Technical Memorandum

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Pay Factors for Asphalt-Concrete Construction:

Effect of Construction Quality on Agency Costs

Prepared for

California Department of Transportation

by

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1.0 INTRODUCTION

The quality of the construction process is a major factor in determining how well a pavement will perform under traffic loading and when subjected to environmental influences. To improve the construction process, quality control/quality assurance (QC/QA) procedures and pay incentives have been instituted in recent years. It is the objective of this report to demonstrate a rational and feasible method for quantitatively establishing penalties/bonuses for asphalt concrete construction with the initial emphasis placed on new asphalt concrete pavement construction.

The approach makes use of performance models for asphalt concrete used to interpret the results of the CAL/APT program (*1*) and WesTrack (*2*). The performance model for fatigue resulted from the CAL/APT program while the one for rutting came from the WesTrack accelerated pavement test program. For both modes of distress the system considers the means and variances of asphalt content, air-void content, asphalt-concrete thickness, and aggregate gradation. In estimating damage under traffic loading, the pavement is treated as a multilayer, elastic system. The performance models compute the distribution of pavement life, expressed as ESALs, using Monte Carlo simulation techniques.

Costs are established using a cost model which considers only the time to the next rehabilitation activity. It understates agency costs by ignoring possible effects of construction quality on future rehabilitation costs: it ignores future rehabilitation activity beyond the first cycle. It requires an exogenous estimate of future rehabilitation costs, traffic growth, expected years of new-pavement life, and a discount rate representing the time value of money.

The development of single sets of pay factors including both fatigue and rutting reflects the following. The recommended bonus for superior work is the smaller of that for either fatigue or rutting. For asphalt content, there are no bonuses for "dry" mixes. While such mixes may be rut resistant, they may lead to early fatigue distress. The penalty for larger-than-target asphalt content is determined by reduction in rutting resistance caused by surplus asphalt. For asphalt-concrete thickness, the recommended pay factors are based only on fatigue performance while for aggregate gradation, the recommended pay factors are based primarily on rutting. For air-void content, the recommended pay factors reflect both fatigue and rutting considerations.

2.0 CONCEPT

Contractor pay incentives serve at least two objectives: (1) they encourage the contractor to construct pavements with significantly improved performance in comparison to those meeting minimum specification requirements, while at the same time, maintaining costs at reasonable levels; and (2) they provide a rational alternative for dealing with marginally inadequate/adequate construction. Many factors must be considered in the establishment of pay schedules that not only realize these objectives but are mutually agreeable to the highway agency and the contractor.

The approach taken herein for the development of pay factors focuses primarily on the economic impacts to the highway agency. In this approach, the assumption is that an appropriate penalty for inferior construction should be the *added cost to the agency* and that the bonus for superior construction should be no greater than the *added savings to the agency.*

For new construction, for example, these agency costs/savings are associated primarily with subsequent pavement rehabilitation. Inferior construction hastens the need for future rehabilitation and may increase the cost of rehabilitation as well. As a result, inferior construction increases the present worth of future rehabilitation costs. Superior construction, on the other hand, reduces the present worth of these costs, largely by deferring the future rehabilitation. The difference in present worths of rehabilitation costs, as constructed versus as specified and as expected, provides a rational basis for setting the level of penalty/bonus for inferior/superior construction quality.

3.0 MODELS

To compute the differential present worth of future rehabilitation requires two different types of models: (1) a performance model or models for determining the effect of construction quality on expected pavement performance; and (2) a cost model for translating these effects into rehabilitation dollars.

Two performance models are described herein: one for fatigue cracking and the other for rutting. For most construction situations, both performance models must be utilized to develop appropriate pay factors. For this situation, the pay factors resulting from the use of the performance models are based on the distress mode yielding the most beneficial consequence to the agency; namely, smaller bonus and larger penalty. There may be circumstances in which either of the two distress modes will be applicable. These situations will not be discussed herein although the necessary information to do so is included.

The performance model used for *fatigue* is based on the mix analysis and design system originally developed as a part of SHRP (*3*), extended to efficiently treat in-situ temperatures (*4*), calibrated to the current Caltrans flexible pavement design system (*5*), extended to incorporate construction variability (*6*), and used in interpreting the results of HVS tests on flexible pavements, both new and overlaid, constructed at the Richmond Field Station according to Caltrans Standards (*1*). The model used for rutting is based on mix performance data developed at WesTrack (*2*).

In estimating damaging strains under traffic for fatigue cracking, the pavement is treated as a multilayer elastic system. For rutting, the performance model is based on regression analysis although multilayer elastic analysis was used in its development as well. In both models, Monte Carlo simulations are used to obtain distributions of pavement lives.

The cost model considers only the time to the next rehabilitation activity; i.e., it ignores future rehabilitation measures beyond the first cycle. It requires an estimate of future rehabilitation cost; it considers annual inflation of rehabilitation costs, traffic growth, expected years of the constructed life of the asphalt concrete, and a discount rate representing the time value of money.

3.1 Performance Models

The processes embedded within the performance models are illustrated schematically in Figure 3.1. Figure 3.1a shows the process for fatigue cracking and Figure 3.1b is that for rutting. Central to these processes is the random selection of construction variable including air-void content, asphalt content, aggregate gradation, and asphalt concrete thickness.[1] For rutting, the variables considered are air-void content, V_{air}, asphalt content, P_{Wasp}, and aggregate gradation expressed in terms of the percent passing the No. 200 (0.075 mm) sieve, P_{200}, and the fraction passing the No. 8 (2.38 mm) sieve and retained on the No. 200 (0.075 mm) sieve, *fa*. For fatigue, the variables include air-void content, asphalt content, and asphalt concrete thickness, *t*.

3.1.1 Variability Considerations

To consider the variability referred to in Figures 3.1a and 3.1b, the random selection of the variables assumes normally distributed random variables with known or assumed means and

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[1] While not shown in Figure 3.1a (fatigue cracking) because it is only incidental to the computations, a random selection was also made of the foundation modulus, a modulus representing the composite effects of base, subbase, and subgrade layers in an "equivalent" two-layer system.

variances. Of particular significance are the variances that might be expected under normal construction operations. Estimates of these variances were obtained from a combination of literature evaluation, back calculation of moduli from Falling Weight Deflectometer (FWD) measurements, and data collected as a part of the WesTrack project (*7*). A summary of these results are presented in Table 3.1.

The totals in Table 3.1 include not only materials and construction components, but also components resulting from testing and sampling. To consider only materials and construction effects, the testing and sampling components were removed from the variance estimates using information contained in Table 3.2. Table 3.3 summarizes the results of this analysis, which is briefly described in Appendix A (*6*). The equations for estimating the standard deviation of asphalt-concrete thickness were developed as an approximate way to handle multilift construction. Among the assumptions made in their development was that the coefficient of variation of thickness in single-lift construction is about 14 percent.

3.1.2 Fatigue Cracking

The performance model used for fatigue follows the procedure illustrated schematically in Figure 3.1a. It is based on the procedure described in Reference (*5*) utilizing fatigue test data representative of mixes containing dense-graded aggregates meeting State of California specifications.[2]

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[2] These gradings generally lie closer to the 0.45 curve than either the *fine* or *coarse* gradings used at WesTrack; however, the fatigue response of these mixes is likely similar to that of the mixes with the fine grading used at WesTrack.

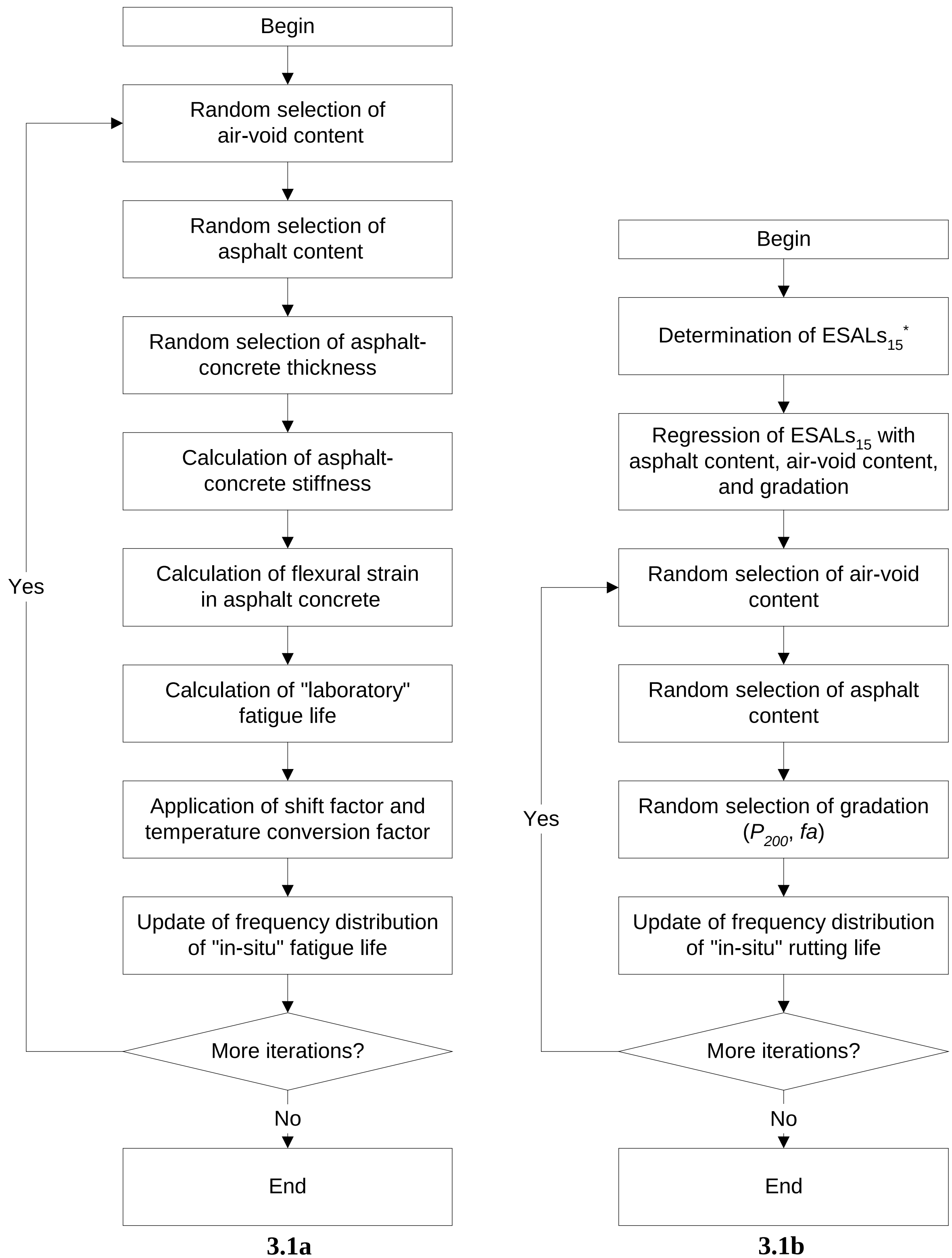

Figure 3.1 Outlines of performance model simulations for fatigue cracking and rutting.

Table 3.1 Construction Variation of Mix and Structural Characteristics

Property	Measure of Variation	Value or Range	Source
Asphalt Content	Standard Deviation	0.15–0.44%	Table 12.46 (*7*)
	Standard Deviation	0.1–0.4%	Individual WesTrack sections (*7*)
	Standard Deviation	0.31%	WesTrack composite (*7*)
	Standard Deviation	0.3%	Table 3 (*8*)
Air-void Content	Standard Deviation	0.9–1.9%	Table 12.55 (*7*)
	Standard Deviation	0.4–1.5%	Individual WesTrack sections (*7*)
	Standard Deviation	1.5%	WesTrack composite (*7*)
	Standard Deviation	1.94%	Table 3 (*8*)
Thickness	Coefficient of Variation	12.5–15%	Table 12.58 (*7*)
	Standard Deviation	0–0.5 cm	Individual WesTrack sections (*7*)
	Standard Deviation	0.58 cm	WesTrack composite (*7*)
	Standard Deviation	0.99 cm	Table 3 (*8*)
Foundation Modulus	Coefficient of Variation	11.3–14.7%	HVS test sections at UCB (*1*)
	Coefficient of Variation	17.3–44.7%	Segment of highway in KY*
	Coefficient of Variation	3.6–17.7%	Individual WesTrack sections (*7*)
	Coefficient of Variation	14.2–28.5%	WesTrack composite (*7*)

* Unpublished data, Kentucky DOT

Table 3.2 Materials/Construction Component of Total Construction Variance

Property	Materials/Construction Component (%)	Source
Asphalt Content	40	Figure 7 (*9*)
	61	Table 3 (*8*)
Air-Void Content	60	Table 8 (inferred) (*9*)
	90	Table 3 (*8*)
Thickness	95	Table 3 (*8*)
Foundation Modulus	70	Assumed

Table 3.3 Variation of Mix and Structural Characteristics for Monte Carlo Simulations

Property	Total Standard Deviation	Percentage of Variance Due to Materials/Construction	Materials/Construction Component of Standard Deviation
Asphalt Content	0.30%	40	0.19%
Air-Void Content	1.6%	60	1.2%
Asphalt Concrete Thickness, *t*	$0.200 \cdot t^{0.69} (cm)$	80	$0.173 \cdot t^{0.69} (cm)$
Foundation Modulus	30% (coefficient of variation)	70	25%

Multilayer elastic analysis with ELSYM5 was used to simulate the stress and strain states with structures designed according to the State of California procedures. Table B-1 in Appendix B provides a summary of the pavement structures analyzed. Loading consisted of a dual-tire assembly of 9000 lbs. (40 kN) with a center-to-center spacing of 12 in. (300 mm) and a tire contact pressure of 100 psi (690 kPa). The critically stressed location for fatigue was assumed to be at the bottom boundary of the asphalt concrete layer.

As noted above, mix properties for use in the analysis were obtained by testing a representative mix, the constituents for which included an AR-4000 asphalt cement from a source in the Central Valley and a granite from the Logan quarry in Watsonville. The aggregate gradation passed between the middle limits of the Caltrans 3/4 in. medium and coarse gradations.

Stiffness, S_{mix}, and fatigue life, N_f, calibrations for this mix at 20°C (68°F) are as follows (*5*):

$$S_{mix} = \exp(15.259 - 0.7577 V_{air} - 0.17233 P_{Wasp}) \quad \textbf{(3.1)}$$

$$N_f = \exp(-22.0012 - 0.164566 V_{air} + 0.575199 P_{Wasp} - 3.71763 \ln \varepsilon_t) \quad \textbf{(3.2)}$$

Each of the Monte Carlo simulations produced an independent estimate of the laboratory fatigue life, N_f. The corresponding simulated in-situ life, ESALs, was computed by applying a shift factor, SF, and a temperature conversion factor, TCF, as follows:

$$ESALs = \frac{N_f \cdot SF}{TCF} \quad \textbf{(3.3)}$$

The shift factor is an empirically derived factor that accounts for differences between the laboratory and the in-situ pavement in the rate at which fatigue damage accumulates with each load application. For computations reported herein, the shift factor was calibrated to the Caltrans design model following procedures described in Reference (*5*). Thickness replaced strain as the independent variable, however, and engineering judgement was used to develop reasonable estimates for the thickest and thinnest pavement sections. The shift factor was computed as follows:

$$SF = 30.48 + 6.44(t - 12) \quad \text{for } t > 12 \tag{3.4}$$

$$SF = 0.3771t^2 - 2.6109t + 7.5121 \quad \text{for } 3.6 \le t \le 12 \tag{3.5}$$

and

$$SF = 3 \quad \text{for } t < 3.6 \tag{3.6}$$

in which t is the asphalt-concrete thickness in *inches*. The temperature conversion factor, *TCF,* is given by:

$$TCF = 1.754 \ln t - 1.256 \tag{3.7}$$

$$TCF = 1.175 \quad \text{for } t < 4 \tag{3.8}$$

For the analyses reported herein, the 10th percentile fatigue life was used as the basic performance estimate. This life corresponds to about 10 percent fatigue cracking in the wheel paths. As verified by sensitivity analysis, incremental agency costs due to off-target construction (of either inferior or superior quality) are not significantly affected by the chosen performance percentile (at least within a reasonable range of the 1st to the 20th percentile) (*10*).

Target values and standard deviations for asphalt content and air-void content are shown in Table 3.4. This Table also contains an expression for the standard deviation of thickness (*10*) used to develop this parameter for the sections analyzed. Table B-1 (Appendix B) contains a summary of the four pavement sections used in the analyses. These are typical of California construction for the range in traffic as defined by the Traffic Index (range 7–13).[3] Table B-1 also

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[3] The Traffic Index provides a measure of the applied traffic expressed as ESALs according to the following relation: $ESALs = 1.2895 \times 10^2 (TI)^{8.2919}$

contains the target standard deviations for thickness for the four sections, computed according to the equation in Table 3.4.

Table 3.4 Construction Targets

Variable	Mean	Total Standard Deviation (Including Sampling and Testing)	Percent of Variance Attributed to Materials and Construction
Asphalt Content (%)	5.0	0.3	40
Air-Void Content (%)	7.0	1.5	60
Mineral Filler (%)	5.5	0.9	75
Fine Aggregate (%)	30.0	3.0	85
Asphalt-Concrete Thickness (in.)	4 pavement structures	$0.15 \times \text{AC thickness}^{0.69}$	75

With these targets, Monte Carlo simulations were performed to quantify the effects of construction quality on simulated in-situ fatigue performance.[4] Each investigation employed either 100,000 simulations (air-void content/relative compaction and asphalt-concrete thickness) or 200,000 simulations (asphalt content). The levels and ranges used for these simulations are shown in Table 3.5.

Table 3.5 Levels and Ranges for Variable Evaluated

Variable	Mean		As-Constructed Standard Deviation	
	Levels	Range	Levels	Range
Asphalt Content	21	4.0 to 6.0	9	0.114 to 0.266
Air-Void Content	21	5.00 to 9.75	9	0.648 to 1.596
Mineral Filler	21	3.0 to 8.0	9	0.4674 to 1.0906
Fine Aggregate	21	24.0 to 36.0	9	1.6596 to 3.8724
Thickness	21 for each of 4 pavement sections	-1.0 to 1.0	9	4.8% to 11.2%

[4] For fatigue, the effects of P_{200} were not included. Reference (*2*) describes the basis for the decision.

Results, for a structure identified as 11AB20 (Table B-1) are shown in Figures 3.2 through 3.4 illustrating the effects of air-void content, asphalt content, and asphalt concrete thickness, respectively.

To illustrate the effects of air-void content (as a measure of mix compaction) on agency costs, the information presented in Figure 3.2 will be utilized. For this example, a maximum acceptable air-void content has been set at 9.75 percent. Because the air-void content is considered to be a random variable, some violation of this maximum level during construction is expected. Figure 3.5 illustrates how the tolerable level of non-compliance affects the acceptability of various combinations of the average and the standard deviation of air-void content. As the tolerable level of non-compliance increases, larger and more variable air-void contents are judged to be acceptable. For the example shown herein, as well as for subsequent calculations, the tolerable level of non-compliance has been set at 1 percent. This relatively small (1 percent) failure percentage provides a reasonable probabilistic interpretation to what has been viewed as a largely deterministic specification.

The influence of as-constructed air-void content on pavement performance is shown in Figure 3.6. The best performance is associated with small averages and small standard deviations of air-void content; that is, a consistently well-compacted asphalt concrete layer. Details of the performance model used to produce Figure 3.6 are summarized in Table 3.6.

The highway agency can reasonably expect typical construction variability (a standard deviation of air-void content of about 1.2 percent). It can also reasonably expect construction operations to be in compliance with the specifications, in this case, a 1-percent failure tolerance of the 9.75 percent air-void requirement. The expected pavement performance in this case, corresponding to the target air-void content of 7 percent, is about 16,500,000 ESALs (Figure

3.7). This is a reasonable target against which to measure both inferior (less than 16,500,00 ESALs) and superior (more than 16,500,000 ESALs) construction.

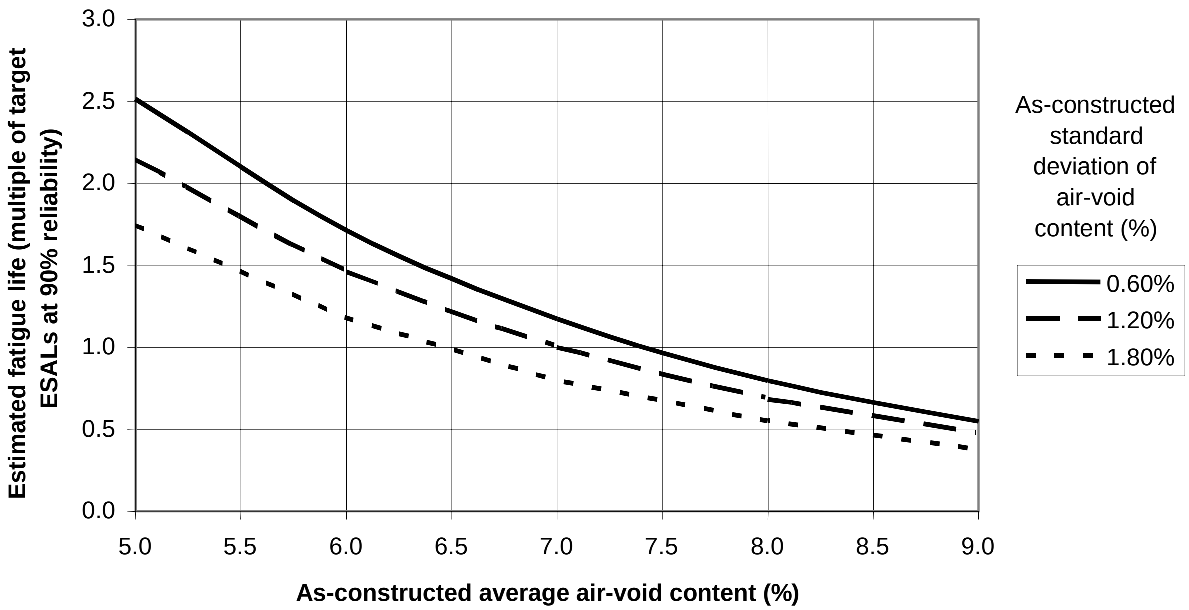

Figure 3.2. Effects of as-constructed air-void content on pavement fatigue performance.

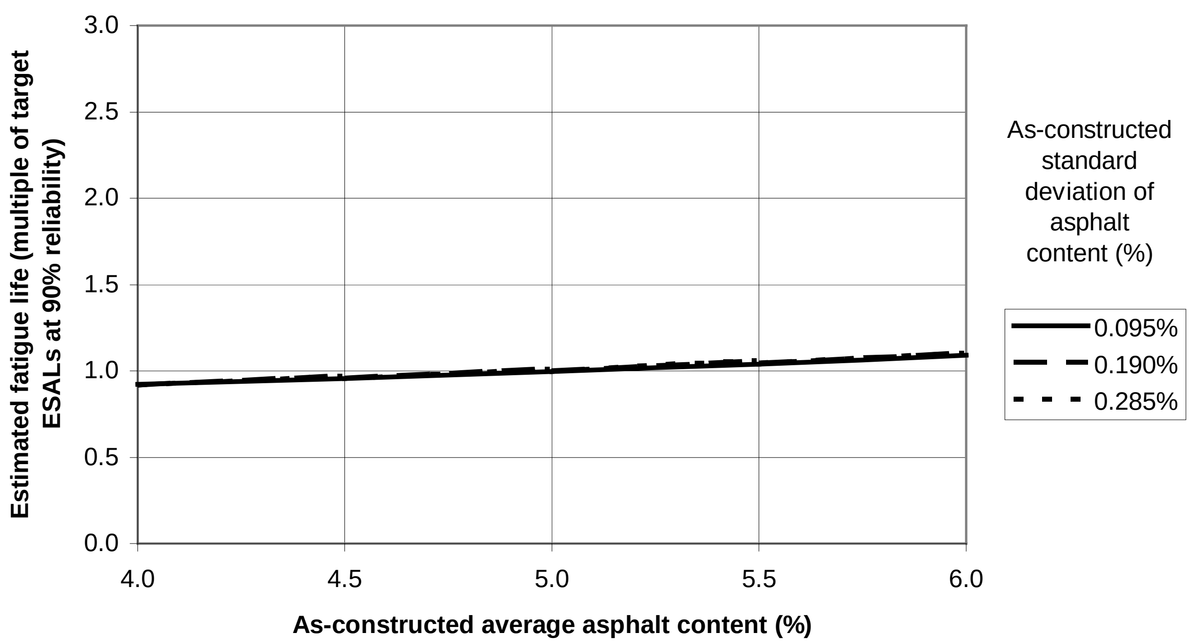

Figure 3.3. Effects of as-constructed asphalt content on pavement fatigue performance.

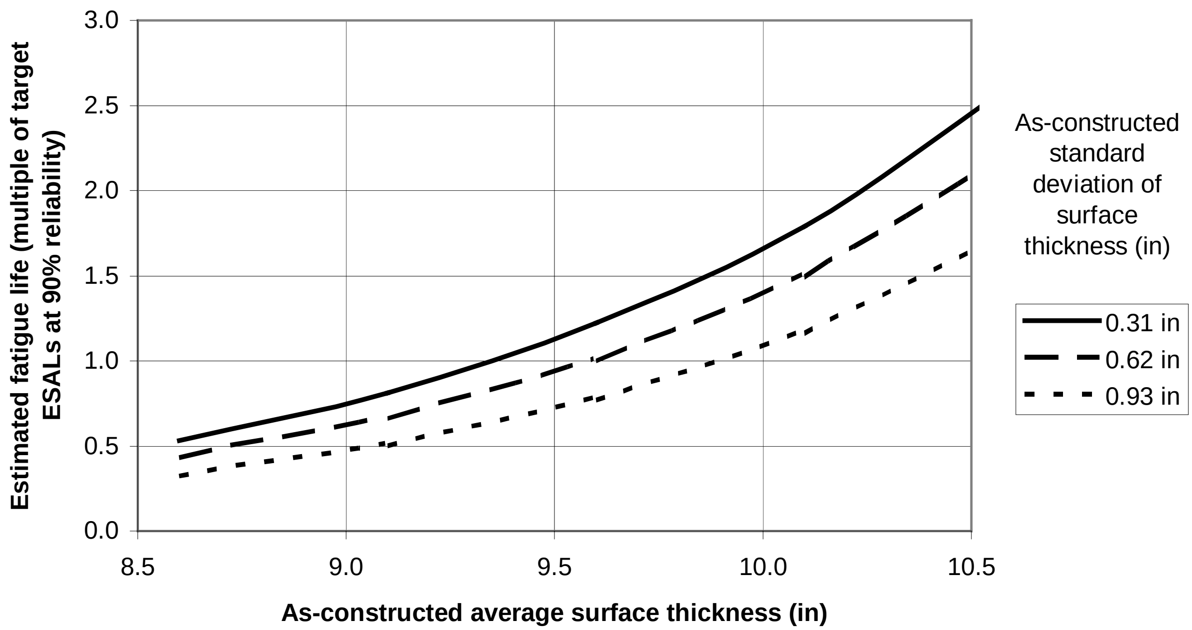

Figure 3.4. Effects of as-constructed surface thickness on pavement fatigue performance.

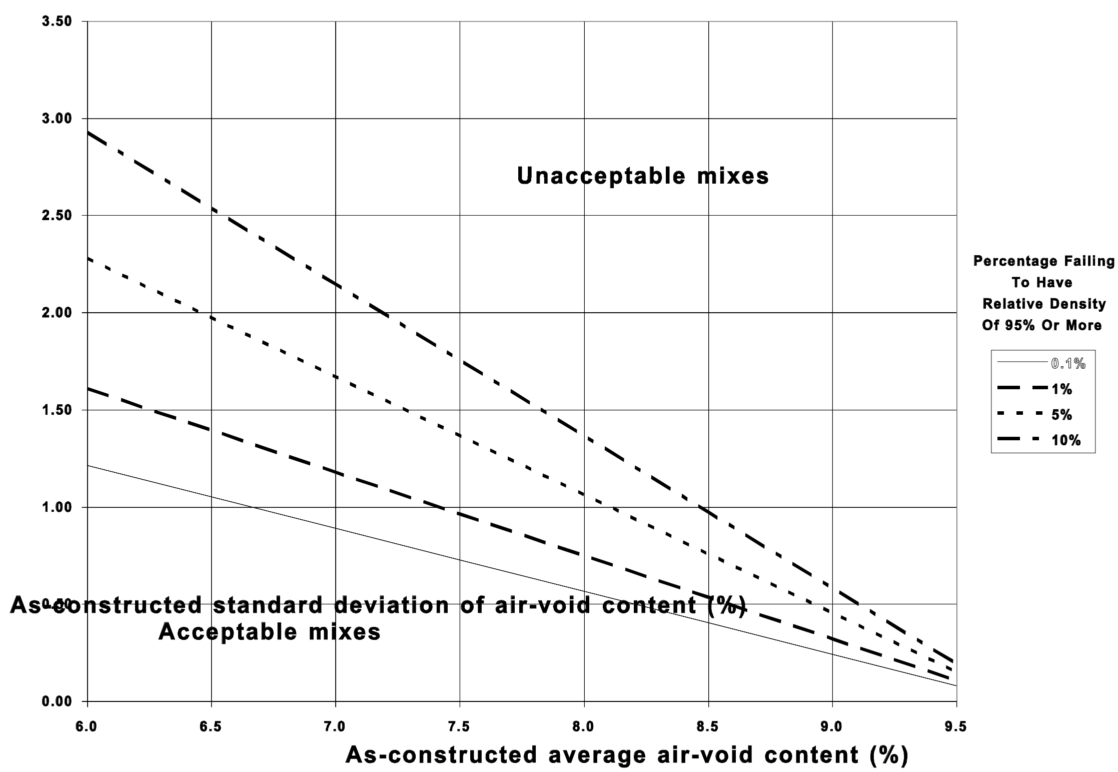

Figure 3.5. Effect of specification failure level on acceptability of mix compaction.

Table 3.6 Summary of Parameters in Example

Context	**New Pavement Construction**
Performance Model	90-percent reliability California coastal temperatures Average asphalt content, 5% Standard deviation of asphalt content, 0.19% Standard deviation of thickness, 0.6 in. Coefficient of variation of foundation modulus, 25%
Construction Specification	7.0% target air-void content 9.75% maximum air-void content 1% tolerable failure
Performance Expectation	16,500,000 ESALs
Pavement Structure	9.6-in. asphalt concrete (E = varies, v = 0.40) 6-in. aggregate base (E = 25,000 psi, v = 0.45) 8.4-in. aggregate subbase (E = 20,000 psi, v = 0.45) Subgrade (E = 12,200 psi, v = 0.50)

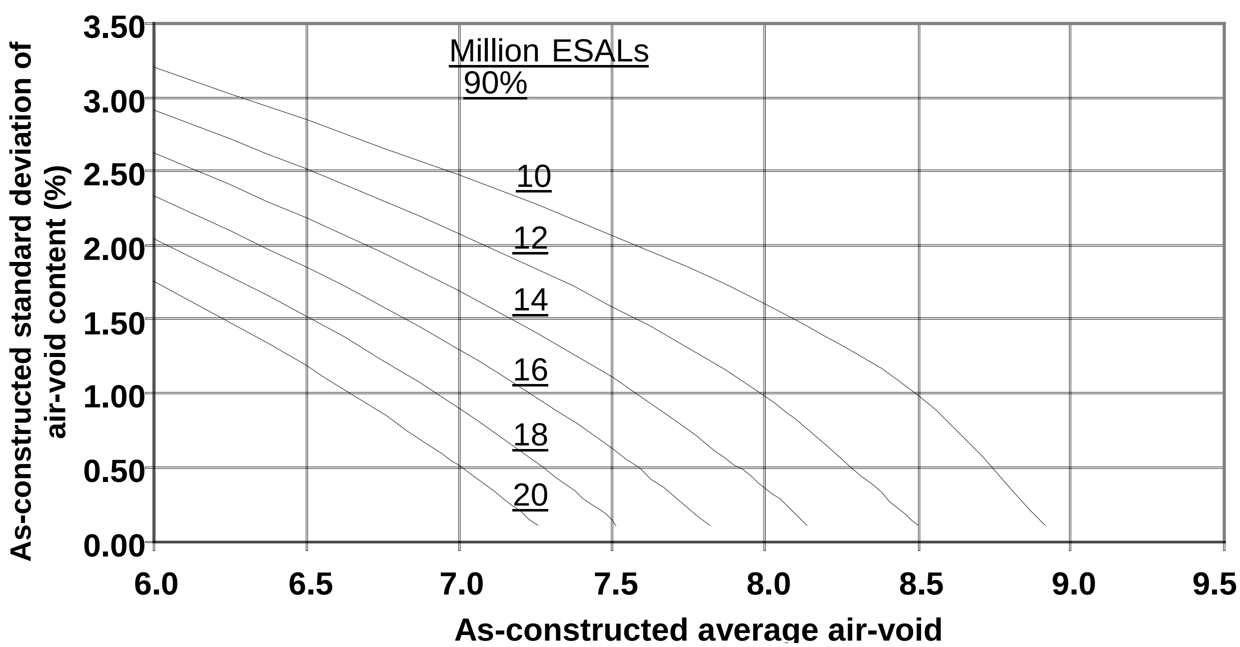

Figure 3.6. Influence of air-void content on pavement performance.

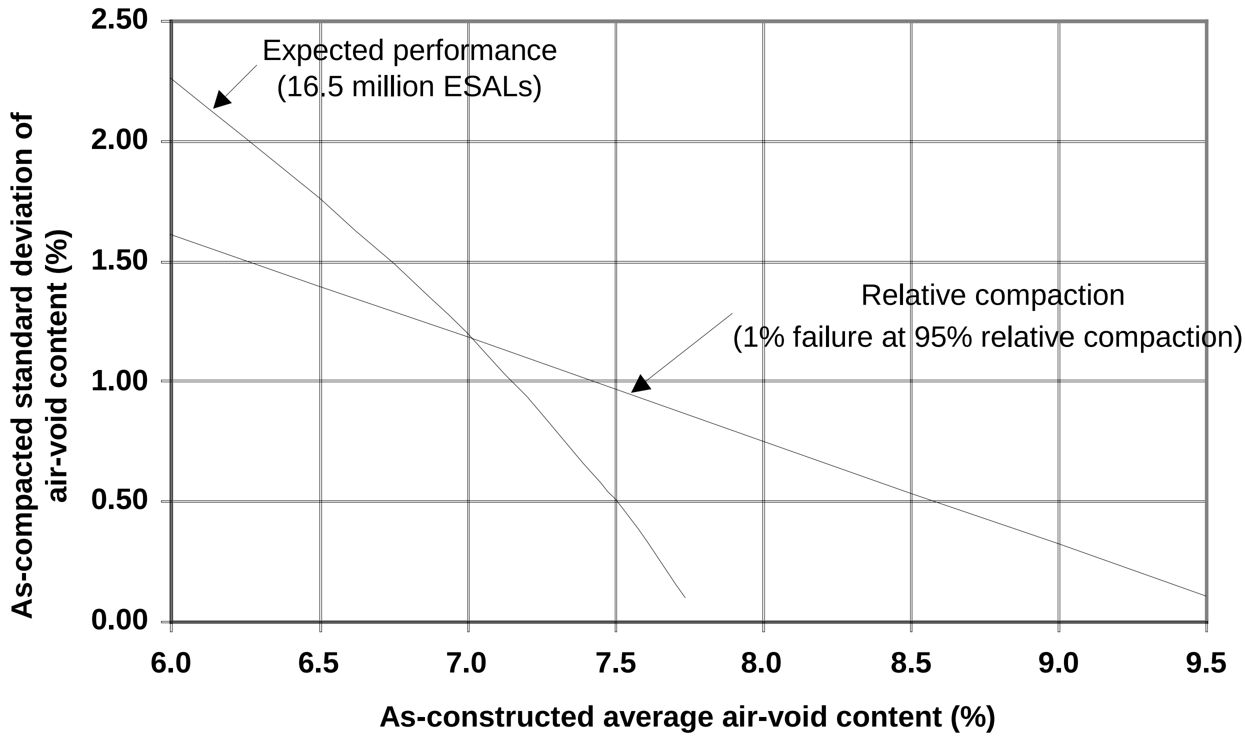

Figure 3.7. Expected pavement performance.

Contractor penalties can reasonably be extracted when the relative compaction specification is not met *and* when performance is inferior. This penalty zone is highlighted in the upper right of Figure 3.8. Contractor bonuses can reasonably be awarded when the relative-density specification is met *and* when performance is superior. This bonus zone is highlighted in the lower left of Figure 3.8. For other cases, no pay adjustment seems to be appropriate. Although the left, wedge-shaped zone of Figure 3.8 represents conditions having better-than-expected performance, a bonus should not be awarded because construction fails to meet specification requirements. The right, wedge-shaped zone of Figure 3.8 represents complying conditions, but performance fails to meet expectations and, hence, construction does not justify a contractor bonus. The presence of these two wedge-shaped zones, due in part to the probabilistic nature of both specification compliance and pavement performance, may explain traditional problems in trying to link relative-compaction specifications with performance.

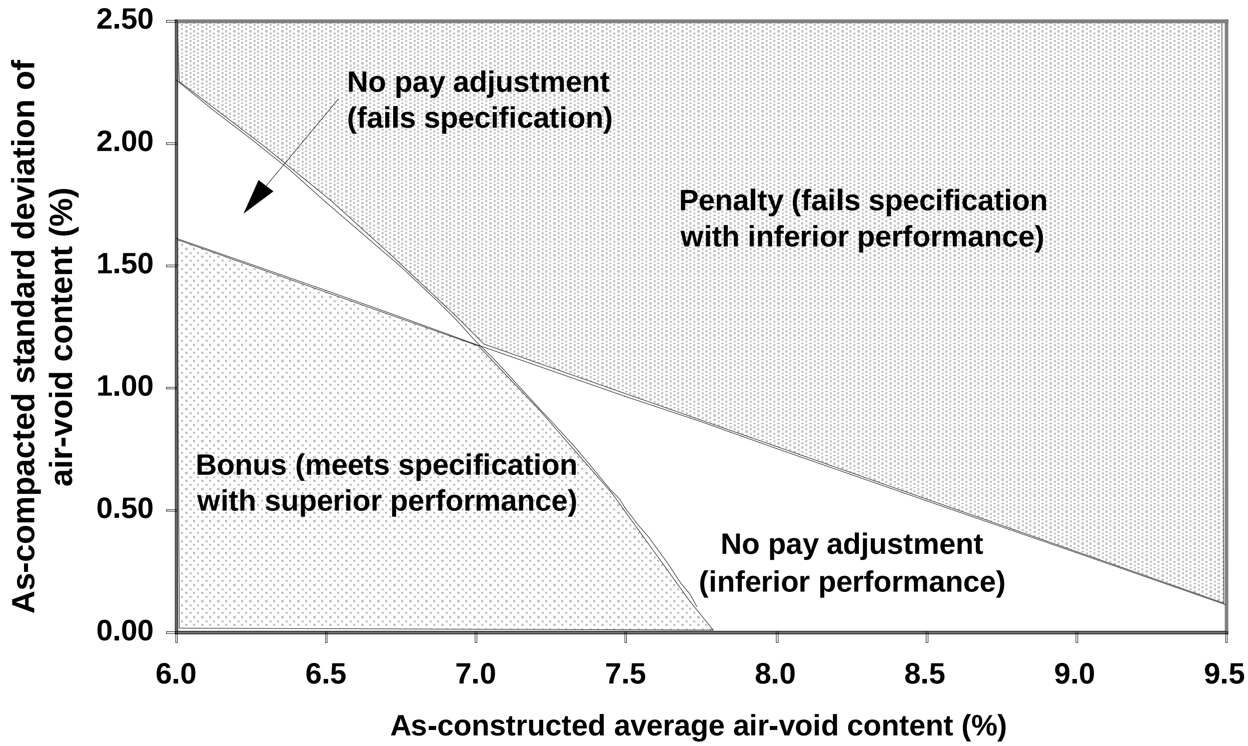

Figure 3.8. Influence of air-void content on contractor pay adjustment.

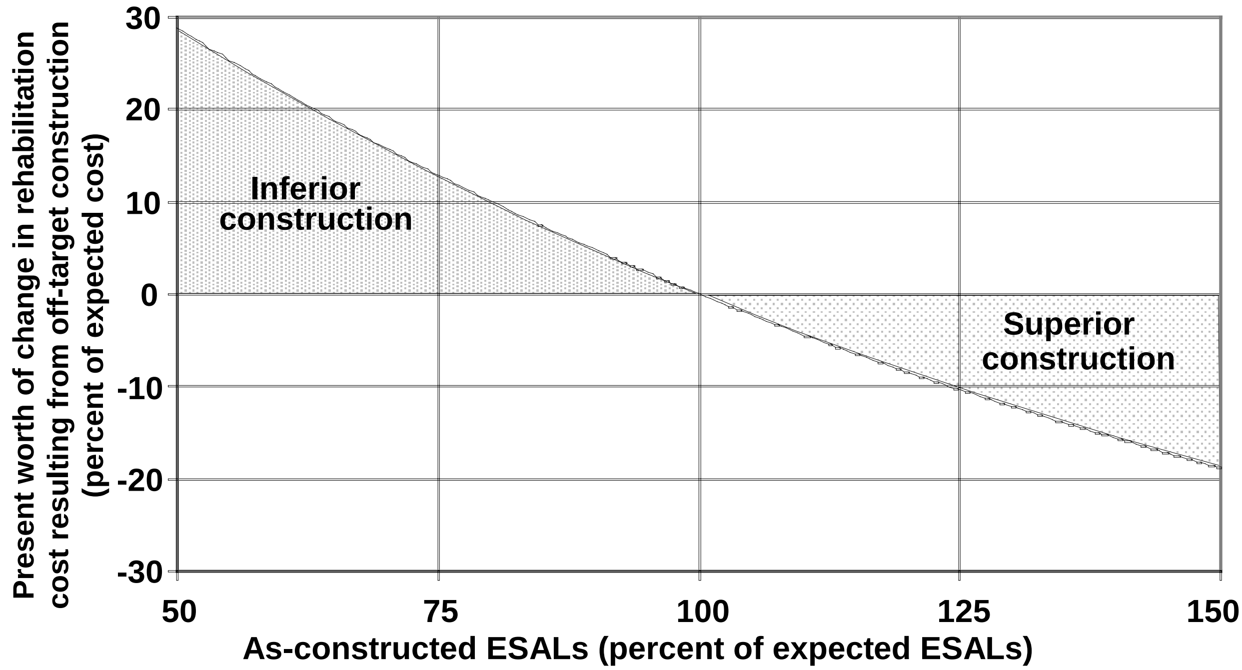

Figure 3.9. Influence of pavement performance on pay factors.

The cost model to be discussed subsequently is based on a comparison between the as-constructed pavement performance and the expected performance (16.5×10^6 ESALs). A qualitative indication of the results of the use of the cost model is shown in Figure 3.9.

3.1.3 Permanent Deformation

The performance model used for permanent deformation is a regression equation based on performance data obtained from the WesTrack experiment (*2*). This model includes the effects of air-void content, asphalt content, and aggregate gradation. The resulting equation has the following form:

$$\ln(ESALs_{rd}) = a_0 + a_1 \cdot P_{Wasp} + a_2 \cdot V_{air} + a_3 \cdot fa + a_4 \cdot P_{Wasp}^{\ 2} + a_5 \cdot V_{air}^{\ 2} + a_6 \cdot fa^2 + a_7 \cdot P_{Wasp} \cdot V_{air} + a_8 \cdot V_{air} \cdot fa + a_9 \cdot P_{200} \cdot fa \quad \textbf{(3.9)}$$

where:

$\ln(ESALs)$ = natural logarithm of *ESALs* to specific rut depth (mm),

e.g., rd = 15 mm (0.6 in.)

$a_0 \ldots\ldots a_9$ = regression coefficients, Table 3.7

Table 3.7 Regression Coefficients Relating ln(ESALs) to Mix Variables for Specific Levels of Rutting

	Downward Rut Depth (mm)					
	3	**6**	**9**	**12**	**15**	**18**
Constant	4.15659	32.1396	35.6119	26.5116	19.6304	15.5941
P_{Wasp}	4.80344	-4.13639	-4.9073	-1.07049	1.67468	3.32617
V_{air}	-0.271222	-0.9128258	-0.695417	-0.655977	-0.608102	-0.57752
fa	-0.0513972	-0.0561651	-0.060186	-0.066391	-0.0625076	-0.0665384
P_{Wasp}^2	-0.637872	0.113609	0.174723	-0.18449	-0.430036	-0.574549
V_{air}^2	0.162333	0.0152498	0.0176358	0.0161092	0.0204602	0.0197888
fa^2	0.00134321	0.00146158	0.00160422	0.00165989	0.00170736	0.00171777
$P_{Wasp} \cdot V_{air}$	0.0275229	0.143108	0.103099	0.0964891	0.0809674	0.0765997
$V_{air} \cdot fa$	-0.00849295	-0.00903533	-0.010073	-0.00935616	-0.01012	-0.00986111
$P_{200} \cdot fa$	0.00863251	0.00886307	0.00964144	0.00927116	0.00949051	0.00962141
R^2	0.993	0.991	0.992	0.991	0.996	0.997

This equation is based on analysis of both the field performance of 23 test sections which exhibited rutting (but no fatigue cracking) and the results of simple shear tests on laboratory-prepared mixes containing gradings representative of the *coarse* and *fine* gradings at WesTrack. Three gradings were used for each of the mixes; the target values and two variations of these gradings. The ranges for each of the gradings are shown in Figure 3.10. Also shown in this figure are representative gradings for the Caltrans 19.5-mm (3/4-in.) maximum coarse and medium gradings. It will be noted that the range of gradings encompasses those likely to be used for asphalt concrete in California. Reference (*2*) describes the procedure used to combine the field and laboratory measured performance data.

Figures 3.11, 3.12, 3.13, and 3.14 illustrate the effects of specific mix parameters for ESALs to a rut depth of 15 mm (0.6 in.). While other rut depths could be used for these computations, the 15-mm rut depth was considered reasonable since it is in the range where remedial action is required.

Using Equation 3.9 and the procedure shown in Figure 3.1b, a series of Monte Carlo simulations were performed to define relationships between ESALs to 10-percent rutting [15 mm (0.6 in.) or more] and the various mix parameters shown in Table 3.5. Figures 3.15 and 3.16 illustrate the effects of as-constructed asphalt content and air-void content on the ESALs to 10-percent rutting (15 mm or more) for a range in standard deviations for each of the parameters. Figure 3.17 and 3.18, respectively, illustrated the same information but plotted in the form of asphalt content and air-void content versus as-constructed standard deviation of the associated parameter. Isolines of ESALs to 10 percent rutting (15 mm or more) are shown in each of the figures. Also shown are the construction targets.

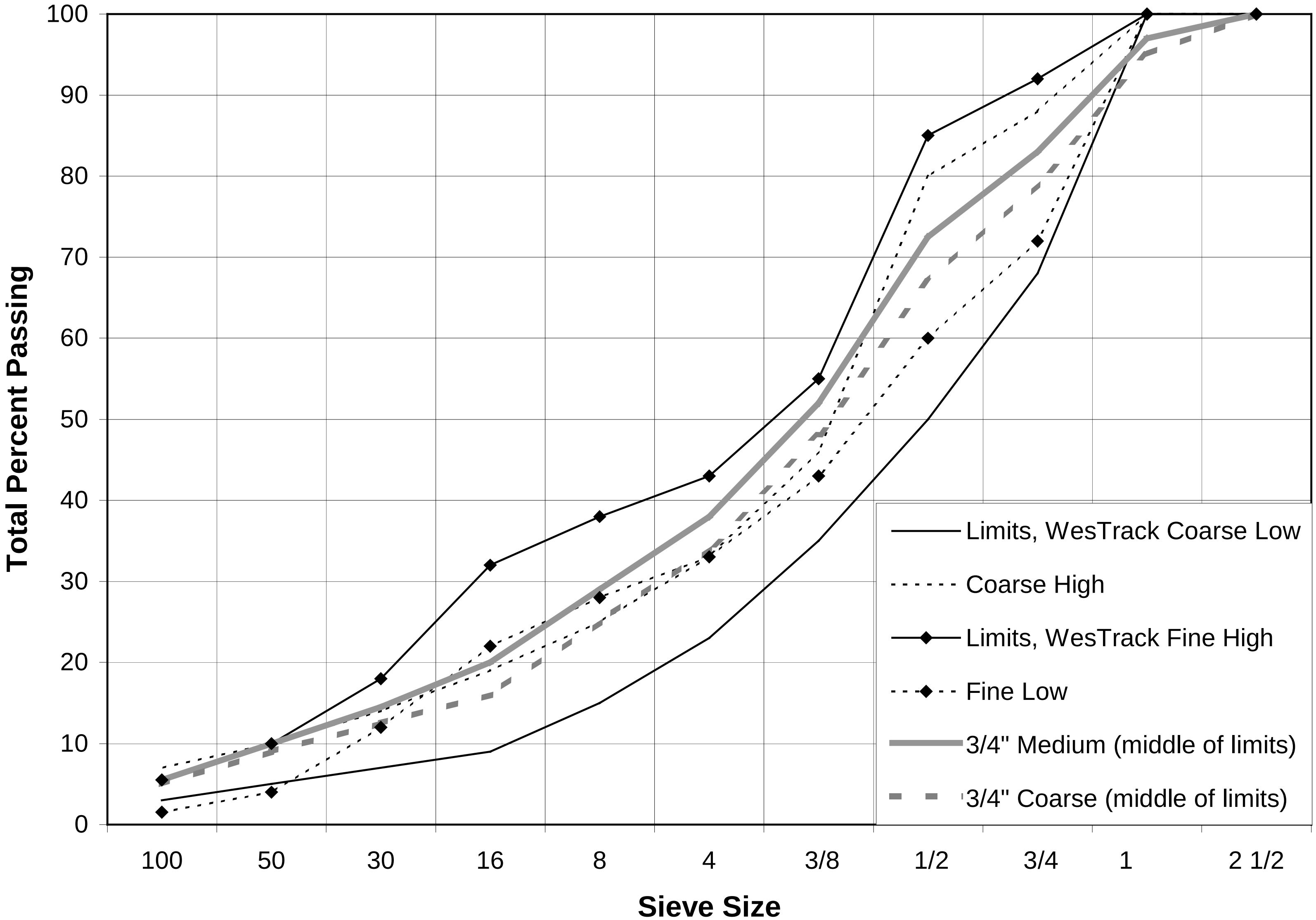

Figure 3.10. Range of aggregate gradings for WesTrack mixes compared with representative Caltrans gradings.

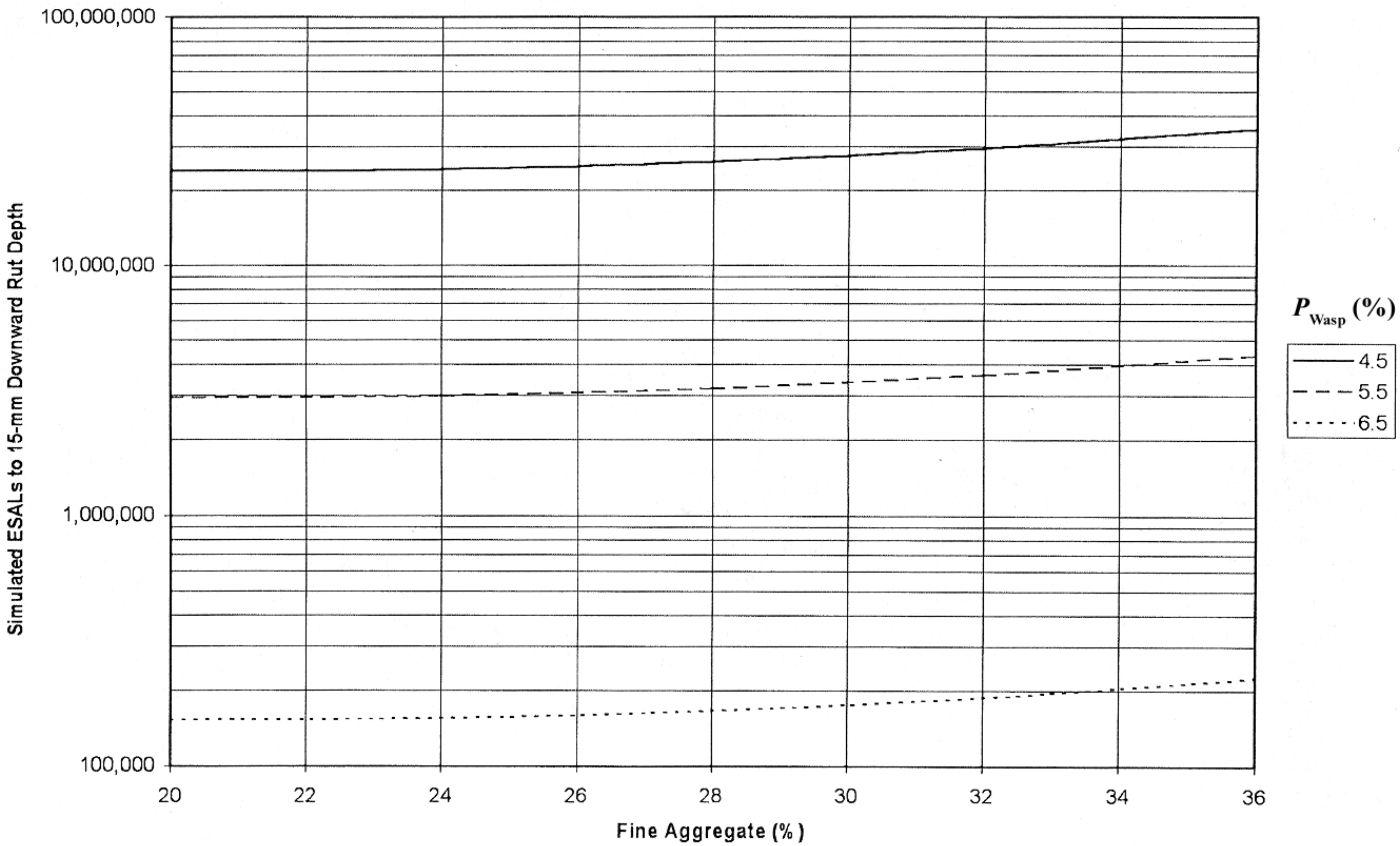

Figure 3.11. Effect of mix variables on simulated ESALs to 15 mm (0.6 in.) rut depth for a range in fine aggregate contents; V_{air} = 6.5%, P_{200} = 6.0%.

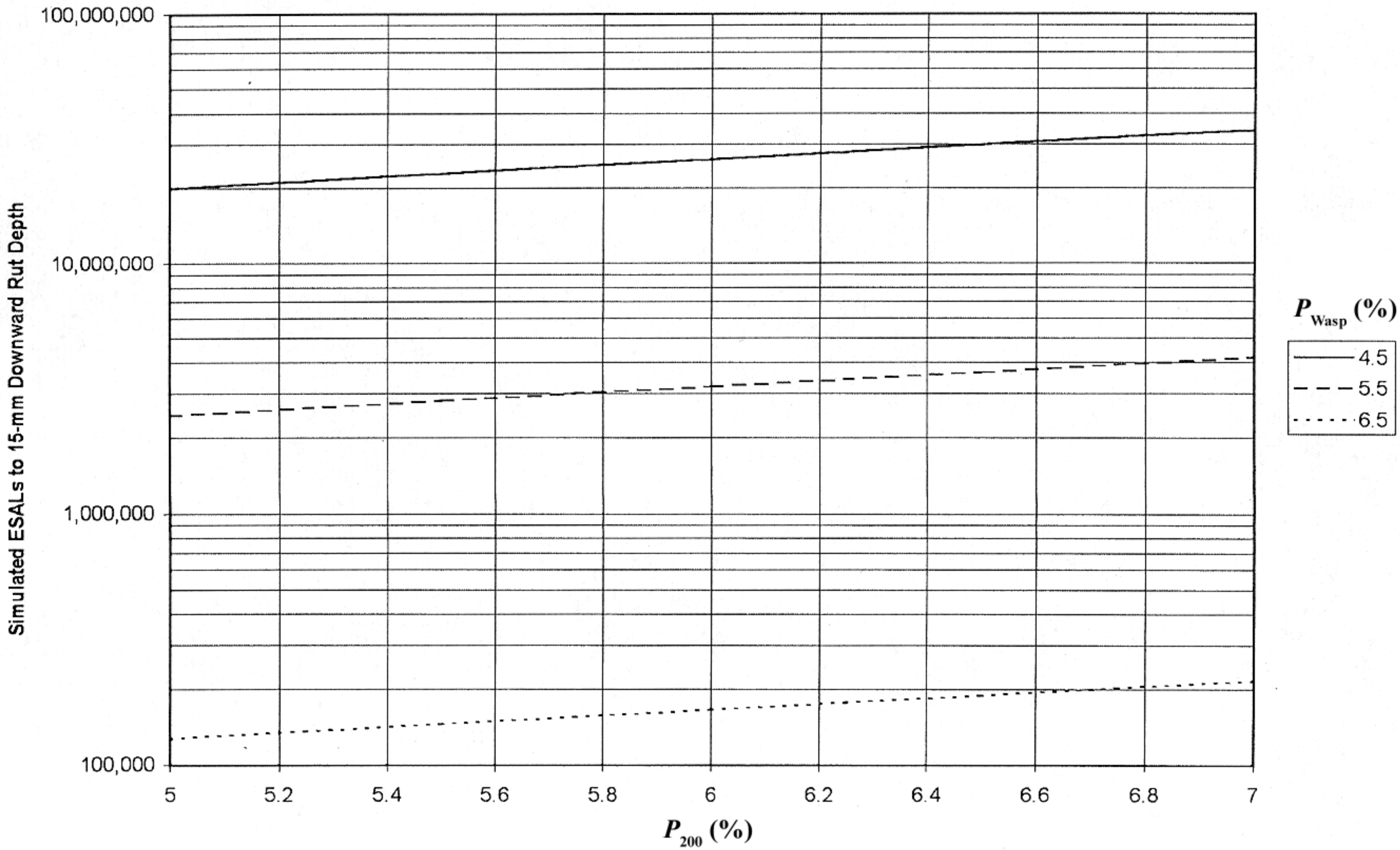

Figure 3.12 Effect of mix variables on simulated ESALs to 15 mm (0.6 in.) rut depth for a range in P_{200}; V_{air} = 6.5%, fine aggregate = 28%.

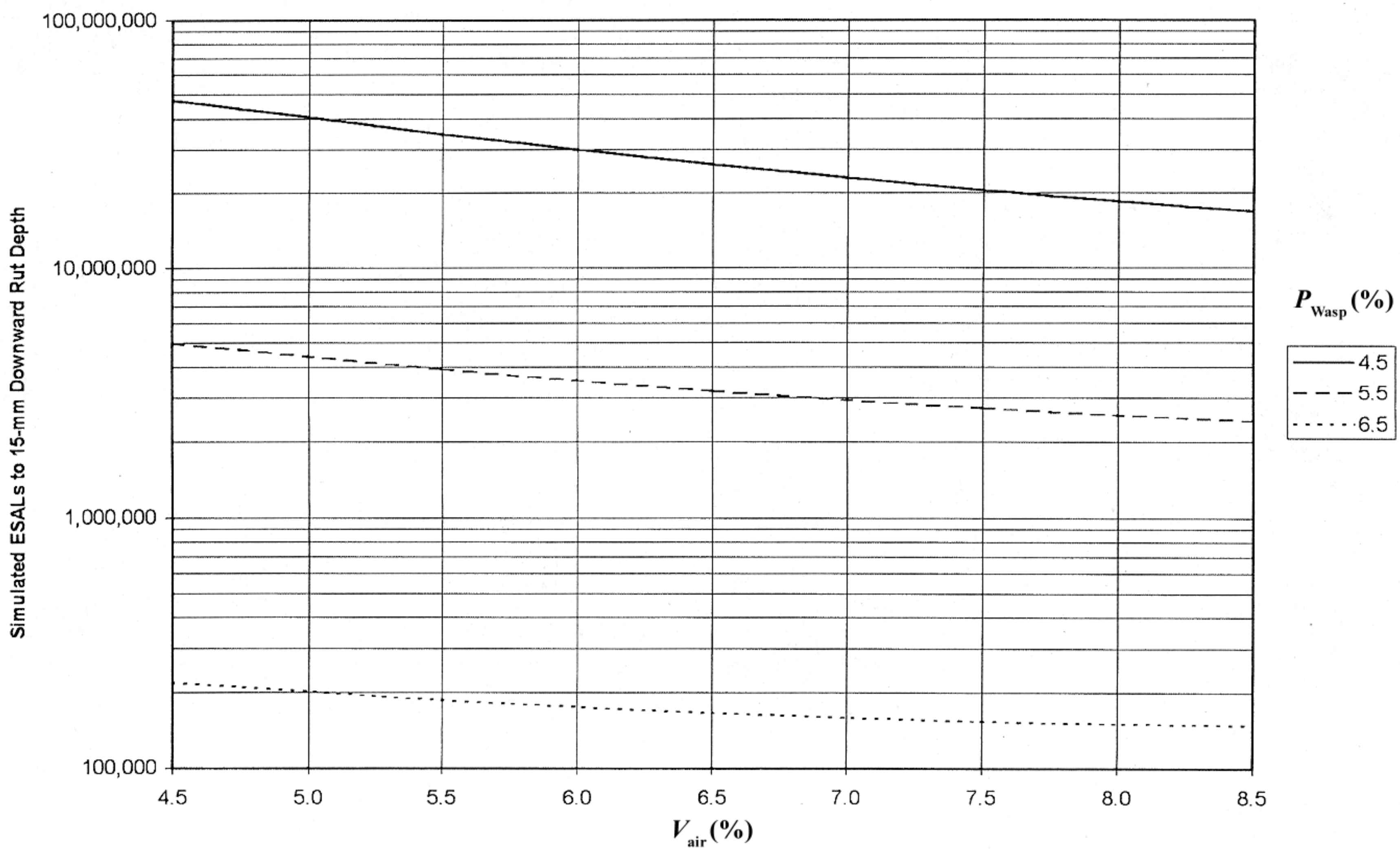

Figure 3.13. Effect of mix variables on simulated ESALs to 15 mm (0.6 in.) rut depth for a range in air-void contents; P_{200} = 6.0%, fine aggregate = 28%.

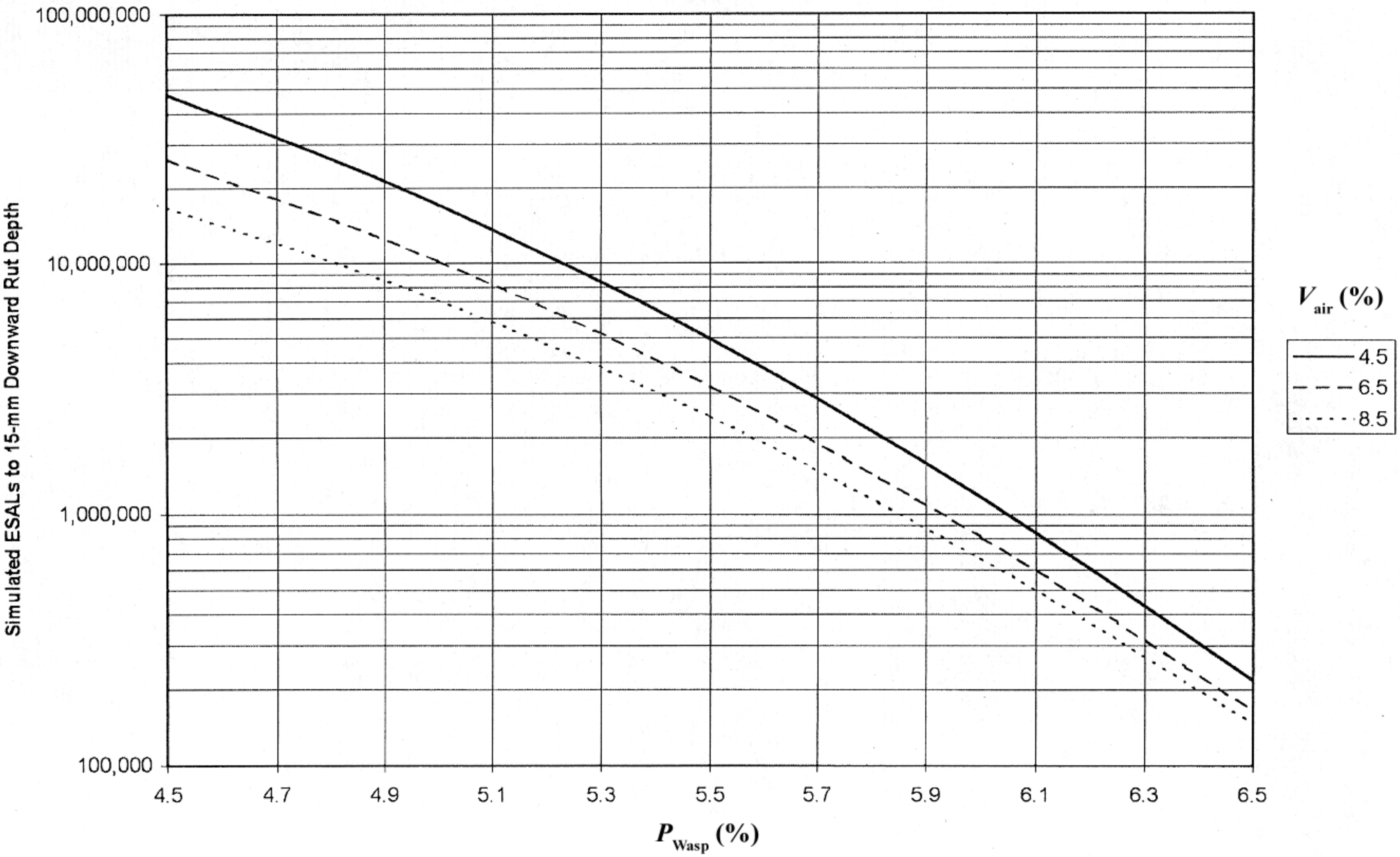

Figure 3.14. Effect of mix variables on simulated ESALs to 15 mm (0.6 in.) rut depth for a range in asphalt contents; P_{200} = 6.0%, fine aggregate = 28%.

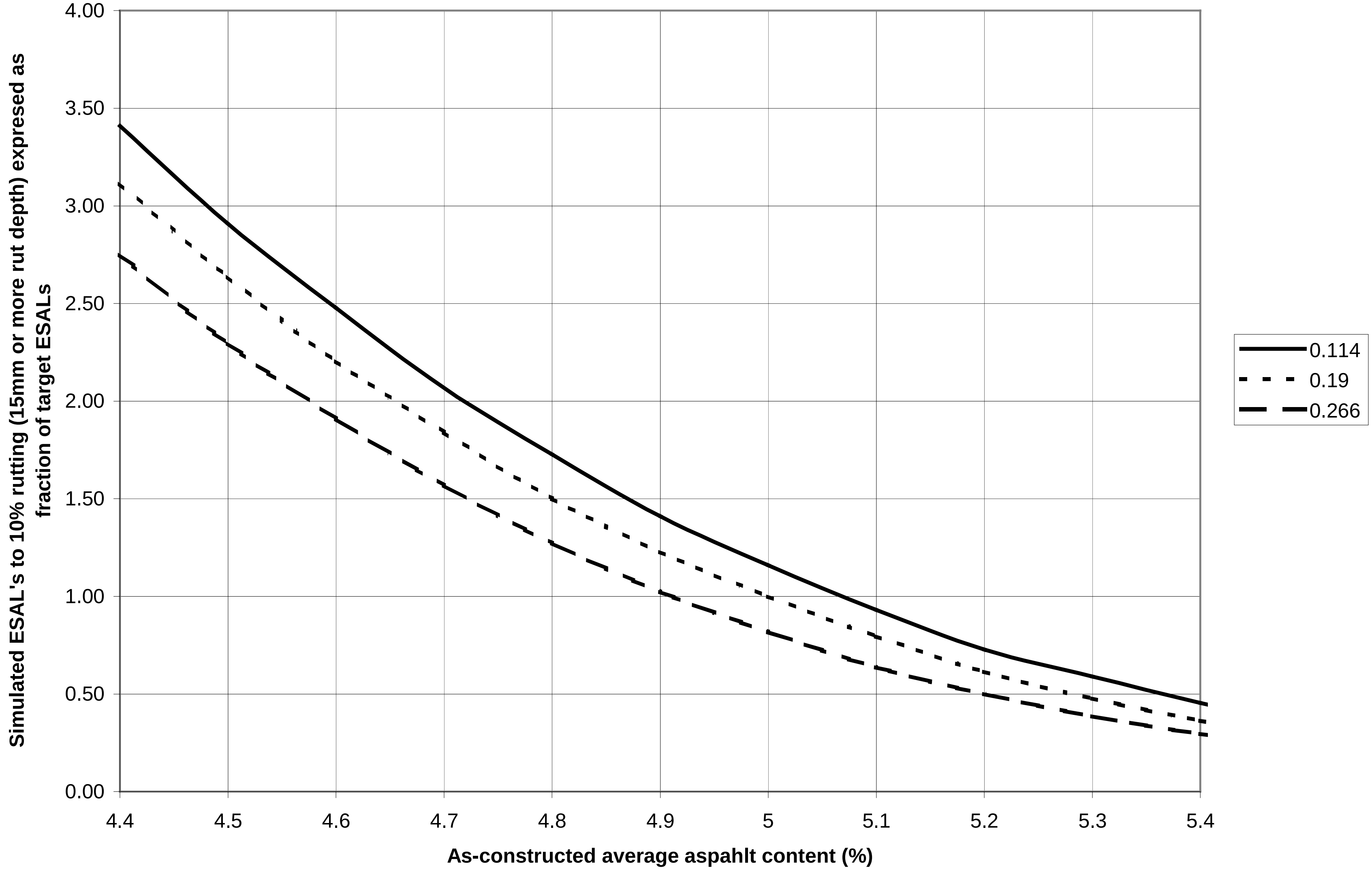

Figure 3.15. Influence of as-constructed asphalt contetn on rutting performance.

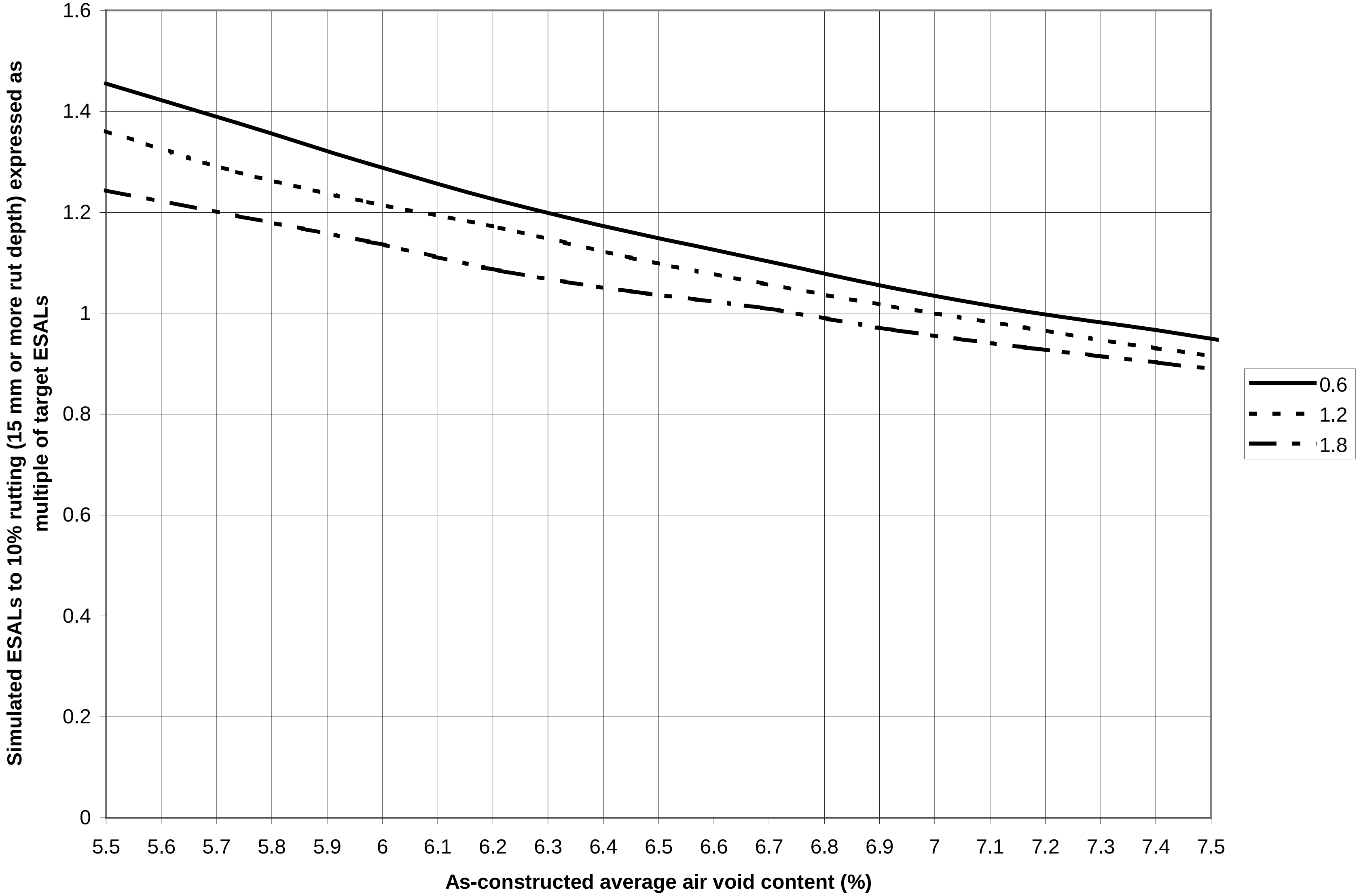

Figure 3.16. Influence of as-constructed air-void content on rutting performance.

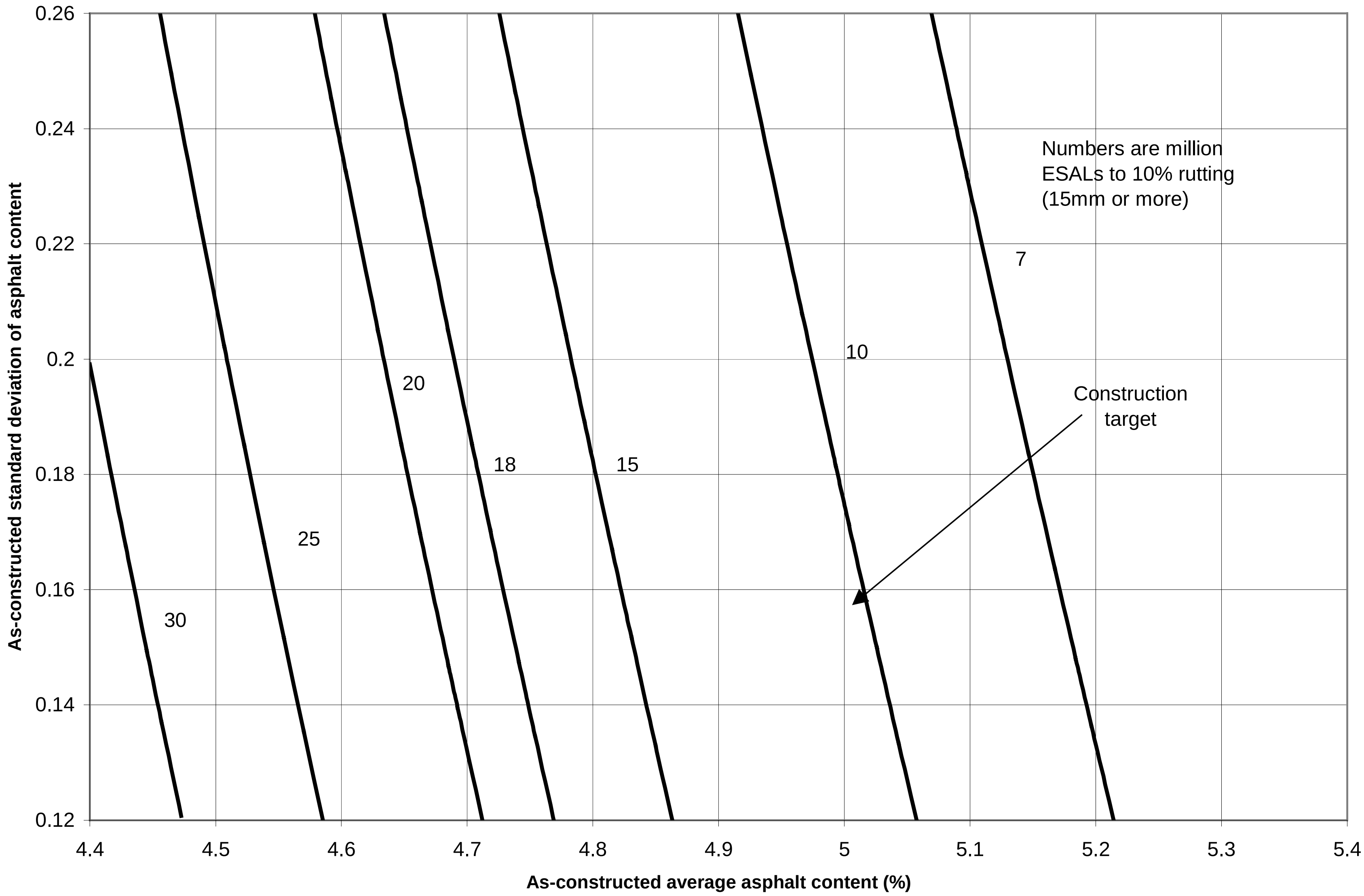

Figure 3.17. Influence of as-constructed asphalt content on pavement rutting performance.

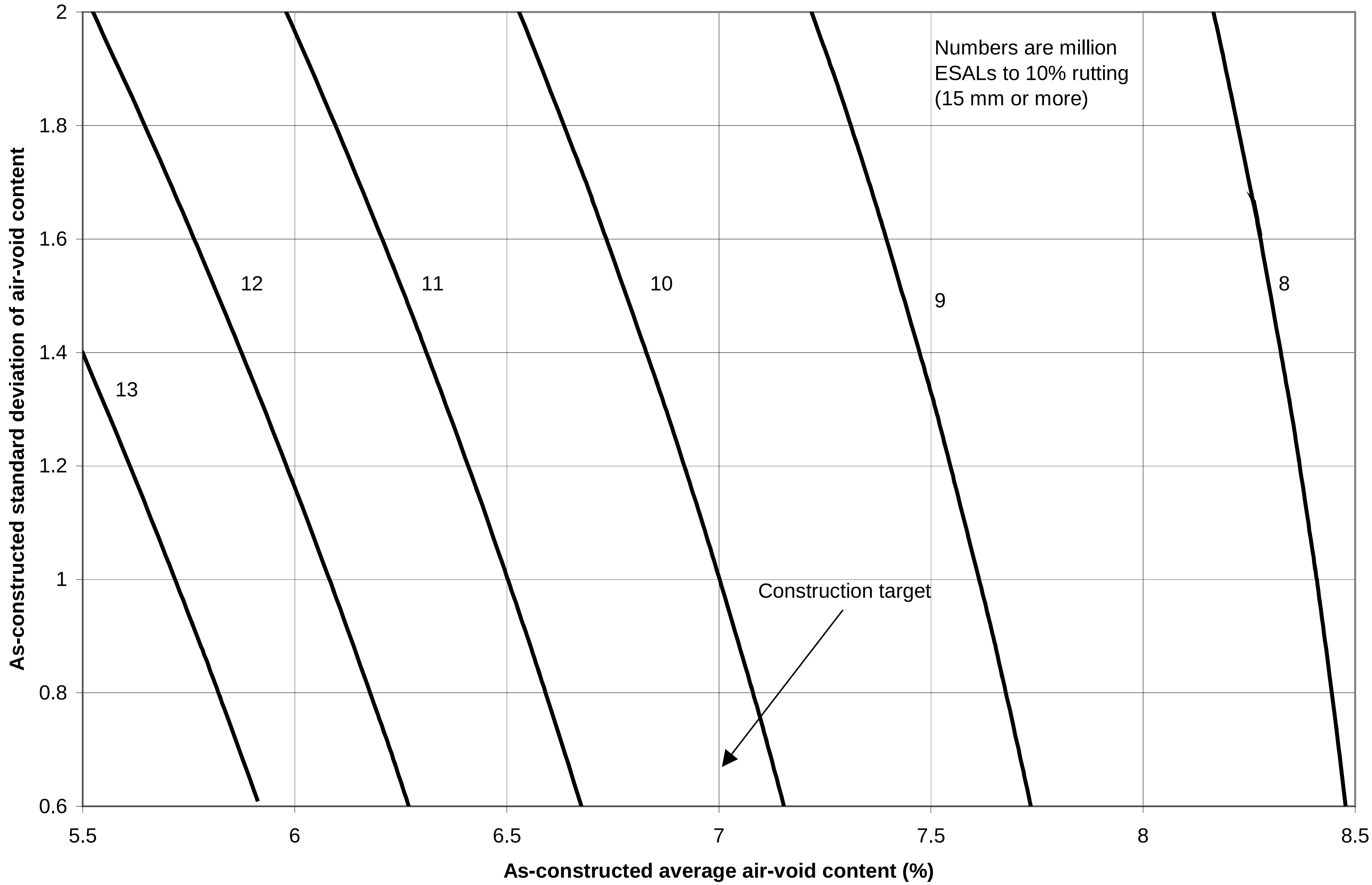

Figure 3.18. Influence of as-constructed asphalt content on pavement rutting performance.

3.2 Cost Model

The performance models yield the 10th percentile in-situ lives for ruts (15 mm depth) and fatigue cracking (10 percent in wheel paths) for both expected or on-target construction quality as well as off-target construction quality. The relative performance, *RP,* the performance input to the cost model, is computed as follows:

$$RP = \frac{off\text{ - }target\ ESALs}{on\text{ - }target\ ESALs} \tag{3.10}$$

The first step in the cost model is to determine the off-target pavement life in years, *OTY,* that results from the simulated performance differential. Assuming that traffic grows geometrically, the off-target pavement life is computed as follows:

$$OTY = \frac{\ln\left(1 + RP\left[(1+g)^{TY} - 1\right]\right)}{\ln(1+g)} \tag{3.11}$$

in which g is the annual rate of traffic growth expressed as a decimal and TY is the number of years of pavement life resulting from on-target construction activity.

The cost model assesses the present worth of moving the first rehabilitation cycle from its on-target position, *TY,* to its off-target position, *OTY.* The net present worth, expressed as a percentage of the rehabilitation costs (in current-year dollars) is described in the following paragraphs.

Assume that:

1. C is the resurfacing /rehabilitation cost in current-year dollars;
2. The pavement life, *TY,* is assumed to be 20 years;
3. r is the annual rate of growth in resurfacing/rehabilitation cost, that is, the construction cost index;
4. d is the annual discount rate; and

5. *OTY* is the pavement life due to off-target construction.

Then on-target construction will result in:

1. a future cost of $C(F/P, r\%,20)$ at the end of the 20-year target period; or
2. an annual equivalent of $C(F/P, r\%,20)(A/F,d\%,20)$ for 20 years.

where:

F = future worth

P = present worth

A = annuity amount

Off-target construction will result in:

1. a future cost of $C(F/P, r\%,20)$ at the end of the off-target period; or
2. an annual equivalent of $C(F/P, r\%,OTY)(A/F,d\%,OTY)$ for *OTY* years.

In the event that the *OTY* is less than the target period, the off-target construction increases the agency costs over the expected life of 20 years by the present worth of the difference between these annual cost streams over the *OTY* period. These costs are illustrated schematically in Figure 3.19. Their present worth is:

$$[C(F/P,r\%,OTY)(A/F,d\%,OTY)-C(F/P,r\%,20)(A/F,d\%,20)](P/A,d\%,OTY)$$

The equation for this expression is:

$$\Delta PW = C\left(\frac{(1+r)^{OTY}}{(1+d)^{OTY}-1}-\frac{(1+r)^{20}}{(1+d)^{20}-1}\right)\left(\frac{(1+d)^{OTY}-1}{(1+d)^{OTY}}\right) \quad \textbf{(3.12)}$$

When *OTY* exceeds the target life, the service life for comparison purposes may be set at either the target life, in this example, 20 years, or the longer *OTY*. It should be noted that if the longer period is chosen, it is beneficial to the contractor’s interests.

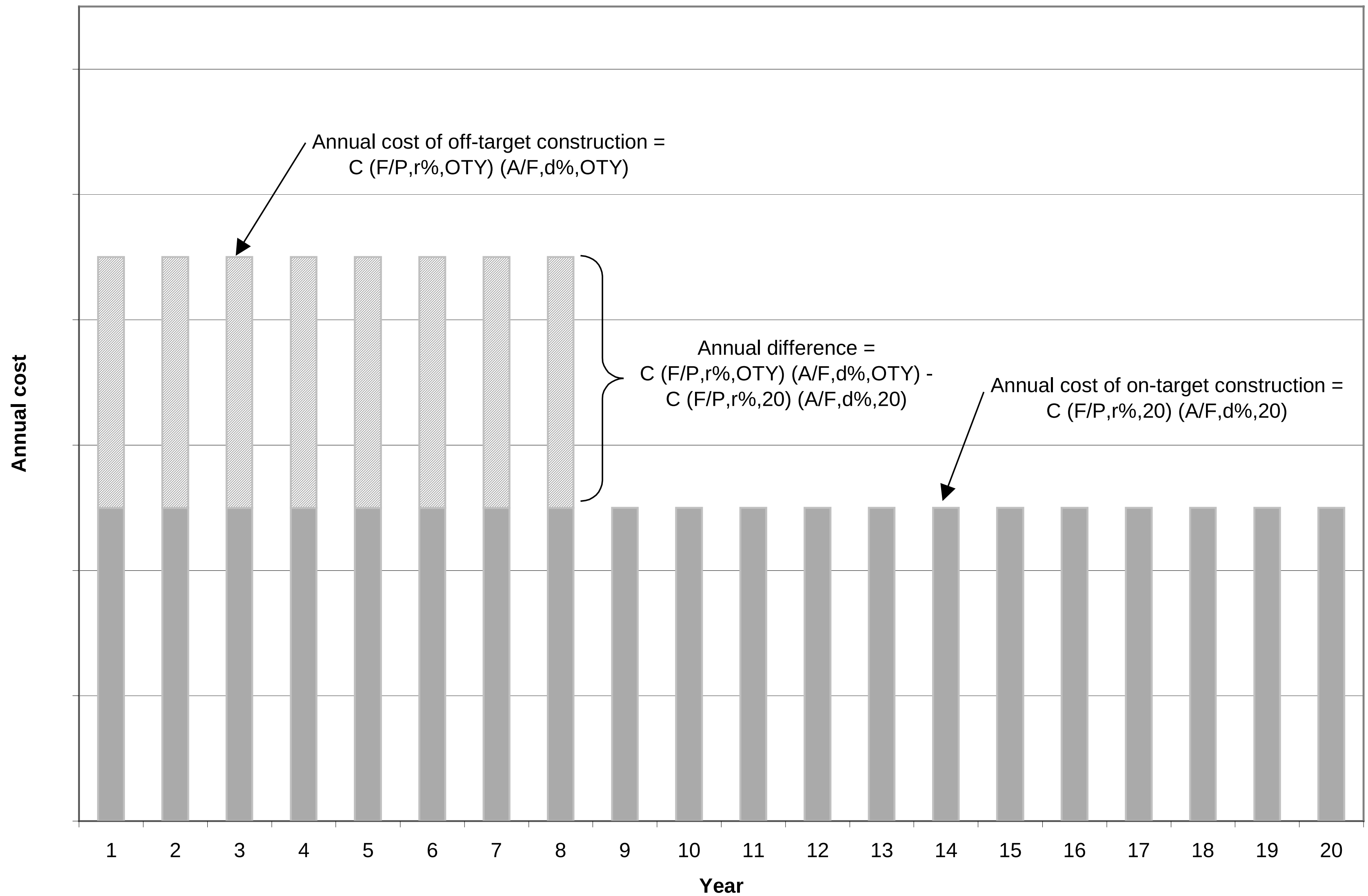

Figure 3.19. Schematic illustration of annual costs of on-target and off-target construction.

While the majority of the pay factor computations to be presented subsequently are based on the assumption of a target pavement life of 20 years (time to first rehabilitation), some computations will be presented for other target values (*TY*) ranging from 10 to 30 years.

4.0 PAY FACTORS

With the information presented in Section 3, it is then possible to determine the construction pay factors. The following considerations are reflected in the recommended pay factor schedules included herein:

1. One pay-factor should apply to all new construction; that is, job-specific pay factors are undesirable
2. The contractor should generally be charged a penalty for inferior construction which is out of specification, the magnitude of which should equal the full added cost to the agency for failure to meet the construction target;
3. The contractor should generally be rewarded for superior construction which is within specification, the magnitude of which should be some fraction of the full added benefit to the agency resulting from improved pavement performance;
4. Pay factor schedules should incorporate average and standard-deviation categories consistent with the accuracy within which estimates are determined from field measurements; and
5. The standard deviation of pay-factor schedules must reflect expected testing and sampling errors as well as materials/construction variables.

For the actual pay factors developed in this section, bonuses for superior construction and penalties for inferior construction reflect full agency cost increments. Eventually it will be necessary to make a decision for the fraction of the bonus to be paid for superior construction as noted in item (3) above. In addition, the examples reflect the following:

1. The sole construction quality effect is the date of first resurfacing/rehabilitation.
2. Both fatigue and rutting distress are reflected in the pay factor schedule. Each entry in the pay factor schedule is based on the distress mode yielding most beneficial consequence to the agency, namely, smaller bonus or larger penalty.
3. Pay factors are determined independently for each pay quantity. The combined pay factor is computed by the following equation:

$$\textit{Combined pay factor} = (1 + pf_{ac})(1 + pf_{av})(1 + pf_{mf})(1 + pf_{fa})(1 + pf_t) - 1 \qquad \textbf{(4.1)}$$

   in which all pay factors are expressed as decimals. Section 4.4 describes the basis for this simplified expression for combining pay factors. For convenience, the definitions which are utilized are summarized as follows:

   a) Asphalt content (*ac*): Percentage of asphalt by weight of total mixture
   b) Air-void content (*av*): Percentage of air voids by volume of total mixture
   c) Mineral filler (*mf*): Aggregate passing 0.074 mm (No. 200) sieve expressed as a percentage by weight of aggregate
   d) Fine aggregate (*fa*): Aggregate passing 2.36 mm (No. 8) sieve and retained on 0.074 mm (No. 200) sieve expressed as a percentage by weight of aggregate
   e) Rutting life: ESALs to 10-percent of rutting with downward depths of 15 mm or more based on WesTrack performance
   f) Fatigue life: ESALs to 10-percent cracking based on Caltrans experience as summarized by the Caltrans analysis and design model.

4.1 Pay Factors—Twenty-Year Expected Pavement Life

The computations in this section, in addition to the assumption of a 20-year expected pavement life (*TY* in Equation 3.4) are based on the following cost parameters:

1. 2% annual rate of inflation in resurfacing/rehabilitation cost (*r*)
2. 2.5% annual rate of traffic growth (*g*)
3. 5% discount rate (*d*)
4. Rutting failure results in resurfacing which costs 20% of the cost of new pavement construction in current-year dollars
5. Fatigue failure results in rehabilitation which costs 50% of the cost of new pavement construction in current-year dollars.

The cost implications of off-target construction have been determined according to the procedure described in Section 3.3. Tables 4.1 through 4.4 present the results of the rutting analysis based on the WesTrack model for rutting. Tables 4.5 through 4.7 present the results of the fatigue analysis using the California model. Tables 4.5 through 4.7 present the results of the fatigue analysis using the California model. Tables 4.8 through 4.12 present the results of the combined analysis showing results most favorable to the agency.

With this information, it is then possible to establish pay-factor tables. These are shown in Tables 4.13 through 4.17 for each of the five factors considered. The pay factors for air-void content do not include the effects of either, a) the area where the specification is met but the performance is inferior to that of the target, or b) the area where the specification is not met but the performance is superior to that of the target (Figure 3.8).

Table 4.1 Effect of off-target asphalt content on future agency resurfacing cost based on rutting in WesTrack pavements (change expressed as a percent of new pavement construction cost).

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
4.0	-13.9	-13.9	-13.8	-13.8	-13.7	-13.6	-13.5	-13.4	-13.3
4.1	-13.4	-13.4	-13.3	-13.2	-13.1	-13.0	-12.9	-12.8	-12.6
4.2	-12.8	-12.7	-12.6	-12.5	-12.4	-12.2	-12.1	-11.9	-11.7
4.3	-12.0	-11.9	-11.8	-11.6	-11.5	-11.3	-11.2	-10.9	-10.8
4.4	-11.1	-11.0	-10.8	-10.7	-10.5	-10.3	-10.0	-9.8	-9.5
4.5	-10.0	-9.9	-9.6	-9.5	-9.2	-9.0	-8.7	-8.5	-8.1
4.6	-8.7	-8.5	-8.3	-8.1	-7.8	-7.5	-7.2	-6.9	-6.5
4.7	-7.2	-7.0	-6.7	-6.5	-6.2	-5.8	-5.5	-5.0	-4.7
4.8	-5.5	-5.3	-4.9	-4.7	-4.3	-3.9	-3.5	-3.1	-2.6
4.9	-3.7	-3.3	-3.0	-2.6	-2.2	-1.8	-1.3	-0.9	-0.4
5.0	-1.6	-1.2	-0.9	-0.4	0.0	0.5	0.9	1.5	2.0
5.1	0.7	1.0	1.5	1.9	2.3	2.8	3.4	3.9	4.4
5.2	3.0	3.3	3.8	4.2	4.8	5.2	5.8	6.2	6.8
5.3	5.3	5.7	6.1	6.6	7.1	7.6	8.1	8.5	9.0
5.4	7.6	8.0	8.5	8.9	9.3	9.8	10.2	10.7	11.1
5.5	9.8	10.2	10.6	10.9	11.4	11.8	12.2	12.6	13.1
5.6	11.8	12.1	12.5	12.9	13.2	13.6	14.0	14.3	14.7
5.7	13.5	13.9	14.2	14.5	14.8	15.2	15.4	15.8	16.0
5.8	15.1	15.3	15.7	15.9	16.2	16.4	16.7	16.9	17.2
5.9	16.4	16.6	16.8	17.1	17.3	17.5	17.7	17.9	18.1
6.0	17.4	17.6	17.8	18.0	18.2	18.3	18.5	18.6	18.7

Table 4.2 Effect of off-target air-void content on future agency resurfacing cost based on rutting in WesTrack pavement (change expressed as a percent of new pavement construction cost).

As-constructed air-void content (%)	As-constructed standard deviation of relative compaction (multiple of 1.2%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
5.00	-5.1	-5.0	-4.9	-4.8	-4.6	-4.3	-4.3	-4.0	-3.8
5.25	-4.5	-4.4	-4.2	-4.2	-3.9	-3.9	-3.6	-3.5	-3.2
5.50	-3.9	-3.8	-3.7	-3.5	-3.4	-3.2	-3.1	-3.0	-2.7
5.7	-3.4	-3.2	-3.1	-2.9	-2.8	-2.6	-2.6	-2.4	-2.1
6.00	-2.7	-2.7	-2.5	-2.4	-2.2	-2.2	-2.0	-1.9	-1.7
6.25	-2.2	-2.1	-2.0	-1.9	-1.7	-1.6	-1.4	-1.4	-1.2
6.4	-1.6	-1.5	-1.5	-1.3	-1.3	-1.1	-1.0	-0.9	-0.7
6.7	-1.1	-1.0	-0.9	-0.9	-0.8	-0.6	-0.6	-0.5	-0.3
6.9	-0.6	-0.5	-0.4	-0.4	-0.3	-0.3	0.0	0.0	0.1
7.1	-0.1	0.0	0.0	0.1	0.2	0.3	0.3	0.4	0.5
7.4	0.3	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.9
7.6	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.2	1.2
7.85	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.6	1.5
8.1	1.6	1.6	1.6	1.7	1.7	1.8	1.8	1.9	1.9
8.3	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.1
8.6	2.3	2.3	2.4	2.4	2.4	2.4	2.5	2.5	2.4
8.8	2.6	2.7	2.6	2.7	2.7	2.7	2.7	2.7	2.7
9.0	2.9	2.9	2.9	2.9	2.9	3.0	2.9	3.0	2.9
9.3	3.2	3.1	3.2	3.1	3.2	3.1	3.2	3.1	3.1
9.5	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.3
9.75	3.6	3.6	3.6	3.7	3.5	3.6	3.5	3.6	3.5

Table 4.3 Effect of off-target mineral filler on future agency resurfacing cost based on rutting in WesTrack pavement (change expressed as a percent of new pavement construction cost).

As-constructed average mineral filler (%)	As-constructed standard deviation of mineral filler (multiple of 0.7794%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
3.00	6.9	7.0	7.0	7.2	7.3	7.4	7.5	7.7	7.8
3.25	6.2	6.3	6.4	6.5	6.6	6.7	6.9	7.0	7.1
3.50	5.5	5.5	5.7	5.8	6.0	6.0	6.2	6.3	6.5
3.75	4.7	4.9	5.0	5.1	5.2	5.4	5.5	5.7	5.8
4.00	4.1	4.1	4.2	4.4	4.4	4.6	4.8	5.0	5.0
4.25	3.4	3.4	3.6	3.6	3.8	3.9	4.0	4.2	4.4
4.50	2.6	2.7	2.8	2.9	3.0	3.1	3.3	3.4	3.6
4.75	1.9	2.0	2.0	2.2	2.3	2.5	2.5	2.8	2.8
5.00	1.1	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2.1
5.25	0.4	0.4	0.6	0.7	0.8	0.9	1.1	1.2	1.4
5.50	-0.5	-0.3	-0.3	-0.1	0.0	0.2	0.3	0.5	0.6
5.75	-1.2	-1.1	-1.0	-0.8	-0.7	-0.6	-0.4	-0.2	-0.1
6.00	-1.9	-1.8	-1.7	-1.7	-1.4	-1.4	-1.2	-1.1	-0.8
6.25	-2.7	-2.5	-2.4	-2.3	-2.3	-2.1	-1.9	-1.8	-1.6
6.50	-3.4	-3.3	-3.2	-3.0	-3.0	-2.8	-2.7	-2.4	-2.4
6.75	-4.1	-4.0	-3.8	-3.8	-3.7	-3.5	-3.4	-3.3	-3.1
7.00	-4.8	-4.7	-4.6	-4.5	-4.4	-4.3	-4.1	-4.0	-3.8
7.25	-5.5	-5.3	-5.4	-5.2	-5.1	-4.9	-4.8	-4.7	-4.5
7.50	-6.1	-6.1	-6.0	-5.9	-5.8	-5.6	-5.5	-5.3	-5.2
7.75	-6.8	-6.7	-6.6	-6.6	-6.4	-6.3	-6.1	-6.1	-5.8
8.00	-7.4	-7.3	-7.3	-7.2	-7.1	-7.0	-6.8	-6.7	-6.6

Table 4.4 Effect of off-target fine aggregate on future agency resurfacing cost based on rutting in WesTrack pavement (change expressed as a percent of new pavement construction cost).

As-constructed average fine aggregate (%)	As-constructed standard deviation of fine aggregate (multiple of 2.7659%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
24.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
24.6	0.2	0.1	0.2	0.1	0.1	0.0	0.1	0.0	0.1
25.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.0
25.8	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0
26.4	0.3	0.2	0.3	0.2	0.2	0.1	0.1	0.1	0.1
27.0	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
27.6	0.2	0.2	0.1	0.2	0.1	0.2	0.1	0.1	0.0
28.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0
28.8	0.2	0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.1
29.4	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	-0.1
30.0	0.1	0.0	0.1	0.0	0.0	0.0	-0.1	-0.1	-0.1
30.6	0.0	0.0	0.0	-0.1	0.0	-0.1	-0.1	-0.2	-0.1
31.2	-0.1	-0.1	-0.2	-0.1	-0.2	-0.1	-0.2	-0.2	-0.2
31.8	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.2	-0.4
32.4	-0.3	-0.4	-0.3	-0.4	-0.3	-0.4	-0.3	-0.4	-0.4
33.0	-0.4	-0.4	-0.4	-0.5	-0.4	-0.5	-0.5	-0.5	-0.4
33.6	-0.6	-0.5	-0.6	-0.6	-0.6	-0.5	-0.7	-0.6	-0.7
34.2	-0.6	-0.7	-0.7	-0.7	-0.7	-0.7	-0.8	-0.7	-0.8
34.8	-0.8	-0.8	-0.8	-0.9	-0.8	-0.9	-0.8	-1.0	-0.8
35.4	-1.1	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.1	-1.1
36.0	-1.2	-1.2	-1.2	-1.2	-1.2	-1.1	-1.2	-1.1	-1.3

Table 4.5 Effect of off-target asphalt content on future agency rehabilitation cost based on Caltrans fatigue model (change expressed as a percent of new pavement construction cost).

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
4.0	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3
4.1	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
4.2	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
4.3	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
4.4	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	2.0
4.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
4.6	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
4.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4.8	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7
4.9	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.1	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
5.2	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7
5.3	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
5.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4
5.5	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7
5.6	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.0	-2.0
5.7	-2.5	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4
5.8	-2.8	-2.8	-2.8	-2.8	-2.8	-2.7	-2.7	-2.7	-2.7
5.9	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1
6.0	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 4.6 Effect of off-target air-void content on future agency rehabilitation cost based on Caltrans fatigue model (change expressed as a percent of new pavement construction cost).

As-constructed air-void content (%)	As-constructed standard deviation of relative compaction (multiple of 1.2%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.3**	**1.4**	**1.6**
5.00	-20.4	-19.9	-19.3	-18.7	-18.1	-17.4	-16.7	-15.9	-15.1
5.25	-18.7	-18.1	-17.5	-16.9	-16.2	-15.4	-14.7	-13.9	-13.0
5.50	-16.8	-16.2	-15.6	-14.9	-14.2	-13.4	-12.6	-11.8	-10.9
5.7	-14.9	-14.3	-13.6	-12.9	-12.1	-11.3	-10.5	-9.7	-8.8
6.00	-12.9	-12.2	-11.5	-10.8	-10.0	-9.2	-8.4	-7.5	-6.6
6.25	-10.8	-10.1	-9.4	-8.6	-7.9	-7.0	-6.2	-5.3	-4.3
6.4	-8.7	-8.0	-7.3	-6.5	-5.7	-4.8	-3.9	-3.0	-2.1
6.7	-6.6	-5.8	-5.1	-4.3	-3.4	-2.6	-1.7	-0.8	0.2
6.9	-4.4	-3.6	-2.8	-2.0	-1.2	-0.3	0.5	1.5	2.4
7.1	-2.2	-1.4	-0.6	0.2	1.0	1.9	2.8	3.7	4.6
7.4	0.1	0.8	1.6	2.4	3.2	4.1	5.0	5.9	6.8
7.6	2.3	3.0	3.8	4.6	5.4	6.3	7.2	8.0	9.0
7.85	4.5	5.3	6.0	6.8	7.6	8.4	9.3	10.2	11.1
8.1	6.7	7.4	8.2	8.9	9.7	10.5	11.4	12.2	13.1
8.3	8.8	9.6	10.3	11.0	11.8	12.6	13.4	14.2	15.1
8.6	10.9	11.6	12.4	13.1	13.8	14.6	15.3	16.1	16.9
8.8	13.0	13.7	14.3	15.0	15.7	16.5	17.2	17.9	18.7
9.0	15.0	15.6	16.3	16.9	17.6	18.3	19.0	19.7	20.4
9.3	16.9	17.5	18.1	18.7	19.3	20.0	20.6	21.3	21.9
9.5	18.7	19.2	19.8	20.4	21.0	21.5	22.1	22.7	23.3
9.75	20.4	20.9	21.4	21.9	22.5	23.0	23.5	24.1	24.6

Table 4.7 Effect of off-target asphalt-concrete thickness on future agency rehabilitation cost based on Caltrans fatigue model (change expressed as a percent of new pavement construction cost).

Difference between as-measured average asphalt-concrete thickness and design thickness (in.)	As-constructed standard deviation of asphalt-concrete thickness (multiple of 8%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
-1.0	17.7	18.5	19.2	19.9	20.7	21.4	22.3	23.0	23.8
-0.9	15.9	16.7	17.4	18.2	19.0	19.8	20.6	21.4	22.3
-0.8	14.0	14.8	15.6	16.4	17.2	18.1	18.9	19.8	20.7
-0.7	12.0	12.8	13.6	14.5	15.3	16.2	17.1	18.0	18.9
-0.6	9.9	10.8	11.6	12.5	13.3	14.2	15.1	16.1	17.1
-0.5	7.8	8.6	9.5	10.4	11.3	12.2	13.1	14.1	15.1
-0.4	5.6	6.4	7.3	8.2	9.1	10.1	11.0	12.0	13.1
-0.3	3.3	4.2	5.0	5.9	6.9	7.9	8.9	9.9	11.0
-0.2	1.0	1.9	2.7	3.7	4.6	5.6	6.6	7.6	8.8
-0.1	-1.3	-0.5	0.5	1.4	2.3	3.3	4.3	5.3	6.4
0.0	-3.5	-2.7	-1.9	-1.0	0.0	1.0	2.0	3.0	4.1
0.1	-5.8	-5.0	-4.1	-3.2	-2.3	-1.4	-0.3	0.7	1.8
0.2	-7.9	-7.1	-6.3	-5.5	-4.6	-3.6	-2.7	-1.6	-0.6
0.3	-10.1	-9.3	-8.5	-7.7	-6.8	-5.9	-5.0	-4.0	-2.9
0.4	-12.1	-11.3	-10.6	-9.8	-8.9	-8.1	-7.1	-6.2	-5.2
0.5	-14.1	-13.3	-12.6	-11.8	-11.0	-10.2	-9.3	-8.4	-7.4
0.6	-16.0	-15.3	-14.6	-13.8	-13.0	-12.2	-11.4	-10.5	-9.5
0.7	-17.9	-17.2	-16.5	-15.8	-15.0	-14.2	-13.4	-12.5	-11.6
0.8	-20.0	-19.3	-18.5	-17.7	-17.0	-16.2	-15.4	-14.5	-13.7
0.9	-22.3	-21.4	-20.6	-19.8	-19.0	-18.2	-17.3	-16.5	-15.6
1.0	-24.8	-23.9	-22.9	-22.0	-21.2	-20.3	-19.4	-18.6	-17.7

Table 4.8 Effect of off-target asphalt content on future agency resurfacing/rehabilitation costs (change expressed as a percent of new pavement construction cost).

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
4.0	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3
4.1	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
4.2	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
4.3	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
4.4	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	2.0
4.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
4.6	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
4.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4.8	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7
4.9	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
5.0	0.0	0.0	0.0	0.0	0.0	0.5	0.9	1.5	2.0
5.1	0.7	1.0	1.5	1.9	2.3	2.8	3.4	3.9	4.4
5.2	3.0	3.3	3.8	4.2	4.8	5.2	5.8	6.2	6.8
5.3	5.3	5.7	6.1	6.6	7.1	7.6	8.1	8.5	9.0
5.4	7.6	8.0	8.5	8.9	9.3	9.8	10.2	10.7	11.1
5.5	9.8	10.2	10.6	10.9	11.4	11.8	12.2	12.6	13.1
5.6	11.8	12.1	12.5	12.9	13.2	13.6	14.0	14.3	14.7
5.7	13.5	13.9	14.2	14.5	14.8	15.2	15.4	15.8	16.0
5.8	15.1	15.3	15.7	15.9	16.2	16.4	16.7	16.9	17.2
5.9	16.4	16.6	16.8	17.1	17.3	17.5	17.7	17.9	18.1
6.0	17.4	17.6	17.8	18.0	18.2	18.3	18.5	18.6	18.7

Table 4.9 Effect of off-target air-void content on future agency resurfacing/rehabilitation costs (change expressed as a percent of new pavement construction cost).

As-constructed air-void content (%)	As-constructed standard deviation of relative compaction (multiple of 1.2%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.3**	**1.4**	**1.6**
100.00	-5.1	-5.0	-4.9	-4.8	-4.6	-4.3	-4.3	-4.0	-3.8
99.75	-4.5	-4.4	-4.2	-4.2	-3.9	-3.9	-3.6	-3.5	-3.2
99.50	-3.9	-3.8	-3.7	-3.5	-3.4	-3.2	-3.1	-3.0	-2.7
99.25	-3.4	-3.2	-3.1	-2.9	-2.8	-2.6	-2.6	-2.4	-2.1
99.00	-2.7	-2.7	-2.5	-2.4	-2.2	-2.2	-2.0	-1.9	-1.7
98.75	-2.2	-2.1	-2.0	-1.9	-1.7	-1.6	-1.4	-1.4	-1.2
98.50	-1.6	-1.5	-1.5	-1.3	-1.3	-1.1	-1.0	-0.9	-0.7
98.25	-1.1	-1.0	-0.9	-0.9	-0.8	-0.6	-0.6	-0.5	0.2
98.00	-0.6	-0.5	-0.4	-0.4	-0.3	-0.3	0.5	1.5	2.4
97.75	-0.1	0.0	0.0	0.2	1.0	1.9	2.8	3.7	4.6
97.50	0.3	0.8	1.6	2.4	3.2	4.1	5.0	5.9	6.8
97.25	2.3	3.0	3.8	4.6	5.4	6.3	7.2	8.0	9.0
97.00	4.5	5.3	6.0	6.8	7.6	8.4	9.3	10.2	11.1
96.75	6.7	7.4	8.2	8.9	9.7	10.5	11.4	12.2	13.1
96.50	8.8	9.6	10.3	11.0	11.8	12.6	13.4	14.2	15.1
96.25	10.9	11.6	12.4	13.1	13.8	14.6	15.3	16.1	16.9
96.00	13.0	13.7	14.3	15.0	15.7	16.5	17.2	17.9	18.7
95.75	15.0	15.6	16.3	16.9	17.6	18.3	19.0	19.7	20.4
95.50	16.9	17.5	18.1	18.7	19.3	20.0	20.6	21.3	21.9
95.25	18.7	19.2	19.8	20.4	21.0	21.5	22.1	22.7	23.3
95.00	20.4	20.9	21.4	21.9	22.5	23.0	23.5	24.1	24.6

Table 4.10 Effect of off-target mineral filler on future agency resurfacing/rehabilitation costs (change expressed as a percent of new pavement construction cost).

As-constructed average mineral filler (%)	As-constructed standard deviation of mineral filler (multiple of 0.7794%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
3.00	6.9	7.0	7.0	7.2	7.3	7.4	7.5	7.7	7.8
3.25	6.2	6.3	6.4	6.5	6.6	6.7	6.9	7.0	7.1
3.50	5.5	5.5	5.7	5.8	6.0	6.0	6.2	6.3	6.5
3.75	4.7	4.9	5.0	5.1	5.2	5.4	5.5	5.7	5.8
4.00	4.1	4.1	4.2	4.4	4.4	4.6	4.8	5.0	5.0
4.25	3.4	3.4	3.6	3.6	3.8	3.9	4.0	4.2	4.4
4.50	2.6	2.7	2.8	2.9	3.0	3.1	3.3	3.4	3.6
4.75	1.9	2.0	2.0	2.2	2.3	2.5	2.5	2.8	2.8
5.00	1.1	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2.1
5.25	0.4	0.4	0.6	0.7	0.8	0.9	1.1	1.2	1.4
5.50	-0.5	-0.3	-0.3	-0.1	0.0	0.2	0.3	0.5	0.6
5.75	-1.2	-1.1	-1.0	-0.8	-0.7	-0.6	-0.4	-0.2	-0.1
6.00	-1.9	-1.8	-1.7	-1.7	-1.4	-1.4	-1.2	-1.1	-0.8
6.25	-2.7	-2.5	-2.4	-2.3	-2.3	-2.1	-1.9	-1.8	-1.6
6.50	-3.4	-3.3	-3.2	-3.0	-3.0	-2.8	-2.7	-2.4	-2.4
6.75	-4.1	-4.0	-3.8	-3.8	-3.7	-3.5	-3.4	-3.3	-3.1
7.00	-4.8	-4.7	-4.6	-4.5	-4.4	-4.3	-4.1	-4.0	-3.8
7.25	-5.5	-5.3	-5.4	-5.2	-5.1	-4.9	-4.8	-4.7	-4.5
7.50	-6.1	-6.1	-6.0	-5.9	-5.8	-5.6	-5.5	-5.3	-5.2
7.75	-6.8	-6.7	-6.6	-6.6	-6.4	-6.3	-6.1	-6.1	-5.8
8.00	-7.4	-7.3	-7.3	-7.2	-7.1	-7.0	-6.8	-6.7	-6.6

Table 4.11 Effect of off-target fine aggregate on future agency resurfacing/rehabilitation costs (change expressed as a percent of new pavement construction cost).

As-constructed average fine aggregate (%)	As-constructed standard deviation of fine aggregate (multiple of 2.7659%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
24.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
24.6	0.2	0.1	0.2	0.1	0.1	0.0	0.1	0.0	0.1
25.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.0
25.8	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0
26.4	0.3	0.2	0.3	0.2	0.2	0.1	0.1	0.1	0.1
27.0	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
27.6	0.2	0.2	0.1	0.2	0.1	0.2	0.1	0.1	0.0
28.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0
28.8	0.2	0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.1
29.4	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	-0.1
30.0	0.1	0.0	0.1	0.0	0.0	0.0	-0.1	-0.1	-0.1
30.6	0.0	0.0	0.0	-0.1	0.0	-0.1	-0.1	-0.2	-0.1
31.2	-0.1	-0.1	-0.2	-0.1	-0.2	-0.1	-0.2	-0.2	-0.2
31.8	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.2	-0.4
32.4	-0.3	-0.4	-0.3	-0.4	-0.3	-0.4	-0.3	-0.4	-0.4
33.0	-0.4	-0.4	-0.4	-0.5	-0.4	-0.5	-0.5	-0.5	-0.4
33.6	-0.6	-0.5	-0.6	-0.6	-0.6	-0.5	-0.7	-0.6	-0.7
34.2	-0.6	-0.7	-0.7	-0.7	-0.7	-0.7	-0.8	-0.7	-0.8
34.8	-0.8	-0.8	-0.8	-0.9	-0.8	-0.9	-0.8	-1.0	-0.8
35.4	-1.1	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.1	-1.1
36.0	-1.2	-1.2	-1.2	-1.2	-1.2	-1.1	-1.2	-1.1	-1.3

Table 4.12 Effect of off-target asphalt concrete thickness on future agency resurfacing/rehabilitation costs (change expressed as a percent of new pavement construction cost).

Difference between as-measured average asphalt-concrete thickness and design thickness (in)	As-constructed standard deviation of asphalt-concrete thickness (multiple of 8%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
-1.0	17.7	18.5	19.2	19.9	20.7	21.4	22.3	23.0	23.8
-0.9	15.9	16.7	17.4	18.2	19.0	19.8	20.6	21.4	22.3
-0.8	14.0	14.8	15.6	16.4	17.2	18.1	18.9	19.8	20.7
-0.7	12.0	12.8	13.6	14.5	15.3	16.2	17.1	18.0	18.9
-0.6	9.9	10.8	11.6	12.5	13.3	14.2	15.1	16.1	17.1
-0.5	7.8	8.6	9.5	10.4	11.3	12.2	13.1	14.1	15.1
-0.4	5.6	6.4	7.3	8.2	9.1	10.1	11.0	12.0	13.1
-0.3	3.3	4.2	5.0	5.9	6.9	7.9	8.9	9.9	11.0
-0.2	1.0	1.9	2.7	3.7	4.6	5.6	6.6	7.6	8.8
-0.1	-1.3	-0.5	0.5	1.4	2.3	3.3	4.3	5.3	6.4
0.0	-3.5	-2.7	-1.9	-1.0	0.0	1.0	2.0	3.0	4.1
0.1	-5.8	-5.0	-4.1	-3.2	-2.3	-1.4	-0.3	0.7	1.8
0.2	-7.9	-7.1	-6.3	-5.5	-4.6	-3.6	-2.7	-1.6	-0.6
0.3	-10.1	-9.3	-8.5	-7.7	-6.8	-5.9	-5.0	-4.0	-2.9
0.4	-12.1	-11.3	-10.6	-9.8	-8.9	-8.1	-7.1	-6.2	-5.2
0.5	-14.1	-13.3	-12.6	-11.8	-11.0	-10.2	-9.3	-8.4	-7.4
0.6	-16.0	-15.3	-14.6	-13.8	-13.0	-12.2	-11.4	-10.5	-9.5
0.7	-17.9	-17.2	-16.5	-15.8	-15.0	-14.2	-13.4	-12.5	-11.6
0.8	-20.0	-19.3	-18.5	-17.7	-17.0	-16.2	-15.4	-14.5	-13.7
0.9	-22.3	-21.4	-20.6	-19.8	-19.0	-18.2	-17.3	-16.5	-15.6
1.0	-24.8	-23.9	-22.9	-22.0	-21.2	-20.3	-19.4	-18.6	-17.7

Table 4.13 Contractor pay factors for asphalt content (percentage of future resurfacing/rehabilitation cost in current-year dollars).

Difference between as-measured average asphalt content and design asphalt content (%)	As-measured standard deviation of asphalt content (%)		
	Below 0.255	0.255 to 0.345	Above 0.345
-1.10 to -0.91	-3	-3	-3
-0.90 to 0.71	-3	-3	-3
-0.70 to -0.51	-2	-2	-2
-0.50 to -0.31	-1	-1	-1
-0.30 to -0.11	-1	-1	-1
-0.10 to 0.09	0	0	-1
0.10 to 0.29	-3	-5	-6
0.30 to 0.49	-8	-9	-11
0.50 to 0.69	-12	-13	-14
0.70 to 0.89	-15	-16	-17
0.90 to 1.09	-18	-18	-19

Table 4.14 Contractor pay factors for air-void content (percentage of future resurfacing/rehabilitation cost in current-year dollars).

As-measured average relative compaction (%)	As-measured standard deviation of relative compaction (%)		
	Below 1.32	1.32 to 1.78	Above 1.78
100.25 to 99.76	5	5	4
99.75 to 99.26	4	3	3
99.25 to 98.76	3	2	2
98.75 to 98.26	2	1	1
98.25 to 97.76	1	0	-1
97.75 to 97.26	-1	-3	-6
97.25 to 96.76	-5	-8	-10
96.75 to 96.26	-10	-12	-14
96.25 to 95.76	-14	-16	-18
95.75 to 95.26	-17	-19	-21
95.25 to 94.76	-21	-22	-24

Table 4.15 Contractor pay factors for asphalt-concrete thickness (percentage of future resurfacing/rehabilitation cost in current-year dollars).

Difference between as-measured average asphalt-concrete thickness and design thickness (in)	As-measured standard deviation of asphalt-concrete thickness (%)		
	Below 7.85	7.85 to 10.62	Above 10.62
-1.10 to -0.89	-18	-21	-23
-0.90 to -0.69	-15	-17	-20
-0.70 to -0.49	-11	-13	-16
-0.50 to -0.29	-6	-9	-12
-0.30 to -0.09	-2	-5	-8
-0.10 to 0.09	3	0	-3
0.10 to 0.29	7	5	2
0.30 to 0.49	11	9	6
0.50 to 0.69	15	13	10
0.70 to 0.89	19	17	15
0.90 to 1.09	24	21	19

Table 4.16 Contractor pay factors for mineral filler (percentage of future resurfacing/rehabilitation cost in current-year dollars).

Difference between as-measured average mineral filler and design mineral filler (%)	As-measured standard deviation of mineral filler (%)		
	Below 0.765	0.765 to 1.035	Above 1.035
-2.75 to -2.26	-7	-7	-8
-2.25 to -1.76	-6	-6	-6
-1.75 to - 1.26	-4	-4	-5
-1.25 to -0.76	-3	-3	-3
-0.75 to -0.26	-1	-2	-2
-0.25 to 0.24	0	0	0
0.25 to 0.74	2	1	1
0.75 to 1.24	3	3	3
1.25 to 1.74	5	4	4
1.75 to 2.24	6	6	5
2.25 to 2.74	7	7	7

Table 4.17 Contractor pay factors for fine aggregate (percentage of future resurfacing/rehabilitation cost in current-year dollars).

Difference between as-measured average fine aggregate and design fine aggregate (%)	As-measured standard deviation of fine aggregate (%)		
	Below 2.55	**2.55 to 3.45**	**Above 3.45**
-6.6 to - 5.5	0	0	0
-5.4 to -4.3	0	0	0
-4.2 to -3.1	0	0	0
-3.0 to -1.9	0	0	0
-1.8 to -0.7	0	0	0
-0.6 to 0.5	0	0	0
0.6 to 1.7	0	0	0
1.8 to 2.9	0	0	0
3.0 to 4.1	1	1	1
4.2 to 5.3	1	1	1
5.4 to 6.5	1	1	1

4.2 Pay Factors—Influence of Expected Pavement Life and Cost Parameters

The pay factors computed in the previous section are based on what are considered "reasonable" cost parameters and a target design life of 20 years.

In discussions with Caltrans staff, some different parameters have been suggested. For example, Caltrans currently uses an annual rate of inflation for pavement costs of 3.5 percent. In addition, a variety of design periods are used:

Category	**Design Period**
New pavement	40
Rehabilitated pavement (urban)	30-35
Rehabilitated pavement (rural)	10-20
CapM[5]	5

The influence of some of these parameters on pay factors is analyzed in this section.

The first study involved changing the target pavement life to 10 years and increasing the annual inflation rate to 3.5 percent. The other factors were the same as used in Section 4.1., i.e.,

[5] CapM refers to Capital Preventative Maintenance projects

g = 2.5 percent, d = 5 percent, and the cost of rehabilitation for rutting and fatigue were 20 and 50 percent of new pavement construction, respectively.

Tables 4.18 through 4.20 show the cost implications of off-target construction for both rutting and fatigue and their combined values. Table 4.21 summarizes the pay factors for asphalt content. It will be noted that the negative pay factors for low asphalt content are larger than those for the 20-year target pavement life (Table 4.13) whereas the negative factors for high asphalt content are similar to those in the table.

Tables 4.22 through 4.25 show the contractor pay factors for air-void content, AC thickness, mineral filler, and fine aggregate. Of particular significance are the more severe pay factors associated with pavement thickness variations for the 10-year target life as compared to the 20-year life. The effects of aggregate grading on pay factors is relatively little influenced by pavement life, i.e., 10 years versus 20 years.

Tables 4.26 through 4.35 illustrate the same pay factor determination for 30 and 20 year target lives using an annual inflation rate of 3.5 percent. It will be noted that the inflation rate has the most significant impact on pay factors for AC thickness (Table 4.23 versus Table 4.28 versus Table 4.33).

4.3 Comparison of Current Caltrans Pay Factors with Those Obtained from Performance Models Presented Herein

Caltrans personnel supplied information for an overlay project on SR-299 in Trinity County between Salyer and Del Loma.(*11*) Construction started in June 1999 and was completed in March 2000. In July 1999 bleeding was observed in the eastbound lane. During the period July 7 to July 23, 1999 the contractor placed an average of 2300 tonnes per day. Table 4.36 lists the pay factors and daily AC tonnage for this period. It will be noted that the

Table 4.18 Effect of off-target asphalt content on future agency resurfacing cost based on rutting in WesTrack pavements (change expressed as a percent of new pavement construction cost); target life = 10 years, r = 3.5 percent

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
4.0	-27.0	-26.9	-26.7	-26.5	-26.3	-26.0	-25.8	-25.4	-25.3
4.1	-25.5	-25.4	-25.1	-24.9	-24.6	-24.4	-24.0	-23.7	-23.3
4.2	-23.8	-23.6	-23.3	-23.0	-22.7	-22.4	-22.0	-21.7	-21.2
4.3	-21.8	-21.5	-21.3	-20.9	-20.6	-20.1	-19.8	-19.3	-18.9
4.4	-19.6	-19.3	-18.9	-18.6	-18.2	-17.7	-17.2	-16.7	-16.1
4.5	-17.1	-16.8	-16.4	-16.0	-15.4	-15.1	-14.4	-14.0	-13.2
4.6	-14.5	-14.0	-13.7	-13.2	-12.7	-12.1	-11.5	-10.9	-10.3
4.7	-11.5	-11.2	-10.6	-10.1	-9.6	-9.0	-8.4	-7.6	-7.1
4.8	-8.5	-8.1	-7.5	-7.0	-6.4	-5.8	-5.1	-4.5	-3.7
4.9	-5.4	-4.9	-4.4	-3.7	-3.2	-2.5	-1.8	-1.2	-0.5
5.0	-2.2	-1.7	-1.2	-0.6	0.0	0.7	1.2	2.0	2.6
5.1	0.9	1.3	1.9	2.5	3.0	3.6	4.3	4.9	5.6
5.2	3.8	4.3	4.8	5.3	6.0	6.4	7.1	7.6	8.3
5.3	6.6	7.1	7.5	8.0	8.5	9.0	9.6	10.0	10.5
5.4	9.1	9.5	10.0	10.4	10.8	11.3	11.7	12.2	12.6
5.5	11.3	11.7	12.1	12.4	12.9	13.2	13.6	13.9	14.3
5.6	13.2	13.5	13.8	14.2	14.5	14.8	15.1	15.5	15.7
5.7	14.8	15.1	15.3	15.6	15.9	16.2	16.4	16.7	16.9
5.8	16.1	16.3	16.6	16.8	17.0	17.2	17.4	17.6	17.8
5.9	17.2	17.4	17.5	17.7	17.9	18.1	18.2	18.4	18.5
6.0	18.0	18.2	18.3	18.5	18.6	18.7	18.8	18.9	19.0

Table 4.19 Effect of off-target asphalt content on future agency rehabilitation cost based on Caltrans fatigue model (change expressed as a percent of new pavement construction cost); target life = 10 years, r = 3.5 percent.

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
4.0	16.4	16.4	16.4	16.4	16.7	16.7	16.7	16.7	16.7
4.1	14.6	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9
4.2	13.0	13.0	13.0	13.0	13.0	13.3	13.3	13.3	13.3
4.3	11.2	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
4.4	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	10.0
4.5	8.0	8.0	8.0	8.3	8.3	8.3	8.3	8.3	8.3
4.6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
4.7	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	5.1
4.8	3.1	3.1	3.1	3.1	3.1	3.4	3.4	3.4	3.4
4.9	1.4	1.4	1.7	1.7	1.7	1.7	1.7	1.7	1.7
5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.1	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7
5.2	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3
5.3	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9
5.4	-6.7	-6.7	-6.5	-6.5	-6.5	-6.5	-6.5	-6.5	-6.5
5.5	-8.3	-8.3	-8.3	-8.3	-8.1	-8.1	-8.1	-8.1	-8.1
5.6	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-9.6	-9.6
5.7	-11.6	-11.4	-11.4	-11.4	-11.4	-11.4	-11.4	-11.4	-11.4
5.8	-13.2	-13.2	-13.2	-13.2	-13.2	-12.9	-12.9	-12.9	-12.9
5.9	-14.6	-14.6	-14.6	-14.6	-14.6	-14.6	-14.6	-14.6	-14.6
6.0	-16.4	-16.4	-16.4	-16.4	-16.4	-16.4	-16.1	-16.1	-16.1

Table 4.20 Effect of off-target asphalt content on future agency resurfacing/rehabilitation costs (change expressed as a percent of new pavement construction cost); target life = 10 years, r = 3.5 percent.

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
4.0	16.4	16.4	16.4	16.4	16.7	16.7	16.7	16.7	16.7
4.1	14.6	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9
4.2	13.0	13.0	13.0	13.0	13.0	13.3	13.3	13.3	13.3
4.3	11.2	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
4.4	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	10.0
4.5	8.0	8.0	8.0	8.3	8.3	8.3	8.3	8.3	8.3
4.6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
4.7	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	5.1
4.8	3.1	3.1	3.1	3.1	3.1	3.4	3.4	3.4	3.4
4.9	1.4	1.4	1.7	1.7	1.7	1.7	1.7	1.7	1.7
5.0	0.0	0.0	0.0	0.0	0.0	0.7	1.2	2.0	2.6
5.1	0.9	1.3	1.9	2.5	3.0	3.6	4.3	4.9	5.6
5.2	3.8	4.3	4.8	5.3	6.0	6.4	7.1	7.6	8.3
5.3	6.6	7.1	7.5	8.0	8.5	9.0	9.6	10.0	10.5
5.4	9.1	9.5	10.0	10.4	10.8	11.3	11.7	12.2	12.6
5.5	11.3	11.7	12.1	12.4	12.9	13.2	13.6	13.9	14.3
5.6	13.2	13.5	13.8	14.2	14.5	14.8	15.1	15.5	15.7
5.7	14.8	15.1	15.3	15.6	15.9	16.2	16.4	16.7	16.9
5.8	16.1	16.3	16.6	16.8	17.0	17.2	17.4	17.6	17.8
5.9	17.2	17.4	17.5	17.7	17.9	18.1	18.2	18.4	18.5
6.0	18.0	18.2	18.3	18.5	18.6	18.7	18.8	18.9	19.0

Table 4.21 Contractor pay factors for asphalt content (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 10 years, r = 3.5 percent.

Difference between as-measured average asphalt content and design asphalt content (%)	As-measured standard deviation of asphalt content (%)		
	Below 0.255	0.255 to 0.345	Above 0.345
-1.10 to -0.91	-16	-17	-17
-0.90 to 0.71	-13	-13	-13
-0.70 to -0.51	-10	-10	-10
-0.50 to -0.31	-7	-7	-7
-0.30 to -0.11	-3	-3	-3
-0.10 to 0.09	0	0	-2
0.10 to 0.29	-4	-6	-8
0.30 to 0.49	-10	-11	-12
0.50 to 0.69	-13	-15	-15
0.70 to 0.89	-16	-17	-18
0.90 to 1.09	-18	-19	-19

Table 4.22 Contractor pay factors for air-void content (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 10 years, r = 3.5 percent.

As-measured average air-void content (%)	As-measured standard deviation of relative compaction (%)		
	Below 1.32	1.32 to 1.78	Above 1.78
4.8 to 5.10	8	7	6
5.15 to 5.7	6	5	4
5.75 to 6.20	4	3	3
6.25 to 6.65	2	2	1
6.7 to 7.05	1	0	-1
7.1 to 7.55	-1	-3	-6
7.6 to 8.05	-5	-8	-10
8.1 to 8.55	-10	-12	-14
8.6 to 8.95	-14	-16	-18
9.0 to 9.45	-17	-19	-21
9.5 to 10.0	-21	-22	-24

Table 4.23 Contractor pay factors for asphalt-concrete thickness (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 10 years, r = 3.5 percent.

Difference between as-measured average asphalt-concrete thickness and design thickness (in)	As-measured standard deviation of asphalt-concrete thickness (%)		
	Below 7.85	7.85 to 10.62	Above 10.62
-1.10 to -0.89	-117	-135	-155
-0.90 to -0.69	-89	-107	-128
-0.70 to -0.49	-62	-79	-99
-0.50 to -0.29	-34	-51	-70
-0.30 to -0.09	-9	-24	-42
-0.10 to 0.09	13	0	-16
0.10 to 0.29	31	21	8
0.30 to 0.49	47	38	27
0.50 to 0.69	59	52	44
0.70 to 0.89	70	64	57
0.90 to 1.09	80	74	68

Table 4.24 Contractor pay factors for mineral filler (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 10 years, r = 3.5 percent.

Difference between as-measured average mineral filler and design mineral filler (%)	As-measured standard deviation of mineral filler (%)		
	Below 0.765	0.765 to 1.035	Above 1.035
-2.75 to -2.26	-8	-9	-9
-2.25 to -1.76	-7	-7	-8
-1.75 to - 1.26	-5	-6	-6
-1.25 to -0.76	-4	-4	-4
-0.75 to -0.26	-2	-2	-3
-0.25 to 0.24	0	0	-1
0.25 to 0.74	3	2	1
0.75 to 1.24	5	4	4
1.25 to 1.74	7	7	6
1.75 to 2.24	9	9	8
2.25 to 2.74	12	11	11

Table 4.25 Contractor pay factors for fine aggregate (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 10 years, r = 3.5 percent.

Difference between as-measured average fine aggregate and design fine aggregate (%)	As-measured standard deviation of fine aggregate (%)		
	Below 2.55	2.55 to 3.45	Above 3.45
-6.6 to -5.5	0	0	0
-5.4 to -4.3	0	0	0
-4.2 to -3.1	0	0	0
-3.0 to -1.9	0	0	0
-1.8 to -0.7	0	0	0
-0.6 to 0.5	0	0	0
0.6 to 1.7	0	0	0
1.8 to 2.9	0	0	1
3.0 to 4.1	1	1	1
4.2 to 5.3	1	1	1
5.4 to 6.5	2	2	2

Table 4.26 Contractor pay factors for asphalt content (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 30 years, r = 3.5 percent.

Difference between as-measured average asphalt content and design asphalt content (%)	As-measured standard deviation of asphalt content (%)		
	Below 0.255	0.255 to 0.345	Above 0.345
-1.10 to -0.91	-4	-4	-4
-0.90 to 0.71	-3	-3	-3
-0.70 to -0.51	-2	-2	-2
-0.50 to -0.31	-2	-2	-2
-0.30 to -0.11	-1	-1	-1
-0.10 to 0.09	0	0	-1
0.10 to 0.29	-3	-4	-5
0.30 to 0.49	-7	-8	-9
0.50 to 0.69	-11	-12	-13
0.70 to 0.89	-14	-15	-16
0.90 to 1.09	-17	-18	-18

Table 4.27 Contractor pay factors for air-void content (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 30 years, r = 3.5 percent.

As-measured average relative compaction (%)	As-measured standard deviation of relative compaction (%)		
	Below 1.32	1.32 to 1.78	Above 1.78
100.25 to 99.76	4	3	3
99.75 to 99.26	3	3	2
99.25 to 98.76	2	2	1
98.75 to 98.26	1	1	1
98.25 to 97.76	0	0	-1
97.75 to 97.26	-1	-3	-6
97.25 to 96.76	-5	-8	-10
96.75 to 96.26	-10	-12	-14
96.25 to 95.76	-14	-16	-18
95.75 to 95.26	-17	-19	-21
95.25 to 94.76	-21	-22	-24

Table 4.28 Contractor pay factors for asphalt-concrete thickness (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 30 years, r = 3.5 percent.

Difference between as-measured average asphalt-concrete thickness and design thickness (in)	As-measured standard deviation of asphalt-concrete thickness (%)		
	Below 7.85	7.85 to 10.62	Above 10.62
-1.10 to -0.89	-25	-28	-32
-0.90 to -0.69	-19	-23	-27
-0.70 to -0.49	-14	-17	-21
-0.50 to -0.29	-8	-11	-15
-0.30 to -0.09	-2	-6	-9
-0.10 to 0.09	3	0	-4
0.10 to 0.29	8	5	2
0.30 to 0.49	12	10	7
0.50 to 0.69	16	14	11
0.70 to 0.89	20	17	15
0.90 to 1.09	24	21	19

Table 4.29 Contractor pay factors for mineral filler (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 30 years, r = 3.5 percent.

Difference between as-measured average mineral filler and design mineral filler (%)	As-measured standard deviation of mineral filler (%)		
	Below 0.765	0.765 to 1.035	Above 1.035
-2.75 to -2.26	-6	-6	-6
-2.25 to -1.76	-5	-5	-5
-1.75 to - 1.26	-3	-4	-4
-1.25 to -0.76	-2	-2	-3
-0.75 to -0.26	-1	-1	-2
-0.25 to 0.24	0	0	0
0.25 to 0.74	1	1	1
0.75 to 1.24	2	2	2
1.25 to 1.74	4	3	3
1.75 to 2.24	4	4	4
2.25 to 2.74	5	5	5

Table 4.30 Contractor pay factors for fine aggregate (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 30 years, r = 3.5 percent.

Difference between as-measured average fine aggregate and design fine aggregate (%)	As-measured standard deviation of fine aggregate (%)		
	Below 2.55	2.55 to 3.45	Above 3.45
-6.6 to - 5.5	0	0	0
-5.4 to -4.3	0	0	0
-4.2 to -3.1	0	0	0
-3.0 to -1.9	0	0	0
-1.8 to -0.7	0	0	0
-0.6 to 0.5	0	0	0
0.6 to 1.7	0	0	0
1.8 to 2.9	0	0	0
3.0 to 4.1	0	0	0
4.2 to 5.3	1	1	1
5.4 to 6.5	1	1	1

Table 4.31 Contractor pay factors for asphalt content (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 20 years, r = 3.5 percent.

Difference between as-measured average asphalt content and design asphalt content (%)	As-measured standard deviation of asphalt content (%)		
	Below 0.255	0.255 to 0.345	Above 0.345
-1.10 to -0.91	-7	-7	-7
-0.90 to 0.71	-5	-5	-5
-0.70 to -0.51	-4	-4	-4
-0.50 to -0.31	-3	-3	-3
-0.30 to -0.11	-1	-1	-1
-0.10 to 0.09	0	0	-1
0.10 to 0.29	-3	-5	-6
0.30 to 0.49	-8	-9	-11
0.50 to 0.69	-12	-13	-14
0.70 to 0.89	-15	-16	-17
0.90 to 1.09	-18	-18	-19

Table 4.32 Contractor pay factors for air-void content (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 20 years, r = 3.5 percent.

As-measured average relative compaction (%)	As-measured standard deviation of relative compaction (%)		
	Below 1.32	1.32 to 1.78	Above 1.78
100.25 to 99.76	4	3	3
99.75 to 99.26	3	3	2
99.25 to 98.76	2	2	1
98.75 to 98.26	1	1	1
98.25 to 97.76	0	0	-1
97.75 to 97.26	-1	-3	-6
97.25 to 96.76	-5	-8	-10
96.75 to 96.26	-10	-12	-14
96.25 to 95.76	-14	-16	-18
95.75 to 95.26	-17	-19	-21
95.25 to 94.76	-21	-22	-24

Table 4.33 Contractor pay factors for asphalt-concrete thickness (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 20 years, r = 3.5 percent.

Difference between as-measured average asphalt-concrete thickness and design thickness (in)	As-measured standard deviation of asphalt-concrete thickness (%)		
	Below 7.85	7.85 to 10.62	Above 10.62
-1.10 to -0.89	-46	-52	-60
-0.90 to -0.69	-35	-42	-50
-0.70 to -0.49	-25	-31	-39
-0.50 to -0.29	-17	-20	-28
-0.30 to -0.09	-4	-10	-17
-0.10 to 0.09	5	0	-6
0.10 to 0.29	13	9	3
0.30 to 0.49	20	16	12
0.50 to 0.69	26	23	19
0.70 to 0.89	31	28	25
0.90 to 1.09	37	34	31

Table 4.34 Contractor pay factors for mineral filler (percentage of future resurfacing/rehabilitation cost in current-year dollars) ; target life = 20 years, r = 3.5 percent.

Difference between as-measured average mineral filler and design mineral filler (%)	As-measured standard deviation of mineral filler (%)		
	Below 0.765	0.765 to 1.035	Above 1.035
-2.75 to -2.26	-7	-7	-8
-2.25 to -1.76	-6	-6	-6
-1.75 to - 1.26	-4	-4	-5
-1.25 to -0.76	-3	-3	-3
-0.75 to -0.26	-1	-2	-2
-0.25 to 0.24	0	0	0
0.25 to 0.74	2	1	1
0.75 to 1.24	3	3	3
1.25 to 1.74	5	4	4
1.75 to 2.24	6	6	5
2.25 to 2.74	7	7	7

Table 4.35 Contractor pay factors for fine aggregate (percentage of future resurfacing/rehabilitation cost in current-year dollars); target life = 20 years, r = 3.5 percent.

Difference between as-measured average fine aggregate and design fine aggregate (%)	As-measured standard deviation of fine aggregate (%)		
	Below 2.55	2.55 to 3.45	Above 3.45
-6.6 to - 5.5	0	0	0
-5.4 to -4.3	0	0	0
-4.2 to -3.1	0	0	0
-3.0 to -1.9	0	0	0
-1.8 to -0.7	0	0	0
-0.6 to 0.5	0	0	0
0.6 to 1.7	0	0	0
1.8 to 2.9	0	0	0
3.0 to 4.1	0	0	0
4.2 to 5.3	1	1	1
5.4 to 6.5	1	1	1

Table 4.36 Pay Factor Summary—Overlay Project, SR 299, Trinity County, July 1999

AC Pay Factor and Tonnes Summary					
Date	**Day**	**Sample**	**Pay Factor**	**Daily Tonnes**	**Total Tonnes**
07/06/99	Tue	1-5	1.0087	2,093	2,093
07/07/99	Wed	6-13	1.0447	3,569	5,662
07/08/99	Thu	14-20	1.0407	3,186	8,849
07/09/99	Fri	21-28	1.0367	3,547	12,395
07/12/99	Mon	29-36	1.0311	3,482	15,877
07/13/99	Tue	37-40	1.0341	1,838	17,715
07/14/99	Wed	41-47	1.0291	3,347	21,062
07/16/99	Fri	48-53	1.0281	2,866	23,928
07/19/99	Mon	54-61	1.0311	3,507	27,435
07/20/99	Tue	62-68	1.0291	2,930	30,364
07/21/99	Wed	69-76	1.0341	3,590	33,954
07/22/99	Thu	77-79	1.0371	1,635	35,590
07/23/99	Fri	80-83	1.0371	1,606	37,195

contractor received a bonus for the project even though a segment of the resurfacing exhibited bleeding. The project thus provided an opportunity to compare pay factors developed in Section 4.2 with those currently used in the Caltrans Specifications *Quality Control/Quality Assurance for Asphalt Concrete.*

From an analysis of the mix data for the project which had been supplied by Caltrans, the mix tends to be a “critical” mix; that is, small increases in asphalt content lead to significant decreases in mix stability as measured by the stabilometer. It was also noted that the contractor appeared to operate on the high side of the binder content range.

Using data prepared by one of the contractor’s testing laboratories (June 8, 1999), a significant reduction in stability occurs in the range 5.0 to 5.5 percent binder content, a reduction from 46 to 23, with a corresponding reduction in air-void content from 2.6 to 1.5 percent. These air-void content determinations are based on the computation procedure described in CA Test Method 367 using aggregate specific gravities determined in accordance with CA Test Methods 206 and 207.

With a critical mix, if the original Hveem procedure were followed, one would back off 0.5 percent from the binder content corresponding (in this case) to S=37. This would suggest a binder content of 4.7 percent as the target value. Secondly, a stricter control in binder content would be placed, that is ±0.3 percent.

Data from tests on field cores indicate binder contents, reported in the District 3 Materials Lab memo data August 1999, to be on the high side resulting in low stabilometer values associated with low air-void contents.

Using pay factors reported in Section 4.2 and *considering only binder content,* a pay factor of about 0.9 would be obtained. This is based on an actual value 0.4 percent above the actual target value of 4.8 percent and a standard deviation of 0.3 percent resulting in an off-target life of about 4 years. If the standard deviation in binder content were larger or the actual value larger than that stated, the pay factor would be further reduced. The effects of the improved relative compaction would tend to increase the factor slightly; however, this would not overcome the potential for bleeding such as was observed on some of the sections.

It must be emphasized that the pay factor determinations (Section .42) are based on a 10-year life for a mix constructed at the target value for binder content and the rutting performance model developed from the WesTrack data.

If the same target life was used, i.e., 10 years and the off-target life was assumed to be 1 year, then the pay factor used would be substantially less than the value of 0.9 noted above.

4.4 Combined Pay Factors

Combined pay factors can be determined from the information presented in, for example, Tables 4.13 through 4.17 using Equation 4.1. This equation results from a series of simulations reported in Reference (*10*), as discussed below.

Considering only fatigue performance, 10 conditions (five for air-void content and five for thickness), which individually resulted in a "constant" pay factor of about –20 percent, were selected. The combination effects from the simulations are shown in Table 4.37. Interestingly, the combination pay factor is about –36 percent, when both air-void content and thickness are off-target with individual pay factors of –20 percent each. This suggests the possibility that the combination pay factor as a decimal fraction, *cpf*, might be expressed as follows:

$$cpf = (1 + pf_{av})(1 + pf_t) - 1 \qquad \textbf{(4.2)}$$

in which the individual pay factors are expressed as decimal fractions instead of percents.

To further investigate this possibility, the simulations of Table 4.38 were performed. Again, the focus was on air-void content/relative compaction and thickness because these are the dominant parameters of interest. This time, however, the as-constructed conditions were selected to yield large ranges in individual pay factors including bonuses (instead of –20 percent). Next, calculations for comparable conditions using the above equation yielded results summarized in Table 4.39. Although there is one notable difference at one extreme (96.1 percent versus 69.1 percent), results of the combined simulations (Table 4.38) and the computations (Table 4.39) are in remarkable agreement. As a result, Equation 4.2 seems suitable for determining pay factors for combined conditions. An extension to include asphalt content yields the following recommendation for computing combined contractor pay factors:

$$cpf = (1 + pf_{av})(1 + pf_{ac})(1 + pf_{t}) - 1 \qquad \textbf{(4.3)}$$

Equation 4.3, following completion of the WesTrack analyses, was extended to include the effects of aggregate gradation as follows:

$$Combined\ Pay\ Factor\,(CPF) = (1 + pf_{ac})(1 + pf_{av})(1 + pf_{mf})(1 + pf_{fa})(1 + pf_{t}) - 1 \qquad \textbf{(4.4)}$$

Consider the following using Tables 4.13 through 4.17. A contractor has compacted a mix to an air-void content of 5.0 percent (target value = 7 percent) with standard deviation of 1.6 percent; the asphalt content was 0.5 percent above target with a standard deviation of 0.4 percent; the mineral filler was 0.5 percent above target with a standard deviation of 1.2 percent; the fine aggregate was on target with a standard deviation of 3 percent; and the thickness was 0.3 in. below target with a standard deviation of 8.5 percent.

For these conditions, the combined pay factor is:

$$CPF = (1 - 0.14)(1 - 0.04)(1 - 0.01)(1 - 0)(1 - 0.08) = 0.83\ or\ 83\%$$

Table 4.37 Pay Factors for Combination Conditions (from Simulations) (Conditions Set to Yield Individual Pay Factors of About –20 Percent)

Surface Thickness (in.)		Average Air-Void Content (%)				
		7.000	7.755	8.040	8.325	8.610
Average	Standard Deviation	Standard Deviation of Air-Void Content (%)				
		1.200	1.686	1.378	1.028	0.637
9.6	0.620	0.0	-20.3	-19.6	-19.7	-20.3
8.8	0.353	-21.0	-37.8	-37.2	-36.5	-36.0
9.0	0.587	-20.7	-36.9	-36.5	-36.6	-36.8
9.2	0.791	-20.7	-36.2	-36.3	-36.7	-37.4
9.4	0.975	-20.6	-35.2	-36.2	-36.9	-38.2

Table 4.38 Pay Factors for Combination Conditions (from Simulations) (Conditions Set to Yield Varying Individual Pay Factors)

Surface Thickness (in.)			Average Air-Void Content (%)				
			5.95	7.09	7.00	7.09	8.80
Average	Standard Deviation	Individual Pay Factor	Standard Deviation of Air-Void Content (%)				
			.0570	.0570	1.200	1.710	1.520
			Individual Pay Factor				
			0.262	0.060	0.000	-0.097	-0.320
10.5	0.60	0.340	96.1	41.6	33.9	23.5	-2.8
9.9	0.60	0.123	39.3	18.2	12.2	2.5	-22.8
9.6	0.62	0.000	23.2	6.3	0.0	-9.5	-32.0
9.3	0.70	-0.134	11.3	-8.6	-13.7	-22.5	-41.1
8.5	0.80	-0.408	-24.0	-38.5	-41.0	-45.3	-56.5

Table 4.39 Pay Factors for Combination Conditions (from Calculations) (Conditions Set to Yield Varying Individual Pay Factors)

Surface Thickness (in.)			Average Air-Void Content (%)				
			5.95	7.09	7.00	7.09	8.80
Average	Standard Deviation	Individual Pay Factor	Standard Deviation of Air-Void Content (%)				
			.0570	.0570	1.200	1.710	1.520
			Individual Pay Factor				
			0.262	0.060	0.000	-0.097	-0.320
10.5	0.60	0.340	69.1	42.0	34.0	21.0	-8.9
9.9	0.60	0.123	41.7	19.0	12.3	1.4	-23.6
9.6	0.62	0.000	26.2	6.0	0.0	-9.7	-32.0
9.3	0.70	-0.134	9.3	-8.2	-13.4	-21.8	-41.1
8.5	0.80	-0.408	-25.3	-37.2	-40.8	-46.5	-59.7

It is possible to prepare a combined pay factor table like that shown in Reference (*10*). However, with the five variables of Equation (4.4), it is recommended that Equation (4.4) be used to calculate the combined pay factor, particularly if pay factors are computed based on the results of one-day or shorter operations, even though the paving project may have a duration of many days.

5.0 DISCUSSION

The approach presented herein should be applicable to virtually any type of hot mix, although as a check, additional laboratory testing would be required. It is likely that both bonuses and penalties may be understated because only the first rehabilitation cycle is considered. Nevertheless, understated penalties/bonuses are likely to be more appropriate than overstated ones for pilot or demonstration use at this time.

The pay factor tables contained herein reflect a full bonus for superior construction and a full penalty for inferior construction. Based on current practice, the bonus to be awarded should not exceed some prescribed level somewhat less than the maximum values shown herein. Currently, the upper limit for Caltrans is a bonus of 5 percent. Also, as noted in Section 4.1, the pay factors for air-void content do not include the effects of either area, Figure 3.8, where the specification is met but the performance is inferior to that of the target or the area where the specification is not met but the performance is superior to that of the target.

Recognizing some of the limitation noted herein, the pay factors provide a reasonable starting point for hot mix asphalt concrete construction considering the combined effects of rutting and fatigue cracking or only one of the distress modes if that is considered to be suitable.

For example, if only rutting is to be considered, for a target life of 20 years, the pay factors should include those for asphalt content, air-void content, and aggregate gradation shown in Tables 4.13, 4.14, 4.16, and 4.17. For fatigue for the 20-year target, the pay factors for asphalt content, air-void content, and thickness shown in Tables 4.13 through 4.15 should be included. (N.B. These tables are based on an inflation rate of 2.5 percent and rehabilitation costs which are 0.2 times the initial construction cost for rutting and 0.5 time the cost for fatigue.)

For an inflation rate of 3.5 percent, Tables 4.21 through 4.25 contain combined pay factors for a 10-year target life while Tables 4.26 through 4.30 and 4.31 through 4.35 contain the same information for target lives of 30 and 20 years, respectively. It will be noted that the pay factors for the target life of 30 years are equal or less than those for 20 and 10 year periods.

It must be emphasized that the development of appropriate pay-factor schedules must be viewed as an incremental process evolving over some time frame. Among future refinements that can be considered are the following:

1. Incorporation of ride quality as a product of the construction process;
2. Inclusion, if desired, of maintenance and user costs;
3. Extension to include rehabilitation activities; and
4. Extension to include cement concrete pavements.

Moving from concept to practice is possible at this time. However, a number of questions must be answered by Caltrans: Does interest focus on new pavements and/or overlays and can initial consideration be limited to asphalt concrete applications as described herein? Help is needed from Caltrans staff to validate the variances that have been utilized herein to insure that they are representative of current construction practice. In addition to the example presented in Section 4.3, a number of past construction projects should be reviewed to evaluate their distribution relative to any pay-factor schedule that is ultimately proposed.

Other questions include:

1. Are the parameters used herein those most suitable for Caltrans usage?
2. Is the recommended procedure for displaying individual pay factors and the procedure used to develop combined pay factors suitable?
3. How does this approach for pay factor determination relate to the QC/QA program envisioned by Caltrans, including other construction-quality considerations?
4. How best can the CAL/APT program support the Caltrans initiative for demonstrating a new or modified approach for pay factors for asphalt concrete construction and what is the timeline for such a program?

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APPENDIX A: RELIABILITY AND VARIABILITY CONSIDERATIONS

To provide an acceptable level of risk in asphalt mix design and pavement performance without excessive cost, reliability analysis can be used. Reliability, as considered in this report, is the probability that a mix and/or a pavement structure will provide satisfactory performance for a specific design period. To achieve a given level of reliability requires estimates of the variance in: 1) traffic estimates; 2) variability as a function of asphalt content, degree of compaction (as measured by air-void content), and aggregate gradation; and 3) pavement structure variables including asphalt concrete thickness and stiffnesses and thicknesses of the supporting layers.

This appendix contains a brief summary of both *reliability* and *variability* considerations used to estimate the pay factors presented in this report.

Reliability

As stated above, reliability, as considered herein, is the probability that an asphalt mix or pavement structure will provide satisfactory performance throughout the selected design period. The reliability level for each specific situation is set by the designer. Larger levels of reliability reduce the chances of accepting deficient mixes; however, the tradeoff is the potentially larger cost associated with reducing the number of acceptable materials or mixes or increasing the thickness of the asphalt concrete.

Reliability is introduced in the mix design and analysis system by a reliability multiplier, *M*, which is calculated as follows:

$$M = e^{Z\sqrt{\mathrm{var}(\ln N)+\mathrm{var}(\ln ESALs)}} \qquad \textbf{(A-1)}$$

in which e = the base of natural or Naperian logarithms, *Z* = a factor depending solely on the design reliability, var(ln *N*) = the variance of the logarithm of the laboratory fatigue or rutting life under the standard 40-kN (9,000-lb.) wheel load, and var(ln *ESALs*) = the variance of the estimate of the logarithm of the deign ESALs. *Z* is related to design reliability as follows:

Design reliability (percent)	*Z*
95	1.64
90	1.28
80	0.84
60	0.253
50	0.000

To estimate the *var(ln N)* and *var(ln ESALs)* requires estimates of the variabilities in the parameters which are used to determine the two variances. These variances are discussed in the next section.

Variability

Variability associated with forecasts of design ESALs is not well defined at this time.[6] In the absence of better information, var (ln *ESALs*) has been assumed to 0.300. This estimate is based primarily on judgement of the authors of this report. As a point of reference, the 1993 *AASHTO Design Guide* (*13*) suggests that actual traffic may be 1.6 times that predicted at one-standard-deviation level. For an assumed log normal distribution, this produces a *var(ln ESALs)* of about 0.22. Thus the value selected would appear to be "reasonably" conservative.

The *var(ln N)*, as developed in this analysis, is a function of both testing and construction variabilities. Two components of construction variability have been considered: those affecting mix behavior and those affecting permanent structure behavior.

[6] Results of the Long Term Pavement Performance (LTPP) Program (*12*) should eventually provide a better defined estimate of traffic variability.

As currently developed, *var(ln N)* is thus the sum of three components as follows:

$$\mathrm{var}(\ln N) = s_t^2 + s_m^2 + s_s^2 \qquad \textbf{(A-2)}$$

in which s_t^2 = the testing variance, s_m^2 = the mix variance, and s_s^2 = the structure variance.

Consider first the testing variance, s_t^2, for fatigue. Testing variability reflects a combination of factors including: 1) the inherent variability in fatigue measurements (associated both with specimen preparation as well as testing equipment and procedures; 2) the nature of the laboratory testing program; and 3) the extent of extrapolation necessary for estimating fatigue life (using a least-squares, best-fit line) at the design strain level. The var(ln *N*) is calculated as follows:

$$\mathrm{var}(\ln N) = s^2\left(1 + \frac{1}{n} + \frac{\left(X - \bar{x}\right)^2}{q\sum\left(x_p - \bar{x}\right)^2}\right) \qquad \textbf{(A-3)}$$

in which s^2 = the variance in logarithm of fatigue life measurements, n = the number of test specimens, X = ln(in-situ strain) at which ln(N) must be predicted, $\bar{x}$ = average ln(test strain), q = number of replicate specimens at each test strain level, and x_p = ln(strain) at the pth test strain level.

The mix fatigue study conducted as an initial art of the CAL/APT Program (*5*) was used to determine the testing variance. Replication which was built into the experiment design permitted computation of the inherent variance (s^2) in the logarithm of fatigue life measurements. The experiment design involved 15 different mixes (five asphalt contents and three air-void contents) tested at each of two strain levels with nominally three replicates at each of the 30 combinations (a few small-strain tests had four replicates). A total of 96 observations were included in calculating the sample variance using the following relationships:

$$s^2 = \frac{\sum_{k=1}^{d} WSS_k}{n-d} \quad \textbf{(A-4)}$$

and

$$WSS_k = \sum_{i=1}^{n_k} \left(\ln N_i - \ln N_k\right)^2 \quad \textbf{(A-5)}$$

in which WSS_k = within sum of squares for factor level combination k (air-void content, asphalt content, and strain level), n = number of observations (96), d = number of factor level combinations (30), $\ln N_i$ = logarithm of measured fatigue life for specimen i, $\ln N_k$ = average logarithm of measured fatigue lives of specimens for factor level k, and n_k = number of replicates at factor level k.

The best estimate of the overall sample variance of the natural logarithm of the fatigue life was calculated using the aforedescribed procedure to be 0.220. The sample variance obtained in the SHRP A-003A expanded test program, using the same testing equipment and procedures, was 0.152. Because of greater replication in the current study [three versus two in Reference (*14*)] and smaller strain levels [150 and 300 microstrain versus 400 and 700 microstrain in Reference (*14*)], 0.220 seems to be the best possible estimate of s^2 at the current time. It was used in developing the shift factors in the mix design and analysis model and is recommended for use for mix design purposes.

For fatigue, the *materials* and *construction* components of variability were determined in the following manner.

Potentially important mix variables include asphalt content and air-void content. Fortunately, the necessary data for quantitative evaluation of these variables is available, namely, construction variances and, for a typical mix, relationships with mix stiffness and fatigue life (*5*). Other potentially important mix variables, such as aggregate gradation, were excluded from consideration. This decision was supported by laboratory test data repeated by other investigators, [e.g., Hicks et al. (*15*)] and by analyses of the fatigue performance, both in the laboratory and the field, of the mixes used at WesTrack (*2*).

Structural variables include thickness of the asphalt concrete layer and stiffnesses and thicknesses of other supporting layers. Asphalt concrete thickness was a critical factor to be considered, and construction variance data was available. The supporting layers are more problematic because knowledge of the variabilities of foundation layer thicknesses and moduli appears to be limited, and complexity of the necessary analysis increases with increases in the number of layers. As a result, it was decided to simplify the process by identifying an equivalent single layer for which effects were similar to the multilayer supporting layers. The equivalent single layer has been characterized by its modulus, and the variance of this equivalent modulus was evaluated from post-construction falling weight deflectometer (FWD) measurements.(*7*)[7]

Estimates of the variances of asphalt content, air-void content, and asphalt-concrete thickness were obtained from a combination of literature review and WesTrack test data. Summary results are presented in Section 3. These totals include not only materials and construction components but also components resulting from testing and sampling. The latter components must be removed from the variance estimates in order to isolate materials and construction effects: Table 3.2, Section 3, summarizes the necessary data.

Table 3.3, Section 3, provides a summary of the quantities used to represent reasonable estimates of materials/construction variability associated with conventional construction practice. The equations for estimating the standard deviation of asphalt-concrete thickness were developed as an approximate way to handle multilift construction. Among the assumptions made in their

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[7] Table 3.1 in Section 3 contains a listing of the sources of FWD measurements used.

development was that the coefficient of variation of thickness in single-lift construction is about 14 percent, as stated in Section 3.

While the testing variance, s_t^2 can be obtained from direct computations, using Equation 4.3, computing the mix variance, s_m^2, and the structure variance, s_s^2, is more complex. Fortunately, Monte Carlo simulation is a convenient and relatively quick way to obtain the necessary estimates. For the design pavement structure and test temperature, each simulation proceeds as follows. A random selection is made of asphalt content and air-void content. The mix stiffness is determined from these random selections, and a "mean" pavement strain is calculated (ELSYM5). A randomly selected adjustment is made to this strain level to account for random variations in surface thickness and support modulus. The fatigue life is then computed from the random selections of tensile strain and the asphalt and air-void contents. The process is repeated until the desired degree of convergence has been reached. In work to date, distributions of all of the four construction variables have been assumed to be normal. The Monte Carlo simulations include both testing variability and construction variability.

With the variance estimates, Monte Carlo simulation was used to produce estimates of *var(ln N)* for the 18 hypothetical pavements summarized in Table B-1 to illustrate the process. Stiffness and fatigue relationships contained in Section 3 (Equations 3.1 and 3.2) together with target asphalt and air-void contents of 5 and 8 percent respectively, were utilized.

Figure A-1 illustrates the level and components of var(ln*N*) for each of the 18 structures. The testing portion of the total variance increases significantly with the increases in pavement thickness associated with larger traffic indices principally because of the increased level of extrapolation to the smaller strain levels. Construction variability is important for all of the pavements but is a much greater portion of the total variability for the less substantial pavements which accompany smaller traffic indices. The structures component of construction variability is slightly greater for thinner than for thicker pavements while a reverse trend is observed for the mix component.

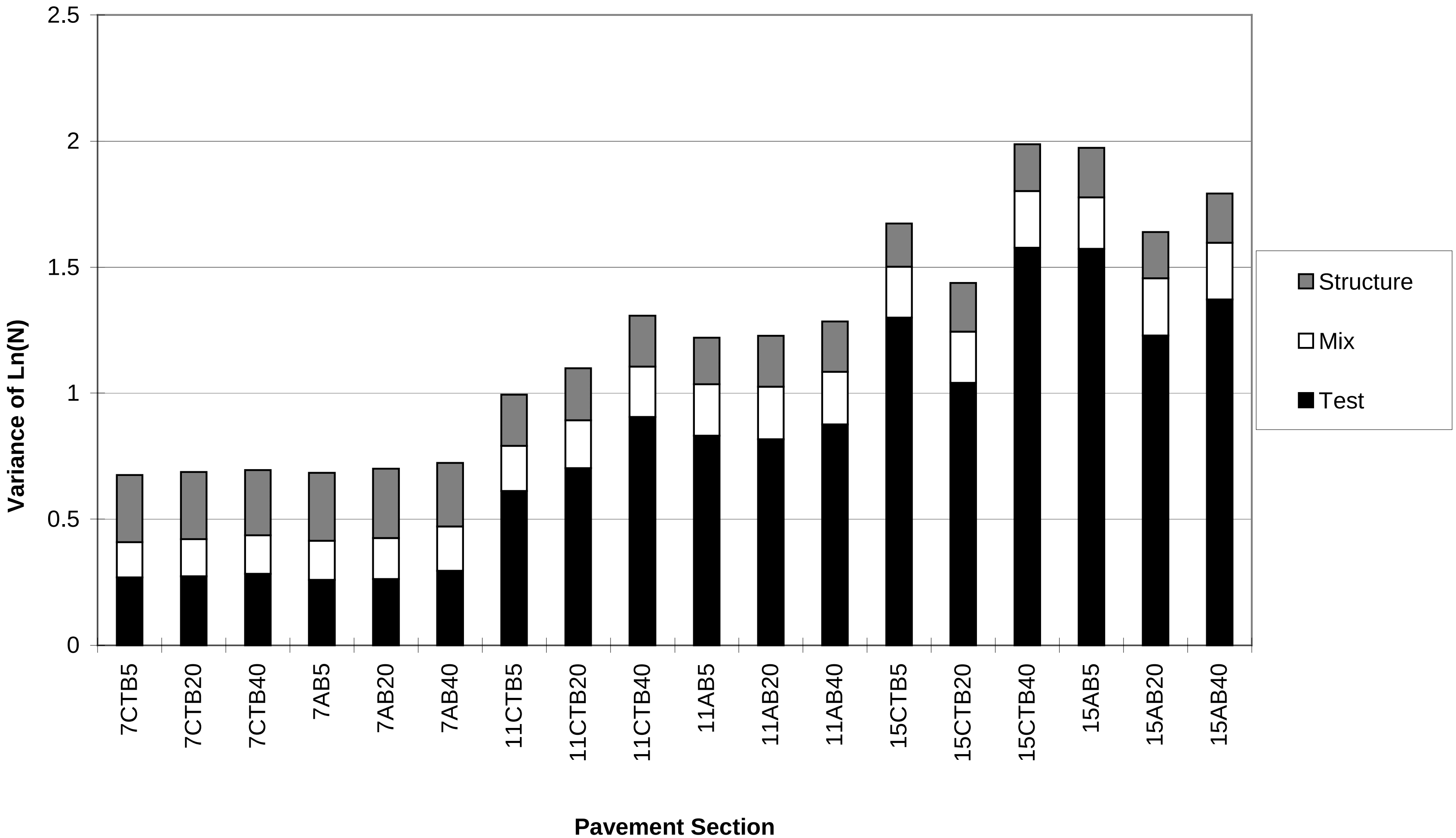

Figure A-1. Major components of testing and construction variance.

APPENDIX B

Table B-1 Pavement Structures

Designation	Layer	Target Thickness (in.)	Modulus (psi)	Poisson's Ratio	Target Standard Deviation
7AB20	Surface Base Subbase Subgrade	3.6 7.2 6.0 -	Variable 30,000 20,000 12,200	0.40 0.45 0.45 0.50	0.314
9AB20	Surface Base Subbase Subgrade	6.6 6.6 7.8 -	Variable 30,000 20,000 12,200	0.40 0.45 0.45 0.50	0.476
11AB20	Surface Base Subbase Subgrade	9.6 6.0 8.4 -	Variable 25,000 20,000 12,200	0.40 0.45 0.45 0.50	0.620
13AB20	Surface Base Subbase Subgrade	10.2 7.8 12.6 -	Variable 25,000 20,000 12,200	0.40 0.45 0.45 0.50	.0640

APPENDIX C: ANALYTICALLY-BASED APPROACH TO RUTTING PREDICTION

As a part of the WesTrack Project to develop a performance related specification (PRS) for asphalt concrete (AC) construction, two approaches to develop performance models for rutting were developed.(*2*) One, based on regression of both field and laboratory test data, has been described in Section 3 herein and used to develop pay factors for rutting included in Section 4. The other, though not used, is briefly described in this Appendix so that it might serve to provide a more general approach to pay factor determination if so desired. It is referred to as a mechanistic-empirical performance model.

Mechanistic-Empirical Approach

In this approach, the pavement is assumed to behave as a multi-layered elastic system. An idealization of a specific asphalt pavement is show in Figure C-1 together with key parameters used to estimate rut depth development with traffic, i.e., τ, γ^e, and ε_v.*

The three parameters can be determined on an hour-by-hour basis and a program like the Integrated Climate Model (ICM) (*16*) can be used to define temperature distributions both with time and depth in the AC to permit estimates of mix stiffnesses. For convenience, if a program like ELSYM5 is used, it is recommended that the AC layer be subdivided into three layers with thicknesses from top to bottom of 25 mm (1 in.), 50 mm (2 in.), and the remaining AC thickness as the third layer to simulate the effects of temperature gradients on mix stiffness. In the computations a constant Poisson's ratio of 0.35 is suggested. If programs are available with capability of treating more than 5 layers, the third layer can be further subdivided to produce a

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*τ, γ^e = elastic shear stress and strain at a depth of 50 mm (2 in.) below outside edge of tire
ε_v = elastic vertical compressive strain at the subgrade surface

more representative stiffness distribution in the AC layer.

Moduli of the underlying layers can also be varied to reflect seasonal influences on the stiffness moduli of those layers. Poisson's ratio in the range 0.35 to 0.4 are recommended for untreated granular layers and 0.4 to 0.45 for untreated fine-grained (subgrade) soils.

In this approach, rutting in the asphalt concrete was assumed to be controlled by shear deformations. Accordingly, the computed values for τ and γ^e at a depth of 50 mm (2 in.) beneath the edge of the tire are used for the rutting estimates, as shown in Figure C-1. Densification of the asphalt concrete is excluded in these estimates since it has a comparatively small influence on surface rutting.

In simple loading, permanent shear strain in the AC is assumed to accumulate according to the following expression:

$$\gamma^i = a \cdot \exp(b\tau)\gamma^e n^c \qquad \textbf{(C-1)}$$

where

γ^i = permanent (inelastic) shear strain at 50 mm (2 in.) depth

τ = shear stress determined at this depth using elastic analysis

γ^e = corresponding elastic shear strain

n = number of axle load repetitions

a, b, c = regression coefficients

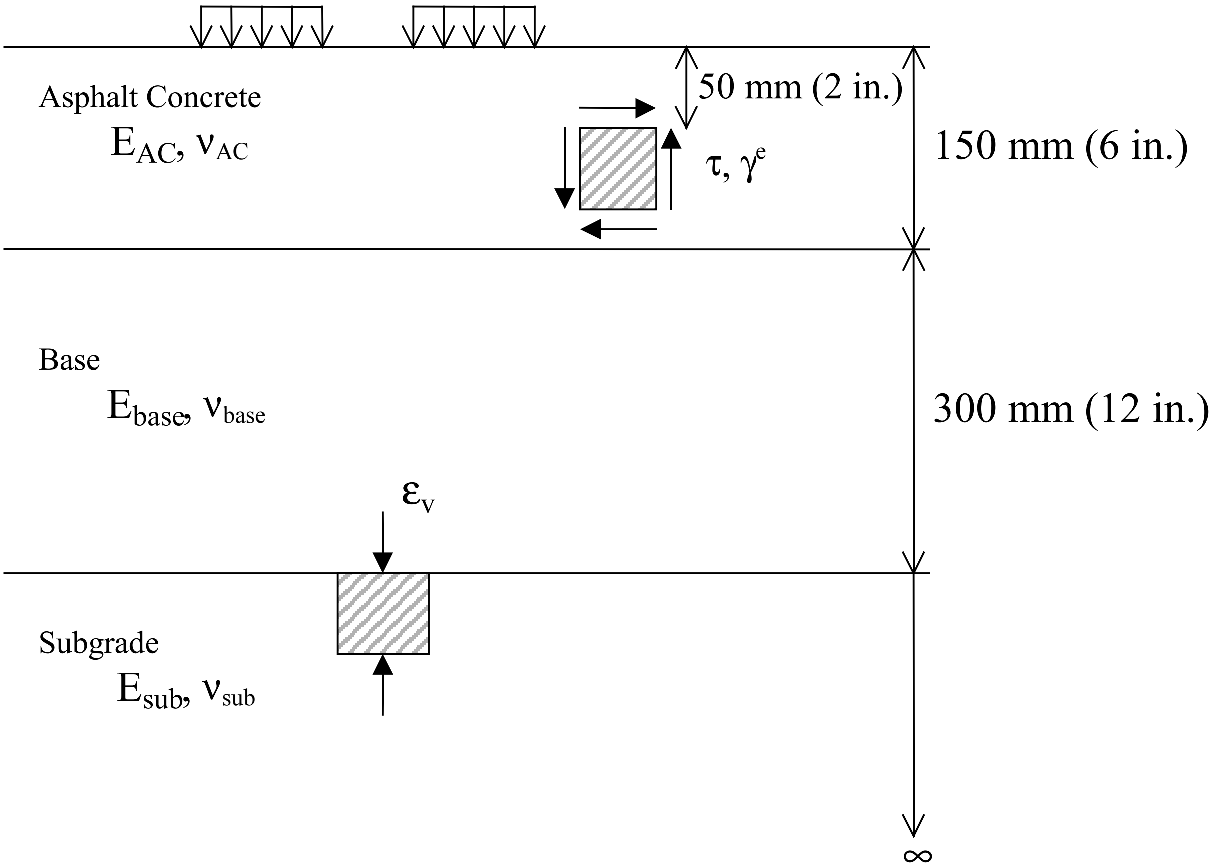


Figure C-1. WesTrack pavement respresentation for mechanistic-empirical modeling for rutting.

The time-hardening principle is used to estimate the accumulation of inelastic strains in the asphalt concrete under in-situ conditions. The resulting equations are as follows:

$$a_j = a \cdot \exp(b\tau)\gamma_j^e \qquad \textbf{(C-2)}$$

$$\gamma_1^i = a_1[\Delta n_1]^c \qquad \textbf{(C-3)}$$

$$\gamma_j^i = a\left[\left(\gamma_{j-1}^i / a_j\right)^{(1/c)} + \Delta n_1\right]^c \qquad \textbf{(C-4)}$$

where:

j = j^{th} hour of trafficking

γ = elastic shear strain at the j^{th} hour

Δn = number of axle load repetitions applied during the j^{th} hour

The concept is illustrated schematically in Figure C-2.

Rutting in the AC layer due to the shear deformation is determined from the following:

$$rd_{AC} = K\gamma_j^i \qquad \textbf{(C-5)}$$

K ranges from about 5.5 for a 150-mm (6-in.) layer to 10 for a 12-in. thick AC layer when the rut depth, rd_{AC}, is expressed in inches.(*17*)

To estimate the contribution to rutting from base and subgrade deformations, a modification to the Asphalt Institute subgrade strain criteria (*18*) is utilized. The equation expressing the criterion for 12.5 mm (0.5 in.) of surface rutting is:

$$N = 1.05 \times 10^{-9} \varepsilon_v^{-4.484} \qquad \textbf{(C-6)}$$

where:

N = the allowable number of repetitions

ε_v = the compressive strain at the top of the subgrade

Since these criteria do not address rutting accumulation in the pavement structure, rut depth (*rd*) contributed by the unbound layers was assumed to accumulate as follows:

$$rd = dn^e \qquad \textbf{(C-7)}$$

where

d, e = experimentally determined coefficients

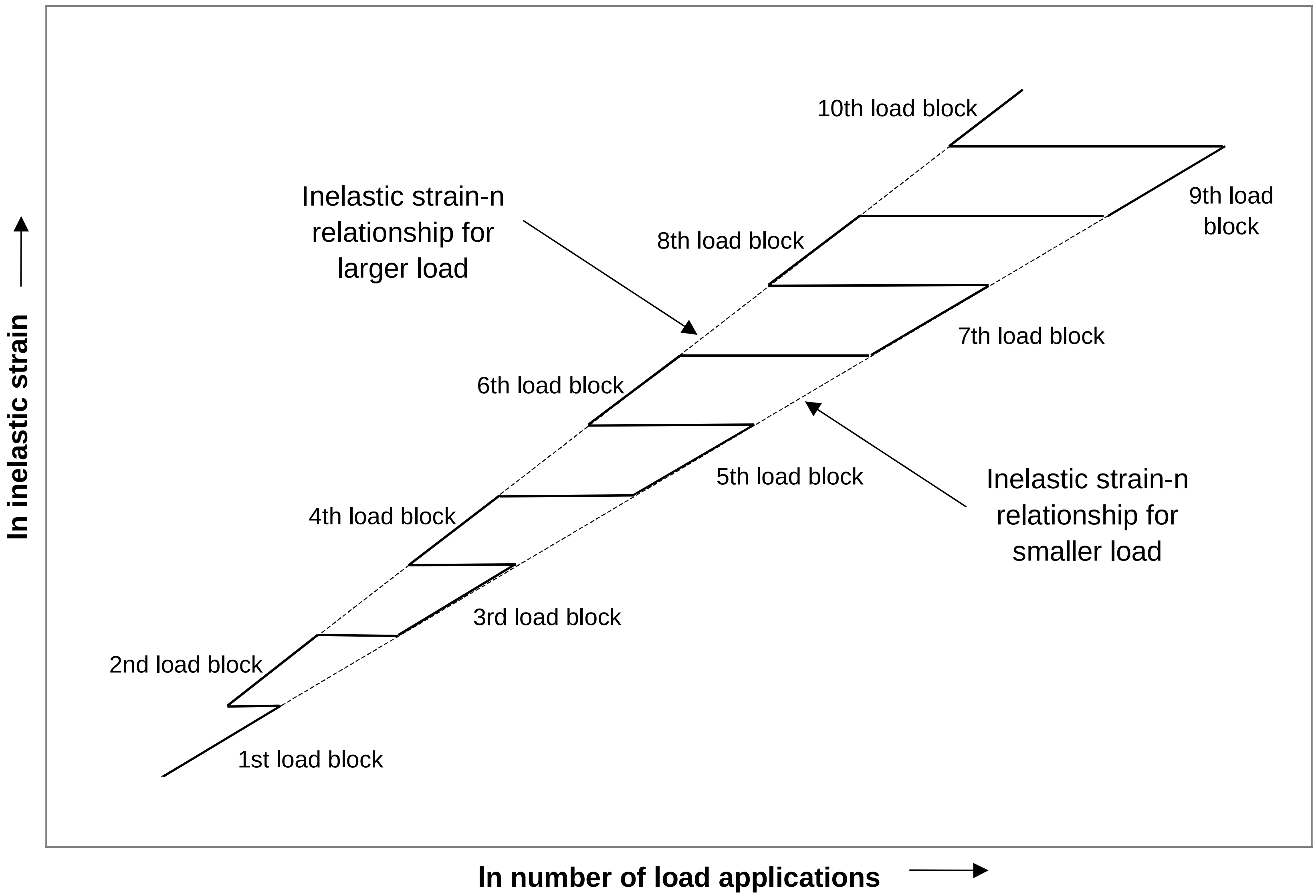


Figure C-2. Time-hardening provedure for plastic strain accumulation under stress repetitions of different magnitudes in compound loading.

Least squares analyses for the WesTrack data suggest that the value for d in Equation C-7 using the Asphalt Institute criteria is:

$$d = f \Big/ \left[1.05 \times 10^{-9} \varepsilon_v^{\,-4/484}\right]^e \qquad \textbf{(C-8)}$$

where:

f = 3.548

e = 0.372

Using the time-hardening principle, as was used for the asphalt concrete, rut depth accumulation can be expressed in a form similar to Equation (C-4), i.e.:

$$rd_j = d_j \left[\left(rd_{j-1} / d_j\right)^{1/0.372} + \Delta n_j\right]^{0.372} \qquad \textbf{(C-9)}$$

The framework for rut-depth estimation, using Equations C-1, C-4, and C-9 is illustrated in Figure C-3. This approach has a distinct advantage over the direct regression approach in that it permits prediction of rut depth as a function of traffic and environment as well as a function of mix parameters.

For WesTrack, 13 sections were used to calibrate the coefficients of Equations C-1 and C-7. Initially, a value for b = 0.0487 in Equation C-1 was used based on the results of RSST-CH tests. Subsequently, a value of b = 0.071 (10.28 in metric units) was determined to provide better correspondence between measured and computed rut depths.

Using the procedure illustrated in Figure C-3, least squares regression provided values of a and c for each of the 23 WesTrack sections where rutting without observed fatigue cracking was obtained. These are summarized in Table C-1. It will be noted that the average root mean square error (RMSE) for rut depth for the 24 sections is 0.051 in. Figures C-4, C-5, C-6, and C-7 illustrate comparisons between computed and measured rut depths for Section 4 (*fine*), Section 19 (*fine-plus*), Section 7 (*coarse*), and Section 38 (*replacement, coarse*).

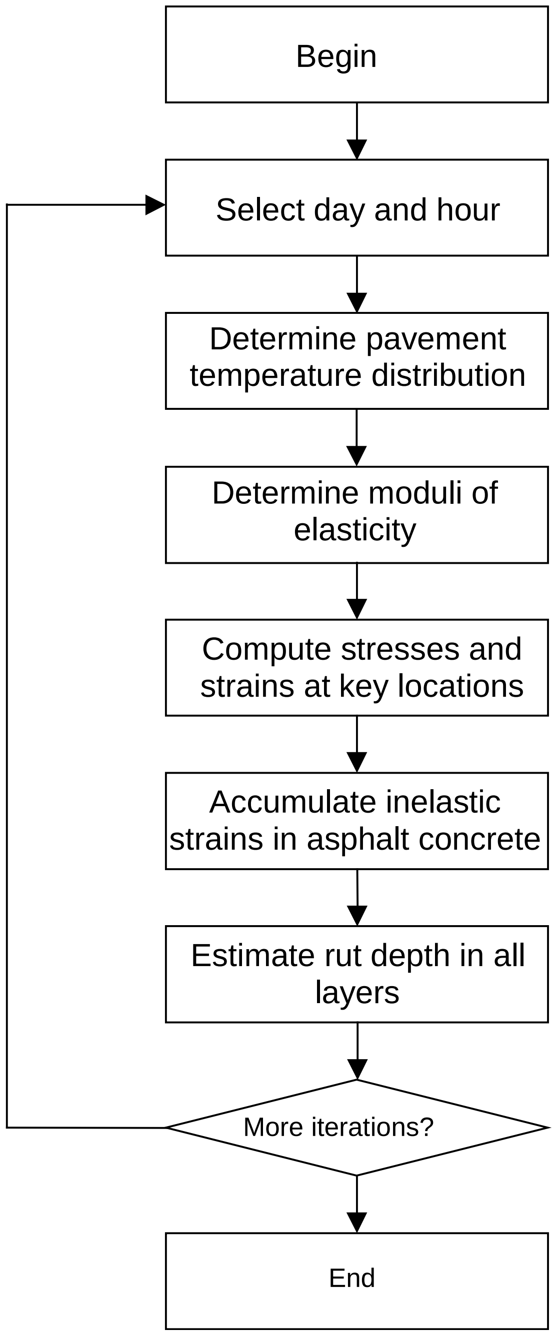


Figure C-3. Framework for rut depth estimates.

Table C-1 Calculated ESALs to a range in rut depths for a constant loading of 60 trucks/hour, WesTrack environment.

	ESALs to rut depth, in.									
Section	**2.5 mm**	**5.1 mm**	**7.6 mm**	**10.2 mm**	**12.7 mm**	**15.2 mm**	**17.8 mm**	V_{air}	P_{Wasp}	P_{200}
1	28,039	252,287	820,069	3,591,871	9,204,604	18,398,845		8.6	5.69	5.1
4	236,708	611,416	1,359,344	2,773,927	3,863,423	5,878,847	7,019,202	6.9	5.24	4.4
7	63,999	153,055	227,630	316,256	408,645	513,061	624,134	7.6	6.28	6.4
9	110,563	234,749	352,391	497,064	651,076	854,130	1,082,798	3.2	6.07	5.2
11	117,174	482,548	2,448,516	6,534,875	12,923,017			8	5.5	5.5
12	116,657	435,335	1,585,887	5,124,824	9,010,004	15,295,397		3.8	5.35	6
13	95,473	225,983	355,542	517,591	707,157	945,578	1,273,364	6	6.01	5.7
14	10,769	161,277	329,455	962,944	3,077,647	6,489,484	11,865,398	7.7	6.22	4.9
15	29,167	287,582	1,834,871	6,728,613	16,439,353			8.8	5.55	5.2
18	189,538	666,122	2,747,063	6,158,581	9,973,563	15,910,029		4.6	6.22	5.1
19	18,607	180,272	368,802	1,021,007	2,988,579	5,954,150	9,437,925	6	5.41	5.8
20	8,338	92,423	234,398	499,951	1,380,435	3,205,796	6,357,843	10.4	5.4	5.2
21	76,781	176,680	255,239	346,170	455,231	556,356	688,619	3.6	6.25	5.4
22	7,119	177,636	916,839	8,948,966				6.9	4.76	5.3
23	69,331	224,904	446,813	905,331	2,231,318	3,215,667	5,376,272	5.8	5.78	7
24	26,867	105,733	202,299	308,313	447,466	632,476	929,569	7.5	5.9	6.6
25	58,393	153,644	234,776	335,143	459,322	584,865	766,798	3.1	6.33	6.7
35		929	3,339	53,879	375,289	2,160,805	3,499,640	8.75	6.12	5.6
37		2,971	23,206	85,712	217,934	461,473	1,216,154	9.55	6.14	5.7
38	819	31,835	489,242	3,054,882	7,271,094	16,890,972		7.7	5.55	6.2
39	1,530	47,133	489,200	2,725,955	5,423,810	10,857,714		5.5	5.94	5.7
54		902	2,835	44,886	276,540	1,991,198	3,010,916	7.3	6.11	5.8
55	2,282	29,129	89,868	231,453	454,256	883,673	1,985,619	4.3	6.04	6

(1 in. = 25.4 mm)

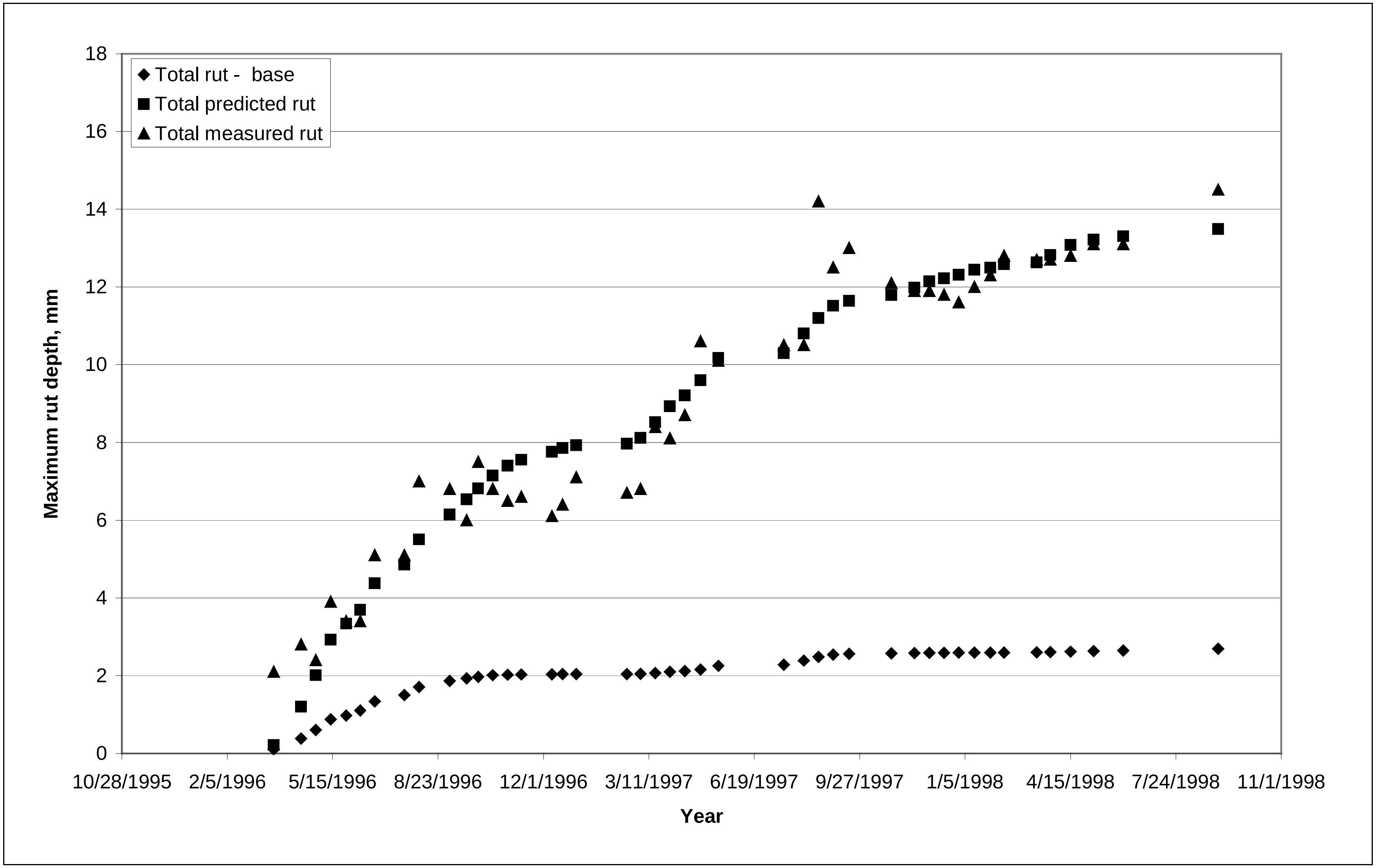
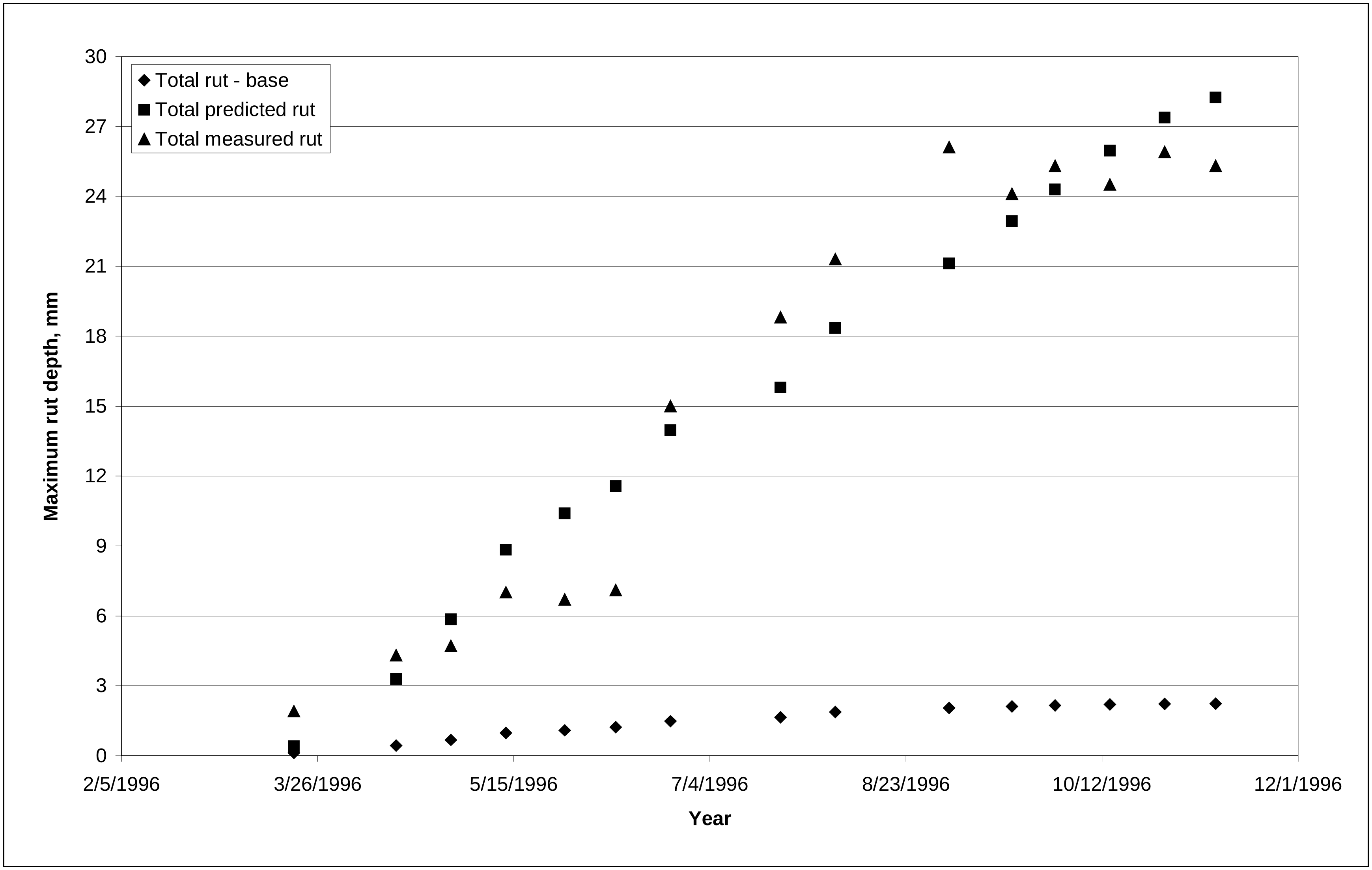
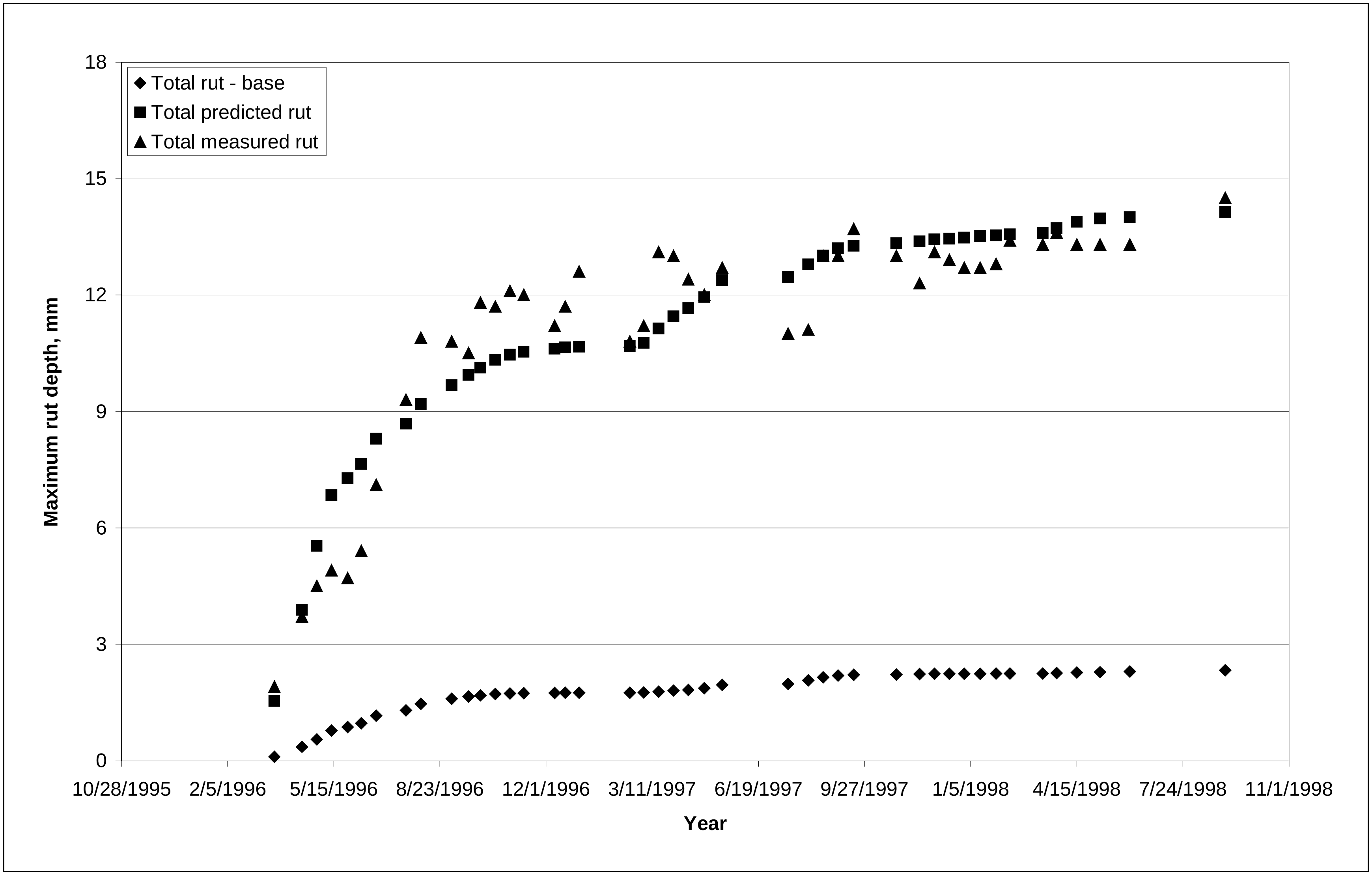


Figure C-4. Comparison between computed and measured rut depth versus time; Section 4.



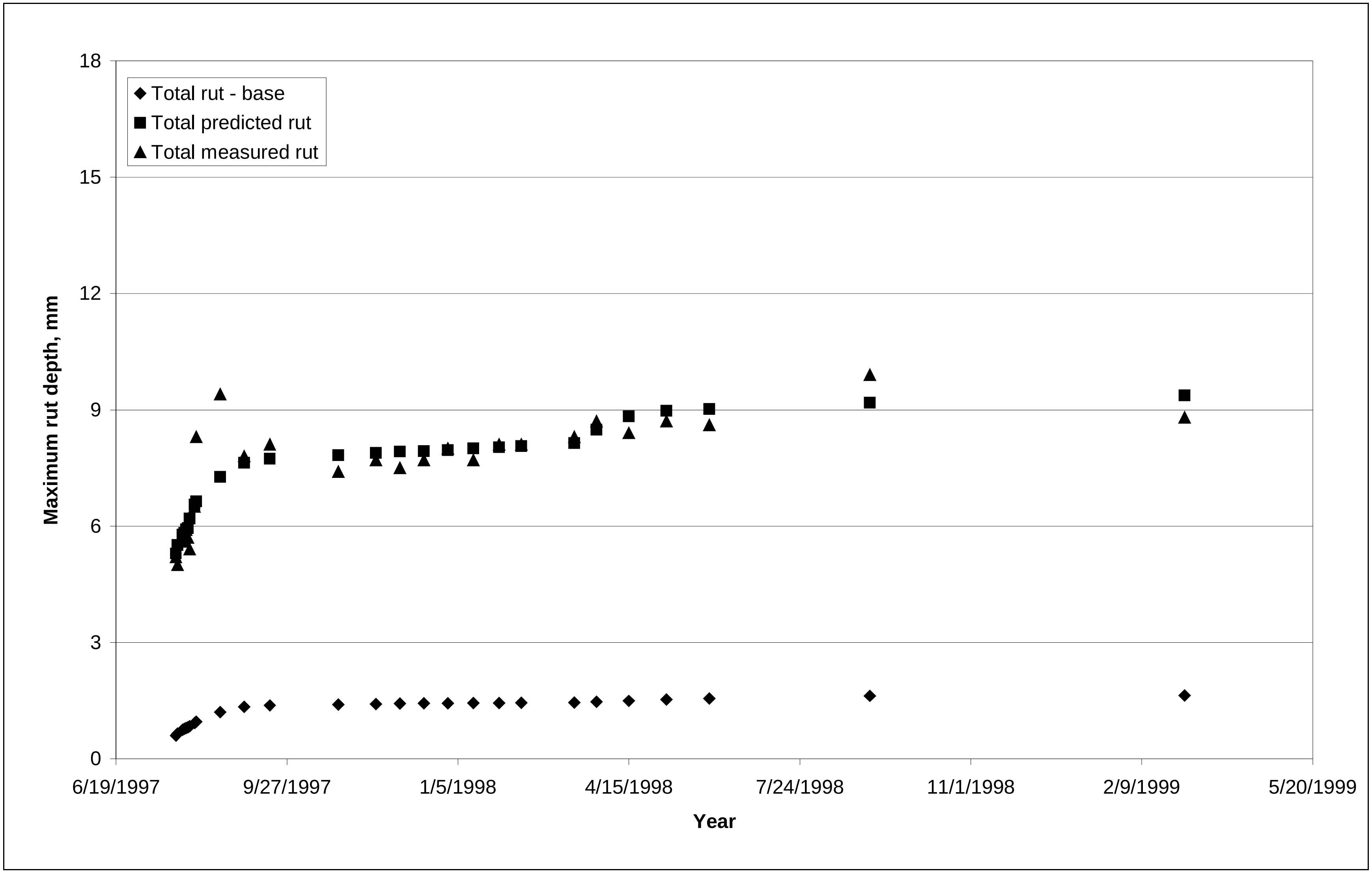
(1 in. = 25.4 mm)

Figure C-5. Comparison between computed and measured rut depth versus time; Section 7.



(1 in. = 25.4 mm)

Figure C-6. Comparison between computed and measured rut depth versus time; Section 19.



(1 in. = 25.4 mm)

Figure C-7. Comparison between computed and measured rut depth versus time; Section 38.

Expressions reported in Reference (*2*) for defining *field a* and *c* could be used if mixes similar to those used at WesTrack are being evaluated. For wider applications, however, it is desirable to have relationships not limited to these types of mixes.

An approach recommended at this time makes use of the results of the laboratory RSST-CH test and the mix variables-asphalt content and air-void content-to determine *field a* and *c* values. A series of regressions were performed for the 23 WesTrack sections shown in Table C-1 considering these variables. Results of the calibrations are shown in Table C-2 for *ln(field a)* and Table C-3 for *field c*. In these tables, *lab a* is from the expression:

$$\gamma^i = an^b \tag{C-10}$$

obtained from analysis of the RSST-CH results as shown in Figure C-8. The term *rsst 5* corresponds to the repetitions corresponding to a value of γ^i = 5 percent, also illustrated in Figure C-8.

From the analyses, Regression 6 in both Tables C-2 and C-3 is recommended for use to define *a* and *c* for use in the ME procedure briefly summarized herein.

Table C-2 Calibration of equations for simulating ln(*field a*) based on mix and RSST variables.

	Regr. 1	Regr. 2	Regr. 3	Regr. 4	Regr. 5	Regr. 6
Constant	14.9116	24.7107	24.3317	24.9718	25.3649	20.4844
P_{Wasp}	-3.67001	-5.02990	-5.04342	-5.23716	-5.71438	-5.12624
V_{air}						0.313875
$P_{Wasp} \cdot V_{air}$	0.0823738					
rsst5					6.219E-05	9.699E-05
laba	1301.81	1622.41	1745.07	1858.91	2472.96	2264.05
R^2	0.611	0.629	0.684	0.752	0.888	0.951
Sections Omitted	None	14	14, 15	1, 14, 15	1, 14, 15, 19	1, 4, 14, 15, 19

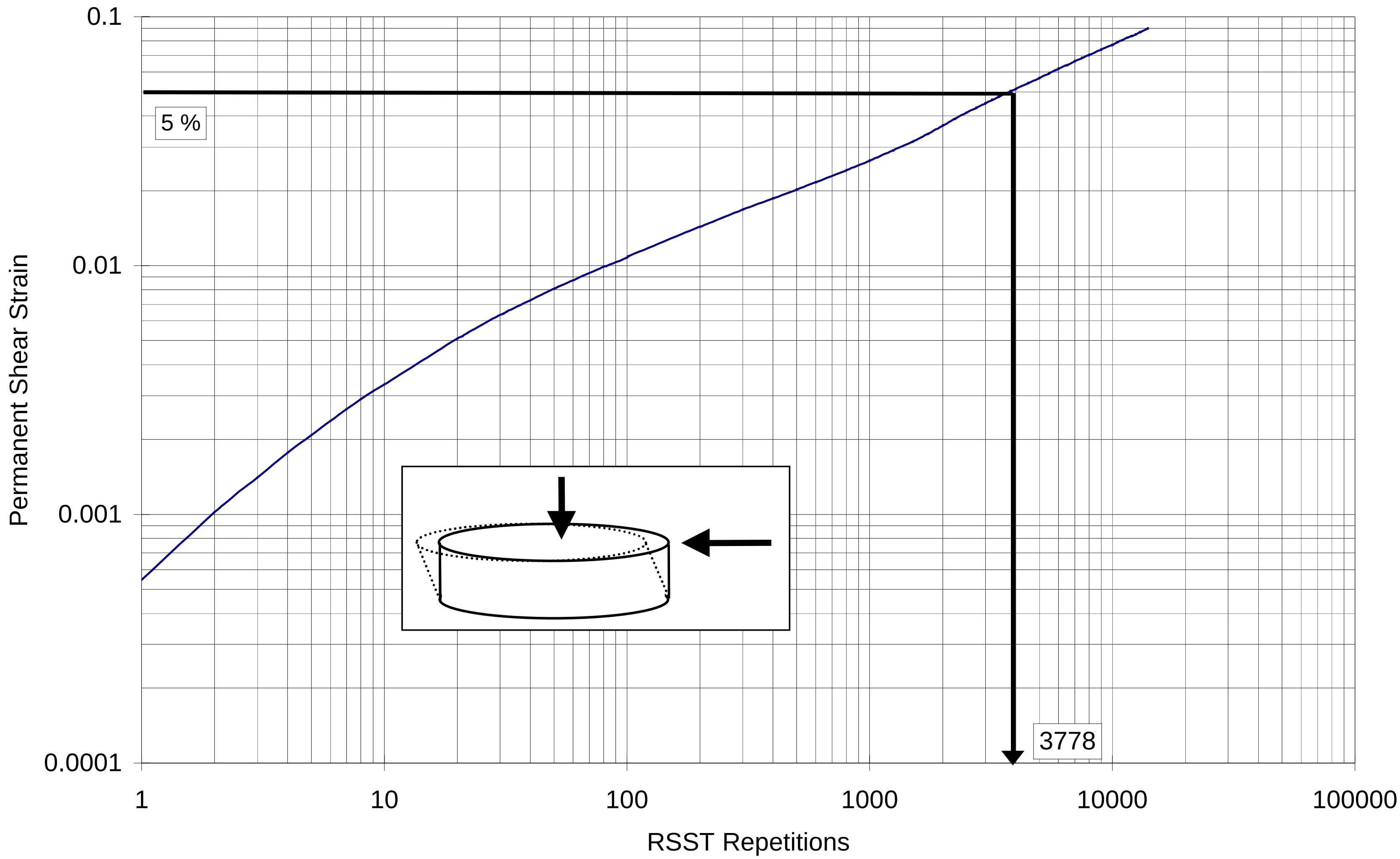


Figure C-8. Permanent shear strain, γ^i, versus load repetitions, *n*; rsst = 3778.

Table C-3 Calibration of equations for simulating *field c* based on mix and RSST variables.

	Regr. 1	Regr. 2	Regr. 3	Regr. 4	Regr. 5	Regr. 6
Constant	-0.944102	-1.75309	-1.72144	-1.77798	-1.83917	-1.49931
P_{Wasp}	0.312598	0.426673	0.427803	0.444915	0.493348	0.452398
V_{air}						-0.0217923
$P_{Wasp} \cdot V_{air}$	-0.0064968					
rsst5					-6.216E-06	-8.575E-06
lab a	-87.5258	-113.452	-123.693	-133.748	-190.11	-175.759
R^2	0.556	0.591	0.648	0.728	0.890	0.936
Sections Omitted	None	14	14, 15	1, 14, 15	1, 14, 15, 19	1, 4, 14, 15, 19