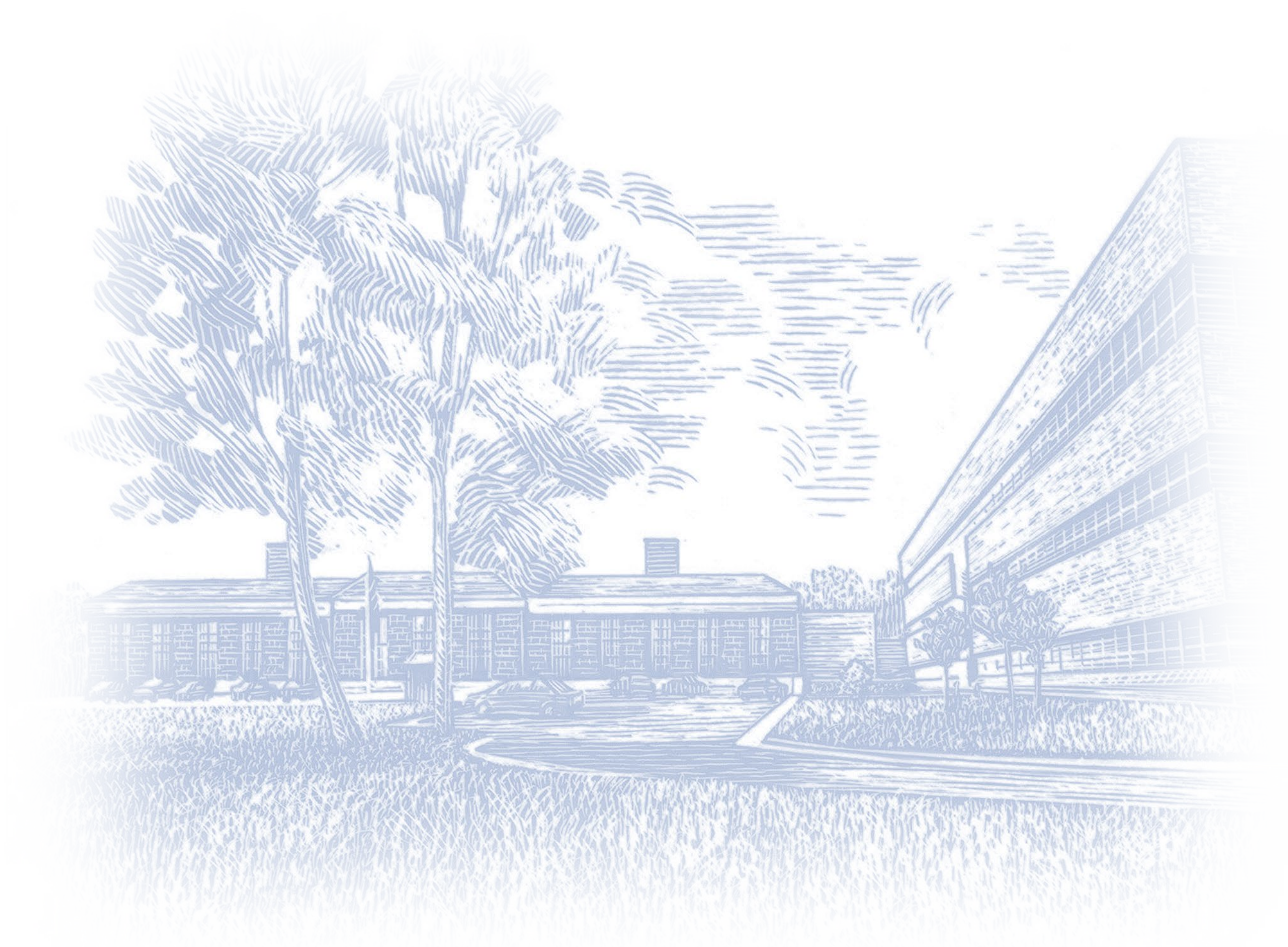
Volume 1: Practical Guide, Final Report and Appendix A

Publication No.: FHWA-RD-98-155 **FEBRUARY 1999**



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Foreword

This report (FHWA-RD-98-155), the first of a four-volume set of reports, presents guidelines and recommendations to assist a highway agency in developing and using performance-related specifications for portland cement concrete pavement construction. Included in this report are revised and improved performance-related specifications initially developed under a previous research contract. Using these recommended performance-related specifications, a highway agency can, upon construction, predict the performance of a pavement and forecast the pavement's life-cycle costs. The benefits to the agency from using such specifications can be significant. This report will be of interest to engineers concerned with quality assurance, specifications, and construction of concrete pavements.

Sufficient copies of this report are being distributed to provide a minimum of 3 copies to each FHWA resource center and division office, and 10 copies to each State Highway agency. Direct distribution is being made to the division offices. Additional copies for the public are available from the National Technical Information Services (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161.

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Introduction

Performance-related specifications (PRS) have been developed for jointed plain concrete pavements (JPCP), based on prototype specifications developed under a previous Federal Highway Administration (FHWA) research project.(1,2,3) Even though many useful and innovative PRS concepts were developed under the earlier project, it was recognized that the prototype specifications had many limitations that made their use impractical. Therefore, much of the research conducted under this project focused upon revising the prototype specifications to make them more practical, acceptable, and implementable.

Under this project, a revised, improved PRS prototype has been developed. In an attempt to bridge the gap between currently used construction specifications and fully implementable PRS, three different specification levels (simply titled *Level 1, Level 2 and Level 3*) were developed. The revised specifications address two of the three specification levels (Levels 1 and 2) and are presented in Appendix A. Level 3 is considered a futuristic specification that includes rapid nondestructive testing for all acceptance quality characteristics (AQC's).

Background

Over the past 25 years, there has been a growing interest in the development of PRS for highway pavement construction. Currently, PRS are defined as specifications that describe the desired levels of key materials and construction AQC's (e.g., concrete strength, slab thickness, and initial smoothness) that have been found to correlate strongly with fundamental engineering properties that predict pavement performance.(4) True PRS not only describe the desired AQC quality levels but use the measured AQC quality to predict subsequent pavement performance, thus providing the basis for rational acceptance and price adjustments.(4) Therefore, the PRS methodology can be used to relate quality of pavement construction to the estimated performance and life-cycle costs (LCC's) of a given pavement lot. This ability leads to the identification of optimum levels of AQC construction quality and the rational determination of pay adjustments for specific pavement lots.(1,2,3)

The basic concepts making up PRS are not new, as they are essentially improved quality assurance (QA) specifications. QA specifications and PRS are similar in that they specify the desired product quality rather than the desired product performance. However, in PRS, when you specify quality, you know what performance you are specifying. Another major difference comes from the methods used to determine the overall lot pay adjustment. Conventional QA acceptance plans use engineering judgment to establish individual AQC pay adjustments (and weighting factors for each) for determining the overall price adjustment for the lot(5) PRS, however, use mathematical models (taking AQC values into account) to estimate future pavement performance and corresponding LCC's to compute one overall price adjustment.(5)

Another advantage of PRS is their ability to identify desirable levels of AQC quality that provide a desired pavement performance. Most current specifications are unable to identify the true value of the measured AQC quality that is being produced. Using the PRS methodology, for a specified AQC (say, concrete strength), the performance of the pavement can be estimated using established relationships. Therefore, the desired concrete strength quality can be determined based on observing the range of performance coming from specifying different values for concrete strength. A more focused investigation of this kind will allow an agency to identify the optimum levels of AQC quality that provide the best balance between costs and performance for a given project. It has been estimated that such improvements in quality control (QC) procedures could produce long-term benefits to agencies and users measured in billions of dollars.(6)

PRS also provide a rational basis on which pay adjustments can be determined. Using PRS, lot pay adjustments are based on the difference between the LCC's associated with the target (as-designed) pavement and those associated with the actual (as-constructed) pavement. First, the agency chooses AQC target values (desired material and construction AQC quality levels). These AQC targets are used to predict the future performance (using mathematical distress prediction models) and the associated estimated future LCC's defining the as-designed pavement. (Note: The future LCC's include those maintenance and rehabilitation costs expected to be incurred by the agency [maintenance and rehabilitation of the pavement] and potential users [user costs may be included by the agency] over the life of the project, assuming a given rehabilitation policy.) The estimated LCC's corresponding to the as-designed AQC quality are then summarized into one overall LCC (LCC_{DES}) representing the AQC quality of the as-designed pavement. Next, the as-constructed AQC quality is measured at the time of construction on the in situ pavement. The measured as-constructed AQC values are used to predict the future pavement performance and associated LCC's (using the same distress indicator and cost models used in the determination of LCC_{DES}) defining the as-constructed pavement. The estimated LCC's corresponding to the measured as-constructed AQC quality are then summarized into one overall LCC (LCC_{CON}) representing the AQC quality of the as-constructed pavement.

An *incentive* pay adjustment is computed if the as-constructed AQC quality is measured to be better than the agency-specified target values (due to an increase in pavement life, resulting in a corresponding decrease in LCC's). Conversely, a *disincentive* pay adjustment is computed if the as-constructed AQC quality is measured to be poorer than the agency-specified target values (due to a decrease in pavement life, resulting in a corresponding increase in LCC's).[1,2,3] The amount of the pay adjustment (incentive or disincentive) is based on the direct comparison of LCC_{DES} and LCC_{CON}.

The development of PRS requires a thorough understanding of how material and construction AQC's affect the performance and costs of a pavement. Unfortunately, the effects of all material and construction AQC's on performance are not well understood. At present, only one agency is known to use PRS. However, research and development progress has been made, sponsored by FHWA, on the development of PRS for both asphalt concrete (AC) and portland cement concrete (PCC) pavements. This report documents the latest development for PCC pavements and represents a product that is ready for implementation.

Some of the recognized benefits of PRS to a State highway agency (SHA) are the following:

- PRS require the establishment of clear AQC target values (means and standard deviations) that define the pavement quality for which the agency is willing to pay 100 percent of the contractor bid price.

- PRS provide a straightforward method for determining rational (LCC-driven) pay adjustments (incentives and disincentives) that are applied when a higher or lower level of quality (as compared to the chosen AQC target values) is produced by the contractor.

- PRS relate the quality of pavement construction to the performance and subsequent LCC's of a given pavement lot. This ability provides the opportunity to identify optimum levels of AQC construction quality that would minimize LCC's while maintaining the desired performance.

- The clear and rational methodology of PRS (including fair incentives and disincentives during construction) is expected to lead to significantly improved highway construction quality levels, better pavement performance, and reduced pavement LCC.

Project Objectives And Scope

The focus of this study was to conduct research that will continue the advancement toward the development of a fully practical and implementable PRS for PCC pavement construction. Specifically, the contract objectives were the following:

1. Develop a detailed field/laboratory plan and conduct the required testing to establish additional (as well as improve existing) relationships between PCC pavement construction AQC's and pavement performance (distress indicator models).

2. Develop a detailed field/laboratory plan and conduct required testing to establish the typical variabilities associated with the AQC's chosen for inclusion in the revised prototype PRS. This field/laboratory work is to supplement findings from an extensive literature search.

3. Develop improved prototype PRS (Level 2) through a critical review and refinement of the initial draft prototype and the addition of performance-related construction criteria.

4. Develop a simplified PRS (Level 1) methodology that can be immediately implemented by SHA's with minimal changes to their existing sampling and testing plans. Demonstrate this Level 1 methodology for one SHA by developing recommended acceptance plans with price adjustments.

5. Demonstrate the Level 1 and Level 2 PRS methodologies on an actual construction project to obtain experience, verify/confirm their effectiveness, identify potential problem areas, and assess their reasonableness. This field trial is labeled as a *shadow* field trial because the PRS are not the governing specifications. SHA acceptance procedures and contractor pay are not in any way affected by the shadow field trial.

6. Provide training to personnel from FHWA's Office of Technology Applications (OTA), enabling them to conduct three additional *shadow* PRS field trials during the fiscal year 1997. Provide *as needed* assistance to OTA by participating in pre-construction meetings, assisting during the conduct of the field trials, and presenting the field trial results at State follow-up meetings.

7. Obtain data from SHA's in order to perform comparative analyses of actual price adjustments awarded to the contractor versus those that would theoretically have been assessed if PRS Level 1 had governed the projects.

Advisory Panel

An experienced advisory panel was assembled to provide guidance to the research team in addressing the many complex issues of the project. The panel was comprised of representatives from SHA's, industry, PCC construction, and academia who were collectively knowledgeable in the areas of PCC pavement design, PCC pavement construction, PCC materials, statistics/variability, and specification development. The advisory panel provided valuable assistance to the research team by conducting comprehensive reviews of the prototype specifications and approach, providing input into the selection of potential AQC's for investigation in the laboratory/field investigations, and reviewing all pertinent project documentation. Members of the advisory panel included:

- Jim Hall, Illinois Department of Transportation.
- Steve Horton, Colorado Department of Highways.
- Ken McGhee, Consultant.

- Lee Powell, Ballenger Paving.
- Doug Schwartz, Minnesota Department of Transportation.
- Clint Solberg, American Concrete Pavement Association.
- Garland Steele, Consultant, Steele Engineering, Inc.

Research Approach

The research team began by conducting a comprehensive literature search to identify previous studies where variations of concrete pavement AQC's had been measured and documented in an unbiased manner. Eleven different potential AQC's were targeted in the search. These included the following:

- Concrete strength.
- Slab thickness.
- Entrained air content.
- Initial smoothness.
- Percent consolidation around dowels.
- Tie bar depth.
- Sawcut depth.
- Sawcut timing.
- Dowel bar misalignment.
- Effectiveness of curing.
- Depth of tining.

The results of the literature search (specifically, the assessment of the amount of available variability data for each of the investigated AQC's) were used to identify and prioritize needed supplemental laboratory/field investigations. As a result of the data collected in the literature search, laboratory/field variability investigations were selected to collect additional data for the following six AQC's only:

- Concrete strength.
- Slab thickness.
- Entrained air content.
- Percent consolidation around dowels.
- Tie bar depth.
- Sawcut depth.

No additional data were deemed necessary for the investigation of the typical variability of initial smoothness. Although the results of the literature search concluded that more information was required to investigate the typical variability of sawcut timing, dowel bar misalignment, effectiveness of curing, and depth of tining, the conduct of additional laboratory/field work investigating these AQC's was believed to be too complicated and expensive to be included as part of this research study.

A comprehensive laboratory/field investigation of material- and construction-related variables was conducted to facilitate the following tasks:

- Establishment of guidelines for levels of as-designed variability, based on typical values of as-constructed variability.

- Development of new construction-related performance prediction (distress indicator) models, or improvement of existing models.

Based on preliminary variability-related data collection results, it was determined that there was insufficient sawcut depth and tie bar depth data to develop construction-related performance models for these AQC's. Therefore, the model development/improvement tasks under this contract consisted of the following:

- Laboratory analysis of concrete strength, including relationships between flexural and compressive strength, maturity methods, and the prediction of 28-day strengths from early age strengths (3 to 5 days).

- Modification/calibration of an existing transverse joint spalling model to include air content and concrete strength.

- Modification of an existing transverse joint faulting model to incorporate the effects of the percent consolidation at doweled joints.

Capabilities Of Developed PRS

Drawing upon the comprehensive reviews of the prototype PRS by the advisory panel members, the results of the literature search, and the results of the extensive laboratory/field investigations, the prototype PRS were revised into more practical and accurate specifications. Some of the improvements to the prototype PRS include the following:

- Inclusion of percent consolidation around dowels as a construction-related AQC.

- Inclusion of improved distress indicator models for transverse slab cracking, transverse joint faulting, transverse joint spalling, and present serviceability rating (PSR) (an indicator of smoothness), as well as the inclusion of an international roughness index (IRI) model for predicting smoothness over time.

- More available maintenance and rehabilitation (M & R) activities available for inclusion in a defined M & R plan.

- Clearer definition of lots and sublots.

- Recommendations for typical variabilities of the included AQC's.

- Improved sampling and testing plan recommendations, including the ability to have different numbers of samples per sublot for each AQC.

- Improved strategies for measuring and accepting concrete strength.

- Development of a practical and readily implementable PRS (Level 1).

A simplified version of the PRS was developed and included as part of the revised PRS. This simplified methodology (Level 1) uses the basic concepts of the original prototype PRS; however, because of a few important characteristics, it is believed to be more practical and readily implementable by a proactive SHA. One important characteristic of the Level 1 approach is that a SHA can most likely use its current sampling and testing methods with only slight modifications. The overall Level 1 lot pay factor is also determined in a more straightforward manner than the method used in the prototype. Individual pay factors are determined for each AQC using predetermined curves or equations. The overall lot pay factor is then computed using a simple mathematical function (composite pay factor [CPF] equation) of the individual AQC pay factors. The computed Level 1 CPF is actually an estimate of the pay factor computed using the Level 2 method. Because the simplified Level 1 PRS procedure is a practical approach that is immediately implementable, it is a very useful first step in introducing general PRS concepts to a SHA.

PRS Computer Software

The original PRS computer software, PaveSpec was also greatly improved under the current contract. The revised software, PaveSpec 2.0, offers much more functionality than its predecessor and offers a much more user-friendly environment. Specific improvements in PaveSpec 2.0 include:

- The ability to demonstrate both Level 1 and Level 2 specifications.
- The ability to enter actual field data and determine acceptance pay factors.
- The ability to have a different number of samples per sublot for each AQC.
- Automatic determination of random sample locations.
- A more robust M & R plan.
- The inclusion of improved distress indicator models.
- The ability to investigate a specification prior to going to the field (using simulated data).
- The ability to create and save groups of variables as named *modules*. The following modules are used in PaveSpec 2.0: Design Traffic, Climatic Data, M & R Plan, Pavement Design, and Unit Costs.
- The inclusion of a sensitivity analysis section.
- Improved tabular and graphical output.
- Improved user's guide.

Field Demonstration Trials

The Level 1 and revised Level 2 specifications were both demonstrated under this project using three different investigation methods.

The first method consisted of demonstrating both specification levels on four actual construction projects (one conducted by the project research team and three by OTA personnel). The purpose of these field trials was to obtain experience, verify/confirm each specification's effectiveness, identify potential problem areas, and assess the overall reasonableness of both specification levels (Level 1 and Level 2).

Second, Level 1 pay factor curves (and corresponding equations) were developed for three typical PCC pavement designs for a chosen SHA. The three typical designs were developed to represent medium, heavy, and very heavy traffic conditions. An analysis of the observed pay factor trends (within and between typical designs) was completed and presented.

Third, historical data were collected from SHA's in order to perform comparative analyses of the actual price adjustments awarded to the contractor versus those that would theoretically have been assessed if the Level 1 PRS had governed the projects. Data were collected for a total of 41 lots (7 PCC projects) from 3 different SHA's.

The results of these demonstrations are summarized and presented in volume II (appendix B).

Sequence Of Report

This volume is designed as a stand-alone document highlighting the practical output of this work. It will assist a pavement owner in using the PRS (included in appendix A in this volume) for the acceptance of as-constructed pavement lots.

- Chapter 2 provides a brief definition and summary of the general evolution of PRS.
- Chapter 3 contains a summary of, and quick reference to, many of the important PRS-related terms.
- Chapter 4 introduces the key PRS concepts used in the development and application of the current revised PRS prototype.
- Chapter 5 provides guidelines and recommendations for assisting the agency in developing a project-specific PRS (this includes guidance in making the many general PRS decisions, as well as in selecting appropriate values for the numerous required PRS inputs).
- Chapter 6 provides guidelines for making general pay adjustment decisions.
- Chapter 7 outlines the step-by-step procedures required to generate the preconstruction output for both Level 1 and Level 2 specification types.
- Chapter 8 presents the step-by-step procedures used to determine contractor pay adjustments for as-constructed pavement lots.
- Chapter 9 provides a summary of the research conducted and recommendations for future research.

Several appendixes are included in support of the final report. Appendix A (presented in this volume) contains the complete stand-alone revised PRS prototype (for both Levels 1 and 2). Appendix B (volume II) contains a complete description of all demonstrations of the revised PRS prototype, including:

- Documentation of the four shadow field trials.
- Development of the Level 1 pay factor curves for three typical designs in a chosen SHA.
- Comparison of actual pay vs. estimated PRS pay conducted using historical data.

  Appendix C (volume III) provides a summary of the literature search. Appendix D (volume III) contains details of the laboratory and field studies conducted to investigate typical AQC variability. Appendix E (volume III) presents details of the distress prediction models (including improvements made under this project) used in the PaveSpec 2.0 computer software. Appendix F (volume III) contains an annotated bibliography of the sources reviewed during the conduct of the literature search. Appendix G (volume IV) is the user guide for the PaveSpec 2.0 computer software that was revised under this project.

Brief Definition of PRS

Introduction

Performance-related specifications (PRS) have capabilities beyond traditional QA specifications. These capabilities include clearly defining lots and sublots (for all sampling and testing), the subsequent sampling and testing of key AQC's that relate directly to the future performance of the constructed pavement, and predicting future LCC's used to compute contractor pay adjustments (incentives and disincentives). Thus, the level of quality (expressed as a mean and standard deviation) achieved for each of the key AQC's can be related directly to rationally computed pay adjustments based on sound economic principles.

The initial ground-breaking work on PRS was done by R.M. Weed for the New Jersey Department of Transportation.[(7)] This work provided a basis for the prototype PRS developed under a previous FHWA research study. (See references 1, 2, 3, and 8.) The prototype used an innovative approach that considered the estimated future LCC of the pavement as the overall measure of quality. Under the prototype, target values (means and standard deviations) must be established for four key AQC's (concrete strength, slab thickness, entrained air content, and initial smoothness). These AQC's are then measured from the in situ pavement during construction. The computed as-constructed AQC lot means are then used in established mathematical models to predict key distress indicators (transverse joint faulting, transverse cracking, transverse joint spalling, and PSR) over a chosen analysis period. The amount of the pay adjustment is then based on the AQC quality-related increase or decrease in future LCC's expected to be incurred by the agency over the chosen analysis life of the project (assuming a given rehabilitation policy). A computer software program, PaveSpec, was developed to demonstrate the prototype specification.

Although the prototype PRS were based on rational concepts, researchers realized that an attempt to implement such specifications would most likely be met with resistance. This resistance would result from the general unfamiliarity with the current PRS concepts, the dependency of computed pay adjustments on the PaveSpec software, the additional costs associated with strongly emphasized in situ testing, and the need to simulate the actual pay factor in the field. Under the current research project, a strategy was developed to aid in the acceptance and implementation of the revised prototype PRS. This involved the development of three different PRS implementation levels. Each of these is described in detail in the following section.

Three Levels Of PRS Implementation

The overall goal of PRS research is to progress toward developing ideal PRS that incorporate all important AQC's of PCC pavements that not only affect pavement performance, but are also under the control of the contractor. As a means of achieving this goal, future research should attempt to:

- Identify distress indicators that significantly affect pavement performance (these drive the PRS).
- Identify the AQC's and other variables that directly affect each identified distress indicator.
- Develop early age, rapid, reliable, easy, and cost-effective field tests that measure the in situ quality level of each identified AQC.
- Develop accurate distress indicator prediction models that are dependent on the measured quality level mean and variability of each identified AQC (none of the current models are directly dependent upon variability).

- Develop a practical, yet comprehensive, method for the calculation of overall lot pay adjustments using sound economic principles.

Obviously, much research is needed to develop and implement an ideal PRS. Such an effort will take much more research and funding. Therefore, as a means of organizing the envisioned work needed to develop these ideal PRS, three different levels (chronological steps) of PRS implementation were proposed. These three levels are defined as follows:

- Level 1—Simplified PRS:Developed as a simplified version of the original prototype PRS. It is believed that the current Level 1 acceptance testing would not differ greatly from the procedures currently used by SHA's. AQC quality can be approximately assessed using selected parts of the agency's current AQC sampling and testing methods for core strength, entrained air content, slab thickness, percent consolidation around dowels, and initial smoothness.

The Level 1 pay factor computation method is based on calculating independent pay factors for each AQC (all other AQC's are assumed to be equal to the target values). Each of these pay factors is determined from a series of developed pay factor versus AQC mean curves. These curves, each specific to a different as-constructed AQC standard deviation, are created by correlating simulated lot pay factors over a range of AQC means. Each computed pay factor is, therefore, a function of the measured as-constructed mean and standard deviation, target mean and standard deviation, and sample size. Final payment for the lot is based on a chosen CPF equation (expressed as a simple mathematical function of the independently determined AQC pay factors). This Level 1 CPF is an estimate of the pay factor determined using the more rigorous procedures of Level 2.

- Level 2—Transitional PRS: The Level 2 specifications generally use the same concepts and procedures developed for the original prototype PRS.[1,2,3] The Level 2 specifications represent the dynamic transition from the original prototype specifications presented in the final report of a previous FHWA research project to the ultimate goal of Level 3.[1,2,3] The Level 2 PRS encourage the use of more in situ and nondestructive sampling and testing that can be used to accept pavement lots at much earlier ages (e.g., using 3-day core compressive strength results for the acceptance of concrete strength). The Level 2 PRS also require more computer simulation to compute pay adjustments.

The Level 2 pay factor computation method calculates lot pay factors by directly comparing simulated as-designed (target) and as-constructed LCC's. Interactions of AQC's are included in the simulations (e.g., an increase in concrete strength may counteract a deficiency in slab thickness). The pay factor calculation is based on the premise of liquidated damages. Final payment for the lot is based on the simulated pay factor determined using the PaveSpec software.

- Level 3—Ideal PRS: The Level 3 specifications represent the ideal specifications that will eventually be achieved with much future research. Such specifications would include many more AQC's that are not currently measurable. Also, these AQC's would be measured using reliable early age methods that are both in situ and nondestructive.

Each level may differ in the number of AQC's included, the sampling and testing methods required for each AQC, the distress indicator prediction models used to predict pavement performance, and the computation method for payment adjustments. The details of the three proposed PRS levels of implementation are summarized in table 1.

The original PRS prototype and corresponding computer program (PaveSpec) have been updated and revised under this current research project. The revised PRS prototype addresses both Level 1 and Level 2 PRS acceptance procedures and is included as appendix A (in this volume).

Table 1. Details of the three proposed PRS implementation levels.

PRS Level	Included AQC's	Primary Method of Acceptance Testing	Pre-Construction Output	
Level 1—Simplified PRS	As a minimum, it is recommended that those AQC's currently measured for acceptance be included. Those AQC's available for inclusion in a Level 1 PRS are the following: • Concrete strength • Slab thickness • Entrained air content • Initial smoothness • Percent consolidation around dowels	Generally, current SHA acceptance sampling and testing procedures. The designation of sublots must be used for sampling.	Simulated individual AQC pay factor charts and corresponding equations (functions of measured AQC mean and standard deviation). Each individual AQC pay factor chart is developed independent of the other AQC's (i.e., the other AQC's are held constant at their target values).	In[illegible] computed mean and standard deviation representing the as-constructed AQC samples. The overall lot pay factor is computed using a chosen composite pay factor equation.
Level 2—Transitional PRS	All of the following available AQC's are recommended for inclusion in a Level 2 specification: • Concrete strength • Slab thickness • Entrained air content • Initial smoothness • Percent consolidation around dowels	Acceptance testing of AQC's is conducted using the best available sampling and testing technology with the focus being on in situ and nondestructive testing procedures.	Simulated overall as-designed lot LCC mean. This simulated value reflects the interactions among all AQC's (e.g., a deficiency in slab thickness may be counteracted by a proficiency in concrete strength). No pay factor "charts" are developed.	One overall lot pay factor is determined by estimating the one as-constructed lot LCC that reflects the measured AQC quality (means and standard deviations). The overall lot pay factor is computed as a function of the simulated as-designed and estimated as-constructed LCC means.
Level 3—Ideal PRS (Future)	All AQC's that affect PCC pavement performance and are under the control of the contractor should ideally be included in a Level 3 specification.	All AQC's are sampled from the in situ pavement using rapid nondestructive testing procedures.		

PRS-Related Definitions

Introduction

Before an agency begins using the revised PRS prototype, it must understand a number of PRS-related terms. This chapter is provided as a summary of, and quick reference to, the main PRS-related terms. These definitions are organized in alphabetical order for the user's convenience.

Definitions

Acceptance Quality Characteristics (AQC's): Inherent measurable pavement characteristics that significantly affect pavement performance, are under the direct control of the contractor, and are measurable at or near the time of construction. AQC's considered under the current PRS include concrete strength, slab thickness, entrained air content, initial smoothness, and percent consolidation around dowel bars.

Analysis Period: Period of time over which future M & R costs are to be considered in an LCC analysis. The analysis period is typically defined as twice the chosen initial pavement design life.

AQC Target Values: Agency-chosen AQC means and standard deviations that define the agency's desired quality (the AQC quality for which the agency is willing to pay 100 percent of the bid price).

As-Constructed Lot Life-Cycle Cost (LCC_{CON}): The estimated post-construction LCC used to represent the as-constructed pavement lot quality. This value is based (in part) on the measured as-constructed AQC values (means and standard deviations).

As-Constructed Pavement: The actual concrete pavement constructed by the contractor. The as-constructed quality level of each pavement lot is assessed based on AQC sampling and testing (using defined AQC acceptance procedures) of the as-constructed pavement.

As-Designed Lot Life-Cycle Cost (LCC_{DES}): The estimated post-construction LCC used to represent the as-designed pavement quality. This value is based on the as-designed AQC target values (means and standard deviations) selected by the agency.

As-Designed Pavement: The desired concrete pavement, as defined by the agency. The desired quality level of the pavement is specified in terms of target as-designed AQC means and standard deviations.

Buyer: That organization or entity ultimately responsible for the purchase of the materials and work required for the completion of a highway or transportation contract. May be used interchangeably with the terms agency, purchaser, consumer, or owner.[9]

Constant Values: Project-specific variables required by the distress indicator and cost models that do not differ between the as-designed and as-constructed pavements. These variables define many of the pavement's characteristics and can be grouped into general categories such as traffic, project location and description, climatic conditions, slab design and support, load transfer, and M & R unit costs.

Construction Pass: The defining width of an ongoing paving operation. This definition is used since the width of paving may consist of more than one traffic lane.

Discount Rate: Used to translate actual LCC's into equivalent present worth costs. It is estimated as the difference between the interest and inflation rates over a long time period, representing the real value of money over time. The interest rate, often referred to as the *market* interest rate, is associated with the cost of borrowing money and represents the earning power of money.[10] The inflation rate is typically defined as the rate of increase in the prices of goods and services (construction of highways) and represents changes in the purchasing power of money.[10]

Distress Indicator: A measure of the condition of an existing pavement section at a particular point in time.[4] These key pavement distresses are used to define pavement performance. Distress indicators included in the current PRS approach include transverse slab cracking, transverse joint faulting, transverse joint spalling, and pavement smoothness over time. Within the PRS, the distress indicators are predicted (over a chosen analysis period) using the best available empirical or mechanistic models. Model inputs include project-specific constant values and representative mean values of the selected AQC's.

Equivalent Single-Axle Load (ESAL): An 80-kN single-axle traffic loading. The ESAL is the standard traffic measure used by most SHA's and design methods. Average daily traffic (ADT) numbers are translated into equivalent ESAL's. Many of the distress indicator models are functions of the cumulative ESAL's applied over the chosen analysis life.[11]

Expected Pay (EP) Curve: A graphic representation of an acceptance plan that shows the relation between the actual quality of a lot and its expected pay (i.e., mathematical pay expectation, or the average pay the contractor can expect to receive over the long run for submitted lots of a given quality).[4]

Global Rehabilitation Activities: Rehabilitation activities applied to the entire lot at one time in response to declining *global* pavement conditions. These activities are specifically applied to address pavement condition indicators such as decreasing pavement smoothness, increasing amounts of localized distress, or increasing amounts of applied localized rehabilitation. Trigger values for these pavement condition indicators must be selected to determine the timing of a global rehabilitation. Examples of global rehabilitation activities include AC overlays, PCC overlays, and diamond grinding.

In Situ Sampling: AQC sampling procedures in which samples are taken directly from or on the in-place concrete pavement (e.g., cores and surface profile measurements).

Initial Design Life: Amount of time for which the chosen pavement design is expected to carry traffic loads without the application of a global rehabilitation (AC overlay, PCC overlay, diamond grinding).

International Roughness Index (IRI): The IRI is based on simulation of the roughness response of a car traveling at 80 km/h. It is a ratio of the accumulated suspension motion of the car divided by the distance traveled. The scale ranges from 0 (perfectly smooth surface) to 20,000 mm/km, with larger values indicating greater roughness. A value of 3,000 mm/km is often considered to be the breaking point between "rough" and "smooth" pavements on high-speed highways.

Jointed Plain Concrete Pavement (JPCP): A PCC pavement type characterized by short joint spacing (less than 6 m) and no reinforcing steel mesh or bars. JPCP pavements may or may not be constructed with dowels at the transverse joints. These pavements typically include tie bars at longitudinal joints. Slab thickness for this pavement type have historically ranged from 152 to 254 mm; however, newer pavements are being constructed with thickness of 305 mm or more.

Life-Cycle Cost (LCC): The estimated cumulative present worth cost of a pavement lot over a specified analysis period. The LCC, as used in PRS, may include estimated future maintenance, rehabilitation, and user costs over a chosen analysis period. The initial construction cost is not included in the LCC since it is identical for both the as-designed and the as-constructed pavements. LCC values are expressed in units of present worth dollars (PW$) per kilometer.

Localized Rehabilitation Activities: Rehabilitation activities that may be used to correct *localized* pavement distresses. Localized distresses are defined as those that may affect an individual joint (transverse joint spalling and transverse joint faulting) or slab (transverse slab cracking).

Lot: A discrete quantity of constructed pavement to which an acceptance procedure (and corresponding pay adjustment) is applied. All pavement placed within a lot should consist of the same mix design and material sources, should be subjected to the same support conditions (base type, base thickness, subbase type, subbase thickness, subgrade treatment), and should consist of the same design characteristics (joint spacing, drainage, shoulder type, dowel-bar diameter, traffic, and AQC design values).

Lot Length: Equal to one day's production or less. The minimum lot length should not be less than 0.16 km. Any section of lesser length will be added to the preceding lot or succeeding lot.

Lot Width: The lot width is defined as the total width of pavement, one or more traffic lanes, being placed at one time in the mainline paving process. This paving width is also referred to as a construction pass,since it describes the total width of pavement being placed in one pass of the paving train. The entire width of a widened lane is included; however, shoulders are to be excluded.

Maintenance Activities: Routine activities performed as preventive measures. This maintenance is typically applied at certain fixed intervals of time over the life of a pavement lot (commonly on an annual basis). Examples of maintenance activities include transverse crack and joint sealing.

Maintenance and Rehabilitation (M & R) Plan: The defined set of rules used to predict the type and timing of future M & R activities. Expected localized and global rehabilitation activities are determined based on chosen trigger values applied to each distress indicator. Maintenance activities are applied by defining the amount and application frequency (e.g., seal 100 percent of the transverse joints every 2 years).

Maximum Quality Limit (MQL): Agency-chosen maximum limit for acceptable AQC specimen sample quality. If an AQC specimen sample value is measured to have greater quality than the defined MQL, the representative specimen sample value (used in the acceptance procedures) is set equal to the defined MQL (i.e., the contractor does not receive credit for quality provided in excess of the MQL). For concrete strength, slab thickness, entrained air content, and percent consolidation around dowels, better quality than the MQL is identified by specimen sample values *greater than* the MQL; however, for initial smoothness, better quality than the MQL is identified by specimen sample values *less than* the MQL.

Nondestructive Testing: AQC sampling and testing methods conducted on the in-place pavement, without disturbing the pavement's structural integrity or surface characteristics.

Operating Characteristic (OC) Curve: A graphic representation of an acceptance plan that shows the relationship between the actual quality of a lot and the probability of its acceptance at various payment levels.[(4)]

PaveSpec 2.0: The revised PRS specification simulation software developed under this research project. This software is used to demonstrate the PRS approach by simulating pavement performance, determining corresponding LCC's, generating preconstruction output, and computing pay adjustments. Its specific functions are described in the *PaveSpec 2.0 User Guide* (appendix G, volume IV).

Pay Adjustment: The actual pay adjustment (incentive or disincentive in PW$) for the as-constructed lot. The computation of the lot pay adjustment differs between the Level 1 and Level 2 PRS.

> *Level 1 Pay Adjustment*—The Level 1 pay adjustment is computed using the determined Level 1 lot composite pay factor (CPF). The actual Level 1 lot pay adjustment is computed using the relationship presented in equation 1.

$$PAY_{LOT} = BID * (PF_{COMPOSITE} – 100) * LOT_{LENGTH} \qquad (1)$$

where

PAY_{LOT} = Adjusted payment paid to the contractor for the as-constructed lot, $.

BID = Contractor bid price, $/km.

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$PF_{COMPOSITE}$ = Determined Level 1 lot CPF, percent (e.g., 101 percent is expressed as 101.0).

LOT_{LENGTH} =Measured actual as-constructed lot length, km. *Level 2 Pay Adjustment*—The Level 2 pay adjustment is computed using the determined Level 2 lot pay factor. The actual Level 2 lot pay adjustment is computed using the relationship presented in equation 2. $PAY_{LOT} = BID * (PF_{LOT} – 100) * LOT_{LENGTH}$ (2)

where

PAY_{LOT} = Adjusted payment paid to the contractor for the as-constructed lot, $.

BID = Contractor bid price, $/km.

PF_{LOT} = Determined Level 2 overall lot pay factor, percent (e.g., 101 percent is expressed as 101.0).

LOT_{LENGTH} = Measured actual as-constructed lot length, km.

Pay Factor (PF): The percent of the bid price that the contractor is paid for the construction of a concrete pavement lot. There are a number of different pay factor-related definitions used within this report.

Basic Pay Factor Definition—The underlying equation used to compute a pay factor for a given lot (based on the comparison of LCC's) is presented as equation 3. This equation is used to compute the pay factor for each simulated lot. $PF_{LOT} = 100 * (BID + [LCC_{DES} – LCC_{CON}])/BID$ (3)

where

PF_{LOT} = Overall pay factor for the as-constructed lot, percent.

BID =Representative contractor's unit bid price for the lot, $/km.

LCC_{DES} = As-designed life-cycle unit cost for the lot (computed using target AQC's), PW$/km.

LCC_{CON} =As-constructed life-cycle unit cost for the lot (computed using AQC test results from the as-constructed lot), PW$/km. *Level 1 Individual AQC Pay Factors*—The pay factors (associated with the measured AQC's) computed using the developed Level 1 individual AQC pay factor equations. Each Level 1 AQC pay factor (expressed as a percentage) is a function of the measured as-constructed AQC lot mean and standard deviation. (Note: Level 1 individual AQC pay factor equations are based on data simulated using the PaveSpec 2.0 computer software.) The final Level 1 individual AQC pay factors may be limited to agency-chosen pay factor practical limits.

Level 1 Composite Pay Factor—The overall pay factor (expressed as a percentage) for an as-constructed lot computed using a Level 1 specification. This pay factor is determined using the agency-defined CPF equation (a simple mathematical function of the individual Level 1 AQC pay factors). The final Level 1 lot CPF (which may be limited to agency-chosen pay factor practical limits) is used to determine the contractor's Level 1 lot pay adjustment.

Level 2 Pay Factor—The overall pay factor (expressed as a percentage) for an as-constructed lot computed using a Level 2 specification. This pay factor is computed using equation 3 and may be limited to agency-chosen pay factor practical limits. The PaveSpec 2.0 computer software is used to simulate the required LCC_{DES} based on SHA-defined AQC target values, and estimate the LCC_{CON} based on the measured as-constructed AQC samples. Performance-Related Specifications (PRS): Construction specifications placed on key materials and construction AQC's (e.g., concrete strength, slab thickness) that have been demonstrated to correlate strongly with long-term pavement performance. These specifications are based on quantified relationships (or mathematical models) that relate measured AQC's to subsequent pavement performance and the corresponding costs.

Present Serviceability Rating (PSR): An indicator of pavement smoothness based on the subjective ratings of users. The PSR is expressed as a number between 0 and 5 with the smaller values indicating greater pavement roughness. The scale is translated into general pavement condition description categories using the following translations.[11]

0 - 1 Very poor.

1 - 2 Poor.

2 - 3 Fair.

3 - 4 Good.

4 - 5 Very good.

Present Worth (PW) Method: A discounted cash flow analysis that involves the conversion of all of the present and future costs to a base of today's costs.[10] Expected future costs are translated into equivalent present worth costs using equation 4.

$$PW_{COST} = C / (1 + i)^T \quad (4)$$

where

PW_{COST} = Present worth of yearly cost (C).

C = M & R, or user cost incurred during year T.

T = Year during which the observed cost (C) was incurred.

i = Chosen discount rate.

Quality Assurance (QA): All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements of quality. Within an organization, QA serves as a management tool. In contractual situations, QA serves to provide confidence in the supplier.[9]

Quality Control (QC): The sum total of activities performed by the seller (producer, manufacturer, or contractor) to make sure that a product meets contract specification requirements. Within the context of highway construction, QC includes materials handling and construction procedures; calibration and maintenance of equipment; production process control; and any sampling, testing, and inspection done for these purposes.[9]

Rejectable Quality Limit (RQL): Agency-chosen minimum limit for acceptable AQC specimen sample quality. If an AQC specimen sample value is measured to have poorer quality than the defined RQL, AQC retesting procedures will apply. For concrete strength, slab thickness, entrained air content, and percent consolidation around dowels, poorer quality than the RQL is identified by specimen sample values *less than* the RQL; however, for initial smoothness, poorer quality than the RQL is identified by specimen sample values *greater than* the RQL.

Sample Mean: The average of n random AQC sample values. This sample mean is computed using equation 5.

$$MEAN_{SAMPLES} = \sum(x_i\square)/n \quad (5)$$

where

$MEAN_{SAMPLES}$ = The computed mean of *n* random AQC samples.

x_i = 1 to n random sample values.

n = Total number of random samples.

(Note: If *m* replicate samples are taken from each sampling location, the mean of each set of *m* test results is used to define a random sample value.)

Sample Standard Deviation: An estimate of the true population standard deviation, σ. If this estimate is to be unbiased, a correction factor must be applied. This unbiased sample standard deviation is computed using equation 6.

$$SD_{SAMPLES} = (\{[\sum(x_i - MEAN_{SAMPLES})^2]/(n-1)\}/m)^{0.5} / C_{SD} \quad (6)$$

where

$SD_{SAMPLES}$ = The computed unbiased standard deviation of all of the random sample values.

$MEAN_{SAMPLES}$ = The computed mean of all of the random sample values.

n = Total number of random samples.

x_i = 1 to n sample values.

m = The number of replicate specimen test results used to compute one sample value.

C_{SD} = Correction factor (based on the total sample size, n) used to obtain unbiased estimates of the actual lot sample standard deviation, σ. Appropriate C_{SD} values are determined using table 2.

Table 2. Correction factors used to obtain unbiased estimates of the actual standard deviation

Number of Sample Values, n	Correction Factor, C_{SD}
2	0.7979
3	0.8862
4	0.9213
5	0.9399
6	0.9515
7	0.9594
8	0.9650
9	0.9693
10	0.9726
30	0.9915
50	0.9949

(Note: Unbiased estimates of the standard deviation are automatically calculated and used in the determination of lot pay factors within PaveSpec 2.0.)

Sample Value: An AQC value used to represent one sample location within a sublot. A representative sample value may be the direct measured value from one test taken at a sample location (no replicate test result values, i.e., *m*=1), or equal to the mean of *m* replicate test result values (from m replicate tests) taken at the same sample location.

Seller: Any entity providing materials and work required for the completion of highway or transportation work. This includes the contractor and all subcontractors. The term may be used interchangeably with producer or supplier.(9)

Sublot: A portion of a lot. Each lot is divided into sublots of approximately equal surface area. Sublot lengths are selected so that one or more samples may be taken from each sublot for each considered AQC. The minimum sublot length cannot be less than 0.16 km (to accommodate the measurement of initial smoothness). Any section of lesser length will be added to the preceding sublot. Note that in PRS, measurements for all AQC's must be obtained from each sublot so that performance can be predicted.

Target Sublot Length: The chosen default linear length for each sublot. Each as-constructed sublot should initially be assumed to be equal to this target sublot length.

Test Result Value: The computed AQC value from one AQC test. For concrete strength, slab thickness, and entrained air content, this is the testing result from one specimen. For initial smoothness, this is the value obtained from one pass of the profilograph.; For percent consolidation around dowels, this is the value obtained from one relative density comparison.

Transverse Joint Faulting: A difference in elevation between the adjacent slabs across a transverse joint or crack. Faulting is primarily caused by the erosion of the supporting material from underneath the leave slab and a buildup of the loose material underneath the approach slab at the joint.(12) The development of transverse joint faulting greatly adds to the roughness of the pavement.Transverse joint faulting is expressed as an average faulting per joint in units of mm.

Transverse Joint Spalling: The breakdown or disintegration of the concrete (near the surface) at a transverse joint. Spalled transverse joints are rated as having low-, medium-, or high-severity spalling. Under the PRS approach, transverse joint spalling is expressed in terms of the number of medium- or high-severity spalled joints per unit length (number of spalled joints per km).(12)

Transverse Slab Cracking: Cracks occurring parallel to transverse joints and at the midslab of JPCP slabs. The transverse cracking predicted for the PRS is due solely to fatigue of the slabs from the application of traffic loading. Typically, these midslab cracks begin as a single crack at the edge of the slab and propagate through the entire slab.(12) Transverse cracks are rated as having low, medium, or high severity. Under the PRS approach, transverse slab cracking is expressed in terms of the number of all severity cracks per unit length (number of cracks per km).

Key Concepts

Introduction

This chapter provides a number of key concepts related to the current PRS approach that must be understood before attempting to use the revised PRS prototype. The chapter starts with a general discussion of pavement performance and how it is defined under the PRS approach. The specific step-by-step PRS procedure used to predict the performance of a given lot is presented. Next, the concept of computing and using the lot LCC as the overall measure of quality (for both the as-designed and as-constructed pavements) is explained. The step-by-step procedures used to compute an overall lot LCC are discussed. Finally, the procedures used to compute Level 1 and Level 2 pay adjustments (based on the estimated as-designed and as-constructed LCC's) are explained.

Prediction Of Pavement Performance

The underlying concept of PRS is that knowledgeable decisions related to pavement lot acceptance and corresponding pay adjustments are based on the predicted pavement performance. Under the current PRS approach, pavement performance is expressed in terms of different identified pavement distresses, referred to as distress indicators. In a previous PRS study, many distress indicators were identified that were not only assumed to have a significant effect on the service life of the pavement, but were also under the control of the contractor.[(1)] Based on each identified distress indicator's significance to concrete pavement performance and the availability of mathematical-based prediction models, the following four distress indicators were selected for inclusion in the original, and also the revised, prototype PRS:[(1)]

- Transverse joint spalling.
- Transverse joint faulting.
- Transverse slab cracking.
- Pavement smoothness over time.

Although the chosen distress indicators are exclusively related to the concrete slab, distress indicators related to other pavement components (such as the subgrade, base, and shoulders) should eventually be included in more comprehensive PRS. The current PRS methodology allows for the eventual inclusion of any number of distress indicators.

These four distress indicators included in the revised PRS are predicted over a chosen analysis period using the best prediction models available. These mathematical models are functions of a series of defined project-specific constant values (e.g., traffic, climatic variables, design characteristics, drainage and support conditions, project dimensions, and unit costs) and relevant AQC sample means. The general inputs and outputs for each of the available PRS distress indicator models are shown in figure 1.Each distress indicator model is explained in detail in appendix E (volume III).

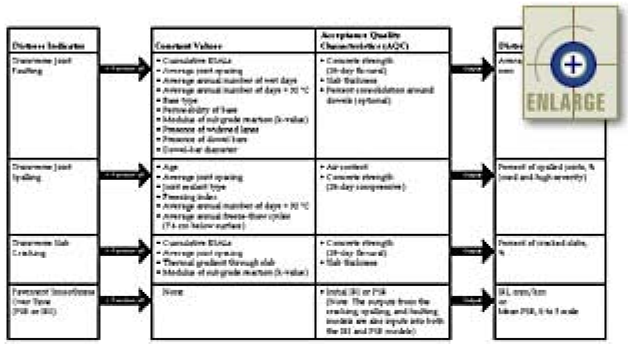

Figure 1. Inputs and outputs of the distress indicator prediction models available in the revised PRS prototype.

Although pay adjustments are applied on a *lot* basis, pavement performance is predicted for each *sublot* under the current PRS approach. A sublot is a discrete amount of pavement (part of a lot) from which AQC's are measured. A chosen number of AQC samples are taken from each sublot and tested using agency-approved testing procedures. Note that the number of samples per sublot may differ for each AQC. The sublot means of the AQC testing values, and the project-specific constant values, are then used in the distress indicator models to predict the respective sublot distresses over time. This procedure is repeated for every sublot within a lot; therefore, the performance of the entire lot is defined in terms of the independently predicted sublot distresses. Because the predicted sublot distresses are dependent on the representative sublot AQC means, changes in the between-sublot quality level impact the predicted between-sublot performance. Figure 2 illustrates an example of the procedure used to predict the pavement performance of a given lot. (Note: The AQC sampling types and frequencies chosen for this example are for illustration purposes only.)

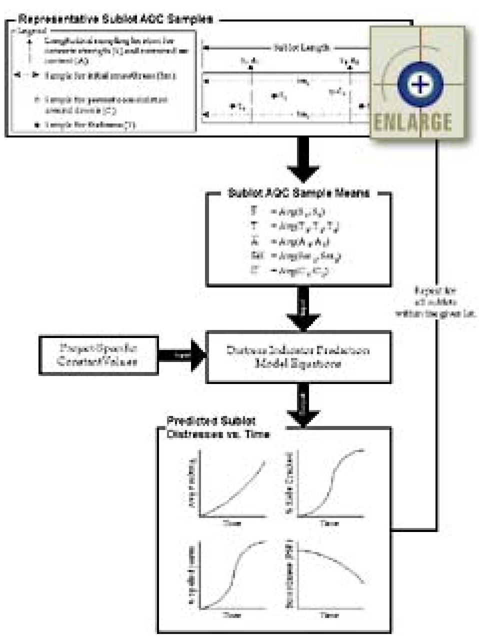

Figure 2. Process for predicting the pavement performance of a given lot (sample types and number of samples per sublot are for illustration purposes only).

LCC As The Overall Lot Quality Characteristic

A driving concept of the current PRS approach is that the predicted future LCC of a pavement lot is the overall quality characteristic used for determining contractor pay adjustments. The lot LCC can generally be defined as the cumulative PW value of the future pavement performance-related costs expected to be incurred by the SHA (and users, if so desired) over the chosen analysis period. This LCC definition is, of course, very much dependent on what specific types of costs the agency chooses to include. Under the current PRS approach, the agency may choose to consider not only expected M & R costs, but user costs as well. Each of the specific cost types available for inclusion are discussed in more detail below.

Agency-Incurred LCC's

The costs incurred by the agency include all of the M & R costs expected to be required to keep the pavement lot in service (at an acceptable quality level) over the chosen analysis period. Rehabilitation costs are divided into localized and global rehabilitation costs. Each of these agency-incurred cost types is discussed separately below.

Maintenance costs are those costs associated with the application of day-to-day maintenance activities performed to address safety and operational concerns and prevent the rapid deterioration of the pavement structure. These activities are generally referred to as *preventive* or *routine* maintenance. This maintenance is typically applied at certain fixed intervals of time over the life of a pavement lot (commonly on an annual basis). The current PRS approach limits maintenance costs to those resulting from transverse crack and transverse joint sealing.

Local rehabilitation costs are those resulting from the application of localized rehabilitation activities (used to correct localized distresses). Localized distresses are those that affect an individual joint (transverse joint spalling and transverse joint faulting) or an individual slab (transverse slab cracking). The current PRS approach considers costs resulting from the following local rehabilitation activities:

- Full-depth or partial-depth repairs addressing transverse joint spalling.
- Full-slab or partial-slab replacements addressing transverse slab cracking.

Global rehabilitation costs are those costs resulting from activities applied to the entire pavement lot in response to declining *global* pavement conditions. These activities are specifically applied to address pavement conditions such as decreasing pavement smoothness, increasing amounts of localized distress, or increasing amounts of applied localized rehabilitation. These activities are referred to as *global* because they are applied to the entire lot (all sublots) at the same point in time (based on the consideration of the individual performance of all sublots within the lot). In the current PRS approach, global rehabilitation costs can be the result of AC overlays, PCC overlays, or diamond grinding.

User-Incurred LCC's

The concept of having the contractor pay adjustment dependent on estimated future costs incurred by pavement users has long been debated when discussing PRS. User costs are defined as pavement condition-related costs incurred by the users of the facility over the chosen analysis period. The current PRS approach allows the consideration of the following four user cost types defined by McFarland and presented in a recent report discussing LCC's:[10,13]

- Travel-time costs—motorist delay costs spurred by detours, work zones, or closures associated with construction, rehabilitation, and maintenance activities. These costs can be a major portion of total user costs. Rougher pavements can reduce traffic speeds, representing another source of travel-time costs.

- Vehicle operating costs—costs associated with fuel and oil consumption, tire wear, emissions, maintenance and repair, and depreciation. Like travel-time costs, these costs make up a significant percentage of the total user costs.

- Accident costs—costs associated with accidents due to rough or slippery roads. American Association of State Highway and Transportation Officials (AASHTO) has subdivided accident costs into fatal accidents, nonfatal accidents, and property damage.(14) These costs can be a significant portion of the total user costs; however, they are very difficult to estimate because the value of a human life and the cost of a debilitating injury are very controversial.

- Discomfort costs—costs associated with rough roads. This category is probably the most difficult to estimate and generally contributes little to total user costs in North America, particularly in light of the smoother pavements required for heavily trafficked pavements.

The inclusion of user costs in the lot LCC's used to compute PRS pay adjustments continues to be a controversial issue. In response, the revised prototype PRS allows for the inclusion of a specified *percentage* of the estimated total user costs over the chosen analysis period. This percentage may be set equal to zero if an agency does not wish to include any user costs. The inclusion of user costs does, however, allow the SHA to emphasize the effects of pavement smoothness on LCC's and subsequent pay adjustments.

Calculation of the Representative LCC for a Given Lot

The calculation of the representative LCC for a given lot is based on estimating all of the future maintenance, rehabilitation, and user costs (if included) related to the predicted performance of the given lot. The performance of the lot, defined in terms of sublot distresses versus time, is predicted using the procedure outlined in figure 2. An agency-defined M & R plan is applied to these streams of sublot distresses in order to determine when and what type of M & R activities are expected to be applied. Typically, a series of defined pavement conditions (individual distress levels, combinations of distress levels, and limits on the number of applied localized repairs) is used to trigger localized and global rehabilitation.

Following is the step-by-step procedure used to determine the particular timing of M & R activities and their associated costs, which are, in turn, summarized into a representative lot LCC.

1. *Determine the estimated yearly maintenance and local rehabilitation activities for each sublot.* As the pavement distresses are predicted for each sublot at each year over the chosen analysis period, M & R activities are applied to each sublot in accordance with the agency-defined M & R plan. The details of the M & R plan can be based on time (e.g., replace cracked slabs every 5 years) or individual distress volume (e.g., replace spalled joints when 20 percent of the joints are spalled). Figure 3 shows an example of the relationships between the predicted distress indicators and the application of corresponding localized rehabilitation for a given sublot (as defined by the applicable M & R plan).

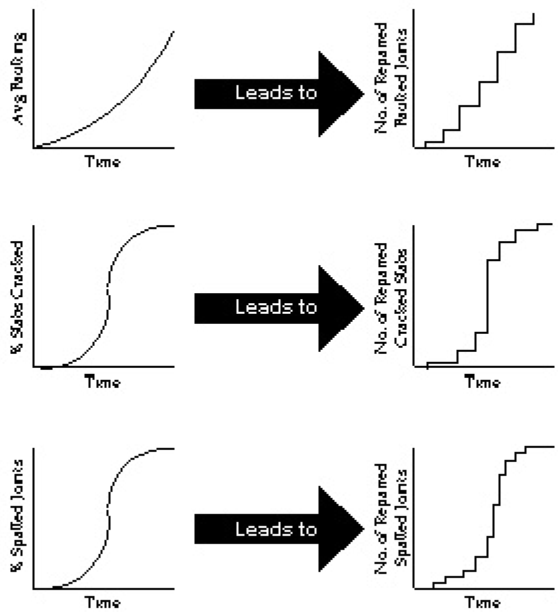

Figure 3. Example of the relationships between the predicted distress indicators and the application of corresponding localized rehabilitation for a given sublot.

2. The schedule of applied maintenance is slightly more complex, as it depends not only on the scheduled *timing* of the maintenance activities (defined in the M & R plan), but also on the *amounts* of the predicted localized distress. For example, as the total linear feet of predicted slab cracking increases, so does the amount of required crack sealing. Similarly, every transverse joint that is replaced to correct spalling results in two new joints (both sides of the new patch) that require sealing.
3. *Determine the year of first global rehabilitation*. The lot LCC is greatly influenced by the chosen timing and type of global rehabilitation activities. This is primarily due to the magnitude of these costs in relation to the maintenance and localized rehabilitation costs. The revised prototype provides the agency with the following two options for determining when the first global rehabilitation is to be applied to the entire lot:
   a. *Lot threshold trigger values on distress or localized rehabilitation values*—The first option involves identifying lot threshold trigger values to be applied to either the cumulative sublot distresses or cumulative localized rehabilitation activities predicted to occur in all sublots within the lot. Specifically, this may involve a comparison of any or all of the following types of items to predetermined critical lot threshold trigger values:
      - *Individual distress indicators*—i.e., percent (or number) of cracked slabs, percent (or number) of spalled joints, and average faulting per joint.
      - *Combinations of individual distress indicators*—e.g., apply global rehabilitation if percentage of cracked slabs = 20 percent and percentage of spalled joints = 30 percent.
      - *Applied levels of localized rehabilitation*—e.g., apply global rehabilitation when a total of 20 percent of the transverse joints have been repaired for spalling.

Predicted distresses, and their corresponding required localized rehabilitation, are estimated each year over the progressing life of the pavement. The computed cumulative distresses, or localized rehabilitation, are then compared to the agency-defined lot threshold trigger values. When a computed cumulative distress or localized rehabilitation value surpasses a predefined lot threshold trigger value, the first global rehabilitation is triggered for application at that age.

An example of this lot threshold trigger value method is illustrated in figure 4. For this example, the agency has chosen to determine the timing of the first global rehabilitation based on two different lot threshold trigger values: (1) if the *cumulative percentage of replaced slabs* due to cracking equals 20 percent or (2) if the *average sublot PSR* equals 2.5. Both of these trigger values are checked each year over the progressing life of the pavement. For this particular example, it is the average sublot PSR that is the controlling criterion, since it reaches its respective trigger value at an earlier age than the percentage of cracked slabs. The average sublot PSR reaches a value of 2.5 at an age of 17.5 years, while the percentage of cracked slabs did not reach its trigger value of 20 percent until year 19.25. Therefore, the first global rehabilitation is scheduled to be applied to the lot (all sublots) at an age of 17.5 years.

b. *Percentage of sublots failed (PSF)*—The second option involves directly comparing the individually determined sublot distress or localized distress values (rather than the lot cumulative values) to agency-defined sublot threshold trigger values. When a distress or localized rehabilitation value for a sublot surpasses a predefined sublot threshold value, the sublot is labeled *failed*. This process is used to independently determine the estimated age of failure for each sublot in the lot. The agency then defines the timing of the global rehabilitation (for application to the entire lot) in terms of a PSF threshold value (e.g., an AC overlay will be applied to the entire lot when 20 percent of the sublots have been labeled as *failed*). When the computed PSF value equals the agency-defined PSF threshold value, the first global rehabilitation is triggered for application at that age.

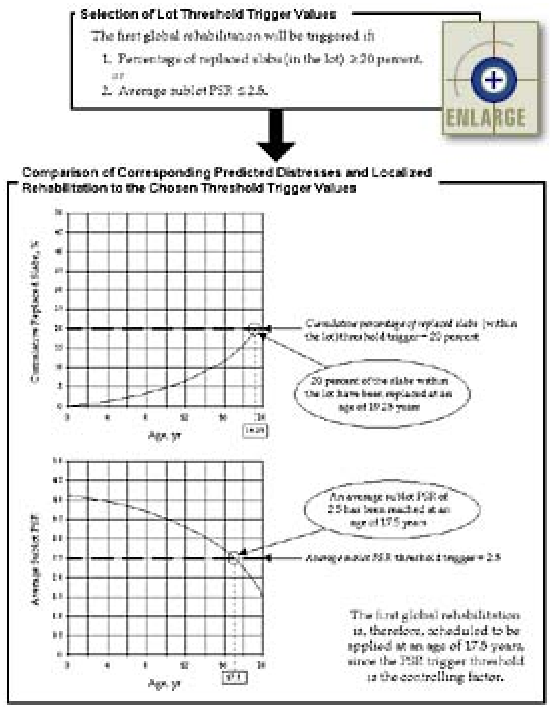

Figure 4. Example of the lot threshold trigger method used to determine the timing of the first lot global rehabilitation.

An example of this PSF method is illustrated in figure 5. For this example, the lot is made up of six sublots. The agency-defined PSF threshold value is 20 percent; therefore, this threshold value will be surpassed when two of six sublots are labeled as failed (33 percent > 20 percent). The independently determined sublot failure ages are shown for each sublot within the example lot. These sublot failure ages are then used to create a plot of PSF versus age. Based on the individually determined sublot failure ages and an agency-defined PSF threshold value of 20 percent, the first global rehabilitation is scheduled to be applied when the second sublot fails at an age of 19.50 years. It is strongly recommended that a trigger value of 10 to 30 PSF be used as the lot trigger value for determining global rehabilitation. This criterion is realistic and provides for a reasonable effect of variability on the LCC and pay adjustment.

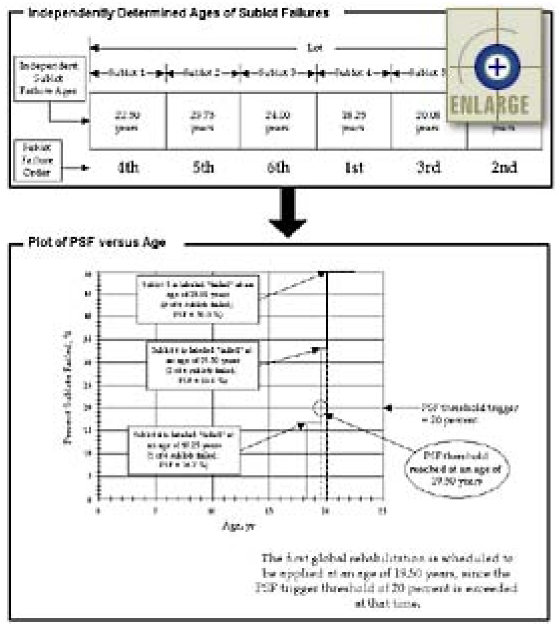

Figure 5. Example of the PSF method used to determine the timing of the first lot global rehabilitation.

2. *Determine types and life spans of additional global rehabilitation applications.* After the timing of the first global rehabilitation is determined, the agency must define the types and timings of additional global rehabilitation applications. Each global rehabilitation activity is applied with an assumed life span (e.g., apply an AC overlay with an assumed 15-year overlay life). Additional global rehabilitation activities are then applied at the end of each assumed life span. (Note: Each additional global rehabilitation does not have to be of the same activity type as the preceding applied rehabilitation. For example, the agency could choose to apply diamond grinding for the first and second global applications, and then follow those with AC overlay applications until the end of the analysis period.) Global rehabilitation activities may have different assumed life spans (e.g., an AC overlay may be assumed to last 15 years, whereas diamond grinding may be assumed to last 8 years).

3. *Determine the estimated yearly maintenance and rehabilitation costs for each sublot*. The next step is to calculate the costs associated with the predicted M & R application schedule. Maintenance and localized rehabilitation costs are only incurred up until the application of the first global rehabilitation. After the application of the first global rehabilitation, a simplified maintenance and localized rehabilitation plan (determined by the agency) is assumed. Figure 6 shows an example of the estimation of different M & R costs (for one sublot) as they are applied over the analysis life of the pavement.

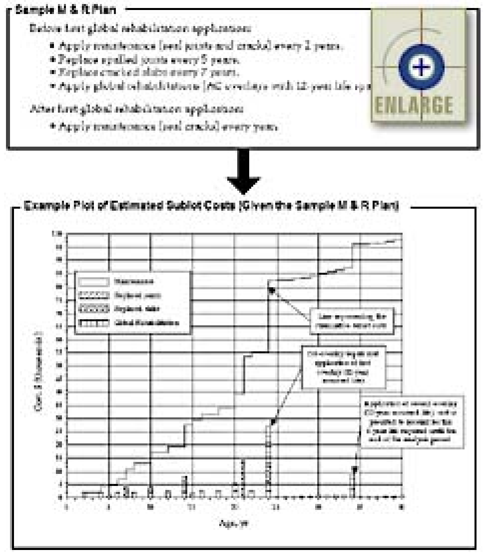

Figure 6. Example showing the estimation of different M & R costs for one sublot (over the chosen analysis life).

4.
5. *Determine the estimated yearly user costs for each sublot (optional).* As mentioned previously, the prototype allows the inclusion of a percentage of the estimated user costs. User costs (accident, delay, discomfort, and vehicle operating) are computed as a function of road type (e.g., two-lane-undivided, four or more lanes-divided), yearly traffic, and level of smoothness. The process starts with determining the current level of smoothness at the start of each year of the analysis period. A user *cost per vehicle per kilometer* is then determined as a function of road type and level of smoothness. The expected amount of traffic (number of vehicles on the pavement) for the year is then used to determine a total yearly user cost value expressed in *dollars per kilometer*. Knowing the sublot length allows for the calculation of actual user cost dollars associated with that particular sublot. The agency-chosen *percentage* of these calculated yearly user costs is then used to determine the respective stream of yearly user costs for the given sublot. Note that user costs are typically very large in comparison to the M & R costs calculated in step 4.

6. *Determine the total present worth LCC for each sublot.* The stream of maintenance, rehabilitation, and user costs are next expressed in terms of present worth costs using the defined present worth method. Summarizing the yearly costs into one PW LCC representing the sublot is key to the prototype approach. The sublot LCC's represent the overall quality characteristic used to define the quality of each sublot (and, therefore, the quality of each lot). Each estimated yearly cost is expressed in terms of present worth by using equation 4. These specific streams of yearly costs for each sublot are, therefore, translated into PW sublot LCC's.

7. *Calculate the representative lot LCC.* The final step in the calculation of the representative LCC for a given lot is to summarize all of the calculated sublot PW LCC's. Each sublot LCC is expressed in PW dollars rather than PW dollars per kilometer. Therefore, the representative lot LCC is calculated by summing all of the independently calculated sublot LCC's for the lot. The overall lot LCC may then be expressed in terms of *PW LCC per kilometer* by dividing the total lot present worth LCC by the appropriate lot length (in kilometers).

This entire lot LCC calculation process can be represented mathematically by the cost relationship shown in equation 7.

$$LCC_{LOT} = \Sigma_{\text{ΑΛΛ ΣΥΒΛΟΤΣ}} \Sigma_{\text{ΨΕΑΡΣ}} [\text{ΠΩ(ΜΝΤ)} + \text{ΠΩ(ΛΡ)} + \text{ΠΩ(ΓΡ)} + (\text{Α}/100)*\text{ΠΩ(ΥΧ)}] \quad (7)$$

where

LCC_{LOT} =Total present worth lot LCC, PW$.

PW(MNT) = Present worth of maintenance costs, PW$.

PW(LR) = Present worth of localized rehabilitation costs, PW$.

PW(GR) = Present worth of global rehabilitation costs, PW$.

A = Percentage of user costs to be included. (e.g., 3 percent is entered as 3).

PW(UC) = Present worth of user costs, PW$.

Comparisons Of As-Designed And As-Constructed LCCs

Pay adjustments under the revised prototype approach are based on a direct comparison of representative LCC's determined independently for both the as-designed and as-constructed pavement lots. Both as-designed and as-constructed representative lot LCC's are determined using the procedure described in the previous section.

Project-Specific Characteristics

The agency begins this comparison for a given project by defining and fixing those items that will not differ between the as-designed and as-constructed LCC determinations. These project-specific decisions include the following:

- **Constant Variables**—Specific design characteristics grouped into categories such as traffic, project location and description, climate, materials, base, and load transfer.
- **Definition of Performance**—The specific set of distress indicator models used to define pavement performance. These may include any or all of the following: transverse slab cracking, transverse joint faulting, transverse joint spalling, and pavement smoothness over time (expressed in terms of PSR or IRI).
- **Included Acceptance Quality Characteristics**—The AQC's that are sampled and used for acceptance. These may include any or all of the following: concrete strength, slab thickness, entrained air content, pavement smoothness, and percent consolidation around dowels.
- **Acceptance Sampling and Testing Plan**—The specific sampling and testing procedures used for each of the included AQC's. These include the sampling and testing methods, number of samples per sublot, and the timing of sampling.
- **Maintenance and Rehabilitation Plan**—The defined set of rules used to predict the type and timing of future M & R activities.
- **Cost-Related Items**—The cost-related items associated with the prediction of future M & R activities. These include items such as the M & R activity unit costs, percentage of included user costs, and the selected discount rate.

With all of these project-specific components held constant, the only variables that may differ between the as-designed and as-constructed pavements are the means and standard deviations of the chosen AQC's. Therefore, the difference between the resulting as-designed and as-constructed lot LCC's is the direct result of differences in the AQC quality.

Basic Pay Factor and Pay Adjustment Principles

The actual pay adjustment (incentive or disincentive) for a given lot is calculated as the difference between the as-designed LCC (LCC_{DES}) and the as-constructed LCC (LCC_{CON}). This pay adjustment may be expressed as a percentage of the representative contractor bid price for the given lot of concrete pavement. This relationship to the bid price is termed the *pay factor* (see equation 3).

Simulation of the Representative As-Designed Lot LCC

The representative as-designed lot LCC is simulated using the PaveSpec 2.0 computer software. As-designed target AQC means and standard deviations are selected by the agency and used to define the agency-desired pavement quality. If the as-constructed pavement is found to exactly match this desired quality (based on conducted AQC acceptance sampling and testing), the contractor will receive 100 percent of the submitted bid price (on average). The PaveSpec 2.0 software is used to simulate AQC sample sets (from the target AQC distributions) for N as-designed pavement lots. Each of the N simulated AQC sample sets results in the calculation of one possible LCC representing the as-designed target lot. The overall representative as-designed target LCC is, therefore, computed as the average of the N simulated lot LCC's. This process is illustrated in figure 7.

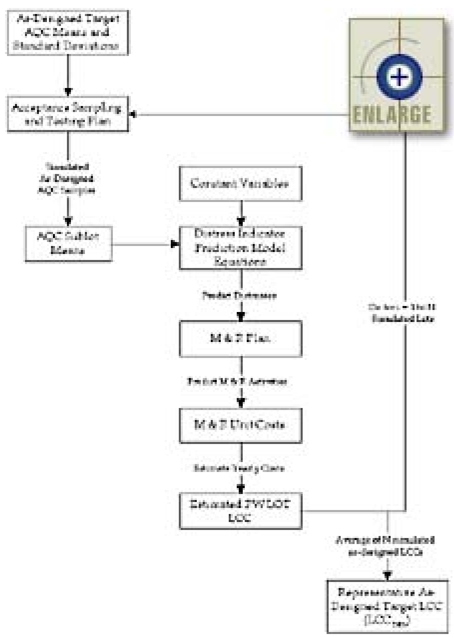

Figure 7. Flow chart showing the process used to simulate the representative as-designed lot LCC (LCC_{DES}).

Level 1 Pay Adjustments

Simulation of the Level 1 Individual AQC Pay Factor Curves

The data flow process used to compute the LCC for any one as-constructed lot is exactly the same as that used to compute the LCC for any one target as-designed simulated lot. As mentioned previously, the same constant variables, distress indicator models, acceptance sampling and testing plan, M & R plan, and cost models are used for both the as-designed and as-constructed lot simulations. The only difference between the procedures involves the AQC means and standard deviations used to define the quality of the as-designed and as-constructed pavement lots.

If a Level 1 pay adjustment approach is chosen, independent pay factor charts and corresponding equations are developed for each AQC. These pay factor charts are developed prior to the bidding on the project and are made available to the contractor. Hypothetical combinations of individual AQC means and standard deviations are selected and assumed to be equal to the as-constructed pavement lot quality. For each hypothetical combination, a representative as-constructed LCC is simulated using exactly the same procedure used for the simulation of the representative as-designed lot LCC (i.e., N AQC sample sets are simulated, resulting in N computed lot LCC's—the representative as-constructed lot LCC is computed as the mean of the N simulated as-constructed LCC values). Pay factors associated with each representative as-constructed LCC (hypothetical combination of AQC mean and standard deviation) are then determined using equation 3. (Note: Since these curves must be made available prior to accepting contractor bids, a representative bid price is used to compute the pay factors making up these curves [see the section titled *Selecting an Appropriate Bid Price for Developing Level 1 Preconstruction Output* in chapter 5, for more information]). Individual pay factor curves are constructed for specific levels of AQC standard deviation (chosen by the agency), and over a chosen range of AQC means, using the simulated representative as-constructed LCC's. Best-fit regression equations are then determined, representing the data making up the individual AQC pay factor curves. An example of a Level 1 pay factor chart for concrete strength is shown in figure 8.

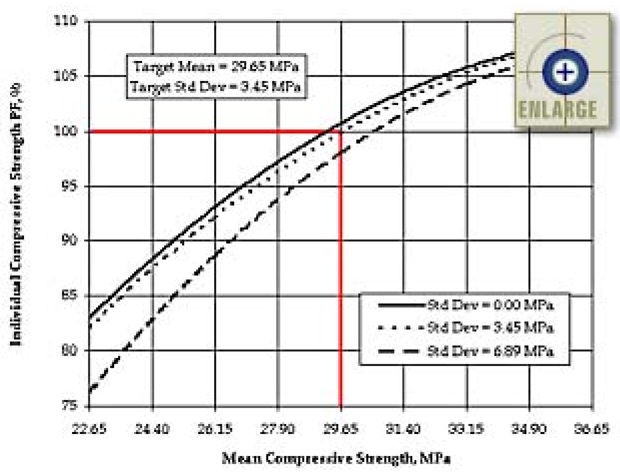

Figure 8. Example of an individual Level 1 pay factor chart for concrete strength.

It is important to emphasize that only one AQC is allowed to vary at a time when developing these Level 1 AQC pay factor curves. For example, when representative pay factors are being simulated for the individual concrete strength pay factor chart, all simulated pay factors (from hypothetical combinations of concrete strength mean and standard deviation) are determined with the other AQC means and standard deviations (for slab thickness, air content, initial smoothness, and percent consolidation) set equal to their target values. Figure 9 contains a flow chart showing the general simulation process used to develop Level 1 AQC pay factor curves and corresponding pay factor regression equations. A more detailed step-by-step procedure for generating these Level 1 AQC pay factor curves and corresponding pay factor regression equations is presented in chapter 7.

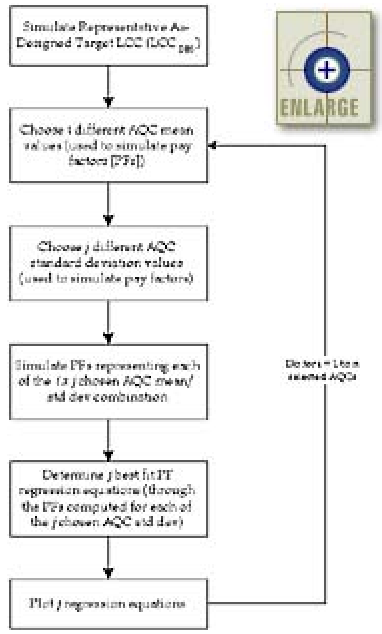

Figure 9. Flow chart showing the process used to develop Level 1 AQC pay factor charts and corresponding equations.

Level 1 Composite Pay Factors

After the construction of an actual pavement lot, the agency takes samples from the pavement in accordance with the chosen acceptance sampling and testing plan. The AQC sampling and testing values measured in the field (for the given lot) are summarized into representative lot AQC means and standard deviations. The lot means and standard deviations are then used in the individual AQC pay factor regression equations to determine the corresponding independent AQC pay factors. The procedure used to determine individual AQC Level 1 pay factors from the pay factor charts is described in more detail in chapter 7.

Finally, the overall representative as-constructed Level 1 lot pay factor is determined by combining the individually calculated AQC pay factors into one CPF representing the lot. The CPF equation essentially provides the appropriate weighting factors for each independently determined AQC pay factor. This specific CPF function is determined by the agency. A more detailed discussion of the commonly used CPF equations is contained in chapter 6 in the section titled *Defining a Level 1 Composite Pay Factor Equation*. Figure 10 contains a flow chart showing the general process used to compute a Level 1 lot CPF.

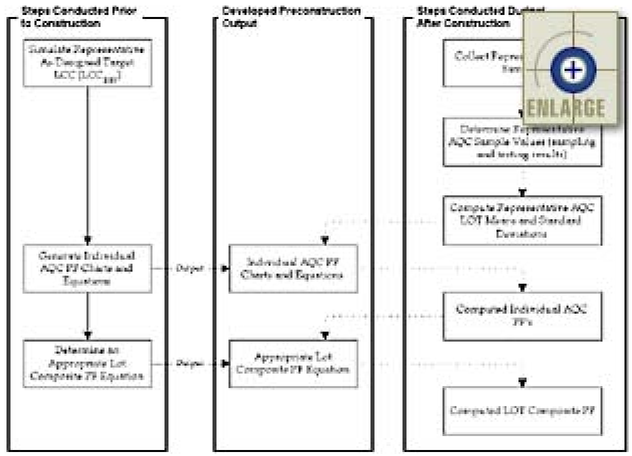

Figure 10. Flow chart showing the process used to determine a Level 1 lot composite pay factor.

Level 2 Pay Adjustments

The Level 2 pay adjustment does not require the use of a CPF equation. The lot pay factor is directly computed through simulation with the PaveSpec 2.0 software. After the placement of the as-construction pavement lot, samples are taken from each sublot according to the agency-chosen acceptance sampling and testing plan. Each set of AQC sublot samples is then statistically summarized to obtain AQC means representing each sublot. The sublot means are used in the chosen distress indicators to predict sublot performance, predicted sublot M & R activities, and their associated sublot LCC's. Finally, these sublot LCC's are summarized into one representative lot present worth LCC. The overall as-constructed lot pay adjustment and pay factor are then determined using this calculated as-constructed lot LCC in equations 1 and 2, respectively. Figure 11 contains a flow chart showing the general simulation process used to calculate a Level 2 lot pay factor.

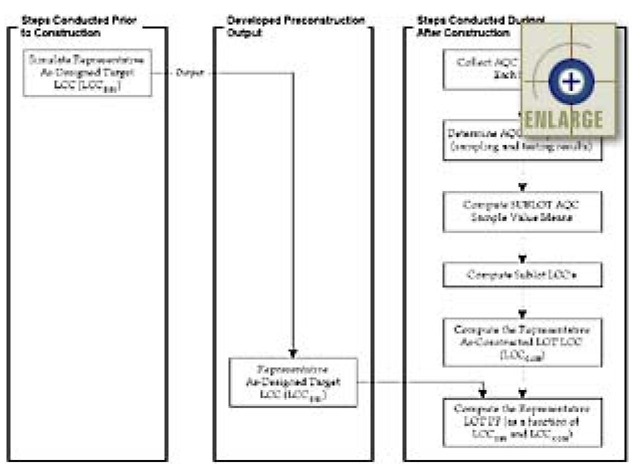

Figure 11. Flow chart showing the process used to determine a Level 2 lot pay factor.

Major Differences Between Level 1 and Level 2 Pay Adjustment Procedures

Three of the primary differences between the Level 1 and 2 pay adjustment procedures include the following:

1. *Preconstruction Output*—Individual AQC pay factor curves are simulated using Level 1 procedures; the only Level 2 preconstruction output is the simulation of a representative as-designed LCC (LCC_{DES}).

2. *Simulation of Pay Factors*—Individual Level 1 AQC pay factor curves are simulated by holding all other AQC's at their target values; Level 2 pay factors allow for the simultaneous varying of all included AQC's (i.e., tradeoffs in AQC quality can occur).

3. *Overall Lot Pay Factor Calculation Method*—The overall Level 1 CPF is calculated as a function of the individually determined AQC pay factors computed using the simulated AQC pay factor charts and equations; the overall Level 2 pay factor is calculated directly using equation 3 in this volume. All required LCC's are determined using the PaveSpec 2.0 software.

It is important to emphasize that the Level 1 lot CPF is actually an estimate of the computed Level 2 lot pay factor. The Level 2 approach represents a simulated construction, sampling, testing, performance, and M & R over many years. Level 1 is a simplified method used to estimate the same pay factor as determined in Level 2, using more conventional pay factor curves.

Operating Characteristic Curves

Operating characteristic (OC) curves must be generated by the agency to determine if the chosen acceptance plan will perform as intended. The OC curves used with the PRS approach are similar to those used for conventional accept/reject acceptance plans, except that a set of OC curves is needed to reflect different payment options.[15] An example of the OC curves, commonly constructed for adjustable payment acceptance plans using actual lot percent defective procedures, is illustrated in figure 12. Each set of OC curves is specific to a chosen sampling plan (i.e., number of sublots per lot, number of AQC samples per sublot, and types of AQC samples and tests). The development of these curves is an integral part of the specification development process in that they provide the agency and the contractor with information regarding their respective risk. Similar OC curves can be developed for Level 1 specifications using the PaveSpec 2.0 computer software. The OC curves developed under the PRS approach are plots of probability of acceptance at the pay level specified versus AQC mean (rather than percent defective). More detailed information regarding the development of these curves using PaveSpec 2.0 is contained in chapter 7 in the section titled *Developing Operating Characteristic Curves*.

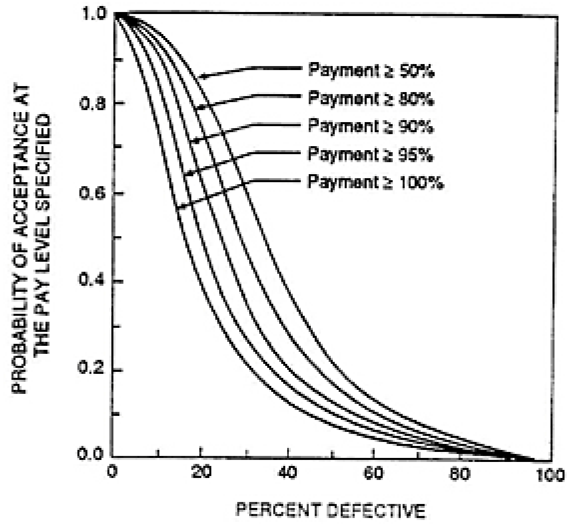

Figure 12. Example of typical OC curves for an adjustable payment acceptance plan.[(15)]

Guidelines for Inputs

Introduction

To use the revised PRS prototype specification successfully, the agency must understand the implications of each decision made while developing or using the specification. These include general PRS decisions such as selecting the distress indicators used to define performance and the AQC's chosen to be included for acceptance, as well as more specific items such as defining appropriate values for the required constant variables. This chapter is designed to provide the typical user of the specification with the practical information required to make intelligent PRS-related decisions.

Defining Pavement Performance

As previously stated, an underlying concept of a PRS is that knowledgeable decisions related to pavement lot acceptance and corresponding pay adjustments are based on the predicted pavement performance. In fact, the PRS is driven by key distress indicators. In the current PRS approach, pavement performance may be defined in terms of the development of any or all of the following distress indicators:

- Transverse joint spalling.
- Transverse joint faulting.
- Transverse slab cracking.
- Pavement smoothness over time (expressed in terms of PSR or IRI).

When developing a PRS for a given project, the agency must choose any or all of these distress indicators to define the pavement's performance. Those distress indicators not included in the chosen definition of performance will not be subjected to trigger values and, therefore, will not result in any responsive M & R activities or associated costs. For example, if transverse slab cracking is not included in the agency's definition of performance, slab replacement costs will not be incurred. It is recommended that all four of these distress indicators be used to define the pavement's performance.

Selection Of Included AQCs

Along with defining a pavement's performance by selecting distress indicators, the agency must also decide which AQC's are to be sampled and tested for acceptance. To make these selections, the agency must be aware of the interdependent relationships between distress indicator models and AQC's (these relationships are shown in figure 1). For example, if an agency includes transverse slab cracking in its definition of pavement performance, it is recommended that the agency choose to measure slab thickness and concrete strength since they are both key factors in the transverse slab cracking distress indicator model. If the agency were to choose not to sample an AQC that is required by a chosen distress indicator model, distress predictions would be made by holding that particular AQC at its target mean value. The revised PRS allows pay adjustments to be based on the measurement of any or all of the following five AQC's:

- Concrete strength (affects transverse joint faulting, transverse joint spalling, and transverse slab cracking directly; affects pavement smoothness indirectly).
- Slab thickness (affects transverse joint faulting and transverse slab cracking directly; affects pavement smoothness indirectly).
- Entrained air content (affects transverse joint spalling directly; affects pavement smoothness indirectly).
- Initial smoothness (affects pavement smoothness over time directly).
- Percent consolidation around dowels (affects transverse joint faulting directly; affects pavement smoothness indirectly).

Based on the agency's selected definition of pavement performance, intelligent decisions must be made to define what AQC's are to be included in the PRS. It is recommended that the agency first identify those AQC's that are included in the selected distress indicator equations, as indicated above. From those included AQC's, the agency is encouraged to measure only those AQC's that it currently feels comfortable measuring. If this final selected list of AQC's greatly differs from AQC's required for the selected distress indicator models, it is recommended that the agency revisit its choices for included distress indicators. Because of the existence of these interdependent relationships between included distress indicator models and measured AQC's, the selection of both should be looked at as an iterative process.

Identification Of Constant Variable Values

Any developed PRS should be project-specific because the predicted performance of any pavement is directly dependent on project-specific variables. These variables fall into three categories: design-related characteristics, climatic characteristics, and applied traffic loads. Variables representing each of these three categories are used in the agency-chosen distress indicator models to predict pavement performance. These variables are labeled *constant* because they do not change between the as-designed and as-constructed pavements. (Note: Figure 1 shows a list of the constant variables required by each distress indicator model.)

Once the governing agency identifies the distress indicator models used to define pavement performance and the AQC's to be accepted, the next step is to assign values to the required constant variables that represent the project's specific design, traffic, and climatic conditions. In an effort to help agencies with the selection of appropriate constant variable values, brief descriptions of each of the possible constant variables are included below. The variables are divided into the three main categories (design, climatic, and traffic) for clarification.

Design-Related Variables

Pavement Type—Although the current specification is only valid for JPCP, the agency must identify whether the chosen pavement design is to be constructed *with* or *without* dowel bars.

Road Location—Calculated user costs (vehicle operating costs) are dependent on the roughness of the pavement over time, as well as the location of a road.[13] The road location setting is defined as either *rural* and *urban*.

Lane Configuration—Calculated user costs are also dependent on the identified lane configuration of a road.[13] The lane configuration is defined as a combination of road type (divided or undivided) and total number of lanes (includes all travel lanes in both directions). Divided pavements are those in which the traffic traveling in opposite directions is divided by a barrier or median. The current approach allows the agency to select from the following six different lane configuration choices:

- 2-lanes, undivided pavement.
- 4-lanes, undivided pavement.
- 4-lanes, divided pavement.
- 6-lanes, divided pavement.
- 8-lanes, divided pavement.
- 10-lanes, divided pavement.

Initial Design Life—The total expected amount of time for which the chosen pavement design is expected to carry traffic loads without the application of a global rehabilitation (AC overlay, PCC overlay, diamond grinding). This is the initial design life used in the common pavement design procedures.

Analysis Period—Period of time over which future M & R costs are to be considered in an LCC analysis. The analysis period is typically defined as twice the chosen design life (as a minimum) to ensure that future impacts of M & R are considered.

Lane Width—The agency must define the individual widths of each traffic lane. Typical pavements are constructed using traffic lanes that are 3.7 meters in width. However, many agencies are now constructing widened outer traffic lanes (typically 4.3 meters in width) in an attempt to reduce the development of transverse slab fatigue cracking. The defined lane widths are used to calculate sublot and lot areas. The presence of a widened outer traffic lane is an input required by the transverse joint faulting and transverse cracking models.

Average Transverse Joint Spacing—The transverse joint faulting, transverse joint spalling, and transverse slab cracking distress indicator models all have average transverse joint spacing as a required input. JPCP's are typically constructed using constant joint spacings (e.g., every 4.6 meters) or random joint spacings (e.g., using a repeated pattern of 4.0-4.3-4.6-5.2 m). If a constant joint spacing is used, the constant value is used as the average transverse joint spacing in the distress indicator models. If a random joint spacing is selected, the appropriate transverse joint spacing is set equal to the mean of the joint spacings included in the repeated series. For example, a random joint spacing series of 4.0-4.3-4.6-5.2 m would have a mean transverse joint spacing value of 4.5 m.

Effective Modulus of Subgrade Reaction (k-value)—An effective subgrade k-value is a required input for the transverse joint faulting and slab cracking distress indicator models. The appropriate value for use in these models is the effective modulus of subgrade reaction (including seasonal variations) calculated for design purposes. (Note: This value is for the subgrade, not the top of base.) Additional information on determining an appropriate effective subgrade k-value is contained in appendix HH of Volume 2 of the 1993 *AASHTO Guide for Design of Pavement Structures*.[14]

Base Type—The specified base type is a required input for the transverse joint faulting model. The current approach allows the agency to select from the following granular (unbound) and stabilized base types:

- None.
- Asphalt-treated aggregate.
- Cement-treated subgrade.
- Cement-treated aggregate.
- Crushed stone, gravel, or slag (untreated).
- Gravel (uncrushed).
- Lean concrete.
- Lime-treated subgrade.

- Limerock.
- Pozzolanic-aggregate mixture.
- Sand.
- Soil aggregate mixture.
- Soil cement.

Dowel Diameter—If the pavement is selected to be constructed with dowel bars, the agency must identify the dowel diameter. The dowel diameter is a required input in the transverse joint faulting distress indicator model and is expressed in units of mm.

Base Permeability Factor—Information regarding the permeability of the base material is required for the transverse joint faulting model. This model includes a base permeability dummy factor as an input. This dummy variable is set equal to 0 when the base is not considered to be permeable and is set equal to 1 when the base is considered to be permeable.

PCC Modulus of Elasticity—The transverse joint faulting model requires a value for the PCC modulus of elasticity. The appropriate modulus of elasticity is expressed in units of MPa.

Climatic Variables

Mean Annual Daily Average Temperature—The transverse slab cracking distress indicator model requires knowledge about the mean annual daily average temperature. Although the distress model does not require this variable as a direct input, it is used by the agency, along with the average annual total precipitation, to determine the climatic region in which the project exists. Mean annual daily average temperature data are readily available from most climatic databases.

Average Annual Total Precipitation—The average annual total precipitation is used in combination with the mean annual daily average temperature to determine the climatic region in which the project exists. Annual precipitation data are readily available from most climatic characteristic databases.

Average Daytime Thermal Gradient—An estimate of the average daily thermal gradient through the slab is a required input of the transverse slab cracking distress indicator model. An estimated thermal gradient value may be determined as a function of slab thickness and determined climatic region. The United States is divided into four climatic regions based on the mean annual daily average temperature and average annual total precipitation. The appropriate climatic region is determined using table 3. After determining the appropriate climatic region, an appropriate average daytime thermal gradient through the slab may be determined as a function of climatic region and design thickness using table 4.

Table 3. Identification of climatic regions in the United States based on mean annual average daily temperature and average annual total precipitation.

Average Annual Total Precipitation	Mean Annual Average Daily Temperature	
	≤ 13 ºC	> 13 ºC
≤635 mm	Dry-Freeze Region	Dry-Nonfreeze Region
> 635 mm	Wet-Freeze Region	Wet-Nonfreeze Region

Table 4. Average daytime thermal gradient through the slab based on slab thickness and climatic region.[16]

Average Daytime Thermal Gradient, ºF/in			
Slab Thickness, mm	Wet-Nonfreeze Climatic Region	Dry/Wet-Freeze Climatic Regions	Dry-Nonfreeze Climatic Region
203	1.40	1.13	1.41
229	1.30	1.05	1.31
254	1.21	0.96	1.21
279	1.11	0.87	1.10
305	1.01	0.79	1.00

Note: The average daytime thermal gradients shown in this table are in units of ºF/in. The transverse slab cracking distress indicator model requires that the gradient be entered in these units.

1 ºC/cm = 4.572 ºF/in

Average Annual Number of Wet Days—The transverse joint faulting distress indicator model requires knowledge about the average annual number of wet days.Data for this variable are included in most available climatic databases.

Number of Days Above 90 ºF (32 ºC)—The average annual number of days in which the daily maximum temperature exceeds 90 ºF (32 ºC) is a climatic input required by the transverse joint faulting distress indicator model. Daily temperature data are readily available in most climatic databases.

Mean Freezing Index—The mean freezing index is a measure of the severity of frost for a region, expressed in terms of degree-days. The transverse joint faulting and spalling distress indicator models require the mean freezing index as a direct input. Although freezing index data are readily available in most climatic characteristic databases, values may be estimated for the continental United States using figure 13.

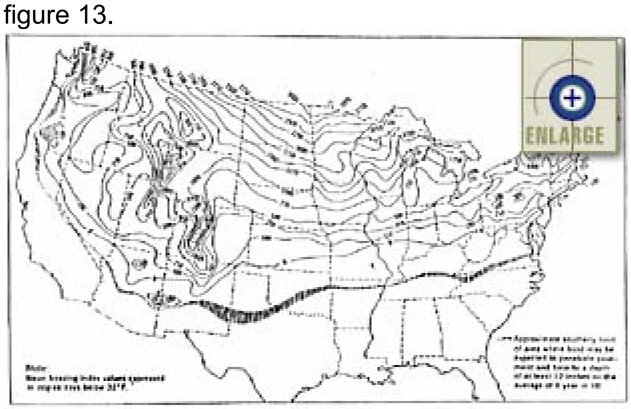

Figure 13. Distribution of mean freezing index values in the continental United States (Note: This chart is expressed in English units).[17]

Annual Freeze-Thaw Cycles (at 7.6 cm below the surface)—The current transverse joint spalling distress indicator requires knowledge about the number of annual freeze-thaw cycles (FTC's) in the pavement (specifically, at 7.6 cm below the pavement's surface). It is to be noted that the number of "in pavement" FTC data is much different than the typically reported number of "air" FTC's. However, it has been found that the number of "in pavement" FTC's may be reasonably estimated from the measured daily maximum temperatures. One "in pavement" FTC may be assumed to occur whenever the measured daily maximum temperature stays at or below freezing (0º C) for at least 2 consecutive days (48 hours).

For example, if consecutive daily maximum temperatures were to read 4, 0, –1, 6 (all in ºC), this would constitute one "in pavement" FTC since the temperature stayed at or below freezing on days 2 and 3 (0 and –1 ºC, respectively). If the consecutive daily maximum temperatures were to read 2, 0, –1, –4, –8, 4 (all in ºC), this would still constitute only one "in pavement " FTC since the temperature stayed at or below freezing on days 2 through 5 (0, –1, –4 and –8 ºC, respectively). However, a series of consecutive daily maximum temperatures reading 2, 0, 5, –2, 5 (all in ºC), results in zero "in pavement" FTC's since the maximum daily temperature stayed at or below freezing for only 1 day (0 on day 2).

Transverse Joint Sealant Type—The transverse joint spalling model is dependent on the type of transverse joint sealant material selected for use on the pavement. In the current approach, the agency may choose from the following three sealant types:

- None (transverse joints are not sealed).
- Liquid asphalt sealant.
- Preformed compression seal.

Presence of Salt—Research in a previous study showed that the development rate of transverse joint spalling was significantly increased when salt (calcium chloride) was used for deicing purposes.(1) The presence of salt was, subsequently, included as an input in the current transverse joint spalling distress indicator model. The agency must, therefore, identify if salt (calcium chloride) is regularly used on the pavement.

Traffic-Related Variables

Total Cumulative Design ESAL's—The transverse slab cracking and transverse joint faulting models are very much dependent on the number of ESAL's expected to be applied over the analysis life of the pavement.The current PRS approach requires knowledge about the total number of ESAL's expected to be applied in the pavement's first year of service or the total cumulative number of ESAL's to be applied over the pavement's design life. Either one of these values, in combination with information on the identified traffic growth pattern (discussed below), allows for the calculation of the ESAL's expected to be applied in every year of the pavement's analysis life. The current PRS approach also allows for the calculation of these yearly ESAL values based on known average daily traffic (ADT) information.

Traffic Growth Pattern—The agency must define the traffic growth *rate* and growth *type* for a given pavement project. The growth rate defines the annual increase in the applied yearly ESAL's (expressed as a percentage). The defined growth type determines how that percentage is applied and is selected by the agency as either *simple* or *compound*.

Simple Growth Type Method—If the agency selects a simple traffic growth type, the traffic is assumed to follow a linear relationship over time. Yearly ESAL values using the simple growth method may then be determined using equation 8.

$$ESAL_n = ESAL_I + (n – 1) * [ESAL_I * (Rate /100)] \quad (8)$$

where

$ESAL_n$ = Estimated applied ESAL's at year n.

$ESAL_I$ = Initial ESAL's applied during year one of the pavement's service life.

n = Year of pavement service life for which ESAL's are being calculated.

Rate = Chosen traffic growth rate, expressed as a percentage (e.g., if 7.5% is the chosen growth rate, "Rate" = 7.5).

Compound Growth Type Method—If the agency selects a compound traffic growth type, each year's traffic increase is assumed to be calculated as a constant percentage of the previous year's applied ESAL's (compounded). Yearly ESAL values using the compound growth method may then be determined using equation 9.

$ESAL_n = ESAL_I * [1 + (Rate / 100)]^{(n-1)}$ (9)

where

$ESAL_n$ = Estimated applied ESAL's at year n.

$ESAL_I$ = Initial ESAL's applied during year one of the pavement's service life.

n = Year of pavement service life for which ESAL's are being calculated.

Rate = Chosen traffic growth rate, expressed as a percentage (e.g., if 7.5% is the chosen growth rate, "Rate" = 7.5).

Selection Of AQC Target Values

Identifying the as-designed AQC target values (means and standard deviations) is one of the most important tasks facing the governing agency. These chosen target AQC's are used to define the agency's desired pavement quality. In the current PRS approach, this desired quality is defined as the quality for which the agency is willing to pay 100 percent of the contractor-submitted bid price. If the contractor constructs a pavement that is measured to have better AQC quality than that defined by the as-designed target AQC's, then (on average) the contractor will receive an incentive payment (greater than 100 percent of the bid price). Conversely, if the as-constructed AQC pavement quality is measured to be less than that defined by the as-designed AQC target values, then (on average) the contractor will receive a disincentive payment (less than 100 percent of the bid price).

Initially, it is recommended that the PRS quality levels (AQC target values) be set to represent the quality levels specified under the agency's current specifications. If appreciably lower quality levels are specified for the target values, the result will be decreased performance. If appreciably higher quality levels are specified, contract bid prices are likely to increase. While such higher quality levels (with attendant higher bid prices) might well result in lower overall LCC's, it would be difficult for an agency to justify increases in specified quality without the agency first having some experience with PRS (i.e., knowledge of the effect of specified quality on bid price and expected performance).

For an agency to select AQC target levels that represent the quality levels currently being specified, the agency must have a thorough understanding of its current specifications, and particularly its acceptance plans.The agency must first identify the AQC quality levels (means and standard deviations) for which its current acceptance plans are asking. Sometimes, these quality levels are not obvious. In fact, the currently specified quality levels may be different than what the agency actually desires (i.e., something other than what the agency intended to specify). To identify exactly what quality level the agency is currently specifying, the agency's expected payment (EP) curves should be utilized. The EP curve is a graphic representation of an acceptance plan that shows the relation between the actual quality of a lot and its expected pay.[4]That quality level (on an EP curve), for which the agency is willing to pay 100 percent of the contractor-submitted bid price, should be interpreted as the currently specified quality level for each AQC. If the agency has not developed EP curves, computer programs are currently available (such as R.M. Weed's OCPLOT) to assist the highway agency in their development.[18] If the agency acceptance plan cannot easily be converted to an EP curve, it is suggested that the agency develop a new acceptance plan so that the SHA can clearly determine the quality level currently being specified. The new acceptance plan should, of course, consider the typical quality levels being achieved by contractors in the State.

The agency-defined AQC target values are dependent on the chosen AQC acceptance sampling and testing plan. The recommended AQC means and standard deviations may change based on test type and number of replicate test results. For example, if concrete strength were being measured using 28-day cylinder compressive strengths, the AQC target values would be very different than those recommended for the case where 28-day beams were being tested for flexural strength. It is important to have knowledge of the proposed acceptance sampling and testing plan prior to construction so that the appropriate AQC target values can be defined.

As stated previously, initially, the target means should be selected to be equal to the AQC values for which the contractor would expect to receive 100 percent pay. Ideally, these values should correspond to the values used for design purposes. Target standard deviations should be determined by analyzing historical AQC data or by referring to published estimates of standard deviations (appendix D has a number of recommended values from the literature and field and laboratory testing conducted under this project). If the agency has a reasonable amount of good historical data representative of an AQC, it is strongly recommended that the agency analyze these data to determine appropriate AQC target means and standard deviations. The following steps can be used to determine target values based on historical AQC construction data:

1. Identify an AQC for which target values need to be determined (e.g., concrete strength).

2. Identify the sampling and testing type to be used for accepting the AQC in the field (e.g., cylinders from material taken from in front of the paver).

3. Identify historical projects that not only use the same sampling and testing types, but are also believed to have been constructed with AQC quality matching that desired by the agency.

4. Compute the sample mean and unbiased standard deviation of all of the representative sample test results (from each sample location) for each project. Sample means are computed using equation 5. Unbiased sample standard deviations are computed using equation 6. The target standard deviation includes both testing and process or materials variation.

5. Analyze the computed project AQC unbiased standard deviations and use them to identify appropriate AQC target standard deviations. (Note: The computed sample means should be checked against the assumed target means.) The computed data should give the agency knowledge about what type of quality has been provided on similar paving projects by the contractors. It is up to the agency to interpret these results and decide on appropriate AQC target means and standard deviations that define the true quality desired.

Although historical data should ideally be used to determine appropriate AQC target means and standard deviations, the initial recommendations for determining these values are summarized in table 5.

Table 5. Initial recommendations for determining AQC target means and standard deviations.

Acceptance Quality Characteristics	Initial Recommendations for Target Mean	Initial Recommendations for Target Standard Deviation
Concrete Strength	The target mean should be interpreted from a developed EP curve. This value should be equal to the current agency mean strength input used in the pavement design procedure (see note 1).	These values should be based on historical project testing data. If no historical data are readily available, the values may initially be based on published data, or on the laboratory and field data collected under this research study (see appendix D). Both the variations due to testing and to materials should be included. See note 4.
Slab Thickness	The target mean should be interpreted from a developed EP curve. This value should be equal to the current agency design thickness determined from the pavement design procedure (see note 2).	
Entrained Air Content	The target mean should be set equal to the current agency-designed entrained air content. This AQC is only significant in areas with significant freezing temperatures.	
Initial Smoothness	The target mean should be interpreted from a developed EP curve. See note 3.	
Percent Consolidation Around Dowels	The target mean should be determined from testing conducted by the agency to determine typical levels achieved, or from published data (see).	

Notes:

1. The *AASHTO Guide for Design of Pavement Structures* requires a flexural strength, third-point loading, 28 days curing (M_r). If another testing type is selected for the AQC (such as 28-day cylinder compressive strength [f'_c]), then a correlation using the project materials must be established and utilized. For example, if the design input to AASHTO is 4.48 MPa flexural

strength, and the correlation is $f'c = (M_r/0.83035)^2$, then the corresponding target mean would be based on a design compressive strength of 29.13 MPa. If strength at any other time than 28 days is desired for the AQC, then correlations with maturity must be established for the project materials.

2. Most design procedures, such as the AASHTO design procedure, include a formal engineering reliability design provision. Others include various safety factors. Either of these approaches result in a slab design thickness that already includes a large safety factor or high design reliability. Thus, the design slab thickness is the mean slab thickness that is desired in the field, not an arbitrarily increased value.

3. The value specified here for the profile index (PI) should be related to the level of initial PSR specified for the AASHTO design procedure. The lower the PI specified, the higher the design initial PSR.

4. The standard deviation is highly dependent upon the number of replicate tests involved. For example, if the mean of two concrete cylinders (both from one batch of concrete) represents one test for a site, the standard deviation for this case will be less than for the case when only one cylinder is used to represent the site. Typical standard deviation values obtained from field projects are discussed in appendix E.

Definition Of Lots And Sublots

It is important for the agency to clearly define lots and sublots when using the prototype PRS. The following definitions are recommended for use.

Definition of a Lot

A lot is defined as a discrete quantity of as-constructed pavement to which an acceptance procedure (and corresponding pay adjustment) is applied. All pavement placed within a lot is assumed to have similar characteristics (e.g., traffic loadings, design properties, mix design, support, and representative as-designed AQC distributions). It is recommended that the lot length always be set equal to *one day's production* unless a significant within-day change occurs in one of the pavement characteristics (e.g., change in aggregate source or stoppage of the paving operations for a significant amount of time). If such a change does occur, it is recommended that a new lot be started at that point in the paving. The lot width is defined as the total width of pavement (one or more traffic lanes) being placed at one time in the mainline paving process. This paving width is also defined as a *construction pass* since it describes the total width of pavement being placed in one pass of the paving train. (Note: The width of a construction pass can change within a project depending on the number of lanes being paved at one time.) Shoulders are not included in the width of a lot; however, when applicable, the entire width of a widened traffic lane is to be considered as part of the mainline paving.

Definition of a Sublot

A sublot is simply defined as a portion of a lot. Each lot is divided into sublots of approximately equal surface area, based on the total linear amount of paving expected in the lot. More specifically, within the prototype PRS, sublots represent the smallest unit of pavement for which pavement performance is predicted (from distress indicators). Therefore, sublot lengths are defined so that all AQC's can be independently sampled from each defined sublot.

Selecting an Appropriate Target Sublot Length

Under the PRS approach, the sublot size is defined in terms of the linear length of longitudinal paving. The minimum sublot length should not be less than 0.16 km; this limit is required to accommodate the measurement of initial smoothness with a California profilograph. Although a maximum sublot length need not be defined, it is recommended that the agency try to select a sublot length that will result in a minimum of three sublots per lot. An appropriate maximum sublot length could then be defined as one-third of the total linear length of longitudinal paving expected for a typical pavement lot (one day of paving). An appropriate sublot length range for a given project can, therefore, be represented by the relationship presented as equation 10.

$$0.16 \text{ km} \leq PAVING_{SUBLOT} \leq PAVING_{SUBLOT\text{-}MAX} \qquad 10$$

where

$PAVING_{SUBLOT}$ = Chosen target sublot length for the project (expressed in km).

$PAVING_{SUBLOT\text{-}MAX}$ = Recommended maximum sublot length (based on the recommended minimum of three sublots per lot). This value is calculated as $PAVING_{LOT}/3$ and expressed in km.

$PAVING_{LOT}$ = Estimated total linear length of longitudinal paving expected for a typical pavement lot (expressed in km).

If the maximum sublot length ($PAVING_{SUBLOT\text{-}MAX}$) is calculated to be less than the chosen minimum sublot length (0.16 km), it is recommended that the chosen sublot length be set to the minimum of 0.16 km. Otherwise, it is recommended that the chosen sublot length be subjectively selected from the computed range (the range shown in equation 10) based on knowledge about the chosen acceptance sampling and testing plan. The agency must determine how many AQC samples and tests are to be taken from each sublot in the field. It is believed that the costs of conducting the required acceptance sampling and testing will greatly influence the selected sublot length. A discussion of the selection of an appropriate acceptance sampling and testing plan is contained in this chapter in the section titled *Selecting an AQC Acceptance Sampling and Testing Plan.*

Determining the Target Number of Sublots Per Lot

The target number of sublots per lot is estimated based on the agency-chosen target sublot length ($PAVING_{SUBLOT}$) and the estimated total linear length of longitudinal paving for a typical pavement lot ($PAVING_{LOT}$). This relationship is shown in equation 11.

$$NUMSUBS_{TARGET} = PAVING_{LOT} / PAVING_{SUBLOT} \qquad (11)$$

where

$NUMSUBS_{TARGET}$ = Estimated target number of sublots per lot (based on the chosen target sublot length).

$PAVING_{LOT}$ = Estimated total linear length of longitudinal paving expected for a typical pavement lot (expressed in km).

$PAVING_{SUBLOT}$ = Chosen target sublot length (expressed in km).

As an example, if it were estimated that a contractor would pave 1.2 km per day ($PAVING_{LOT}$ = 1.2 km) with a target sublot length of 0.32 km ($PAVING_{SUBLOT}$ = 0.32 km), the target number of sublots per lot ($NUMSUBS_{TARGET}$) would be calculated as the following (using equation 11).

$NUMSUBS_{TARGET} = PAVING_{LOT} / PAVING_{SUBLOT}$

$= 1.2 \text{ km} / 0.32 \text{ km}$

$= 3.75$ sublots per lot

For this example, the typical number of sublots per lot would then be three or four. Therefore, the agency should develop preconstruction output for the cases of three and four sublots (as a minimum). More information on choosing appropriate ranges of numbers of sublots per lot is provided in the section titled *Selecting Simulation Parameters*.

Determining Actual Sublot Lengths in the Field

Since the amount of paving varies from lot to lot, a method for dividing the as-constructed pavement lot into sublots is required. The following defines this procedure.

1. The first sublot of a lot is typically defined as that amount of pavement that starts at the lot's identified starting station and has a linear length of longitudinal paving equal to the chosen target sublot length ($PAVING_{SUBLOT}$). If a significant problem occurs in the field (requiring the start of a new lot) while the length of the first sublot is less than the chosen target sublot length, the sublot will be assumed to represent the entire lot and will be accepted by another method approved by both the agency and contractor.

2. Additional sublots (each with a length equal to the chosen target sublot length) are defined consecutively until paving operations are complete for the given lot. Using this approach, all sublots will be equal to the chosen target sublot length except for the last sublot in the lot. The length of the final sublot in a lot is determined using the following rules.
   a. If the length of the last sublot in a lot is less than the chosen minimum sublot length (recommended to be 0.16 km), the material is assumed to be included as part of the previous sublot. It is recommended that at least one additional sample location (for each AQC) be selected to represent the additional material. (Note: The tests for initial smoothness will be extended to include the new material.)

   b. If the length of the last sublot in a lot is greater than the chosen minimum sublot length (recommended to be 0.16 km), but less than the chosen sublot length, then the actual measured final sublot length will be used.

Overall, it is recommended that the agency decide on a target sublot length that is practical for the amount and type of sampling and testing being conducted. This chosen target sublot length should then be used to lay out all the sublots prior to the paving of each lot. This can be done on a day-by-day (lot-by-lot) basis. Therefore, only the final sublot of each lot should differ from the chosen target sublot length.

Selecting An AQC Acceptance Sampling And Testing Plan

Acceptance of the as-constructed pavement is based on the field sampling of all of the included AQC's chosen by the agency. The PRS approach ideally focuses on using in situ samples for acceptance, since these samples provide a true indication of the properties of the as-constructed pavement. Better estimates of the in situ quality will ideally lead to better estimates of future pavement performance. Although the current movement is toward in situ sampling, any agency-approved sampling and testing methods may be utilized as long as they are performed in accordance with one of the following standard specifications:

- American Association of State Highway and Transportation Officials, *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II Tests*.(19)

- American Society for Testing and Materials (ASTM), *Annual Book of ASTM Standards, Section 4, Construction, Road and Paving Materials*.(20)

An agency should, therefore, be able to implement the PRS prototype approach without making major changes to its current sampling methods.

There is also a current movement toward obtaining early age AQC test results to provide the contractor with quick feedback regarding the measured as-constructed pavement quality. Any test method chosen for use in a PRS should ideally be timely, economical, nondestructive, reliable, and reproducible. Although the current PRS approach does not require the use of such early age testing methods, they should be considered where appropriate.

Available AQC Sampling and Testing Procedures

The following sections discuss the currently recommended AQC sampling and testing methods and their use within the PRS approach. Until the agency gains adequate experience with the current PRS approach and its procedures, it is strongly recommended that the agency continue to use AQC sampling and testing procedures with which it feels completely comfortable.

Concrete Strength

Three of the distress indicator models (transverse joint faulting, transverse fatigue cracking, and transverse joint spalling) included in the current PRS approach require concrete strength as an input. Specifically, these models require a 28-day (equivalent laboratory maturity) flexural strength using a third-point loading. Therefore, the agency must choose a sampling and testing procedure that results in a direct measurement or indirect estimation of this required 28-day flexural strength.

Traditionally, the 28-day flexural strength has been measured directly by conducting flexural strength testing on beams at 28 days of equivalent laboratory maturity. However, most agencies have abandoned the practice of using beams for acceptance and have concentrated on easier, more practical methods of estimating strength (such as 28-day cylinder compressive strength). In addition, there has been a movement toward accepting concrete strength based on early age (3-, 7-, or 14-day) strength tests. The selection of a concrete strength sampling and testing plan requires that the agency decide on a sampling type, the timing of sampling, a test type, and the timing of testing. Some of the more typical concrete strength sampling and testing choices available to an agency are described in more detail below.

Sampling Specimen Types for Concrete Strength

It is recommended that the sample concrete strength be measured using beams, cylinders, or cores. If beams or cylinders are selected, these samples are cast at the time of construction. If cores are selected, they are to be extracted from the pavement at an agency-chosen time between 3 and 28 days of equivalent laboratory maturity. The details of each sampling type are presented in the following sections.

Beams. Beam specimens (with agency-specified dimensions) are to be molded, handled, and cured in accordance with AASHTO T-23, *Making and Curing Concrete Test Specimens in the Field*.(19) Beam specimens for each sublot are made with plastic concrete taken from in front of or behind the paver at predetermined random longitudinal sampling locations. Random longitudinal sampling locations are identified in accordance with the guidelines set forth in the section titled *Selecting a Random Longitudinal Sampling Location*. The number of beam specimens per sampling location (replicate specimens) and the number of sampling locations per sublot are defined by the agency in accordance with the guidelines set forth in the section titled *Recommended Number of AQC Samples Per Sublot*.

Cylinders. Cylinder specimens are molded, handled, and cured in accordance with AASHTO T-23, *Making and Curing Concrete Test Specimens in the Field*.(19) All cylinder specimens are cast in molds with a nominal length-to-diameter ratio of 2. An appropriate cylinder specimen diameter is determined based on the following:

- A minimum 102-mm cylinder diameter is used when the maximum aggregate size is 32 mm or less.
- A minimum 152-mm cylinder diameter is used when the maximum aggregate size is greater than 32 mm.

Cylinder specimens for each sublot are made with plastic concrete taken from in front of or behind the paver at predetermined random longitudinal sampling locations. Random longitudinal sampling locations are determined in accordance with the guidelines set forth in the section titled *Selecting a Random Longitudinal Sampling Location*. The number of cylinder specimens per sampling location (replicate specimens) and the number of sampling locations per sublot are defined by the agency in accordance with the guidelines set forth in the section titled *Recommended Number of AQC Samples Per Sublot*.

Cores. Core specimens are extracted from the hardened pavement slab between 48 and 72 hours after placement, in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.(19) Core specimens are extracted from the hardened concrete slab at predetermined random sampling locations. Random sampling core locations are determined in accordance with the guidelines set forth in the section titled *Selecting a Random Core Location*. The number of core specimens per sublot is defined by the agency in accordance with the guidelines set forth in the section titled *Recommended Number of AQC Samples Per Sublot*.

An appropriate core specimen diameter is determined based on the following:

- A minimum 102-mm diameter is used when the maximum aggregate size is 32 mm or less.
- A minimum 152-mm diameter is used when the maximum aggregate size is greater than 32 mm.

Prior to testing, all core specimens are trimmed to a nominal length-to-diameter ratio of 2.; A correction factor is applied (in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*) to cores having a length-to-diameter ratio of less than 1.94, whereas cores having a length-to-diameter ratio between 1.94 and 2.10 require no such correction.(19) Cores with a length-to-diameter ratio exceeding 2.10 are reduced in length to fall within the ratio limits of 1.94 to 2.10.

Timing of Concrete Strength Testing

The agency must define the timing of the concrete strength specimen testing to be used in estimating the 28-day (equivalent 28-day laboratory maturity) flexural strength (third-point loading) of the as-constructed pavement. Each specimen (molded beam, molded cylinder, or extracted core) is tested independently and translated (if necessary) into an M_R at an equivalent 28-day laboratory maturity.

The timing of concrete strength specimen testing is defined by the agency and expressed in terms of an equivalent laboratory maturity. The agency-chosen timing of concrete strength specimen testing must meet the following requirements:

- Testing must not be conducted until the specimen achieves a maturity of at least 72 hours (3 days) of the equivalent laboratory curing condition maturity.
- Testing must be conducted at or before the point when the specimen achieves a maturity equal to 672 hours (28 days) of the equivalent laboratory curing condition maturity.

Testing-Related Procedures (Conducted Prior to Specimen Testing)

The agency must perform the following testing-related laboratory and field procedures (as required) in preparation for concrete strength specimen testing.

Development of Mix-Specific Maturity Curves

Prior to the placement of any as-constructed pavement, the agency must develop required mix-specific maturity curves in the laboratory. The representative maturity curves (expressed as flexural, compressive, or split-tensile strength versus maturity) are determined using the Arrhenius maturity method and in accordance with ASTM C-1074, *Standard Practice for Estimating Concrete Strength by the Maturity Method*.[20] The required developed maturity curves (and corresponding equations) are included as *Series A* attachments to the specification (see appendix A in this volume). This laboratory maturity calibration is only required if sample testing is conducted when the equivalent laboratory maturity is less than 28 days.

These mix-specific strength to maturity relationships are determined prior to construction by the testing laboratory contracted to develop the concrete mixture design. The following procedure is used by the laboratory personnel to develop these required relationships.

11. Obtain adequate amounts of the coarse and fine aggregates, cement, fly ash, and admixtures that will be used for the production of the as-constructed concrete pavement.

12. Cast a sufficient number of concrete beam and cylinder specimens in the laboratory in accordance with AASHTO T-126, *Making and Curing Concrete Test Specimens in the Laboratory*.[19] Note: It is recommended that a minimum of 18 specimens be cast for each strength type being investigated (i.e., 18 beams for flexural strength testing, and 18 cylinders each for both compressive and split tensile strength testing).

13. Until the time of specimen testing, store the cast specimens under standard laboratory curing conditions (in accordance with AASHTO T-126, *Making and Curing Concrete Test Specimens in the Laboratory*).[19] The maturity of the specimens should also be measured over this curing period.

14. Test the respective specimens at incremental ages of strength development in accordance with the following AASHTO standards:

- Compressive strength of cylinders—AASHTO T-22, *Compressive Strength of Cylindrical Concrete Specimens*.(19)

- Split-tensile strength of cylinders—AASHTO T-198, *Splitting Tensile Strength of Cylindrical Concrete Specimens*.(19)

- Flexural strength (third-point loading) of beams—AASHTO T-97, *Flexural Strength of Concrete (Using Simple Beam With Third-Point Loading)*.(19)

The number of testing ages should be sufficient to enable the user to confidently predict strength from maturity. As a minimum, it is recommended that three specimens be tested (for each strength type) at equivalent laboratory maturities of 1, 3, 5, 7, 14, and 28 days.

15. Plot the measured strength values (for each strength type) versus the measured maturity values.

16. Determine appropriate best-fit regression equations representing each strength versus maturity relationship. The required developed maturity curves (and corresponding equations) are included as *Series A* attachments to the PRS (see appendix A in this volume).

Development of Mix-Specific Inter-Strength Relationships

Prior to the placement of any as-constructed pavement, the agency must also develop required mix-specific inter-strength relationships (i.e., compressive-to-flexural-strength, and/or split-tensile-to-flexural strength relationships) in the laboratory. These specific inter-strength relationships are determined by comparing the different 28-day maturity strength values measured for the development of the appropriate maturity curves. The required inter-strength relationships (curves and equations) are included as *Series B* attachments to the PRS (see appendix A in this volume).

It is recommended that the compressive-to-flexural-strength equation be assumed to have the following form:

$$M_{R(28\text{-}day)} = A * (f'_{C(28\text{-}day)}{}^{0.5}) \quad (12)$$

where

$M_{R(28\text{-}day)}$ = Estimated flexural strength (third-point loading) at a 28-day equivalent laboratory maturity, MPa.

$f'_{C(28\text{-}day)}$ = Estimated compressive strength at a 28-day equivalent laboratory maturity, MPa.

A = Mix-specific coefficient determined through calibration using the means of the measured compressive and flexural strength data at a 28-day equivalent laboratory maturity.

The mix-specific coefficient (A) is determined using the computed compressive and flexural strength 28-day maturity sample means (used in the development of the maturity curves). Equation 12 is solved for A using these computed sample means. Although the equation form shown in equation 12 is recommended, any agency-accepted equation relating compressive to flexural strength may be used.

It is recommended that the split-tensile-to-flexural-strength equation be assumed to have the following form:

$M_{R(28\text{-}day)} = A * (ST_{(28\text{-}day)}/B)^{0.75}$ (13)

where

$M_{R(28\text{-}day)}$ = Estimated flexural strength (third-point loading) at a 28-day equivalent laboratory maturity, MPa.

$ST_{(28\text{-}day)}$ = Estimated split-tensile strength at a 28-day equivalent laboratory maturity, MPa.

A = Mix-specific coefficient determined through calibration using the means of the measured compressive and flexural strength data (at a 28-day equivalent laboratory maturity) in equation 12.

B = Mix-specific coefficient determined through calibration using the means of the measured split-tensile and flexural strength data (at a 28-day equivalent laboratory maturity).

The mix-specific coefficient (B) is determined using the computed split-tensile and flexural strength 28-day maturity sample means (used in the development of the maturity curves). Equation 13 is solved for B, by knowing A and using these computed sample means.

Specific Concrete Strength Testing Procedures

Representative flexural strength (third-point loading) values at a 28-day equivalent laboratory maturity are determined for each specimen using one of the following three testing procedures.

17. *Flexural Testing of Beams*. If the concrete strength of the as-constructed pavement is to be evaluated using beam specimens tested in flexural strength (third-point loading), then the following procedure is applied.

    - Each beam specimen is tested (at an agency-defined equivalent laboratory maturity) for flexural strength (third-point loading) in accordance with AASHTO T-97, *Flexural Strength of Concrete (Using Simple Beam With Third-Point Loading)*.[19]

    - Each testing result is translated to a 28-day flexural strength (28-day equivalent laboratory maturity) using a developed mix-specific flexural strength (third-point loading) versus maturity curve and equation, and in accordance with the guidelines set forth in the section titled *Using Maturity Curves and Inter-Strength Relationships to Estimate the Equivalent 28-day Flexural Strength*. (Note: The developed maturity curve and corresponding equation are included in the *Series A* attachments to the PRS [see appendix A in this volume].) No maturity translations need to be applied if beam specimens are tested directly at a 28-day equivalent laboratory maturity.

18. *Compression Testing of Cylinders or Cores*. If the concrete strength of the as-constructed pavement is to be estimated using cylinder or core specimens tested in compression strength, then the following procedure applies.

    - Each core specimen is tested (at an agency-defined equivalent laboratory maturity) for compressive strength in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.*[19] Each cylinder specimen is tested (at an agency-defined equivalent laboratory maturity) for compressive strength in accordance with AASHTO T-22, *Compressive Strength of Cylindrical Concrete Specimens.*[19]

- Each testing result is translated into a 28-day compressive strength (28-day equivalent laboratory maturity) using a developed mix-specific compressive strength versus maturity curve and equation, and in accordance with the guidelines set forth in the section titled *Using Maturity Curves and Inter-Strength Relationships to Estimate the Equivalent 28-day Flexural Strength*. (Note: The developed maturity curve and corresponding equation are included in the *Series A* attachments to the PRS [see appendix A in this volume].) No maturity translations need to be applied if cylinder or core specimens are tested directly at a 28-day equivalent laboratory maturity.

- Each estimated core or cylinder compressive strength (at a 28-day equivalent laboratory maturity) is translated into a representative 28-day flexural strength using a developed mix-specific compressive strength to flexural strength inter-strength relationship (curve and corresponding equation). (Note: The developed inter-strength relationship is included as a *Series B* attachment to the PRS [see appendix A in this volume].)

19. *Split-Tensile Testing of Cylinders or Cores*. If the concrete strength of the as-constructed pavement is to be estimated using cylinder or core specimens tested in split-tensile strength, then the following procedures apply.

    - Each core specimen is tested (at an agency-defined equivalent laboratory maturity) for split-tensile strength in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.(19) Each cylinder specimen is tested (at an agency-defined equivalent laboratory maturity) for split-tensile strength in accordance with AASHTO T-198, *Splitting Tensile Strength of Cylindrical Concrete Specimens*.(19)

    - Each testing result is translated to a 28-day split-tensile strength (28-day equivalent laboratory maturity) using a developed mix-specific split-tensile strength versus maturity curve and equation, and in accordance with the guidelines set forth in the section titled *Using Maturity Curves and Inter-Strength Relationships to Estimate the Equivalent 28-day Flexural Strength*.(Note: The developed maturity curve and corresponding equation are included in the *Series A* attachments to the PRS [see appendix A in this volume].) No maturity translations need to be applied if cylinder or core specimens are tested directly at a 28-day equivalent laboratory maturity.

    - Each estimated core or cylinder split-tensile strength result (at a 28-day equivalent laboratory maturity) is translated into a representative 28-day flexural strength using a developed mix-specific split-tensile strength to flexural strength inter-strength relationship (curve and corresponding equation). (Note: The developed inter-strength relationship is included as a *Series B* attachment to the PRS [see appendix A in this volume].)

Measuring Maturity in the As-Constructed Pavement

If the agency selects core specimens as the sampling type, the maturity of the as-constructed pavement is monitored for each sublot. Temperatures are measured at one central location per sublot using a thermocouple placed at mid-depth of the pavement slab (the thermocouple is embedded into the pavement using an agency-approved method). The thermocouple is connected to an agency-approved maturity meter. The maturity meter should begin recording pavement temperatures at the time when the thermocouple becomes completely covered with concrete. Temperatures are measured for a given sublot until all of the cores representing the sublot are extracted from the as-constructed pavement.

Using Maturity Curves and Inter-Strength Relationships to Estimate the Equivalent 28-day Flexural Strength

As stated earlier, the strength measured for each sampled concrete strength specimen must be translated into an equivalent 28-day (28 days of equivalent laboratory maturity) flexural strength. The procedures for estimating this 28-day flexural strength differ depending on the agency-chosen sample type, test type, and timing of testing. The general procedure used to determine an appropriate equivalent 28-day flexural strength value (for a given sample specimen) involves using the following procedures. All testing is conducted using the agency-chosen testing method.

20. Conduct the as-constructed strength testing at an agency-chosen maturity (MAT_A) to obtain a *measured* strength value ($STR_{MEASURED\text{-}MAT(A)}$).

21. Determine the *expected* strength value at the agency-chosen MAT_A using the appropriate maturity curve. Note that the appropriate maturity curve is that developed for the agency-chosen testing method (i.e., if the agency chooses to conduct compressive testing of cylinder sample specimens, then the compressive strength versus maturity curve is used).

22. Compute the difference ($DIFF_{MAT(A)}$) between the measured strength testing value and the expected strength value (both determined at the agency-chosen MAT_A) using equation 14.

$$DIFF_{MAT(A)} = [STR_{MEASURED\text{-}MAT(A)} - STR_{EXPECTED\text{-}MAT(A)}] \quad (14)$$

where

$DIFF_{MAT(A)}$ = Computed difference between the measured strength value and the expected strength value. Strength is measured in units of MPa.

$STR_{MEASURED\text{-}MAT(A)}$ = Measured strength value at the agency-selected equivalent laboratory maturity. Strength is measured in units of MPa.

$STR_{EXPECTED\text{-}MAT(A)}$ = Expected strength value (from the appropriate maturity curve) at the agency-selected equivalent laboratory maturity. Strength is measured in units of MPa.

23. Determine the expected strength at an equivalent laboratory maturity of 28 days ($MAT_{28\ days}$) from the appropriate maturity curve.

24. Compute the estimated representative strength at an equivalent laboratory maturity of 28 days ($MAT_{28\ days}$) by adding the computed strength difference ($DIFF_{MAT(A)}$) to the expected 28-day *expected* strength. This relationship is shown in equation 15.

$$STR_{ESTIMATED\text{-}MAT(28\ days)} = [STR_{EXPECTED\text{-}MAT(28\ days)} + DIFF_{MAT(A)}] \quad (15)$$

where

$STR_{ESTIMATED\text{-}MAT(28\ days)}$ = Estimated equivalent 28-day strength value (strength type is the same as the agency-chosen testing type) at an equivalent laboratory maturity of 28 days. Strength is measured in units of MPa.

$STR_{EXPECTED-MAT(28\ days)}$ = Expected strength value (from the appropriate maturity curve) at an equivalent laboratory maturity of 28 days. Strength is measured in units of MPa.

$DIFF_{MAT(A)}$ = Computed difference between the measured strength value and the expected strength value. Strength is measured in units of MPa.

Figure 14 shows an example of translating from a measured strength value to an equivalent 28-day maturity value of the same strength type (i.e., the procedure outlined in these first five steps).

25. Translate the estimated 28-day strength value for the agency-chosen testing type ($STR_{ESTIMATED(28\ days)}$) into an equivalent 28-day flexural strength (third-point loading) value using an appropriately developed inter-strength relationship equation.

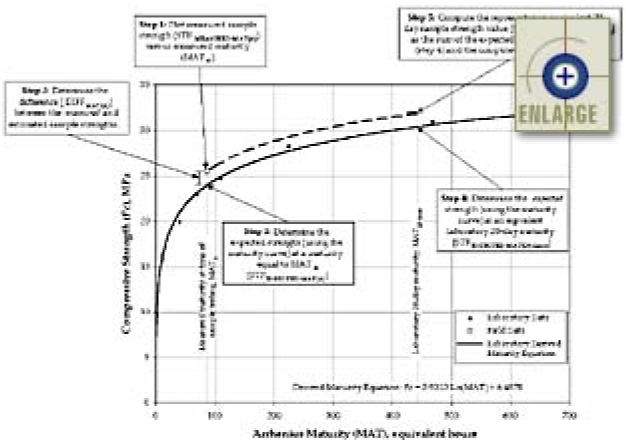

Figure 14. Example of using a developed maturity curve to translate from a measured strength value to a representative 28-day expected strength value.

Finally, the mean of all of the estimated equivalent 28-day flexural strength values (representing each sample specimen from one sample location) is computed and used to represent that sample location. Some of the steps of the procedure may not be required, depending on the agency-chosen sampling and testing procedures.

Slab Thickness

Two of the distress indicator models (transverse joint faulting and transverse fatigue cracking) included in the current PRS approach require slab thickness as an input. The thickness of the as-constructed pavement is determined by measurements taken on cores extracted from each sublot making up an as-constructed pavement lot. Core specimens are extracted from the hardened pavement slab between 48 and 72 hours after placement, in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.(19) All cores used for the acceptance of slab thickness must have a minimum diameter of 102 mm. The representative thickness of each core is determined in accordance with AASHTO T-148, *Measuring Length of Drilled Concrete Cores.*(19)

Slab thickness is measured on all cores extracted for the evaluation of concrete strength; these measured values are used in lieu of extracting additional slab thickness cores. When required, randomly selected slab thickness core locations (independent of any cores taken for the evaluation of concrete strength) are determined in accordance with the section titled *Selecting a Random Core Location*. The number of slab thickness core specimens per sublot is defined by the agency in accordance with the guidelines set forth in the section titled *Recommended Number of AQC Samples Per Sublot*.

Entrained Air Content

The measured entrained air content of the pavement slab is included as an optional input in the transverse joint spalling model included in the current PRS approach. Although it is officially considered optional, it is recommended that the agency choose to measure entrained air content if transverse joint spalling is to be included in the definition of pavement performance. If entrained air content is selected for measurement in the field, the following sampling and testing procedures apply.

The entrained air content of the as-constructed pavement is determined using one of the following agency-approved sampling and testing methods:

26. *Pressure Meter Tests of Plastic Concrete*. Plastic concrete is taken from in front of or behind the paver at predetermined random longitudinal sampling locations. Random longitudinal sampling locations are identified in accordance with the guidelines set forth in the section titled *Selecting a Random Longitudinal Sampling Location*. If beams or cylinder specimens are required for the estimation of concrete strength, entrained air content pressure meter tests may be conducted at the same longitudinal locations used for the strength investigation. If behind-the-paver samples are chosen, material is removed from the slab using an agency-approved method.

    If the agency believes there is a significant difference between the air content of the material in front of and behind the paver, it is recommended that the samples be taken behind the paver. Instead of taking all samples behind the paver, the agency may develop a relationship between entrained air content in front of and behind the paver. Samples may then be taken in front of the paver, and adjusted using the developed relationship. Samples taken behind the paver should ideally be taken within a vibrator path.

    The plastic concrete removed from in front of or behind the paver is tested with an agency-approved air pressure meter in accordance with AASHTO T152, *Air Content of Freshly Mixed Concrete by the Pressure Method*.[19] The number of pressure meter tests per sampling location (replicate specimens) and the number of sampling locations per sublot are defined by the agency in accordance with the guidelines set forth in the section titled *Recommended Number of AQC Samples Per Sublot*.

    Representative entrained air content values (expressed as a percentage) for each *sample per sublot* are computed as the average of the entrained air content results determined for the replicate specimens at each random sampling location.

27. *Linear Traverse Tests of Hardened Concrete Cores*. Core specimens are extracted from the hardened concrete slab at predetermined random sampling locations. Random sampling core locations are determined in accordance with the guidelines set forth in the section titled *Selecting a Random Core Location*. Core specimens are extracted from the hardened pavement slab, between 48 and 72 hours after placement, in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.[19] All cores used for the acceptance of entrained air content must have a minimum diameter of 152 mm. The number of core specimens per sublot are defined by the agency in accordance with the guidelines set forth in the section titled *Recommended Number of AQC Samples Per Sublot*.

    Linear traverse testing is performed on each extracted hardened concrete core specimen in accordance with ASTM C-457, *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*.[20] Testing may occur at any time after the extraction of the core specimen. The measured entrained air content (expressed as a percentage) for each extracted core is used as the representative entrained air content value for that sampling location.

Initial Smoothness

The two smoothness-related distress indicator models (PSR and IRI) included in the current PRS approach require initial smoothness as an input. The PSR distress indicator model requires an initial PSR, whereas the IRI model requires an initial IRI. The selection of an initial smoothness sampling and testing plan requires that the agency answer the following three questions:

28. *What type of initial smoothness measuring device is to be used?* The agency may measure initial smoothness with a California or similar profilograph (used to compute a profile index [PI]) or an inertial profiler (used to compute IRI).

29. *What type of initial smoothness indicator is to be computed?* If the agency chooses to measure initial smoothness using a California profilograph, the agency may reduce the profile traces using a 0.0-mm or a 5.1-mm blanking band. The 0.0-mm blanking band is strongly recommended over the 5.1-mm blanking band. Pavements accepted using a 5.1-mm blanking band may still be quite rough to the driver, and this is not adequate. These reductions result in the computing of corresponding profile indices ($PI_{0.0\text{-mm}}$ and $PI_{5.1\text{-mm}}$, respectively). If the agency chooses to measure initial smoothness using an inertial profiler, the initial smoothness indicator is expressed in terms of IRI.

30. *Is smoothness over time to be expressed in terms of PSR or IRI?* Finally, the agency has the option of predicting smoothness over time in terms of PSR or IRI. A correlation between PI and PSR or IRI is required.

Figure 15 shows the relationships between these three agency decisions. The following sections provide details regarding the sampling and testing of initial smoothness.

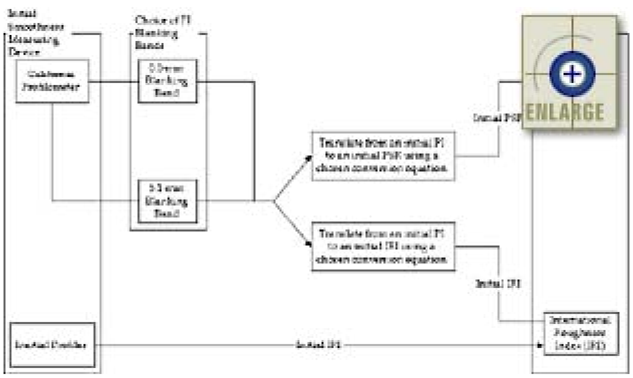

Figure 15. Flow chart showing the available methods for handling smoothness under the PRS approach.

Sampling of Initial Smoothness

The initial smoothness of the pavement is quantified in terms of a PI (using a California profilograph) or IRI (using an agency-approved inertial profiler). If a California profilograph is used, the measurements are made in accordance with the following procedures:

- The resulting profilogram is to be recorded on a scale of 254 mm or full-scale, vertically.

- Motive power may be manual or by propulsion unit attached to the assembly.

- The profilograph is moved longitudinally along the pavement at a speed no greater than 4.8 km/h to minimize bounce.
- The results of the profilograph test will be evaluated as outlined in the California Department of Transportation (Caltrans) specification CA-526.
- All profile indices are to be determined using a 0.0- or 5.1-mm blanking band.

If a profiling device is used to measure initial IRI, measurement is made in accordance with provided agency-approved procedures.

Regardless of the chosen sampling method, a minimum of two pavement profiles (one in each wheelpath) must be measured for each lane within each defined sublot. The total number of required pavement profiles per sublot is defined by the agency in accordance with the guidelines set forth in the section titled *Recommended Number of AQC Samples Per Sublot*. The location of a *wheelpath* is 0.92 m from a longitudinal joint or longitudinal pavement edge and parallel to the centerline of the mainline paving. For widened traffic lanes, the outer wheelpath is 0.92 m from the pavement-edge paint stripe, rather than the outer pavement edge. Each profile should terminate 4.5 m from each bridge approach pavement or existing pavement that is joined by the new pavement. The PI or IRI determined for each profile is converted to a standard unit of mm/km.

During the initial paving operations, or after a long shutdown period, the pavement surface must be tested with the appropriate profile measuring device. Membrane curing damaged during the testing operation must be repaired by the contractor and at the contractor's expense. If the initial pavement smoothness, paving methods, and paving equipment are acceptable, paving operations may proceed. After initial testing, profiles of each day's paving will be run prior to continuing paving operations.

The agency will apply the following appropriate limits based on the chosen initial smoothness indicator (PI or IRI):

> *If an average PI / IRI of _____ mm/km [limit to be inserted by the agency] is exceeded in any daily paving operation, the paving operation will be suspended and not resume until corrective action is taken.*

Within each sublot, all areas represented by high points having deviations in excess of _____ mm (limit to be inserted by the agency—10 mm is recommended) in 7.6 m or less must be corrected at the contractor's expense. Corrections must be made using an approved profiling device or by removing and replacing the pavement, as directed by the engineer. Bush hammers or other impact devices must not be used. Where corrections are made, the surface texture is re-established to provide a uniform texture equal to the surrounding uncorrected pavement by the contractor and at the contractor's expense.

Choosing an Appropriate Blanking Band for Computing Profile Index

When measuring initial smoothness using a California profilograph, the resulting profilograms may be reduced using a 0.0- or 5.1-mm blanking band. Currently, most SHA's measure initial smoothness in terms of $PI_{5.1\text{-mm}}$; however, more agencies are starting to move toward using $PI_{0.0\text{-mm}}$. As mentioned previously, it is strongly recommended to use the $PI_{0.0\text{-mm}}$ as it provides better control over initial smoothness.

Converting From a Profile Index to an Initial PSR or IRI

Under the PRS approach, if an agency decides to measure initial smoothness in terms of $PI_{0.0\text{-mm}}$, the agency must develop their own conversion equation from $PI_{0.0\text{-mm}}$ to initial PSR or IRI. Unfortunately, there is little published information regarding such conversion equations. If the agency does not wish to develop a relationship based on $PI_{0.0\text{-mm}}$, initial smoothness may be measured in terms of $PI_{5.1\text{-mm}}$ and converted to an initial PSR or IRI using an available conversion equation. Many such relationships have been developed under past research. Some of the currently available $PI_{5.1\text{-mm}}$ to initial PSR and $PI_{5.1\text{-mm}}$ to initial IRI relationships are summarized in tables 6 and 7. The agency-chosen relationship is an input in the PaveSpec 2.0 computer software.

Table 6. Published relationships between measured PI (using a 5.1-mm blanking band) and initial PSR.[21]

Equation	Source
$PSR = 5.0 – 0.0714(PI_{5.1\text{-mm}})$	Darter et al.[2]
$PSI = –0.04762(PI_{5.1\text{-mm}}) + 4.443$	Walker and Lin[22]
$PSI = 4.06 – 0.0256(PI_{5.1\text{-mm}})$	Uddin, Hudson, and Elkins[23]

Note: Present serviceability index (PSI) is used interchangeably with PSR. Also, the PI required by these equations is expressed in units of in/mi.

Table 7. Published relationships between measured PI (using a 5.1-mm blanking band) and initial IRI.

Equation	Source
$IRI = 52.9 + 6.0(PI_{5.1\text{-mm}})$	Kombe and Kaleva[24]
$IRI = 73.7 + 2.83(PI_{5.1\text{-mm}})$	Kombe and Kaleva[24]
$PI_{a.p.} = –22.3 + 0.3(IRI)$	Goulias, Dossey, and Hudson[25]
$IRI = 36.4 + 3.11(PI_{5.1\text{-mm}})$(for PI=5-7 in/mi)	Kulakowski and Wambold[26]

Note: The PI required by these equations is expressed in units of in/mi.
1.0 in/mi = 15.78 mm/km

Measuring Initial Smoothness in Terms of IRI

If the agency chooses to measure initial smoothness in terms of IRI (directly), the only available option is to predict smoothness over time in terms of IRI (see figure 15). Although there are currently no reliable methods for measuring initial IRI on newly placed concrete, research continues in this area. In anticipation of the development of such an initial IRI measurement method, this option was included in the revised PRS prototype.

Percent Consolidation Around Dowels

The measured percent consolidation around dowels is included as an optional input in the transverse joint faulting model included in the current PRS approach. If percent consolidation around dowels is selected for measurement in the field, the following sampling and testing procedures apply.

The representative percent consolidation around one randomly selected dowel bar in a sublot is determined based on a comparison of the density of two selected cores extracted from the hardened concrete slab. Core specimens are extracted from the hardened pavement slab between 48 and 72 hours after placement, in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.[19] All cores used for the acceptance of percent consolidation around dowels must have a minimum diameter of 102 mm.

The first of the two required cores is taken through a predetermined randomly selected dowel bar in a randomly selected transverse joint (random sampling core locations are determined in accordance with the guidelines set forth in the section titled *Selecting a Random Dowel Location*). The outside edge of the core through the randomly selected dowel bar must not be within 60 mm of a defined wheelpath or pavement edge, 100 mm of a vibrator path, or 50 mm of a transverse joint. The dowel bar piece is separated from the concrete core material by an agency-approved method. The density of this concrete material is measured in a saturated surface dried condition in accordance with ASTM C-642, *Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete*[20], and labeled as $DEN_{THROUGH\text{-}DOWEL(n)}$.

The second of the two required cores is taken at a location along a line passing through the first core (through the dowel bar) and parallel to the centerline of the pavement unit. The specific longitudinal location of this second core is assumed to be at midslab of the leave slab (the slab away from the joint in the direction of traffic) adjacent to the randomly selected transverse joint. The density of this concrete material is measured in a saturated surface dried condition in accordance with ASTM C-642, *Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete*[20], and labeled as the $DEN_{MID\text{-}SLAB(n)}$.

The number of samples per sublot (i.e., pairs of cores) is defined by the agency in accordance with the guidelines set forth in the section titled *Recommended Number of AQC Samples Per Sublot*. The maximum of all of the midslab core densities measured within the given lot ($MAX\text{-}DEN_{MID\text{-}SLAB}$) is determined and assumed to represent the density of a core with 100 percent consolidation. The representative percent consolidation for each sampling location (set of cores) is, therefore, determined using equation 16.

$$\%Consolidation=(DEN_{THROUGH\text{-}DOWEL(n)} / MAX\text{-}DEN_{MID\text{-}SLAB})*100 \quad (16)$$

Retesting Procedures

Additional sampling and testing for any of the AQC's for acceptance testing may be requested at any time by the contractor or by the agency. Retesting is, however, *required* if any AQC test results are found to be of lesser quality than agency-defined rejectable quality limits (RQL's). These limits define the minimum quality allowed to stay in place (and subjected to a pay adjustment) on the as-constructed pavement. For concrete strength, slab thickness, air content, and percent consolidation around dowels, retesting is required if the measured sample value is *less than* the defined RQL; however, for initial smoothness, retesting is required if the measured sample value is *greater than* the defined RQL.

At the same time, the agency defines maximum quality limits (MQL's) to be applied to each AQC specimen sample value. The MQL's define the limit on the additional quality (beyond the target values) for which the agency is willing to pay an incentive. Therefore, if a specimen sample value is measured to be of greater quality than the defined MQL, the representative specimen sample value (used in the acceptance procedures) is set equal to the defined MQL (i.e., the contractor will not receive credit for quality provided in excess of the MQL). For concrete strength, slab thickness, air content, and percent consolidation around dowels, the MQL is an *upper* limit on quality; however, for initial smoothness, the MQL is a *lower* limit on quality.

The purpose of retesting is to determine if the AQC quality provided by the contractor is truly less than the quality defined by the RQL. If retesting procedures determine conclusively that an identified area of pavement is deficient in quality (having lesser quality than the respective agency-defined RQL), the result will be the removal and replacement of the identified area. AQC sampling and testing values from the replaced material is then used in replacement of the original sampling and testing results for that sampling location. However, the AQC samples taken from the replaced material are subjected to MQL's equal to the respective AQC target values (i.e., the contractor may not get credit for AQC quality better than the target values when material has been removed and replaced).

If retesting procedures determine conclusively that an identified area of pavement is not deficient in quality (having greater quality than the respective agency-defined RQL), the additional AQC samples taken for retesting are added to the original AQC sample value set. The average of all the AQC sampling and testing results (original and retesting) representing a sampling location is then used as the representative AQC value for that sampling location. If the contractor and agency agree that a testing error occurred when determining an AQC test value, this test value is excluded from the acceptance process.

Selection of Appropriate RQL's and MQL's

The agency should choose RQL and MQL values carefully, so they truly define the range of AQC quality that the agency desires. The selected RQL's should identify the absolute minimum quality that the agency will accept as part of the as-constructed pavement. Any lesser quality pavement will be removed and replaced. The selected MQL's should identify the absolute maximum quality for which the agency is willing to pay an incentive. These quality limits provide the agency with a method of defining practical limits that keep the focus of the contractor on the as-designed target quality values. In turn, the contractor knows exactly how much additional quality he can provide (in excess of the AQC target values) and still expect to get paid an incentive. Again, it is important to stress that under the PRS approach, the AQC target values represent the true agency-desired quality.

All AQC test values that are measured to be between the agency-defined RQL and MQL will be kept in place and used for acceptance. Pay adjustments are determined and based on this measured AQC quality.

Specific Retesting Responsibilities

The specific retesting procedures are identified by the agency and provided as part of the specification. The agency will conduct all of the sampling and testing for any retesting activities. The conditions for determining whether the agency or contractor is responsible for the cost of the retesting will be determined in accordance with the specific retesting procedures provided in the specification. The pavement may only be retested once in accordance with the retesting methods provided in the specification. The sublot retesting sampling locations are determined in accordance with the guidelines set forth in the section titled *Selection of Random Sampling Locations*.

Recommended Number of AQC Samples Per Sublot

The number of AQC samples per sublot has a large effect on the risks to the agency and contractor. The recommended number of samples per sublot (for each AQC) is specific to the chosen sampling and testing method. Figure 16 shows the effect of the number of samples per sublot on the as-designed present worth LCC standard deviation for a typical example (3 sublots per lot, 500 lots per simulation). Each point on the chart represents the standard deviation of 500 simulated lot LCC's. This computed standard deviation is an indicator of the risks or uncertainty involved in estimating the LCC from small sample sizes.

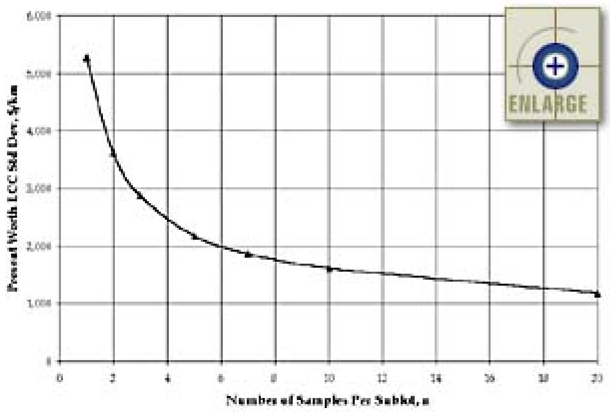

Figure 16. Example showing the typical effects of number of samples per sublot on the LCC standard deviation (3 sublots per lot, 500 lots per simulated point)

The points making up the chart in figure 16 were simulated by setting four different AQC's (concrete strength, slab thickness, entrained air content, and initial smoothness; percent consolidation around dowels was not included in this example) equal to their target means and standard deviations. At each simulation point, all of the included AQC's used the sample size reflected in the chart (i.e., for the simulated point where n = 10, 10 samples per sublot were taken for each of the four included AQC's).

Figure 16 shows that there is great benefit of using more than one sample per sublot. It also shows that the LCC standard deviation tends to stabilize for sample sizes greater than or equal to five. Therefore, it is recommended that sample sizes of two to five samples per sublot be used for acceptance in the field. It is, however, recognized that it may not be practical to take three to five samples per sublot for all AQC sampling types (e.g., linear traverse testing for entrained air content). Hence, it is recommended that the agency select AQC sample size by balancing the risk of errors in quality determination with the practicality and cost of sampling and testing. It is important to note that regardless of the number of samples per sublot chosen for each AQC, the selected number of AQC samples per sublot will be the same for both as-constructed and as-designed simulations. Therefore, the same effects of simulation error or bias on the simulated LCC's will be present in both the as-constructed and as-designed representative LCC means. Table 8 shows recommended minimum number of samples per lot for different AQC sampling and testing types.

Table 8. Recommended minimum number of samples per sublot for different sampling and testing methods.

AQC	Sample Type	Testing Type	Recommended Minimum Number of Sampling Locations per Sublot, n	Recommended Minimum Number of Replicate Samples per Sampling Location
Concrete Strength	Beams	28-day modulus of rupture	2–5	2
		Early age modulus of rupture		
	Cylinders	28-day compressive	2–5	2
		Early age compressive		
		8-day split-tensile		
		Early age split-tensile		
	Cores	28-day compressive	2–5	N/A
		Early age compressive		
		28-day split-tensile		
		Early age split-tensile		
Slab Thickness	Cores	N/A	2–5	N/A
Entrained Air Content	Fresh Concrete	Air pressure meter	3–5	2
	Cores	Linear traverse	1–3	N/A
Initial Smoothness	Profile Index	California profilograph	2 times the number of lanes (inner and outer wheelpaths of each lane)	None

	IRI	Inertial profiler	2 times the number of lanes (inner and outer wheelpaths of each lane)	None
Percent Consolidation Around Dowels	Pairs of Cores	Relative density comparison	1–3	None

Note: IRI = *international roughness index*

Selection of Random Sampling Locations

Selecting a Random Longitudinal Sampling Location

Random longitudinal sampling locations need to be identified whenever concrete strength or entrained air content is determined using samples of plastic concrete. Plastic concrete will be taken from in front of the paver (or behind the paver for air content, if so desired) at every randomly determined longitudinal sampling location. These estimated sampling locations are determined for each sublot in a given lot prior to the start of the paving of that lot (typically, these longitudinal sampling locations are determined on a day-to-day basis, before the start of that day's paving). Each specific required longitudinal sampling location (within a given sublot) may be determined using the following procedures:

36. Determine one random number (between 0 and 1) using an agency-approved random number generation method.

37. Identify the target sublot length ($PAVING_{SUBLOT}$) (expressed in meters).

38. Multiply the random number by $PAVING_{SUBLOT}$ to determine the longitudinal offset from the sublot's starting station.

As an example, let us assume that we have a project with a target sublot length of 200 m ($PAVING_{SUBLOT}$ = 200 m). A random number is generated to be 0.422 using an agency-approved random generation method. Therefore, the longitudinal offset from the sublot's starting station is computed as 200 m * 0.422 = 84.4 m. This example is illustrated in figure 17.

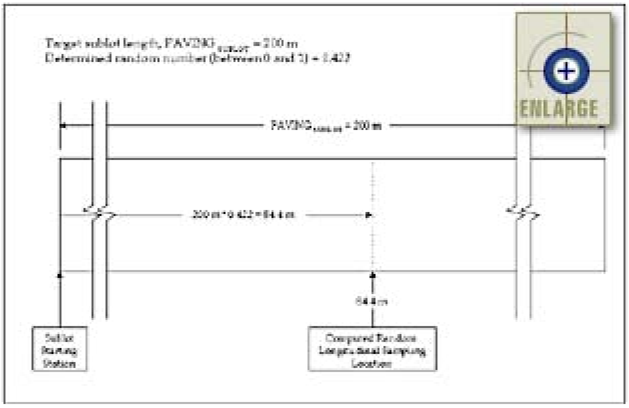

Figure 17. Example of locating a randomly selected longitudinal sampling location.

Selecting a Random Core Location

Random core sampling locations need to be identified whenever concrete strength, slab thickness, or entrained air content is estimated based on core samples taken from the hardened concrete slab. These estimated core sample locations are determined within each sublot in a given lot prior to the start of the paving of that lot. Again, these random core locations are typically determined on a day-to-day basis, before the start of that day's paving. Each random core location requires the determination of a longitudinal and horizontal offset within a sublot. Each specific required core location (within a given sublot) may be determined using the following procedures:

39. Determine two random numbers (between 0 and 1) using an agency-approved random number generation method.
40. Identify the target sublot length ($PAVING_{SUBLOT}$) (expressed in meters).
41. Identify the lot width (the width of the construction pass) (expressed in meters).
42. Multiply the first random number by $PAVING_{SUBLOT}$ to determine the core's longitudinal offset from the sublot's starting station.
43. Multiply the second random number by the lot width to determine the core's horizontal offset from the construction pass outside edge (the edge closest to the outer shoulder).

This process is demonstrated by the following example:

- Determined random numbers: 0.345 and 0.645.
- Agency-chosen target sublot length ($PAVING_{SUBLOT}$): 200 m.
- Lot width: 7.32 m.

The longitudinal offset is calculated to be 200 m * 0.345 = 69 m, and the horizontal offset from the outer edge is calculated to be 7.32 m * 0.645 = 4.7 m. The agency may choose to apply restrictions to the randomly generated core locations to avoid sampling near joints or directly in the wheelpaths. This example is illustrated in figure 18.

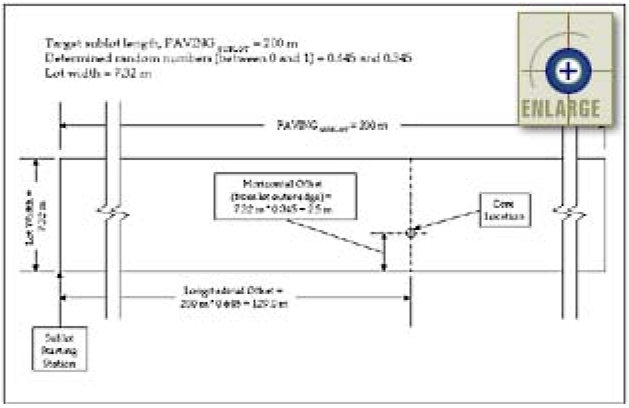

Figure 18. Example of locating a randomly selected core location.

Selecting a Random Dowel Location

The selection of a random dowel location for the testing of percent consolidation around dowels first involves the selection of a random transverse joint, followed by the selection of a random dowel bar within the selected transverse joint. Each required core location (within a given sublot) may be determined using the following procedure:

47. Determine two random numbers (between 0 and 1) using an agency-approved random number generation method.

48. Identify the target sublot length ($PAVING_{SUBLOT}$) (expressed in meters).

49. Define the average transverse joint spacing (expressed in meters).

50. Determine the number of dowel bars to be placed within one transverse joint.

51. Determine the number of actual transverse joints expected to fall within the target sublot length, computed by dividing $PAVING_{SUBLOT}$by the chosen average transverse joint spacing.

52. Multiply the first random number by the number of actual transverse joints observed to fall within the given sublot. Round this number to the nearest integer.Number the transverse joints (consecutively) within the sublot, and use the determined integer to locate the transverse joint to be investigated.

53. Multiply the second random number by the number of dowel bars placed within one transverse joint. Round this number to the nearest integer. Number the dowel bars (consecutively) within the transverse joint, and use the determined integer to locate the dowel bar to be investigated.

This process is demonstrated by the following example:

- Determined random numbers: 0.246 and 0.302.
- Agency-chosen target sublot length ($PAVING_{SUBLOT}$): 200 m.
- Average transverse joint spacing: 4.57 m.
- Number of dowel bars in one transverse joint: 23.

First, the number of actual transverse joints in the sublot with a length equal to $PAVING_{SUBLOT}$ is computed to be 43.8 joints by dividing $PAVING_{SUBLOT}$ by the chosen average transverse joint spacing (i.e., 200 m/4.57 m = 43.8 joints). This computed value is then rounded down to 43 and used as the number of joints appearing in the sublot. After the 43 joints are numbered consecutively in the sublot, the computed number of joints (43 joints) is then multiplied by the first random number (0.246) to determine the selected transverse joint for investigation. For this example, this specific joint is determined as 43 joints * 0.246 = 10.6 joints (rounded to 11). Therefore, the eleventh joint in the sublot is chosen to conduct the percent consolidation sampling.

Next, the specific dowel bar to be investigated must be determined. After the 23 dowel bars are numbered for the joint (starting at the outer edge), the second random number (0.302) is multiplied by the number of dowel bars in one transverse joint (23) to determine the specific dowel bar for investigation. This dowel bar is determined to be 0.302 * 23 = 6.95, which is then rounded to 7. Therefore, for this example, dowel bar #7 of transverse joint #11 is investigated for percent consolidation. This example is illustrated in figure 19.

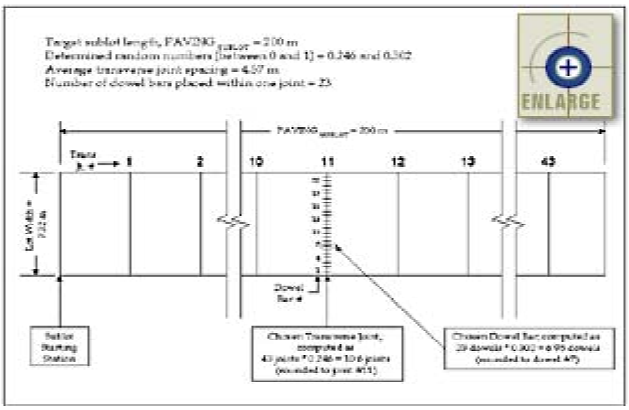

Figure 19. Example of locating a randomly selected dowel bar for the investigation of percent consolidation around dowels.

Selecting a Maintenance and Rehabilitation Plan

The agency must identify an M & R plan for use in the PRS approach. The agency is encouraged to define an M & R plan that closely resembles that actually used in the field. An M & R plan consists of identifying the type and frequency of routine maintenance, localized rehabilitation, and global rehabilitation activities. More information on each of these categories is included below.

Maintenance Activities

The current PRS approach limits routine maintenance activities to the following three:

- Transverse joint sealing.
- Longitudinal joint sealing.
- Transverse crack sealing.

The agency must decide which of these three activities (if any) are to be included in the yearly M & R cost calculations. For each chosen maintenance activity, the agency must define the frequency of maintenance application (in terms of years). For example, the agency may choose to seal transverse joints every 3 years, whereas transverse crack sealing may be addressed every year. In addition to determining the frequency of maintenance application, the agency must also identify the amount of maintenance to be applied during each visit to the field. The agency answers this question by identifying the percentage of joints or cracks to seal at each scheduled visit to the field.

Local Rehabilitation Activities

Localized rehabilitation activities are defined as those that may be used to correct *localized* pavement distresses. Localized distresses are defined as those that may affect an individual joint (transverse joint spalling and transverse joint faulting) or slab (transverse slab cracking). The current PRS approach provides the agency with the following choices for localized rehabilitation activities as they relate to the respective distresses:

- *Transverse joint spalling* may be addressed with full- or partial-depth repairs.
- *Transverse slab cracking* may be addressed with full or partial slab replacements.

As with the chosen routine maintenance activities, the agency must define which local rehabilitation activities to apply and when to apply them. This is accomplished by the following three steps:

63. The agency must select one of the available localized rehabilitation activities to address every one of the three distress indicators (transverse joint spalling, transverse joint faulting, and transverse slab cracking) chosen to define pavement performance.

64. The agency must decide at what frequency to apply these localized rehabilitation activities. Under the current PRS approach, the frequency of each selected activity is defined in terms of years (i.e., transverse slab cracking is addressed with full-depth slab replacements that are applied every 5 years).

65. The agency must decide how much of the required localized rehabilitation to apply at each application year (application years are defined by the chosen application frequency). For example, instead of repairing 100 percent of the predicted cracked slabs every 5 years, an agency may choose to only correct 50 percent of the cracked slabs in any one localized rehabilitation application year.

The agency is encouraged to define a localized rehabilitation plan that closely resembles the rehabilitation activities actually used by the agency in the field.

Global Rehabilitation Activities

Global rehabilitation activities are those activities that are applied to the entire lot (all sublots within the lot) at one time in response to declining *global* pavement conditions. These activities are specifically applied to address pavement condition indicators such as decreasing pavement smoothness (IRI or PSR), increasing amounts of localized distress, or increasing amounts of applied localized rehabilitation. Trigger values for these pavement condition indicators are typically defined to determine the timing of a global rehabilitation. The current PRS approach limits the global rehabilitation activities to the following three:

- AC overlays.
- PCC overlays.
- Diamond grinding.

As with the chosen localized maintenance activities, the agency must define which global rehabilitation activity to apply and when to apply it. This is accomplished by the following three steps:

69. The agency must select one of the three available global rehabilitation policies to address deteriorating global conditions.

70. The agency must define the method used to determine the timing of the first scheduled global rehabilitation. The current PRS approach allows the agency to base the timing of this first global rehabilitation on either lot threshold trigger values (on distress or localized rehabilitation values) or the computed PSF. It is recommended that the first year of lot global rehabilitation be determined using the PSF concept. More details are provided on these decisions in chapter 4, within the section titled *Calculation of the Representative LCC for a Given Lot*.

71. The agency must define an expected life of the chosen global rehabilitation. Rather than predict pavement performance after the first applied global rehabilitation, the current PRS approach assumes that subsequent global rehabilitations (of the same global rehabilitation type) will be applied at a fixed time interval equal to the chosen global rehabilitation life.

Again, the agency is encouraged to define a global rehabilitation plan that closely resembles the rehabilitation activities actually used by the agency in the field.

Cost-Related Decisions

Maintenance and Rehabilitation Unit Costs

The agency must define unit costs for each of the M & R activities chosen for inclusion in the M & R plan. These selected unit costs, combined with knowledge of the predicted yearly distresses, allow for the calculation of the yearly M & R costs. The unit costs for the possible M & R activities are typically expressed in the following formats.

<u>Maintenance Unit Costs</u>

- Transverse joint sealing—Dollars per linear meter of sealing or dollars per transverse joint.
- Longitudinal joint sealing—Dollars per linear meter of sealing.
- Transverse crack sealing—Dollars per linear meter of sealing or dollars per transverse crack.

<u>Localized Rehabilitation Unit Costs</u>

- Full-depth joint repairs—Dollars per square meter or dollars per transverse joint.
- Partial-depth joint repairs—Dollars per square meter or dollars per transverse joint.
- Full slab replacements—Dollars per square meter or dollars per slab.
- Partial slab replacements—Dollars per square meter.

<u>Global Rehabilitation Unit Costs</u>

- AC overlays—Dollars per square meter.

- PCC overlays—Dollars per square meter.
- Diamond grinding—Dollars per square meter.

It is recommended that current agency cost records be reviewed in order to obtain the most accurate unit cost values possible for each of the chosen M & R activities.

Inclusion of User Costs

Under the current PRS approach, the agency has the option to include user costs in the pay factor determination process. User costs are expressed in dollars per kilometer per vehicle and are made up of the following four components:

- Accident.
- Delay from roughness (not from lane closures).
- Discomfort.
- Vehicle operating.

User costs are calculated for each year based on the predicted pavement smoothness (PSR or IRI). Details of the user cost calculations are presented in chapter 4, in the section titled *Calculation of the Representative LCC for a Given Lot*.

Under the current approach, the agency may define a certain percentage of these calculated yearly user costs to be included in the overall lot LCC. If the agency does not feel that any user costs should influence the pay factor, this chosen user cost percentage may be set to zero. However, if user costs are included, it is recommended that the agency include a specific percentage that results in pay factors with which the agency is comfortable. Typically, user cost percentages up to 5 percent have resulted in reasonable pay factors. Larger percentages result in pay adjustments that are quite high.

Selecting a Discount Rate

The agency is required to select a discount rate to be used in determining PW LCC's. As defined previously, the discount rate is estimated as the difference between the interest and inflation rates, representing the real value of money over time. This relationship is shown below in equation 17.

$$DISCOUNT = INTEREST - INFLATION \quad (17)$$

where

DISCOUNT = Estimated discount rate, percent.

INTEREST = Estimated interest rate, percent.

INFLATION = Estimated inflation rate, percent.

The interest rate, often referred to as the *market* interest rate, is associated with the cost of borrowing money and represents the earning power of money.[10] The inflation rate is typically defined as the rate of increase in the prices of goods and services (construction of highways) and represents changes in the purchasing power of money.[10] In 1997, FHWA recommended that LCC's should be calculated using "a reasonable discount rate that reflects historical trends over long periods of time."[10] Past research in the U.S. has revealed that the real long-term rate of return on capital (i.e., the discount rate) has generally been between 3 and 5 percent.[10,27] It is recommended that the agency select an appropriate discount rate value from this 3- to 5-percent range.

Selecting an Appropriate Bid Price for Developing Level 1 Preconstruction Output

If the agency chooses to compute lot pay factors using Level 1 pay adjustment procedures, an appropriate bid price is required to develop the preconstruction output. This appropriate bid price is required since this preconstruction output must be developed prior to the project being let (prior to obtaining any contractor bids). It is recommended that the agency compute this appropriate bid price as the average of the unit bid prices observed on similar paving projects during the previous year (in dollars per square meter). The agency may use data from other past years; however, those costs should be updated to include the effects of inflation.

Selecting Simulation Paramaters

Number of Simulation Lots

The generation of preconstruction output involves the simulation of lot LCC's. The as-designed lot LCC's for both Level 1 and Level 2, as well as the points making up the Level 1 individual AQC pay factor curves, are determined as the average of "n" simulated lots. Although the simulated LCC mean is generally found to stabilize when n is greater than 200 to 250, it is suggested that the agency use a representative value of n = 500. Additional simulations beyond n = 500 do not change the mean LCC's significantly.

Simulations for Different Numbers of Sublots Per Lot

Although the sampling and testing plan is easily identified for each as-constructed sublot, it is not as easy to identify the number of sublots that will make up each as-constructed lot in the field. The number of actual as-constructed sublots will most likely vary from lot to lot (day to day) due to changes in weather, plant and paver equipment problems, and other factors. Because the simulated preconstruction output (Level 1 individual AQC pay factor curves and the Level 2 as-designed target LCC) is dependent on the number of sublots per lot, this preconstruction output must then be simulated for the different numbers of projected sublots per lot. This task is easily accomplished within the PaveSpec 2.0 software by defining the range of number of sublots per lot for which simulations will be completed.

After determining the target number of sublots per lot (NUMSUBS—see the section titled *Definition of a Sublot* [in chapter 5]), it is recommended that the agency generate representative preconstruction output for a range of 1 to NUMSUBS + 3. For example, if the target number of sublots per lot was estimated as NUMSUBS = 4, it would be recommended that the agency generate preconstruction output for the cases of 1 to 7 sublots. If an agency chooses to simulate only one particular case for use in acceptance, it is recommended that the preconstruction output resulting from the simulation of NUMSUBS per lot be used.

Guidelines for Pay Adjustments

Introduction

When developing a PRS for use in the field, the agency must make some important pay adjustment-related decisions. One of these decisions involves deciding whether to use Level 1 or Level 2 pay adjustment procedures. If the agency chooses to accept as-constructed pavement using Level 1 pay adjustment procedures, an appropriate lot composite pay factor (CPF) equation must be determined. Finally, the agency must determine how pay factors are to be limited when making final contractor pay adjustments. This chapter is designed to provide the agency with the information required to make these decisions.

Selecting A Pay Adjustment Procedure (Level 1 Or Level 2)

The current revised PRS prototype specification allows the agency to choose from two different pay adjustment procedures (representing the two different PRS implementation levels). Level 1 is offered as a simplified (and, therefore, more immediately implementable) method of estimating the results obtained from Level 2. Table 9 reiterates some of the main differences between the two PRS implementation levels.

Table 9. Key differences between PRS Level 1 and Level 2 pay adjustment procedures.

Characteristic	Level 1	Level 2
Primary Method of Acceptance Testing	Current acceptance tests used by the agency.	In situ acceptance testing is recommended.
Included Acceptance AQC's	Only those AQC's (of the available five) historically measured by the agency for acceptance.	Any or all of the five AQC's available for inclusion in the PRS.
Preconstruction Output	Individual pay factor charts for each AQC. Each is developed assuming that the other AQC's are held constant at their target values.	One simulated overall as-designed lot LCC (reflecting the interactions between AQC's).
Overall Lot Pay Factor Method	Determined as a simple mathematical function of the individual AQC pay factors (CPF equation). This CPF estimates the pay factor obtained from the Level 2 direct simulation.	Determined directly through simulation of all AQC's. The closest simulation of actual field conditions.

It is strongly recommended that an agency gain experience with the current PRS approach using Level 1. Although the Level 1 pay factor is only an estimate of the computed Level 2 pay factor, at this time, the Level 1 approach is by far the most practical of the two approaches as it provides important preconstruction output desired by both the agency and the contractor. After gaining experience with the

Level 1 approach, an agency may begin using the Level 2 approach or a combination of Level 1 and Level 2.

Defining a Level 1 Composite Pay Factor Equation

It is recommended that the governing CPF equation be a simple mathematical relationship of the independently determined AQC pay factors. A number of different simple equation forms are currently used by agencies to determine CPF equations. These same concepts may be used to determine CPF's using the Level 1 PRS approach. Four specific CPF equation forms are discussed in more detail in the following sections.

Weighted Average

The *weighted average* CPF method involves multiplying each calculated individual AQC pay factor by agency-chosen AQC weighting factors. Each of the AQC weighting factors is "determined through empirical observation or other engineering considerations," as stated in the AASHTO *Implementation Manual for Quality Assurance*.[28] Using this method, the resulting lot CPF is determined using equation 18.

$$CPF_{LOT} = \sum(PF_n*W_n) / \sum(W_n) \qquad (18)$$

where

CPF_{LOT} = Calculated Level 1 lot CPF.

n = Total number of AQC's included in the Level 1 specification (e.g., if the agency chooses to only include concrete strength and slab thickness, then n =2).

PF_n = Independently determined Level 1 pay factors for each of the n AQC's included in the Level 1 specification.

W_n = Respective weighting factors for each of the n AQC's included in the Level 1 specification.

An example illustrating the weighted average method is as follows:

Let's assume that the AQC's included in the specification consist of concrete strength, slab thickness, entrained air content, and initial smoothness. Therefore, the relevant calculation results are shown in table 10. Substituting the appropriate calculated values into equation 18 gives the following:

$$CPF_{LOT} = [\sum(PF_n* W_n) / \sum(W_n)]$$

$$= [543.5 / 5.3]$$

$$= 102.5 \text{ percent}$$

Therefore, for this example, the contractor would receive a pay incentive equal to 2.5 percent of the submitted bid price.

Table 10. Example calculations demonstrating the weighted average CPF method.

AQC	AQC number (n)	Individual AQC PF (PF_n)	AQC PF Weighting Factor (W_n)	PF_n* W_n
Concrete Strength	1	106.5	1.3	138.5
Slab Thickness	2	102.3	1.5	153.5
Entrained Air Content	3	98.5	1.0	98.5
Initial Smoothness	4	102.0	1.5	153.0
—	—	—	$\sum(W_n) = 5.3$	$\sum(PF_n*W_n) = 543.5$

Note: PF = *pay factor*.

Simple Average Method

The *simple average* CPF method involves computing the average of the calculated individual AQC pay factors. The resulting lot CPF equation is computed using equation 19.

$$CPF_{LOT} = \sum(PF_n) / n \quad (19)$$

where

CPF_{LOT} = Calculated Level 1 lot CPF.

n = Total number of AQC's included in the Level 1 specification.

PF_n = Independently determined Level 1 pay factors for each of the n AQC's included in the Level 1 specification.

An example illustrating the simple average method is as follows:

Assuming the same included AQC's and measured individual AQC pay factors used in the weighted average method example, equation 19 then becomes the following:

$CPF_{LOT} = \sum(106.5 + 102.3 + 98.5 + 102.0) / 4$

$= (409.3) / 4$

$= 102.3$ percent

Therefore, using the simple average method for this example, the contractor would receive a pay incentive equal to 2.3 percent of the submitted bid price.

Summation Method

The *summation* CPF method involves summing the individual AQC pay adjustments (difference between the computed AQC pay factor and 100 percent). The resulting lot CPF equation is computed using equation 20.

$$CPF_{LOT} = \sum(PF_n - 100) + 100 \quad (20)$$

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where

CPF_{LOT} = Calculated Level 1 lot CPF.

n = Total number of AQC's included in the Level 1 specification.

PF_n = Independently determined Level 1 pay factors for each of the n AQC's included in the Level 1 specification.

An example illustrating the summation method is as follows:

Assuming the same included AQC's and measured individual AQC pay factors used in the previous examples, equation 20 then becomes the following:

$CPF_{LOT} = \sum(PF_n - 100) + 100$

$= (106.5 - 100) + (102.3 - 100) + (98.5 - 100) + (102.0 - 100) + 100$

$= 6.5 + 2.3 - 1.5 + 2.0 + 100$

$= 109.3$ percent

Therefore, using the summation method for this example, the contractor would receive a pay incentive equal to 9.3 percent of the submitted bid price.

Product Method

The *product* CPF method involves multiplying the individual AQC pay factors (expressed as decimals, e.g., 103 percent = 1.03). The resulting lot CPF equation is expressed in equation 21.

$$CPF_{LOT} = (PF_1 * PF_2 * \ldots\ldots\ldots * PF_n) / (100)^{n-1} \quad (21)$$

where

n = Total number of AQC's included in the Level 1 specification.

PF_1 to PF_n = 1 to n independently determined Level 1 AQC pay factors.

An example illustrating the *product* method is as follows:

Assuming the same included AQC's and measured individual AQC pay factors used in the previous examples, equation 21 then becomes the following:

$CPF_{LOT} = (PF_1 * PF_2 * \ldots\ldots\ldots * PF_n) / (100)^{n-1}$

$= (106.5 * 102.3 * 98.5 * 102.0) / 100^3$

$= 109.5$ percent.

Therefore, using the product method for this example, the contractor would receive a pay incentive equal to 9.5 percent of the submitted bid price.

Selecting an Appropriate CPF Method

The goal is to determine the overall lot CPF that represents the performance that actually occurs over time. The Level 2 PRS simulation gives the best available estimate of the true pay factor. Of the four CPF methods presented in this section, the product method has typically been found to most closely approximate this Level 2 pay factor. However, agencies are encouraged to choose an appropriate CPF method after conducting comparisons of the available CPF methods using the *sensitivity analysis* portion of the PaveSpec 2.0 software.

Selecting Pay Factor Limits

Although the agency indirectly limits pay factors by defining appropriate MQL's for the quality of each AQC (see the section titled *Retesting Procedures* in chapter 5), an agency should also apply direct limits to the calculated individual AQC pay factors, the overall lot pay factor, or both. This pay factor limiting process is

Let's use the product method for illustration purposes. For the chosen example, all five AQC's are included in the specification. The assumed AQC pay factors for use in the example consist of the following:

- Concrete Strength: PF_{STR} = 108.5
- Slab Thickness: PF_{THK}= 105.3
- Entrained Air Content: PF_{AIR} = 99.5
- Initial Smoothness: PF_{SM} = 96.4
- Percent Consolidation: PF_{CON} = 102.4

The CPF for the lot (without applying any pay factor limits) is calculated as the following, using equation 21:

CPF_{LOT} = $(PF_1 * PF_2 * \ldots\ldots\ldots *PF_n) /(100)^{n-1}$
= $(108.5 * 105.3 * 99.5 * 96.4 * 102.4) /100^4$

= 112.2 percent
The following sections show the different methods by which this calculated CPF of 112.2 percent may be limited.

Limiting the Overall Lot CPF

The agency may choose to limit the overall lot pay factor to an agency-chosen subjective value. For our example, let's assume the agency feels that it cannot pay more than 106 percent of the bid price due to budgetary limits. Therefore, the calculated lot CPF of 112.2 percent would be limited to the agency-chosen 106-percent value. For this case, the contractor would then receive a 6-percent incentive payment for the project.

Limiting Individual AQC Pay Factors

Another approach for limiting pay factors for budgetary purposes is to apply limits to the individual AQC pay factors. For our example, let's assume that each of the individual AQC pay factors is limited to 103 percent. Table 11 shows a comparison of the individual AQC pay factors and resulting overall lot CPF's for both cases of with and without applied AQC limits.

Table 11. Example of limiting individual AQC pay factors (CPF calculated using the product method).

AQC	Individual AQC Pay Factors	
	Without Limits	All Limited to 103%
Concrete Strength	108.5	103.0
Slab Thickness	105.3	103.0
Entrained Air Content	99.5	99.5
Initial Smoothness	96.4	96.4
Percent Consolidation	102.4	102.4
Calculated Lot CPF	112.2	104.2

Using the 103-percent individual AQC limits, the overall lot CPF is then calculated to be 104.2 percent. For this case, the contractor would then receive a 4.2-percent incentive payment for the project.

Step-By-Step Guide – PRS Preconstruction

Introduction

After the agency makes all of the decisions required to develop a project-specific PRS, the final step required before actually using the specification is the generation of the appropriate preconstruction output. This chapter is provided as a step-by-step guide to generating preconstruction output for both Level 1 and Level 2 specifications.

Identifying Required Inputs

A number of steps are the same whether the agency chooses a Level 1 or Level 2 pay adjustment procedure. These steps require the collection of much project-specific information required to conduct LCC simulations. The specific steps for identifying the required inputs are detailed below.

Step 1—Define the General Project Information. The general project information should be identified as a first step. This information includes items such as project location, lane configuration, starting and ending stations, and lane widths. These are selected in accordance with the guidelines presented in the section titled *Design-Related Variables*, in chapter 5 of this volume.

Step 2—Define Pavement Performance. The agency must select the distress indicators that will be used to define pavement performance. These are selected in accordance with the guidelines presented in the section titled *Defining Pavement Performance*, in chapter 5 of this volume.

Step 3—Select the AQC's to be Included in the Specification. The agency must select the AQC's that are to be sampled and tested for acceptance. These are selected in accordance with the guidelines presented in the section titled *Selection of Included AQC's*, in chapter 5 of this volume.

Step 4—Define the Required Constant Values. A number of design-, climatic-, and traffic- related variables must be defined for use in the chosen distress indicator models. These are selected in accordance with the guidelines presented in the section titled *Identification of Constant Variable Values*, in chapter 5 of this volume.

Step 5—Define the AQC Acceptance Sampling and Testing Plan. The agency must define the sampling and testing procedures to be used in measuring the AQC's in the field. This plan not only defines the actual required sampling and testing methods to be used, but also defines the number of samples per sublot, the methods for determining random sampling locations, and some general information on retesting. The defined acceptance sampling and testing plan is determined in accordance with the guidelines presented in the section titled *Selecting an AQC Acceptance Sampling and Testing Plan*, in chapter 5 of this volume.

Step 6—Define the Required As-Designed AQC Target Values. The agency must select as-designed target means and standard deviations for each of the included AQC's. (Note: The selected means and standard deviations are dependent on the selected sampling and testing plan—defined in step 5.) Guidelines for selecting appropriate target values (interpreting existing specifications or from historical AQC construction data) are presented in the section titled *Selection of AQC Target Values*, in chapter 5 of this volume.

Step 7—Define Lots and Sublots. Lots and sublots must be clearly defined for the project. This primarily consists of defining the target lengths of each. The definitions for both lots and sublots are determined in accordance with the guidelines presented in the section titled *Definition of Lots and Sublots*, in chapter 5 of this volume.

Step 8—Define the Maintenance and Rehabilitation Plan. The agency must select an appropriate M & R plan to be used for the specific project. This involves selecting the type and frequency of application for maintenance, localized rehabilitation, and global rehabilitation activities. The defined M & R plan is determined in accordance with the guidelines presented in the section titled *Selecting a Maintenance and Rehabilitation Plan*, in chapter 5 of this volume.

Step 9—Define the Included Costs. The agency must identify the particular costs to be included in the overall lot LCC. These decisions include identifying the M & R unit costs associated with the chosen M & R activities, deciding on an appropriate percentage of user costs to be included, and determining an appropriate discount rate. All of these cost-related decisions are made in accordance with the guidelines presented in the section titled *Cost-Related Decisions*, in chapter 5 of this volume.

Step 10—Define the Simulation Parameters. In order to conduct any LCC simulations for the as-designed or as-constructed pavement, the agency must define the required simulation parameters, such as the number of simulation lots required to simulate a lot LCC and the appropriate range of number of sublots per lot. These simulation-related parameters are determined in accordance with the guidelines presented in the section titled *Selecting Simulation Parameters*, in chapter 5 of this volume.

Step 11—Choose the Appropriate Pay Adjustment Procedure. The agency must select one of two pay adjustment methods available in the prototype PRS—Level 1 or Level 2. Level 1 should be selected for initial implementation of PRS. This decision is made in accordance with the guidelines presented in the section titled *Selecting a Pay Adjustment Procedure (Level 1 or Level 2)*, in chapter 6 of this volume. The details for each of these pay adjustment methods are explained separately in the following sections.

Level 1—Generating Individual AQC Pay Factor Curves

For the Level 1 specification, the preconstruction output involves simulating data points making up the individual AQC pay factor charts. Each AQC pay factor chart is made up of a series of pay factor curves (each specific to a different AQC standard deviation) plotted over a chosen AQC mean range. Pay factor regression equations are fit through the data making up each pay factor curve. Individual AQC pay factors may then be determined using the developed regression equations (or read directly from these charts) by knowing the as-constructed AQC lot means and standard deviations. If the measured AQC standard deviation does not exactly match that of one of the simulated pay factor curves, the pay factor is determined by interpolating between the appropriate pay factor equations. An explanation of the development of the Level 1 pay factor curves (and corresponding pay factor regression equations) is contained in more detail in this section.

Level 1, Step 12—Simulate the As-Designed LCC. In order to calculate pay factors for different hypothetical levels of as-constructed AQC quality, the representative target as-designed LCC must first be simulated. The PaveSpec 2.0 specification simulation software is used to estimate representative target as-designed LCC's for the different numbers of sublots per lot chosen by the agency (see the section titled *Selecting Simulation Parameters*, in chapter 5 of this volume). For example, the agency may decide to simulate as-designed LCC's for three different scenarios where the number of sublots per lot would equal 3, 4, and 5. Each of these simulated LCC's (representing a specific number of sublots per lot) is a function of many different agency-defined variables, including the number of simulation lots, acceptance and sampling plan, M & R plan, AQC target values, analysis life, and chosen costs. Individual Level 1 pay factor charts will be developed independently for each scenario chosen by the agency.

Level 1, Step 13—Choose a Range of As-Constructed Means for Each AQC. Reasonable ranges of AQC means are selected that will define the values used in the simulation of the Level 1 AQC pay factor curves. These chosen ranges of AQC simulation means are based on the chosen AQC target values. The agency is required to define the range of the AQC means and the number of simulation points within the range. The agency-chosen values will be used to define the x-axis range of the developed Level 1 pay factor charts. It is recommended that the boundary conditions of this range be defined as the agency-defined AQC RQL's and MQL's (see the section titled *Retesting Procedures* in chapter 5 of this volume).

Level 1, Step 14—Choose a Range of As-Constructed Standard Deviation Levels for Each AQC. The pay factor curves (contained in the Level 1 pay factor charts) depend not only on the as-constructed AQC mean, but also on the as-constructed AQC standard deviation. Therefore, it is important to choose a range of as-constructed standard deviation levels that will show the influence of the AQC variability. Three to five different levels of standard deviation are typically chosen for each AQC. (One of the chosen standard deviation levels should always be the AQC target standard deviation.)

Level 1, Step 15—Simulate As-Constructed LCC's and Calculate an Independent AQC Pay Factor for Each Hypothetical As-Constructed Mean/ Standard Deviation Pair. The hypothetical as-constructed mean/standard deviation pair values (coming from combinations of means and standard deviations defined in Level 1, steps 13 and 14, respectively) are used to define individual simulation sessions in PaveSpec. Each AQC is investigated independently for each simulation session (e.g., if strength is being investigated, all of the other AQC as-constructed means and standard deviations are set equal to the target values). Each mean/standard deviation pair is used in PaveSpec to simulate a corresponding representative as-constructed LCC mean ($AC\text{-}LCC_{MEAN}$). A pay factor is calculated for each hypothetical pair using equation 3 in chapter 3 of this volume. (Note: Pay factors are calculated using an agency-selected appropriate bid price determined in accordance with the guidelines set forth in the section titled *Selecting an Appropriate Bid Price for Developing Level 1 Preconstruction Output* in chapter 5.)

Level 1, Step 16—Determine Individual AQC Pay Factor Regression Equations. Best fit regression equations are defined for each set of simulated pay factors related to each as-constructed AQC standard deviation (chosen in Level 1, step 14). These individual pay factor equations are generated using the PaveSpec 2.0 software.

Level 1, Step 17—Plot Pay-Factor Equations vs. AQC Mean. The defined pay factor regression equations (determined in Level 1, step 16) can be graphed easily as a function of the AQC mean. Pay factor charts (containing plots of all of the regression equations defined in Level 1, step 16) are then plotted for each AQC independently. These charts are created for each number of sublots per lot chosen by the agency (see the section titled *Selecting Simulation Parameters* in chapter 5 of this volume).

Level 1, Step 18—Define the CPF Equation. The agency must define a governing CPF equation in accordance with the guidelines presented in the section titled *Defining a Level 1 Composite Pay Factor Equation*, in chapter 6 of this volume.

Level 1, Step 19—Define Pay Factor Limits. The agency must define pay factor limits that are applied to the computed individual AQC pay factors, or the lot CPF, or both. Any chosen pay factor limits are determined in accordance with the guidelines presented in the section titled *Selecting Pay Factor Limits*, in chapter 6 of this volume.

Level 2—Simulating The As-Designed LCC

For a Level 2 specification, the preconstruction output only involves the simulation of the target as-designed life-cycle cost (LCC_{DES}). Overall lot pay factors are calculated directly as a function of this LCC_{DES}, the determined as-constructed LCC (LCC_{CON}), and the contract bid price (using equation 3 in chapter 3 of this volume). This Level 2 LCC_{DES} is determined using the same procedure described in *Level 1, Step 12*.

Developing Operating Characteristic Curves

Under the Level 1 PRS, operating characteristic (OC) curves are generated for each AQC using the PaveSpec 2.0 computer software. Each set of OC curves is developed specific to a defined sampling plan (i.e., number of sublots, number of samples per sublot, and sample and test types). The following steps outline the general procedure used within the software to generate these charts:

For each AQC, the following applies:

1. Distributions of pay factors for different AQC mean values (over the chosen range of AQC means) are simulated by setting the as-constructed AQC standard deviation equal to the target value. Each distribution is the result of a minimum of 500 simulated lot pay factors.

2. Pay factor means and standard deviations (computed at each hypothetically chosen AQC mean) are plotted over the chosen range of AQC means. Relationships of pay factor mean and pay factor standard deviation versus AQC mean are determined. Figures 20 and 21 illustrate these respective relationships for slab thickness on an example project. Figure 20 is commonly referred to as an expected pay (EP) curve.

3. The user must define the different pay factor acceptance levels for which the probability of acceptance will be investigated (e.g., PF ≥ 80%, PF ≥ 100%, PF ≥ 110%).

4. Finally, OC curves for each of the chosen pay factor acceptance levels are plotted using the results of steps 1 through 3. Figure 22 contains the example OC chart plotted using the relationships determined for the slab thickness example (determined in step 2).

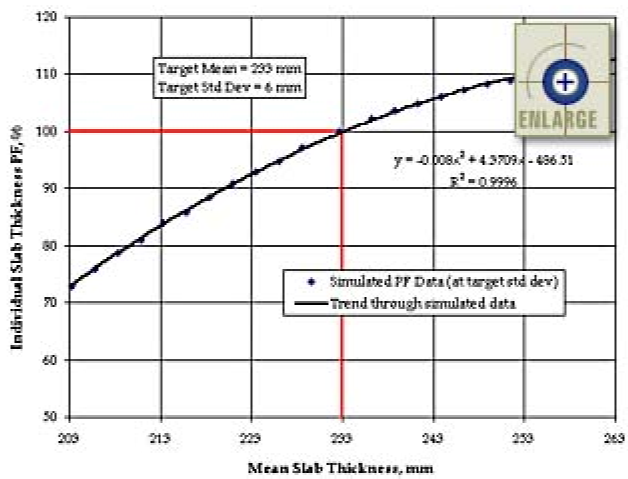

Figure 20. Example of a simulated pay factor mean versus AQC mean relationship used to develop OC curves for a Level 1 PRS.

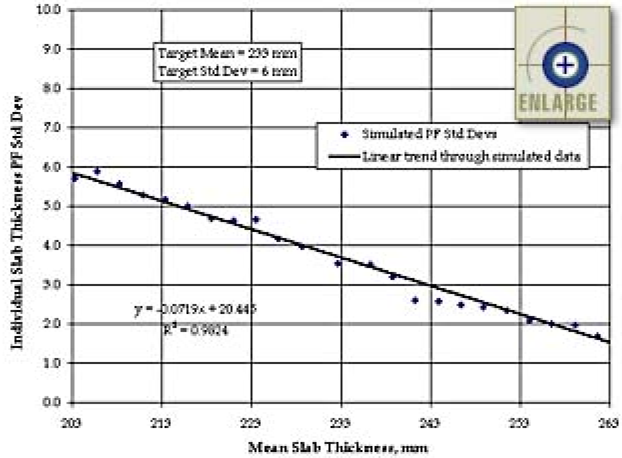

Figure 21. Example of a simulated pay factor standard deviation versus AQC mean relationship used to develop OC curves for a Level 1 PRS.

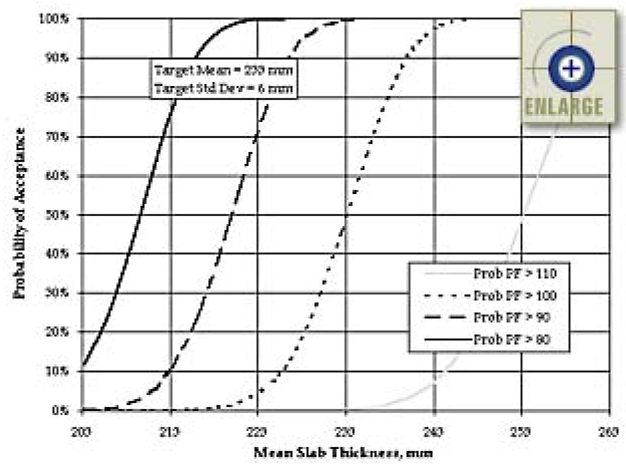

Figure 22. Example of an OC curve constructed for a Level 1 PRS—case of four sublots and two samples per sublot (for each AQC). This chart reflects the relationships presented in figures 20 and 21.

Different examples of interpreting figure 22 are given as the following:

- If the contractor wishes to have a 50-percent probability that he/she will obtain a PF ≥ 100 percent, then a mean slab thickness of 233 mm must be constructed.
- If the contractor wishes to have a 90-percent probability that he/she will obtain a PF ≥ 100 percent, then a mean slab thickness of 240 mm must be constructed.

- If the contractor wishes to have a 90-percent probability that he/she will obtain a PF ≥110 percent, then a mean slab thickness of 260 mm must be constructed.

- f the contractor actually builds a mean slab thickness of 223 mm (the target was 233 mm), the probability that he/she will receive a PF ≥100 percent is approximately 5 percent. The probability that he/she will receive a PF ≥ 90 percent is 70 percent.

Step-By-Step Guide – Pay Adjustments

Introduction

After the agency has defined the specification and developed the corresponding project-specific preconstruction output, the agency may then use the developed specification for acceptance. PRS-related contractor pay adjustments are then determined based on the actual samples taken from the as-constructed pavement lot (in accordance with the agency-defined AQC acceptance sampling and testing plan). This chapter describes the procedures to be used by an agency to determine Level 1 or Level 2 pay adjustments for a given as-constructed pavement lot.

Step 1: Dividing The As-Constructed Pavement Lot Into Sublots

To judge the quality of the as-constructed in-place pavement lot, the agency must conduct sampling and testing in accordance with the previously chosen acceptance sampling and testing plan. (Note: The defined acceptance sampling and testing plan is determined in accordance with the guidelines presented in the section titled *Selecting an AQC Acceptance Sampling and Testing Plan*, in chapter 5 of this volume.) As a first step in the sampling of the pavement, the pavement lot is divided into sublots. Prior to the placement of any paving for the given lot, the agency must estimate the starting and ending stations of all of the sublots expected to be paved within that lot. These specific stations are determined by assuming sublot lengths equal to the chosen *target sublot length* (the target sublot length is determined in accordance with the guidelines presented in the section titled *Selecting an Appropriate Target Sublot Length*, in chapter 5 of this volume). An appropriate number of expected sublots are defined so that sublots are defined well past the expected lot length (see the section titled *Definition of Lots and Sublots* in chapter 5 of this volume).

Step 2: Determining The As-Constructed Acceptance Sampling Locations

The estimated sublot starting and ending stations allow the agency to determine random sampling locations prior to the placement of any pavement within the lot. For each AQC, the appropriate number of random sampling locations per sublot is identified by the agency in accordance with the guidelines presented in the section titled *Recommended Number of AQC Samples Per Sublot*, in chapter 5 of this volume. (Note: The chosen AQC sample types determine what sampling locations are required.) Specific sample locations are, therefore, determined based on the agency-chosen sample specimen types and in accordance with the guidelines presented in the section titled *Selection of Random Sampling Locations*, in chapter 5 of this volume.

Step 3: Conducting Lot Acceptance Sampling And Testing

Once the paving begins for a given lot, the actual sublot lengths are determined in accordance with the guidelines presented in the section titled *Determining Actual Sublot Lengths in the Field*, in chapter 5 of this volume. The appropriate sample specimens are taken at the random sample locations identified in the previous step. If replicate samples are taken at a given sampling location (e.g., three cylinders molded from a batch of concrete taken from one randomly selected longitudinal sample location), the replicate sample specimen testing values are averaged to give one AQC testing value representing the sample location. These sample location *representative* testing values are used to define the quality of the pavement lot.

Step 4: Determining The Overall Lot Pay Factor

The procedures used to determine an overall lot pay factor differ for Level 1 and Level 2 specifications. The Level 1 overall lot pay factor is computed using a chosen composite pay factor equation, while the Level 2 pay factor is based on a direct comparison of the simulated as-designed LCC mean and the estimated as-constructed LCC. The details of both of these procedures are described separately below.

Level 1—Determining the Overall Level 1 Lot CPF

If the Level 1 procedure is used to calculate the pay adjustment, the following steps apply:

<u>Summarizing the As-Constructed AQC Acceptance Data for the Lot</u>

The first step in calculating a Level 1 lot pay adjustment requires that the measured as-constructed AQC acceptance data be summarized for the entire lot. Therefore, all of the *representative* testing values (representing every sample location within the lot—all sublots are included) are summarized into one lot mean and unbiased standard deviation for each AQC. These AQC lot means and unbiased standard deviations are then used in the developed individual AQC pay factor curves and equations.

<u>Computing the Individual Pay Factors for Each AQC</u>

Individual pay factors are determined independently for each AQC based on the respective lot means and unbiased standard deviations computed in the previous section. For each AQC, the representative lot mean and unbiased standard deviation is used in the following step-by-step procedure to determine individual AQC Level 1 pay factors:

a. Compute the representative as-constructed AQC lot mean and unbiased sample standard deviation.

b. Identify the two regression equations that *surround* the AQC lot unbiased standard deviation. For example, if the AQC lot unbiased standard deviation for strength is 0.48 MPa, and regression equations have been developed for the cases of 0.00, 0.45, and 0.90 MPa, then the two equations surrounding the AQC lot unbiased standard deviation would be those represented by the 0.45 and 0.90 MPa.

   If the AQC lot unbiased standard deviation exactly matches one of the standard deviations used in the development of the regression equations, then that matching regression equation is used in step b. If the AQC lot unbiased standard deviation is larger or smaller than any of the standard deviations used to simulate the individual AQC pay factor curves, the agency must choose one of the following methods for acceptance.

   i. *Choose the simulated AQC pay factor curve closest to the AQC lot unbiased standard deviation*—i.e., if the AQC lot unbiased standard deviation for strength is 1.00 MPa, and regression equations had been developed for the cases of 0, 0.45, and 0.90 MPa only, the agency could choose to estimate the corresponding pay factor using the pay factor equation representing the closest standard deviation. Therefore, since 1.00 MPa is closest to 0.90 MPa, the pay factor equation developed for the case of standard deviation equal to 0.90 MPa would be used.

   ii. *Resimulate a pay factor regression equation for the case of the AQC lot unbiased standard deviation*—i.e., if the AQC lot unbiased standard deviation for strength is 1.00 MPa, and regression equations had been developed for the cases of 0, 0.45, and 0.90 MPa only, the agency could choose to resimulate a pay factor equation for the case where the standard deviation is equal to 1.00 MPa.

c. Use the computed AQC lot mean in the one or two pay factor regression equations (identified in step b) to compute respective pay factors. If only one governing pay factor equation is identified under step b, then the computed pay factor (using that single equation) represents the individual AQC pay factor for the lot. If two pay factors are computed (one each using the two surrounding pay factor regression equations), then the individual AQC pay factor representing the lot must be determined using the interpolation procedures outlined in step d.

d. Use the AQC lot unbiased standard deviation to interpolate between the independent pay factors determined using the two surrounding pay factor regression equations. The interpolated pay factor is then used to represent the individual AQC pay factor for the lot. The representative lot pay factor is then interpolated using equation 22.

$$AQC\text{-}PF_{LOT} = PF_{HIGH} + (PF_{LOW} - PF_{HIGH}) * [(SD_{HIGH} - SD_{UNB})/(SD_{HIGH} - SD_{LOW})] \quad (22)$$

where

$AQC\text{-}PF_{LOT}$ = Representative individual AQC pay factor, percent.

PF_{HIGH} = Individual AQC pay factor (for measured AQC lot mean) determined using the pay factor equation based on the larger of the two surrounding standard deviation values, percent.

PF_{LOW} = Individual AQC pay factor (for measured AQC lot mean) determined using the pay factor equation based on the smaller of the two surroundingstandard deviation values, percent.

SD_{HIGH} = Larger of the two *surrounding* standard deviation values.

SD_{LOW} = Smaller of the two *surrounding* standard deviation values.

SD_{UNB} = Computed AQC lot unbiased sample standard deviation.

e. Any agency-identified pay factor limits may be applied to the Level 1 individual AQC pay factors. The limited pay factors, therefore, become the representative AQC pay factors used to compute the overall lot CPF. Individual AQC pay factor limits shall be selected in accordance with the guidelines presented in the section titled *Selecting Pay Factor Limits*, in chapter 6.

Finally, this procedure is repeated so that representative individual AQC pay factors are determined for each AQC included in the specification.

<u>Computing the Level 1 Lot CPF</u>

For Level 1, the overall lot CPF is calculated using the specific CPF equation determined by the agency in accordance with the guidelines presented in the section titled *Defining a Level 1 Composite Pay Factor Equation*, in chapter 6. Just as with the individual AQC pay factors, the agency has the option to apply pay factor limits to the computed lot CPF. The limited CPF, therefore, is the representative CPF used to compute the overall lot pay adjustment. Any such lot CPF pay factor limits shall be selected in accordance with the guidelines presented in the section titled *Selecting Pay Factor Limits*, in chapter 6.

Level 2—Determining the Overall Level 2 Lot Pay Factor

If the Level 2 procedure is used to calculate the pay adjustment, the following steps apply:

Summarizing the As-Constructed AQC Acceptance Data for Each Sublot

The first step in calculating the Level 2 lot pay adjustment requires that the measured as-constructed AQC representative testing values be summarized for each sublot independently. The means of these AQC testing values are computed for each sublot and are then used to define the as-constructed quality of the pavement lot in the PaveSpec 2.0 software. The future performance and corresponding lot LCC's (over the agency-chosen analysis period) related to the computed AQC sublot means are determined using the PaveSpec 2.0 software. The total PW value of the predicted lot LCC's (LCC_{CON}) is used as the overall measure of quality for the as-constructed lot. The overall Level 2 lot pay factor is then computed as a function of this LCC_{CON}, the simulated as-designed LCC (LCC_{DES}), and the actual contractor bid price ($BID_{CONTRACTOR}$) using equation 3 in chapter 3.

As with the Level 1 CPF, the agency has the option to apply pay factor limits to the computed overall Level 2 lot pay factor. The limited lot pay factor, therefore, is the representative pay factor used to compute the overall lot pay adjustment. Any such lot pay factor limits shall be selected in accordance with the guidelines presented in the section titled *Selecting Pay Factor Limits*, in chapter 6.

Step 5: Computing The Lot Pay Adjustment

The total payment to the contractor for the as-constructed lot may be determined using equation 23.

$$\text{Contractor Lot Payment} = BID_{CONTRACTOR} * (PF_{LOT} / 100) * LOT_{LENGTH} \quad (23)$$

where

Contractor Lot Payment = Adjusted payment paid to the contractor for the as-constructed lot, $.

$BID_{CONTRACTOR}$ = Actual contractor bid price, $/km.

PF_{LOT} = Representative overall pay factor for the as-constructed lot, percent. (Note: This is either the Level 1 lot CPF, or the Level 2 overall lot pay factor. This pay factor will take into account any pay factor limits identified by the agency.)

LOT_{LENGTH} = Measured actual as-constructed lot length, km.

Conclusions Recommendations

Under this research project, the prototype PRS (developed under previous FHWA research) was revised and expanded to make it more practical.[1,2,3] Different implementation levels of the PRS were defined (Levels 1, 2, and 3), with the simplified PRS (Level 1) designed to be immediately implementable. This report (four volumes) was offered as a practical guide to using the revised prototype PRS (included as appendix A in this volume) for the acceptance of JPCP lots. It discussed all aspects of the research, including the step-by-step procedures for developing and using the PRS, results of demonstrations of the PRS methodology (see volume II), explanations of supplementary laboratory and field studies (see volume III), and the user guide for the revised PaveSpec 2.0 PRS demonstration software (see volume IV). Based on the research conducted under this project, the following conclusions and recommendations have been compiled.

Conclusions

- The PRS that have been developed for JPCP highways are based on sound economic, engineering, and statistical concepts. The PRS have been field tested in several projects as shadow specifications, and reasonable results were obtained from these projects, as documented in appendix B (volume II) of this report. The PRS are now ready for the next step of implementation in an actual field situation where contractor pay is under the PRS.
- Implementation of the PRS for JPCP will require: (1) the tailoring of the PRS to the project and obtaining of many inputs and decision criteria and (2) adequate training of both SHA and contractor staff in PRS concepts and applications.
- The PRS for JPCP are specifications on key material and construction AQC's that have been shown to correlate significantly with the performance of the pavement. Through the use of PRS, a methodology is provided by which the quality of pavement construction can be related to the performance of the pavement and then to LCC's. Thus, rational contractor pay adjustments can be made for each constructed lot.
- PRS have the capability to identify an optimum level of construction quality that would minimize overall LCC's, yet still meet performance requirements. Selection of target quality levels of AQC's (means and standard deviations) and other factors in the PRS are required by SHA's.
- The PRS are driven by key distress indicators that control performance and, hence, the LCC of the pavement. For JPCP, these include transverse cracking of the slab, joint faulting, joint spalling of the slab, and pavement smoothness.
- Based on the key JPCP distress indicators, the following AQC's were selected for use in the PRS: concrete strength, air content, consolidation around the dowel bars, slab thickness, and initial smoothness. The PRS can include any or all of these AQC's.
- Both the mean value and the within-lot variability of each of the AQC's are considered in computing the contractor pay factor.
- Three different specification levels (simply titled *Level 1*, *Level 2*, and *Level 3*) were developed to aid in the implementation process. Level 1 is fully implementable and utilizes current SHA test procedures for AQC's and simplified contractor pay factor computation procedures. Pay factors computed using Level 1 are designed to closely estimate those obtained from the more accurate

simulation conducted under Level 2. Level 3 is a futuristic concept where all testing is nondestructive and rapid.

- Future LCC's of the pavement are predicted, discounted, and summed as a present worth. LCC's include both M & R costs to the agency, as well as certain highway user costs based on pavement roughness. If these as-constructed pavement lot results indicate an increase or decrease in performance over that of the target as-designed pavement lot, appropriate pay adjustments are made.

- The simulated field trials made it clear that practical limitations must be placed on contractor pay factors. These limits are placed both on pay factors for individual AQC's and on the overall lot pay factor.

- A comprehensive laboratory/field investigation of concrete material- and construction-related variables was conducted and results were documented. This included the following:

    1. Concrete strength testing (relationships between flexural and compressive strength and other tests, maturity methods, and the prediction of 28-day strengths from early age strengths at 3 to 5 days).

    - An investigation of testing and construction variability.

    - Correlation of concrete consolidation at dowels and measured load transfer.

- The Level 1 PRS were demonstrated by developing pay factor charts representing typical JPCP designs in a chosen SHA (Iowa). The three typical designs were chosen based on medium, heavy, and very heavy traffic levels. Three general trends observed from the exercise included:

    1. Pay factors increased as the quality of the measured AQC mean improved.

    2. At a given AQC mean, pay factors increased as the measured AQC standard deviation decreased.

    3. Pay factor curves generally became flatter as traffic level increased.

A complete summary of these results is included in appendix B (volume II).

- The PaveSpec 2.0 PRS demonstration software is an integral part of the revised PRS approach, and is used in combination with the developed practical guide (volume I) to develop PRS. The PaveSpec 2.0 software provides user-friendly capabilities for simulating a lot. These include the simulation of the construction of a lot, sampling and testing, performance prediction, LCC summation, and computation of pay factors. The PaveSpec 2.0 software is an invaluable tool for demonstrating and clarifying the revised PRS concepts.

Recommendations

- The PRS are now ready for field implementation where contractor pay depends on the PRS. Successful implementation by a SHA will require considerable preparation of the PRS, along with significant training of the agency and contractor personnel.

- The PRS are expected to lead to higher quality construction, improved performance, and lower LCC's. The main reason for this is the inclusion of several key AQC's (concrete strength, slab thickness, entrained air content, initial smoothness, and percent consolidation around dowel bars) with incentive/ disincentive pay factors. The rational computation of these contractor pay factors for each AQC and the overall constructed lot should give agencies support for implementing a PRS.

- Each SHA wishing to implement PRS for JPCP must tailor the specifications and pay computation procedure to local project conditions. This includes the following: model calibration; AQC's; target means and variability; pay factor limits; AQC limits; sample size; selection of key distress indicators; selection of tests for each AQC; field management of sampling and testing, and computation of pay factors; M & R plan; and procedures to choose trigger values for distresses.

- The PRS can be utilized to optimize design by helping to select AQC values that lower LCC's while still meeting performance requirements. Very little work has been done in this regard to date, and much more is needed to fully demonstrate the value of PRS.

- Many improvements to the existing PRS for JPCP are still needed. The implementation of PRS will be a major effort, and limitations will certainly develop. These must be overcome with further research and development. Following are some specific areas of further development and improvements that are needed for PRS for concrete pavements:

    1. Improved user cost models are clearly needed in PRS. The existing user cost models need updating and do not include traffic delay costs from lane closures for M & R.

    2. Improved distress and roughness prediction models are needed. Those in PaveSpec 2.0 are the best available at this time, but they certainly could be improved upon given the extent of LTPP data now available.

    3. Additional AQC's could be included to make PRS more comprehensive. These could include joint sawing depth, surface texture, concrete mixture components (cement, aggregates, etc.), and improved ways to measure early strength. In addition, inclusion of base course quality, subgrade quality, and shoulders would be valuable to PRS.

    4. Additional pavement types: continuously reinforced concrete pavement, jointed reinforced concrete pavement, and unbonded concrete overlays.

    5. Development of more rapid, nondestructive testing for concrete strength measurement.

- Additional work is needed in developing and improving the PRS for Levels 2 and 3. Level 2 requires the running of simulations to compute a lot pay factor. While this provides a correct pay factor, it is a "black box" to the agency and contractor. Level 3 needs more rapid nondestructive tests on the in situ pavement lot.
- Use of pavement management system (PMS) data support PRS implementation. Such aspects as calibration of distress models, validation of distress models, and validation and improvement of M & R life-cycle costing are important.
- After the conduct of initial implementation projects, there will be a need to better investigate the benefits of PRS as compared to conventional QA/QC specifications.
- Finally, considerable training in PRS concepts and practice will be needed for SHA, contractor, and industry personnel.

Appendix A

Introduction

This document provides construction specifications for jointed plain concrete pavement (JPCP) that includes the measurement of several key acceptance quality characteristics (AQC's). Each of the AQC's (mean and standard deviation) is related to performance and, thus, to life-cycle costs (LCC's) over a chosen analysis period. The incentive/disincentive pay factors are computed based on expected future performance and costs.

The format and content of these Performance-Related Specifications (PRS) are based in part on the following American Association of State Highway and Transportation Officials (AASHTO) Guide Specifications for Highway Pavement Construction:

- *Guide Specifications for Highway Construction*, 1993.[29]
- *Quality Assurance Guide Specification*, February 1996.[9]
- *Implementation Manual for Quality Assurance*, February 1996.[28]

DIVISION 100. GENERAL PROVISIONS

Section PRS-101. Definitions

The following definitions are applicable to this Specification:

Acceptance Quality Characteristics (AQC's): Inherent measurable pavement characteristics that significantly affect pavement performance, are under the ULect control of the contractor, and are measurable at or near the time of construction. AQC's considered under the current PRS include concrete strength, slab thickness, entrained air content, initial smoothness, and percent consolidation around dowel bars.

Analysis Period: Period of time over which future M & R costs are to be considered in an LCC analysis. The analysis period is typically defined as twice the chosen initial pavement design life.

AQC Target Values: Agency-chosen AQC means and standard deviations that define the agency's desired quality (the AQC quality for which the agency is willing to pay 100 percent of the bid price).

As-Constructed Lot Life-Cycle Cost (LCC_{CON}): The estimated post-construction LCC used to represent the as-constructed pavement lot quality. This value is based (in part) on the measured as-constructed AQC values (means and standard deviations).

As-Constructed Pavement: The actual concrete pavement constructed by the contractor. The as-constructed quality level of each pavement lot is assessed based on AQC sampling and testing (using defined AQC acceptance procedures) of the as-constructed pavement.

As-Designed Lot Life-Cycle Cost (LCC_{DES}): The estimated post-construction LCC used to represent the as-designed pavement quality. This value is based on the as-designed AQC target values (means and standard deviations) selected by the agency.

As-Designed Pavement: The desired concrete pavement, as defined by the agency. The desired quality level of the pavement is specified in terms of target as-designed AQC means and standard deviations.

Buyer: That organization or entity ultimately responsible for the purchase of the materials and work required for the completion of a highway or transportation contract. May be used interchangeably with the terms **agency**, **purchaser**, **consumer**, or **owner**.[(9)]

Constant Values: Project-specific variables required by the distress indicator and cost models that do not differ between the as-designed and as-constructed pavements. These variables define many of the pavement's characteristics and can be grouped into general categories such as traffic, project location and description, climatic conditions, slab design and support, load transfer, and M & R unit costs.

Construction Pass: The defining width of an ongoing paving operation. This definition is used since the width of paving may consist of more than one traffic lane.

Discount Rate: Used to translate actual LCC's into equivalent present worth costs. It is estimated as the difference between the interest and inflation rates over a long time period, representing the real value of money over time. The interest rate, often referred to as the *market* interest rate, is associated with the cost of borrowing money and represents the earning power of money.[(10)] The inflation rate is typically defined as the rate of increase in the prices of goods and services (construction of highways) and represents changes in the purchasing power of money.[(10)]

Distress Indicator: A measure of the condition of an existing pavement section at a particular point in time.[(4)] These key pavement distresses are used to define pavement performance. Distress indicators included in the current PRS approach include transverse slab cracking, transverse joint faulting, transverse joint spalling, and pavement smoothness over time. Within the PRS, the distress indicators are predicted (over a chosen analysis period) using the best available empirical or mechanistic models. Model inputs include project-specific constant values and representative mean values of the selected AQC's.

Equivalent Single-Axle Load (ESAL): An 80-kN single-axle traffic loading. The ESAL is the standard traffic measure used by most SHA's and design methods. Average daily traffic (ADT) numbers are translated into equivalent ESAL's. Many of the distress indicator models are functions of the cumulative ESAL's applied over the chosen analysis life.[(11)]

Expected Pay (EP) Curve: A graphic representation of an acceptance plan that shows the relation between the actual quality of a lot and its expected pay (i.e., mathematical pay expectation, or the average pay the contractor can expect to receive over the long run for submitted lots of a given quality).[(4)]

Global Rehabilitation Activities: Rehabilitation activities applied to the entire lot at one time in response to declining *global* pavement conditions. These activities are specifically applied to address pavement condition indicators such as decreasing pavement smoothness, increasing amounts of localized distress, or increasing amounts of applied localized rehabilitation. Trigger values for these pavement condition indicators must be selected to determine the timing of a global rehabilitation. Examples of global rehabilitation activities include AC overlays, PCC overlays, and diamond grinding.

In Situ Sampling: AQC sampling procedures in which samples are taken ULectly from or on the in-place concrete pavement (e.g., cores and surface profile measurement).

Initial Design Life: Amount of time for which the chosen pavement design is expected to carry traffic loads without the application of a global rehabilitation (AC overlay, PCC overlay, diamond grinding).

International Roughness Index (IRI): The IRI is based on simulation of the roughness response of a car traveling at 80 km/h. It is a ratio of the accumulated suspension motion of the car divided by the distance traveled. The scale ranges from 0 (perfectly smooth surface) to 20,000 mm/km, with larger values indicating greater roughness. A value of 3,000 mm/km is often considered to be the breaking point between "rough" and "smooth" pavements on high-speed highways.

Jointed Plain Concrete Pavement (JPCP): A PCC pavement type characterized by short joint spacing (less than 6 m) and no reinforcing steel mesh or bars. JPCP pavements may or may not be constructed with dowels at the transverse joints. These pavements typically include tie bars at longitudinal joints. Slab thicknesses for this pavement type have historically ranged from 152 to 254 mm; however, newer pavements are being constructed with thicknesses of 305 mm or more.

Life-Cycle Cost (LCC): The estimated cumulative present worth cost of a pavement lot over a specified analysis period. The LCC, as used in PRS, may include estimated future maintenance, rehabilitation, and user costs over a chosen analysis period. The initial construction cost is not included in the LCC since it is identical for both the as-designed and the as-constructed pavements. LCC values are expressed in units of present worth dollars (PW$) per kilometer.

Localized Rehabilitation Activities: Rehabilitation activities that may be used to correct *localized* pavement distresses. Localized distresses are defined as those that may affect an individual joint (transverse joint spalling and transverse joint faulting) or slab (transverse slab cracking).

Lot: A discrete quantity of constructed pavement to which an acceptance procedure (and corresponding pay adjustment) is applied. All pavement placed within a lot should consist of the same mix design and material sources, should be subjected to the same support conditions (base type, base thickness, subbase type, subbase thickness, subgrade treatment), and should consist of the same design characteristics (joint spacing, drainage, shoulder type, dowel-bar diameter, traffic, and AQC design values).

Lot Length: Equal to one day's production or less. The minimum lot length should not be less than 0.16 km. Any section of lesser length will be added to the preceding lot or succeeding lot.

Lot Width: The lot width is defined as the total width of pavement, one or more traffic lanes, being placed at one time in the mainline paving process. This paving width is also referred to as a **construction pass**,since it describes the total width of pavement being placed in one pass of the paving train. The entire width of a widened lane is included; however, shoulders are to be excluded.

Maintenance Activities: Routine activities performed as preventive measures. This maintenance is typically applied at certain fixed intervals of time over the life of a pavement lot (commonly on an annual basis). Examples of maintenance activities include transverse crack and joint sealing.

Maintenance and Rehabilitation (M & R) Plan: The defined set of rules used to predict the type and timing of future M & R activities. Expected localized and global rehabilitation activities are determined based on chosen trigger values applied to each distress indicator. Maintenance activities are applied by defining the amount and application frequency (e.g., seal 100 percent of the transverse joints every 2 years).

Maximum Quality Limit (MQL): Agency-chosen maximum limit for acceptable AQC specimen sample quality. If an AQC specimen sample value is measured to have greater quality than the defined MQL, the representative specimen sample value (used in the acceptance procedures) is set equal to the defined MQL (i.e., the contractor does not receive credit for quality provided in excess of the MQL). For concrete strength, slab thickness, entrained air content, and percent consolidation around dowels, better quality than the MQL is identified by specimen sample values *greater than* the MQL; however, for initial smoothness, better quality than the MQL is identified by specimen sample values *less than* the MQL.

Nondestructive Testing: AQC sampling and testing methods conducted on the in-place pavement, without disturbing the pavement's structural integrity or surface characteristics.

Operating Characteristic (OC) Curve: A graphic representation of an acceptance plan that shows the relationship between the actual quality of a lot and the probability of its acceptance at various payment levels.[4]

PaveSpec 2.0: The revised PRS specification simulation software developed under this research project. This software is used to demonstrate the PRS approach by simulating pavement performance, determining corresponding LCC's, generating preconstruction output, and computing pay adjustments. Its specific functions are described in the *PaveSpec 2.0 User Guide* (appendix G, volume IV).

Pay Adjustment: The actual pay adjustment (incentive or disincentive in PW$) for the as-constructed lot. The computation of the lot pay adjustment differs between the Level 1 and Level 2 PRS.

Level 1 Pay Adjustment—The Level 1 pay adjustment is computed using the determined Level 1 lot composite pay factor (CPF). The actual Level 1 lot pay adjustment is computed using the relationship presented in equation 101-1.

$$PAY_{LOT} = BID * (PF_{COMPOSITE} - 100) * LOT_{LENGTH} \quad (101\text{-}1)$$

where

PAY_{LOT} = Adjusted payment paid to the contractor for the as-constructed lot, $.

BID = Contractor bid price, $/km.

$PF_{COMPOSITE}$ = The determined Level 1 lot CPF, percent (e.g., 101 percent is expressed as 101.0).

LOT_{LENGTH} = Measured actual as-constructed lot length, km.

Level 2 Pay Adjustment—The Level 2 pay adjustment is computed using the determined Level 2 lot pay factor. The actual Level 2 lot pay adjustment is computed using the relationship presented in equation 101-2.

$$PAY_{LOT} = BID * (PF_{LOT} - 100) * LOT_{LENGTH} \quad (101\text{-}2)$$

where

PAY_{LOT} = Adjusted payment paid to the contractor for the as-constructed lot, $.

BID= Contractor bid price, $/km.

PF_{LOT} = The determined Level 2 overall lot pay factor, percent (e.g., 101 percent is expressed as 101.0).

LOT_{LENGTH} = Measured actual as-constructed lot length, km.

Pay Factor (PF): The percent of the bid price that the contractor is paid for the construction of a concrete pavement lot. There are a number of different pay factor-related definitions used within this report.

Basic Pay Factor Definition—The underlying equation used to compute a pay factor for a given lot (based on the comparison of LCC's) is presented as equation 101-3. This equation is used to compute the pay factor for each simulated lot.

$$PF_{LOT} = 100 * (BID + [LCC_{DES} - LCC_{CON}])/BID \quad (101\text{-}3)$$

where

PF_{LOT} = Overall pay factor for the as-constructed lot, percent.

BID = Representative contractor's unit bid price for the lot, $/km.

LCC_{DES} = As-designed life-cycle unit cost for the lot (computed using target AQC's), PW$/km.

LCC_{CON} = As-constructed life-cycle unit cost for the lot (computed using AQC test results from the as-constructed lot), PW$/km.

Level 1 Individual AQC Pay Factors—The pay factors (associated with the measured AQC's) computed using the developed Level 1 individual AQC pay factor equations. Each Level 1 AQC pay factor (expressed as a percentage) is a function of the measured as-constructed AQC lot mean and standard deviation. (Note: Level 1 individual AQC pay factor equations are based on data simulated using the PaveSpec 2.0 computer software.) The final Level 1 individual AQC pay factors may be limited to agency-chosen pay factor practical limits.

Level 1 Composite Pay Factor—The overall pay factor (expressed as a percentage) for an as-constructed lot computed using a Level 1 specification. This pay factor is determined using the agency-defined CPF equation (a simple mathematical function of the individual Level 1 AQC pay factors). The final Level 1 lot CPF (which may be limited to agency-chosen pay factor practical limits) is used to determine the contractor's Level 1 lot pay adjustment.

Level 2 Pay Factor—The overall pay factor (expressed as a percentage) for an as-constructed lot computed using a Level 2 specification. This pay factor is computed using equation 101-3 and may be limited to agency-chosen pay factor practical limits. The PaveSpec 2.0 computer software is used to simulate the required LCC_{DES} based on SHA-defined AQC target values, and estimate the LCC_{CON} based on the measured as-constructed AQC samples.

Performance-Related Specifications (PRS): Construction specifications placed on key materials and construction AQC's (e.g., concrete strength, slab thickness) that have been demonstrated to correlate strongly with long-term pavement performance. These specifications are based on quantified relationships (or mathematical models) that relate measured AQC's to subsequent pavement performance and the corresponding costs.

Present Serviceability Rating (PSR): An indicator of pavement smoothness based on the subjective ratings of users. The PSR is expressed as a number between 0 and 5 with the smaller values indicating greater pavement roughness. The scale is translated into general pavement condition description categories using the following translations.[11]

0 – 1 Very poor.
1 – 2 Poor.
2 – 3 Fair.
3 – 4 Good.
4 – 5 Very good.

Present Worth (PW) Method: A discounted cash flow analysis that involves the conversion of all of the present and future costs to a base of today's costs.[10] Expected future costs are translated into equivalent present worth costs using equation 101-4.

$$PW_{COST} = C / (1 + i)^T \qquad (101\text{-}4)$$

where

PW_{COST} = Present worth of yearly cost (C).

C = M & R, or user cost incurred during year T.

T = Year during which the observed cost (C) was incurred.

i = Chosen discount rate.

Quality Assurance (QA): All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements of quality. Within an organization, QA serves as a management tool. In contractual situations, QA serves to provide confidence in the supplier.[9]

Quality Control (QC): The sum total of activities performed by the seller (producer, manufacturer, or contractor) to make sure that a product meets contract specification requirements. Within the context of highway construction, QC includes materials handling and construction procedures; calibration and maintenance of equipment; production process control;

and any sampling, testing, and inspection done for these purposes.[9]

Rejectable Quality Limit (RQL): Agency-chosen mimimum limit for acceptable AQC specimen sample quality. If an AQC specimen sample value is measured to have poorer quality than the defined RQL, AQC retesting procedures will apply. For concrete strength, slab thickness, entrained air content, and percent consolidation around dowels, poorer quality than the RQL is identified by specimen sample values *less than* the RQL; however, for initial smoothness, poorer quality than the RQL is identified by specimen sample values *greater than* the RQL.

Sample Mean: The average of n random AQC sample values. This sample mean is computed using equation 101-5.

$$MEAN_{SAMPLES} = \sum(x_i)/n \qquad (101\text{-}5)$$

where

$MEAN_{SAMPLES}$ = The computed mean of n random AQC samples.

x_i = 1 to n random sample values.

n = Total number of random samples.

(Note: If m replicate samples are taken from each sampling location, the mean of each set of m test results is used to define a random sample value.)

Sample Standard Deviation: An estimate of the true population standard deviation, σ. If this estimate is to be unbiased, a correction factor must be applied. This unbiased sample standard deviation is computed using equation 101-6.

$$SD_{SAMPLES} = (\{[\sum(x_i - MEAN_{SAMPLES})^2]/(n-1)\}/m)^{0.5} / C_{SD} \qquad (101\text{-}6)$$

where

$SD_{SAMPLES}$ = The computed unbiased standard deviation of all of the random sample values.

$MEAN_{SAMPLES}$ = The computed mean of all of the random sample values.

n = Total number of random samples.

x_i = 1 to n sample values.

m = The number of replicate specimen test results used to compute one sample value.

C_{SD} = Correction factor based on the total sample size, n, used to obtain unbiased estimates of the actual lot sample standard deviation, σ. Appropriate C_{SD} values are determined using table PRS-101-01.

Table PRS-101-01. Correction factors used to obtain unbiased estimates of the actual standard deviation.

Number of Sample Values, n	Correction Factor, C_{SD}
2	0.7979
3	0.8862
4	0.9213
5	0.9399
6	0.9515
7	0.9594
8	0.9650
9	0.9693
10	0.9726
30	0.9915
50	0.9949

Note: Unbiased estimates of the standard deviation are automatically calculated and used in the determination of lot pay factors within PaveSpec 2.0.

Sample Value: An AQC value used to represent one sample location within a sublot. A representative sample value may be the ULect measured value from one test taken at a sample location (no replicate test result values, i.e., *m* =1), or equal to the mean of *m* replicate test result values (from m replicate tests) taken at the same sample location.

Seller: Any entity providing materials and work required for the completion of highway or transportation work. This includes the contractor and all subcontractors. The term may be used interchangeably with **producer** or **supplier**.(9)

Sublot: A portion of a lot. Each lot is divided into sublots of approximately equal surface area. Sublot lengths are selected so that one or more samples may be taken from each sublot for each considered AQC. The minimum sublot length cannot be less than 0.16 km (to accommodate the measurement of initial smoothness). Any section of lesser length will be added to the preceding sublot. Note that in PRS, measurements for all AQC's must be obtained from each sublot so that performance can be predicted.

Target Sublot Length: The chosen default linear length for each sublot. Each as-constructed sublot should initially be assumed to be equal to this target sublot length.

Test Result Value: The computed AQC value from one AQC test. For concrete strength, slab thickness, and entrained air content, this is the testing result from one specimen. For initial smoothness, this is the value obtained from one pass of the profilograph. For percent consolidation around dowels, this is the value obtained from one relative density comparison.

Section PRS-110. Quality Assurance

PRS–110.01 Samples, Tests, and Referenced Specifications.

The contractor shall be responsible for the quality of the construction and materials incorporated into the contract. The contractor shall perform all necessary QC inspection, sampling, and testing. All materials will be approved for acceptance through the agency's acceptance procedures. The agency is responsible for determining the acceptability of the construction and materials incorporated therein. The agency may use the results of the contractor's inspection, sampling, and testing as a part of its acceptance procedures, provided the contractor has an approved QC program.

PRS–110.02 Qualified Testing Laboratory.

The agency central laboratory shall be accredited by the AASHTO Accreditation Program (AAP). All testing laboratories (agency, contractor, consultant, or vendor) shall be approved by the agency.

The contractor's QC laboratory shall be furnished and maintained with adequate ventilation, heat, light, water, sink and drainage, electrical or gas outlets (or both), work tables, shelves, and supply cabinets. The laboratory shall be supplied with equipment and materials necessary to perform all tests required by these specifications and shall be maintained in such condition that the equipment will meet the applicable requirements of the agency. (The agency may want to list the specific equipment that is deemed necessary to satisfy the QC testing requirements of the applicable specifications.)

PRS–110.03 Technician Certification.

The agency shall require that individuals who perform one or more of the actual sampling, testing, and inspection functions for the agency, contractor, vendor, or private laboratories be certified.

Certified sampling and testing personnel provide added assurances that the sampling and testing will be performed correctly and that the results will be valid. The certification program recognized by the agency should be one or more of the following:

- National Institute for Certification in Engineering Technologies.
- The American Concrete Institute or other trade association.
- Individually developed agency program.
- Reciprocity between agencies.

For additional information concerning technician certification, see the "Sampling and Testing Personnel" section of the 1996 AASHTO *Implementation Manual for Quality Assurance.*[28]

PRS–110.04 Quality Control.

The contractor shall provide and maintain a QC system that will assure all materials and products submitted to the agency for acceptance will conform to the contract requirements, whether manufactured or processed by the contractor or procured from suppliers, subcontractors, or vendors. The contractor shall perform, or have performed, the inspections and tests required to substantiate product conformance to contract document requirements. The contractor shall also perform, or have performed, all inspections and tests otherwise required by the contract. The contractor's QC inspections and tests shall be documented and provided to the agency. The contractor shall maintain adequate records of all inspections and tests. The records shall include the nature, number, and type of deficiencies found; the quantities rejected by the contractor; and the nature of corrective action taken, as appropriate. The contractor shall maintain standard equipment and qualified personnel as required by the specifications to assure conformance to contract requirements. Procedures will be subject to approval by the agency before the work is started.

The contractor shall prepare a QC plan detailing the type and frequency of inspection, sampling, and testing deemed necessary to measure and control the various properties of materials and construction governed by the specifications. The QC plan shall be submitted in writing to the agency at the preconstruction conference. This plan shall include the following:

- Construction items covered by the plan.
- Tests to be performed.
- Testing frequencies.
- Sampling locations and techniques.
- Documentation procedures, including:

    1. Inspection and test records.
    2. Temperature measurements.
    3. Accuracy, calibration, or recalibration checks performed on production or testing equipment.
    4. Control charts.

The plan shall identify the personnel responsible for the contractor's QC. This should include the name of the company official who will act as a liaison with agency personnel and the names of the certified technicians who will ULect and conduct the inspection program. When required in these specifications, the contractor shall provide a testing facility or laboratory.

Note: The agency should publish, as a separate document, the minimum content of an acceptable QC plan. Examples of minimum content of an acceptable QC plan are provided in the following publications:

- *Appendix A—Guide for Quality Control and Acceptance Requirements for Portland Cement Concrete* from the 1996 AASHTO *Quality Assurance Guide Specification.*[9]

- *Appendix D—Quality Control Plans* from the 1996 AASHTO *Implementation Manual for Quality Assurance.*[28]

PRS–110.05 Acceptance.

The agency is responsible for determining the acceptability of the material produced. Acceptance of the material is based on the inspection of the construction, monitoring of the contractor's QC program, and acceptance test results.

A. *Sampling and Testing.* The acceptance sampling and testing is the responsibility of the agency. The contractor must provide the necessary materials for testing.

   The agency may use the contractor's QC test results as a part of the acceptance procedures, provided:

   1. The agency's inspection and monitoring activities indicate the contractor has followed the approved QC plan, and

   2. The results from the contractor's QC sampling and testing compare favorably with the agency's results in accordance with Section PRS–110.05 (B).

B. *Validation Procedures for QC Test Results*. If the agency is to use the contractor's QC test data, the contractor's test results shall be validated in accordance with appendix F or appendix G of the 1996 AASHTO *Implementation Manual for Quality Assurance*.[28] The appropriate level of significance is left to the agency's discretion.

C.

PRS–110.06 Quality Pay Adjustments.

The lot pay adjustment provisions shall be developed based on the quality of those AQC's chosen by the agency for acceptance under the specifications. The agency will determine lot pay adjustments based on the measured AQC sample and testing results, in accordance with the developed pay adjustment provisions. The contractor shall be paid the amount of the computed adjusted pay on a lot-by-lot basis.

PRS–110.07 Dispute Resolution.

When there are significant discrepancies between the agency's and contractor's test results, dispute resolution procedures will be used.

A. *Procedures for Resolving Differences*. The contractor and agency must agree upon the test methods to be used. If the test method is not in question, then the agency and contractor should look for differences in procedures and correct the inappropriate procedure before moving to third-party resolution.

B. *Third Party Resolution*. The agency's central laboratory or an independent laboratory will be used to determine material quality results. Whichever laboratory is used, it should be AAP accredited and the results shall be binding.

   The contractor will be responsible for the cost associated with the third-party resolution if the final result indicates that the agency's acceptance test results were correct. Likewise, the agency will be responsible for the cost when the final result indicates that the contractor's acceptance test results were correct. For additional information, see the "Dispute Resolution" section of the 1996 AASHTO *Implementation Manual for Quality Assurance*. [28]

DIVISION 500. RIGID PAVEMENT

Section PRS–501. Jointed Plain Cement Concrete Pavement

PRS–501.01 Description.

This work shall consist of constructing a JPCP on a prepared subgrade or base course, in accordance with these specifications. These specifications apply only to the PCC pavement slab placed in the traffic lanes, and specifically address the following: materials, construction requirements, method of measurement, basis of acceptance, and basis of payment. Pavement shoulders are not addressed under these specifications and shall be accepted using conventional acceptance procedures.

The pavement project is divided into one or more lots for acceptance purposes. Each defined lot will be accepted independently based on AQC sampling and testing conducted by the agency. The contractor shall receive 100 percent of the bid price for a lot if the quality of construction exactly equals that of the target as-designed pavement parameters (AQC target means and standard deviations). If the quality of construction for a lot exceeds or is below the target as-designed AQC's, the contractor shall receive a pay adjustment for the lot (incentive or disincentive). The amount of the pay adjustment is determined based on a comparison of the estimated post-construction LCC's determined independently for both the as-designed and as-constructed pavements. All calculations for the LCC-based pay adjustments shall be performed using the PaveSpec 2.0 computer software.

PRS–501.02 Materials.

Materials shall meet the provisions of the following subsections included in the 1993 AASHTO *Guide Specifications for Highway Construction*.[29]

Portland cement 701.01
Fine aggregate 703.01
Coarse aggregate 703.01
Joint filler 707.01
Reinforcing steel 711.01
Curing materials 713.01
Air-entraining admixtures 713.02
Chemical admixtures 713.03
Water 714.01
Fly ash (optional) 714.11
Ground granulated blast-furnace slag 714.12

PRS–501.03 Construction Requirements.

Agency specifications for construction requirements, including contractor process control, shall be placed here.

PRS–501.04 Methods of AQC Measurement.

A. ***Lots***. Each discrete quantity of pavement representing an as-constructed lot shall be accepted independently by the agency. The length of each lot shall be defined as equal to one day's production or less. It is recommended that a lot length always be set equal to the entire day's production unless a significant within-day change occurs in the paving operation (e.g., change in aggregate source, stoppage of the paving operations for a significant amount of time). When applicable, the entire width of a widened traffic lane is to be considered part of the mainline paving.Pavement shoulders are not included as part of a lot.

B. ***Sublots***. The agency shall attempt to divide each as-constructed lot into sublots with lengths equal to the target sublot length. The target sublot length shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume. The length of the last paved sublot within a lot shall be determined in accordance with the guidelines set forth in chapter 5 of this volume. The total number of sublots observed in an as-constructed lot shall be used as the representative number of sublots per lot for the given lot. The width of a sublot is defined by the width of the lot in which the sublot is observed.

If the final total lot length is less than the agency-chosen target sublot length, the lot may be accepted by the engineer upon a visual inspection of the section and a review of process control results. The agency also has the option to add this material to that of the preceding or succeeding lot.

C. ***Definition of Pavement Performance***. The agency shall define future pavement performance in terms of any or all of the following distress indicators:

- Transverse Joint Spalling.
- Transverse Joint Faulting.
- Transverse Slab Cracking.
- Pavement Smoothness Over Time (expressed in terms of PSR or IRI).

The definition of pavement performance shall be made in accordance with the guidelines set forth in chapter 5 of this volume.

D. ***Included Acceptance Quality Characteristics***. The agency shall base the acceptance of an as-constructed pavement lot on any or all of the following AQC's:

- Concrete strength.
- Slab thickness.
- Entrained air content.
- Initial smoothness.
- Percent consolidation around dowels.

The selection of included AQC's shall be accomplished in accordance with the guidelines set forth in chapter 5 of this volume.

E. ***Selection of AQC Target Values.*** The agency shall define the desired AQC lot quality in terms of AQC means and standard deviations (target values). Target values shall be identified for each of the AQC's chosen to be included in the specifications. The specific chosen target values are also dependent on the chosen AQC sampling and testing methods. The selection of AQC target values shall be accomplished in accordance with the guidelines set forth in chapter 5 of this volume.

F. ***Identification of AQC Limits for Acceptance.*** The agency shall define practical maximum and minimum quality limits to be applied to each measured specimen sample value. The maximum limit shall be referred to as the Maximum Quality Limit (MQL), and the minimum limit shall be referred to as the Rejectable Quality Limit (RQL). If the specimen sample value is measured to be of poorer quality than the defined RQL, then retesting procedures shall be applied. If the specimen sample value is measured to be of greater quality than the defined MQL, the representative specimen sample value (used in the acceptance procedures) shall be set equal to the defined MQL (i.e., the contractor shall not receive credit for quality provided in excess of the MQL). The selection of AQC limits (RQL and MQL) shall be accomplished in accordance with the guidelines set forth in chapter 5 of this volume.

G. ***AQC Sampling and Testing Methods***. Acceptance of an as-constructed pavement lot is based on the sampling and testing of key AQC's. Only those AQC's selected by the agency for inclusion in the specifications are to be sampled. AQC samples shall be taken from every sublot within a given lot using agency-defined sampling frequencies (the number of samples per sublot may differ for each included AQC). The number of AQC sampling locations per sublot, and their corresponding random sampling locations within each sublot, shall be determined in accordance with the guidelines set forth in chapter 5 of this volume.

The acceptance sampling and testing for each included AQC shall be conducted using one of the agency preapproved methods that follow. All AQC acceptance sampling shall be performed in accordance with the following standard specifications:

- *American Association of State Highway and Transportation Officials, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II Tests*.[19]
- *American Society for Testing and Materials (ASTM)*, *Annual Book of ASTM Standards, Section 4, Construction*, *Road and Paving Materials*.[20]

All AQC acceptance and testing shall be conducted in accordance with the guidelines set forth in section PRS–110.05, *Acceptance*.

1. *Concrete Strength*. The 28-day flexural strength (third-point loading—28-day modulus of rupture [M_R]) is required for the acceptance of concrete strength. Specific 28-day M_R values representing each sublot sample location shall be determined using the concrete strength sampling and testing procedures defined below.

   a. *Sampling of Concrete Strength*. Samples used in the determination of the 28-day M_R shall consist of one of three methods. [The agency shall select one of the following.]

      i. *Beams*. Beam specimens (with agency-specified dimensions) are to be molded, handled, and cured in accordance with AASHTO T-23, *Making and Curing Concrete Test Specimens in the Field*.[19] Beam specimens for each sublot shall be made with plastic concrete taken from in front of the paver at predetermined random longitudinal sampling locations. Random longitudinal sampling locations shall be identified in accordance with the guidelines set forth in chapter 5 of this volume. The number of beam specimens per sampling location (replicate specimens) and the number of sampling locations per sublot shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume.

ii. *Cylinders*. Cylinder specimens shall be molded, handled, and cured in accordance with AASHTO T-23, *Making and Curing Concrete Test Specimens in the Field*.[19] All cylinder specimens shall be cast in molds with a nominal length-to-diameter ratio of 2. An appropriate cylinder specimen diameter shall be determined based on the following:

- A minimum 102-mm cylinder diameter shall be used when the maximum aggregate size is 32 mm or less.
- A minimum 152-mm cylinder diameter shall be used when the maximum aggregate size is greater than 32 mm.

Cylinder specimens for each sublot shall be made with plastic concrete taken from in front of the paver at predetermined random longitudinal sampling locations. Random longitudinal sampling locations shall be determined in accordance with the guidelines set forth in chapter 5 of this volume. The number of cylinder specimens per sampling location (replicate specimens) and the number of sampling locations per sublot shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume.

iii. *Cores*. Core specimens shall be extracted from the hardened pavement slab between 48 and 72 hours after placement, in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*. [19] Core specimens shall be extracted from the hardened concrete slab at predetermined random sampling locations. Random core locations shall be determined in accordance with the guidelines set forth in chapter 5 of this volume. The number of core specimens per sublot shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume.

An appropriate core specimen diameter shall be determined based on the following:

- A minimum 102-mm diameter shall be used when the maximum aggregate size is 32 mm or less.
- A minimum 152-mm diameter shall be used when the maximum aggregate size is greater than 32 mm.

Prior to testing, all core specimens shall be trimmed to a nominal length-to-diameter ratio of 2. A correction factor shall be applied (in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*) to cores having a length-to-diameter ratio of less than 1.94, whereas cores having a length-to-diameter ratio between 1.94 and 2.10 require no such correction.[19] Cores with a length-to-diameter ratio exceeding 2.10 shall be reduced in length to fall within the ratio limits of 1.94 to 2.10.

b.

c. *Timing of Concrete Strength Testing*. The agency shall define the timing of the concrete strength specimen testing to be used in estimating the 28-day (equivalent 28-day laboratory maturity) flexural strength (third-point loading) of the as-constructed pavement. Each specimen (molded beam, molded cylinder, or extracted core) shall be tested independently and translated (if necessary) into an M_R at an equivalent 28-day laboratory maturity.

The timing of concrete strength specimen testing shall be defined by the agency and expressed in terms of an equivalent laboratory maturity. The agency-chosen timing of concrete strength specimen testing shall meet the following requirements:

- Testing shall not be conducted until the specimen achieves a maturity of at least 72 hours (3 days) of the equivalent laboratory curing condition maturity.
- Testing must be conducted at or before the point when the specimen achieves a maturity equal to 672 hours (28 days) of the equivalent laboratory curing condition maturity.

d. *Testing-Related Procedures (Conducted Prior to Specimen Testing)*. The agency shall perform the following testing-related laboratory and field procedures (as required) in preparation for concrete strength specimen testing.

. *Laboratory Maturity Calibration*. Prior to the placement of any as-constructed concrete pavement, the agency shall develop required mix-specific maturity curves in the laboratory. The representative maturity curves (expressed as flexural, compressive, or split-tensile strength versus maturity) shall be determined using the Arrhenius maturity method, and in accordance with ASTM C-1074, *Standard Practice for Estimating Concrete Strength by the Maturity Method*, and the guidelines set forth in chapter 5 of this volume.(20)The required developed maturity curves (and corresponding equations) shall be included as *Series A* attachments to these specifications. This laboratory maturity calibration is only required if sample testing is conducted when the equivalent laboratory maturity is less than 28 days.

i. *Laboratory-Developed Inter-Strength Relationships*. Prior to the placement of any as-constructed pavement, the agency shall develop required mix-specific inter-strength relationships (i.e., compressive strength to flexural strength, or split-tensile to flexural strength relationships) in the laboratory. These relationships (curves and respective equations) shall be developed in accordance with the guidelines set forth in chapter 5 of this volume. The required inter-strength relationships (curves and equations) shall be included as *Series B* attachments to these specifications.

ii. *Measuring Maturity in the As-Constructed Pavement*. If the agency selects core specimens as the sampling type, the maturity of the as-constructed pavement shall be monitored for each sublot. Temperatures shall be measured at one central location per sublot using a thermocouple placed at mid-depth of the pavement slab (the thermocouple shall be embedded into the pavement using an agency-approved method). The thermocouple shall be connected to an agency-approved maturity meter. The maturity meter shall begin recording pavement temperatures at the time when the thermocouple becomes completely covered with concrete. Temperatures shall be measured for a given sublot until all of the cores representing the sublot are extracted from the as-constructed pavement.

e. *Specific Concrete Strength Testing Procedures*. Representative flexural strength (third-point loading) values, at a 28-day equivalent laboratory maturity, shall be determined for each specimen using one of three specific testing procedures. [The agency shall select one of the following.]

. *Flexural Testing of Beams*—If the concrete strength of the as-constructed pavement is to be evaluated using beam specimens tested in flexural strength (third-point loading), then the following procedure shall apply.

- Each beam specimen shall be tested (at an agency-defined equivalent laboratory maturity) for flexural strength (third-point loading) in accordance with AASHTO T-97, *Flexural Strength of Concrete (Using Simple Beam With Third-Point Loading)*.[19]

- Each testing result shall be translated to a 28-day flexural strength (28-day equivalent laboratory maturity) using the attached mix-specific flexural strength (third-point loading) versus maturity curve and equation, in accordance with the guidelines set forth in chapter 5 of this volume.; The required maturity curve shall be included as a *Series A* attachment to these specifications. No maturity translations need be applied if beam specimens are tested directly at a 28-day equivalent laboratory maturity.

i. *Compression Testing of Cylinders or Cores*—If the concrete strength of the as-constructed pavement is to be estimated using cylinder or core specimens tested in compression strength, then the following procedure shall apply.

- Each core specimen shall be tested (at an agency-defined equivalent laboratory maturity) for compressive strength in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.[19] Each cylinder specimen shall be tested (at an agency-defined equivalent laboratory maturity) for compressive strength in accordance with AASHTO T-22, *Compressive Strength of Cylindrical Concrete Specimens*.[19]

- Each testing result shall be translated to a 28-day compressive strength (28-day equivalent laboratory maturity) using the attached mix-specific compressive strength versus maturity curve and equation, in accordance with the guidelines set forth in chapter 5 of this volume. The required maturity curve shall be included as a *Series A* attachment to these specifications. No maturity translations need be applied if cylinder or core specimens are tested directly at a 28-day equivalent laboratory maturity.

- Each estimated core or cylinder compressive strength (at a 28-day equivalent laboratory maturity) shall be translated into a representative 28-day flexural strength using the attached mix-specific compressive strength to flexural strength inter-strength relationship (curve and corresponding equation). The required inter-strength relationship shall be included as a *Series B* attachment to these specifications.

ii. *Split-Tensile Testing of Cylinders or Cores*—If the concrete strength of the as-constructed pavement is to be estimated using cylinder or core specimens tested in split-tensile strength, then the following procedures shall apply.

- Each core specimen shall be tested (at an agency-defined equivalent laboratory maturity) for split-tensile strength in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.(19) Each cylinder specimen shall be tested (at an agency-defined equivalent laboratory maturity) for split-tensile strength in accordance with AASHTO T-198, *Splitting Tensile Strength of Cylindrical Concrete Specimens*.(19)

- Each testing result shall be translated to a 28-day split-tensile strength (28-day equivalent laboratory maturity) using the attached mix-specific split-tensile strength versus maturity curve and equation, in accordance with the guidelines set forth in chapter 5 of this volume. The required maturity curve shall be included as a *Series A* attachment to these specifications. No maturity translations need be applied if cylinder or core specimens are tested directly at a 28-day equivalent laboratory maturity.

- Each estimated core or cylinder split-tensile strength result (at a 28-day equivalent laboratory maturity) shall be translated into a representative 28-day flexural strength using the attached mix-specific split-tensile strength to flexural strength inter-strength relationship (curve and corresponding equation). The required inter-strength relationship shall be included as a *Series B* attachment to these specifications.

f. *Concrete Strength Acceptance*. The contractor shall furnish paving equipment and employ methods that give the contractor the ability to produce concrete strengths that meet, or better, the agency-defined target concrete strength quality. The agency-desired target concrete strength quality is defined as the mean and standard deviation of the representative concrete strength values computed for a given lot. Representative concrete strength values are determined for each sample location within each sublot (average of replicates within a sampling location). The agency-defined target concrete strength shall be defined in table PRS-501-01 of these specifications. An as-constructed lot with a concrete strength quality that differs from the target concrete strength quality shall be accepted with price adjustments (incentive or disincentive).

View Table PRS-501-01. Agency-Chosen AQC Sampling and Testing Methods, and Target Values.

Table PRS-501-01. Agency-Chosen AQC Sampling and Testing Methods, and Target Values.

Acceptance Quality Characteristic	Specimen Sampling Method	Timing of Sampling	No. of Samples Per Sublot[2]	No. of Replicates Per Sample	Testing Method	Timing of Testing	Target Mean[1]	Target Std. Dev.[1]
Concrete Strength	a. Beams b. Cylinders c. Cores	a. TOC b. TOC c. A	A	a. A b. A c. 1	1. Flexural (third-point) 2. Compressive 3. Split-tensile	A	A	A
Slab Thickness	Cores	A	A	1	Measurement with ruler	n/a	A	A
Entrained Air Content	1. Plastic Concrete 2. Cores	a. TOC b. A	A	a. A b. 1	Pressure meter Linear traverse	a. TOC b. A	A	A
Initial Pavement Smoothness	California Profilograph	A	A	A	PI determined using an agency-specified blanking band	n/a	A	A
Percent Consolidation Around Dowels	Cores	A	A	1	Comparison of relative core densities	A	A	A

2. A—specified by the agency.
   n/a—not applicable.
   TOC—time of construction.
   PI—profile index.
3. [1]Target AQC means and standard deviations are specific to the chosen sampling and testing methods. Appropriate mean and standard deviation values shall be chosen in accordance with the guidelines set forth in chapter 4 of this volume.

   [2]The required number of AQC samples per sublot shall be chosen by the agency in accordance with the guidelines set forth in chapter 5 of this volume.

Representative 28-day flexural strength values shall be determined for each specimen using one of the methods described above. The agency shall define AQC limits (RQL and MQL) to be applied to each specimen value within a sublot. The following procedure shall apply:

- If a specimen strength value is less than the defined RQL, the agency shall begin retesting procedures. Concrete strength retesting procedures are specified in section PRS–501.05, *Methods of AQC Retesting*.

- If a specimen strength value is greater than the defined MQL, the measured specimen strength value shall be reduced to be equal to the chosen MQL. The reduced specimen strength value shall be used for acceptance.

- All specimen strength values greater than or equal to the RQL, and less than or equal to the MQL, shall be used directly for acceptance.

The specimen strength values (including any adjustments) are then averaged within each sampling location to give strength values representative of each sampling location. These sampling location strength values (averages of replicate specimens) are then used in the PaveSpec 2.0 computer software for the acceptance of concrete strength. (Note: The strength value typically referred to as a *sample per sublot* is actually the average value of all of the replicate specimen values at that particular location).

4.
5. *Slab Thickness*

a. *Sampling and Testing of Slab Thickness.* The thickness of the as-constructed slab shall be determined by measurements taken on cores extracted from each sublot making up an as-constructed pavement lot. Core specimens shall be extracted from the hardened concrete slab between 48 and 72 hours after placement, in accordance with AASHTO T-24, Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.(19) All cores used for the acceptance of slab thickness shall have a minimum diameter of 102 mm.

   Slab thickness shall be measured on all cores extracted for the evaluation of concrete strength; these measured values shall be used in lieu of extracting additional slab thickness cores. When required, randomly selected slab thickness core locations (independent of any cores taken for the evaluation of concrete strength) shall be determined in accordance with the guidelines set forth in chapter 5 of this volume. The number of slab thickness core specimens per sublot shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume.

   The representative thickness of each core shall be determined in accordance with AASHTO T-148, *Measuring Length of Drilled Concrete Cores*.(19)

b. *Slab Thickness Acceptance*. The contractor shall furnish paving equipment and employ methods that give the contractor the ability to produce slab thickness that meet, or better, the agency-defined target slab thickness quality. The agency-desired target slab thickness quality is defined as the mean and standard deviation of the slab thickness values measured for a given lot. The agency-defined target slab thickness shall be defined in table PRS-501-01 of these specifications. An as-constructed lot with a slab thickness quality that differs from the target slab thickness quality shall be accepted with price adjustments (incentive or disincentive).

   The agency shall define AQC limits (RQL and MQL) to be applied to each specimen value within a sublot. The following procedure shall apply:

   - If a specimen slab thickness value is less than the defined RQL, the agency shall begin retesting procedures. Slab thickness retesting procedures are specified in section PRS–501.05, *Methods of AQC Retesting*.

   - If a specimen slab thickness value is greater than the defined MQL, the measured specimen slab thickness value shall be reduced to be equal to the chosen MQL. The reduced specimen slab thickness value shall be used for acceptance.

   - All specimen slab thickness values greater than or equal to the RQL, and less than or equal to the MQL, shall be used directly for acceptance.

The specimen slab thickness values (including any adjustments) are then used in the PaveSpec 2.0 computer software for the acceptance of slab thickness.

6. *Entrained Air Content*

a. *Sampling and Testing of Entrained Air Content.* The entrained air content of the as-constructed pavement shall be determined using one of two agency-approved sampling and testing methods. [The agency shall select one of the following.]

. *Pressure Meter Tests of Plastic Concrete*. Plastic concrete shall be taken in front of or behind the paver at predetermined random longitudinal sampling locations. Random longitudinal sampling locations shall be identified in accordance with the guidelines set forth in chapter 5 of this volume. If beam or cylinder specimens are required for the estimation of concrete strength, entrained air content pressure meter tests may be conducted at the same longitudinal locations used for the strength investigation. If behind-the-paver samples are chosen, material shall be removed from the slab using an agency-approved method.

The plastic concrete removed in front of or behind the paver shall be tested with an agency-approved air pressure meter in accordance with AASHTO T-152, *Air Content of Freshly Mixed Concrete by the Pressure Method*.(19) The number of pressure meter tests per sampling location (replicate specimens), and the number of sampling locations per sublot, shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume.

i. *Linear Traverse Tests of Hardened Concrete Cores.* Core specimens shall be extracted from the hardened concrete slab at predetermined random sampling locations. Random sampling core locations shall be determined in accordance with the guidelines set forth in chapter 5 of this volume. Core specimens shall be extracted between 48 and 72 hours after placement, in accordance with AASHTO T-24, Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.(19) All cores used for the acceptance of entrained air content shall have a minimum diameter of 152 mm. The number of core specimens per sublot shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume.

Linear traverse testing shall be performed on each extracted hardened concrete core specimen in accordance with ASTM C-457, *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*.(20) Testing may occur at any time after the extraction of the core specimen. The measured entrained air content (expressed as a percentage) for each extracted core is used as the representative entrained air content value for that sampling location.

b. *Entrained Air Content Acceptance*. The contractor shall furnish paving equipment and employ methods that give the contractor the ability to produce entrained air contents that meet, or better, the agency-defined target entrained air content quality. The agency-desired target entrained air content quality is defined as the mean and standard deviation of the representative entrained air content values computed for a given lot. Representative entrained air content values are determined for each sample location within each sublot (average of replicates within a sampling location). The agency-defined target entrained air content shall be defined in table PRS-501-01 of these specifications. An as-constructed lot with an entrained air content quality that differs from the target entrained air content quality shall be accepted with price adjustments (incentive or disincentive).

The agency shall define AQC limits (RQL and MQL) to be applied to each specimen value within a sublot. Note: Replicate specimens may exist at a sampling location if entrained air content is measured with a pressure meter. The following procedure shall apply:

- If a specimen entrained air content value is less than the defined RQL, the agency shall begin retesting procedures. Entrained air content retesting procedures are specified in section PRS–501.05, *Methods of AQC Retesting*.

- If a specimen entrained air content value is greater than the defined MQL, the measured specimen entrained air content value shall be reduced to be equal to the chosen MQL. The reduced specimen entrained air content value shall be used for acceptance.

- All specimen entrained air content values greater than or equal to the RQL, and less than or equal to the MQL, shall be used directly for acceptance.

If entrained air content is measured using an air pressure meter, replicate samples shall be averaged to give *representative* entrained air content values at each sample location. If entrained air content is measured using linear traverse, the representative values are the entrained air content values measured from each core directly. Regardless of the sample type chosen, the representative values are used in the PaveSpec 2.0 computer software for the acceptance of entrained air content.

7.
8. *Initial Smoothness*

a. *Sampling and Testing of Initial Smoothness*. The initial smoothness of the pavement shall be quantified in terms of a profile index (PI), which will be determined using a California-type profilograph. The profilogram is to be recorded on a scale of 2.54 cm or full-scale, vertically. Motive power may be manual or by propulsion unit attached to the assembly. The profilograph shall be moved longitudinally along the pavement at a speed no greater than 4.8 km/h to minimize bounce. The results of the profilograph test will be evaluated as outlined in the California Department of Transportation (Caltrans) specification CA-526. All profile indices are to be determined using a 0.0- or 5.1-mm blanking band.

A minimum of two pavement profiles (one in each wheelpath) shall be determined for each lane within each defined sublot. The total number of required pavement profiles per sublot shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume. The location of a *wheelpath* shall be 0.92 m from a longitudinal joint or longitudinal pavement edge and parallel to the centerline of the mainline paving. For widened slabs, the outer wheelpath shall be 0.92 m from the pavement edge paint stripe, rather than the outer pavement edge. Each profile shall terminate 4.5 m from each bridge approach pavement or existing pavement that is joined by the new pavement. The PI determined for each profile shall be converted to a standard unit of mm/km.

During the initial paving operations, or after a long shutdown period, the pavement surface shall be tested with the profilograph when the concrete has cured sufficiently to allow testing. Membrane curing damaged during the testing operation shall be repaired by the contractor and at the contractor's expense. If the initial pavement smoothness, paving methods, and paving equipment are acceptable, paving operations may proceed.; After initial testing, profiles of each day's paving will be run prior to continuing paving operations.

If an average PI of _____ mm/km (limit to be inserted by the agency) is exceeded in any daily paving operation, the paving operation will be suspended and not resume until corrective action is taken.

Within each sublot, all areas represented by high points having deviations in excess of _____ mm (limit to be inserted by the agency—10 mm is recommended) in 7.6 m or less shall be corrected at the contractor's expense. Corrections shall be made using an approved profiling device or by removing and replacing the pavement, as directed by the engineer. Bush hammers or other impact devices shall not be used. Where corrections are made, the surface texture shall be re-established to provide a uniform texture equal to the surrounding uncorrected pavement by the contractor and at the contractor's expense. Corrective work shall be completed prior to determining pavement thickness.

b. *Initial Smoothness Acceptance.* The contractor shall furnish paving equipment and employ methods that give the contractor the ability to produce a riding surface that meets, or betters, the agency-defined target initial smoothness quality. The agency-desired target initial smoothness quality is defined as the mean and standard deviation of the representative profile indices computed for a given lot. Representative PI values are determined for each sample location within each sublot (average of replicates within a sampling location). The agency-defined target initial smoothness shall be defined in table PRS-501-01 of these specifications. An as-constructed lot with an initial smoothness quality that differs from the target smoothness quality shall be accepted with price adjustments (incentive or disincentive).

The agency shall define AQC limits (RQL and MQL) to be applied to each specimen PI value within a sublot. For PI, the RQL will be greater than the MQL due to the nature of the measurement (the lower the PI, the better the quality). The following procedures shall apply:

- If a specimen PI value is greater than the defined RQL, the agency shall begin retesting procedures. Initial smoothness retesting procedures are specified in section PRS–501.05, *Methods of AQC Retesting*.

- If a specimen PI value is less than the defined MQL, the measured specimen PI value shall be increased to be equal to the chosen MQL. The increased specimen PI value shall be used for acceptance.

- All specimen PI values less than or equal to the RQL, and greater than or equal to the MQL, shall be used directly for acceptance.

The specimen PI values (including any adjustments) are then averaged within each profile location to give PI values representative of each profile sampling location. These PI values (averages of replicate profile indices) are then used in the PaveSpec 2.0 computer software for the acceptance of initial smoothness. The initial smoothness value, typically referred to as a *sample per sublot*, is actually the average value of all of the replicate specimen values at that particular profile location.

Price adjustments (if any) are based on the as-placed pavement before any retesting or corrective actions are completed.

9.
10. *Percent Consolidation Around Dowels*

a. *Sampling and Testing of Percent Consolidation Around Dowels*. The percent consolidation around dowels representing the as-constructed pavement shall be determined within each sublot using an agency-approved sampling and testing method. The approved sampling and testing method shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume.

The representative percent consolidation around one randomly selected dowel bar in a sublot shall be determined based on a comparison of the density of two selected cores extracted from the hardened concrete slab. Core specimens shall be extracted from the hardened pavement slab between 48 and 72 hours after placement, in accordance with AASHTO T-24, *Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.[19] All cores used for the acceptance of percent consolidation around dowels shall have a minimum diameter of 102 mm.

The first of the two required cores shall be taken through a predetermined randomly selected dowel bar in a randomly selected transverse joint (random selection of a dowel shall be determined in accordance with the guidelines set forth in chapter 5 of this volume). The outside edge of the core through the randomly selected dowel bar shall not be within 0.6 m of a defined wheelpath or pavement edge, 10 cm of a predicted vibrator path, or 5 cm of a transverse joint. The dowel bar piece shall be separated from the concrete core material by an agency-approved method. The density of this concrete material shall be measured in a saturated surface dried condition in accordance with ASTM C-642, *Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete* and labeled as $DEN_{THROUGH\text{-}DOWEL(n)}$.[20]

The second of the two required cores shall be taken at a location along a line passing through the first core (through the dowel bar) and parallel to the centerline of the pavement unit. The specific longitudinal location of this second core shall be assumed to be at midslab of the leave slab (the slab away from the joint in the direction of traffic) adjacent to the randomly selected transverse joint. The density of this concrete material shall be measured in a saturated surface dried condition in accordance with ASTM C-642, *Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete* and labeled as $DEN_{MID\text{-}SLAB(n)}$.[20]

The number of samples per sublot (e.g., pairs of cores) shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume. The maximum of all of the midslab core densities measured within the given lot ($MAX\text{-}DEN_{MID\text{-}SLAB}$) shall be determined and assumed to represent the density of a core with 100-percent consolidation. The representative percent consolidation for each sampling location (set of cores) is, therefore, determined by the following equation:

$$\%\ Consolidation = (DEN_{THROUGH\text{-}DOWEL(n)} / MAX\text{-}DEN_{MID\text{-}SLAB}) * 100. \qquad (501\text{-}1)$$

b. *Acceptance of Percent Consolidation Around Dowels*. The contractor shall furnish paving equipment and employ methods that give the contractor the ability to produce a percent consolidation around dowels that meets, or betters, the agency-defined target percent consolidation quality. The agency-desired target percent consolidation quality is defined as the mean and standard deviation of the percent consolidation values computed for a given lot. The agency-defined target percent consolidation around dowels shall be defined in table PRS-501-01 of these specifications. An as-constructed lot with a percent consolidation quality that differs from the target percent consolidation quality shall be accepted with price adjustments (incentive or disincentive).

The agency shall define AQC limits (RQL and MQL) to be applied to each representative percent consolidation value within a sublot. (Note: A representative percent consolidation value is defined as the computed percent consolidation value representative of one sample location.) The following procedures shall apply:

- If a representative percent consolidation sample value is less than the defined RQL, the agency shall begin retesting procedures. Percent consolidation retesting procedures are specified in section PRS–501.05, *Methods of AQC Retesting*.
- If a representative percent consolidation sample value is greater than the defined MQL, the measured representative sample value shall be reduced to be equal to the chosen MQL. The reduced representative percent consolidation sample value shall be used for acceptance.
- All representative percent consolidation sample values greater than or equal to the RQL, and less than or equal to the MQL, shall be used directly for acceptance.

The representative percent consolidation sample values (including any adjustments) are then used in the PaveSpec 2.0 computer software for the acceptance of percent consolidation around dowels.

PRS–501.05 Methods of AQC Retesting.

Additional sampling and testing for any of the AQC's for acceptance testing may be requested at any time by the contractor or by the agency. The agency shall conduct all of the sampling and testing for any retesting activities.

The following specific conditions shall be applied for determining whether the agency or contractor is responsible for the cost of the retesting:

Insert agency-defined conditions used to define retesting cost responsibility.

The pavement shall be retested only once in accordance with the retesting methods described in this section. Retesting procedures shall be initiated when any measured AQC specimen value fails to meet or exceed the respective agency-defined RQL. The purpose of retesting is to determine if the AQC quality provided by the contractor is truly less than the quality defined by the RQL.

If retesting procedures determine conclusively that an identified area of pavement is deficient in quality (having lesser quality than the respective agency-defined RQL), the result shall be the removal and replacement of the identified area. AQC sampling and testing values from the replaced material shall then be used in place of the original sampling and testing results for that sampling location. However, the measured AQC samples are subjected to MQL's equal to the respective AQC target values (i.e., the contractor may not get credit for AQC quality better than the target values when material has been removed and replaced).

If retesting procedures determine conclusively that an identified area of pavement is not deficient in quality (having greater quality than the respective agency-defined RQL), the additional AQC samples taken for retesting shall be added to the original AQC sample value set (if no testing error occurred). The average of all the AQC sampling and testing results (original and retesting) representing a sampling location shall then be used as the representative AQC value for that sampling location.

The retesting procedures for each AQC are described separately below.

A. *Concrete Strength*. If a concrete strength specimen sample is found to be less than the agency-defined concrete strength RQL, the following procedure shall apply:

Insert agency-defined concrete strength retesting procedures here.

B. *Slab Thickness*. If a slab thickness specimen sample is found to be less than the agency-defined slab thickness RQL, the following procedure shall apply:

Insert agency-defined slab thickness retesting procedures here.

C. *Entrained Air Content*. If an entrained air content specimen sample is found to be less than the agency-defined entrained air content RQL, the following procedure shall apply:

Insert agency-defined entrained air content retesting procedures here.

D. *Initial Smoothness*. If an initial PI specimen sample is found to be less than the agency-defined initial PI RQL, the following procedure shall apply:

Insert agency-defined initial smoothness retesting procedures here.

E. *Percent Consolidation Around Dowels* If a percent consolidation around dowels specimen sample is found to be less than the agency-defined percent consolidation RQL, the following procedure shall apply:

Insert agency-defined percent consolidation around dowels retesting procedures here.

PRS–501.06 Basis of Acceptance

A. *Life-Cycle Costs*. The agency-chosen AQC's are combined into a single characteristic representing the pavement quality, the post-construction LCC of the pavement expected to be incurred over the designated analysis period. The post-construction LCC quality characteristic relates directly to the future performance of the pavement. The post-construction LCC shall be used as the single overall characteristic representing a pavement lot's quality for acceptance.

B. *As-Designed Target Pavement*. The target as-designed pavement is defined as the desired construction quality for which the agency will pay 100 percent of the contractor bid price. It includes target means and standard deviations for each of the AQC's considered in the agency-chosen acceptance plan. The target AQC standard deviations are representative of acceptable AQC variability. These standard deviations are point-to-point variations (including materials and testing variations) for concrete strength, slab thickness, and entrained air content in the slab; variations between longitudinal profiles for initial smoothness; and dowel-to-dowel variations for percent consolidation of concrete.

   The as-designed target lot mean LCC (LCC_{DES}) is determined by simulating an agency-defined number of lots with the AQC means and standard deviations set at the agency-defined target values. (The number of lots used for the simulation shall be defined by the agency in accordance with the guidelines set forth in chapter 5 of this volume.) This simulation of LCC_{DES} shall be accomplished using the PaveSpec 2.0 computer software. The project-specific constant values required for the simulation of LCC's shall be defined by the agency and included as *Series C* attachments to these specifications. Appropriate values for the constant values shall be selected by the agency in accordance with the guidelines set forth in chapter 5 of this volume. The agency-defined AQC target values (means and standard deviations), and the respective acceptance sampling and testing procedures, are defined in table PRS-501-01.

C. *As-Constructed Pavement Lot*. The acceptance of the as-constructed pavement lot is based on the representative AQC testing values measured in accordance with the agency-defined sampling and testing plan summarized in table PRS-501-01. The AQC representative sample values are summarized differently according to the chosen pay adjustment method.

PRS–501.07 Basis of Payment

The agency shall determine contractor pay adjustments using Level 1 or Level 2 pay adjustment methods. The specific procedures for each are described below.

A. *Level 1 Pay Adjustment*. [Recommended for initial implementation of PRS.]

1. *Simulation of the Target As-Designed Lot LCC*. Prior to the placement of any mainline PCC, the agency must determine the one LCC value representing the target as-designed LCC (LCC_{DES}). This LCC_{DES} is determined from simulation procedures (using the PaveSpec 2.0 computer software) and is based on the agency-defined AQC target values (summarized in table PRS-501-01). The LCC_{DES} shall be used as the one overall characteristic representing the quality of the as-designed target pavement.

2. *Development of Individual AQC Pay Factor Charts and Equations*. Prior to the placement of any mainline PCC, individual pay factor charts (and respective equations) shall be developed for each of the AQC's selected by the agency for inclusion in the specification (see section PRS–501.04, *Method of Measurement, Definition of Pavement Performance*). These individual AQC pay factor charts and equations are based on the LCC_{DES} simulated in step 1 and shall be developed using the PaveSpec 2.0 computer software. The required pay factor charts and equations shall be included as *Series D* attachments to these specifications.

3. *Development of a Lot Composite Pay Factor Equation*. Prior to the placement of any mainline PCC, an appropriate lot composite pay factor (CPF) equation shall be determined by the agency in accordance with the guidelines set forth in chapter 6 of this volume. Only those AQC's chosen by the agency for acceptance shall be considered in the CPF equation.

4. *Summary of Representative Lot AQC Sample Values*. When using the Level 1 pay adjustment procedure, all of the representative sample values shall be statistically summarized into representative AQC lot means and standard deviations. (Note: If more than one sample is taken from a single sampling location, the mean of the replicate samples is used as the representative sample value for that location.) These computed AQC lot means and standard deviations are used to define the quality of the as-constructed lot and shall be used as the basis of computed pay adjustments. Specific definitions of sample means and sample standard deviations are contained in the list of definitions included in section PRS–101 of this specification.

5. *Determination of Individual AQC Lot Pay Factors*. Individual lot pay factors shall be determined (for each AQC chosen for acceptance) based on the computed AQC lot means and standard deviations. Individual lot AQC pay factors are determined using the computed lot AQC means and standard deviations in the individual AQC pay factor curves and equations (included as *Series D* attachments to these specifications). Individual AQC pay factor calculations shall be completed in accordance with the procedure set forth in chapter 8 of this volume.

If the agency chooses to apply pay factor limits to any or all of the individual AQC lot pay factors, they must be selected and applied in accordance with the guidelines set forth in chapter 6 of this volume.

6. *Calculation of the Overall Lot CPF*. The CPF for the as-constructed lot shall be computed using the agency-defined CPF equation. The resulting composite lot pay factor ($PF_{COMPOSITE}$) shall be used to determine the actual contractor pay adjustment. If the agency chooses to apply limits (minimum or maximum) to the overall lot CPF, the following shall apply [the agency shall insert appropriate values into the provided blanks]:

   - If $PF_{COMPOSITE}$ is determined to be less than ______ percent, the agency shall make a determination if the work can remain in place. If allowed to remain in place, the agency shall accept the non-specification work using an adjusted CPF of $PF_{COMPOSITE}$ = ______ percent.

   - If $PF_{COMPOSITE}$ is determined to be greater than ______ percent, the agency shall accept the lot using an adjusted CPF of $PF_{COMPOSITE}$ = ______ percent.

   Agency-chosen limits to the overall composite lot pay factor shall be applied in accordance with the guidelines set forth in chapter 6 of this volume.

7. *Adjustment of Contractor Bid Price*. The total payment to the contractor for the as-constructed lot shall be determined using the following equation:

$$PAY_{LOT} = BID * (PF_{COMPOSITE} / 100) * LOT_{LENGTH} \qquad (501\text{-}02)$$

where

PAY_{LOT} = Adjusted payment paid to the contractor for the as-constructed lot, $.

BID = Contractor bid price, $/km.

$PF_{COMPOSITE}$ = The determined Level 1 lot CPF, percent (e.g., 101 percent is expressed as 101.0).

LOT_{LENGTH} = Measured actual as-constructed lot length, km.

B. *Level 2 Pay Adjustment*

1. *Simulation of the Target As-Designed Lot LCC.* Prior to the placement of any mainline PCC, the agency must determine the one LCC value representing the target as-designed LCC (LCC_{DES}). This LCC_{DES} is determined from simulation procedures (using the PaveSpec 2.0 computer software) and is based on the agency-defined AQC target values (summarized in table PRS-501-01). The LCC_{DES} shall be used as the one overall characteristic representing the quality of the as-designed target pavement.

2. *Summary of Representative Sublot AQC Sample Values.* When using the Level 2 pay adjustment procedure, all of the representative sample values (representing each sampling location—including adjusted sample values) within each sublot shall be statistically summarized into specific sublot means for each AQC. (Note: These values are computed in the PaveSpec 2.0 computer software.) These computed AQC sublot

means are used to define the quality of each respective as-constructed sublot and shall be used as the basis for computed pay adjustments for the as-constructed lot.

3. *Simulation of the As-Constructed Lot LCC.* The computed AQC sublot means are used to simulate the one LCC used to represent the actual as-constructed lot (LCC_{CON}). The respective LCC_{CON} shall be computed using the PaveSpec 2.0 computer software. The LCC_{CON} shall be used as the one overall characteristic representing the quality of the actual as-constructed pavement.

4. *Calculation of the Overall Lot Pay Factor.* The overall lot pay factor for the as-constructed lot shall be computed using the following equation:

$$PF_{LOT} = 100 * (BID + [LCC_{DES} – LCC_{CON}]) / BID \quad (501\text{-}03)$$

where

PF_{LOT} = Overall pay factor for the as-constructed lot, percent.

BID = Contractor bid price, $/km.

LCC_{DES} = Simulated representative as-designed target lot LCC (based on target AQC lot means and standard deviations), $/km.

LCC_{CON} = Simulated representative as-constructed lot LCC (based on measured AQC sublot means), $/km.

The resulting overall lot pay factor (PF_{LOT}) shall be used to determine the actual contractor pay adjustment. If the agency chooses to apply limits (minimum or maximum) to the overall lot pay factor, the following shall apply (Note: The agency shall insert appropriate values into the provided blanks.):

- If PF_{LOT} is determined to be less than ______ percent, the agency will make a determination if the work can remain in place. If allowed to remain in place, the agency shall accept the non-specification work using an adjusted lot pay factor of PF_{LOT} = ______ percent.

- If PF_{LOT} is determined to be greater than ______ percent, the agency shall accept the lot using an adjusted lot pay factor of PF_{LOT} = ______ percent.

Agency-chosen limits to the overall lot pay factor shall be applied in accordance with the guidelines outlined in chapter 6 of this volume.

5. *Adjustment of Contractor Bid Price*. The total payment to the contractor for the as-constructed lot may be determined by one of the following equations:

$$PAY_{LOT} = (LCC_{DES} – LCC_{CON}) * LOT_{LENGTH} \quad (501\text{-}04)$$

or

$$PAY_{LOT} = BID * (PF_{LOT} / 100) * LOT_{LENGTH} \quad (501\text{-}05)$$

where

PAY $_{LOT}$ = Adjusted payment paid to the contractor for the as-constructed lot, $.

LCC $_{DES}$ = Simulated representative as-designed target lot LCC (based on target AQC lot means and standard deviations), PW$/km.

LCC $_{DES}$ = Simulated representative as-constructed lot LCC (based on measured AQC sublot means), PW$/km.

BID = Contractor bid price, $/km.

PF $_{LOT}$ = The determined Level 2 overall pay factor for the as-constructed lot, percent (e.g., 101 percent is expressed as 101.0).

LOT $_{LENGTH}$ = Measured actual as-constructed lot length, km.

Attachment Series A—Laboratory Maturity Calibration Curves And Respective Equations

Attachment Series A may contain any or all of the following laboratory-developed concrete strength versus maturity curves (as so required by section PRS–501.04–G.1.c.i, *Laboratory Maturity Calibration* of these PRS specifications):

- Flexural strength (third-point loading) versus maturity.
- Compressive strength versus maturity.
- Split-tensile strength (third-point loading) versus maturity.

Each required curve is developed using the Arrhenius maturity method. The resulting strength versus maturity regression equations, determined in accordance with the guidelines set forth in chapter 5 of this volume, are presented in table PRS–A–1.

(if applicable, insert flexural strength (third-point loading) versus maturity chart here)

Figure PRS–A–1. Laboratory-developed flexural strength (third-point loading) versus maturity chart.

(if applicable, insert compressive strength versus maturity chart here)

Figure PRS–A–2. Laboratory-developed compressive strength versus maturity chart.

(if applicable, insert split-tensile strength versus maturity chart here)

Figure PRS–A–3. Laboratory-developed split-tensile strength versus maturity chart.

Table PRS–A–1. Strength versus maturity regression equations (if applicable).

Maturity Curve	Regression Equation[1]
Flexural Strength (third-point loading)[2]	M_R = **f**(AMAT)
Compressive Strength[3]	f'c = **f**(AMAT)
Split-Tensile Strength[4]	ST = **f**(AMAT)

[1]Regression equations are functions of Arrhenius maturity (AMAT), expressed as an *Equivalent Age (hours)*.
[2] Flexural (third-point loading) strengths are expressed as M_R.
[3] Compressive strengths are expressed as f'c.
[4] Split-tensile strengths are expressed as ST.

Attachment Series B–Laboratory-Developed Inter-Strength Curves And Respective Equations

Attachment Series B may contain one or both of the following laboratory-developed inter-strength relationship curves (as so required by section PRS–501.04–G.1.c.ii, *Laboratory-Developed Inter-Strength Relationships* of these specifications):

- Compressive strength versus flexural strength (third-point loading).
- Split-tensile strength versus flexural strength (third-point loading).

Inter-strength relationships are determined by conducting different strength testing on specimens at the same equivalent maturities. The resulting equations giving the relationships between 28-day (equivalent laboratory maturity) compressive or split-tensile strength and 28-day flexural strength (third-point loading), determined in accordance with the guidelines set forth in chapter 5 of this volume, are presented in table PRS–B–1.

(if applicable, insert compressive versus flexural strength [third-point loading] inter-strength chart here)

Figure PRS–B–1. Laboratory-developed compressive strength versus flexural strength (third-point loading) chart. Each point on the chart represents a comparison of strengths at equivalent maturities.

(if applicable, insert split-tensile versus flexural strength [third-point loading] inter-strength chart here)

Figure PRS–B–2. Laboratory-developed split-tensile strength versus flexural strength (third-point loading) chart. Each point on the chart represents a comparison of strengths at equivalent maturities.

Table PRS–B–1. Inter-strength relationships at an equivalent laboratory maturity of 28 days (if applicable).

28-day Inter-Strength Relationship	Equation
Compressive[1] to Flexural Strength[3]	28-day M_R = **f**(28-day f'c)
Split-Tensile[2] to Flexural Strength[3]	28-day M_R = **f**(28-day ST)

[1]Compressive strengths at an equivalent laboratory maturity of 28 days are expressed as *28-day f'c*.
[2]Split-tensile strengths at an equivalent laboratory maturity of 28 days are expressed as *28-day ST*.
[3] Flexural (third-point loading) strengths at an equivalent laboratory maturity of 28 days are expressed as *28-day M_R*.

Attachment Series C-Project-Specific Constant Values

Attachment Series C consists of a table containing all of the project-specific constant values required to define the as-designed and as-constructed pavements (as stated in section PRS–501.06–B, *As-Designed Target Pavement* of these specifications).

Table PRS–C–1. Table of project-specific constant values.

(insert table of project-specific constant values here)

Attachment Series D–Level 1 Individual AQC Pay Factor Charts And Equations

Attachment Series D shall contain individual pay factor charts (and respective pay factor equations) for all of the AQC's chosen for inclusion in these specifications under section PRS–501.04–D, *Included Acceptance Quality Characteristics*. Each AQC pay factor chart is developed in accordance with the guidelines set forth in chapter 7 of this volume. The resulting pay factor regression equations (developed for specific agency-selected AQC standard deviations in accordance with chapter 7 of this volume) are presented in table PRS–D–1.

(if applicable, insert Level 1 concrete strength pay factor chart here)

Figure PRS–D–1. Level 1 concrete strength pay factor chart.

(if applicable, insert Level 1 slab thickness pay factor chart here)

Figure PRS–D–2. Level 1 slab thickness pay factor chart.

(if applicable, insert Level 1 entrained air content pay factor chart here)

Figure PRS–D–3. Level 1 entrained air content pay factor chart.

(if applicable, insert Level 1 initial smoothness pay factor chart here)

Figure PRS–D–4. Level 1 initial smoothness pay factor chart.

(if applicable, insert Level 1 percent consolidation around dowels pay factor chart here)

Figure PRS–D–5. Level 1 percent consolidation around dowels pay factor chart.

Table PRS–D–1. Level 1 AQC pay factor regression equations (if applicable).

Acceptance Quality Characteristic	As-Constructed Standard Deviation (s)[1]	Pay-Factor Regression Equation[2]
Concrete Strength	STR–s_1	$PF_{STR(1)}$ = **f**(strength mean)
	•	•
	•	•
	•	•
	STR–s_i	$PF_{STR(i)}$ = **f**(strength mean)
Slab Thickness	THK–s_1	$PF_{THK(1)}$ = **f**(slab thickness mean)
	•	•
	•	•

	•	•
	THK–s_j	$PF_{THK(j)}$ = **f**(slab thickness mean)
Entrained Air Content	AIR–s_1	$PF_{AIR(1)}$ = **f**(entrained air content mean)
	•	•
	•	•
	•	•
	AIR–s_k	$PF_{AIR(k)}$ = **f**(entrained air content mean)
Initial Smoothness	SM–s_1	$PF_{SM(1)}$ = **f**(initial smoothness mean)
	•	•
	•	•
	•	•
	SM–s_l	$PF_{SM(l)}$ = **f**(initial smoothness mean)
Percent Consolidation Around Dowels	CON–s_1	$PF_{CON(1)}$ = **f**(percent consolidation mean)
	•	•
	•	•
	•	•
	CON–s_m	$PF_{CON(m)}$ = **f**(percent consolidation mean)

[1]Specific standard deviations are chosen by the agency. Regression equations are typically developed for three to five different agency-chosen standard deviations for each AQC.

[2]Regression equations are functions of the respective AQC measured mean.

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