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PERFORMANCE-RELATED SPECIFICATIONS (PRS) FOR CONCRETE PAVEMENTS IN INDIANA

VOLUME 1
EXECUTIVE SUMMARY

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Volume 1: Executive Summary

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16. Abstract

Performance-Related Specifications (PRS) are specifications that base pavement acceptance and pay adjustment on the projected performance and predicted life-cycle cost (LCC) for a specific pavement. PRS relate measurable quality characteristics with pavement performance through computer simulations that incorporate physical distress models. Previously, work at ERES consultants by Darter and co-workers developed prototype PRS for jointed plain portland cement concrete pavements (PCC) through Federal Highway Administration (FHWA) through a series of research projects. However, before this research program began, pavements have not been constructed using these specifications.

This report describes the Indiana Department of Transportation's (INDOT) experience with developing and implementing the first and second Level 1 PRS projects during the re-construction of a portion of I-465 east of Indianapolis and I-65 north of Clarksville, respectively. This report includes an overview of the concepts behind PRS, the process of developing a Level 1 PRS, lessons learned from implementing the first PRS in the construction of the pavement outside Indianapolis during the summer of 2000, lessons learned from implementing the second PRS in the construction of the pavement outside Clarksville during the summer of 2002, the use of non-destructive testing procedures to obtain measures of pavement quality, sample specifications, and conclusions and recommendations. In general, this specification was well received by both the agency and the contractors. It is believed that lessons learned on these projects will enable future modifications to the development of performance related specifications with the hope that these specifications will enable longer lasting, more cost effective pavements to be constructed.

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LIST OF ACRONYMS AND ABBREVIATIONS

AQC	**Acceptance Quality Characteristic**
FHWA	**Federal Highway Administration**
JPCP	**Joint Plain Concrete Pavement**
INDOT	**Indiana Department of Transportation**
LC	**Life Cycle**
LCC	**Life Cycle Cost**
NDT	**Nondestructive Test**
PF	**Pay Factor**
PRS	**Performance Related Specifications**
QC/QA	**Quality Control / Quality Assurance**

ABSTRACT

Performance-Related Specifications (PRS) are specifications that base pavement acceptance and pay adjustment on the projected performance and predicted life-cycle cost (LCC) for a specific pavement. PRS relate measurable quality characteristics with pavement performance through computer simulations that incorporate physical distress models. Previously, Darter and co-workers [2, 3, 5, 6] developed prototype PRS for jointed plain portland cement concrete pavements (PCC) through Federal Highway Administration (FHWA) research projects. However, to date, pavements have not been constructed using these specifications. This paper describes the Indiana Department of Transportation's (INDOT) experience with developing and implementing the first and second Level 1 PRS projects during the re-construction of a portion of I-465 east of Indianapolis and I-65 north of Clarksville, respectively. This paper includes an overview of the concepts behind PRS, the process of developing a Level 1 PRS, lessons learned from implementing the first PRS in the construction of the pavement outside Indianapolis during the summer of 2000, and the lessons learned between the first and second projects. In general, this specification was well received by both the agency and the contractors. It is firmly believed that lessons learned on these projects will enable future modifications to the specification that will enable longer lasting, more cost effective pavements to be constructed.

INTRODUCTION

A performance related specification (PRS) is a specification that directly relates key material and construction quality characteristics with long-term pavement performance [2, 3, 5, 6]. A PRS can be viewed in part as an improved quality control/quality assurance (QC/QA) specification since both of these specifications identify desired levels of pavement quality rather than a desired pavement performance. However, unlike a conventional QC/QA specification in which a minimum level of quality is established that is believed to correspond with an overall level of performance, PRS directly relate the as-constructed pavement quality with the long-term overall performance using mathematically based distress models and life-cycle cost analysis. The concept of directly relating performance to the quality of the constructed pavement is a revolutionary step forward for the construction industry that can enable a more rational basis for payment adjustment (incentives and disincentives) based on the differences between the value of the actual and specified quality. The PRS approach differs from the current 'Performance-Based' approaches that are being proposed, which base incentives and disincentives on a speculative and somewhat arbitrary improvement in performance, by PRS' ability to link these incentives to simulated, quantifiable, performance. The PRS approach thereby provides an alternative to the current low bid system, in which a contractor can receive full payment for meeting a minimum level of initial quality, by providing an incentive for contractors to provide a higher quality product. In addition, this type of approach may ultimately result in an ability to optimize the cost versus performance characteristic of the concrete pavement system.

BACKGROUND ON PERFORMANCE RELATED SPECIFICATIONS (PRS)

Initial research on the development of PRS for concrete pavements was performed by Weed [14] for the New Jersey Department of Transportation and furthered by the development of prototype PRS by Darter and co-workers [2, 3, 56] over the next decade through a series of FHWA projects [14]. A computer simulation procedure (PaveSpec™) was developed that couples pavement design inputs with distress modeling to enable life-cycle performance of a pavement to be performed. Life-cycle costs can be computed based on the performance of the pavement and the repairs that will be needed in this pavement over its simulated life. The life cycle cost of the pavement with the quality provided by the contractor (as-built pavement) is compared with the life-cycle cost of the pavement that the agency designed (as-designed pavement). The differences in the present worth of both the 'as-designed' and 'as-built' pavements are computed and used to develop rational cost-benefit pay adjustments, thereby linking the incentives and disincentives with anticipated performance. While the following paragraph provides a brief overview of the concepts used in PRS, the reader is referred to available literature for further details and further background [3, 14].

In general, the aforementioned approach relates acceptance quality characteristics (AQC's) with life-cycle performance as determined through the use of pavement distress models. AQC's are measurable features of a pavement that are within the contractor's control that correspond to the overall performance of the pavement. Examples of typical AQC's would include strength, thickness, smoothness, and air-content. Distress models refer to empirical or deterministic relationships that link quality characteristics to the development of damage and deterioration in a concrete pavement. Examples of such deterioration may include transverse joint spalling or faulting. Pavement performance is predicted in the current approach by using the PaveSpec™ software to relate project specific information with the AQC's and distress models. This software uses project specific information such as the traffic, climate, and support conditions to predict what types of distress would occur in a pavement and when these distresses will occur over time. Once the performance of the as-designed pavement has been predicted the as-designed Life-Cycle Cost (LCC) can be computed using the cost associated with repairing a pavement over a specified period of time by utilizing a user-specified repair strategy.

The as-designed LCC is predicted based upon project-specific components, the target AQC values, and the AQC standard deviations associated with a given project. The as-constructed LCC is predicted by repeating this process using the same project-specific components, however all of the AQC means and standard deviations that are used are based on those of the constructed pavement. The difference between the as-designed LCC and the as-constructed LCC is therefore caused by the differences in AQC. The LCC difference is also used to calculate the pay adjustment, for any given lot. The pay adjustment is expressed as a percentage of the bid price, and is termed the pay factor.

Each AQC pay factor is a function of the mean and standard deviation. If the measured mean and standard deviation of the as-constructed pavement is equal to the target mean and standard deviation, the pay factor will be equal to 100%. A bonus or penalty pay factor will result from a greater mean and lower standard deviation, or a lower mean and higher standard deviation, respectively.

Three levels (level 1, 2 and 3) of a PRS have been outlined [2, 3, 56] by which agencies can transition from current construction specifications to the ideal PRS. As one may expect, a level 1 PRS is the simplest version of the PRS. The Level 1 PRS is designed as a first step for implementation by governmental agencies in which only minimal changes are needed to convert from the existing QC/QA specifications. It is anticipated that the sampling and testing procedures used in a Level 1 PRS will not vary significantly from an agency's existing QC/QA procedures, thereby helping to create a smooth transition from the QC/QA approach to the PRS methodology. The price adjustment in a Level 1 PRS is based on a numerical combination of independent pay factors for each of the AQC's. A Level 2 PRS differs from a Level 1 PRS in that a computer simulation is used to directly compute the pay adjustment without the need for combining independent pay factors, as is done in Level 1 PRS. A level 2 PRS encourages the use of more in-situ and nondestructive sampling and testing. A level 3 PRS represents the 'ideal specification' in which all aspects of the concrete pavement construction that are related to pavement performance are measured and used in the life-cycle simulation. The ideal PRS would also nondestructively measure all AQC's, in situ, at early-ages, thereby enabling rapid acceptance and pay adjustment while providing the contractor with immediate feedback.

BACKGROUND ON THE PRS SOFTWARE

The software used in the PRS projects in Indiana is called PaveSpec^{TM}, a life-cycle cost analysis program. PaveSpec was first created in 1993 by ERES Consultants in a FHWA-funded project to develop prototype PRS for portland cement concrete pavement [6]. Since then it has undergone several revisions. The investigation in this study was performed using PaveSpec version 3.0.

PRS can be broken into two types of models: performance-prediction models and maintenance-cost models [11]. These models are combined to calculate the pavement's life-cycle cost, as shown in Figure 1.

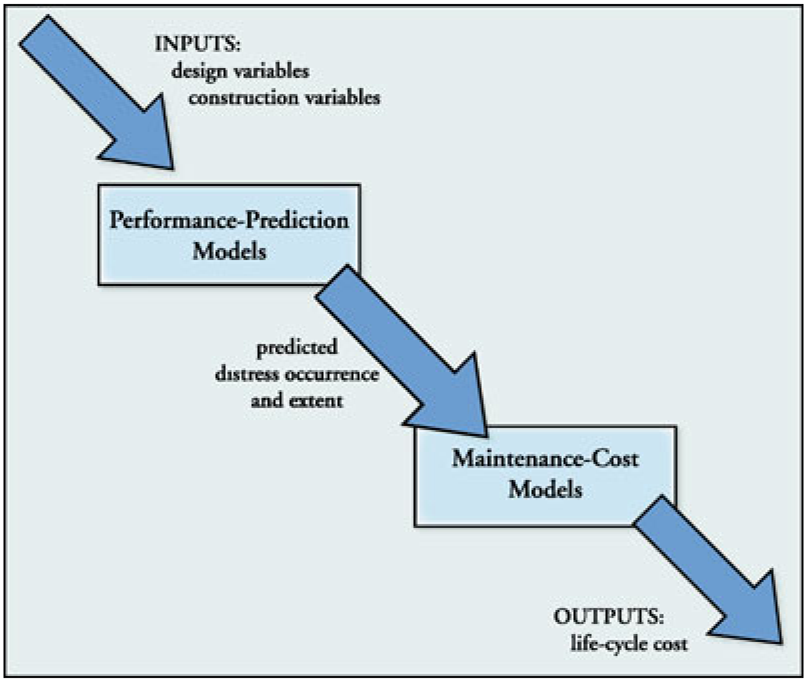


Figure 1: Use of Models in PRS (Kopac 2002)

The four performance-prediction models, e.g. distress models, included in PaveSpec^{TM} 3.0 are shown in Table 1. A table similar to this originally appeared in the guide for a previous version of PaveSpec [5]. However, this was updated for the latest version of the software as used in this project. To effectively use PRS's, the agency must be able to define the performance of the pavement in terms of measurable distresses or deterioration. Different pavements exhibit different distresses. For example, flexible pavements may undergo rutting or alligator cracking, while rigid pavements may experience faulting and spalling.

Table 1: Distress Indicator Models in PaveSec 3.0

Distress Indicator	Constant Value (Input)	Acceptance Quality Characteristics (Input)	Distress Indicator Units (Output)
Transverse Joint Faulting	• Cumulative ESALs • Presence of dowel bars • Dowel bar diameter • Transverse joint spacing • Average annual # of days > 32 °C • Average annual precipitation • Erodibility factor • Modulus of subgrade reaction • Base permeability • PCC modulus of elasticity	• Slab thickness • Percent consolidation around dowels (optional)	Average faulting per joint, mm or in.
Transverse Slab Cracking	• Cumulative ESALs • Climatic zone • Base thickness • PCC modulus of elasticity • Base modulus of elasticity • Modulus of subgrade reaction • Shoulder type • Load transfer efficiency • Transverse joint spacing • Presence of bonded base	• Slab thickness • Concrete strength	Percent of cracked slabs, %
Transverse Joint Spalling	• Age • Joint sealant type • Water-cement ratio • Average annual air freeze-thaw cycles	• Air content • Concrete strength • Slab thickness	Percent of spalled joints, % (medium and high severity)
Pavement Smoothness (IRI)	• Age • Freezing index • Percent subgrade material passing the 0.075 mm (#200) sieve	• Initial IRI (Note: the outputs from the cracking, spalling, and faulting models are also inputs into the IRI model)	IRI, mm/km or in/mi

ESAL = Equivalent Single-Axle Loading
32 °C = 90 °F
IRI = International Roughness Index

Table 1 shows that the inputs for the performance-prediction models can be grouped into two categories: constant-value inputs and AQC's. AQC's are measures of construction quality that are related to the performance of the pavement through the models as shown. The AQC's currently used in PRS are concrete flexural strength, slab thickness, air content, and initial smoothness. Consolidation around the dowels is an optional AQC, which was neither used in the first PRS project nor the second PRS project.

As seen in Figure 1, the output of the distress models is entered into a maintenance-cost model. The maintenance-cost model then estimates the total post-construction life-cycle cost; in other words, the cost of maintenance and rehabilitation that will be necessary for the project life of the pavement [11]. The life-cycle cost also includes a certain percentage of user costs, which are a function of the smoothness of the pavement.

Using the process shown in Figure 1, PaveSpec simulates the as-designed pavement performance and as-constructed pavement performance to form the basis for pay adjustments. Individual lot pay factors are created for each AQC by comparing the as-designed life-cycle cost with the as-constructed life-cycle cost as shown in Equation 1 [5]:

$$PF_{lot} = 100 \times \frac{BID + (LCC_{DES} - LCC_{CON})}{BID}$$ **Equation 1**

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 AQCs), present-worth \$/km, and

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

The importance of the Equation 1 is twofold. First, it reveals that a <u>decrease</u> in the life-cycle cost of an as-constructed pavement results in an <u>increase</u> in contractor pay. Second, Equation 1 impacts the effectiveness of PRS. The performance-prediction models do not have to be 100% accurate for PRS to be effective. Examining the method for calculating payment adjustment in Equation 1 shows that PRS perform a comparative assessment of the life-cycle costs. Errors in the life-cycle cost prediction for as-designed pavements and as-constructed pavement will tend to offset one another. Using Equation

1, the PRS software, PaveSpec, helps create the pay factor charts for individual AQC's to include in the contract documents.

DEVELOPMENTMENT OF THE FIRST PRS IN INDIANA

A PRS was developed and implemented under a joint research project involving INDOT, the FHWA, and Purdue University as a part of a FHWA initiative on the utilization of PRS. This PRS was the first of two PRS projects that was constructed as a part of the current research project while a third PRS project has recently been let for bid. The development of the first PRS required the integration of past PRS research with existing INDOT practices and procedures. The following paragraphs describe the scope and objectives of this project, the input used in the simulations, the pay factor curves used in the contract, specification development, implementation of the PRS, and preliminary construction results. In addition, a summary of lessons leaned from this project will be provided with the goal of assisting other agencies in implementing a PRS of their own.

Project Scope and Objectives for Contract #1: I-465 East of Indianapolis

The objective for the first project was to develop a Level 1 PRS for implementation on a construction project for the 2000 construction season. The decision was made to begin with a Level 1 PRS that utilized as much of the existing INDOT QC/QA specifications as possible. In retrospect, this approach was well received as it allowed the agency and contractors to become accustomed to the changes that occur with the use of PRS. The AQC's that were chosen for measurement included strength, thickness, and initial smoothness of the concrete pavement. A software program called

PaveSpec^{TM} was used to correlate the as-designed pavement AQC's to the as-constructed pavement AQC's in order to determine pay incentives and/or disincentives to the contractor. A pavement section of I-465 on the east side of Indianapolis was chosen for implementation of the Level 1 PRS. The re-construction of I-465 consisted of 6 divided lanes of jointed plain concrete pavement (JPCP) that was designed to have 3.6 m wide lanes, 6 m joint spacing, 0.35 m depth, and a thirty-year service life. The project was completed in 2000.

Development of Data Input for Computer Simulation

Input data was needed to conduct the simulations of the I-465 pavement enabling the pavement performance and life-cycle costs to be estimated. To facilitate the collection of all of the necessary data from the various INDOT divisions (Roadway Management, Operations Support, Research, and Materials and Tests), a blank input table was developed by paging through the software that listed each required input, the options available in the software package to satisfy each input, and the most likely source of the data (see the summary provided in Table 17 and Table 18). As INDOT decided to only measure concrete strength, slab thickness, and initial smoothness, data pertaining to entrained air content and percent consolidation around dowels have not been included. During the first PRS contract, the fresh air content was considered through the current QC/QA procedures.

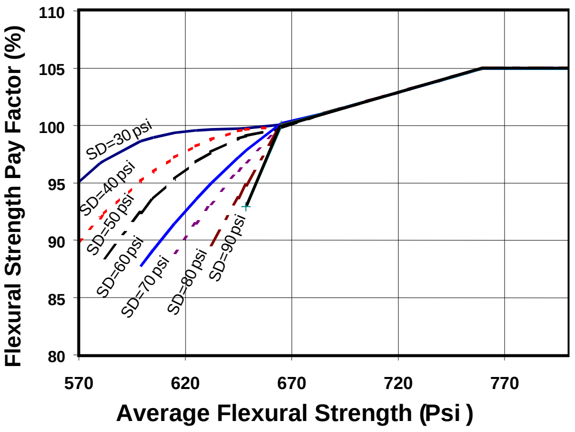
Much of the required information was directly available, such as pavement design, traffic design, project identification, and AQC sampling and testing information. It should be noted, however, that some of the information was not directly available for items like costs, maintenance and rehabilitation plan inputs, climate, and AQC 'as-designed' target value information. Further developments are needed to obtain better input information for this data and to make this information more easily accessible during PRS development.

Performance Simulation and Pay Factor Charts

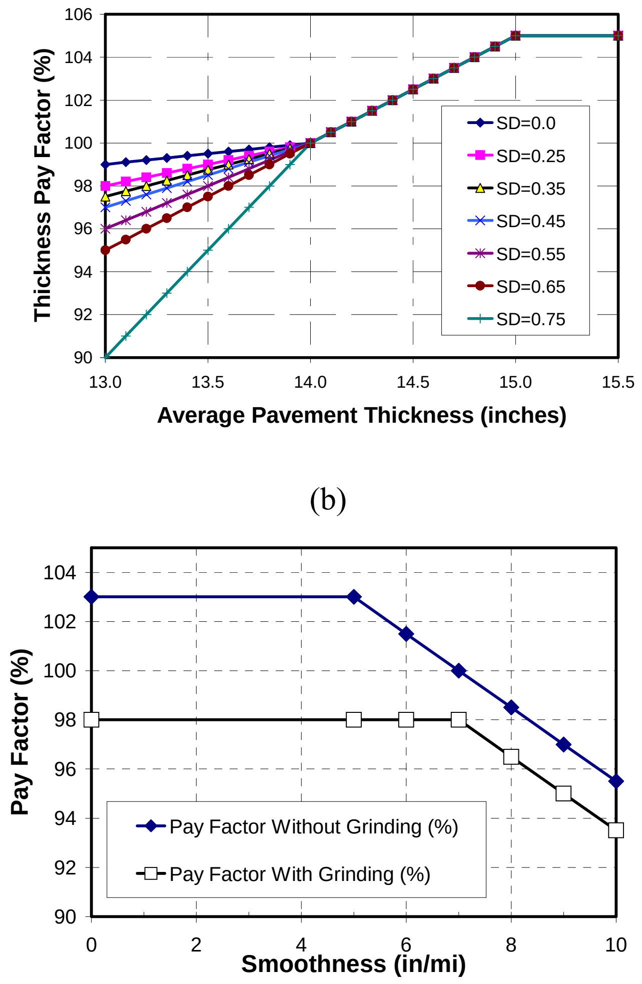
The information from Table 17 and Table 18, located at the end of this paper, was collected and used to simulate the performance of the pavement and to develop pay factor charts for each AQC, for the first project, using PaveSpec^{TM} 2.0. The second project used inputs very similar to Table 17 and Table 18 but used PaveSpec^{TM} 3.0 and included more inputs. Each series of simulated pay factor charts contains a series of curves with each curve specific to a particular standard deviation.

The simulation inputs were systematically varied to determine their overall impact on the pay factor charts that were obtained. After reviewing the effects of the simulations on the pay factor charts, it appeared that there was some variation between the design procedures used by INDOT and the mathematical models used in the software, mainly with respect to the level of reliability that was used in the design procedures and the PRS simulation procedures.

Specifically, the variations in the levels of reliability appear to have resulted in pay factor charts which contained very little incentive for producing pavement with AQC values greater than the target values determined by INDOT. However, there was penalty for producing pavement with AQC values less than the target values determined by INDOT. While this may be a reasonable solution if the pavement is designed to a sufficient thickness at which increasing the thickness may have little impact on improved performance, INDOT realized that it was unlikely that contractors would enthusiastically bid on a project with little incentive and significant opportunity for penalty. Therefore, the pay factor charts were modified to include more incentive. As a result, the pay factors for concrete strengths above the target flexural strength were subjectively chosen to rise linearly from 100% at the design strength to 105% for concrete strength with the maximum AQC (the pay factors below 100% are based on fits of the simulation output). Similarly the pay factors for concrete thicknesses above the target thickness were arbitrarily chosen to rise linearly from 100% at the design thickness to 103% (again the factors below 100% are based on fits of the simulation output). INDOT also capped the maximum smoothness pay factor at 103% and subjectively introduced a 2% penalty for any grinding up to a maximum pay factor of 98%. The basic pay factors used in the first contract are illustrated in Figure 2.



(a)



(b)

(c)

Figure 2: Pay factor Curves for the First Project for (a) Strength, (b) Thickness, and (c) Smoothness

To eliminate difficulties that could arise from reading the exact pay factor off of the graph, a pay factor table was created. While both the graph and table appeared in the specification, the table governed while the graph was used for illustration of the trends in the table.

The composite pay factor equation determines the final pay factor for each lot based on the pay factors for each AQC for that lot. INDOT decided to use a straight average of the pay factors as the composite pay factor equation for the Level 1 PRS. The composite pay factor equation for the mainline pavement therefore included the pay factors for all three AQC's; however, the composite pay factor equation for the shoulder pavement only included the pay factors for two AQC's: flexural strength and thickness. The initial smoothness of the shoulder pavement or ramps were not measured or considered by INDOT.

Development of the Specification Document

While the original FHWA guideline provides sample language for a PRS specification, INDOT wanted to develop the PRS specification to be as consistent as possible with the existing INDOT QC/QA specification. It was believed that this consistency would provide a minimal level of undue anxiety to the contractors bidding on the project. The existing QC/QA specification was therefore used as the baseline, and only changes necessary for the PRS were implemented.

It was determined that to minimize the changes to the PRS specification for each of the subsequent PRS projects (it should be recalled that the inputs and resulting pay factors are specific to each project) an appendix to the specification should be developed that would contain the project specific information. As a result, changes to the body of the specification are not required for additional PRS contracts and only an appendix containing the pay factor charts, minimum and maximum acceptance quality limits, and expressions for determining the aggregate pay factor determination would need to change from project to project. It is anticipated that this could be a valuable time saving option for both the agency and contractor since it will enable them to become familiar with a 'typical' standard document.

IMPLEMENTING THE FIRST LEVEL 1 PRS IN INDIANA

The process of implementing the Level 1 PRS relied heavily on the use of both formal and informal meetings with the contactors to explain and discuss the proposed new specifications. The Indiana Concrete Paving Association assisted in facilitating a discussion with the local contractors at their annual meeting, while the JTRP assisted to facilitate a discussion with contractor and agency personnel at their annual Road School meeting[1]. Presentations were made to both of these groups to describe PRS and outline how PRS differs from the standard QC/QA specification they were currently using. After several informal meetings of this type the contract containing the PRS was let, questions on the PRS were answered at a pre-bid meeting, bids were received, and the contract was awarded. However, additional steps were taken to ensure that the PRS concepts in the contract were clearly understood by contractors. Special time was devoted to understanding the differences associated with PRS at the pre-bid, pre-construction, and partnering meetings to answer any questions concerning PRS.

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[1] Road School is an extension program that initiated in Indiana in 1913 to help local and state officials in the development and maintenance of the roadway network throughout Indiana. Purdue Road School attracts over 1,000 local and state officials, consultants, and suppliers each year to discuss recent advancements in pertinent transportation issues.

In conjunction with the implementation of the Level 1 PRS, a testing program investigating both the conventional AQC testing procedures and nondestructive test (NDT) methods to determine concrete strength and slab thickness. While the complete testing program consisted of laboratory and field-testing [9], this paper will discuss only the AQC's as measured using the conventional AQC's on this project.

DEVELOPMENT OF THE SECOND PRS IN INDIANA

At the conclusion of the first PRS project, it was decided to continue to develop PRS for the second project in much of the same manner as the first. However, some significant changes occurred between the two projects. The following paragraphs describe the scope and objectives of this project and a comparison of the two PRS projects.

Project Scope and Objectives for Contract #2: I-65 North of Clarksville

The objective for the second project was to further develop a Level 1 PRS for implementation on a construction project for the summer of 2002. A section of I-65 near Clarksville, IN was chosen for implementation of the Level 1 PRS. The reconstruction of I-65 consisted of 4 divided lanes of JPCP that was designed to have 3.6 m wide lanes, 6 m joint spacing, 0.35 m depth, and a thirty-year service life. The project was completed on October 18, 2003.

Comparison of the First and Second PRS Projects

Although prototype PRS have been developed for JPCP since 1996, only two projects have been constructed with PRS as of 2003, both in Indiana. The first PRS project in Indiana was constructed in the summer of 2000 on I-465 on the east side of Indianapolis. As part of the project, a research committee was formed to assist INDOT in transitioning from QC/QA specifications to PRS. After the completion of the first project, several shortcomings were noted in the PRS and improvements were suggested. The implementation of this second PRS project was improved based on the lessons learned in the first PRS project. Those lessons included:

- Proper determination of the AQC target mean values
- Consideration of contractor behavior on setting quality targets.
- Simplifying smoothness measurements

The projects had different design characteristics, allowing for some comparison between the PRS use in each. For example, the first year design traffic volume from project #1 to project #2 decreased 33% from 90,700 ADT to 61,200 ADT[2]. The second project was located approximately 180 km (110 miles) south of the first, having a slightly milder climate. A different contractor was awarded the second contract, and a different district office of INDOT was responsible for the project administration. This increased the number of personnel having been involved on at least one PRS project and provided different perspectives and reactions to the use of PRS.

In addition to the project design conditions, the computer software also changed between projects. PRS require performance prediction models to simulate the life-cycle

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[2] Average Daily Traffic

of the pavement, allowing for a comparison between the as-designed and as-constructed life-cycle costs. The software package used to run the life-cycle cost simulations, PaveSpec™, was employed in both projects. However, the first project used version 2.0, while the second project used the updated version 3.0. Specific changes were made in version 3.0 to update the pavement distress models used in PaveSpec [5]. These improvements made data acquisition easier, provided increased accuracy, and correlated better with specific site characteristics. Additionally, many software bugs were fixed.

The design of the two projects was not identical, although the projects were similar. Each was an interstate project in an urban setting. However, different contractor quality targets, otherwise known as AQC's, were chosen for each project. AQC's are measurable pavement characteristics that are related to pavement performance and under the direct control of the contractor. Table 2 summarizes the design AQC values for the two PRS projects in Indiana.

Table 2: AQC's for the (a) first and (b) second PRS Projects in Indiana

	1st Project (R-24432): I-465 east of Indianapolis			
AQC Value	Target Mean	Target Standard Deviation	Rejectable Quality Limit (RQL)	Maximum Quality Limit (MQL)
7-day Flexural Strength	4.6 MPa (665 psi)	0.34 MPa (50 psi)	??? ???	none none
28-day Flexural Strength	4.8 MPa (700 psi)	0.34 MPa (50 psi)	??? ???	none none
Thickness	360 mm (14 in.)	13 mm (0.5 in.)	334 mm (< 13 in)	386 mm (15 in.)
Air Content	not used	not used	not used	not used
Smoothness	110 mm/km (7 in./mile)	50 mm/km (3 in./mile)	155 mm/km (> 10 in./mile)	78 mm/km 5 in./mile

(a)

	2nd Project (R-25715): I-65 north of Clarksville			
AQC Value	Target Mean	Target Standard Deviation	Rejectable Quality Limit (RQL)	Maximum Quality Limit (MQL)
7-day Flexural Strength	4.3 MPa (620 psi)	0.28 MPa (40 psi)	??? ???	??? ???
28-day Flexural Strength	4.5 MPa (650 psi)	0.28 MPa (40 psi)	4.0 Mpa (< 575 psi)	5.5 Mpa (800 psi)
Thickness	380 mm (15 in.)	13 mm (0.5 in.)	360 mm (<14.0 in.)	411 mm (16.0 in.)
Air Content	6.5%	0.5%	< 4.0 % or > 10.0 %	none
Smoothness	110 mm/km (7 in./mile)	50 mm/km (3 in./mile)	160 mm/km (> 10 in./mile)	50 mm/km (3 in./mile)

(b)

Several changes in the design of the two projects can be seen in Table 2. First is the decrease in the target strength mean and standard deviation from the first to the second project. The reason for the decreased is outlined in the “Choosing Target Acceptance Quality Characteristics” subsection of this paper. Second, the mean target thickness was increased 7% from the first to the second project. The Pavement Design Division of INDOT was responsible for this decision. Third, the air content was not designated as an AQC for the first PRS project, but instead it was governed by INDOT’s existing QC/QA specifications. The average value for air content from the QC/QA specifications, 6.5%, was used as the target AQC mean for the second project. Lastly, the target smoothness values between projects were not changed, but the procedure to incorporate the smoothness measurements was modified. The requirement of three individual sublot smoothness measurements was reduced to one overall lot measurement, simplifying the implementation.

LESSONS LEARNED FROM IMPLEMENTATION OF THE FIRST PRS

While the first portion of this paper has provided an account of the experience of implementing the first and second PRS contract in Indiana, as well as a short comparison of the projects, several lessons were learned and used in the further development of PRS for the second contract, which began during the summer of 2002. The following subsections provide an overview of the main difficulties in implementing a PRS and current approach that is being used to overcome these difficulties.

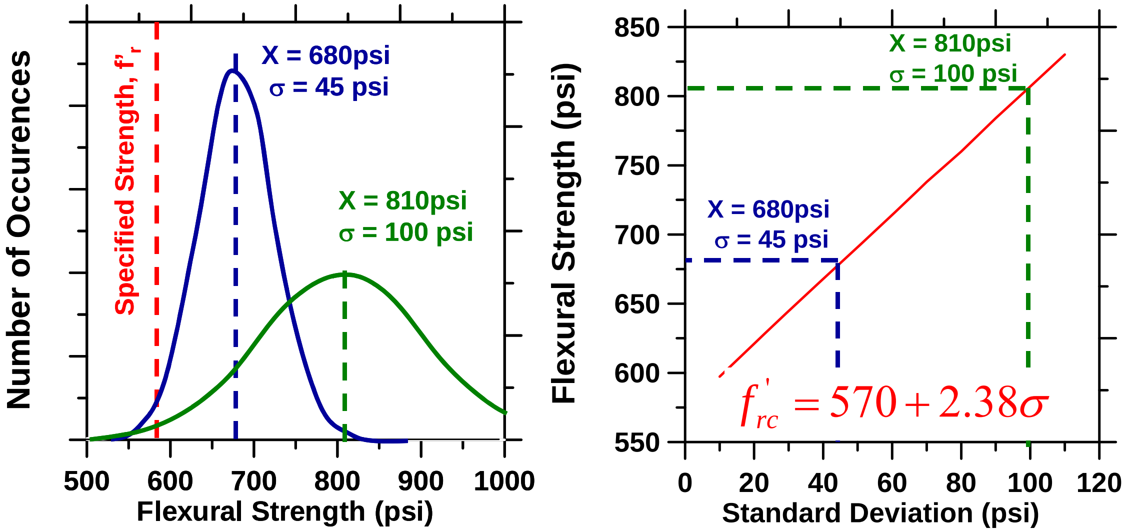
Choosing Target Acceptance Quality Characteristics

It should be noted that one of the most difficult tasks in establishing a PRS is the determination of the 'as-designed acceptance quality characteristics'. The as-designed AQC for thickness for example is simply the specified thickness of the pavement and the selection of this AQC is straightforward; however, this process is not as easy as for other AQC values (i.e., strength) and can significantly impact the bid price and pay factors. The value for flexural strength used in conventional design, method specifications, and QC/QA specifications is taken as the minimal acceptable value. For example, current QC/QA procedures in Indiana utilize a minimum flexural strength of 570 psi.

PRS, however, require the use of an average or mean value of the AQC with a specified standard deviation rather than a minimum acceptance level (i.e., 570 psi). This implies that in the conventional QC/QA approach the contractor will likely choose to target a mean value of strength that will enable them to have a minimal (if any) amount of specimens with measured strength that is below the specified limit. To do this the contractor typically follows an approach like that outlined in ACI 214 [4] where their ‘target average strength’ is defined as the sum of the minimum acceptable strength (570 psi) plus some safety factor (e.g., 2.38 times the standard deviation obtained from their standard material manufacturing process).

As one may expect, a review of the standard deviations that were obtained from previous paving contracts in Indiana illustrated a wide range of variability in the standard deviations of flexural strength measurements, depending on the control processes employed by the contractor. For example, one contractor was observed to have a standard deviation of 45 psi while another contractor had a standard deviation of 100 psi. As a result, it is difficult to establish the target mean strength simply by following the ACI 214 procedure since it is dependent (to some extent) on the variability in the contractors’ process.

To illustrate the role of the target AQC in the development of a PRS a simple conceptual illustration is provided in Figure 3.



(a)

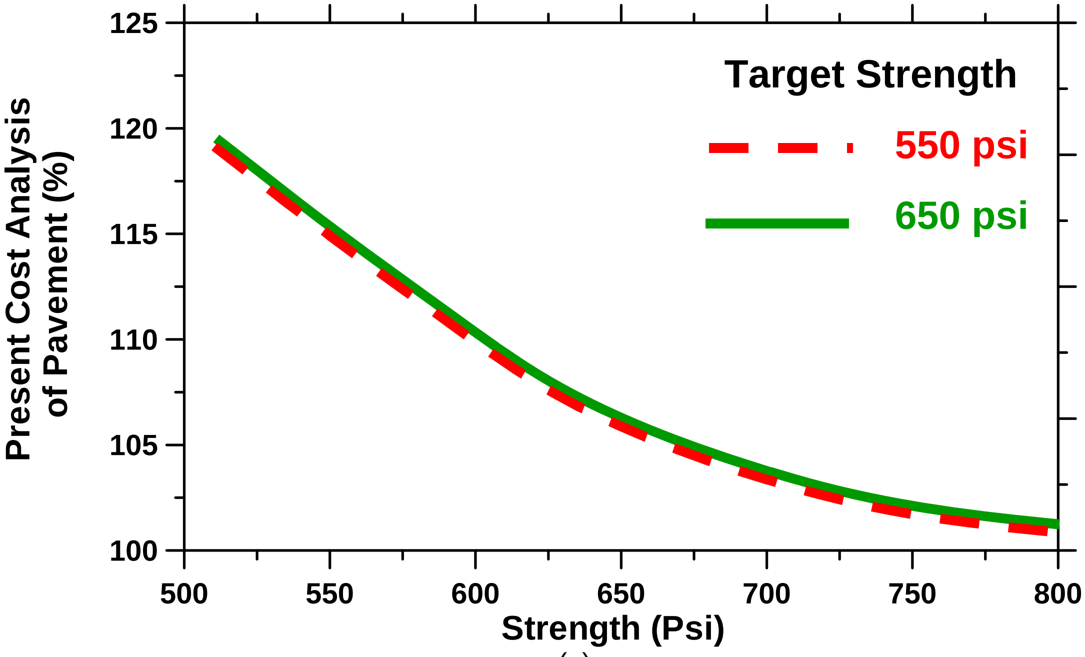
(b)

Figure 3: (a) An illustration of the role of production variability on the target mean required to produce concrete with only a 1 in 1,000 chance of not meeting the specified strength, and (b) the relationship between the as-constructed AQC for flexural strength and the standard deviation.

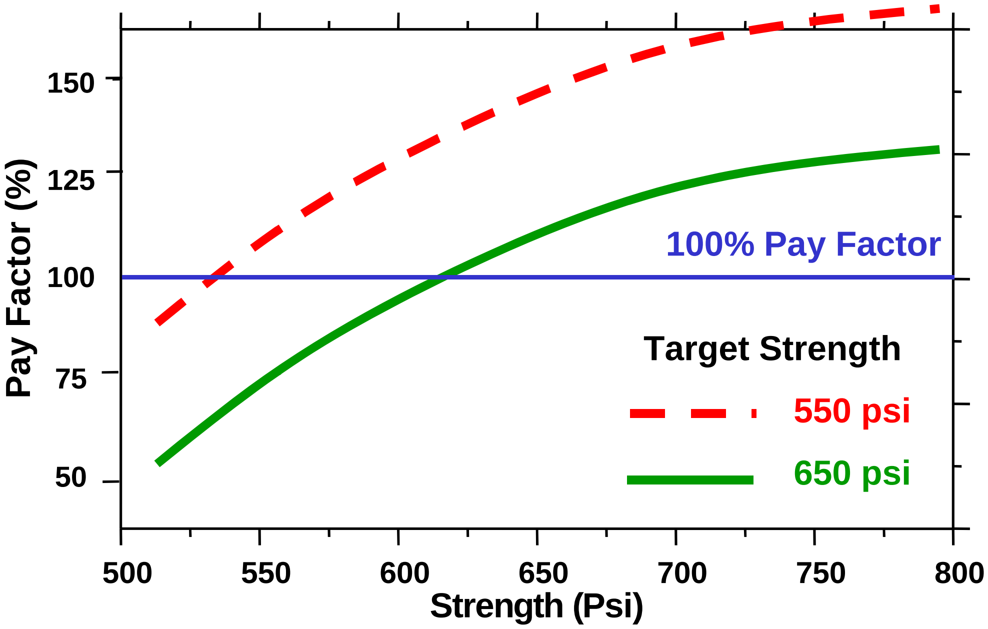
This illustration describes the impact of the as-designed AQC on both the agency and two contractors with different levels of quality control (a standard deviation in flexural strength of 45 psi and 100 psi respectively). If the mean strength were chosen as the minimum required strength based on the contractor with the higher standard deviation, for every one in one thousand beams, the target as-designed strength would be 810 psi. If this value for the AQC was implemented in the standard this would imply that both contractors would need to target a mean strength of 810 psi. As a result, the contractor with the better quality control procedure would essentially be providing a higher quality concrete than they were producing under the conventional QC/QA practices. If the agency establishes the design strength based on the contractor with the higher level of quality control (i.e., the AQC would be 680 psi), the other contractor would fail to meet this target consistently and would need to choose a target strength that is higher than the as-designed AQC to meet the specification.

It can be shown that the 'as-designed' AQC determined using this approach would be directly related to the standard deviation (Figure 3a). Therefore, it appears logical that the agency could establish the target AQC using a standard deviation that is on the lower side of what can be expected in the field to encourage the contractor to take steps to minimize their process control and to reward the contractors who do this. It should, however, be noted that the agency needs take steps to insure that the standard deviation that is specified is higher than the standard deviation that is associated with common variations in the testing method (approximately 25-30 psi for the concrete tested following ASTM C-78 as described in this example).

To link the influence of the 'as-designed' AQC on the PRS, simulations were performed using several different design values of the target AQC's for flexural strength holding all other factors (i.e., the remaining inputs) constant. It can be seen from Figure 4a that irrespective of the design AQC value chosen, the life-cycle costs (LCC) that are predicted were identical (excluding minor variation due to the Monte Carlo simulation process).



(a)



(b)

Figure 4: A comparison of the influence of the target as-designed AQC on the (a) life-cycle cost computation from the program and (b) pay factor.

Identical LCC's occur because the bid price associated with 'as-designed AQC" was not varied since the bid price would be input by the agency before the simulation was performed; additionally, the identical curves occur because the variation in life-cycle costs are driven by the as-built quality characteristics. It should be noted, however, (Figure 4b) that higher incentives for the pay-factor were obtained by using a lower as-designed AQC target value. This can be explained by the fact that the pay factors are influenced by the bid price and the comparison of the as-built and as-designed concrete. Therefore, a lower AQC target value should be expected to correspond with a lower bid price to compensate for the differences in the pay-factor.

Defining Sublots During Construction and Smoothness Determination

It should be noted that the simulations for the pay factors used in the PRS are implemented in sublots and lots. The size of the sublot was maintained consistent with the current INDOT QC/QA specifications, which define a sublot as approximately 2000 m^2 of pavement and a lot as a combination of three sublots. It should be noted, however, that like the current QC/QA specification, the strength, thickness, and air content are determined on the pavement as it is produced. However, unlike the current specifications that measure smoothness on 0.1 mile increments and use these measurements for acceptance and pay factor adjustment, the PRS defined the strength, thickness, air content, and smoothness to correspond with the same concrete.

However, due to the nature of the reconstruction of I-465 (which consisted of a good deal of start-stop paving, two-lane paving, and simultaneous lane and shoulder paving) difficulties were encountered matching the measurement of initial smoothness from the profilogram with the appropriate sublot and lot that was used for strength, thickness, and air content (under the QC/QA procedures). This difficulty occurs since the method of operating the profilograph produces a continuous profilogram. As opposed to the existing QC/QA procedure that would require the profilogram to be sectioned only into 0.1 mile increments, the PRS required the beginning and ending of each sublot and lot to be marked on the profilogram using the project stationing. This required considerable additional effort on the part of INDOT personnel to assign the appropriate smoothness to each sublot as compared to the process used in the current QC/QA approach. Both the contractors and INDOT requested a method of streamlining this process. Additionally, difficulties were experienced with linking the PRS lots and sublots with the paving operation that consisted of paving a traffic lane and a shoulder in a single pass. The main problem with paving the traffic lane and shoulder together occurs due to the shoulders (and ramps) not having a smoothness requirement. As a result, it was awkward to divide the concrete into two appropriate sublots for payment when they were being placed at the same time.

Maximizing Profit as Opposed to Maximizing Pay Factors

PRS can provide an opportunity for contractors to be rewarded fairly and receive incentives if a higher quality product is provided. It should be noted, however, that initially there appeared to be confusion about the incentives. It was initially pointed out that that the costs associated with achieving the highest pay incentives may be greater than the value of the incentive (e.g., the cost of an additional 12 mm of concrete may exceed the incentive received from providing this thicker concrete). This suggests that the benefit of the thicker pavement in terms of reduced life-cycle costs may not be justified. As such, this illustrates an additional benefit of PRS: PRS provides guidance on which 'construction extras' may have real long-term value and which 'construction extras' may not be necessary.

Suggestions for Further Developments in PRS

The current PRS contract was a 'Level 1 PRS' that used pay factor tables that were computed for each of the measurable acceptance quality characteristics (AQC, strength, thickness and smoothness) separately. The pay factors for the AQC's were mathematically combined to compute an 'average' pay factor for the lot. While this approach worked well for this project and would be recommended for the first PRS that an organization implements, it has been proposed that the life-cycle simulation software be used to compute the pay factor directly from the actual acceptance quality characteristics that were measured on a project, producing a single pay factor based directly on life-cycle costs (i.e., a level II PRS). This computation, however, requires the contractors or agency to input the actual acceptance quality characteristics that were measured for a particular paving lot and to perform the simulation themselves using those parameters. While the software makes these calculations straightforward, it was noted during the development of the Level 1 PRS that there were numerous computer inputs (126 in this case; this number has risen with later versions of the software). While many of these inputs may not alter the life-cycle cost or pay factors significantly, some of the inputs may. The potential exists for some of these variables to be input incorrectly or accidentally changed, resulting in the determination of an incorrect pay factor. Since many of these variables are constant after the design of the pavement is completed and out of the control of the contractor, they can not be used for the determination of pay factors; as such, the variables that do not change due to the contractor do not provide any benefit to remain as inputs in the software that would be distributed during the bidding process. Therefore, the move to a level 2 PRS may benefit from a version of the software in which the agency can 'freeze' any of the design variables that are not directly in control of the contractor, thereby minimizing the potential for miscommunication for pay-factor determination due to accidentally placing a wrong input or simulation parameter.

LESSONS LEARNED BETWEEN THE FIRST AND SECOND PRS

Role of the Maximum Quality Limit (MQL)

One lesson learned from the first PRS project in Indiana to the second PRS project was the role of the MQL on the mean and standard deviation determination. A MQL is an upper bound limit that an agency (i.e. INDOT) determines for the basis of keeping or adjusting AQC values. In the first project, when a value was measured to have a greater AQC than the defined MQL, the representative specimen sample value (used in the acceptance procedures) was set equal to the defined MQL (i.e., the Contractor does not receive credit for quality provided in excess of the MQL). For example, the MQL for thickness in the first project was 15 inches. If a value of the insitu pavement at one point within a sublot was measured to be 16 inches, the MQL of 15 inches would be used for the calculation of the average thickness for the sublot and subsequent pay factor. Additionally, the contractor would only be paid for material 15 inches thick at that particular point. In this manner, the agency is protected from paying more for project material than anticipated (i.e. there is no pay for thicknesses over the MQL).

Hence, the MQL is a very useful tool to regulate maximum costs associated with pavement properties (i.e. regulating the maximum value for thickness to cap the total amount of material provided). However, the role of the MQL should be different when calculating the mean and standard deviation for a lot. The values of the mean and standard deviation directly affect the pay factors. Higher mean values result in higher pay factors. Lower standard deviations result in higher pay factors, as shown in Figure 5.

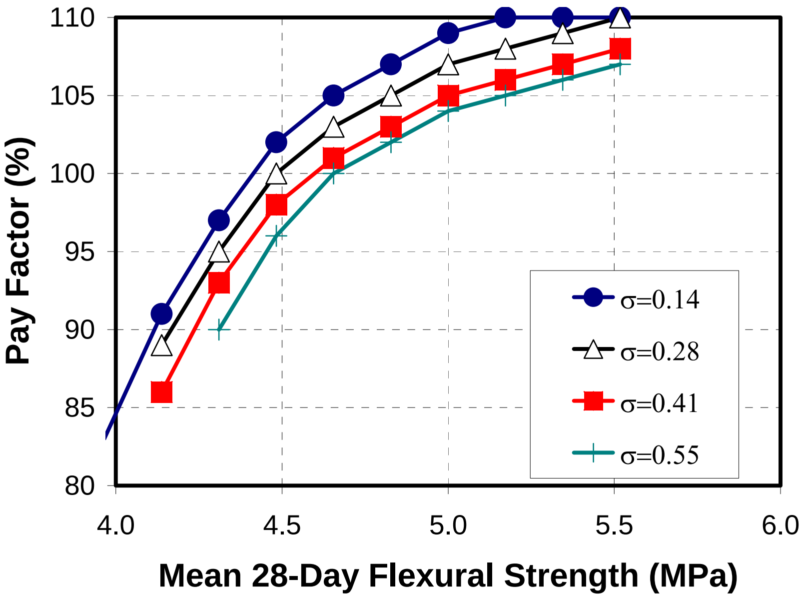


Figure 5: Strength Pay Factor Chart, Project #2

This is true because higher mean values and lower standard deviations result in a higher quality pavement, resulting in a lower LCC for the agency. The actual insitu data for the AQC's should be used for the calculation of the mean and standard deviation, not using a MQL. An example illustrating the necessity of using the actual data is shown in Figure 6**.**

	NOT USING A MQL	USING A MQL
MQL (Mpa)	none	5.5
EXAMPLE 28 DAY FLEXURAL STRENGTH DATA (Mpa)	4.6, 5.4, 5,8, 5.9, 6.1, 6.1	4.6, 5.4, 5.5, 5.5, 5.5, 5.5
MEAN (Mpa)	5.65	5.33
STANDARD DEVIATION (Mpa)	0.60 *	0.38 *
RESULTING PAY FACTOR (%)	106	108

* UNBIASED S.D. VALUES ARE OBTAINED BY DIVIDING TYPICAL S.D. VALUES BY AN ADJUSTMENT FACTOR SUPPLIED BY INDOT (0.9515 FOR THIS CASE)

Figure 6: Importance Associated with Using the MQL and Mean for Pay Factor Determination.

In the example in Figure 6, 28 day flexural strength data taken from project #2 is used to show the difference in pay factor values from two methods: (1) when a MQL is not and (2) when a MQL is used to determine the mean and standard deviations to find the corresponding pay factors. The pay factors are determined by finding the interception of the mean and standard deviation values using Figure 5. The same method could be used for other AQC's (i.e. pavement thickness, air content, etc.). When a MQL is not used, the mean value will be higher (which will increase the pay factor), but there is a possibility for the standard deviation to increase as well (which will decrease the pay factor). In this example, the mean value not using a MQL is 0.32 MPa higher than the value when the MQL is used (implying a higher pay factor when the MQL is not used). However, when the two standard deviations are compared, it is seen that the standard deviation when not using a MQL is 0.22 MPa higher than the value when the MQL is used (implying a lower pay factor when the MQL is not used). As implied, the result is a lower pay factor when the MQL is not used (2% decrease in this example). It should be noted, however, that when the sample data never exceeds the MQL, the results for the two methods will be identical. The differences in pay factors using both methods will vary depending on the specific data collected.

A key concept in PRS is that pavement performance and length of service life is directly related to pavement quality. When the mean and standard deviation are determined from the actual data (not using a MQL), the true pavement quality is determined.

The role of the MQL is to ensure that AQC's are within the constraints set forth by the agencies. One example reason for an agency setting a MQL is to protect the agency from paying more in materials for a project than anticipated; the MQL ensures that contractors are not trying to get paid more for work that isn't necessarily beneficial to the pavement. An agency may also, for example, set a MQL for air content to ensure that the flexural strength loss is not significant; increasing the air content of concrete decreases flexural strength. The MQL should not have a role in determining the mean and standard deviation of the pavement. The actual collected data should be used in the calculations, even if the data exceeds the MQL, in order to obtain a more precise analysis of the overall pavement quality and resulting pay factors.

Separating Sublot Notation for Mainline and Shoulder Pavement Smoothness

In the first PRS project, concerns from INDOT and contractor were voiced in relation to the difficulty in determining the smoothness data for the appropriate smoothness pay factor. Smoothness of the pavement is measured with a devise called a profilograph; however, smoothness is not a requirement for determining pay factors on shoulders or ramps. The final pay factor for the project includes smoothness for the mainline pavement only. When a paving operation paves a traffic lane and a shoulder (or ramp) in a single pass, problems with linking PRS lots to sublots occur due to the shoulder (or ramp) not having a smoothness requirement. In the second PRS, the concerns associated with the smoothness were accommodated. The final pay adjustment was determined first for the combination of the pay factors for strength, thickness, and smoothness of the mainline pavement. Then, slightly different sublot sections were used to determine the pay factor for smoothness of the shoulders and ramps.

PaveSpec™ 2.0 Sensitivity Analysis: Project, Pavement, Traffic, and Climate Inputs

The PRS software used for the analysis of the project, PaveSpec™, requires the input of many variables in order to complete an as-designed LCC analysis to compare to the as-constructed LCC analysis. As explained earlier in this report, the software produces pay factors curves that are used in conjunction with the as-constructed mean and standard deviation AQC values to determine pay factor values. These pay factor values are used to adjust the monetary value given to the contractor from the agency (i.e. the contractor gets an incentive or disincentive corresponding to the quality of pavement that is produced). For the first PRS project, there were a total of 126 input values; due to modifications in the software after the first project, there were more input values for the second project. The inputs can be categorized as inputs for the project, pavement, traffic, and climate. Example inputs are road location, lane configuration, traffic loading, and average annual number of days over 90 degrees fahrenheit.

In addition to input values, models are also used within the PaveSpec^{TM} software to compute a LCC analysis, which produces pay factor curves. The models used in PaveSpec^{TM} are models for AQC's, Life-Cycle (LC), and repair and maintenance. A sensitivity analysis was completed for the input values and models to determine which of the input and model values produced the greatest affect on the pay factor curves. As noted above, there are many input and model values, which makes the possibility of placing an incorrect value into PaveSpec^{TM} very probable. The purpose of the sensitivity analysis was to determine which values had the greatest affect on the final pay factor curves and which values could not be controlled by the contractor. Determining the most significant inputs allows users to concentrate on the accuracy of the most important values, minimizing possible mistakes in the output pay factors and maximizing efficiency in the production of a program. The results of the sensitivity analysis are summarized in the following paragraphs.

To run a life-cycle simulation for PRS using PaveSpec software, information must be entered into a series of input screens. A full list of inputs from the first PRS project can be seen in Table 17 and Table 18. The most critical project design-related inputs were determined and are presented in the following paragraphs. A table summarizing which input values were the most significant is presented at the end of this section in Table 10.

Inputs #10 and #11, as seen in Table 17 and Table 18, pavement type and dowel bar diameter, are values that determine the transverse joint faulting distress. Therefore, a sensitivity analysis was performed to determine the effects on the pavement's life-cycle cost. In this analysis, faulting was used as a measure of pavement performance.

Table 3: Sensitivity Analysis of Pavement Type and Dowel Size

Pavement Type	Dowel size (inch)	Present Worth Life-Cycle Cost per mile	% change in LCC
Doweled JPCP	1.5	$4,580,358	-
Undoweled JPCP	0	$4,715,456	2.9%
Doweled JPCP	0.75	$4,713,943	2.9%
Doweled JPCP	1	$4,654,255	1.6%
Doweled JPCP	1.25	$4,596,510	0.4%

As seen in Table 3, the presence and size of dowel bars does impact the life-cycle simulations slightly. Because faulting also depends on pavement thickness and percent consolidation around the dowels, dowel bar size will become even more important for thinner pavements. For this reason, the dowel bar dimensions are a crucial input in life-cycle simulations, if joint faulting is used as a measure of pavement performance. If joint faulting is not used, these inputs are not critical.

Input #14, joint sealant type, affects the way spalling is predicted in the software. Although several joint sealant options are listed, an inspection of the spalling model calculation reveals that effectively only two options exist: preformed and non-preformed seals [6]. Non-preformed seals include liquid asphalt, silicone, and the absence of seals. Therefore, an analysis is only necessary to examine the impact of preformed seals on the model.

Table 4: Sensitivity Analysis of Joint Sealant Type

Joint Sealant Type	Maximum Spalling Predicted (70 years)	LCC (PW) per mile	% change from standard
Silicone	86%	$5,028,605	-
Preformed Compression Seals	0.01%	$4,494,704	-11%

As shown in Table 4, within a standard range of the flexural strengths, the impact of joint sealant is large. If preformed compression seals are used for joint sealant instead of silicone (current model input), the model effectively predicts no spalling. This causes a large decrease in the life-cycle cost, over 10%. According to this sensitivity analysis joint sealant type is a crucial input in the life-cycle cost simulations.

The design value for the traffic loading (input #20) is one of the most critical inputs in PRS. These values are generally set by the Pavement Design division of INDOT, thereby avoiding confusion as to what values to use in the PRS. However, changing the traffic loading can result in changes in the total life-cycle cost of the pavement. Simulations were run for the typical ranges of traffic volumes for Indiana interstate highways [7].

Table 5: Sensitivity Analysis of Traffic Loading

Traffic Loading at year 1	% change in traffic loading	Present Worth Life-Cycle Cost per mile	% change in LCC
12,000 ADT	-80%	$956,781	-79%
45,900 ADT	-25%	$3,423,970	-25%
61,200 ADT	0%	$4,535,397	-
76,500 ADT	+25%	$5,650,991	+25%
100,000 ADT	+63%	$7,361,285	+62%
166,000 ADT	+171%	$12,164,662	+168%

As seen in Table 5, the amount of traffic has a great effect on the total life-cycle cost on the pavement. This is, to some extent, due to the increased deterioration of the pavement under higher loading. However, the life-cycle cost is impacted to a much greater extent by the rise in user costs as the traffic volume increases. Similarly, if the total number of users decreases, the total life-cycle cost decreases proportionally. Correct traffic volume, therefore, is of high importance to an engineer creating a PRS.

It can be deduced that as the traffic volume increases, the incentives and disincentives for the various AQCs will also increase. This is because higher volumes of traffic correspond to greater impacts on the users when the pavement deteriorates due to lower quality. This is illustrated in Figure 7.

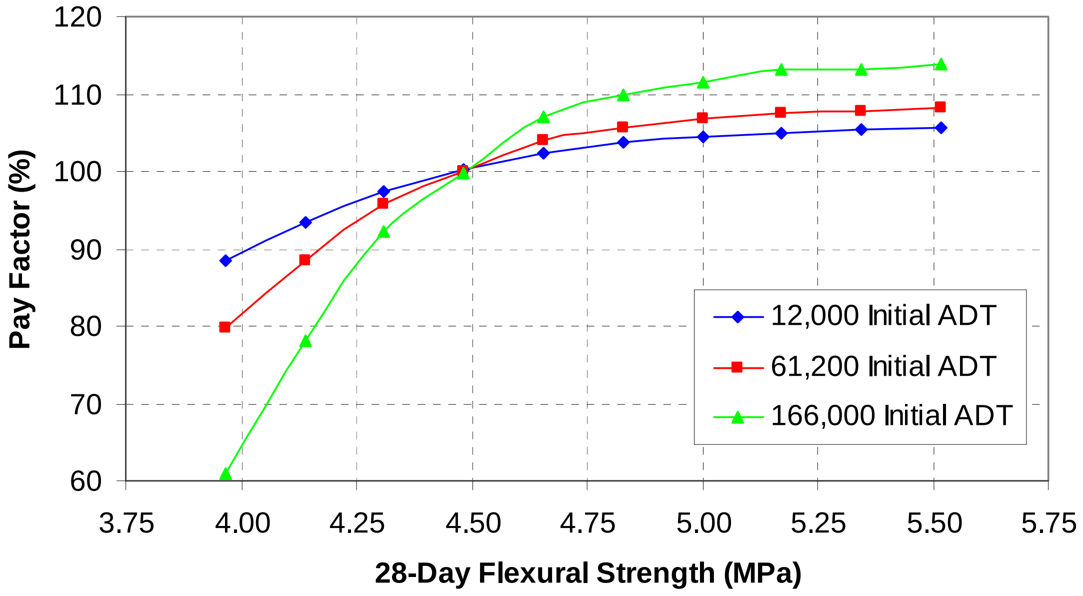


Figure 7: 28-Day Flexural Strength Pay Factors for Different Traffic Volumes

In Figure 7, quality is measured by the 28-day flexural strength of the pavement. The values are shown for a standard deviation of 0.27 MPa (40 psi). The pay factor (PF) awarded to the contractor is on the left axis. Under different traffic volumes, pavements constructed with the same strength earn different bonuses. As seen in the figure, higher traffic volumes lead to higher pay adjustments. PRS then can potentially make an even greater impact on quality in areas with high traffic volumes.

Traffic growth rate (input #21), is equally as important to the model as the predicted traffic loading. National urban traffic growth rates, up to 9%, were modeled in the software [15]. The default growth rate of 2.53% was based on the initial and 10-year predicted traffic volumes for the project, provided by INDOT.

Table 6: Sensitivity Analysis of Traffic Growth Rate

Growth Rate	% change in G.R.	Present Worth Life-Cycle Cost per mile	% change in LCC
2.53%	-	$4,535,481	-
-1.00%	-140%	N/A	N/A
0.00%	-100%	$2,304,641	-49%
5.00%	98%	$10,976,937	142%
9.00%	256%	$66,418,179	1364%

The first conclusion noted from the sensitivity analysis in Table 6 is that the software does not allow negative growth rates. The effects of changing the growth rate are similar to changing the traffic volume. A small increase in the growth rate can result in a large change in the life-cycle cost. The traffic growth rate is as critical as the traffic volume in the simulation. High growth areas can lead to accelerating distress, making initial pavement quality even more important.

Input #22 is the traffic growth type, defined as either simple or compound. The default value for this input is compound. A sensitivity analysis is shown in Table 7.

Table 7: Sensitivity Analysis of Traffic Growth Rate Type

Growth Rate	Present Worth Life-Cycle Cost per mile	% change in LCC
Compound	$4,535,481	-
Simple	$3,612,099	-20%

Table 7 shows the effects of changing the growth rate from compound to simple, still using the same inputs for traffic loading and the growth rate. The simple growth rate results in a smaller total loading, and therefore, a smaller life-cycle cost.

The user has the option of using either ADT or ESAL as the method of traffic measurement. If ADT is selected, inputs #23 through #25 are used to determine the ESAL to ADT ratio. Input #23 is the ESAL:ADT directional factor. This input expresses the percentage of traffic that is found in the design direction. For one-way streets, this value is 100%, for two-way roads, it is 50%.

Table 8: Sensitivity Analysis of Directional Factor

Directional Factor	% change in DF	Present Worth Life-Cycle Cost per mile	% change in LCC
0%	-100%	$368,743	-92%
25%	-50%	$2,305,018	-49%
50%	-	$4,535,481	-
75%	50%	$6,753,930	49%
100%	100%	$8,991,522	98%

As seen in Table 8, the directional factor has a large impact on the life-cycle simulations. The change in life-cycle cost is proportional to the change in the directional factor. Although this is a crucial input in the software, the value is fixed by INDOT at 50% and should not require additional analysis [8].

The annual number of freeze-thaw cycles (input #28) is a crucial input in the transverse joint spalling model. It is, in fact, the driving force behind the distress.

Table 9: Sensitivity Analysis of Annual Air Freeze-Thaw Cycle Variation

Air Freeze-Thaw Cycles	Present Worth Life-Cycle Cost per mile	% change in LCC
0	$4,555,351	-11.5%
30	$4,739,965	-8.0%

65	$5,150,071	-
90	$5,346,460	3.8%
102	$5,427,069	5.4%
110	$5,476,466	6.4%

The results in Table 9 show that as climates become more severe in terms of freezing and thawing, the life-cycle costs associated with those pavements will increase. This is due to pavements showing an increase in spalling in these climates. Since the spalling model includes the AQCs of strength, thickness, and air content, increased freeze-thaw cycles will impact the pay factor graphs. This is especially evident in the air content pay factors, as shown in Figure 8. Therefore, freeze-thaw cycles are a very important input in PRS. Pavements constructed in freeze-thaw susceptible climates will be heavily influenced by the air content AQC.

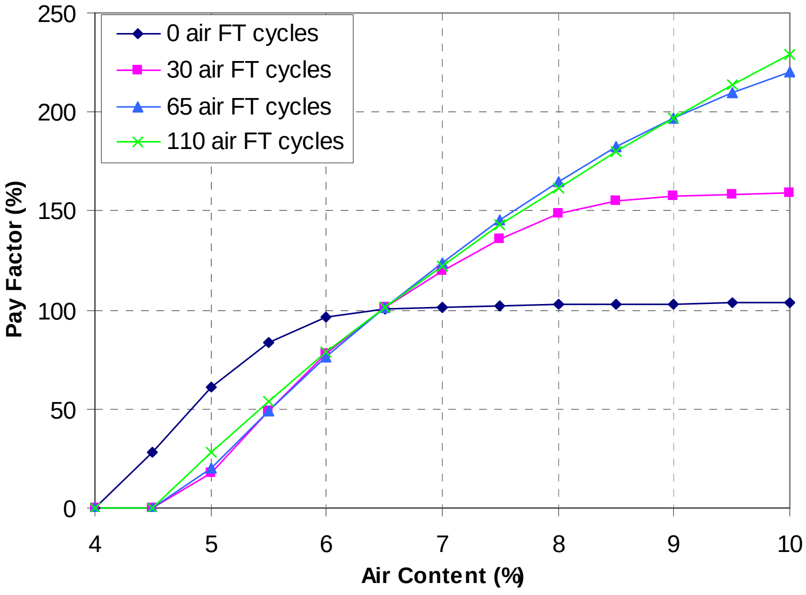


Figure 8: Pay Factors in Different Freeze-Thaw Climates

After a sensitivity analysis was completed for all of the inputs, the most critical project and design-related inputs were determined, as summarized in Table 10. The results show that the inputs which determine traffic loading and impact the spalling model are the most significant in PRS.

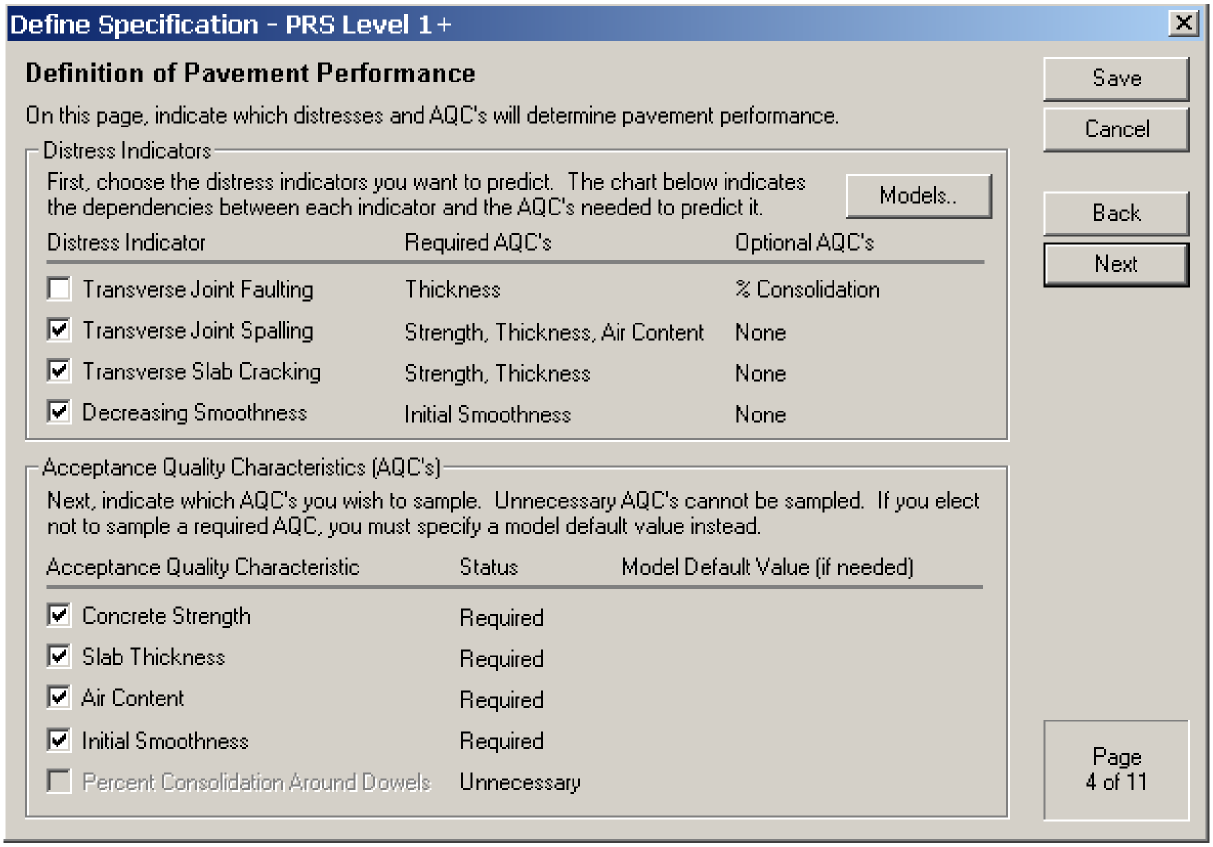
Table 10: Summary of Most Significant Constant Value Inputs in PRS

Input name	Maximum observed change in Life-cycle cost for given range in simulations
Dowel Size	2.9%
Joint Sealant	-11%
Traffic loading	168%
Traffic Growth Rate	1364%
Traffic Growth Type	20%
ESAL:ADT Directional Factor	98%
Annual Air Freeze-Thaw Cycles	-11.5%

PaveSpec^{TM} 2.0 Sensitivity Analysis: AQC, LC, and Repair and Maintenance Models

In addition to the input values reviewed in the preceding paragraphs in this section, the PRS software assesses pavement performance through the use of distress prediction models. When using the life-cycle software, the user has the option to include four different prediction models and the AQC's, which are required to run those models. A summary of the most significant inputs in these models is presented at the end of this subsection.

The input screen indicating where information is to be entered into the program is shown in Figure 9 with a summary of the inputs in Table 11.



Definition of Pavement Performance

On this page, indicate which distresses and AQC's will determine pavement performance.

Distress Indicators

First, choose the distress indicators you want to predict. The chart below indicates the dependencies between each indicator and the AQC's needed to predict it.

Distress Indicator	Required AQC's	Optional AQC's
☐ Transverse Joint Faulting	Thickness	% Consolidation
☑ Transverse Joint Spalling	Strength, Thickness, Air Content	None
☑ Transverse Slab Cracking	Strength, Thickness	None
☑ Decreasing Smoothness	Initial Smoothness	None

Acceptance Quality Characteristics (AQC's)

Next, indicate which AQC's you wish to sample. Unnecessary AQC's cannot be sampled. If you elect not to sample a required AQC, you must specify a model default value instead.

Acceptance Quality Characteristic	Status	Model Default Value (if needed)
☑ Concrete Strength	Required	
☑ Slab Thickness	Required	
☑ Air Content	Required	
☑ Initial Smoothness	Required	
☐ Percent Consolidation Around Dowels	Unnecessary	

Figure 9: Input Screen for Defining Pavement Performance

Table 11: Definition of Pavement Performance

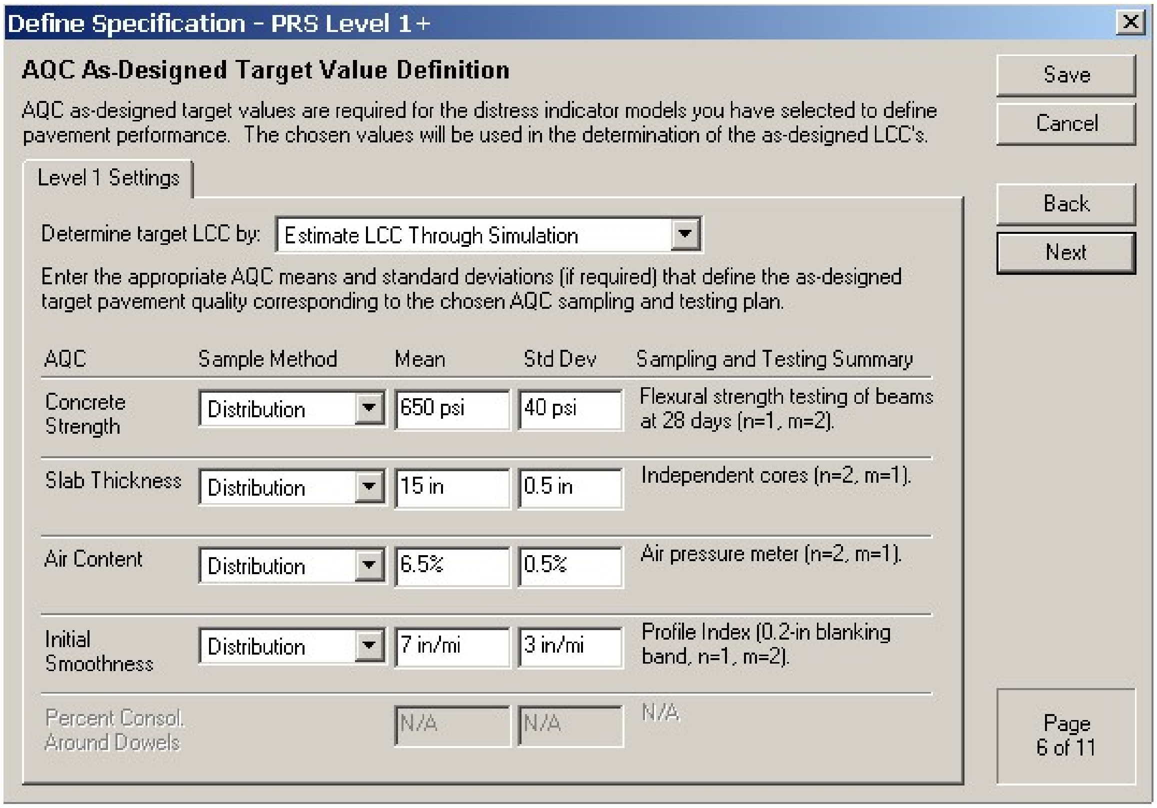
No.	Input	Options	Project Value	Source
32	Distress indicators to be modeled	Transverse Joint Faulting, Transverse Joint Spalling, Transverse Slab Cracking, Decreasing Smoothness	Transverse Joint Spalling[1], Transverse Slab Cracking, Decreasing Smoothness	User
33	Acceptance quality characteristics to be considered	Concrete Strength, Slab Thickness, Air Content, Initial Smoothness, Percent Consolidation around Dowels	Concrete Strength, Slab Thickness, Air Content, Initial Smoothness	User

[1] Spalling Model coefficient A = 0.5

The definition of pavement performance is a fundamentally important part of PRS. The distress models are directly related to the design inputs and AQCs (strength, thickness, air content, initial smoothness, and percent consolidation around the dowels).

As a default, all four distress models are selected. However, the agency can choose not to include some models and even modify others. For example, on the Indiana PRS project, it was decided to limit the effects of the spalling model on the second PRS project. It should be noted that the faulting model was not used as a measure of pavement performance in the Indiana projects.

The inputs defining the AQC target values and standard deviations for the first project are found in Figure 10 (inputs #53 to #58). This is one of the most critical aspects of PRS, because it sets the goals that the contractor tries to achieve, and these values will greatly impact the pay factors. The targets define the quality value for which the agency is willing to pay 100% of the bid price to the contractor. Also, the simulations are run using the assumed targets and standard deviations.



AQC As-Designed Target Value Definition

AQC as-designed target values are required for the distress indicator models you have selected to define pavement performance. The chosen values will be used in the determination of the as-designed LCC's.

Determine target LCC by: Estimate LCC Through Simulation

Enter the appropriate AQC means and standard deviations (if required) that define the as-designed target pavement quality corresponding to the chosen AQC sampling and testing plan.

AQC	Sample Method	Mean	Std Dev	Sampling and Testing Summary
Concrete Strength	Distribution	650 psi	40 psi	Flexural strength testing of beams at 28 days (n=1, m=2).
Slab Thickness	Distribution	15 in	0.5 in	Independent cores (n=2, m=1).
Air Content	Distribution	6.5%	0.5%	Air pressure meter (n=2, m=1).
Initial Smoothness	Distribution	7 in/mi	3 in/mi	Profile Index (0.2-in blanking band, n=1, m=2).
Percent Consol. Around Dowels		N/A	N/A	N/A

Figure 10: Input Screen for Defining AQC As-Designed Target Values

The target values for strength (input #53) and thickness (input #56) were varied and the resulting life-cycle costs plotted in Figure 11.

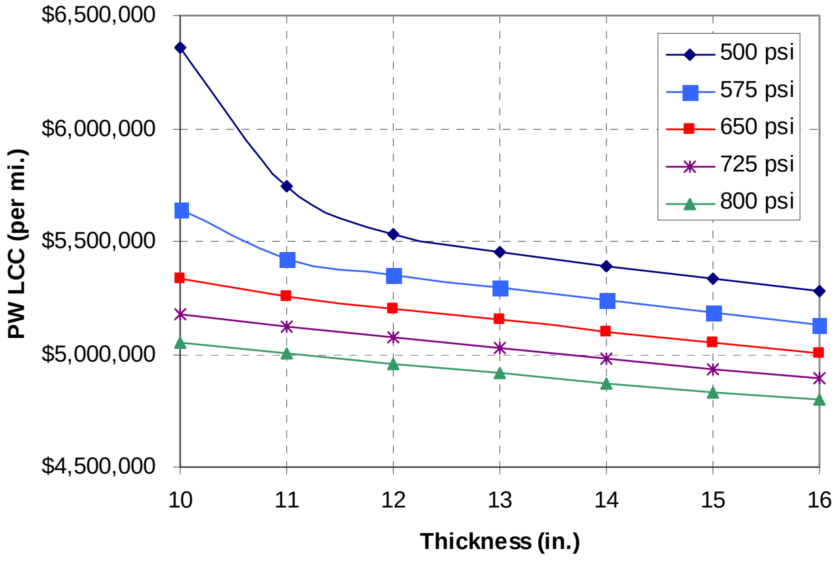


Figure 11: Present Worth Life-Cycle Cost Versus AQC Target Means

As can be seen in Figure 11, the life-cycle costs tend to increase as the quality levels (strength, thickness) decrease. This is the rational basis for the pay factors. It is also seen that according to the software, a change of 75 psi has a greater affect than one whole inch of thickness.

An experiment was run to determine the thickness at which point cracking becomes an issue for the model. Using the mean values only of the AQCs (air content = 6.5%, 28 flexural strength = 650 psi, initial smoothness = 7 in./mi.), ten simulations were run, and the maximum predicted cracking was plotted against the thickness of the pavement. Figure 12 shows that maximum cracking begins to increase in pavements which are about 275 mm thick or less.

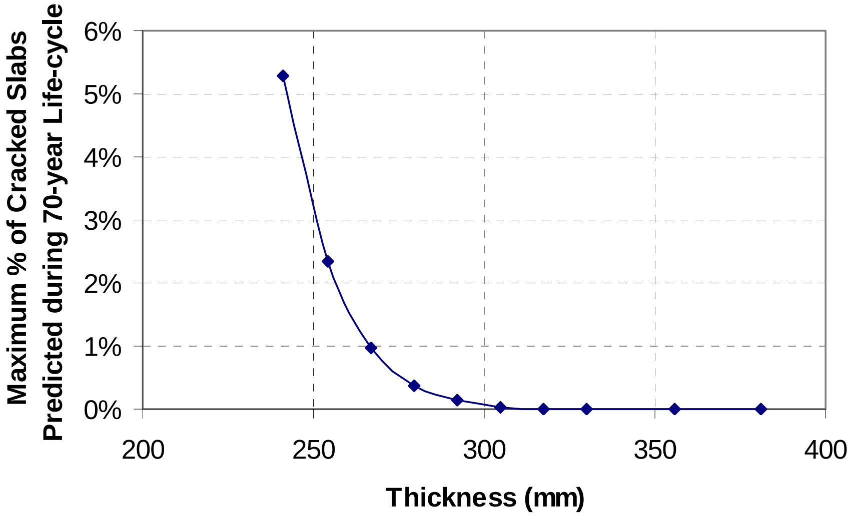


Figure 12: Maximum Predicted Cracking Versus Pavement Thickness

The target AQC mean is important to PRS. However, the standard deviation of the AQC can play as important role as well. Figure 13 shows the impact of the standard deviation on the life-cycle cost.

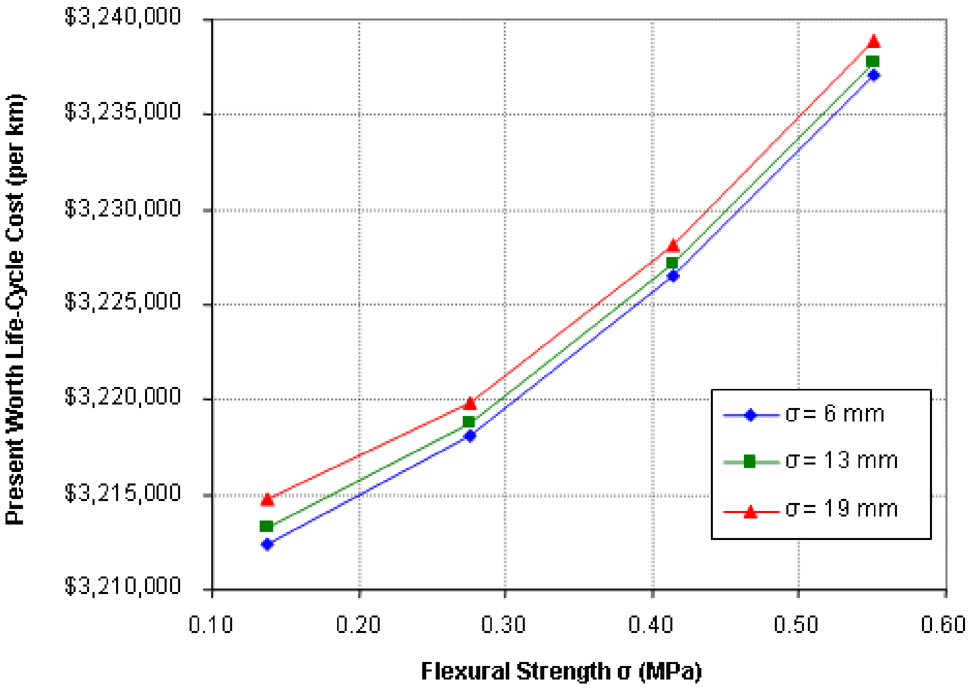


Figure 13: Present Worth Life-Cycle Cost Versus AQC Target Standard Deviation

As seen in Figure 13, as standard deviations become smaller, the total life-cycle cost decreases. The notion of sublot failure is the driving force behind this phenomenon. For example, if three sublots were constructed, one with average quality, one slightly above-average, and one slightly-below average, the life-cycle costs would not be proportional to the quality level. That is, the difference in costs between the below-average sublot and the average sublot would be disproportionately more than the difference between the above-quality sublot and the average one. PRS enters an important concept into concrete construction: average pavement quality level is not the only important factor, but the quality control as well. This can be shown further in the analyses for smoothness and air content.

Table 12: Analysis of Air Content Variations

Air Content	Present Worth Life-Cycle Cost per mile	% change in LCC
4%	$5,183,973	14%
5%	$4,860,269	7%
6%	$4,643,331	3%
7%	$4,527,944	-
8%	$4,501,676	-1%
9%	$4,497,194	-1%
10%	$4,495,509	-1%

Decreases in the average air content, as shown in Table 12, show that as the air content decreases, the life-cycle cost increases. As was the case for strength and thickness, as the standard deviation decreases, the life-cycle cost increases. PRS, therefore, rewards increased quality control that leads to lower standard deviations.

Table 13: Analysis of Initial Smoothness Variations

Initial Smoothness	Present Worth Life-Cycle Cost per mile	% change in LCC
3 in./mi.	$4,488,895	-1.0%
4 in./mi.	$4,499,287	-0.7%
5 in./mi.	$4,508,402	-0.5%
6 in./mi.	$4,520,752	-0.3%
7 in./mi.	$4,532,706	-
8 in./mi.	$4,549,369	0.4%
9 in./mi.	$4,559,320	0.6%
10 in./mi.	$4,572,288	0.9%

Table 13 shows how the life-cycle cost changes with initial smoothness. As the initial smoothness improves, the life-cycle cost decreases, resulting in a bonus to the contractor.

Table 14: Analysis of Smoothness Standard Deviations

Smoothness Standard Deviation	**Present Worth Life-Cycle Cost per mile**	**% change in LCC**
0	$5,148,919	0.0%
2	$5,148,436	0.0%
3	$5,146,457	0.0%
4	$5,145,177	0.0%
6	$5,150,961	0.1%
8	$5,161,722	0.3%
10	$5,159,679	0.3%

Conversely, as the standard deviation increases, the life-cycle cost increases, as seen in Table 14, resulting in a disincentive to the contractor.

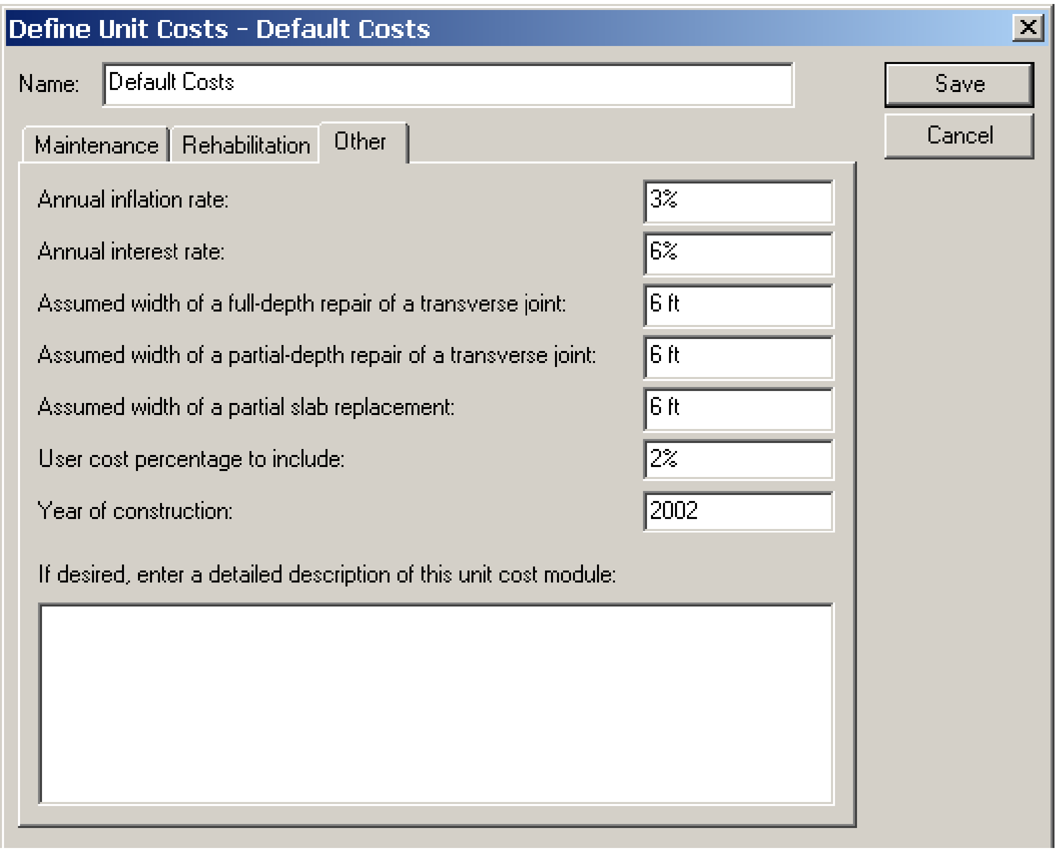
Table 15: Analysis of Air Content Standard Deviations

Air Content Standard Deviation	**Present Worth Life-Cycle Cost per mile**	**% change in LCC**
0.5%	$4,532,980	-
1%	$4,573,096	1%
1.5%	$4,636,819	2%
2%	$4,700,229	4%

Table 15 shows the standard deviation of the air content also has a large impact on the life-cycle cost. As the standard deviation increase, the life-cycle cost also increases.

As the AQC values are made more favorable (increased in the case of thickness, strength, and air content, but lowered in the case of initial smoothness), the as-designed, or simulated, life-cycle cost will decrease. This in turn will impact the pay factors substantially

The last section of the Unit Cost Information page, entitled "Other costs," has the most critical inputs in the PaveSpec program, according to the analysis. The inputs (#90, #91, and #99 through #103), are shown in Figure 14. The values used for the first project are shown in Table 16.



Name: Default Costs

Annual inflation rate: 3%

Annual interest rate: 6%

Assumed width of a full-depth repair of a transverse joint: 6 ft

Assumed width of a partial-depth repair of a transverse joint: 6 ft

Assumed width of a partial slab replacement: 6 ft

User cost percentage to include: 2%

Year of construction: 2002

If desired, enter a detailed description of this unit cost module:

Figure 14: Input Screen for Other Life-Cycle Cost Analysis Information

Table 16: Other Life-Cycle Cost Analysis Variables

No.	Input	Typical Ranges	Project Value	Source
90	User cost percentage to include	0 – 5%	2%	User
91	Year of construction	-	2002	User
99	Annual inflation rate	-	3%	User
100	Annual interest rate	-	6%	User
101	Assumed width of full depth repair of transverse joint	-	6 ft	User
102	Assumed width of partial depth repair of transverse joint	-	6 ft	User
103	Assumed width of partial slab replacement	-	6 ft	User

Annual inflation and interest rates (inputs #99 and #100) were estimated by a INDOT and FHWA research committee as being average values expected for highway agencies. These values have a minor effect on the estimated life-cycle costs; an increase in the inflation rate will increase the life-cycle cost, and an increase in the interest rate will result in a decrease in life-cycle costs. However, it is recommended that the values as shown be used.

The width of assumed repairs (inputs #101 through #103) will also not noticeably affect the life-cycle cost. The values were taken to be half of the lane width (input #3).

The greatest effect on the life-cycle cost of the pavement is the percentage of user costs included (input #90). User costs are defined by McFarland [10] and include travel-time, vehicle operation, accidents, and discomfort costs. Hoerner and Darter [6] note that the inclusion of user costs is a controversial issue, but the FHWA believes that they are a necessary part of life-cycle cost analysis since user cost savings "are the single most important benefit in justification of most highway improvements" [13].

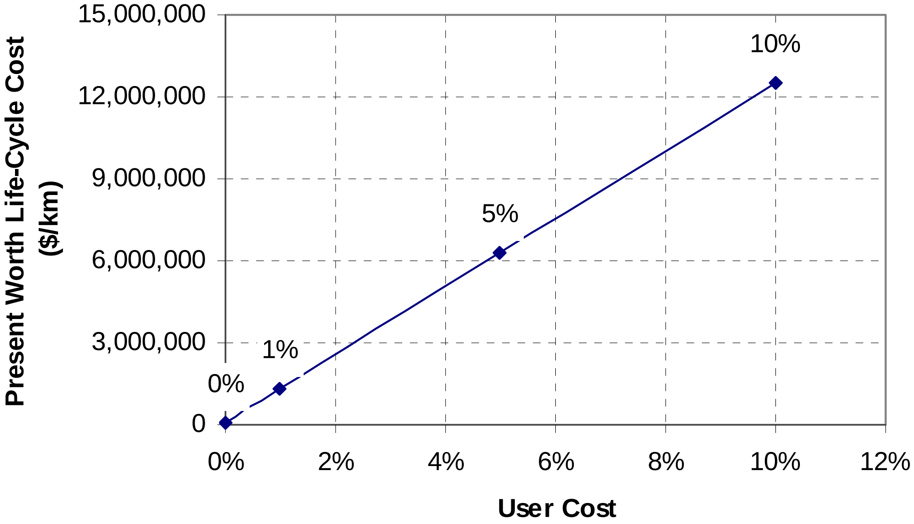


Figure 15: Life-Cycle Costs Versus User Cost Percentage Included

As seen in Figure 15, higher percentages included tend to make the overall life-cycle cost so high as to render the analysis moot. Hoerner and Darter [6] stated that user cost percentages up to 5% was reasonable, but INDOT has found that reasonable pay factors were generated when the percentage was set at 2%. User cost percentage to be included is a highly subjective input. It is recommended that the user run several trials with varying percentages and select the one which generates pay factors that match the agencies experience and expectations.

The year of construction (input #91) is used to inflate the user costs to a present day value. User costs are calculated from tables created by McFarland in 1972, and so PaveSpec adjusts the user costs to reflect the value of a dollar at the year of construction.

The most important conclusion to draw from this sensitivity analysis is that the percentage of user costs to include in the life-cycle cost analysis is the most significant variable for impacting the total life-cycle cost, when compared with the standard inputs for INDOT. Emphasis should be placed on determining the user cost percentage that INDOT is comfortable including, and assuring that the inflation rate and discount rate are the accepted values for use within the department.

Bid price (input #107) plays an important role in the generation of the level one pay factors. The pay factors are calculated from the difference in the as-designed and the as-constructed post-construction life-cycle cost. That difference is taken as a percentage of the bid price. So, with smaller bid prices, the incentives increase. With larger bid prices, the incentives decline. This is shown in Figure 16. This has a profound effect on the agency, as the average bid price should be used for PRS purposes. This information, however, is an estimate, since in level one PRS, the pay factors must be included in the bid document. An advantage in level two PRS is that the pay factors are calculated by the program as the construction progresses and test results are entered. The bid price used in level two is the actual bid price the contractor submitted.

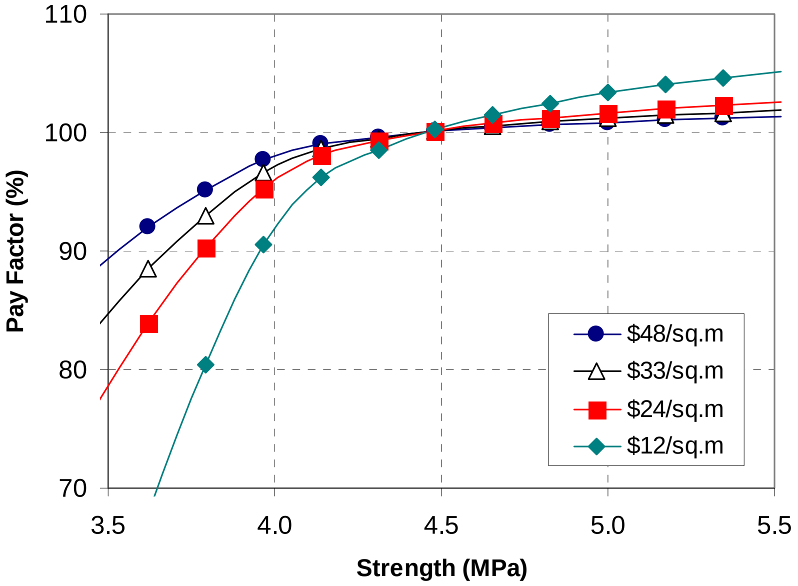


Figure 16: Pay Factor Variation with Bid Price

An important conclusion about the pay factors is that they become closer to 100% with an increase in bid price. Although the pay factors are fixed into the contract in level 1 PRS, in Level 2 PRS, they are a function of the bid price, because the bid price is not fixed until the contract is signed. Therefore, the contractor has incentive to submit a competitive bid, because the positive pay factors (bonuses) actually increase with the lower bids.

Using data collected from previous concrete projects in Indiana, an equation was developed to estimate the bid price per the thickness of the pavement. This is shown in Figure 17.

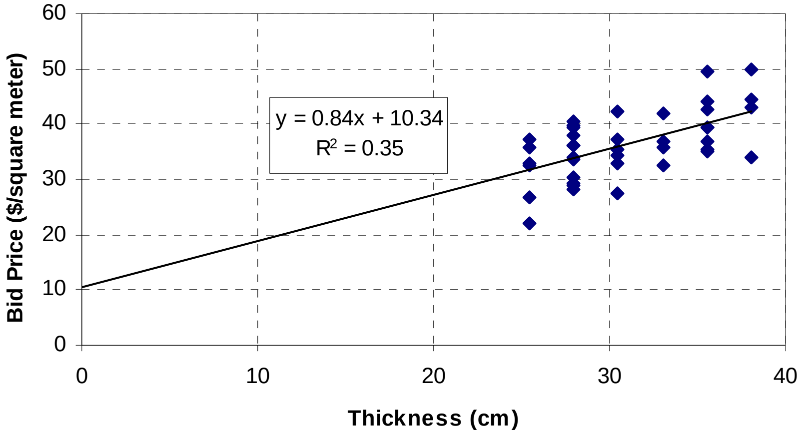


Figure 17: Bid Price Versus Pavement Thickness

The analysis life (input #133) should not be confused with the design life of the pavement. They are in fact not the same. The design life of the pavement is the engineer's estimate of how long the pavement will perform under the expected loading without requiring major rehabilitation, such as an asphalt overlay. The analysis period is the length of time during which all life-cycle costs are considered. This should include user costs and maintenance costs, as well as the cost to rehabilitate the pavement when it reaches the end of its design life. In PRS, the analysis period is approximately twice the design life, 30 and 60 years, respectively. However, the model should be reviewed to ensure that the analysis life is long enough to include at least one rehabilitation. In the case of the most recent project in Indiana, the analysis life was changed to 70 years for this reason.

This section has discussed an overview of the most important inputs in the life-cycle cost simulation for PRS that deal with AQC's, life-cycle, and repair and maintenance models. The most significant inputs, as revealed by this investigation are as follows:

- AQC targets chosen
- interest and inflation rates
- percentage of user costs included in the simulation
- average bid price

SUMMARY

This paper has provided documentation for the implementation of the first and second Performance Related Specification (PRS) for portland cement concrete pavements (PCCP) in Indiana. This paper provided an overview of what a PRS is, the steps used in implementing a Level I PRS, the outcome of implementing this specification, as well as the lessons learned during this process. It should be noted that PRS can provide an incentive for contractors to provide a product with a higher quality by using performance simulations to link the quality of the pavement with long-term maintenance and repair costs and using this information to determine pay incentives and disincentives. The following is a list of the main topics covered by this paper.

- PRS' may provide an opportunity for contractors to be rewarded or penalized in a rational manner. Contractors will receive incentives if a higher quality product is used due to the potential reduction in maintenance and repair costs over the life cycle of the pavement. PRS also penalizes the contractor for a lower quality product to offset the potential costs the agency will incur throughout the life of the pavement.
- A design input table was developed and utilized to identify the key inputs that are needed to develop the specification. This design input table is beneficial in that it can be used to identify the sources of data for future specification development.
- It was observed that a two-part specification could be used to provide a document that would be consistent from contract to contract and information that would be contract specific. The contract specific information would be presented in an appendix.
- The selection of the as-designed quality characteristic values (AQC, e.g., design strength) is not a trivial matter. The as-designed AQC values have no impact on the as-built life-cycle costs. However, the as-designed AQC values can significantly impact the bid price and pay factors. Higher incentives for the pay-factors are obtained by using lower as-designed AQC values that would correspond with a lower-bid price.
- The utilization of lots and sublots that matched the material as it is placed to the where the smoothness was measured showed some complexities. It is suggested that a separate pay factor be used to describe the smoothness that is measured on a sublot that may not be identical to the sublot of as-produced concrete.

- Due to the numerous operator inputs, it is believed that the move to a Level 2 PRS may benefit from a version of the software in which the agency can ‘freeze’ any design variables not controlled by the contractor.
- Further research is needed to extend the use of PRS. Developments are suggested in the areas of drainage and subgrade properties, utilization of non-destructive testing, better quantification of the variability associated with pavement construction.
- The role of the maximum quality limit (MQL) is to ensure that AQC’s are within the constraints set forth by the agency. However, the mean and standard deviation should be determined from the actual data (not using the MQL).
- The results of a sensitivity analysis for the PRS software, PaveSpec^{TM}, show the inputs which affect the software outputs most significantly. When a software user knows these most impacting inputs, accuracy of the output and efficiency of running the program can be increased by focusing efforts on these inputs.

ACKNOWLEDGEMENTS

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contents of this paper do not reflect the official views or policies of INDOT or FHWA; therefore, this report does not constitute a standard, specification, or regulation. Additionally, the authors are responsible for the information presented herin.

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Table 17: Data Input Values for the First Project Within Pavespec^{TM}

No.	*MODEL INPUT REQUIRED*	*INPUT VALUES PROVIDED BY INDOT*
1	Traffic direction	- North and south bound
2	Lane configuration	- 6 lanes divided (by barrier wall)
3	Lane width	- 12.0 ft
4	All lanes to be accepted by PRS	- Yes
5	Inner lane cracking as % of outer lane	- 100
6	Outer lane widening	- No
7	Road location	- Urban
8	Project length	- 7979 ft
9	Design life	- 30 years
10	Pavement Type	- Jointed Plain (JCJP), Doweled
11	Dowel bar diameter	- 1.5 in.
12	Transverse joint spacing	- 6 m
13	PCC modulus of elasticity	- 3.4×10^6 psi
14	Joint sealant type	- Silicone
15	Base Type	- Crushed stone, gravel or slag # 53D)
16	Base permeability	- Permeable
17	Modulus of subgrade reaction	- 100 psi/in
18	Design traffic measure to be used	- ADT
19	Year of traffic information considered	- 1
20	Traffic loading at that year	- ADT = 90,700
21	Traffic growth rate	- 1.5 %
22	Traffic growth type	- Compound
23	ESAL:ADT – directional factor	- 50 %
24	Percentage of trucks	- 11 %
25	Average truck load equivalency factor	- 1.115 ESAL's per truck
26	Average annual freezing index	- 100 ^{o}F-days
27	Average annual number of wet days	- 126 days
28	Average annual freeze-thaw cycles	- 15
29	Average annual number of days over 90^{o}F	- 18 days
30	Presence of salt	- Yes
31	Climate zone description	- Wet-freeze
32	Distress indicators to be modeled	- Transverse slab cracking - Decreasing smoothness
33	Acceptance quality characteristics to be considered	- Concrete strength - Slab thickness - Initial smoothness
34	Sample type to be used	- Beams
35	Timing of cores (if appropriate)	- N/A
36	Sampling locations per sublot	- 1
37	Samples per sampling location	- 2

No.	*MODEL INPUT REQUIRED*	*INPUT VALUES PROVIDED BY INDOT*
38	Target time of testing	- 28-days (Testing will be conducted at 7 days, however the 28 day strength, i.e. the maturity, will be determined outside of the program.)
39	Test Maturity (if not 28-days in No. 38 above)	- N/A
40	Core to cylinder relationship (if required)	- N/A
41	Laboratory-created maturity equation (if required)	- N/A
42	Compressive to flexural relationship (if required)	- N/A
43	Sample type	- Independent cores
44	Timing of samples	- After 4-days
45	Sampling locations per sublot	- 2
46	Samples per sampling location	- 1
47	Indicator of smoothness over time to be used	- International roughness index (IRI)
48	Initial smoothness indicator to be used	- Profile index (0.2-inch blanking band)
49	Initial to 'over-time' translation equation to be used	- Linear equation ($y = 3.11x + 36.4$) (Equation from Volume 1.)
50	Number of pass locations per sublot	- 2
51	Number of passes per sampling location	- 2
52	Profilograph reduction method	- Manual
53	Concrete strength mean	- 700 psi - flexural
54	Concrete strength standard deviation	- 50 psi
55	Slab thickness mean	- 14.0 in.
56	Slab thickness standard deviation	- 0.5 in.
57	Initial smoothness mean	- 7 in/mile
58	Initial smoothness standard deviation	- 3 in/mile
59	Maintain transverse joints	- Yes
60	% of transverse joints to be sealed (if yes in no. 59 above)	- 40%
61	Regularity of maintenance (if yes in no. 59 above)	- 5
62	Maintain longitudinal joints	- Yes
63	% of longitudinal joints to be sealed (if yes in no. 62 above)	- 25%
64	Regularity of maintenance (if yes in no. 62 above)	- 5
65	Maintain transverse cracks	- Yes

Table 18: Additional Data Input Values for the First Project within PaveSpec^{TM}

68	Define localized rehabilitation plan	1. Always do full-depth repairs to 100% of spalled joints. 2. If cumulative percentage of cracked slabs exceeds 10% then consider the sublot failed. 3. If cumulative percentage of spalled joints exceeds 10% then consider the sublot failed. 4. If average transverse joint faulting exceeds 0.25 inch then consider the sublot failed. 5. If percent failed sublots exceeds 25% then begin global rehabilitation Scenario 1.
69	Repair spalled joints prior to global rehabilitation	- Yes
70	% of spalled joints to be repaired (if yes in no. 69 above)	- 100%
71	Description of repair to be undertaken (if yes in no. 69 above)	- Partial depth repairs
72	Repair cracked slabs prior to global rehabilitation	- Yes
73	% of cracked slabs to be repaired (if yes in no. 72 above)	- 100%
74	Description of repair to be undertaken (if yes in no. 72 above)	- Partial slab replacements
75	Description of 1st global rehabilitation to apply	- AC overlay
76	Assumed life of 1st global rehabilitation	- 7 years
77	Smoothness at start and end of 1st global rehabilitation	- 90 – 200
78	Description of 2nd global rehabilitation to apply (if required)	- AC overlay
79	Assumed life of 2nd global rehabilitation	- 7 years
80	Smoothness at start and end of 2nd global rehabilitation	- 95 – 200
81	Description of 3rd global rehabilitation to apply (if required)	- AC overlay
82	Assumed life of 3rd global rehabilitation	- 5 years
83	Smoothness at start and end of 3rd global rehabilitation	- 100 – 200
84	Description of 4th global rehabilitation to apply (if required)	- AC overlay
85	Assumed life of 4th global rehabilitation (years)	- 3
86	Smoothness at start and end of 4th global rehabilitation	- 105 - 200
87	Cost of transverse joint sealing	- \$1.20 per ft
88	Cost of longitudinal joint sealing	- \$1 per ft

89	Cost of transverse crack sealing	- \$1 per ft
90	User percentage cost to include	- 1%
91	Year to use for user cost inflation	- 1999
92	Cost of full-depth repairs of transverse joints	- \$159 yd^2
93	Cost of partial-depth repairs of transverse joints	- \$364 yd^2
94	Cost of slab replacement	- N/A
95	Cost of partial slab replacement	- \$135 yd^2
96	Cost of AC overlay (if selected in no. 75, 78, 81 or 84)	- \$11 per yd^2 (1st = \$9, 2nd = \$11.20, 3rd = \$21.08)
97	Cost of PCC overlay (if selected in no. 75, 78, 81 or 84)	- N/A
98	Cost of diamond grinding (if selected in no. 75, 78, 81 or 84)	- N/A
99	Annual Inflation Rate	- 3%
100	Annual Interest Rate	- 6%
101	Assumed width of full depth repair of transverse joint.	- 6 ft
102	Assumed width of partial depth repair of transverse joint	- 6 ft
103	Assumed width of partial slab replacement	- 6 ft
104	Number of lots to simulate at each factorial point	- 500
105	Minimum number of sublots per lot to simulate	- 3
106	Maximum number of sublots per lot to simulate	- 3
107	Average bid price per pavement area	- \$20/yd^2
108	Analysis life	- 60 years
109	Lowest mean value	- 600 psi at 28-days
110	Highest mean value	- 800 psi at 28 days
111	Total number of mean values	- 9
112	Lowest standard deviation	- 30 psi
113	Highest standard deviation	- 80 psi
114	Total number of standard deviations	- 6
115	Lowest mean value	- 13 in.
116	Highest mean value	- 15 in.
117	Total number of mean values	- 9
118	Lowest standard deviation	- 0.25 in.
119	Highest standard deviation	- 0.75 in.
120	Total number of standard deviations	- 7
121	Lowest mean value	- 5 in/mile
122	Highest mean value	- 10 in/mile
123	Total number of mean values	- 6
124	Lowest standard deviation	- 0 in/mile
125	Highest standard deviation	- 4.5 in/mile
126	Total number of standard deviations	- 6