ACCEPTANCE PROCEDURES FOR DENSE-GRADED MIXES

Literature Review

SPR 323

RESEARCH

Oregon Department of Transportation

ACCEPTANCE PROCEDURES
FOR DENSE-GRADED MIXES

Literature Review

SPR 323

by

James R. Lundy
Department of Civil, Construction and Environmental Engineering
Oregon State University
Corvallis, Oregon 97331

for

Oregon Department of Transportation
Research Group
200 Hawthorne Ave. SE, Suite B-240
Salem, Oregon 97301-5192

and

Federal Highway Administration
400 Seventh Street S.W.
Washington, D.C. 20590

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16. Abstract

Recent literature related to acceptance procedures for dense-graded mixtures is summarized. Current state of practice and development of acceptance procedures are reviewed. Many agencies are reducing the number of process control-related parameters included in their specification (e.g., gradation), moving toward an end-result specification. End-result specifications are suited to Oregon's needs at present; however, performance-related specifications currently do not appear to be suited to Oregon needs. Many agencies are increasing the use of mix volumetrics in specifications, in part because the use of Superpave mixes is increasing and these mixes are designed using mix volumetrics. Recommended specifications for Superpave and stone-matrix asphalt mixes are available and have been implemented by some states. Pay factor equations have been formulated that allow separation of the parameter mean and standard deviation, thus encouraging the contractor to hit the job mix formula target and minimize the process variability.

Implementation of any specification requires the development and analysis of operational characteristic curves, and these curves can only be developed if acceptable and rejectable quality levels and owner and contractor risks can be defined. Computer programs are available that allow the rapid development of these curves. Simulation of the performance of specifications, as well as analysis of contractor and owner risks, are also possible through the use of simulation software such as ILLISIM.

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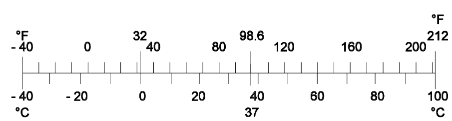
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	Megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement (4-7-94 jbp)

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This report does not constitute a standard, specification, or regulation.

ACCEPTANCE PROCEDURES FOR DENSE-GRADED MIXES
LITERATURE REVIEW

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1.0 INTRODUCTION

The Oregon Department of Transportation (ODOT) began using statistical specifications for asphalt pavements with provisions for incentives and disincentives in 1985. The goals of these specifications are to remove bias from the inspection process and provide contractors with incentives for quality control efforts that result in an improved product. Improvements in product quality are judged through the measurement of mix component characteristics under the assumption that these characteristics can be related to improved pavement performance.

1.1 PROBLEM STATEMENT

It is assumed that a field-placed mix adhering to the job mix formula (JMF) will provide economic long-term performance, provided that other construction controls are met (thickness, smoothness, etc.). Under the current specification, if the aggregate gradation, asphalt content and level of compaction stay within broadband limits, contractors are rewarded for the consistency of the produced mix rather than how closely the field-placed mix agrees with the job mix formula (JMF). Thus, incentives may be paid for mixes that do not necessarily provide superior long-term performance.

ODOT continues to implement the Superpave technology. Superpave mixes are currently designed and field controlled using volumetrics. Many of the volumetric parameters included in Superpave are not currently included in ODOT acceptance/pay factors. If the full implementation of Superpave mixes is to continue, then appropriate acceptance procedures must be developed.

Finally, current pay factor items may not be sufficient to ensure high-quality pavement performance. Other constituents such as pavement smoothness, thickness, voids in mineral aggregate, voids filled with asphalt may provide better control of pavement quality.

1.2 BACKGROUND

A questionnaire was distributed to ODOT project managers, region materials inspectors and region assurance specialists in 1990. The majority of ODOT highway construction personnel favored the use of incentive/disincentive specification. Survey results showed that 76 percent believed that the bonus pay system improved cooperation with the contractors, and that 57 percent considered the bonus pay system effective (*Scholl 1991*). Despite the general approval of the pay factor specification for dense-graded mixture, some concerns have been recently raised.

The Oregon Department of Transportation paid incentives for dense graded mixes totaling approximately $6,300,000 and disincentives of about $750,000 between 1985 and 1998. If the Department and the public received an equivalent or greater benefit in terms of improved pavement performance, then the money was well spent. However, there is some evidence suggesting that the payment of incentives is not always associated with improved pavement performance (*Remily 1999*).

ODOT reports that on some projects the existing pay factors have not encouraged contractors to effect changes that would improve mix performance. This may be due to the current mean/standard deviation approach used to establish mix acceptance and project incentives. Under this approach, contractors are rewarded for minimizing the variation of a specific mix property or quantity (e.g., asphalt content) about the mean of that property. This mean may or may not be equal to the mix design targets (JMF) established by the ODOT mix design procedure.

There are other statistical techniques available to establish the acceptability of the mix, based on variation of the measured property about a desired value. The conformal index (CI) is a direct measure of process capability and can be used to accurately estimate the size and incidence of deviations from the quality level target, such as the approved target job mix formula (*Cominsky, et al. 1998*). The current standard deviation approach is a measure of precision, and the CI is a measure of accuracy or degree of conformance with the target.

1.3 OBJECTIVES

This study investigates statistical acceptance procedures and makes recommendations to ensure that the pay factor calculations encourage the contractor to make mix and construction adjustments that will improve long-term pavement performance.

Specific objectives include:

1. Determine which factors best relate to pavement quality and should be measured for acceptance and potential incentives/disincentives.

2. Investigate sampling procedures, including frequency and locations of sampling.

3. Using the information gathered above, identify the most appropriate acceptance procedure for dense-graded asphalt mixes. Consideration will be given to the most appropriate statistical method and combination of pay factors.

4. Develop an acceptable implementation plan and evaluate the impacts to verify results.

1.4 SCOPE

This interim report provides a summary of available literature relevant to quality control and quality assurance programs, with the goal of identifying the most important quality acceptance factors for constructing dense-graded asphalt concrete pavements and the means to include them in the pay factor calculation.

2.0 STATE OF THE PRACTICE

The use of contractors to construct public roads, and specifications to control that construction, date from at least the 1850s. Method specifications were described as far back as the mid-19th century (*Gillespie 1849*). Construction specifications have evolved from method specifications, which dictate contractor process, to end-product specifications, which measure material properties that are thought to relate to performance. The next step, performance-related specifications, will directly relate expected pavement performance to measured mix properties. The evolution of construction specifications in the United States is well documented in numerous National Cooperative Highway Research Program (NCHRP) Syntheses. As shown in Table 2.1, these syntheses cover approximately the last 25 years.

Table 2.1: NCHRP syntheses related to specifications

Synthesis Number	NCHRP Title
38	Statistically Oriented End-Result Specifications (1976)
65	Quality Assurance (1979)
102	Material Certification and Material-Certification Effectiveness (1983)
120	Professional Resource Management and Forecasting (1985)
145	Staffing Considerations in Construction Engineering Management (1989)
146	Use of Consultants for Construction Engineering and Inspection (1989)
163	Innovative Strategies for Upgrading Personnel in State Transportation Departments (1994)
195	Use of Warranties in Road Construction (1994)
212	Performance Related Specifications for Highway Construction and Rehabilitation (1995)
232	Variability in Highway Pavement Construction (1996)
263	State DOT Management Techniques for Materials and Construction Acceptance (1998)

2.1 BRIEF HISTORY OF SPECIFICATIONS

The most complete summary of the development of highway construction specification is available in NCHRP Synthesis 212 (*Chamberlin 1995*). The very thorough documentation contained in that report will not be repeated here. There are some critical events impacting the development of specifications that are worth summarizing.

Though not the first analysis of variability of highway materials and construction, the AASHTO Road Test (1956-1962) provided the most comprehensive and well-documented measurement of variability. The Road Test specifications were intended to represent specifications typical of those used on a large highway construction program (*Carey and Shook 1966*). Yet despite considerable effort, Carey and Shook concluded:

> Briefly summarizing, we want to show that with many more well-trained inspectors than could economically be used in normal construction, with high-speed testing techniques, with a large-scale materials laboratory on site, with the ability to control in detail the contractor's construction procedures, with a highly competent and cooperative contractor who was well paid for everything he was required to do, and the eyes of the highway fraternity on the back of our necks, we were still unable to meet the specifications of many of the construction items within a country mile.

The magnitude of the measured variation at the Road Test surprised many highway engineers (*NCHRP Syntheses 38 and 65*). Carey and Shook went on to say:

> Sampling plans now being used are not adequate for estimating the true characteristics of materials or construction items for which the specifications are written, and certainly cannot guarantee 100 percent compliance to the specification limits.

In addition to the revelation that construction variations were higher than expected, several high-profile highway failures occurred about the time of the AASHO Road Test. The failures resulted in the formation of a U.S. Congressional Committee, and ultimately Congress threatened to pass laws making it a federal offense to "knowingly incorporate" any non-complying materials in highway work (*NCHRP Synthesis 38*). Changes in the traditional acceptance procedures and a higher level of accountability were required, given the documented AASHO Road Test construction variability and Congress' threat to become involved in construction specification (*Chamberlin 1995*).

The events of the 1960s led to alternate methods of measuring the characteristics of materials and construction (M&C) items and their compliance with specification limits. These efforts eventually were termed "statistical quality assurance (SQA)" or "end result specification (ERS)." These alternate methods recognized the inherent variability of M&C variables and acknowledged that 100 percent compliance was impractical.

The development of the new standards led to increased communication between the contractor and the agency regarding the feasibility of 1) contractors assuming more responsibility for quality control, and 2) highway agencies judging acceptance on the characteristics of the end product (e.g., end result). The standards ultimately distinguished between the responsibilities of the vendor (for quality control) and the purchaser (for specification and quality assurance). One consequence of this process was that more rapid testing methods were developed (*Halstead 1993*).

The elements of an ideal quality assurance system were described by Chamberlin in 1968 and are shown in Figure 2.1. Although not specifically described in Chamberlin's model, both statistically based sampling and acceptance criteria are essential to a successful specification.

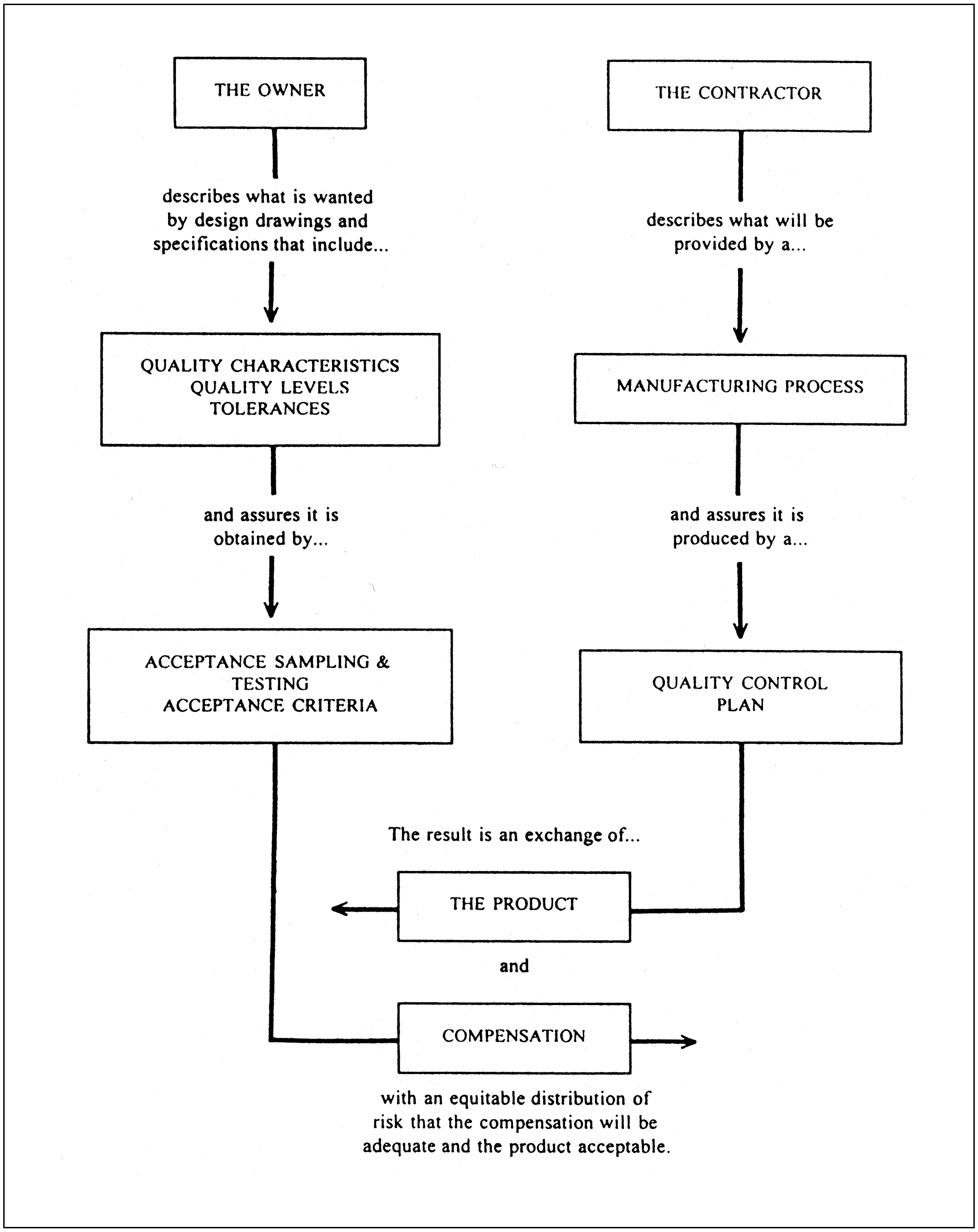

Figure 2.1: Elements of an ideal quality assurance system (after *Chamberlin 1968*)

Many SQA techniques were adopted from the procurement procedures developed by the U.S. Department of Defense (*Military Standard 414 1957*). Early implementations of end result specifications only included disincentives. These adjustments allowed the acceptance of materials deficient in terms of specification, but not without value, as an alternative to removal. Most of the early disincentives were related to the loss of pavement performance through the judgment of agency engineers.

The quality assurance system shown in Figure 2.1 implies that compensation will be commensurate with the acceptability of the product. Incentives as well as disincentives should be a part of the ideal quality assurance system.

Full implementation of statistical end result specifications proceeded slowly even though the applicable statistical sampling and decision theory had been fully developed for highway construction by the early 1970s (*Chamberlin 1995*). In particular, agencies were slow to implement incentives. This was due, in part, to the reasons cited by Chamberlin: 1) the inability to identify or measure the essential performance-related characteristics of the end product; 2) the inability to quantify substantial compliance and to determine price adjustment factors that relate to reduced or enhanced value; and 3) the uncertainty as to value to be gained from the cost of implementing statistically based end result specifications (*Chamberlin 1995*).

Chamberlin suggests that while the use of end-result specifications may improved compliance and provide improved evidence of compliance, in themselves they do not guarantee improved performance. Improved performance relies on understanding the relationship between factors controlled during construction and the performance of the finished product. As will be discussed below, these relationships are only just beginning to emerge.

2.2 RECENT DEVELOPMENTS

Despite the fact that definitive performance relationships are not yet available for most factors controllable during construction, the development of quality assurance specifications continues. In fact there has been a call for a national policy for the management of quality (*Afferton, et al 1992*). Several recent surveys suggest that many agencies have implemented some form of quality assurance specifications, many with some form of incentive/disincentive pay schedule.

2.2.1 Current Practice

NCHRP Synthesis 232 (*Hughes 1996*) reports that 42 of 48 respondents to a survey stated they included incentive or disincentive in their pay schedule, while four did not. Asphalt concrete material or construction factors for which incentives or disincentives are used are shown in Table 2.2. Disincentives were used more frequently than incentives except for ride quality. At the time of this survey, volumetric properties were not routinely used on pay factor calculation.

Table 2.2: DOT use of incentive and disincentive pay schedules (after *Hughes 1996*)

Material Property or Construction Factor	Incentive	Disincentive
Aggregate Gradation	6	21
Asphalt Content	8	25
Volumetric Properties	3	10
Compaction	14	31
Thickness	5	26
Ride Quality	21	25

In NCHRP Synthesis 263 (*Smith 1998*), 35 of 41 survey respondents indicated that they included some form of incentive/disincentive as part of their materials and construction acceptance process. Thirty-one of the 35 agencies reported some form of incentive/disincentive for hot-mix asphalt as shown in Table 2.3. Acceptance specifications that include smoothness are the most common (21 of 31) followed by density specifications (14 of 31). Specification incentives or disincentives associated with thickness are the least common. The survey was sent to Departments of Transportation in September 1996. Detailed information on the characteristics of these specifications was not available.

Table 2.3: HMA specification attributes with incentive/disincentive factors (after *Smith 1998*)

State	HMA Density	HMA Mix	Asphalt Content	Aggregate Gradation	HMA Thickness	Smoothness
Alabama	x	x	x			x
Alaska	x			x		
Arkansas		x				x
Arizona						x
Connecticut	x			x		
California	x	x	x	x		
Illinois					x	x
Iowa						x
Maine	x		x	x		
Maryland	x		x	x		x
Michigan	x					x
Minnesota						x
Missouri						x
Nebraska						x
New Hampshire		x				
New Jersey		x				x
New Mexico	x	x	x	x		
Nevada		x				
North Carolina						x
North Dakota						x
Ohio						x
Oklahoma	x		x	x		x
Pennsylvania	x		x		x	x
South Carolina	x				x (base)	x
Tennessee			x	x		x
Texas		x				x
Utah	x		x	x		
Vermont		x				
Washington	x		x	x		
Wisconsin						x
Wyoming	x			x		x
Totals	**14**	**9**	**10**	**11**	**3**	**21**

Mahoney and Backus reported the results of a survey conducted in April 1999 (*Mahoney and Backus 1999*). Although fewer states responded to the questionnaire than to the Synthesis 263 questionnaire, the results provide additional information on SQA specifications in use and under development. Twelve responses were received from 50 states surveyed. Quality control and assurance results are summarized in Table 2.4. Most agencies require contractor QC measures on mix process (i.e., binder content, gradation) or construction (i.e., density) elements that are amenable to rapid testing/reporting. Volumetrics (i.e., VMT, VMA) are also included by many agencies. Quality assurance measures generally follow the QC program requirements, with 6 of the 12 states requiring or developing a smoothness requirement.

Table 2.4: 1999 specification information (after *Mahoney 1999*)

State	Contractor QC Requirements				Agency QA Requirements				
	Aggregate Gradation	Binder Content	In-Place Density	Volumetrics	Aggregate Gradation	Binder Content	In-Place Density	Smooth -ness	Volumetrics
AR	x	x	x	VMT, VMA	x	x	x	x	VMT, VMA
FL	x	x	x	VMT	x	x	x	x	VMT
IN	x	x	x	VMT, VMA	x	x	x	x	
KY	x	x	x	VMT, VMA		x	x		VMT, VMA
OH	x	x	x[1]		x	x	x		VMT, VMA
OR	x	x	x	VMT, VMA, VFA[2]	x	x	x	x	VMT, VMA, VFA
RI					x	x	x		
SC	x	x				x	x		VMT, VMA
WA					x	x	x		
WI	x	x	x	VMT	x	x	x	x	VMT
WY	x		x	[3]	x	x	x	[4]	

Notes: [1] Contractor option
[2] Also smoothness, moisture in mix
[3] Mix verification during startup, then once per 20,000 tons
[4] Under development

The 1999 survey reported by Mahoney and Backus also included several other questions on QC/QA requirements (*Mahoney and Backus 1999*). The following statements summarize the responses of the states reporting QC/QA programs:

- Almost all agencies reported that the QC program increased the quality of work performed by the contractor.
- The "typical" QA spec has been in service about 9 years. Most states revise their QA program annually or biannually.
- Only one state (IN) reported the statistical risk to the seller (α) or buyer (β).
- One-third of the states (4) reported that no incentives were allowed; the reminder reported maximum incentives ranged from 105 to 112 percent. Of these states, the average incentive was 103 percent.
- Of the states allowing incentives, most reported that the percentage of jobs receiving bonuses ranged from 60 to 100 (average 85 percent). One state (AR) reported that only 20 percent received bonuses.
- Of the ten states responding to the question, eight reported that virtually no lots were rejected during a typically year. Two reported that "some" (between 10 and 50 percent) lots were rejected.
- Quality assurance lot sizes ranged from 750 tons to 5,000 tons. Some states varied lot size with the attribute tested or use of the material (e.g., base or surface course).

In addition to collecting information on the general use and nature of QC/QA specifications, the survey by Mahoney and Backus asked for copies of current specifications allowing direct comparisons of some elements. Binder content tolerances and density limits are shown in Table 2.5. Other information taken from these states' specifications are reported in the Mahoney report. The report notes that states have developed a wide array of quality requirements and specifications despite the fact that in each case the end product serves essentially the same function (*Mahoney and Backus 1999*).

Table 2.5: Binder content and density requirements

State	**Binder content tolerance**	**Percent Density Requirements [1]**
Florida	+/- 0.55%	96 [2]
Indiana	+/- 0.30 to +/- 0.70% [3]	91.5
Kentucky	+/- 0.50%	96 [2]
Minnesota	+/- 0.4%	91.5
Ohio	+/- 0.6%	92
Oregon	+/- 0.5%	92
Washington	+/- 0.5%	91
Wyoming	+/- 0.25%	92

Notes: [1] Percent of maximum specific gravity unless otherwise noted
[2] Percent of valid control strip density
[3] Depends on number of samples taken

Most states reported using the quality level approach to determine the percent defective or percent within limits (PD and PWL, respectively). The quality level approach is currently used by ODOT. Alternate approaches are discussed below.

2.2.2 Conformal Index

An alternative to the standard deviation approach to specifications is the statistic referred to as the conformal index. The conformal index (CI) is a measure of variation like the standard deviation. However, the comparator is a quality level target (i.e., JMF asphalt content) rather than the mean as is the case for the standard deviation. In other words, the standard deviation is a measure of precision, and the CI is a measure of exactness (accuracy) of degree of conformance with the target. In equation form,

$$\sigma = \frac{\sqrt{\quad (x - \bar{x})^2}}{(n-1)} \qquad CI = \frac{\sqrt{\quad (x - T)^2}}{n} \qquad \textbf{(2-1)}$$

Where T = a target value (JMF) such as design thickness, density, etc.

The attractiveness of the conformal index in QC/QA specifications is that it focuses attention on a target value, and it is this target value that defines the quality level. The CI can be used with either percent within limits (PWL) or percent defective (PD) specifications. Additionally, because the CI normalizes to a target value, direct comparisons may be made by the contractor as to the magnitude of variation about the target for QC purposes; comparisons by the agency of the contractor's conformance to the specification for acceptance purposes; and, if desired, comparisons of performance between contractors, projects, etc. (*Cominsky, et al. 1998*) Tolerance limits for a conformal index approach are shown in the section on Superpave mixes.

Weed examined three measures of variability – average absolute deviation (AAD), conformal index (CI) and percent defective (PD) – to determine the ability of each to discriminate between different distributions (*Weed 1999*). Three hypothetical scenarios were developed, one for each measure of variability as shown in Figure 2.2.

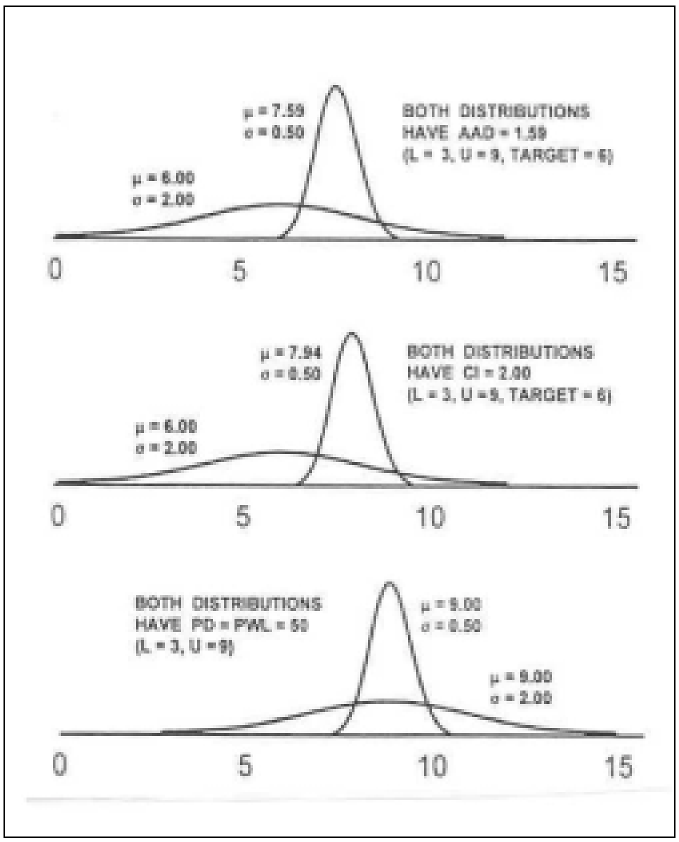

Figure 2.2: Potential weaknesses of common statistical measures of quality (*Weed 1999*)

The figure shows that none of the quality measures are able to distinguish between distributions that would be expected to produce markedly different levels of performance.

Both AAD and CI calculations are based on a target value (usually midway between the upper and lower specification limits). This approach is well suited to use with two-sided specification limits but not well suited to use with a one-sided specification limit for which a single target cannot be defined. Overlay thickness would be one example of a one-sided limit that would not be suited for use with the conformal index.

Weed also points out that the traditional PD approach, and its complement, percent within limits (PWL), have drawbacks when used with one-sided limits. For PWL values above 50, a decrease in standard deviation (with no change in the mean) cause the PWL to increase. However for PWL values less than 50, just the opposite effect occurs. Therefore, unless performance is independent of variability, there could be inconsistency in acceptance procedures particularly as the PWL approaches 50 percent. The alternate approach proposed by Weed is described below.

A different means of incorporating mean and standard deviation into specifications is presented by Weed (*Weed 1999*). This approach avoids the problems of the traditional PWL (PD) approach as well as those of the conformal index and average absolute difference noted above. Weed presents the following general forms of pay equations:

Single Lower Limit:

$$PF = 100 + A\left[\frac{\left\{\bar{x} - B(s) - LIMIT\right\}}{LIMIT}\right] \quad \textbf{(2-2)}$$

Single Upper Limit:

$$PF = 100 + A\left[\frac{\left\{LIMIT - \bar{x} - B(s)\right\}}{LIMIT}\right] \quad \textbf{(2-3)}$$

Double Limits:

$$PF = PF_{MAX} - A\left[\frac{\left\{ABS(\bar{x} - TARGET) + B(s)\right\}}{TARGET}\right] \quad \textbf{(2-4)}$$

Where

PF	=	pay factor (percent),
PF_{MAX}	=	maximum pay factor for double-limit specification,
A, B	=	equation coefficients,
x	=	sample average,
s	=	sample standard deviation,
LIMIT	=	limit for single-limit specification,
TARGET	=	target value for double-limit specification,
ABS	=	absolute value operator.

Equations of this form avoid some of the weaknesses noted for the CI, AAD, and traditional approach. The coefficients A and B would be determined based on the performance of the pavement as affected by the measure under question. The coefficient B is dependent on the sample size since the standard deviation is not an unbiased estimate of the population standard deviation.

Equation 2-2 provides for higher pay factors as the sample mean moves further above a single specification limit and as the standard deviation becomes smaller. Similarly Equation 2-3 yields higher pay factors as the sample mean moves farther below the upper specification limit. Equation 2-4 provides higher pay factors as the sample average approaches the target and as the standard deviation decreases. Equations 2-2 and 2-3 may add or subtract from the constant pay factor of 100. Equation 2-4 could pay incentives up to a maximum of PF_{MAX}. All the pay factors could be limited to some agency-selected maximum (i.e., 105).

Weed also provides for greater flexibility by applying exponents to the terms shown in Equations 2-2 through 2-4. This refinement (shown in Equations 2-5 through 2-7) may be necessary if it were found that performance declined increasingly rapidly as the mean shifts or the standard deviation increases.

Single Lower Limit:

$$PF = 100 + A\left(\frac{\bar{x} - LIMIT}{LIMIT}\right)^C - B\left(\frac{s}{LIMIT}\right)^D \qquad \textbf{(2-5)}$$

Single Upper Limit:

$$PF = 100 + A\left(\frac{LIMIT - \bar{x}}{LIMIT}\right)^C - B\left(\frac{s}{LIMIT}\right)^D \qquad \textbf{(2-6)}$$

Double Limits:

$$PF = PF_{MAX} - A\left(\frac{ABS(\bar{x} - TARGET)}{TARGET}\right)^C - B\left(\frac{s}{TARGET}\right)^D \qquad \textbf{(2-7)}$$

The paper (*Weed 1999*) provides comparisons between the traditional and proposed approaches for both single and double-sided specifications.

2.2.3 Composite Pay Factors

The use of composite pay factors is not new. Many agencies compute a composite pay factor by first calculating individual pay factors (PF) and then combining these using a weighting scheme. The weighting often follows a linear format such as that currently used by Oregon. The magnitude of specific weighting factors is selected using engineering experience, laboratory or field performance data, design equations or some combination of these elements.
Currently Oregon DOT includes the constituents shown in Table 2.6 in their HMA price adjustments.

Table 2.6: AC price adjustment factors (after *ODOT 1996*)

Constituent	Weighting Factor, f
All aggregates passing 37.5, 31.5, 25.0, 19.0 and 12.5 mm sieves	1
All aggregates passing 6.3 mm	5
All aggregates passing 2.00 mm	5
All aggregates passing 425 µm	3
Aggregate passing 75 µm sieve	10
Asphalt	26
Moisture content	8
Compaction (density)	40

The composite pay factor is based on the sum of the individually computed pay factors times the appropriate weighting factors divided by the sum of all weighting factors with an upper limit of 105. As can be seen, approximately 25 percent of the composite pay factor is based on aggregate gradation control. Although the specific weighting factors and constituents vary from state to state, the basic format currently used by ODOT is in use in many other states.

Weed (*Weed 2000*) proposed the introduction of unique composite pay factors based on the idea that the interaction among individual pay factor constituents should not be ignored. For example, an overlay placed with low asphalt content and low field density is more likely to fail early than an overlay placed with adequate asphalt at low field density. Weed contends that current weighting schemes do not take this interaction into account. A simple example taken from Weed (*Weed 2000*) illustrates the concept.

Assume that only air voids and pavement thickness are to be included as pay factors. Under the traditional approach, the rejectable quality level (RQL) might be set at 75 percent defective (PD) for both constituents. Consider the three scenarios shown in Table 2.7. It can be seen that although Case 3 is clearly the worst case, it does not trigger the RQL provision. Weed used a combination of expert opinion and pavement life modeling to arrive at a curve that separates acceptable from rejectable quality work. Further refinement of this equation allowed the development of a composite pay factor of the form:

$$PD^* = 0.807PD_{voids} + 0.669PD_{thick} - 0.00476PD_{voids}PD_{thick} \quad \textbf{(2-8)}$$

A family of curves developed from this equation is shown in Figure 2.3. A given project with 10 percent defective on both thickness and air voids would have a composite percent defective, PD*, of 14 percent. Similarly, a project with 50 percent defective on both thickness and air voids would have a PD* equal to 62 percent.

Table 2.7: Example of an inconsistent rejection provision (after *Weed 2000*)

Case	Air Voids	Thickness	Rejectable?
1	PD = 10	PD = 75 (RQL)	Yes
2	PD = 75 (RQL)	PD = 10	Yes
3	PD = 74	PD = 74	No

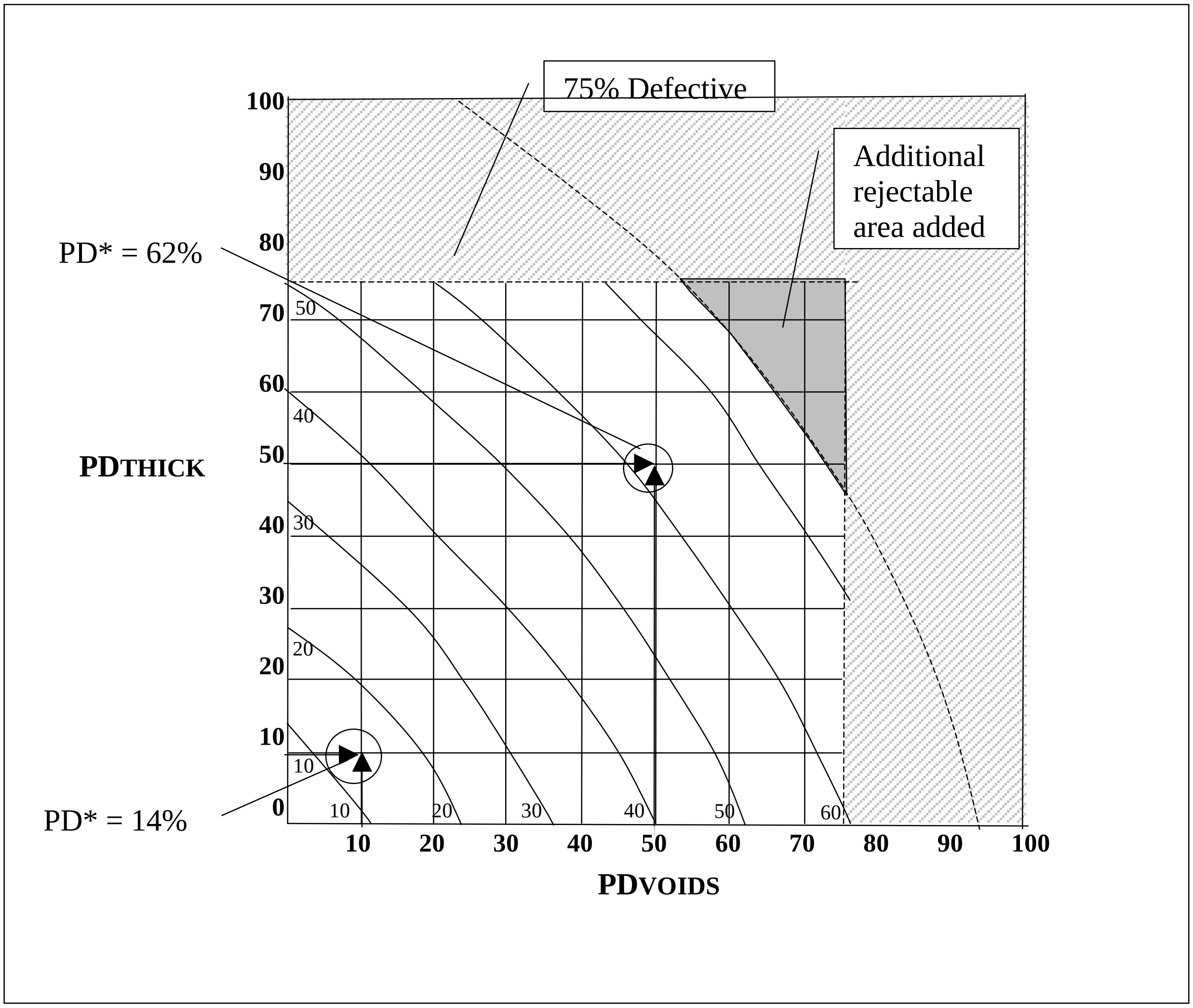

Figure 2.3: Interaction among pay factor constituents (*Weed 2000*)

Additional examination of Figure 2.3 shows that even if an agency's specification allowed rejection of the lot based on any one parameter reaching the RQL (i.e., voids = 75% defective), Weed's approach identifies combinations of parameters that may result in early failures (see the shaded area in Figure 2.3).

This approach is fairly easily implemented when only two or three parameters make up the composite percent defective. The development is considerably more complicated when a fourth or fifth term is added to the equation. Furthermore the extension from a composite percent defective calculation to a composite pay factor relies on the predicted pavement life for a variety of individual percent defective constituents. Given the status of currently available pavement performance prediction models, this extension is difficult.

2.2.4 Performance Related Specifications

Performance-related specifications bring to mind different things to different people, so a set of common definitions is needed. These definitions and associated comments were taken from NCHRP Synthesis 212 (*Chamberlin 1996*).

> A *performance specification* describes how the finished product performs over time. These specifications are not applicable to highway components because the technology is not sufficiently advanced.

The basis for these specifications may result from the Long-Term Pavement Performance project coupled with new tests. The results of these tests would directly relate to the performance of the pavement rather than some mix property.

> *Performance-based specifications* describe desired levels of fundamental engineering properties that are predictors of performance and appear in primary performance prediction relationships. These include properties such as resilient modulus and fatigue that are not amenable to timely acceptance testing.

Performance-based specifications are intended to improve existing levels of quality by focusing on performance properties. Some of the measured materials and construction characteristics cannot be reported to the contractor in a timely manner, precluding adjustments to the construction process.

> A *performance-related specification* (PRS) describes the desired level of material and construction factors that have been found to correlate with fundamental engineering properties that predict performance. These factors are amenable to acceptance testing at the time of construction.

Performance-related specifications are intended to identify the level of quality providing the best balance between cost and performance. Common material factors included in performance-related specifications included air voids, asphalt content, etc.

Presently, the use of performance-related specifications in this country is limited. Chamberlin reported in 1995 that although several federal and state projects were underway, only New Jersey had implemented performance-related specifications and only for PCC and PCC pavements. Subsequent to Chamberlin's report, several projects have worked to develop PRS for use with asphalt concrete.

NCHRP and FHWA funded a five-year study (Westrack) to develop performance-related specifications (PRS) for asphalt concrete. The study was completed February 1, 2000. Initial results of the study were presented during the 2000 TRB meeting at a special one-half day conference. To date, the study has developed PRS based on volumetric factors only. Eventually the Westrack PRS are expected to include elements based on Superpave test results such as those from the SST and IDT. As of early January 2000, these factors had not yet been included in the specifications. Some conference attendees raised questions regarding the broad applicability of these PRS given that all performance data resulted only from testing in Nevada. It is expected that reports will resolve some of these issues, however the use of Westrack-based PRS would require substantial field calibration.

2.3 MIX SPECIFIC SPECIFICATIONS

This project is focused on dense-graded mixtures. Non-traditional dense-graded mixtures such as stone matrix asphalt (SMA) and Superpave mixtures are therefore included within the scope of this project. A transition to Superpave mixes is underway in Oregon, and the use of SMA mixes is increasing. Currently available practice for acceptance of these mixes is described below.

The current ODOT specifications may be accessed at the following internet site: http://www.odot.state.or.us/techserv/roadway/specs/suppl.htm.

2.3.1 Superpave Mixes

A recent NCHRP report (*Cominsky, et al. 1998*) provides guidance on the use of quality control and quality acceptance specifications with Superpave mixes. The report emphasizes that the contractor QC plan is essential to successful Superpave projects. Not all the recommended elements of contractor quality control will be repeated here. Although the report provides excellent guidance on the development and use of control and acceptance procedures, recommendations on pay factors are not included.

Cominsky, et al. recommend a quality acceptance plan that is similar in structure to that currently used by ODOT. The plan determines the total percent within limits (PWL) by first calculating the upper and lower quality indexes (levels). These values are used to estimate the percent within the upper or lower specification limits using tabular values similar to the FHWA tables. The PWL is equal to the sum of the percent within the upper limit and percent within the lower limit minus 100. Recommendations on tolerances on are shown in Table 2.8, based on the use of the standard deviation approach.

Table 2.8: Superpave LTMF tolerances based on standard deviation values (after *Cominsky, et al. 1998*)

Mix Composition Property	Extraction	Nuclear Gauge	Ignition Furnace	Cold Feed
Asphalt Content	± 0.25	± 0.18	± 0.13	
Passing 4.75 mm and Larger sieves	± 3			± 3
Passing 2.36 mm to 150 μm sieves	± 2			± 2
Passing 75 μm sieve	± 0.7			± 0.7
Maximum Theoretical Specific Gravity	± 0.015			
Gyratory Compaction Property				
Air Voids	± 1			
Voids in Mineral Aggregate	± 1			
Voids Filled With Asphalt	± 5			
Bulk Specific Gravity	± 0.022			
Compaction Curve Slope	± 0.40			

As noted earlier, Cominsky et al., also discussed the use of the conformal index approach for use with Superpave mixes as an alternate to the use of standard deviation approach. Recommended tolerances when the conformal index approach is used are shown in Table 2.9.

Table 2.9: Superpave tolerances based on CI values (after *Cominsky, et al. 1998*)

Mix Composition Property	Extraction	Nuclear Gauge	Ignition Furnace	Cold Feed
Asphalt Content	± 0.31	± 0.24	± 0.18	
Passing 4.75 mm and Larger sieves	± 4			± 4
Passing 2.36 mm to 150 µm sieves	± 3			± 3
Passing 75 µm sieve	± 0.8			± 0.9
Maximum Theoretical Specific Gravity	± 0.015			
Gyratory Compaction Property				
Air Voids	± 1			
Voids in Mineral Aggregate	± 1.5			
Voids Filled With Asphalt	± 5			
Bulk Specific Gravity	± 0.028			
Compaction Curve Slope	± 0.50			

Whether acceptance specifications are developed using the standard deviation or conformal index approach, very little information on the performance of Superpave mixes is yet available. This is true nationally and is especially true for Oregon. Certain states are more experienced with these mixes and will likely have performance information available soon. The applicability of this performance information to Oregon is not known.

2.3.2 Stone Matrix Asphalt Mixes

Recent work on specifications for stone matrix asphalt (SMA) mixes is included. An NCHRP report by Brown and Cooley provides guidelines for quality control/quality assurance procedures (*Brown and Cooley 1999*). Many of the recommended QC/QA procedures are not significantly different from procedures used with traditional dense-graded mixes. For example, the authors recommend that standard aggregate and binder testing procedures can be used, so long as provision is made for modified binders as appropriate. Sampling can also be accomplished using standard procedures, although it was noted that SMA mixes are stickier and low binder contents may be reported as a result.

The principal differences are the mixture testing area. Laboratory specimens are to be prepared using a 50-blow Marshall technique (*AASHTO T245*) or with 100 gyrations of the Superpave Gyratory Compactor (SGC). Only 70 gyrations are recommended for aggregates with L.A. Abrasion loss above 30 or when the design traffic levels are less than 1 million ESAL. Air voids in laboratory compacted mixtures should be in the 3-4 percent range. The authors recommend that although Method B of AASHTO T164 is very reliable, it is not suited to field work, due to the length of time needed for the test. They recommend that the asphalt content and gradation should be determined using the ignition furnace (*AASHTO TP53*). The tolerances shown in Table 2.8 are recommended. In-place density should be targeted to 95 percent of maximum theoretical specific gravity. The report also indicates that nuclear density gauges are not as accurate as when used with conventional dense-graded mixes, due to the rough surface texture of SMA mixers. Frequent calibration is therefore required.

Table 2.10: Gradation tolerance for extracted SMA samples

Sieve Size	Percent Passing Tolerance
19.0 mm	± 4.0
12.5 mm	± 4.0
9.5 mm	± 4.0
4.75 mm	± 3.0
2.36 mm	± 3.0
0.60 mm	± 3.0
0.30 mm	± 3.0
0.075 mm	± 2.0
Asphalt Content (%)	± 0.3

3.0 SPECIFICATION DEVELOPMENT

The development of an acceptance specification begins with the identification of measurable mix properties that relate to the desired performance. These properties may include characteristics of the mix itself (i.e., binder content) and properties of the mix after placement (i.e., in-place density). Results from the measurement of the selected mix properties should be available to the producer/contractor and agency in a timely manner, so that production processes can be modified if necessary.

1. <u>Identification of Specification Parameters</u>

Ideally the mix properties should be correlated with pavement performance through explicit relationships. Presently only a few pavement performance models with limited applicability are available. If explicit models are not available, then materials and pavement experts must identify implicit relationships or establish limits for the mix parameter. For example, it is well known that when mix with too much binder is placed, early permanent deformation (rutting) results. While there are laboratory tests that support this relationship, the relationships between field performance and laboratory measurements are not yet well established. Therefore experts must estimate the relationship or determine the reasonable limits for binder content that would minimize the likelihood of rutting.

2. <u>Establish AQL & RQL</u>

Once the models or limits are established, then the pavement experts must establish the acceptable and rejectable quality levels (AQL and RQL, respectively) for each parameter. These two levels were established because it is very difficult to establish a single level of quality that distinguishes between acceptable and rejectable work (*Phillips 1995*). Instead the AQL identifies the range of high quality work while the RQL identifies a minimum quality below which work is rejected. Between the two levels, work is considered to be poor enough to justify a pay reduction but not so poor as to warrant removal (*Weed 1994*). As discussed below, the FHWA and others have provided guidelines for the selection of AQL and RQL.

3. <u>Establish α & β risks</u>

There are risks associated with the acceptance or rejection of construction materials. These risks are inherent in the process, since the true value of a measured parameter cannot be known, only estimated, based on the limited sampling. Variability in the mix itself, sampling procedures, test equipment, and operators all contribute to the overall variability. The risks are of two types. The first type of risk is the contractor's risk, often termed α. This is the risk that the material produced or placed is truly of acceptable quality, but is rejected by the owner (agency). Clearly as this risk increases, the contractor compensates by increasing their bid price to recover the cost of removing acceptable material judged to be of inferior quality. The other risk, β, is the owner's risk that material which should have been rejected is accepted. When inferior quality materials are accepted, the performance of the pavement is adversely affected. The goal of the acceptance plan is to balance these two risks, though perfect balance is rarely achieved.

4. Sampling Plan

Once the AQL, RQL, α and β risks are established, the sampling plan can be developed that meets these criteria. In this context, the sampling plan refers to the number of samples that must be collected to meet the selected criteria (*AASHTO 1995*). AASHTO presents a process for the development of a statistically sound sampling plan. Often criteria require that the number of samples taken is greater than the number of samples historically collected. The cost of increased sampling must be weighed against the benefits of maintaining the desired levels of risk. When fewer samples are collected (or greater), then the α and β risks change even though the AQL and RQL remain constant.

5. OC Curves

The establishment of AQL, RQL, α and β also allow the operational characteristics (OC) curve to be developed. This well-established analytical procedure provides a graphical representation of the discriminating power of the acceptance procedure and ensures that the procedure is fair and effective. Details of OC curves are described below.

6. Pay Factors Established

Finally, the standard OC curve must be extended to include the expected pay factor. The revised OC curve graphically demonstrates the probable pay factor associated with each level of quality. Fairness dictates that when the contractor produces material at a quality level equal to that deemed acceptable by the agency (e.g., AQL), then they should on average receive the full bid price (e.g., pay factor = 1.00). The opportunity to earn at least some degree of bonus payment is necessary in order for a statistical acceptance procedure to pay an average of 100 percent when the work is exactly at the AQL (*Weed 1995*).

When multiple parameters are to be included in the specification, then the individual pay factors may be combined in some way to form a composite pay factor. Alternately, the minimum pay factor from among all pay factors may be used to compute contractor compensation (*Scholl 1991*). Several methods of combining pay factors to form a composite are used. Most agencies use some linear combination of pay factors with weighting factors applied to each component. The agency or a panel of pavement experts and contractors typically determines weighting factors.

In addition to the steps described above, the size of lot to be sampled, number of samples (sublots), location of sampling (means of locating sample within sublot), size (quantity) of sample, appropriate test method, and action to be taken with result (non-compliance action, hold for total lot results, etc.) must be incorporated into the acceptance plan (*Puangchit, et al. 1982*). Each of these facets of the acceptance plan must be communicated to contractor and agency personnel.

3.1 ELEMENTS OF QUALITY ACCEPTANCE

A variety of parameters is used in HMA acceptance plans. As agencies move from prescriptive method specifications to performance-related specifications it appears that the number of parameters is reduced. In part, this trend is related to the goals of allowing the producer/contractor to innovate and control their process. As performance models that are more generally applicable become available, it may be that simple test(s) will allow the number of included parameters to be further reduced. This trend is shown schematically in Figure 3.1 and demonstrates that agency involvement would be reduced even further if warrants or design/build options were used.

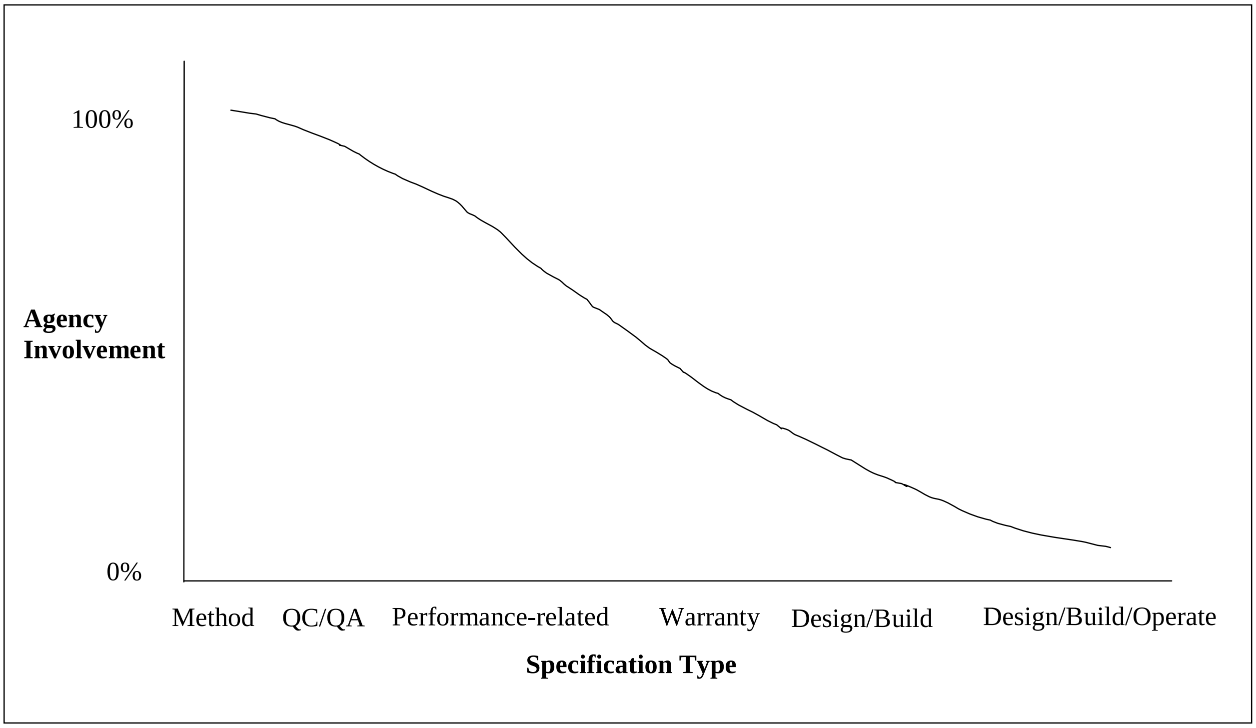

Figure 3.1: Agency involvement in HMA specifications (after *Schmitt, et al. 1998*)

The cost associated with acceptance testing is also of interest. Schmitt summarized information on the time required to complete various acceptance testing supplied by both agencies and contractors (*Schmitt 1998*). These data are shown in Table 3.1. The data provide a practical means of establishing the frequency of testing based on contractor production.

Table 3.1: Minimum time requirements for HMA tests (after *Schmitt 1998*)

Test	Time, hours	Number of tests per 10-hour workday
Aggregate Gradation		
Coldfeed	1.75	5
Hot Bins	2.00	5
Plant Mixing		
Asphalt Content – Extraction	1.25	8
Asphalt Content – Ignition	1.00	10
Aggregate Gradation	2.50	4
Volumetrics	2.25	4
Density		
Cores	0.50	20
Nuclear Density Gauge	0.20	50

Acceptance plan parameters generally fall into one of two categories, production/mix property measurements or construction parameters. Each of these categories is discussed below.

3.1.1 Production/Mix Properties

The properties of the mix or mix constituents are measured either before or after mixing is completed. Often the mix is sampled and laboratory compacted specimens are prepared. The properties of the specimen are measured, and the values are compared to the job mix formula (JMF) values. As discussed below, sampling may be conducted on a quantity basis (i.e., once per 500 tons) or on a time basis (once every three hours). Quantity-based sampling has several advantages over time-based sampling. A given quantity of material can be tracked through plant mixing and laydown operations. Potential mix storage problems can be avoided and both small and large producers are tested at the same rate.

A recent paper by Schmitt, et al. surveyed state agencies and contractors to determine current practice with respect to acceptance testing (*Schmitt, et al. 1998*). Some of the survey results are summarized below.

3.1.1.1 Gradation

Schmitt reported results on the role of gradation in acceptance testing for forty state agencies (*Schmitt 1998*). The majority of agencies (30 of 40) use tonnage to define sublot and lot size, with sublot sizes ranging from 500 to 2000 tons. Some agencies use time to specify sublot and lot, for example one test for each three-hour increment. Other agencies only test aggregate gradation once for each mix design. Aggregates are sampled on the coldfeed or from the hot bins (17 of 41), from the truck (15 of 41) or from the mat (9 of 41). The most common measure of acceptance is quality level analysis similar to that currently used in Oregon.

The Oregon procedure currently includes up to nine aggregate sizes in their acceptance specification for dense-graded mix, depending on the maximum aggregate size. Schmitt reported that the most common aggregate sieve size used in pay adjustments is the 75 μm (25 of 40). The next most common sieve sizes are the 2.36 and 4.75 mm.

Although the majority of states report using weighted pay factors (25 of 38) to compute the composite pay factor, no consensus was found in the weighting factors assigned. Twelve states specify that the minimum individual pay factor be used in computing the composite pay factor (*Schmitt 1998*). For example, if binder content and density are each PWL = 90 but the air voids are PWL = 80, then the PWL 80 would be used to compute the composite pay factor.

3.1.1.2 Mix Volumetrics

According to Schmitt, twenty-nine of forty-two state agencies specify mix volumetrics in their acceptance plans. Most agencies (15 of 29) sample the mix from truck while nine sample from the mat. Plant discharge is used by only four of the 29 agencies. Air voids is the most common mix volumetric reported, followed by voids in mineral aggregate. Only one state reports using void filled with asphalt, and one state includes the theoretical maximum specific gravity. As noted above, an increased use of mix volumetrics is expected as more states move to the Superpave system.

3.1.1.3 Performance Indicator Tests

Although some form of strength/performance tests is routinely conducted during the mix design phase, very few states currently use any "strength" tests as part of their acceptance plan. Schmitt reported that two of forty-two states use stability testing while the other agencies do not include any strength testing in their acceptance plan. Work is underway to develop a performance test suited to use in mix design and acceptance testing. The implementation date of the device is not known but is expected to be several years in the future.

3.1.2 Construction Elements

Many agencies include density, smoothness or both in their acceptance plans. Smoothness is particularly important because this parameter is most closely relative to the public's perception of the quality of the project.

3.1.2.1 Density

Most state agencies measure field density based on sublots and lots described by tonnage, though a few states specify a lot based on area (*Schmitt 1998*). Approximately equal numbers of agencies use cores and nuclear density gauges. Most states follow the ASTM D2950-91 recommendation that at least seven cores/nuclear density measurements be used to establish the conversion factor. Most states reference the theoretical maximum specific gravity (TMD) while some state use the laboratory maximum specific gravity for their reference density. Schmitt reports that more states are planning to use TMD based on Superpave procedures.

3.1.2.2 Smoothness

Of the forty agencies responding, 26 reported including smoothness in their acceptance procedures. Fourteen did not include smoothness. The majority of the 26 agencies used 0.1 mile as the sublot size and the total project length as the lot size. Twelve of 26 agencies used the California Profilograph and judged acceptability based on the Profile Index (PI). No information was available on whether the PI was computed by hand or by means of computer evaluation. Blanking band vary from zero to 0.2 inch. Increasing use of profilers is reported (*NCHRP 1999*).

3.2 OPERATIONAL CHARACTERISTIC CURVES

Operational characteristic (OC) curves graphically represent the discriminating power of the acceptance procedure. They have been widely used in industrial applications for many years and are essential to the development of an equitable incentive/disincentive acceptance plan. A typical curve is shown in Figure 3.2.

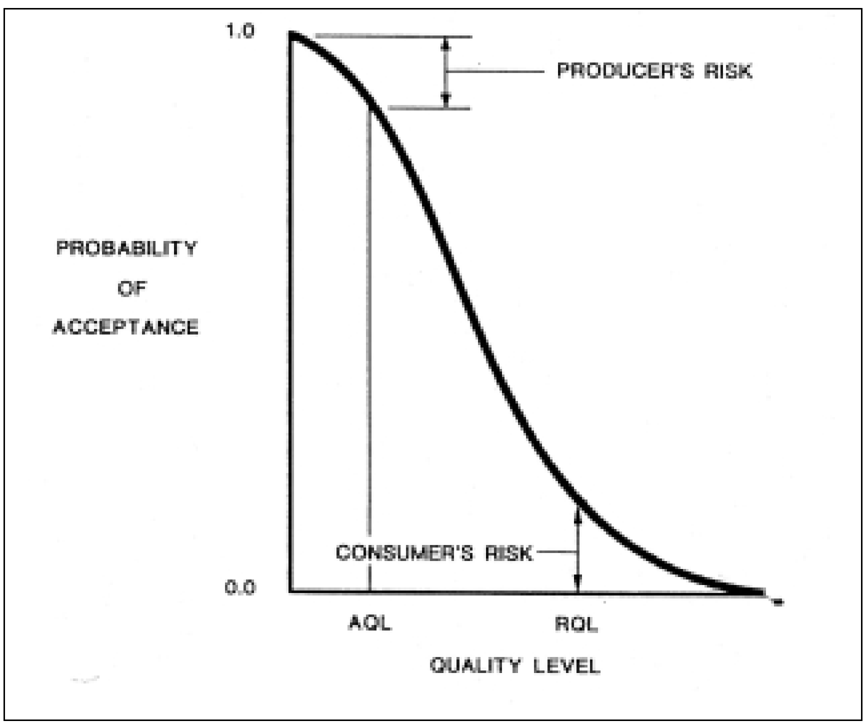

Figure 3.2: Conventional OC curve (after *Weed 1995*)

Four key elements of the OC curve and the acceptance plan are shown in Figure 3.2. These are the contractor and agency's risks (α and β risks) and the acceptable and rejectable quality levels (AQL and RQL). Each of these factors must be selected before the OC curve can be developed. The construction of OC curves is fairly straightforward once the risk and quality levels are set. The procedure is described in AASHTO Recommended Practice R 9-90. (*AASHTO 1995*). In addition, computer programs (i.e., OCPLOT) are available that allow rapid construction of the curves. (*Weed 1995*).

Recommended risk levels are provided in the AASHTO Recommended Practice based on the criticality of the parameter, where criticality is used to express the relative importance of the various factors. Probability values are shown in Table 3.2 for each of the four levels of criticality. Definitions of each level are included in the Appendix. It is noted that it may not always be necessary or practical to match these idealized values.

Table 3.2: Guidelines for α and β risks

Classification	Probability of Acceptance at RQL (buyer's risk)	Probability of Acceptance at AQL	Seller's Risk at AQL
Critical	0.005	0.950	0.050
Major	0.050	0.990	0.010
Minor	0.100	0.995	0.005
Contractual	0.200	0.999	0.001

Another form of OC curve is shown in Figure 3.3. Here the probability of acceptance is replaced with the expected pay factor. In the example shown, material produced at the AQL would receive, on average, a pay factor of 100 while truly superior work would receive a bonus of up to 102. RQL work would receive a pay factor of 70. The opportunity to earn a bonus is necessary in order for a statistical acceptance procedure to pay an average of 100 percent when the work is at the AQL. Unless bonuses and reductions are allowed to balance out, the average pay factor will be biased downward. Contractors producing material at an acceptable quality level would not receive 100 percent pay on average, unfairly penalizing them for work that is of acceptable quality (*Weed 1995*).

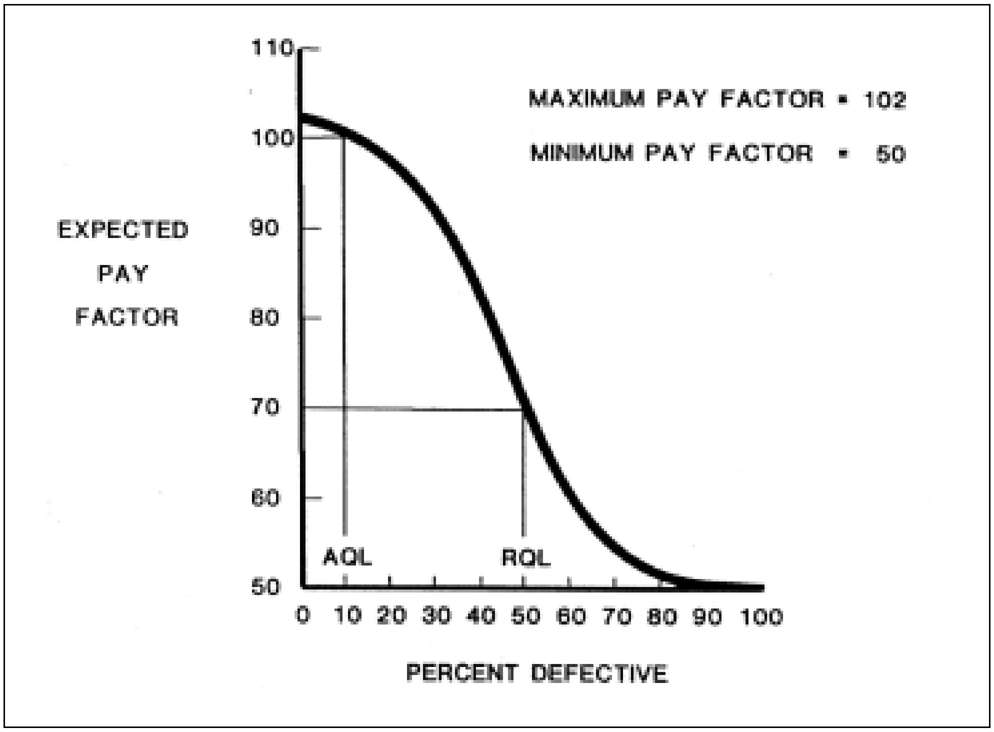

Figure 3.3: Typical OC curve for statistical acceptance procedure with adjusted pay schedule (after *Weed 1995*)

The development of OC curves is based on first determining the percent defective in each lot using a beta distribution function and coupling the percent defective to the noncentral *t* distribution. The noncentral *t* distribution allows the probability of acceptance to be determined for each level of population percent defective. The OC curve results from plotting the probability of acceptance against the percent defective. Additional details on the theory of the beta and noncentral *t* distributions are described in the AASHTO manual (*AASHTO 1995*).

3.2.1 Construction Variability

Variability in construction and material production is inevitable. The magnitude of the variability plays an important role in both the development of the construction specification and in its implementation. Consider the following example.

Assume that the JMF binder content is 5.5 percent and that pavement experts have determined that binder contents that vary more than ± 0.5 percent from the JMF value result in poor performance (either raveling or flushing). Further assume that a typical standard deviation for binder content is 0.25 percent. If the AQL is 10 percent, then Figure 3.4 illustrates a process that could be used to set the tolerance for binder content.

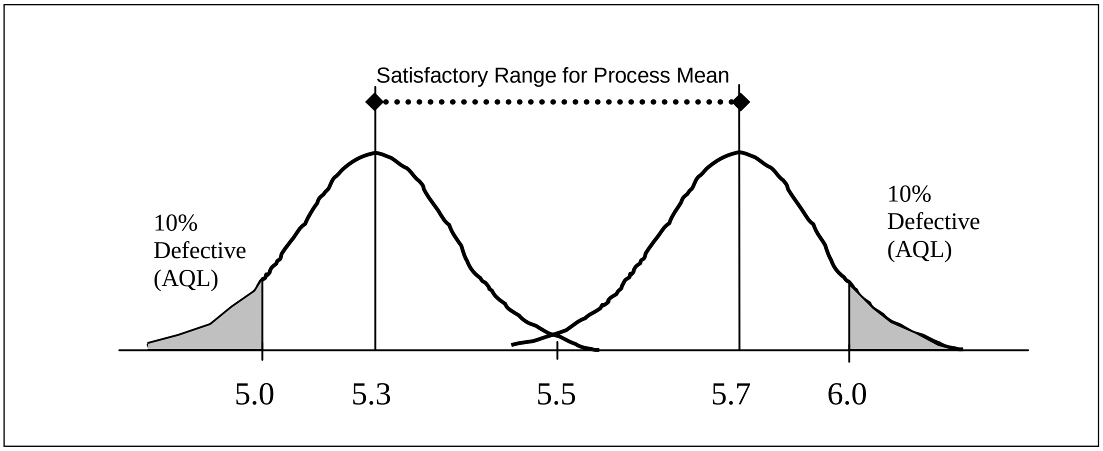

Figure 3.4: Illustration of latitude permitted in setting process mean

This example demonstrates the importance of the standard deviation in setting the tolerance for any of the specification parameters.

Construction variability was summarized in a recent NCHRP Synthesis (*Hughes 1996*). Only the information on hot mix asphalt is included here. The standard deviation of asphalt content was founded to vary from 0.15 to 0.44 percent (see Table 3.3). The variability was found to be different for different test procedures. Only limited information was available for ignition testing. No information on the number of projects or data points was reported.

Table 3.3: Typical asphalt content variability (*Hughes 1995*)

Source	Year	Test	Std. Dev., %
Arkansas	1994	Extraction	0.21
Virginia	1994	Extraction	0.18
Virginia	1994	Nuclear	0.21
NCAT	1994	Nuclear	0.19
NCAT	1994	Centrifuge	0.44
NCAT	1994	Ignition	0.30
Washington	1993	Extraction	0.24
Colorado	1993	Extraction	0.15
Kansas	1988	Nuclear	0.27
Virginia	1988	Extraction	0.19
Pennsylvania	1980	Extraction	0.25
BPR	1969	Extraction	0.28
Virginia	1968	Extraction	0.25

All these data are for virgin mixes, e.g., without recycled asphalt pavement (RAP). Two agencies (Louisiana and Indiana) studied the effects of RAP on the standard deviation of asphalt content. Standard deviations for mixes containing 20 to 30 percent RAP were not significantly different from those for mixes containing no RAP.

It was also reported that two studies compared DOT and contractor results. Alabama DOT reported a DOT standard deviation of 0.239 compared to 0.170 for contractor tests when both used the nuclear test. Virginia reported 0.21 and 0.18 for extraction and nuclear testing, respectively, while contractor test results were 0.16 and 0.13 for extraction and nuclear tests. It was noted that these results were taken from limited studies.

Hughes also presented the standard deviations for volumetric properties of laboratory compacted specimens. Data on air voids, VMA and voids filled with asphalt were included for several different compaction techniques. The results are shown in Table 3.4. It is interesting to note that the average results for the SHRP gyratory and Marshall compaction techniques are very similar though the SHRP gyratory is slightly lower.

Table 3.4: Standard deviations of volumetric properties from laboratory compacted mixtures

Source	Year	Compactor	Air Voids, %	VMA, %	VFA, %
NCHRP	1995	SHRP Gyratory	0.70	0.90	4.24
FHWA	1994	SHRP Gyratory	0.5	0.4	-
Virginia	1994	Marshall	0.86	0.7	3.5
Colorado	1993	Texas Gyratory	0.3	0.3	2.7
Colorado	1993	Linear Kneading	1.3	-	-
Colorado	1993	French Plate, 100 mm	1.4	-	-
Colorado	1993	French Plate, 50 mm	0.7	-	-
FHWA	1991	Marshall	0.7	0.6	-
West Virginia	1989	Marshall	0.5	-	-
Virginia	1989	Marshall	0.9	0.9	4.1

Variability of air voids in field compacted mixes is also reported by Hughes. Table 3.5 shows data from six agencies. The standard deviations of the field compacted mixes are 2 to 3 times that reported for laboratory compacted specimens. Hughes notes that this difference must be reflected when specifying field air voids, and he recommends specification limits of 3 to 8 percent. The same limits could be applied to field density (percent compaction).

Table 3.5: Standard deviations of air voids for roadway compacted mixtures (*Hughes 1995*)

Source	Year	Method	Air Voids, %
California	1995	Cores	1.9
New Jersey	1995	Cores	1.5
Ontario	1995	Cores	1.6
Colorado	1993	Cores	1.0
Washington	1993	Nuclear	0.9
Virginia	1984	Cores	1.3

Hughes also reported variability in pavement smoothness. Only limited data are available, in part because smoothness is often reported as a single value for a project rather multiple measurements taken over the length a project. The standard deviations of computerized profilographs are available and range from 0.008 to 0.016 m/km (0.5 to 1.0 in/mile). Hughes also reported on a study conducted by the FHWA Western Federal Lands Highway Division in 1994. A California-type profilograph was used to determine the profile indices for new construction dense-graded mixes and multi-lift dense-graded overlay projects. The pooled standard deviations were 0.030 m/km (1.9 in/mi) and 0.035 m/km (2.2 in/mi) for the new construction and overlay projects, respectively.

Data are also available from Oregon DOT projects (*Remily 2000*). These data are summarized in Table 3.6.

Table 3.6: ODOT variability data

CONSTITUENT	No. of Data Points (projects)	Ave COV	Ave St Dev	No. of Sublots in project	
				Min.	Max.
Pb, % (Incinerator)	81	3.04	0.17	3	89
Pb, % (Meter Method)	60	1.20	0.07	3	40
Air Voids, %	18	15.4	0.6	5	89
VMA, %	18	3.9	0.6	5	89
Compaction, %	116	0.6	0.6	3	89

These data were collected from a variety of large and small projects constructed by several different contractors. Mix property data were taken from specimens prepared using gyratory compaction equipment. The variability on ODOT projects is generally lower than that reported by Hughes.

3.2.2 Simulation Procedures

The uses of operational curves are essential to the successful development of specifications. Additional information on the performance of a proposed specification, however, can be gained through simulation. Questions that can be answered using simulation techniques that cannot be answered with OC curves alone include:

- Sensitivity of risks (contractor and agency) to specific levels of variability in the measurement device; and
- Production variability, i.e., density variability across or along the mat.

Simulation analysis also allows examination of the tradeoff between number of samples and risk.

The development of simulation software is beyond the scope of this project; however, Illinois DOT recently contracted with the University of Illinois to prepare such software. The result of this effort, ILLISIM, will be released within 3 months.

4.0 SUMMARY

4.1 CONCLUSIONS

Based on the review of available literature, the following conclusions appear warranted:

- Performance related specifications should not be implemented in Oregon at this time.
- With increasing use of end-result specifications, more of the responsibility for process control is being left to the contractor/producer. This leads to fewer pay items with more agency attention given to in-place mix properties.
- Risks (contractor and agency) associated with the implementation of acceptance procedures and specifications are not well understood by most agencies. Furthermore, changes in sample sizes often result in changes in relative balance among these risks.
- Increased use of non-traditional mixes (i.e., Superpave and stone matrix) has brought about an increased use of mix volumetrics in acceptance specifications.
- Other researchers (principally Weed) have developed alternate formulation for pay factor equations that allow the process mean and standard deviation to independently affect the final pay factor.
- Alternate forms for calculation of composite pay factors have been developed. These allow the interaction of mix properties to be taken into account.
- Operating characteristic curves are essential to the success of acceptance specifications.
- Simulation enhances the information provided by the OC curve analysis by giving additional details of relative risks to agency and contractor.

4.2 RECOMMENDATIONS

- The number of items included in the ODOT specification for dense-graded mixes should be reduced. Specific parameters should be selected by the project Technical Advisory Committee.
- As more applicable performance models become available, a model-based type of specification should be considered for dense-graded mixes.
- An alternate pay factor equation should be used that rewards contractors for producing and placing materials at the job mix formula target values with low standard deviations.

- Operating characteristics curves must be developed for each parameter and the owner and contractor risks clearly communicated. This information should be supplemented through the use of simulation analysis.

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APPENDIX

TERMINOLOGY

Terminology (*Chamberlin 1995,* unless otherwise noted)

Acceptable Quality Level	That level of lot percent defective at or below which the work is considered to be satisfactory.
Acceptance Program	All factors that comprise the agency's determination of the degree of compliance with contract requirements and value of a product (*AASHTO 1995*).
Adjustable payment	Positive and/or negative pay adjustments, sometimes referred to as incentives and disincentives, which reflect changes in the worth of the product resulting from departures from the level of acceptable quality.
Beta Distribution	A statistical distribution that underlies the percent defective estimation process used with variables acceptance procedures.
Buyer's risk	The probability that an acceptance plan will erroneously accept a lot that is truly rejectable.
Criticality	The relative importance of various factors affecting the safety, serviceability, cost and/or contractual requirement pertaining to a particular item of work. *Critical* – When the requirement is essential to preservation of life. *Major* – when the requirement is necessary for the prevention of substantial economic loss. *Minor* – when the requirement does not materially affect performance. *Contractual* – when the requirement is established only to provide uniform standards for bidding.
End-result	Specifications based on measurable attributes or properties of the finished product, rather than on the processes used to produce the product.
Lot	A discrete quantity of material or work to which an acceptance procedure is applied.
Noncentral t Distribution	A statistical distribution used to develop operating characteristics curves for variables acceptance procedures.
Operating Characteristics Curve	A graphical representation of an acceptance plan's capability to discriminate between satisfactory and unsatisfactory work.

Performance modeled	Specifications based on attributes that are related to performance of the finished product through quantitative relationships, or models, that have been validated for the specific materials and climatic conditions anticipated.
Performance specification	One that describes how the finished product should perform over time. For highways, performance is typically described in terms of changes in physical condition of the surface or its response to load, or in terms of the cumulative traffic required to bring the pavement to a condition defined as "failure." Such specifications are not applicable to highway pavement components (e.g., soils, subgrades, subbases, bases, riding surfaces) because the technology is not sufficiently advanced, but may be applicable to some manufactured highway products (portland cement concrete, light standards).
Performance-based specification	One that describes desired levels of fundamental engineering properties (e.g., resilient modulus, creep properties, fatigue properties) that are predictors of performance and appear in primary performance prediction relationships (i.e., models that can be used to predict pavement stress, distress or performance from combinations of factors representing traffic, environment, roadbed, and structural conditions). For the most part, these properties are not amenable to timely acceptance testing.
Performance-related specification	One that describes a desired level of material and construction factors that have been found to correlate with fundamental engineering properties that predict performance. These factors are amenable to acceptance testing at the time of construction.
Quality Control	The sum total of activities performed by the seller (producer, manufacturer, and/or contractor) to make sure that a product meets contract specification requirements (*AASHTO 1995*).
Seller's risk	The probability that an acceptance plan will erroneously reject a lot that is truly acceptable.
Statistical Quality Assurance	All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality (*AASHTO 1995*).
Statistically based	Sampling plans and decision criteria that consider the variability inherent in the finished product, as well as in the processes of sampling and testing.
Variables acceptance plan	A statistical acceptance procedure based on characteristics that are measured rather than counted and which involves the computation of statistical parameters.