Development of End Result Specification for Pavement Compaction

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In 1992 the Ontario Ministry of Transportation (MTO) developed a new, statistically based end result specification (ERS) for the acceptance of hot-mix asphalt. As part of the ERS phase-in plan for hot mix, the specification for pavement compaction was introduced to the industry with the intent for full implementation by 1995. The acceptance procedure employs a percent-within-limits specification using the lot mean and standard deviation to ensure that the desired compaction is achieved. Using a life-cycle cost analysis, the appropriate payment factors were calculated on the basis of the expected life of the final product. Operating characteristic curves were developed to analyze buyers' and sellers' risks and to evaluate the expected payment factors for the acceptance plan. Simulations were carried out to assess the effects of the proposed price adjustment system. The system provides a bonus for consistent compaction that exceeds a specified quality level and an adjustment in contract price for work that does not comply with the specification.

Over the past 15 years, the Ontario Ministry of Transportation (MTO) has been moving toward replacing many of its existing method specifications with statistically based end result specifications (ERSs). In 1987 MTO began its phase-in of ERS for hot mix, and in 1991 the first specification incorporating price adjustments for deficient material was implemented for the acceptance of hot mix based on asphalt cement content and full aggregate gradation. ERSs for other highway construction materials such as unbound aggregates, Portland cement concrete, and bridge-deck waterproofing were already in place.

At the start of this process MTO recognized the need to move slowly into ERS to allow stakeholders a chance to understand this new concept. A phase-in plan was developed in consultation with industry for the development and implementation of future ERSs. On the basis of the plan tabled in 1992, the pavement compaction specification is scheduled for implementation on 10 to 15 contracts in 1994 and on 50 percent of the new contracts in 1995. In addition to this formal implementation, MTO is offering contractors the option to mutually agree to have hot mix accepted under the new special provision without price reductions provided they perform process control and take responsibility for rejectable material.

The new specification was developed in fall 1992 and was presented to the Ontario Road Builders Association in March 1993. The specification is based on a percent-within-limits (PWL) philosophy. This approach is different from the one used for the first ERS implemented in 1991, which is based on a variability-known acceptance plan that assumed a constant or known variability. The PWL system was chosen primarily because it is considered to be a better indicator of quality. The use of a PWL system was recommended in a report (*1*) prepared on behalf of MTO to review ministry ERSs.

As part of the development and implementation of the new specification, the ministry and road builders agreed to carry out field simulations during fall 1993 to allow MTO staff and contractors the opportunity to gain experience with the specification (and the PWL acceptance system). The simulation would also provide an opportunity for industry to develop a quality-control (QC) plan and to identify any problems with the proposed specifications.

In Ontario QC is the responsibility of the contractor; although it is not the intent of MTO to specify QC requirements, the importance of good QC cannot be understated.

This paper includes a limited statistical analysis of historical data and describes the development of the new specification as well as a simulation study to illustrate how the acceptance plan works. Data from the 1992 construction season were used to simulate a distribution of the estimated PWL. Operating characteristic (OC) curves are shown based on the PWL distribution and continuous price adjustment schedule.

BACKGROUND

Compaction is considered to be one of the most important factors that affect the ultimate performance of hot-mix asphalt (HMA) pavement (*2*). Pavement compaction is critical for the development of internal strength and good durability properties. The literature indicates that for each 1 percent increase in air voids above 7 percent, there is a 10 percent decrease in the service life of the pavement (*3*).

The current specification for pavement compaction classifies rollers on the basis of roller width, roller diameter, and static mass and requires a contractor to use a specified combination of rollers depending on the rate of hot-mix production. The pavement compaction requirements (amended by special provision for MTO contracts) specify that the lot average shall be equal to or greater than 92 percent of the theoretical maximum relative density (MRD) with no single test value less than 90 percent. An additional requirement of this special provision is that the pavement density is corrected on the basis of actual core thickness. The correction factor C adjusts the pavement density by +0.1 percent for every 1-mm deviation below 40 mm; if the core thickness is less than 25 mm, the core is not used for compaction calculations and a replacement core is taken. The correction factor C accounts for the effect of thin lifts on compaction; it originated from a previous compaction specification that stipulated the level of compaction based on lift thickness.

$$\text{Percentage compaction} = \frac{\text{BRD}}{\text{MRD}} \times 100 + C$$

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where

BRD = bulk relative density of individual core,
MRD = theoretical maximum relative density determined for lot, and
C = thickness correction factor (0.1 percent for each whole millimeter that pavement course thickness is less than 40 mm).

Under the existing specification, lots are based on a day's production and acceptance is based on core samples; three random cores are taken when the day's production is less than or equal to 1500 T, and one core is obtained for each 500 T when the production is greater than 1500 T. This system does not price-adjust material that does not meet specification.

A review of the 1991 data indicated that not all mix types were attaining the same level of compaction and that some mix types had a large percentage of material below the specification limit. To improve the overall quality of the pavements being constructed, MTO elected to proceed with an ERS for pavement compaction.

DATA ANALYSIS

The pavement compaction data from all 1992 contracts were compiled and analyzed by contract, mix type, and region. A statistical analysis was conducted to determine the mean, standard deviation, and coefficient of variation for each population tested. Frequency histograms were plotted to verify that the populations are distributed normally.

A summary of the analysis for pavement compaction is presented in Table 1. The 1992 data were compared with a more limited study performed on 1991 data, which indicated essentially similar trends in both construction seasons. Typical frequency histograms for some of the mix types are shown in Figure 1.

The histograms plotted for each mix type confirmed that the populations are approximately normally distributed. The data analysis also shows that there are significant differences in the pavement compaction being attained for the various mix types. However, from the data analyzed it is unclear whether this variance is due to construction (i.e., improper compaction) or to mix characteristic (i.e., gradation, aggregate type, etc.). The most noticeable difference observed was for the compaction attained for DFC and HDBC mixes. These mixes are premium mixes incorporating 100 percent crushed aggregates and are used on high-volume roadways in Ontario.

The population mean for all mixes was 93.0 percent, with a standard deviation of the lot means of 2.0 percent. The pooled standard deviation was found to be 1.6 percent; the coefficient of variation (or measure of relative dispersion) ranged from 1.1 percent (for RHM) to 2.4 percent (for HL 8). The overall coefficient of variation using the pooled standard deviation was 1.7 percent.

To study the effect of the correction factor applied to cores less than 40 mm, the data were analyzed to determine the pavement densities for each mix type corrected and uncorrected. The analysis shows that the correction factor was applied on approximately 20 percent of the lots tested. However, most of these corrections were for minor deviations in thickness; 50 to 60 percent of the lots receiving a correction were corrected by only 0.1 percent. The data also indicate that the average and standard deviations for each mix type were virtually the same for the uncorrected data versus corrected data versus all data excluding the corrected values.

ACCEPTANCE PLAN

There are two commonly used acceptance plans (involving inspection by variables) for evaluating hot-mix quality characteristics. They are referred to in AASHTO R9-91 (Acceptance Sampling Plans for Highway Construction) as "variability known" and "variability unknown." These methods evaluate the acceptability of the material on the basis of mean and variability measured by testing. The variability-known acceptance plan assumes that the variability is known and constant. This type of plan evaluates the lot mean on the basis of acceptance criteria developed using an assumed (or known) variability for the lot. The plan then separately evaluates the lot variability to ensure that it is less than the assumed (or specified) value.

Acceptance may be determined using either the mean and range method or the mean and standard deviation method. The standard deviation method is normally used and is recommended by AASHTO, mainly because all the samples are used to measure variability rather the range method, which uses only the highest and the lowest values of a lot.

The variability-unknown type of acceptance plan assumes the lot variability to be unknown. The PWL method estimates the normal distribution of the material on the basis of the mean and standard

TABLE 1 Analysis of 1992 Compaction Data

Mix Type	Lot Mean (%)	Std. Dev. of Lot Means	Coefficient of Variation	Minimum Lot Mean	Maximum Lot Mean	No. of Lots Analyzed
DFC	90.9	1.78	2.0	85.6	96.6	193
HDBC	91.6	1.65	1.8	87.6	96.6	324
HL1	93.9	1.54	1.6	89.7	98.3	94
HL3	92.8	1.46	1.6	87.0	95.8	78
HL4	93.7	1.57	1.7	88.1	98.9	741
HL8	93.7	2.24	2.4	88.3	97.6	90
MDBC	94.7	1.30	1.4	91.7	96.9	47
RHM	93.6	1.07	1.1	90.1	96.1	130
Total	93.0	1.97	2.1	85.6	98.9	1697

[a]Dense Friction Course, [b]Heavy Duty Binder Course, Hot Laid, [c]Medium Duty Binder Course, [d]Recycled Hot Mix[e]
NOTE: Mix types as follows: DFC =

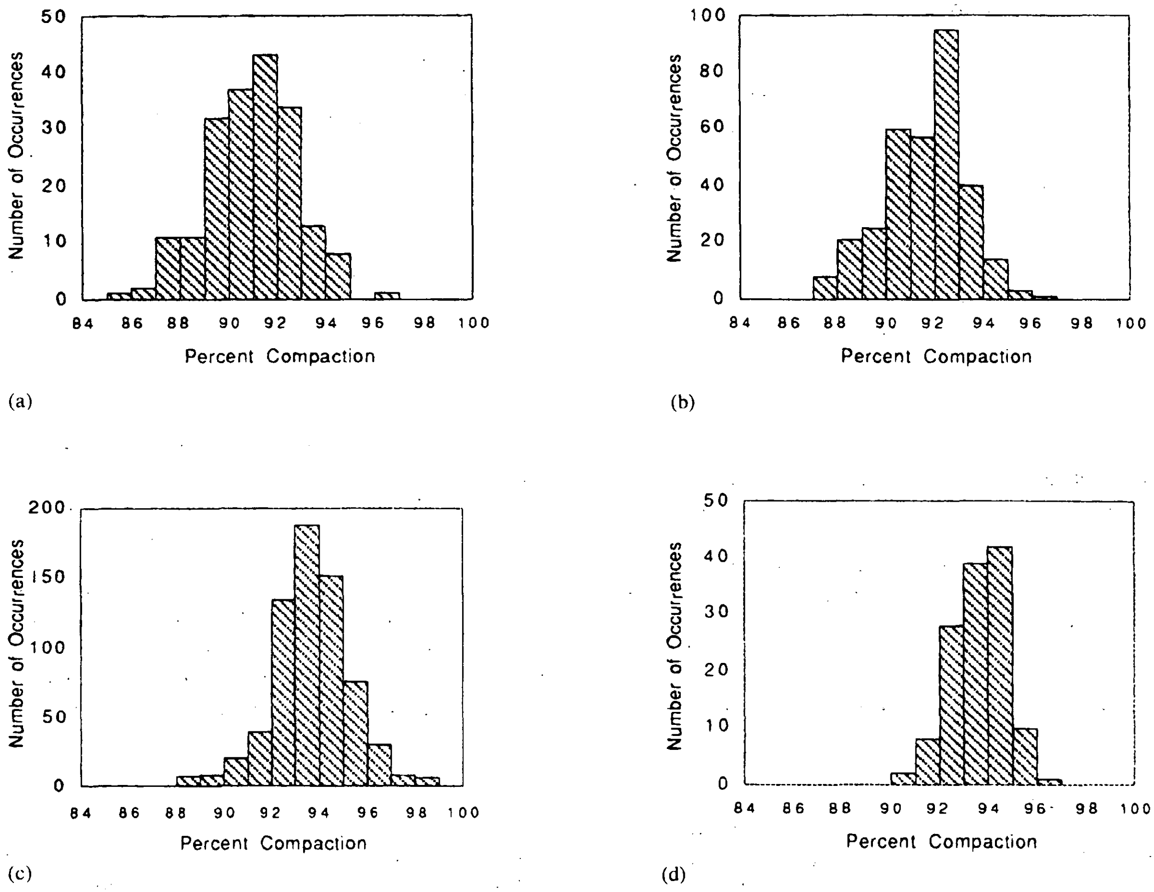


FIGURE 1 Frequency histograms for several mix types: *a,* DFC; *b,* HDBC; *c,* HL-4; *d,* RHM.

deviation of the test values. The distribution is then used to determine an estimate of the percentage of material within a lower or upper limit. The major advantage of this method is that the mean and variability (standard deviation) are used together in the same "equation" to estimate the quality of the material.

The acceptance plan developed for pavement compaction is based on a PWL principle. This method was selected for several reasons. It is widely accepted that PWL specifications are more efficient and beneficial for the contractor and the owner. Generally, this system provides a better estimate of the lot quality and is considered to be more effective. The estimate of PWL is unbiased and will most likely lead to fewer disputes about material quality. This system encourages uniformity of the end product, thereby improving the overall quality of the pavement (*4*). Last, because the standard deviation is a better measure of variability, fewer samples are required than when using the lot range. AASHTO R9–91 states that a range plan requires 12 samples to provide the same estimate of variability as a standard deviation plan using 10 samples.

SAMPLING PLAN

Several factors should be considered in determining the sampling frequency and lot size. The number of samples taken for a lot should be sufficient to ensure that the testing accurately represents the lot. Using a small number of samples will result in a high risk of incorrectly accepting unsatisfactory work (buyer's risk), a high risk of incorrectly rejecting good work (seller's risk), or both. From the buyer's perspective, the quantity of testing must also be practical to ensure that the cost is not excessive and that the testing can be carried out in a timely manner with the available resources. The lot size must be large enough to justify the expense of testing. However, if the lot is too large, the consequences associated with unacceptable material may become too severe. Another concern with a large lot is that the material is not uniform. This could occur from a change in the contractor's process or from other factors such as a major change in environmental conditions, which can affect compaction.

Lot sizes typically are based on either 1 day's production or a specific quantity. An advantage of decisioning a lot size on a daily basis is that environmental conditions and operational characteristics (i.e., rolling pattern or roller operator) are likely to remain more or less the same. These conditions and characteristics can deviate more when the lot size is based on a specified quantity, especially when production is slow or is stopped in the middle of a lot. However, with proper process control a contractor should be able to produce a uniform product.

To simplify the administration of accepting hot mix, it was decided that the lot sizes for pavement compaction would parallel the lot sizes specified for the current ERS for acceptance of asphalt cement content and aggregate gradation. Under this system a lot is normally defined as 2000 T of HMA with four sublots of equal portions. From the OC curves generated, a sampling frequency of six samples per lot (one per 333-T sublot) was chosen for the pavement compaction acceptance plan.

OC CURVES AND RISK ANALYSIS

The analysis of risk is considered to be an essential procedure when developing any ERS. By knowing the risks involved a contractor can establish a quality level that normally will guarantee full payment. Likewise, the owner can with some level of confidence ensure that product meets specification. The most common way to analyze risk is by developing OC curves. These curves generally relate the probability of acceptance or expected payment with a specific level of quality (i.e., PWL).

PRICE ADJUSTMENT SCHEDULE

Adjusted pay schedules are common with most ERSs. Price reductions normally are used to deal with materials that do not entirely meet specification but are not considered to be so substandard that removal or repair is required. To determine the appropriate pay adjustments, the design life of the pavement is compared with an expected life for the pavement (as-built) discounted over the life cycle of the pavement. This method is considered suitable provided a quality-versus-performance relationship can be established (*5*).

CALCULATION OF APPROPRIATE PAY FACTOR

The appropriate pay factors were determined using a life-cycle costing analysis with the model shown later. This analysis takes into account the original cost of hot mix (M_c) and allows for two resurfacings within the life span. The design life of the original pavement and each subsequent overlay is 10 years. This is typical of a design analysis performed by MTO. Inflation and interest rates are assumed to be 3.0 and 7.0 percent, respectively.

The appropriate pay factor is based on the present-worth cost of construction plus the cost of rescheduling the pavement rehabilitation due to loss of service life. The equation was derived from basic engineering economics formulas; it has been shown to produce a reliable pay factor relationship provided the input values are reasonably accurate (*5*). The appropriate pay factor was calculated to be 0.63 using the following data:

$$PF = \frac{M_c + (R^{DL} - R^{EL}) * \left(R_1 + \dfrac{R_2 R^{EO}}{1 - R^{EO}}\right)}{M_c}$$

where

M_c = cost of hot mix = \$45/T,
R_1 = cost of first resurfacing = \$60/T,
R_2 = cost of second resurfacing = \$60/T,
D_L = design life = 10 years
E_L = expected life = 8 years (20 percent loss of service life due to poor compaction),
E_O = expected life of overlays = 10 years (single lift),
I_F = inflation rate = 3.0 percent,
I_N = interest rate = 7.0 percent, and
R = 1.03 / 1.07 = 0.96.

(Resurfacing costs include the cost of removal.)

Using this model, appropriate pay factor curves were plotted for different standard deviations measured from the 1992 data for pavement compaction. A computer simulation was then used to develop a continuous pay schedule. The expected payment curve shown was generated by computer program (*5,6*). For comparison, the payment equation has been plotted with the appropriate pay factor curves (Figure 2) and the expected payment curve (Figure 3).

Several key observations can be made from these curves:

1. The appropriate pay factors determined using the different standard deviation values show the relationships between uniformity (or variability) and the estimated PWL. It is apparent that as the lot standard deviation increases, the price adjustment increases (pay factor decreases).
2. The payment curve shows that the minimum pay factor was determined to be 0.65 based on an expected life–to–design life ratio of 0.80. A bonus of 3 percent will be paid for lots exceeding the desired compaction level. A lot is deemed to be rejectable and may be subject to repair if the PWL is less than 50.
3. A comparison of payment curve and the expected pay factor curve revealed that at acceptable quality level (AQL), the actual payment is artificially higher than the expected payment curve. This was done to eliminate any bias by imposing price adjustments for material considered to be of AQL or better (i.e., 90 PWL). The flat area on the pavement compaction curve between 90 and 95 PWL was created primarily to simplify administration. This area would allow for a zone in which the material is accepted at full price. The difference in this area of the curve is small for an expected payment of 95 PWL. The remainder of the payment schedule curve matches the expected payment curve very closely up to about 70 percent PWL (30 percent defective), after which the payment curve separates from the expected payment curve. This separation is attributed primarily to the number of samples tested (n) and decreases as n becomes larger. The noted difference can be justified by the highway agency to account for the future maintenance, engineering, and administrative cost associated with the acceptance of deficient material at a reduced price (*5*).

ACCEPTANCE PROCEDURE

Acceptance for pavement compaction is to be based on the estimated PWL in accordance with the upper and lower specification limits provided in Table 2. The limits were determined on the basis of the data analyzed and reflect the level of compaction attained for the various mix types.

The lot mean and standard deviation will be used to estimate the lot PWL. The PWL will be calculated by determining the quality indexes, Q_l and Q_u, based on the following equations:

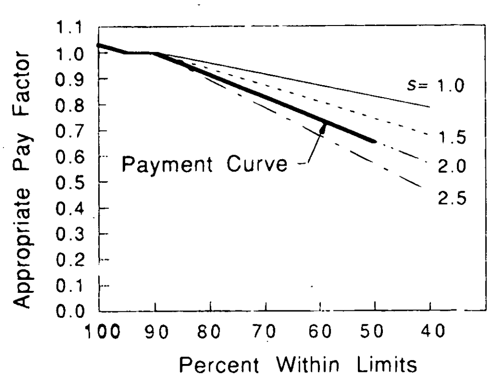


FIGURE 2 Appropriate pay curves.

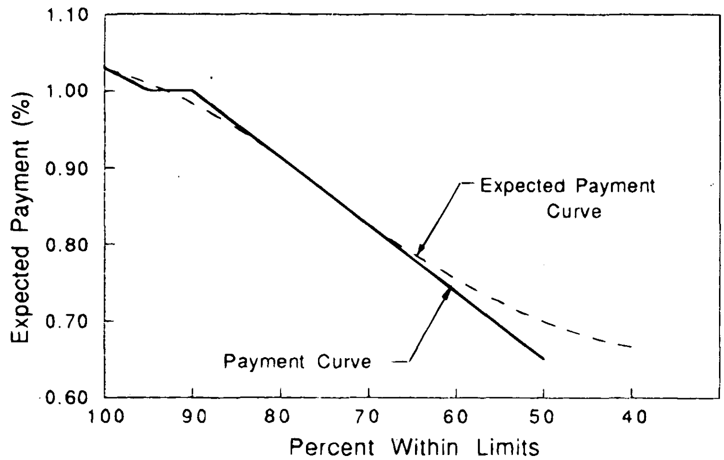


FIGURE 3 Expected payment curves.

$$Q_l = \frac{\overline{X} - \text{LL}}{s} \quad (1)$$

$$Q_u = \frac{\text{UL} - \overline{X}}{s} \quad (2)$$

where

Q_u = upper quality index,
Q_l = lower quality index,
UL = upper limit,
LL = lower limit,
X = lot mean, and
s = lot standard deviation.

The quality indexes are then used to determine the percentage of material above the lower limit and the percentage of material below the upper limit from the quality index table in the special provision. The total PWL for the lot is calculated using Equation 3:

$$\text{PWL} = (P_L + P_U) - 100 \quad (3)$$

where P_L is percentage within lower limit and P_U is percentage within upper limit.

SIMULATION ANALYSIS

To analyze the impact of the proposed specification, simulations were carried out using the 1992 compaction data. Although these simulations provide a good approximation of the impact of the proposed specification, it should be understood that three factors may slightly misrepresent the outcome of simulations. First, the previous compaction specification in place at the time that the data were collected did not effectively consider the uniformity of the mix. Second, the old system did not deter the contractor from overcompacting the mat. Third, the lack of a clear procedure to account for poor compaction did not encourage the contractor to provide good process control.

The compaction results from 11 DFC contracts were analyzed to stimulate the effect of the specification. A summary of the results from this simulation is presented in Figure 4. The results indicate that 22 percent of the lots would receive a bonus and 65 percent of the lots would receive less than full payment (before retesting or repairs). In all cases, these lots failed to comply with the specification requirements because of low compaction. The average compaction payment factor for a lot would be about 91.5 percent of the contract price. From the 1992 data, the overall price adjustment for DFC is expected to be $3.40/T. The high number of price-reduced and rejectable lots is a concern to both the ministry and the hot-mix industry. Unfortunately, the severe consequences of accepting hot mix with less than 89.5 percent compaction (greater than 10.5 percent air voids) restrict the ministry's ability to lower the specification limits.

The compaction results from 21 HL-4 contracts were analyzed to simulate the effect of the specification. A summary of the results from this simulation is presented in Figure 5. Sixty-four lots (42 percent) would receive a bonus, and 68 lots (44 percent) would receive less than full payment. Of the 12 rejectable lots, 9 were determined to be rejectable primarily because of overcompaction, which was not addressed by the previous specification. Overall, the results indicate reasonable compliance, with more than half the lots being accepted at full price or receiving a bonus. The average compaction payment factor for a lot would be about 95.9 percent of the contract price. The estimated overall price adjustment for HL-4 is anticipated to be approximately $1.50/T.

TABLE 2 Tolerance Limits for Pavement Compaction

Mix Type	LL(%)	UL(%)
HL1, HL2, HL3, HL3A, HL4, HL8, MDBC, RHM, hot in-place recycled mix and hot in-place recycled mix with integral overlay	91.5	97.0
HDBC	90.5	97.0
DFC	89.5	98.0

OC CURVES

A computer program was used to generate 12,000 independent random compaction results based on the various population character-

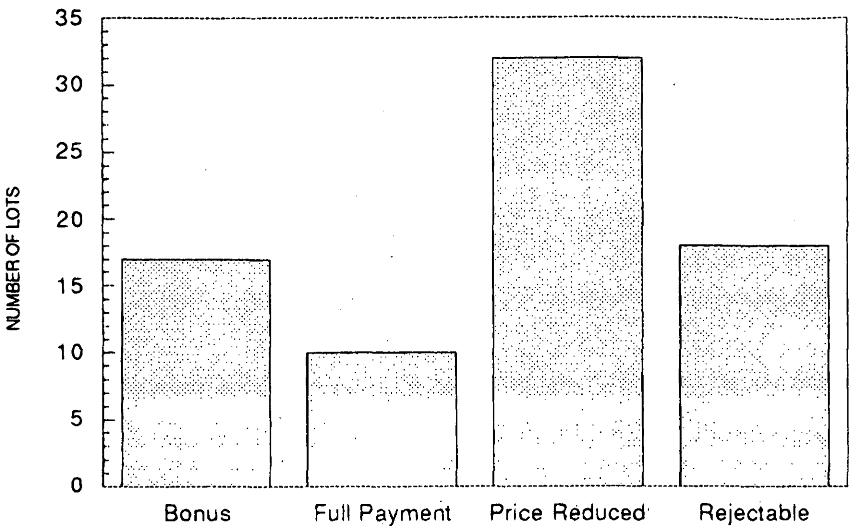


FIGURE 4 Simulation results for DFC mixes.

istics for each of the mix classifications. The results were separated into 2,000 lots with six samples each to form points for the OC curves shown in Figure 6.

The OC curves indicate that the acceptance plan worked as intended. The expected pay factors are high for population means at the desired level of compaction with low variability (standard deviations). Accordingly, the expected pay decreases as the variability increases and the population mean deviates from the expected target. The specification should provide an incentive for contractors to reduce variability and achieve an overall better end product.

SUMMARY

The primary objective of this paper was to develop ERSs for pavement compaction. The acceptance plan has been described in detail. The new specification is based on a PWL concept that can be adopted for most materials used in highway construction.

The data compiled from the 1992 contracts were used to determine the acceptance limits and to establish a continuous price adjustment schedule. On the basis of these data, the overall price adjustment for conventional mixes was estimated to be on the order of $1.50/T.

To verify that the plan can be implemented and is fair to both MTO and the road builders, it was agreed to run a field simulation in fall 1993, incorporating different mix types and paving conditions across the province. The simulation would give MTO construction personnel and contractors a chance to gain experience with the acceptance plan and, more important, to determine if any modifications are required to the specifications. Modifications could entail loosening or tightening the acceptance limits, changing the sample size, or reducing or increasing payment for a given PWL.

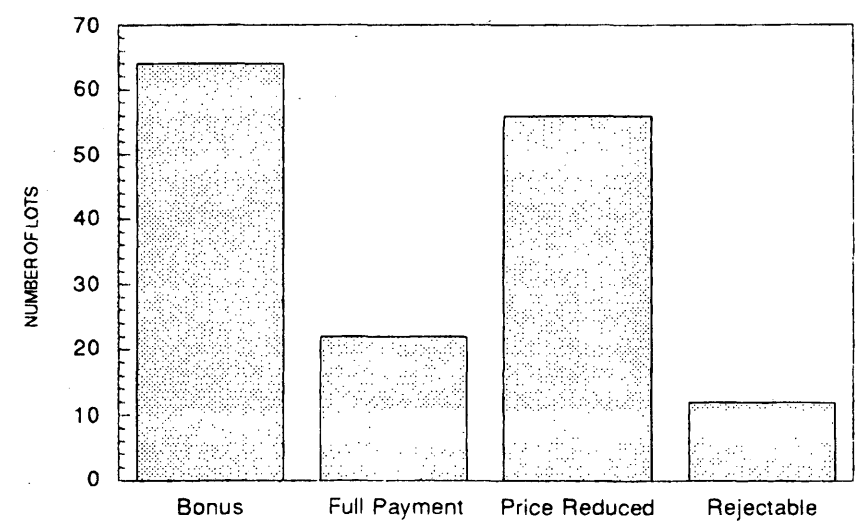
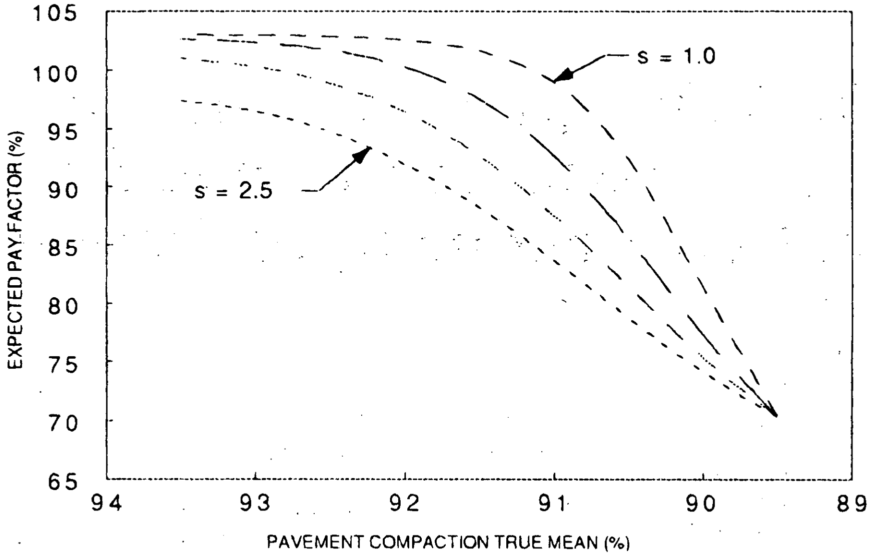


FIGURE 5 Simulation results for HL-4 mixes.



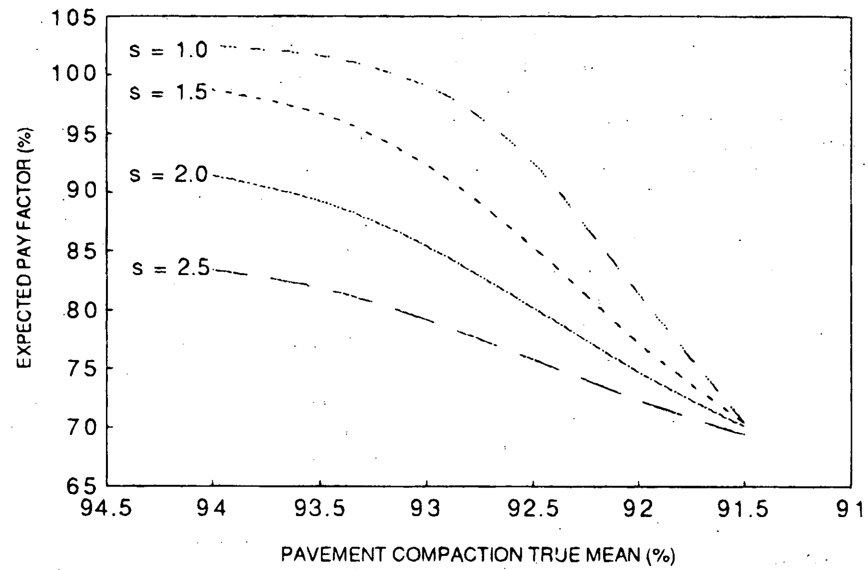


FIGURE 6 OC curves for pavement compaction: *top,* DFC; *bottom,* all other mixes.

RECOMMENDATIONS

The 1993 field simulation results should be reviewed, and if the specification shows satisfactory performance, it should be implemented with full price adjustment on selected contracts advertised in the 1994 construction season. The proposed ERS should be applied to all mix types analyzed in this study.

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