# Statistical Evaluation of Highway Materials Specifications

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A statistical evaluation of some of the major highway materials specifications is reported. The data for analysis and evaluation were obtained from historical sources, with limited amounts from research sources for asphaltic concrete, base course, and concrete characteristics. The data were analyzed by computer and standard statistical procedures.

The analysis indicates that (a) most of the historical data tend to follow normal distribution; (b) in general, there is considerable variation in production and construction control for different contractors; and (c) furthermore, there is a lack of compatibility between currently used specification limits and statistical parameters. The report describes the various single-sampling plans for lot acceptance. The use of control charts for control and acceptance of portland cement and asphaltic concrete is also demonstrated.

•THIS report is concerned with the evaluation of certain highway materials specifications using statistical quality control techniques. It is condensed from three previous reports on the subject (1, 2, 3).

In its simplest form, quality refers to the quality of conformance; that is, does the end product conform to some preset standard? If it does, then the product is said to have quality built into it. Control is the mechanism whose primary function is the prevention of defects. Thus, statistical quality control is a systematic procedure that involves random collection of representative data and analysis of the data to determine whether all or any part is drawn from within or without a chance-cause system. The analysis results in conclusions based on predetermined levels of confidence and probability.

In industry, application of such techniques has provided an important tool to both the producer and the consumer for acceptance and/or rejection of the manufactured products. Highway construction need not be considered different from any manufacturing industry—there is a producer, identified as a contractor; there is a consumer, which is the state highway department; and finally, there is the manufactured product, which could be the finished roadway or any related structure. Realizing this, highway engineers have directed their attention to application of techniques to (a) determine the basic pattern of variability concerning each material characteristic, (b) determine process capabilities, (c) aid in the establishment of realistic specifications, and (d) aid in better overall producer-consumer relationships.

While it is fundamentally true that the only excuse for specifications in any regard is to outline some necessary phase of performance, it is also true that these specifications need to be based on facts. Whenever specifications go into the realm of conjecture, then difficulty is made certain, costs pyramid, and waste is inevitable.

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## SCOPE

The program of statistical evaluation of highway construction materials for writing realistic specifications was initiated in 1963 in cooperation with the U.S. Bureau of Public Roads. The project was broken down into three phases: hot mix asphaltic concrete, soil and aggregate base course, and concrete and concrete aggregates. Each of these phases was further subdivided to include the following specific characteristics:

Hot mix asphaltic concrete

1. Bitumen content
2. Mechanical analysis of extracted aggregate
3. Marshall stability
4. Percent voids
5. Roadway density
6. Mixing (discharge) temperature**

Soil and aggregate base course

1. Aggregate base course
   a. Density
   b. Gradation of sand-clay-gravel
   c. Thickness
2. Stabilized sand-clay-gravel and sand-shell base course
   a. Density*
   b. Thickness*
3. Stabilized soil cement base course
   a. Density*
   b. Thickness*
   c. Width**
   d. Moisture content for mixing and compaction**

Concrete and concrete aggregates

1. Compressive strength (28-day)
2. Air content
3. Slump (paving and structural)*
4. Gradation of coarse and fine aggregate**
5. Thickness of pavement

In the foregoing list, items marked with an asterisk (*) were those for which data for statistical evaluations were collected from research as well as historical sources. A double asterisk (**) indicates that data were from research sources only.

## OUTLINE OF WORK

### Collection and Processing of Data

Historical—A quality control program necessitates gathering vast amounts of data. Furthermore, it is almost implicit that these data are unbiased, and a religious adherence to random selection of samples is usually necessary to ensure this lack of bias. To accomplish this, a specially designed sampling plan (using random number tables) would have been an ideal approach in obtaining data necessary for development of statistical parameters for various characteristics. However, aside from selecting jobs under construction in various parts of the state, this controlled field experiment would have also involved considerable amounts of time and personnel. Therefore, it was decided that much of the information residing, untouched, in long rows of filing cabinets could be used to advantage without resorting to any additional sampling and testing.

After careful selection of projects on the basis of their geographic locations, quality of workmanship, and type of material, data were accumulated using daily inspection reports, laboratory reports, and record test reports as sources. In adopting such an approach,

it is assumed that (a) the currently used sampling and testing techniques are sound, and (b) the data are representative and free of any bias. A limitation to the latter assumption is that the data may not have come from a randomly selected sample and there may be some bias in reporting. In statistical evaluation, an out-of-specification result is just as important as the one within the specification limits, for only then can a true estimate of variability be ascertained. Therefore, a statistical reliability check was made on the historical data to verify the assumption. [In essence the normality assumption was verified. A straight-line trend of the cumulative frequency distribution data on normal probability paper gives empirical evidence of the normality assumption.]

Research—Variability measurements for some of the characteristics (those marked with two asterisks) were also determined from controlled field experiments using the following sampling plan: For slump of paving and structural concrete, four random trucks were sampled on each project with two replicate determinations per truck. This gave a total of 72 individual observations for each type of concrete (representing nine separate contractors). The tests were performed with different equipment by various operators.

For coarse and fine aggregate gradation, two replicate determinations were made on eight randomly selected samples from each separate stockpile (representing each separate source). For fine aggregate, 16 individual tests were performed on each source for a total of 144 observations over the nine sources. For Grade A and B coarse aggregate, a total of 96 and 80 tests were made over the six and five sources respectively. Sampling was performed by different individuals, whereas testing was accomplished with one operator using the same equipment.

The bituminous hot-mix discharge temperatures were obtained using the Bureau of Public Roads suggested random sampling procedures (4).

The raw data were analyzed using an IBM 1620 computer and standard statistical procedures.

### Test Results

Because any attempt to include all the data obtained in the study would make this report unnecessarily bulky, only those data pertinent to the text are presented. The complete results from the original study are available elsewhere (1, 2, 3).

## RELATIONSHIP BETWEEN SPECIFICATIONS AND STATISTICAL PARAMETERS

### Theoretical Considerations

Figure 1A symbolizes a relationship between specification tolerance limits and statistical parameters using an idealized normal distribution curve. It indicates excessive variation with respect to the tolerance limits. This situation is untenable and three solutions are available to modify this situation:

1. Remove or reject the fringe lying outside each tolerance by measuring each and every item, which is undoubtedly a costly procedure.
2. Find a new and better method to measure the characteristic, which involves research and delay.
3. Revise the limits by making them wider. There is no point in making specifications so tight that they cannot be enforced.

Figure 1B shows a situation where the curve just clears the inside limits. At first, this might seem to be perfect. However, on second thought, there does not seem to be any allowance for operating tolerance, and the dotted line shows how the measurements would be outside the limits with only a slight shift in the mean.

The most comfortable situation is illustrated in Figure 1C, where some leeway for sampling, testing, or material variation is allowed. Under this condition adequate conformance with specification tolerance can be expected.

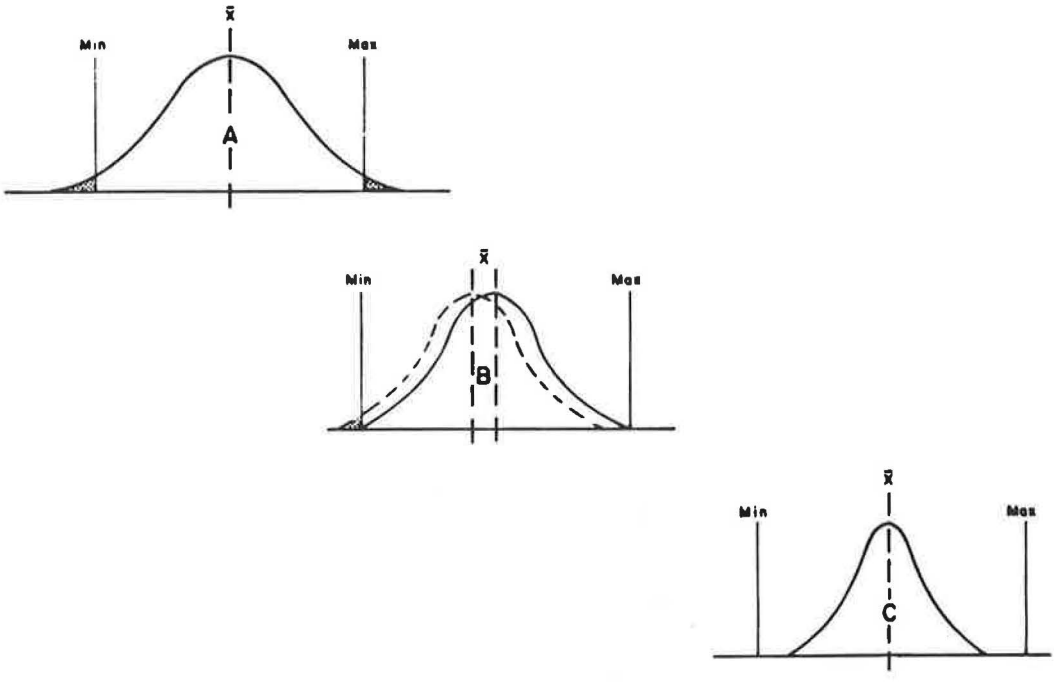


Figure 1. Some distributional aspects of specifications.

## Practical Considerations

Asphaltic Concrete—To better exemplify the above relationships, consider the data in Figure 2, which represents actual plant control data taken from several different plants in the state. The result is an interesting comparison of different plants operating toward the same specification. Again, for the purpose of illustration an ideal bell-shape curve is shown. In each case, the two solid vertical lines indicate job-mix limits representing ±0.3 percent variation in allowable asphalt content from the design value. Statistical information was obtained from Table 1 (symbols and definitions are listed in the Appendix). The dashed vertical lines represent the overall mean for each plant. The shaded area in each case represents the percentage of observations outside the job mix. These data warrant the following comments:

For plant 1, the process is well able to meet the job mix requirement since the process or overall mean is well centered toward the desired mean (design value) and the natural variability is equal to the allowable variability (±0.3 percent).

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 is 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 the mean is so close to the lower job limit, will have some values below this limit. Likewise, the variability is also large.

For plant 7, although the mean is at 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.

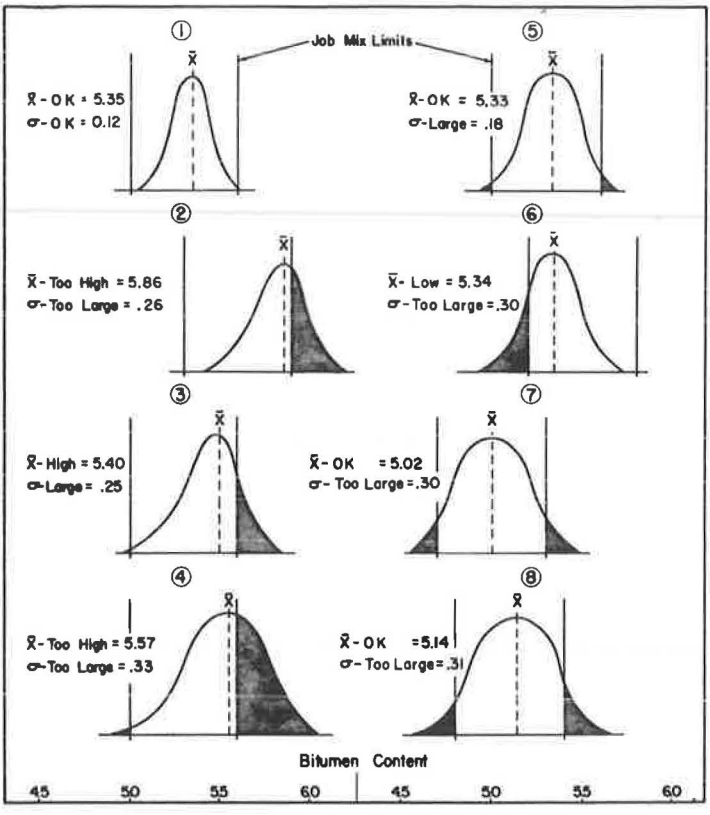


Figure 2. Graphical relationship between specifications (job mix) and statistical parameters for bitumen content—centrifuge extractor (wearing course mix).

TABLE 1

VARIATION IN BITUMEN CONTENT DETERMINATION FOR DIFFERENT HOT-MIX PLANTS

| Plant | n | $\overline{X}$ | $\sigma^2$ | $\sigma$ | Maximum Difference | | | % Outside Job Mix |
|---|---|---|---|---|---|---|---|---|
| | | | | | Within Day | Between Days | Between $X_1$, $X_2$ | |
| **Centrifuge—Wearing Course Mix** | | | | | | | | |
| 1 | 68 | 5.35 | 0.014 | 0.12 | 0.36 | 0.37 | 0.53 | (5.3) 0 |
| 2 | 44 | 5.86 | 0.068 | 0.26 | 0.80 | 0.89 | 0.97 | (5.6) 50 |
| 3 | 94 | 5.40 | 0.063 | 0.25 | 0.81 | 1.03 | 1.13 | (5.3) 16 |
| 4 | 54 | 5.57 | 0.144 | 0.33 | 0.91 | 0.75 | 1.61 | (5.3) 48 |
| 5 | 68 | 5.33 | 0.032 | 0.18 | 0.66 | 0.65 | 0.84 | (5.3) 6 |
| 6 | 56 | 5.34 | 0.090 | 0.30 | 0.71 | 1.06 | 1.15 | (5.5) 23 |
| 7 | 36 | 5.02 | 0.090 | 0.30 | 0.58 | 0.91 | 1.13 | (5.0) 22 |
| 8 | 68 | 5.14 | 0.096 | 0.31 | 0.73 | 0.92 | 1.31 | (5.1) 19 |
| **Centrifuge—Binder Course Mix** | | | | | | | | |
| 1 | 44 | 4.16 | 0.014 | 0.12 | 0.35 | 0.29 | 0.50 | (4.2) 9 |
| 2 | 42 | 4.22 | 0.057 | 0.24 | 0.36 | 0.72 | 1.01 | (4.2) 14 |
| 3 | 30 | 4.34 | 0.036 | 0.19 | 0.51 | 0.29 | 0.64 | (4.2) 17 |
| 4 | 38 | 4.57 | 1.225 | 0.35 | 0.78 | 1.03 | 1.48 | (4.3) 40 |

( )—Design content.

TABLE 2

SUMMARY OF STATISTICAL RESULTS ON BITUMEN CONTENT AND GRADATION USING CENTRIFUGE METHOD

| Category | n | $\bar{X}$ | $\sigma^a$ | $\sigma_p$ | Job Mix | % Outside Job Mix |
|---|---|---|---|---|---|---|
| | | Gradation, percent passing | | | | |
| Wearing course mix (8 plants) | | | | | | |
| 3/8-in. sieve | 484 | 93.10 | 5.46 | 2.35 | ±7 | 5 (0) |
| No. 4 sieve | 482 | 65.60 | 10.95 | 3.31 | ±7 | 9 (4) |
| No. 10 sieve | 490 | 53.10 | 9.33 | 3.05 | ±5 | 11 (10) |
| No. 40 sieve | 494 | 31.90 | 5.67 | 2.39 | ±4 | 10 (9) |
| No. 80 sieve | 480 | 15.60 | 3.09 | 1.75 | ±4 | 7 (2) |
| No. 200 sieve | 484 | 8.50 | 1.01 | 1.00 | ±2 | 10 (5) |
| Percent bitumen | 488 | 5.37 | 0.066 | 0.25 | ±0.3 | 21 (22) |
| Binder course mix (4 plants) | | | | | | |
| 3/4-in. sieve | 160 | 94.50 | 6.89 | 2.63 | ±7 | 4 (1) |
| 1/2-in. sieve | 160 | 74.50 | 16.32 | 4.04 | ±7 | 13 (8) |
| No. 4 sieve | 156 | 44.50 | 7.51 | 2.74 | ±7 | 1 (1) |
| No. 10 sieve | 158 | 32.20 | 6.59 | 2.56 | ±5 | 19 (5) |
| No. 40 sieve | 158 | 23.51 | 4.28 | 2.08 | ±4 | 13 (5) |
| No. 80 sieve | 154 | 10.20 | 1.59 | 1.26 | ±4 | 5 (0) |
| No. 200 sieve | 154 | 4.93 | 0.67 | 0.82 | ±2 | 2 (1) |
| Percent bitumen | 154 | 4.32 | 0.045 | 0.21 | ±0.3 | 20 (14) |

( )—Obtained from areas under normal curve above and below assumed mean of zero.

Plant 8 indicates the same condition as plant 7.

In these cases, it is seen that in spite of the process being centered at the nominal value (plants 5, 7, and 8), the extent of variability is so large that some of the values must necessarily fall outside the two limits. If 100 percent conformance is required, then it is almost essential for the process mean to be centered around the nominal value (design value) and the variability or standard deviation to be equal to or less than 0.10 percent. A slight shift in either of these values will result in some observations falling outside the limits.

TABLE 3

SUMMARY OF STATISTICAL RESULTS ON BITUMEN CONTENT AND GRADATION USING REFLUX METHOD

| Category | n | $\bar{X}$ | $\sigma^a$ | $\sigma_p$ | Job Mix | % Outside Job Mix |
|---|---|---|---|---|---|---|
| | | Gradation, percent passing | | | | |
| Wearing course mix (7 plants) | | | | | | |
| 3/8-in. sieve | 266 | 95.84 | 7.55 | 2.75 | ±7 | 13 (1) |
| No. 4 sieve | 266 | 71.21 | 10.70 | 3.27 | ±7 | 14 (4) |
| No. 10 sieve | 266 | 56.09 | 9.59 | 3.10 | ±5 | 20 (10) |
| No. 40 sieve | 266 | 34.96 | 6.01 | 2.45 | ±4 | 13 (10) |
| No. 80 sieve | 266 | 16.95 | 3.76 | 1.94 | ±4 | 6 (4) |
| No. 200 sieve | 266 | 8.03 | 1.48 | 1.22 | ±2 | 11 (10) |
| Percent bitumen | 266 | 5.50 | 0.096 | 0.31 | ±0.3 | 32 (32) |
| Binder course mix (3 plants) | | | | | | |
| 3/4-in. sieve | 54 | 92.70 | 16.28 | 4.03 | ±7 | 9 (8) |
| 1/2-in. sieve | 54 | 74.17 | 22.43 | 4.73 | ±7 | 15 (14) |
| No. 4 sieve | 54 | 46.24 | 8.22 | 2.87 | ±7 | 2 (0) |
| No. 10 sieve | 54 | 39.44 | 7.10 | 2.67 | ±5 | 19 (6) |
| No. 40 sieve | 54 | 26.11 | 4.85 | 2.20 | ±4 | 13 (7) |
| No. 80 sieve | 54 | 10.81 | 1.75 | 1.34 | ±4 | 0 (2) |
| No. 200 sieve | 54 | 5.44 | 0.90 | 0.95 | ±2 | 2 (3) |
| Percent bitumen | 54 | 4.19 | 0.061 | 0.25 | ±0.3 | 11 (22) |

( )—Obtained from areas under normal curve above and below assumed mean of zero.

TABLE 4

VARIATION IN MARSHALL STABILITY FOR DIFFERENT HOT-MIX PLANTS

| Plant | n | $\bar{X}$ | $\sigma^2$ | $\sigma$ | Maximum Difference | | | % Outside Specification |
|---|---|---|---|---|---|---|---|---|
| | | | | | Within Day | Between Days | Between $X_1$, $X_2$ | |
| **Wearing Course Mix** | | | | | | | | |
| 1 | 140 | 1977 | 79524 | 282 | 899 | 975 | 1496 | 1.4 (1500) |
| 2 | 66 | 1957 | 55696 | 236 | 804 | 652 | 1151 | 3.0 (1500) |
| 3 | 180 | 1444 | 35721 | 189 | 841 | 688 | 990 | 8.9 (1200) |
| 4 | 108 | 1455 | 30625 | 175 | 492 | 520 | 910 | 3.7 (1200) |
| 5 | 136 | 1521 | 28224 | 168 | 603 | 443 | 975 | 1.5 (1200) |
| 6 | 104 | 1463 | 52441 | 229 | 883 | 794 | 1093 | 11.5 (1200) |
| 7 | 72 | 1623 | 116964 | 342 | 1070 | 978 | 1767 | 5.6 (1200) |
| 8 | 138 | 1624 | 57121 | 239 | 570 | 570 | 1785 | 29.7 (1500) |
| **Binder Course Mix** | | | | | | | | |
| 1 | 82 | 1628 | 47089 | 217 | 1024 | 492 | 1395 | 1.2 (1200) |
| 2 | 72 | 1625 | 73441 | 271 | 678 | 813 | 1192 | 0 (1200) |
| 3 | 60 | 1303 | 26244 | 162 | 566 | 360 | 667 | 0 (1000) |
| 4 | 57 | 1423 | 34225 | 185 | 632 | 603 | 829 | 0 (1000) |

( )—Specification limit.

This clearly establishes the fact that acceptance tolerances for any quality characteristic, such as job mix tolerances for bitumen content and extracted aggregate gradation, must be based on the magnitude of the variability that is to be expected using the existing facilities of men, machinery, and materials. Any attempt to enforce the limits other than those realistically derived on the basis of variability will undoubtedly result in off-specification measurements. This point is emphasized in Tables 2 and 3, which illustrate the percentage of measurements that could be expected to fall outside the job mix tolerances applicable to these data. The wearing course data were taken from the eight different plants just described for bitumen content. The binder course data are from four separate plants. In the last column, the numbers in parentheses represent the theoretical percentage that can be expected to fall outside the tolerances. For example, as many as 10 percent of the results on the No. 10 sieve will be outside the job mix tolerance of ±5.0 percent from the design value. This percentage would be 5 for binder course mix. Similarly, for bitumen content the percentage would be 22 and 32 for

TABLE 5

SUMMARY OF STATISTICAL RESULTS ON ROADWAY DENSITY AND DISCHARGE TEMPERATURE

| Project | n | $\bar{X}$ | $\sigma_a^2$ | $\sigma_t^2$ | $\sigma^2$ | $\sigma$ | Min. | Max. |
|---|---|---|---|---|---|---|---|---|
| **Roadway Density (percent of laboratory)** | | | | | | | | |
| A | 60 | 98.14 | — | — | 1.24 | 1.11 | 94.1 | 99.5 |
| B | 92 | 98.81 | — | — | 1.06 | 1.03 | 95.7 | 102.0 |
| C | 110 | 96.60 | — | — | 3.04 | 1.74 | 93.7 | 102.8 |
| D | 135 | 98.26 | — | — | 2.10 | 1.45 | 90.7 | 100.9 |
| E | 138 | 97.57 | — | — | 1.61 | 1.28 | 94.6 | 100.4 |
| F | 219 | 97.89 | — | — | 2.48 | 1.58 | 89.6 | 100.8 |
| G | 252 | 97.01 | — | — | 3.40 | 1.84 | 90.5 | 103.0 |
| Pooled values | | 97.64 | | | 2.76 | 1.66 | | |
| **Discharge (mixing) Temperature (deg F)** | | | | | | | | |
| A | 200 | 324.03 | 128.84 | 9.44 | 138.28 | 11.76 | 280 | 370 |
| B | 200 | 316.23 | 253.02 | 5.61 | 258.63 | 16.08 | 275 | 350 |
| C | 200 | 316.43 | 119.30 | 1.53 | 120.83 | 10.99 | 285 | 360 |

wearing and binder course mixes respectively, using a job mix tolerance of ±0.3 percent from the design value.

On the basis of these relationships and the data in Tables 1 through 5, the following comments seem warranted:

1. 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.
2. An overall standard deviation of much less than 0.2 percent in asphalt content cannot be expected with the production, sampling, and testing methods at hand. If this value is considered realistic, then an asphalt content tolerance of 0.6 percent for individual specimens should be specified. A tolerance of this magnitude would allow for the inevitable variation due to sampling, testing, material, and probability.
3. The variability for Marshall stability as indicated by the standard deviation is considerably different for each plant. Furthermore, lack of uniformity in production is evidenced by considerable between-days variation.
4. The analysis of variance results for discharge temperature indicate that process variance is the greatest contributor. This is also reflective of batch-to-batch and day-to-day production variation. The variation in density control for different contractors is also evident from the sigma values.

## Base Course

Highway construction involves numerous processes. The foregoing discussion has involved the production process. After production, the product is delivered to the job site where the construction process takes over. Here, too, variability presents itself depending on the caliber of workers, efficiency of machinery, and quality of materials.

As in the case of bitumen content, relationships between specifications and statistical parameters are illustrated in Figure 3 for base course compaction. Statistical information is given in Table 6. The figure illustrates that, for all test results to conform to the minimum specification of 95 percent, the process (construction) needs to

TABLE 6

SUMMARY OF STATISTICAL RESULTS ON STABILIZED BASE COURSE COMPACTION

| Project | n | $\bar{X}$ | $\sigma^a$ | $\sigma$ | Min. | Max. | % Outside Specification |
|---|---|---|---|---|---|---|---|
| Stabilized Soil Cement | | | | | | | |
| A | 1000 | 98.71 | 3.84 | 1.96 | 88.6 | 104.8 | 3.6 |
| B | 736 | 98.98 | 8.83 | 2.97 | 89.2 | 116.8 | 2.6 |
| C | 630 | 97.69 | 7.48 | 2.73 | 86.1 | 105.4 | 10.0 |
| D | 615 | 99.11 | 8.98 | 3.00 | 85.2 | 108.2 | 5.2 |
| E | 527 | 98.94 | 9.98 | 3.16 | 90.8 | 104.2 | 4.4 |
| F | 290 | 99.90 | 10.82 | 3.29 | 89.3 | 110.0 | 5.5 |
| G | 280 | 99.43 | 10.20 | 3.19 | 90.4 | 107.9 | 2.1 |
| H | 265 | 98.40 | 9.19 | 3.03 | 88.3 | 105.7 | 7.9 |
| I | 110 | 98.63 | 15.86 | 3.98 | 86.3 | 115.2 | 6.1 |
| Stabilized Sand Clay Gravel | | | | | | | |
| J | 468 | 102.74 | 26.67 | 5.16 | 90.0 | 127.4 | 2.8 |
| K | 134 | 99.97 | 16.85 | 4.11 | 91.0 | 111.4 | 5.2 |
| Stabilized Sand Shell | | | | | | | |
| M | 385 | 100.49 | 22.68 | 4.75 | 83.0 | 114.3 | 9.4 |
| Pooled Values of the Above | | | | | | | |
| | 5440 | 99.28 | 10.93 | 3.31 | | | |

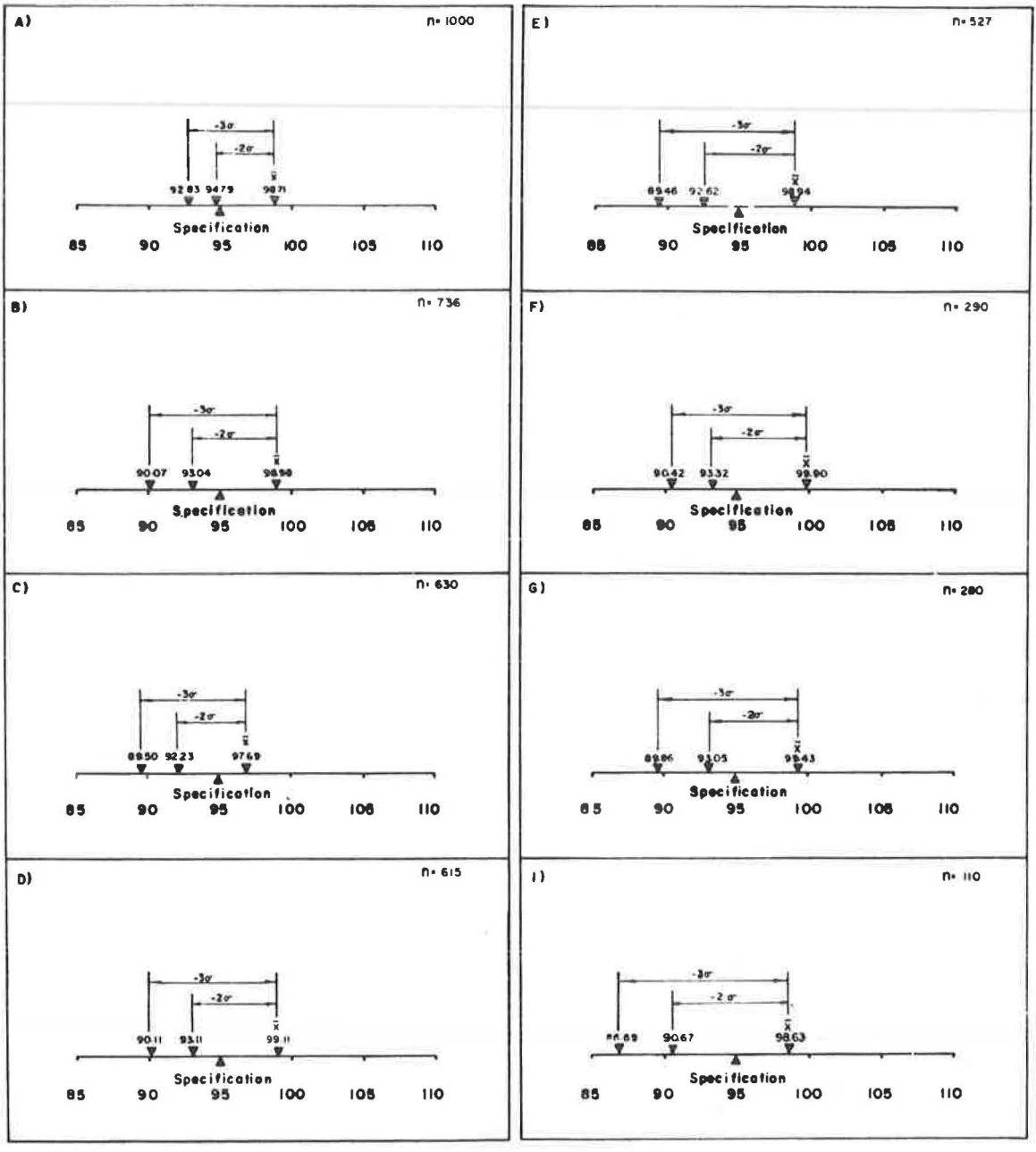


Figure 3. Relationships between specifications and statistical parameters for stabilized base course compaction.

TABLE 7

SUMMARY OF STATISTICAL RESULTS ON STABILIZED BASE COURSE THICKNESS

| Project | n | $\bar{X}$ | $\sigma^a$ | $\sigma$ | Min. | Max. | % Outside Specification | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Below | Above |
| **Stabilized Soil Cement, 6-in. Thickness** | | | | | | | | |
| A | 292 | 6.14 | 0.18 | 0.42 | 5.00 | 7.50 | 3.40 | 1.40 |
| B | 207 | 6.25 | 0.30 | 0.55 | 5.00 | 9.00 | 1.00 | 2.90 |
| C | 162 | 6.60 | 0.19 | 0.42 | 5.50 | 7.75 | 0 | 8.00 |
| D | 143 | 5.84 | 0.15 | 0.39 | 5.00 | 7.50 | 0.70 | 0.70 |
| E | 141 | 6.51 | 0.27 | 0.52 | 5.00 | 8.00 | 4.30 | 4.30 |
| **Pooled Values of the Above** | | | | | | | | |
| | 946 | 6.25 | 0.22 | 0.47 | | | | |
| **Stabilized Soil Cement, 8-in. Thickness** | | | | | | | | |
| F | 272 | 8.61 | 0.42 | 0.65 | 6.00 | 11.30 | 0.70 | 11.80 |
| **Stabilized Sand Clay Gravel** | | | | | | | | |
| G | 134 | 7.92 | 0.28 | 0.53 | 7.00 | 9.30 | 11.90 | 0.70 |
| H | 100 | 8.10 | 0.16 | 0.40 | 7.00 | 9.30 | 1.00 | 0 |
| **Unstabilized (Raw) Sand Clay Gravel** | | | | | | | | |
| I | 77 | 8.14 | 0.32 | 0.56 | 7.50 | 10.80 | 0 | 3.90 |
| **Pooled Values of the Above** | | | | | | | | |
| | 583 | 8.30 | 0.33 | 0.57 | | | | |

TABLE 8

SUMMARY OF STATISTICAL RESULTS ON BASE COURSE CHARACTERISTICS

| Characteristic | n | $\bar{X}$ | $\sigma^a$ | $\sigma_p$ | Min. | Max. | % Outside Specifications |
|---|---|---|---|---|---|---|---|
| Compaction, percent | | | | | | | |
| Stabilized | 5440 | 99.28 | 10.93 | 3.31 | 85.2 | 116.8 | 5.1 (95) |
| Raw | 556 | 103.53 | 8.66 | 2.93 | 96.0 | 114.6 | 7.0 (100) |
| Thickness, inches | | | | | | | |
| 6 | 946 | 6.25 | 0.22 | 0.47 | 5.00 | 9.00 | 5.2 (-0.5, + 1) |
| 8 | 583 | 8.30 | 0.33 | 0.57 | 6.00 | 11.00 | 18.5 (-0.75, + 1.25) |
| 10 | 210 | 10.23 | 0.86 | 0.93 | 5.50 | 14.00 | 9.0 (-1, + 1.50) |
| Gradation of SCG "A," percent passing | | | | | | | |
| ¾ in. | 609 | 89.8 | 6.43 | 2.53 | 73. | 98. | 1.1 (75-95) |
| No. 4 | 609 | 55.54 | 20.65 | 4.53 | 43. | 72. | 11.7 (40-60) |
| No. 40 | 609 | 32.68 | 26.72 | 5.17 | 17. | 60. | 7.6 (20-45) |
| No. 200 | 609 | 14.17 | 6.31 | 2.51 | 5. | 24. | 8.2 (10-20) |
| Gradation of SCG "B," percent passing | | | | | | | |
| No. 4 | 1001 | 66.73 | 27.36 | 5.20 | 48. | 85. | 6.8 (50-75) |
| No. 40 | 1001 | 41.70 | 28.78 | 5.40 | 15. | 65. | 7.5 (20-50) |
| No. 200 | 1001 | 16.82 | 16.40 | 4.05 | 4. | 40. | 11.8 (12-25) |
| Moisture content, percent | | | | | | | |
| Soil cement | 326 | — | 3.40 | 1.85 | — | — | — (±2) |
| Width, feet | | | | | | | |
| 22 | 47 | 21.82 | 0.075 | 0.27 | 20.75 | 23.1 | — |
| 26 | 30 | 26.53 | 0.158 | 0.40 | 26.1 | 27.6 | — |

( )—Specification limits.

be maintained at 95 + 3(σ), where σ is the standard deviation of the characteristic. Conversely, for all results to be acceptable, the specification needs to be changed to $\bar{X}$ - 3(σ). For example, for Contractor A, whose σ was 1.96 and $\bar{X}$ = 98.71, the lower specification limit should be 98.71 - 3(1.96) or 97.83 percent for 100 percent conformance. On the other hand, if we are ready to relinquish, say, 2.5 percent of the results, then the specification may be set at 98.71 - 2(1.96) percent. Similarly, for Contractor B, who had a larger value of σ and $\bar{X}$, the lower limit should be 90.07 percent for 100 percent acceptance and 93.04 percent for 97.5 percent acceptance.

Similar reasoning can be applied to other contractors, as indicated in the figure.

Data presented in Figure 3 and Tables 6 through 8 can be summed up in the following statements:

1. The variability for base course compaction and thickness is considerably different for different contractors (projects). This variability is more pronounced for cement stabilized aggregate base course than for stabilized soil cement base course.
2. For raw or unstabilized aggregate base course, the variability is less than that for stabilized base course.

## Concrete

Figure 4 illustrates the relationships between currently used concrete specifications and statistical parameters. Statistical information was obtained from Table 9. The figure once again illustrates that, for all measurements to conform to the specification limits, the process needs to be maintained at the center of the specification limits and the variability at such magnitude as to embrace all the results on either side of the central value (±3σ). For example, for slump of paving concrete, the process should have been maintained at 2.25 in., and the variability equal to or less than 0.25 in. for all measurements to fall inside the current requirements. However, this not being the case, as much as 42 percent of the results failed to meet the specification limits. The reason for such a large amount of nonconforming results seems obvious. Notice the

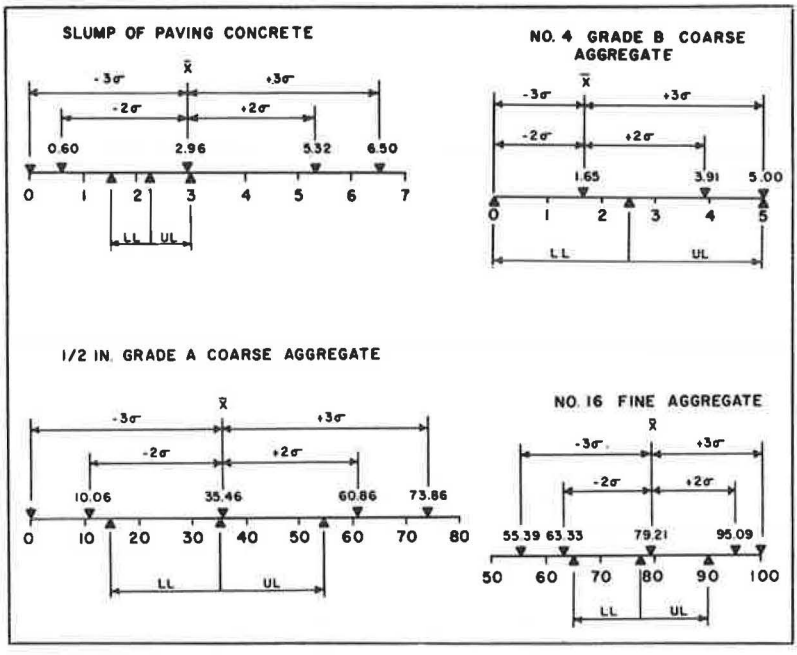


Figure 4. Relationships between specifications and statistical parameters for concrete characteristics.

TABLE 9

SUMMARY OF STATISTICAL RESULTS ON CONCRETE CHARACTERISTICS

| Characteristic | n | $\bar{X}$ | $\sigma^2$ | $\sigma_p$ | Min. | Max. | % Outside Specifications |
|---|---|---|---|---|---|---|---|
| Slump of concrete, inches | | | | | | | |
| Paving | 72 | 2.96 | 1.39 | 1.18 | 0.75 | 5.75 | 41.7 (1.5-3) |
| Structural | 72 | 2.98 | 0.77 | 0.88 | 1.00 | 6.00 | 20.8 (2-4) |
| Structural* | 211 | 3.15 | 1.06 | 1.03 | 1.00 | 6.75 | 19.9 (2-4) |
| Air content, percent* | | | | | | | |
| Structural | 158 | 3.87 | 0.60 | 0.78 | 2.00 | 6.00 | 4.4 (3-6) |
| Gradation of fine aggregate, percent passing | | | | | | | |
| No. 4 | 144 | 97.82 | 2.21 | 1.50 | 92.1 | 99.9 | 2.8 (95-100) |
| No. 16 | 144 | 79.21 | 62.96 | 7.94 | 56.6 | 91.6 | 9.7 (65-90) |
| No. 50 | 144 | 15.93 | 42.71 | 6.54 | 7.2 | 31.6 | 1.4 (7-30) |
| No. 100 | 144 | 2.06 | 1.63 | 1.28 | 0.3 | 5.7 | 0 (0-7) |
| Gradation of grade "A" coarse aggregate, percent passing | | | | | | | |
| 1 in. | 96 | 95.60 | 14.83 | 3.85 | 82.7 | 99.9 | 7.3 (90-100) |
| ¾ in. | 96 | 75.41 | 117.50 | 10.85 | 46.1 | 88.8 | 2.1 (40-88) |
| ½ in. | 96 | 35.46 | 162.33 | 12.70 | 4.6 | 60.2 | 13.5 (15-55) |
| No. 4 | 96 | 1.35 | 1.48 | 1.22 | 0.2 | 5.5 | 0 (0-6) |
| Gradation of grade "B" coarse aggregate, percent passing | | | | | | | |
| ¾ in. | 80 | 73.09 | 196.56 | 14.02 | 23.3 | 91.8 | 11.3 (40-85) |
| No. 4 | 80 | 1.65 | 1.29 | 1.13 | 0.3 | 5.0 | 0 (0-5) |
| Compressive strength, psi* | | | | | | | |
| Structural | 608 | 5150 | 528896 | 727 | 2690 | 7774 | 0.3 (3000 min) |
| Prestressed | 702 | 6393 | 851004 | 922 | 3803 | 9823 | 0.7 (5000 min) |
| Unreinforced | 436 | 3220 | 564852 | 752 | 1410 | 5134 | 1.4 (1800 min) |
| Thickness of pavement, inches* | | | | | | | |
| 8 | 379 | 8.29 | 0.088 | 0.30 | 7.46 | 9.58 | — |
| 9 | 371 | 9.20 | 0.083 | 0.29 | 8.55 | 11.69 | — |
| 10 | 461 | 10.34 | 0.069 | 0.27 | 9.41 | 11.48 | — |

( )—Specification limits. *Historical data.

proximity between historical and research statistical parameters for slump of structural concrete (Table 9).

Once again, it is possible to make the following observations from the data in Tables 9 and 10:

1. In general, there is considerable variation in concrete production from batch to batch, as indicated by the larger between-trucks-within-site component of variance in Table 10.
2. A testing variance of 0.10 can be expected due to chance alone in slump determination.
3. For fine aggregate, by far the largest source of variance is contributed by the stockpile component. For coarse aggregate, however, samples within the stockpile component show greater variance than between stockpile components. This indicates a need for a closer look at the currently used stockpiling and sampling procedures.
4. It is probable, from the values in Table 9 for precast prestressed concrete, that a 28-day average strength of 7700 psi is about the minimum average strength allowable, if it is desired to have all of the test cylinders break at or above the present minimum requirement of 5000 psi.

Clearly, much information can be gained by comparing the variability characteristics of the different plants, contractors, and the like, not necessarily for the purpose of condoning one plant and its operator or one contractor and the inspectors, but rather to obtain insight into the basic pattern of variability that can be expected from an adequately controlled operation or process. Data collected from different plants or contractors,

TABLE 10

COMPONENTS OR VARIANCE FOR SLUMP AND AGGREGATE GRADATION
(Analysis of Variance)

| Source of Variance | Components of Variance | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Paving | | | | Structural | | | |
| **Slump** | | | | | | | | |
| Sites | 0.24 | | | | 0.40 | | | |
| Trucks/sites | 1.08 | | | | 0.31 | | | |
| Error | 0.11 | | | | 0.11 | | | |
| **Gradation of fine aggregate** | No. 4 | | No. 16 | | No. 50 | | No. 100 | |
| Stockpiles | 1.90 | | 57.69 | | 0 | | 1.34 | |
| Samples/stockpiles | 0.32 | | 10.72 | | 39.88 | | 0.40 | |
| Error | 0.20 | | 0.70 | | 5.36 | | 0.04 | |
| **Gradation of coarse aggregate** | 1 In. | | ¾ In. | | ½ In. | | No. 4 | |
| Grade | A | B | A | B | A | B | A | B |
| Stockpiles | 9.97 | — | 40.72 | 97.49 | 26.72 | — | 0.72 | 0.20 |
| Samples/stockpiles | 5.65 | — | 77.62 | 116.47 | 132.04 | — | 0.76 | 0.94 |
| Error | 0.84 | — | 6.41 | 3.58 | 9.18 | — | 0.13 | 0.22 |

representing a cross section of the industry in the state, can be analyzed, and the resulting statistical information (means and sigmas), when pooled, will serve as a guide for the evaluation of tentative specifications. If nothing else, it will definitely help make a comparative analysis of existing and derived specifications and determine whether there is justification for revision of "intuitive" specifications.

## ACCEPTANCE SAMPLING BY VARIABLES

Whenever acceptance is to be based on sampling of bulk material, such as a stockpile of aggregate or a batch of concrete or hot-mix, "variables sampling plans" are most likely to be used. In such plans, the characteristic in question is measured along a continuous scale in terms of pounds per cubic foot, inches, psi, seconds, etc., as opposed to "attributes inspection," where an item is classified as either defective or nondefective, or by the number of defects in it. A practical advantage of using the variables inspection plan is the reduced sample size required for specified degrees of protection.

The acceptance function of any inspection must be coupled with a well-adopted sampling plan, which should specify (a) the size of the sample, (b) the critical value or values of the variable for lot acceptance, and (c) the probability of accepting bad products and rejecting good ones.

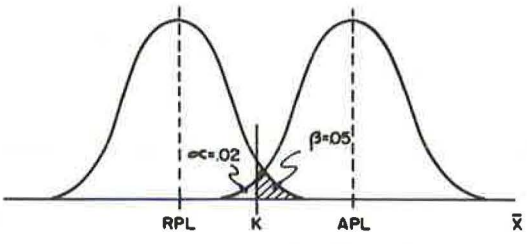


Figure 5. Distribution of $\bar{X}$ for APL and RPL and the corresponding risks (one-way protection on means).

A strict application of the variables sampling plan requires a rather strong assumption concerning the distribution of the quality characteristic under consideration, namely, that it be normal. The frequency distribution of many measurements is roughly normal, and hence, from a practical point of view, this assumption is considered valid.

### One-Way Protection on Means

Basically, the plan calls for determination of sample size n and acceptance tolerance E and operates as follows:

1. Select a random sample of size n from the lot.
2. Find $\bar{X}$, the mean of this lot.
3. If $\bar{X}$ is greater than or equal to some value K, accept the lot; otherwise, reject it or take corrective action.

With any sampling plan, we are required to assume what is called the producer's and consumer's risk. In acceptance sampling, there is always a chance that one may erroneously reject a good lot, which would be a sacrifice for the producer or contractor. This is the producer's risk, $\alpha$. On the other hand, one may accept a bad lot erroneously, which would be a risk for the consumer or the state, $\beta$. What can be considered satisfactory risks depends on the criticality of the variable and the economics of sampling and testing. However, if the variable is considered critical enough to affect the successful performance of the end product, then the risks should be adopted accordingly. It is believed that for a major characteristic such as compaction of base course, the producer's risk can be set at 0.02 and the consumer's risk at 0.05; $\alpha = 0.02$ means that the probability of rejecting lots of acceptable mean quality is 0.02. Likewise, $\beta = 0.05$ means that 5 percent of the time bad lots would be acceptable if offered by the contractor. This is shown graphically in Figure 5.

To determine the value of n, the sample size, two equations are needed. The simultaneous solution of these two equations, containing standardized normal deviations associated with $\alpha$ and $\beta$, will give the desired sample size and the acceptance limits (2, 5).

## Two-Way Protection on Means

The preceding plan was for variables requiring only one-way protection. Similar reasoning can be applied to variables requiring two-way protection.

Again, assuming normal distribution of sample means, the problem can be illustrated graphically as in Figure 6. Once again, the choice on risks will depend on the criticality of the characteristic.

These single-sampling plans were based on the statistic $\frac{\bar{X} - \bar{X}'}{\sigma/\sqrt{n}}$ where $\sigma$, the universe standard deviation, was assumed known. However, when this value is not known the statistic $\frac{\bar{X} - \bar{X}'}{s/\sqrt{n}}$ can also be used, s being the sample standard deviation. For small samples, say, $n \leq 12$, the statistic $\frac{\bar{X} - \bar{X}'}{R}$ can be used. R in this case represents the range or the difference between the maximum and the minimum value in the group (5).

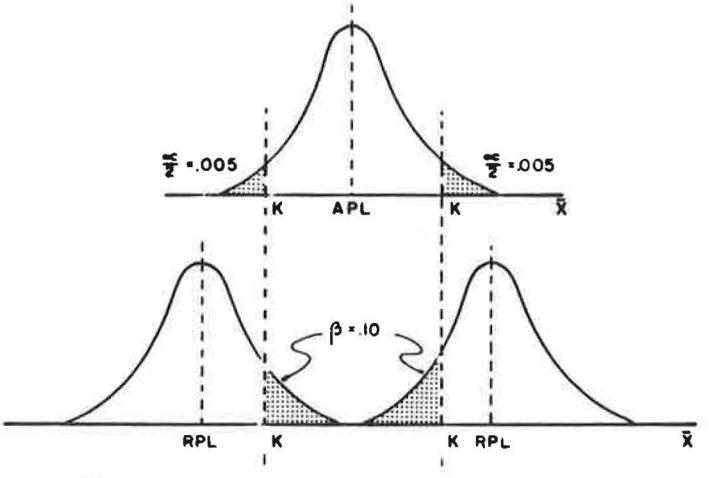


Figure 6. Distribution of $\bar{X}$ for APL and RPL and the corresponding risks (two-way protection on means).

## CONTROL CHARTS

Control of any repetitive process, such as production of portland cement concrete or asphaltic concrete, is of prime importance. A control chart is a statistical tool that gives a visual indication of the state of control of any production process. It is an instrument to be used in specification, production, and inspection and when so used brings these three phases of industry into an interdependent whole (6).

The variables control charts most commonly used are average or $\bar{X}$-charts and range or R-charts. An $\bar{X}$-chart shows variation in the averages of samples. On it are drawn the central line and upper and lower control limits.

A sample of n items is taken from the process at some interval of time or quantity, and after determining the quality measurement, the average of these n items is plotted on this chart. As long as the points fall within the band, the process is considered to be in control. If a point falls outside the control limits, the process is said to be out of control and an investigation is made to find the assignable cause of this variation. The R-charts are similar, except that instead of means of n items, the ranges are plotted and any point outside the band indicates lack of control with respect to the variability of the process.

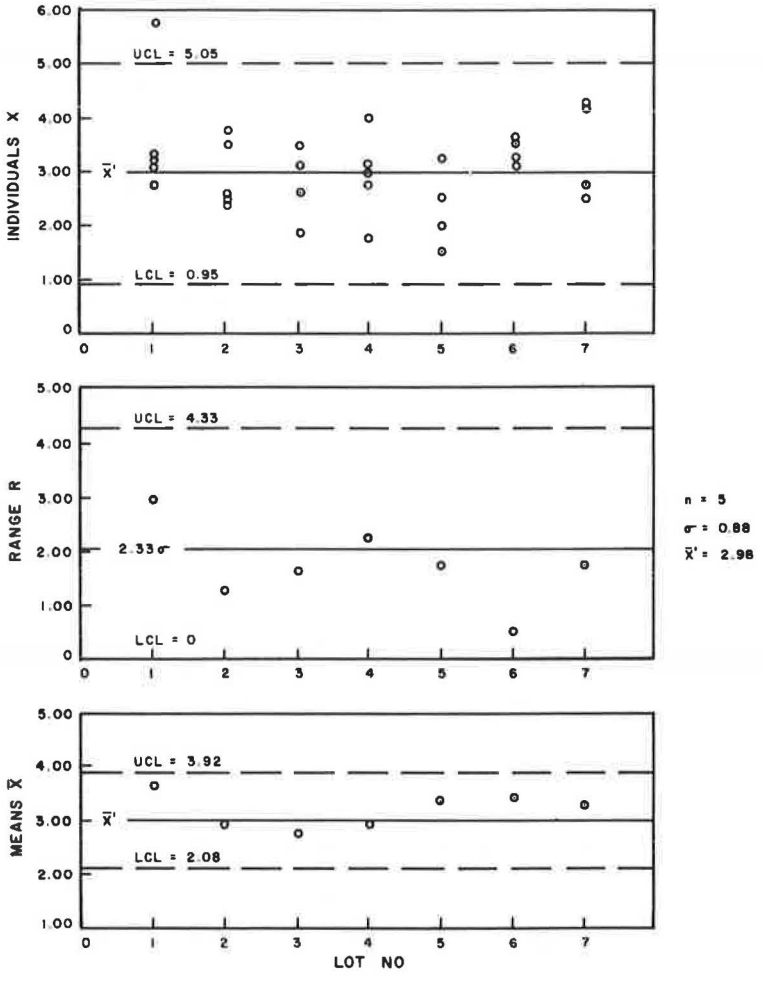


Figure 7. Control charts for acceptance and control of production (slump of structural concrete).

Sometimes the charts can be used as dual-purpose charts—to control current production and also for acceptance of the lot. Figure 7 shows the use of such charts for slump of structural concrete. To illustrate the dual purpose of the charts, the slump measurements were arranged consecutively in subgroups of five. Interesting observations can be made from these charts. For example, the chart for means shows Lot 1 to have slump values close to the upper limit, which suddenly drop to the central value for Lot 2 and keep on decreasing to a value where they barely meet the lower tolerance limit for Lot 5. Adjustments were made to bring the process in control, as indicated for Lot 6.

If a point falls outside the limits on the $\bar{X}$-chart, the chart for individuals will show whether the shift in the mean was due to one value or to the whole group, as illustrated by Lot 1 on the chart for individuals. The middle chart represents a control chart for ranges, and illustrates the shift of variability from lot to lot.

## SUMMARY

An attempt has been made to present some of the major findings obtained in the Louisiana study on quality control analysis of highway construction materials (1, 2, 3). It was shown how historical data can be used to calculate statistical parameters. It was further shown how the variables sampling plan can be constructed and applied in cases where the standard deviation is known. The lack of compatibility between currently used specification limits and statistical parameters was also brought forth in the analysis. The terminal criteria of the entire study are summarized in Tables 11, 12, and 13.

The effectiveness of the sampling plan discussed in the tables can only be evaluated when applied to actual jobs during construction. Therefore, it is suggested that:

1. Three separate projects for each of the major material characteristics (soils, concrete, and asphaltic concrete) be selected for such an evaluation. The sampling plans for means and individuals and the corresponding acceptance limits can be incorporated in the contract specifications as special provisions for research purposes only.
2. Control charts be utilized whenever a production process is involved. Such charts, in addition to serving as important tools for control of current production, can serve as a permanent record of production, sampling, testing, and acceptance.

TABLE 11

SUMMARY OF SUGGESTED LIMITS FOR ASPHALTIC CONCRETE

| A. Job Mix Tolerances | Control Limits | |
|---|---|---|
| | Average of 2 Tests | Individual Test |
| 3/4-in. sieve | ±6 | ± 9 |
| 1/2-in. sieve | ±9 | ±12 |
| 3/8-in. sieve | ±7 | ±10 |
| No. 4 sieve | ±7 | ±10 |
| No. 10 sieve | ±6 | ± 9 |
| No. 40 sieve | ±5 | ± 7 |
| No. 80 sieve | ±4 | ± 5 |
| No. 200 sieve | ±2 | ± 3 |
| Percent bitumen | ±0.4 | ±0.6 |
| Mix temp., deg F | ±25 | ±40 |
| **B. Marshall Stability and Flow** | **Acceptance Limits, Average of 4 Tests** | **Control Limits, Individual Test** |
| AC-5, BC, and WC (Type 1, 2, 4) | 1100 min 15 max | 800 min 18 max |
| AC-3, BC, and WC (Type 1, 2, 4) | 1200 min 15 max | 900 min 18 max |
| **C. Roadway Density** | **Average of 5 Tests** | **Individual Test** |
| Percent of laboratory density | 96 | 93 |

TABLE 12

SUMMARY OF SUGGESTED LIMITS FOR SOIL AND AGGREGATE BASE COURSE

| Characteristic | Acceptance Limits | Control Limits |
|---|---|---|
| A. Compaction (percent) | Average of 5 Tests | Individual Test |
| Raw | 101 min | 95 min |
| Stabilized | 96 min | 90 min |
| B. Thickness (in.) | Average of 4 Tests | Individual Test |
| 6 | 5.50-6.75 | ±1.50 |
| 8 | 7.50-9.00 | ±1.75 |
| 10 | 9.00-11.50 | ±2.75 |
| C. Gradation of SCG "A" (percent passing) | | |
| ¾-in. | 87-93 | 83-98 |
| No. 4 | 50-61 | 43-70 |
| No. 40 | 26-39 | 17-49 |
| No. 200 | 11-17 | 7-22 |
| D. Gradation of SCG "B" (percent passing) | | |
| No. 4 | 60-73 | 51-83 |
| No. 40 | 35-49 | 26-58 |
| No. 200 | 11-17 | 5-29 |
| E. Moisture content (percent) | | |
| Soil cement | ±2 | — |
| F. Width (feet) | | |
| Less than 22 | ±4 in. | — |
| Greater than 22 | ±6 in. | — |

TABLE 13

SUMMARY OF SUGGESTED LIMITS FOR CONCRETE AND CONCRETE AGGREGATES

| Characteristic | Acceptance Limits | Control Limits |
|---|---|---|
| A. Slump of Concrete (in.) | Average of 5 Tests | Individual Test |
| Paving | 1.75-4.25 | 6.50 max |
| Structural | 2.00-4.00 | 5.75 max |
| B. Thickness of pavement (in.) | | |
| 8-in. uniform | 7.75 min | — |
| 9-in. uniform | 8.75 min | — |
| 10-in. uniform | 9.75 min | — |
| C. Gradation of fine aggregate (percent passing) | | |
| | Average of 4 Tests | |
| No. 4 | 96-100 | 95-100 |
| No. 16 | 70-90 | 62-95 |
| No. 50 | 8-24 | 3-29 |
| No. 100 | 0-4 | 0-5 |
| D. Gradation of Grade "A" coarse aggregate (percent passing) | | |
| 1-in. | 90-100 | 88-100 |
| ¾-in. | 60-90 | 53-97 |
| ½-in. | 20-52 | 10-60 |
| No. 4 | 0-3 | 0-4 |
| E. Gradation of Grade "B" coarse aggregate (percent passing) | | |
| ¾-in. | 55-90 | 45-100 |
| No. 4 | 0-3 | 0-4 |

3. The process control be transferred to the contractor for effective implementation of the overall program.

The Louisiana Department of Highways has prepared tentative special provisions for field evaluation of the suggested asphaltic concrete specifications. These are included in the Appendix. The specifications are by no means complete or final, but they do represent suggestions from construction personnel and the contractor group. Fortunately, the latter has indicated favorable response to the overall approach. While the approach is not new, the application is. Considerable effort will be needed to accommodate this change.

Summing up, the correctness of any specification is determined by the mathematical relationship between use and production coupled with cost. Specifications should be based fundamentally on facts and these must be known first. They must come from a study of the product, of its use, and its production. Last but not least, the correct specifications mean an open, cooperative effort by the producer and consumer. Each must be conversant with the problems of the other and both must be willing to study the overall problem.

## ACKNOWLEDGMENT

Most of the data presented here were obtained in the study entitled "Quality Control Analysis," Research Project No. 63-1G, under the HPR program in cooperation with the U. S. Bureau of Public Roads.

The opinions, findings, and conclusions expressed in this publication reflect the views of the authors and not necessarily those of the Bureau of Public Roads.

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# *Appendix*

## DEFINITIONS

The mean, $\bar{X}$, is a measure of central tendency of a group of measurements. Mathematically,

$$\bar{X} = \frac{\Sigma X_i}{n}$$

where

$X_i$ = individual observations, and
n = number of observations in a group.

The standard deviation, $\sigma$ (sigma), is a measure of the dispersion of the measurements from their mean. The mathematical definition is

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

where

$X_i$, $\bar{X}$ and n are as above.

The variance, $\sigma^2$, is the square of the standard deviation.
The standard error, $\sigma_{\bar{x}}$, is the standard deviation of the mean of several samples and is estimated by

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

The pooled standard deviation, $\sigma_p$, is the average standard deviation of several samples and is estimated by

$$\sigma_p = \sqrt{\frac{(n_1 - 1)\,\sigma_1^2 + (n_2 - 1)\,\sigma_2^2 + \ldots + (n_k - 1)\,\sigma_k^2}{n_1 + n_2 + n_3 + \ldots + n_k - k}}$$

SYMBOLS

APL—An Acceptable Process Level that yields product quality that should be accepted almost all of the time.
E—The specification tolerance that determines acceptance limits.
K—The desired value for acceptance of the lot.
k—The number of subgroups.
LL—Lower limit.
n—The number of observations in a group.
$P_a$—The probability of accepting good material having the desired average value.
$P_r$—The probability of rejecting bad material having the lowest acceptable average.
RPL—A Rejectable Process Level that yields product quality that should be rejected almost all of the time.
UL—Upper limit.
$\alpha$—The producer's risk or the probability of rejecting lots of acceptable mean quality.
$\beta$—The consumer's risk or the probability of accepting lots of rejectable mean quality.
$\Sigma$—A symbol for summation of values.
$\sigma_a^2$—The inherent process variance.
$\sigma_t^2$—The variance due to test method.

## SPECIAL PROVISIONS FOR BITUMINOUS PAVEMENTS SECTION 501 & 502 OF THE STANDARD SPECIFICATIONS FOR ROADS & BRIDGES

## SECTION 501 PLANT MIX PAVEMENTS—GENERAL

### 501.01 DESCRIPTION

The second paragraph of this subsection is amended to read as follows:

This work shall consist of one or more courses of bituminous mixture constructed on the prepared foundation in accordance with these specifications and the specific requirements of the type under contract, and in reasonably close conformity with the lines, grades, thicknesses, and typical cross sections shown on the plans or established

by the Engineer. Work will be accepted on a lot to lot basis as described in subsection 502.04.

501.02 COMPOSITION OF MIXTURE

Delete this subsection and substitute the following:

The bituminous plant mix shall be composed of a mixture of aggregate, filler, if required and bituminous material blended together. The several aggregate fractions shall be sized, graded and combined in such proportions that the resulting mixture meets the physical characteristics of these specifications.

(a) Quality Control of Mixes: The Contractor will assume full responsibility for the quality control of the mixes supplied to the Department. He will assume responsibility for the initial determination and all necessary subsequent adjustments in proportioning of materials used to produce the specified job mix and other physical characteristics. The Contractor will have available at all times during the plant operation, the testing equipment necessary to perform the required tests and analyses.

The Contractor will be required to have present during the initial set up and for all subsequent adjustments of the plant for quality control of the mixes, a Certified Asphaltic Concrete Technician. A Certified Asphaltic Concrete Technician is that person who is capable of designing the asphaltic concrete mixes at the plant. He will also be capable of conducting any tests and/or analyses necessary to put the plant into operation and to produce a mixture within the requirements of the specifications. The certification will be awarded by the Department upon satisfactory completion of an examination.

The Department's Inspector will also be a Certified Asphaltic Concrete Inspector. He will never assume by act or word the responsibility of testing and analysis of the mix for control purposes, calculations or the setting of dials, gages, scales and meters. Such duties are to be assumed only by the Contractor.

In the event the Contractor is not in a position to provide a Certified Asphaltic Concrete Technician as specified in the previous paragraphs for quality control of mixes, then the Department shall be so notified in writing prior to operation of the plant. Upon request from the Contractor, the Chief Engineer may furnish on a loan basis, a Certified Asphaltic Concrete Technician from within the Department's personnel, at a cost of $50.00 per day charged to the Contractor. However, this will not relieve the Contractor of the responsibility of controlling the mix. The Chief Engineer may also authorize rental of Department's Laboratory testing equipment at a rate of $5.00 per day of possession.

(b) Job Mix Formula: No work shall be started nor any mixture accepted until the Contractor has submitted in writing for approval, his intended source of all component materials and his job mix formula for the mixture he proposes to furnish. The formula so submitted shall indicate a single definite percentage of aggregate passing each required sieve size, a single percentage of bituminous material to be added to the aggregate, a single temperature at which the mixture is to be produced and the wet and dry mixing time.

(c) Approval of Job Mix Formula: Following the initial set up of the asphaltic concrete mix according to the Contractor's submitted job mix formula, the plant shall operate at least 30 minutes prior to sampling of the mix by the Engineer. Four trucks shall be sampled at random for determination of Marshall Test properties as based on one briquette per sample. Only two of these samples shall be analyzed for bitumen content and extracted gradation. The plant may continue to operate while the samples are being analyzed at the plant laboratory and the material produced prior to obtaining these results may be accepted. The average of these four samples will conform to the requirements for Marshall Stability and Flow as specified in Table 1.

Dry and wet mixing time shall be such as to give 95% or better coating of the coarse aggregate particles when tested in accordance with AASHO T 195. Other pertinent design properties shall be as specified in the Laboratory Manual. The bitumen content and extracted gradation shall be within the job mix formula initially submitted by the Contractor. In the event the samples fail to meet the requirements of the design criteria, immediate adjustments shall be made to correct the mix. Any mix that does

TABLE 1

| Type of Mix | Marshall Stability @ 140°F, lbs. | Flow 1/100" |
|---|---|---|
| Type 1, 2, & 4 | | |
| AC-3, BC & WC | 1650 | 15 Max |
| AC-5, BC & WC | 1500 | 15 Max |
| Type 3 | | |
| AC-3, Base | 1650 | 15 Max |
| AC-3, Binder | 1830 | 15 Max |
| AC-3, Wearing | 2250 | 15 Max |

not meet the design, while the plant is being adjusted until the design criteria are met, will be paid for at 50% of the contract unit price of the aggregate provided the mix is satisfactory for the use intended.

The Engineer may permit the Contractor to change the job mix formula provided the changed job mix meets all the physical requirements of the specifications. The request to make this change shall be made in writing by the Contractor to the Engineer.

(d) Application of Job Mix Formula and Allowable Tolerances for Control of Mixes: Maintenance of adequate control on the quality of bituminus mixes shall be the responsibility of the Contractor. In order to check this control, the Contractor shall obtain a minimum of two samples of the mixture from each lot. A lot shall be considered as one day's production of the mixture. He shall obtain these samples using a stratified random sampling plan. One of the samples shall represent the morning control and the other indicative of the afternoon control. The time at which to obtain these two samples shall be set by the Contractor using random number tables.

The Contractor shall conduct his operations so as to produce a mixture conforming to the approved job mix formula except that variations shall be permitted within specified control limits for individual and average of two samples. Results of each lot shall be charted on the Control Charts for Individuals and Averages. The upper and lower control limits for individuals and averages shall be set at the following values from the specified job mix formula.

TABLE 2

| U. S. Sieve | Control Limits | |
|---|---|---|
| | Individual | Average of 2 Tests |
| 3/4 inch and larger | ± 9 | ± 8 |
| 1/2 inch | ±12 | ± 9 |
| 3/8 inch | ±10 | ± 7 |
| No. 4 | ±10 | ± 7 |
| No. 10 | ± 9 | ± 6 |
| No. 40 | ± 7 | ± 5 |
| No. 80 | ± 5 | ± 4 |
| No. 200 | ± 3 | ± 2 |
| % Bitumen | ±.6 | ±.4 |
| Temp. of Mix, °F.* | ±40 | ±25 |

* As based on the approved mixing temperature measured after discharge.

When the tendency of the individual test results on the control charts indicate that the mix falls outside of the control limits for individuals, then the Contractor shall make adjustments to bring the mix into the job mix formula.

Individual materials from more than one source shall not be used alternately nor mixed when used in surface courses without the written consent of the Engineer. Where additional sources of materials are approved, a job mix formula shall be established and approved before the new material is used. When unsatisfactory results or other conditions make it necessary, the Contractor may be required to establish a new job mix formula.

## 501.15 MIXING

The second paragraph of this subsection is amended to read as follows:

After the required amounts of aggregate and bituminous material have been introduced into the mixer, the materials shall be mixed until a complete and uniform coating of the particles and a thorough distribution of the bituminous material throughout the aggregate is secured. Dry and wet mixing time shall be submitted by the Contractor on the basis of a single determination and will conform to the minimum requirement given in Subsection 501.02(c).

## 501.18 SURFACE TOLERANCES

Delete this subsection and substitute the following:

(a) Job Control Testing: The Contractor shall test the surface of the completed course with a 10 foot straight edge. Necessary corrections shall be made to the Engineer's satisfaction.

(b) Acceptance Testing: The surface shall be tested by the engineer, using a rolling 10-foot straight edge at randomly selected longitudinal and transverse locations in accordance with LDH designation TR . The sample shall consist of one path of the rolling straight edge, 500 feet in length, and shall be selected using random sampling procedures. This sample shall represent each lot. A lot shall constitute one day's production of bituminous mix. In the event that a lot results in less than 500 linear feet of roadway, then the entire lot shall be tested. All surface tolerance testing shall be done as soon as practical after the construction of the lot.

Two surface tolerance settings shall be used for the testing of a sample as shown below:

| | |
|---|---|
| Types 1, 2 and 4 Mixes and Shoulders: | 1/8 inch and 3/16 inch. |
| Type 3 Mix: | |
| Asphaltic Concrete Base Course | 3/8 inch and 1/2 inch. |
| Asphaltic Concrete Binder Course | 1/4 inch and 1/2 inch. |
| Asphaltic Concrete Wearing Course | 1/8 inch and 3/16 inch. |

Whenever sections of pavement do not meet the requirements for surface tolerances, an adjustment in the unit price for the lot of the mixture shall be made as further outlined in Subsection 502.12.

For type 3 mix the maximum deviation from grade established by the engineer or cross section at any point shall not be more than:

| | |
|---|---|
| Asphaltic Concrete Base Course (Second and Intermediate layers) | 1/2 inch. |
| Asphaltic Concrete Binder | 3/8 inch. |
| Asphaltic Concrete Wearing Course and Each Successive Layer | 1/4 inch. |

When tested longitudinally from a stringline or comparable method applied parallel to the surface on any 25 or 50 foot section, such section shall not vary more than the specified limits given in the following schedule.

| Interval | Base, Second and Intermediate Layers | Binder | Wearing |
|---|---|---|---|
| 25 feet | 1/2 inch | 3/8 inch | 1/4 inch |
| 50 feet | 5/8 inch | 1/2 inch | 3/8 inch |

The above requirements shall be met 95 percent of the time with no single measurement to exceed the specification requirements by more than ½ of the tolerance specified. Any deviation below the 95 percent tolerance will require correction of all deficient areas.

Any irregularities in the base or any intermediate course may be corrected by either skin patching, featheredging, or full depth patching, where appropriate, and where it can be completed in a satisfactory manner.

To correct the irregularities of the finished surface, skin patching will not be permitted. When the requirements specified above are not met, and the contractor elects to remove the section in question, then it will be done at his expense, to a minimum depth of one inch and replace it with additional mixture meeting these requirements. Featheredging at any intermediate point will not be permitted on the pavement except when specified on the plans or in the special provisions.

## SECTION 502 ASPHALTIC CONCRETE PAVEMENT

### 502.04 PHYSICAL PROPERTIES OF MIXTURE FOR ACCEPTANCE

Delete this subsection and substitute the following:

The Contractor shall design his mix with the intent that compacted specimens of the mixture shall conform to the properties in Table 3 when tested in accordance with LDH Designation: TR 305, for an average of four samples taken from each lot after it is placed in the trucks using random sampling procedures. A lot shall be considered as one day's production of bituminous mix. A stratified random sampling plan shall be utilized such that two of the four samples are obtained during the morning and the other two during the afternoon using LDH Designation: S . The time at which these acceptance samples are obtained from the trucks shall be set by the Engineer using random number tables.

Compaction of mixtures for Marshall Stability and Flow determination shall be conducted by the Engineer's personnel at the plant. The testing and final approval of the mixture will be done by the District Laboratory.

When the average of four tests is outside of the acceptance limits specified for the average of the four test results for Marshall stability, an adjustment in the unit price for the lot of the mixture shall be made as further outlined. No adjustment in the unit price will be made for mixture being outside the limits on the individual results except as noted below.

Whenever it is not possible to sample the whole lot (four samples) due to unfavorable circumstances caused by plant breakdown or inclement weather or other causes, then the acceptance limits will be as shown in Table 3 as based on the number of tests made during the time the plant was in operation. In no event will the number of tests or samples be less than four for more than six hours of plant operation and less than two for four hours of operation.

In the event the plant operates for less than four hours and only one sample has been obtained, then the mix will be accepted on the basis of limits for one sample.

When the average of the number of tests representing the period the plant was in operation for the day is outside the acceptance limits for Marshall stability shown in Table 3 for the average of the number of samples tested during the day, an adjustment in the unit price for the lot of the mixture represented by the number of samples shall be made as further outlined in Subsection 502.12.

No adjustment in the unit price shall be made for mixes being outside the limits on the Flow for the average of the lot or the individual test result.

### 502.05 HANDLING OF AGGREGATES

Delete the second paragraph of this subsection.

### 502.06 PREPARATION OF ASPHALT AND AGGREGATES

Delete the second paragraph. The third and fourth paragraphs of this subsection are amended to read as follows:

TABLE 3

| Type of Mix | Acceptance Limits for Marshall Stability Average of: (Samples) | | | | Control Limits for Flow Average of: (Samples) | | | |
|---|---|---|---|---|---|---|---|---|
| | 4 | 3 | 2 | 1 | 4 | 3 | 2 | 1 |
| Type 1, 2, & 4 | | | | | | | | |
| AC-3, BC & WC | 1200 Min | 1150 Min | 1050 Min | 900 Min | 15 Max | 15 Max | 15 Max | 18 Max |
| AC-5, BC & WC | 1100 Min | 1050 Min | 1000 Min | 800 Min | 15 Max | 15 Max | 15 Max | 18 Max |
| Type 3 | | | | | | | | |
| AC-3, Base | 1200 Min | 1150 Min | 1050 Min | 900 Min | 15 Max | 15 Max | 15 Max | 18 Max |
| AC-3, Binder | 1450 Min | 1400 Min | 1300 Min | 1100 Min | 15 Max | 15 Max | 15 Max | 18 Max |
| AC-3, Wearing | 1800 Min | 1700 Min | 1600 Min | 1350 Min | 15 Max | 15 Max | 15 Max | 18 Max |
| Shoulder | 1100 Min | 1050 Min | 1000 Min | 800 Min | 15 Max | 15 Max | 15 Max | 18 Max |

The temperature of the bituminous mixtures, when discharged from the mixer, shall be within the limits prescribed in Table 2 of Subsection 501.02.

The dried mineral aggregate for any of the various type mixtures shall be combined in the plant in the proportionate amount of each fraction of aggregate required to meet the job mix formula. The bituminous material shall be measured and introduced into the mixer. Prior to adding bituminous material, the combined mineral aggregate shall be thoroughly mixed dry, after which the proper amount of asphalt shall be sprayed over the mineral aggregate and mixed to produce a homogeneous mixture in which all particles of the mineral aggregate are uniformly coated. The mixing time shall be submitted by the Contractor in the job mix formula and approved by the Engineer. Suitable locking means shall be provided for this regulation.

## 502.09 COMPACTION

The second and ninth paragraphs of this subsection are amended to read as follows:

The highest contact pressure that will give the required density will be used for the pneumatic roller.

Rolling shall continue until all roller marks are eliminated. Upon completion of the rolling procedures, five pavement samples shall be obtained from each compacted lot at locations determined in accordance with the stratified random sampling plan within 24 hours after placement of the mix. In the event this falls on a holiday or a Sunday and the Contractor's crews are not working, then the sampling will be done the following day. A lot shall be considered as the number of linear feet of mix laid during the days' operation. The linear feet laid during the day shall be subdivided into five sections of approximately equal length and one sample shall be obtained from each of the five sections using random number tables. In no event will the number of samples representing a full day's production or a fraction thereof be less than five. The density requirement for individual samples and for the average of five samples shall be as prescribed in Table 4 when determined in accordance with LDH Designation TR 304.

Payment will be made as outlined in Subsection 502.12. No adjustment in the unit price will be made for density tests outside the limits for individual tests.

TABLE 4

| | Type of Mix | Acceptance Limits | Control Limits |
|---|---|---|---|
| | | Average of 5 Samples | Individual Samples |
| Traffic Lanes | 1 and 4 | 96% min of briq. density | 93% min of briq. density |
| Traffic Lanes | 2 | 92% min of briq. density | 89% min of briq. density |
| Traffic Lanes | 3- 1st lift of asphalt conc. base course | 95% min of briq. density | 92% min of briq. density |
| | -All additional layers of asph. conc. base course | 97% min of briq. density | 94% min of briq. density |
| | -WC and BC | 97% min of briq. density | 94% min of briq. density |
| Shoulders | 1, 2, 3 and 4 | 93% min of briq. density | |

In the event the sampling location as determined by random sampling procedures indicates obvious bad spots that are to be replaced, or falls within two feet of the edge of the pavement, then an additional sampling location shall be determined and used.

## 502.12 BASIS OF PAYMENT

Delete this subsection and substitute the following:

The quantities of aggregate and asphalt in the completed and accepted asphaltic concrete pavement will be paid for at the respective contract unit prices per ton on a lot basis.

Whenever the mix does not conform to requirements for acceptance of mixes as provided in Subsection 501.18, 502.04 and 502.09 of these Special Provisions, payment shall be made at a unit price per ton of bituminous plant mix course of the type specified in accordance with the following:

Adjustment for Stability:

(a) When the mix is to be accepted on the basis of the average of four, three, two or one Marshall stability test result, then the payment per unit price shall be made as outlined in Schedule No. 1-A, 1-B, 1-C or 1-D respectively.

(b) For shoulder mixes representing more than 2,000 tons, the payment per unit price shall be made as outlined in Schedules 1-A through 1-D under AC-5 (column 2).

(c) No adjustment in the unit price shall be made on shoulder mixes used for turnouts, and similar miscellaneous areas representing less than 2,000 tons.

(d) The lower percent of contract price shall be used for final adjustment in unit price for mixes that are deficient in Marshall stability, roadway density, and surface tolerances.

SCHEDULE NO. 1 -ADJUSTMENT IN BID PRICE PER TON FOR MARSHALL STABILITY

| | Average of Four Marshall Stabilities | | | Percent of Contract Price/Ton of Aggregate Per Lot |
|---|---|---|---|---|
| Type 1, 2, & 4 WC, BC Type 3, Base AC-3 | Type 1, 2, & 4 WC, BC AC-5 | Type 3 Binder AC-3 | Type 3 Wearing AC-3 | |
| A | | | | |
| 1650 and higher | 1500 and higher | 1830 and higher | 2250 and higher | 105% Payment |
| 1200 to 1649 | 1100 to 1499 | 1450 to 1829 | 1800 to 2249 | 100% Payment |
| 1100 to 1199 | 1000 to 1099 | 1350 to 1449 | 1650 to 1799 | 95% Payment |
| 1000 to 1099 | 900 to 999 | 1200 to 1349 | 1450 to 1649 | 80% Payment |
| Below 1000 | Below 900 | Below 1200 | Below 1450 | 50% or Remove |
| B | Average of Three Marshall Stabilities | | | |
| 1150 and higher | 1050 and higher | 1400 and higher | 1700 and higher | 100% Payment |
| 1100 to 1149 | 1000 to 1049 | 1350 to 1399 | 1625 to 1699 | 95% Payment |
| 1000 to 1099 | 900 to 999 | 1200 to 1349 | 1450 to 1624 | 80% Payment |
| Below 1000 | Below 900 | Below 1200 | Below 1450 | 50% or Remove |
| C | Average of Two Marshall Stabilities | | | |
| 1050 and higher | 1000 and higher | 1300 and higher | 1600 and higher | 100% Payment |
| 1000 to 1049 | 950 to 999 | 1250 to 1299 | 1525 to 1599 | 95% Payment |
| 900 to 999 | 800 to 949 | 1100 to 1249 | 1350 to 1524 | 80% Payment |
| Below 900 | Below 800 | Below 1100 | Below 1350 | 50% or Remove |
| D | One Marshall Stability Test Result | | | |
| 900 and higher | 800 and higher | 1100 and higher | 1350 and higher | 100% Payment |
| Below 900 | Below 800 | Below 1100 | Below 1350 | 50% or Remove |

SCHEDULE NO. 2 - ADJUSTMENT IN BID PRICE PER TON FOR ROADWAY DENSITY

| | Average of Five Roadway Samples | | | Percent of Contract Price/ Ton of Aggregate Per Lot |
|---|---|---|---|---|
| Type 1 & 4 (WC, BC) | Type 3 (1st lift of Base Course) | Type 3 (Additional lifts of Base Course, AC & BC) | Type 2 (WC & BC) & Shoulder Mix | |
| 100.1% & More | 100.1% & More | 100.1% & More | 100.1% & More | 100% Payment |
| 98 - 100% | 97 - 100% | 99 - 100% | 97 - 100% | 105% Payment |
| 96 - 97.9% | 95 - 96.9% | 97 - 98.9% | 92 - 96.9% | 100% Payment |
| 95 - 95.9% | 94 - 94.9% | 96 - 96.9% | 90 - 91.9% | 95% Payment |
| 93 - 94.9% | 92 - 93.9% | 94 - 95.9% | 89 - 89.9% | 80% Payment |
| Below 93% | Below 92% | Below 94% | Below 89% | 50% or Remove |

SCHEDULE NO. 3 - ADJUSTMENT IN BID PRICE PER TON FOR SURFACE TOLERANCE

| Linear Percent of Sample Exceeding Surface Tolerance | | Percent of Contract Price/Ton of Aggregate Per Lot |
|---|---|---|
| Lower Tolerance Setting | Upper Tolerance Setting | |
| 1% or less. | None | 105 % Payment |
| 1 to 2%. | 0.5% or Less. | 100 % Payment |
| More than 2%. | 0.5 to 0.75%. | 95 % Payment |
| More than 2%. | 0.75 to 1.5%. | 80 % Payment |
| More than 2%. | More than 1.5%. | 50 % or Remove |

Adjustment for Roadway Density

For roadway density, the payment per unit price shall be adjusted as in Schedule No. 2 for the average of five samples in a lot.

Adjustment for Surface Tolerance

For surface tolerances, when measured by 10 foot rolling straight edge, the payment per unit price shall be adjusted as in Schedule No. 3 for the sample in a lot.