Heavy-Duty Asphalt Pavements in Pennsylvania: Evaluation for Rutting

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Thirty-four heavy-duty asphalt pavements encompassing poor to excellent rutting performance were evaluated. The objective was to identify the pavement properties (materials, mixture design, construction, and postconstruction) that typify good- and bad-performing pavements. Eleven pavement cores were obtained from each pavement to determine in-place voids in the total mix, mix composition, coarse aggregate fractured face count, fine aggregate particle shape and texture, and recovered asphalt cement properties. The mix from the pavement cores was heated and recompacted using three compactors: gyratory testing machine, rotating base/slanted foot mechanical Marshall compactor, and static base conventional mechanical Marshall compactor. All project data such as job-mix formula, construction data, and traffic data were obtained. Rut depths were measured on each project using a profilograph device. Some 60 independent variables covering the mix design, construction, and postconstruction for each pavement were selected to determine their effect on the rut depth (dependent variable). The extensive data were analyzed using correlation analysis, linear regression analysis methods, and stepwise multiple variable analysis methods. A rutting model was also developed. Recommendations were made to the Pennsylvania Department of Transportation to improve and optimize the resistance of asphalt paving mixtures to rutting for heavy-duty pavements. The main recommendations are (*a*) use at least 75 percent crushed sand in the fine aggregate, (*b*) use 75 blows per side compactive effort using a rotating base/slanted foot Marshall compactor, (*c*) design mix with at least 4.0 percent air voids, and (*d*) improve production quality control to ensure that the mixes "as placed" are reasonably close to the mixes "as designed."

Premature rutting of hot mix asphalt (HMA) pavements has been experienced in several states in the United States in recent years due to increased traffic loads and truck tire pressures. Recent surveys in Illinois and Texas indicate that the tire pressures have increased substantially. Tire pressures averaged 661 kPa (96 psi) and 689 kPa (100 psi) in Illinois and Texas surveys, respectively.

The Pennsylvania Department of Transportation's (PennDOT's) first major asphalt pavement rutting was experienced on I-70 in Washington County during early summer 1986. Additional cases of rutting have occurred since. A special provision for designing the HMA pavements for heavy-duty pavements was developed by PennDOT and implemented in 1987. The salient features contained in the special provisions are use of (*a*) larger size (38-mm or 1½-in.) aggregate in binder and base courses, (*b*) coarse aggregate with at least 85 percent two or more fractured faces, (*c*) at least 75 percent manufactured sand in the fine aggregate, and (*d*) Marshall specimens made with 75 blows on each side. However, there was a need to evaluate several heavy-duty pavements constructed in the past with and without the special provision so that the pavement properties (materials, mixture design, construction, and postconstruction) that typify good and bad pavements could be identified. This will facilitate changes to PennDOT's current material specifications, mix design, and construction procedures to cope with the increased truck loads and tire pressures.

DATA COLLECTION, SAMPLING, AND TESTING PLAN

Thirty-four heavy-duty pavements encompassing poor to excellent rutting performance were identified by PennDOT. All Interstate highways and highways with average daily traffic of more than 20,000 or more than 1,000 daily 8,172-kg (18-kip) equivalent single-axle load (ESAL) applications are defined as heavy-duty pavements.

Data Collection

The following data were collected for all projects:

1. Average climatic conditions;
2. Average daily traffic, percent trucks, and 8,172-kg (18-kip) ESALs per day;
3. Details of underlying pavement structure and overlay;
4. Job-mix formula (JMF) including the Marshall design data; and
5. Construction data such as mix composition, Marshall test data, and field compaction.

These data are contained elsewhere (*1*).

Sampling and Testing Plan

Eleven cores 152.4 mm (6 in.) in diameter were obtained during spring 1989 from a representative 1 lane-mi segment (travel lane) of each project (Figure 1). Five cores (numbered C1 through C5) were obtained at random locations longitudinally from the inside wheel track of this segment. The five

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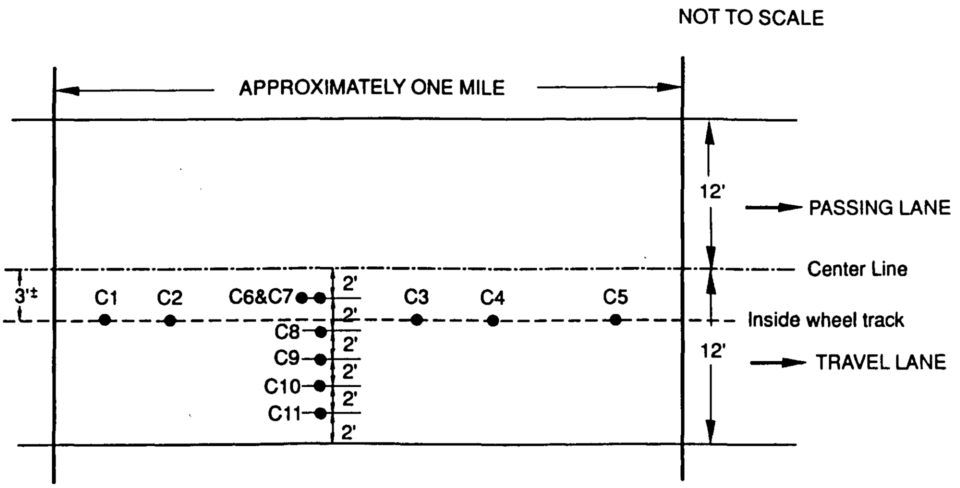

FIGURE 1 Core sampling plan.

cores from each project (total of 170 cores) were tested as follows:

1. Thickness of layers (all cores),
2. Bulk specific gravity (all cores),
3. Theoretical maximum specific gravity,
4. Extraction—asphalt content and gradation (all cores),
5. Coarse aggregate (retained on No. 4 sieve)—fractured face count (one core), and
6. Fine aggregate—particle shape and texture [determined in terms of percent void content using the National Aggregate Association procedure (*1*)].

Five additional cores 152.4 mm (6 in.) in diameter (C7 through C11) were obtained across the pavement, 2 ft center to center, at the worst (maximum rutting) location of the selected segment, as shown in Figure 1. The testing program for these transverse cores is shown in Figure 2. Essentially, the following tests were run:

1. Bulk specific gravity of layers (all cores) to determine in-place voids in the total mix (VTM);
2. Static unconfined creep test (two cores); and
3. Bulk specific gravity, stability, and flow tests on two specimens recompacted by three compaction methods: (*a*) gyratory testing machine (GTM), (*b*) rotating base, slanted foot mechanical Marshall compactor, and (*c*) static base conventional mechanical Marshall compactor.

The thickness of all layers in Cores C7 through C11 was accurately measured before sawing the layers and used to obtain the profiles of the underlying layers once the surface profile was established. One core (C6) was taken beside Core C7 as shown in Figure 1. Aged asphalt cement was recovered by the Abson method from this core and tested for penetration at 25°C (77°F) and viscosity at 60°C (140°F).

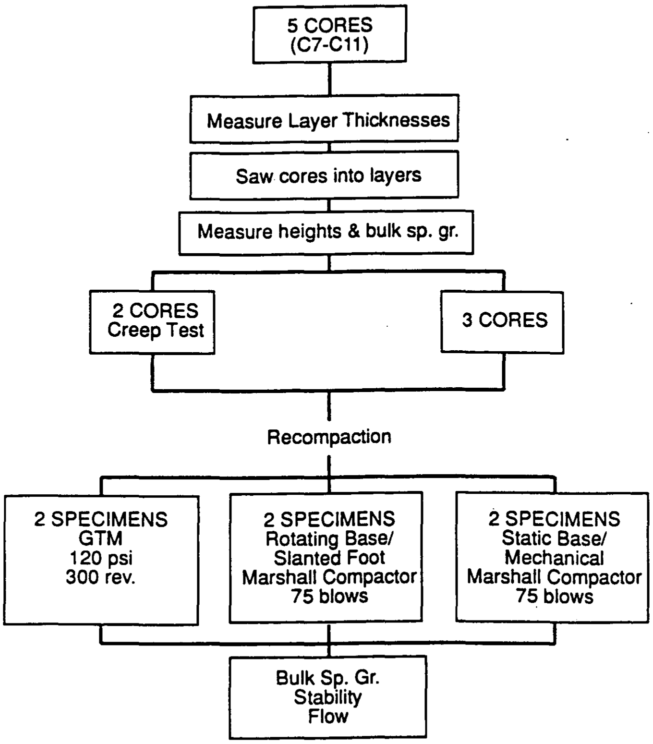

FIGURE 2 Flowchart for testing cores C7 through C11.

Measurements of Rut Depth

A transverse surface profile of the lane adjacent to Cores C7–C11 (Figure 1) was obtained using a profilograph device. Cores taken transversely across the pavement were used to help determine the amount of rutting in the top layer and the underlying layers. This was done by drawing a profile of the layers using the core layer thicknesses. The amount of rutting was determined for the top layer by subtracting the rut depth in the second layer from the rut depth at the surface. The rut depth in the second layer was determined by subtracting the rut depth in the third layer from the rut depth in the second layer.

PROJECT DETAILS AND TEST DATA

Project Location Details

It was planned to evaluate 35 sites. However, Site 21 was deleted by PennDOT, and there are no data for that site. The locations of the 34 project sites scattered across Pennsylvania are given elsewhere (*1*). The pavement condition rating was subjectively determined for each pavement as follows:

Maximum Rut Depth (in.)	*Age of Overlay (years)*	*Rating*
0–⅛	—	Excellent
⅛–¼	>3	Excellent
⅛–¼	≤3	Good
¼–⅜	>3	Good
¼–⅜	≤3	Fair
⅜–¾	>3	Fair
⅜–¾	≤3	Poor
>¾	—	Poor

The subjective rating proved to be fairly reasonable on subsequent rut depth/traffic load data analyses, which will be discussed later. Only 4 of the 34 projects did not have concrete pavements underneath the HMA overlay. The age of the HMA overlays as of 1990 summer ranged from 2 to 19 years. On the basis of the subjective rating of the 34 projects, 10 were excellent, 9 were good, 12 were fair, and 3 were poor.

Traffic and Climatological Data

Detailed traffic and climatological data for the projects are given elsewhere (*1*). The average daily traffic ranged from 5,925 to 41,000 vehicles per day, and the ESALs ranged from 440 to 9,288 per day. The total estimated traffic carried by the pavements in this study ranged from less than 1 million ESALs to more than 30 million ESALs. The average yearly temperature ranged from 8.6°C (47.6°F) to 12°C (53.7°F), which is a very narrow range.

Mix Design Data

Detailed mix design data obtained from the JMF of the wearing course (Layer 1) and the binder course (Layer 2) are given elsewhere (*1*). The data include asphalt content, gradation, mix design compactive effort, specimen specific gravity, theoretical maximum specific gravity, VTM, voids in the mineral aggregate (VMA), percent voids filled with asphalt (VFA), Marshall stability, and flow. An ID-2W mix (a dense-graded wearing course mix with 12.5-mm or ½-in. top size) was used in Layer 1 of most projects. Similarly, an ID-2 B (a dense-graded binder course mix with 25.4-mm or 1-in. top size) was used in Layer 2 of most projects. The average mix design data for the mixtures for Layers 1 and 2 are given in Table 1.

All mixes were designed using the Marshall method. The number of blows per face used for the Layer 1 mixtures was 50 for 24 projects, 65 for 3 projects (Pennsylvania Turnpike), and 75 for 7 projects. The number of blows per face for the Layer 2 mixtures was 50 for 21 projects and 75 for 7 projects, with no data being available for 6 projects. The average VTM of the Layer 1 mixtures is below the midpoint of the 3 to 5 percent range generally recommended for the mix design. The average VTM is less than 4.0 percent for the Layer 2 mixtures. Only 7 of the 34 projects had design VTM equal to or greater than 4.0 percent. The Layer 1 design stability values are generally very high, and the flow values are within the acceptable range of 6 to 16. The average Layer 2 design stability value is 2,318 lb. Although satisfactory, this is lower than that of the wearing courses. The average flow value is slightly higher than the wearing courses.

TABLE 1 Average Mix Design Data

	Layer 1		Layer 2	
	Average	Range	Average	Range
Asphalt Content	6.2	5.0 to 8.75	4.7	4.0 to 5.2
VTM or Air Voids, %	3.6	2.8 to 4.5	3.7	2.6 to 4.4
VMA, %	16.6	14.5 to 22.4	13.6	12.2 to 14.3
VFA, %	78.5	73.9 to 83.9	72.7	67.2 to 79.0
Stability, lbs.	2514	2019 to 3666	2318	1477 to 3100
Flow, 0.01 inches	10.9	8 to 15	11.6	9 to 14
Passing No. 8	42.6	35 to 50	28.3	19 to 30
Passing No. 200	4.6	3.0 to 6.0	4.3	2.5 to 5.0

Construction Data

Detailed project construction data on VTM, asphalt content, and the material passing 12.5-mm (½-in.), 2.36 (No. 8), and 75-μm (No. 200) sieves are given elsewhere (*1*). The statistical analysis of VTM data obtained at the time of construction in HMA pavement is as follows.

	Wearing Course	*Binder Course*
Number of projects	29	19
Mean VTM	5.79	4.75
Standard deviation (VTM)	1.01	1.32
95 percent confidence limits	3.8–7.8	2.1–7.4

The data indicate that the level of compaction in both layers was generally acceptable. Lower voids (about 1 percent) were achieved in the binder course than in the wearing course.

Longitudinal Core (C1–C5) Test Data

Mix Composition

The detailed test data are given elsewhere (*1*). Mix composition was determined by extracting core samples. Generally the asphalt content measured from the cores was deficient from the JMF asphalt content for both wearing and binder courses. The percentage of material passing the 2.36-mm (No. 8) sieve was also generally higher than the JMF values for both wearing and binder courses. As expected, these values are higher than those obtained on loose mixes at the time of construction because some degradation takes place under rolling, under subsequent traffic, and from coring and sawing operations. The percentage of minus 75 μm (No. 200) was also significantly higher than the JMF values for both courses.

VTM

The statistical analysis of VTM data obtained by testing cores C1 through C5 is as follows.

	Wearing Course	*Binder Course*
Number of projects	34	27
Mean VTM	3.17	3.02
Standard deviation (VTM)	1.54	1.38
95 percent confidence limits	0.0–7.4	0.3–5.9

The average VTM values in both courses are very low. According to past experience, HMA pavements approach the potential for rutting when the VTM is approximately 3 percent or less. Since these are average values, obviously there are many projects that have VTM less than 3 percent. The average mix design VTM values were 3.6 and 3.7 percent, respectively, for wearing and binder courses as reported earlier. Further examination of VTM data obtained on projects in service for 3 or more years (at the time of coring in 1989) indicates even lower values. The older projects have average VTM values of 2.61 and 2.85 percent, respectively, for wearing and binder courses. Thus, the VTM data indicate that the Pennsylvania HMA mixtures are compacted by traffic generally to a higher degree than by laboratory compaction. Therefore, the laboratory compaction effort needs to be increased.

Recovered Aggregate Properties

The summary of the recovered aggregate properties is as follows:

	Wearing		*Binder*	
	Average	*Range*	*Average*	*Range*
Coarse aggregate (%)	48	32–57	68	53–78
Crushed faces (%)	93	66–100	100	100
Fine aggregate (%)	52	43–68	32	22–47
Natural sand (%)	24	0–100	23	0–100

Transverse Core (C7–C11) Test Data

The following observations were made on the basis of the statistical analysis of the detailed data obtained from Cores C7–C11 and reported elsewhere (*1*).

1. Average VTM values of 3.75 and 3.83 percent, respectively, were obtained for wearing and binder courses. The average VTM values are higher than those obtained from cores C1 through C5 sampled longitudinally. This can be attributed to the location of cores—cores C1 through C5 were obtained in the inside wheel track (where most densification occurs), whereas cores C7 through C11 were obtained transversely across the pavement, including areas other than wheel tracks. Cores C7 through C11 were taken at a location where the most rutting had occurred. Previous work at NCAT (*2*) showed that rutting was related to low air voids. However, the low void content did not always occur exactly in the wheel paths. As a result the 20th percentile air void content (80 percent higher and 20 percent lower) from voids obtained across the pavement lane were used in correlations with rutting. The results indicated that the use of the 20th percentile air void content was reasonable when compared with the use of the average or minimum air void content.

The average 20th percentile VTM values are 3.01 and 3.10 percent for wearing and binder courses, respectively, and are very close to the average values obtained from cores C1 through C5. As discussed earlier in the case of test data from cores C1 through C5, these values of VTM are considered low and will increase the potential for rutting.

2. The average percentages of VTM obtained in recompacted specimens are as follows:

	Average VTM in Recompacted Specimens	
Compactor	*Wearing Course*	*Binder Course*
Gyratory	2.44	2.00
Marshall Rotating Base	1.74	1.96
Marshall Static Base	2.04	2.46

The Marshall compactor with rotating base and slanted foot gave the highest density (least VTM) for both wearing and binder courses and thus can be used to obtain near maximum potential compaction of mixes, which is likely to be achieved under 2 to 3 years' traffic. Surprisingly, the gyratory compactor gave the least density (lower than the conventional Marshall method using static base) for the wearing course. However, the gyratory compactor provided samples with higher density than the conventional static base mechanical Marshall compactor in the case of binder course mixes containing larger aggregates (25 to 38 mm or 1 to 1½ in. maximum size). This indicates that the gyratory compaction is more effective in densifying the mix when the maximum aggregate size is increased. On the basis of the preceding data it appears that the mechanical Marshall compactor with rotating base and slanted foot should be used for both wearing and binder course mixes to minimize the potential of overasphalting mixes designed for heavy-duty pavements and high-pressure truck tires.

3. Average gyratory shear index (GSI) values were 1.35 and 1.26 for wearing and binder courses, respectively. Whereas a value of 1.00 is considered ideal to prevent rutting, values up to 1.20 may be acceptable. Therefore, both average values are on the high side and indicate a high potential for rutting.

4. Average 60-min permanent deformation values (static unconfined creep test at 40°C or 104°F) for wearing and binder courses were observed to be close: 11.90×10^{-4} and 11.27×10^{-4} in./in., respectively. No reliable deformation threshold values are available in the literature. A stress level of 103.5 kPa (15 psi) was used in the creep test. The static unconfined creep test as used in this study did not indicate the potential for rutting.

Rut Measurement Data

Maximum surface rut depth at the worst location of all projects ranged from 1.0 mm (0.04 in.) to 40 mm (1.66 in.), averaging 10.9 mm (0.43 in.). The average rut depth in the wearing course is 2.5 mm (0.10 in.) greater than in the binder. On most projects, the thicknesses of wearing course and binder course were 38 mm (1.5 in.) and 51 mm (2 in.), respectively. There are several projects where the underlying layers contributed significantly to the total surface rut depth. The 15 poor to fair projects can grouped into three general categories as shown below. It appears that in a majority of cases the underlying layers (including the binder course) contributed to the surface rut depth.

Type	*No. of Project*
1. Projects in which the underlying layers contributed significantly (in addition to the wearing course) toward the total surface rut depth.	10
2. Projects in which the underlying layers were primarily responsible for the total surface rut depth.	2
3. Projects in which most rutting was contributed by the wearing course only.	3

STATISTICAL ANALYSIS OF DATA AND DISCUSSION OF RESULTS

Independent Variables

Five broad categories of 60 independent variables covering the mix design, construction, and postconstruction data for each pavement were selected to determine the effect these variables might have on rutting. The 60 variables are listed elsewhere (*1*). The data were analyzed using correlation analysis, linear regression analysis methods, and stepwise multiple variable analysis methods. The objective was to identify the independent variables that significantly affect rutting and to establish their threshold values, if possible. Rutting is a complex phenomenon. It is doubtful that any single independent variable could predict rutting reliably. In addition, within each layer one bad property (for example, excessive asphalt content) can nullify other good properties (such as 0 percent natural sand and 100 percent fractured face count). There are also numerous interactions between the properties. Therefore, very low correlation coefficients were obtained when only one independent variable at a time was examined (*1*).

The stepwise multiple variable analysis method appeared more promising in obtaining a reasonable correlation to the dependent variable. Two stepwise procedures were used to analyze the groups of independent variables. The dependent variable used is the average surface rut depth in inches divided by the square root of total traffic, as discussed later.

The two stepwise procedures used were the forward and backward methods. In the forward selection procedure, the single variable that is most correlated to the dependent variable in a step is added to the multiple regression equation until no variables remain that, when added to the model, reduce the deviations sum of squares at a 0.5 significance level. In the backward procedure, the single variable that is least correlated to the dependent variable in a step is deleted from the multiple regression equation. The procedure stops when all variables remaining in the model are significant at the 0.1 level. Only the data from the forward selection method will be discussed in this paper.

Dependent Variables

The dependent variable selected for analysis was rut depth. It is well established that traffic affects rutting in pavements. The total estimated traffic experienced by the pavements in this study ranged from less than 1 million ESALs to more than 30 million ESALs. By dividing the rut depth by some function of traffic, the pavements could be normalized to a rate of rutting that would allow, for example, two pavements with 12.7-mm (½-in.) ruts of differing age to be compared on the basis of this rate of rutting. The initial densification for a rutted pavement follows a direct relationship with traffic. However, after initial densification the rate of rutting decreases with an increase in traffic until a condition of plastic flow occurs and the rate of rutting again increases. Previous work by Brown and Cross (*2*) and Parker and Brown (*3*) has shown that expressing the rate of rutting as a function of the square root of total traffic better models pavement behavior when compared with other expressions for the rate of rutting.

Figure 3 is a histogram showing all sites with increasing rate of rutting. The sites have been labeled E (excellent), G (good), F (fair), or P (poor) on the basis of the subjective performance rating discussed earlier. A value of 0.00020 for rut depth in inches divided by the square root of ESALs generally divides E and G sites from F and P sites. Therefore, the value 0.0002 can reasonably be considered as a threshold above which

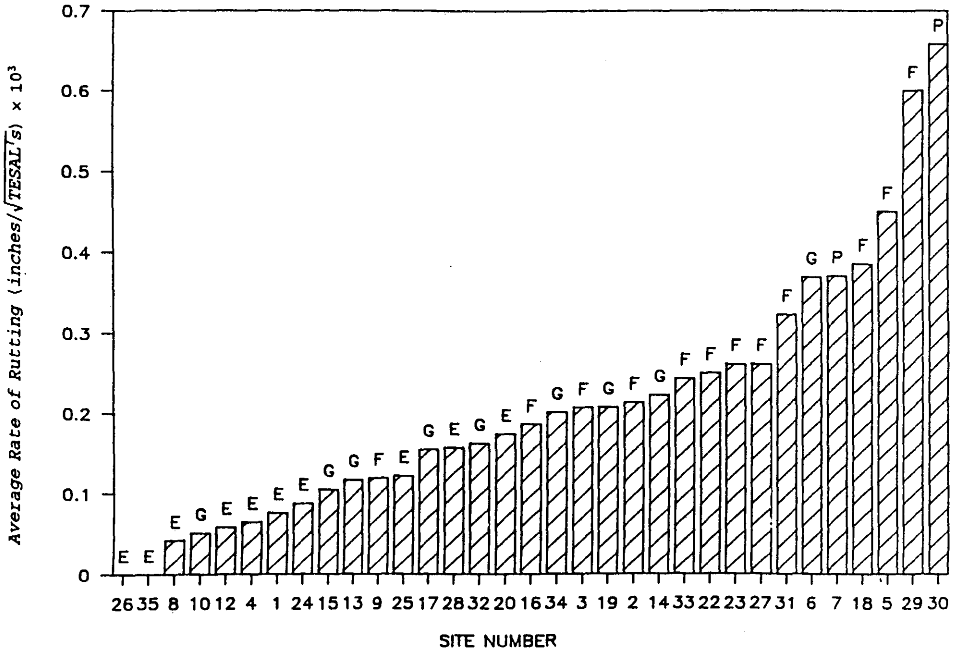

FIGURE 3 Pavement rutting and rate of rutting.

pavements are expected to develop undesirable amounts of rutting. This value also agrees with similar values established by Parker and Brown for Alabama highways (*3*).

Statistical Analysis

Mix Design Variables

The 10 mix design variables investigated included the mix composition (asphalt content and gradation) and Marshall mix design parameters such as VTM, VMA, number of blows per side, stability, flow, stability/flow, and Metcalf's bearing capacity calculated from stability and flow values (*4*). The results of the correlation analysis for the 10 mix design variables are given elsewhere (*1*). Generally, poor correlations were obtained. This is probably due to the difference between the mix "as designed" and the mix "as placed" in terms of both mix composition and compacted density. The in-place unit weights after traffic exceed the mix design unit weight, which indicates that the mix design compactive effort is inadequate. This could account for the poor correlations between mix design variables and rutting. Because of the change in mix composition, the recompacted mix properties were investigated to determine trends.

Table 2 gives the significant independent variables obtained from stepwise regression analysis using the forward selection procedure. However, the R-square values are considered low because of the difference between the mix "as designed" and the mix "as placed."

Construction Variables

These variables included data obtained at the time of construction such as mix composition (asphalt content and gradation) and VTM in as-constructed mat. According to stepwise regression analysis (Table 3), the percentages passing the 2.36-mm (No. 8) and 75-μm (No. 200) sieves, VTM, and the asphalt content (binder mix only) were selected as significant independent variables, although the R-square values are low.

Postconstruction Longitudinal Variables (Cores C1–C6)

The percentages of material passing the 2.36-mm (No. 8) and 75-μm (No. 200) sieves, the percentage of crushed particles in the coarse aggregate, the percentage of natural sand, average VTM, and the asphalt content were selected as the most significant independent variables (Table 4). There is a significant improvement in R-square values compared with those in mix design and construction variables.

TABLE 2 Summary of Stepwise Regression Analysis for Mix Design Variables

Step	Variable Entered	Number In	Partial R-square	Model R-square
	Wearing Mix (All Variables R-square = 0.33)			
1	Passing #8	1	0.2445	0.2445
2	# Blows	2	0.0280	0.2725
3	Stability	3	0.0190	0.2915
4	Flow	4	0.0124	0.3040
	Binder Mix (All Variables R-square = 0.43)			
1	Flow	1	0.1382	0.1382
2	Passing #200	2	0.0469	0.1852
3	VMA	3	0.0666	0.2517
4	Passing #8	4	0.0792	0.3308
5	% Asphalt Cement	5	0.0726	0.4035

TABLE 3 Summary of Stepwise Regression Analysis for Construction Variables

Step	Variable Entered	Number In	Partial R-square	Model R-square
	Wearing Mix (All Variables R-square = 0.34)			
1	Passing #8	1	0.2787	0.2787
2	Passing #200	2	0.0385	0.3172
3	VTM	3	0.0272	0.3444
	Binder Mix (All Variables R-square = 0.47)			
1	Passing #8	1	0.1895	0.1895
2	VTM	2	0.0788	0.2684
3	Passing #200	3	0.1678	0.4362
4	% AC	4	0.0346	0.4708

Postconstruction Transverse and Longitudinal Variables

The transverse variables (C7–C11 core test results) and the longitudinal variables (C1–C6 core test results) were combined to create a new data set. The new data set included the variables that could be performed during mix production quality control to determine whether a quality control test program using recompacted samples of the produced mix could predict rutting. The variables were divided into three groups for analysis on the basis of the recompactive method used. The three groups included GTM recompaction, static base Marshall recompaction, and rotating base Marshall recompaction. The variables selected were asphalt content, average in-place VTM, percent passing the 2.36-mm (No. 8) and 75-μm (No. 200) sieves, recovered asphalt penetration and viscosity, percent crushed particles, percent natural sand in the fine aggregate, creep, and the recompacted properties of stability, flow, stability/flow ratio, bearing capacity, VTM, and VMA. The stepwise regression analysis results using the three recompactive methods are similar (*1*). Table 5 gives the significant independent variables when the rotating base Marshall compactor was used for recompaction.

TABLE 4 Summary of Stepwise Regression Analysis for Postconstruction Longitudinal Variables

Step	Variable Entered	Number In	Partial R-square	Model R-square
	Wearing Mix (All Variables R-square = 0.55)			
1	Passing #8	1	0.4373	0.4373
2	Passing #200	2	0.0341	0.4714
3	Crushed Particles	3	0.0206	0.4920
4	% Natural Sand	4	0.0122	0.5042
5	Average VTM	5	0.0161	0.5203
6	%AC	6	0.0189	0.5392
	Binder Mix (All Variables R-square = 0.64)			
1	% AC	1	0.2435	0.2435
2	Passing #8	2	0.0873	0.3308
3	Crushed Particles	3	0.0811	0.4119
4	Average VTM	4	0.0857	0.4976
5	Viscosity	5	0.1008	0.5985
6	Passing #200	6	0.0369	0.6354

TABLE 5 Summary of Stepwise Regression Analysis for Rotating Base Recompacted Variables

Step	Variable Entered	Number In	Partial R-square	Model R-square
Wearing Mix (All Variables R-square = 0.73)				
1	Passing #8	1	0.4393	0.4393
2	Stability	2	0.1333	0.5726
3	Rotating VMA	3	0.0544	0.6270
4	Average VTM	4	0.0649	0.6919
5	% Natural Sand	5	0.0144	0.7063
6	Rotating VTM	6	0.0087	0.7151
Binder Mix (All Variables R-square = 0.93)				
1	Rotating VTM	1	0.3970	0.3970
2	Viscosity	2	0.1794	0.5764
3	Passing #8	3	0.0553	0.6317
4	Crushed Particles	4	0.0448	0.6765
5	Average VTM	5	0.0424	0.7189
6	Rotating VMA	6	0.0473	0.7662
7	Creep	7	0.0343	0.8005
8	Stability	8	0.0380	0.8385
9	Stability/Flow	9	0.0617	0.9002
10	Penetration	10	0.0160	0.9162
11	% Natural Sand	11	0.0130	0.9292

Rutting Model

The preceding analyses indicate that many variables contribute to rutting and that no one variable adequately predicts rut depths. Many of the variables used, such as recovered penetration and viscosity, contribute to rutting. However, they cannot be controlled or predicted during design and construction. A meaningful model to predict rutting would contain variables that both significantly contribute to the model and can be controlled during design and construction. Eight variables were selected to represent mix properties that are controllable during design and construction. The mix design variables were not used because they were not representative of the mix "as placed." These eight variables are the 20th percentile VTM from cores C7–C11 to represent the mix design VTM; the VMA calculated from recompacted samples to represent mix design VMA; the percent passing the 12.5-mm (½-in.), 2.36-mm (No. 8), and 75-μm (No. 200) sieves and the percent crushed faces from the in-place cores (C1–C5); the recompacted flow to represent the mix design flow; and the recompacted mix stability. Two models for each mix type, wearing and binder, were developed for each of the three compaction methods (*1*). Only the rotating base Marshall model will be discussed here.

Rotating Base Marshall Model

The eight selected variables for predicting rutting have an R-square of 0.38 for the wearing mix and 0.49 for the binder mix. The stepwise procedure selected all variables as significant except recompacted flow for the wearing mix with an R-square of 0.37. The model is shown in Figure 4. For the

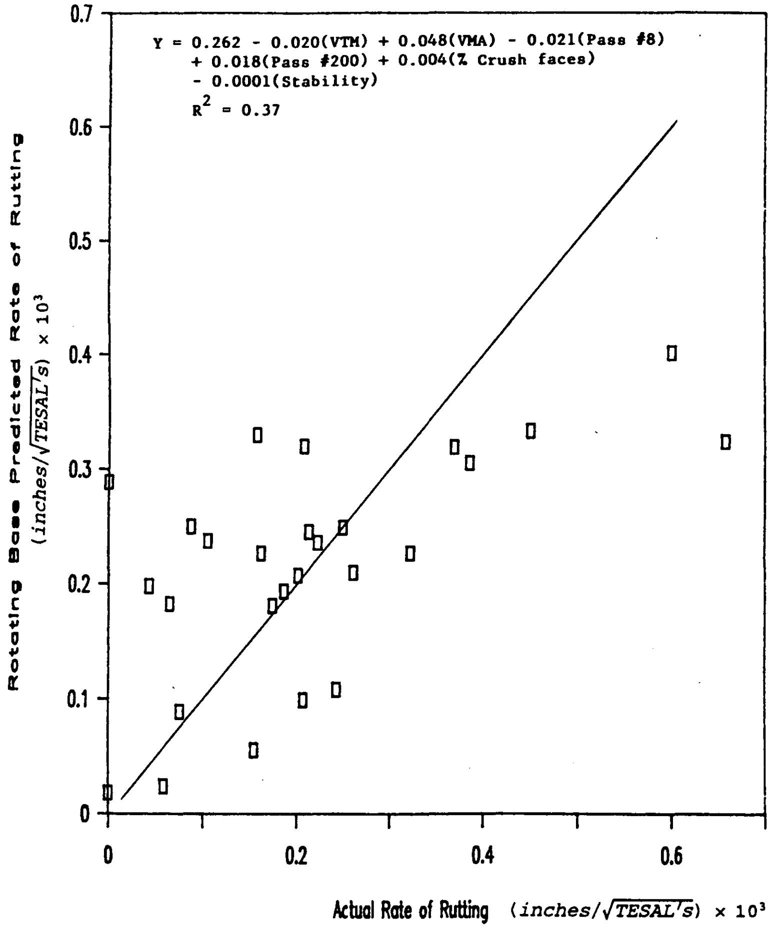

FIGURE 4 Rate of rutting model for rotating base Marshall compaction (wearing course mix).

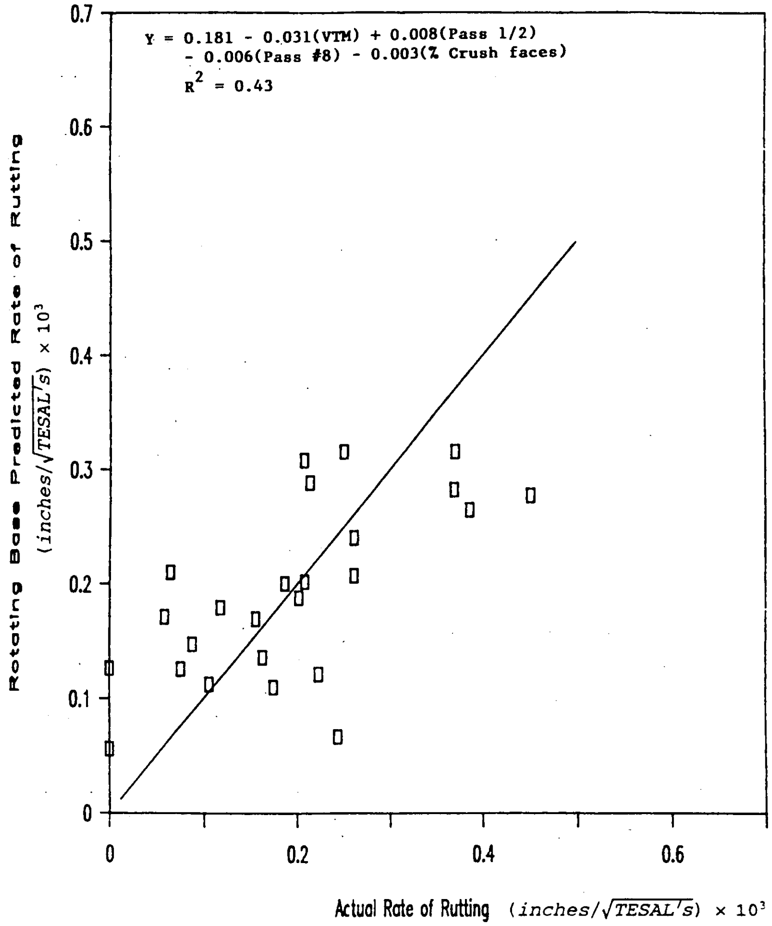

FIGURE 5 Rate of rutting model for rotating base Marshall compaction (binder course mix).

binder mix the 20th percentile VTM, the percent crushed faces, and the percent passing the 12.5-mm (½-in.) and the 2.36-mm (No. 8) sieves contributed significantly with an R-square of 0.43 as shown in Figure 5.

Heavy-Duty Specifications

As mentioned earlier, 7 of the 34 projects evaluated were constructed using the heavy-duty specifications implemented by PennDOT in 1987. The seven projects were in service for only 2 to 3 years at the time of this evaluation. Four of the seven heavy-duty pavements were rated good to excellent. The remaining three pavements rated poor to fair were designed with low mix design VTM (less than 4 percent). Maximum mix design VTM of 4.0 percent was incorporated in the specification later. The average rate of rutting for all seven pavements is 0.00010 in. per square root ESALS, and 0.00005 when the latter three are excluded. Both of these values are well below the threshold value of 0.00020 determined earlier. Therefore, it appears that the current PennDOT heavy-duty specifications have minimized the rutting problem.

Summary

Obviously, rutting is a complex phenomenon, as evidenced by the many independent variables selected by the stepwise procedure as significantly contributing to rutting. Each selected variable must be considered in designing the HMA mix and controlling HMA construction quality. Ideally, a simple, end-result test method capable of determining rutting potential is needed that can be used to design the HMA mix in the laboratory and control its quality on a daily basis in the field. Until such a test method is available, it is prudent to minimize the rutting problem by using specifications for mix composition, mix design, and construction quality control that are based on significant independent variables and their respective recommended values.

THRESHOLD ANALYSIS

Threshold values were identified for mix design variables and postconstruction variables (*1*). The various threshold values were determined for the preceding parameters by examining plots of the percent fair to poor pavements occurring at greater than or less than a given value of that parameter. A change in the slope of the line indicates an increase or decrease in the occurrence of fair to poor pavements, giving a threshold value. If a change in slope was not very apparent, the values corresponding to about 10 percent fair/poor sites were considered. Threshold values identified for in-place VTM (at the time of coring), percent natural sand in the fine aggregate, and GSI only will be discussed here. Figure 6 shows the per-

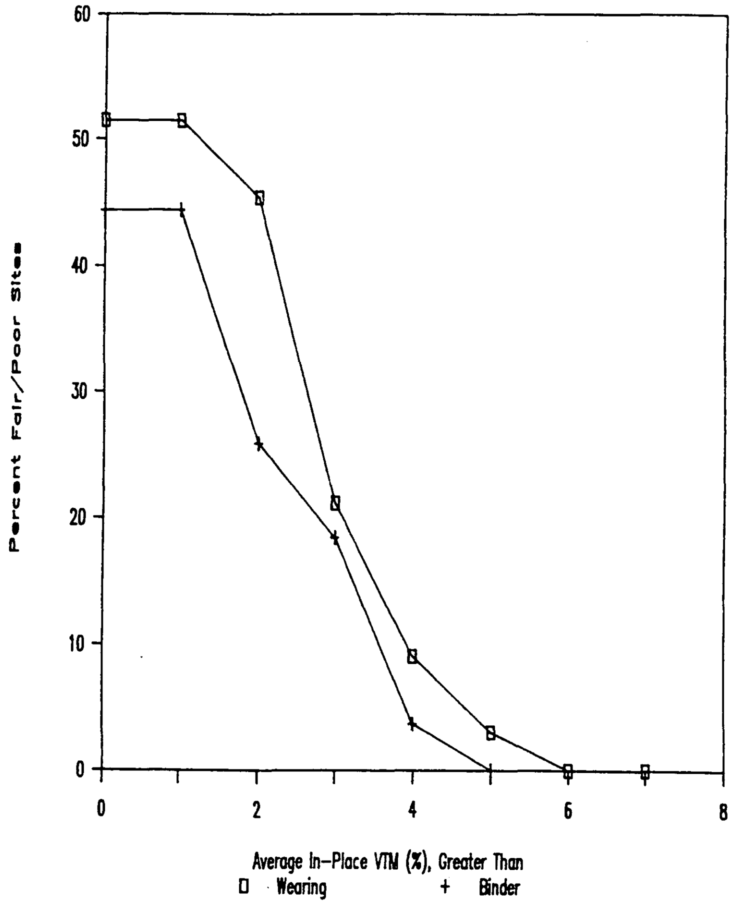

FIGURE 6 Average in-place VTM versus percent fair and poor pavements.

centage of pavements rated fair to poor at greater than a given air void content versus rutting for the wearing and binder mixes. The plot shows a change in the slope of the line at 3.0 percent VTM for the wearing mixes and 2.0 percent VTM for the binder mixes. Below these threshold values, the occurrence of fair to poor pavements increased.

Figure 7 shows the relationship between the percent natural sand in the fine aggregate and the percent fair to poor pavements. It appears that mixes with less than 20 percent natural sand in the fine aggregate contained fewer fair to poor pavements than mixes with more than 20 percent natural sand in the fine aggregate. Ten pavements had no natural sand in either wearing or binder course mixes. Of these 10 pavements, 8 were good to excellent and 2 were fair in performance.

Similarly, a GSI threshold plot showed a significant increase in the percentage of fair to poor pavements when the GSI exceeded 1.2 for both wearing mixes and binder mixes. Average GSI values of 1.35 and 1.26 for wearing and binder courses, respectively, obtained in this study are on the high side and indicate potential for rutting.

RECOMMENDATIONS

The following recommendations were made to improve and optimize the resistance of PennDOT HMA mixes on heavy-duty pavements.

Materials

1. Coarse aggregate retained on the 4.75-mm (No. 4) sieve should continue to have at least 85 percent of particles with two or more fractured faces for wearing and binder courses.
2. Fine aggregate should continue to have at least 75 percent crushed sand in the fine aggregate for both wearing and binder courses. Encourage use of 100 percent crushed sand if possible.

Mix Design

1. Use 75 blows per side compactive effort using a rotating base/slanted foot Marshall compactor. This will minimize the potential overasphalting of mixes designed for heavy-duty pavements and high-pressure truck tires.
2. Design mixes with at least 4.0 percent air voids.

Mix Production Quality Control

1. The mixes "as placed" were generally finer than mixes "as designed." Better mix gradation control is necessary during production.
2. Air void content in laboratory-compacted samples of "produced mix" is more important than that of the "designed

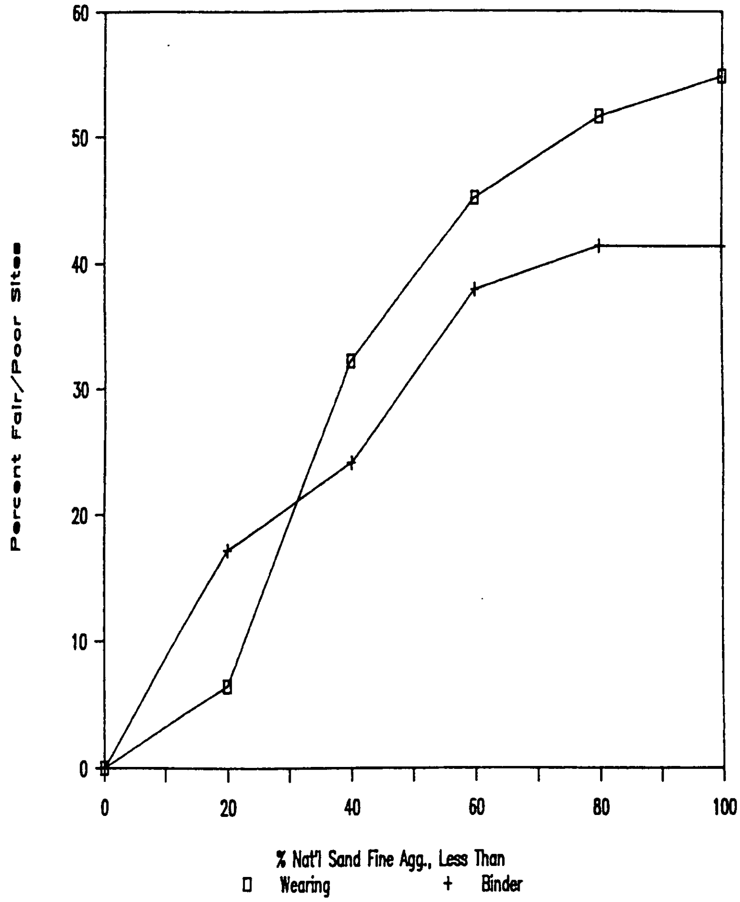

FIGURE 7 Percent natural sand in fine aggregate versus percent fair and poor pavements.

mix." Air void content should not be allowed to fall below 3.0 percent.

ACKNOWLEDGMENT

This research was sponsored by PennDOT in cooperation with FHWA.

REFERENCES

1. P. S. Kandhal, S. A. Cross, and E. R. Brown. *Evaluation of Bituminous Pavements for High Pressure Truck Tires.* Report FHWA-PA-90-008-87-01. Pennsylvania Department of Transportation, 1990.
2. E. R. Brown and S. A. Cross. A Study of In-Place Rutting of Asphalt Pavements. *Proc., Association of Asphalt Paving Technologists,* Vol. 58, 1988.
3. F. Parker and E. R. Brown. *A Study of Rutting of Alabama Asphalt Pavements.* Final Report, Project ST 2019-9. Alabama Highway Department, 1990.
4. C. T. Metcalf. Use of Marshall Stability Test in Asphalt Paving Mix Design. In *Highway Research Board Bulletin 234,* HRB, National Research Council, Washington, D.C., 1959.
