 lbs. of else.

Page 34, Paragraph 10, Line 3
Should read single test result instead of single test results.

Page 40, Paragraph 1, Line 3
Should read numerical specification limits instead of numerical spceification limits.

Louisiana
DEPARTMENT OF HIGHWAYS
P. O. BOX 4245, CAPITOL STATION
BATON ROUGE, LA. 70804

IN REPLY PLEASE REFER TO
FILE NO.

November 18, 1964

QUALITY CONTROL ANALYSIS
Research Project No. 63-1G
HPR 1(2)

Materials Engineers
American Association of State
Highway Officials

Enclosed is a report entitled, QUALITY CONTROL ANALYSIS PART I - ASPHALTIC CONCRETE.

This report covers the first phase of an investigation undertaken to study the application of statistical quality control techniques for highway construction materials. It involves statistical evaluation of results from several hot mix plants to determine the pattern of variability with respect to bituminous hot mix characteristics.

Any comments or suggestions concerning this report will be invited.

Very truly yours,

L. W. Harrell

L. W. Harrell
Testing & Research Engineer

VA:jk
Enclosure
cc: Mr. J. C. Breaux
Mr. R. E. Bollen, HRB
Mr. C. R. Foster
Mr. C. A. McKeogh
Mr. J. M. Griffith

LOUISIANA DEPARTMENT OF HIGHWAYS

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QUALITY CONTROL ANALYSIS
PART I - ASPHALTIC CONCRETE

by

S. C. SHAH
Research Evaluation Engineer

Research Report No. 15

Research Project No. 63-1G
Louisiana HPR 1(2)

Conducted by
LOUISIANA DEPARTMENT OF HIGHWAYS
Testing and Research Section
in Cooperation with
U. S. Department of Commerce
BUREAU OF PUBLIC ROADS

November 1964

SYNOPSIS

This is the first in a series of reports on the quality control analysis of highway construction materials. Subsequent parts will deal with the analysis of results of the physical characteristics of soils and concrete materials.

This report deals with the statistical evaluation of results from several hot mix plants to determine the pattern of variability with respect to bituminous hot mix characteristics.

Individual test results when subjected to frequency distribution indicated normal (Gaussian) distribution. Further analysis showed the overall variability of each characteristic for binder course mixes to be less than that for wearing course mixes. Also, the natural tolerances for bitumen content and aggregate gradation were outside the engineering (job mix) tolerances indicating a need for either a much closer control in plant operation and materials uniformity or a revision in engineering tolerances.

For bitumen content, a standard deviation of 0.2% would be normal and for 100% conformance a tolerance of 0.6% should be specified if 3σ is considered realistic specification limit. However, an allowable tolerance of 0.5% would cast off only 1% of the results. For aggregate gradation, if the inevitable variations due to crushing and screening operation, changes in stockpile and bin proportions, and sampling and testing are taken into consideration, then the limits for the job mix tolerance should be:

± 9% for No. 4 and larger sieves
± 7% for No. 10 sieve
± 6% for No. 40 sieve
± 5% for No. 80 sieve
± 3% for No. 200 sieve

The variability in the case of Marshall stability was considerably different for each plant. Furthermore, lack of uniformity was indicated as evidenced by considerable between-days variation.

If acceptance tolerances are to be written in the specifications, then the number of samples to be tested for a particular characteristic should be specified. For Marshall stability, eight random samples obtained from trucks representing a day's operation should be tested. Furthermore, if the minimum specifications are to be met 100 per cent of the time, then it is essential that the process average be maintained at 3σ above the minimum requirement, or $3(190) = 570$ lbs. above the absolute minimum specified for the type of mix.

QUALITY CONTROL ANALYSIS

PART I - ASPHALTIC CONCRETE

INTRODUCTION

Variability is inherent in all manufactured products, be it nuts, bolts, glass tubes or asphalt aggregate mixes. In the case of bituminous hot mix itself, any or all of the following sources can produce variations in the final product.

1. Type of aggregate
2. Proportion of aggregate
3. Proportion of asphalt
4. Temperature of aggregate
5. Temperature of asphalt
6. Mixing temperature
7. Other intangible sources

Variations are further introduced when the mixture is sampled and tested for a particular characteristic (mechanical analysis, strength etc.).

The above sources of variations, translated in statistical language can be broken down into two classes: (1) systematic, which is generally identifiable and attributed to differences in cause system, and (2) random, which is due to a large number of small independent causes within a system of causes and is not identifiable. For instance, the quality of output of the morning shift may differ from that of the evening shift and the quality of output of plant A may differ from that of plant B even under identical operating conditions. But, though we may account for the variability between shifts and between plants, there still remains a variability of a random nature within shifts and within plants. Thus, when all non-random types of variations have been eliminated or taken into consideration quantitatively and the probability distribution of the random variation has been discovered, the process is said to be in control. Such a state of control is desired for several reasons: (1) determine whether the quality of the product is satisfactory for the intended use; (2) provide a sound basis of making specifications. There is no point in making the specifications so tight that they can not be economically enforced. On the other hand, if it appears that the natural tolerances are far inside the upper and/or lower specification limits, then these limits should usually be changed.

This report is concerned with the application of statistical quality control technique to writing specifications for bituminous hot mix. Application of such technique in the industry has proven quite satisfactory as a means of acceptance and/or rejection of the manufactured products and also as a criteria for hunting for source of trouble. It has also been applied by some on laboratory and plant mixed bituminous hot mix samples (1, 2, 3, 4)*. On AASHO Road Test, they were applied in several phases of construction material control. The method has many important applications including writing of specifications more realistically and providing for sounder relation between engineering and production.

PURPOSE OF STUDY

The main purpose of this study was to provide information relative to difference between currently used bituminous hot mix specifications and what may realistically be expected on a well controlled production, operation or test; in other words, to check the validity of current bituminous hot mix specifications concerning certain variables and furthermore, if deemed necessary, recommend necessary revisions of these specifications on the basis of statistical findings from this study.

SCOPE OF STUDY

The study was initiated in 1963 by the Louisiana Department of Highways in cooperation with the Bureau of Public Roads. Since the physical characteristics involved in the production, sampling and testing of bituminous hot mix are numerous, it was decided to consider only those which have been a consistent problem to the Department as well as the producer in meeting the current specification requirements. Therefore, after careful consideration, it was decided to subject the following physical characteristics to statistical analysis for variability measurements.

1. Bitumen content using:
    a. Centrifuge extractor
    b. Reflux extractor

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* Numbers in parenthesis refer to list of references at the end of this report.

2. Mechanical analysis of extracted aggregate
3. Marshall stability
4. Per cent voids

PROCEDURE

Collection of Data

Two approaches were available in obtaining data necessary for development of statistical parameters for various characteristics. One called for testing samples obtained using a specially designed sampling plan that would have ensured sufficient randomness in sample selection whereas the other called for the use of data obtained from currently used sampling techniques used in the field, the former so designed as to enable the partitioning of different components of variance due to sampling, testing, and materials through Analysis of Variance technique. However, after considering various factors such as time, personnel, etc. implicated in implementation of such a procedure, it was decided to resort to the latter approach of collecting data from current projects under construction or recently constructed from the following sources:

1. Daily inspection plant reports
2. Laboratory reports

In adopting such an approach it is assumed that -

1. The current sampling and testing techniques are sound.
2. The construction methods are adequate.
3. The data are representative and free of any bias.

A limitation to the last one is that the samples may not be truly randomly selected ones since they were not obtained by use of randomizing methods such as random number tables. It is almost implicit in any statistical analysis that the data are unbiased and a random selection of samples is usually necessary to insure this lack of bias. The data collected for this study were those reported by plant inspectors in their daily report. However, since the daily samples were obtained at irregular intervals using current sampling methods it is felt that such intervals contribute a certain degree of randomness in sample selection. Samples obtained at exactly the same time interval each day would have, however, made this selection bias.

Selection of Projects

Major portion of the time was spent on selection of projects. After carefully screening several of these located in different parts of the State to ensure that data were representative of close job control, twelve were finally selected for this study. These projects were identified according to the plants producing the hot mix. These plants were essentially the same type (automatic batch type) and capable of producing on the average of 100 to 120 tons of mix per hour. A day's run is generally represented by four density and strength measurements and two bitumen content and gradation determinations.

Sampling and Testing Methods

Unless otherwise mentioned, the sampling methods are according to LDH Designation S 202 - Standard Method of Sampling Bituminous Mixtures. The test methods are according to -

1. LDH Designation: TR 308 - 62 - Method of Test for Bitumen Content of Paving Mixtures by Centrifuge.
2. AASHO Designation: T 184 - Method of Test for Bitumen Content of Paving Mixtures by Reflux Extractor (excluding sections 5i, 5j, 5k, and 5l).
3. LDH Designation: TR 309 - 62 - Method of Test for Mechanical Analysis of Extracted Aggregate.
4. LDH Designation: TR 305 - 62 - Method of Test for Stability and Flow of Asphaltic Concrete Mixtures - Marshall Method.

The currently used specifications by the Department for job conformance are indicated in Tables I and II.

The entire study is confined to hot mix - hot laid sand - gravel mixtures.

ANALYSIS OF DATA

Frequency Distribution

One of the most commonly used methods of describing pictorially variations of individual observations from within a sample is by means of frequency distribution. In examining data of such type (or any other type) it will be found that the individual observations group themselves about the central value so that there are roughly equal numbers on either side of this central value and small divergencies from this central value occur more frequently than large ones. When this happens, the resulting curve assumes what is termed a Gaussian or Normal distribution which has a symmetrical bell shape. This is

TABLE I

ALLOWABLE TOLERANCES FOR JOB MIX

U. S. Sieve	Tolerances - % Passing
No. 4 and larger	± 7.0
No. 10	± 5.0
No. 40	± 5.0
No. 80	± 4.0
No. 200	± 2.0
Bitumen Content, %	± 0.3

TABLE II

REQUIREMENT FOR PHYSICAL PROPERTIES OF THE COMPACTED MIXTURE

Grade of Asphalt	60-70 pen.	80-100 pen.
	Binder and Wearing	Binder and Wearing
Marshall Stability @ 140°F, lb.	1200 min.	1000 min.
Flow, 1/100 Inch	15 max.	15 max.

These requirements are intended to be the average of all the samples tested for any three consecutive days' operation for the project.

The design of the mix is based on a standard deviation of plus 400 pounds; however, the average for any individual day cannot be less than 200 pounds below the minimum specified above.

TABLE III

TYPICAL FREQUENCY DISTRIBUTION DATA
(PLANT 8 - PER CENT PASSING NO. 200 SIEVE)

Class Interval - 0.6

x	f	fx	x^2	$f(x)^2$	Σf	Σf, %
-6	2	-12	36	72	2	2.5
-5	2	-10	25	50	4	5.0
-4	1	- 4	16	16	5	6.3
-3	5	-15	9	45	10	12.5
-2	12	-24	4	48	22	27.5
-1	15	-15	1	15	37	46.3
0	18	0	0	0	55	68.8
1	13	13	1	13	68	85.0
2	7	14	4	28	75	93.8
3	2	6	9	18	77	96.3
4	2	8	16	32	79	98.8
5	1	5	25	25	80	100.0

one of the most important distributions in statistics and forms the basis for subsequent analysis of the present data. Its use is the same as that of any other distribution curve: the relative frequency with which a variable will take on values between two points is the area under the curve between the two points on the horizontal axis.

Table III shows typical frequency distribution data for per cent passing No. 200 sieve for plant 8. Graphical representation of such distributions for other aggregate fractions and bitumen content is shown in Figures 1 through 4. In spite of the limited number of observations, the curves do suggest a normal distribution as indicated by the bell shape. Departure from this tendency (No. 4 and No. 40 sieves) can be attributed to sampling and testing errors. The lower half of these figures which is a cumulative frequency distribution curve on normal probability paper gives empirical evidence of the normality assumption and further indicates that the data may be considered amenable to further treatment by established statistical procedures for writing realistic specifications.

Some of the important characteristics of such normal probability curves can be used to represent the accumulated data on different characteristics. If the horizontal axis of this curve is represented by the normal deviate (which is the number of standard deviations of the measurements above or below the mean value), then the area under the normal curve between any two values of the normal deviate (Z_1 and Z_2) gives the probability that an observation from the population will have a value between Z_1 and Z_2. The probability of an item falling inside and also outside the range of mean ± Z (normal deviate) is tabulated below. These values are some of those frequently referred to.

Normal Deviate (Z)	Probability of Falling	
	Inside the range	Outside the range
.5	.5	.5
1.	.6827	.3173
1.96	.95	.05
2.00	.9545	.0455
2.575	.99	.01
3.	.9973	.0027

Choice of Estimators of Parameters

Since it is impossible to obtain a true mean and standard deviation of the population, it is necessary to make good estimates of these parameters. That

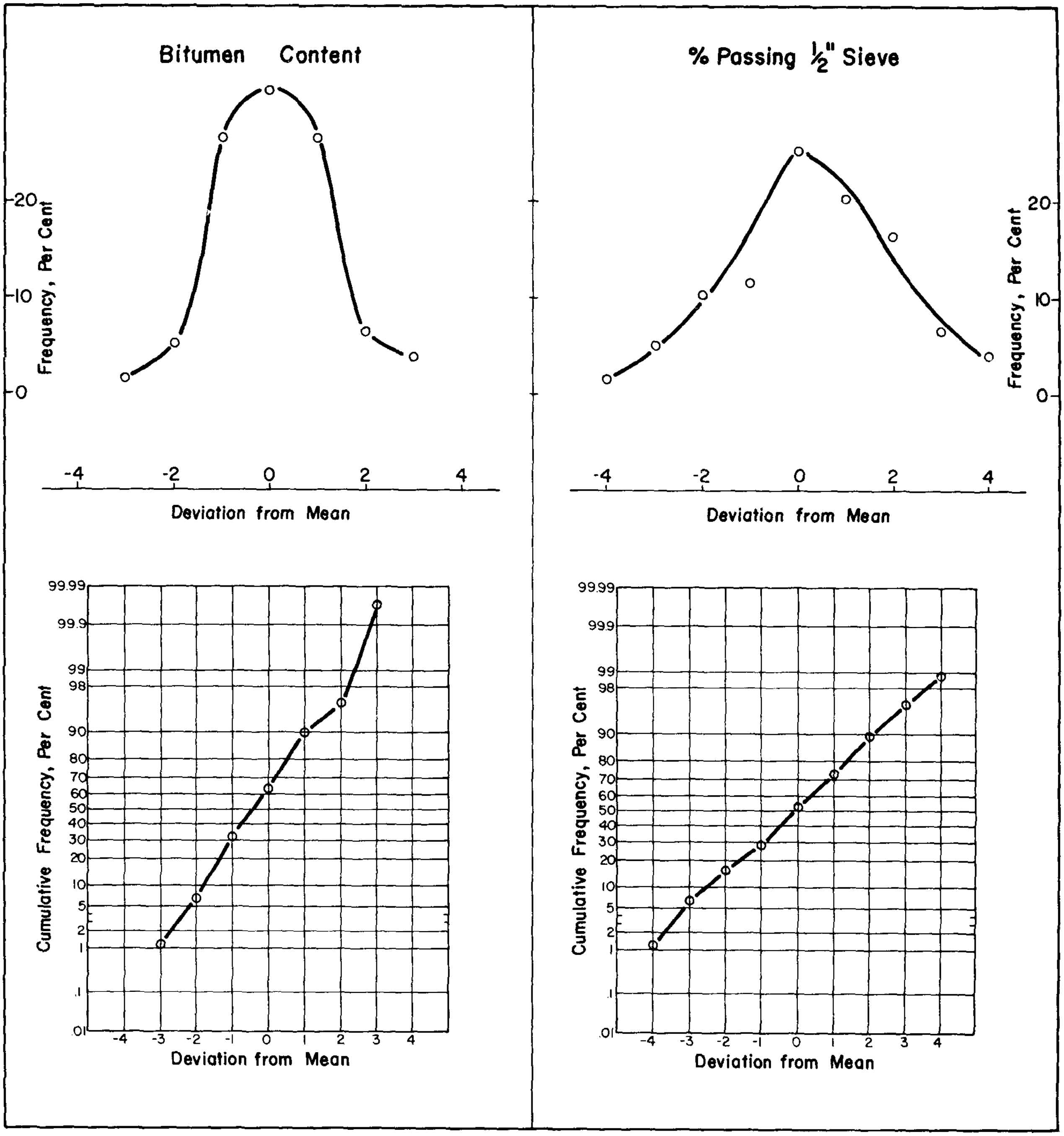

Figure 1 - Frequency Distributions for Bitumen Content and 1/2" Size Aggregate Deviations (Wearing Course Data from Plant 8)

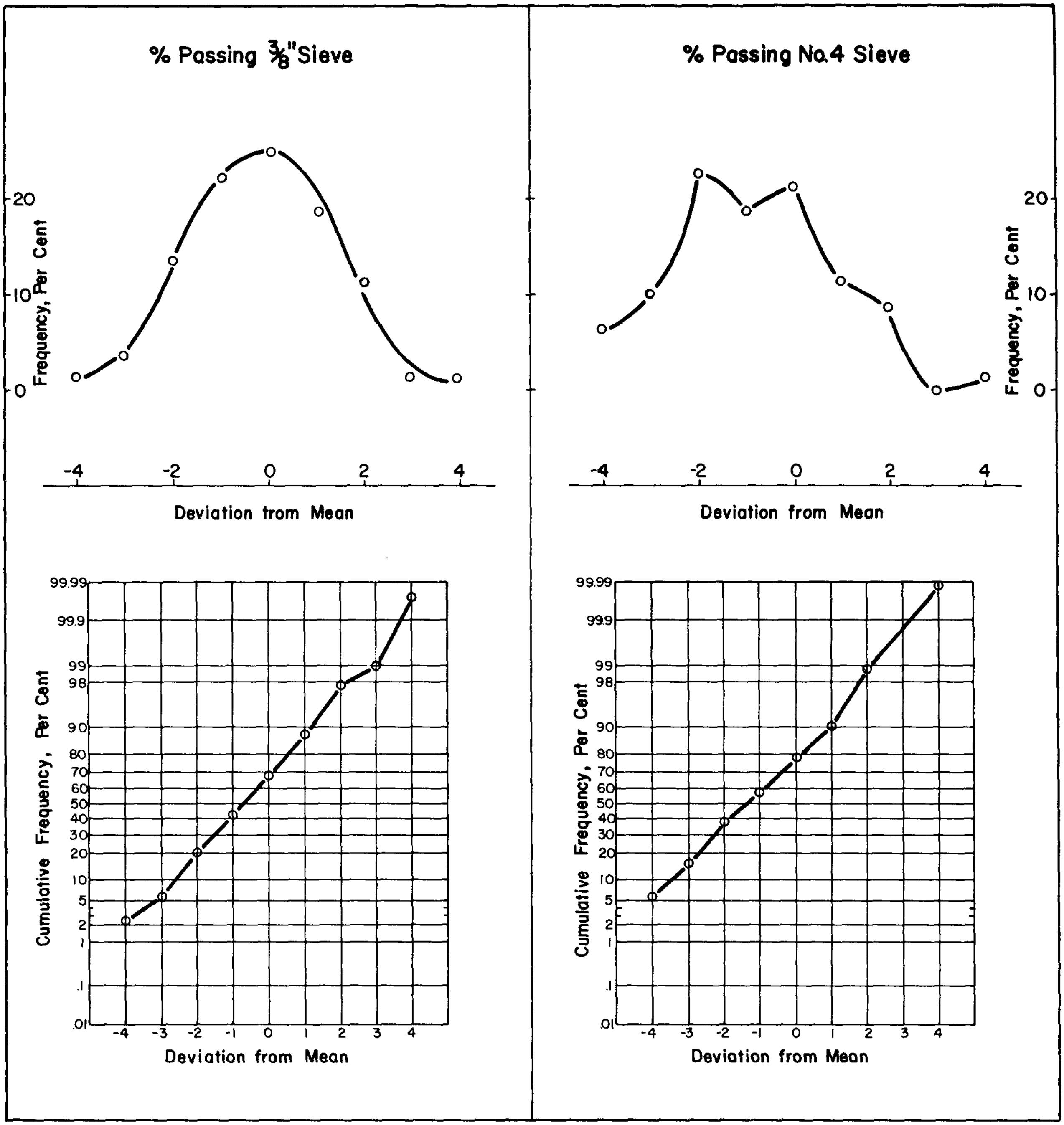

Figure 2 - Frequency Distributions for 3/8" Size and No. 4 Size Aggregate Deviations (Wearing Course Data from Plant 8)

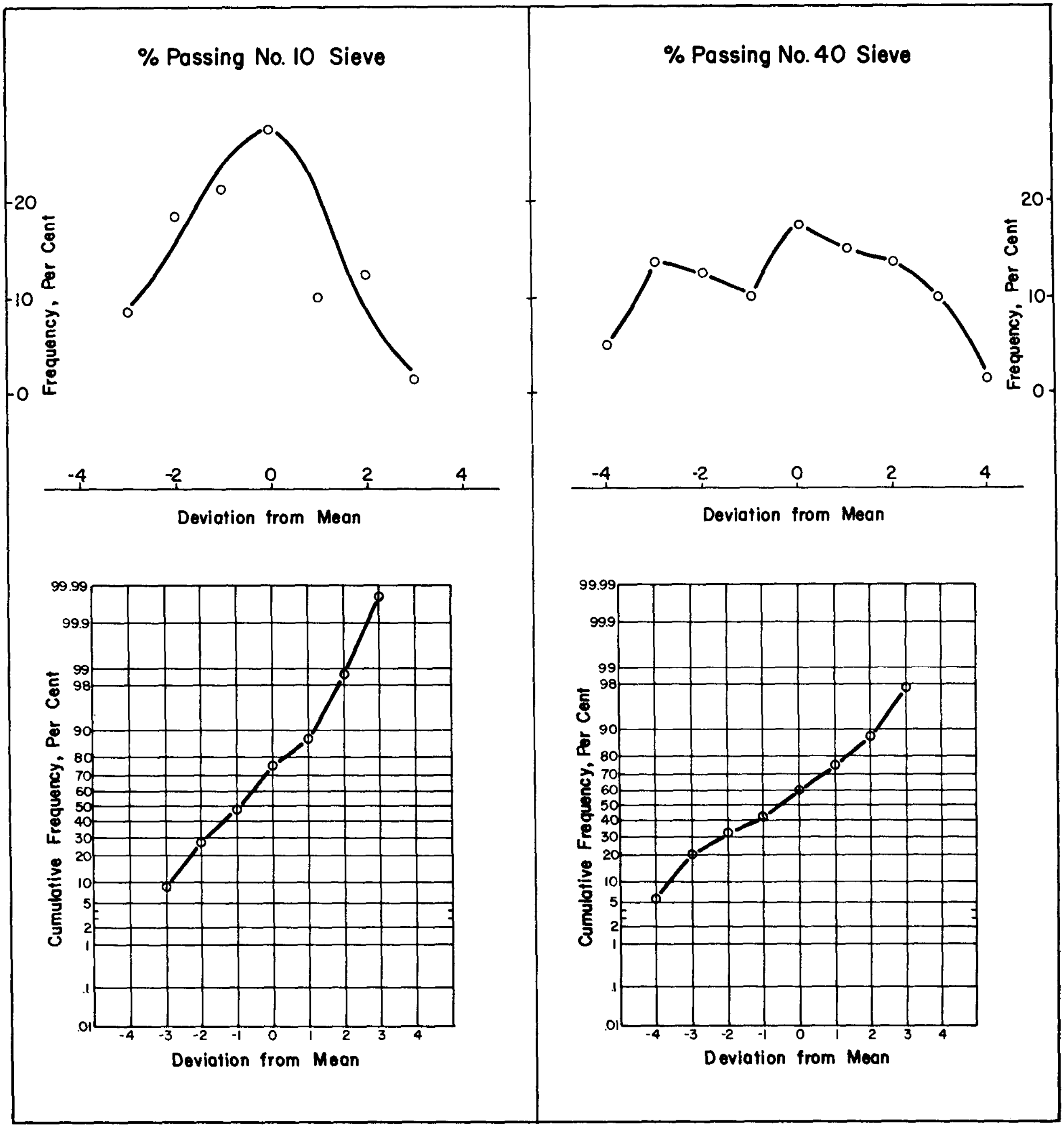

Figure 3 - Frequency Distributions for No. 10 and No. 40 Size Aggregate Deviations (Wearing Course Data from Plant 8)

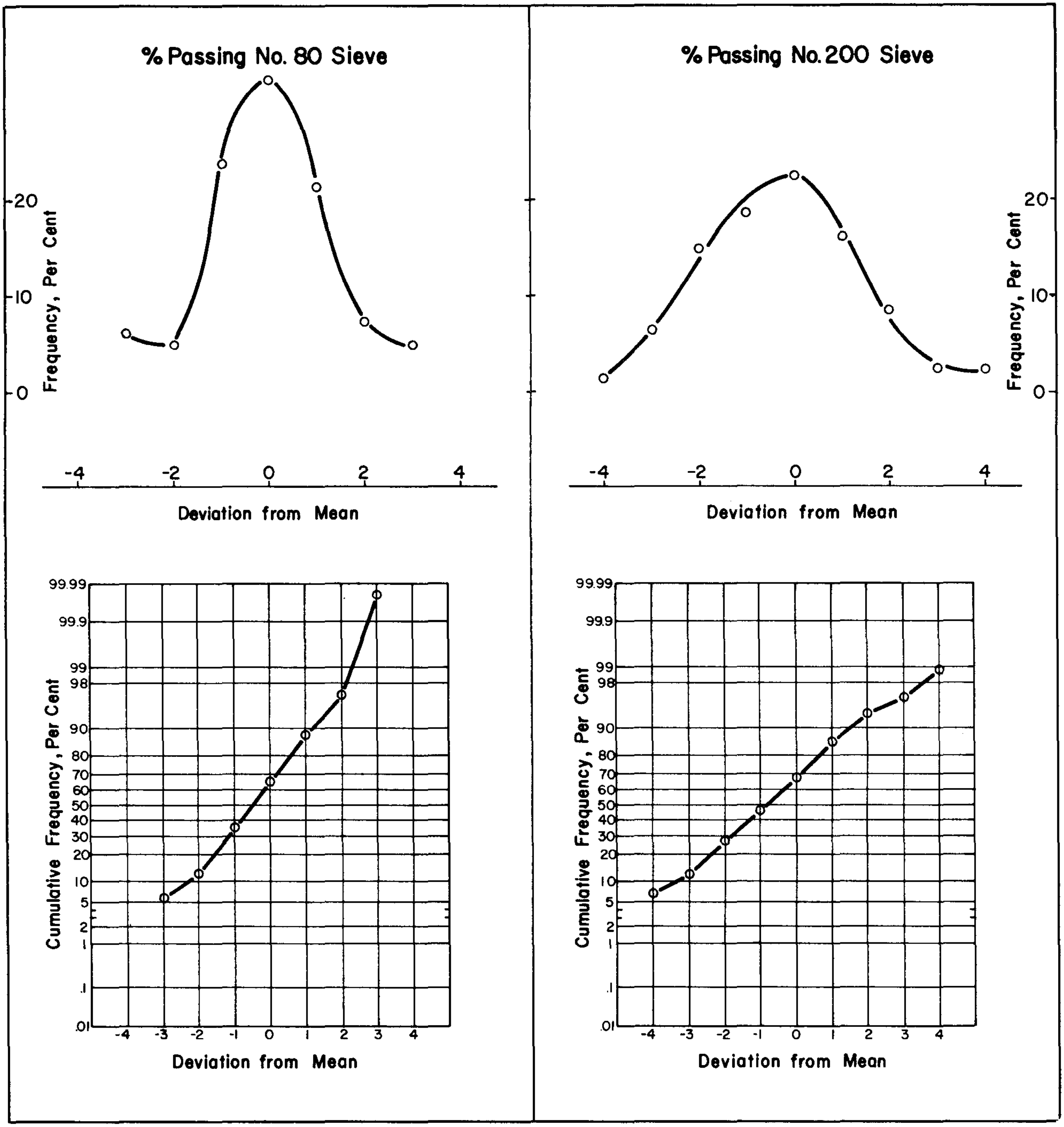

Figure 4 - Frequency Distributions for No. 80 and No. 200 Size Aggregate Deviations (Wearing Course Data from Plant 8)

specification limits be closely related to the actual behavior of the process is one of the many reasons for these parameters to be unbiased and efficient.

Measure of Central Tendency

In the present case it will be assumed the arithmetic mean $\bar{X}$ of the sample is both an unbiased and efficient estimator of the population mean.

Measure of Variability

In quality control work, it is common practice to compute the range R from a number of small samples, obtain the mean $\bar{R}$ of these values and compute standard deviation which is assumed to be an unbiased estimate of the true population standard deviation. Also, sample standard deviation when obtained by dividing the sum of squared deivations by the number of degrees of freedom N-1 can be assumed to be an unbiased estimate of population standard deviation.

The Control Chart as a Means of Writing Specifications

The basis of all control charts is that any varying quantity forms a distribution if chance or random causes alone are at work and that any such distribution has a mean and a standard deviation.(5) Also, very few points will fall outside the limits of ± 3 standard deviation due to random causes alone. The computed band or limits depict the normal pattern of variability of the statistical measure in question.

Tables IV through XI show summary of statistical results of bitumen content and aggregate gradation by Centrifuge method. The tables subscripted with letter "a" in the lower half of the page represent summary of results by Reflux method. The limits referred to as individual and average limits indicate the control limits within which all observations or the average of each subgroup respectively should fall if random causes alone were at work. Any point outside these limits indicates lack of process control and presence of some assignable cause which could be contributing to this lack of control. Figures 5 and 6 show graphical representation of the control limits for individuals for bitumen content and aggregate gradation for plant 1. Parenthesised numbers in the tables represent values computed after elimination of observations falling outside the individual control limits.

TABLE IV

SUMMARY OF STATISTICAL RESULTS FOR BITUMEN CONTENT (Centrifuge)

Plant	Sub Group	Standard Deviation Based on $\bar{R}$	Standard Deviation Based on All Samples	Limits X	Limits $\bar{X}$	Max. Differences Within Day	Max. Differences Between Days	Max. Differences Between X_1, X_2	Per Cent Bitumen Design	Per Cent Bitumen $\bar{\bar{X}}$
WEARING COURSE MIX										
1	36 (34)	0.10 (0.10)	0.16 (0.12)	±0.30 (±0.30)	±0.21 (±0.21)	0.36 (0.36)	0.81 (0.37)	0.86 (0.53)	5.30	5.38 (5.35)
2	22	0.22	0.26	±0.66	±0.47	0.80	0.89	0.97	5.60	5.86
3	48 (47)	0.23 (0.21)	0.26 (0.25)	±0.69 (±0.63)	±0.48 (±0.46)	0.92 (0.81)	1.03 (1.03)	1.19 (1.13)	5.30	5.40 (5.40)
4	27	0.36	0.33	±1.08	±0.77	0.91	0.75	1.61	5.30	5.57
5	34	0.16	0.18	±0.48	±0.34	0.66	0.65	0.84	5.30	5.33
6	28	0.22	0.30	±0.66	±0.47	0.71	1.06	1.15	5.50	5.34
7	18	0.21	0.30	±0.63	±0.46	0.58	0.91	1.13	5.00	5.02
8	40 (34)	0.28 (0.27)	0.38 (0.31)	±0.84 (±0.81)	±0.59 (±0.57)	0.73 (0.73)	1.01 (0.92)	1.71 (1.31)	5.10	5.08 (5.14)
BINDER COURSE MIX										
1	22	0.11	0.12	±0.33	±0.24	0.35	0.29	0.50	4.20	4.16
2	24 (21)	0.17 (0.15)	0.30 (0.24)	±0.51 (±0.45)	±0.36 (±0.32)	0.52 (0.36)	1.00 (0.72)	1.21 (1.01)	4.20	4.28 (4.22)
3	15	0.24	0.19	±0.72	±0.51	0.51	0.29	0.64	4.20	4.34
4	19	0.34	0.35	±1.02	±0.72	0.78	1.03	1.48	4.30	4.57

NOTE: Parenthesised numbers above and in subsequent tables represent values computed after elimination of observations falling outside the control limits.

TABLE IV (a)

SUMMARY OF STATISTICAL RESULTS FOR BITUMEN CONTENT (Reflux)

WEARING COURSE MIX

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	Per Cent Bitumen Design	Per Cent Bitumen $\bar{\bar{X}}$
1	36	.26	1.20	5.30	5.19
2	20	.27	1.10	5.60	5.74
3	48	.31	1.40	5.30	5.23
4	26	.35	1.50	5.30	5.69
5	32	.13	0.50	5.30	5.32
6	26	.26	1.10	5.50	5.06
8	78	.45	1.55	5.10	5.21

BINDER COURSE MIX

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	Per Cent Bitumen Design	Per Cent Bitumen $\bar{\bar{X}}$
1	22	.30	1.40	4.20	4.20
3	14	.22	.80	4.20	4.15
4	18	.18	.80	4.30	4.22

TABLE V

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION
PER CENT PASSING 3/4 & 1/2 INCH SIEVES (Centrifuge)

Plant	Sub Group	Standard Deviation Based on		Limits		Max. Differences			% Passing 3/4" Sieve	
		$\bar{R}$	All Samples	X	$\bar{X}$	Within Day	Between Days	Between X_1, X_2	Design	$\bar{\bar{X}}$
BINDER COURSE MIX										
1	22	3.67	3.73	±11.01	±7.78	12.50	9.75	18.60	94.60	90.04
2	24	1.70	2.10	± 5.10	±3.60	7.00	6.15	8.40	97.20	96.48
3	15	1.50	1.81	± 4.50	±3.18	4.10	4.40	7.10		93.29
4	19	2.12	3.13	± 6.36	±4.49	6.20	7.75	10.10	96.80	95.52
BINDER COURSE MIX									% Passing 1/2" Sieve	
1	22	5.15	5.07	±15.45	±10.92	17.80	15.60	23.80	64.70	69.10
2	24	4.02	3.80	±12.06	± 8.52	10.30	11.50	16.20	78.50	75.92
3	15	3.18	3.93	± 9.54	± 6.74	8.30	12.90	16.30	75.20	70.72
4	19	2.24	2.88	± 6.72	± 4.75	7.80	6.60	11.80	82.60	81.84

TABLE V (a)

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION

PER CENT PASSING 3/4 AND 1/2 INCH SIEVES (Reflux)

BINDER COURSE MIX

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	% Passing 3/4" Sieve	
				Design	$\bar{\bar{X}}$
1	22	5.20	21.00	94.60	89.63
3	14	2.97	10.00		93.29
4	18	2.87	12.00	96.80	95.83
				% Passing 1/2" Sieve	
1	22	6.30	18.00	64.70	71.28
3	14	2.74	12.00	75.20	70.64
4	18	3.71	13.00	82.60	80.44

TABLE VI

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION PER CENT PASSING 3/8 INCH SIEVE (Centrifuge)

Plant	Sub Group	Standard Deviation Based on		Limits		Max. Differences			% Passing 3/8" Sieve	
		$\bar{R}$	All Samples	X	$\bar{X}$	Within Day	Between Days	Between X_1, X_2	Design	$\bar{\bar{X}}$
WEARING COURSE MIX										
1	36	1.66	1.99	±4.98	±3.53	6.10	5.75	7.50	95.50	94.70
2	22 (21)	1.42 (1.32)	1.95 (1.85)	±4.26 (±3.96)	±3.01 (±2.80)	3.90 (3.20)	5.90 (5.90)	8.20 (7.30)	96.80	94.62 (94.76)
3	48 (47)	2.05 (1.97)	2.62 (2.54)	±6.15 (±5.91)	±4.36 (±4.18)	7.60 (5.50)	10.35 (10.35)	12.60 (12.10)	90.00	92.20 (92.32)
4	27 (26)	1.95 (1.75)	3.00 (2.70)	±5.85 (±5.67)	±4.14 (±3.71)	6.00 (6.00)	8.50 (6.65)	12.60 (9.70)	89.10	94.43 (94.81)
5	34 (29)	1.59 (1.29)	3.52 (1.82)	±4.77 (±3.87)	±3.38 (±2.73)	9.90 (5.40)	13.50 (6.55)	19.70 (7.30)	92.30	94.72 (95.91)
6	28 (26)	1.27 (1.09)	2.29 (1.63)	±3.81 (±3.27)	±2.71 (±2.31)	4.00 (3.10)	5.50 (5.25)	8.80 (7.00)	95.90	95.05 (95.05)
7	18	2.07	2.61	±6.21	±4.40	7.00	7.50	14.00	91.00	94.02
8	40 (39)	2.92 (2.75)	3.12 (2.95)	±8.76 (±8.25)	±6.20 (±5.83)	11.00 (9.60)	10.00 (8.30)	18.30 (14.70)	88.00	86.42 (86.55)

TABLE VI (a)

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION

PER CENT PASSING 3/8 INCH SIEVE (Reflux)

WEARING COURSE MIX

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	% Passing 3/8" Sieve	
				Design	$\bar{\bar{X}}$
1	36	1.54	7.00	95.50	94.58
2	20	2.36	11.00	96.80	93.90
3	48	2.74	10.00	90.00	93.15
4	26	2.44	11.00	89.10	95.77
5	32	3.39	14.00	92.30	95.06
6	26	1.67	7.00	95.90	94.08
8	78	3.38	10.50	88.00	87.23

TABLE VII

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION
PER CENT PASSING NO. 4 SIEVE (Centrifuge)

		Standard Deviation Based on		Limits		Max. Differences			% Passing # 4 Sieve	
Plant	Sub Group	$\bar{R}$	All Samples	X	$\bar{X}$	Within Day	Between Days	Between X_1, X_2	Design	$\bar{\bar{X}}$
WEARING COURSE MIX										
1	36	2.81	2.66	±8.43	±5.96	10.00	7.25	14.50	66.30	66.16
2	22	1.87	2.40	±5.61	±3.96	4.60	6.90	10.20	65.40	65.87
3	48 (46)	3.14 (3.09)	3.90 (3.55)	±9.42 (±9.27)	±6.66 (±6.55)	10.80 (10.80)	13.25 (12.65)	21.10 (18.70)	67.00	68.27 (68.31)
4	27	2.60	3.90	±7.80	±5.51	7.90	13.15	14.60	62.80	68.36
5	34 (31)	3.26 (2.67)	4.70 (3.92)	±9.78 (±8.01)	±6.91 (±5.66)	14.29 (9.00)	16.10 (11.45)	24.00 (16.80)	68.90	69.39 (69.84)
6	28 (24)	3.19 (2.97)	3.80 (3.30)	±9.57 (±8.91)	±6.76 (±6.30)	8.28 (8.00)	11.50 (10.95)	16.60 (16.10)	66.60	67.03 (70.79)
7	18 (16)	2.61 (2.66)	3.50 (2.76)	±7.83 (±7.98)	±5.53 (±5.64)	9.28 (8.20)	13.50 (8.20)	19.30 (11.80)	62.90	70.85 (67.86)
8	40 (39)	3.25 (3.02)	3.50 (3.30)	±9.75 (±9.06)	±6.89 (±6.40)	13.80 (9.80)	10.15 (10.15)	14.60 (12.80)	67.00	65.27 (65.19)
BINDER COURSE MIX										
1	22	3.65	2.95	±10.95	±7.74	11.90	6.60	12.20	43.20	41.57
2	24 (22)	2.60 (2.27)	3.32 (2.60)	±7.80 (±6.81)	±5.51 (±4.81)	7.30 (7.30)	13.60 (7.35)	15.80 (10.50)	43.70	41.25 (41.23)
3	15	2.25	2.50	±6.75	±4.77	5.70	5.65	10.20	42.00	44.05
4	19	2.57	2.80	±7.71	±5.45	5.80	8.45	11.20	51.90	52.02

TABLE VII (a)

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION

PER CENT PASSING NUMBER 4 SIEVE (Reflux)

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	% Passing # 4 Sieve	
				Design	$\bar{\bar{X}}$
WEARING COURSE MIX					
1	36	2.30	10.00	66.30	68.17
2	20	3.08	12.00	65.40	66.00
3	48	3.32	14.00	67.00	68.38
4	26	3.67	15.00	62.80	71.39
5	32	3.65	14.00	68.90	70.53
6	26	2.18	8.00	66.60	71.46
8	78	3.69	10.50	67.00	66.69
BINDER COURSE MIX					
1	22	2.86	9.00	43.20	43.00
3	14	2.88	11.00	42.00	45.14
4	18	2.86	9.00	51.90	51.06

TABLE VIII

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION PER CENT PASSING NO. 10 SIEVE (Centrifuge)

Plant	Sub Group	Standard Deviation Based on		Limits		Max. Differences Within	Between	Between	% Passing # 10 Sieve	
		$\bar{R}$	All Samples	X	$\bar{X}$	Day	Days	X_1, X_2	Design	$\bar{\bar{X}}$
WEARING COURSE MIX										
1	36	2.24	2.51	± 6.72	±4.75	6.20	6.10	11.20	50.00	50.48
2	22 (21)	1.72 (1.65)	2.45 (2.28)	± 5.16 (± 4.95)	±3.65 (±3.50)	5.60 (5.60)	8.15 (7.25)	11.10 (8.80)	49.60	48.67 (48.46)
3	48 (43)	2.43 (2.19)	3.38 (2.84)	± 7.29 (± 6.57)	±5.15 (±4.64)	10.70 (7.80)	12.70 (10.75)	17.00 (13.00)	55.00	54.54 (55.00)
4	27 (26)	2.11 (2.17)	2.90 (2.60)	± 6.33 (± 6.51)	±4.47 (±4.60)	7.50 (7.50)	11.50 (9.05)	12.60 (10.90)	49.80	52.74 (52.47)
5	34	2.65	3.43	± 7.95	±5.62	10.90	10.20	15.20	55.60	54.19
6	28	2.89	4.00	± 8.67	±6.13	9.00	12.90	16.50	53.20	53.62
7	18 (17)	3.17 (3.25)	4.17 (3.60)	± 9.51 (± 9.75)	±6.72 (±6.89)	10.80 (10.80)	12.05 (12.05)	16.60 (14.50)	51.90	52.91 (53.47)
8	40	2.79	3.00	± 8.37	±5.91	10.90	10.90	12.20	56.00	55.01
BINDER COURSE MIX										
1	22	3.34	2.80	±10.02	±7.08	6.50	7.30	12.40	37.40	35.73
2	24 (23)	2.03 (2.01)	2.70 (2.50)	±6.09 (±6.03)	±4.30 (±4.26)	6.60 (6.60)	7.85 (6.85)	12.20 (10.50)	36.80	32.89 (32.69)
3	15	2.34	2.32	±7.02	±4.96	5.50	5.85	10.10	37.00	38.80
4	19	2.19	2.60	±6.57	±4.64	6.00	8.10	8.90	44.90	43.26

TABLE VIII (a)

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION

PER CENT PASSING NUMBER 10 SIEVE (Reflux)

WEARING COURSE MIX

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	% Passing # 10 Sieve Design	$\bar{\bar{X}}$
1	36	2.79	10.00	50.00	51.25
2	20	2.50	10.00	49.60	46.65
3	48	3.46	15.00	55.00	54.00
4	26	2.75	13.00	49.80	54.73
5	32	2.45	10.00	55.60	54.53
6	26	3.25	11.00	53.20	54.15
8	78	3.45	10.50	56.00	56.05

BINDER COURSE MIX

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	% Passing # 10 Sieve Design	$\bar{\bar{X}}$
1	22	2.59	9.00	37.40	36.86
3	14	2.65	11.00	37.00	39.21
4	18	2.76	9.00	44.90	42.78

TABLE IX

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION
PER CENT PASSING NO. 40 SIEVE (Centrifuge)

		Standard Deviation Based on		Limits		Max. Differences			% Passing # 40 Sieve	
Plant	Sub Group	$\bar{R}$	All Samples	X	$\bar{X}$	Within Day	Between Days	Between $X_1 . X_2$	Design	$\bar{\bar{X}}$
WEARING COURSE MIX										
1	36 (34)	2.07 (1.96)	2.63 (2.25)	±6.21 (±5.88)	±4.39 (±4.77)	7.00 (5.60)	10.85 (6.55)	12.80 (9.80)	32.80	31.49 (31.17)
2	22	1.48	2.00	±4.44	±3.14	4.30	5.05	8.40	30.50	30.05
3	48	2.19	2.35	±6.57	±4.64	6.90	8.00	9.90	36.00	33.93
4	27 (26)	1.60 (1.61)	2.10 (1.85)	±4.80 (±4.83)	±3.39 (±3.41)	5.90 (5.90)	7.30 (4.95)	9.50 (8.30)	27.30	29.16 (28.96)
5	34 (32)	2.19 (2.04)	3.58 (2.62)	±6.57 (±6.12)	±4.64 (±4.33)	6.70 (6.70)	11.60 (9.75)	15.50 (10.90)	34.40	28.28 (28.28)
6	28	2.67	3.22	±8.01	±5.66	6.80	10.45	14.50	33.50	35.06
7	18 (17)	2.05 (2.09)	2.72 (2.22)	±6.15 (±6.27)	±4.35 (±4.43)	6.00 (6.00)	9.45 (5.85)	12.40 (9.60)	31.60	30.36 (30.77)
8	40	1.87	2.13	±5.61	±3.96	6.60	5.80	8.20	35.00	34.15
BINDER COURSE MIX										
1	22	2.72	2.50	±8.16	±5.77	7.10	5.75	10.50	25.50	24.95
2	24 (23)	1.42 (1.60)	1.95 (1.59)	±4.26 (±4.80)	±3.01 (±3.39)	6.50 (6.50)	7.60 (4.20)	9.80 (6.50)	23.40	21.19 (20.95)
3	15	1.53	1.82	±4.59	±3.24	4.40	5.35	8.20	26.00	26.60
4	19	1.82	2.22	±5.46	±3.86	6.40	6.45	4.70	25.80	22.48

TABLE IX (a)

SUMMARY OF STATISTICAL RESULTS FOR AGGREGATE GRADATION

PER CENT PASSING NUMBER 40 SIEVE (Reflux)

WEARING COURSE MIX

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	% Passing # 40 Sieve Design	$\bar{\bar{X}}$
1	36	2.18	9.00	32.80	32.58
2	20	1.67	7.00	30.50	30.60
3	48	2.65	11.00	36.00	36.31
4	26	1.92	6.00	27.30	27.19
5	32	2.27	9.00	34.40	29.75
6	26	2.96	13.00	33.50	36.23
8	78	2.67	8.50	35.00	36.17

BINDER COURSE MIX

Plant	Number of Observations	Standard Deviation	Maximum Difference Between Days	% Passing # 40 Sieve Design	$\bar{\bar{X}}$
1	22	2.36	9.00	25.50	25.64
3	14	2.59	9.00	26.00	28.36
4	18	1.59	6.00	25.80	24.94

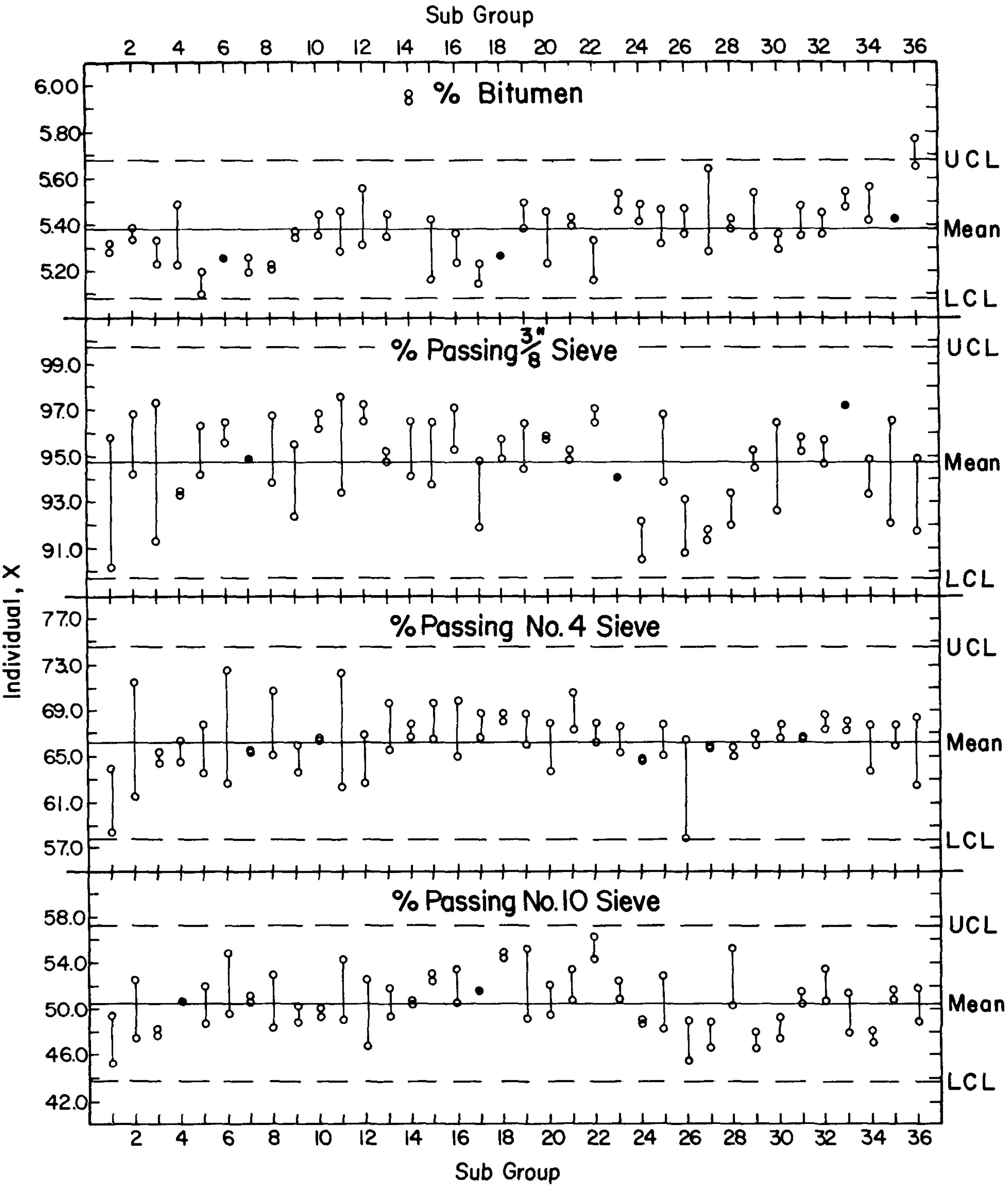

Figure 5 - Control Charts for Individuals -Bitumen Content. Per Cent Passing 3/8", No. 4 and No. 10 Sieves (Wearing Course Data from Plant 1)

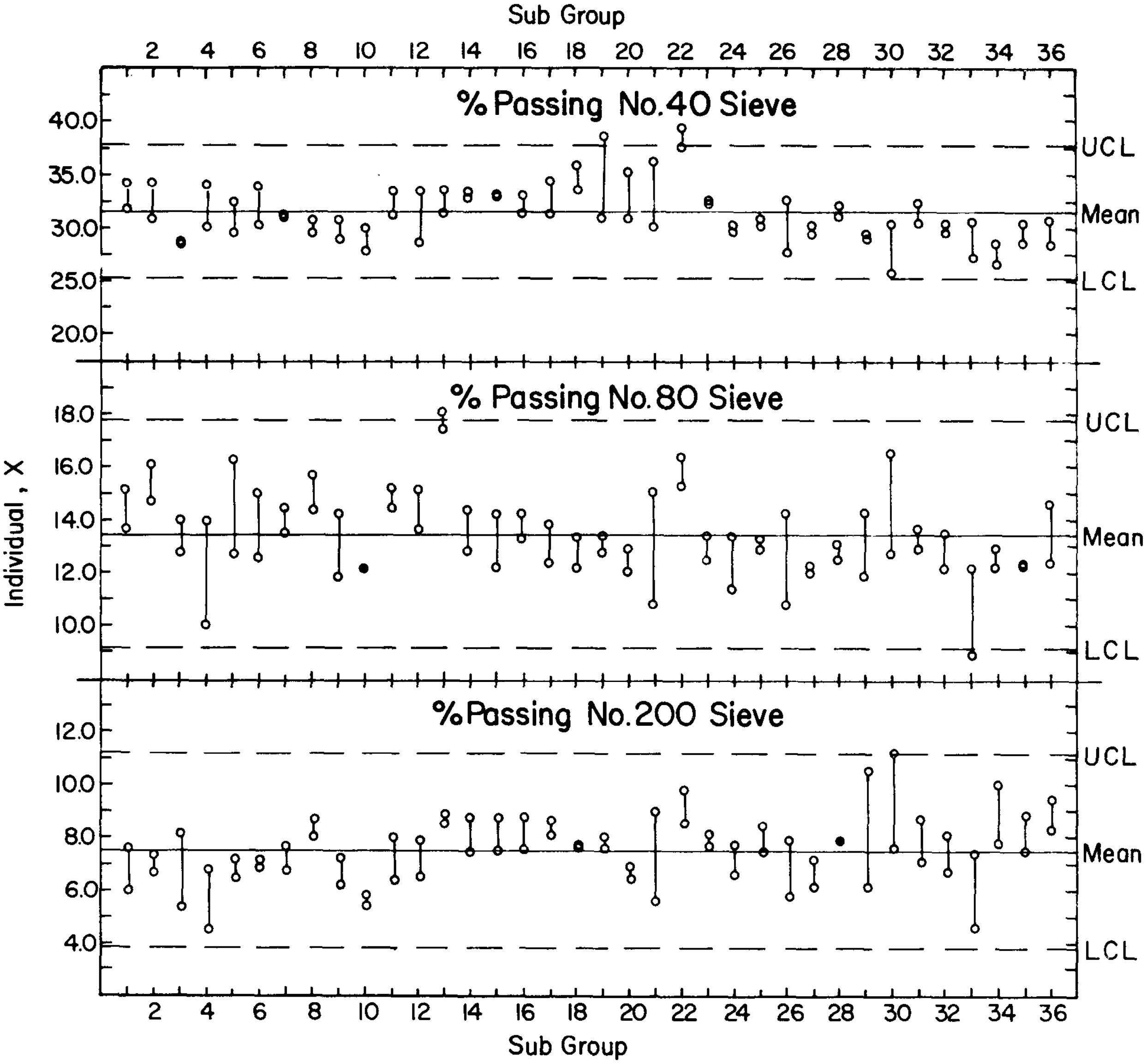

Figure 6 - Control Charts for Individuals - Per Cent Passing No. 40, No. 80, and No. 200 Sieves. (Wearing Course Data from Plant 1)

RELATIONSHIP BETWEEN SPECIFICATIONS AND PARAMETERS

Bitumen Content (Centrifuge Method)

Having established the parameters, it would be interesting to look into the relationship between these parameters and specifications. Figures 7 and 8 represent graphical relationship between specification and distribution of individual test results for bitumen content. The shaded area in each case represents the precentage of observations outside the job mix.

For plant 1, the process is well able to meet the job mix requirement since

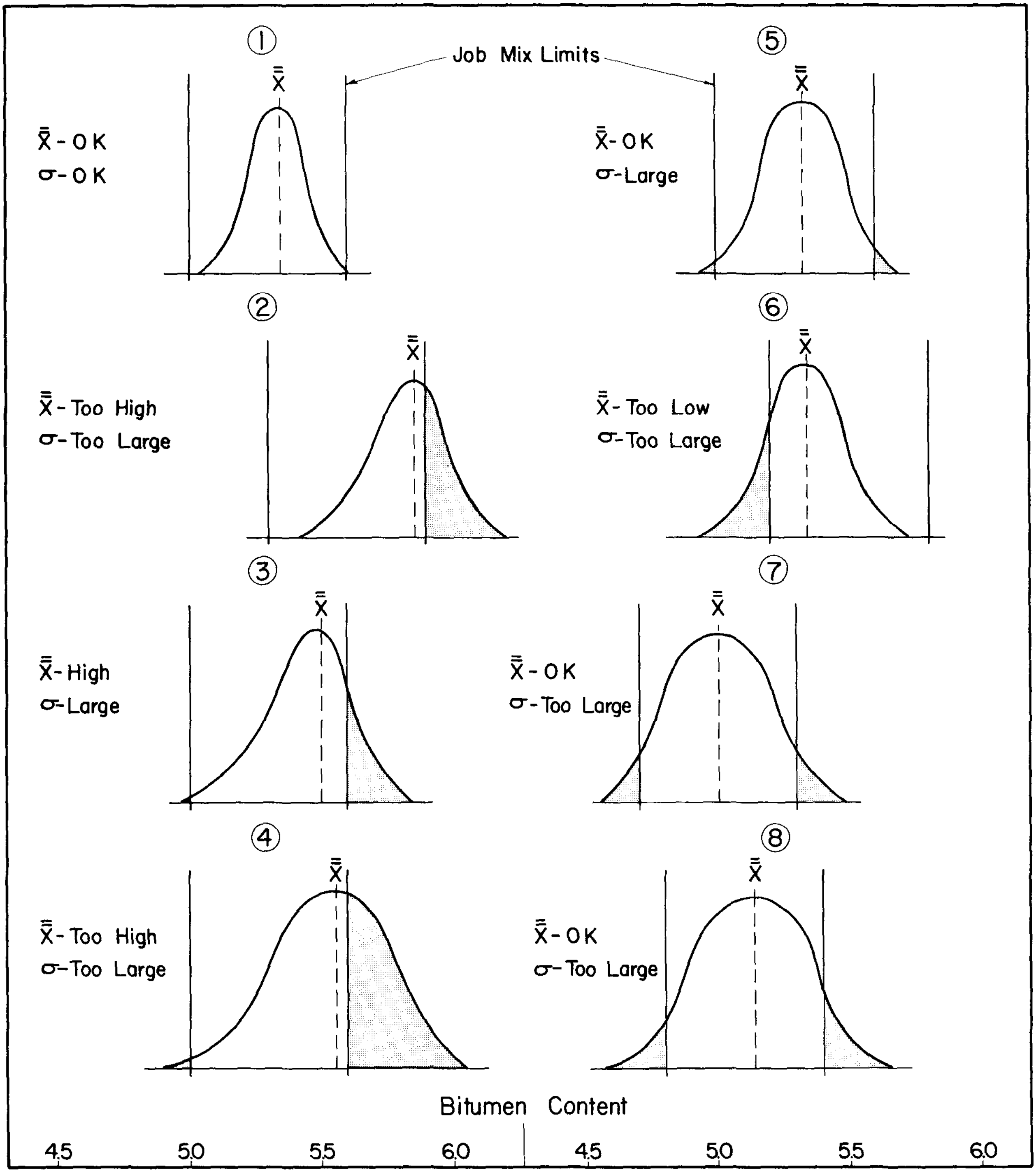

Figure 7 - Graphical Relationship between Specifications (Job Mix) and Statistical Parameters for Bitumen Content - Centrifuge Extractor (Wearing Course Mix)

the process mean is well centered towards the desired mean and the natural tolerance equal to the engineering tolerance.

For plant 2, however, the mean is almost at the upper job mix limit. Hence some values will necessarily fall outside the upper limit. Likewise, the standard deviation is also large.

Plant 3 has the same variability as plant 2 although the mean is not as far out to the right.

For plant 4, the mean as well as the variability are too large.

For plant 5, the variability needs to be reduced in order for all specimens to conform to the job mix. The mean, however, is well centered.

Plant 6, because of the mean being so close to the lower job mix limit, will have some values below this limit. Likewise, the variability is also large.

For plant 7, although the mean is on the nominal, there is still a substantial portion of the material both too high and too low. The solution will be to cut the process variability.

Plant 8 indicates the same condition as the one for plant 7.

Similar reasoning can also be applied to the four binder course mixtures, Figure 8.

In the cases discussed above it is seen that in spite of the process being centered at the nominal value, the extent of variability is so large that some of the values are bound to fall outside the two limits. If 100% conformance is required, then it is almost essential for the process mean to be centered around the nominal value (design value) and the variability equal to or less than 0.10%. A slight shift in either of these values will result in some observations falling outside the limits.

If control charts were plotted using the limits indicated in Tables IV through XI, then the fact that some points fall outside these limits would indicate lack of process control. The question is; "what should be done to bring the process in control?" Three alternatives are available to accomplish this:

1. Change the process
2. Resort to 100 per cent sampling
3. Change or revise the specifications

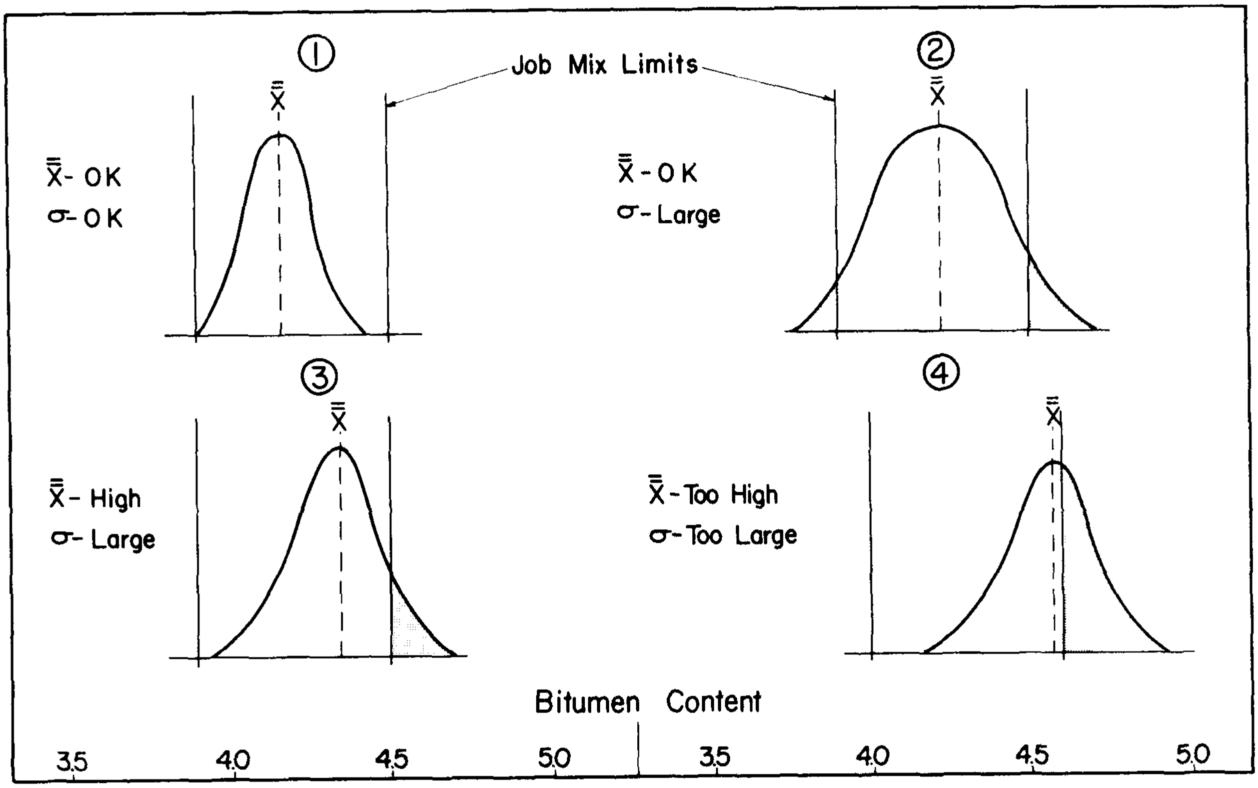

Figure 8 - Graphical Relationship Between Specifications (Job Mix) and Statistical Parameters for Bitumen Content - Centrifuge Extractor (Binder Course Mix)

Changing the process may be simple but the number of sources constantly working to introduce variations may make this prohibitively expensive.

The second approach may likewise prove expensive and time consuming. Furthermore, the nature of the product would not make this approach feasible. This is because the product at the time it is being tested and the results evaluated is already hauled on the job site for its intended use.

Sometimes the specifications have been set arbitrarily without due consideration for their necessity from the view point of use or economy of production or even to the past performance of the plant. Generally, in comparing control limits for individual observations with specifications, it will be found that the former falls within the latter provided these specifications have been set realistically or maximum control has been maintained. However, with the exception of plant 1, these control limits are twice as wide as the specification limits.

Therefore, on the basis of performance of each plant with respect to population characteristics and the inevitable variations due to aggregate gradation, bitumen content, sampling and testing and also cyclic and erratic shifts, a standard deviation of 0.2% would be imminent from a well controlled production and a spread of 6σ would be necessary if 100% conformance is desired. Table XII gives confidence interval for different tolerances of X, for a standard deviation of 0.2, zero mean and assuming normal distribution. If the process mean, however, is not maintained at the nominal value, some of the observations will fall outside the limits depending on the position of this mean with respect to the nominal value.

TABLE XII TOLERANCE FOR BITUMEN CONTENT

Tolerance for X	Per cent of Samples within the Confidence Interval
.6	100
.5	99
.4	95
.3	87
.25	79
.2	68
.1	38

It is known that a spread of 6σ or 1.2% in bitumen content variation will normally affect the physical characteristics of the mixture especially specific gravity and Marshall stability. However, when bitumen content was plotted against Marshall stability for plants 6 and 8, Figure 9 was obtained. A considerable amount of scatter is indicated by the figure and points to the fact that the bitumen content variation within ±.6% by weight of the mixture will not be reflected to any significant degree in Marshall stability and/or specific gravity as indicated by Figure 10 which shows bitumen content - per cent voids scatter for the same two plants. Similar relationships for binder course data are shown in Figures 11 and 12.

Gradation of Extracted Aggregate

Another important factor in the production of bituminous mixtures which is prone to sporadic changes is the gradation of different size aggregate. This is indicated in Tables V through XI. It can be seen that the variability for binder mixes is in general less than for wearing course mixes with respect to finer fractions. However, for these binder mixes the coarser fractions show considerably higher variability measurements. This indicates that the limits

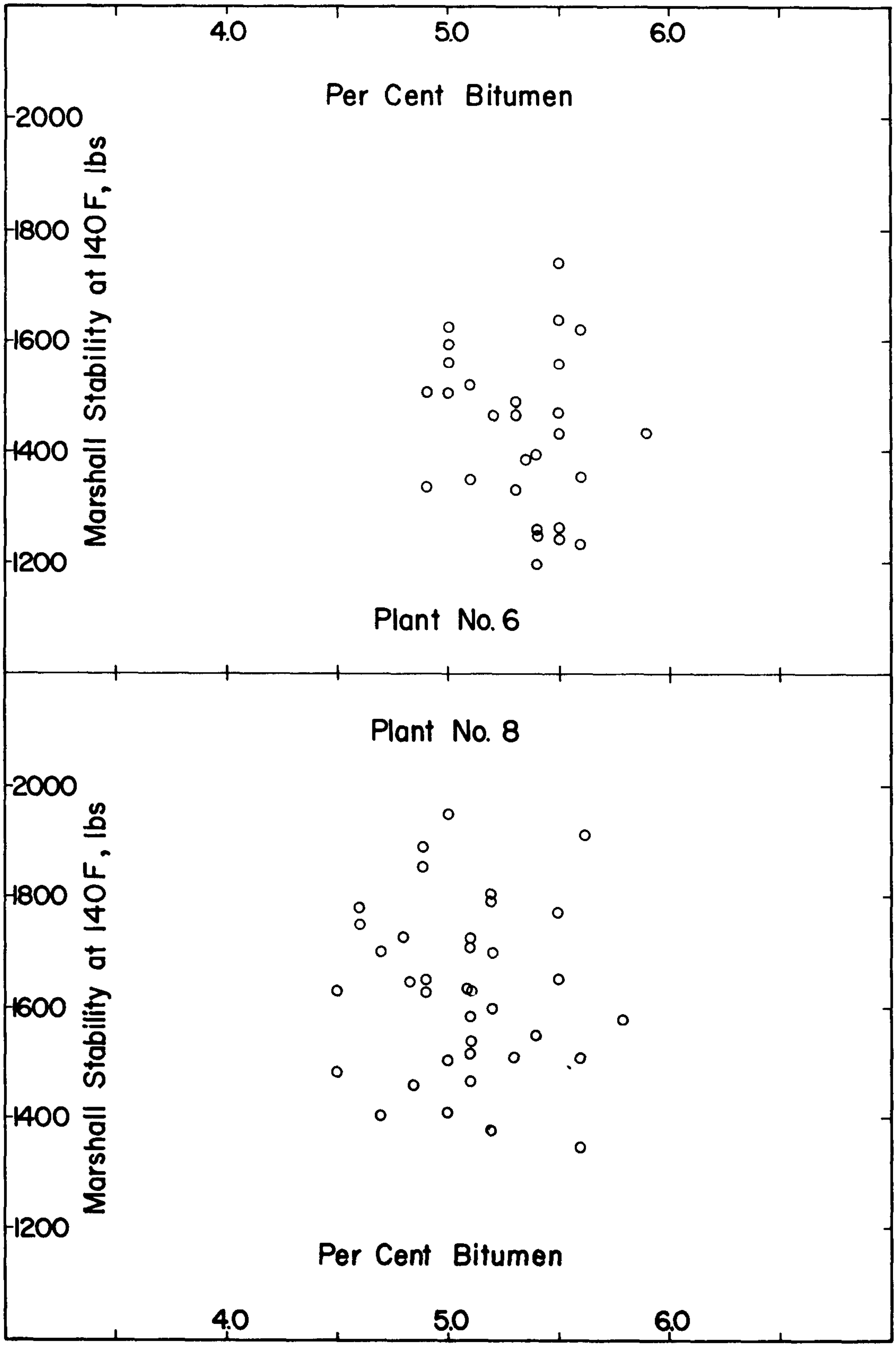

Figure 9 - Fluctuations in Marshall Stability Values for Corresponding Fluctuations in Bitumen Content (Wearing Course Mix)

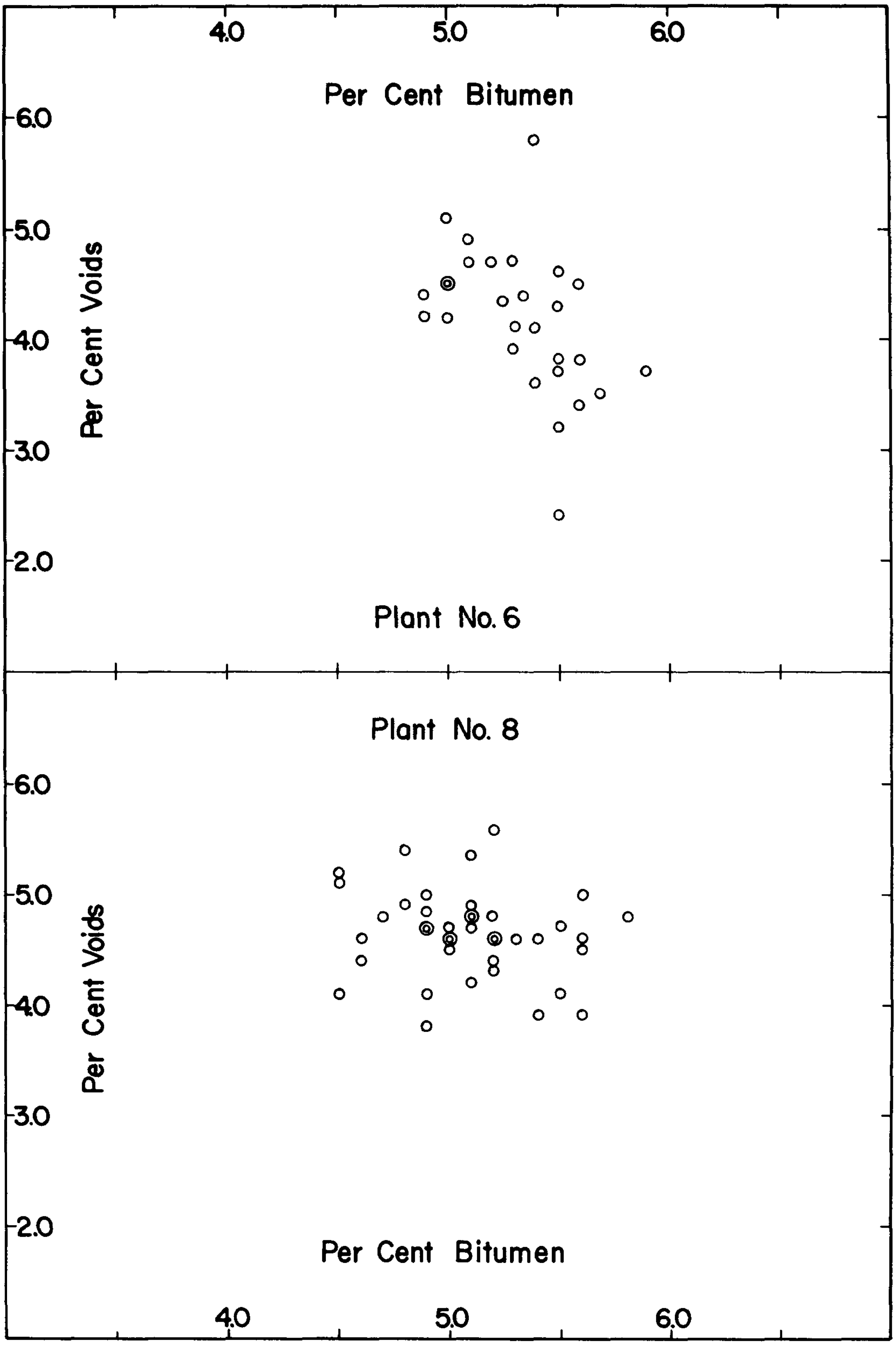

Figure 10 - Fluctuations in Per Cent Voids for Corresponding Fluctuations in Bitumen Content (Wearing Course Mix)

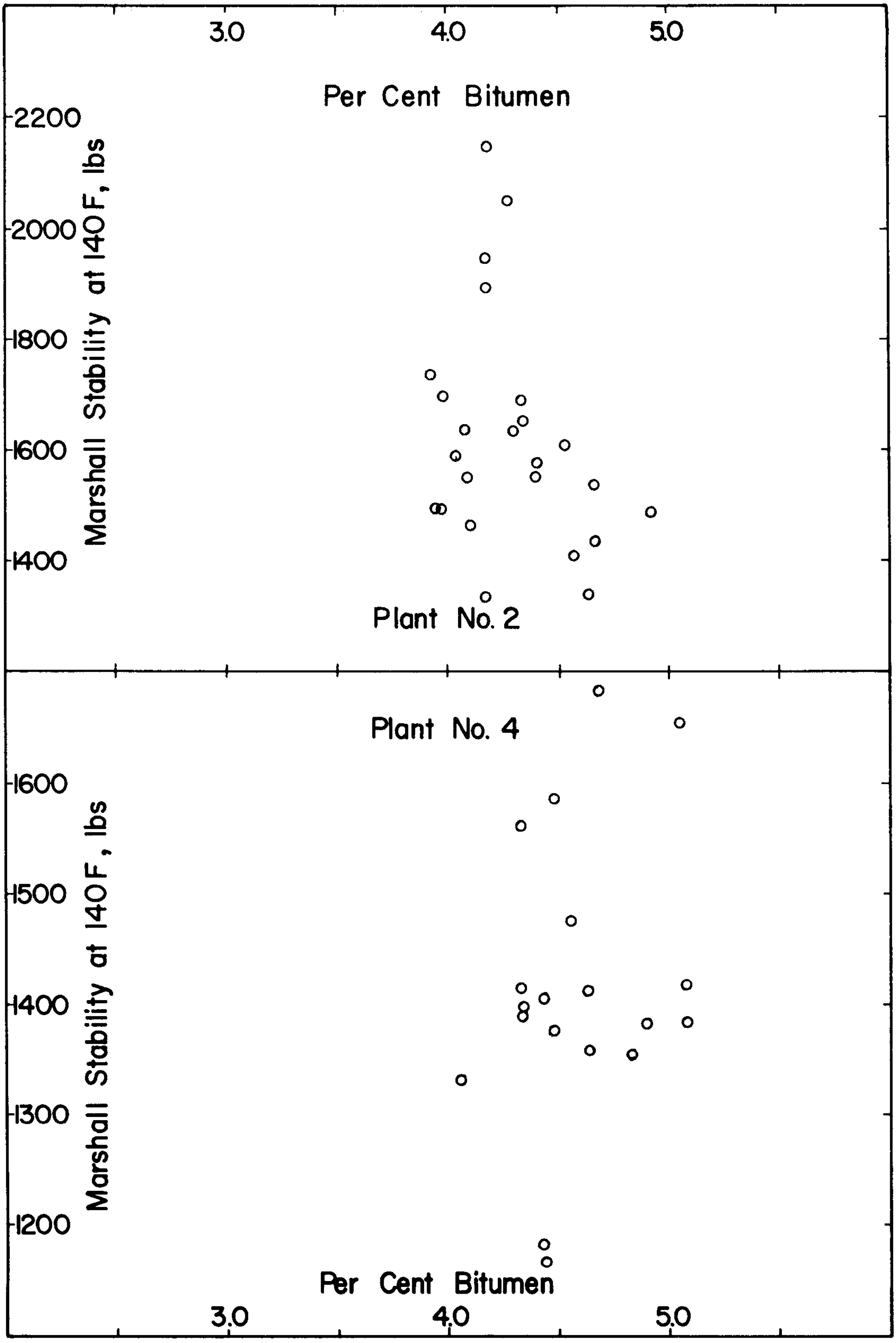

Figure 11 - Fluctuations in Marshall Stability Values for Corresponding Fluctuations in Bitumen Content - (Binder Course Mix)

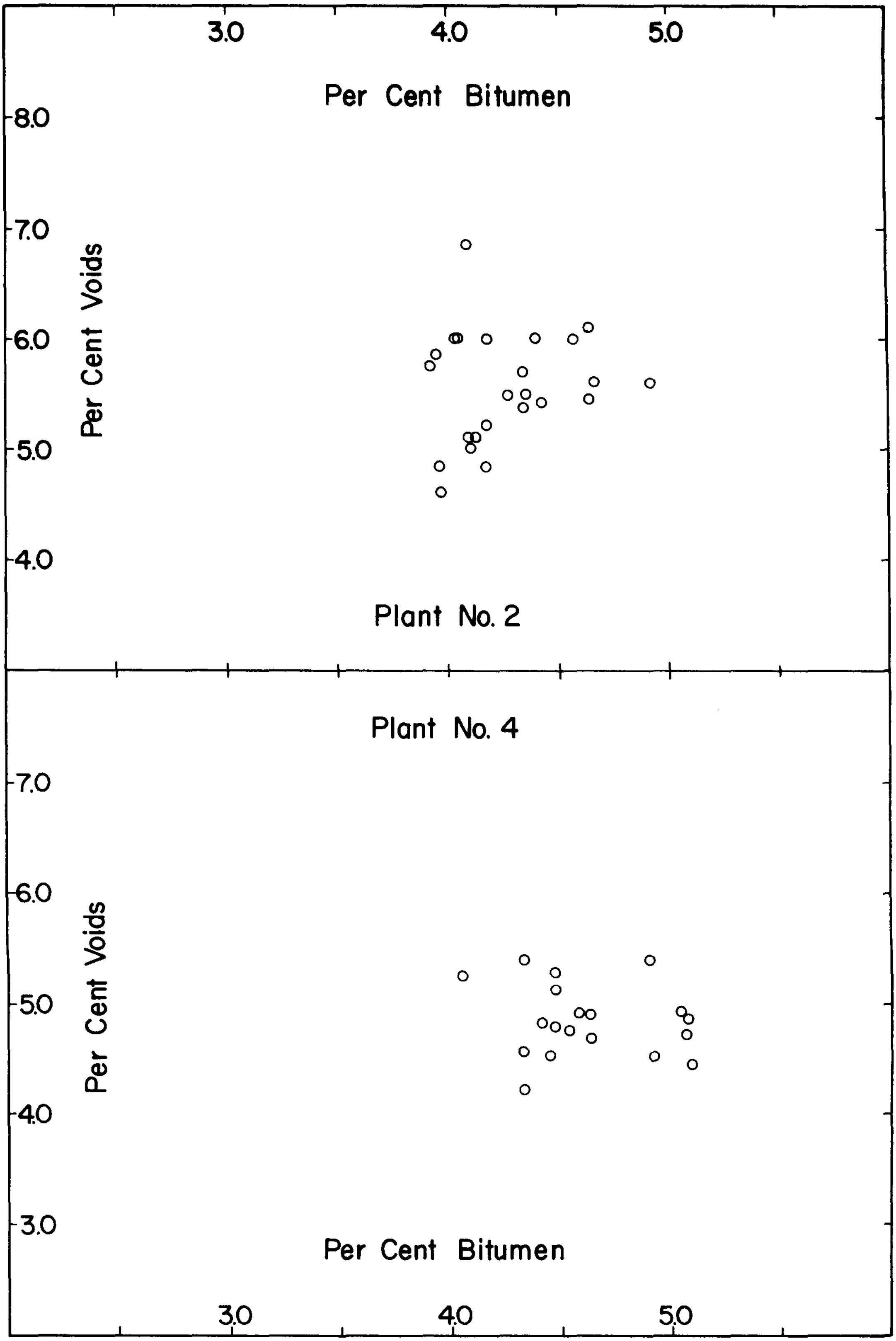

Figure 12 - Fluctuations in Per Cent Voids for Corresponding Fluctuations in Bitumen Content (Binder Course Mix)

would be more realistic if it takes into account the relative importance of coarse and fine aggregate fractions. For example, the wearing coarse mixes where the proportion of finer fractions is considerably more than the coarser ones indicate greater susceptibility to variations than coarser fractions (3/8"). The reverse is indicated for binder coarse mixes where the proportion of larger size aggregate is considerably more than the finer fractions.

Another important factor to be considered in setting aggregate gradation limits is the type of aggregate, whether crushed or natural. Crushed stone aggregate is known to be less variable than natural aggregate, the variability of the former, however, dependent to a certain degree on the crushing and screening operation.

If all the above sources of variations are taken into consideration, then the present job mix requirements (Table I) stipulated as the maximum permissible variation limits for all types of mixes seems somewhat narrower than to be expected from a hot mix plant. The limits should be wide enough to take into account the variations due to crushing and screening operation, sporadic changes in stockpile material, bin proportions and the volume and frequency of sampling and testing. It is suggested at the present time that the following tolerance limits for job mix be adopted until such time as further research dictates any changes. These values were arrived at by pooling standard deviation values of different aggregate fractions using centrifuge extractor (Tables V through XI). The pooled values are indicated in Table XIII.

U. S. Sieve	Job Mix Tolerances
No. 4 and larger	± 9.0
No. 10	± 7.0
No. 40	± 6.0
No. 80	± 5.0
No. 200	± 3.0

It should be mentioned that the No. 4 sieve was used as a critical sieve in estiablising limits for larger sieves. Furthermore, the limits do not represent 3σ limits but a little less than 3σ which in relation to normal probability would cast off between 1 to 2% of the results.

So far the discussion has been confined to results by Centrifuge method which is mainly used in the field for job control. However, a check sample is also analysed in the laboratory using Reflux method. Tables IV(a) through XI(a) which

TABLE XIII

POOLED STANDARD DEVIATION OF BITUMEN CONTENT AND AGGREGATE GRADATION BY CENTRIFUGE AND REFLUX METHODS

	Pooled Standard Deviation			
	Centrifuge		Reflux	
U. S. Sieve	W. C.	B. C.	W. C.	B. C.
3/4 Inch	-	2.63	-	4.03
1/2 Inch	-	4.00	-	4.73
3/8 Inch	2.35	-	2.75	-
No. 4	3.30	2.72	3.27	2.87
No. 10	3.10	2.56	3.10	2.67
No. 40	2.40	2.10	2.45	2.20
No. 80	1.75	1.24	1.94	1.34
No. 200	1.00	.80	1.22	.90
% Bitumen	.25	.21	.32	.25

represent summary of statistical results by Reflux method, justify the following comments.

1. There is a wider variation in bitumen content and aggregate gradation for wearing course mixes than for binder course mixes.

2. The overall variability is relatively larger than that indicated by centrifuge method for both wearing and binder mixes.

3. Occurance of "low" asphalt content by this method is more pronounced as compared to "high" asphalt contents by Centrifuge method.

Numerous factors contribute to such abnormal fluctuations in test results. For example, the loss of fines during washing process and brushing from the filter paper and the bowl ring into the pan contribute to both "high" asphalt content and corresponding low aggregate material. In the case of Reflux method, insufficient washing period may contribute to "low" asphalt content. However, it is believed that such fluctuations stem from individual non-standard practices. A comprehensive interlaboratory cooperative test coupled with field inspection survey would throw some light into the subject and consequently help in standardizing these testing procedures.

Marshall Stability

The destructive nature of this test makes it mandatory to prepare a different briquet each time. This naturally introduces a certain amount of variation due to sampling and testing in addition to those already present due to the mix itself. The overall variance is composed of within run variation, between runs within day variation and between day variation. Each of these components reflect to a certain degree the source of variation. For instance, the within run variation may reflect the precision of the testing method, the between runs within day component reflects variations due to sampling and some due to the mix itself. The between day component mainly reflects the capability of the plant to produce a uniform mixture over a longer period of time. Such partitioning of variance requir careful design of experiment. Since the present data do not come from such a factorial design, only the less commonly measures of variability are presented to show the extent of variation. This is presented in Table XIV. The magnitude of variation as indicated by the range is considerable in most cases with plant No. 7 showing the greatest. The standard deviation likewise varies from 168 lbs for plant 5 to 342 lbs for plant 7. Furthermore, the table indicates that the average variability for binder course mix is less than for wearing course mix. The capability of the plant to produce a uniform mixture regardless of the mix type is shown by plant 3 for which the variability is considerably less

TABLE XIV

SUMMARY OF STATISTICAL RESULTS FOR MARSHALL STABILITY

		Standard Deviation Based on		Limits		Max. Differences			Marshall Stab, lbs.	
Plant	Sub Group	$\bar{R}$	All Samples	X	$\bar{X}$	Within Day	Between Days	Between X_1,X_2	Specs.	$\bar{\bar{X}}$
WEARING COURSE MIX										
1	36	195	282	± 585	± 293	899	975	1496	1500	1977
2	22	178	236	± 533	± 308	804	652	1151	1500	1957
3	45	131	189	± 393	± 197	841	688	990	1200	1444
4	27	125	175	± 374	± 187	492	520	910	1200	1455
5	34	149	168	± 446	± 223	603	443	975	1200	1521
6	28	157	229	± 471	± 235	883	794	1093	1200	1463
7	18	226	342	± 677	± 339	1070	978	1767	1200	1623
8	40	223	239	± 669	± 335	984	570	1285	1500	1624
BINDER COURSE MIX										
1	22	181	217	± 543	± 272	1024	492	1395	1200	1628
2	24	216	271	± 647	± 373	678	813	1192	1200	1625
3	15	150	162	± 456	± 228	566	360	667	1000	1303
4	19	159	185	± 477	± 275	632	603	829	1000	1423

TABLE XV

SUMMARY OF STATISTICAL RESULTS FOR PER CENT VOIDS

		Standard Deviation Based on		Limits		Max. Differences			Per Cent Voids[1]	
Plant	Sub Group	$\bar{R}$	All Samples	X	$\bar{X}$	Within Day	Between Days	Between X_1,X_2	Specs.	$\bar{\bar{X}}$
WEARING COURSE MIX										
1	36	.50	.50	±1.50	± .75	2.20	1.60	2.40	3-5	4.32
2	22	.59	.40	±1.76	± .60	1.50	.90	2.10	3-5	4.16
3	45	.34	.50	±1.03	± .52	1.50	1.33	2.20	3-5	3.92
4	27	.48	.77	±1.45	± .73	2.30	2.85	3.80	3-5	3.81
5	34	.45	.51	±1.36	± .68	2.00	1.23	2.50	3-5	3.63
6	28	.75	.80	±2.25	±1.13	4.00	3.43	6.20	3-5	4.26
7	18	.52	.73	±1.55	± .78	2.20	1.83	3.60	3-5	4.35
8	40	.54	.61	±1.62	± .81	2.60	1.88	3.60	3-5	4.65
BINDER COURSE MIX										
1	22	.42	.58	±1.26	± .63	1.70	1.68	2.80	4-6	5.53
2	24	.48	.65	±1.45	± .84	1.90	2.23	3.00	4-6	5.51
3	15	.33	.36	±1.00	± .50	1.10	0.70	1.50	4-6	4.08
4	19	.35	.44	±1.05	± .70	1.40	1.17	2.00	4-6	4.83

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[1] Based on the apparent specific gravity of the aggregate.

than for other plants. This, however, may not hold true for other mixes.

Figure 13 graphically compares the specification limits and the natural spread of the wearing course mix test results. Examination of these figures warrants the following comments.

In all the cases, the specification limits do not coincide with the natural limits even though a "State of Control" prevails.

For plant 1, if the minimum specification of 1500 lbs is to be observed, the process mean should be maintained three above this minimum specification; viz. $\bar{\bar{X}} = 1500 + 3(282) = 2346$ lbs.

Likewise, for plant 2, the process mean should be centered at 2208 lbs.

In the case of plant 3, where the minimum specification requirement is 1200 lbs, the process mean will have to be shifted to 1200 + 3(189) or 1593 lbs of else 9.7% of the results will be below the minimum.

For plants 4, 5, and 6, the proportion of values that could be expected to fall outside minimum requirement are as indicated in the figure if the process mean is not maintained 3σ above the minimum.

For plant 7, the variability is extremely high compared to other plants. This was because of the wide fluctuations in stability values between individual samples as can be seen in Table XIV.

For plant 8, the reason for such high percentage of values falling below the minimum seems obvious.

The observed natural limits for individuals and averages indicated in Table XIV are related to the volume of sampling and testing. It is thus essential to decide whether these limits are for single test results or for means of several results based on specified number of runs or days. Most of the specifications require that a minimum stability value must be met by a single briquet. Some, however, require the same minimum be satisfied by an average value of a set of briquets prepared from a single truck sample.

The pooled value for standard deviation was obtained using sigmas from plants 3, 4, 5, and 6 only. Plant 7 was not considered because of excessive fluctuation and the remaining plants because of different design requirements. These were presented mainly to show the increase in variability measurement with increased specification requirement for stability test values.

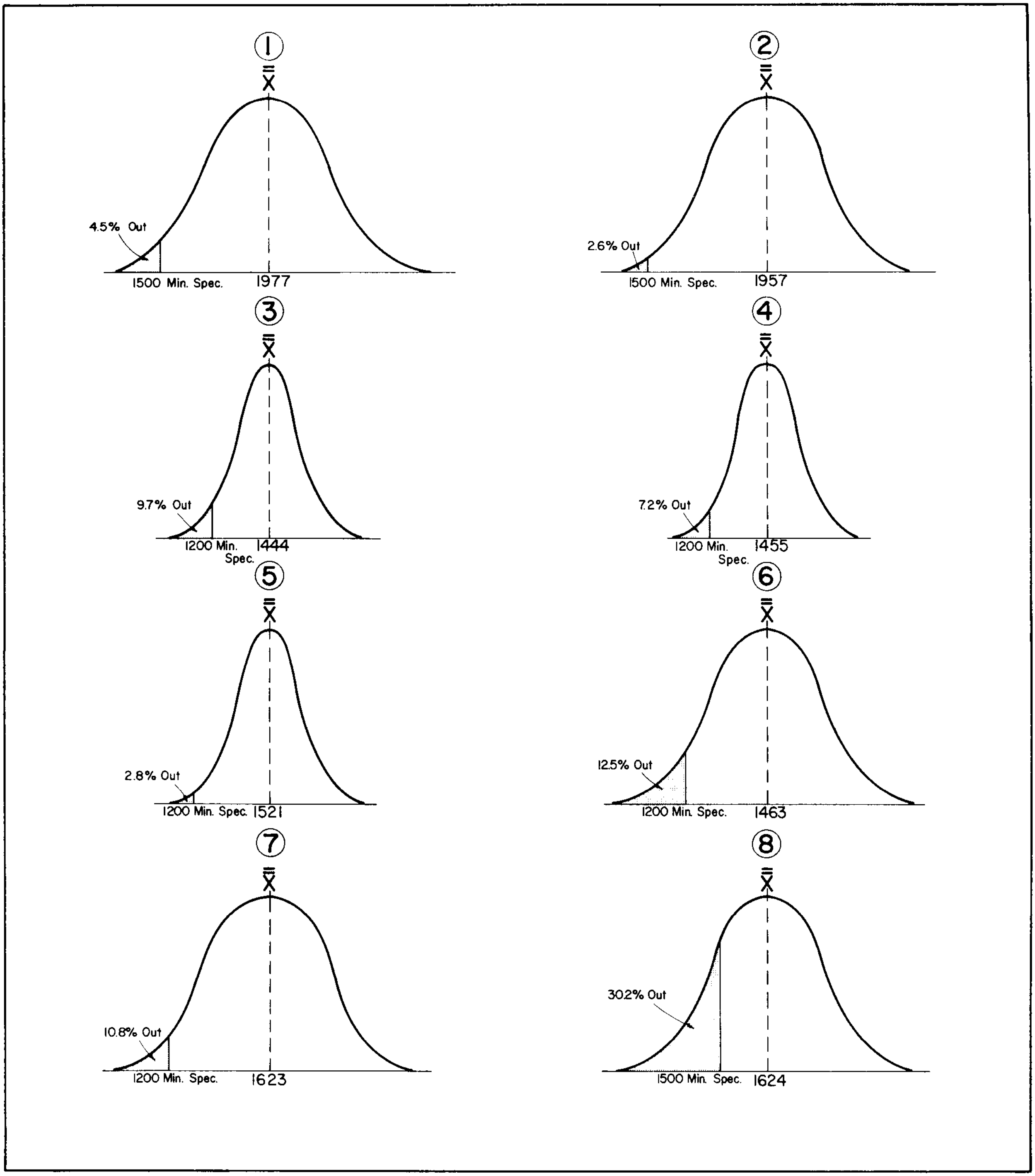

Figure 13 - Process Variation vs. Specification Requirements for Marshall Stability - (Wearing Course Mix)

Per Cent Voids

The current specification does not set forth any requirement for this particular characteristic. However, during design of the mix, a certain amount of control has to be exercised on this characteristic or else an adverse condition may result in the compacted pavement.

Before deletion of the specification requirement for this physical characteristic, a spread of 3% was required for both types of mixes, wearing and binder. This implies that the standard deviation not exceed 0.5% for any mix, if 3σ is considered realistic for 100% conformance. This criteria seems to agree with the natural spread in most cases as indicated in Table XV under individual limits. However, some points are bound to exceed the limits if the process mean is not centered at the nominal value. Futhermore, it is seen that the binder course mix shows less variability than wearing course mix.

ACCEPTANCE SAMPLING PLANS

In the preceding discussion, probability statements were made whereby for normal distribution of the data a certain percentage of observations could be expected to fall between some chosen number of standard deviations above or below a certain mean value. Nothing was mentioned about the number of samples to be tested in order to meet a certain predetermined risk. These risks called the consumer's and producer's risk are always present in any lot acceptance sampling plan and the number of samples that should be tested is dependent on the level of control desired.

Consumers (Department in this case), when accepting a certain lot or batch of material, always run a risk of accepting some bad material if offered to him by the producer. This is the consumer's risk. Likewise, the producer, in spite of offering good material, has to cope with a risk of being rejected by the consumer. This is the producer's risk. Thus it is seen that the probability of accepting good material should be high and the cost of rejecting some good material (producer's risk) should be justified. The great advantage of acceptance limits is that they provide definite criteria for acceptance or rejection of a lot or batch or what have you. Needless to say that the number of tests on which the decision is to be based should be specified. A number of formulas are available for calculation of the size of sample necessary for a given or desired tolerance. One of these has been suggested by Quality Control Task Group of the U.S. Department of Commerce, Bureau of Public Roads.(6) Following values are those suggested in the reference.

SUGGESTED ACCEPTANCE LIMITS

Level of Control	Acceptance Limits (UL, LL)		No. of Tests to be Averaged (n)
	Averages $\bar{X}' \pm T_s$	Individuals $X_s \pm T_i$	
99.5%	$\bar{X}' \pm 0.67\sigma$	$\bar{X}_s \pm 2.41\sigma$	6
95.0%	$\bar{X}' \pm 1.04\sigma$	$\bar{X}_s \pm 2.76\sigma$	5
90.0%	$\bar{X}' \pm 1.29\sigma$	$\bar{X}_s \pm 2.79\sigma$	4
80.0%	$\bar{X}' \pm 1.78\sigma$	$\bar{X}_s \pm 2.93\sigma$	3

SAMPLING PLAN FOR MINIMUM STABILITY REQUIREMENT

Minimum specification requirement for this characteristic protects the Department from placing the mix on the road that may fail during its service life. If 1000 lbs is considered the absolute allowable minimum (Table II), then it is only necessary to devise a sampling plan that will protect against, say, too low a mean but which is not concerned with how high the mean may be. If the process is maintained at, say, 1400 lbs, then for normal distribution and σ (pooled) equal to 190 lbs, approximately 1.8% of the results would be below the absolute minimum. If criticality is not of prime importance, then this value can be assumed to be acceptable. However, if the process is maintained at 1200 lbs, then as many as 15% of the results would be below the minimum which would obviously be undesirable and unacceptable. If the consumer's and producer's risks are set at .05 and .15 respectively, then the number of observations that would be necessary for this level of control would be 8 and the mean of these 8 measurements should be at least 1330 lbs in order for the batch and/or lot to be acceptable. If less than this value, then the batch and/or lot should be rejected.

Thus the sampling plan should be: obtain 8 random samples representing a days operation; mold and test specimens. If the mean stability of these 8 is at least 1330 lbs, the day's output should be considered acceptable, otherwise reject the material or take corrective action.

Figure 14 is a graph showing the distributions of $\bar{X}$ for acceptable and rejectable quality levels and the corresponding risks.

Figure 15 which is the operating characteristic (OC) curve for the above

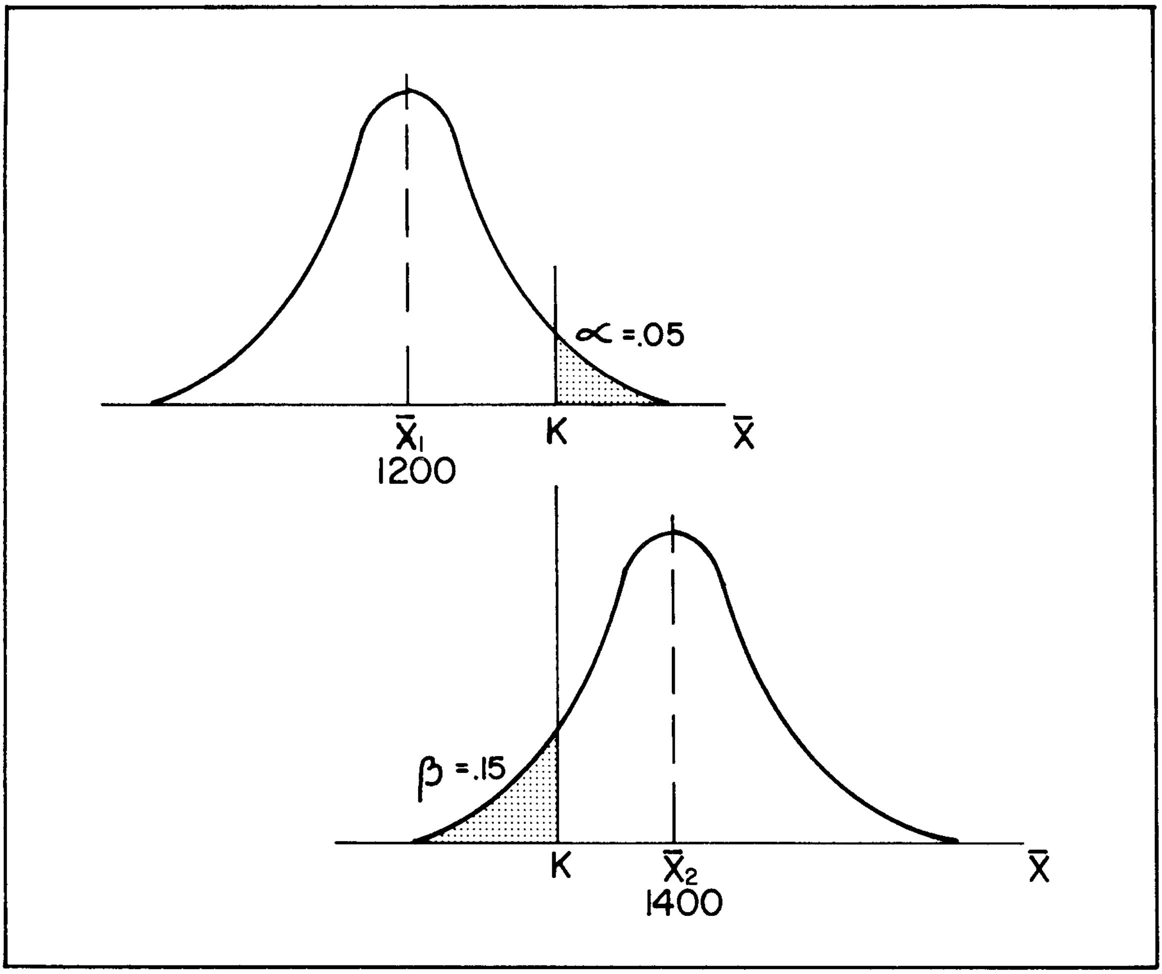

Figure 14 - Distributions of $\bar{x}$ for Acceptable and Rejectable Quality Levels and Corresponding Risks

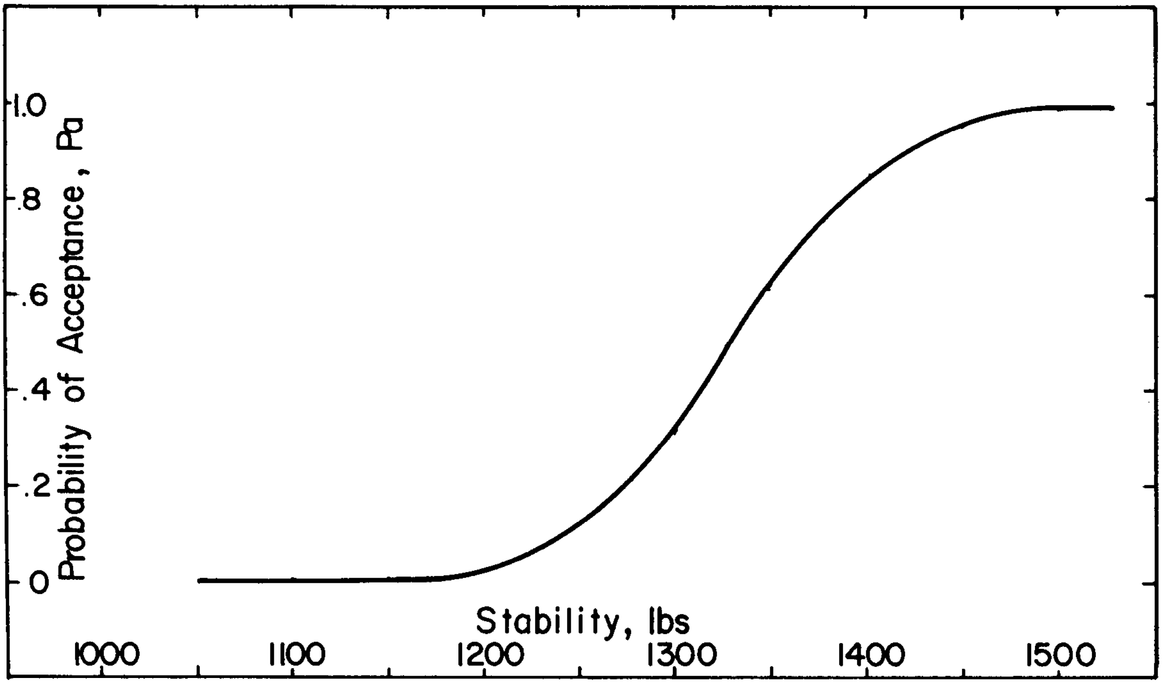

Figure 15 - OC Curve for the Sampling Plan for Stability

sampling plan indicates the following:

1. As the average stability increases, the probability of acceptance also increases.

2. The risk of acceptance of average stability below 1200 lbs is less than .03 and rapidly approaches zero as $\overline{X}$ decreases.

3. For a day's average of above 1400 lbs, the risk of rejection is less than .15 and rapidly approaches zero as $\overline{X}$ increases.

4. At intermediate band (straight portion) the probabilities of acceptance and rejection are both high.

ACCEPTANCE SAMPLING PLAN AND ITS LIMITATIONS

Establishing such acceptable tolerance limits as indicated above and elsewhere in the report is one aspect but what should be done if an individual or an average of a batch or lot does not meet the specified limits? In manufacturing industry where such acceptance sampling and testing is used to a greater degree, the answer would be relatively simple. The lot or batch of the product is rejected and a new lot tested. If it passes, it is shipped to the desired location for its intended use. However, the problem is not that simple when it comes to the production of bituminous hot mix and application of such acceptance plans. The product after it is sampled from the truck to be tested for conformance with respect to the desired characteristic , it is on its way to the job site where it is laid on the road and rolled. In fact, considerable amount of material may have been hauled before the results could be evaluated. If the results fall short of the acceptance limits then there is but one of two things that can be done, either reject the lot and/or batch or take corrective action. The latter action would be the more appropriate since rejection can only be made effective by cost penalty and such an action is subject to criticism from the producer group. Then, how should one go about hunting for the source of trouble so that corrective action can be taken. Although the problem is more a concern of the producer rather than the Department, the latter's burden is by no means diminished since he is required to indicate where the source of trouble lies. In this respect, control charts can be adequately used as a criteria for looking for an assignable cause of variation. A point outside the control limits could be taken as a signal for corrective action. The charts would also provide a history of the performance of each plant on the basis of which realistic specification limits can be set up.

SUMMARY

In the preceding sections an attempt has been made to determine the extent of variability in asphalt aggregate mixes using data collected from completed projects and on the basis of this variability numerical spceification limits were established using statistical quality control approach. Use of such technique does not guarantee against occurance of values that would fall outside the specification limits but it does however provide an insight into the basic pattern of variability with respect to each plant, material, or test (control chart). The capability of some plants to produce a more uniform mixture than others was also indicated. The analysis can be summed up in the following statements.

1. The close agreement between individual sample aggregate gradation and general specification requirements for most plants indicated adequate amount of control in the production process, sampling and testing.

2. The overall variability of each characteristic in the case of binder course mixes was generally less than for wearing course mixes.

3. The overall variability of bitumen content using centrifuge method was less than that indicated by reflux method.

4. The natural tolerances for bitumen content and aggregate gradation are outside the engineering tolerances (job mix) indicating a need for either a much closer control in plant operation, sampling and testing or a revision in engineering tolerances.

5. An asphalt content tolerance of 0.6% for individual specimens should be specified. A tolerance of this magnitude would allow for the inevitable variation due to sampling, testing, material and probability. However, 0.5% tolerance would cast off only 1% of the results whereas the currently used tolerance of 0.3% would reject almost 13% assuming normal distribution.

6. The wide range in allowable bitumen content indicated in 5 would not produce any adverse effect on the physical characteristic of the mix as indicated by Figures 9 through 12.

7. The inevitable sporadic variation in aggregate gradation indicates loosening of current job mix limits especially for finer fractions. On the basis of current frequency and volume of sampling and testing, it is felt that the following job mix tolerance be adopted until such time as further research dictate changes.

U. S. Sieve	Job Mix Tolerances
No. 4 and larger	± 9.0
No. 10	± 7.0
No. 40	± 6.0
No. 80	± 5.0
No. 200	± 3.0

8. The variability for Marshall stability as indicated by standard deviation is considerably different for each plant. Furthermore, lack of uniformity in production was indicated by this characteristic as evidenced by considerable between-days variation.

9. Although no requirements are specified for per cent voids, the previously used criteria of 3.0% spread seems adequate for preliminary design of the mixes.

10. If statistical quality control techniques are to be written in specifications, then it is highly essential that these specifications definitely state how the techniques are to be applied. If they are to be used as indicated in this report, then it must state specifically the definite number of samples to be obtained from separate batches, representing any one period of operation. The following are the required values for extraction and stability samples.

Bitumen Content and Gradation

One measurement on each of three separate batch samples representing any one period of operation. The individual test results should fall within the prescribed limits.

Marshall Stability and Other Physical Requirement

Eight samples from trucks representing a day's operation. The process average to be maintained at 3(190) = 570 lbs. above the absolute minimum specified for the type of mix.

SCOPE FOR FUTURE STUDY

In the preceding analysis no attempt was made to separate the variability due to sampling and testing because of lack of adequate data and consequently an assumption had to be made regarding the techniques to be sound. Since sampling and testing are inherent parts of any plant variability, it is necessary to partition the components of variance contributing to the overall variance. This can be done by application of Analysis of Variance technique which calls for designing of the experiment whereby different variance components can be calculated. Such an analysis would provide an important tool for improvement in currently used techniques if so indicated by the components of variance.

Thus, it is suggested that a separate research study be set up whereby a precalculated number of truck samples shall be taken at random (using random number tables). This number will have to depend on the level of confidence required to provide an estimate of the true value of the characteristic as also on the amount of time and the number of personnel necessary to conduct each test.

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APPENDIX

FORMULAE

1. Standard Deviation (based on $\bar{R}$)

$$\sigma' = \frac{\bar{R}}{1.13}$$

2. Sample Standard Deviation

$$\sigma' = \sqrt{\frac{\Sigma\ (X - \bar{X})^2}{N - 1}}$$

3. Limits

Individual, $X = \pm 3 \frac{\bar{R}}{1.13}$

Average, $\bar{X} = \pm 3 \frac{\bar{R}}{1.13\sqrt{n}}$

4. Standard Devation (Pooled)

$$\sigma_p = \sqrt{\frac{(N_1 - 1)\, s_1^2 + (N_2 - 1)\, s_2^2 + \ldots\ (N_k - 1)\, s_k^2}{N_1 + N_2 + N_3 + \ldots + N_k - k}}$$

SYMBOLS USED

k = Number of subgroups

N = Number of observations

n = Number of observed values in a subgroup

$\bar{R}$ = The average of a number of ranges

s = Variance of the population

σ' = Estimate of the true value of sigma

X = A measured value of a characteristic

$\overline{X}$ = Sum of N observations divided by the number of observations

$\overline{\overline{X}}$ = A grand average or the average of averages

UCL = Upper Control Limit

LCL = Lower Control Limit