Research Report
KTC-01-22/SPR 187-97-1F

KENTUCKY TRANSPORTATION CENTER

College of Engineering

DEVELOPMENT OF CONCRETE QC/QA SPECIFICATIONS FOR HIGHWAY CONSTRUCTION IN KENTUCKY

(Final Report)

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16. Abstract

There is a growing trend toward quality-based specifications in highway construction. A large number of quality control/quality assurance (QC/QA) specifications shift the responsibility of day-to-day testing from the state DOH to the contractor. This requirement for contractor-performed quality control testing has been partly due to the fact that state agencies are operating with a smaller pool of employees compared to previous years. Another driving force has been the application of performance-based specifications and realization that the contractor and the producer need some degree of flexibility in order to be more efficient and innovative. This report presents the background information behind the development of the new QC/QA Concrete specifications in Kentucky. Findings of this study have already been implemented in the form of a Special Note for QC/QA Concrete, which is expected to be fully implemented by the year 2002. The QC/QA Special Note encourages the Contractor to produce a consistent quality product by giving incentives. Conversely, it penalizes the Contractor for poor quality, and/or inconsistent quality. The Special Note has been written with quality and innovation in mind. That is why it allows the Contractor and the Producer to follow the ACI-318 procedures for concrete mix design as well as the Kentucky Transportation Cabinet recipe mixes.

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DEVELOPMENT OF CONCRETE QC/QA SPECIFICATIONS FOR HIGHWAY CONSTRUCTION IN KENTUCKY

(Final Report)

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Executive Summary

There is a growing trend toward quality-based specifications in highway construction. A large number of quality control/quality assurance (QC/QA) specifications shift the responsibility of day-to-day testing from the state DOH to the contractor. This requirement for contractor-performed quality control testing has been partly due to the fact that state agencies are operating with a smaller pool of employees compared to previous years. Another driving force has been the application of performance-based specifications and realization that the contractor and the producer need some degree of flexibility in order to be more efficient and innovative. This report presents the background information behind the development of the new QC/QA Concrete specifications in Kentucky. Findings of this study have already been implemented in the form of a Special Note for QC/QA Concrete, which is expected to be fully implemented by the year 2002. The QC/QA Special Note encourages the Contractor to produce a consistent quality product by giving incentives. Conversely, it penalizes the Contractor for poor quality, and/or inconsistent quality. The Special Note has been written with quality and innovation in mind. That is why it allows the Contractor and the Producer to follow the ACI-318 procedures for concrete mix design as well as the Kentucky Transportation Cabinet recipe mixes.

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Chapter 1: Introduction and Background

1.1. Introduction

During the 1960's and 1970's the Federal Highway Administration (FHWA) began to encourage the use of quality control / quality assurance (QC/QA) specifications, which were intended to be statistically based (FHWA, 1973). Since then, state transportation agencies have shown varying degrees of success in implementation of quality assurance specifications. Many states are in the process of developing their own QC/QA specifications.

The National Quality Initiative (NQI) was formed as a partnership between industry stakeholders such as: officials from the FHWA, American Association of State Highway and Transportation Officials (AASHTO), material suppliers, and contractors. This group met to discuss the need to continually improve the quality of the design, construction, and maintenance of the nation's system of highways. The NQI steering committee developed an initial long-range plan to move into some of the more pervasive quality issues in the highway industry. This long-range plan was intended to be a flexible document that was supposed to be modified as necessary. The initial plan was conceived to provide a long-term commitment to continuous improvement rather than a short-term program. Some of the overall objectives of this long-range plan included:

- Considering international applications and technology for possible use.

- Building regional and national consensus on issues in this country that may enhance cost, quality, and performance of U.S. highway system. This included such issues as specifications, design and design assumptions, training and certification requirements, laboratory quality control requirements and accreditation.

- Improving the technology and technology sharing through research, training, incentives, demonstration, and use of information-sharing techniques.

- Heightening the awareness for quality and encouraging the use of quality improvement techniques, partnering, and state-of-the-art planning, design, construction, and maintenance techniques in the highway industry.

- Providing a follow-up mechanism for Transportation Circular 386 on "Innovative Contracting Practices" (TRB 1991 and, Tuggle 1994) to explore new ways of contracting and providing increased quality and quality incentives in the highway industry.

The New Jersey DOT was the first state agency to implement a statistically based Performance Related Specifications. Mr. Richard M. Weed was responsible for the original development of the New Jersey Specifications. In 1989, Mr. Weed also initiated the development of a software package. This package enables the user to analyze both pass/fail and pay adjustments. It can also construct operating characteristic curves, plot control charts, and perform statistical comparisons (Weed 1995, 1996, and 1999).

In the year 2000, the FHWA released the following publication: "latest Guidelines for Developing Performance-Related Specifications for PCC Pavements" on a CD-ROM to predict the future maintenance, rehabilitation, and other life-cycle costs of PCC pavements (FHWA-RD-00-131, August 2000). This instructive CD contains a four-volume report detailing guidelines for implementing performance-related specifications (PRS), as well as the 2.0 version of the PaveSpec software. The Indiana DOT used the PaveSpec software in connection with their efforts to develop performance related specifications for I-465 in Indianapolis.

1.2. Specification Types in Construction Industry

Generally, there are four types of specifications recognized in the construction industry (Burati and Hughes 1993, Chamberlin 1995). These are commonly known as:

- Proprietary Product Specifications
- Method Specifications
- End-result Specifications
- Performance Specifications

1.2.1. Proprietary Product Specifications

This type of specification refers to some specific product or its equivalent in its clauses. Therefore, it limits the competition and often results in a cost increase. Since buyer has to accept the product as a “black box”, the buyer’s risk is much higher than the other three types of specifications.

1.2.2. Method Specifications

This type of specification outlines a specific materials selection and construction operation process to be followed by the contractor in providing a product. Since there is no specific product specified, this type of specification allows competition among various suppliers and contractors. But, because the buyer sets the requirements for materials and methods, the owner has to bear the responsibility of the performance.

1.2.3. End-result Specifications

The final characteristics of the product are stipulated in the end-result specification and the contractor is given considerable freedom in achieving those characteristics. It may specify, a limit or a range for any given material and/or construction characteristic. The risk for the contractor or agency depends on how the acceptance limits and processes are specified.

1.2.4. Performance Related Specifications (PRS)

This type of specification holds the contractor responsible for the finished product’s performance. Thus, the contractor assumes considerable risk for the performance of the finished product. This type of specification is often used in conjunction with some type warranty. The challenge here is to use “true” performance indicators, which may not be available for all materials and processes.

1.3. Experience of other Agencies

Most of the U.S. highway agencies are in various stages of adopting end-result specifications plus QC/QA management schemes. It is important to note that materials do not always conform to specifications. Therefore, specifications must be designed to reward good quality, and penalize poor quality. The FHWA report reveals that many states are actively implementing QC/QA concepts into their specifications (FHWA, 2000). Table 1.1 presents a summary of the FHWA survey results.

Table 1.1 – Survey of State DOTs (Courtesy of FHWA, 2000)

State DOT	**With Formal QC/QA System**	**Without Formal QC/QA**	**QC/QA in Development**
Alabama		X	
Alaska		X	
Arizona	X		
Arkansas	X		
California		X	
Colorado	X		
Connecticut		X	
Delaware		X	
District of Columbia			X
Florida			X
Georgia	X		
Hawaii			X
Idaho		X	
Illinois	X		
Indiana	X		
Iowa			X
Kansas	X		
Kentucky	X		
Louisiana	X		
Maine		X	
Maryland	X		
Massachusetts		X	
Michigan	X		
Minnesota	X		
Mississippi		X	
Missouri		X	
Montana	X		
Nebraska			X
Nevada			X
New Hampshire		X	
New Jersey	X		

Table 1.1 – Continued –
Survey of Sate DOTs
(Courtesy of FHWA, 2000)

State DOT	With Formal QC/QA System	Without Formal QC/QA	QC/QA in Development
New Mexico			X
New York			X
North Carolina		X	
North Dakota		X	
Ohio		X	
Oklahoma			X
Oregon	X		
Pennsylvania	X		
Puerto Rico	X		
Rhoda Island		X	
South Carolina			X
South Dakota			X
Tennessee	X		
Texas			X
Utah			X
Vermont		X	
Virginia		X	
Washington			X
West Virginia	X		
Wisconsin	X		
Wyoming	X		

Chapter 2: Specification Concepts

2.1. QC/QA and PRS Concepts

Adjustable Payment Schedules are an integral part of a well-written specification. It can be justified that withholding a portion of the contracted price is related to the estimated loss of service life and performance. Based upon the work of Mr. Richard M. Weed, one of pioneer researchers in this area, the relationships between performance and deviation from specified quality were proposed (FHWA 1998). Using this methodology, the measured acceptance quality characteristics (AQC), which may include: concrete strength, slab thickness, initial smoothness, etc., are directly related to pavement performance through mathematical relationships. Performance is defined by key distress types, and smoothness may be related to the future maintenance, rehabilitation, and user costs of the highway.

If the economic impact of varying quality can be quantified, the results can be used to adjust the price of the finished product by giving either a penalty or a bonus. The penalty should not be more than the present worth of the estimated additional cost associated with deficient quality. On the other hand, the bonus must be estimated on the basis of how much performance potential is enhanced by exceeding the minimum measures of quality. Establishing a link between measured AQC's and future life-cycle costs (LCC's) by a mathematical formula is an on-going area of research.

2.2. History of Statistical Specifications

The history of quality control is as old as the manufacturing or construction industry itself. During the Middle Ages, quality control was addressed to a large extent by the long periods of training required by the guilds. The concept of specialization of labor was introduced during the Industrial Revolution. As a result, a single worker no longer made the entire product, only a portion. This change brought about a decline in workmanship and caused the quality to sufffer. Therefore, it became necessary to inspect the finished product. In 1924, Walter A. Shewhart of Bell Telephone Laboratories developed a statistical chart for the control of product variables (Grant, 1988). This chart is considered to be the beginning of statistical quality control. Later in the same decade, (H.F. Dodge and H.G. Romig 1959), both of Bell Telephone Laboratories, advocated an acceptance sampling as a substitute for 100% inspection. Thereafter, the value of statistical quality control became apparent in large scale. The American Society for Quality was formed in 1946 (Besterfield 1998)

Sampling is a method for checking the quality of a part as an evidence of the quality of the whole. Thus, characteristics of the sample of a lot are usually assumed to be indicative of the entire lot. Therefore, sampling plans are used as a statistical tool to decide which lots of the product to accept or which lots to reject. Ideally, a sampling plan should reject all bad lots while accepting all good lots. However, because acceptance/rejection decisions are made based upon a sample of the lot and not the entire lot, there is always a risk of not catching a bad lot. Quantification of this risk will be described later in this report.

Statistical tools such as the histogram, control charts, and operating characteristic curves organize sample information into a format which is simple to understand. Random sampling is the key to a valid statistically-based QC/QA. A statistical sampling plan assesses compliance with the specifications in a manner which allows for natural variability. Calibration of field testing equipment and batch plants and training of all personnel (the Contractor's and the Department's representatives) are of great importance. A Contractor's incentive to provide competent field personnel becomes apparent when pay factors are based upon Contractor-performed test data.

A basic requirement for most of statistical tools is that samples are taken from a normally distributed population. But well-defined normal distributions become evident only after a relatively large amount of data have been collected. Normality may not be readily apparent until the entire project is evaluated using techniques such as histogram, skewness and kurtosis, probability plots, and chi-square test. The minimum recommended sample size for each technique to get a reasonable representation of normality is given in Table 2.1 (Besterfield, 1998).

Table 2.1 - The minimum recommended sample size to test normality

Technique	Minimum recommended sample size
Histogram	50
Skewness and Kurtosis	100
Probability Plots	30
Chi-Square Goodness of Fit Test	125

2.3. Outline of Statistical QC/QA Specifications

The following is a summary of statistical concepts behind QC/QA Specification in highway construction.

- A test is performed on a sample from a lot. Therefore, a test can only estimate the quality of the lot. Greater confidence in sampling can be gained through more frequent testing per lot.
- Stratified random sampling technique is the most appropriate technique for use in concrete construction. It involves setting up a fair and random selection after dividing the total quantity into lots and sublots.

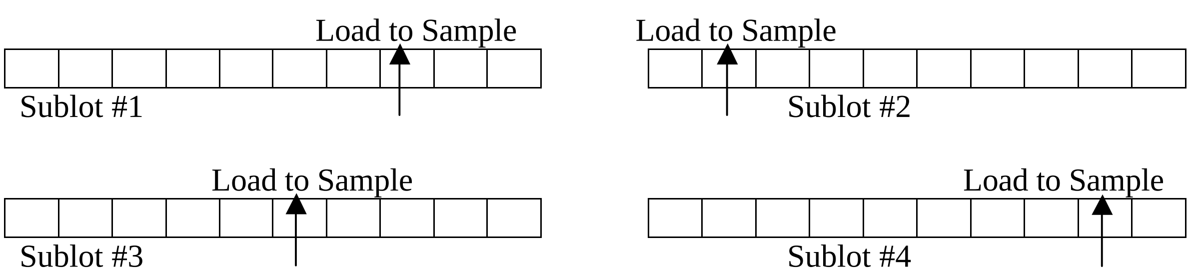

Figure 2.2 - Stratified Random Sampling (For example: One Lot = 4 Sublots, One Sublot = 10 Truck Loads)

- Operating characteristic curve is an effective method to address the consumer's risk and producer's risk involved with the sampling plan. However, generating such a curve may be cumbersome.
- A certain amount of variation normally exits within a lot. Hence, the QC/QA specification should be written such that it can tolerate a reasonable amount of variation. Testing personnel should be fully trained so that operator errors can be minimized. Additionally, the field personnel must be able to be capable of discerning the difference between inherent variability and variability caused by inadequate quality management or lack of process control.
- Specification should also include special provisions for small quantities which do not lend themselves to valid statistical analyses.

2.4. Control Charts for Process Control

One could say that the variability is a law of nature; no two natural items in any category are the same (Besterfield, 1998). As long as these sources of variation fluctuate in a random manner, a stable pattern of many random causes develops. Those causes of variation that are large in magnitude, and therefore readily identified, are classified as assignable causes. When only chance causes are present in the process, the process is considered to be in a state of statistical control. However, when an assignable cause of variation is also present, the variation will be excessive, and the process is classified as out of control, or beyond the expected natural variation (Samson 1970, Grant 1988, Duncan and Acheson 1952).

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In order to track the status of variations in quality, control charts are used. The control chart method is a means of depicting variations that occur around an average and within a range (Besterfield, 1998). It is a graphical record of a particular measure of quality. It shows whether or not the process is in a stable state.

If the samples are taken from a normally distributed population, variations among sampling pool may be expected to occur within plus or minus three standard deviations ($\pm 3\sigma$) from the average. This range covers 99.73% of all data. Thus, the central lines and trial control limits for the $\overline{X}$ chart and R chart are obtained as follow:

The central line of the $\overline{X}$ chart; $\overline{\overline{X}} = \dfrac{\sum_{i=1}^{g} \overline{X}_i}{g}$ (2.1)

The central line of the R chart; $\overline{R} = \dfrac{\sum_{i=1}^{g} R_i}{g}$ (2.2)

The Upper Control Limit of $\overline{X}$ chart, $UCL_{\overline{X}} = \overline{\overline{X}} + 3\sigma_{\overline{X}}$ (2.3)

The Lower Control Limit of $\overline{X}$ chart, $LCL_{\overline{X}} = \overline{\overline{X}} - 3\sigma_{\overline{X}}$ (2.4)

The Upper Control Limit of R chart, $UCL_R = \overline{R} + 3\sigma_R$ (2.5)

The Lower Control Limit of R chart, $LCL_R = \overline{R} - 3\sigma_R$ (2.6)

where

$\overline{\overline{X}}$ = average of lot averages (i.e. average of $\overline{X}_i$)

$\overline{X}_i$ = average of i^{th} lot

g = number of lots

$\overline{R}$ = average of lot ranges (i.e. average of R_i)

R_i = range of the i^{th} lot (i.e. the difference between the highest and the lowest observed values)

$\sigma_{\overline{X}}$ = the population standard deviation of the lot averages

σ_R = the population standard deviation of the range

The calculations are often simplified by using the product of the range ($\overline{R}$) and a factor (A_2) to replace the three standard deviation term ($A_2\overline{R} = 3\sigma_{\overline{X}}$) in the formulas for the $\overline{X}$ chart. For the R chart, the range $\overline{R}$ is used to estimate the standard deviation of the range (σ_R). Therefore, the derived formulas are:

$$UCL_{\overline{X}} = \overline{\overline{X}} + A_2\overline{R} \quad (2.7)$$

$$LCL_{\overline{X}} = \overline{\overline{X}} - A_2\overline{R} \quad (2.8)$$

$$UCL_R = D_4\overline{R} \quad (2.9)$$

$$LCL_R = D_3\overline{R} \quad (2.10)$$

Where A_2, D_3, and D_4 are factors that vary with the sample size and are found in most statistical tables.

In addition to $\overline{X}$ and R control charts, the Sample Standard Deviation control Charts, Moving Average and Moving Range Charts, Median and Range Charts, X Charts can also be used to monitor a process. From the concrete producer’s point of view, he/she must pay close attention to the control limits in addition to the specification limits. These control limits should not only be within the specification limits, but also the centerline must be close to the target value (typically, the mid-point in the specification range). Finally, the Kentucky QC/QA Concrete Special Note does not specifically require preparation of control charts; however, it is strongly recommended to monitor the progress of the QC/QA projects using some type of a control chart.

Chapter 3: Kentucky QC/QA Special Note

3.1. Introduction

This research was a coordinated effort between representatives from the Kentucky Transportation Cabinet (KYTC), Federal Highway Administration (FHWA), Kentucky concrete industry, and the University of Kentucky (UK). These representatives served on a Study Advisory Committee (SAC), which monitored the progress of the research. Throughout the course of this study, several draft versions of the QC/QA Special Note were prepared by the UK research team and were presented to the SAC. In addition to the SAC's critical review, a number of public forums were held to obtain a wider feedback from various parties who may be impacted by the new specifications. The issues that proved to be of significant interest were:

- Training and qualifications,
- Lot sizes and quantity management,
- Materials testing and, testing frequency, and
- Pay factors.

The final version of the QC/QA Special Note represents a workable model, which proved to be an acceptable compromise to all parties involved.

The QC/QA Special Note for Concrete, which was developed as a part of this research study, is currently being implemented on experimental projects. It is expected that after trial evaluations, the Kentucky Transport Cabinet Department's Standard Specifications for Road and Bridge Constructions will include the proposed concrete QC/QA specifications by the year 2002. The following sections summarize key components of this QC/QA Special Note.

3.2. Key Components

The most significant parts of this Special Note are the quality control plan, sampling plan, and the pay adjustment equations based on statistical methods (percent within limits).

3.2.1. Contractors Responsibilities

a) Quality Control Plan (QCP): It is the contractor's responsibility to submit his/her Quality Control Plan at least 15 calendar days prior to commencing the concrete operations, and to ensure the concrete producer performs his/her responsibilities.

The QCP is a documentation of the following items:

- General Project Information (location, description, route etc.),
- Field Office (location, key contact information),
- Field Quality Control Personal (names, level of qualification, contact information),
- Field Sampling and Testing (steps, personal, and protocols),
- Failing Tests and Defective Work (steps to be taken),
- Field Documentation (procedures, data recording, and reporting protocols), and
- Pre-Construction Meeting (schedules, procedures, key contact information).

b) **Field Testing Technicians:** All field tests for slump, air content, temperature, and casting cylinders must be only performed by ACI Level - I Technicians in accordance with the Kentucky Methods.

c) **Materials Testing:** The Kentucky QC/QA Special Note removes the responsibility from the Department to perform the day-to-day testing for process control/quality control (QC), and assigns the Contractor in charge of that. Additionally, acceptance testing is conducted by the Contractor. However, all concrete quality tests may be inspected and witnessed by the KYTC Project Engineer. The contractor must perform start-up slump, air content, and temperature testing each day of placement for each class of concrete in accordance with Table 3.1.

Table 3.1 - Start-up Testing Frequency

Class of Concrete	**Minimum Start-up Testing Frequency**
AAA, AA, D, D Mod, & S	First unit & any 2 of the next 4 units
A,A Mod, & B	First unit & any 2 of the next 6 units
P	First unit & any 2 of the next 8 units

Note: The first unit is that unit with acceptable start up results. If the first fresh concrete truck of the day showed a failing result, it must be rejected and the next truckload should be considered as the first load of the day. It may be necessary to repeat this process until the first acceptable load is delivered.

Once the first acceptable load has been established, The Contractor (or his/her qualified designee) does the acceptance testing according to a random scheme, which is selected by the KYTC Project Engineer. The Contractor does not have advance knowledge of the location selected by the Engineer for acceptance testing until shortly before testing.

All randomly selected samples for payment will be included for pay factor calculations, regardless of their failing or passing status. This is because some poor material may have already been placed prior to discovering a failing result. Additionally, the quantity of rejected concrete is not counted in the lot quantity. If the randomly selected production unit is outside the specification limits for slump, temperature, or air content, the Contractor must return to the Start-up Testing Frequency.

d) **Trip Tickets:** The Contractor must collect and ensure the data of acceptability of age, mixing revolutions, the amount of water (if required) and additional mixing revolutions (if required) on the trip tickets.

e) **Documentation:** The Contractor must record all job site test results and provide a summary of them with corresponding sublot/lot identification numbers and the trip tickets to the engineer. The test results must include results of all concrete rejected, if any.

f) **Other Testing:** The Contractor is responsible for all sampling and other testing for the purpose of either load application, or opening to traffic. These results will not be used for pay calculations.

3.2.2. Concrete Producer Responsibilities

The Concrete Producer is required to design concrete mixtures, and to perform quality control and process control testing in compliance with the Department's Specifications. He/She must submit a Concrete Producer Quality Control Plan to the Department prior to the start of concrete production for the project.

a) Concrete Producer Quality Control Plan: The Concrete Producer Quality Control Plan is a documentation of the following items:

- Project Information (location, description, etc.),
- Producer’s Information (name, location, reference no, type of plant),
- Quality Control Laboratory Information (name and location, contact information),
- Classes/Types of Concrete (mix design, admixtures etc.),
- Material Sampling and Testing (names, level of certification, contact information),
- Scale Certifications/ Calibrations (name of certified company and date),
- Concrete Truck Certification (truck number, type of certification, expiration data, fresh concrete dispatch log),
- Raw Materials Sources (aggregates, cement, fly ash, admixtures, source contact information),
- Testing Responsibilities (aggregates, cement, fly ash, admixtures, fresh concrete, hardened concrete, contact information), and
- Documentation (protocols, data forms).

b) Mix Design Options: The Concrete producer must submit mix designs to the Contractor using either Option-A (Kentucky Mix Design) or Option-B (ACI-318 Mix Design, ACI 1998) at least 15 calendar days prior to commencing concrete operations. The minimum required 28-Day Compressive Strengths of each class of concrete are given in the Table 3.2. The idea behind including the ACI-318 mixes in the KYTC list of approved concrete mixtures was to encourage innovation by the concrete Producers and Contractors. However, it was felt by the Research Advisory Committee that a 10% margin of safety should be added to the ACI-318 mixes in order to make them similar to KYTC mixtures in terms of their cement content.

Table 3.2 - Properties and requirements for various classes of concrete

Concrete, Class	Max. Free Water By w/c Ratio (lbs/lbs)	Target Air Content (%)	Min. 28-Day Comp. Strength (psi)	
			Option A (Kentucky Mix Design)	Option B (ACI 318 Mix Design)
A	0.49	6	3,500	3,850
A Mod	0.47	6	3,500	3,850
AA	0.42	6*	4,000	4,400
AAA	0.40	6*	5,500	6,050
B	0.66	6	2,500	2,750
D	0.44	6	4,000	4,400
D Mod	0.42	6	5,000	5,500
M1 with Type I Cement	0.33	6	4,000	N/A
M2 with Type III Cement	0.38	6	4,000	N/A
S	0.53	6	4,000	4,400
P	0.49	6*	3,500	3,850

* - The air content shall be 7%± 2% when coarse aggregate sizes #8, #78, or #9-M are used.

3.2.3. Department Responsibilities

a) **Verification Testing:** The KYTCDOT will verify the acceptance testing results at the rate of 25 percent (one out of every four tests). When the side-by-side verification test results exceed the tolerance limits given in Table 3.3, the discrepancy must be resolved in accordance with a set of dispute resolution protocols.

Table 3.3 - Acceptance/ Verification Tolerance

Test	**Tolerance**
Air Content	0.75 %
Compressive Strength	15 %
Temperature	3^0F
Slump	25% of maximum limit

b) Evaluation/Investigation of Poor Quality Lots: When an individual compressive strength test result falls more than 500 psi below the minimum required or the Strength-PWL for a lot is less than 75, a core evaluation of the in-place concrete (of the lot) will be required. If core strengths are equal to or greater than 90% of the minimum required compressive strength, the core strengths will be substituted for the low cylinder(s) to determined Strength-PWL. If core strengths are below 90% of the minimum required compressive strength, a design analysis will be required to determine if strength is adequate. If strength is determined to be adequate, the core strengths will be substituted for the low strength cylinder(s) to determine PWL. If strength is determined not to be adequate, the lot or sublot containing the failing concrete shall be removed and replaced at the Contractor's expense. The Contractor may be given the option of obtaining additional cores to more accurately identify the extent of removal required.

When Air Content PWL is less than 60%, the engineer must evaluate the specific lot to determine its acceptance/rejection, and any corrective work needed.

c) Random Testing Frequency: The engineer will select random samples based on the Start-up Testing Frequency (Table 3.1) and the Lot Size (Table 3.4)

Table 3.4 - Lot Size

Concrete Class	Lot Size (4-sub-lots per lot)	Sublot Size
AAA, AA, D, D Mod, & S	200 cubic yards	50 cubic yards
A, A Mod, & B	200 cubic yards	50 cubic yards
P	4000 square yards	1000 square yards

If the total quantity of the project is less than 8000 yd^2 for Class-P, or 400yd^3 for structural concrete, then the sublots are defined in the Table 3.5.

Table 3.5 - Number of Sublot for small projects

Structural Classes (CY)	Class-P (SY)	Total Sublots – Equally Divided
<100	<2,000	Accept based upon plastic concrete test results
100 to ≤ 200	2,000 to ≤ 4,000	4
200 to ≤ 250	4,000 to ≤ 5,000	5
250 to ≤ 300	5,000 to ≤ 6,000	6
300 to ≤ 400	6,000 to ≤ 8,000	One standard lot, plus a second smaller lot with four sublots

3.2.4. Measurement

The Department will measure Class-P Concrete and Structural Concrete according to the appropriate subsections of the Department Specification. As mentioned earlier, the department will not measure the strength and air content of the Class-P Concrete and Structural Concrete as a separate pay unit, but will analyze the strength and air content data as provided by the contractor to calculate an adjusted Contract unit price for each separate lot of each concrete type.

3.2.5. Dispute Resolution

a) Avoidance of Disputes: It is both the Department's and the contractor's responsibilities to take every effort to avoid disputes. The following steps ensure that all data are reliable, unbiased, and truly representative of the product quality.

- Ensuring personnel and laboratory facilities meet the specified certification requirements.
- Ensuring that all samples are obtained in accordance with KM 64-113, Sampling Materials by Random Number Sampling.
- Ensuring communication of test results between parties occurs within the specified time limits
- Discussing all questions regarding the specifications, KM's or sampling and testing procedures during the pre-construction, pre-paving, or any similar type of meeting to clarify any confusion.
- Resolving disputes at the lowest appropriate level of authority.

b) Levels of Dispute Resolutions: When the contractor's acceptance test results and the Department's verification test results are not within the specific tolerances, and a dispute is therefore unavoidable, the following levels are the levels to resolve the dispute:
- **Project Level Dispute Resolution:** Both the Engineer and the contractor will attempt to determine the reason for the discrepancy at the project level by having testing personnel review previous tests and other possible factors.
- **Materials Central Laboratory (MCL) Level:** The MCL will conduct further investigation on reviewing test data, checking both the engineer's and the contractor's calculations, inspecting of the instruments etc.
- **Third Party Resolution Level:** if the dispute is not resolved at the project or the MCL level the department and the contractor will use a mutually agreed upon laboratory. The results of this laboratory will be final and binding. If the independent laboratory testing and investigation indicates that the Department's tests are correct, the contractor will pay the cost of the investigation.

When the dispute is resolved at any level, and the Department's verification tests are correct, the Department will base the Contractor's pay on the Department's verification test results rather than on the Contractor's assurance test results. When the Department's verification tests are not correct, the Department will base the contractor's pay on the Contractor's acceptance testing as the appropriate Section or Subsection specifies.

3.2.6. Payment

The payments will be adjusted for a lot based on the Percent Within Limits (PWL) of both Compressive Strength and Air Content of the lot (AASHTO 1996). The Pay Factor equations were defined such that a lot having 90% within the specified limits will receive 100% pay factor, and a lot having 100% within limits will receive 102.5% pay factor.

a. Air Pay Factor: The Air Content Pay Factor is calculated using the following equation:

$$\text{Air Pay Factor} = 52.5 + 0.5 \text{ X } (\text{Air-PWL}) \qquad (3.1)$$

The limits for the Air-PWL calculations are given in the Table 3.6. It is important to note that acceptance limits are ± 2.0 % of target Air Content for all classes of concrete.

However, the ± 2.5 % of target Air Content is only for PWL calculations of structural concrete in order to accommodate issues related to concrete pumping and small lots.

Table 3.6 – Air Limits for PWL Calculations

Class of the Concrete	The limits for the Air PWL Calculations
Class-P Concrete	± 2.0 % of target Air Content
Structural Concrete	± 2.5 % of target Air Content

Note: Target Air Content is given in the Table 3.2

b) Strength Pay Factor: The Strength Pay Factor is calculated using the following equation:

Strength Pay Factor = 52.5 + 0.5 X (Strength-PWL) (3.2)

Since there is no upper limit for compressive strength, only the lower limit will be considered for PWL calculations and PWL (upper) will be set to 100%.

c) Total Pay factor (per lot): The Total Pay Factor will be calculated using the following equation:

Total Pay Factor (per lot) = 0.5 X Air Pay factor + 0.5 X Strength Pay Factor (3.3)

In real practice, especially when concrete is used in small scale for structural work, the contractor may find it difficult to maintain the uniformity of the concrete properties in the overall project. Therefore, it is necessary to achieve a "fair and balanced" set of bonus and penalty conditions. For the Class-P concrete, the equation 3.3 gives 2.5 % maximum bonus of the unit bid price for a lot; however, the penalty will be as much as 13.75% of the unit bid price. The ranges of possible Bonus/Penalty conditions are given in the Table 3.7. Therefore, the QC/QA Special Note recommends limiting the penalty to 5 % of the unit bid price for structural concrete, and 13.75% of the unit bid price for Class-P Concrete. A final correction in pay for each lot is made to adjust for as-designed versus as-delivered quantities based upon the following relationships:

Design Quantity Correction Factor = Design Quantity / Delivered Quantity (3.4)

Design Quantity Unit Price = Adjusted Unit Price (per lot) X Design Quantity Correction Factor (3.5)

The latest version of the Special Note (June 11, 2001) includes example calculations.

Table 3.7 - Possible Bonus/Penalty Boundary Conditions for a lot

PWL		Bonus/Penalty per lot	Capped Bonus/Penalty per lot	
Air Content	**Strength**	**(without the cap)**	**Class-P Concrete**	**Structural Concrete**
100	100	2.5% (bonus)	2.5% (bonus)	2.5% (bonus)
95	95	0.0% (neutral)	0.0% (neutral)	0.0% (neutral)
60*	75*	-13.75% (penalty)	-13.75% (penalty)	-5.0% (penalty)

*If Air-PWL is less than 60% or Strength PWL is less than 75% for a lot, a special evaluation by the Engineer is required.

3.3. QC/QA Concrete Software

With the implementation of the QC/QA Special Note, some additional calculations and procedures will be added to both the Contractor's and the Engineer's day-to-day workload. In order to address this issue, a computer software was developed by the University of Kentucky researchers to assist with statistically-based pay factor calculations and data recording. The software does all of the necessary calculations based upon "as delivered quantities". A final adjustment is made based upon the "as deigned" quantity for the project.

Table 3.8 - Input and Output Parameters of the UK-QC/QA Software

Input Parameters	Output Parameters
General Data (Dates, Names, Location)	PWL values (Air and Strength)
Number of Sublot per Lot	Pay Factors (Air-PF, Strength-PF, Total-PF)
Original Contract Unit bid price	Warnings for violation of Specifications
Acceptance Test Data (Air, Strength, Slump, and Temperature)	Creation of random sample scheme for verification test.
Core Strength Data (if needed)	Quantity Management, Lots Generated
Concrete Mix Design type (Class, Option, Aggregate Size)	Statistical Analysis (Average, Standard Deviation, and PWL)
Verification Test Data (Air, Strength, Slump, and Temperature)	Data Log Reports
Upper and Lower Specification Limits (Air and Strength) for PWL Calculations	Core Data Analysis (if needed)
Options to Change Specifications Limits	Adjusted Unit Bid Price (bonus/penalty)
Data Entry Facility	Project Summary Charts

3.4. Analysis of Pay Factors

This section is devoted to an analysis of pay factors associated with the QC/QA Concrete Special Note. Assuming that the sample size is four (each lot having four sublots), and the Air Content can be measured up to one decimal place, the number of possible sublot combinations for an acceptable lot is 2,825,761. This means that there are 2,825,761 combinations of totally acceptable sublots with Air Contents in the 4.0% to 8.0% range.

The relationship between the Cumulative Probability of Occurrence versus Pay Factor for the Class-P concrete is given in Figure 3.1. It shows that 50% of total possible sublot combinations (1,412,648/2,825,761) potentially can be penalized, and 37.6% of sublots (1,062,807/2,825,761) potentially can receive maximum bonus. This is only true, if Strength Pay Factor is 100%, and each combination has equal probability of occurrence.

The relationship between the Cumulative Probability of Occurrence versus Pay Factor for the Structural concrete is given in Figure 3.2. It shows that only 14% of total possible sublot combinations may be penalized by Pay Factor Equations, and 75% of them can get the maximum bonus.

In actual practice, the probability of occurrence may not be the same for all possible lot combinations. This is because the Contractor will try to improve the PWL by taking corrective action based upon previous lots data. This has a tendency to bias the random process; however, it will result in a better quality product. Thus, the probability to penalize a lot is much less than the theoretically calculated values reported above. Figure 3.3 and Figure 3.4 show the relationship between the Total Pay Factor and the sublot standard deviation and average. These figures demonstrate that the system is more forgiving (tolerates large standard deviations) if the average air content hovers around the middle of specifications limits. However, the system becomes less forgiving (does not tolerate large standard deviations) if the average air content gets close to the threshold of acceptable limits. Figure 3.5 shows the downside of producing concrete close to the threshold limits. Figure 3.6 demonstrates the advantage of operating in the mid-range of specifications limits. In summary, the Special QC/QA Note rewards the Concrete Producer and the Contractor for a having a tight quality control over their processed.

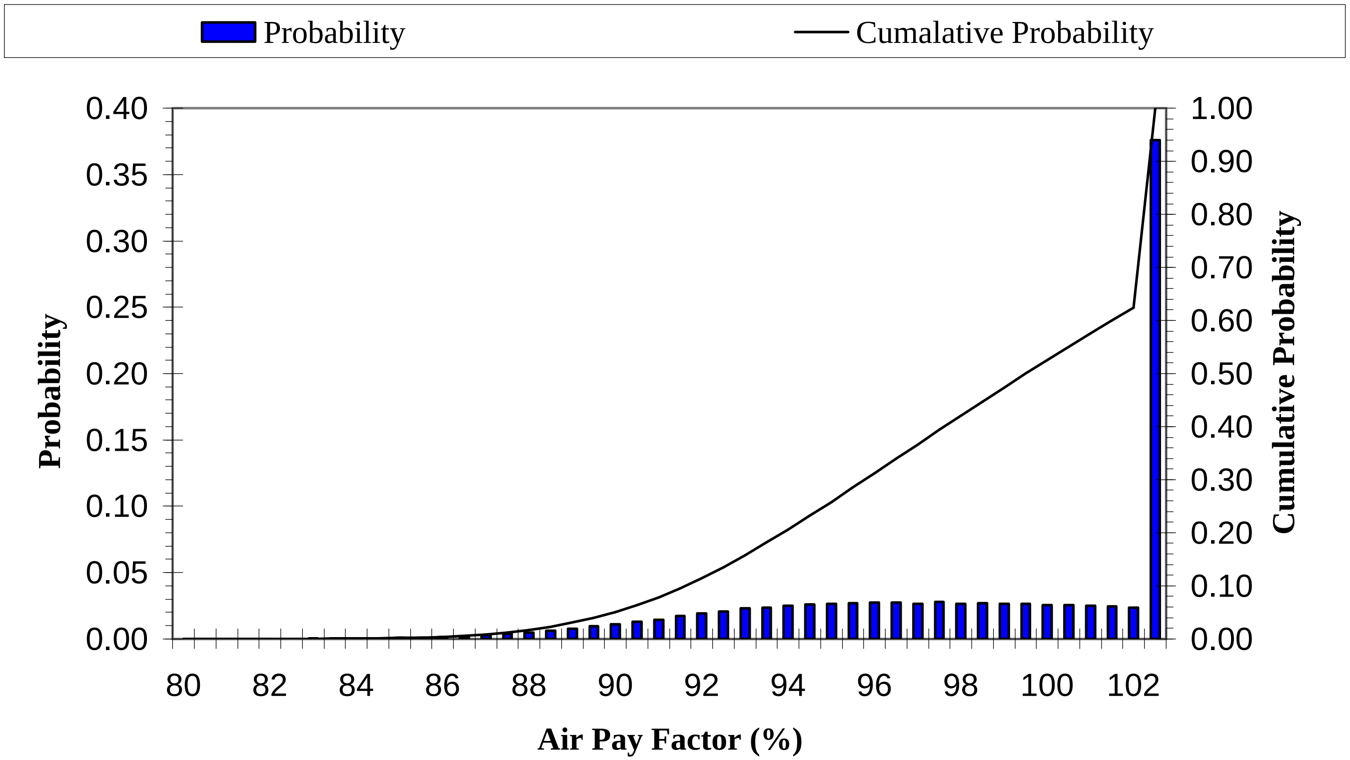

Figure 3.1. Probability of Various Air Pay Factors for Class-P Concrete.

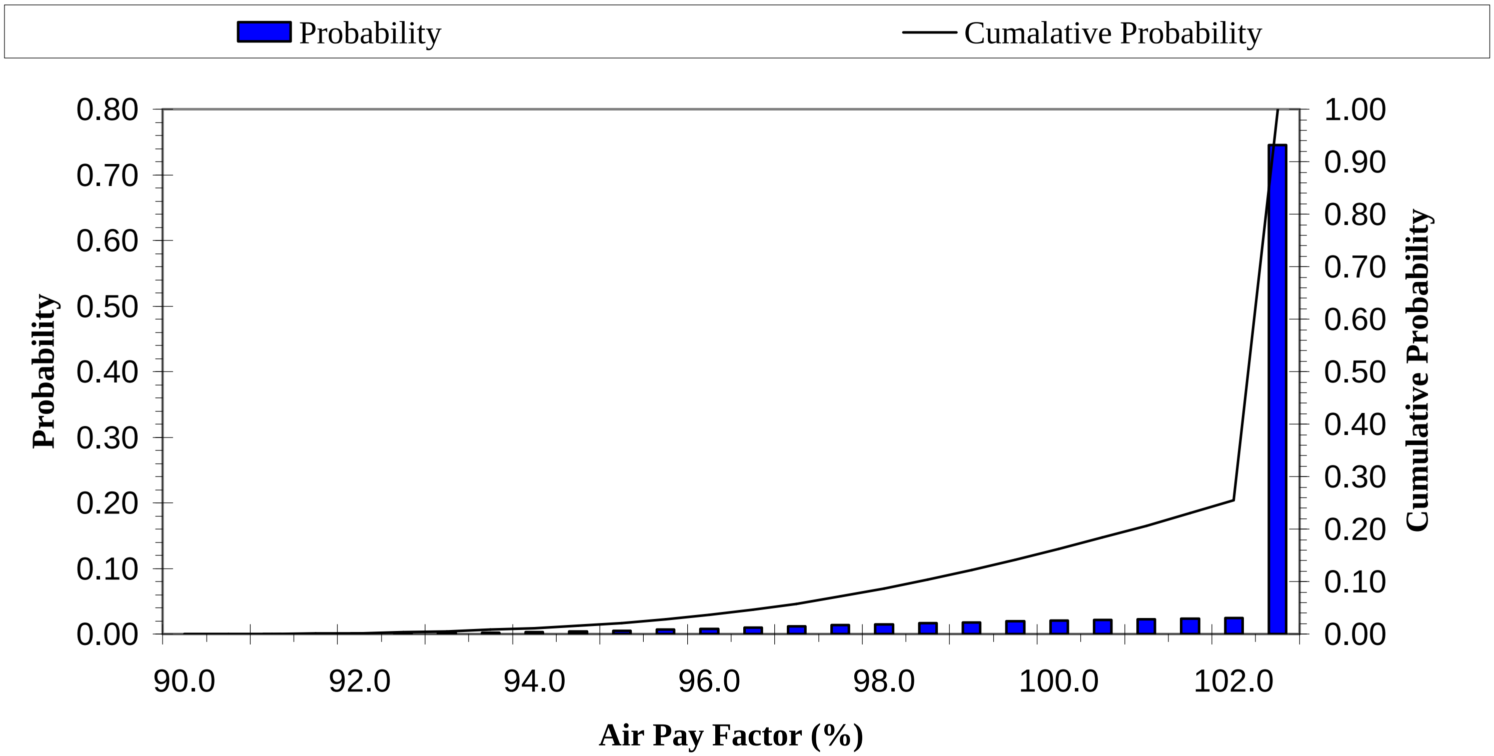

Figure 3.2. Probability of Various Air Pay Factors for Structural Concrete.

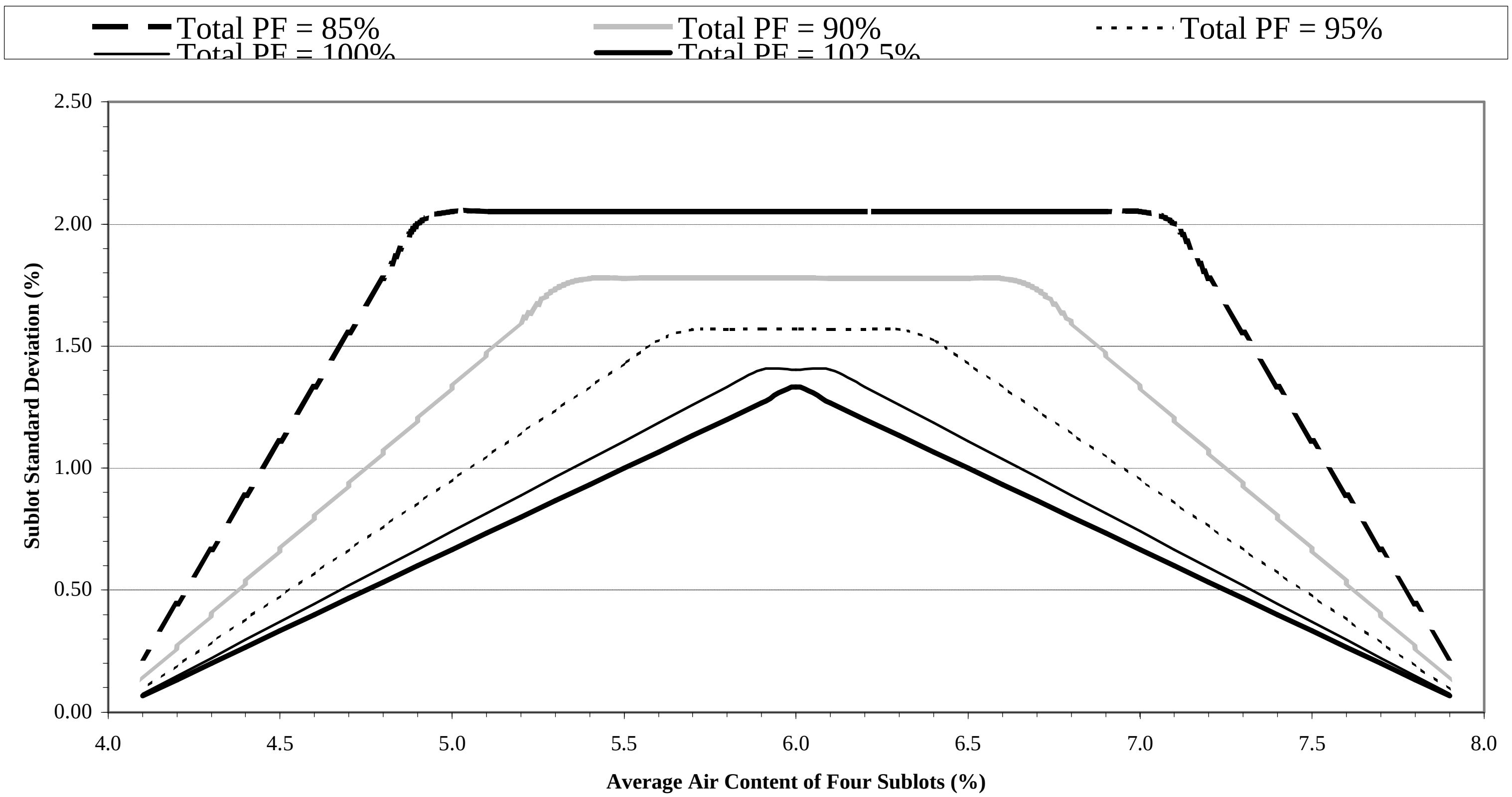

Figure 3.3. The Effects of Air Content Average and Standard Deviation on Total Pay Factor for Class-P Concrete (assuming Strength PF=102.5%).

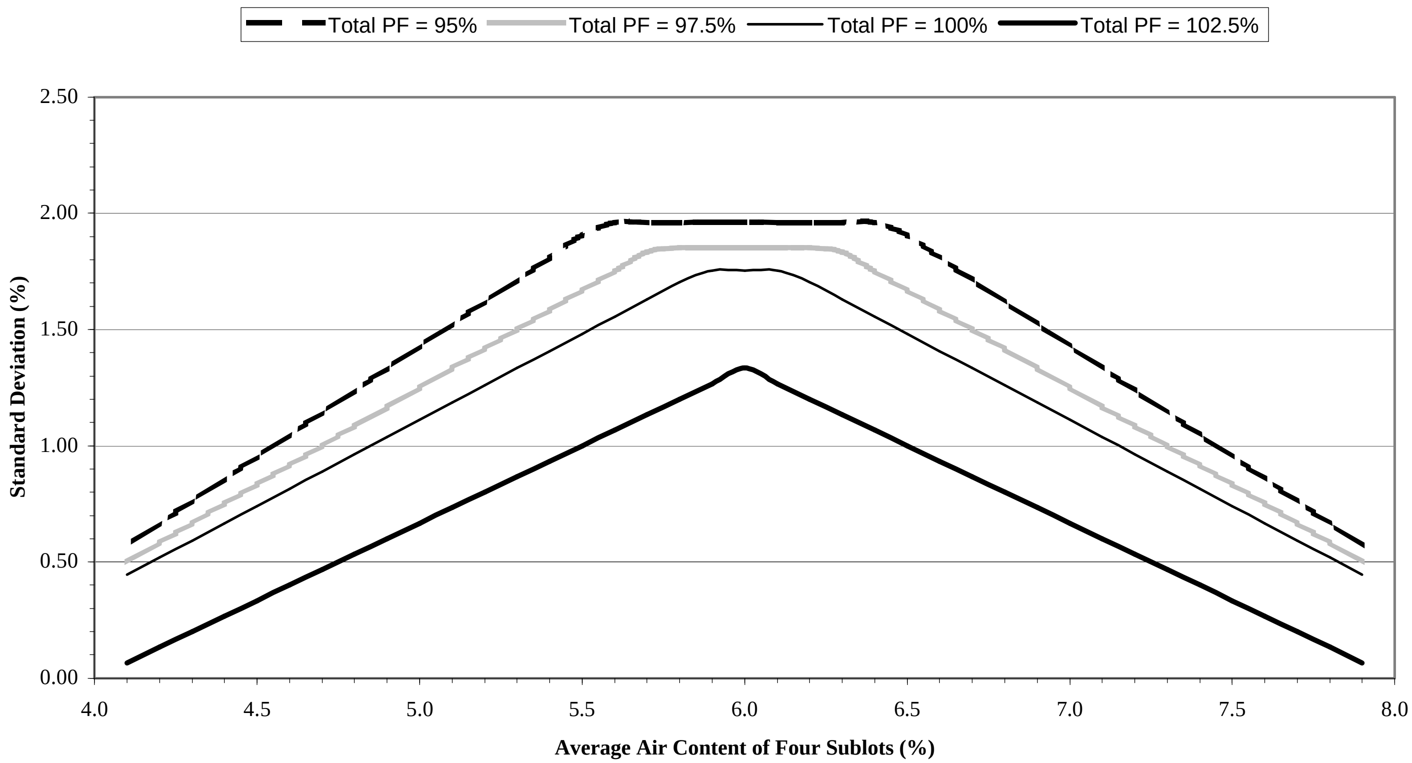

Figure 3.4. The Effects of Air Content Average and Standard Deviation on Total Pay Factor for Structural Concrete (assuming Strength PF=102.5%).

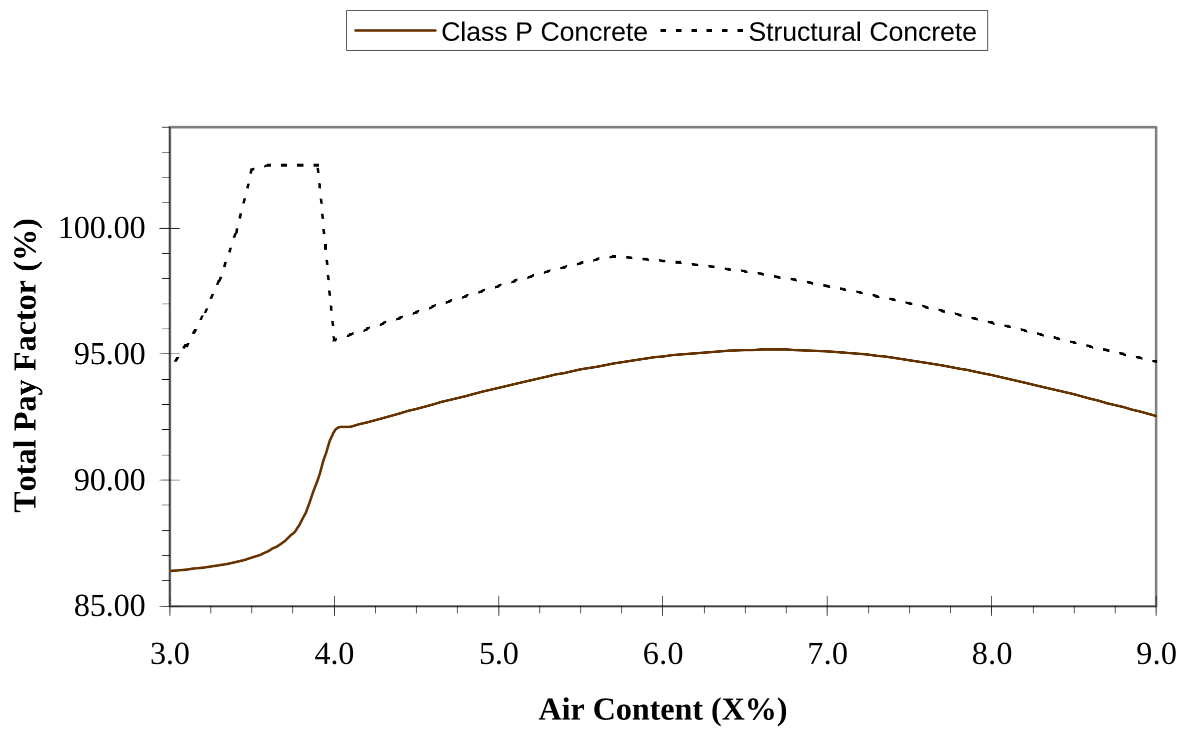

Figure 3.5. The Negative Consequences of Operating Close to the Specifications Threshold (example: 4% air threshold).

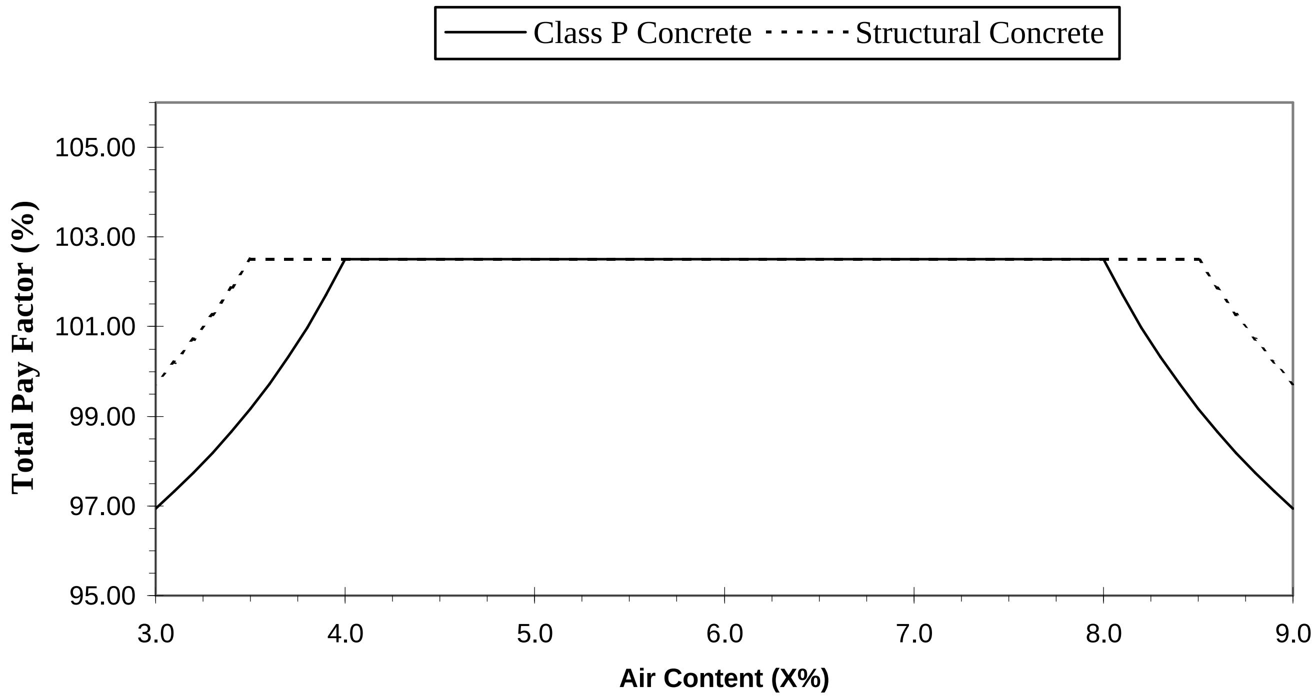

Figure 3.6. The Advantage of Operating in the Mid-Rabge of Specifications (four example sublots: 6%, 6%, 6%, X%).

Chapter 4: Risk Analysis

4.1. Operating Characteristic (OC) Curves

A sampling plan can measure the quality of only a small portion of the total quantity. Therefore, there is always a chance of accepting an undesirable lot. The OC Curve is a widely accepted tool to quantify the "Seller's Risk"(or Producer's Risk, α) and "Buyer's Risk" (or Consumer's Risk, β).

a) Key elements of an OC Curve

- **Acceptable Quality Level (AQL):** The AQL is a percent defective that is the base line requirement for the quality of the Producer's product. The Producer would prefer the sampling plan to have a *high probability of accepting* a lot that has a defect level less than or equal to the AQL.

- **Rejectable Quality Level (RQL):** The RQL is a designated high defect level that would be unacceptable to the Consumer. The Consumer would prefer the sampling plan to have a *low probability of accepting* a lot with a defect level as high as the RQL.

- **The Producer's Risk (**a**):** The Producer's Risk is the probability of non-acceptance of a lot that has a defect level equal to or below the AQL. The Producer suffers when this occurs, because a lot with acceptable quality gets rejected. This risk is frequently set at 5% in the manufacturing industry, and it can range from 0.1% to 10% or more (Besterfield,1998). Since α is expressed in terms of the probability of non-acceptance, it cannot be located on an OC curve unless it is specified in terms of probability of acceptance. This conversion is given below:

$$\text{Probability of Acceptance, } P(a) = 1 - \alpha \tag{4.1}$$

- **The Consumer's Risk (**b**):** The Consumer's Risk is the probability of acceptance of a lot with a defect level equal to or higher than the RQL. The Consumer suffers when this occurs, because a lot with unacceptable quality gets accepted. This Risk is frequently given as 10% in the manufacturing industry (Besterfield,1998).

- **Lot Acceptance Sampling Plan**: A sampling plan must include a set of rules for making acceptance decisions. The acceptance/rejection is decided based upon estimating the level of defectives in a sample. The QC/QA Special Note uses the following decision points for air content: AQL = 95% (corresponding to 100% pay), RQL = 60% (corresponding to close examination and possible rejection and removal), Acceptance Limit = 60%, and Sample Size = 4. Similarly, for strength: AQL = 95%, RQL = 75%, Acceptance Limit = 75%, and Sample Size = 4.

– **Operating Characteristic (OC) Curve:** The OC curve depicts the probability of accepting a lot (Y-axis) versus percent defectives (X-axis). Figure 4.1 demonstrates this in a decision table format.

		RESULT OF DECISION	
		ACCEPT the Lot	REJECT the Lot
QUALITY OF LOT	Good Lot (AQL)		Producer's Risk (TYPE I ERROR)
	Bad Lot (RQL)	Consumer's Risk (TYPE II ERROR)	

Figure 4.1 - Decision Table Defining Producer's Risk and Consumer's Risk of a Lot

b) Ideal OC Curve

When an acceptance plan is employed, there are conflicting interests between the Consumer and the Producer. The Producer wants all acceptable lots to be accepted, and the Consumer wants all unacceptable lots to be rejected. Only an ideal OC curve, as shown in Figure 4.2, can achieve this with a 100% inspection plan. Real life situations are not as black or white. Normally, there is a “gray area” where the buyer has to content with the risk of accepting poor quality product. Similarly, the seller must content with the risk of rejecting an acceptable quality product. This phenomenon is the result of less than 100% inspection.

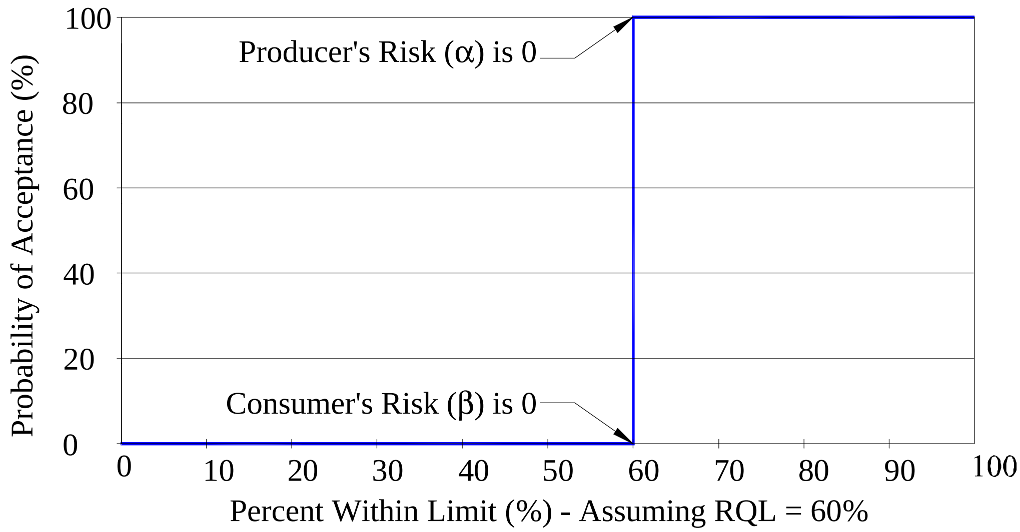

Figure 4.2 - Ideal OC Curve (by 100% inspection)

4.2. Types of OC Curves

There are two types of OC curves. Type-A curve gives the probability of accepting of an isolated finite lot. With a finite situation, the Hypergeometric Probability Distribution is used to calculate the acceptance probabilities. The formula for the Hypergeometric Distribution is constructed of three combinations (total combinations, nonconforming combinations, and conforming combinations) and given by the Equation 4.2.

$$P(d) = \frac{C_d^D C_{n-d}^{N-D}}{C_n^N} \tag{4.2}$$

where

P(d)	= Probability of "d" nonconforming units in a sample of size "n"
C_n^N	= Combinations of all units
C_d^D	= Combinations of nonconforming units
C_{n-d}^{N-D}	= Combinations of conforming units
N	= Number of units in the lot (population)
n	= Number of units in the sample
D	= Number of nonconforming units in the lot
d	= Number of nonconforming units in the sample
N-D	= Number of conforming units in the lot
n-d	= Number of conforming units in the sample

As stated earlier, Type-A OC curves is based on isolated finite lot with the combination of nonconforming units. However, it is hard to distinguish a discrete unit in concrete construction, which is a continuous process for the most part. Therefore, usage of type-A OC curve is limited to the manufacturing of discrete units.

Type-B curve gives the probability of accepting of an infinite lot. Thus, it is assumed that the lots come from a continuous product stream. In this case, the binomial distribution is the exact distribution form; however, the Poisson distribution is commonly used as a simple and close approximation. The formulas for the Binomial Probability

Distribution and the Poisson Probability Distribution are given by the Equations 4.3 and 4.4, respectively.

Binomial Probability Distribution , $P(d) = \frac{n!}{d!(n-d)!} p_0^d q_0^{n-d}$ (4.3)

where

P(d)	= Probability of d nonconforming units
n	= Number in the sample (e.g. number of sublots in a lot)
d	= Number nonconforming in the sample
p_o	= Proportion nonconforming in the population
q_o	= Proportion conforming ($1-p_o$) in the population

Poisson Probability Distribution, $P(c) = \frac{(np_0)^c}{c!} e^{-np_0}$ (4.4)

where

P(c)	= Probability of nonconforming units (c-units)
c	= Count of nonconformities in a lot (number of defectives)
np_o	= Average count
e	= 2.718281…

4.3. Poisson Distribution OC Curve

The Poisson Distribution is applicable when sample size (n) is quite large and proportion nonconforming (p_0) is small. Figure 4.3 shows four OC Curves, which represent four sampling plans with different combinations of sample size(n) and the acceptance number or the number of defectives (c = 0 or 1 for the case of QC/QA Special Note). The respective values of α and β are given in Table 4.1.

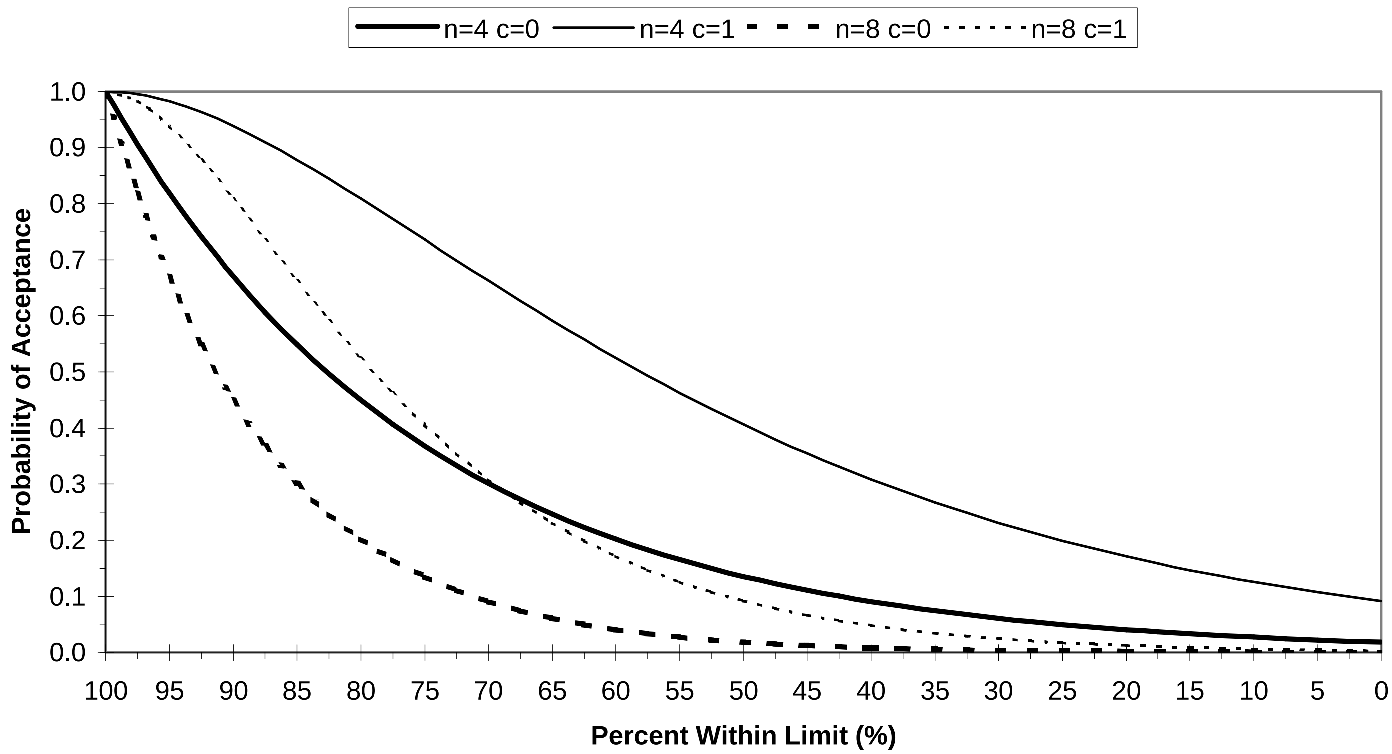

Figure 4.3. Operating Characteristics Curves using the Poisson Distribution.

Table 4.1 - Buyer's and Seller's Risks associated with sampling plans (using the Poisson Distribution)

Sample Size (n)	Acceptance Number (c)	Buyer's Risk (α) Assuming AQL = 60%	Seller's Risk (β) Assuming AQL = 95%
4	0	20.2%	18.1%
4	1	52.5%	1.8%
8	0	4.0%	33.0%
8	1	17.1%	6.2%

As the sample size increases, the slope of the OC curve becomes steeper and approaches a straight vertical line. Sampling plans with large sample sizes are better able to discriminate between acceptable and unacceptable quality. Therefore, fewer lots of unacceptable quality are accepted, and fewer lots of acceptable quality are rejected.

The main disadvantage of this type of OC Curve is that there are no provisions for the AQL and RQL in the input parameters of the Poisson Distribution. In this case, the only input parameters are the sample size (n), acceptance number (c), and proportion of nonconforming (p_0). But it is not reasonable to assume the distribution will be the same for any given project. When AQL and RQL are specified, it is reasonable to assume that the distribution will vary based on these two limits.

In addition to this weakness, it is not reasonable to assume a proportion of nonconforming units of any lot for given concrete Producer is unique throughout the entire project. In real practice, each lot is considered to have different proportion of nonconforming, which is estimated from each lot's data.

4.4. FHWA Software for OC Curve

Under the Demonstration Project 89 on Quality Assurance Software for the Personal Computer, a program called OCPLOT was developed for generating OC curves (FHWA-SA-96-026). It randomly generates sample sets of the desired size from a normal population for each of several known levels of quality. The main objective of the use of OC Curve in the performance related specification is to analyze the Buyer's Risk and the Seller's Risk. The QC/QA Special Note specifies two different criteria for Air Content and Compressive Strength (as previously stated: RQL = 60% and AQL = 95% for Air Content, and RQL = 75% and AQL = 95% for Compressive Strength). The OC Curves developed under a trial and error process for these two Acceptance Plans are shown in Figure 4.4 and Figure 4.5 and their associated Risks are tabulated in Table 4.2.

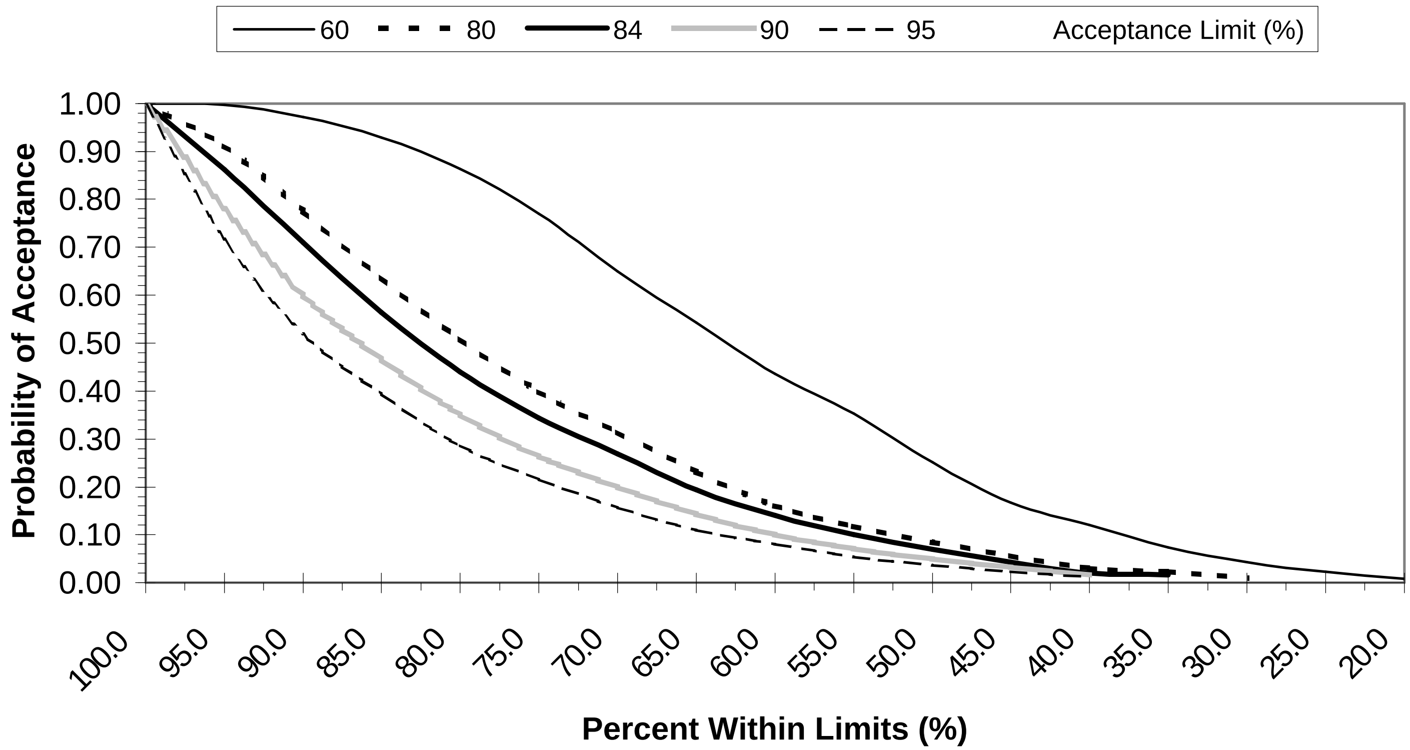

Figure 4.4. Operating Characteristics Curves using the FHWA-OCPLOT Software. Class-P Concrete (n=4, AQL = 95%, RQL = 60%).

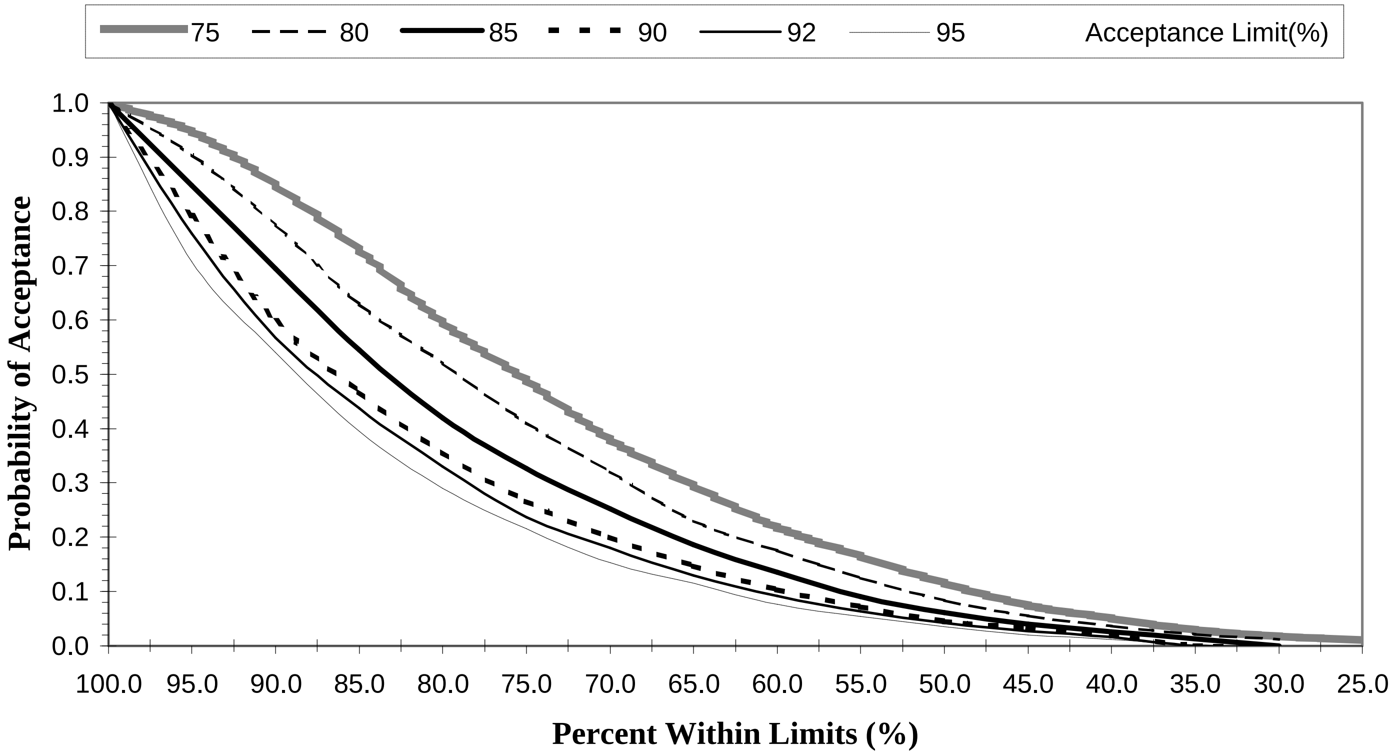

Figure 4.5. Operating Characteristics Curves using the FHWA-OCPLOT Software. Structural Concrete (n=4, AQL = 95%, RQL = 75%).

Table 4.2 - Buyer’s and Seller’s Risks Associated with Various Levels of Acceptance PWL Limit (using the OCPLOT,(FHWA-SA-96-026)

		Acceptance PWL (%)	Seller’s Risk (α)	Buyer’s Risk (β)
Accepting Sampling Plan No.1 (for Strength criterion)	N = 4 AQL = 95% RQL = 75% Single-Sided	75**	0.053	0.489
		80	0.096	0.411
		85	0.153	0.326
		90	0.208	0.266
		92*	0.241	0.237
		95	0.293	0.215
Accepting Sampling Plan No.2 (for Air Content criterion)	N = 4 AQL = 95% RQL = 60% Double-Sided	60**	0.003	0.436
		80	0.089	0.161
		83	0.118	0.146
		84*	0.138	0.140
		85	0.140	0.135
		86	0.154	0.130
		90	0.220	0.100
		95	0.283	0.072

Note:- * Denotes the most suitable Acceptance Limit, which results in similar α and β,
** Denotes existing Special Note conditions.

Analyzing Table 4.2 and Figures 4.4 and 4.5, one can clearly see that the Acceptance Quality Levels should be approximately 92% and 84% for Strength and Air Content criteria, respectively, in order to balance the buyer's and seller's risks. This issue may be addressed in future modifications to the QC/QA specifications.

The Producer/Contractor can use this method to estimate his/her risk for the lot rejection at various levels of PWL. Therefore, various levels of Producer's Risk were analyzed and linked to their associated Pay Factor. These values are given in Table 4.3 and Table 4.4 for Air Content parameter and Strength parameter, respectively.

Table 4.3 - Various Levels of Seller's Risk and Air Pay Factors Associated with Lot PWL Values

Lot Air Content PWL (%)	Seller's Risk for rejecting the lot (%)	Most Probable Air Pay Factor (%)*
100.0	0.0	102.5
95.0	0.3	100.0
90.0	2.8	97.5
85.0	7.1	95.0
80.0	13.6	92.5
75.0	23.0	90.0
70.0	35.1	87.5
65.0	45.7	85.0
60.0	56.4	82.5
55.0	64.7	80.0
50.0	74.9	77.5
45.0	83.3	75.0
40.0	88.0	72.5
35.0	92.6	70.0
30.0	95.7	67.5
25.0	97.7	65.0
20.0	99.1	62.5

* Assuming sample lot PWL of a given lot is approximately equal to the population lot PWL.

Table 4.4 - Various Levels of Seller's Risk and Strength Pay Factors Associated with Lot PWL Values

Lot Strength PWL (%)	Seller's Risk for rejecting the lot (%)	Most Probable Strength Pay Factor (%)*
100.0	0.0	102.5
95.0	5.3	100.0
90.0	15.2	97.5
85.0	27.1	95.0
80.0	40.5	92.5
75.0	51.1	90.0
70.0	62.0	87.5
65.0	70.5	85.0
60.0	78.2	82.5
55.0	83.5	80.0
50.0	88.5	77.5
45.0	92.6	75.0
40.0	94.9	72.5
35.0	97.1	70.0
30.0	98.3	67.5
25.0	99.0	65.0
20.0	99.1	62.5

* Assuming sample lot PWL of a given lot is approximately equal to the population lot PWL.

It is clear from Tables 4.3 and 4.4 that a lot with a high PWL would have the best pay potential. To ensure a high PWL along with a low risk of rejection, a Contractor must maintain sublot Air Content values within the range 5.0% to 7.0% in Class-P concrete or 4.8% to 7.2% in Structural concrete for lot Air-PWL=100% . For the Strength-PWL, keeping all sublot strength values above the minimum 28-day Compressive Strength with a uniform margin of safety assures Strength PWL of 100% for a lot.

Overall, it can be concluded that OCPLOT method simplifies balancing the buyer's and seller's risks by predicting a reasonable Accepting Limit in between RQL and AQL. However, the following items are some major disadvantages of the OCPLOT procedure.

- There is no provision to judge the buyer's risk when all test data fall within the specification limits.
- The Upper and Lower Specification Limits for the Air Content are 6%± 2% or 7%± 2% depending on the type of coarse aggregate in the mix. If a sublot is out of the specification limits, it will be rejected from the lot, but the failing numbers and passing numbers will be combined to come up with a Pay Factor for that lot. The Rationale is that some poor material may have already been placed prior to catching the poor sublot. In such a case, the Pay Factor will be determined based upon four passing sublots plus one poor sublot (i.e. total of five sublots). However, the OCPLOT does not make any provisions for dealing with the rejected sublot and any follow-up consequences.

- When it comes to rewarding the uniformity, the PWL may be misleading. It does not distinguish between uniformity around a desirable target, as opposed to uniformity around the threshold of unacceptable concrete.

- The straight PWL calculations can result in misleading conclusions. For example, a contractor placing a concrete with Air Content hovering around the lower threshold of specifications limits (e.g. Lot-A: 4.0%, 4.1%. 4.1%, and 4.1%) will be rewarded for having a high PWL. Under this scenario, the Contractor does not have any incentive to change his/her procedures to move the Air Content average toward the middle of specifications, which is more desirable (e.g. Lot-B: 4.1%, 5.0%, 5.5%, and 6.0%). In fact, any change will result in enlarging the standard deviation and will reduce his/her pay. For example, Lot-A Air-PWL=100% while Lot-B Air-PWL=97.33%. However, it is important for the Contractor to note that the chance of acceptance of Lot-A is 55.8%, while the chance of acceptance of Lot-B is 98.8% (see trends in Figure 4.3). This means that the Contractor who is operating right on the threshold has a much higher risk of having a given lot rejected. Thus, the Contractor should move the process gradually toward a desirable target (i.e. the midrange of specifications).

  Therefore, blind application of PWL procedures may at times be too much penalty-oriented. Additionally, the "blind-PWL" must be replaced with a "smart-PWL", which provides incentives for moving the process toward desirable targets.

The following recommendation is a two-step process to address the aforementioned problems in future versions of the QC/QA concrete specifications:

a) Step-1. If a sublot value is outside the specification range, the lot should be rejected. If it is decided not to reject such a lot based upon its high PWL, then a second-order adjustment is needed. This second-order adjustment must account for the severity of the specifications limits violation.
b) Step-2. If all of the sublot values are within the specification limit, the PWL values can be used for a first order pay adjustment. However, a second-order adjustment must be made to account for the closeness of the sublot values to a desirable target within the specification limits. This is intended to serve as an incentive to reward changes in the process control to achieve desirable targets.

Chapter 5: QC/QA Field Trial Projects

5.1. Overview of Trial Projects

A summary of pilot projects for the trial implementation of the Special Note is given in Table 5.1. The table below reflects only the projects for which data were available at the time when this report was being prepared.

Table 5.1 – List of projects selected as pilot for QC/QA trails

County	Project	Type	Number of Available Lot Data
Jefferson	Gene Snyder Freeway	Class-P	53
Kenton	Short Way	Class-A	7
Madison	Bridge Project	Class-A	2
Madison	Culvert Project	Class-A	1
Madison	Structure	Class-AAA	6
Boone	Donaldson Road	Class-P	33

Comparing to other projects, the Gene Snyder project provided the largest amount of field data, and it played a key role in our data analyses.

5.2. Summary of Field Data

This section presents a summary of data from several trial projects. It is important to note that the QC/QA Special Note evolved throughout several versions from 1999 through 2001. Therefore, the trial projects employed whatever version of the Special Note which was available at the time.

Table 5.2 – Summary of Field Data for Pilot Projects

County	Project	Type	Average Values	
			Air Content (%)	Strength (psi)
Jefferson	Gene Snyder Freeway	Class-P	5.507	6069
Kenton	Short Way	Class-A	5.763	4854
Madison	Structure	Class-AAA	5.300	4612
Boone	Donaldson Road	Class-P	5.215	6150

Table 5.3 presents the summary of the Lot Pay Factors of these pilot Projects. All four projects yielded in pay bonuses. However, all of this may be somewhat biased toward less penalties during the experimental phase of the Special Note. During this time period, penalties are not fully applied, only bonuses are in full force. This was done in order to entice Contactors to volunteer for trial projects.

Table 5.3 also depicts the rationale behind the need for some leniency with Air-PWL criteria for structural application as opposed to paving applications. This is because it is more difficult to achieve a uniform air content in structural applications due to issues related to pumping of fresh concrete and multiple small lots.

Table 5.3 - Summary of Lot Pay Factors of Four pilot projects

Pay	**Project**			
	Gene Snyder Freeway	Kenton Short Way	Madison Class-AAA	Donaldson Road
Proportion of penalized lots to the total lots of the project	3.85%	20.00%	40.00%	3.03%
Proportion of lots given maximum bonus to the total lots of the project	84.62%	60.00%	60.00%	81.82%
Average Lot Pay Factor of the Project	102.18%	101.22%	100.61%	102.20%

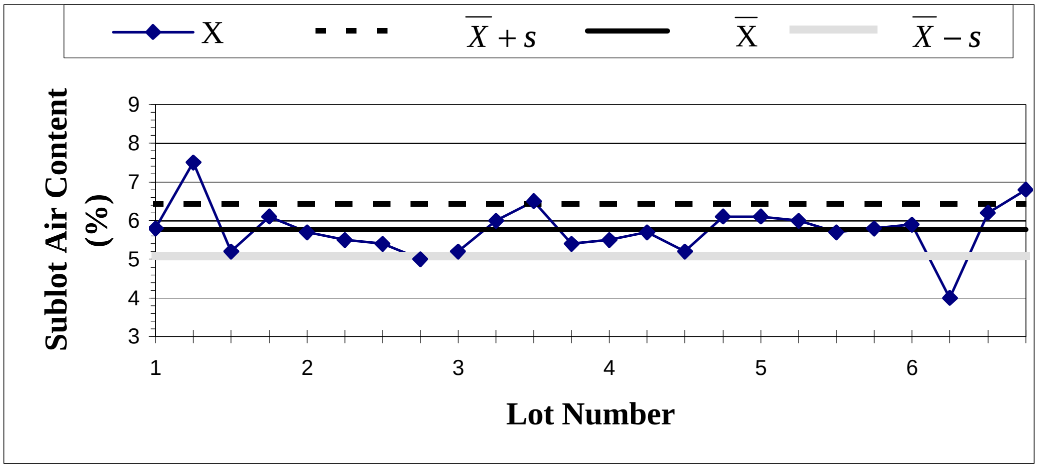

Figure 5.1a - The Air Content Data of the Kenton Co. Project.

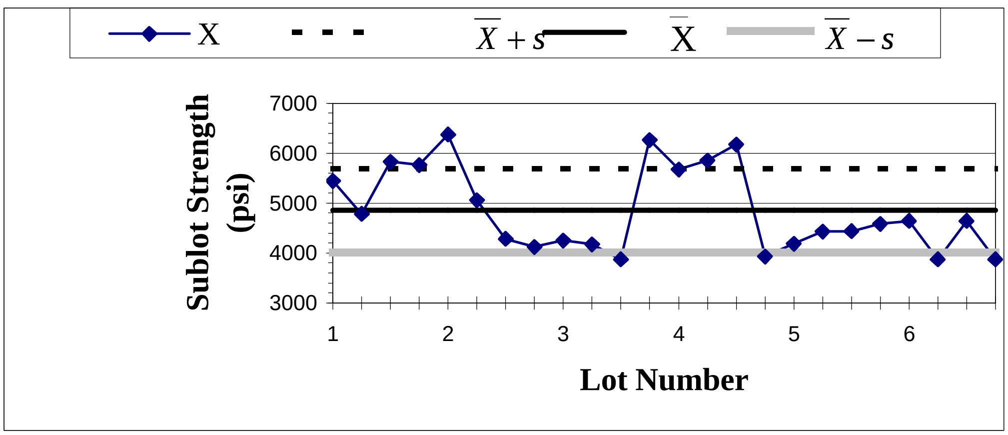

Figure 5.1b - The Strength Data of the Kenton Co. Project.

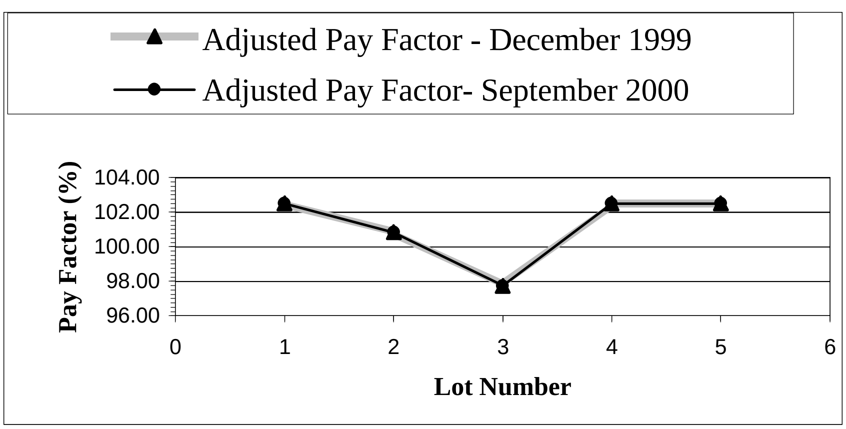

Figure 5.1c - The Adjusted Pay Factors of the Kenton Co. Project.

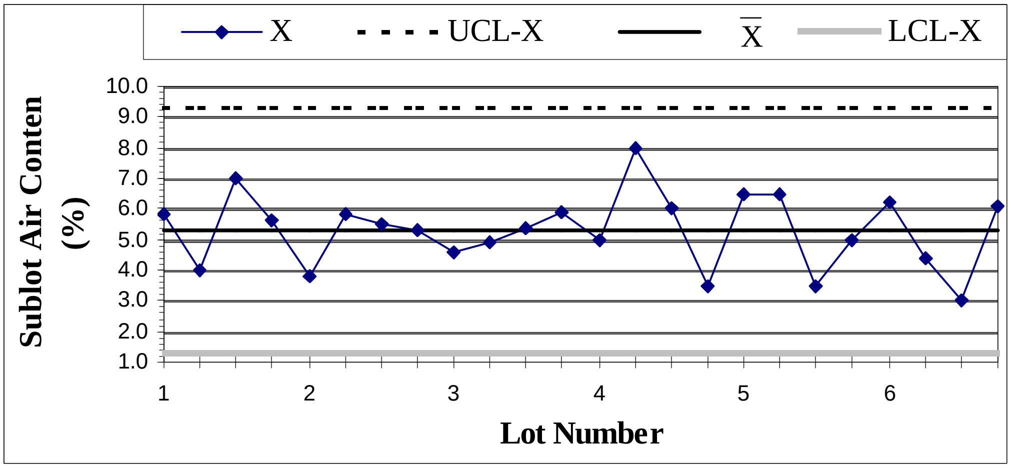

Figure 5.2a The Air Content Data of the Madison Co. (Class-AAA) Project.

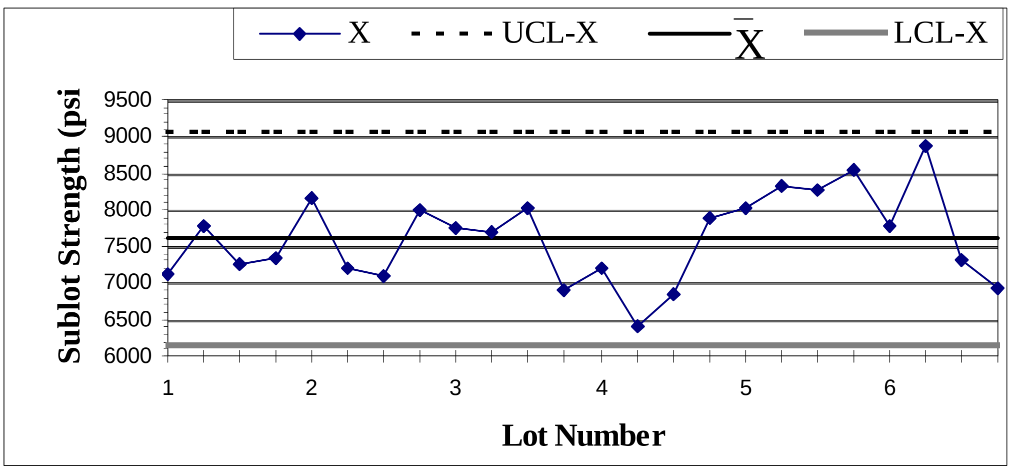

Figure 5.2b The Strength Data of the Madison Co. (Class-AAA) Project.

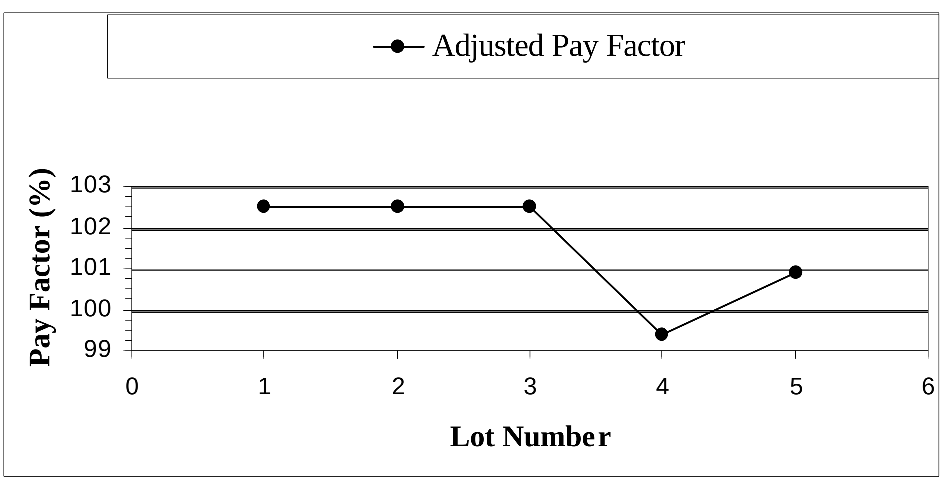

Figure 5.2c The Adjusted Pay Factors of the Madison Co. (Class-AAA) Project.

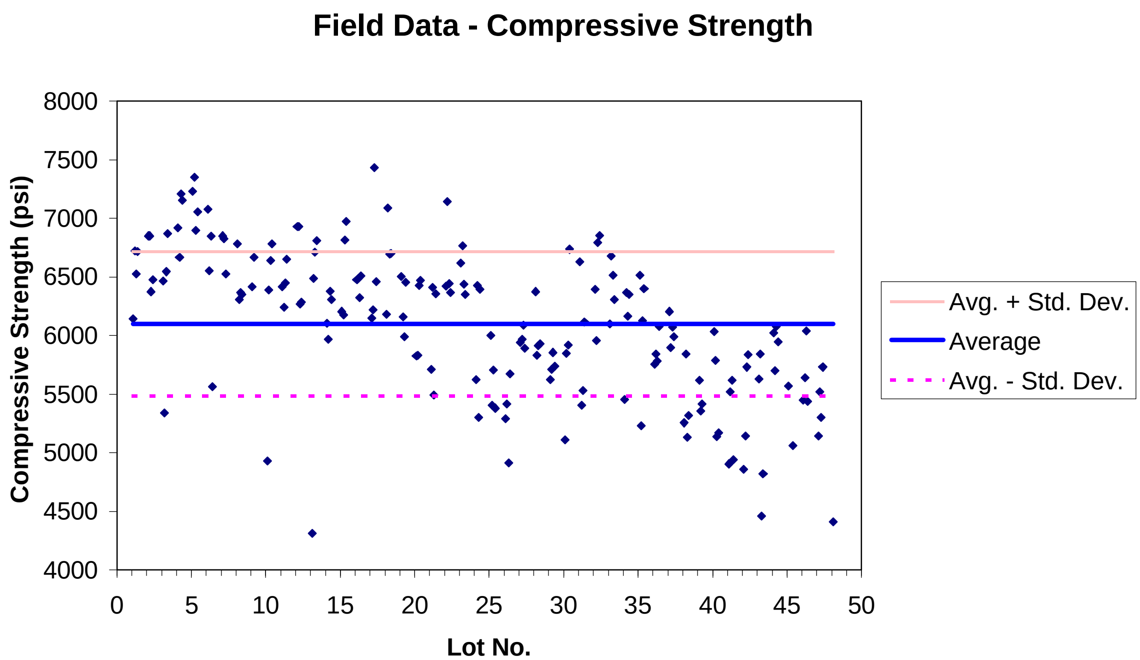

Figure-5.3a. Compressive Strength Data (Class-P), Gene Snyder Highway, Kentucky.

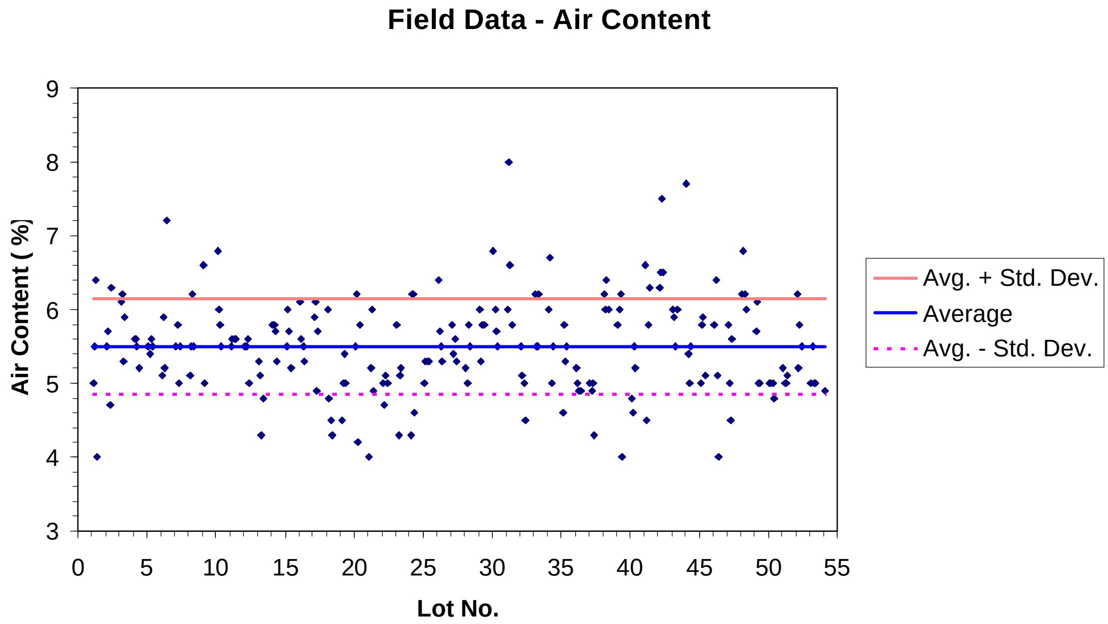

Figure 5.3.b. Air Content Data (Class-P), Gene Snyder Highway, Kentucky.

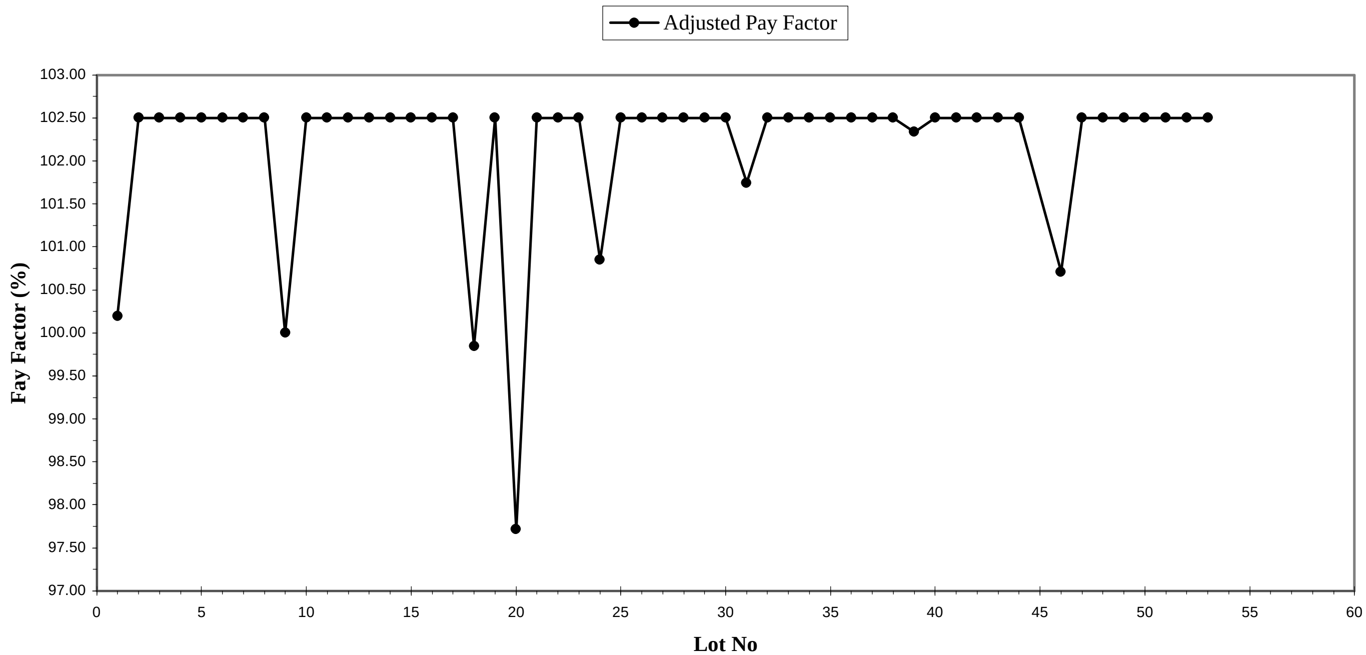

Figure 5.3c. Pay Factors (Class-P), Gene Snyder Highway, Louisville, Kentucky.

Chapter 6: Conclusions and Recommendations

The Kentucky QC/QA Concrete Special Note denotes a major step forward toward emphasizing quality. The new Kentucky specifications combine statistical theory and engineering experience. The following items are the key components of the Concrete QC/QA specifications in Kentucky:

1. The Special Note addresses the variability of materials by applying a widely accepted statistical procedure (Percent Within Limits).
2. The QC/QA Special Note encourages the Contractor to produce a quality product by giving incentives. Conversely, it penalizes the Contractor for poor quality, and/or inconsistent quality.
3. The procedure is relatively simple to understand and follow. All the procedures for the pay adjustments are well documented. A software was developed by the University of Kentucky researchers as a tool for data analysis, pay calculations, and data documentation.
4. The QC/QA Special Note puts the burden on the Contractor and the Producer to perform testing for Process Control, Quality Control, and Acceptance. The Engineer may witness all testing and will only perform verification testing. This scheme removes the burden of acceptance testing away from the Cabinet, which is compatible with the current trends toward more outsourcing and/or privatization.
5. Because Quality Control Plans must be submitted in advance, the potential for disputes between the agency and the Contractor will be reduced. If disputes do arise, the QC/QA Special Note has outlined proper guidelines to be followed by both parties.
6. By introducing a start-up procedure for the concrete parameters such as Air Content, Slump, and Temperature, a closely monitored start-up process is put in place.
7. The Special Note has been written with quality and innovation in mind. That is why it allows the Contractor and the Producer to follow the ACI-318 procedures for mix design as well as the Kentucky Transportation Cabinet recipe mixes

The following items are recommended for the future development in this area:

1. Analyses show that the buyer's risk is still higher than the seller's risk, even after the new specifications are fully implemented (see Table 4.2). This higher Consumer's Risk can only be overcome by having narrower acceptable limits (i.e. introducing tougher PWL limits or tighter specification limits). It is true that tougher limits may cause a situation that a lot may be rejected based upon a low PWL while having all of its sublot parameters within the specification limits. This is a sensitive issue for the industry and introduces a major departure from our current way of thinking.
2. The PWL concept rewards uniformity. However, a batch may be uniform around an undesirable threshold. In order to avoid rewarding such a case, the PWL procedure must be used in a "Smart-PWL" manner, and not as a "Blind-PWL." The "Smart-

PWL" rewards the Contractor for making changes in the process to move away from a uniform, but marginally acceptable material to a more desirable material.

3. The QC/QA Special Note gives equal weight to Air Content and Strength parameters. It is advisable to review this issue.
4. The procedures for the quality control and assurance of the non-pay related concrete parameters (such as temperature and slumps) could be improved. The variations of these parameters should also be analyzed by the statistical methods.
5. It is recommended that data on all QC/QA projects in Kentucky be monitored and, if needed, specification limits and pay factor be modified (Cominsky et al 1998).
6. The suppliers and sub-contractors often complain that they do not receive any portion of a contractor's bonus, and yet they are asked to share in the penalties. Clearly, this is a one-way street, and we need to pursue avenues by which a true team approach to quality can be realized. All major participants in a construction project should feel that they are capable of sharing in the bonus/penalty. It is true that the sate DOH cannot mandate the contractual relationship that a contractor has with his/her suppliers and sub-contractors. However, it may be possible to encourage a bonus/penalty-sharing plan. Although the specifics of this plan may need to remain confidential, but the existence of such a plan is what could be encouraged by the DOH.

Far from being perfect, the new QC/QA Special Note does provide an opportunity to improve the quality of concrete construction in Kentucky. This is especially true, since the Special Note encourages the contractor to produce a consistent quality product by giving incentives.

The anecdotal information in Kentucky indicates that the cost of QC/QA projects may increase in order to accommodate additional quality control activities by the Contractor and Producer. So far, competitive forces have prevented this from materializing. It would be very interesting to track the cost and performance histories on QC/QA projects and investigate any correlation. Additionally, there may be regions within the state that may need special consideration because of their limited access to competitive pool of highly qualified Producers and Contractors.

The successful implementation of any new set of specifications hinges upon the trust between various parties. The experience with trial projects in Kentucky has demonstrated that the parties involved have contributed in good faith to the trial implementation. This is good news for future implementation and building more trust.

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