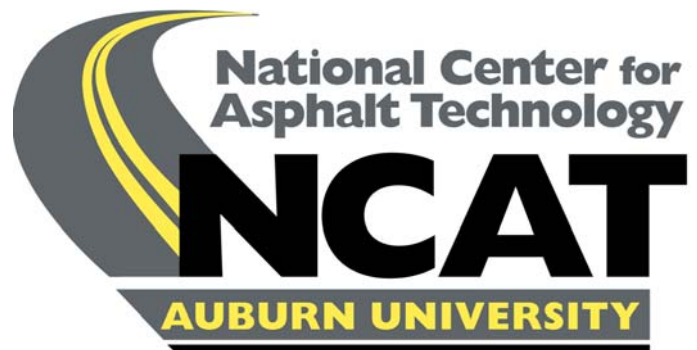# HEAVY DUTY ASPHALT PAVEMENTS IN PENNSYLVANIA: AN EVALUATION FOR RUTTING

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ABSTRACT

Thirty-four heavy duty asphalt pavements encompassing poor to excellent performance in terms of rutting were evaluated in this study. The objective was to identify the pavement properties (materials, mixture design, construction and post construction) which typify good and bad performing pavements.

Eleven pavement cores were obtained from each pavement to determine in-place voids in the total mix (VTM), mix composition, coarse aggregate fractured face count, fine aggregate particle shape & texture, and recovered asphalt cement properties. The mix from the pavement cores was heated and recompacted using three compactors: gyratory testing machine (GTM), rotating base/slanted foot mechanical Marshall compactor, and static base conventional mechanical Marshall compactor, All project data such as job-mix formula (JMF), construction data, and traffic data were obtained. Rut depths were measured on each project using a profilograph device.

Some sixty independent variables covering the mix design, construction, and post construction for each pavement were selected to determine their effect on the rut depth (dependent variable). The extensive data was 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 (PennDOT) 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) utilize 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."

HEAVY DUTY ASPHALT PAVEMENTS IN PENNSYLVANIA: AN EVALUATION FOR RUTTING

Prithvi S. Kandhal, Stephen A. Cross, and E. Ray Brown

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/or increased 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) first major asphalt pavement rutting was experienced on Interstate 70 in Washington County during early summer of 1986. Additional cases of rutting have occurred since that time. 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: (a) use of larger size (38mm or 1 1/2 inches) aggregate in binder and base courses, (b) use of coarse aggregate with at least 85 percent two or more fractured faces, (c) use of at least 75 percent manufactured sand in the fine aggregate, and (d) use of 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 post construction) which 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/or tire pressures.

DATA COLLECTION, SAMPLING AND TESTING PLAN

Thirty-four (34) heavy duty pavements encompassing poor to excellent performance in terms of rutting were identified by PennDOT. All interstate highways, and highways carrying more than 20,000 ADT (average daily traffic) 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 was collected for all projects:
1. Average climatic conditions.
2. Average daily traffic (ADT), percent trucks, and 8,172 kg (18-kip) equivalent single axle loads (ESAL) per day.
3. Details of underlying pavement structure and overlay.
4. Job-mix formula (JMF) including the Marshall design data.
5. Construction data such as mix composition, Marshall test data and field compaction.

This extensive data is contained in a PennDOT report prepared by Kandhal, Cross and Brown (*l*).

Sampling and Testing Plan

Eleven 152.4mm (6-inch) diameter cores were obtained during spring of 1989 from a <u>representative</u> one lane mile segment (travel lane) of each project (Figure 1). Five cores numbered Cl -C5 were obtained at random locations longitudinally from the inside wheel track of this segment. These five cores from each project (total 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).
6. Fine aggregate - particle shape and texture (determined in terms of percent void content using the National Aggregate Association procedure given in Ref. 1).
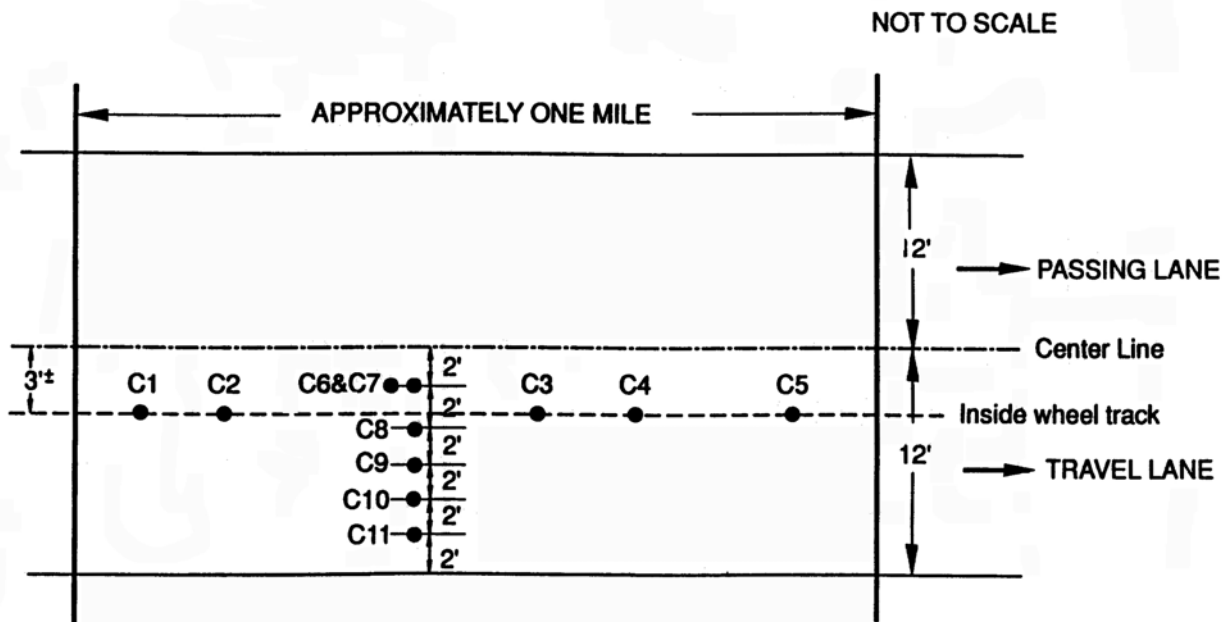

Figure 1. Core Sampling Plan

Five additional 152.4mm (6-inch) diameter cores (C7-C11) were obtained across the pavement, two feet 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 (2 cores).
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-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).
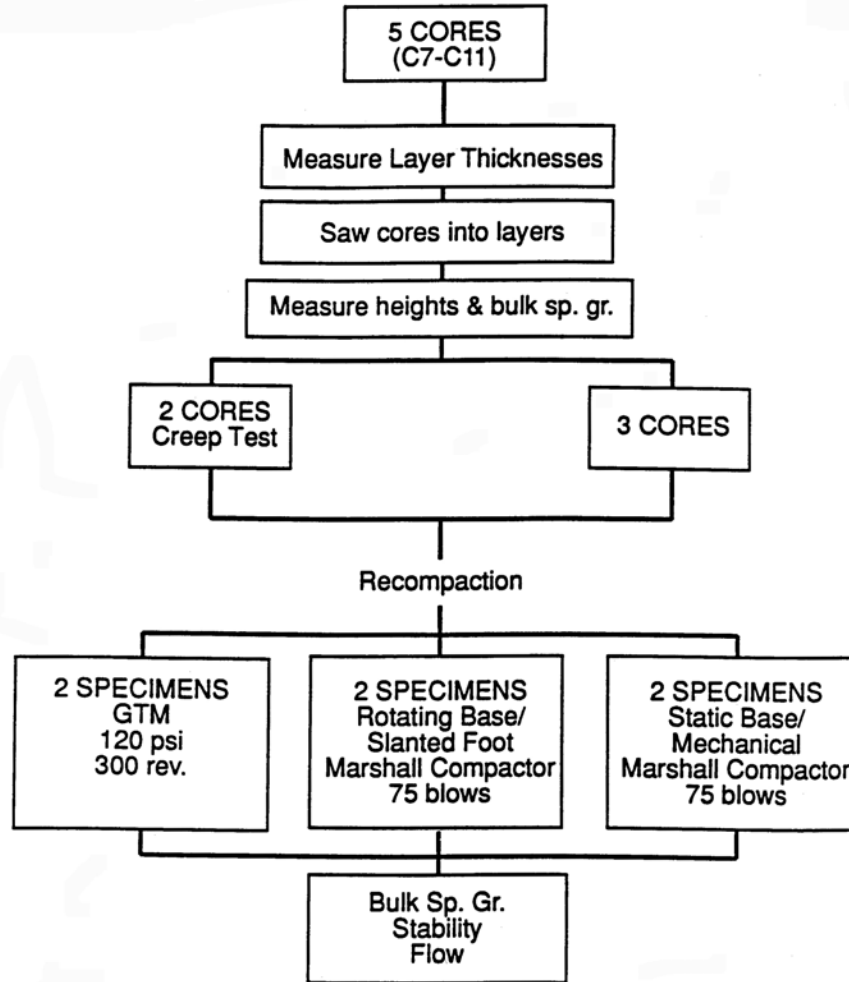
Figure 2. Flow Chart for Testing Cores C7-C11

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 layer(s). 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 No. 21 was deleted by PennDOT and, therefore, there is no data for this site. The locations of the 34 project sites scattered across Pennsylvania are given in Reference 1. The pavement condition rating was subjectively determined for each pavement as follows.

Max, Rut Depth (inch)	Age of the Overlay, Years	Rating
0-1/8	---	Excellent (E)
1/8-1/4	>3	Excellent (E)
1/8-1/4	#3	Good (G)
1/4-3/8	>3	Good (G)
1/4-3/8	#3	Fair (F)
3/8-3/4	>3	Fair (F)
3/8-3/4	#3	Poor (P)
>3/4	---	Poor (P)

The subjective rating proved to be fairly reasonable on subsequent rut depth/traffic load data analyses which will be discussed later. Only four 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 two to 19 years. Based on the subjective rating of the 34 projects, 10 were excellent, 9 were good, 12 were fair, and three were poor.

Traffic and Climatological Data

Reference *1* contains detailed traffic and climatological data for the projects. The average daily traffic ranged from 5,925 to 41,000 vehicles per day, and the ESALs ranged from 440 to 9288 per day. The total estimated traffic carried by the pavements in this study ranged from less than one million ESALs to over 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 job-mix formula (JMF) of the wearing course (Layer 1) and the binder course (Layer 2) is given in Reference *1*. The data includes asphalt content, gradation, mix design compactive effort, specimen specific gravity, theoretical maximum specific gravity, VTM, VMA (voids in the mineral aggregate), % VFA (voids filled with asphalt), Marshall stability and flow. An ID-2W mix (a dense graded wearing course mix with 12.5mm or 1/2 inch top size) was used in Layer 1 of most projects. Similarly, an ID-2 B (a dense graded binder course mix with 25.4mm or 1 inch top size) was used in Layer 2 of most projects. The average mix design data for the Layer 1 and 2 mixtures is given in Table 1.

All mixes were designed using the Marshall method. The number of blows/face used for the Layer 1 mixtures was 50 for 24 projects, 65 for three projects (Pennsylvania Turnpike), and 75 for seven projects. The number of blows/face for the Layer 2 mixtures was 50 for 21 projects, and 75 for seven projects with no data being available for six projects. The average VTM of the Layer 1 mixtures is below the midpoint of the 3-5 percent range generally recommended for the mix design. The average VTM is less than 4.0 percent for the Layer 2 mixtures. Only seven of the 34 projects had design VTM equal to or greater than 4 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 2318 lbs, although satisfactory, 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 12.5mm (1/2 inch), 2.36 (No. 8), and 75**:** m (No. 200) sieves, is given in Reference 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% Confidence Limits	3.8 - 7.8	2.1 - 7.4

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

Longitudinal Core (Cl - C5) Test Data

Mix Composition
Again, the detailed test data is given in Reference 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 2.36mm (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**:** m (No. 200) was also significantly higher than the JMF values for both courses.

Voids in Total Mix WTM)
The statistical analysis of VTM data obtained by testing cores Cl 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% 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 which 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 which were in service for three or more years (at the time of coring in 1989) reveals even lower values. These older projects have average VTM values of 2.61 and 2.85 percent, respectively for wearing and binder courses. Thus, the VTM data indicates that the Pennsylvania HMA mixtures are compacted by traffic generally to a higher degree than that provided 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 to 57	68	53 to 78
% Crushed Faces	93	66 to 100	100	100
% Fine Aggregate	52	43 to 68	32	22 to 47
% Natural Sand	24	0 to 100	23	0 to 100

Transverse Core (C7-C11) Test Data

The following observations were made based on the statistical analysis of the detailed data obtained from Cores C7-C11 and reported in Reference *1*.

1. Average VTM values of 3.75 and 3.83 percent, respectively, were obtained for wearing and binder courses. These average VTM values are higher than those obtained from cores Cl 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 utilized in correlations with rutting. The results indicated that the use of the 20th percentile air void content was reasonable when compared to the use of the average or minimum air void content.

   The average 20th percentile VTM values are 3.01 and 3.10 percent, respectively, for wearing and binder courses, and are very close to the average values obtained from cores Cl 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:

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

It is significant to note that 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 two-three 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 (25-38mm or 1-1 1/2 inches maximum size). This indicates that the gyratory compaction is more effective in densifying the mix when the maximum aggregate size is increased. Based on 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 over-asphalting mixes designed for heavy duty pavements and high pressure truck tires.

3. Average GSI (gyratory shear index) 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 l.20 may be acceptable. Therefore, both average values are on the high side and indicate a high potential for rutting.

4. Average 60-minute 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 and 11.27 x 10^{-4} inch/inch, 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 1.0mm or 0.04 inch to 40mm or 1.66 inches, averaging 10.9mm (0.43 inch). The average rut depth in the wearing course is 2.5mm (0.10 inch) greater than in the binder. On most projects, the thicknesses of wearing course and binder course were 38mm (1.5 inches) and 51mm (2 inches), respectively. There are several projects where the underlying layers contributed significantly to the total surface rut depth. The 15 poor to fair projects can be broken down 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 10 the wearing course) towards 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 where most rutting was contributed by the   3
     wearing course only.

STATISTICAL ANALYSIS OF DATA AND DISCUSSION OF RESULTS

Independent Variables

Five broad categories of sixty (60) independent variables covering the mix design, construction, and post construction data for each pavement, were selected to determine the effect these variables might have on rutting. All 60 variables are listed in Reference *1*. The data was analyzed using correlation analysis, linear regression analysis methods and stepwise multiple variable analysis methods. The objective was to identify the independent variables which significantly affect rutting, and to establish their threshold values, if possible. Rutting is a complex phenomenon and it is doubtful that any one independent variable alone could predict rutting with any degree of confidence. Additionally, 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 utilized to analyze the groups of independent variables. The dependent variable utilized is the average surface rut depth in inches divided by the square root of total traffic, as discussed later.

The two stepwise procedures utilized were the forward and backward methods. In the forward selection procedure, the single variable which 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 which 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. Due to space limitations, the data from the forward selection method only will be discussed in this paper.

Dependent Variables

The dependent variable selected for analysis was rut depth. It is a well established fact 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 over 30 million ESALs. By dividing the rut depth by some function of traffic the pavements could be normalized to a rate of rutting which would allow, for example, two pavements with 12.7mm (1/2 inch) ruts of differing age to be compared based on 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 to 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) and P (poor) based on the subjective performance rating discussed earlier. It can be seen that 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, this value of

0.0002 can reasonably be considered as a threshold value above which 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*).
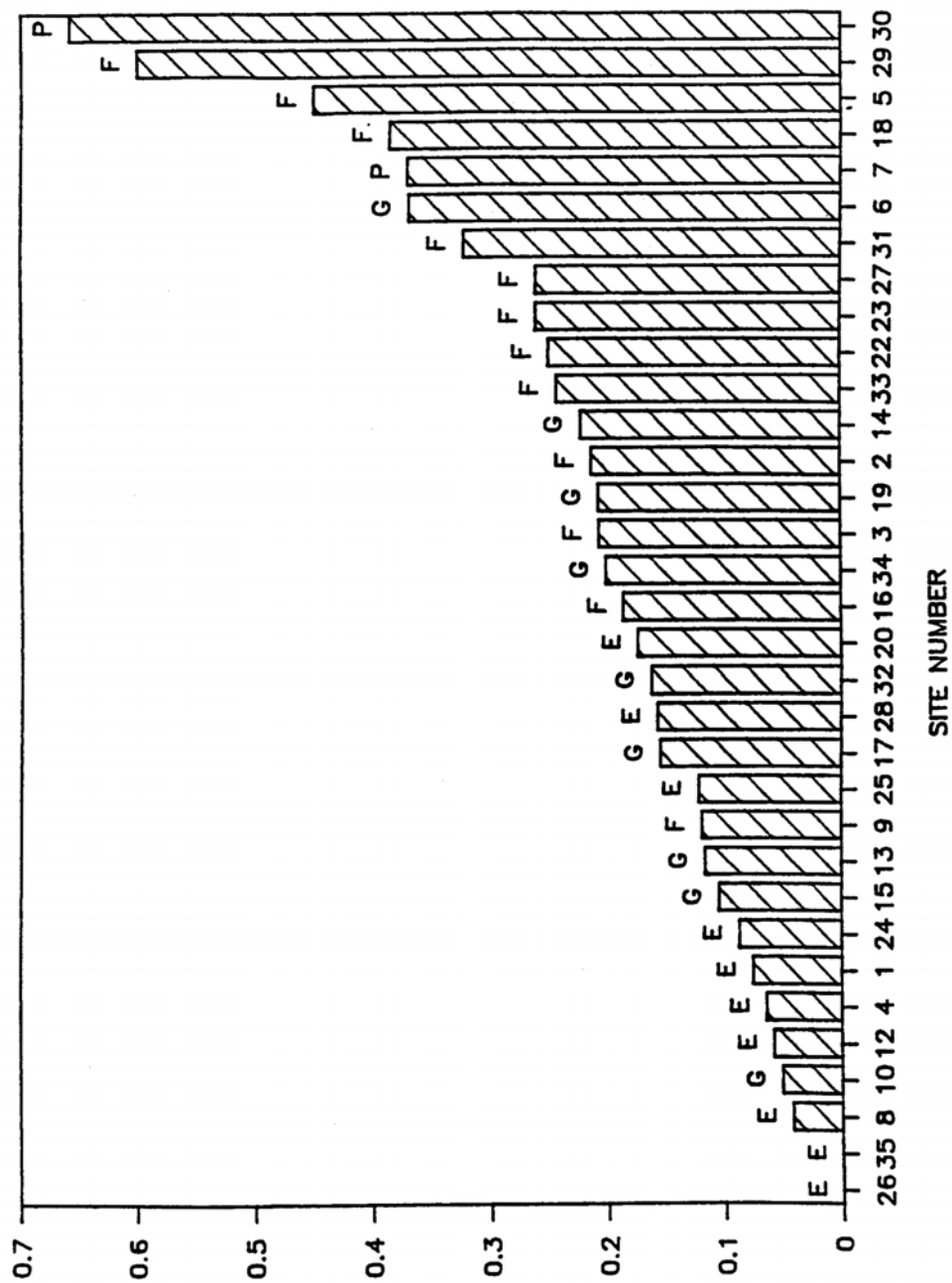
Figure 3. Histogram of Pavement Rating and Rate of Rutting

Statistical Analysis

Mix Design Variables

The ten 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 ten mix design variables are given in Reference *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 not only mix composition but also 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 and 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 due to the difference between the mix "as designed" and the mix "as placed."

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

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 2.36mm (No. 8) and 75**:** m (No. 200) sieves, VTM, and the asphalt content (binder mix only) were selected as significant independent variables, although the R-square values are low.

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

Post Construction Longitudinal Variables (Cores C1-C6)

The percentages of material passing 2.36mm (No. 8) and 75**:** m (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 to those in mix design and construction variables.

Table 4. Summary of Stepwise Regression Analysis For Post Construction 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

Post Construction 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 if a quality control test program utilizing recompacted samples of the produced mix could predict rutting. The variables were divided into three groups for analysis based on the recompactive method utilized. These three groups included gyratory testing machine (GTM) recompaction, static base Marshall recompaction, and rotating base Marshall recompaction. The variables selected were asphalt content, average in-place VTM, percent passing the 2.36mm (No. 8) and 75**:** m (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 utilizing the three recompactive methods are quite similar (*1*). Table 5 shows the significant independent variables when the rotating base Marshall compactor was used for recompaction.

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 show that many variables contribute to rutting and that no one variable adequately predicts rut depths. Many of the variables utilized, such as recovered penetration and viscosity, contribute to rutting. However, they can not 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/or construction. Eight variables were selected to represent mix properties that are controllable during design and construction. The mix design variables were not utilized 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 12.5mm (1/2 inch), 2.36mm (No. 8) and 75**:** m (No. 200) sieves and the percent crushed faces from the in-place cores (Cl -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 binder mix the 20th percentile VTM, the percent crushed faces and the percent passing the 12.5mm (1/2 inch) and the 2.36mm (No. 8) sieves contributed significantly with an R-square of 0.43 as shown in Figure 5.

Heavy Duty Specifications
As mentioned earlier, seven of the 34 projects evaluated were constructed using the heavy duty specifications implemented by PennDOT in 1987. These 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 inches 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 contributes significantly to rutting and, therefore, must be considered while designing the HMA mix and controlling HMA construction quality. Ideally, a simple, end-result test method capable of determining rutting potential is needed which 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 use specifications for mix composition, mix design, and construction quality control, which are based on significant independent variables and their respective recommended values, to minimize the rutting problem.
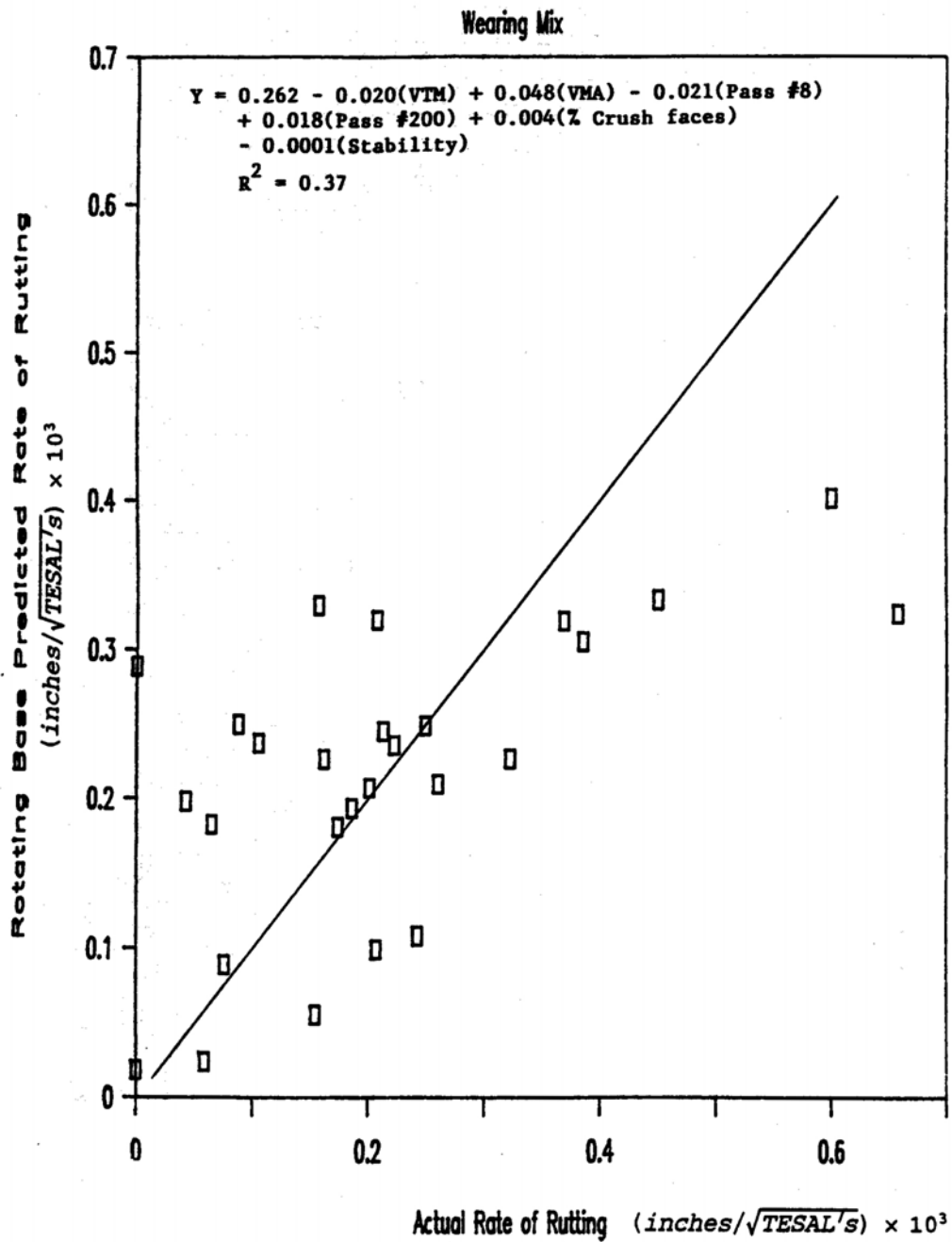
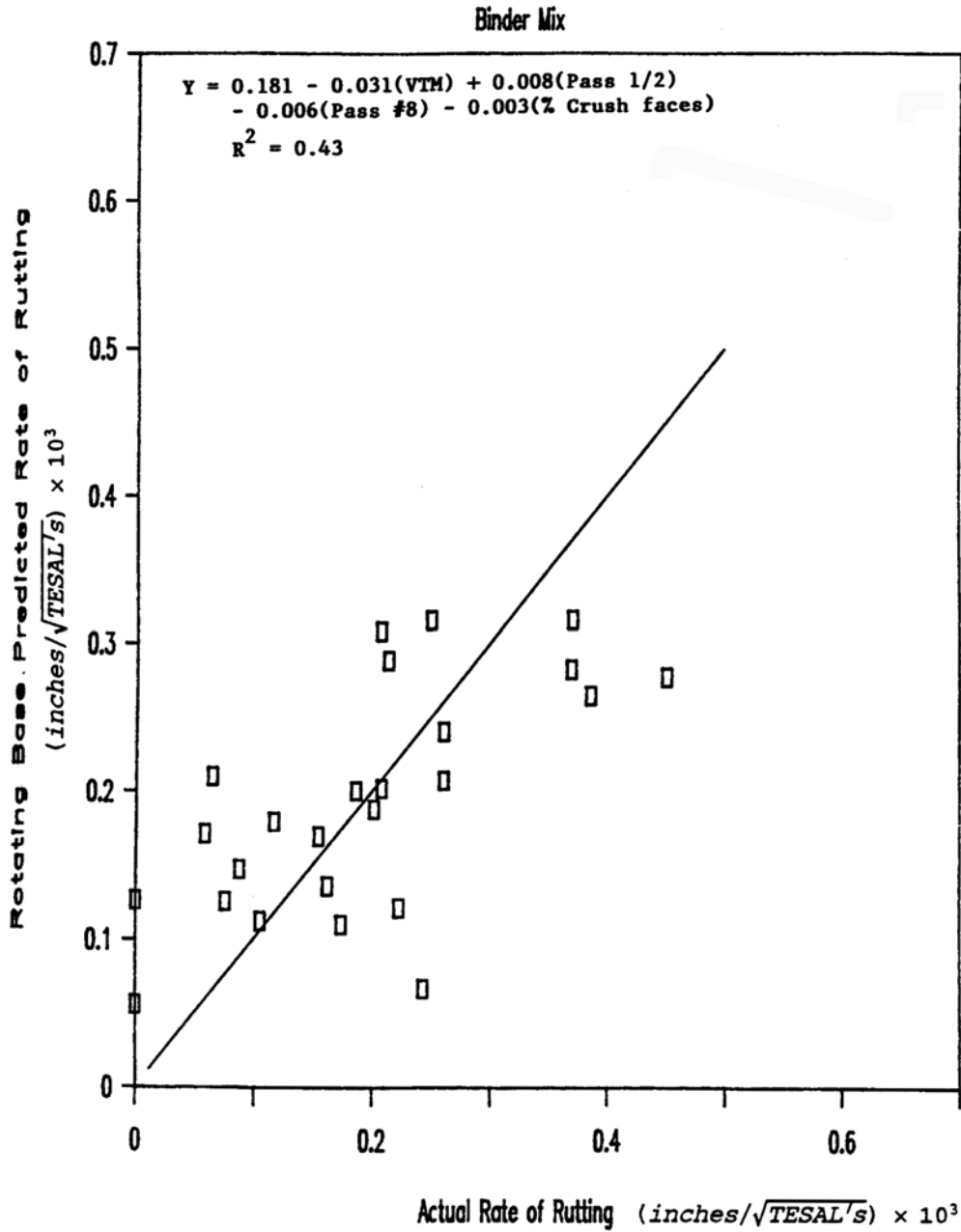**Figure 4. Rate of Rutting Model for Rotating Base Marshall Compaction (Wearing Course Mix)**

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Binder Mix

$$Y = 0.181 - 0.031(VTM) + 0.008(Pass\ 1/2)$$
$$- 0.006(Pass\ \#8) - 0.003(\%\ Crush\ faces)$$
$$R^2 = 0.43$$

Rotating Base Predicted Rate of Rutting $(inches/\sqrt{TESAL's}) \times 10^3$

Actual Rate of Rutting $(inches/\sqrt{TESAL's}) \times 10^3$

Figure 5. Rate of Rutting Model for Rotating Base Marshall Compaction (Binder Course Mix)

THRESHOLD ANALYSIS

Threshold values were identified for mix design variables and post construction variables (*1*). The various threshold values were determined for the above 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 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, then 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 percent 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 over 20 percent natural sand in the fine aggregate. Ten pavements had no natural sand in both wearing and binder course mixes. Of these ten pavements, eight were good to excellent and two 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 4.75 mm (No. 4) sieve should continue to have at least 85 percent of particles with 2 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. Utilize 75 blows per side compactive effort using a rotating base/slanted foot Marshall compactor. This will minimize the potential over-asphalting 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 mix." Air void content should not be allowed to fall below 3.0 percent.
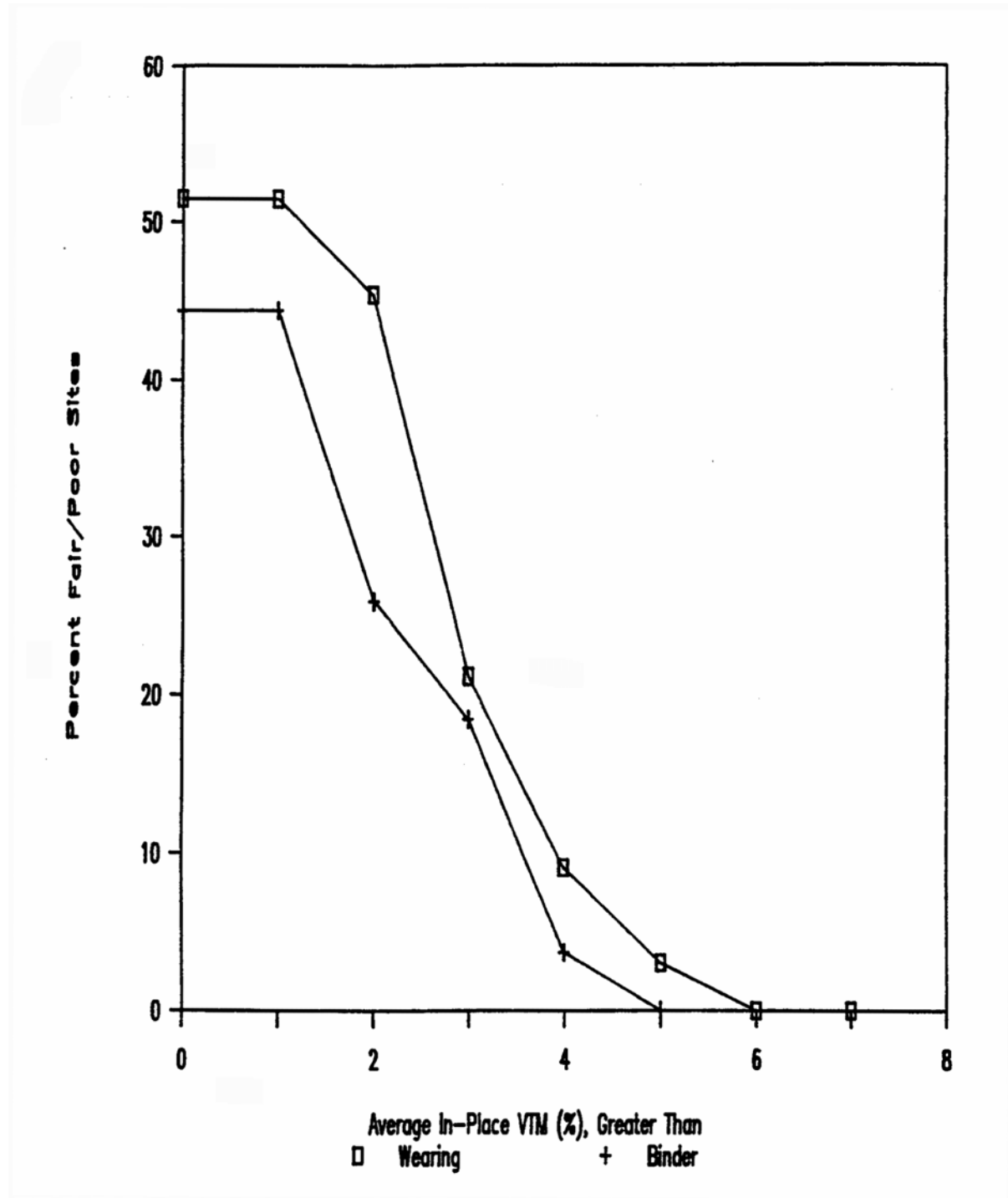
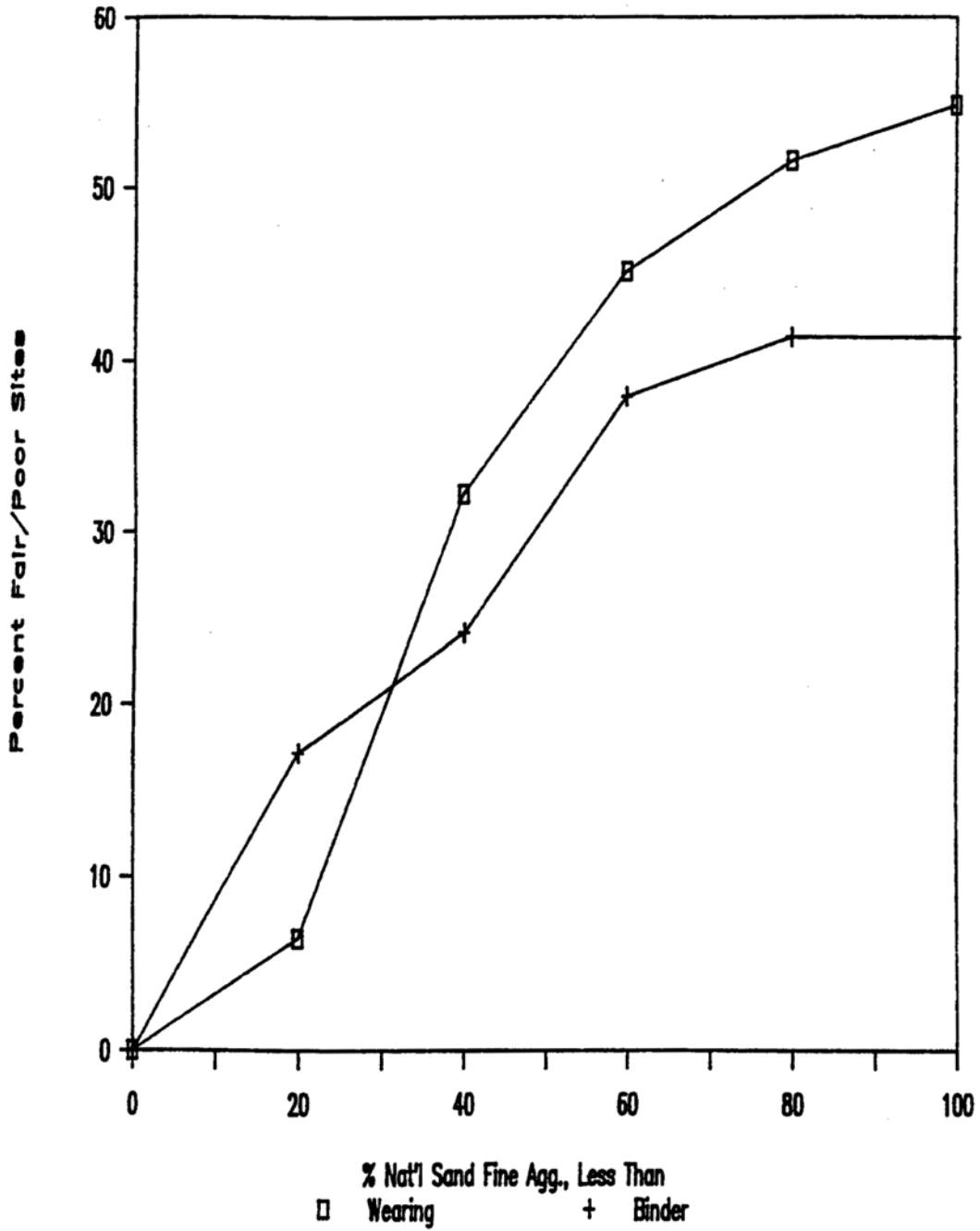**Figure 6. Average In-Place VTM vs. Percent Fair and Poor Pavements**

Figure 7. Percent Natural Sand in Fine Aggregate vs. Percent Fair and Poor Pavements

ACKNOWLEDGMENT

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