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# Performance-Related Specifications for Concrete Pavements

Volume II:

Appendix A—Prototype Performance-Related Specification  
Appendix B—PaveSpec Users Guide  
Appendix C—Annotated Bibliography

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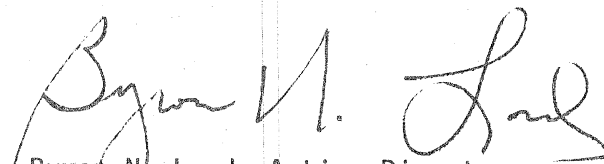
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## FOREWORD

This report is one volume of a three-volume set of reports presenting the results of a study to further the development of performance-related specifications for portland cement concrete pavement construction. Laboratory testing was conducted to fill several gaps in the knowledge of portland cement concrete. Drawing upon the results of the laboratory testing, the underlying theory of performance-related specifications was considerably extended, and a prototype performance-related specification was developed. Also, a computer program was developed for use with the specification to assist in simulation and in generating pay adjustments. This report contains two appendixes which will be of interest to engineers concerned with quality assurance, specifications, and construction of concrete pavements.

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Byron N. Lord, Acting Director  
Office of Engineering and Highway  
Operations Research and Development

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16. Abstract <p>This study continued the development of performance-related specifications (PRS) for concrete pavements. Drawing upon previous work, a prototype PRS was developed that considers the expected life-cycle cost of the as-constructed pavement as the overall measure of quality. The approach calls for measurement of <i>in situ</i> concrete properties and explicitly considers variability and multiple quality characteristics in the determination of pay adjustments. Extensive laboratory testing was conducted to determine material relationships needed in the prototype PRS, and a detailed test plan has been developed for the evaluation of construction variables (e.g., dowel misalignment) that significantly affect concrete pavement performance, but are not currently accounted for in the specification. A computer program, PaveSpec, has been developed for use with the specification in simulation and in generating pay adjustments.</p> <p>This volume includes supporting documentation for the research study. The prototype PRS is included in its entirety in appendix A. This specification is complete for pilot testing, verification, and validation on simulated and then actual construction projects. Appendix B contains a users guide for the PaveSpec computer program that has been developed for use with the specification. Appendix C presents an annotated bibliography of literature pertinent to construction specifications.</p> <p>This volume is the second in a series. The other volumes are:</p> <p style="margin-left: 40px;">FHWA-RD-93-042 Volume I: Development of a Prototype Performance-Related Specification FHWA-RD-93-044 Volume III: Appendix D—Laboratory Testing Procedures and Testing Results Appendix E—Review of Recent Studies and Specifications</p>					
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# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

## APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>					<b>LENGTH</b>				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
<b>AREA</b>					<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>	mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>	m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	square meters	m <sup>2</sup>	m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>	km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>					<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>	m <sup>3</sup>	cubic meters	35.71	cubic feet	ft <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>	m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
<b>MASS</b>					<b>MASS</b>				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
<b>TEMPERATURE (exact)</b>					<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
<b>ILLUMINATION</b>					<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>	cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>					<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

\* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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# LIST OF ACRONYMS AND ABBREVIATIONS

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A	Air Content
AAMAS	Asphalt-Aggregate Mixture Analysis System
AASHTO	American Association of State Highway and Transportation Officials
A-C	As-Constructed
AC	Asphalt Concrete
ACI	American Concrete Institute
A-D	As-Designed
ADT	Average Daily Traffic
AEQ	Air-Entraining Quantity
AGE	Age of Specimens at Time of Testing
AGED	Age of Specimens at Time of Testing Deviation from Mean Value
AIR	Air Content
AIRD	Air Content Deviation from Mean Value
AQL	Acceptable Quality Level
ARR	Arrhenius Maturity
ASR	Alkali-Silica Reactivity
ASTM	American Society for Testing and Materials
CAG	Coarse Aggregate Geometry
CAGD	Coarse Aggregate Geometry Deviation from Mean Value
CAH	Coarse Aggregate Hardness
CAHD	Coarse Aggregate Hardness Deviation from Mean Value
CAM	Coarse Aggregate Maximum Size
CAP	Coarse Aggregate Volume Percentage
CAPD	Coarse Aggregate Volume Percentage Deviation from Mean Value
CAQ	Coarse Aggregate Quantity
CAT	Coarse Aggregate Type
CEP	Cement Volume Percentage
CEPD	Cement Volume Percentage Deviation from Mean Value
CEQ	Cement Quantity
CET	Cement Type
CH	Crushed-Hard
COV	Coefficient of Variation
CPF	Composite Pay Factor
CRCP	Continuously Reinforced Concrete Pavement
CS	Crushed-Soft
CSL	Consolidation Level
CSLD	Consolidation Level Deviation from Mean Value
DDE	Dynamic Data Exchange
DOT	Department of Transportation
$E_c$	Concrete Elastic Modulus
EMS	Error Mean Square
EP	Expected Pay Value
ESAL	Equivalent Single-Axle Load

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# LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

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$f'_c$	Concrete Compressive Strength
F-T	Freeze-Thaw
FAM	Fine Aggregate Fineness Modulus
FAP	Fine Aggregate Volume
FAQ	Fine Aggregate Quantity
FAT	Fine Aggregate Type
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
HRWR	High-Range Water Reducer
G	Gradation
GPR	Ground-Penetrating Radar
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavement
JRCP	Jointed Reinforced Concrete Pavement
$\bar{L}$	Void Spacing Factor
LCC	Life-Cycle Cost
$LCC_{con}$	Life-Cycle Cost of the As-Constructed Pavement
$LCC_{des}$	Life-Cycle Cost of the As-Designed Pavement
LTPP	Long-Term Pavement Performance
M&C	Materials & Construction
MESAL	Millions of ESAL's
MR	Concrete Modulus of Rupture (Flexural Strength)
MS	Mean Square
n	Number of Samples (= Number of Sublots)
NCHRP	National Cooperative Highway Research Program
NDT	Nondestructive Testing
NS	Nurse-Saul Maturity
OC	Operating Characteristic
PCC	Portland Cement Concrete
PD	Percent Defective
PDL	Percent Defective Length
PF	Pay Factor
PPA	Percent Pay Adjustment
PRH	Percent Relative Humidity
PRS	Performance-Related Specifications
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
PV	Pulse Velocity
PWT	Percent Within Tolerance
Q	Quality Index
QC	Quality Characteristics
QCSP	Quality Characteristic and Sampling Parameters
R	Initial Roughness

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# LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

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R <sup>2</sup>	Coefficient of Determination
Rep. RMS	Replicate Root Mean Square
Rep. MS	Replicate Mean Square
RH	Round-Hard
RMS	Root Mean Square
RQL	Rejectable Quality Level
RS	Round-Soft
S	Concrete Strength
S <sub>con</sub>	Standard Deviation of the LCC of the As-Constructed Pavement
SEE	Standard Error of Estimate
SHA	State Highway Agency
SHRP	Strategic Highway Research Program
SSD	Saturated Surface Dry
ST	Concrete Splitting Tensile Strength
Std. Dev.	Standard Deviation
T	Slab Thickness
TRB	Transportation Research Board
UC	User Cost
WAP	Water Volume Percentage
WAQ	Water Quantity
WASHTO	Western Association of State Highway and Transportation Officials
WC	Water-Cement Ratio
WCD	Water-Cement Ratio Deviation from Mean Value
WIM	Weigh-In-Motion
WWF	Welded-Wire Fabric

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## APPENDIX A—PROTOTYPE PERFORMANCE-RELATED SPECIFICATION

### 1. DESCRIPTION

This work shall consist of constructing a jointed plain or jointed reinforced portland cement concrete pavement on a prepared subgrade or base course, in accordance with this specification. This specification applies only to the concrete pavement placed in the traffic lanes. It does not include items related to joints (such as sawing, dowel placement, sealant), reinforcement, surfacing texturing, base, subbase, or shoulders.

This specification includes acceptance sampling and testing by the Agency for the lot. Based on these results, the Contractor shall receive 100 percent of the bid price for the lot if the quality of construction equals that of the target as-designed pavement. If the quality of construction is below or above the target as-designed pavement, the Contractor shall receive a pay adjustment for the lot. All calculations for life-cycle costs shall be performed using the PaveSpec computer software.

### 2. DEFINITIONS

The following definitions are applicable to these specifications:

**Quality Characteristics:** Inherent characteristics of the pavement that significantly affect the performance of the pavement. This specification includes concrete strength, slab thickness, entrained air content, and initial roughness as quality characteristics.

**Lot:** A discrete quantity of constructed pavement to which an acceptance procedure is applied. A lot shall be equal to one day's production or less. The lot shall consist of a pavement one or more traffic lanes wide (but shall not include a shoulder).

**Sublot:** A portion of a lot. The lot is divided into sublots of approximately equal surface area. This specification requires that sublots are uniquely defined for all sampling in that one or more samples of all quality characteristics are taken from each defined sublot.

**As-Designed Pavement:** The pavement as defined by the engineer. The desired quality level of the pavement is specified in section 6.03, As-Designed Target Pavement.

**As-Constructed Pavement:** The *in situ* concrete pavement lot as constructed by the Contractor.

**Life-Cycle Cost (LCC):** The total cost of a lot over the pavement's analysis period. LCC in this specification consists of the estimated future rehabilitation costs over the

analysis period and is expressed in terms of present worth through use of a specified discount rate. The initial construction cost is not included in the LCC since it is identical for both the as-designed and the as-constructed pavements.

**Percent Defective (PD):** The percent of the lot falling above the mean target as-designed LCC value, as defined in section 6.03, As-Designed Target Pavement.

**Pay Factor:** The percent of the bid price that the Contractor is paid for the construction of a lot of concrete pavement. It is calculated as follows:

$$\text{Pay Factor} = 100 ( \text{BID} + \text{DIFF} ) / \text{BID} \quad (1)$$

where:

BID = Contractor's bid price for the lot, \$  
DIFF =  $LCC_{des} - LCC_{con}$   
 $LCC_{des}$  = As-designed life-cycle cost for lot, \$  
 $LCC_{con}$  = As-constructed life-cycle cost for lot, \$

### 3. MATERIALS

Agency specifications for materials requirements are placed here.

### 4. CONSTRUCTION REQUIREMENTS

Agency specifications for construction requirements, including Contractor process control, are placed here.

### 5. METHOD OF MEASUREMENT

#### 5.01 Sampling

Acceptance of the as-constructed pavement is based on *in situ* tests of the as-constructed pavement lot. All sampling shall be performed by the Agency in accordance with the following standard specification: American Society of Testing and Materials (ASTM) D3665, Standard Practice for Random Sampling of Construction Materials.

The lot shall be divided into approximately equal area sublots, within which each quality characteristic shall be sampled. The minimum length of a subplot shall be approximately 0.1 mi (0.16 km) to accommodate the measurement of longitudinal roughness. The random selection process illustrated in ASTM D3665 shall be used within each subplot to select locations for the individual samples of strength, thickness, and air content.

A minimum of three sublots is required per lot. If a lot is constructed that is less than 0.3-mi (0.5-km) long, making it impossible to obtain a minimum of three sublots



of 0.1 mi (0.16 km) each, the lot shall be accepted by the engineer upon a visual inspection of the section and a review of process control results.

Specific sampling requirements for the quality characteristics are stated in section 5.03, Concrete Strength; section 5.05, Slab Thickness; section 5.06, Air Content; and section 5.07, Pavement Roughness. The following acceptance guidelines are provided for the four quality characteristics:

Quality Characteristic	Point of Acceptance	Lot Size	Sublot Size
Entrained air content of concrete	Measured behind paver, after concrete placement, or from cores	Maximum: one day's production  Minimum: 0.3-mi (0.5-km) long (3 sublots)	Approximately 0.1-mi (0.16-km) long
Thickness of slab	Cores drilled from hardened concrete		
Strength of concrete	Cores drilled from hardened concrete		
Roughness of surface	Profilograph measurement		

### 5.02 Testing (General)

Any standard test may be used to measure the quality characteristics in the acceptance plan, provided the following conditions are satisfied:

1. The standard test method is pre-approved by the Agency.
2. A pre-approved conversion factor to convert the acceptance test concrete strength result to the strength characteristic specified in the design is applied (for example, a 72-h core compressive strength is used for acceptance, but the design specifies a 28-d flexural strength). Each Agency should develop their own conversion factors for specific tests and for the specific concrete materials used in the project.
3. Slab thickness and strength shall be measured on each core sample taken from a sublot.
4. Air content shall be measured from either hardened concrete (determined by conducting a linear traverse on a different core than those taken for strength and thickness) or from the plastic concrete sampled behind the paver (determined using a conventional air pressure meter).

5. Roughness shall be measured over the same subplot as designated for strength, thickness, and air content.

All acceptance testing shall be conducted and paid for by the Agency, except as stated under section 5.08, Retesting Procedures.

### 5.03 Concrete Strength

*In situ* concrete strength shall be determined after a minimum of 72 h of equivalent laboratory curing condition maturity from placement. Two cores shall be cut from the slab in each subplot and tested to determine the concrete strength. (Note: A minimum of two cores are required, but the Agency may specify more if desired.) The retrieved cores shall be measured for thickness prior to strength testing.

The procedure for coring cylinders from the pavement is specified in AASHTO T23, Obtaining and Testing Drilled Cores and Sawed Beams of Concrete and in ASTM C42, Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.

Specimens shall be kept moist during coring operations, during transport to the testing facility, and prior to testing. This may be accomplished by covering the samples with a wet blanket of burlap or other suitable absorbent material. The material shall be kept wet until testing. Specimens shall be transported to the testing facility in such a way as to not damage them. (Note: The minimum 40-h water submersion requirement of ASTM C42 prior to core testing is waived.)

Either standard compression or splitting tensile strength tests shall be conducted by the Agency within 4 h of removal of the core from the concrete slab as follows.

#### 5.03.01 Compressive Strength

The compressive strength of cylindrical core concrete specimens shall be determined using AASHTO T22, Concrete Strength of Cylindrical Concrete Specimens or ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

A minimum 4-in (102-mm) diameter core shall be used when the maximum aggregate size is 1.25 in (32 mm) or less. A minimum 6-in (152-mm) diameter core shall be used when the maximum aggregate size is greater than 1.25 in (32 mm).

The cores shall be trimmed to a nominal length-diameter ratio of 2. A correction factor in accordance with ASTM C39 must be applied to cores having a length-diameter ratio of less than 1.94, while cores having a length-diameter ratio between 1.94 and 2.10 require no such correction. Cores with a length-diameter ratio exceeding 2.10 shall be reduced in length to fall within the ratio limits of 1.94 to 2.10.

The mean compressive strength of the cores from each subplot shall then be adjusted using maturity methods to obtain an equivalent mean 28-d compressive strength under standard laboratory-cured conditions. This equivalent mean 28-d compressive strength shall then be converted to a third-point loading flexural strength using an approved relationship developed from the specific concrete mixture for the lot.

The estimated mean 28-d third-point loading flexural strength shall be used as the strength of the subplot sample.

#### 5.03.02 Splitting Tensile Strength

The splitting tensile strength shall be determined using AASHTO T128, Standard Method of Splitting Tensile Strength of Cylindrical Concrete Specimens or ASTM C496, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.

The mean splitting tensile strength of the cores from each subplot shall then be adjusted using maturity methods to an equivalent mean 28-d splitting tensile strength under standard laboratory-cured conditions.

The equivalent mean 28-d splitting tensile strength shall then be converted to a mean third-point loading flexural strength using an approved relationship developed from the specific concrete mixture for the lot.

The estimated 28-d mean third-point loading flexural strength shall be used as the strength of the subplot sample.

#### **5.04 Maturity Adjustment**

The concrete strength results obtained from each core at a minimum 72 h of equivalent laboratory curing must be adjusted to obtain an equivalent 28-d, standard laboratory-cured flexural strength under third-point loading. The adjustment is determined from curves derived from the actual, onsite project materials in accordance with ASTM C1074, Standard Practice for Estimating Concrete Strength by the Maturity Method. Information on this adjustment is found in section 8.01, Maturity Adjustment Example.

(Note: If the onsite project materials are changed any time during construction, all maturity adjustments must be re-calculated based upon the maturity equations developed for the new materials.)

#### **5.05 Slab Thickness**

The thickness of the *in situ* pavement shall be determined by measurements taken in accordance with AASHTO T148, Standard Method of Measuring Length of Drilled Concrete Cores or ASTM C174, Standard Test Method for Measuring Length of

Drilled Concrete Cores. (Note: This test method is not applicable when a permeable base layer is used.)

The same core samples used to determine slab thickness shall be used to determine concrete strength. The mean slab thickness of the cores taken in each subplot shall be used as the thickness of the subplot sample.

#### 5.06 Air Content

(Note: The following procedures refer specifically to projects located in freeze areas where deicing salts are used and entrained air content is critical to concrete durability. If the project is not located in this type of climate, air content should be controlled on a simple acceptance/rejection basis when sampled using conventional procedures. In place of the following, the Agency's normal air content specification should replace this section.)

The air content of the *in situ* slab shall be determined in each subplot according to one of the following methods:

1. Plastic concrete is removed at a random location from behind the paver in the subplot and tested with an approved air pressure meter according to AASHTO T152, Air Content of Freshly Mixed Concrete by the Pressure Method, or ASTM C231, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. Standard procedures for rodding the sample shall be used.
2. An approved test method that is capable of determining the air content of plastic *in situ* concrete taken from behind the paver at a random location in the subplot shall be used.
3. A linear traverse is performed on a hardened concrete core sample according to ASTM C457, Standard Test Method For Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. Separate core samples shall be taken at random locations from each subplot exclusively for linear traverse testing.

Two samples per subplot are required regardless of the method used. The mean air content determined using any of the above methods shall be used as the air content of the subplot sample.

#### 5.07 Pavement Roughness

Pavement roughness shall be tested with a standard profilograph device in accordance with specific procedures. (Note: One such device is the California profilograph as described in California Department Of Transportation specification CA-526.) Roughness shall be measured as soon as the concrete has hardened sufficiently so that it can be tested without damage.

Profile measurements shall be made 3 ft (0.9 m) from and parallel to each longitudinal traffic lane edge of pavement. (Note: Two traffic lanes would require four profiles.) The roughness measurements shall be conducted along the length of each subplot and the measurement converted to the standard unit of in/mi (m/km). All roughness profile measurements for the subplot shall then be averaged. Roughness measurements taken prior to any surface correction shall be used as the roughness of the subplot sample.

For each longitudinal profile, all bumps exceeding Y in (mm) (level set by the Agency for specific device) are required to be ground. If the mean roughness for the lot (prior to any corrective work) exceeds the as-designed target roughness by more than Z in/mi (m/km) (level set by the Agency for specific device), longitudinal diamond grinding along the entire lot is required to reduce roughness to equal or less than the target value plus Z in/mi (m/km).

#### **5.08 Retesting Procedures**

Additional sampling and testing for any of the quality characteristics 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 Agency shall pay for the sampling and testing if any of the equipment is found to be out of calibration, if an operator error has occurred, or if retesting is requested by the Agency and values equal to or exceeding the as-designed target values are obtained.

The Contractor shall pay for the sampling and testing if the Contractor requested the retesting and neither the equipment is out of calibration nor an operator error has occurred.

The pavement shall be retested only once in accordance with section 5, Method of Measurement. The subplot retesting sampling locations shall be in accordance with section 5.01, Acceptance Sampling. Except for cases of testing errors (that are agreed upon by both the Contractor and the Agency), initial test results shall be included along with the retests in the acceptance process by averaging all values from each subplot.

#### **5.09 Laboratory Control**

Agency laboratory control requirements placed here.

### **6. ACCEPTANCE**

#### **6.01 Quality Characteristics**

The acceptance of a single lot is based on the following quality characteristics of the concrete pavement:

- Strength of concrete slab.
- Thickness of slab.
- Air content of concrete slab.
- Roughness of slab surface.

These quality characteristics are combined into a single quality characteristic, the future LCC of the pavement. The future LCC quality characteristic relates directly to the future performance of the pavement. The future LCC shall be used as the single overall quality characteristic for acceptance.

## 6.02 Life-Cycle Costs (LCC)

The LCC for both the target as-designed ( $LCC_{des}$ ) and the as-constructed ( $LCC_{con}$ ) pavement lots shall include only the estimated future rehabilitation costs. The future rehabilitation costs consist of full-depth repairs, slab replacement, and overlays, according to a specified rehabilitation policy. These costs are calculated over the designated design analysis period and expressed as a present worth cost. All cost calculations are performed using the PaveSpec computer software.

(Note: The rehabilitation policy used to calculate the  $LCC_{con}$  must be specified by the Agency. Three options exist: (1) Policy A—individual sublots are rehabilitated independently of one another through full-depth repairs, slab replacements, and overlays, (2) Policy B—individual sublots are rehabilitated by slab replacements and full-depth repairs independently of one another, with the entire lot overlaid when a critical amount of distress has occurred over the entire lot, and (3) Policy C—same as Policy B, but when a critical amount of distress has occurred over a selected percent of sublots, the entire lot is overlaid.)

## 6.03 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 bid price. It includes target means and standard deviations for each of the quality characteristics considered in the acceptance plan. The target standard deviations of the quality characteristics are representative of acceptable quality. These standard deviations are point-to-point variations (including testing errors) for strength, thickness, and air content in the slab, and variations between longitudinal profiles for initial roughness.

The lot target as-designed mean  $LCC_{des}$  is determined by simulating a large number of lots using the target means and standard deviations of the quality characteristics.

The as-designed target quality characteristics are the mean values of thickness, strength, air content, and roughness set by the designer as mean targets to be achieved for the as-constructed lot. The means and standard deviations for the target as-designed quality characteristics are as follows for this contract (the following are example values only):

Quality Characteristic	Mean	Standard Deviation
Compressive Strength, lbf/in <sup>2</sup>	5000	500
Slab Thickness, in	12.0	0.25
Air Content, percent	6.5	0.5
Roughness, in/mi	7.0	1.0

1000 lbf/in<sup>2</sup> = 6.9 MPa  
1 in = 25.4 mm  
1 mi = 1.6 km

The constant, as-designed pavement inputs specified for this contract are given in attachment no. 1. (Note: These inputs are the same for the as-constructed lot.)

#### 6.04 As-Constructed Pavement Lot

The as-constructed pavement lot shall be divided into sublots (a minimum of three) and each randomly sampled and tested in accordance with section 5, Method of Measurement. The subplot mean sample values of strength, thickness, air content, and roughness, along with a selected rehabilitation policy, are used to calculate the expected future LCC<sub>con</sub> for the as-constructed lot using the PaveSpec program as specified in section 6.02, Life-Cycle Costs. The rehabilitation costing policy to be used in PaveSpec shall be as follows for this contract: (Example: Use policy C, see section 6.02, "Life-Cycle Costs [LCC].")

#### 6.05 Percent Defective Calculation

The percent defective of the as-constructed lot is defined as the proportion of the lot having an LCC<sub>con</sub> greater than the LCC<sub>des</sub>, and is calculated as follows:

$$Q = (LCC_{des} - LCC_{con}) / S_{con} \quad (2)$$

where:

- LCC<sub>des</sub> = As-designed target life-cycle cost, \$  
(computed as specified under section 6.03)
- LCC<sub>con</sub> = As-constructed life-cycle cost of lot, \$  
(computed as specified under section 6.04)
- S<sub>con</sub> = Standard deviation of LCC between as-constructed sublots, \$

The percent defective of the LCC<sub>con</sub> is determined from table C in AASHTO R9, using sample size (n) and Q. The sample size (n) is equal to the number of sublots.

#### 6.06 Rejected Quality Level

The constructed lot shall be rejected and removed at the Contractor's expense if, after retesting, any of the quality characteristics exceed the following limits:

1. The mean lot as-constructed thickness is less than 90 percent of the as-designed target value.
2. The mean lot as-constructed concrete flexural strength is less than 75 percent of the as-designed target value.
3. The mean lot as-constructed total air content is less than 65 percent of the as-designed target value. (Note: This requirement is only for projects in freeze areas where deicing salts are used.)

#### 6.07 Retesting

If retesting of any of the quality characteristics is requested by either the Agency or the Contractor, this shall be carried out as described in section 5.08. A new mean for the quality characteristic involved shall then be used to determine a new as-constructed  $LCC_{con}$  for the lot. The original  $LCC_{con}$  value shall be disregarded.

### 7. BASIS OF PAYMENT

The Contractor shall be paid based upon the achieved quality of the as-constructed pavement lot. The payment due the Contractor shall be adjusted by a pay factor when the constructed pavement lot quality level varies from the as-designed pavement quality level.

The pay factor shall be determined using the following equation for percent defective less than 90 percent.

$$\text{Pay Factor} = A - B * \text{Percent Defective} \quad (3)$$

(Note: The constants A and B will vary with different projects. They are determined by the Agency through simulation using the PaveSpec program.)

When the percent defective is 90 percent or larger, the following equation applies.

$$\text{Pay Factor} = 10*A + 900*B - 450 + (-0.1*A - 9*B + 5.0) * \text{Percent Defective} \quad (4)$$

The total payment to the Contractor for the lot shall be equal to the following:

$$\text{Contractor Lot Payment} = \text{Lot Bid Price} * \text{Pay Factor} / 100 \quad (5)$$

### 8. EXAMPLE CALCULATIONS

#### 8.01 Maturity Adjustment Example

The concrete maturity method is used to extrapolate earlier age (less than 28 d) *in situ* compressive or splitting tensile strength to a 28-d, standard-cured strength. Concrete strength as a function of maturity is established using methods described in



## ASTM C1074, Standard Practice for Estimating Concrete Strength by the Maturity Method.

A best-fit line is fitted through a plot of strength versus maturity. Transformation of variables using square root, logarithmic, or inverse function may be necessary. Strengths used in developing the maturity function should range from a 1-d equivalent standard-cured maturity through at least a 35-d equivalent standard-cured maturity.

Temperature is monitored soon after concrete placement. Since curing temperatures vary with depth, temperatures should be periodically monitored at a minimum of three elevations away from slab edges and joints. Average temperatures should be used to calculate maturity. Maturity is incrementally accumulated throughout the testing and retesting process. Maturity is then calculated at the time of coring and used to extrapolate 28-d standard-cured strengths.

For example, assume the maturity at the time of coring is 3733 °C-h (6720 °F-h), and the maturity of 28-d, standard-cured cylinders is 14,933 °C-h (26,880 °F-h). The core compressive strength must be extrapolated out 11,200 °C-h (20,160 °F-h). Laboratory testing has produced the following mix-specific maturity equation:

$$\log f'_c = (-278/\text{MAT}) + 3.7456$$

where:

$$\begin{aligned} f'_c &= \text{Concrete compressive strength, lbf/in}^2 \\ \text{MAT} &= \text{Maturity, } ^\circ\text{C-h} \end{aligned}$$

It is assumed that the core compressive strength will continue at the same rate as the laboratory, standard-cured cylinder strength. For a core compressive strength of 4800 lbf/in<sup>2</sup> (33.1 MPa) at a maturity of 3733 °C-h (6720 °F-h), the equivalent maturity is backcalculated as 4320 °C-h (7775 °F-h). At 28 d, the extrapolated maturity is 15,520 °C-h (27,936 °F-h), and the corresponding 28-d, standard-cured compressive strength is 5340 lbf/in<sup>2</sup> (36.9 MPa).

The 28-d extrapolated compressive strength is then converted to a 28-d flexural strength using approved relationships between flexural and compressive strength developed from project materials.

### 8.02 Pay Factor Example

A lot 1 mi (1.6 km) in length is constructed with two traffic lanes. The lot is divided into 10 equal length sublots of 0.1 mi (0.16 km) each. The sampling plan calls for two samples of each quality characteristic from each sublot. The rehabilitation policy specified is "C," as described in section 6.02, Life-Cycle Costs (LCC).

The as-designed  $LCC_{des}$  mean was determined from simulation using the target means and standard deviations for the target quality characteristics given below. The mean  $LCC_{des}$  was determined to be \$66,462/mi (\$41,298/km).

Quality Characteristic	Mean	Standard Deviation
Compressive Strength, lbf/in <sup>2</sup>	5000	500
Slab Thickness, in	12.0	0.25
Air Content, percent	6.5	0.5
Roughness, in/mi	7.0	1.0

1000 lbf/in<sup>2</sup> = 6.9 MPa

1 in = 25.4 mm

1 mi = 1.6 km

The following as-constructed *in situ* results for strength, thickness, air content, and roughness were obtained for the lot:

Pavement Section	Compressive Strength (lbf/in <sup>2</sup> )	Thickness (in)	Air Content (percent)	Roughness (in/mi)	LCC (\$/mi)
As-designed	5000	12.0	6.5	7.0	66,462
Sublot 1	4626*	12.0*	6.4*	6.4*	65,495
Sublot 2	5284	12.2	6.4	8.1	58,094
Sublot 3	5155	12.1	6.4	6.5	59,583
Sublot 4	5271	12.1	6.2	7.5	59,364
Sublot 5	5383	11.8	5.9	7.2	63,566
Sublot 6	5218	11.9	6.6	5.2	61,217
Sublot 7	4220	11.8	7.1	7.2	74,817
Sublot 8	5630	11.8	6.1	6.5	60,649
Sublot 9	5094	11.7	7.1	7.2	64,893
Sublot 10	4941	12.2	7.1	7.7	60,315
Mean	5082	11.9	6.6	7.0	62,799
Std. Dev.	403	0.20	0.4	0.8	4,879

\* Mean of two samples  
 1000 lbf/in<sup>2</sup> = 6.9 MPa  
 1 in = 25.4 mm  
 1 mi = 1.6 km

The percent defective of the as-constructed lot is defined as the proportion of the lot having an  $LCC_{con}$  greater than the as-designed LCC ( $LCC_{des}$ ). The percent defective is calculated as follows:

$$Q = (LCC_{des} - LCC_{con}) / S_{con} = + 0.75$$

where:

$$\begin{aligned} LCC_{des} &= \$ 66,462 \\ LCC_{con} &= \$ 62,799 \\ S_{con} &= \$ 4,879 \end{aligned}$$

The percent defective as-constructed  $LCC_{con}$  is determined from AASHTO R9, table C. Using a sample size of  $n = 10$  and a quality index of  $Q = + 0.75$ , the percent defective is found to be 23.10 percent.

The pay factor is calculated using the following equation obtained from simulation with the PaveSpec software for this specific example project.

$$\begin{aligned} \text{Pay Factor} &= 102.85 - 0.06 * \text{Percent Defective} \\ &= 102.85 - 0.06 * 23.10 \\ &= 101.5 \text{ percent of bid price} \end{aligned}$$

The bid price for this 1-mi (1.6 km) concrete pavement lot is \$281,600. Thus, the Contractor's pay for this lot is  $\$281,600 * 1.015 = \$285,824$ .

## ATTACHMENT NO. 1

(Note: Place here all constant inputs for the as-designed and as-constructed pavements.)

---

## APPENDIX B-PAVESPEC USERS GUIDE

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# INTRODUCTION

## System Requirements and Recommendations

PaveSpec is written for the Windows 3.1 operating system. It will not run on earlier versions of Windows, including Windows 3.0. Windows 3.1 will run only on IBM-compatible PC's with at least:

- 1 megabyte of RAM.
- 286-class processor or better.
- Hard disk.
- Graphics monitor.

In addition to the Windows 3.1 requirements, PaveSpec requires:

- Mouse or other pointing device.
- Approximately 1 megabyte of hard disk space.

These are the bare-minimum requirements for PaveSpec. While PaveSpec will attempt to run on such a system, the performance level will likely be too low for most practical uses. As a *usable* minimum, we recommend a system with at least:

- 4 megabytes of RAM (at least 8, and virtual memory, is ideal). Less than 4 megabytes of memory, or the absence of virtual memory, will limit the range of many of PaveSpec's session parameters.
- 386SX or better processor, preferably with a math coprocessor (486 or better is ideal).
- VGA or better monitor (ideally an 800 x 600 pixels or 1024 x 768 pixels).

While PaveSpec has been tested on several computers, an exhaustive test for compatibility with all computers has not been performed.

## Output Compatibility

Because PaveSpec is a Windows program, it offers compatibility with all major printers, including PostScript printers, HP LaserJet printers, and the Epson printer line. It also is compatible with all major video adapter types (VGA, Super-VGA, TIGA, and so on).

**PaveSpec also offers ASCII file and clipboard output.**

**PaveSpec can also serve as a Dynamic Data Exchange (DDE) server and client.**



# PAVESPEC BASICS

PaveSpec is a complex program that provides the simulation of the acceptance plan of a performance-related specification (PRS) for concrete pavement. It is a research tool, and is not intended for commercial use at this time. Perhaps the simplest way to describe how it works is to start with what it can do, then move on to some terms and a basic explanation of its inner workings.

The next chapter, Using PaveSpec, will describe how to put PaveSpec to work.

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## What Can PaveSpec Do?

- Overall objective is to provide realistic simulation of a performance-related specification (PRS) acceptance plan.
- Simulates target as-designed and as-constructed pavement lots and performs sampling and testing for quality characteristics. Inputs define the as-designed and as-constructed pavements.
- Directly considers four key quality characteristics: concrete strength, air content, slab thickness, and initial roughness.
- Predicts key distress indicators (faulting, cracking, spalling, PSR) over analysis period and applies rehabilitation policy to results.
- Estimates rehabilitation costs, called the life-cycle costs (LCC), of a particular lot over a defined analysis period. Various rehabilitation policies are available for the lot.
- Compares LCC of an as-constructed lot to target as-designed lot. From this comparison, calculates a pay adjustment factor based on the principal of liquidated damages.
- Compares many as-constructed lots, with varying quality characteristics, to a simulated target as-designed lot, to obtain a distribution of pay factors.
- Generates a pay factor versus percent defective curve through simulation of a large number of as-constructed lots.
- Varies the as-constructed lot quality characteristics iteratively and predicts LCC's and pay factors at each iteration point. For example, the user may, while holding the other characteristics constant, vary strength from 5,000 to 6,000 lbf/in<sup>2</sup> (34.5 to 41.4 MPa) over 10 steps. PaveSpec also performs iteration of multiple quality characteristics.
- Generates factorial tables of as-constructed life-cycle costs by all four quality characteristics. These tables can be used to look up LCC's without the use of a computer.
- Generates pay-factor contour plots for any two chosen quality characteristics.

---

## Introduction to PaveSpec

The basic unit of PaveSpec's computation is the *prediction*. A prediction is an estimate of the *life-cycle cost (LCC)* of a *lot*. A lot is a section of pavement, defined in terms of length, width, location, and many other *constant variables*, and also in terms of the *quality characteristics*—concrete strength, thickness, air content, and initial roughness. The quality characteristics are the measured construction characteristics of the pavement that directly affect the performance of the pavement. The LCC is an estimate of the rehabilitation (and, optionally, user) costs for a pavement lot over its design life, expressed in present worth costs. Figure 1 illustrates the procedure for computing LCC.

Predictions are useful in that they allow comparison of two different pavement lots in an effort to quantify the effect of the difference on rehabilitation costs. This is the fundamental use for PaveSpec 1.0: to compare the life-cycle costs of an *as-designed* conceptual pavement against the *as-constructed* pavement lot. The primary output of this type of comparison is a *pay factor*. The pay factor (PF) is the percentage of the bid price the contractor receives for building such a lot. This can either be a reduction for worse-than-designed lot quality (PF < 100 percent) or an increase for a higher-than-designed lot quality (PF > 100 percent).

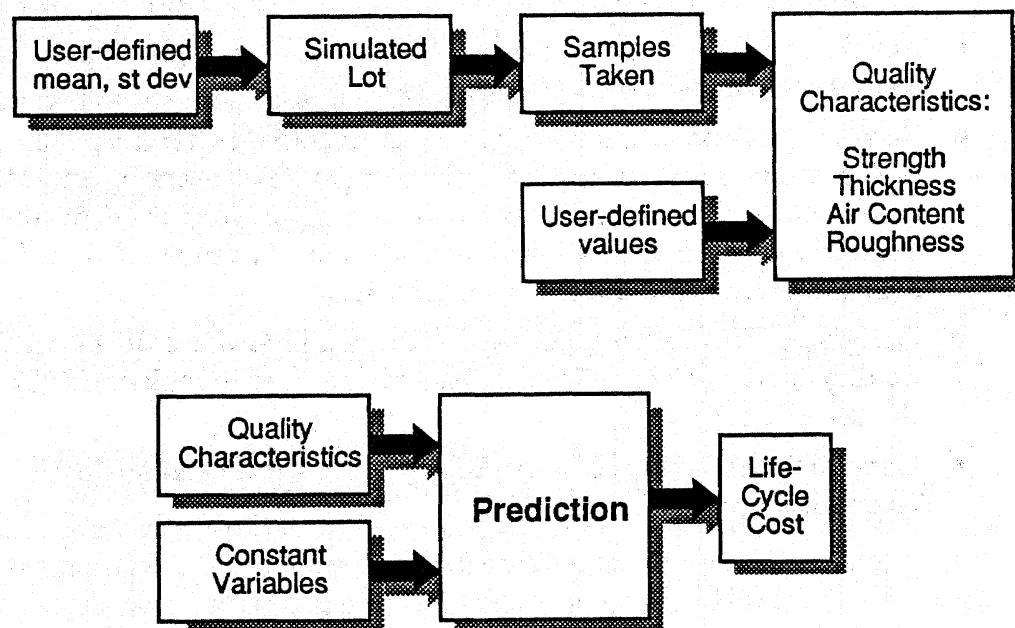


Figure 1. Acquiring quality characteristics (top), and their use in predicting LCC (bottom).

---

PaveSpec can either predict a lot based on set quality characteristic values, or sample the quality characteristics from a simulated *in situ* lot. In the latter case, the simulated lot contains independent, normally distributed values for each of the quality characteristics from which PaveSpec takes any number of samples per subplot. The mean of these samples in each subplot is assumed to be the mean of the subplot, simulating the effect of sampling and testing error. The user has control over the number of samples taken, the variation of each quality characteristic within the pavement lot, and which quality characteristics will be sampled (versus a user-defined constant value).

To begin an as-designed versus as-constructed comparison, the user sets the *constant variables* that apply equally to the as-designed and as-constructed cases and the *quality characteristics* that form the difference between the two; PaveSpec then predicts performance and LCC of each and presents the comparison as its output. As mentioned above, the primary output from such a comparison of the as-designed and as-constructed lot LCC is the *pay factor*. The equation for the pay factor is simply:

$$\text{Pay Factor} = 1 - \frac{\text{A-D LCC} - \text{A-C LCC}}{\text{Bid Price}} \times 100$$

- where:
- A-C LCC = Life-cycle costs of as-constructed pavement lot.
  - A-D LCC = Life-cycle costs of as-designed pavement lot.
  - Bid Price = The total pavement lot cost offered as the contractor bid for construction.

Therefore, if the calculated as-designed and as-constructed costs are the same for a lot, the contractor would receive 100 percent pay; otherwise an increase or decrease would occur.

PaveSpec can obtain LCC for the **target as-designed** pavement lot by using one of three methods. First, the user can specify the A-D LCC. Second, PaveSpec can calculate the A-D LCC using only the means of the as-designed quality characteristics (all quality characteristics have a standard deviation equal to zero). The LCC resulting from the second case is referred to as the *standard* as-designed life-cycle cost. Third, PaveSpec can simulate a series of as-designed lots by using *target values* (agency defined means and standard deviations) of the quality characteristics.

PaveSpec can do much more than a simple A/B comparison for a single pay factor. It uses *subplot prediction, distribution, and iterations* to generate more complex results, stored in tables and portrayed in graphs. These capabilities are examined in the following sections.

---

## Sublot Prediction

PaveSpec uses sublot prediction to generate two outputs: a *quality index* (Q) and *percent defective*, which is the proportion of the lot having an as-constructed A-C LCC greater than the as-designed A-D LCC mean. When the user selects sublot prediction, the user specifies the number of sublots within the lot; PaveSpec then divides the lot into equal-area sublots and predicts the performance and LCC of each of the sublots according to the rehabilitation policy.<sup>1</sup> (See figure 2.) The mean and standard deviation of the life-cycle costs of all the sublots are used to calculate the quality index (Q) from the equation:

$$Q = \frac{A - D \text{ LCC} - A - C \text{ LCC}}{\sigma_{A-CLCC}}$$

- where:
- A-D LCC = Mean target as-designed life-cycle cost, from simulation.
  - A-C LCC = Mean of life-cycle costs calculated for all sublots of the as-constructed pavement lot.
  - $\sigma_{A-CLCC}$  = Standard deviation of life-cycle costs calculated for all sublots of the as-constructed pavement lot.

Percent Defective is a function of Q, and n, the number of samples (in this case, n is the number of sublots). See also Quality Index (Q) and Percent Defective on p. 34.

---

<sup>1</sup>See pages 77 and 78 for a description of optional rehabilitation policies.

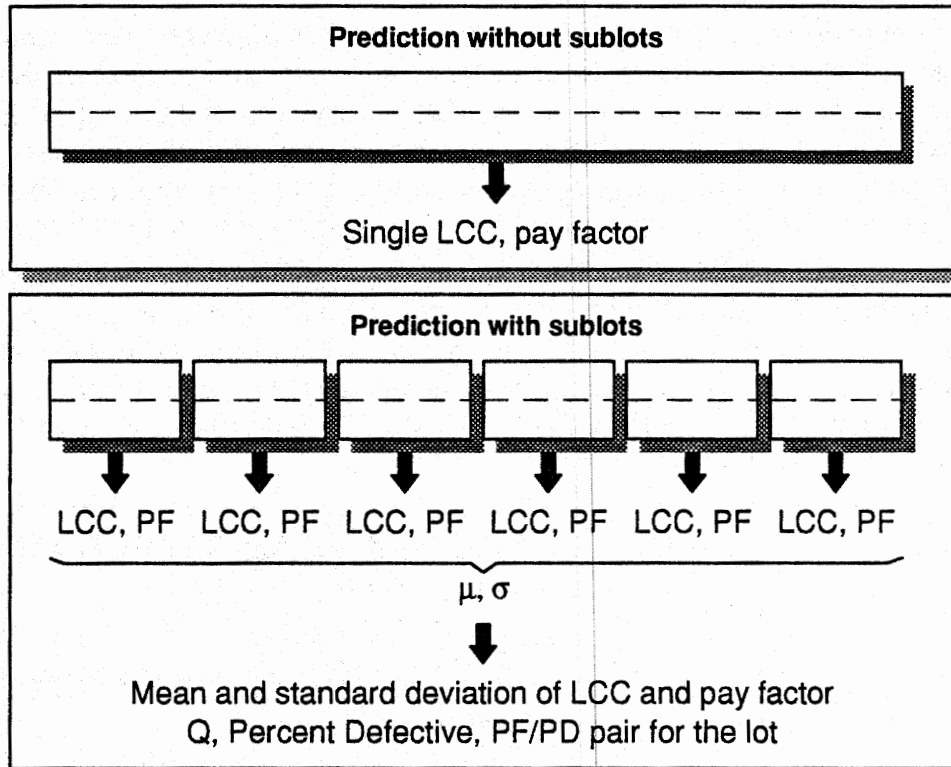


Figure 2. The difference between subplot prediction and lot (non-sublot) prediction.

When subplot predictions are used, the user may also opt to generate a Pay Factor (PF) vs. Percent Defective table and graph. PaveSpec records the PF and PD for each simulated lot and plots the result on a PF-PD graph (see p. 35 for details). The user may also use iterations and distributions to create a multidimensional PF-PD table (see Iterations, p. 26, and Distributions, next section).

---

## Distributions

If the user wants to quantify the life-cycle cost variability over a number of predictions, the user can use the Distributions option to calculate the mean and standard deviation of the outputs over a *series* of runs. For each of the outputs that change between as-constructed lot predictions (LCC, pay factor, Q, percent defective, and so on), PaveSpec calculates and reports the mean and standard deviation (figure 3).<sup>2</sup>

For each prediction, PaveSpec normally uses the same user-defined means and standard deviations of strength, thickness, air content, and initial roughness. The only difference between predictions are the locations, and therefore the values, of the samples. The user, however, can choose to introduce variability using new lots for each prediction, or a combination of new lot and new samples (see Seeds, p. 32).

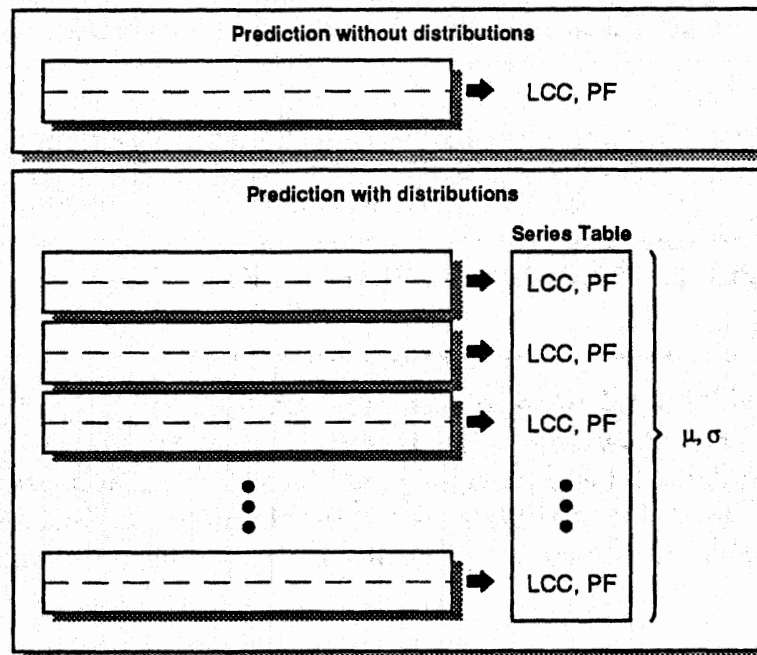


Figure 3. Comparison of with-distributions and without-distributions prediction.

---

<sup>2</sup> If both distributions and subplot predictions are active, PaveSpec calculates the mean and standard deviation of only the *means* of the life-cycle costs and pay factors.

---

## Iterations

Iterations are perhaps the most complicated of PaveSpec's features. They are used to investigate the effect of changing the key quality characteristics, either one at a time, or several at a time. For example, the user might want to:

- Determine how the pay factor varies with strength.
- Determine how increasing construction variation in the slab thickness affects the percent defective.
- Find what mean value of thickness will result in a 95-percent pay factor, given various values of strength.
- Get a complete analysis of the relationship between all the quality characteristics.

PaveSpec provides iterations as the means by which the user can investigate these questions and many others. Simply put, they involve repeating predictions for several (or even thousands) of different input values.

---

### Iteration Types

PaveSpec can iterate the quality characteristics using three methods: No Iterations, Linear Interpolation, and Factorial ( $X^K$ ) Interpolation.

#### No Iterations.

No iterations are performed.

#### Linear Interpolation.

When a variable is linearly interpolated, PaveSpec will run a prediction for each of N steps, interpolated between a user-defined low and high value. The number of steps is also defined by the user, and this number applies to all variables. For example, the user can specify that strength be advanced from 5,000 to 6,000 lbf/in<sup>2</sup> (34.5 to 41.4 MPa) over a total of 6 steps: 5,000 lbf/in<sup>2</sup> (34.5 MPa), 5,200 lbf/in<sup>2</sup> (35.9 MPa), 5,400 lbf/in<sup>2</sup> (37.2 MPa), 5,600 lbf/in<sup>2</sup> (38.6 MPa), 5,800 lbf/in<sup>2</sup> (40.0 MPa), and 6,000 lbf/in<sup>2</sup> (41.4 MPa). If the user also chooses to iterate thickness, it, too, will use a total of six steps from the low to the high value; for example, for thickness from 9 in to 10 in (229 to 254 mm), the predictions would be:



Prediction	Strength	Thickness
1	5,000 lbf/in <sup>2</sup>	9.0 in
2	5,200	9.2
3	5,400	9.4
4	5,600	9.6
5	5,800	9.8
6	6,000	10.0

1,000 lbf/in<sup>2</sup> = 6.9 MPa

1 in = 25.4 mm

### **X<sup>K</sup> Interpolation.**

Also known as a factorial iteration. All the combinations of each of X linearly interpolated values of each of the K variables will be run; the total predictions are then X<sup>K</sup>. For example, if strength and thickness are chosen (K=2), and the user specifies X=3, there will be a total of nine (3<sup>2</sup>) predictions:

Prediction	Strength	Thickness
1	5,000 lbf/in <sup>2</sup>	9.0 in
2		9.5
3		10.0
4	5,500 lbf/in <sup>2</sup>	9.0 in
5		9.5
6		10.0
7	6,000 lbf/in <sup>2</sup>	9.0 in
8		9.5
9		10.0

1,000 lbf/in<sup>2</sup> = 6.9 MPa

1 in = 25.4 mm

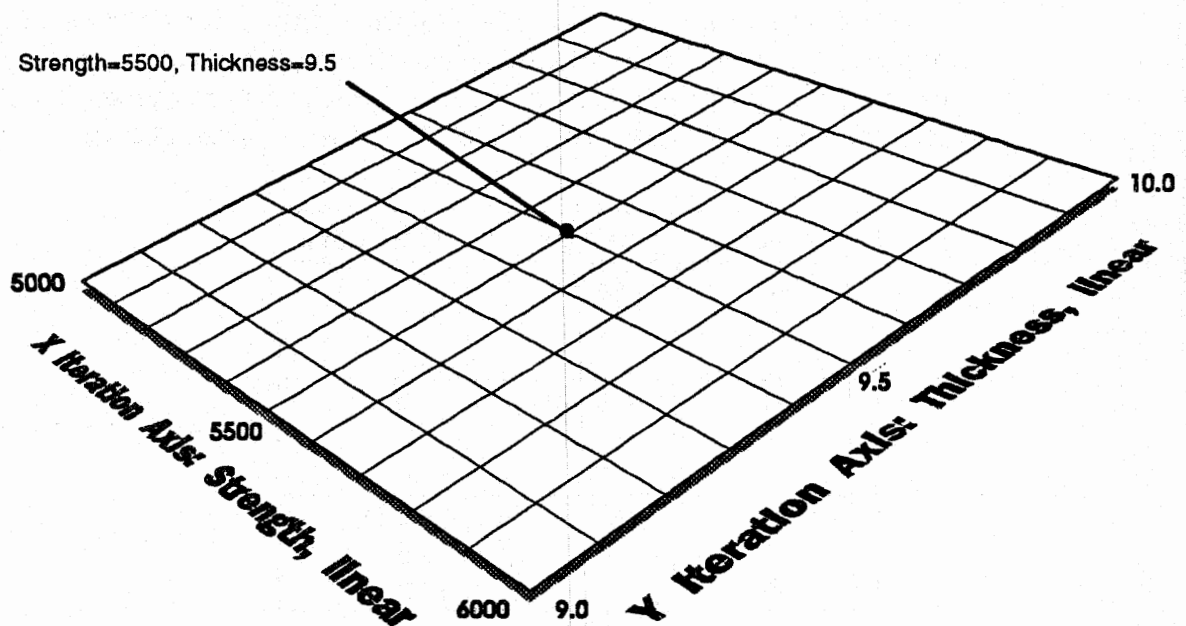
The user can specify the value of X. K is determined by the total number of variables the user chooses to so iterate.

---

## Iteration Axes

PaveSpec uses two *iteration axes*, called X and Y, to implement a variety of sessions. Each of the axes is completely independent of the other, and any of the quality characteristics can be iterated along either axis (or, in some cases, both). Each axis can be one of the types described above (none, linear, or  $X^K$ ). For example, it is entirely permissible to run a linear, 11-step axis on X and an  $X^K$  iteration on Y with  $X=4$ . PaveSpec will generate a prediction for each point in the two-dimensional plane formed by the X and Y axes. Figure 4 shows such a plane.

---



$$1,000 \text{ lbf/in}^2 = 6.9 \text{ MPa}$$

$$1 \text{ in} = 25.4 \text{ mm}$$

Figure 4. An illustration of iteration axes.

---

In this example, both the X and Y axes have been set for 11 steps. Strength has been assigned to the X axis, with a low value of 5,000 lbf/in<sup>2</sup> (34.5 MPa) and a high value of 6,000 lbf/in<sup>2</sup> (41.4 MPa). Thickness has been assigned to the Y axis, with a low value of 9 in (229 mm) and a high value of 10 in (254 mm). A total of 121 predictions would be run—one for each point in the two-dimensional plane shown here. The point shown corresponds to just one of the 121 predictions that would be run, assuming that distributions were not selected.

---

For the as-constructed case, which normally uses sampling, PaveSpec can iterate both the means and standard deviations of the source distributions of any of the quality characteristics. When sampling is used, the user can have the mean iterated along one axis (for example, X), and the standard deviation along the other (Y), assuming both axes are enabled. PaveSpec will run a prediction for each combination.

Of course, when iterations, subplot prediction, and distributions are selected, it can add (actually, multiply) up to a large number of predictions: namely, the product of the number of points along the X axis, the number of points along the Y axis, the number of distribution runs, and the number of sublots.<sup>3</sup>

---

<sup>3</sup> In the case where the user chooses to iterate the number of sublots, the total number of predictions depends on the low and high values and the number of steps.

---

## Lot Simulation and Sampling

The fundamental source of variability in PaveSpec's predictions is the simulation and sampling of an *in situ* lot.

PaveSpec simulates a lot by assuming a normal distribution for each of the quality characteristics. It establishes a particular value from this distribution for every point on an X-Y grid corresponding to the lot (the X axis is along the pavement, the Y axis is across it).<sup>4</sup> The resolution of this grid is user-definable, but is usually set to 0.5 ft (0.15 m). To obtain quality characteristic values for any X-Y point on the grid, a square area, with dimensions of the user-defined grid resolution, is centered on each simulated grid point (anchor points). Every sample point falling within this area is assumed to have the same quality characteristic values as those simulated for the anchoring grid point. Each of the quality characteristics is entirely independent of the others at each anchoring grid point.

The user must specify both the number of sublots in the lot, and the number of samples to be taken from each subplot. PaveSpec divides the lot into equal-sized sublots and takes the required number of samples from uniformly-distributed random locations within the subplot. The location and values for each sample depends entirely on the seeds used (see Seeds, p. 32). The number of samples taken within a subplot can range from 1 to 100 (as long as the total number of samples for the lot, i.e., number of sublots times number of samples per subplot, does not exceed 1000). The mean of these subplot samples will be used in the predictions. Quality characteristics, including concrete strength, air content, and slab thickness are all sampled using the X-Y grid. Initial roughness sampling is explained on p. 31.

---

<sup>4</sup> The X and Y axes mentioned here are of no relation to the X and Y iteration axes.

---

## Roughness Sampling

Roughness is unique as a quality characteristic because it may be sampled in two different ways, depending on the Session settings. It will either be sampled linearly along the lot using a *roughness interval*, shown in figure 5, or in the same way as an X-Y quality characteristic.

When PaveSpec samples roughness linearly, it takes one sample at set intervals along the lot that must correspond to the subplot intervals.

---

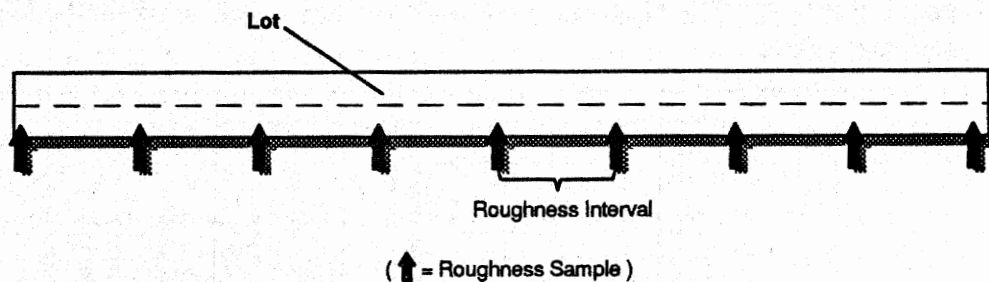


Figure 5. Linear roughness sampling.

---

Thus, the number of samples taken depends on the roughness interval (length of subplot) and the length of the lot that determines the number of sublots. A minimum length of a roughness interval is 0.1 mi (0.16 km) so that an adequate length can be measured.

Linear sampling is always done when sublots are not predicted. If subplot prediction is enabled, the user has the option of sampling roughness for the whole lot and using that mean for each subplot, or sampling roughness for each subplot independently. When sampling is done in the as-designed case, roughness is always sampled for each subplot. The mean initial roughness value is converted to an initial PSR value for use in prediction. If more than one sample is taken, the values are averaged and only the mean is used in prediction.

---

## Seeds

PaveSpec, as is the case with all computer programs, cannot generate truly random numbers; it relies on the concept of a pseudo-random *seed* that approximates a uniformly random number source. From a uniform random number, PaveSpec simulates a normally-distributed random function using the polar method.

PaveSpec uses a set of seeds, each for generating a different random number set. The two basic seeds are the *lot seed* and the *sampler seed*. The lot seed controls the actual sample values in the lot—that is, the value the sampler finds at a particular spot. The sampler seed, on the other hand, controls the *location* of the samples taken.

---

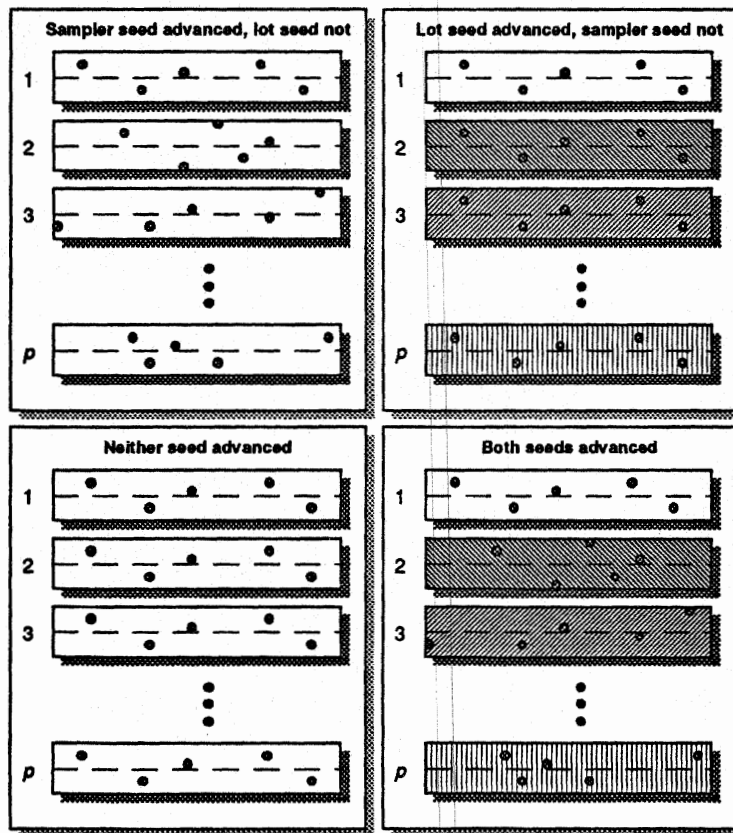


Figure 6. The four options for seed advancement over  $p$  predictions.

---

The user may select a specific starting value for each seed, or use a random seed (set by PaveSpec using a function of the time of day); the user may also decide whether to advance each seed after every prediction. Why would the user want this control? For the sake of control over the source of variability. If the lot seed is advanced but the sampler seed is not, the variability will come from the lot simulation method. If the sampler seed is advanced but the lot seed is not, the variability will come from choosing different points on the same pavement (figure 6). These should be carefully chosen depending on the purpose of the prediction.

---

### As-Designed Seeds

When sampling from the as-designed lots, PaveSpec assumes a zero starting seed and advances the seeds in the same manner as for the as-constructed distribution case. That is, each lot in the as-designed case corresponds to a distribution run in the as-constructed case. If the user sets the starting seeds for the as-constructed case to zero, the as-designed and as-constructed cases should have the exact same sample location and values. This allows the user to compare predictions on exactly the same sample set.

Since the as-designed side of the program does not support iterations, this correlation only applies to the first iteration; if iterations are not used, then this correlation is absolute, assuming:

- Number of sublots for the as-designed and as-constructed cases are the same (which they definitely should be).
- Number of as-designed lots is equal to the as-constructed distribution runs.
- As-constructed samples are both set to zero (0).

If the user does not wish to establish this correlation, the user may set the starting as-constructed seeds to something other than zero.

---

## Quality Index (Q) and Percent Defective

One of the key results PaveSpec can generate is the Percent Defective of a lot. The percent defective is the proportion of the as-constructed lot for which the A-C LCC is greater than the target mean for the designed pavement (A-D LCC). A lot with 0 percent defective falls completely in the acceptable range, while 100 percent defective indicates that none of the lot was acceptable.

Percent Defective is calculated by predicting the set number of sublots and obtaining a distribution of life-cycle costs and pay factors. The first step is to calculate the Quality Index (Q), which is simply the difference between the as-constructed subplot A-C LCC mean and A-D LCC, divided by the standard deviation of the as-constructed sublots' A-C LCC, or:

$$Q = \frac{A-D LCC - A-C LCC}{\sigma_{A-CLCC}}$$

- where:
- A-D LCC = Mean target as-designed life-cycle cost, from simulation.
  - A-C LCC = Mean of life-cycle costs calculated for all sublots of the as-constructed pavement lot.
  - $\sigma_{A-CLCC}$  = Standard deviation of life-cycle costs calculated for all sublots of the as-constructed pavement lot.

Percent Defective is then calculated as a function of Q and the number of sublots (n). Percent defective is always 50 percent when Q=0; it decreases toward 0 as Q increases, and increases toward 100 percent as Q decreases. It is determined specifically from AASHTO R 9-90, table C, using Q and the number of sublots (n).



---

## The Pay Factor-Percent Defective Relationship

The pay factor is the percentage of the original contractor's unit bid price that will be paid by the agency for a given lot. The pay factor should be 100 percent if the contractor builds a lot that exactly meets the target as-designed mean and standard deviation of the quality characteristics (strength, thickness, air content, and initial roughness). The targets are defined by both means and standard variations. If the contractor provides better quality, then the pay factor will be greater than 100 percent. If lower quality, the pay factor will be less than 100 percent. This is all in accordance with the legal principle of liquidated damages where pay is withheld (or additional pay given) at the time of construction to cover the cost of (or savings on) future rehabilitation made necessary by defective work (or superior quality work).

The relationship of the pay factor to percent defective must be established through simulation for each project, as it may differ depending on many factors involved, such as design traffic level. The relationship between the percent defective LCC sublots and the pay factor is obtained through a simulation technique.

First, the as-designed pavement lot is defined by using one of the three methods (specific, standard, simulated target) described on p. 22. The simulated target method is strongly recommended.

Next, as-constructed lots are simulated given any desired means and standard deviations of the quality characteristics. A large variety of cases, ranging from very bad to very good quality may result. Actually, any reasonable values could be used. The idea is to cover a wide range of percent defective from 0 to 100 percent, with plenty of points to obtain a good curve. From this data, a simple linear relationship based on the points between identified limits of percent defective is obtained.

The graph can be observed in the Calculate Menu, PF-PD Equation. This equation is best generated by setting the AC-LCC quality characteristics equal to the AD-LCC quality characteristics and simulating about 100 lots. The resulting equation can be used for computing the pay factor.

---

## Probability of Acceptance, OCC, and Expected Pay

The actual quality of an as-constructed lot is never known. Due to the sampling process, risk exists for both the contractor (the seller) for rejection of satisfactory work, and to the agency (the buyer) for accepting unsatisfactory work.

Analyzing the risks associated with any particular acceptance scheme is usually accomplished by constructing the operating characteristic curve (OCC).

For specifications containing adjusted pay schedules, the concept of an OC curve must be modified since the acceptance plan does neither "accept" nor "reject" (except for very poor lot quality), but rather calculates a pay factor for the lot based on the quality characteristics sample and the contractor is paid accordingly. When an adjusted pay schedule is used, the "expected pay" (or EP) is computed (through simulation) over a range of lot percent defective and plotted similar to an OC curve (called an EP curve).

PaveSpec version 1.0 does not have the capability to compute the expected pay factor curve automatically, however, it can provide the data required to establish the graph for a given acceptance plan and project. This is accomplished through a simulation of sampling from each of many lots that have a wide range of percent defective (i.e., 0 to 100 percent). For each point on the EP curve, the coordinates are determined as follows:

A large number of samples (50 or more) are obtained through simulation of a given lot using PaveSpec for specific as-designed and as-constructed quality characteristics. This results in a series of predictions of the lot pay factor and of the lot percent defective.

Percent defective is determined as the mean percent defective from all of the samples.

Pay factor is determined as the mean pay factor from all of the samples.

This procedure establishes a single point on the expected pay (or EP) curve. This process is repeated many times by varying the quality characteristics so that a range of pay factors and percent defectives are obtained. The resulting EP curve relates the probable contractor payment to a level of quality (percent defective) in the pavement lot that is a graphical representation of the operation of the specific acceptance plan.

---

## Tables and Data Persistence

PaveSpec generates many tables as it runs: those related to individual predictions, summaries of multiple predictions, and some miscellaneous tables. This section will briefly describe these tables, primarily for the sake of establishing the rationale for discarding data as it runs. A complete description of each of the tables mentioned below is found in Table and Graph Windows (p. 47).

---

### Lot Prediction, Series, and Session Summary Tables

Whenever PaveSpec predicts a lot, it always generates two tables: Distresses and Costs. Distresses records the predicted distresses in the lot, by year and type; Costs records the rehabilitation costs by year, type, and with and without present worth adjustment. PaveSpec stores the as-designed case in one set of tables, and the as-constructed in another. When sampling is used, PaveSpec also generates a Samples and a Roughness Samples table, which contain the actual values and locations of the samples taken for the lot.

When sublots are not used, these tables are two-dimensional tables; when sublots are used, the tables become three-dimensional tables—one plane for each subplot, plus a plane for the totals and averages. In addition, when subplot prediction is used, an Acceptance table is created, listing the life-cycle costs and pay factors for each subplot, along with a summary at the bottom of the table.

---

## PaveSpec Tables and Persistence

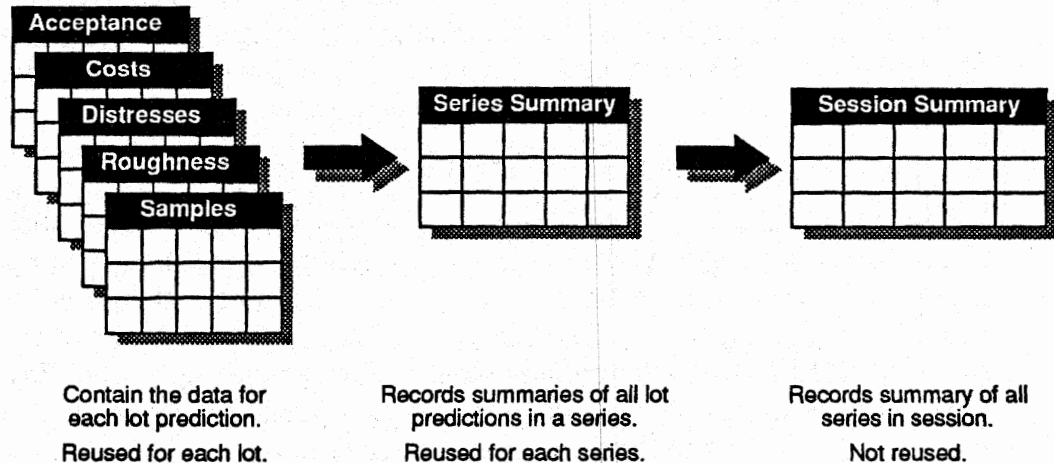


Figure 7. Tables, table usage, and persistence in a session.

---

These tables take up a substantial amount of space—sometimes as much as several megabytes or more, if many sublots are used. When one adds distributions and iterations, the amount of space necessary to store all of the results would be impractical for most computers. Therefore, when iterations or distributions are selected, PaveSpec uses a memory-limiting strategy to keep only the data that is necessary to create a summary table, called the Session Summary, which contains a selected summary of all the predictions (figure 7).

An intermediate table called the Series Summary is created when distributions are selected. This table records the means and standard deviations of each of the lots for each of the distribution runs. For example, if 30 distribution runs are selected, the Series Summary will record the life-cycle costs,  $Q$ , percent defectives, and so on, for each of the 30 lots. After each lot is finished predicting, PaveSpec copies these basic results from the Samples, Roughness Samples, Distresses, Costs, and Acceptance tables to the Series Summary table. Then these tables are used again for the next lot prediction. The total memory used by PaveSpec is thus actually constant.<sup>5</sup>

The fact that the data is discarded after each lot and each series does not mean that it is not ultimately available to the user. Double-clicking with the mouse on any of the entries in the Session Summary table will recreate the Series Summary table for that series by re-running the predictions that went into that series.

---

<sup>5</sup> In the case where the user chooses to iterate the number of sublots, the prediction tables will be of varying sizes. To accomplish this, PaveSpec eliminates and recreates these tables whenever the number of sublots changes during the session.

Similarly, double-clicking on any of the entries in the Series Summary table will recreate the Distresses, Costs, Acceptance, Samples, and Roughness Samples tables for the lot so identified. While this access method is not instantaneous, it does allow the user to get to any of the source data in a reasonable amount of time.

---

### **The PD-Related Tables**

When the user chooses to predict sublots, thereby generating pay-factor/percent-defective (PF-PD) pairs, PaveSpec can create a PF-PD table. This table will be two-dimensional if distribution runs are not selected, three-dimensional if they are (the third dimension corresponds to the number of distribution runs chosen). The user can see the table in graphical and numeric forms.

---

### **As-Designed and Target A-D LCC Tables**

The user may choose to simulate the as-designed case with a series of as-designed lots. Two tables are formed when this happens: the As-Designed Summary table and the Target A-D LCC Summary table. The target A-D LCC is computed as the mean of all lot simulation runs (usually 100 or more). The As-Designed Summary table contains the means and standard deviations of all of the as-designed lots and sublots.

---

### **The LCC Lookup Table**

If the user chooses to run sampled and iterated as-constructed predictions, PaveSpec also generates a Life-Cycle Cost lookup table. This table is generated by running a means-only prediction (that is, without sampling) for each iteration point. The user can then look up the reference value for that iteration point in the table; or, a user without a computer can use the table to look up the life-cycle cost predicted for a particular combination of input quality characteristics.

This table is normally used when  $X^k$  iteration is chosen for both axes, allowing a user to get an approximate life-cycle cost for any combination of quality characteristics. Of course, these LCC's only apply to the current project.

---

## The Session

All of the settings described in the preceding sections are stored together in a Session. Specifically, the session contains the following information:

- Values of all of the quality characteristics for the as-designed and as-constructed cases.
- Iteration axes' settings, including the number of steps and type.
- Use of and quantity of distribution runs.
- Whether subplot predictions are used, and other variables corresponding to the use of subplot predictions.

Note that the constant variable settings (all other inputs for the project) do not belong to the set of information stored in a session. These settings apply to all sessions.

Tables generated by PaveSpec are not stored with the session. They are replaced when another session is run, or lost when the user leaves PaveSpec.

The user can create new sessions, copy sessions, or delete sessions. Each session can be given a name and is available in the File menu when PaveSpec starts.

See the following chapter for more information.

---

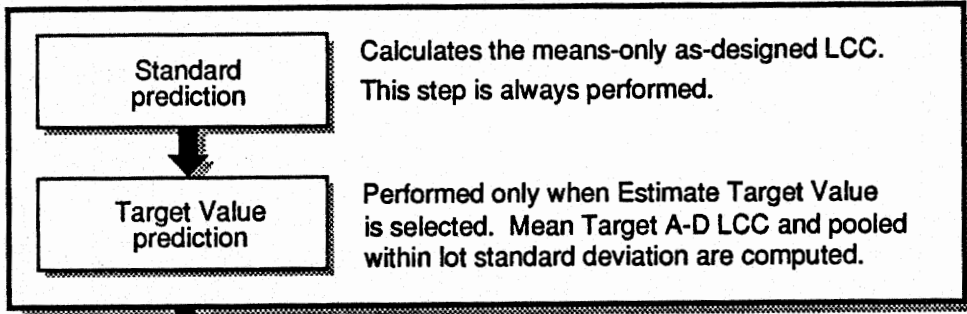
## Sequence of Events

Every session has the same basic agenda, but most sessions skip one or more parts of it. Every session has both the as-designed portion and the as-constructed portion.

See figure 8 for an explanation of the sequence of events in a session.

---

### As-Designed



### As-Constructed

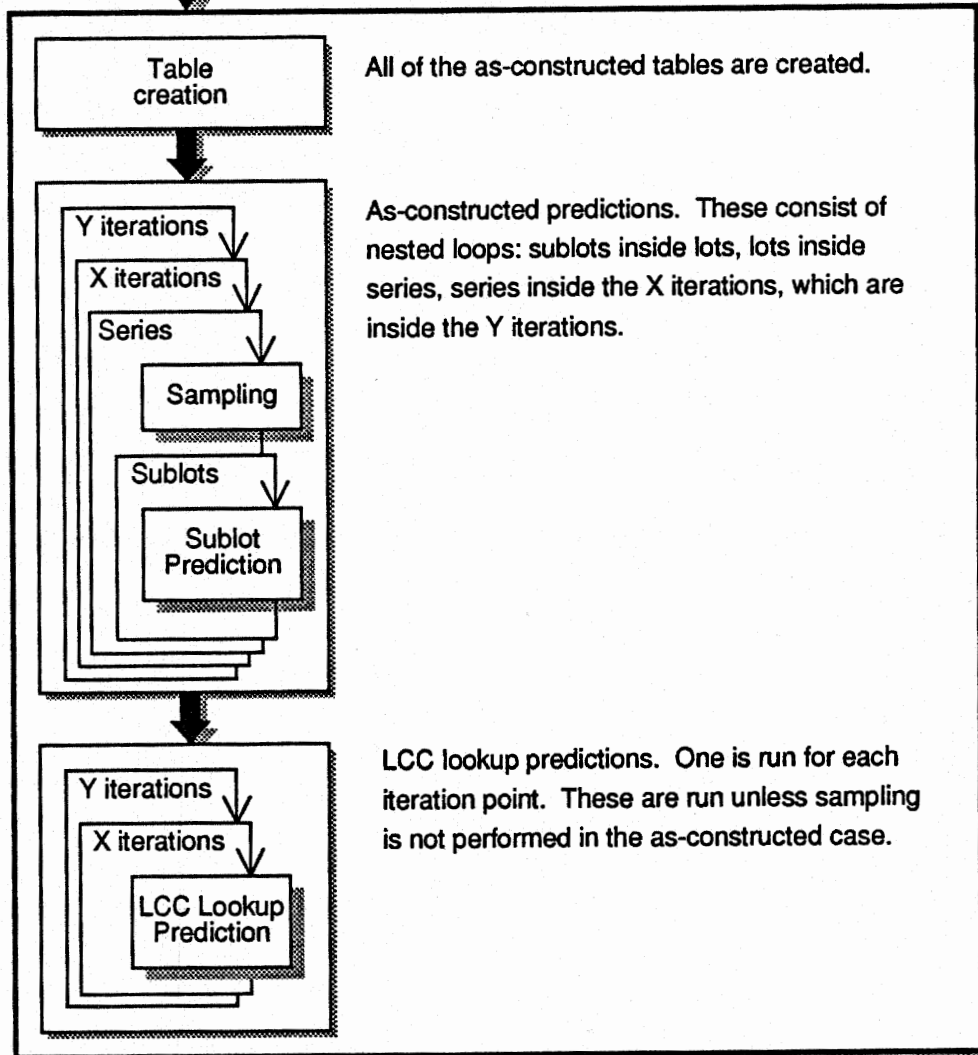


Figure 8. The sequence of events during a session.

---





# USING PAVESPEC

The easiest way to get familiar with PaveSpec is to run through some examples. This chapter will briefly describe the PaveSpec environment, then explain how to set up four different sessions. A description of PaveSpec's menus and tables is also included.

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---

## The PaveSpec Window

---

### Bringing Up the PaveSpec Window

When PaveSpec is properly installed, you should be able to double-click on its icon in the Program Manager to run it. After a startup screen showing the PaveSpec logo and credits, the main PaveSpec window will appear.

### The Main PaveSpec Window

Below is an explanation of each of the parts of the PaveSpec window. (Note: See also your Windows documentation for more information, including how to use the keyboard with the menus, how to use PaveSpec with other applications, and so on.)

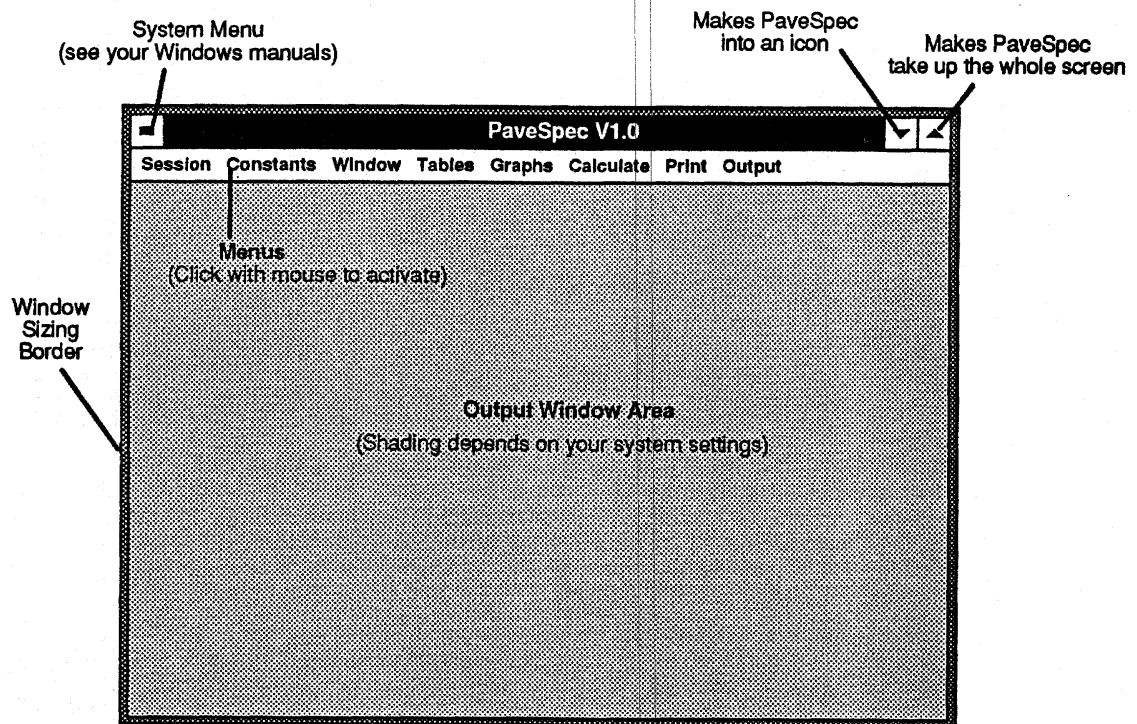


Figure 9. A typical PaveSpec window, before running a session.

If you want to make the PaveSpec window larger, you can resize it using the sizing border, or maximize the window to full-screen by clicking on the Maximize button (the up arrow in the top-right corner). Click again on the Maximize button to restore the window to its normal size. You can also click on the Minimize (iconize) button to make PaveSpec into an icon at the bottom of your Windows desktop.

---

## Table and Graph Windows

When PaveSpec is running a session, or is done with a session, there will normally be table and graph viewing windows inside the Output Window Area that you can move and resize with the mouse, using their individual sizing borders (figure 10). In addition, you can use the Window menu to tile or cascade (automatically arrange), or close all windows.

---

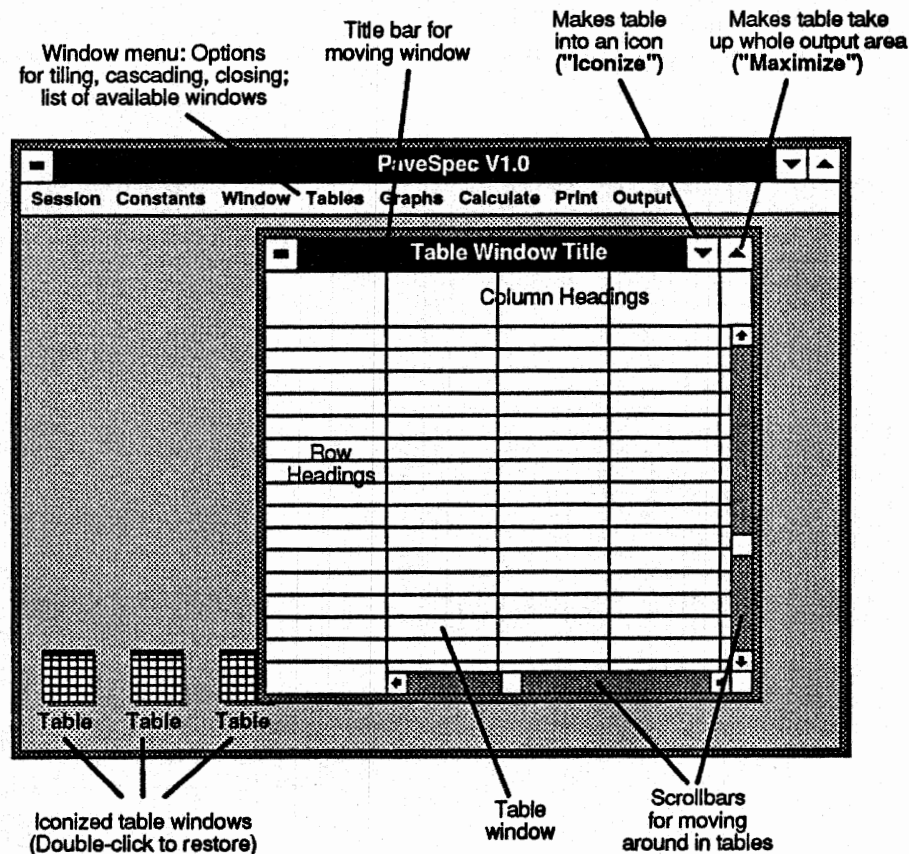


Figure 10. A table window inside PaveSpec's Output Window Area.

---

When the table is too large to fit in the table window, PaveSpec only shows a part of it at a time. Resize the window, or use the scrollbars, to see the remainder of the table.

You can move between windows using several different methods:

- Click on the window you want to view. If it's an icon, double-click to restore it to a normal window.
- Use the <CTRL+F6> key combination to move from one window to the next.
- Choose the window by name from the Windows menu, the Tables menu, or the Graphs menu.

If you want to see all of the non-iconized windows at once, choose "Tile" from the Window menu. If you want to make the current window take up the entire Output Window Area, click on the windows' Maximize button.

### Using Two-Dimensional and Three-Dimensional Tables

Two- and three-dimensional tables have a particular user interface that is only available with the mouse. Figure 11 illustrates the control you have over these tables, including the ability to swap the visible axes to see the table in the row-column arrangement you want.

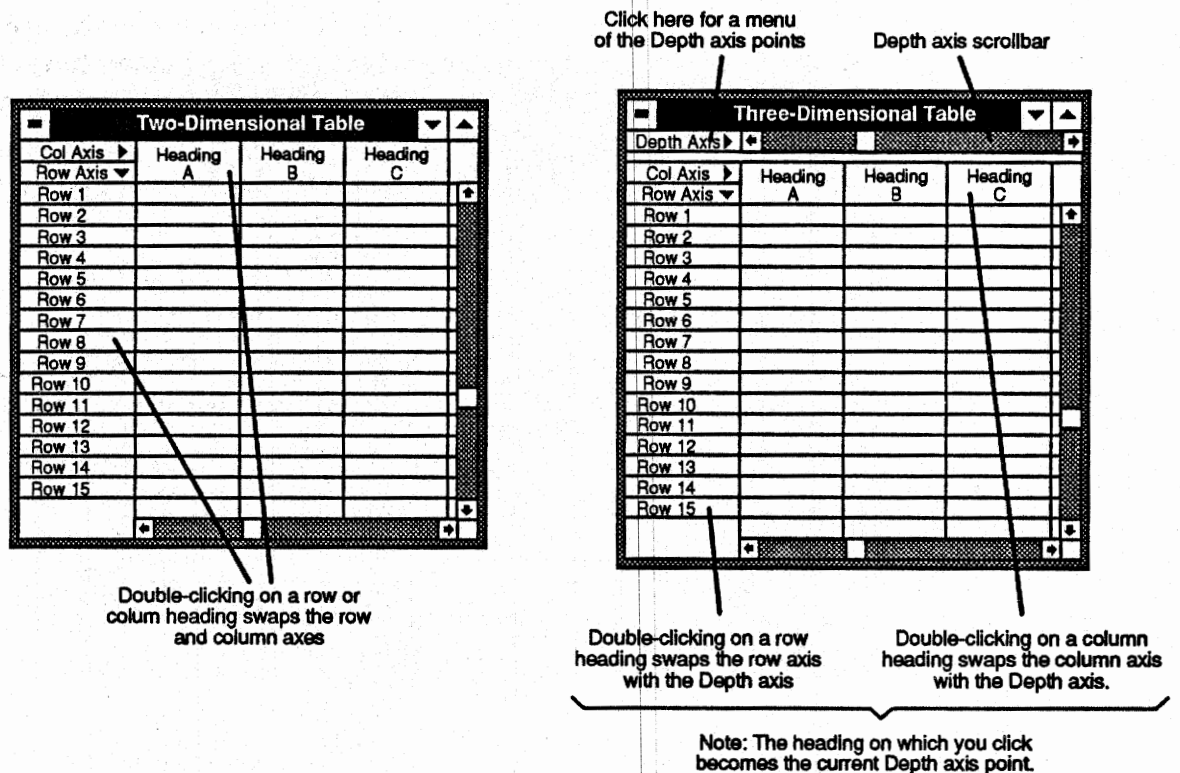


Figure 11. Using two-dimensional and three-dimensional tables.

A one-dimensional table (not shown) can only be viewed as rows.

### Changing the Table Font

You may also change the font PaveSpec uses in table windows by selecting "Table font.." from the Window menu. This will bring up a Choose Font dialog box in which you may select the best type font face and size to suit your needs.

### Leaving PaveSpec

You can leave PaveSpec at any time by double-clicking on the system menu, or choosing "Exit" from the Session menu.

---

## Session Examples: Introduction

Following this introduction, you will find a number of examples. The aim of these sections is to introduce you to both PaveSpec's user interface and PaveSpec's organizational scheme in a step-by-step manner.

A brief explanation of the examples:

1. *Simple comparison.* Shows how to compare a single as-designed lot to a single as-constructed lot to obtain a single pay factor.
2. *Sampling and distributions.* Sampling from multiple as-constructed lots to obtain a distribution of pay factors for the lot comparison in the previous example. This example could also be run by sampling many times from the same lot by simply disabling the "Advance after each prediction" check box under "Initial Lot Seed" in the Seeds dialogue box.
3. *Sublot prediction and determining target A-D LCC.* How to obtain the target A-D LCC and the pay-factor vs. percent-defective curve.
4. *Iterating quality characteristics.* Iterating two quality characteristics independently to obtain a pay factor contour plot.

You may wish to read through the Menus section and the Dialog Boxes section before reviewing these examples to familiarize yourself with their contents.

Examples of all of the Constant Variable dialogue boxes are included on the following pages.

## Constant Variable Dialogue Boxes

### Traffic...

**Constant variables: Traffic**

Calculate ESALS from ADT

**ADT to ESAL Ratio**

Directional factor:  %

Percent trucks:  %

Percent trucks in outer lane:  %

Average truck load equivalency factor:  ESALS/truck

**Initial Value:**

ADT for all lanes:

Outer-lane ESALs (millions):

**Growth factor**

%

Simple

Compound

### Project...

**Constant variables: Project**

**Pavement Type:**

**Road location:**

**Design life:**  years

**Project length:**  mi.

**Number of lanes in one direction:**

**Lane width:**  ft.

**Total shoulder width:**  ft.

**Joint spacing:**  ft.

**Minimum pay factor:**  %

**Determine costs for**

One direction only

Both directions



### Materials and Climatic...

**Constant variables: Climatic and Materials**

Annual temperature range:  °F

Freezing index:  degree-days

Average annual precipitation:  in.

Annual freeze-thaw cycles:

Salt present

Materials:

- "D" cracking present in slab
- Reactive aggregate in slab
- Liquid sealant in joint
- Prefomed compression seal in joint

OK Cancel

### Base...

**Constant variables: Base**

Type of base:

Modulus of subgrade reaction:  PSI/in.

Subgrade soil type:

- Fine-grained (A4-A7)
- Coarse-grained (A1-A3)
- Longitudinal subdrains present

OK Cancel

### Load Transfer...

**Constant variables: Load Transfer**

Dowel bar diameter:  in.

Area of reinforcement steel:  in<sup>2</sup>/ft.

Tied PCC shoulder:

OK Cancel

Cost...

Constant variables: Costs		
Construction bid, traffic lanes:	<input type="text" value="20"/>	\$/yd <sup>2</sup>
Cost of overlay:	<input type="text" value="9"/>	\$/yd <sup>2</sup>
Cost of joint patching:	<input type="text" value="80"/>	\$/yd <sup>2</sup>
Cost of slab replacement:	<input type="text" value="70"/>	\$/yd <sup>2</sup>
Annual interest rate:	<input type="text" value="6"/>	%
Annual inflation rate:	<input type="text" value="3"/>	%
First year of cost analysis:	<input type="text" value="1993"/>	
User cost coefficient:	<input type="text" value="0"/>	%

Rehabilitation...

Constant variables: Rehabilitation			
<b>Overlay Triggers</b>			
	Sublot overlays:	Lot overlays:	
		Mean	PSF
<input checked="" type="checkbox"/> PSR:	<input type="text" value="3"/>	<input type="text" value="3"/>	<input type="text" value="3"/>
<input checked="" type="checkbox"/> Cracking:	<input type="text" value="67"/>	<input type="text" value="67"/>	<input type="text" value="67"/> cracks/mi
<input checked="" type="checkbox"/> Spalling:	<input type="text" value="75"/>	<input type="text" value="75"/>	<input type="text" value="75"/> jts/mi
<input checked="" type="checkbox"/> Faulting:	<input type="text" value="0.12"/>	<input type="text" value="0.12"/>	<input type="text" value="0.12"/> in.
<input type="checkbox"/> Override initial PSR value:		<input type="text" value="4.5"/>	
Initial PSR after overlay:		<input type="text" value="4.5"/>	
Overlay life:		<input type="text" value="10"/>	years
Width of joint patch:		<input type="text" value="6"/>	ft.
Percent inner-lane cracking:		<input type="text" value="10"/>	%
After overlay, percentage of joints patched until next overlay:		<input type="text" value="0"/>	%

## Advanced...

Advanced Options			
Full-depth-repair PSR coefficient:	<input type="text" value="0.015"/>		<input type="button" value="OK"/>
Percent defective zero threshold:	<input type="text" value="0.1"/>	%	<input type="button" value="Cancel"/>
Flexural strength coef. exponent:	<input type="text" value="10"/>	<input type="text" value="0.5"/>	
Min-Max range for spalling ratio:	<input type="text" value="1"/>	<input type="text" value="3"/>	
Normal distribution simulation method:	<input type="radio"/> Polar	<input checked="" type="radio"/> Cosine	
<input checked="" type="checkbox"/> Verbose status window			

---

## **Example 1: Simple Comparison.**

This example will demonstrate how you can compare a single as-designed lot to a single as-constructed lot to obtain a single pay factor without any simulation. It will also serve as an introduction to PaveSpec's dialog boxes and menus.

Before you begin defining this session, you'll need to look at each of the dialog boxes listed under the Constants menu. They contain all of the background variables used during the prediction process. If any of the values are incorrect for your project, you'll need to set them to appropriate values.

---

### **1. Start a New Session.**

After you've checked the constant variables, you're ready to start the first session.

- **Select "New.." from the Session menu.**

The Define Session dialog box appears.

The Define Session dialog box gives you access to all of PaveSpec's session controls. (Note: Your Define Session dialog box will have a different appearance than the one shown in figure 12 if you have a VGA or grayscale monitor.)

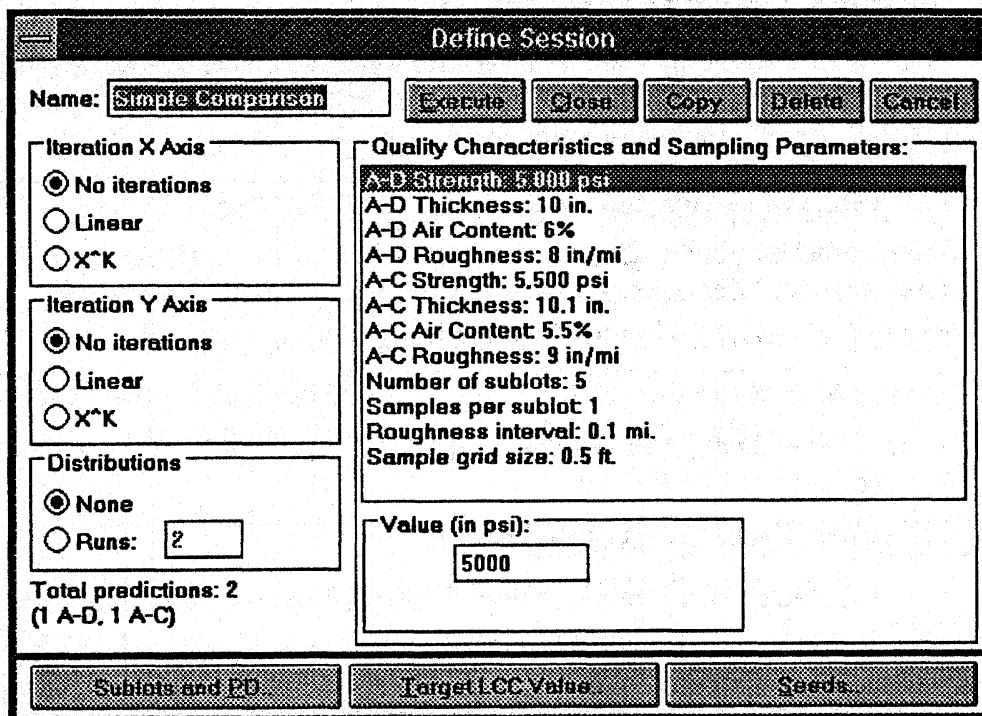


Figure 12. An example of the Define Session dialog box.

Let's look at the Define Session dialog box as a first step. Along the top of the dialog box, you'll find the name of the session (for this example, we've typed "Simple Comparison"), and five options: Execute, Close, Copy, Delete, and Cancel.

- Clicking the mouse on Execute (or pressing Alt-E) will start the session running.
- Close (or Alt-C) will save your changes and close the dialog box.
- Copy will make a copy of this session and let you edit the copy.
- Delete will delete this session. You'll be prompted for confirmation first.
- Cancel will undo any changes you make to the session and close the window.

Along the left side are the options for iterations, distributions, and a total of the number of predictions to be run (broken down into as-designed and as-constructed). We won't use iterations or distributions in this example, so you may leave them as they are.

Across the bottom of the dialog box are three buttons, each of which will bring up another dialog box with more options. These will be covered in other examples.

The remainder of the dialog box is devoted to setting the as-designed and as-constructed quality characteristic values, as well as the number of sublots, samples per subplot, roughness interval, and sample grid size.

Since most of the options discussed in PaveSpec Basics are not enabled by default, and you aren't using any of these options, we only need to set the quality characteristic values for this example.

---

## 2. Defining the Generation Method for the As-Designed Lot.

This example will use the as-designed quality characteristics means only. To make sure that PaveSpec is using this method, follow these steps:

- **Click on the Target LCC Value button, or press Alt-T.**

The Session: Target A-D LCC dialogue box will appear. Make sure the "Use means-only A-D LCC" radio button is selected.

- **Click on the OK button.**

---

## 3. Set the Quality Characteristics.

The next step is to set the as-designed and as-constructed quality characteristics values.

Our example will use these values for the as-designed and as-constructed lots:

Quality Characteristic	As-Designed	As-Constructed
Compressive Strength	5,000 lbf/in <sup>2</sup>	5,500 lbf/in <sup>2</sup>
Thickness	10 in	10.1 in
Air Content	6 percent	5.5 percent
Initial Roughness	8 in/mi	9 in/mi

$$1,000 \text{ lbf/in}^2 = 6.9 \text{ MPa}$$

$$1 \text{ in} = 25.4 \text{ mm}$$

$$1 \text{ in/mi} = 0.01578 \text{ m/km}$$

You may, of course, use any values you like.

To change any of the entries in the Session Variables listbox, follow these steps:

- **In the list box, click on the entry you want to change.**

The selected entry is highlighted and the value of the variable is shown in the edit control just below the listbox. The Value: group box shows the units used for the variable. If the variable can be sampled, Specify and Sample radio buttons will appear to reflect whether the variable is to be sampled or specified directly (no sampling).

- **Click on the edit control just below the list box, or press TAB.**

The cursor is placed in the edit control.

➤ Use the DEL, backspace, and number keys to change the value.

The new value is shown in the edit control.

When you change to another control, the listbox will be updated with the value you modified. Repeat these three steps for each of the eight quality characteristics listed above. None of the four other variables (sublots, samples, roughness interval, sample grid size) have any effect on this session, since no sampling or subplot prediction is used.

---

#### 4. Execute the Session.

When you execute the session, PaveSpec will predict the as-designed and as-constructed lots, calculate the pay factor, and present the results.

➤ Click on the Execute button, or press Alt-E.

The Session Running window appears, and the session executes.

On most computers, this session will take very little time, since there are only two predictions. In fact, you may not be able to read any of the messages in the Session Running window before it is completed. When the session is completed, the Session Summary table appears and the Session Running window disappears.

The pay factor is listed first.

Q and percent defective are not calculated, since sublots were not used. They will be blank.

The as-designed and as-constructed present worth costs per mile are predicted and shown in the Session Summary table (see page 83).

Use the scrollbar to view the remainder of the table, if you wish.

---

## Example 2: Sampling and Distributions.

In this example, you will sample from multiple as-constructed lots to obtain a distribution of pay factors for the lot comparison in the previous example. You will add standard deviations to each of the as-constructed quality characteristics, from which PaveSpec will sample and predict each lot separately. The as-designed LCC will remain a constant as in example 1.

---

### 1. Make a Copy of the Simple Comparison Session.

Bring up the Simple Comparison dialog box, which was created in the previous example. If you haven't done the previous example, you'll need to create a new session, or modify another session, to match the settings for this example.

- From the Session Menu, choose Simple Comparison.

The Define Session dialog box will appear with the Simple Comparison session loaded.

- Click on Copy.

PaveSpec makes a copy of the Simple Comparison session and presents you with the copy. Note that the session's name was copied; you'll need to change it.

- Type "Sampling and Distributions."

The name of the new session is changed. This name will appear on the Sessions menu once we execute the session. You may not be able to see all of the name in the edit control, but it's there.

Now that the session is created, you'll need to add the necessary elements for sampling and distributions.



---

## 2. Add Standard Deviations to the As-Constructed Lot.

In order for PaveSpec to sample, it needs to know the population standard deviation of the as-constructed lot. For this example, we'll use these values for the quality characteristics:

Quality Characteristic	As-Designed Mean	As-Constructed Mean	As-Constructed Std. Deviation
Compressive Strength	5,000 lbf/in <sup>2</sup>	5,500 lbf/in <sup>2</sup>	500 lbf/in <sup>2</sup>
Thickness	10 in	10.1 in	0.2 in
Air Content	6 percent	5.5 percent	0.5 percent
Initial Roughness	8 in/mi	9 in/mi	1.0 in/mi

$$1,000 \text{ lbf/in}^2 = 6.9 \text{ MPa}$$

$$1 \text{ in} = 25.4 \text{ mm}$$

$$1 \text{ in/mi} = 0.01578 \text{ m/km}$$

In general, you can select which of the quality characteristics to sample. In this example, we'll sample them all; however, if it is desired to not treat, say air content as a quality characteristic, it would have a constant value for the as-constructed lot. To change any of the sampled quality characteristics in the Session Variables listbox, follow these steps:

- In the list box, click on the as-constructed (A-C) entry you want to change.

The selected entry is highlighted and the value of the variable is shown in the edit control just below the listbox. The Value: group box shows the units used for the variable. The Specify and Sample radio buttons will appear to reflect whether the variable is to be sampled or specified directly (no sampling). The Specify option will be selected unless you've set it otherwise before.

- Click on Sample.

The radio button will be selected and the listbox and edit control will be updated to show the standard deviation as well. If you haven't set it before, the standard deviation will be zero.

Be sure to click on Sample *before* entering the standard deviation; otherwise, PaveSpec ignores it.

- **Click on the edit control just below the list box, or press TAB.**

The cursor is placed in the edit control.

- **Use the DEL, backspace, and number keys to change the value.**

The format for a sampled quality characteristic is Mean, StDev. For example, to set Strength to a mean of 5,750 lbf/in<sup>2</sup> (39.6 MPa) and a standard deviation of 700 lbf/in<sup>2</sup> (4.8 MPa), enter "5,750,700". It doesn't matter if there are spaces between the numbers and comma.

As before, when you change to another control, the listbox will be updated with the value you selected. Repeat the steps above to set the standard deviations for each of the as-constructed quality characteristics.

---

### 3. Set the Sampling Parameters.

PaveSpec needs to know how many sublots and samples per subplot to use. Note that we're not predicting sublots, but it still needs this information to know how to stratify the lot and how many samples to take from each subplot so created. The total samples taken will be the product of these two.

- **Set the number of sublots to five (5).**

PaveSpec will use five sublots in the lot.

- **Set the number of samples per subplot to two (2).**

PaveSpec will take two samples from each subplot and calculate the mean of the two samples.

The other sampling parameters are the roughness interval and the grid size.

The roughness interval is the distance between roughness samples along the lot, and must be set equal to the length of a subplot. A subplot of 0.1 mi (0.16 km) is the preferred length for measurement. The total roughness samples taken will be equal to the number of sublots. The default lot length is 1 mi (1.61 km), and the default roughness interval is 0.1 mi (0.16 km). Therefore, PaveSpec will take ten samples under these defaults.

The grid size is described on p. 30. The default (0.5 ft [0.15 m]) is sufficient for this example.

---

### 4. Enable Distributions.

In order to make this session more interesting, we'll sample from multiple lots to get a series of pay factors. PaveSpec will calculate the mean and standard deviation of the as-constructed present worth cost and pay factors and report them in the Session Summary table.

- **Click on the Runs radio button in the Distributions group.**

Distributions is selected and the control for the number of runs is enabled.

- Move the cursor to the edit control by pressing TAB or clicking with the mouse.

The cursor moves to the Runs edit control. This sets the number of distribution runs to execute.

- Set the Runs to twenty (20).

PaveSpec will predict 20 as-constructed lots.

Your session is now ready to execute. The Define Session dialog box should look like the one shown in figure 13.

Define Session

Name: Sampling and Distributio   Execute   Close   Copy   Delete   Cancel

Iteration X Axis  
 No iterations  
 Linear  
 X^K

Iteration Y Axis  
 No iterations  
 Linear  
 X^K

Distributions  
 None  
 Runs: 20

Total predictions: 21  
(1 A-D, 20 A-C)

Quality Characteristics and Sampling Parameters:  
A-D Strength: 5,000 psi  
A-D Thickness: 10 in.  
A-D Air Content: 6%  
A-D Roughness: 8 in/mi  
A-C Strength: Sample: 5,500 psi, 500  
A-C Thickness: Sample: 10.1 in., 0.2  
A-C Air Content: Sample: 5.5%, 0.5  
A-C Roughness: Sample: 9 in/mi, 1  
Number of sublots: 5  
Samples per subplot: 2  
Roughness interval: 0.1 mi.  
Sample grid size: 0.5 ft.

Value (in psi):  
5000

Sublots and ED   Target LCC Value   Seeds

Figure 13. The Sampling and Distributions session dialog box.

## 5. Execute the Session.

When you execute the session, PaveSpec will predict the as-designed lot. Then it will sample and predict the 20 as-constructed lots, calculating a pay factor for each. When PaveSpec is done, it will present the results.

- Click on the Execute button, or press Alt-E.

The Session Running window appears, and the session executes.

This session will take somewhat longer. PaveSpec will inform you of its progress through the Session Running window. When PaveSpec is done, it will report the mean and standard deviation of the pay factor and as-constructed present worth cost per mile from each run.

You may look at the data from each run by switching to the Series Summary table, which is in an icon at the bottom of the PaveSpec window. Double-click on the Series Summary icon to view the record for each of the predictions.

You may notice that the roughness values for each of the runs is the same. This is because PaveSpec, by default, uses the same lot for each run; it just picks different sample points for the first three quality characteristics. By contrast, unless you're predicting sublots, the roughness samples will always come from the same points, thereby returning the same value for initial roughness. If you want to have Initial Roughness resampled for each lot, you'll need to have PaveSpec generate a new lot for each run. To do this, select "Advance after each prediction" for the lot seed under the Seeds.. dialog box in the Define Session window.

We assumed certain values for the quality characteristics. You may want to try this session using different values to test their effect on the pay factor.

---

### Example 3: Sublot Prediction and Target A-D LCC.

In this example, you'll learn how to estimate target A-D LCC through simulation of as-designed pavement lots, and how to obtain a pay-factor vs. percent-defective curve. These two activities are closely related, so it's natural to put them in the same example. For a review of the target A-D LCC and the calculation of percent defective, see p. 34.

Recall that sublot prediction works by dividing each lot into a series of sublots (p. 24). Each sublot is then predicted (distress indicators and rehabilitation costs) and the mean and standard deviation of the lot LCC are used to estimate percent defective.

Percent defective is dependent not only on the mean and standard deviation of the as-constructed sublot life-cycle costs, but also on the target as-designed life-cycle cost. The target as-designed LCC is estimated through simulation of many as-designed predictions. This is done using the means and standard deviations for the as-designed lot's quality characteristics.

When you choose to estimate target A-D LCC, PaveSpec will also create two other tables for you to view: the Target A-D LCC Summary table and the As-Designed Summary table. The Target A-D LCC Summary contains the intermediate values used to actually calculate target A-D LCC, and the value so calculated. The As-Designed Summary lists the life-cycle costs for each of the sublots and the lot mean and standard deviation.

You must select both the number of as-designed lots and sublots for simulation of the target mean A-D LCC. You can specify up to 1,000 sublots and 1,000 lots, but more typical values are 5 and 100, respectively. The recommended case would have the same number of as-designed and as-constructed sublots.

In this example, we will obtain a simple version of the PF/PD curve by running a series of simulations; each run will be a lot with sublot predictions. The PF/PD curve will contain points that represent the range of pay factors and percent defectives for the same target A-D LCC mean.

---

#### 1. Make a Copy of the Sampling and Distributions Session.

First, bring up the Sampling and Distributions dialog box that was created in the previous example. If you haven't done the previous example, you'll need to create a new session, or modify another session, to match the settings for this example.

- From the Session Menu, choose **Sampling and Distributions**.

The Define Session dialog box will appear with the Sampling and Distributions session loaded.

➤ Click on Copy.

PaveSpec makes a copy of the Sampling and Distributions session and presents you with the copy. Note that the session's name was copied; you'll need to change it.

➤ Type "Sublots/Target A-D LCC".

The name of the new session is changed. This name will appear on the Sessions menu once we execute the session. You may not be able to see all of the name in the edit control, but it's there.

Next, we'll add the elements necessary for subplot prediction and target A-D LCC.

---

## 2. Enable Sublot Prediction.

By default, subplot prediction is not enabled. Therefore, we need to instruct PaveSpec to perform it.

➤ Click on the "Sublots and PD.." button.

The Session: Sublots and Percent Defective Options dialog box appears (figure 14).

Session: Sublot and Percent Defective Options

Use sublots for sample location purposes only

Predict sublots individually, generate %-defectives

Sublot roughness:

Use lot mean for all sublots

Sample sublots individually

Overlay application:

Each subplot overlaid independently

Overlays applied to entire lot

Trigger on average of subplot distresses

Trigger on percent-sublot-failures:

19 % failed sublots

OK

Cancel

Figure 14. Example of the Sublot and Percent Defective dialog box.

➤ Click on the "Predict sublots individually..." radio button.

The button is checked and the other options are enabled.

➤ Click on the "Sample sublots individually" radio button, under "Sublot Roughness".

The button is checked.

- Click on the "Overlays applied to entire lot" radio button, under "Overlay Application."

The button is checked and the other options are enabled.

- Enable the "Trigger on percent-sublot-failures" check box, under "Overlay Application."

The check box is checked and the "% failed sublots" edit box is enabled.

- Set the number of "% failed sublots" equal to 19.
- Click on OK.

The dialog box is removed.

---

### 3. Enable Target A-D LCC Estimation.

We need to turn on Target A-D LCC estimation and also set a few parameters.

- Click on the "Target LCC Value.." button.

The Session: Target A-D LCC Estimation dialog box appears (figure 15).

---

Session: Target A-D LCC

Specify Target A-D LCC:  \$/mi.

Estimate Target A-D LCC through simulation:  
Number of prediction lots:   
Number of sublots:

Use means-only A-D LCC

Figure 15. The Target A-D LCC dialog box.

- 
- Click on the "Estimate Target A-D LCC through simulation" radio button.
  - Set number of prediction lots to ten (10) for example.  
You can set this to a higher value if you want a more accurate Target A-D LCC (i.e., 100).
  - Set number of sublots to five (5).  
We'll set the as-constructed sublots to the same value later.
  - Click on OK.

The dialog box is removed.

PaveSpec will predict 10 lots of 5 sublots each for the as-designed case when we execute the session.

---

#### **4. Set the Number of As-Constructed Sublots.**

We're going to use five as the number of sublots. Actually, the as-constructed lot in the field controls the number of sublots.

- **Set the number of sublots to five (5).**

You'll need to click on "Number of Sublots" in the list box, then enter 5 in the edit control.

---

#### **5. Set the As-Designed Standard Deviations.**

The last step before executing is to enable sampling of the as-designed quality characteristics and to specify the standard deviations of each.

- **Set as-designed strength to Sample 5,000, 450 lbf/in<sup>2</sup> (34.5, 3.1 MPa).**

You'll need to click on A-D Strength in the list box, then click on Sample, then enter "5000, 450" in the edit control.

- **Set as-designed thickness to Sample 10, 0.1 in (254, 2.5 mm).**

- **Set as-designed air content to Sample 6, 0.5 percent.**

- **Set as-designed initial roughness to Sample 8, 1 in/mi (0.13, 0.02 m/km).**

Follow the same steps as for as-designed strength for each of these cases.



PaveSpec now has all the information necessary to generate our simple PF/PD curve. Your session dialog box should now look something like the one shown in figure 16:

Figure 16. The Sublot Target A-D LCC session dialog box settings.

#### 6. Make Sure Distributions are Set to Twenty (20).

If the "None" radio button is selected, do the following:

- Click on the "Runs" radio button under "Distributions".

The "Runs" radio button is selected and the edit box for "Runs" is enabled.

#### 7. Execute the Session.

- Click on the Execute button, or press Alt-E.

The Session Running window appears, and the session executes.

PaveSpec will sample and predict the as-designed lots: 10 each, with 5 sublots per lot. The results of these runs are stored in the As-Designed Summary table and used to compute the pay factor.

Finally, it will run the as-constructed lot. PaveSpec predicts the life-cycle costs of each of the five sublots, determines the mean A-C LCC, and then computes the pay factor for the lot. The results of the session are distributed among several tables. The Target A-D LCC and lot A-C LCC are shown in the Session

Summary table. The pay factor versus percent defective curve is in the PF vs. PD table/graph. Pick the PF vs. PD option in the Tables menu to view the points making this graph, or pick the PF-PD Equation option in the Calculate menu to observe the linear equation passing through a selected range of the points.

---

## Example 4: Iterating Quality Characteristics.

This example demonstrates iterations. Iterations are used to vary one or more of the quality characteristics to gauge their effect on LCC, pay factor, percent defective, etc.

Iterations are generally used for two purposes:

- Understanding or illustrating the effect of one or more quality characteristics on life-cycle cost or pay factor.
- Completing the pay-factor versus percent defective curve. Recall that in our previous example we used subplot prediction to generate the middle-to-high portion of the curve; by iterating one or more of the quality characteristic means, we can obtain more points toward the bottom end of the graph. Sampling must be used for this application.

If you haven't already, read the section in PaveSpec Basics on iterations (p. 26). It gives an introduction to the material in this example.

We'll only be using the linear iterations in this example. If  $X^k$  iteration were chosen, you would be able to consider all four quality characteristics. However, you can't get much of a contour plot using four quality characteristics.

Contour plots allow you to get a straightforward, visual impression of the effect of two different quality characteristics.

This example will show how to get a contour plot of pay factor versus strength and thickness. You can easily modify this session to get a plot of any two quality characteristics.

---

### 1. Make a Copy of the Sublots/Target A-D LCC Session.

First, open the Sublots/Target A-D LCC session that was created in the previous example. If you haven't done the previous example, you'll need to create a new session, or modify another session, to match the settings for this example.

- **From the Session menu, choose Sublots/Target A-D LCC.**

The Define Session dialog box will appear with the Sublots/Target A-D LCC session loaded.

- **Click on Copy.**

PaveSpec makes a copy of the Sublots/Target A-D LCC session and presents you with the copy. Note that the session's name was copied; you'll need to change it.

➤ Type "Iterations".

The name of the new session is changed. This name will appear on the Sessions menu once we execute the session.

---

**2. Set the Iteration Parameters.**

Next, we'll modify the session to reflect our example. Our goal is to iterate compressive strength linearly from 4,500 to 5,500 lbf/in<sup>2</sup> (31.0 to 37.9 MPa), in 11 steps, and thickness from 9.5 to 10.5 in (241 to 267 mm), also in 11 steps.

You may wonder why we're using 11 steps and not 10. PaveSpec wants to know how many steps to use *in total*—this includes the starting and ending steps. In other words, it is the number of points along the axis, not the number of gaps between points. For our example, 11 steps will provide 100-lbf/in<sup>2</sup> (0.69-MPa) steps in strength and 0.1-in (2.5-mm) steps in thickness. As a further example, if we wanted more detail, we'd use 21 steps for one or both of the quality characteristics.

We're also going to iterate strength and thickness independently. This means that strength will be iterated along the X axis, and thickness along the Y axis. If we iterated them both along the same axis, we wouldn't get a contour plot, and we also wouldn't get an independent analysis.

We'll use the following values for our iterations:

Quality Characteristic	Iter. Axis	As-Designed Mean	As-Constructed Starting Value	As-Constructed Ending Value
Strength	X	5,000 lbf/in <sup>2</sup>	4,500 lbf/in <sup>2</sup>	5,500 lbf/in <sup>2</sup>
Thickness	Y	10 in	9.5 in	10.5 in
Air Content	-	6 percent	6 percent	6 percent
Initial Roughness	-	8 in/mi	8 in/mi	8 in/mi

$$1,000 \text{ lbf/in}^2 = 6.9 \text{ MPa}$$

$$1 \text{ in} = 25.4 \text{ mm}$$

$$1 \text{ in/mi} = 0.01578 \text{ m/km}$$

Note that we're going to keep air content and initial roughness at their as-designed values. In another application, a contractor may want to get a contour plot for different values of the other quality characteristics.

➤ In the Iteration X Axis group, click on Linear.

Linear iteration is selected and the Steps edit control appears.

➤ Set the number of X steps to 11.

You can hit TAB to move to the edit control, or click with the mouse.

- In the Iteration Y Axis group, click on Linear.

Linear iteration for the Y axis is selected, and the Steps edit control appears.

- Set the number of Y steps to 11.

You can hit TAB to move to the edit control, or click with the mouse.

You may notice that the number of predictions has grown to a frightening value; this is because subplot prediction is still on, which multiplies our iterations by a factor of 100. You'll turn this off after you set the quality characteristics.

- Click on A-C Strength in the QC list box.

The current value for strength and its sampling setting is shown. You'll also notice that a new box appears next to the Value group indicating the Iteration options.

- Click on Specify in the Value group.

Sampling is disabled and Specify is enabled. The value also changes to 5,500 with no standard deviation, since there is no sampling.

- Click on X in the Iterate group.

X is checked and the Value group now shows a starting-end ending value for strength. The default ending value is 4,000 lbf/in<sup>2</sup> (27.6 MPa), which was the original value before we selected 5,500 lbf/in<sup>2</sup> (37.9 MPa).

- Set the starting value to 4,500 and the ending value to 5,500.

The easiest way to do this is to highlight the value in the Start edit control with the mouse, and type "4500" to replace the selection. Then press TAB, which highlights the value in the End edit control. Type "5500" to replace that selection.

Strength is now set to iterate from 4,500 lbf/in<sup>2</sup> to 5,500 lbf/in<sup>2</sup> (31.0 to 37.9 MPa) along the X iteration axis. As a side point, PaveSpec doesn't care whether you go from 4,500 to 5,500 or 5,500 to 4,500 lbf/in<sup>2</sup> (31.0 to 37.9 or 37.9 to 31.0 MPa). It automatically goes backwards to adjust. Therefore, if you want to show how pay factor decreases with decreasing strength (that is, reverse the X axis), just reverse the starting and ending value. The same, of course, applies to the Y axis.

You'll also notice that the iteration setting and starting and ending value for strength is now reflected in the QC list box.

Now we'll set the Thickness iteration values.

- Click on A-C Thickness in the QC list box.

The current value for thickness and its sampling setting is shown.

➤ **Click on Specify in the Value group.**

Sampling is disabled and Specify is enabled. The value also changes to 10.1 with no standard deviation.

➤ **Click on Y in the Iterate group.**

Y is checked and the Value group now shows a starting-end ending value for thickness.

➤ **Set the starting value to 9.5 and the ending value to 10.5.**

Thickness will now be iterated along the Y axis from 9.5 to 10.5 in (241 to 267 mm).

Now that strength and thickness are set, all that is left for quality characteristics is to set air and roughness to their as-designed values.

➤ **Click on A-C Air Content in the QC list box.**

The current value for sampled air content is shown in the Value group.

➤ **Click on Specify in the Value group.**

Sampling is disabled and Specify is enabled. The value also changes to 5.5 percent with no standard deviation.

➤ **Set the value to 6.**

Air content will now be a constant 6 percent for all the predictions.

➤ **Click on A-C Roughness in the QC list box.**

The current value for sampled roughness is shown in the Value group.

➤ **Click on Specify in the Value group.**

Sampling is disabled and Specify is enabled. The value also changes to 9 in/mi (0.15 m/km) with no standard deviation.

➤ **Set the value to 8.**

Initial roughness will now be a constant 8 in/mi (0.13 m/km) for all the predictions.

That's a lot to change for a session. Now is a good time to make the point that PaveSpec maintains up to 20 different sessions, so you can keep a session around for your main applications. Once you've created the session, just make small modifications, rather than having to go through all these steps every time. In fact, if you find contour plots important, you may want to create sessions for each of the six two-quality characteristic contour plots, naming them Strength vs. Thickness, Strength vs. Air Content, and so on.

Now that the iteration settings are done, all we need to do is to turn off subplot prediction.

---

### 3. Turn Off Target Value Estimation.

For simplification of this example, we will use the standard as-designed LCC (coming from the means only of the quality characteristics) instead of simulating the as-designed LCC.

- Click on the "Target LCC Value.." button.

The Session: Target Value Estimation dialog box appears.

- Click on the "Estimate LCC target value.." checkbox.

This will clear the checkbox and disable the other options (they will be grayed). Only one prediction for as-designed LCC (using the means of the quality characteristics) will be performed.

- Click on OK.

The dialog box is removed.

---

### 4. Turn Off Distributions and Sublot Prediction.

When 20 distributions runs are enabled, we're going to do 20 predictions for every iteration point, or  $20 \times 11 \times 11$ , not including the 5 sublots per lot. In fact, distributions and sublot prediction don't make any sense for this session, since we're not going to sample. There won't be any deviation in the results for a given iteration point or between sublots. If you tried to run this session as-is, PaveSpec would give you a warning message, but you'd still be allowed to run it if you wanted.

- Click on the "None" radio button in the Distributions group.

Distributions are disabled.

- Click on the "Sublots and PD.." button.

The Session: Sublots and Percent Defective Options dialog box appears.

- Click on the "Use sublots for sample location.." radio button.

Predict sublots is disabled, the control is unchecked, and the other options are disabled (grayed).

- Click on OK.

The dialog box is removed.

Now we won't be doing 100 predictions for each iteration point.

Now we're all ready to run the session. Notice that the total predictions are now as we expect:

- One as-designed prediction to get the as-designed life-cycle cost.
- A total of 121 ( $11 \times 11$ ) predictions for the X and Y iterations.

These combine for a total of 122 predictions. Depending on the speed of your computer, and your appetite for precision, you can increase the number of steps

along the X or Y (or both) axes. You'll likely want to specify either 21 or 51 to get attractive intermediate values: 21 steps means strength steps of 50 lbf/in<sup>2</sup> (0.34 MPa) or thickness steps of 0.05 in (1.3 mm); 51 steps means strength steps of 20 lbf/in<sup>2</sup> (0.14 MPa) or thickness steps of 0.02 in (0.51 mm).

---

## 5. Execute the Session.

- Click on "Execute" or press Alt-E.

The session executes.

The session consists of two basic steps: the as-designed predictions and the as-constructed predictions.

When it's done, you'll be presented with the Session Summary table, which lists in numeric form all the data for the iterations. If you want to look at the Pay Factor plane of the table, double-click on the "Pay Factor" heading along the left-hand side of the window. You can use the scrollbars to move around the table.

---

## 6. Generate the Pay Factor Contour Plot.

- From the Calculate menu, choose "Pay Factor contour plot.."

The Generate Pay Factor Contour Plot dialog box appears (figure 17). If you want, you can change the smoothing factor, but a value of 1 should be sufficient for this example.

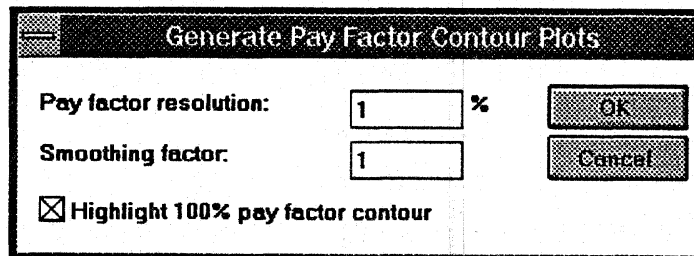


Figure 17. Pay Factor Contour Plot dialog box.

- 
- Click OK.

PaveSpec creates a pay factor contour plot window.

If you used the default values for the Pay Factor contour plot parameters, you'll see a highlighted 100-percent pay factor line and contour lines for every five percentage points away from 100 percent (e.g., 95 percent, 90 percent, 85 percent, etc.).

You may want to try generating a contour plot with greater ranges for strength or thickness, or substituting another quality characteristic.



---

## Menus

PaveSpec's options are found in eight menus:

- **Session:** options related to the management of sessions.
- **Constants:** access to the constant variables.
- **Window:** tiling and cascading of windows, and a list of the windows available.
- **Tables:** a list of all the tables PaveSpec generates.
- **Graphs:** a list of all the graphs PaveSpec generates.
- **Calculate:** a list of post-session computations PaveSpec can perform.
- **Print:** options for printing the active table or graph window.
- **Output:** ASCII file and clipboard output.

Each of these is described below.

---

### Session Menu

Session
Session1
Session2
Session3
....
SessionN
New..
Resume
Save all settings
About PaveSpec..
Exit

The session menu gives the user access to his/her sessions; it is analogous to the File menu in most Windows applications. PaveSpec uses a single file to store all sessions, and presents them all by name in this menu. This allows the user to name his sessions more useful names, since they are not restricted to eight characters.

The first section in the menu lists the names of the sessions. Selecting one of these brings up the Session Define dialog box with all the settings for that session. The user may then execute the session from there.

**New..** creates a new session with defaults for all fields.

**Resume** is enabled when a session is paused. Selecting Resume will continue the session.

**Save all settings** saves all sessions and the constant variables to disk. This is also done automatically when the you leave PaveSpec.

Exit quits PaveSpec and saves all settings. If you do not wish to save settings upon exit, hold down the SHIFT key while selecting Exit.

---

### Constants Menu

Constants
Traffic..
Project..
Materials and Climatic..
Base..
Load transfer..
Cost..
Rehabilitation..
Advanced..

Each of the options in this menu brings up a dialog box containing the constant variables of each class:

- **Traffic** - Directional factor, percent trucks, percent trucks in outer lane, average truck load equivalency factor, ESAL's, ADT, and growth factor. For traffic, one interesting option is the ability to calculate ESAL's from a user input for ADT (average daily traffic). If the check box for this option is not selected, the ADT and ESAL values will be independent. When the box is selected, the following variables are used.
  - ADT for all lanes - total ADT for the given pavement (both directions).
  - Outer lane ESAL's - number of ESAL's (in millions) used for analysis of the design lane, one direction.
  - Directional factor - the percent of trucks in one direction.
  - Percent trucks - the percentage of the ADT that are considered trucks.
  - Percent trucks in outer lane - percent of total trucks in one direction that are considered to be in the design lane.
  - Average truck load equivalency factor - the translation from total trucks to total ESAL's. Ratio of average ESAL's per truck.
  - Growth Factor - the initial ESAL's are increased each year according to either a simple or compound growth rate.

Outer-lane ESAL's are then equal to the ADT for all lanes multiplied by the directional factor, percent trucks, percent trucks in outer lane, and the average truck load equivalency factor. This is then the starting design lane ESAL value.

- **Project** - Pavement type, road location, design life, project length, number of lanes, lane width, shoulder width, joint spacing, minimum pay factor, and number of directions.
- **Materials and climatic** - Annual temperature range, freezing index, precipitation, D-cracking, reactive aggregate, liquid sealant, and preformed compression seal.
- **Base** - Type of base, modulus of subgrade reaction, subgrade soil type, and longitudinal subdrains present.
- **Load transfer** - Dowel bar diameter, area of reinforcement steel, and tied PCC shoulder.
- **Costs** - Construction bid, cost of overlay, joint patching, slab replacement, annual interest rate, annual inflation rate, and first year of cost analysis.
- **Rehabilitation** - Overlay triggers for all three rehabilitation cases (PSR, Cracking, Spalling, Faulting), override initial PSR value, PSR after overlay, overlay life, width of joint patch, inner-lane cracking as a percentage of outer lane, and percentage of joints patched until next overlay after overlay placed.

The Rehabilitation dialogue box determines how life-cycle costs will be computed and is, therefore, extremely important. First, a number of terms and variables are defined.

**Overlay Triggers** - these are critical values used to trigger an AC overlay. Individual triggers for PSR, Cracking, Spalling, and Faulting can be enabled by using the respective check boxes in the Rehabilitation dialogue box.

**Override initial PSR value** - allows the user to set the PSR value for year zero. If the check box is enabled, the initial roughness values will not affect the pavement performance (i.e., will not be a quality characteristic).

**Initial PSR after overlay** - this is the user's choice of the pavement's starting condition after an overlay has been placed.

**Overlay life** - number of years until another overlay will be placed.

**Width of joint patch** - width (in longitudinal direction) of a patch used in replacing a spalled joint. This input is used for the determination of costs.

**Percent inner-lane cracking** - percentage of the total cracking predicted for the design lane (lane with heaviest traffic), which is assumed to occur in each inner lane. For example, if it is predicted that the design lane contains 50 transverse cracks, and the percent inner-lane cracking value was set to 10 percent, for each inner lane of the

pavement, 5 transverse cracks would be computed. This value is used in the calculation of costs only. (Note: If the pavement only has one lane in each direction [no inner lanes], this value will not affect costs.)

After overlay, percentage of joints patched until next overlay - this is an approximate way to obtain some after-overlay rehabilitation cost. This determines the percentage of total reflection cracks over joints that will fail before the next overlay. This is based on the assumption that a failed joint will be replaced the year of its failure. A linear trend is used to calculate individual year values. See "PaveSpec Distress and Cost Models" for more detail.

Finally, it is important to explain the choices included within the **Overlay Triggers** box. PaveSpec allows three choices of how overlays are to be applied. The three columns of trigger values are related to the three methods.

The first category is Sublot overlays. If the "Each sublot overlaid independently" radio button is selected in the *Session: Sublot and Percent Defective Options* dialogue box, then overlays are assumed to be applied to each sublot independently, based on the **Sublot overlays** column in the *Constant Variables: Rehabilitation* dialogue box.

The second category is entire Lot overlays. If the "Overlays applied to entire lot" radio button is selected in the *Session: Sublot and Percent Defective Options* dialogue box, then overlays are assumed to be applied to the entire lot. Two choices are available for this option: (1) If the "Trigger on average of sublot distresses" check box is enabled in the *Session: Sublot and Percent Defective Options* dialogue box, the average distresses for all sublots are compared to the **Lot overlays: Mean** column in the *Constant Variables: Rehabilitation* dialogue box, and (2) If the "Trigger on percent-sublot failures" check box is enabled in the *Session: Sublot and Percent Defective Options* dialogue box, the user input for "% failed sublots" determines when an overlay is placed for the whole lot. A failed sublot is determined by comparing the predicted sublot distresses with those in the **Lot overlays: PSF (percent sublots failed)** column in the *Constant Variables: Rehabilitation* dialogue box.

- **Advanced** - Options for development use only.

---

## Window Menu

Window
Tile
Cascade
Close all
Table Font..

The Window menu contains options for management of PaveSpec's windows.

**Tile** causes the non-iconized windows to be arranged in a grid.

**Cascade** causes the non-iconized windows to be arranged in a staggered fashion.

**Close all** removes all windows.

**Table Font..** brings up a dialog box that lets you select the font that PaveSpec uses for the text in tables.

---

## Tables Menu

Tables
Constant Inputs
Session Summary Series Summary
LCC Lookup Pay Factor Look-up
As-Designed Quality Characteristics As-Designed Distresses As-Designed Costs As-Designed Samples As-Designed Roughness Samples As-Designed Summary Target A-D LCC Summary
As-Constructed Quality Characteristics As-Constructed Distresses As-Constructed Costs As-Constructed Samples As-Constructed Roughness Samples As-Constructed Acceptance
PF vs. PD

The Table menu lists all of the tables that PaveSpec generates. Depending on the session and its state of execution, some or all of these tables will be available. If a table is not available, its name will be grayed out.

Selecting a non-grayed table from this list will do one of the following:

- If a window displaying this table already exists and is not iconized, another window will be created, allowing different parts or planes of the table to be viewed at the same time.
- If the window displaying this table exists, but is in an iconized state, it will be restored to a window, but no new window will be created.
- If no window for this table exists, a new window will be created and displayed.

---

## Graph Menu

### Graph

Pay factor contours Operating Characteristic
---

This menu, like the table menu, governs PaveSpec windows. Depending on the session and its state of execution, some or all of these graphs will be available. If a graph is not available, its name will be grayed out.

Selecting a non-grayed graph from this list will do one of the following:

- If the window displaying this graph exists, but is in an iconized state, it will be restored to a window, but no new window will be created.
- If no window for this graph exists, a new window will be created and displayed.

---

## Calculate Menu

### Calculate

Pay factor contour plot..
PF-PD equation.. Pay factor lookup Tables..

The options in this menu are available generally after the session executes.

**Pay factor contour plot** creates a graph of contours of the pay factors generated by the session.

**PF-PD equation** allows you to determine the linear regression equation for the Pay factor as a function of percent defective for non-rejected lots. This equation is then used in the next two options; therefore, you'll need to run this in order to access them.

**Pay factor lookup table** creates a pay factor versus life-cycle cost mean and standard deviation table using the equation determined in PF-PD Equation.

---

## Print Menu

Print
Table..
Graph..
Visible plane..
All planes..
Summary Report..

The Print menu gives you access to the print options *for the active window*. If you want to print a particular window, click on it with the mouse or select it from the Tables menu, then choose this menu. Depending on the type of table or graph, certain options in the Print menu will become available to you. Selecting any of the options in this menu will bring up a dialog box allowing you to enter the font, title, subtitle, and footer for the table or graph, and, for tables, control over the row height and column width.

**Table..** is available when the active window contains a one- or two- dimensional table. It will print the entire table, tiling it if necessary.

**Graph..** is available when the active window contains a graph. Some windows contain only a graph, while some others contain a graph and a table. In either case, selecting this option will print only the graph.

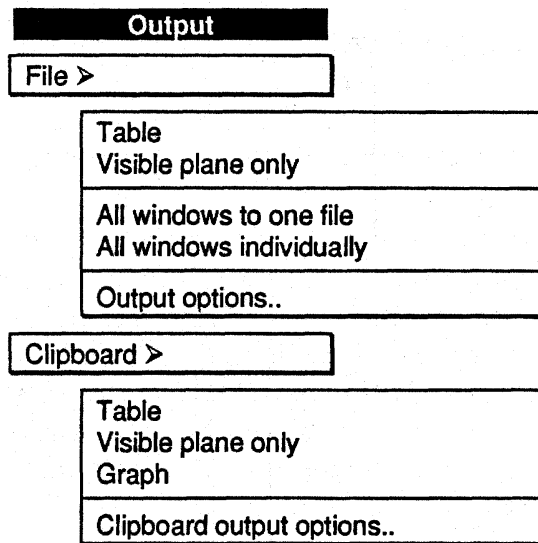
**Visible plane..** is available when the active window is a three-dimensional table. It will cause only the currently selected plane in the window to be printed.

**All planes..** is available when the active window is a three-dimensional table. It will cause all of the planes in the table to be printed. The planes printed are those parallel with the plane selected in the window.

**Summary Report..** causes the Session Summary, Constant Variables, Pay Factor/Percent Defective, As-Designed Changing, LCC Lookup, and Pay Factor Lookup tables to be printed in succession.

---

## Output Menu



The output menu gives you access to ASCII file and clipboard output. Any of the tables can be output to a file that you choose, or to the clipboard for pasting into other Windows applications.

Each of PaveSpec's tables has options for both file and clipboard output, including delimiters, titles, row and column headings, and so on. These options are available under **Output options..** and **Clipboard output options..**

The other options on the menus are:

### File Submenu

These options are for ASCII file output.

- **Table** - Outputs the entire selected table.
- **Visible plane only** - Outputs only the plane visible in the selected window.
- **All windows to one file** - Outputs all of the existing windows to a file. Individual tables are sent in their entirety as if they were sent using **Table**, above; each table's output is concatenated to the previous output.
- **All windows individually** - This has the same effect as selecting each window individually and sending it to its default file output.
- **Output options..** - Sets the output options for files.

### Clipboard Submenu

These options are for ASCII clipboard output.

- **Table** - Outputs the entire selected table to the clipboard.
- **Visible plane only** - Outputs only the plane visible in the selected window.
- **Graph** - Outputs a selected graph.
- **Clipboard output options** - Sets the options for clipboard output.



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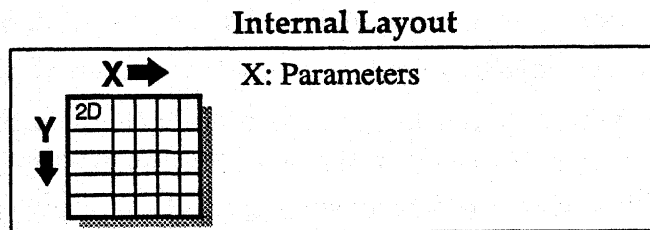
## PaveSpec Tables

This section lists each of the tables that PaveSpec generates, a description of what data is found in each one, and from where that data comes. It also will indicate any of the other user interface options that are available and the internal layout of the table. This last description is important if you want to use Dynamic Data Exchange with PaveSpec.

---

### Constant Inputs

The Constant Inputs table contains nearly all the information in the Constants dialog boxes, plus some of the values calculated from the constants ("derived" constants). These include the total project bid price, area of the project, and so on.



---

### Session Summary

The Session Summary table contains the condensed information from the entire session. This table is always three-dimensional: By default, the column headings are the parameters (explained below), the row headings correspond to points along the X Iteration axis, and the depth axis corresponds to the points along the Y Iteration axis.

If X Iterations are not used, the X Iterations axis will be of length one.

If Y Iterations are not used, the Y Iterations axis will be of length one.

The parameters are always the same, but some are not used for some sessions. The first seven correspond to without-user cost values, the next seven to with-user cost values. Otherwise they are the same:

- Pay Factor: Determined by the standard relationship, not the PF-PD equation. It is simply  $1 - (A-C \text{ LCC} - A-D \text{ LCC}) / \text{BidPrice}$ . Bid price is listed in the constant inputs, and the life-cycle costs are shown below the Q and percent defective figures.
- Q: This can have three different meanings:
  - Q will be blank if you did not predict sublots.

If you predicted sublots, but did not enable distributions, Q contains the result of the equation:

$$Q = \frac{A - D \text{ LCC} - A - C \text{ LCC}}{\sigma_{A-C \text{ LCC}}}$$

where A-C LCC is the set of as-constructed life-cycle cost of the individual sublots.

If you chose to predict sublots and generate distributions, then Q is the mean and standard deviation of the Q from each of the distribution runs.

- **Percent defective:** Like Q, this can have three different meanings:
  - Percent defective will be blank if you did not predict sublots.
  - If you predicted sublots, but did not enable distributions, percent defective is a function of Q and the number of sublots.
  - If you chose to predict sublots and generate distributions, then percent defective is the mean and standard deviation of the percent defective from each of the distribution runs.
- **As-designed life-cycle cost:** This will be the same for all iteration points. It is simply the life-cycle cost determined by the as-designed prediction.
- **As-constructed life-cycle cost:**
  - If you predicted sublots, but did not enable distributions, this is the mean and standard deviation of the life-cycle cost from each of the sublots.
  - If you predicted sublots and enabled distributions, this is the mean and standard deviation of the means of the life-cycle costs from each of the distribution runs.

The next four parameters are the inputs to the sampler for each point on the iteration grid—not the actual samples taken. To see the samples taken, you'll need to inspect the series summary, quality characteristics, or acceptance tables.

- **As-Constructed Strength.**
- **As-Constructed Thickness.**
- **As-Constructed Air Content.**
- **As-Constructed Initial Roughness.**

The final four parameters are the sampling parameters:

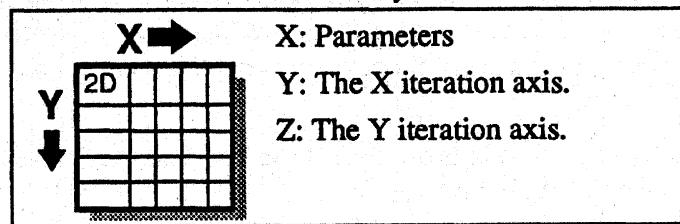
- **Number of sublots.**
- **Number of samples per subplot.**

- Roughness interval.
- Sampling grid size.

### Special User Interface

When you double-click on any of the elements in the Session Summary table, PaveSpec will re-run the series corresponding to that point, recreating the Series Summary table (if any), or the Acceptance (if subplot predictions are enabled), As-Constructed Quality Characteristics, As-Constructed Distresses, and As-Constructed Costs tables if distributions were not enabled.

### Internal Layout




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### Series Summary

The Series Summary table is the repository for the results of each distribution run within a series. PaveSpec uses the Series Summary table for each of the iteration points. If distributions are enabled, the table will be a true two-dimensional table, otherwise, PaveSpec still uses the table, but removes it when it's done with the session to avoid confusion.

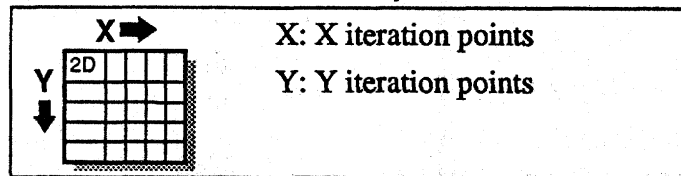
This table contains the same parameters as in the Session Summary table, except:

- The Q and percent defectives will be blank if subplot predictions were not run. Otherwise, they will reflect the Q and PD for the subplot predictions. If you did predict sublots, but they are still blank, it means that the deviation between sublots was extremely close to zero, preventing the calculation of Q. This could be caused by having your as-constructed deviations too low, or in a range that will always result in the same life-cycle cost (for example, very high air content as compared to the as-designed case).
- The quality characteristics (strength, thickness, air, roughness) are the actual sampled values. If sublots are enabled, they are the means of the means of the subplot samples.

### Special User Interface

When you double-click on any of the elements in the Series Summary table, PaveSpec will re-run the lot or sublots associated with that element, creating the Acceptance (if subplot predictions are enabled), As-Constructed Quality Characteristics, As-Constructed Distresses, and As-Constructed Costs tables.

### Internal Layout



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### LCC Look-Up

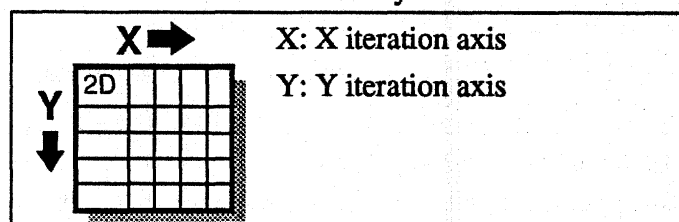
This table contains the value of the life-cycle cost for the means-only predictions for each point on the iteration grid. PaveSpec automatically generates this table after the as-constructed runs if both iterations and sampling are enabled. The purpose of this table is to provide a reference for the with-sampling values, and also to provide a table in which to look up life-cycle costs without the use of a computer.

The LCC lookup table is intended to be used with  $X^K$  iterations, because in a single session the user can get:

- Pay factor-percent defective graph.
- Pay factor-percent defective equation.
- Pay factor lookup table.

With the LCC lookup and PF lookup tables, one can obtain a pay factor for a lot without the use of a computer.

### Internal Layout



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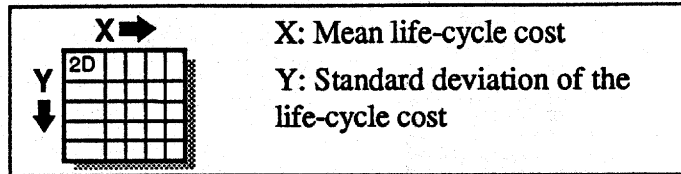
### Pay Factor Look-Up

This table contains the pay factor associated with a lot based on the mean and standard deviation of the life-cycle cost of its sublots. This pay factor is calculated from the PF-PD equation. It comes in without-user cost and with-user cost versions.

To generate these tables, you'll need to first run a session that generates pay factor-percent defective pairs in order to obtain a PF-PD equation. Next, calculate the PF-PD equation by choosing upper and lower quality levels under "PF-PD equation.." in the Calculate menu. Finally, choose "Pay factor lookup tables.." in the Calculate menu and specify the starting and ending values and the number of steps along the mean and standard deviation axes.

These tables always have two dimensions, and no special user interface.

### Internal Layout

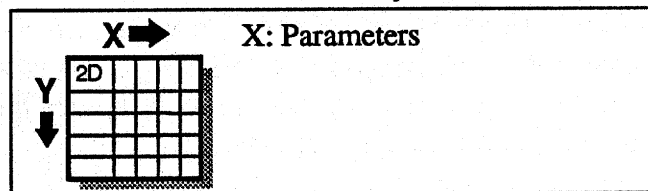


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### As-Designed Quality Characteristics

This table holds the as-designed quality characteristics. This is simply a copy of the as-designed values in the session dialog box.

### Internal Layout



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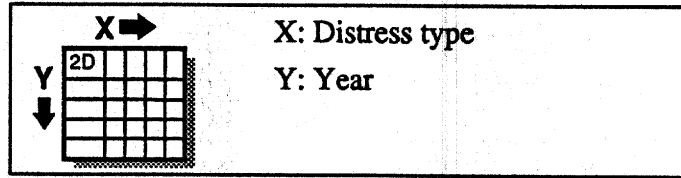
### As-Designed Distresses

This table contains the distresses, by year and type, of the standard as-designed prediction. The distresses recorded are:

- Traffic, measured in mega-ESAL's, or MESAL's. The starting value and growth rate and type are determined by the settings in the Traffic dialog box under the Constants menu.
- Faulting, measured in inches.
- Cracking, measured in feet per mile.
- Spalling, measured in joints per mile.
- Total repairs, which are the cumulative total of the cracks repaired and spalls repaired.
- Repair cracks, which are the total number of cracks repaired in the given year.
- Repair spalls, which are the number of spalled joints repaired in the given year.
- Present serviceability rating (PSR) for the given year.

This table is always a two-dimensional table and has no special user interface.

## Internal Layout



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### As-Designed Costs

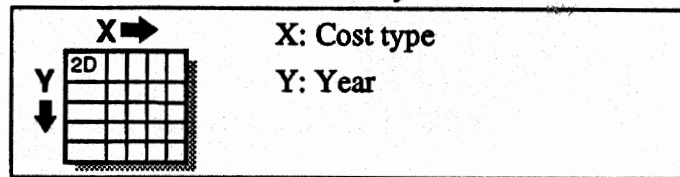
This table records the actual costs associated with the rehabilitation of the distresses for the as-designed lot. Most of the costs are based on the values in the Costs dialog box under the Constants menu.

- **Repair cracks:** The amount projected in the given year to repair the number of cracks in the outer lane reported in the distresses table. Based on the number of cracks and the slab replacement cost.
- **Repair spalls:** The amount projected in the given year to repair the number of spalled joints reported in the distresses table. Based on the number of spalled joints and the cost of joint patching.
- **Rehabilitation total:** A function of the previous two costs, and the number of lanes. PaveSpec assumes that the inner lanes will have a certain percentage of the cracking found in the outer lane. The total repair cost for cracking will be the repair cracks cost, times the percentage of inner-lane cracking, times the number of inner lanes. The percentage is specified in the Rehabilitation dialog box. PaveSpec assumes the spalling repair is done across all of the lanes, so it is the Repair Spalls cost, above, times the number of lanes. The total crack and spall repair costs combined is the Rehabilitation Total amount.
- **User cost** is based on the PSR level, functional classification of highway, geometrics, and traffic for the given year.
- **Overlay cost** is the cost for the given year projected for overlay. The overlay cost is zero unless an overlay is actually performed in that year. Otherwise, it is the total project area, including the shoulders, times the overlay cost. If the overlay is within its design life of the end of the lot design period, its cost is prorated.
- **Total** is the overlay cost plus the Rehabilitation Total cost plus user cost.
- **Total without-user costs** is the overlay cost plus the rehabilitation cost.

The second half of the costs table are the above costs adjusted for present worth. The present discount rate (the difference between the inflation and interest rates) is used to determine present worth.

The As-Designed Costs table has no special user interface.

#### Internal Layout



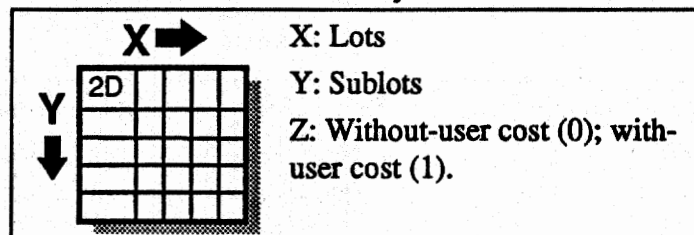
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#### As-Designed Summary

This table is created whenever target A-D LCC is estimated. It records all of the lot and subplot life-cycle costs. It does not record any of the distresses or other data, but it does summarize each lot to report mean and standard deviation of the life-cycle costs of the sublots.

The As-Designed Summary table has no special user interface.

#### Internal Layout



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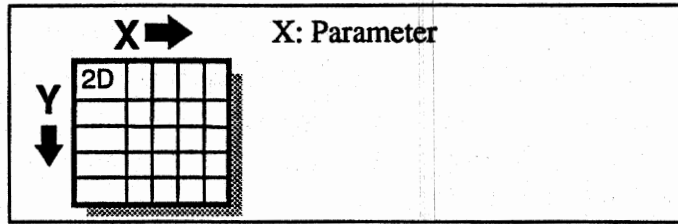
#### Target A-D LCC Summary

As with the As-Designed Summary, this table is created whenever target A-D LCC is estimated. It records the series of values that determine target A-D LCC:

- Target A-D LCC is the value PaveSpec calculated through simulation.
- S is the pooled standard deviation of the as-designed lot life-cycle cost predictions.
- Number of lots is simply the number of as-designed lots. It is provided for documentation's sake.
- Number of sublots is the number of sublots per as-designed lot.

This table has no special user interface.

### Internal Layout



### As-Constructed Quality Characteristics

This table holds the as-constructed quality characteristics for each of the sublots of the most recent lot prediction (see Tables and Data Persistence, p. 37). If subplot predictions are enabled, this table is two-dimensional, with the second dimension corresponding to the subplot number; otherwise, it is one-dimensional.

### Internal Layout

If subplot predictions are not enabled:		X: Parameter (strength, thickness, air content, initial roughness)
If subplot predictions are enabled:		X: Parameter Y: Sublot number

### As-Constructed Distresses

This table contains the distresses, by year and type, of the most recent as-constructed prediction (see Tables and Data Persistence, p. 37). The distresses recorded are:

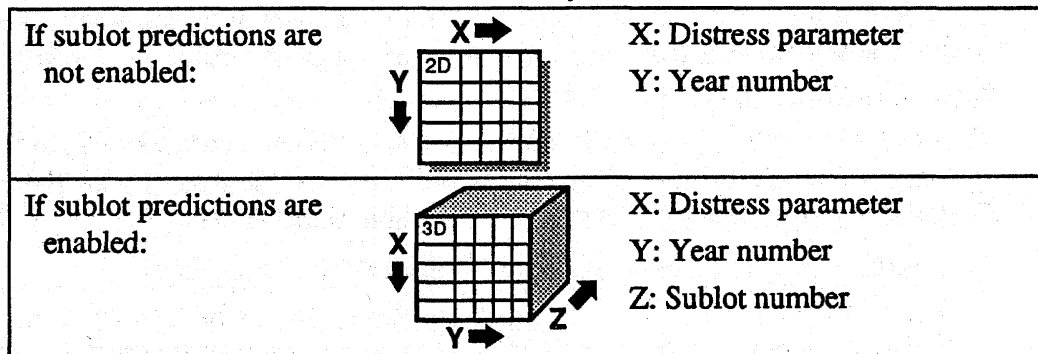
- Traffic, measured in mega-ESAL's, or MESAL's. The starting value and growth rate and type are determined by the settings in the Traffic dialog box under the Constants menu.
- Faulting, measured in inches.
- Cracking, measured in feet per mile.
- Spalling, measured in joints per mile.
- Total repairs, which are the cumulative total of the cracks repaired and spalls repaired.
- Repair cracks, which are the total number of cracks repaired in the given year.



- Repair spalls, which are the number of spalled joints repaired in the given year.
- Present serviceability rating (PSR) for the given year.

This table is two-dimensional (parameter and year) if subplot predictions are not enabled, and three-dimensional (subplot) if subplot predictions are enabled. This table has no special user interface.

#### Internal Layout




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#### As-Constructed Costs

This table records the actual costs associated with the rehabilitation of the distresses for the most recent as-constructed lot (see Tables and Data Persistence, p. 37). Most of the costs are based on the values in the Costs dialog box under the Constants menu.

- **Repair cracks:** The amount projected in the given year to repair the number of cracks in the outer lane reported in the distresses table. Based on the number of cracks and the slab replacement cost.
- **Repair spalls:** The amount projected in the given year to repair the number of spalled joints reported in the distresses table. Based on the number of spalled joints and the cost of joint patching.
- **Rehabilitation total:** A function of the previous two costs, and the number of lanes. PaveSpec assumes that the inner lanes will have a certain percentage of the cracking found in the outer lane. The total repair cost for cracking will be the repair cracks cost, times the percentage of inner-lane cracking, times the number of inner lanes. The percentage is specified in the Rehabilitation dialog box. PaveSpec assumes the spalling repair is done across all of the lanes, so it is the Repair Spalls cost, above, times the number of lanes. The total crack and spall repair costs combined is the Rehabilitation Total amount.
- **User cost** is based on the PSR, functional classification of highway, geometrics, and traffic for the given year.

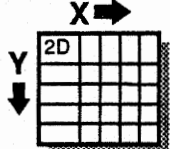
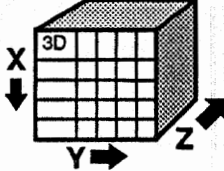
- Overlay cost is the cost for the given year projected for overlay. The overlay cost is zero unless an overlay is actually performed in that year. Otherwise, it is the total project area, including the shoulders, times the overlay cost. If the overlay is within its design life of the end of the lot design period, its cost is prorated.
- Total is the overlay cost plus the Rehabilitation Total cost.
- Total without-user costs is the overlay cost plus the rehabilitation cost.

The second half of the costs table are the above costs adjusted for present worth. The present discount rate (the difference between the inflation and interest rates) is used to determine present worth.

The last two rows in the table contain the total of each column and the total cost per mile of each column. If subplot predictions are enabled, the last Z-axis plane of the table holds the averages of all the sublots, by year.

The As-Constructed Costs table has no special user interface.

#### Internal Layout

If subplot predictions are not enabled:		X: Cost parameter Y: Year number, followed by cost totals and totals per mile
If subplot predictions are enabled:		X: Cost parameter Y: Year number; followed by cost summaries Z: Sublot number, followed by lot summary

---

#### As-Constructed Acceptance

The Acceptance table contains a summary of the lot, including the costs and pay factors by subplot, Q, and percent defective.

Most of the parameters correspond to the sublots. They are arranged across the columns as:

- Sublot: Sublot number.
- Strength: For Sublots, the mean value of the strength samples for the subplot. For Summary, this is the mean and standard deviation of all of the subplot sample values. For Sampler Inputs, it is the sampler distribution from which all samples are taken.
- Thickness: Same as for strength.
- Air content: Same as for strength.
- Roughness: Same as for strength.

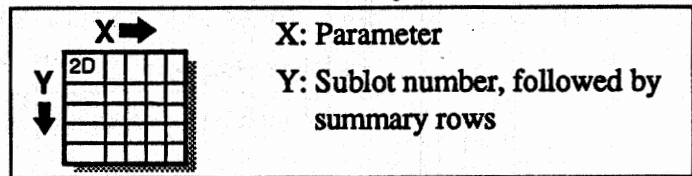
- LCC/mi: The life-cycle cost per mile of the subplot. The summary row for this column contains the mean and standard deviation of these life-cycle costs.
- Pay factor: The pay factor for each subplot is based on the LCC. The summary row for this column contains the mean and standard deviation of these pay factors.

The rows of the table correspond to:

- Sublots: One row for each of the sublots in the lot.
- Summary: The mean and standard deviation of each of the columns.
- Sampler inputs (quality characteristic columns only): The sampler mean and standard deviation specified by the user.
- Q: Used only in the LCC columns, it shows the Q for the lot (calculated from the number of sublots), the as-designed target value LCC, and the mean and standard deviations of the as-constructed life-cycle costs.
- Percent Defective: Used only in the LCC columns, it shows the percent defective calculated from Q, above.

This table is always two-dimensional and has no special user interface.

#### Internal Layout




---

#### Samples - As-Designed and As-Constructed

These tables contains the values and placement of each of the XY samples taken for each simulated lot or subplot.

Each of these sampling parameters is recorded for each sample:

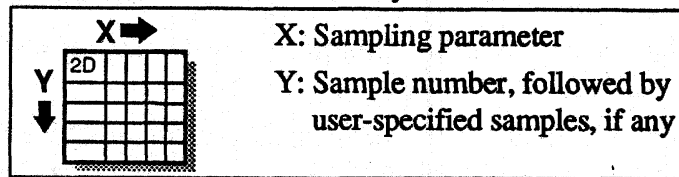
- Sublot: The number of the subplot from which the sample comes.
- X (ft): The actual location, along the pavement (longitudinal), of the sample.
- Y (ft): The actual location, across the pavement (latitudinal), of the sample.
- Strength: The value PaveSpec sampled for Strength. If Strength was not sampled, this column will be blank.
- Thickness: The value PaveSpec sampled for Thickness. If Thickness was not sampled, this column will be blank.
- Air Content: The value PaveSpec sampled for Air Content. If Strength was not sampled, this column will be blank.

- **Initial Roughness:** The value PaveSpec sampled for Initial Roughness. If Thickness was not sampled, this column will be blank. If you did not choose to sample roughness for each subplot, this value will be the same for all rows, the mean of the roughness samples in the Initial Roughness Samples table (below).

If you specified additional sample points, they are listed in the rows following the standard lot and subplot samples.

These tables always have two dimensions and have no special user interface.

#### Internal Layout

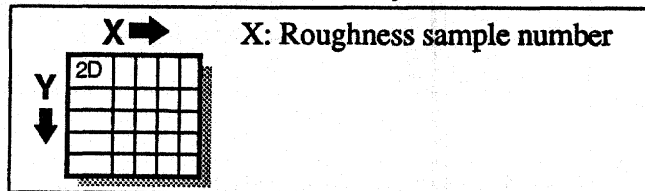



---

#### Initial Roughness Samples - As-Designed and As-Constructed

These tables contain the values of the roughness samples, assuming roughness was not sampled by sublots. These tables are always one-dimensional, with the sample values simply listed by sample number. If roughness was not sampled, the same value (the specified value) will be listed for all sample numbers.

#### Internal Layout




---

#### Pay Factor versus Percent Defective

This table holds the pay factor-percent defective points generated whenever you predict sublots and also choose to generate the PF/PD table. It also displays them in graphical format; the points that are shown is determined by the selection in the table (see Special User Interface, below).

The first two dimensions of the table always correspond to the X and Y iteration axes; if distributions are enabled, the table becomes a three-dimensional table, with the Z axis representing the distribution runs.

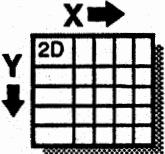
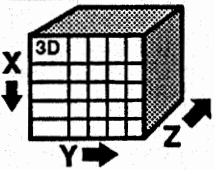
#### Special User Interface

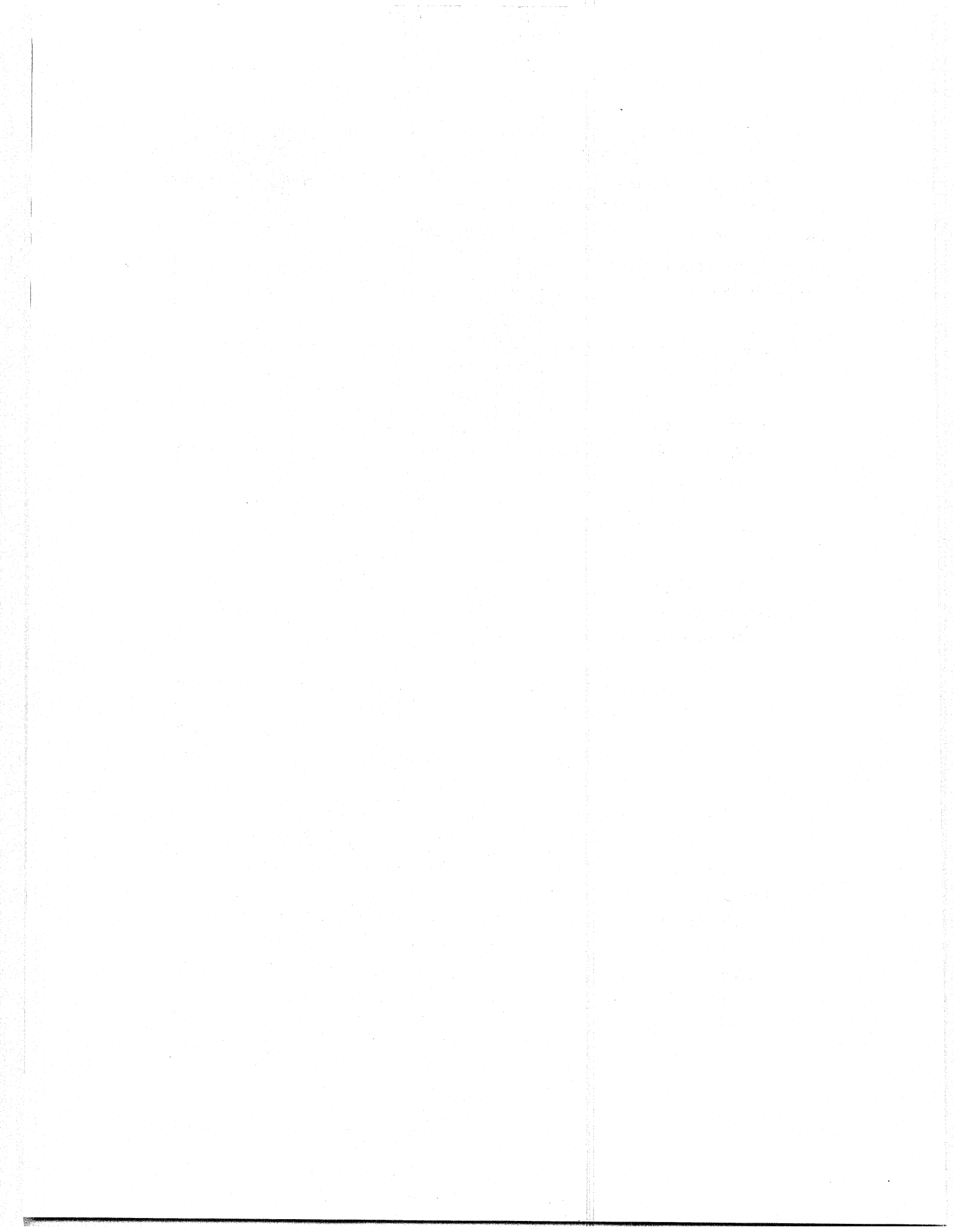
The following user actions determine the points shown.

- All data points are shown initially.
- If you double click on any element, all points will be displayed.

- If you click on any element, the points belonging to the selected iteration point (that is, all points of the same distribution series) are displayed.
- If you click on a row or column header, all the points corresponding to that row or column in the table are displayed.

**Internal Layout**

<p>If distributions are not enabled:</p>		<p>X: X iteration points Y: Y iteration points</p>
<p>If distributions are enabled:</p>		<p>X: X iteration points Y: Y iteration points Z: Distribution runs</p>



# PAVESPEC DISTRESS AND COST MODELS

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PaveSpec predicts four different pavement distresses and one rideability indicator for JPCP and JRCP pavements. The distresses include Transverse Joint Faulting, Transverse Cracking, Transverse Joint Spalling, and Pumping (Pumping is only used to feed back into the cracking prediction model). The rideability indicator is the Present Serviceability Rating (PSR), which is a function of the estimated distresses and the maintenance and rehabilitation needed to correct them. The sources for the models are listed below.

#### Transverse Joint Faulting

- "Performance of Jointed Concrete Pavements," Volume III, Publication No. FHWA-RD-89-138, Federal Highway Administration, November 1990.

#### Transverse Cracking

- "Portland Cement Concrete Pavement Evaluation System," NCHRP Report 277, Transportation Research Board, 1985.

#### Transverse Joint Spalling

- "Performance of Jointed Concrete Pavements," Volume III, Publication No. FHWA-RD-89-138, Federal Highway Administration, November 1990.
- Modifications based on work under this contract.

#### Pumping

- "Portland Cement Concrete Pavement Evaluation System," NCHRP Report 277, Transportation Research Board, 1985.

#### Present Serviceability Rating (PSR)

- "Performance of Jointed Concrete Pavements," Volume III, Publication No. FHWA-RD-89-138, Federal Highway Administration, November 1990.

The following pages describe each of the listed models in detail.

---

## Transverse Joint Faulting

Two separate joint faulting models were used: one for non-doweled pavements and one for doweled pavements. The two are described separately.

---

### Faulting of *Doweled* Concrete Pavements

$$\text{FAULTING} = \text{CUMESALS}^{0.5280} * [0.1204 + 0.04048 * (\text{BSTRESS} / 1000)^{0.3388} + 0.007353 * (\text{JTSPACE} / 10)^{0.6725} - 0.1492 * (\text{KVALUE} / 100)^{0.05911} - 0.01868 * \text{DRAINS} - 0.00879 * \text{ESUPPORT} - 0.00959 * \text{SOILTYPE}]$$

Where:

FAULTING = Mean transverse joint faulting, in

CUMESALS = Cumulative ESAL's, millions

BSTRESS = Maximum Concrete bearing stress, lbf/in<sup>2</sup>

$$= f_d * P * T * [K_d * (2 + \text{BETA} * \text{OPENING}) / (4 * E_s * I * \text{BETA}^3)]$$

BETA =  $[K_d * \text{DOWEL} / (4 * E_s * I)]^{0.25}$

$f_d$  =  $2 * 12 / (l + 12)$ , Distribution factor

$l$  = Radius of relative stiffness

$$= [E_c * \text{THICKNESS}^3 / (12 * (1 - u^2) * \text{KVALUE})]^{0.25}$$

$E_c$  = Concrete modulus of elasticity, lbf/in<sup>2</sup>

$$= 14.4 * 150^{1.5} * \text{MR}_{28}^{0.77}$$

$I$  = Moment of inertia of dowel bar cross section, in<sup>4</sup>

$$= 0.25 * 3.1416 * (\text{DOWEL} / 2)^4$$

THICKNESS = Slab thickness, in

$\text{MR}_{28}$  = Concrete modulus of rupture at 28 days, lbf/in<sup>2</sup>

$u$  = Poisson's Ratio

$P$  = Applied wheel load, lb

$T$  = Percent transferred load

$K_d$  = Modulus of dowel support, lbf/in<sup>3</sup>

DOWEL = Diameter of dowel bars, in

$E_s$  = Modulus of elasticity of the dowel bar, lbf/in<sup>2</sup>  
 OPENING = Average transverse joint opening, in  
 =  $CON * JTSPACE * 12 * (ALPHA * TRANGE / 2 + e)$   
 JTSPACE = Average transverse joint spacing, ft  
 CON = Adjustment factor due to base/slab frictional  
 restraint  
 = 0.65 if stabilized base  
 = 0.80 if aggregate base or lean concrete base with  
 bond breaker  
 ALPHA = Thermal coefficient of contraction of PCC, set to  
 0.000006 /°F  
 TRANGE = Annual temperature range, °F (min. avg. January temp. -  
 max. avg. July temp.)  
 e = Drying shrinkage coefficient of PCC, in/in  
 KVALUE = Effective modulus of subgrade reaction on top of the  
 base, lbf/in<sup>2</sup>/in  
 DRAINS = 1 if edge subdrains exist, 0 if no edge subdrains  
 ESUPPORT = 1 if edge support exists, 0 if no edge support  
 SOILTYPE = 1 if A-1 to A-3, 0 if A-4 to A-7

---

### Faulting of *Undoweled* Concrete Pavements

$$\text{FAULTING} = \text{CUMESALS}^{0.2500} * [0.000038 + 0.01830 * (100 * \text{OPENING})^{0.5585} + 0.000619 * (100 * \text{DEFLAMI})^{1.7229} + 0.0400 * (\text{FI} / 1000)^{1.9840} + 0.00565 * \text{BTERM} - 0.00770 * \text{ESUPPORT} - 0.00263 * \text{SOILTYPE} - 0.00891 * \text{DRAINS}]$$

Where:

FAULTING = Mean transverse joint faulting, in

CUMESALS = Cumulative ESAL's, millions

OPENING = Average transverse joint opening, in

$$= \text{CON} * \text{JTSPACE} * 12 * (\text{ALPHA} * \text{TRANGE} / 2 + e)$$

CON = Adjustment factor due to base/slab frictional restraint

= 0.65 if stabilized base

= 0.80 if aggregate base or lean concrete base with bond breaker

JTSPACE = Average transverse joint spacing, ft

ALPHA = Thermal coefficient of contraction of PCC, set to 0.000006 / °F

TRANGE = Annual temperature range, °F (min. avg. January temp. - max. avg. July temp.)

e = Drying shrinkage coefficient of PCC, in/in

DEFLAMI = Ioannides' corner deflection, in

$$= P * (1.2 - 0.88 * 1.4142 * a / l) / (\text{KVALUE} * l^2)$$

l = Radius of relative stiffness

$$= [E_c * \text{THICKNESS}^3 / (12 * (1-u^2) * \text{KVALUE})]^{0.25}$$

E<sub>c</sub> = Concrete modulus of elasticity, lbf/in<sup>2</sup>

$$= 14.4 * 150^{1.5} * \text{MR}_{28}^{0.77}$$

P = Applied wheel load, lb

a = Radius of the applied load, set to 5.64 in (143 mm),

assuming tire pressure = 90 lbf/in<sup>2</sup> (0.62 MPa)

- KVALUE** = Effective modulus of subgrade reaction on top of the base, lbf/in<sup>2</sup>/in
- THICKNESS** = Slab thickness, in
- u** = Poisson's Ratio, set to 0.15
- MR<sub>28</sub>** = Concrete modulus of rupture at 28 days, lbf/in<sup>2</sup>
- BTERM** = Base type factor;  
=  $CUMESALS^{0.2076} * (0.4546 + 0.5115 * GB + 0.07279 * CTB + 0.03183 * ATB - 0.03714 * OGB - 0.06441 * LCB)$
- GB** = Dummy variable for dense-graded aggregate base, 1 if aggregate base, 0 otherwise
- CTB** = Dummy variable for dense-graded, cement-treated base, 1 if cement-treated base, 0 otherwise
- ATB** = Dummy variable for dense-graded, asphalt-treated base, 1 if asphalt-treated base, 0 otherwise
- OGB** = Dummy variable for open-graded aggregate base or open-graded asphalt-treated base, 1 if open-graded base, 0 otherwise
- LCB** = Dummy variable for lean-concrete base, 1 if lean-concrete base, 0 otherwise
- FI** = Freezing index, Fahrenheit Degree-Days
- DRAINS** = 1 if edge subdrains exist, 0 if no edge subdrains
- ESUPPORT** = 1 if edge support exists, 0 if no edge support
- SOILTYPE** = 1 if A-1 to A-3, 0 if A-4 to A-7

---

## Transverse Cracking

Two separate transverse cracking models were used: one for Jointed Plain Concrete Pavements (JPCP) and one for Jointed Reinforced Concrete Pavements (JRCP). The two are described separately.

---

### Cracking in Jointed Plain Concrete Pavements (JPCP)

$$\text{CRACKING} = \text{CUMESALS}^{2.755} * [3092.4 * (1 - \text{SOILTYPE}) * \text{RATIO}^{10.0}] + \text{CUMESALS}^{0.5} * (1.233 * \text{TRANGE}^{2.0} * \text{RATIO}^{2.868}) + \text{CUMESALS}^{2.416} * (0.2296 * \text{FI}^{1.53} * \text{RATIO}^{7.31})$$

Where:

CRACKING = Cumulative length of cracking of medium and high severities, ft/mile

CUMESALS = Cumulative ESAL's, millions

SOILTYPE = 1 if A-1 to A-3, 0 if A-4 to A-7

RATIO = Westergaard's edge stress / PCC modulus of rupture

TRANGE = Annual temperature range, °F

FI = Mean Freezing Index, Fahrenheit degree-days

STRESS = Westergaard's edge stress  
 $= (0.572 * 9000 / \text{THICKNESS}^{2.0}) * [4 * \text{LOG}_{10}(\text{L}/\text{B}) + 0.359]$

L =  $[(4,200,000 * \text{THICKNESS}^{3.0}) / (12 * (1 - 0.2^{2.0}) * \text{KVALUE})]^{0.25}$

B =  $[1.6 * (6.4)^2 + \text{THICKNESS}^2]^{0.5} - 0.675 * \text{THICKNESS}$

THICKNESS = Slab thickness, in

KVALUE = Effective modulus of subgrade reaction, lbf/in<sup>2</sup>/in

4,200,000 = Assumed elastic modulus of PCC slab, lbf/in<sup>2</sup>

0.20 = Assumed Poisson's ratio of PCC slab

6.4 = Assumed wheel load radius, in

---

**Cracking in Jointed Reinforced Concrete Pavements (JRCP)**

$$\text{CRACKING} = \text{CUMESALS}^{0.897} * [7130.0 * \text{JTSPACE} / (\text{ASTEEL} * \text{THICKNESS}^{5.0})] + \text{CUMESALS}^{0.1} * (2.281 * \text{PUMPING}^{5.0}) + \text{CUMESALS}^{2.16} * [1.81 / (\text{BASETYPE} + 1)] + \text{AGE}^{1.3} * [0.0036 * (\text{FI} + 1)^{0.36}]$$

Where:

**CRACKING** = Cumulative length of cracking of medium and high severities, ft/mile

**CUMESALS** = Cumulative ESAL's, millions

**JTSPACE** = Average transverse joint spacing, ft

**ASTEEL** = Area of reinforcing steel in pavement, in<sup>2</sup>/ft

**THICKNESS** = Slab thickness, in

**PUMPING** = Pumping severity (from pumping model),  
0 = no pumping, 3 = high pumping

**BASETYPE** = Type of base under PCC slab, 0 if granular base, 1 if stabilized base (cement, asphalt, etc.)

**AGE** = Time since construction, years

**FI** = Mean Freezing Index, Fahrenheit degree-days

---

## Transverse Joint Spalling

The current spalling model consists of three phases: The first phase calculates the spalling resulting mainly from incompressibles in the joint. Phase two calculates an as-constructed to as-designed ratio that depends on the application of calcium chloride (salt), freeze-thaw cycles, as well as the difference between as-designed and as-constructed air content and compressive strength. Phase three uses the product of the results of phase one and ratio from phase two, and applies a linear correction to remove aberrations from the data. Each of these phases are described in detail in the following sections.

---

### Phase One of Joint Spalling (Cumulative Spalling)

The spalling resulting from incompressibles in the joint comes from the transverse spalling model offered in "Performance of Jointed Concrete Pavements," Volume III, Publication No. FHWA-RD-89-138, November 1990. This model outputs a yearly cumulative spalling value for number of medium-high joint spalls/mile. This number is based on pavement age, sealant type, freezing index, presence of D-cracking, and presence of reactive aggregate in the case of jointed reinforced concrete pavements (JRCP). Few, if any, of the pavements upon which these models are based showed spalling or scaling attributable to low air content. The two specific models are the following.

#### (1) Phase One Spalling in *Jointed Plain Concrete Pavements (JPCP)*

$$\text{SPALLING} = \text{AGE}^{2.178} * [0.0221 + 0.5494 * \text{DCRACK} - 0.0135 * \text{LIQUISEAL} - 0.0419 * \text{PREFSEAL} + 0.0000362 * \text{FI}]$$

Where:

SPALLING = Number of medium-high joint spalls/mile

AGE = Age since construction, years

DCRACK = 0 if no D-cracking exists, 1 if D-cracking exists

LIQUISEAL = 0 if no liquid seal in joints, 1 if liquid seal in joints

PREFSEAL = 0 if no preformed compression seal, 1 if seal exists

FI = Mean Freezing Index, Fahrenheit degree-days



## (2) Phase One Spalling in *Jointed Reinforced Concrete Pavements (JRCP)*

$$\text{SPALLING} = \text{AGE}^{4.1232} * [0.00024 + 0.0000269 * \text{DCRACK} + 0.000307 * \text{REACAGG} - 0.000033 * \text{LIQUISEAL} - 0.0003 * \text{PREFSEAL} + 0.00000014 * \text{FI}]$$

Where:

- SPALLING = Number of medium-high joint spalls/mile
- AGE = Age since construction, years
- DCRACK = 0 if no D-cracking exists, 1 if D-cracking exists
- LIQUISEAL = 0 if no liquid seal in joints, 1 if liquid seal in joints
- PREFSEAL = 0 if no preformed compression seal, 1 if seal exists
- FI = Mean Freezing Index, Fahrenheit degree-days
- REACAGG = 0 if no reactive aggregate exists, 1 if reactive aggregate exists

The results of the phase one models do not change between the as-constructed and as-designed pavements, because the inputs are design-related only. Phase two will account for the differences between the as-constructed and as-designed pavements.

---

### Phase Two of Joint Spalling (AC/AD Ratio)

Phase two calculates an as-constructed to as-designed ratio that is dependent on the application of calcium chloride (salt), freeze-thaw cycles, and the difference between as-designed and as-constructed air content and compressive strength. This ratio is based on an equation, described below, coming from the extensive laboratory study performed under this contract and described in volume I, chapter 4.

#### Equation (19)

Three equations were offered in the laboratory study described in volume I, chapter 4. Equation (21) was chosen for use. This equation is as follows.

$$\% \text{SPALL} = 22.6 + 75.1 * \text{SALT} * \text{Log}(N) - 78.0 * \text{SALT} - 11.7 * \text{AIR} * \text{SALT} - 0.00478 * \text{FC}$$

Where:

- %SPALL** = Number of medium-high joint spalls/mile  
**SALT** = Age since construction, years  
**N** = 0 if no D-cracking exists, 1 if D-cracking exists  
**AIR** = 0 if no liquid seal in joints, 1 if liquid seal in joints  
**FC** = 0 if no preformed compression seal, 1 if seal exists

The output of equation (21) is an estimate of the amount of the joint length that will spall (as a percentage). Because of this, the values coming from this equation are subjected to a lower limit of 0 and an upper limit of 100.

The ratio uses equation (21) in the following manner.

---

$$\text{AC-AD ratio} = (\text{AC \%SPALL}) / (\text{AD \%SPALL})$$

---

**AC %SPALL** = Equation (21) value (%) using as-constructed values

**AD %SPALL** = Equation (21) value (%) using as-designed values

Limits were also selected for this ratio for practical reasons. The lower limit was selected to be 1.0. This choice is based on the assumption that pavement performance does not benefit when the as-constructed air content becomes greater than that of the as-designed air content. The upper limit, after experimentation, was chosen to be 3.0. Some additional explanation is needed to support this choice.

The need for an upper limit can be better explained by looking at the behavior of the ratio and its causes. Without subjecting the ratio to an upper limit, the behavior tends to be zero until a very large jump occurs. The following figure is an example showing the general behavior of the ratio for typical values. Note, the ratios used for the figure were subjected to an upper limit of 50 (reasonably large) in order to better observe the differences of the data.

AC-AD Ratio vs. Age (ratio is subjected to an upper limit of 50)

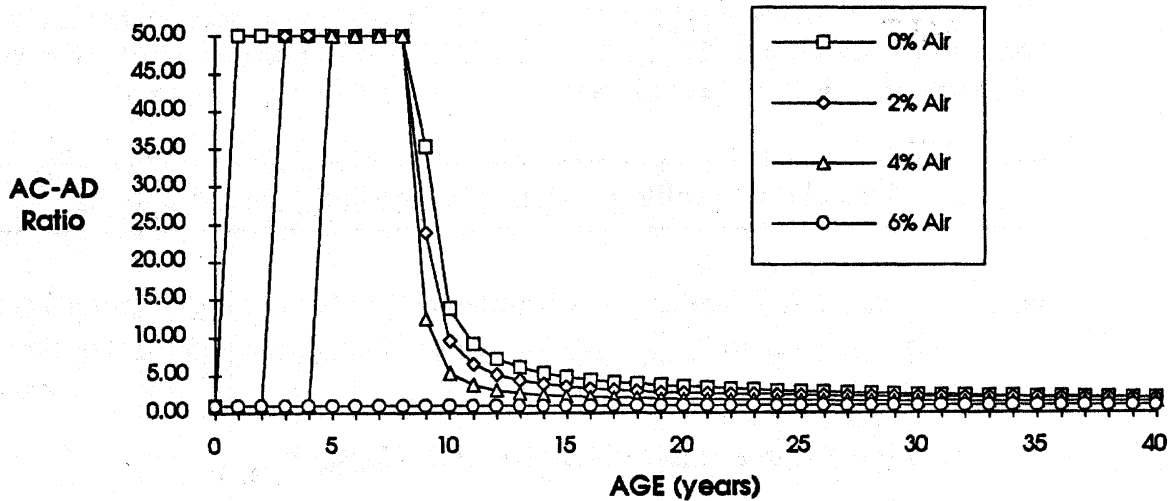


Figure 18. Typical behavior of the AC-AD ratio for an as-designed air content of 6 percent.

Figure 18 shows another behavioral trait of the ratio, which is its decrease and approach of the lower limit of 1.0 as cumulative freeze-thaw cycles increase.

This large jump can be explained by looking more closely at the makeup of the ratio, and the comparative behavior of the numerator and denominator. First, both the numerator and denominator increase lognormally with freeze-thaw cycles. The numerator will, however, always increase sooner or at the same time as that of the denominator. This is because the as-constructed air content will only affect spalling if it is equal to, or less than that of the as-designed air content. Because of this, an as-constructed number is generally divided by a smaller as-designed number, therefore causing large initial jumps in the AC-AD ratio when the as-designed number is very close to zero. In order to make the algorithms of phase three valid over all reasonable ranges for the inputs, the upper limit of 3.0 was chosen based on a combination of experimental data and engineering judgment.

### Phase Three of Joint Spalling (Linear Correction)

Phase three can be explained in two parts: The first consists of multiplying the spalling values obtained in phase one by the AC-AD ratios from phase two. The second consists of removing the erroneous data resulting from the jumps in AC-AD ratio, described in phase 2. Each of these will be explained independently.

### (1) Multiplication of Phase One Results by AC-AD Ratio

The final form of the joint spalling model is based on the product of the phase one results for cumulative spalling and the AC-AD ratios from phase two. This equation is listed as follows:

---

$$\text{Cumulative Spalling} = \text{Phase One Spalling} * (\text{AC-AD ratio})$$

---

where: Cumulative Spalling = Cumulative number of spalled joints per mile  
Phase One Spalling = Cumulative spalling from FHWA-RD-89-138

### (2) Linear Correction of Jumps in AC-AD Ratio

This problem of large jumps in the AC-AD ratio was solved by assuming that the spalling values in the area of the jumps would be replaced by linear values. This line was assumed to pass through zero at year zero, and meets with the curve at a point where the slope of the line most matched that of the original curve. First, it is helpful if we state that values are calculated for all years of the analysis period (n years). Therefore, in order to find the point where the data becomes linear, the analysis starts by analyzing the spalling values of the last 2 years of the analysis period (n and n-1). If the y-intercept of a line passing through these two values is less than zero, the two spalling values are then valid and the algorithm would proceed to the next set of spalling values (n-1 and n-2). This procedure continues until the y-intercept associated with two values becomes greater than zero. At that point, a line is assumed to join the lessor (value at the least age) spalling value with the point of zero at time zero. The values of spalling for all years covered by the linear manipulation then fall on the line.

Together, these three phases make up the spalling model used in the current version of PaveSpec. It is recognized that many assumptions are being made to use such a ratio described in phase two; however, it is noted that the recommendations of this project include one calling for future research in this area. For this case, it was important to obtain a simple coefficient that provides a reasonable trend in joint spalling, based on quality characteristics that differ from as-designed to as-constructed. The previously described AC-AD ratio is offered as a first attempt at such a coefficient.

---

## Pumping

Two separate pumping models were used: one for Jointed Plain Concrete Pavements (JPCP) and one for Jointed Reinforced Concrete Pavements (JRCP). Pumping feeds into the transverse cracking model. Each of the two models are described separately.

---

### Pumping in *Jointed Plain Concrete Pavements (JPCP)*

$$\begin{aligned} \text{PUMPING} = & \text{CUMESALS}^{0.443} * [-1.479 + 0.255 * (1 - \text{SOILTYPE}) \\ & + 0.0605 * \text{SUMPRECIP}^{0.5} + 52.65 / \text{THICKNESS}^{1.747} \\ & + 0.0002269 * \text{FI}^{1.205}] \end{aligned}$$

Where:

PUMPING = Pumping severity (from pumping model),  
0 = no pumping, 3 = high pumping

CUMESALS = Cumulative ESAL's, millions

SOILTYPE = 1 if A-1 to A-3, 0 if A-4 to A-7

SUMPRECIP = Average annual precipitation, cm

THICKNESS = Slab thickness, in

FI = Mean Freezing Index, Fahrenheit degree-days

---

### Pumping in *Jointed Reinforced Concrete Pavements (JRCP)*

$$\begin{aligned} \text{PUMPING} = & \text{CUMESALS}^{0.670} * [-22.82 + (26102.2 / \text{THICKNESS}^{5.0}) - \\ & 0.129 * \text{DRAINS} - 0.118 * \text{SOILTYPE} + 13.224 * \\ & \text{SUMPRECIP}^{0.0395} + 6.834 * (\text{FI} + 1)^{0.00805}] \end{aligned}$$

Where:

PUMPING = Pumping severity (from pumping model),  
0 = no pumping, 3 = high pumping

CUMESALS = Cumulative ESAL's, millions

SOILTYPE = 1 if A-1 to A-3, 0 if A-4 to A-7

SUMPRECIP = Average annual precipitation, cm

**THICKNESS** = Slab thickness, in

**FI** = Mean Freezing Index, Fahrenheit degree-days

**DRAINS** = 1 if edge subdrains exist, 0 if no edge subdrains

---

## Present Serviceability Rating (PSR)

Two separate spalling models were used: one for Jointed Plain Concrete Pavements (JPCP) and one for Jointed Reinforced Concrete Pavements (JRCP). PSR is needed for the determination of time of overlay. Each of the two models are described separately.

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### PSR of *Jointed Plain Concrete Pavements (JPCP)*

$$\begin{aligned} \text{PSR} &= \text{INTPSR} - 0.0182 * \text{TOTFAULT} \\ &\quad - 0.00313 * \text{SPALLSPM} \\ &\quad - 0.00162 * \text{CRACKSPM} \\ &\quad - 0.00317 * \text{FDRPM} \end{aligned}$$

Where:

PSR = Mean panel rating of pavement  
(0 to 5 AASHTO scale)

TOTFAULT = Cumulative transverse joint faulting, in/mile  
= FAULTING (in/joint) \* Number of Joints per mile

SPALLSPM = Number of spalled joints per mile to be fixed  
= (Cumulative spalled joints per mile to date) -  
(Cumulative spalled joints per mile fixed to date)

CRACKSPM = Number of transverse cracks per mile to be fixed  
= (Cumulative number of cracks per mile to date) -  
(Cumulative number of cracks per mile fixed to date)

FDRPM = Total number of full depth repairs per mile  
= [(Total Number of Slabs Replaced) + (Total Number of Joints Patched)] / Project Length (mi)

INTPSR = Initial PSR value, either a user input or determined by the following initial roughness equation:

$$\text{INTPSR} = 0.0714 * \text{Initial Roughness (in/mi)}$$

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### PSR of Jointed Reinforced Concrete Pavements (JRCP)

$$\begin{aligned} \text{PSR} &= \text{INTPSR} - 0.0539 * \text{TOTFAULT} \\ &\quad - 0.00372 * \text{SPALLSPM} \\ &\quad - 0.00425 * \text{CRACKSPM} \\ &\quad - 0.000531 * \text{FDRPM} \end{aligned}$$

Where:

PSR = Mean panel rating of pavement  
(0 to 5 AASHTO scale).

TOTFAULT = Cumulative transverse joint faulting, in/mile  
= FAULTING (in/joint) \* Number of Joints per  
mile

SPALLSPM = Number of spalled joints per mile to be fixed  
= (Cumulative spalled joints per mile to date) -  
(Cumulative spalled joints per mile fixed to date)

CRACKSPM = Number of transverse cracks per mile to be fixed  
= (Cumulative number of cracks per mile to date) -  
(Cumulative number of cracks per mile fixed to date)

FDRPM = Total number of full depth repairs per mile  
= [(Total Number of Slabs Replaced) + (Total Number of  
Joints Patched)] / Project Length (mi)

INTPSR = Initial PSR value, either a user input or determined by the  
following initial roughness equation:

$$\text{INTPSR} = 0.0714 * \text{Initial Roughness (in/mi)}$$



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## Cost Models and Procedures

The following is the procedure used to calculate life-cycle costs (without user costs) in PaveSpec.

1. Calculate Distresses and PSR at each year from the previously listed models.

---

### Rehabilitation Before an Overlay

#### Replacement of Cracked Slabs

2. Determine the amount of cumulative transverse cracking present at each year from the distress model (ft/mile).
3. Convert cracking to cumulative cracking for the entire project (ft),  
= Cumulative cracking (ft/mile) \* Project length (mile).
4. Determine the current year's cracking,  
= Cumulative cracking (ft) - Cumulative cracking fixed to date (ft).
5. Convert the cumulative cracking still needed to be fixed into cracked slabs needed to be replaced for the current year. This is accomplished by dividing the cumulative cracking by 18 ft (5.5 m) of cracking per cracked slab, which represents an average amount of linear cracking per slab.
6. Add the current year's slabs replaced to the cumulative slabs replaced to date and increment the full depth repairs by the same number.
7. The cost to replace a cracked slab is calculated by the following:  
= Cost of replacing a slab (\$/sy) \* Area of a slab (sy).

#### Replacement of Spalled Joints

8. Determine the number of Cumulative Spalled Joints per mile, at each year, from the distress model.
9. Convert cumulative spalled joints per mile to the total number of spalled joints for the entire project,  
= Cumulative Spalled Joints per mile \* Project length (miles).
10. Determine the current year's spalled joints (# joints),  
= Cumulative Spalled Joints - Fixed Cumulative Spalled Joints.
11. Add current year's spalled joints repaired to the Fixed Cumulative Spalled Joints and increment the full depth repairs by the same number.
12. The cost of patching a spalled joint is calculated by the following:  
= Cost of Patching a joint (\$/sy) \* Lane width (ft) \* Chosen width of patch (ft) \* (1 yd<sup>2</sup>/9 ft<sup>2</sup>).

13. The current year's replaced slabs and patched joints are then used to update the PSR (dependent on full depth repairs) at the end of the year. This PSR value is the value that is compared to the PSR trigger value (if selected as a trigger) to determine if an overlay is required. (See *Constants Menu: Rehabilitation - Overlay Triggers* on p. 78.)

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### Rehabilitation After an Overlay

14. Rehabilitation is applied by assuming that a certain percentage of joints (user input, After Overlay Joint Percentage, see *Constants Menu: Rehabilitation* on p. 77) will need to be replaced during the life of an overlay. This overlay life is a user input as well. The total cost of repairing this percentage of joints is divided equally among the years of the overlay life. The following equation calculates this total cost.

$$\text{AFTER OVERLAY REHABILITATION COST} = (\text{After Overlay Joint Percentage}) * [\text{Project length (mi)} * 5280 \text{ (ft/mile)} / \text{JTSPACE (ft)}] * [\text{Joint Patch Width (ft)} * \text{Total Width (ft)} / 9] * \text{Cost of Patching a Joint (\$/sy)}.$$

$$\text{Total Width} = \text{Number of Lanes} * \text{Lane Width (ft)} + \text{Total Width of Shoulders (ft)}.$$

---

### Total Project Rehabilitation Costs

15. Rehabilitation costs for the entire project are calculated as follows. The costs to replace slabs (calculated above) are for one outer lane only. Therefore, to get an idea of total project costs, the following assumptions were made: The user has an input to specify the Percent of Inner Lanes Cracking (see *Constants Menu: Rehabilitation* on p. 77). This estimates the amount of cracking in EACH inner lane based on one percentage. From this, a TOTAL PROJECT CRACKING COST becomes:

$$= \text{Outer Lane Cracking Cost} * 2 + [\text{Percent Inner Lane Cracking (\%)} * \text{Outer Lane Cracking Cost}] * (\text{Total Number Of Lanes} - 2).$$

For Joint Full Depth Repair, the cost calculated above is valid for each lane, therefore, the TOTAL PROJECT JOINT FULL DEPTH REPAIR COST becomes:

$$= \text{One Lane Joint Repair Cost (\$/sy)} * \text{Number of Lanes}.$$

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### Cost of Overlay

16. Overlays are first placed based on the current year's distress and PSR values and the user identified trigger values. Note: These trigger values are dependent on the particular rehabilitation policy selected for the session (see *Constants Menu: Rehabilitation - Overlay Triggers* on p. 78.) After an overlay is placed, the PSR value is reset to a user-inputed value. The decrease in PSR after an overlay is considered to be linear from the reinitialized value to the trigger value, over the overlay life (also a user input). The cost of an overlay is determined by the total project square yardage (including the shoulders) times the cost of an overlay (\$/sy).

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### Total Project Yearly Costs

17. The total project yearly costs are calculated by summing the current year's maintenance costs and overlay costs.

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### Present Worth of Yearly Costs

18. Present worth values of the yearly total costs are used for the life-cycle cost calculations. These values are calculated at each year by the following equation:

$$= \text{YearlyCost (\$)} * [1 + (\text{Discount Rate (\%)} - \text{Inflation Rate (\%)} / 100)] \\ (\text{Current Age}).$$

---

### Total Life-Cycle Costs

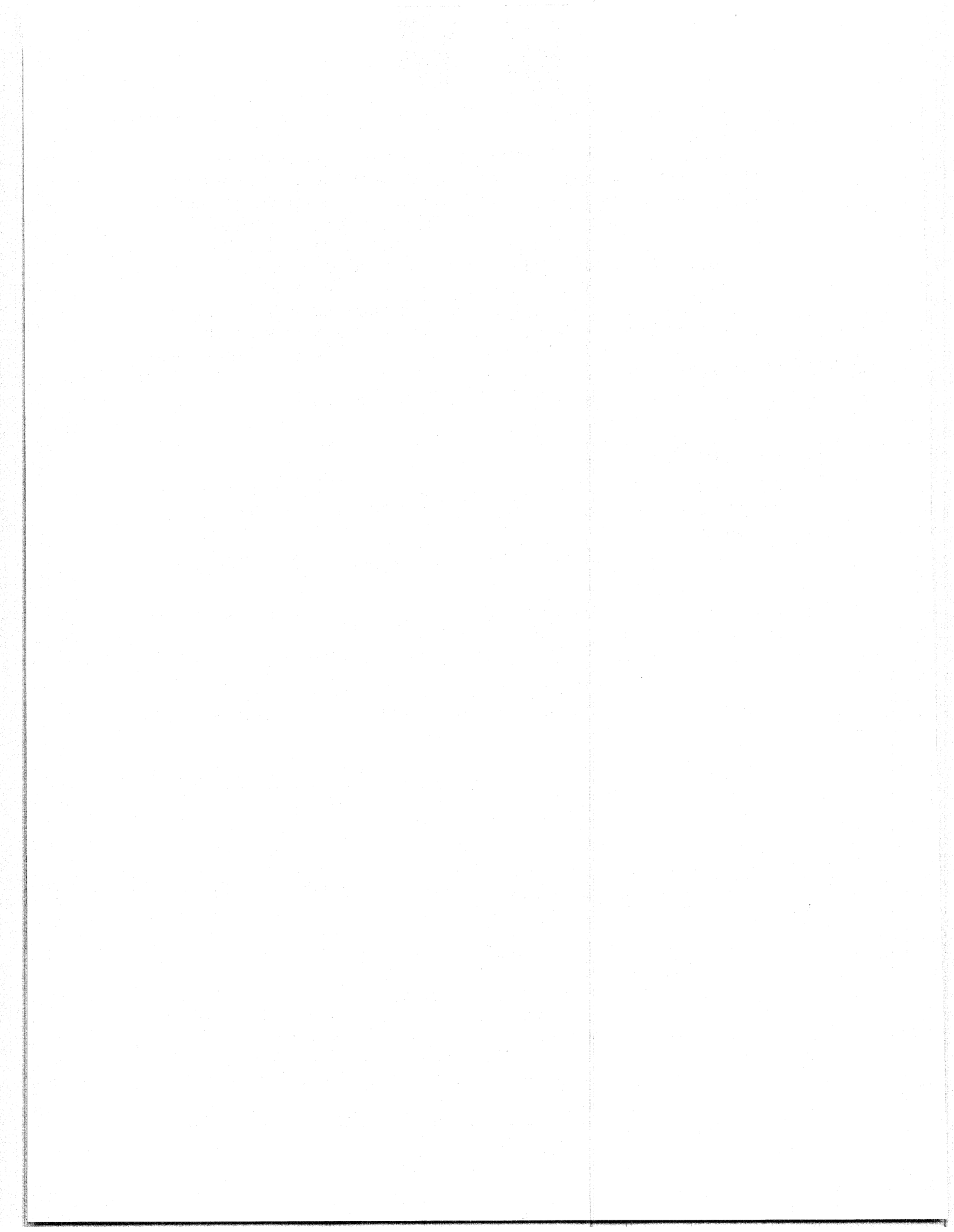
19. Total life-cycle costs result from the sum of the PRESENT WORTH YEARLY COSTS and the BID PRICE.

Where the bid price is calculated in (\$/sy) by the following equation:

$$\text{BIDPRICE} = \text{Cost of Construction (\$/sy)} * \text{Number of Lanes} * \text{Lane width (ft)} * 5280 \text{ (ft/mile)} * \text{Project Length (miles)} * (1 \text{ yd}^2/9 \text{ ft}^2).$$

### Conversion Table:

$$\begin{aligned} 1,000 \text{ lbf/in}^2 &= 6.9 \text{ MPa} \\ 1 \text{ in} &= 25.4 \text{ mm} \\ 1 \text{ ft} &= 0.3048 \text{ m} \\ 1 \text{ mi} &= 1.61 \text{ km} \\ 1 \text{ in/mi} &= 0.01578 \text{ m/km} \\ 1 \text{ yd}^3 &= 0.765 \text{ m}^3 \\ 1 \text{ yd}^2 &= 0.836 \text{ m}^2 \end{aligned}$$



## APPENDIX C—ANNOTATED BIBLIOGRAPHY

Afferton, K. C., "Implementing Statistically Based Specifications," *Transportation Research Circular*, Number 172, Transportation Research Board, October 1975, pp. 1-19.

This report describes a statistically based, end-result specification that the New Jersey Department of Transportation has developed for the thickness of bituminous concrete pavement. This specification requires decisions on acceptability to be made for each bituminous paving item (surface, binder, and stabilized base) separately and on a lot-by-lot basis. A lot is established as approximately 15,000 yd<sup>2</sup> (12,542 m<sup>2</sup>) of paving item. An acceptable lot is one having a quality level of thickness equal to or better than that obtained on past projects. The methods used to determine lot acceptability are patterned after the variability-unknown procedures of Military Standard 414. A reduced payment schedule for unacceptable lots was included in the specification as a practical means of dealing with slight thickness deficiencies. In developing the schedule, consideration was given to the loss in pavement serviceability that a thickness deficiency could potentially cause. An analysis was made of the first 16 projects completed under statistically based specifications. A total of 269 lots containing 836,000 tons (760,000 metric tons) of bituminous paving materials were involved. The specification performed quite well, matching closely the performance predicted by the specification's theoretical operating characteristic curve. However, because of concern expressed by field personnel, a revision that permits crediting of thickness excesses from one paving item to another was considered.

Afferton, K. C., J. Friedenrich, and R. M. Weed, "Managing Quality: Time for a National Policy," *Transportation Research Record* 1340, Transportation Research Board, 1992, 36 pp.

One of the Nation's most valuable assets is the highway system; our economic well-being depends strongly on the condition of our roads and bridges. Any means by which the system can be more effectively constructed and maintained warrants thoughtful consideration. Statistical quality assurance—currently in use or under development in approximately three quarters of the States—has proven to be a very effective tool to encourage high quality construction. However, although statistical specification writing must now be recognized as a thoroughly scientific activity, there is great disparity in the applications from State to State and many current practices and published standards are far from optimal. Part I of this paper, "Facing the Problem," stresses the need for a general upgrading of quality assurance practices and suggests that the time is overdue for the establishment of a more uniform and thorough approach to a discipline upon which so much depends. Part II, "Obstacles to Overcome," describes a variety of technical, managerial, political, and cultural obstacles that must be overcome if the transformation is to be made. Part III, "Fundamental Concepts," outlines how this might be accomplished by setting forth a

series of fundamental principles that have been demonstrated by successful application to be both practical and effective. Finally, Part IV, "Plan of Action," presents a plan of action that should significantly increase the effectiveness of transportation quality assurance practices nationwide.

**Anderson, D. A. and D. R. Luhr, *Framework for Development of Performance-Related Specifications for Hot-Mix Asphaltic Concrete*, NCHRP Report No. 332, Transportation Research Board, 1990, 118 pp.**

The initial work described in this paper was focused on the development of a conceptual framework for developing performance-related specifications that can be applied to highway materials and pavement construction. The framework that was developed is general in nature so that it can be applied to highway materials in general. However, hot-mix asphalt pavement was used in the examples and demonstrations. A number of alternative strategies for demonstrating the conceptual framework were identified, and a preferred strategy was selected for implementation. A report detailing the conceptual framework and including a research plan for the remainder of the project was prepared. Sensitivity analyses were conducted of various models that relate material and construction variables to fundamental mixture response, and fundamental mixture response variables to fundamental pavement response, in order to demonstrate techniques that can be used by other researchers to evaluate the sensitivities of various models (algorithms) that could be incorporated into the specifications framework. A laboratory study was conducted to demonstrate the technique that should be used to develop models that relate nonconformance of mixture and construction variables to variations in fundamental mixture response variables. For this purpose, a two-level partial factorial study was conducted. The study variables were asphalt and aggregate type, air voids, asphalt content, and percent passing the no. 200 sieve. An experimental plan for a field study was developed for the purpose of developing or verifying relationships between materials and construction variable nonconformance and pavement performance. A review of observational and experimental databases was also included. The utility of expert systems in the development of performance-related specifications was investigated; they were not used during the development of the framework. A framework for developing a statistically based, performance-related acceptance payment plan was developed. The plan consists of a formal procedure that can be used to evaluate the acceptability of a given lot of material and to allocate payment in proportion to the anticipated performance of the pavement. A paper demonstration of the conceptual framework was conducted. Several materials and construction variables were chosen and realistic data for these variables were assumed. A performance model was evoked and the annualized cost of the target and as-constructed pavement were computed. These results were used, in conjunction with the payment schedule, to determine the contractor's payment for a hypothetical project.

**Arena, Jr., P. J., "Actual Application of End Result Specifications and the Role of Commercial Testing Laboratories in Applying Them," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions, Volume 42, 1973, pp. 482-498.***

The objective of this report is to explain what an end-result specification may consist of, how it can be applied, and what role commercial testing laboratories can play in applying it. In April 1971, the Louisiana Department of Highways adopted an end-result specification on all asphalt concrete projects. This specification was a result of approximately 5 years of preliminary work and simulation on several projects before it was fully implemented. The control testing is the sole responsibility of the contractor; the acceptance testing is the responsibility of the Highway Department. In most cases, the contractors do not have the personnel to design an asphalt concrete mix, nor to do the daily control testing that is required of them. This is where commercial testing laboratories are most beneficial. The end-result, hot-mix specifications as employed here require that the asphaltic concrete technician who is responsible for the quality control and acceptance testing for both the State and the contractor be certified by the State Highway Department. The results of the actual application of the end-result specifications indicate that the contractor should receive at least 98 percent pay 95 percent of the time. Nearly 1.3 percent of the mixes evaluated resulted in the contractor receiving 80 percent of the contract unit price, while 5.5 percent resulted in the contractor receiving 95 percent of the contract unit price. There were no penalties at 50 percent, nor were there any removal and replacement of the pavement. Of the 724 lots, 64 resulted in penalties, 93.7 percent of which were due to deficiencies in roadway density; the remainder were due to deficiencies in Marshall stability.

**Armstrong, J. P., "Accelerated Strength Tests for Quality Control of Concrete Pavements," *Proceedings: Fourth International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, April 18-20, 1989, pp. 519-530.***

This paper presents the results of a laboratory-based effort to evaluate potential methods of obtaining flexural strength for pavement quality control within 24 hours by accelerated test methods. The current Corps of Engineers pavement design procedure is based on and specify 28- and 90-day flexural strengths for roads and airfields, respectively. Quality control of pavement strengths use correlated 7- and 14-day flexural strengths to identify strength problems as early as possible, but compliance with specifications still depends on the 28- and 90-day strengths. These lengthy test times are not adequate to identify pavement strength problems, particularly with today's rapid construction techniques. To determine the most effective 1-day measure of concrete quality, accelerated (24 hours in an elevated water bath) and 14-day flexural, splitting tensile, and compressive strengths were compared to 28- and 90-day flexural strengths. Three concrete mixtures were prepared by varying water-cement ratios to provide a wide strength range. Ten batches of each mixture were cast into beams and cylinders for testing. A total of 1,061 specimens were fabricated and tested. Based upon the coefficient of

determination ( $R^2$ ) for the regression equations, the warm water method provides reliability ( $R^2 = 0.894$  to  $0.945$ ) equal to, if not greater than, the 14-day tests ( $R^2 = 0.785$  to  $0.920$ ) in predicting 28- and 90-day flexural strengths.

**"Asphalt Cost Control Without Quality Loss," *Better Roads*, Volume 60, Number 2, February 1990, pp. 36-38.**

This article covers the latest developments in pavement management, performance-related specifications, recyclability, and modifiers in terms of how they affect asphalt cost control. It notes that the FHWA 1993 requirement for in-place pavement management systems for government-funded road agencies is motivating long-term thinking. It is anticipated that the low-bid system, which can also mean low quality construction with an associated higher cost in subsequent rehabilitation, will no longer work. Common use of performance-based specifications is predicted in the future.

**Barros, R., R. M. Weed, and J. Willenbrock, "Software Package for Design and Analysis of Acceptance Procedures Based on Percent Defective," *Transportation Research Record* 924, 1983, pp. 85-93.**

The trend toward statistical end-result specifications has led to the development of construction specifications based on the concept of percent defective. To analyze the risks and determine the effectiveness of the acceptance procedures associated with these specifications, operating characteristic curves must be constructed. Although most of the necessary theory is available in one form or another, many potential users do not have a working knowledge of the noncentral  $t$  and  $beta$  distributions necessary for this development. The underlying theory, several useful references, and a computer program that greatly simplifies the design and analysis of the type of statistical acceptance procedure normally used with end-result specifications is presented. The computer program presented in this paper should allow the procedure to be utilized by individuals who have only a basic theoretical background. The resulting effects should include the simplification of the work of agencies planning to develop additional statistical specifications, and the ability to more formally check existing specifications whose risk levels may be far from optimal. This added convenience may serve to overcome the reluctance of the few agencies who have yet to realize the advantages of statistical quality assurance.

**Bock, B. T. and P. A. Okamoto, "Evaluation of Dowel Placement Using a Dowel Bar Inserter," *Proceedings: Fourth International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, April 1989, pp. 641-649.**

This paper presents the results of several field investigations to evaluate the effectiveness of automatic dowel bar inserter equipment to properly place dowel bars in rigid pavements. The results of three studies using the ground penetrating radar



technique to measure dowel bar misalignment are summarized. A commercially available radar system capable of locating steel embedded in concrete was used. Overall, the dowel bar inserter performed well compared to the basket assembly construction. Dowel depth, misalignment (vertical and horizontal), and longitudinal displacement were generally comparable.

**Bryden, J. E., "Development of a Specification to Control Rigid Pavement Roughness," *Transportation Research Record* 535, Transportation Research Board, 1975, pp. 1-13.**

This paper describes the development of a specification for surface tolerances for new pavements. It was found that the 25-ft (7.6-m) California profilograph provides more detailed information than the 10-ft (3-m) straightedge specified at the time of the paper and correlated highly with the roadmeter. It can therefore be used to control pavement roughness during construction to ensure user satisfaction. Specifications were developed relating payment received by the contractor to the riding quality produced; a reduced payment schedule based on the cost of overlaying rougher pavement at an earlier age was selected as the most effective means of enforcing the quality levels specified. The author reports that these new specifications can be met using current procedures and equipment.

**Chipperfield, E., and T. Welch, "Studies on the Relationships Between the Properties of Road Bitumens and Their Service Performance," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 36, 1967, pp. 421-488.**

The subject of this paper is two large-scale road trials that have been laid in Europe to study the behavior of eight bitumens in asphalt concrete wearing courses subjected to medium to heavy traffic in areas with hot/dry and cold/wet climates. In addition to the differences between the bitumens, a number of other factors were included in the experiments to allow for the variations in grading, binder content, and the adhesion characteristics of the aggregates typical of those likely to occur in the design and construction of asphaltic concrete surfacings. In each road trial, two types of mix design, two types of aggregate, and three binder contents for each type of mix were investigated. *In situ* measurements included deformation, air voids, and skid-resistance. Conventional laboratory measurements included changes in viscosity and chemical composition. In an attempt to link some of the experiences in the U.S. to the present field and laboratory studies, assessments were made on trial bitumens. Fundamental laboratory measurements included rheological measurements at short loading times and at long loading times. The paper describes the design and construction of the two road trials and gives a progress report on the field performance of the test sections. Also included is a report on the laboratory data and research studies directly associated with the changes observed so far in the bitumens. Four years after the laying of the road trials, results included the following:

- Slight deformation has been observed, but no correlation with bitumen properties has yet become evident.
- Skid resistance is predominantly controlled by aggregate type.
- Much of the hardening normally attributed to the first few months in service really occurs during the laying/compaction operation.
- Bitumens recovered from the coarse-graded mixtures have not shown significantly more hardening than have the corresponding bitumens recovered from the dense-graded mixes.

Darter, M., W. Hudson, and J. Brown, "Statistical Variations of Flexible Pavement Properties and Their Consideration in Design," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 42, 1973, pp. 589-615.

It is the purpose of this paper to illustrate the existing variations of flexible pavement properties and show how they may be considered in design. The probabilistic or stochastic design theory that has been developed makes it possible to design for a specific level of reliability. The Texas flexible pavement system is used as an example throughout the paper to illustrate the concepts. The statistical variations and uncertainties of important pavement parameters associated with flexible pavements are first examined. Then, the theory and concepts are developed to make it possible to consider the variabilities of the design parameters and design models. Finally, the method is illustrated by a design example.

Dellert, R., "Application of End-Result Specifications to the Production and Laydown of Bituminous Mixtures," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 41, 1972, pp. 21-48.

This paper documents a bituminous concrete end-result specification based on statistical concepts that was undertaken to demonstrate that the major items in the specification are workable, that it is possible to control the production and lay-down to obtain a positive adjustment in bid price, and to improve the specification. The three items selected for testing and to adjust the unit price are gradation and asphalt content, thickness, and density. The smoothness of the pavement was also measured and quantities deducted for bumps. The plant control was the responsibility of the two contractors who hired the same consultant to perform this service. The successful completion of the contract, with the first contractor receiving payment of 103 percent for good control and the second contractor receiving payment of 93.5 percent, indicates that the major items in the end-result specification are reasonable and workable. It was determined that minor modifications in the gradation acceptance on the large-size aggregate are indicated, and that the thickness limits should be evaluated dependent on the condition of the base and number of lifts to be placed.

**Di Cocco, J., *Quality Assurance for Portland Cement Concrete, Final Report, Report No. FHWA-RD-73-77, Federal Highway Administration, September 1973, 157 pp.***

The work reported here results from the recognition that although quality assurance had been successfully used in most industries, the construction industry and State agencies were only then beginning to recognize its importance. This paper attempts to show how the elements of quality assurance can be applied to concrete. Concrete uniformity and compliance with specifications requirements, under the current degree of process control and inspection, are reviewed, and are found to be poor. The paper discusses techniques that producers should use to achieve compliance with concrete requirements, including three case studies to show that process control does lead to compliance. It is also stressed that process control is the responsibility of the producers, but recognizing that inspecting agencies (having done most of the testing in the past) may have more pertinent information than producers, guidelines are suggested for producers to use until they accumulate data of their own. Current inspection schemes are reviewed, with particular attention to those used in New York. It is concluded that these schemes afford little protection to concrete buyers and alternative, statistically sound sampling plans are suggested for inspection of fresh and hardened concrete. The advantages and shortcomings of the suggested plans are discussed, along with the monetary value of such plans as applied to concrete. Finally, recognizing the trend toward the improper use of acceptance control charts for inspection of construction materials, these tools are reviewed and it is concluded that concrete acceptance control charts are inappropriate and should not be used in concrete inspection. Included in the appendixes is a section on air-content correlations in which results indicate that over the range of dosage of air-entraining agent (13.0 to 21.2 oz/yd<sup>3</sup> [0.50 to 0.82 L/m<sup>3</sup>]), correlation between air content and quantity of air-entraining agent could not be shown.

**Duthie, J., "Proposed Bitumen Specifications Derived from Fundamental Parameters," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions, Volume 41, 1972, pp. 70-117.***

This paper illustrates how bitumens of the same penetration or viscosity grading, but of different rheological characteristics, can behave differently in practice. To enable the engineer to assess bitumen behavior under different times of loading and temperatures, a method based on fundamental rheological principles is presented for determining the mechanical properties of bitumens. In an attempt to limit the differences in performance that can arise among bitumens of identical penetration or viscosity grading, this method is used to derive bitumen grading specifications, which are modifications to the AASHO viscosity-grading specifications. To allow the viscosity-grading system to be extended to meet paving requirements in the majority of countries, two new high viscosity grades are proposed.

**Elliott, R. P. and M. Herrin, "Relative Life Effects of Mix Composition and Density Variation," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 54, 1985, pp. 209-237.**

This paper presents the results of the laboratory and data analysis phase of a study conducted to develop a rational basis for asphalt construction quality assurance pay schedules. As a part of the study, a procedure was established for estimating the relative life effects of variations in asphalt concrete mix composition and density based on the load-associated failure modes of fatigue cracking and surface rutting. Laboratory data generated from the testing of typical Illinois surface and binder mixes were subsequently analyzed using the procedure. The relative life effects determined by the procedure are believed to be generally representative of the dense-graded asphalt concrete mixes used in Illinois and in much of the United States. However, the relative life effects for a specific mix in a specific application could differ significantly from those identified. On the basis of the analyses conducted during this study, several conclusions were made. Variations in asphalt content and density were shown to significantly affect the creep behavior and split tensile strength of asphalt concrete mixes. Reduced density and increased asphalt content significantly increase the rate of rut development, apparently independent of pavement design. The relative fatigue life of an asphalt surface is reduced by lower density and by deviations of the asphalt content from the job mix formula. The relative life effects based on rut development are of about the same magnitude as the effects based on fatigue. Finally, the gradation variations used in the study were not found to have a statistically significant effect on mix stiffness or split tensile strength. However, the average split tensile strengths of the coarse and fine gradation specimens were found to be about 10 percent lower than the average strengths of the job mix formula specimens.

**Elliott, R. P., "A Value Concept for Pavement Construction Pay Adjustment Schedules," *Transportation Research Record* 1040, Transportation Research Board, 1985, pp. 45-48.**

In this paper, a value concept is presented that can serve as a basis for developing rational payment schedules for pavement construction. Provisions are made for incorporating both the average and standard deviation of material test results into a pay determination scheme that is based on the relative pavement life effects. The concept is based on the recognition that at the time a pavement is considered to have failed, only a small percentage of the surface actually exhibits severe distress. As a result, the life of the pavement is controlled not by the average or fiftieth percentile of the material, but by a lower percentile representative of the actual surface distress. The concept is incomplete in that it considers, for example, a material property-life relationship that decreases in only one direction, and is based on estimated population parameters. Nevertheless, the concept has been practically applied to small samples and without defining the acceptable distribution.

**Elliott, R. P., *Value Concept for Developing Construction Pay Schedules with Application to Asphalt Paving*, Ph.D. Thesis, University of Illinois at Urbana-Champaign, 1984.**

The primary objective of this study was to develop and demonstrate a rational procedure for the establishment of pavement construction pay adjustment schedules. A rational procedure was defined as one that would provide a mechanism by which pay adjustments could be established that would reflect the impact of construction variability on the expected life of the pavement. The procedure was required to consider both the mean and the variability of any construction test parameter used for pay determination as determined from a small number of samples and was to include a method for incorporating relationships between the test parameters and the expected life of the pavement. The secondary objective of this study was to use the developed concept to establish payment schedules for asphalt pavement construction. The efforts taken to meet this objective involved identifying the pavement life effects of asphalt mix variability and determining an "acceptable level of variability." These were accomplished by analyzing over 2,300 field density and extraction tests from past construction projects to determine normal variability and evaluating laboratory test results in conjunction with theoretical pavement behavior models to establish load-associated material property-pavement life relationships. The pay schedules developed from these analyses take into account variations in asphalt content, gradation, and density. The schedules were developed based on a 15-70-15 percentile distribution of penalty, 100 percent (bid price), and bonus pay; but provisions were made that enables highway administrators to modify the schedules for other distributions. A methodology was also developed and used to convert the gradation portion of the schedules from a percent passing and retained basis to a percent passing basis. The practicality of the resulting schedules was subsequently evaluated using field test data from past quality assurance projects.

**Elliott, R. P. and M. Herrin, "Development of an Asphalt Construction Pay Schedule Based on the Value Concept," *Transportation Research Record* 1056, Transportation Research Board, 1986, pp. 10-20.**

This paper presents and demonstrates a pay adjustment approach applied to asphalt paving. It contrasts sharply with the pavement construction pay adjustment schedules in common use that have generally been based on a somewhat arbitrary selection of "acceptability limits," with the adjusted pay based on a concept of percentage of construction within these limits. Acceptability limits are selected to represent the capabilities of good contractors. To assure this, the limits are established through an analysis of actual construction test data. For this study, these data include more than 2,300 field density and 2,300 field extraction tests conducted on random samples from past construction projects. The pay adjustments for work outside the identified acceptability limits are then set on the basis of the anticipated relative effect of such deviations on pavement service life. This relative life effect was determined by a quasi-theoretical analysis of laboratory data in which the effects of variations in mixture composition and density were studied. The framework

around which the schedule is developed is called the value concept. This concept serves as a rational basis for the establishment of pavement construction pay schedules. As such, it provides a means for considering both the average and the variability (standard deviation or range) of construction test results and provides a mechanism for setting pay adjustments that reflect the impact of construction variability on expected pavement life. Application of the schedule to past quality assurance project data indicated that, on the average, contractors would receive slightly less pay with this schedule than they would have with the quality assurance pay schedule previously used in Illinois. To compensate for this and to provide added incentive for quality construction, it was recommended that bonus pay be increased from 105 to 110 percent of the contract bid price.

**Epps, J. and W. Kari, "Factors to be Considered in Developing Performance-Related Specifications," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 52, 1983, pp. 271-291.**

This paper classifies specifications into four types: proprietary product, method, end-result, and performance. The reasons that performance-based specifications are preferred and needed are shown. The influence of changes in construction, traffic, structural design, environmental factors, and material properties is discussed. The development of asphalt specifications is also reviewed. The major needs in paving research required to verify the performance-based specifications are reviewed, including development of recommended practice for field evaluation of performance, long range funding, and development of field test programs.

**Fowler, G. and W. Gulden, *Investigation of Location of Dowel Bars Placed By Mechanical Implantation*, Federal Highway Administration, FHWA/RD-82/153, May 1983, 32 pp.**

This report describes the results of work conducted to determine the location of dowel bars placed by mechanical implantation and in basket assemblies. A 1 percent stratified random sample of bars was selected for coring to determine depth, horizontal and vertical rotation, and vertical alignment. Measurements were also made with a metal detector on additional bars. The study found much better results with the basket assemblies in terms of alignment and rotation. It was noted that saw-cut location affected longitudinal alignment to a large extent on both basket and implanted dowels. It was noted that no pavement distress related to dowel bar misplacement had occurred after 3 years of traffic, even for those locations with dowel bars possessing extremely large vertical and horizontal rotation.

Fromm, H., "A Statistical Evaluation of Sampling Methods and Bituminous Concrete Compaction," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions, Volume 47, 1978, pp. 372-397.*

Two possible solutions to the difficulties encountered in the sampling of bituminous hot mix, the only method by which to judge its production process, are discussed in this paper. A major problem is that if a sample is to be representative of the process, then complete mixing must occur with no subsequent segregation. To determine if it was possible to sample the material at the hot plant, an experiment was designed to compare two methods of sampling the material from the pile in the truck box with the standard sampling method already in use—that of taking a sample from the road behind the paver. This paper describes the two experimental designs and test results, and evaluates the effect of sampling methods on the overall average value of the property being tested. In addition, the paper includes a review of an experiment that was conducted to determine the number of rolling passes necessary to obtain maximum compaction. The results of the bituminous hot mix sampling experiment indicate that the hot mix plants ran reasonably steady with few long-term variations and that the variations present were of a short-term nature from batch to batch due to operator error, mechanical error, or material fluctuations. The largest component of the apparent variation from sample to sample was due to sampling and testing error and the smaller component was due to plant and material variations. The plate sampling method (sample taken from the road behind the paver) was found to be least subject to variation and gave the most consistent results. In the compaction investigation, it was shown that the precision of the method of determining compaction is good, but local mix variations and segregation lead to wide variations that must be taken into account in determining whether or not a contract meets specifications.

Gonzalves, G. and J. Eisenberg, *Implications of Statistical Quality Control of Portland Cement Concrete, Report No. 8, HPP 1-12 (152), Arizona Department of Transportation, May 1975, 140 pp.*

The overall objective of the research described in this paper was to statistically determine the quality of reasonably good portland cement concrete pavement, as constructed by modern construction methods and a competent contractor. The study was made on the basis of a statistically designed experiment, from which parameters were obtained for various specification requirements of concrete, and historical data, consisting of measurements obtained without random sampling. This statistically designed experiment gives information with regard to variances due to material, sampling, and testing for aggregates and portland cement concrete pavement. For historical data, no analysis of variance was done. In addition, information with regard to skewness and kurtosis are of special interest for studies with regard to the nature of distributions. Statistical parameters were obtained for aggregates on the basis of percent passing and percent retained. Such analysis indicates the underlying causes of variance, and thus aids in better control of aggregate production and utilization. Another study was made of conformal index, which can be considered as

a measure of the capability of the construction process, and indicates the deviations from the approved job-mix formula, unlike the standard deviation which gives the measure of the deviations from the mean of a population. A study was also made on the variations of coarse aggregate used in the concrete and as obtained from the pavement. The basis of the analysis is the Wilcoxon matched-pairs signed-ranks test. Lastly, a comparison was made of normal project sampling and random sampling. The statistical parameters obtained by the two methods of sampling on the same project showed the variations possible by different methods of project control. Based on the results of data analyses, recommendations are given for future studies.

*Guide Specifications for Highway Construction, AASHTO, 1988, 283 pp.*

This set of specifications is complementary to AASHTO *Standard Specifications for Highway Bridges*. Together the two sets of specifications present widely used items of work in highway construction. The guide specifications provide the specification writer with information and topics to be covered and expounded on in a detailed project construction specification. The guide specifications is separated into divisions concerning general provisions, earthwork, base course, flexible pavements, rigid pavement, concrete pavement rehabilitation, and miscellaneous construction.

Harrison, R., C. Bertrand, and W. R. Hudson, "Measuring the Smoothness of Newly Constructed Concrete Pavement for Acceptance Specifications," *Proceedings: Fourth International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, Report No. FHWA-RD-89-208, April 1989, pp. 601-614.

The objective of this paper is to report the progress that the staff at the University of Texas at Austin, Center for Transportation Research (CTR), have made in developing standards, instrumentation, and routines that can be used by the Texas State Department of Highways and Public Transportation to develop smoothness acceptance specifications on newly constructed concrete pavements. The paper presents a brief historical background and reports the key results of an AASHTO survey conducted in 1984 to ascertain smoothness specifications being utilized at that time, and the resulting guide specification recommended by AASHTO and evaluated by CTR. A modification to the AASHTO guide specification is then discussed, and implications of the bonus and penalty categories are also discussed. A high resolution profiling device, the Dipstick, which can be used to quantify pavement surface data, has been tested with other roughness devices and the results are presented. Finally, a California-type Profilograph was employed on newly constructed reinforced concrete to test the proposed specification prior to its trial adoption. Problems with the Profilograph were identified that could make the proposed standards difficult to implement. CTR staff believe that a combination of Profilograph and Dipstick instruments, together with a modification to the categories within the Texas draft specification, would result in a more equitable and enforceable standard.



Haviland, J. E. and R. W. Rider, "Construction Control of Rigid Pavement Roughness," *Highway Research Record* 316, Highway Research Board, 1970, pp. 15-28.

Results of a 2-year study of cause-effect relationships involved in roughness of concrete pavements are reported in this paper. Data were derived both from analog traces obtained in each wheelpath within hours after concrete placement on randomly selected pavements, and from qualitative observations of paving methods. Sampled construction consisted of 184 sections of 1- and 2-lane pavement built under 62 different contracts with 8 different form-type finishing machines and 3 different slipform pavers. Statistical analysis was held to a minimum by uncontrolled interactions, but the following five factors were found to be common and outstandingly significant in relation to roughness throughout the contracts studied: backing up of the last finishing machine, absence of a float, use of fewer than three screeds, use of a crown section as compared to a uniformly sloping section, and lane-at-a-time paving. Nine other construction phenomena producing roughness, common to many projects but found less frequently than these five, are also covered in some detail.

Hudson, S. B. and G. W. Steele, "Developments in the Prediction of Potential Strength of Concrete from Results of Early Tests," *Transportation Research Record* 558, Transportation Research Board, 1975, pp. 1-12.

This paper presents findings of a continuation of previously published work to investigate the practicality of using early tests of concrete cylinders for the quality control of concrete. The scope of the study described includes concrete of four cement constants proportioned to simulate conditions where part of the cement was inadvertently omitted. Specimen cylinders, 1 to 3 days old, were tested. Results of tests at early ages based on sulfur mortar caps were compared with results based on Celotex pressure pads. The findings indicate that 1- to 3-day-old specimens can be tested without pretreatment or special conditioning to provide reliable estimates of minimum compressive strengths at 28 days. In addition, the findings indicate that these specimens can be prepared for tests by means of disposable pressure pads in lieu of the usual sulfur mortar caps and at a savings of time and equipment requirements. The data obtained made possible the simplification of the previously developed prediction equation and the development of two alternate prediction equations.

Hughes, C. S., "A Density Specification with Pay Factors," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 52, 1983, pp. 357-361.

In this paper an account is given of a 1976 density study, and the analysis of the resulting data. The study was motivated by a concern for the adequacy of the compaction being attained on the interstate that was nearing completion in the early

1970s, since no one method was being used consistently to check densities. The pre-1978 specification is analyzed to determine its severity, and a more realistic specification that contained pay factors based on performance criteria is developed. In developing the pay factors, the primary assumption was that they should be consistent with pavement life. The present worth concept was used for the price adjustments derived from the average values over the density interval considered. The specification was developed in an effort to improve pavement performance through increased densities. While no direct indications of improved performance had been noted at the time of the paper, the improved densities achieved through the specification are readily apparent. The improvement in density after implementation of the specification was steady and, contrary to earlier beliefs, it was achieved primarily through improved mix design as opposed to increased rolling.

**Hughes, C. S., "Methods of Compaction Control," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 36, 1967, pp. 309-324.**

The first portion of the paper consists of a tabulation and brief discussion of the results of a questionnaire concerning the compaction control procedures in current use by the various State highway departments. End-result specifications, which are used by approximately 80 percent of the highway departments in the country, require two procedures in order to determine compliance. One is a standard reference density procedure used to provide the basis for determining compaction compliance. The second is a field test procedure for measuring density. Information was gathered regarding the type of standard reference density procedure used as a basis for determining compaction compliance and how density or percent voids in the field are measured. The second portion of the paper describes a control strip technique using nuclear testing that Virginia uses to control the compaction of bituminous concrete. Finally, the effectiveness of the various methods of compaction control is compared.

**Hughes, C. S., *Performance-Related Specifications for Bituminous Concrete*, Final Report, Report No. FHWA-VA-85-11, Virginia Highway and Transportation Research Council, November 1984, 38 pp.**

This report discusses the philosophy and evolution of performance-related specifications. The properties of most importance in the construction of asphaltic concrete pavements, as well as the associated specifications, are listed and discussed, including durability, flexibility, fatigue resistance, stability, skid resistance, impermeability, workability, ride quality, and specified thickness. The direct and indirect measurements in material, design, and construction that are discussed include fatigue tests, indirect tension, Marshall stability, skid measurements, straight edge and roughometer tests, coring for thickness testing, aggregate type, quality and gradation, asphalt grade, asphalt temperature susceptibility, mix design, moisture content, temperature, uniformity, stripping tests, adhesion to underlying layers, placement temperature, and field density. The importance of specifications

established to control uniformity or to provide a standard basis for bidding is mentioned. Recommendations for making the Virginia Department of Highways and Transportation's specifications for bituminous concrete as performance-related as practical are presented.

**Hughes, C. S., "State of the Art: State Acceptance of Bituminous Concrete Production and Construction Using Quality Assurance Specifications," *Quality Assurance in Pavement Construction*, ASTM STP 709, American Society of Testing and Materials, December 1980, pp. 11-18.**

This paper reports on the state of the art, from the standpoint of State agencies, of the use of statistical quality assurance procedures for the acceptance of bituminous concrete production and construction. Information on the procedures being used by the 50 State highway agencies, as of the spring of 1978, was obtained through a questionnaire and is reported. The paper deals with two areas involving bituminous concrete: production, which primarily encompasses determining the asphalt content and gradation of the aggregate, and construction, which comprises the roughness, thickness, and density of the pavement. The responses to the questionnaires showed that 25 agencies, at that time, had a statistical quality assurance specification for accepting production, although three of these agencies stated that the program was still experimental. For construction, 25 States, coincidentally, also reported employing a statistical quality assurance program. Most of these had a specification dealing with density. The estimated annual dollar savings were reported to be from \$100,000 to \$1,000,000. For those agencies not using quality assurance specifications at the time of the questionnaire, the specifications of most interest were those for production and for the density and roughness of the pavement. Eleven agencies indicated that they were not then using nor were they contemplating the use of statistical quality assurance specifications.

**Hunter, J. S. and O. J. Pendleton, "On The Importance of Statistical Science in Transportation," *Transportation Research Record* 1340, Transportation Research Board, 1992, 2 pp.**

This paper explains the different roles of statistical science in the quest for obtaining quality in transportation. Sound statistical science must be combined with modern technology if the United States is to meet the transportation quality objectives. Success will require standardized measurements, the collection of information-laden data, resourceful data analysis, and the planning for new data. These quantitative arts must be combined with methods for problem-solving and decision-making under uncertainty. Statistical science thus joins the engineering sciences in the never-ending pursuit of transportation quality.

***Implementation of Quality Control — Quality Acceptance in Oklahoma, Oklahoma Department of Transportation, no date, 8 pp.***

This report briefly summarizes the steps taken in, and the results of, the Oklahoma Department of Transportation's implementation of quality control-quality acceptance. The basic elements of the specification included the provision that the contractor is responsible for quality control, while the Oklahoma Department of Transportation is responsible for quality assurance, and that pay adjustments are made for materials and workmanship outside of the specification. The characteristics for determination of acceptance and payment included asphalt cement content, gradation, air voids, Hveem stability, roadway density, and smoothness/rideability.

***Incentive/Disincentive Provisions, Final Report, NEEP Project 24, Federal Highway Administration, 1977, 20 pp.***

This report briefly describes the results of a project entitled, "The Use of Incentive and Disincentive Provisions Regarding Quality and Completion Time for Federal Highway Construction," whose objective was to evaluate the use of incentive and disincentive provisions in improving the quality of federal-aid highway construction projects or expediting their completion. Included are summaries of reports for the following States, where incentive/disincentive provisions have been utilized: New Hampshire, Maryland, Connecticut, Colorado, Maine, Kansas, Illinois, and New Mexico. It is concluded that the use of incentive/disincentive provisions is not intended for, nor effective on, all types of projects. They are mainly intended for reconstruction projects. These provisions have proven to be effective in reducing completion time. The States have found that the increase in costs due to the use of incentive/disincentive provisions has been more than offset by reduced inflationary costs, minimized inconvenience to the traveling public caused by delays, increased safety through the construction zone, and reduced expenses associated with maintaining traffic control during construction.

***Irick, P. E., "A Conceptual Framework for the Development of Performance-Related Materials and Construction Specifications," *Transportation Research Record* 1126, Transportation Research Board, 1987, pp. 1-27.***

The purpose of this paper is to identify and bring together pavement design and performance concepts that can provide a systematic basis for the development of performance-related specifications for materials and construction (M&C) factors. The concepts form a framework in which the elements are interrelated and support the development of performance-related specifications. Essential inputs and outputs for algorithms for the development of such specifications are described in detail. It is assumed that the conceptual framework for specifications development includes eight sets of relationships among the process variables and nine sets of inputs or outputs for the relationships. Independent variables are selected that have predictable effects on performance-related output variables. From these independent variables, variables

appearing explicitly in prediction functions (EPF) are selected and subdivided into traffic factors, environmental factors, and pavement structure factors. EPF variables can be replaced by surrogate prediction factors (SPF) when M&C control for these secondary variables is easier to provide. Other secondary variables are the control factors (CF), which have predictable effects on EPF or SPF variables. EPF variables related to the M&C process are denoted MCF. In general, a stochastic prediction model consists of a prediction function that may be completely known from mechanistic considerations; that may be partially known except for undetermined constants; or that may be assumed to be a linear combination of linear, curvilinear, and interaction effects (with undetermined constants) among the independent variables. When the effect of error values is added to the prediction function, the prediction model can be compared to the experimental design, and analyses of variance and covariance and regression analysis can be applied. General forms of prediction equations for stress and distress, stress-load equivalence relationships, traffic prediction relationships, relationships among M&C specification factors, and performance-cost relationships are presented. Pavement design criteria and M&C specification factors are added as the initial conditions for the definition of a pavement design for a given pavement requirement. It is assumed that the M&C specification will be derived in every case from computational algorithms, although development of these algorithms requires results from future research.

Irick, P. E., S. B. Seeds, M. G. Meyers, and E. D. Moody, *Development of Performance-Related Specifications for Portland Cement Concrete Construction*, FHWA Report No. FHWA-RD-89-211, Federal Highway Administration, May 1990, 271 pp.

This paper describes the development of a suitable conceptual framework of relationships between materials and construction test results and pavement performance for portland cement concrete pavements. An attempt was made to locate existing data that confirmed some or all of these relationships. The paper outlines a laboratory and field testing program necessary to supplement the existing data. Finally, the results of the implementation of the laboratory and field tests necessary to develop a relationship between one material and construction variable and performance are discussed. Recommendations for further study are then given.

Jones, W. H. and J. A. Scherocman, "End-Result Specifications — A Contractor's Viewpoint," *Quality Assurance in Pavement Construction*, ASTM STP 709, American Society for Testing and Materials, December 1980, pp. 27-35.

The opinions of one contractor regarding end-result specifications are summarized in this paper. The drawbacks of method-type specifications, as far as a contractor is concerned, are described and include the penalizing of a competent asphalt paving contractor by requiring the contractor to use prescribed equipment, materials, and methods to construct a particular pavement. The benefits of end-result specifications are also listed, including the fact that they allow the contractor to use available

resources to accomplish the required end product in the manner of preference. Also described is a paving project that is actually contracted under end-result specifications by the Indiana State Highway Commission. This contract, awarded to Magaw Construction, accepted the asphalt content, aggregate gradation, and pavement surface smoothness on the basis of statistical-type specifications. The quality control exercised by the contractor was excellent, with the penalties assessed being equal to only 1.24 percent of the value of the paving work. Although a lack of knowledge by State personnel of the significance of end-result specifications and differences in sampling and testing techniques have, in the past, caused the assessment of many of the penalty points, it is concluded in the paper that the differences in the results obtained could be reduced on future projects, however, through the use of a certified asphalt technician approach to end-result specifications.

**Jorgenson, J. L., "Development and Trial Use of Acceptance Sampling Plans for Asphalt Construction," *Highway Research Record* 357, Highway Research Board, 1971, pp. 35-38.**

This paper responds to the fact that the research on variability in asphalt construction in North Dakota brought to light many characteristics of current acceptable construction. Single test results exhibited a large variability, causing many of the measurements to be outside the specifications. The gradation band at that time was only partially effective in controlling aggregate gradation. Payments to the contractor were independent of the quality of work. This paper expands on these observations and discusses their implications for improving specifications. Advantages of using statistically based construction specifications are listed. Also discussed is an analysis of data that were collected from five asphalt construction projects in North Dakota in the summer of 1968 for the purpose of simulating the use of statistically based construction specifications. The results of that simulation show that normal plant operations based on realistic target values will result in payments at or near 100 percent of contract price. The following recommendations are made: target values for all significant variables must be specified in the plans and specifications, acceptance limits with appropriate price adjustments must be specified in the plans and specifications, and it is necessary to rewrite current specifications to take out many of the restrictive control rules, thus allowing the contractor a freer hand in conducting the work.

**Kalcheff, V. and D. Tunnicliff, "Effects of Crushed Stone Aggregate Size and Shape on Properties of Asphalt Concrete," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 51, 1982, pp. 453-483.**

This paper documents a comprehensive laboratory experiment, conducted in order to provide meaningful data to quantify the benefits of high stability mixtures containing crushed aggregates. The primary objectives were to evaluate the role of the size and proportion of coarse aggregate, fine aggregate shape, and increased quantity of

mineral filler in asphalt concrete paving mixtures. A characterization of the fine aggregate particle shape was made using the National Crushed Stone Association shape index test method. Testing included Marshall stability and flow; repeated load, triaxial compression; static indirect tensile splitting strength; repeated load, indirect tensile splitting resistance; and compaction and permanent deformation. Several conclusions applicable to the mixtures used in this study were drawn. Optimum asphalt content of properly designed asphalt paving mixtures can be reduced by using more coarse aggregate, larger coarse aggregate, and more mineral filler. Mixtures containing crushed coarse and fine aggregates, with or without high proportions of mineral filler, should be much more resistant to permanent deformation from repeated traffic loadings, and much less susceptible to the effects of temperature and high initial void content than comparable mixes containing natural sand. Differences in behavior between mixtures containing manufactured sands of distinctly different particle shape were not observed, but important differences in mixture behavior were observed between those containing natural sand and those containing manufactured sands. In all cases, the manufactured sand resulted in improved mixture behavior.

**Kandhal, P., "Specifications for Compaction of Asphalt Pavements," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 52, 1983, pp. 362-377.**

The development of compaction specifications during the past 20 years in Pennsylvania is presented in this paper. It describes the compaction specifications in the early 1960's; premature pavement distress during 1974 to 1977, in the form of loss of fines and ravelling; and the resulting statistically designed investigations conducted to determine the cause of this premature distress. Also outlined in the paper are the recommendations of an interdepartment committee formed in 1979 to develop an action plan for durable bituminous concrete overlays, and for eliminating premature failures. Finally, a restricted performance specification for bituminous concrete developed in 1978 and fully implemented in 1979 is reviewed, as well as current additions to it.

**Kari, W., "Mix Properties as They Influence Compaction," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 36, 1967, pp. 295-309.**

This paper is concerned with the properties of the mix that affect the compaction process. The influence of asphalt viscosity, aggregate gradation, filler content, and the mix bearing capacity on the compaction process are reviewed. It is shown that each mix appears to have an optimum bearing capacity that permits maximum compaction to occur under a given roller. Corrective measures are listed for difficulty experienced in the field of achieving density with an understressed high-bearing capacity mix, as well as for weak mixes, where the roller sinks into the mix, shoves laterally, or checks excessively.

Kennedy, T. W., "Asphalt '90 — Special Report: Performance-Based HMA Specs Major SHRP Goal," *Roads and Bridges*, Volume 28, Number 1, January 1990, pp. 81-84.

This article outlines the goals of the Strategic Highway Research Program (SHRP) in the area of performance-based specifications. In short, SHRP will develop model, performance-based specifications for asphalt binders and asphalt-aggregate mixtures. These specifications will allow the engineer to select an asphalt binder and an asphalt-aggregate mixture on the basis of the performance required of the asphalt pavement under the present and predicted traffic and environmental conditions. A working concept of the performance-based asphalt binder specification has been developed to guide and to coordinate the many components of the SHRP program. Asphalt binder specifications will employ physical properties as surrogates for significant chemical, or compositional factors that influence pavement performance. Performance-based specifications must be founded on a set of validated relationships between binder and mixture properties (and/or surrogate tests), and field (pavement) performance that establishes the required response ranges to control fatigue cracking, permanent deformation (rutting), low-temperature cracking, aging, and water sensitivity. The conceptual specification includes requirements related to the behavior of the asphalt binder during hot mix production and pavement construction. The model performance-based specifications, as well as other products of the SHRP asphalt research program, will be available for appraisal by the highway community by early 1993.

Kennedy, T. W., H. L. Von Quintus, and T. Mitchell, "Pavement Performance As Affected by Materials Testing Program," *Transportation Research Record* 1034, Transportation Research Board, 1985, pp. 153-158.

A summary is presented of a study aimed at providing a means by which an organization can determine the cost-effectiveness of individual tests, test methods, and associated sampling frequencies for tests used in controlling the quality of pavement materials as related to effects on performance. Appropriate procedures have been developed and are briefly discussed, including critical considerations and limitations due to lack of suitable stochastic models to predict performance and contractor response to changes in testing frequency. These procedures are embodied in the computer program COSTOP1, which was developed to assist State highway agencies in determining the optimum test frequency for a single test or the optimum test program for multiple tests to produce the greatest return for every dollar spent on testing. COSTOP1 is general and modular so that testing programs for all paving construction and materials can be evaluated, and new models and differing repair strategies may be easily defined and input. Preliminary results indicate that higher frequencies of testing than commonly used would be cost effective, decreasing the equivalent annual pavement costs by much more than the additional testing costs.



Komlos, K., F. Kruml, and Z. Homolka, "Judgement of Concrete Quality in Transportation Structures," *Transportation Research Record* 652, Transportation Research Board, 1977, pp. 76-80.

This paper deals with the present method of judgment of the quality of fresh and hardened concrete used in transportation structures in Czechoslovakia. Standard methods and criteria are presented for estimating properties of fresh concrete mixes and hardened concretes for different types of structures. In the case of hardened concretes, destructive and nondestructive methods of testing concrete properties are analyzed and evaluation techniques are given. The problems of quality control of cements and aggregates are studied. The judgment of the acceptability of fresh concretes in relation to their composition and workability is analyzed. Requirements are presented for such properties as concrete strength and properties related to short- and long-term deformation. Sclerometric and acoustic methods of nondestructive testing are discussed. Various methods for the judgment of acceptability of concrete are analyzed by using large and small samples and standard Czechoslovakian specifications. Statistical evaluation is emphasized. Acceptability criteria for safety, homogeneity, and economy are presented. The intent of this paper is to show the complexity of the judgment procedures used in the quality control of concrete on the basis of current Czechoslovakian standards. Judgment of concrete quality involves the choice of the physico-mechanical characteristics to be tested and the testing procedures and evaluation methods to be used. This paper addresses all of these problems. The possibility of using a refined procedure of quality control for concrete produced over longer periods is also discussed.

LaHue, S. P., "Quality Assurance and Quality of Construction," *Quality Assurance in Pavement Construction*, ASTM STP 709, American Society of Testing and Materials, December 1980, pp. 3-10.

Modern quality assurance (QA) systems, including statistically based specifications being reviewed and adopted by many States throughout the nation, are discussed in this paper. The U.S. Federal Highway Administration's initial involvement in quality assurance started in 1963. At that time, the Office of Research and Development's efforts were directed toward arousing the highway industry's interest in quality assurance and developing guidelines in this area. Currently, there are 21 States using quality assurance specifications as their normal specifications for asphaltic concrete construction. In addition, there are seven States that are developing or using quality-assurance specifications for asphaltic concrete on selected trial projects. Part of the reasoning for the shift toward the adoption of modern quality assurance systems by State highway agencies can be attributed to their efforts to apply sound management techniques to the highway industry. The adoption and application of sound management techniques has become essential in this age of increasing costs and reduced revenues and will lead to a better-performing highway system.

Latham, J., "Method Versus End Specifications," *Civil Engineering*, May 1982, pp. 22-28.

This article outlines a number of factors that may influence changes made in respect to specifications in the not-too-distant future. The three basic types of specifications used worldwide—method specifications, end-result, or performance specifications, and the combination of end-result and method specifications—are discussed. These three types of specifications and the tests associated with them are compared using examples of compaction of soil and bituminous materials in the U.S., U.K., and Europe. A few types of new equipment used in the control of compaction specifications are also briefly discussed.

Majidzadeh, K. and G. Ilves, *Correlation of Quality Control Criteria and Performance of PCC Pavements*, FHWA/RD-83/014, Federal Highway Administration, March 1984.

The interrelationship between concrete pavement quality indicators and pavement performance is presented in this report. In the study reported here, a literature review was conducted to help identify pavement quality indicators, such as water/cement ratio, strength, slump, air content, and so forth. A detailed field investigation was carried out in five States to collect quality-indicator data. A pavement conditioning rating (PCR) procedure was developed to collect PCR data for various pavement sections. Linear and nonlinear statistical analyses were conducted to develop models interrelating quality control data with PCR data. The results of the statistical analyses and the nature of the models developed are discussed in detail.

Majidzadeh, K., G. Ilves, M. Luther, and P. Kopac, "Correlation of Quality-Control Data and Performance of PCC Pavements," *Transportation Research Record 924*, Transportation Research Board, 1983, pp. 93-99.

The interrelationship between concrete pavement quality indicators and pavement performance is presented in this report. In the study reported here, a literature review was conducted to help identify pavement quality indicators, such as water/cement ratio, strength, slump, air content, and so forth. A detailed field investigation was carried out in five States to collect quality indicator data. A pavement conditioning rating (PCR) procedure was developed to collect PCR data for various pavement sections. Linear and nonlinear statistical analyses were conducted to develop models interrelating quality control data with PCR data. The results of the statistical analyses and the nature of the models developed are discussed in detail.

**Meininger, R. C. and N. R. Nelson, "Concrete Mixture Evaluation and Acceptance for Air Field Pavements," *Proceedings: Aircraft/Pavement Interaction—An Integrated System*, ASCE, September 1991, pp. 199-224.**

Evaluation of the strength of portland cement concrete using flexural and compressive strength tests is examined. Problems with the use of flexural testing in the field are discussed and alternative specifications approaches to minimize testing problems and to provide an organized way of troubleshooting and settling low strength problems are covered. Data are presented from case studies that show the effect of different specification strategies. Also included are suggested quality control and troubleshooting protocols that should be included in specifications to improve data and information available and to handle low strength tests. The procedure includes evaluation of the project data, as well as the proper use of nondestructive tests and testing of cores when necessary.

**Meyer, F., A. Cheetham, and R. Haas, "A Coordinated Method for Structural Distress Prediction in Asphalt Pavements," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 47, 1978, pp. 160-189.**

This paper describes the research conducted to develop a flexible pavement distress prediction procedure including verification with field data. The overall method used in the distress prediction method, and the research approach followed to develop the procedure are outlined. The proposed distress models are verified using test road data, and the use of the package for pavement design systems is illustrated. Finally, the advantages and limitations of the method are discussed. Some fairly complex laboratory and analytical investigations, regarding permanent deformation, fatigue cracking, and low temperature cracking, as well as sensitivity analyses to determine simplifications and approximations have been performed. The result is a simple, approximate, coordinated package capable of estimating the type and amount of distress from standard design inputs for many alternatives in a very small amount of computer time. The distress prediction subroutine developed is suitable for incorporation into flexible pavement design systems, since the inputs are compatible with design system variables and the execution time required is very small.

**Molnar, J. T., "Controlling Aggregate Properties for Compliance with Statistical Specifications," *Quality Assurance in Pavement Construction*, ASTM STP 709, American Society for Testing and Materials, December 1980, pp. 19-26.**

The paper outlines aggregate process control procedures applicable to both single-plant and multiple-plant operations. The elements in establishing a control program covered here include: the basic plan, the selection and training of the technicians, the sampling locations, and rapid testing and reporting methods. The main benefit of an effective control program is that it minimizes the chance of incurring penalties in the form of price reductions when the aggregate is used in products that fail to conform

to the requirements of statistical or end-result specifications. Other benefits are also discussed.

**Moore, R. M., J. P. Mahoney, R. G. Hicks, and J. E. Wilson, "Overview of Pay-Adjustment Factors for Asphalt Concrete Mixtures," *Transportation Research Record* 821, Transportation Research Board, 1981, pp. 49-56.**

This report discusses a research project initiated in the fall of 1979 by the Oregon State Highway Division and Oregon State University, with participation from the University of Washington, to study the impact of variations in material properties on asphalt pavement life. The study was aimed at developing a rational approach to assessing the effects of variations from specification limits so that a firm basis could be established for the development of pay factors. To collect information on the status of quality control procedures and the use of pay adjustment factors, a questionnaire was distributed to all State agencies, the District of Columbia, and the Federal Highway Administration. Each agency was asked to respond to questions on their current method for acceptance or rejection of asphalt concrete paving materials and related pay-adjustment factors. Analysis of the results indicates the following:

- Most State agencies will accept one or more property characteristics of asphalt concrete that are outside specification tolerances.
- Most State agencies apply a pay adjustment factor to accepted materials that are outside specification tolerances.
- Only 26 percent of the State agencies consider their pay factors to be proportional to reduced pavement serviceability.
- Approximately half of the agencies consider pay factor plans to be effective in encouraging compliance with specifications.
- There is a wide disparity in the pay adjustment factors used by the different agencies.

**Nichols, Jr., F., "Meaningful Specifications for Bituminous Paving Aggregate," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 52, 1983, pp. 345-356.**

The principle thrust of this paper is on the importance of consistent gradations of the aggregates used in high-type bituminous mixtures. The trend toward acceptance of aggregates on the basis of the producer's certification of quality in lieu of acceptance testing by the contracting agency is discussed. The role that must be played by the contractor in maintaining the quality of the aggregate, as produced, through all subsequent operations is also emphasized. Attention is called to NCHRP Report 100, published in 1970, setting forth 52 items of needed research to better relate aggregate properties to their performance in highway construction. Further research is called for to establish appropriate limits on such inherent aggregate properties as abrasion resistance, soundness, toughness, and hardness to ensure acceptable performance.

**Okamoto, P. A., "Field Evaluation of Dowel Placement Along a Section of Interstate 45 in Texas," *Transportation Research Record* 1186, Transportation Research Board, 1988, pp. 16-34.**

The results of a field investigation conducted to determine the effectiveness of an automatic dowel bar inserter at properly placing dowel bars in rigid pavements are presented. The study was conducted during February and March 1987 along a section of I-45, south of Dallas, Texas. A commercially available radar system, capable of quickly and easily locating reinforcing bars and other embedded steel in concrete, was used to examine the experimental dowel placement. The automatic dowel bar inserter was used to install dowel bars over a portion of the project and, over the remainder of the project, dowel bars were placed on baskets. Results indicated that the dowel bar alignment at inserter joints is as good or better than that at the basket assembly joints.

**Oluokun, F. A., E. G. Burdette, and J. H. Deatherage, "Elastic Modulus, Poisson's Ratio, and Compressive Strength Relationships at Early Ages," *ACI Materials Journal*, January/February 1991, pp. 3-10.**

This paper presents the results of an experimental investigation into the relative relationships between the elastic modulus, Poisson's ratio, and the cylinder compressive strength of concrete, especially at early ages. The applicability of some of the existing relations between these properties on concrete at early ages was also examined. Tests were performed on four different concrete mixes using conventional (6- by 12-in [152- by 305-mm]) cylinders, and results were obtained for ages ranging from 6 hours to 28 days. Analysis of the test results show that the compressive strength and the elastic modulus are related, and an increase in one is, in general, similarly reflected by an increase in the other. The commonly accepted relationship that the elastic modulus of concrete is proportional to the 0.5 power of the cylinder compressive strength was found to be accurate for the elastic modulus at ages 12 hours and above. Poisson's ratio was found to be insensitive to both the age and the richness of the concrete mix and did not change appreciably with compressive strength development.

**Oluokun, F. A., E. G. Burdette, and J. H. Deatherage, "Splitting Tensile Strength and Compressive Strength Relationship at Early Ages," *ACI Materials Journal*, March/April 1991, pp. 115-121.**

This paper presents the results of an experimental investigation into the relative relationships between concrete compressive strength and its splitting tensile strength, especially at early ages. Also presented is an examination of the applicability of some of the existing relationships between these properties to concrete at early ages. Analysis of the test results show that the compressive strength and the splitting tensile strength are related, and an increase in one, in general, is similarly reflected in an increase in the other. The commonly accepted 0.5 power relationship between the

compressive strength and the splitting tensile strength was found to be inaccurate at all ages. In fact, the tensile strength was found to be proportional to the 0.79 power of the cylinder compressive strength. An alternate relationship between the tensile strength and the compressive strength is proposed.

Oswald, T. H. and J. L. Burati, Jr., "Can Total Quality Management Work in the Public Construction Arena?," *Transportation Research Record* 1340, Transportation Research Board, 1992, 7 pp.

Total quality management (TQM) has been demonstrated to increase productivity and profitability in numerous applications in manufacturing and some service industries. However, its viability as a major management philosophy in engineering and construction has not been widely established. The same is true in the general area of government agency operations and, more specifically, in the field of public sector construction. In this paper, the principles and operational elements of TQM are discussed in terms of the unique characteristics of public construction. The quality improvement programs of three major federal construction agencies are discussed, and conclusions are drawn concerning the success factors for making TQM work in public construction.

Pell, P. and K. Cooper, "The Effect of Testing and Mix Variables on the Fatigue Performance of Bituminous Materials," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 44, 1975, pp. 1-37.

The purpose of this paper is to summarize and briefly review an extensive laboratory investigation, lasting 5 years, delving mainly into the effect of mix variables on the fatigue strength of bituminous materials. Forty-eight test series were carried out on a wide variety of base course and wearing course mixes of both the gap-graded and continuously graded type. The aim was to try to identify quantitatively the significant variables and produce general relationships for defining laboratory fatigue performance. Fatigue life often depends on the method of testing, and most laboratory fatigue tests have been carried out under uniaxial stress conditions, either in flexure or in direct loading, while in practice the material is subject to complex three-dimensional stressing, some tests were also carried out in direct tension-compression at various temperatures with the specimens subject to different confining stresses.

*Proceedings of Region Eight Quality of Highway Construction Workshop*, Utah State University, September 1979, 202 pp.

A Region 8 "Quality of Highway Construction Workshop" was hosted by the Utah Department of Transportation and the FHWA, Region 8, Office of Construction and Maintenance on September 12-14, 1979, at Utah State University. The proceedings

include formal papers, reports, remarks, discussions, and formal workshop presentations made at the workshop. Topics covered at the workshop included the adequacy of current construction quality as related to flexible and rigid pavements; specifications and how they relate to a quality end product; legal ramifications of specifications; the question of who determines the quality of the work—the designer, inspector, or contractor; the effects of staffing on the quality of work; and the effect of inflation on the quality of highway construction.

Puangchit, P., R. G. Hicks, J. E. Wilson, and C. A. Bell, "Development of Rational Pay Adjustment Factors for Asphalt Concrete," *Transportation Research Record 911*, Transportation Research Board, 1983, pp. 70-79.

The purpose of this paper is to report on efforts to develop a rational procedure for establishing pay adjustment factors for asphalt concrete mixtures by finding a relation between asphalt concrete quality and pavement serviceability that would indicate whether the work should be accepted or rejected and how much compensation should be paid. The specific objectives are as follows:

- To determine the most important factors that affect the properties of asphalt concrete mixtures.
- To evaluate the effect of variations in these factors on the life of pavement projects in Oregon.
- To develop pay adjustment factors consistent with the latest engineering principles.
- To compare these values with those currently used by other agencies in the Pacific Northwest.

In this study, data from laboratory-prepared samples from the North Oakland-Sutherlin, Castle Rock-Cedar Creek, and Warran-Scappoose projects were analyzed by using the Statistical Interactive Programming System. Regression analysis techniques were used to develop predictive models of pavement performance life based on each of the mix characteristics. The asphalt concrete mixture properties evaluated in this study were percentage of air voids, asphalt content, gradation, and aggregate type used. Percentage of air voids or mix density is found to be the most dominant factor and most highly significant in controlling both fatigue cracking and rutting failure. The mix that had low void content showed remarkably long fatigue life and high performance deformation resistance. The best performance life was obtained when the asphalt content and the amount of fines were at an optimum level. Deviation from optimum content in either of these properties causes a reduction in pavement life. The amount of voids and the optimum asphalt content appeared to be a function of the aggregate type used. The analysis indicates that for the mix deviations considered, fatigue cracking is more critical to reduction in life than rutting. Therefore, the pay adjustment factors were developed based on fatigue performance life as opposed to a proposed standard pavement life. Summary tables of recommended pay adjustment factors as well as comparisons with others currently used are also included.

*Quality Assurance and Acceptance Procedures, Special Report, Number 118, Highway Research Board, 1971, 23 pp.*

This report was prepared to summarize the state of the art and highway department needs in the area of quality assurance and acceptance procedures. Part I includes brief summaries of the following topics in the state of the art: aggregates, bituminous construction, concrete construction, construction practices, and general materials. Part II summarizes the HRB Committee on Quality Assurance and Acceptance Procedures' thoughts on future quality assurance and acceptance procedures needs in specifications, laboratory standardization, and information handling systems.

**"Quality Assurance in Highway Construction," *Public Roads*, Volume 35, Numbers 6-11, 1969.**

Statistically based quality control methods have been used successfully in industry for many years. According to research results, statistical quality assurance methods also should be adaptable to highway construction, provided that governing specifications are properly written and sampling and testing variations are established to conform to the conditions of the locality in which they will be applied. In these issues, the *Public Roads* research staff presents an interpretative summary of the progress in its research program for the statistical approach to quality assurance in highway construction. The presentation consists of six parts:

1. Introduction and concepts.
2. Quality assurance of embankments and base courses.
3. Quality assurance of portland cement concrete.
4. Variations of bituminous construction.
5. Summary of research for quality assurance of aggregate.
6. Control charts.

**Rawe, R. P. and T. A. Ruhl, "Alternative Airfield Pavement Quality Control," *Proceedings: Aircraft/Pavement Interaction—An Integrated System*, ASCE, September 1991, pp. 291-305.**

In recent years, the cost of maintaining quality control during airfield construction projects has concerned airport operators and engineers alike. This paper addresses the possibilities of decreasing quality control costs by obtaining alternate concrete cylinder strengths to standard flexural strength beams. Observed data indicates a significant relationship between these strengths; however, the predictability of the models to estimate flexural strength can vary considerably between projects. This suggests that one general model can not adequately predict flexural strengths from compressive or split tensile strengths. Data suggest that models be generated for each project during the mix design phase. The model then could be used to find concrete strength deficiencies, which could be verified with additional flexural strength tests. Of course, such testing must gain widespread acceptance from the



design and construction community as well as from the Federal Aviation Administration (FAA).

**Rosenblueth, E., L. Esteva, and J. E. Damy, "Bonus and Penalty in Acceptance Criteria for Concrete," *Journal of the American Concrete Institute, Proceedings* Volume 71, Number 9, September 1974, pp. 466-472.**

Criteria are laid down to decide on the price that should be paid per cubic yard of concrete, including bonuses or penalties, as a function of the strength supplied and of the specified strength, as well as when a concrete element should be strengthened or demolished and replaced. The criteria are such as to make the owner's utility independent of the strength of the concrete supplied by the contractor. Initial cost and present value of the consequences of failure are taken into account. Three possibilities of structural failure are analyzed: on application of permanent loads, a Poisson process, and combinations of these two conditions. The first possibility idealizes behavior under gravity loads while the second corresponds to earthquake- and wind-like loading. A cursory analysis is included of the effects of differences in strength between control cylinders and concrete cores.

**Shilstone, Sr., J. M., "Quality Management for Concrete Pavement Under Performance Standards," *Transportation Research Record* 1340, Transportation Research Board, 1992, 7 pp.**

Alternative methods are being researched to develop ways to replace traditional highway contracting practices with performance standards. This will force major changes in both agency and contractor responsibilities for construction planning and quality management. Engineering formulas can be used to calculate structural solutions. These formulas do not resolve durability needs. There is no accepted means to define, in measurable terms, the characteristics of a concrete pavement that will be durable in typical highway environments. Methods are described whereby existing pavements with excellent and poor performance histories may be surveyed and used to define "durable concrete" and act as the basis for performance standards for durability. The method for specifying, controlling, and verifying construction to meet the desired durability objectives are outlined.

**Shook, J. F., M. A. Diaz, M. Stroup-Gardiner, and S. B. Seeds, *Performance-Related Specifications for Asphalt-Concrete, Phase II*, FHWA-RD-91-070, Federal Highway Administration, January 1992, 230 pp.**

The objective of this study was to further the development of performance-related specifications for asphalt pavement construction by: (1) conducting laboratory studies of the relationships between material and construction (M&C) variables and fundamental response variables, and the relationships between fundamental response

variables and pavement performance indicators; and (2) developing a detailed plan for an accelerated field test at a test track facility.

The laboratory study performed for this research focused on the development of secondary prediction relationships, which are equations that establish the relationship between M&C variables and fundamental response variables. The results of the laboratory study indicate that compaction level had more influence on mixture properties than any other variable in the experiment. A technique for estimating compaction effects using measurable specimen properties was found and resulted in a compaction index equation. The prediction equations can be used with an estimated compaction index to relate measured mixture properties to optimum properties. These equations can also be used to predict relative effects of proposed changes in materials and construction specifications on performance-related mixture properties. When used with equations that relate performance-related mixture properties to pavement performance, the equations derived in this study can be used to establish penalties for non-conformance to specifications limits.

**Shook, J. F. and M. A. Diaz, *Performance-Related Specifications for Asphalt-Concrete, Phase II—Proposed Plans for Accelerated Pavement Test Track Study*, FHWA-RD-91-071, Federal Highway Administration, January 1992, 62 pp.**

To assist in the development of performance-related specifications for asphalt pavements, a plan for an accelerated pavement test track study is described in this report. The objectives of the study are to:

- Verify or modify laboratory-developed prediction equations.
- Relate the predicted performance of test sections obtained from the equations to actual performance under real traffic and environmental conditions.
- Develop data that can be used to extend the findings to other traffic and environmental conditions.
- Develop data that can be used to extend the findings to materials not included in the original study.
- Develop data that may be used to confirm or modify existing material-performance relationships.
- Use and test the applicability of methods for determining pay factors.

***Standard Specifications for Construction of Roads and Bridges on Federal Projects*, Federal Highway Administration, 1985, 702 pp.**

This book is formatted to the extent possible after the AASHTO *Guide Specifications for Highway Construction* to promote nationwide uniformity and consistency of specifications and contractual matters in highway construction. These specifications are designed to prevent controversy in the administration of contracts and to encourage high quality work and cost-effective production and construction methods.

**"Statistically Oriented End-Result Specifications," *Synthesis of Highway Practice* 38, Transportation Research Board, 1976, 40 pp.**

This report describes current technology for the application of end-result specifications based on information from all sources, including some outside of the transportation field. To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, an analysis was conducted on the available information assembled from numerous sources, including a large number of State highway and transportation departments. A topic panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report. This synthesis is an immediately useful document that records practices within the limitations of the knowledge available at the time of its preparation. Major topics include trends in specifications for materials and construction, problems associated with statistically oriented specifications, contractor's and producer's quality control systems, contracting agency acceptance procedures, current practices in highway agencies, and comments from the trade associations and procedures.

**Steele, G., J. O'Leary, and C. Miller, "A Quality Assurance System for Acceptance of Asphaltic Materials," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 43, 1974, pp. 178-190.**

The first part of this paper traces the evolution of the quality assurance system for liquid asphaltic materials used in paving mixtures, or as a part of the paving structure. It reviews early systems and the "presampling/pretesting system." It then follows a description of the system being implemented in West Virginia at the time of the paper. This quality assurance system was designed to address the total manufacture, loading, and delivery cycle. Experience to date indicates that the new generation of systems are optimizing the effectiveness of resources available for West Virginia's quality assurance program.

***Strategic Highway Research Program Research Plans*, Final Report, NCHRP Project Number 20-20, Transportation Research Board, American Association of State Highway and Transportation Officials, and Federal Highway Administration, May 1986, 616 pp.**

Seven contract agencies, each supported by an advisory committee of representatives from the highway community, have worked intensively for almost 1 year to develop well defined plans for the performance of research in the six technical areas that constitute the Strategic Highway Research Program. This document represents a compilation of the reports prepared by the seven contract agencies and constitutes in total, a workplan for carrying out a program that is anticipated to provide the greatest surge in highway research that this Nation has ever witnessed. Included in the report are sections outlining the detailed planning for research in the six SHRP technical areas: asphalt properties; long-term pavement performance; maintenance

effectiveness; bridge component protection; cement and concrete; and snow and ice control on highways and bridges.

***Synthesis of Statistical Parameters for Highway Construction, Final Report, Report Number FHWA-WV-80-002, February 1980, 230 pp.***

This report summarizes the results of a research project that covered an appreciable time span with a series of five reports as the work progressed. The initial objectives were to obtain unbiased measurements of the magnitude of variation and the level of characteristics of materials and construction. The final objective was to develop and evaluate quality assurance specifications. Results of tests on both structural concrete and portland cement concrete pavement indicate that the level and overall variation of compressive strength is satisfactory on most projects, but within-test variation is higher than normal. A new bituminous sampling procedure was developed that gives results comparable to AASHTO, but is more convenient and safer. The density of a bituminous concrete pavement determined with a nuclear meter showed that there was a definite pattern of density gradient across the longitudinal joint. Construction of two projects having quality assurance acceptance plans as a contract requirement have shown, in part, that the requirement that the contractor provide his own quality control resulted in a more uniform and increased level of quality; and Department personnel indicated that paperwork was far less than on previous projects.

***Tayabji, S. D., Dowel Placement Tolerances, FHWA/RD-86/042, Federal Highway Administration, May 1986, 36 pp.***

This report presents results of an investigation conducted to develop placement tolerances for dowels at concrete pavement joints. A theoretical analysis of dowel misalignment was attempted. The purpose of the analysis was to compute restraint stresses induced in the concrete pavement for different levels of dowel misalignment. However, because of the complexity of correctly incorporating the three-dimensional nature of dowel misalignment, the theoretical analysis was not completed. The effect of dowel misalignment was then investigated in the laboratory by conducting pull-out tests on sections of concrete slabs incorporating a joint and dowels with different levels of misalignment. Test results indicate that pull-out loads were relatively low for dowel misalignment levels of less than 1 in per 18-in (25 mm per 457-mm) length of dowel bars and a maximum joint opening of 0.25 in (6.4 mm). Because of the limited amount of laboratory data, no recommendations were made to establish new acceptable levels of dowel misalignment.

Tayabji, S. D., "Dowel Placement Tolerances for Concrete Pavements," *Transportation Research Record* 1062, Transportation Research Board, 1986, pp. 47-54.

The results of an investigation conducted to develop placement tolerances for dowels at concrete pavement joints are presented. A theoretical analysis of dowel misalignment was attempted. The purpose of the analysis was to compute restraint stresses induced in the concrete pavement for different levels of dowel misalignment. However, because of the complexity of correctly incorporating the three-dimensional nature of dowel misalignment, the theoretical analysis was not completed. The effect of dowel misalignment was then investigated in the laboratory by conducting pull-out tests on sections of concrete slabs incorporating a joint and dowels with different levels of misalignment. Test results indicate that pull-out loads were relatively low for dowel misalignment levels of less than 1 in per 18-in (25 mm per 457-mm) length of dowel bars and a maximum joint opening of 0.25 in (6.4 mm). Because of the limited amount of laboratory data, no recommendations were made to establish new acceptable levels of dowel misalignment.

Tayabji, S. D. and P. A. Okamoto, "Field Evaluation of Dowel Placement in Concrete Pavements," *Transportation Research Record* 1110, Transportation Research Board, 1987, pp. 101-109.

Presented in this paper are the results of a laboratory and field investigation conducted to determine the effectiveness of the radar device for evaluating dowel bar misalignment and to evaluate the effectiveness of an automatic dowel bar inserter to properly place dowel bars in rigid pavements. A commercially available radar system, capable of locating steel embedded in concrete, was used. The laboratory study indicated that dowel bars placed about 5 in (127 mm) below the concrete surface could be located reasonably accurately by the radar system. In the laboratory, the standard deviation obtained for the differences between the actual and measured individual readings was 0.24 in (6.1 mm). The field evaluation, conducted during June 1986 along a section of I-86 in Idaho, indicated that the radar system was capable of determining the location of the dowel bars placed in concrete pavements. However, the degree of accuracy was noted to be operator dependent and test results must be considered in statistical terms.

Tuggle, D. R., "FHWA Demonstration Project No. 89, Quality Management and a National Quality Initiative," *Transportation Research Record* 1340, Transportation Research Board, 1992, 5 pp.

Quality assurance specifications and programs in the highway construction industry have been evolving since the 1960's. Within the last decade, there has been increasing attention to promoting quality products and services throughout the U.S. economy. There has also been an increased level of interest within the highway community. Although there is currently significant interest and many independent

activities associated with what has now become known as quality management, there is a need to coordinate these many activities. There is also a need to increase awareness in and build support from upper management, and to provide technical skills and tools to those responsible for implementing quality management programs and specifications. A coordinated effort among the Federal Highway Administration, the American Association of State Highway and Transportation Officials, the highway construction industry, and others is being formulated to provide oversight and direction toward increasing emphasis in quality management and other construction quality and performance issues. This effort has been termed the "National Quality Initiative." FHWA's Demonstration Project No. 89, Quality Management, can provide the vehicle to implement the activities under the initiative.

**Tunncliff, D., "Quality Control of Bituminous Paving from the Beginning," *Asphalt Paving Technology: Proceedings of the Association of Asphalt Paving Technologists Technical Sessions*, Volume 42, 1973, pp. 440-481.**

The origin of modern controls and the resulting variability was studied in an effort to develop a better understanding of control systems. Practices with sheet asphalt in 1900 are mentioned and pavements built under patents issued to F. J. Warren are described. These include Bitulithic, Warrenite, Warrenite-Bitulithic, Topeka, and Black Bass. The quality control system used by Warren Brothers (illustrated by typical Bitulithic specification) controlled aggregate gradation and asphalt content, job mix formula and tolerances, including mix temperature delivered to the job, temperature controls of bitumen aggregate, mixing and mix at the plant, weather and limitations, detailed plant requirements, machine laydown, detailed roller and rolling requirements, and smoothness requirements. Variability by design is considered and variability in construction is discussed. Patented pavement, gradation and bitumen content, gradation, asphalt content, and density of modern pavements are detailed. The limitation of variability is discussed. It is urged that controls should distinguish between satisfactory and unsatisfactory pavements. Satisfactory control can be maintained without excluding good construction and unnecessarily increasing costs. Controls should be tailored to accommodate the characteristics of different mixtures, the requirements of the pavement, and the conditions encountered in construction. Either the conventional process control system or the newer end-result specifications can be made to function satisfactorily for modern construction.

**Van de Fliert, C. and H. Schram, "Quality Control of Pavements in the Netherlands," *Transportation Research Record* 652, Transportation Research Board, 1977, pp. 71-75.**

A brief historical review of the main elements of the development of quality control in road construction in the Netherlands is given. In this development, the continuing deliberation on technical specifications and methods of construction between the State Road Laboratory and committees of experts for contractors' organizations plays an essential part. The general principles of the nonstatistical quality control systems

applied since 1968 as well as the statistical system developed during the past few years are explained based on 10 years of experience in the quality control of more than 250 road works. In the Netherlands, the separation between the responsibility for daily production control exercised by the contractor and the acceptance control exercised by the engineer after completion of the job is of great importance. Acceptance control concerns layer thickness, strength of soil cement, density, bitumen content of asphalt mixtures, skid resistance, and roughness of the road surface. Finally, issues of costs and benefits for jobs of inferior quality and the payment deductions required in such cases are discussed.

**Vlatas, D. and R. Smith, "Implications of Life Cycle Performance Specifications," Preprint of Paper Presented at the 68th Annual Meeting of the Transportation Research Board, Paper No. 88037, January 1989, 13 pp.**

The professional, managerial, and legal implications of using life-cycle performance specifications are presented in this paper. Changes in the roles of the parties using life-cycle performance specifications are discussed. Life-cycle performance specifications are a cost-effective means of procuring highway pavements that will provide satisfactory service over their design life. This approach can improve quality, reduce costs, and expedite the construction process. The basis of the process is the development of models of expected performance. These models will be used to predict whether the pavement is expected to perform as required over the life of the project. Tests are performed at the end of construction to determine whether the expected performance is likely to be achieved. Adjustments in payment can be made, based on the performance model predictions. The ramifications of adopting life-cycle performance specifications are discussed.

**Von Quintus, H. L., J. B. Rauhut, T. W. Kennedy, and P. R. Jordahl, *Cost Effectiveness of Sampling and Testing Programs*, FHWA Report No. FHWA/RD-85/030, Federal Highway Administration, January 1985, 377 pp.**

This report documents studies aimed at providing a means of establishing priorities among quality control tests and of optimizing sampling frequencies of each test, based on the effects of material properties measured on the performance of the pavements. Appropriate procedures were developed and are discussed, including critical considerations and limitations due to lack of suitable stochastic models to predict performance and contractor response to changes in testing frequency.

These procedures are embodied in the computer program "COSTOP1," which was developed to assist State highway agencies in determining the optimum test frequency for a single test or the optimum test program for multiple tests to produce the greatest return for every dollar spent on testing. COSTOP1 is general and modular so that the testing programs for all paving construction and materials can be evaluated, and new models and differing repair strategies may be easily defined and input.

**Weed, R. M., "Adjusted Pay Schedules: New Concepts and Provisions,"**  
*Transportation Research Record 986*, Transportation Research Board, 1984, pp. 32-37.

Shortly after the AASHO Road Test had furnished a wealth of statistical data on pavement construction and performance, highway agencies began to use this data to develop end-result specifications based on statistical concepts. These specifications usually included adjusted pay schedules, the development of which was sometimes quite arbitrary. More recently, attempts have been made to improve both the accuracy with which pay schedules are established and the fairness with which they are administered. In this paper, the rationale underlying several recent advances in the state of the art is discussed. Included are the use of the principle of liquidated damages to relate pay reductions to the anticipated monetary loss resulting from substandard work, the development of the crediting concept to overcome a basic inequity of many existing pay schedules, and the establishment of bonus provisions that provide additional incentive by awarding payment slightly in excess of the contract price for superior quality work.

**Weed, R. M., "Development of Multi-Characteristic Acceptance Procedures for Rigid Pavement,"** *Transportation Research Record 885*, Transportation Research Board, 1982, pp. 25-35.

The manner in which the American Association of State Highway and Transportation Officials (AASHTO) design method can be used to develop multicharacteristic acceptance procedures for rigid pavements is outlined in this paper. The AASHTO equation is used to compute both the expected load-bearing capacity based on the as-built characteristics of the pavement and the desired load-bearing capacity based on the design parameters. The ratio of these two values is then used to determine the appropriate pay adjustment, which may be either positive or negative. Sensitivity tests are performed to verify the reliability of this approach and computer simulation is used to demonstrate the effectiveness of several different acceptance procedures of this type. A secondary study is conducted to determine how the procedure based on the AASHTO equation compares with several other methods of treating multiple pay factors to obtain a single overall pay factor. Under the assumption that the AASHTO method is the fundamentally correct approach, the method of multiplying individual pay factors together is shown to be among the best of the other methods that were tested.

**Weed, R. M., "Equitable Graduated Pay Schedules: An Economic Approach,"**  
*Transportation Research Record 691*, Transportation Research Board, 1978, pp. 27-29.

This paper presents an approach for establishing graduated pay schedules that are realistic, equitable, and legally defensible. The method consists of determining the present worth of the extra expense anticipated as a result of work of deficient quality. An appropriate pay schedule is developed on the premise that it would be justifiable to withhold this amount from the contract price. The method is applicable in the



case of construction items for which data are available that relate quality to performance. An example is given in which concrete pavement is evaluated in terms of compressive strength.

**Weed, R. M., "Method to Establish Pay Schedules for Rigid Pavements,"**  
*Transportation Research Record* 885, Transportation Research Board, 1982, pp. 18-24.

An equation is derived in this paper to compute the appropriate pay factor for any quality level of rigid pavement. The measure of quality used in this development is the estimated load-bearing capacity of the pavement, although the results may be applied to specifications based on other quality measures. The appropriate pay adjustment is considered to be the present worth of any expense or savings expected to occur in the future as the result of a departure from the specified level of quality, and it may be positive or negative. Sensitivity tests demonstrate that the method is reliable provided the input variables are determined with reasonable accuracy. By using input values typical of a relatively urbanized area, this procedure indicates that a minimum pay factor of about 60 percent is appropriate for the poorest quality work and a maximum pay factor of about 115 percent is justified for work of truly superior quality. Additional factors are cited that, although unquantified, would tend to lower the minimum pay factor and raise the maximum pay factor. Finally, pay schedules are developed, the operating-characteristic curves of which closely approximate the theoretically derived relationship.

**Weed, R. M., *Statistical Specification Development*, FHWA/NJ-88-017, New Jersey Department of Transportation, 1989, 318 pp.**

This report combines a substantial amount of new material with material from more than a dozen recent Transportation Research Board papers to provide guidance in all phases of statistical specification development. Written at a level that assumes the reader has a familiarity with basic quality assurance principles and terminology, it develops several original concepts in detail. An interactive computer program for the development and analysis of statistical acceptance procedures is described. Also included is the Fortran coding for several subroutines useful for computer simulation and a variety of other statistical applications. Finally, the implementation of a statistical specification for portland cement concrete based on many of these principles is described.

**Weed, R. M., "Unbiased Graduated Pay Schedules," *Transportation Research Record* 745, Transportation Research Board, 1980, pp. 23-28.**

The bias present in conventional graduated pay schedules and alternative graduated pay schedules designed to be unbiased are presented in this report. Conventional graduated pay schedules are biased in the sense that, on the average, they provide less than 100 percent payment for a product that is exactly at the acceptable quality

level. The quality index on which they are based is an essentially unbiased indicator of the percent defective of the population, but because the highest level in the pay table is 100 percent, the average pay factor will usually be somewhat less. This may create serious problems in certain instances, but can be overcome by developing unbiased pay schedules that are linear functions of the estimate of the population percent defective. This approach can be applied to both continuous and stepped pay schedules and, in both cases, pay factors greater than 100 percent are permitted. These are used to establish credit that may be applied to offset lower pay factors within specified time intervals throughout a construction project. This method is mathematically sound and produces the desired average pay factor at all quality levels. It is not the same as a bonus provision because the overall pay factor for each time period is still limited at 100 percent. The preparation of tables for estimating percent defective is reviewed, and both continuous and stepped pay schedules based on this measure are developed. Operating characteristics curves and optimization curves are presented to compare these approaches and assess their effect on bidding strategies.

**Welborn, J. Y., *State-of-the-Art in Asphalt Pavement Specifications*, Final Report, Report No. FHWA-RD-84-075, Federal Highway Administration, July 1984, 180 pp.**

This report summarizes the development of asphalt pavement specifications from 1950 through the 1980s, with primary emphasis on the state of the art in 1984. The great increase in highway construction beginning in the 1950s made evident the need for better control of materials and construction. A comprehensive research and development program was begun to use statistical methods for quality assurance in highway construction. The effort since has resulted in quality control and acceptance plans that are used in specifications to some degree by more than 30 States. The quality assurance specifications usually assign the responsibility for control of materials and construction to the contractor. Acceptance and method for pay adjustment for noncompliance are highway agency responsibilities; surveys show a wide disparity in pay adjustment factors. Performance-related specifications based on distress modes and contributing factors are also described. Studies indicate that the most predominant forms of distress are cracking (load and nonload), distortion, disintegration, roughness, and reduced skid resistance. Contributing material factors and evaluation methods are outlined for each of the performance-related distress modes. The report also summarizes the problem of reflection cracking, its contributing factors, and methods of overlay design and special treatments to prevent or minimize this form of distress condition. Recommendations are to encourage the effort to continue development of quality assurance specifications based on sound engineering judgment and to develop detailed performance-related specifications with optimum mix-design requirements to meet the need for structural capacity, rideability, and skid resistance.

Whiting, D. A. and S. D. Tayabji, *Relationship of Consolidation to Performance of Concrete Pavements*, FHWA/RD-87/095, Federal Highway Administration, February 1988, 144 pp.

A study was made of the influence of consolidation on properties of portland cement concrete. Consolidation was found to have a strong influence on compressive strength, bond of concrete to reinforcing steel, and permeability of concrete. There is a lesser effect of consolidation on resistance to freezing and thawing. There is a loss of about 30 percent in compressive strength for every 5 percent decrease in consolidation. As part of the study, a variety of nuclear density gauges were evaluated for use in monitoring consolidation of concrete. A model acceptance sampling plan for concrete consolidation is proposed. The plan provides for buyer's and seller's risks of 5 percent and was tested in Idaho and Iowa. The field testing indicated that monitoring concrete pavement consolidation is practical and economically feasible.

Willenbrock, J. H., *A Manual for Statistical Quality Control of Highway Construction, Volume I*, Purchase Order No. 5-1-3356, Federal Highway Administration/National Highway Institute, January 1976.

A number of agencies are currently implementing or are seriously considering the implementation of highway construction specifications that are based on the principles of statistical quality control. This manual was developed to assist in the understanding of statistical quality control and in the implementation of those types of specifications. The first volume has been designed to provide a coverage of the basic statistical concepts and techniques that form the foundation for statistically based specifications.

Willenbrock, J. H. and P. A. Kopac, *A Methodology for the Development of Price Adjustment Systems for Statistically Based Restricted Performance Specifications*, Final Report, Report Number FHWA-PA-74-27(1), Pennsylvania Department of Transportation, October 1976, 169 pp.

This report presents a methodology that can be used to develop price adjustment systems suited for statistically based, restricted performance specifications. An example of the use of this methodology for a specific situation, that of bituminous concrete paving for the Pennsylvania Department of Transportation, is also presented. Three approaches are proposed for the development of a price adjustment system. These are:

- The performance or serviceability approach.
- The cost of production approach.
- The trial-and-error operating characteristic curve approach.

A fourth approach, the cost of quality control, is also examined, but cannot be fully developed at this time because of the limited cost data that are available.

Willenbrock, J. H. and P. A. Kopac, "Development of Price-Adjustment Systems for Statistically Based Highway Construction Specifications," *Transportation Research Record* 652, Transportation Research Board, 1977, pp. 52-57.

This paper is essentially a summary of the above report entitled, "A Methodology for the Development of Price Adjustment Systems for Statistically Based Restricted Performance Specifications."

Willenbrock, J. H. and P. A. Kopac, "Development of a Highway Construction Acceptance Plan," *Transportation Research Record* 691, Transportation Research Board, 1978, pp. 16-22.

Acceptance plans are being developed for highway construction inspection that require that the quality of a lot submitted by a contractor for acceptance be estimated by calculating the percentage that meets specification limits. This type of acceptance plan was initially developed in the early 1950s for use in Military Standard 414 for the inspection by variables of government procurement. The theory that underlies such acceptance plans is presented. Tables developed to facilitate the estimation of lot quality from small sample sizes are given. Four cases are considered:

1. Both the population mean and population standard deviation are known.
2. The population mean is known and population standard deviation is unknown.
3. The population mean is unknown and population standard deviation is known.
4. Both the population mean and population standard deviation are unknown.

In the fourth case, the one that most often applies in construction situations, two methods of estimation are possible: the range method and the standard deviation method. Although the range method has been used exclusively in highway construction, it is suggested that consideration be given to using the standard deviation method.

