Report No. CDOT-DTD-R-93-14

# HBP QA/QC PILOT PROJECTS CONSTRUCTION IN 1992

Bud A. Brakey
Colorado Department of Transportation
4201 East Arkansas Avenue
Denver, Colorado 80222

Interim Report
June, 1993

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| CDOT-DTD-R-93-14 | | |

| 4. Title and Subtitle | 5. Report Date / 6. Performing Organization Code |
|---|---|
| Interim Report for the Hot Bituminous Pavement QA/QC Pilot Projects Constructed in 1992 | 5. Report Date: June 1993<br>6. Performing Organization Code: |
| 7. Author(s)<br>Bud A. Brakey | 8. Performing Organization Rpt.No.<br>CDOT-DTD-R-93-14 |
| 9. Performing Organization Name and Address<br>Colorado Department of Transportation<br>4201 E. Arkansas Ave.<br>Denver, Colorado 80222 | 10. Work Unit No. (TRAIS)<br>11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>Colorado Department of Transportation<br>4201 E. Arkansas Ave.<br>Denver, Colorado 80222 | 13. Type of Rpt. and Period Covered<br>Interim Report - 1 Year<br>14. Sponsoring Agency Code |

15. Supplementary Notes

A final report shall be written after the 1993 paving season.

16. Abstract

Evaluation of hot bituminous pavement construction has been based on passing or failing specified values. Tests were performed on aggregate gradation, asphalt cement content and compaction of the asphalt mix. The results of these tests are numerical values. Quality Level Analysis uses the numerical values of the tests and the laws of statistical analysis to assign a numerical value to the quality of a construction project. This gives the agency a basis for implementing an incentive payment for projects with above average quality.

Such a specification was written and tried on a few projects in 1992. This report details the results of those projects.

**Implementation:**

The specification has been included on several more projects that were awarded during the 1993 paving season. A final report will be written after the results of those projects are analysed.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| Quality, Assurance, Level, Statistics, Incentive. | No Restrictions: This report is available to the public through the National Technical Info. Service. Springfield, VA 22161 |

| 19.Security Classif. (report) | 20.Security Classif. (page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 57 | |

## TABLE OF CONTENT

# EXECUTIVE SUMMARY

The Colorado Department of Transportation took a step toward increasing the quality of the transportation system by trying a pilot program of Quality Level Analysis of hot bituminous pavement in 1992. The program consisted of writing a new and innovative specification for acceptance of hot bituminous pavement and implementing it on a few of its biddable projects.

Quality Level Analysis (QLA) uses the laws of Mathematics and, more specifically, the laws of Statistical Analysis to measure and evaluate the quality of a product. Using data gathered from asphalt paving projects in 1990 and 1991, a level of quality was assumed to be average. For the pilot program in 1992, if the product was better than average, a financial incentive was added to the payment for work. When the product was less than average, a financial disincentive or penalty was subtracted from the payment for work. Of the approximately 2,000,000 tons of asphalt mix bid in 1992, 282,000 tons were included in the pilot program.

No new tests were added to the agency's materials testing program. The tests used in the evaluation were aggregate gradation, asphalt cement content and compaction of the asphalt mat. This was the basis for quality acceptance and incentive payments.

The contractor was required to conduct another materials testing program for measuring quality control of the product. The same tests were required. The contractor was not restricted from conducting any other tests that they wished to. Exchange of information from test results was encouraged. The contractor's test results were not used for quality acceptance.

Initial analysis of the pilot program indicated an improvement over the average results of 1990 and 1991 asphalt paving projects. Since the amount of asphalt mix within the pilot program was considered to be smaller than originally hoped for (about 14% of all asphalt mix) and only seven of 25 field offices were involved, the pilot program has been extended for another year. At the end of the 1993 asphalt paving season another report will be written.

# HBP Pilot QA/QC Interim Report
# Construction Season of 1992

## HISTORY OF CDOT ACCEPTANCE PROCEDURES

Since about 1969, the Colorado Division of Highways, now known as the Colorado Department of Transportation (CDOT), has had a statistically based acceptance specification[1] (SBAS) which includes procedures for measuring the percent within tolerances for various construction materials. Formulas are included for disincentive payments (price adjustments, "P") to the contractor for those materials not in reasonably close conformity with the specifications. There are no provisions for incentive payments for improved quality and uniformity beyond the minimum requirements of the specifications.

The SBAS is based on lots containing from three to seven randomally selected samples, the lots are evaluated for variability by the range method (rather than standard deviation). A minimum of approximately 85 percent of the distribution must be within tolerances for the contractor to receive full payment. "P" is applied as the average values move toward or outside the limits, up to 25 percent. Materials with a "P" greater than 25 may be accepted, with various constraints, by engineering evaluation.

Over the 25-year history of the SBAS there have been only a few significant changes made to it. Today it is used primarily for aggregate sieve analyses, asphalt cements, liquid asphalts, and hot bituminous pavements (HBP). The HBP elements evaluated are field compaction, asphalt content and sieve analysis.

Originally, portland cement concrete (PCC) materials, both structural and pavement, were included in the SBAS. Gradually, separate sampling and acceptance procedures for these products have been developed to meet CDOT and industry needs. For the most part, PCC acceptance procedures are not statistically based; however, acceptance is generally based on the average of several samples.

Very little headway has been made towards shifting the responsibility for process control of aggregates, HBP and PCC to industry. Contractors and producers have continued to rely heavily on the CDOT acceptance tests for necessary process control information. Many of the producers do have their own laboratories (or routinely use private facilities) in order to monitor their products. But for CDOT work, acceptance tests are a primary source of information.

**QUALITY ASSURANCE/QUALITY CONTROL TYPE SPECIFICATIONS**

In about 1988, CDOT and the HBP Industry began to develop interest in quality assurance/quality control (QA/QC) type specifications. The primary components of QA/QC specifications are a sound, statistically based acceptance plan by the buyer, and a well organized process control procedure by the seller. A third part of the equation, considered essential by many, is a reasonable payment schedule (which may include disincentive and *incentive* payments) based upon statistically measured quality.

At about the time CDOT began developing interest in QA/QC, a WASHTO QA Task Group (TG) was organized to prepare a Model QA[2] specification. The CDOT materials engineer was a member of the TG. Early drafts from the WASHTO TG, supplemented by information from FHWA, provided the model for a 1989 CDOT QA\QC draft specification which was included as a special provision in about 20 projects constructed in 1990 and 1991. The specification was primarily applicable to HBP, but for a number of reasons, was not successfully implemented[3].

In early 1991, CDOT formed the Colorado Flexible Pavement Oversight Group. Prominent consultants, industry representatives and CDOT managers were invited to an organizational meeting in April. A broad agenda was established, with suggested objectives. Task groups were organized for many subject categories. The main Oversight Group met several times in 1991 and a number of successful efforts have been accomplished through its work.

One important need identified by the Oversight Group was development and implementation of QA/QC specifications for asphalt pavement construction. A QA\QC task group was formed and met independently several times in 1991. There was general consensus by the members, with full support by CDOT administrators, that a serious new effort should be made to develop and implement a specification. In October of 1991, CDOT employed Bud Brakey (former CDOT Staff Materials Engineer and more recently, Asphalt Institute District Engineer) as a consultant to work with the TG to develop and implement a pilot specification. Under direct supervision of the Staff Materials Engineer, with frequent reviews by the TG and CDOT managers, the consultant began a six-month effort that resulted in a pilot specification being implemented on seven projects in 1992.

Included in the pilot program, and considered key for its successful implementation, were the following:

- Support by industry (achieved by their involvement in the pilot development, training and informational meetings).
- Support by CDOT administrators, managers and personnel using the specification (by communication and training).
- Adequate training of all concerned (many sessions held for all levels).
- Provisions for incentive, as well as disincentive payments, tied directly to the quality level (QL) of work produced.
- A functional computer program to calculate QLs and pay factors (PF) which would store data and print usable reports (developed by CDOT computer technicians, updated and revised as needed on the projects).
- Early interim analysis of the first construction data in order to measure objectives. (Diskettes of the project computer files were provided at the close of the 1992 construction season for data analysis). The analysis follows.

## ANALYSIS OF THE PILOT PROJECTS

*Pilot Scope*

There were seven projects let to contract in 1992 with the HBP pilot QA/QC specification[4] included. There were two contracts in CDOT Region 1 (one was for two locations combined), two in Region 2, one in Region 3, one in Region 4, and one in Region 6. Region 5, in the southwest corner of the State was the only one without a pilot project. One of the projects in Region 1, on I 70 between Copper Mountain and Frisco, included 145,000 tons of HBP. Because of the short, mountain construction season, only 65,000 tons were placed in

1992. That quantity is included in the analysis as one of the seven projects. under the pilot specification, 282,000 tons were placed. A limited analysis of the bidding on the seven contracts shows the following:

**PILOT PROJECT BID ANALYSIS**

| Region | Identity | Quant. M T | Engrs Est. | Low Bid | % of Estimate |
|---|---|---|---|---|---|
| 1 | R1J1 | 65 | 25.00 | 24.20 | 96.8 |
| 1 | R1J2 | 43 | 32.00 | 28.30 | 88.4 |
| 2 | R2J1 | 25 | 27.00 | 21.05 | 78.0 |
| 2 | R2J2 | 24 | 17.00[1] | 14.50 | 85.3 |
| 3 | R3J1 | 58 | 18.00[1] | 16.96 | 94.2 |
| 4 | R4J1 | 23 | 38.00[2] | 30.85 | 81.2 |
| 6 | R6J1 | 44 | 30.90 | 29.00 | 93.9 |
| | TOTAL | 282 | | | |
| Aver., W'ted by Tons | | | 26.10 | 23.52 | 90.1 |

[1] Did not include asphalt cement.

[2] Included traffic control.

CDOT 1992 weighted averages and total (for same HBP categories), 783,000 tons, $25.50 estimate, $23.34 bid, or 91.5% of estimate.

The CDOT cost estimate unit used normal procedures for estimating costs on the pilot projects; that is, no loading of any kind was assigned to the HBP estimates bid under QA/QC. The above tabulation indicates the successful bidders apparently had no unusual concern about the specification. This can be attributed, at least partly, to the involvement of industry in the pilot development, plus training and communication efforts on the part of CDOT staff.

At the close of construction season in 1992, the Materials Branch conducted a survey of field personnel who had involvement with the QA/QC pilots. Appendix "A" contains the survey results. By about a two thirds majority, there is acceptance of the specification and the notion that it reasonably meets initial objectives. The results of the survey were used as a guide for some minor changes in the pilot specification as it was carried over for another season.

It had been intended originally to have approximately 20 pilot projects in 1992. Due to required lead time in bidding, difficulty in locating larger projects close enough to quality control facilities, etc; it became necessary to settle for a reduced pilot effort. In order to accumulate enough data for valid analysis and to allow greater contractor and State personnel familiarization, CDOT decided to continue the pilot for another season before drafting a Standard QA/QC specification. The 1992 data has been evaluated, however, in order to provide an interim measurement as to how well the original objectives are being met.

***Evaluation of Pilot Statistical Data***

A primary measurement of conformity to specifications, by statistical procedures, is QL, or percent within tolerances. The two dominant parameters used to calculate QL are the standard deviation (SD) of the individual measurements within a lot and the distance the lot average ($\overline{X}$) is inside tolerance limits ($\overline{X}$ - T).

To visualize how SD and $\overline{X}$ contribute to QL; just consider that with lower variability (smaller SD) and movement of $\overline{X}$ towards the center of the specification bands ($T_C$), QL will increase. An evaluation parameter of interest was how close the pilot $\overline{X}$s were to $T_C$ or target. Did the incentive concept result in $\overline{X}$ being more centrally located? With the current SBAS, it is possible to receive 100 percent payment when $\overline{X}$ is just a small distance inside the limits (there is no incentive to move closer to $T_C$).

The three elements included in the pilot specifications, for PF based on QL, are asphalt content, sieve analysis (both from the fresh, loose HBP mixture) and percent relative density of the compacted pavement (as a percent of maximum theoretical density, or Rice). Each specification sieve was evaluated for QL. The lowest QL on any specified sieve in a lot is used to determine the PF for the sieve analysis element. As expected, the #8 sieve turned out to be the critical sieve for nearly all lots. On the Region 6 project (R6J1), the 3/8" sieve was critical. This information shows up in the pilot analysis.

Tables 1 - 3 give the results of the pilot analysis to quantify reduction in variability (smaller SD), movement of $\overline{X}$ towards $T_C$, and increase in QL compared to historical data. Changes in the directions indicated imply that product quality has increased. The driving force behind this, of course, is incentive payment for higher QLs and disincentive payment for lower QLs. Requiring the contractor to take nearly full responsibility for his process should provide innovative actions to achieve incentive payments.

To normalize the data, the raw values for SD and distance from target are also expressed as a decimal of the historical value. Table 5 has detailed information to be discussed later, but may be referred to for the number of tests in the historical data and on each pilot project. The historical data represents most of the routine HBP work completed in 1990 and 1991.

Only a few projects have been awarded in the last year or so under a special provision with new, tighter tolerances on the No. 8 through 1/2" sieves. As an example, the standard tolerance is ±8% on the No. 8, while the special provision calls for a ±4%. All the HBP (Grading SF) on R1J1 had the tighter tolerances, as did 40,000 tons of SF on R6J1. All other HBP on the pilots had the more lenient tolerances. The Tables indicate these differences.

Asphalt Content

Table 1 summarizes the analysis of asphalt content tests. The SD for asphalt content on each of the projects is lower than the historical weighted average. The mean value of 0.13 for all pilots is 0.73 of the State value of 0.18. On six of the seven projects the average distance of the lot values is closer to target than was the historical average. On each project the QL is higher than the historical value. The pilot averages 96.9 compared to 88.0. The increase of 8.9 percent is a significant improvement in quality.

A seller's risk analysis for a double-limit specification shows the distance from tolerance limits to the process $T_C$ must be 1.9 SD for the risk to be 5 percent for receiving less than PF = 1.0 when the process is right on target. An additional width of 0.6 SD is necessary, for a 95 percent probability of PF = 1.04. Therefore, the specifications should be about 3.8 to 5.0 typical (or historical) SD in width. Bands narrower than 3.8 SD provide excessive seller's risk, wider than 5.0 SD make incentive payments unrealistically easy to achieve. The average asphalt content of 0.13 x 5.0 = 0.65; the band width of 0.6 is adequate. It should not be tightened to less than ±0.25 or excessive seller's risk will result.

Relative Density

Relative density tests are summarized in Table 2. On four of the seven projects, the SD for relative density percent decreased from the historical value of 1.05. The distance from target was less on five of the seven projects; the average being 0.71 of State. The average QL of the pilots increased by 5.6 percent; not as much improvement as for asphalt content, but still significant.

Noteworthy is that only two or three years ago, CDOT changed from requiring a minimum of 95 percent of laboratory density (by kneader compactor) to requiring 92 to 96 percent of maximum theoretical (Rice) density. In practice, this amounted to increasing the required minimum field density about one percent. For some mixtures and compaction procedures it was difficult to meet the new requirement, even before going into the pilot program. Considering this, the improved density quality level on the pilots is meaningful.

The bar graphs in Figures 1 - 4 illustrate the Pilot SDs, $\overline{X}$ distances from target and QLs as compared to historical data. Each of the three elements, asphalt content, relative density and sieve analysis is portrayed. Figure 5 is a relative frequency histogram for relative density. The apparent skewness of the values is exaggerated because the mean value is 0.7 percent below target and the normal distribution values at 91 percent are missing (skewness = mean - mode/SD). There is a slight positive skewness of 0.30, longer tail to the right.

It appears that based on nuclear field density tests, the contractors may have specifically rolled areas where their process control tests showed results below the minimum tolerance of 92 percent. If the rolling effort had been increased for the entire surface when occasional low values were found, the mean would have shifted to the right and the QL would have increased significantly. Rolling only the low density areas does increase QL a little; but as depicted on the histogram, the distribution formula takes its shape as if the missing values were there, even if they are not. To raise the QL a meaningful amount, **all areas with process values below the target of 94 percent should have additional compaction.**

Another interesting point is evident from the chart; only two percent of the reported values were at 96 percent (upper tolerance), and none were above. The upper limit may be unnecessary. If the contractors bring their process closer to the target of 94 (with SD = 1.0), they will receive some reduction in incentive payment when they have occasional high values. This could be self defeating. A contractor might decide it is just as well be low and get disincentives as to be high and get them; as it takes less rolling effort to be on the low side.

Per the discussion on asphalt content, a double limit band should be about 5.0 SD wide if a contractor is to receive 1.05 with a 95 percent probability when he is right on $T_C$. This means a 1.0 percent wider band than now specified, for SD = 1.0. However, the SD could possibly be reduced as low as 0.70 with careful process control (two pilot projects had 0.72), so leaving the current band width at 4.0 percent might encourage uniformity. In plotting and analyzing these data, it seems that reporting to the closest 0.1 percent would make field analysis more sensitive to increased rolling effort. For a very critical element, this could be important. It is recommended that these changes in limits and reporting be carefully evaluated.

<u>Percent Passing No. 8 Sieve,</u>

A summary of the #8 sieve test results is listed in Table 3. As discussed above, two tolerance widths were included in the pilot projects, ±4% for SF and ±8% for C and CX. Where applicable, both conditions are shown in the Table. As shown in Table 5, there was not nearly as much historical data available for the tighter tolerances. Based on this small sample, the SD is much smaller for ±4 than for ±8. This suggests that the producers can meet the tighter tolerance when specified, and that it is about the correct width for the current process capability.

Although the ±4 tolerances were met satisfactorily on R1J1, there were problems on R6J1. From discussions with CDOT project personnel and the contractor's representatives, there may have been lack of communications or some misunderstandings about the pilot specifications. In addition the plant may have had inadequate aggregate handling facilities. These happenings, more so than too narrow a specification band width, probably caused the low sieve analysis QL.

All the projects with the lenient tolerance of ±8% were "freebies" to the producers. The average SD was 0.73 of State; the average distance from target was 0.80 of State. The QLs ranged from 96.6 to 100, with an average of 99.6, while the State was 99.0. When there are wide tolerance bands that have traditionally been met easily, it is hard to show much improvement. It is recommended the tolerances in the Standard specifications be revised to agree with those being used with the experimental Grading "SF".

Project Composite PFs and Mean Quality Levels, Table 4

The pilot specification, Section 105[4], requires a composite PF for the HBP Item be computed by weighting the three element average PFs. The weighting factors (W) are 30 for asphalt content, 50 for relative density, and 20 for sieve analysis (each element PF multiplied by its respective "W", totaled and divided by 100). Table 4 lists a QL for each project, this value was determined by weighting each element QL (as reported in Tables 1-3) by its "W". The Item PFs came directly from the respective project QPM computer results, where the project element PFs are the average of the lot PFs, weighted by *quantity*.

*General Discussion of The QL and PF DATA*

During the development phase of the Pilot specifications, there was considerable discussion relative to impact on the contractors by disincentive PFs when QLs were in the range of ± 50. By the WASHTO Model[2] QA specification procedures, for "n" = 10, a PF of 0.75 is assigned when the QL reaches 50 (lot

$\overline{X}$ is right on tolerance limit). Because of concern by industry, the PF formulas were eased such that there was a gradual reduction in the severity of penalties when the QL was below about 85. Actually, for higher QLs the pilot formulas yielded slightly lower PFs than WASHTO[2]. This was a trade-off, and was provided partly to help the industry "buy in" to pilot effort.

Under QC type specifications, where the contractor has developed a quality control plan that is monitored closely by the engineer and contractor on a daily basis, there is only a small probability of receiving a very low PF on an individual element, to say nothing of having a worst case composite PF. There were 282,000 tons of HBP placed by 33 separate processes for three elements (on the seven contracts). Table 5 summarizes most of the pilot construction data related to QL, PF, lots and processes. From the Table, for R2J1, there was a 16 sample process for density with a QL of 72.4. This was the lowest *process* QL reported; using the WASHTO[2] PF table for "n" = 16, the PF would have been 0.907, far above the critical 0.75 value. Three processes had QLs of 70 - 79, five had QLs of 80 - 89, and 25 had QLs of 90+.

The 33 processes were broken into 163 lots of "n" = 3 to "n" = 27, with an average size of "n" = 6. The lowest QL (for a sieve analysis lot of 5), was 50; even using the WASHTO[2] PF table, the PF would have been 0.82, still significantly above the critical 0.75 value.

Out of 964 individual samples selected for the several elements, not a single sample was greater than the distance "V" out side the tolerances, the point by formula where a single-sample lot would receive PF = 0.75. The "V" factor is approximately one historical SD. Two of the processes with QLs in the 70s were on the same project where there may have been implementation problems. Based on the interim evaluation, it appears there is less than a one percent chance that an element process will receive a PF of under 0.90 or a small lot a PF of under 0.80.

In Table 5 there are three columns, 3, 4 and 6, containing QLs. Each element QL in Column 3 is the average of the lot QLs, weighted by the tons represented. Each number in "Item weighted by 'W'" row for each project is the average of the element values weighted by their "W". Where there was only one process for each element on a project, the weighted PF in Column 7 came directly from QPM report. If there were two processes for each element (the only other case), the weighted Item PF is the average of the two, weighted by the tons represented by each.

The pilot specification includes a unique concept that allows the acceptance sampling frequency to be reduced when the moving average of 5 samples has a QL (MQL) of 87 or better, called condition Green. When the MQL is at 65 - 86, condition Yellow exists, which requires return to the specified increased sampling frequency. When MQL is below 65, certain actions are required by the Contractor and Engineer, including remaining on an increased sampling schedule and instituting a check testing program between acceptance and quality testing personnel. The QPM software automatically adjusts to a default frequency (which can be overrode) as the color code conditions change.

Initially, CDOT wanted to reduce their testing effort from normal requirements where the process was well controlled by the Contractor. The contractors were concerned that if they happened to get out of control, a few widely spaced samples could represent a large quantity of material subject to reduced payment. Some CDOT personnel also had concerns about buyer's risk in accepting material at a higher PF based on infrequent samples.

The changes in sampling frequency, based on the MQL was a way of addressing these concerns, while examining the philosophy of reduced sampling frequency under a QA/QC specification. There has been some criticism of the concept because of its complexity (the QPM handled it well), and because the procedure (for determining PF for a process) sometimes evaluated different lot sizes ("n") from two sampling frequencies. The pilot has worked well and has not invalidated the unique statistical procedures specified.

This gets us back to Column 3. The average QLs for the elements were calculated from the series of lot QLs, some with closely spaced samples and some with widely spaced samples, weighted by tons represented. This condition did not exist for relative density. Because good density is so important for pavement performance, and since nuclear tests can be made rapidly, no reduction in testing frequency was allowed for condition Green.

The effect of this can be seen when comparing Column 3 to Column 4. Column 4 is the average QL of the lots in each process weighted by "n". As an example, Lot #1 QL of 80 x 3 samples plus Lot #2 QL of 97 x 7 samples divided by 10 equals 91.9 when weighted by "n". In contrast, if weighted by tons, the same lots might yield this: Lot #1 QL of 80 x 1500 T plus Lot #2 QL of 97 x 17,500 T equals 95.7 when weighted by tons. The examples would be appropriate for asphalt content, with a reduced frequency of 1/2500 tons and an increased frequency of 1/500 tons.

In almost all cases the asphalt content and sieve analysis QLs weighted by "n" were lower than when weighted by tons. This is because the procedure provided for reduced testing only when the QLs were high. But because there were many changes in sampling frequency and the average lot size was small (about 6 tests), there is not as much disparity as might be expected. For the entire pilot study, (see last line of Table 5) the Column 3 average QL (weighted by tons) is 92.8 compared to the Column 4 average QL (weighted by "n") of 92.3. Note that for each asphalt density process, QL is the same whether weighted by tons or "n". This is because each sample uniformly represented 500 tons.

The WASHTO[2] Pay Factor Table is, in reality, a probability table. As sample size ("n") changes, the probabilities of accurately estimating the true $\overline{X}$ of the process changes also. Probability, or risk, is related to the square root of "n", expressed as the Standard Error of the Means (SEM) = $SD/\sqrt{n}$. As an example, for HBP relative density, the pilot average SD is 1.0. Using this value, for "n" = 4, SEM = 0.5; for "n" = 16, SEM = 0.25 and for "n" = 64, SEM = 0.125. This can be visualized as so: If a series of lots of "n" = 4 size were taken from a process, the standard deviation of the means of the lots would be 0.5 and so on, up to a SD of the means of 0.10 for a series of lots of "n" = 100 each. The $\overline{X}$ of a 64-sample lot would have a 95 percent probability of being within plus or minus 0.25 ($2 \times 1.0/\sqrt{64}$) of the true mean of the process, while a 4-sample lot would have a 95 percent probability of $\pm 1.0$ percentage points.

The following tabulation is from the WASHTO[2] Tables and shows the QLs required for PF = 1.0 (and Quality Index [$(T_L - \overline{X})/SD$], or Q) as "n" changes:

**SUMMARY FROM WASHTO QL/PF TABLES**

QL & Q Required for PF = 1.0 as "n" Varies

| QL | "n" | Q | QL | "n" | Q | QL | "n" | Q |
|---|---|---|---|---|---|---|---|---|
| 93 | >200 | 1.47 | 86 | 15 - 18 | 1.08 | 81 | 7 | 0.90 |
| 91 | 70 - 200 | 1.34 | 85 | 12 - 14 | 1.04 | 80 | 6 | 0.87 |
| 90 | 38 - 69 | 1.28 | 84 | 10 - 11 | 1.00 | 78 | 5 | 0.82 |
| 89 | 26 - 37 | 1.22 | 83 | 9 | 0.96 | 74 | 4 | 0.72 |
| 87 | 19 - 25 | 1.12 | 82 | 8 | 0.93 | 68 | 3 | 0.62 |

The WASHTO[2] PF Table is based on paying 1.0 for a QL of 93, when there is no allowance for sampling error ("n" = 200 - infinity). Per the above tabulation, Q = 1.47 for "n" >200. The table has a variable risk or probability factor built into it. When "n" >14, the WASHTO Table allows a 95 probability (Q = 1.65 SEM), for "n" = 8 - 14, a 94 % probability (Q = 1.56 SEM), and "n" <8, a 93% probability (Q = 1.50 SEM).

We will test data with "n" = 36, where SEM = 0.17. To allow for sampling error, then 1.65 x 0.17 = 0.28; that is we should pay 1.0 when $\overline{X}$ is 0.28 SD closer to the tolerance limits than required for the total distribution. Therefore, 1.47 - 0.28 = 1.19; per the above tabulation for "n" = 36, the closest QL is 89.

Let us test this at another "n"; say 9 (SEM = 0.33) where 1.56 SEM = 0.51. Then 1.47 - 0.51 = 0.96; per the above tabulation for "n" = 9, QL = 83. Once more, for "n" = 4 (SEM = 0.5) where 1.50 SEM = 0.75. Then 1.47 - 0.75 = 0.72; per the tabulation for "n" = 4, the closest QL is 74. These examples demonstrate that in the WASHTO Table, PF in relation to QL in the WASHTO table is based on the probabilities associated with sample size (or sampling error).

The next step is to determine what constitutes a sample "n". It is contended that the average of 25 four-sample lots from a continuous process gives the same probability of a true $\overline{X}$ estimate as if the entire 100 values were averaged. This is logical, and mathematically correct. If a single four-sample lot is looked at in isolation, then Q x SD/$\sqrt{4}$ is the probability distance from the true mean. But when all 100 samples are taken from a single process, the probability of estimating the true process mean is related to $\sqrt{100}$, not $\sqrt{4}$. Therefore, the proper way to use the WASHTO PF table is to select the "n" column (or formula for the column) based on the number of values in the process, whether or not the process is broken into lots.

The effect on PFs determined by different methods was studied using the Pilot data and is summarized in Table 5; Columns 7, 8 and 9. The PFs reported in Column 7 are those officially determined for the projects and come from the QPM reports. By QPM, the element PFs are computed on each lot, then averaged for the process (weighted by the tons in each lot). The QLs reported in Column 3 correspond with the Column 7 PFs (average "n" = 6). The pilot pay formulas change as lot sizes change, but the adjustment is capped at 8; that is, for lots larger than that, the formula for "n" = 8 is used.

Column 8 reports the PFs determined strictly by the WASHTO PF[2] table, based on individual lot sizes. The Column 8 PFs correspond to the Column 4 QLs (the process average QL weighted by "n" in each lot). From the last line in Table 5, this interpretation gives an overall pilot average of PF = 1.04 compared to the 1.028 actually paid. This refutes some local opinions that the pilot formulas were more generous than WASHTO[2].

Next, we compared the average lot QLs in Column 4 to the process QLs in Column 6. The question being: Is the average QL of the lots in a process essentially the same as the QL determined from lumping all measurements together as if they were one large lot? The Standard Difference of the QLs for the 33 processes is 1.3, meaning that 68 percent of the sets of values were within 1.3 QL points of each other. The overall pilot data, last line of Table 5, show the average by lot to be just 0.4 points higher than by process. It is concluded that the average QL from a number of lots in a process essentially equals the QL of the overall process. In the Table, where the two values are not within a couple of points (there were 4 such cases), there were probably significant changes on those projects which would have triggered process changes had this been monitored. If the four cases were removed, the Standard Difference is 0.6.

Accepting the premise that a process QL is properly quantified by either procedure, it is illogical to pay more for the process just because it was measured by a number of small batches rather than a single large one. Hence, the same formula for each lot in a process (based on the process "n", and probability) should be used to determine the process PF.

The PFs in Column 9 (by total process) were computed from the QLs in Column 5 in order to compare payment by process to payment by lots. The average PF by process is 1.008 and by lots is 1.04. This is discussed further below.

***Incentive/Disincentive Payments by Various Procedures***

The total incentive, or disincentive payments on the pilots, compared to CDOT standard procedure is of interest. The current standard does not allow incentives, so only negative adjustments can be compared. Table 6 presents a summary of what payments might have been made on the pilot projects by three different schemes, compared to the pilot procedure. To normalize the results, a theoretical bid price of $25.00 (within a dollar or so of average bid price for 1992) was assigned to the entire 282,000 Pilot tons, for a total of $7.05 million.

Using the $25.00 figure, by the specified pilot procedure, there would have been a total incentive payment of $231,530 and total disincentive of $36,950 for a net incentive of $194,580. This is a 2.8 percent incentive payment over bid price, in agreement with the pilot average figure, last line, Column 7, in Table 5. The second and third columns in Table 6, reveal that had we paid, using the WASHTO[2] table (lot basis), the total incentive payment would have been approximately $100,000 more (1.2 percent) than by the pilot procedure, in agreement with Table 5.

If payment had been made under the proposed method of using the process "n" to select the WASHTO[2] pay formula, total incentive would have been only $49,370, or about 3.0 percent less than the WASHTO[2] lot method. Line 2 in Table 6 shows that relative density accounts for about $175,000 of the $235,000 difference between the two WASHTO[2] procedures. Based on one test per 500 tons, with no reduction for condition Green, each pilot density process was measured with a relatively large number of measurements. This produced more accurate estimates of the true process means; but we paid under the lot system, giving extra payment for risk that was not there.

Note that for asphalt content and sieve analysis, because the seller's risk is greater with less measurements, there is less disparity in payments made by the two methods. This really needs to be looked at with the premise that we are asking for a 93 percent QL for PF = 1.0, and if we could measure every pound or square foot, we would require that. There would be no risk to the contractor due to sampling error. As we reduce the number of samples, the seller's risk increases. If we reduced the sampling frequency for density (fewer samples from a process), we should pay 1.0 at a lower QL because of a greater risk of not accurately estimating the true QL. There is a trade-off, but we should not pay more just because we measure a given process QL in small increments rather than one large one.

Finally, in this study, we were interested in comparing the number of lots with disincentive PFs (<1.0) for the pilots to what would have happened under the current Standard Section 105[1]. The last column in Table 6 shows that there would have been only two 5000-ton lots price adjusted for sieve analysis (by $18,907). This compares favorably to what would have happened under the WASHTO[2] process procedure, and is a little more severe than WASHTO[2] by lot or the pilot method. However, by the more lenient current formulas, there would have been no disincentive payments for any of the lots for the other elements.

*Discussion of Possible Benefits to CDOT from the QA/QC Pilot*

A principal objective of QA/QC is to transfer responsibility for process control to the Contractors. A potential benefit to CDOT is higher quality work (due to incentive payments), and in addition, reduced testing and inspection as the producers gradually take over process control. The only initial tools we have for measuring quality are the QL formulas. And indeed, the quality level of the pilots was almost five percent higher than the quality level of the past two years HBP production. Whether we will be able to measure, or discern a similar benefit in pavement performance may be difficult to determine.

Conceptually, there appears to be initial achievement of higher quality pavements, but more time and study are needed to be conclusive.

It may be debatable whether there was any measurable personnel or dollar savings to CDOT, particularly when offset by the extra cost in training and familiarization required for the pilot implementation. Discounting these extra costs, some savings can be documented.

At the normal sampling schedule of 1/500 tons, there would have been 564 tests for asphalt content on the 282,000 tons, compared to 214 actually reported. Likewise, at 1/1000 tons for sieve analysis, there would have been 282 tests, while 180 were reported. A total of 452 field tests were saved for the two elements. Considering equipment use, travel and reporting time, these tests are worth approximately $50.00 to $100.00 each. At $75.00, the savings would be about $34,000. This would not nearly offset the $194,000 bonus paid, but remember, we supposedly paid the incentive for extra quality.

There were other areas of possible benefits not documented. Although the testing schedule for relative density of 1/500 tons was not reduced on the pilots, it is believed the contractors took over the role of miscellaneous check testing to determine need for extra rolling. On regular projects this has traditionally been done by CDOT personnel, in addition to acceptance testing. How much effort this saved, if any, is debatable, but it is potential.

In addition, considerable time must have been saved in reporting. Current procedure is laborious, requiring copying all test results, dates, location, Project Numbers, etc, on to multi-copy forms, either by hand or by typing. The QPM program produced printouts of all test data, QL calculations, project data, etc, satisfactory for report procedures by just photo copying.

Currently all field data received in the Central laboratory is input into a master computerized data base for historical evaluation. This requires a full time technician. Eventually, the QPM data can be fed electronically into the data base freeing up most of the technician's time for other duties. Of course, this is not tied directly to QA/QC, and probably will occur in the future anyway, but the pilot effort may speed the implementation.

Another potential for savings exists. As QA/QC is fully implemented, it is expected that contractors who have good process control procedures will have bidding advantage over those whose control is not so good. Some of their incentive payments will show up as lower bid prices, partially offsetting the cost to CDOT, making the increased quality even a better bargain. In addition, there will be a tendency for inefficient contractors to either sharpen up their quality control or drop out, thereby indirectly contributing to higher quality work. Most contractors seem to hold this viewpoint, also.

*Summary*

In summary, at the half way point, the pilot program appears to be successfully meeting the goals originally conceived. The contractors are accepting the QA/QC Pilot with minimal problems to date. Most CDOT personnel appear to be ready for full implementation. The pilot specifications will need to be fine-tuned before they are turned into a Standard, but it appears there will be a good data base with which to work.

Acceptance sampling frequency, when CDOT tests show the *contractor's* process is under control (the Green, Yellow, Red procedure[4]), needs to be studied. In the pilots, this notion has served a purpose, but it may be that acceptance sampling frequency across the board can be reduced to approximately the *average* rate used on the pilots, with no change in frequency based on contractor's control. The risk to CDOT and the contractors could *possibly* increase slightly, but better process control should more than offset this.

In need of particular scrutiny are the pay factor formulas in relation to quality level and the lot or process size. The WASHTO[2] Pay Factor table appears to be a reasonable way to assign PFs based on QL, if used properly, on a process basis. It is questionable whether all the "n" increments listed are necessary. From 4 to 6 increments should distribute risk adequately. The PCCP pilot specification uses just four increments.

The specification tolerance widths appear to be about right for asphalt content and relative density. For sieve analysis, Grading C and CX should have the tolerances revised to equal the Grading SF tolerances. A final evaluation and report is anticipated when the HBP pilot QA/QC program is completed at the close of the 1993 construction season.

## REFERENCES

1. COLORADO DEPARTMENT OF TRANSPORTATION, Standard Specifications for Road and Bridge Construction, 1991; Subsection 105.03, Conformity with Plans and Specifications.

2. WASHTO Model Quality Assurance Specifications, Prepared for WASHTO Subcommittees on Materials and on Construction, in cooperation with the FHWA, August, 1991.

3. Summary Review of 1990-1991 QA/QC Projects and Development of 1992 QA/QC Specifications, by Staff Materials Branch, CDOT, March, 1992.

4. Standard Specification Revisions of Sections 105, Control of Work; and 106, Control of Material; to be used with the 1992 Pilot Projects, by the Staff Materials Branch, CDOT, March, 1992.

**TABLE 1**
**HBP PILOT QA/QC EVALUATION**
**ASPHALT CONTENT**
**State Mean & Means for Pilot Projects**
**Standard Deviation, Distance From Target & QL**

| Identif-ication | Standard Deviation | | Distance - Target | | Quality Level |
|---|---|---|---|---|---|
| | Value | Val/St | Value | Val/St | |
| State | 0.18 | 1.00 | 0.07 | 1.00 | 88.0 |
| R1J1 | 0.14 | 0.78 | 0.06 | 0.86 | 96.8 |
| R1J2 | 0.08 | 0.44 | 0.02 | 0.29 | 100 |
| R2J1 | 0.13 | 0.72 | 0.09 | 1.29 | 95.3 |
| R2J2 | 0.14 | 0.78 | 0.05 | 0.71 | 99.4 |
| R3J1 | 0.13 | 0.72 | 0.06 | 0.86 | 98.3 |
| R4J1 | 0.15 | 0.83 | 0.03 | 0.43 | 98.9 |
| R6J1 | 0.16 | 0.89 | 0.04 | 0.57 | 90.8 |
| Mean, wt by No. of Tons | 0.13 | 0.73 | 0.05 | 0.74 | 96.9 |

**TABLE 2**
**HBP PILOT QA/QC EVALUATION**
**RELATIVE DENSITY**
**State Mean & Means for Pilot Projects**
**Standard Deviation, Distance From Target & QL**

| Identif-ication | Standard Deviation | | Distance - Target | | Quality Level |
|---|---|---|---|---|---|
| | Value | Val/St | Value | Val/St | |
| State | 1.05 | 1.00 | 1.00 | 1.00 | 84.0 |
| R1J1 | 0.96 | 0.91 | 0.70 | 0.70 | 92.0 |
| R1J2 | 0.84 | 0.80 | 1.14 | 1.14 | 85.6 |
| R2J1 | 0.75 | 0.71 | 1.20 | 1.20 | 89.2 |
| R2J2 | 1.13 | 1.08 | 0.39 | 0.39 | 93.6 |
| R3J1 | 1.04 | 0.99 | 0.36 | 0.36 | 93.9 |
| R4J1 | 1.26 | 1.20 | 0.85 | 0.85 | 80.0 |
| R6J1 | 1.14 | 1.09 | 0.57 | 0.57 | 89.2 |
| Mean, wt by No. of Tons | 1.00 | 0.96 | 0.71 | 0.71 | 89.6 |

**TABLE 3**
**HBP PILOT QA/QC EVALUATION**
**PERCENT PASSING No. 8 SIEVE**
**State Mean & Means for Pilot Projects**
**Standard Deviation, Distance From Target & QL**

| Identification | Standard Deviation | | Distance - Target | | Quality Level |
|---|---|---|---|---|---|
| | Value | Val/St | Value | Val/St | |
| State ±8 | 2.59 | 1.00 | 1.82 | 1.00 | 99.0 |
| ±4% | 1.77 | 1.00 | 0.91 | 1.00 | 94.6 |
| R1J1 ±4% | 1.95 | 1.10 | 1.00 | 1.18 | 95.1 |
| R1J2 ±8% | 1.86 | 0.72 | 1.53 | 0.84 | 96.6 |
| R2J1 ±8% | 2.39 | 0.93 | 1.74 | 0.96 | 98.3 |
| R2J2 ±8% | 1.95 | 0.75 | 3.21 | 1.76 | 99.2 |
| R3J1 ±8% | 1.83 | 0.71 | 0.50 | 0.27 | 99.9 |
| R4J1 ±8% | 1.78 | 0.69 | 0.20 | 0.11 | 99.9 |
| R6J1 ±8% | 1.15 | 0.44 | 2.00 | 1.10 | 100 |
| ±4% | 3.00 | 1.69 | 0.60 | 0.66 | 78.1 |
| Mean, wt by Tons ±8% | 1.90 | 0.73 | 1.46 | 0.80 | 99.6 |
| ±4% | 2.49 | 1.40 | 0.79 | 0.93 | 88.3 |

**TABLE 4**
**HBP PILOT QA/QC EVALUATION**
**State & Project Item Composite PFs**
**& Mean Quality Levels (Weighted by "W" Factors)**

| Identity | Quantity | Quality Level | Pay Factor |
|---|---|---|---|
| State | N/A | 88.1 | |
| R1J1 | 65M T | 94.1 | 1.031 |
| R1J2 | 43M T | 92.7 | 1.028 |
| R2J1 | 25M T | 92.9 | 1.029 |
| R2J2 | 24M T | 96.5 | 1.039 |
| R3J1 | 58M T | 96.6 | 1.039 |
| R4J1 | 23M T | 89.7 | 1.020 |
| R6J1 | 44M T | 85.8 | 1.006 |
| Total | 282M T | ---- | ----- |
| Mean Pilot Weighted by Quantity | | 92.8 | 1.028 |

**TABLE 5**
**HEP PILOT QA/QC EVALUATION**
**Comparison of Pilot PF Formula vs WASHTO PF Curves**
**For Various Methods of Determining QL**

| Project Identity Col 1 | Element or Item Col 2 | Pilot QL $\bar{X}$ for All Lots Col 3 | Proc QL $\bar{X}$ Weighted by lot n Col 4 | 'n' Each Process Col 5 | QL Each Process Col 6 | Pilot $\bar{X}$ PF, by Lots Col 7 | WASHTO $\bar{X}$ PF, by Lots Col 8 | WASHTO PF for each Process Col 9 |
|---|---|---|---|---|---|---|---|---|
| State Hist. Data | Asph % | | 88.0 | 4027 | | 1.014 | 1.042 | 0.990 |
| | Dens % | | 84.0 | 1865 | | 1.002 | 1.023 | 0.960 |
| | #8, ±8% | | 99.0 | 2317 | | 1.049 | 1.049 | 1.047 |
| | ±4 | | 94.6 | 146 | | 1.043 | 1.043 | 1.035 |
| Item W'ted | by "W" | | 88.1 | 8355 | | 1.014 | 1.034 | 0.986 |
| R1J1 | Asph % | 96.8 | 95.1 | 40 | 94.8 | 1.039 | 1.045 | 1.029 |
| | Dens % | 92.0 | 92.0 | 130 | 91.0 | 1.026 | 1.040 | 1.000 |
| | #8, ±4% | 95.1 | 95.9 | 34 | 93.9 | 1.033 | 1.044 | 1.030 |
| Item W'ted | by "W" | 94.1 | 93.7 | 204 | 92.7 | 1.031 | 1.043 | 1.015 |
| R1J2 | Asph % | 100 | 100 | 14 | 100 | 1.050 | 1.050 | 1.050 |
| | | 100 | 100 | 17 | 100 | 1.050 | 1.050 | 1.050 |
| | Dens % | 85.3 | 85.3 | 49 | 82.9 | 1.005 | 1.025 | 0.945 |
| | | 85.9 | 85.9 | 44 | 86.6 | 1.006 | 1.027 | 0.975 |
| | #8, ±8% | 99.1 | 98.2 | 12 | 99.6 | 1.050 | 1.050 | 1.049 |
| | | 100 | 100 | 15 | 100 | 1.050 | 1.050 | 1.050 |
| Item W'ted | by "W" | 92.7 | 92.6 | 151 | 92.3 | 1.028 | 1.041 | 1.006 |
| R2J1 | Asph % | 98.7 | 97.6 | 16 | 95.2 | 1.046 | 1.048 | 1.041 |
| | | 93.6 | 88.6 | 9 | 90.4 | 1.028 | 1.042 | 1.028 |
| | Dens % | 96.3 | 96.3 | 34 | 90.1 | 1.040 | 1.045 | 1.010 |
| | | 74.0 | 74.0 | 16 | 72.4 | 0.967 | 0.985 | 0.900 |
| | #8, ±8% | 98.3 | 98.5 | 9 | 97.0 | 1.045 | 1.048 | 1.045 |
| | | 98.4 | 98.2 | 6 | 99.2 | 1.046 | 1.048 | 1.046 |
| Item W'ted | by "W" | 92.9 | 91.8 | 90 | 89.4 | 1.029 | 1.041 | 1.008 |
| R2J2 | Asph % | 99.6 | 99.1 | 10 | 99.3 | 1.049 | 1.049 | 1.049 |
| | | 99.1 | 97.2 | 12 | 98.7 | 1.047 | 1.049 | 1.048 |
| | Dens % | 94.4 | 94.4 | 23 | 93.6 | 1.032 | 1.030 | 1.030 |
| | | 92.8 | 92.8 | 25 | 88.9 | 1.025 | 1.041 | 1.009 |
| | #8, ±8% | 100 | 100 | 10 | 99.9 | 1.050 | 1.050 | 1.050 |
| | | 98.2 | 98.3 | 11 | 97.7 | 1.046 | 1.049 | 1.045 |
| Item W'ted | by "W" | 96.5 | 96.4 | 91 | 97.5 | 1.039 | 1.046 | 1.035 |

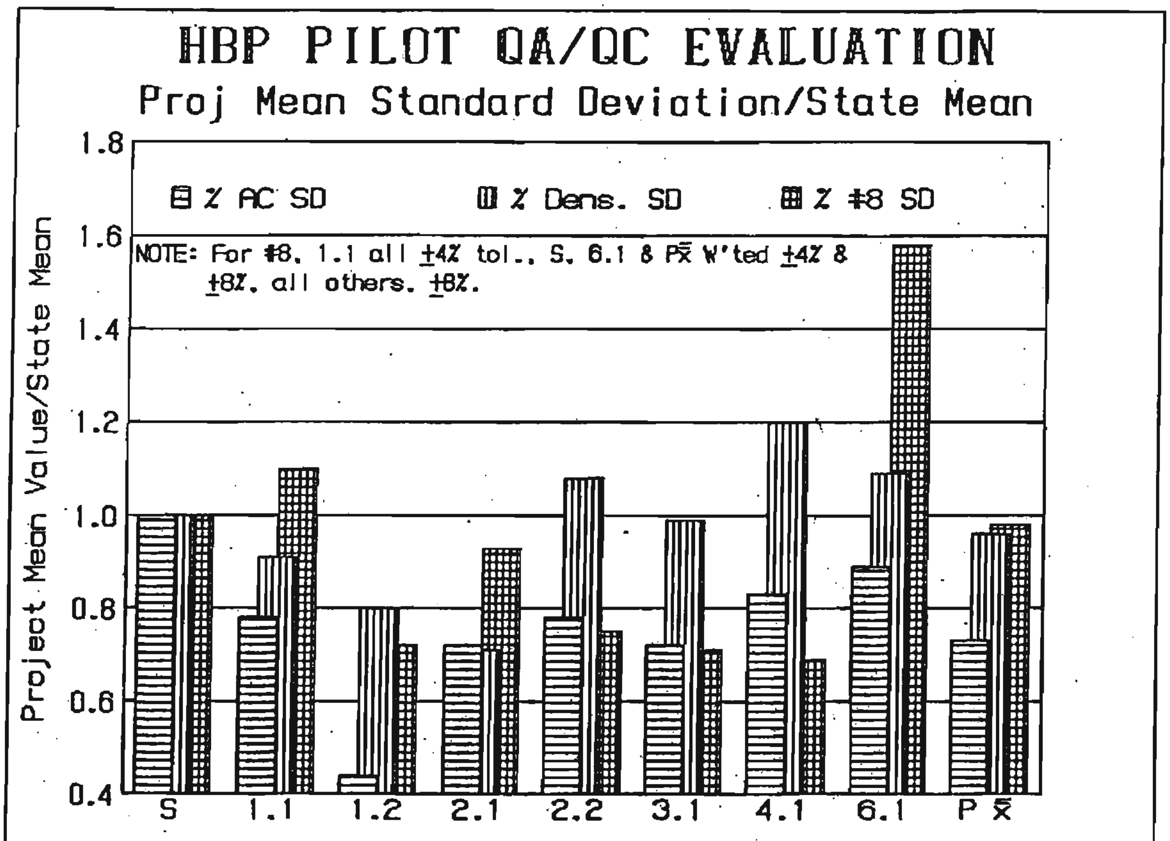
TABLE 5 (Continued)
Pay Factors for Various QLs

| Project Identity Col 1 | Element or Item Col 2 | Pilot QL X for All Lots Col 3 | Proc QL X Weighted by lot n Col 4 | 'n' Each Process Col 5 | QL Each Process Col 6 | Pilot X PF, by Lots Col 7 | WASHTO X PF, by Lots Col 8 | WASHTO PF for each Process Col 9 |
|---|---|---|---|---|---|---|---|---|
| R3J1 | Asph % | 98.3 | 95.7 | 46 | 96.8 | 1.044 | 1.048 | 1.042 |
| | Dens % | 93.9 | 93.9 | 116 | 93.3 | 1.031 | 1.043 | 1.011 |
| | #8, ±8% | 99.9 | 99.9 | 32 | 99.9 | 1.050 | 1.050 | 1.050 |
| Item W'ted | by "W" | 96.5 | 95.6 | 194 | 95.7 | 1.039 | 1.046 | 1.029 |
| R4J1 | Asph % | 98.9 | 97.5 | 14 | 96.5 | 1.047 | 1.049 | 1.043 |
| | Dens % | 80.0 | 80.0 | 46 | 80.8 | 0.992 | 1.010 | 0.935 |
| | #8, ±8% | 99.9 | 99.9 | 11 | 99.8 | 1.048 | 1.049 | 1.049 |
| Item W'ted | by "W" | 89.7 | 89.2 | 71 | 89.3 | 1.020 | 1.035 | 0.992 |
| R6J1 | Asph % | 100<br>89.9 | 100<br>91.7 | 6<br>30 | 100<br>91.9 | 1.050<br>1.020 | 1.050<br>1.036 | 1.050<br>1.000 |
| | Dens % | 77.5<br>88.3 | 77.5<br>88.3 | 7<br>80 | 77.5<br>88.5 | 0.974<br>1.011 | 0.998<br>1.033 | 0.980<br>0.980 |
| | #8, ±8%<br>3/8"±4% | 100<br>72.2 | 100<br>73.3 | 4<br>36 | 100<br>75.0 | 1.050<br>0.967 | 1.050<br>0.976 | 1.050<br>0.900 |
| Item W'ted | by "W" | 85.8 | 86.7 | 136 | 87.3 | 1.006 | 1.027 | 0.976 |
| Element Weighted Average | Asph % | 96.9 | 95.8 | 214 | 95.9 | 1.040 | 1.046 | 1.035 |
| | Dens % | 89.6 | 89.6 | 570 | 88.9 | 1.018 | 1.036 | 0.986 |
| | Sieves | 94.4 | 93.5 | 180 | 93.5 | 1.033 | 1.043 | 1.016 |
| All Pilots Wt'd by W | for Item | 92.8 | 92.3 | 964 | 91.9 | 1.028 | 1.040 | 1.008 |

**TABLE 6**
Estimated Incentive/Disincentive Payments for
Grand Total of Pilot Projects by Various Pay Factor Procedures
**Assumed Total Bid Price of Pilot Proj. Item 403: 282,000 T @ $25 = $7,050,000**

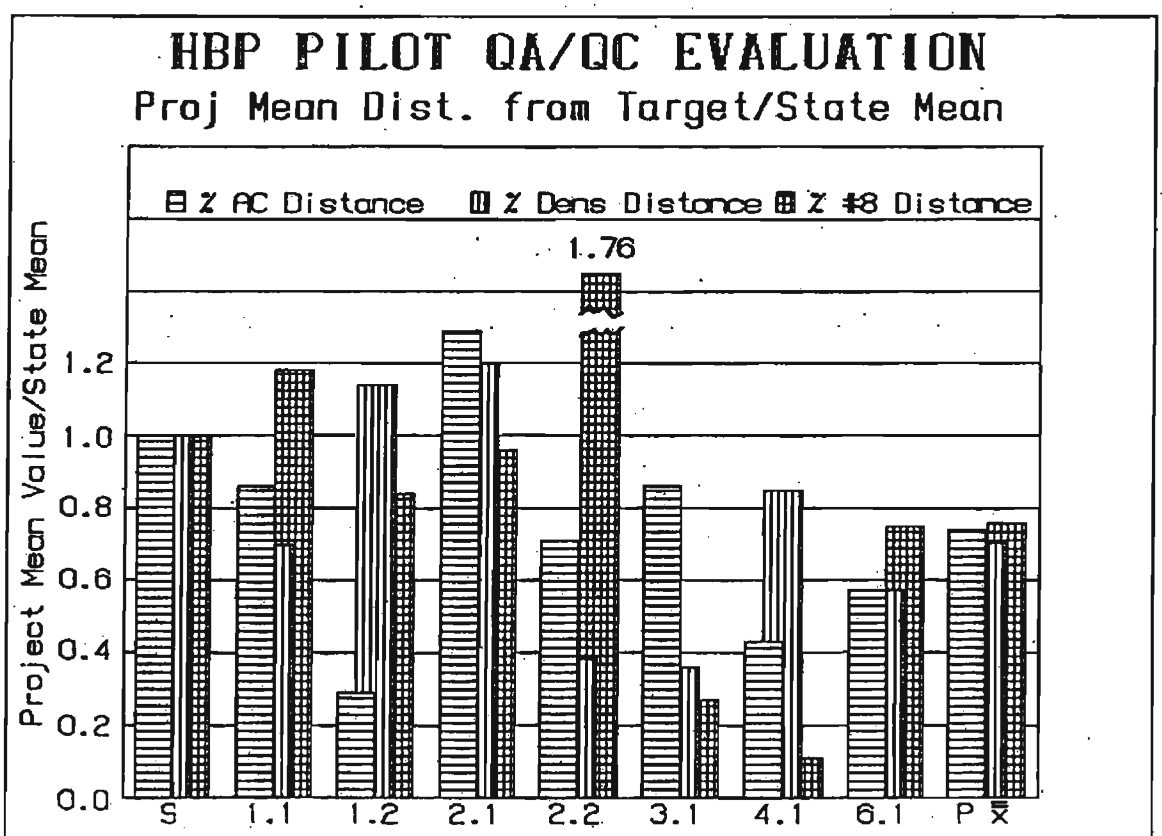
| Element | [1] By Pilot Section 105 Total Pay Adjustment $ | | By WASHTO, Pilot Lots Total Pay Adjustment $ | | By WASHTO Process 'n'[2] Total Pay Adjustment $ | | By Current Std 105.03 |
|---|---|---|---|---|---|---|---|
| | Positive | Negative | Positive | Negative | Positive | Negative | Negative |
| Asphalt Content | 84,925 | (325) | 97,290 | 000 | 76 140 | 000 | 000 |
| Relative Density | 89,895 | (26,145) | 147,638 | (20,738) | 12,776 | (62,126) | 000 |
| Sieve Analysis | 57,010 | (10,480) | 74,655 | (14,025) | 42,580 | (20,000) | (18,907) |
| Grand Total | 231,530 | (36,950)[3] | 319,583 | (34,763)[4] | 131,476 | (82,126) | (18,907)[5] |
| Grand Net | 194,580 | ------------ | 284,820 | ----------- | 49,370 | ------------ | (18,907) |

1 The dollar values listed have been weighted by "W", i.e., the first block value of 84,925 represents an incentive of 283,083 x 0.3 (W for asphalt content).
2 WASHTO PF table used with 'n' as the total samples taken for one single process (all under one job-mix formula).
3 Lots having disincentive PFs: One asphalt content lot, 21 density lots and 7 sieve analysis lots. One project had no disincentive lots and one had only two.
4 Lots having disincentive PFs: Two density lots and 5 sieve analysis lots.
5 Lots having disincentive PFs: Two sieve analysis lots of 5000 tons each on one project, one with a total "P" of 25; the other a "P" of 5.28.



HBP PILOT QA/QC EVALUATION
Proj Mean Standard Deviation/State Mean
% AC SD
% Dens. SD
% #8 SD
NOTE: For #8, 1.1 all ±4% tol., S, 6.1 & P$\bar{\bar{x}}$ W'ted ±4% & ±8%, all others, ±8%.
Project Mean Value/State Mean
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
S
1.1
1.2
2.1
2.2
3.1
4.1
6.1
P $\bar{\bar{x}}$
PROJECT IDENTIFICATION


Fig. 1



HBP PILOT QA/QC EVALUATION
Proj Mean Dist. from Target/State Mean
% AC Distance
% Dens Distance
% #8 Distance
1.76
Project Mean Value/State Mean
1.2
1.0
0.8
0.6
0.4
0.2
0.0
S
1.1
1.2
2.1
2.2
3.1
4.1
6.1
P $\bar{\bar{x}}$
PROJECT IDENTIFICATION


Fig. 2

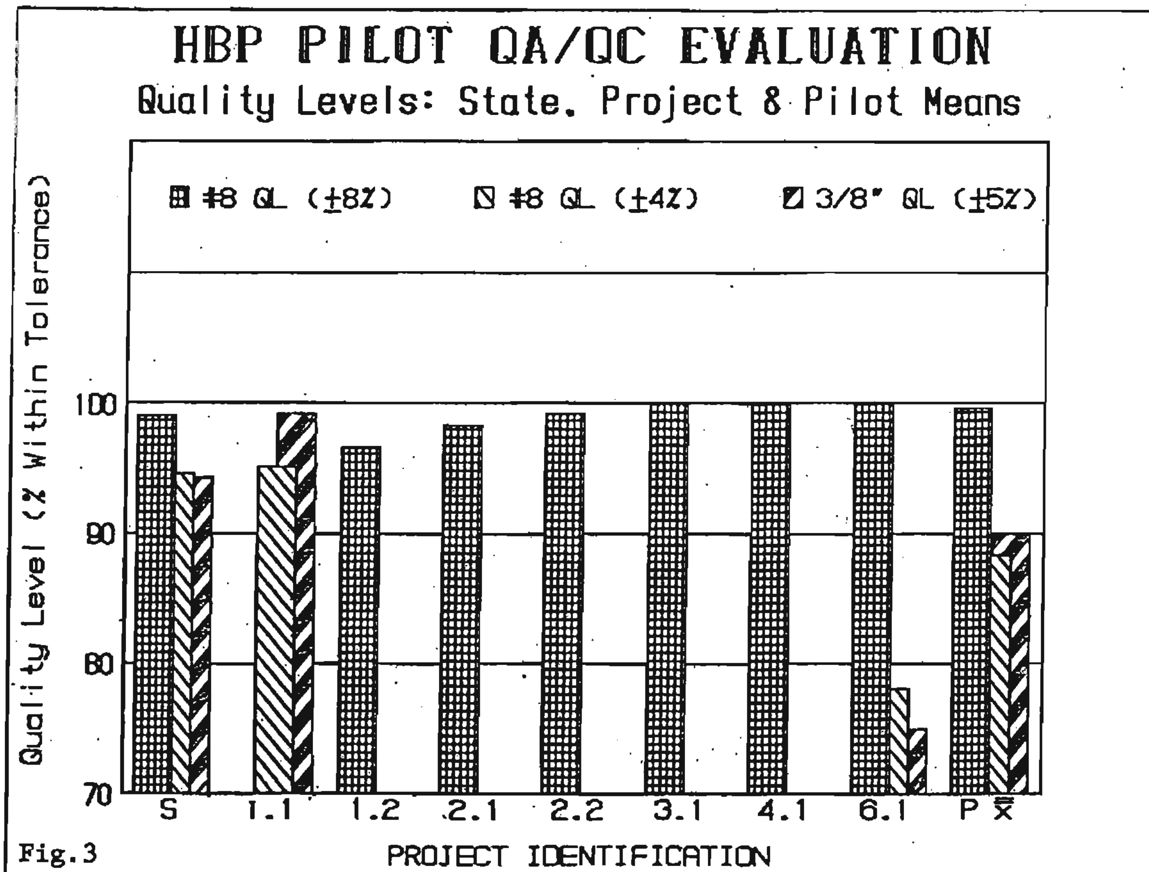

HBP PILOT QA/QC EVALUATION
Quality Levels: State, Project & Pilot Means
#8 QL (±8%)
#8 QL (±4%)
3/8" QL (±5%)
Quality Level (% Within Tolerance)
100
90
80
70
S
1.1
1.2
2.1
2.2
3.1
4.1
6.1
P X̿
PROJECT IDENTIFICATION

Fig. 3

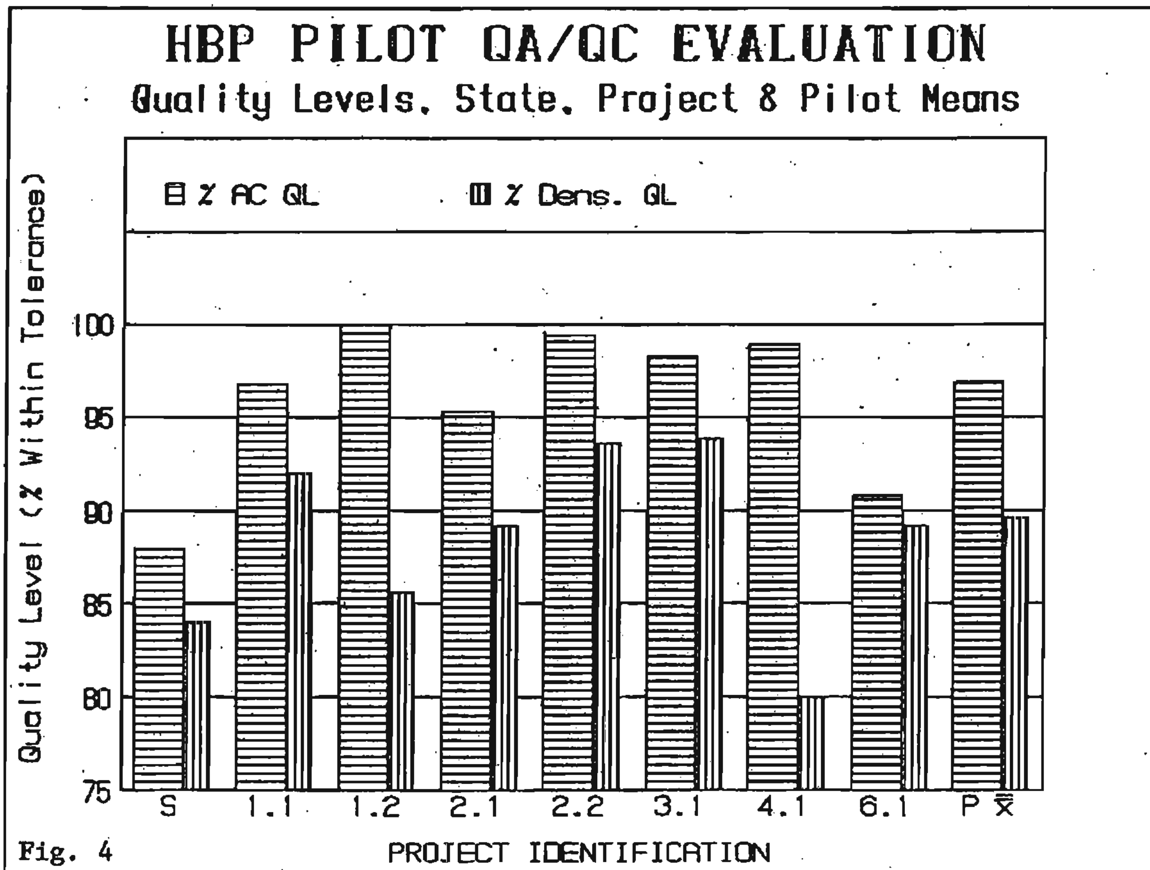

HBP PILOT QA/QC EVALUATION
Quality Levels, State, Project & Pilot Means
% AC QL
% Dens. QL
Quality Level (% Within Tolerance)
100
95
90
85
80
75
S
1.1
1.2
2.1
2.2
3.1
4.1
6.1
P X̿
PROJECT IDENTIFICATION

Fig. 4

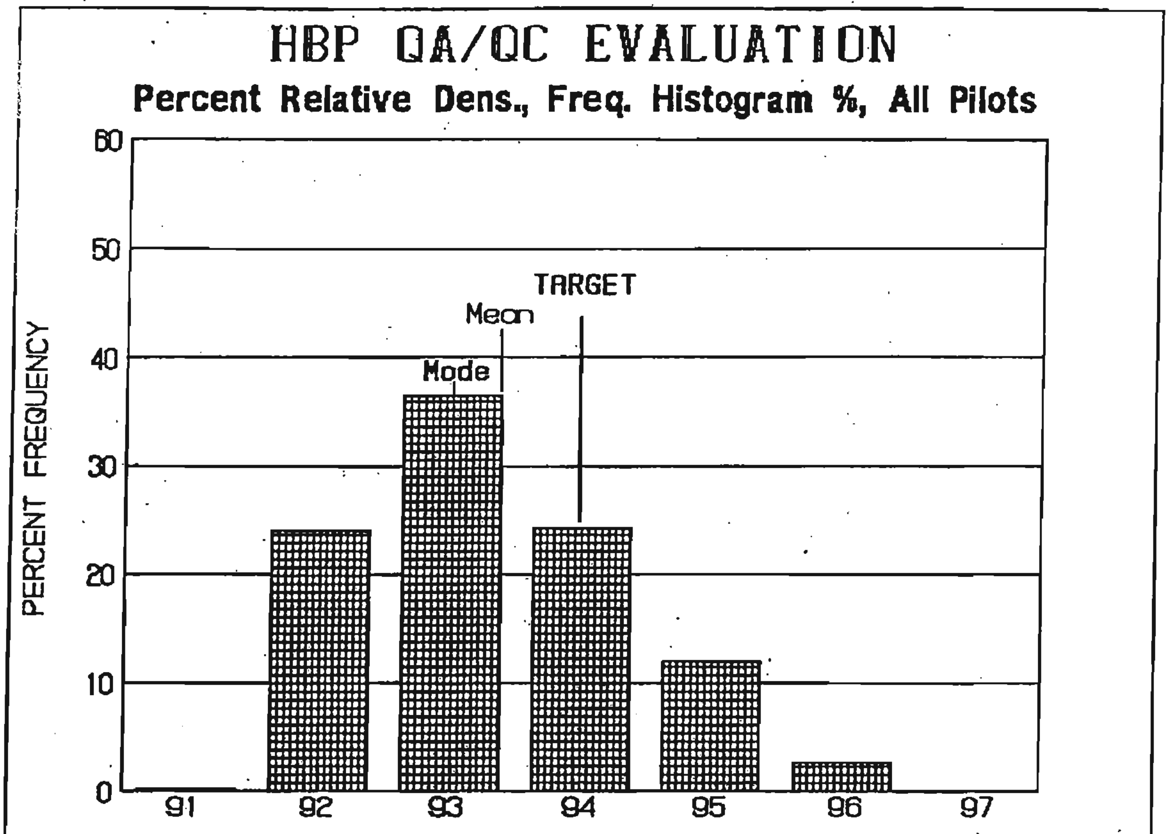

HBP QA/QC EVALUATION
Percent Relative Dens., Freq. Histogram %, All Pilots
PERCENT FREQUENCY
0
10
20
30
40
50
60
TARGET
Mean
Mode
91
92
93
94
95
96
97
PERCENT RELATIVE DENSITY

Fig. 5

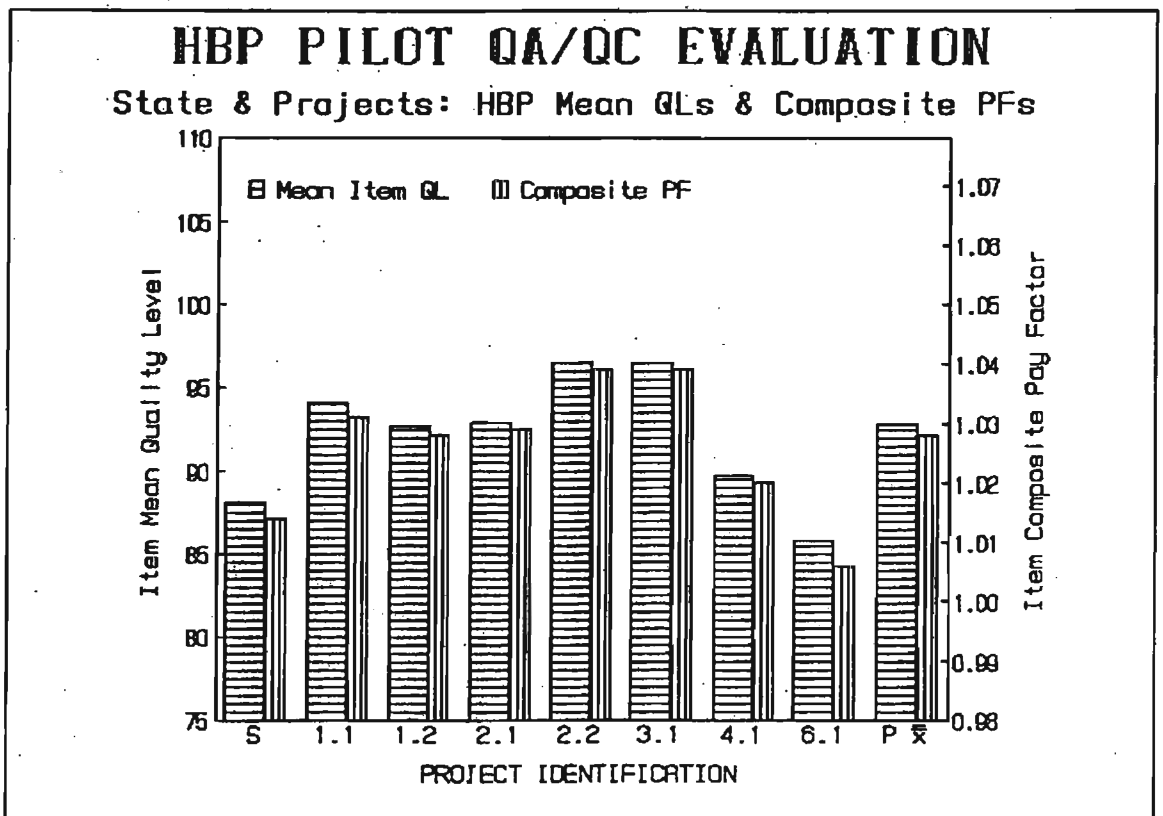
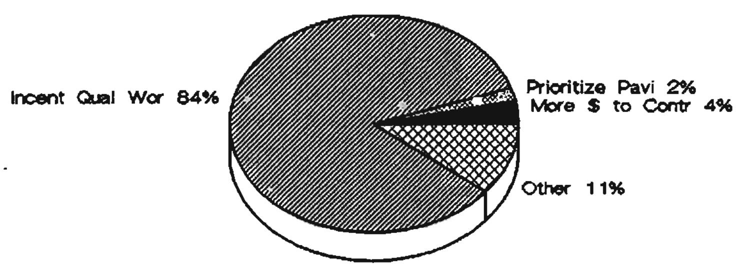

HBP PILOT QA/QC EVALUATION
State & Projects: HBP Mean QLs & Composite PFs
Mean Item QL
Composite PF
Item Mean Quality Level
75
80
85
90
95
100
105
110
Item Composite Pay Factor
0.98
0.99
1.00
1.01
1.02
1.03
1.04
1.05
1.06
1.07
S
1.1
1.2
2.1
2.2
3.1
4.1
6.1
P
PROJECT IDENTIFICATION

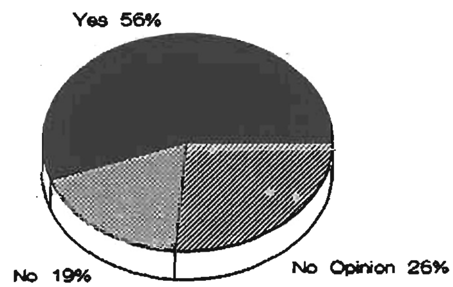
Fig. 6

# Appendix A

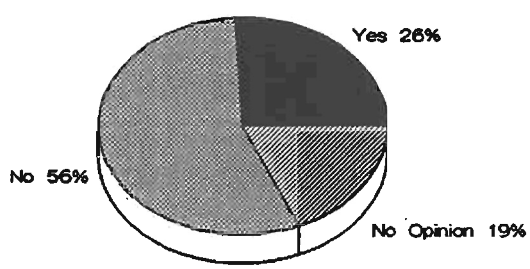
# QUALITY ASSURANCE/QUALITY CONTROL
# 1992 PILOT PROGRAM
## Post Project Questionnaire Results



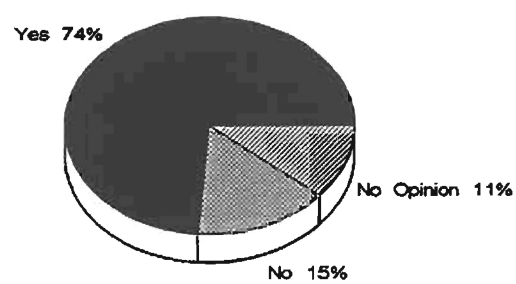

**Goals of 1992 QA/QC program**




**CDOT achieved the Goals on your Project?**

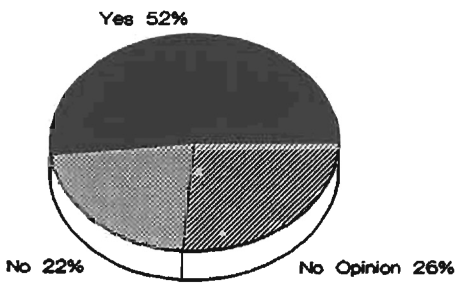



**Did Contractor do Best Job Possible?**

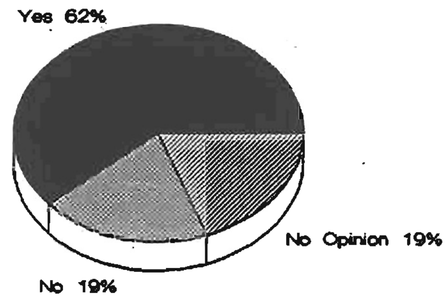



**Contractor put more effort into Project?**

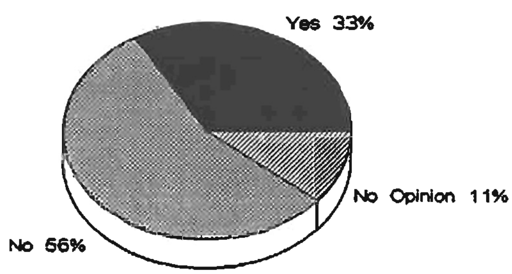
# QUALITY ASSURANCE/QUALITY CONTROL
# 1992 PILOT PROGRAM
## Post Project Questionnaire Results



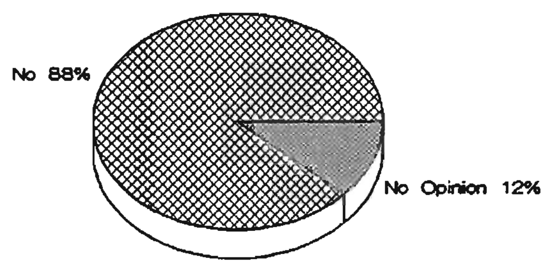

**Contractor tried 'Partnering' ?**




**Contractor provided Process Contrl. Plan**

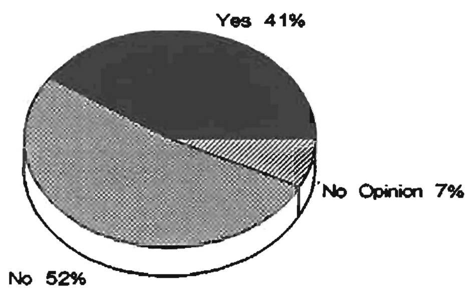



**Incentive was achieved too easily ?**

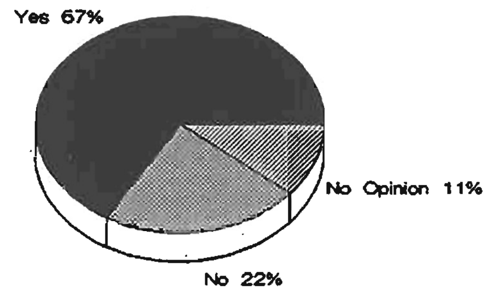



**Penalty for poor work too harsh ?**

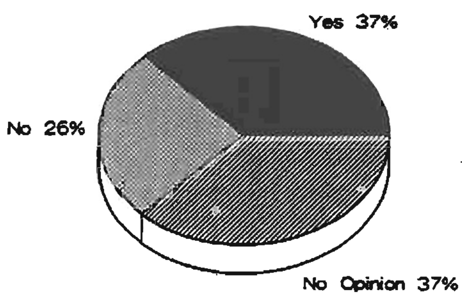
# QUALITY ASSURANCE/QUALITY CONTROL
# 1992 PILOT PROGRAM
## Post Project Questionnaire Results



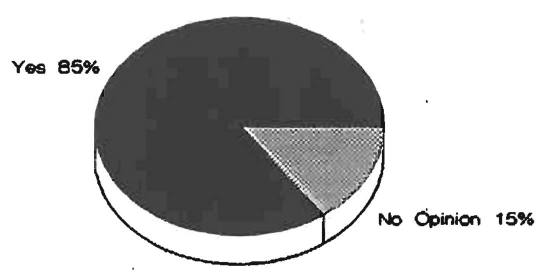

**Special Provisions written well enough ?**




**Support from CDOT Sections adequate ?**



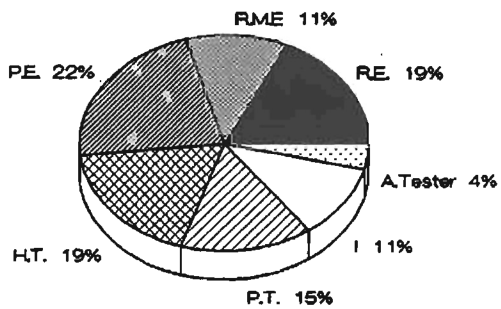

**Computer Program workable ?**



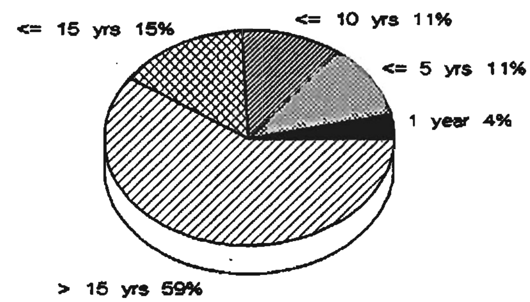

**Computer Printout understandable ?**

# QUALITY ASSURANCE/QUALITY CONTROL
# 1992 PILOT PROGRAM

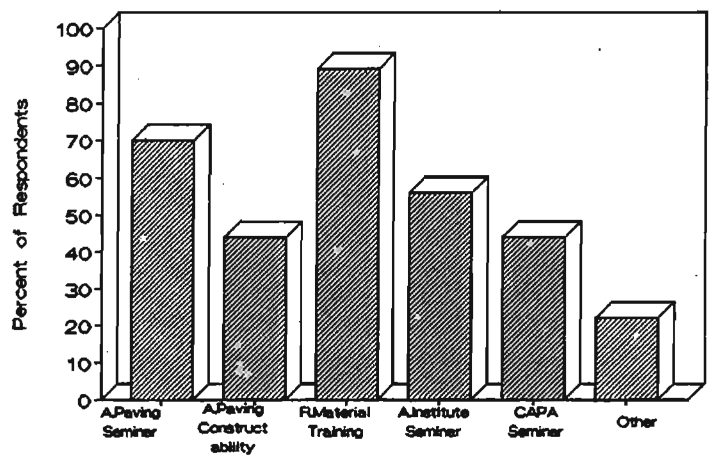
## Post Project Questionnaire Results



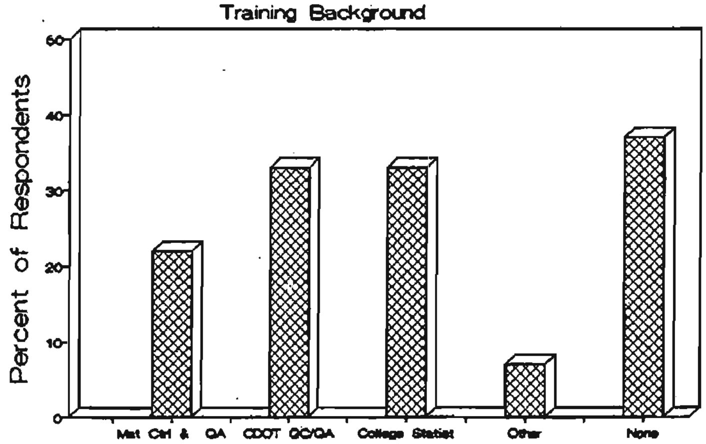

**Questionnaire Participants Job Title**




**Asphalt Paving Construction Experience**




Training Background

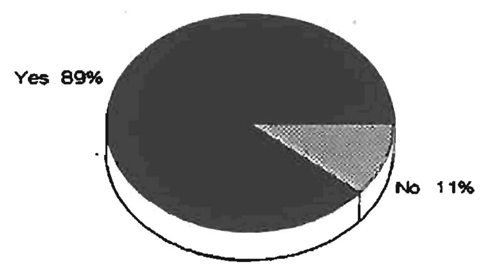



**QC/QA Pilot Program Training Attendance**

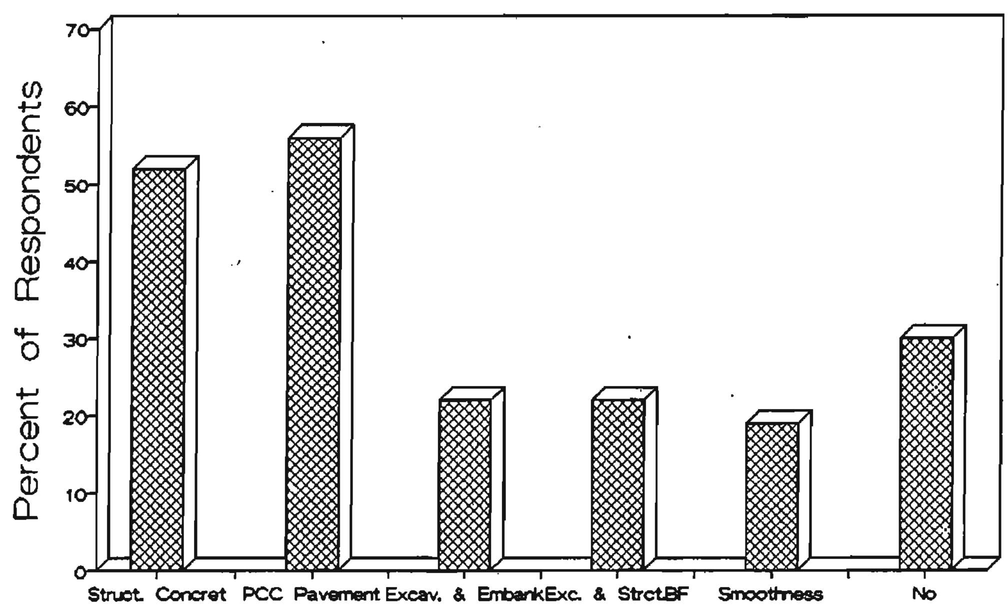
# QUALITY ASSURANCE/QUALITY CONTROL

# 1992 PILOT PROGRAM

## Post Project Questionnaire Results




**Specifications to be used more ?**




Other Material to be controlled ?

# Appendix B

## Section 105 - Control of Work

<<105QA/QC>>

**REVISION OF SECTION 105**
**CONTROL OF WORK**

Section 105 of the Standard Specifications is hereby revised for this project as follows:

Subsection 105.03 shall include the following:

Conformity to the Contract, of all hot bituminous pavement, Item 403, will be determined in accordance with the following:

All work performed and all materials furnished shall conform to the lines, grades, cross sections, dimensions, and material requirements, including tolerances, shown in the Contract.

For those items of work where working tolerances are not specified, the Contractor shall perform the work in a manner consistent with reasonable and customary manufacturing and construction practices.

When the Engineer finds the materials or work furnished, work performed, or the finished product are not in conformity with the Contract and has resulted in an inferior or unsatisfactory product, the work or material shall be removed and replaced or otherwise corrected at the expense of the Contractor.

Materials will be sampled and tested by the Division in accordance with Section 106 and with the applicable schedules and procedures contained in the Division's Field Materials Manual. The approximate maximum quantity represented by each sample will be as set forth in the schedules. Additional samples may be selected and tested at the Engineer's discretion.

Evaluation of materials for pay factors will be done on a lot basis. Lots will consist of a consecutive series of random samples, one from each sublot, for those items and elements listed in Section 106, Table 106-1. All materials produced will be assigned to a lot. Each lot will have a pay factor computed in accordance with the requirements of this Section. Test results determined to have sampling or testing errors will not be used.

Conditions Green, Yellow and Red are described in Section 106. At condition Yellow or Red, a lot will normally be five samples, but may be three to eight samples. The Contractor will be notified of test results of samples taken at condition Yellow or Red.

At condition Green, a lot may be any number of consecutive samples, from three to the maximum necessary to represent the work. At condition Green, a cumulative pay factor will be maintained for each element. As soon as tests are completed and the pay factor computed, the results will be made available to the Contractor upon request.

The Engineer may establish a new lot when there are major changes in materials, a change in the job-mix formula, extended suspension of production or as otherwise deemed necessary. New lots may be established following the close of the pay estimate period. The color reference condition at the close of the estimate period will continue into the new estimate period, except as noted under 106(b)1B. If there are less than three samples in the new lot before the sampling frequency changes, one or two samples from the previous lot, where available, will be used with the short lot to establish characteristics for the pay factor. Otherwise, the material will be evaluated as one-sample lots in accordance with the procedure below.

When it is necessary to represent a quantity by one or two tests, lots will be established represented by one test each, as determined by the Engineer. A lot with test values which deviate from the specifications will be evaluated for pay factor by one of the following formulas. When a test value is above the maximum specified limit, the formula $R = (T_o - T_u)/V$ will be used. When a test value is below the minimum specified limit, the formula $R = (T_L - T_o)/V$ will be used.

Where: R = the value to enter Table 105-4 to find the pay factor (PF).
V = the element value from Table 105-3.
$T_o$ = the individual test value.
See below for $T_u$ and $T_L$

Lots represented by one or two samples will not be evaluated for a PF greater than 1.00.

(a) Each lot of materials or work represented by three or more tests will be evaluated for a pay factor (PF) by one of the following procedures, as indicated:

1. Determine the arithmetic mean ($\bar{X}$) of the several test results for each element of the sample being evaluated:

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

Where: $\Sigma$ = summation of
X = individual test value to $X_n$
n = total number of test values

2. If $\bar{X}$ is outside the specification limits, skip steps 3 to 4 and go to step 5.

3. If $\bar{X}$ is at or inside the specification limits, proceed as follows:

Compute the element standard deviation (s):

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

4. Compute the quality level (QL) and PF as follows:

$$QL = 100 - (p_L + p_u)100$$

where:

$p_L$ = fraction defective at the lower specification limit
$p_u$ = fraction defective at the upper specification limit

The fraction defective is obtained by numerically integrating the beta distribution function:

$$p = \int_{x=0}^{x = Max[0,1/2 - Q\sqrt{n}\ /2(n-1)]} \beta(a,b,x)\ dx$$

where:

p = fraction defective of the population
$\beta(a,b,x)$ = beta distribution function = n/2 - 1
n = sample size
Q = quality index, $(\overline{X} - T_L)/s$ or $(T_u - \overline{X})/s$

$\overline{X}$ = sample mean
s = sample standard deviation
$T_L$, $T_u$ = lower and upper specification limits
x = integration variable

Compute PF by the following formula:

$$PF = 1.05 - (100 - QL)A_n/100$$

Where $A_n$ = multiplication factor, as "n" varies, from Table 105-2A

5. Where $\overline{X}$ is outside the specification limits, compute PF by the following formulas:

Compute R:

$$R = \frac{T_L - \overline{X}_n}{V} \text{ or } \frac{\overline{X}_n - T_u}{V}$$

Where V = The factor for the element from Table 105-3

Compute PF:

$$PF = 0.75 + (1 - R)B_n$$

Where $B_n$ = multiplication factor, as "n" varies, from table 105-4

(b) Where $\bar{X}$ is at, or inside the specification limits, in lieu of using the formulas under (a) above, reasonable approximations of QL and PF can be made by the following procedures (for payment purposes the formulas will be used):

1. Compute the upper quality index ($Q_u$):

$$Q_u = \frac{T_u - \bar{X}}{s}$$

Determine $P_u$ (percent within the upper specification limit which corresponds to a given $Q_u$) from Table 105-1. If $T_u$ is not specified, $P_u$ will be 100.

2. Compute the lower quality index ($Q_L$):

$$Q_L = \frac{\bar{X} - T_L}{s}$$

Determine $P_L$ (percent within the lower specification limit which corresponds to a given $Q_L$) from Table 105-1. If $T_L$ is not specified, $P_L$ will be 100.

3. Determine the Quality Level (QL, the total percent within specification limits):

$$QL = (P_u + P_L) - 100$$

Using QL, determine PF from Table 105-2.

(c) If $\bar{X}$ is outside the specification limits, using R, as computed under (a)5 above, a reasonable approximation of PF can be made from table 105-4 (for payment purposes, the formula will be used).

(d) For a specification that includes a sieve analysis requirement, the entire set of specified sieves will be considered a single element for the interim or estimate period. The $PF_A$ for the element will be the lowest $PF_A$ for any specified sieve.

(e) A pay factor will be determined for each lot of material or work. For pay period estimates, or for any interim time period, each individual element will have the average pay factor ($PF_A$) for all the lots of the period, weighted by the quantities represented by each lot, computed as follows:

$$PF_A = \frac{[M_1(PF_1) + M_2(PF_2) + \ldots\ldots M_j(PF_j)]}{\Sigma M}$$

Where: $M_j$ = Quantity of item represented by the lot.

$PF_j$ = The lot pay factor.

$\Sigma M$ = Sum of Quantities, $M_1$ to $M_j$ (the total quantity for the period).

(f) When there is more than one element for the item, determine the composite pay factor ($PF_C$) for the time period as follows ($\Sigma M$ used to compute each element $PF_A$ must be numerically the same):

$$PF_C = \frac{[W_1(PF_{A1}) + W_2(PF_{A2}) + \ldots\ldots W_j(PF_{Aj})]}{\Sigma W}$$

Where: $W$ = element factor from Table 105-5.
$PF_{Aj}$ = element average pay factor.

$\Sigma W$ = sum of the element factors.

Numbers in the above calculations will be carried to significant figures and rounded according to AASHTO Standard Recommended Practice R-11.

When PF for any element in the lot is between 0.75 and 1.05, the finished product will be accepted at the appropriate pay factor. If PF is less than 0.75, the Engineer may: (1) require complete removal and replacement with specification material at no additional cost to the Division; or (2) where the finished product is found to be capable of performing the intended purpose and the value of the finished product is not affected, permit the Contractor to leave the material in place. If the material is permitted to remain in place, an appropriate price adjustment will be made such that PF will not be greater than 0.75. The final PF for the lot will be used in the applicable formulas when computing the average and composite pay factors.

The Contractor will not have the option of accepting a price reduction in lieu of producing specification material. Continued production of non-specification material will not be permitted. Material which is obviously defective may be isolated and rejected without regard to sampling sequence or location within a lot.

**TABLE 105-1**

**QUALITY LEVEL ANALYSIS BY THE STANDARD DEVIATION METHOD**

| $P_U$ or $P_L$ % | Upper Quality Index $Q_u$ or Lower Quality Index $Q_L$ | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n= 3 | n= 4 | n= 5 | n= 6 | n= 7 | n= 8 | n= 9 | n=10 to n=11 | n=12 to n=14 | n=15 to n=18 | n=19 to n=25 | n=26 to n=37 | n=38 to n=69 | n=70 to n=200 | n=201 to n=x |
| 100 | 1.16 | 1.50 | 1.79 | 2.03 | 2.23 | 2.39 | 2.53 | 2.65 | 2.83 | 3.03 | 3.20 | 3.38 | 3.54 | 3.70 | 3.83 |
| 99 | | 1.47 | 1.67 | 1.80 | 1.89 | 1.95 | 2.00 | 2.04 | 2.09 | 2.14 | 2.18 | 2.22 | 2.26 | 2.29 | 2.31 |
| 98 | 1.15 | 1.44 | 1.60 | 1.70 | 1.76 | 1.81 | 1.84 | 1.86 | 1.91 | 1.93 | 1.96 | 1.99 | 2.01 | 2.03 | 2.05 |
| 97 | | 1.41 | 1.54 | 1.62 | 1.67 | 1.70 | 1.72 | 1.74 | 1.77 | 1.79 | 1.81 | 1.83 | 1.85 | 1.86 | 1.87 |
| 96 | 1.14 | 1.38 | 1.49 | 1.55 | 1.59 | 1.61 | 1.63 | 1.65 | 1.67 | 1.68 | 1.70 | 1.71 | 1.73 | 1.74 | 1.75 |
| 95 | | 1.35 | 1.44 | 1.49 | 1.52 | 1.54 | 1.55 | 1.56 | 1.58 | 1.59 | 1.61 | 1.62 | 1.63 | 1.63 | 1.64 |
| 94 | 1.13 | 1.32 | 1.39 | 1.43 | 1.46 | 1.47 | 1.48 | 1.49 | 1.50 | 1.51 | 1.52 | 1.53 | 1.54 | 1.55 | 1.55 |
| 93 | | 1.29 | 1.35 | 1.38 | 1.40 | 1.41 | 1.42 | 1.43 | 1.44 | 1.44 | 1.45 | 1.46 | 1.46 | 1.47 | 1.47 |
| 92 | 1.12 | 1.26 | 1.31 | 1.33 | 1.35 | 1.36 | 1.36 | 1.36 | 1.37 | 1.37 | 1.39 | 1.39 | 1.40 | 1.40 | 1.40 |
| 91 | 1.11 | 1.23 | 1.27 | 1.29 | 1.30 | 1.30 | 1.31 | 1.31 | 1.32 | 1.32 | 1.33 | 1.33 | 1.33 | 1.34 | 1.34 |
| 90 | 1.10 | 1.20 | 1.23 | 1.24 | 1.25 | 1.25 | 1.26 | 1.26 | 1.26 | 1.27 | 1.27 | 1.27 | 1.28 | 1.28 | 1.28 |
| 89 | 1.09 | 1.17 | 1.19 | 1.20 | 1.20 | 1.21 | 1.21 | 1.21 | 1.21 | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 | 1.23 |
| 88 | 1.07 | 1.14 | 1.15 | 1.16 | 1.16 | 1.16 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 |
| 87 | 1.06 | 1.11 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.13 | 1.13 |
| 86 | 1.04 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 |
| 85 | 1.03 | 1.05 | 1.05 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 |
| 84 | 1.01 | 1.02 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.99 | 0.99 |
| 83 | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.95 | 0.95 | 0.95 |
| 82 | 0.97 | 0.96 | 0.95 | 0.94 | 0.93 | 0.93 | 0.93 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 |
| 81 | 0.96 | 0.93 | 0.91 | 0.90 | 0.90 | 0.89 | 0.89 | 0.89 | 0.89 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 |
| 80 | 0.93 | 0.90 | 0.88 | 0.87 | 0.86 | 0.86 | 0.86 | 0.85 | 0.85 | 0.85 | 0.85 | 0.84 | 0.84 | 0.84 | 0.84 |
| 79 | 0.91 | 0.87 | 0.85 | 0.84 | 0.83 | 0.82 | 0.82 | 0.82 | 0.82 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 |
| 78 | 0.89 | 0.84 | 0.82 | 0.80 | 0.80 | 0.79 | 0.79 | 0.79 | 0.78 | 0.78 | 0.78 | 0.78 | 0.77 | 0.77 | 0.77 |
| 77 | 0.87 | 0.81 | 0.78 | 0.77 | 0.76 | 0.76 | 0.76 | 0.75 | 0.75 | 0.75 | 0.75 | 0.74 | 0.74 | 0.74 | 0.74 |
| 76 | 0.84 | 0.78 | 0.75 | 0.74 | 0.73 | 0.73 | 0.72 | 0.72 | 0.72 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |

## TABLE 105-1 (CONT.)
## QUALITY LEVEL ANALYSIS BY THE STANDARD DEVIATION METHOD

| $P_U$ or $P_L$ % | Upper Quality Index $Q_u$ or Lower Quality Index $Q_L$ | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n= 3 | n= 4 | n= 5 | n= 6 | n= 7 | n= 8 | n= 9 | n=10 TO n=11 | n=12 TO n=14 | n=15 TO n=18 | n=19 TO n=25 | n=26 TO n=37 | n=38 TO n=69 | n=70 TO n=200 | n=201 TO n=X |
| 75 | 0.82 | 0.75 | 0.72 | 0.71 | 0.70 | 0.70 | 0.69 | 0.69 | 0.69 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.67 |
| 74 | 0.79 | 0.72 | 0.69 | 0.68 | 0.67 | 0.66 | 0.66 | 0.66 | 0.66 | 0.65 | 0.65 | 0.65 | 0.65 | 0.64 | 0.64 |
| 73 | 0.76 | 0.69 | 0.66 | 0.65 | 0.64 | 0.63 | 0.63 | 0.63 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 | 0.61 | 0.61 |
| 72 | 0.74 | 0.66 | 0.63 | 0.62 | 0.61 | 0.60 | 0.60 | 0.60 | 0.59 | 0.59 | 0.59 | 0.59 | 0.59 | 0.58 | 0.58 |
| 71 | 0.71 | 0.63 | 0.60 | 0.59 | 0.58 | 0.57 | 0.57 | 0.57 | 0.57 | 0.56 | 0.56 | 0.56 | 0.56 | 0.55 | 0.55 |
| 70 | 0.68 | 0.60 | 0.57 | 0.56 | 0.55 | 0.55 | 0.54 | 0.54 | 0.54 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.52 |
| 69 | 0.65 | 0.57 | 0.54 | 0.53 | 0.52 | 0.52 | 0.51 | 0.51 | 0.51 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| 68 | 0.62 | 0.54 | 0.51 | 0.50 | 0.49 | 0.49 | 0.48 | 0.48 | 0.48 | 0.48 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 |
| 67 | 0.59 | 0.51 | 0.47 | 0.47 | 0.46 | 0.46 | 0.46 | 0.45 | 0.45 | 0.45 | 0.45 | 0.44 | 0.44 | 0.44 | 0.44 |
| 66 | 0.56 | 0.48 | 0.45 | 0.44 | 0.44 | 0.43 | 0.43 | 0.43 | 0.42 | 0.42 | 0.42 | 0.42 | 0.41 | 0.41 | 0.41 |
| 65 | 0.52 | 0.45 | 0.43 | 0.41 | 0.41 | 0.40 | 0.40 | 0.40 | 0.40 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 |
| 64 | 0.49 | 0.42 | 0.40 | 0.39 | 0.38 | 0.38 | 0.37 | 0.37 | 0.37 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| 63 | 0.46 | 0.39 | 0.37 | 0.36 | 0.35 | 0.35 | 0.35 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.33 | 0.33 | 0.33 |
| 62 | 0.43 | 0.36 | 0.34 | 0.33 | 0.32 | 0.32 | 0.32 | 0.32 | 0.31 | 0.31 | 0.31 | 0.31 | 0.31 | 0.31 | 0.31 |
| 61 | 0.39 | 0.33 | 0.31 | 0.30 | 0.30 | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| 60 | 0.36 | 0.30 | 0.28 | 0.27 | 0.27 | 0.27 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.25 | 0.25 |
| 59 | 0.32 | 0.27 | 0.25 | 0.25 | 0.24 | 0.24 | 0.24 | 0.24 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| 58 | 0.29 | 0.24 | 0.23 | 0.22 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| 57 | 0.25 | 0.21 | 0.20 | 0.19 | 0.19 | 0.19 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |
| 56 | 0.22 | 0.18 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| 55 | 0.18 | 0.15 | 0.14 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| 54 | 0.14 | 0.12 | 0.11 | 0.11 | 0.11 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| 53 | 0.11 | 0.09 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| 52 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| 51 | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 |
| 50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**TABLE 105-2**
**Pay Factors**

| Pay Factor | Required Quality Level for a given sample size (n) and given Pay Factor | | | | | |
|---|---|---|---|---|---|---|
| | n= 3 | n= 4 | n= 5 | n= 6 | n= 7 | n = 8 TO n = X |
| 1.05 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1.04 | 96 | 96 | 97 | 97 | 97 | 97 |
| 1.03 | 92 | 93 | 93 | 94 | 94 | 94 |
| 1.02 | 88 | 89 | 90 | 91 | 91 | 91 |
| 1.01 | 83 | 86 | 87 | 88 | 88 | 88 |
| 1.00 | 79 | 82 | 83 | 84 | 85 | 86 |
| 0.99 | 75 | 78 | 80 | 81 | 82 | 83 |
| 0.98 | 71 | 75 | 77 | 78 | 79 | 80 |
| 0.97 | 67 | 71 | 73 | 75 | 76 | 77 |
| 0.96 | 63 | 68 | 70 | 72 | 74 | 74 |
| 0.95 | 58 | 64 | 67 | 69 | 71 | 71 |
| 0.94 | 54 | 60 | 63 | 66 | 68 | 69 |
| 0.93 | 50 | 57 | 60 | 63 | 65 | 66 |
| 0.92 | 46 | 53 | 57 | 60 | 62 | 63 |
| 0.91 | 42 | 49 | 53 | 56 | 59 | 60 |
| 0.90 | 38 | 46 | 50 | 53 | 56 | 57 |
| 0.89 | 33 | 42 | 47 | 50 | 53 | 54 |
| 0.88 | 29 | 39 | 43 | 47 | 50 | 51 |
| 0.87 | 25 | 35 | 40 | 44 | 47 | 49 |

**TABLE 105-2A**
**Multiplication Factors**

| | n = 3 | n = 4 | n = 5 | n = 6 | n= 7 | n = 8 TO n = X |
|---|---|---|---|---|---|---|
| *A | 0.2400 | 0.2769 | 0.3000 | 0.3214 | 0.3396 | 0.3495 |

* Multiplication factor, as "n" varies, for determination of PF by formula when $X_n$ is at, or inside, the specification limits.

**TABLE 105-3**

**"V" Factors for various elements**

| | |
|---|---|
| For Hot Bituminous Pavement: | |
| No. 8 mesh and larger sieves | 2.80 |
| No. 30 mesh sieve | 1.80 |
| No. 200 mesh sieve | 0.80 |
| Asphalt content | 0.20 |
| Percent of maximum density | 1.30 |

**TABLE 105-4**
**Pay Factors as R varies according to lot size**

| PF | n = 1 | n = 3 | n = 4 | n = 5 | n = 6 | n = 7 | n = 8 |
|---|---|---|---|---|---|---|---|
| | R Values | | | | | | |
| 1.00 | 0.00 | | | | | | |
| 0.99 | 0.04 | | | | | | |
| 0.98 | 0.08 | | | | | | |
| 0.97 | 0.12 | | | | | | |
| 0.96 | 0.16 | | | | | | |
| 0.95 | 0.20 | | | | | | |
| 0.94 | 0.24 | | | | | | |
| 0.93 | 0.28 | 0.00 | | | | | |
| 0.92 | 0.32 | 0.06 | | | | | |
| 0.91 | 0.36 | 0.11 | 0.00 | | | | |
| 0.90 | 0.40 | 0.17 | 0.06 | 0.00 | | | |
| 0.89 | 0.44 | 0.22 | 0.13 | 0.07 | 0.00 | | |
| 0.88 | 0.48 | 0.28 | 0.19 | 0.13 | 0.07 | 0.00 | 0.00 |
| 0.87 | 0.52 | 0.33 | 0.25 | 0.20 | 0.14 | 0.08 | 0.08 |
| 0.86 | 0.56 | 0.39 | 0.31 | 0.27 | 0.21 | 0.15 | 0.15 |
| 0.85 | 0.60 | 0.44 | 0.38 | 0.33 | 0.29 | 0.23 | 0.23 |
| 0.84 | 0.64 | 0.50 | 0.44 | 0.40 | 0.36 | 0.31 | 0.31 |
| 0.83 | 0.68 | 0.56 | 0.50 | 0.47 | 0.43 | 0.38 | 0.38 |
| 0.82 | 0.72 | 0.61 | 0.56 | 0.53 | 0.50 | 0.46 | 0.46 |
| 0.81 | 0.76 | 0.67 | 0.63 | 0.60 | 0.57 | 0.54 | 0.54 |
| 0.80 | 0.80 | 0.72 | 0.69 | 0.67 | 0.64 | 0.62 | 0.62 |
| 0.79 | 0.84 | 0.78 | 0.75 | 0.73 | 0.71 | 0.77 | 0.69 |
| 0.78 | 0.88 | 0.83 | 0.81 | 0.80 | 0.79 | 0.79 | 0.77 |
| 0.77 | 0.92 | 0.89 | 0.88 | 0.87 | 0.86 | 0.85 | 0.85 |
| 0.76 | 0.96 | 0.94 | 0.94 | 0.93 | 0.93 | 0.92 | 0.92 |
| 0.75 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.75 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| ≤0.74 | ≥1.51 | ≥1.51 | ≥1.51 | ≥1.51 | ≥1.51 | ≥1.51 | ≥1.51 |
| **B = | 0.25 | 0.18 | 0.16 | 0.15 | 0.14 | 0.13 | 0.13 |

** Multiplication factor, as "n" varies, for determination of PF by formula when $\overline{X}_n$ is outside the specification limits.

## REVISION OF SECTION 105
## CONTROL OF WORK

### TABLE 105-5

**"W" Factors for various elements**

| For Hot Bituminous Pavement: | |
|---|---|
| Sieve analysis.......................... | 20 |
| Asphalt content......................... | 30 |
| Percent of maximum density.............. | 50 |

# Appendix C

## Section 106 - Control of Material

<<106QA/QC>>

**REVISION OF SECTION 106**
**CONTROL OF MATERIAL**

Section 106 of the Standard Specifications is hereby revised for this project as follows:

Subsection 106.03 shall include the following:

All hot bituminous pavement, Item 403, shall be tested in accordance with the following program of process control testing and acceptance testing:

(a) **Process Control Testing.** The Contractor shall be responsible for process control testing on all items in the Contract listed in Table 106-1. Process control testing shall be performed at the expense of the Contractor. The Contractor shall develop a quality control plan for the process control testing which must be based on, and address all of the following:

1. **Control Limits and Charts.** For each specified element, the quality control plan shall be based on the average values of uniform size groups (2 to 5 samples per group) of samples. The control limits and target values shall be stated (or estimated). The control limits must be within the specification limits. In lieu of group averages, on an interim basis, the control plan may be based on single test values. A continuous plot for average values, or single values, with limits and targets shown, shall be made of test values and posted daily on a wall chart.

2. **Frequency of Tests.** The quality control plan shall indicate the sampling frequency, which initially shall not be less than shown in Table 106-1 for normal frequency. The sampling frequency for very large quantity items as identified in the Contract, may be reduced when the process is under control in accordance with Table 106-1. Being under control is defined as follows:

   A. The average values of uniform size groups, composed of two or more samples, are within the process control limits (for at least the quantity represented by ten single samples)

   B. When ten consecutive single samples are within the specifications.

3. **Not Conforming to Limits.** When a group average value is outside the control limits or a single test is outside the specification limits, the process shall be considered as not conforming to plan control limits. In this case, the Contractor shall take immediate action to bring the process back into control. If the cause of the problem is not readily apparent, production shall be suspended until the source of the problem is determined and corrected. A short explanation of actions taken to correct control problems shall accompany the test data. If at reduced sampling frequency, sampling shall revert to the normal frequency (Table 106-1) until the process is under control again.

4. **Point of Sampling.** The material for process control testing shall be sampled by the Contractor using approved procedures. The location where material samples will be taken shall be indicated in the Contractor's quality control plan.

5. **Testing Standards.** The quality control plan shall indicate which testing standards will be followed. Acceptable standards are Colorado Procedures, AASHTO and ASTM. A Colorado Procedure shall be used before AASHTO or ASTM Procedures.

6. **Testing Personnel Qualifications.** The person responsible for the process control testing shall be identified in the Contractor's quality control plan. This person must possess one or more of the following qualifications:

   (A) Registration as a Professional Engineer.

   (B) NICET certification at Level II or higher in the subfield of Highway Materials or Asphalt, Concrete, and Soils.

   (C) A minimum of five years testing experience with soils, asphalt pavement, and concrete.

   Technicians performing tests, if other than the person responsible for process control testing, must possess one or more of the following qualifications:

   (A) A minimum of two years testing experience in the specialty field.

   (B) Certification by a nationally recognized organization such as National Institute For Certification In Engineering Technologies (NICET).

   (C) For the appropriate specialty field, Certification by American Concrete Institute (ACI), or (on an interim basis) by Colorado Asphalt Producers Association (CAPA).

7. **Testing Equipment.** All of the testing equipment used to conduct process control testing shall conform to the standards specified in the test procedures and be in good working order.

8. **Reporting and Record Keeping.** The Contractor shall report the results of the process control tests to the Engineer in writing at least once a day. The Contractor shall make provisions so that the Engineer can inspect the work in progress, plants, sampling, testing in progress and Contractor's testing facilities at any time.

The Contractor shall submit the quality control plan to the Engineer at the preconstruction conference. The Contractor shall not start any work on the project until the Engineer has approved the plan, in writing.

(b) **Acceptance Testing.** Acceptance testing is the responsibility of the Division and need not be addressed in the Contractor's quality control plan. Acceptance testing will conform to the following:

1. **Reference Conditions.** Under acceptance testing, three reference conditions can exist determined by conformity to specification limits and the Quality Level Analysis (QLA) made on the moving average of five consecutive test results. (The QLA at the beginning of production and after major material changes may be made on less than five test results for formation only). The Moving Quality Level (MQL) will be for the purpose of identifying the reference conditions as listed below. The MQL will be calculated in accordance with the procedure in Section 105 for determining Quality Level (QL). The MQL will not be used to determine pay factors. The three quality conditions and actions that may or will be taken are described as follows:

   A. Condition Green will exist for the element when an MQL of 87 or better is reached, or maintained, and the past five consecutive tests meet specifications. Under this condition, the sampling frequency may change to Green or remain at Green as shown in Table 106-1. When changing to Green frequency, the next sample after the above conditions are met becomes the first sample in a new lot.

   B. Condition Yellow will exist for all elements at the beginning of production or when a new lot is established because of changes in materials or the job-mix formula, or following an extended suspension of work. During the initial condition Yellow, under the direction of the Engineer, a testing check program between acceptance and quality testing persons will be conducted for each element. This will be continued until condition Green is established for each element as defined under (A), above. Once an element is at condition Green, if the MQL falls below 87 or a test result falls outside the specification limits, the condition will revert to Yellow or Red as appropriate.

   The test that changes the condition to Yellow or Red will become the first sample in a new lot at the sampling frequency shown in Table 106-1. It will represent the Yellow or Red sublot quantity from which it was selected as determined by dividing the Green sublot into Yellow or Red sublots. The previous lot will represent production up to the beginning of the Yellow or Red representation.

C. Condition Red will exist for an element when the MQL drops below 65. When this condition occurs the Contractor will be notified immediately and a conference scheduled to discuss potential quality problems. Where there is not otherwise a satisfactory resolution as to the cause of the condition Red, additional check testing between quality control and acceptance testing persons will be done until condition Green is established.

2. **Determining the Sieve Analysis Sampling Frequency.** The MQL will be determined using the test results for each specified sieve; if any result causes a change in sampling frequency, the entire sieve analysis sampling frequency will change accordingly.

3. **Point of Sampling for Acceptance Testing.** The point of sampling for acceptance testing will be as shown in the column titled "Point of Acceptance" in the Schedule For Minimum Sampling, Testing, And Inspection, in the CDOH Field Materials Manual.

   Samples for project acceptance testing shall be taken by the Contractor for asphalt cement in accordance with AASHTO T40; hot bituminous mixtures in accordance with CP-41; and a composite of aggregates for hot bituminous mixtures, in accordance with CP-30. The samples shall be taken in the presence of the Engineer. The Contractor shall reduce each sample to the size designated by the Engineer. The Contractor may retain a split of each sample. The Division will determine sample locations and perform the testing for relative compaction of hot bituminous pavement.

All materials being used are subject to inspection and testing at any time prior to or during incorporation into work. Acceptance tests will be made by and at the expense of the Division.

(c) **Testing Schedule.** Process control and project acceptance testing frequency shall be in accordance with Table 106-1. Acceptance sampling and testing procedures will be in accordance with the Schedule for Minimum Materials Sampling,Testing, and Inspection in the Division's Field Materials Manual.

## REVISION OF SECTION 106
## CONTROL OF MATERIAL

TABLE 106-1
TESTING SCHEDULE

| ITEMS AND TEST ELEMENTS | CONTRACTOR PROCESS CONTROL | | PROJECT ACCEPTANCE COLOR REFERENCE | |
|---|---|---|---|---|
| | NORMAL FREQUENCY | REDUCED FREQ., PROCESS UNDER CONTROL, LARGE QUANTITY ITEMS | YELLOW & RED | GREEN (See Note 1) |
| | Tons | Tons | Tons | Tons |
| 403 - Hot Bituminous Pavement | | | | |
| Asphalt Content | 1/500 | 1/1000 | 1/500 | 1/2500 |
| Gradation | 1/1000 | 1/2000 | 1/1000 | 1/3000 |
| Percent Density | 1/500 | 1/500 | 1/500 | 1/500 |

Note 1. This is the approximate maximum sublot size. When changing to Green if the estimated remaining quantity before the end of the project, or estimate period, is such that this frequency will not permit a lot consisting of at least three samples, the sublot size will be reduced accordingly.