NCAT Report 92-05

A NATIONAL STUDY OF RUTTING IN HOT MIX (HMA) PAVEMENTS

By

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February 1992

Paper presented at the 1992 Annual Meeting of the Association of Asphalt Paving Technologists held in Charleston, SC (February 1992)

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DISCLAIMER

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INTRODUCTION

Background

In recent years several states have experienced an increase in the amount and severity of permanent deformation in their hot mix asphalt (HMA) pavements. This increase in permanent deformation, or rutting, has been attributed to the increase in truck tire pressures, axle loads, and volume of traffic.

The current 1986 AASHTO Guide for Design of Pavement Structures is based on 18,000 pound axle loads and tire contact pressures of 75 to 80 psi. Recent studies (*1*, *2*) have shown that truck tire inflation pressures have increased substantially above the 70 to 80 psi. Hudson and Seed (*3*) have shown truck tire pressures to be as high as 140 psi. In the past the quality of the HMA near the surface was sufficient to withstand the stresses induced by the lower tire pressures. However, the increase in tire pressures means that the HMA nearest the pavement surface is under increasingly high stresses and is more susceptible to rutting. The best technology must be used in designing and constructing these mixtures to insure that they resist the increased tire pressures.

Concern for rutting and high truck tire pressures led to a National Symposium on the subject in 1987 (*4*). The conclusions drawn from this symposium were that the higher truck tire pressures and increased truck weights have led to an increase in rutting. The participants also believed that rutting could be minimized with more attention to the selection of materials, mix design and construction.

Several field studies have been undertaken in the last 10 years to try to identify material properties and or design parameters that relate to rutting. Several of these studies were large in scope and involved extensive field sampling and lab testing. Ford (*5*) in Arkansas and Kandhal, et.al (*6*) in Pennsylvania evaluated over thirty pavement sites in each state to determine the material characteristics that related to rutting. Two smaller studies of premature rutting by Parker and Brown (*7*), and Huber and Heiman (*8*) contained data from ten to fifteen pavement sites. Several other case histories have been reported on premature rutting where one or two pavements were analyzed.

Objective

The objectives of this study are to identify the material properties, mix design parameters and construction procedures that affect rutting and to provide information necessary to produce HMA mixtures that will perform satisfactorily and to provide information to identify those mixes with a tendency to rut under today's heavy traffic loadings.

Scope

The NCAT rutting study was initiated in 1987 to evaluate pavements from all areas of the United States encompassing various climatic regions, containing aggregates of differing origins and angularity, encompassing different specifying agencies and construction practices and containing a large sample size to make the results national in scope. This report is part of a larger NCAT study (*9*) and is the conclusion of a preliminary study reported in 1989 (*10*).

Forty-two pavements were sampled from fourteen states (Figure 1) across the United States. Rut depth measurements were made across each pavement to quantify the amount of rutting occurring at each site. The mix design information, construction records and traffic counts were also obtained. A detailed laboratory testing program was performed on samples of the asphalt mixture from these rutted and good performing pavements. The data were analyzed to determine material and mixture properties and to identify procedures that are necessary for construction of rut resistant HMA pavements.

Figure 1. States Participating in Rutting Study

Test Plan

The overall test plan for the rutting study is shown in Figure 2. The plan of laboratory tests for the cores is shown in Figure 3. The field testing consisted of obtaining 6-inch diameter cores, making rut depth measurements, and viewing the pavement layers in a trench cut across the test lane. In general, 6-inch diameter cores were obtained on 1 foot intervals across the traffic lane at each site.

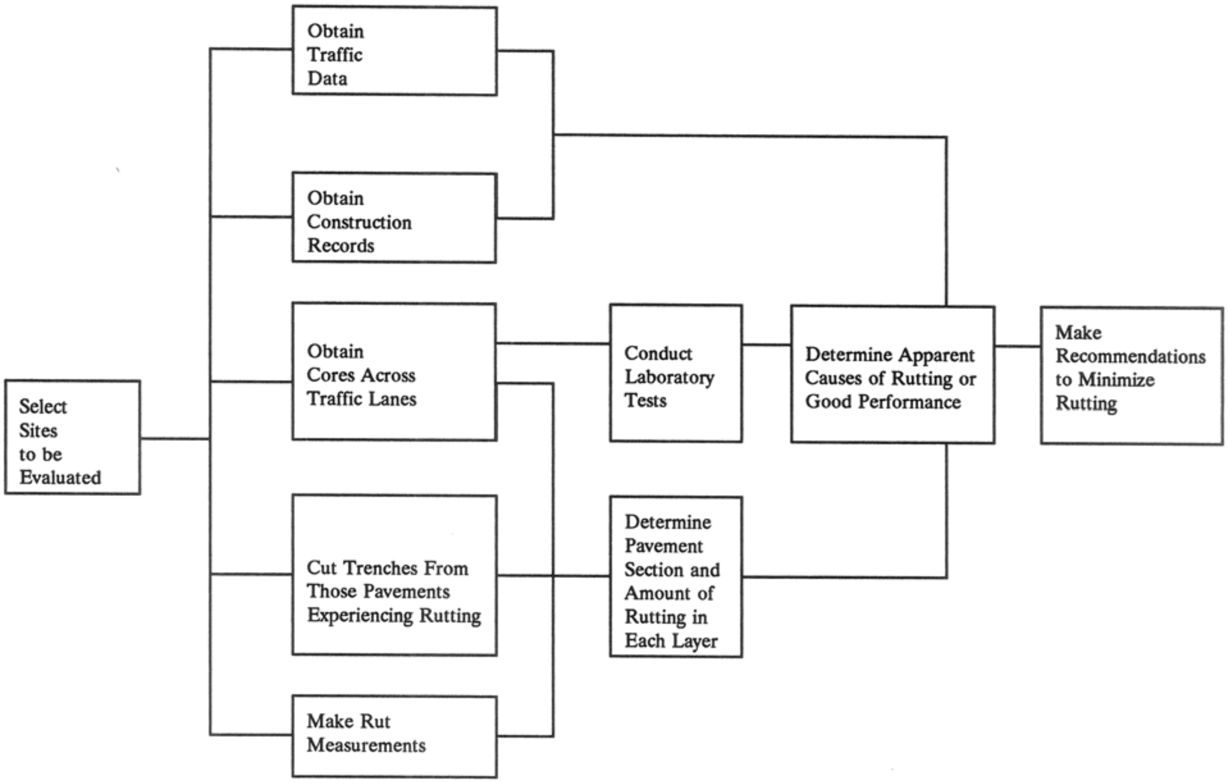

Figure 2. Overall Test Plan

Rut depth measurements were obtained using a 12 foot elevated straightedge to establish a horizontal reference line. The distance from the straightedge to the pavement surface was then recorded to the nearest 1/16 inch at l-foot internals over the proposed core locations.

Tests were conducted in the laboratory to characterize the material and mixture properties. The 6-inch diameter cores were first measured to determine the thickness of each layer of each core. Next, the cores were sawed into their respective pavement layers and the bulk specific gravity (ASTM D2726) determined for each layer. Two cores were used to determine the maximum theoretical specific gravity according to ASTM D2041. The two cores were extracted to determine the asphalt cement content (ASTM D2172) and the gradation of the mineral aggregate (ASTM Cl 17 and C136). The extracted aggregate was further examined to determine the number of crushed faces for the coarse aggregate (retained on the No.4 sieve) and the fine aggregate (passing No.4 and retained on No.30 sieves). The angularity of the fine aggregate (passing No.4 sieve) was determined using the National Aggregate Associations Uncompacted Voids Test, Method A (*11*). The uncompacted void content and the time in seconds for the aggregate to fill the container were determined. The results of the effects of the aggregate properties on rutting have been previously reported by the authors (*12*).

The asphalt cement was recovered from the extracted residue (ASTM D1856) and the absolute and kinematic viscosity (ASTM D2171 and D2170), and penetration (ASTM D5) determined. The penetration was determined at both 77°F (100g, 5 seconds) and 40°F (200g, 60 seconds). The specific gravity of the asphalt cement was determined in accordance with ASTM D70.

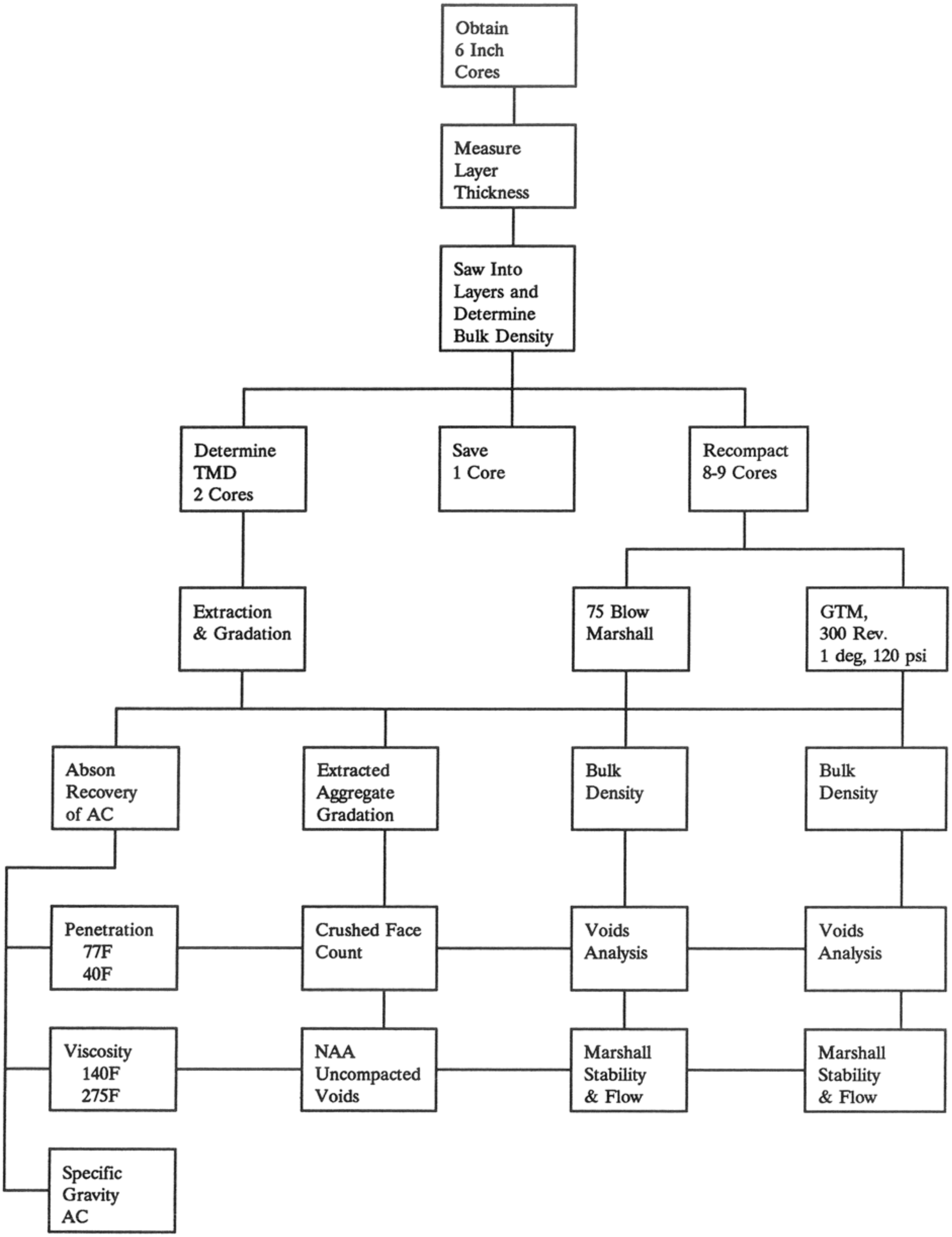

Figure 3. Laboratory Test Plan for 6-Inch Cores

The remainder of the 6-inch diameter cores were heated, broken up and combined by layers and recompacted utilizing two compactive efforts. The compactive efforts were 75 blows per side with the manual Marshall hammer (standard compactive effort) and 300 revolutions, 120 psi, and 1 degree angle with the Gyratory Testing Machine (GTM). Triplicate samples were made at each compactive effort if sufficient material was available. The samples were then tested for unit weight, voids in total mix (VTM), voids in mineral aggregate (W), voids filled (W), Marshall stability and flow. The GTM parameters of gyratory shear index (GSI), gyratory elasto-plasticity index (GEPI) and measured shear strength were also recorded for each GTM compacted sample in accordance with ASTM D3387.

SUMMARY OF TEST RESULTS

General Description of Test Sites

Nine of the 42 sites were original construction that had not been overlaid at the time of sampling. These pavements typically consisted of three or more layers of HMA over a granular base or subbase. Fourteen of the sites consisted of overlays of HMA pavements and typically consisted of two layers of HMA. Nineteen of the sites consisted of overlays of concrete pavements consisting of two or three layers of HMA with the bottom layer being either a base mix or a thin leveling mix.

Most of the test sections were located on level tangents of 4-lane divided highways. Four of the sites (Sites 1, 19, 21 and 25) were located near intersections and the pavements were subjected to static loadings and braking and acceleration forces of tires. Open graded friction courses (OGFC) were found at the surface at sites 2, 3, 5, 18 and 20. The lack of sufficient thickness of the OGFC prevented complete testing of this mixture for the five sites. Two sites (Sites 25 and 37) were sampled and tested but not included in the analysis. Site 25 was located in an area of lane widening and the pavement was not of consistent cross-section across the width of the pavement. Site 37 had experienced extensive maintenance treatments and no test information was available on the upper 3 to 4 inches of the pavement.

Some moisture damage was visually observed in cores from several sites. Moisture damage was the primary mode of distress in two sites (site 3 and 18) and was evident in four other sites (sites 2, 25, 27 and 38). The moisture damaged sites were included in the analysis of the data because in most cases the rutting had occurred in the layers above the stripping. A description of each test site can be found in the NCAT Report 91-8 (9). The traffic data and dates sampled are shown in Table 1.

Rut Depth Measurements

By obtaining rut depth measurements at core locations the pavement cross section could be established. From these data the maximum rut depth at the surface was determined by measuring the vertical distance between a straight line connecting high points on opposite sides of the rut and the low point on the pavement surface near the middle of the rut. The distance from the centerline to the maximum rut depth was also recorded. The average thickness of each pavement layer was determined by averaging the thickness of all cores taken transversely across the pavement. The data for the top two layers is shown in Table 2.

Table 1. Summary of Traffic Information and Pavement Age

Site	Date Sampled	Date Built or Overlaid	Age at Time of Sampling (yrs)	Two-Way AADT (vpd)	Total 18-KIP ESALs (millions)	Truck, % AADT
1	2/18/88	4/79	8.80	33200	13.605	50
2	3/7/88	6/82	5.75	17200	2.048	20
3	3/8/88	9/82	5.50	22700	3.118	22
4	3/9/88	2/75	13.10	29400	2.736	12
5	3/10/88	10/82	5.40	20900	5.030	41
6	9/19/88	10/83	4.90	6475	4.090	34
7	9/88	10/83	4.90	5800	1.698	23
8	9/20/88	9/76	12.00	8150	11.338	34
9	9/21/88	8/86	2.10	83370	2.167	10
10	9/22/88	7/82	6.20	20700	2.947	21
11	9/23/88	10/86	1.90	18900	0.713	16
12	9/88	11/87	0.80	81970	0.417	5
13	9/88	10/87	0.90	102810	2.943	25
14	6/28/88	11/87	0.60	129000	1.459	15
15	6/26/89	7/87	1.90	13800	0.912	28
16	6/27/89	9/87	1.75	13000	0.870	29
17	6/28/89	10/86	2.70	30000	1.654	24
18	8/89	8/84	5.00	12075	1.473	21
19	8/89	4/86	3.30	29400	0.385	3
20	8/89	7/87	2.10	6760	0.334	19
21	7/19/90	11/86	3.70	22085	0.524	6
22	1989	9/83	6.00	10800	4.400	50
23	1989	9/85	4.00	15800	3.300	40
24	1989	1976	13.00	88000	5.300	9
25	5/89	N/A	N/A	N/A	N/A	N/A
26	5/89	1983	6.00	3900	0.584	22
27	5/89	1971	18.00	15300	2.174	9
28	2/27/90	12/88	1.30	20040	0.688	20
29	2/28/90	8/74	15.50	9270	1.379	10
30	3/6/90	7/83	6.70	21240	2.821	17
31	7/90	1980	10.00	28200	6.835	24
32	3/90	6/87	2.75	35500	1.498	12
33	3/90	6/87	2.75	29925	1.102	11
34	3/90	6/87	2.75	46515	1.246	8
35	3/90	6/87	2.75	36225	0.970	8
36	11/90	1976	14.00	9100	6.200	20
37	11/90	1980	10.00	8200	4.800	23
38	11/90	1979	11.00	5800	4.600	28
39	11/88	5/75	13.50	9610	5.200	42
40	3/89	8/83	5.60	11260	1.867	26
41	10/89	5/85	4.40	6925	0.500	14
42	9/90	8/88	2.10	13000	1.486	44

N/A = Data Not Available

Table 2. Summary of Rut Depths and Layer Thicknesses

Site	Layer	Mix Type	Avg Layer Trick (in)	Maximum Surface Rut Depth (in)	Distance from Shoulder to Max Rut Depth
1	1	Surface	2.432	1.500	3
2	1	OGFC	0.800	0.896	9
2	2	Surface	1.275	0.896	
3	1	OGFC	0.693	0.375	4
3	2	Surface	1.568	0375	
4	1	Surface	1.182	0.250	9
5	1	OGFC	0.768	0.625	3
5	2	Surface	1.205	0.625	
6	1	Surface	1.427	0.575	4
7	1	Surface	1.571	0.344	4
8	1	Surface	1.250	0.400	4
9	1	Surface	*	1.000	*
10	1	Surface	0.796	0.125	4
11	1	Surface	1.097	0.550	10
12	1	Surface	1.721	1.450	9
13	1	Surface	1.596	1.656	3
14	1	Surface	2.500	1.480	3
15	1	Surface	1.490	0.094	4
16	1	Surface	1.415	0.547	4
17	1	Surface	1.205	0.463	4
18	1	OGFC	0.858	0.200	3
18	2	Surface	1.790	0.200	
19	1	Surface	1.528	0.390	8
19	2	Surface	1.722	0-390	
20	1	OGFC	0.841	0.317	9
20	2	Surface	1.409	0.317	
21	1	Surface	1.403	1.370	9
22	1	Surface	2.038	0.500	3
23	1	Surface	1.421	0.586	4
24	1	Surface	1.275	0.315	4
25	1	Surface	2.615	0.540	8
26	1	Surface	0.938	0.540	3
27	1	Surface	1.950	0.336	3
28	1	Surface	1.614	0.300	9
29	1	Surface	1.284	0.513	3
30	1	Surface	1.148	0.325	3

Table 2. Summary of Rut Depths and Layer Thicknesses (Continued)

Site	Layer	Mix Type	Avg. Layer Trick (in.)	Maximum Surface Rut Depth (in.)	Distance from Shoulder to Max Rut Depth
31	1	Surface	1.425	1.080	9
32	1	Surface	1.983	0.980	9
33	1	Surface	1.174	0.700	8
34	1	Surface	1301	0.980	9
35	1	Surface	1.239	0.633	8
36	1	Surface	1.523	0.250	10
37	1	OGFC	0.914	1.250	10
37	2	Surface	2.519	1.250	
38	1	Surface	1.694	0.594	
39	1	Surface	1.047	0.406	3
40	1	Surface	1.238	1.000	8
41	1	Surface	1.483	0.568	8
42	1	Surface	1.525	0.036	3

* Data Not Available, Sample From Millings

Mix Design Data

A summary of the mix design parameters and aggregate gradations are shown in Tables 3 and 4, respectively. Mix design information was available on the top layer (excluding OGFC) on all but 4 sites. Twenty-two of 42 pavements evaluated were designed utilizing a 50-blow Marshall mix design and ten utilized a 75-blow mix design. Four sites utilized the Hveem method, however, mix design information was unavailable from these 4 sites.

Construction Data

All available construction quality control data were collected and summarized in Tables 5 and 6. The quality control data were not available on all projects. Some projects had data on gradation and asphalt content but no data on mixture properties such as voids, stability, flow, etc. It appears that the biggest difference between mix design and construction data is the difference in unit weights and voids. The unit weights in laboratory compacted samples during construction were often significantly higher than the mix design unit weights sometimes resulting in low voids during the construction process.

Data From Pavement Cores

Cores were obtained on one foot intervals across the sampled lanes of each pavement tested. The average VTM and 20th percentile VTM were determined for each layer at each site. The 20th percentile is the VTM with 20% of the voids lower than this value. The corresponding average and 80th percentile unit weights were also calculated. The results are shown in Table 7.

Table 3. Summary of Mix Design Properties for Top Layer

Site	AC (%)	VTM (%)	VMA (%)	VF (%)	Unit Weight (pcf)	Marshall		No. Blows Side	Asphalt Cement Grade
						Stab. (Lbs)	**Flow (.01 in)**		
1	63	5.9	19.5	69.8	141.7	1596	11.0	50	85-100
2	*	*	*	*	*	*	*	*	*
3	4.5	6.7	16.7	59.8	142.8	1250	*	50	AC-20
4	6.0	5.4	18.9	71.8	144.4	2440	10.0	50	AC-20
5	*	*	*	*	*	*	*	*	*
6	4.8	4.2	15.4	72.7	146.3	2420	8.0	50	AC-20
7	5.0	4.1	15.7	73.9	147.2	2155	8.0	50	AC-20
8	4.8	5.4	16.8	67.8	147.4	2075	8.0	50	AC-20
9	7.2	4.7	22.5	79.1	142.9	*	*	50	85-100
10	7.0	73	22.1	67.0	135.4	*	*	50	85-100
11	6.5	4.1	18.6	78.0	142.7	*	*	50	120-150
12	6.5	3.0	16.3	81.3	144.3	2322	10.2	75	AC-20
13	6.4	3.1	16.4	81.3	148.9	2347	12.0	75	AC-20
14	5.0	3.0	15.2	80.1	156.2	2051	10.2	75	AC-20
15	7.2	4.8	15.5	69.0	140.4	2875	8.0	75	AC-20
16	7.2	4.8	15.5	69.0	140.4	2875	8.0	75	AC-20
17	6.2	6.5	15.2	59.2	140.4	2875	7.5	75	AC-20
18	*	*	*	*	*	*	*	*	*
19	6.4	3.5	15.8	77.8	146.3	1846	11.0	50	85-100
20	*	*	*	*	*	*	*	*	*
21	6.3	4.0	17.1	76.0	145.5	1470	10.4	50	AC-20
22	5.8	2.6	163	84.0	152.6	1900	9.0	50	85-100
23	5.3	3.5	15.9	78.0	150.8	1995	8.5	50	85-100
24	6.7	2.1	18.8	88.8	159.9	2530	15.0	50	*
26	*	*	*	*	*	*	*	*	*
27	*	*	*	*	*	*	*	*	*
28	6.0	4.0	15.8	74.7	143.3	2120	12.0	75	AC-30
29	5.0	3.2	14.7	78.0	147.5	1600	7.0	75	AC-20
30	7.3	4.4	20.5	78.6	141.6	*	*	75	AC-30
31	*	*	*	*	*	*	*	*	*
32	5.5	3.2	16.4	80.2	152.4	1878	10.3	50	AC-10
33	5.5	3.2	16.4	80.2	152.4	1878	10.3	50	AC-10
34	5.9	3.0	16.4	81.8	145.8	2040	11-3	50	AC-10
35	5.9	3.0	16.4	81.8	145.8	2040	11-3	50	AC-10
36	6.0	*	*	*	*	*	*	50	AC-10
38	6.3	*	*	*	*	*	*	50	AC-10
39	*	*	*	*	*	*	*	*	*
40	6.0	*	*	*	143.1	*	*	50	AC-20
41	5.9	*	*	*	148.5	2491	*	50	AC-20
42	6.1	4.0	16.3	75.7	148.9	2700	10.0	75	AC-20

* = Data Not Available

Table 4. Summary of Mix Design Aggregate Gradations For Top Layer

	Percent Passing										
Site	**1"**	**3/4"**	**1/2"**	**3/8"**	**#4**	**#8**	**#16**	**#30**	**#50**	**# 100**	**#200**
1	100	100	97	91	66	54	43	35	22	13	5.3
2	*	*	*	*	*	*	*	*	*	*	*
3	100	100	98	88	48	30	*	*	*	*	*
4	100	100	98	90	68	56	40	29	18	11	6.0
5	*	*	*	*	*	*	*	*	*	*	*
6	100	100	99	90	60	44	34	25	10	7	5.6
7	100	100	99	89	70	58	48	36	18	8	6.0
8	100	100	99	88	60	45	36	23	13	8	5.8
9	100	100	100	97	72	56	37	21	11	6	2.0
10	100	100	100	99	73	63	49	33	19	10	2.0
11	100	100	100	96	71	53	40	24	16	11	8.0
12	100	100	100	92	62	42	31	25	17	9	5.0
13	100	100	100	92	65	45	26	16	10	9	5.0
14	99	92	82	72	51	37	29	20	11	7	4.0
15	100	100	100	98	55	32	20	13	9	7	5.3
16	100	100	100	98	55	32	20	13	9	7	5.3
17	100	100	100	97	51	30	21	14	8	5	3.6
18	*	*	*	*	*	*	*	*	*	*	*
19	100	100	88	78	55	38	27	21	14	10	6.2
20											
21	100	100	99	84	60	47	35	25	11	6	2.1
22	100	100	97	84	55	42	30	23	19	11	7.6
23	100	100	97	81	51	37	28	22	18	12	7.9
24	100	100	100	100	99	80	54	36	26	20	15.2
26	*	*	*	*	*	*	*	*	*	*	*
27	*	*	*	*	*	*	*	*	*	*	*
28	100	100	100	92	62	43	32	24	13	7	6.0
29	100	100	100	93	60	45	34	25	16	10	5.0
30	100	100	100	100	83	62	46	34	20	11	7.4
31	*	*	*	*	*	*	*	*	*	*	*
32	100	100	92	80	65	53	39	30	19	11	5.7
33	100	100	92	80	65	53	39	30	19	11	5.7
34	100	100	94	85	67	52	39	30	19	11	5.6
35	100	100	94	85	67	52	39	30	19	11	5.6
36	100	100	84	75	52	33	30	28	27	17	10.0
38	100	100	83	72	50	39	30	24	19	13	8.0
39	*	*	*	*	*	*	*	*	*	*	*
40	100	100	100	86	63	58	33	23	15	7	4.0
41	100	100	100	88	72	50	34	24	15	9	5.0
42	100	100	100	95	70	47	28	18	12	8	5.0

* = Data Not Available

Table 5. Average QC/QA Gradation Analysis for Top Layer

	Percent Passing									
Site	**3/4"**	**1/2"**	**3/8"**	**#4**	**#8**	**#16**	**#30**	**#50**	**#100**	**#200**
1	100	99	90	66	52	42	35	22	13	6.1
2	*	*	*	*	*	*	*	*	*	*
3	100	100	90	51	29	*	*	*	*	*
4	100	100	96	71	57	44	35	20	10	5.7
5	*	*	*	*	*	*	*	*	*	*
6	100	100	92	61	42	32	25	12	8	5.7
7	100	100	91	73	60	48	37	22	12	5.8
8	100	100	89	60	44	33	23	15	9	6.6
9	*	*	*	*	*	*	*	*	*	*
10	*	*	*	*	*	*	*	*	*	*
11	100	100	96	74	51	33	21	14	13	10.3
12	100	100	95	60	43	33	27	17	10	5.9
13	100	100	98	67	46	27	16	10	7	5.3
14	92	82	71	49	36	29	21	12	6	3.2
15	100	100	88	65	33	24	17	12	8	5.8
16	100	100	88	60	35	28	18	10	8	5.4
17	100	100	84	53	32	21	14	9	6	4.2
18	*	*	*	*	*	*	*	*	*	*
19	100	100	78	57	41	30	22	15	10	5.4
20	*	*	*	*	*	*	*	*	*	*
21	100	98	82	60	48	36	23	11	6	2.2
22	100	97	85	58	43	31	23	17	11	7.2
23	100	97	81	52	37	28	22	18	13	8.3
24	*	*	*	*	*	*	*	*	*	*
26	*	*	*	*	*	*	*	*	*	*
27	*	*	*	*	*	*	*	*	*	*
28	100	99	92	67	52	40	30	19	10	6.4
29	100	100	93	61	44	33	24	16	10	6.8
30	100	100	100	82	59	44	34	20	10	7.7
31	*	*	*	*	*	*	*	*	*	*
32	100	91	78	63	51	38	28	17	10	5.0
33	100	91	78	63	51	38	28	17	10	5.0
34	100	94	82	64	49	36	27	17	11	5.9
35	100	94	82	64	49	36	27	17	11	5.9
36	100	87	76	55	33	31	29	28	18	9.9
38	100	86	77	54	42	33	27	22	14	8.3
39	*	*	*	*	*	*	*	*	*	*
40	*	*	*	*	*	*	*	*	*	*
41	*	*	*	*	*	*	*	*	*	*
42	100	100	95	67	46	28	18	13	9	6.0

* Data Not Available

Table 6. Average QC/QA Testing for Top Layer Mix Properties

Site	**In-Place**			**Lab Compacted**			
	Asphalt Content (%)	**Voids Total Mix (%)**	**Unit Weight (pcf)**	**Voids Total Mix (%)**	**Unit Weight (pcf)**	**Marshall**	
						Stab. (lbs.)	**Flow (0.01 in)**
1	6.4	*	*	*	*	*	*
2	*	*	*	*	*	*	*
3	4.7	*	*	*	*	*	*
4	6.1	*	*	*	*	*	*
5	*	*	*	*	*	*	*
6	5.2	8.0	141.6	5.0	146.4	*	*
7	5.2	6.9	142.2	4.0	146.8	*	*
8	4.8	*	*	*	*	*	*
9	*	*	*	*	*	*	*
10	*	*	*	*	*	*	*
11	5.5	*	*	2.3	148.0	2247	*
12	6.4	4.7	141.4	*	*	*	*
13	6.1	6.1	143.8	*	*	*	*
14	*	*	*	2.8	156.2	2051	10
15	7.8	5.0	142.6	2.8	145.9	*	*
16	7.4	4.8	143.0	2.2	146.8	*	*
17	6.7	5.7	140.3	*	*	*	*
18	*	*	*	*	*	*	*
19	6.3	6.7	143.0	2.4	149.2	2006	12
20	*	*	*	*	*	*	*
21	6.5	5.1	145.6	4.4	145.9	1645	10
22	5.5	5.5	148.7	*	*	*	*
23	5.1	5.9	147.2	*	*	*	*
24	*	*	*	*	*	*	*
26	*	*	*	*	*	*	*
27	*	*	*	*	*	*	*
28	5.7	*	*	3.6	143.7	1944	*
29	5.0	7.7	140.5	4.2	145.9	2383	10
30	*	*	*	5.5	139.9	1604	*
31	*	*	*	*	*	*	*
32	5.5	3.2	151.8	3.9	150.7	2114	14
33	5.5	2.7	151.9	2.8	151.8	2270	12
34	5.4	1.8	150.1	2.1	149.7	2093	11
35	5.4	1.7	150.3	2.9	148.5	2394	12
36	6.2	*	*	*	*	*	*
38	5.9	*	*	*	*	*	*
39	*	*	*	*	*	*	*
40	*	*	*	*	*	*	*
41	*	*	*	*	*	*	*
42	6.1	*	143.1	*	*	*	*

* Data Not Available

Table 7. Summary of Voids and Unit Weights From Top Layer of In-Place Cores

Site	20th Pcntl VTM (%)	Average VTM (%)	Minimum VTM (%)	80th Pcntl Unit Weight (pcf)	Average Unit Weight (pcf)	Maximum Unit Weight (pcf)
1	0.4	1.1	0.0	151.0	149.9	151.6
2	*	*	*	138.2	135.7	141.6
3	11.3	11.9	11.0	138.3	137.4	138.7
4	3.1	4.3	2.7	147.1	145.3	147.6
5	*	*	*	*	*	*
6	4.6	5.4	3.7	146.0	144.7	147.3
7	2.2	3.2	2.1	148.9	147.3	149.0
8	2.1	3.2	1.7	151.4	149.7	152.0
9	+	+	+	+	+	+
10	5.1	6.1	4.6	141.0	139.5	141.8
11	2.7	4.1	2.0	147.7	145.6	148.8
12	1.3	1.9	1.2	146.2	145.3	146.3
13	3.5	4.9	2.3	148.7	146.6	150.5
14	1.5	2.9	1.0	157.2	154.9	157.9
15	5.5	7.2	5.5	141.2	138.7	141.8
16	3.5	4.1	3.0	144.8	143.9	145.6
17	4.0	6.0	3.5	142.7	139.8	143.5
18	14.6	15.9	13.2	129.1	127.2	131.4
19	0.9	1.4	0.1	151.9	151.1	153.1
20	12.3	12.8	11.9	133.2	132.4	133.7
21	2.2	2.8	1.8	149.5	148.7	150.1
22	1.5	2.0	1.0	156.3	155.4	157.0
23	1.8	2.7	1.2	153.1	151.6	153.9
24	1.4	2.8	1.3	161.1	158.8	161.2
26	3.2	5.7	2.5	141.4	137.7	142.4
27	8.2	8.5	7.7	144.2	143.7	145.0
28	3.5	4.2	3.1	143.9	142.9	144.6
29	2.6	3.7	1.6	147.0	145.4	148.6
30	1.3	2.0	0.9	144.6	143.5	145.3
31	1.1	3.3	0.8	150.8	147.5	151.3
32	3.2	3.7	2.9	154.8	148.8	152.3
33	2.3	3.3	1.6	152.3	150.7	153.4
34	1.4	1.7	1.2	150.2	149.8	150.4
35	1.6	1.9	1.4	150.4	150.0	150.7
36	1.4	1.6	1.4	146.9	146.6	147.0
38	0.8	1.6	0.6	148.4	147.2	148.6
39	4.6	5.9	4.4	141.6	139.7	141.9
40	1.4	2.5	0.9	148.0	146.3	148.7
41	0.9	1.2	0.6	149.2	148.7	149.6
42	5.1	5.9	4.7	146.9	145.7	147.5

* Not Enough Material to Test; + Data Not Available, Sample From Millings

The distance from the centerline to the maximum rut depth was reported in Table 2. It can be seen that the minimum VTM did not always occur in the wheel path and the variation in VTM across the wheel path could be quite large. The 20th percentile VTM was calculated to estimate the VTM in the wheel path because utilizing minimum VTM seemed too severe in some locations and utilizing the average VTM seemed too conservative. Kandhal et.al. (6) reported that the 20th percentile VTM across the pavement was a good approximation of the void content in the wheel path.

The asphalt cement was recovered from the extracted residue and the properties determined. The properties evaluated were absolute and kinematic viscosity, penetration at 77 and 40°F and specific gravity. The results are shown in Table 8.

Recompacted Mix Properties

The recompacted properties of unit weight, VTM, VMA, VFA, Marshall stability and flow were determined for samples compacted with the manual Marshall hammer and the GTM. Parameters including GSI, GEPI and shear stress were measured for the GTM compacted samples. The results for the manual Marshall samples are shown in Table 9 and for the GTM samples in Table 10.

ANALYSIS OF DATA

The general procedure for analysis of the data consisted of performing a linear correlation analysis to determine if the dependent variable rut dept was significantly correlated to the independent variables. If significant correlations were found, the relationship was further investigated using regression analysis. The results presented are limited to the top pavement layer. The relationships found for the second layer are included in the NCAT Report 98-1 (9). The relationships for the second pavement layer were not as strong as for the corresponding first layer.

Outliers were often encountered that did not fit the relationship. An outlier was defined as any point that fell outside the 95% confidence limits of the regression equation. If a plausible explanation existed, the data point was identified as an outlier and the analysis performed without the data point.

Evaluation of Rut Depth Data

Each of the 42 pavements were selected by State DOT personnel as either good or rutted based on a subjective analysis of the rut depth and the age of the pavement. From the data it was decided to represent rate of rutting as the maximum rut depth at the surface in inches divided by the square root of the total traffic in ESALs. A linear relationship for rate of rutting was found to provide high estimates for older pavements, a log function was found to provide low estimates for older pavements, and the square root function appeared to fit all the data better. The chosen expression for rate of rutting agrees with rates of rutting utilized in other work (6, 7).

Table 8. Properties of Asphalt Cement Recovered From Top Layer

Site	Viscosity		Penetration		Specific Gravity Asphalt Cement	Asphalt Content (%)
	275°F (cSt)	140°F (poise)	77°F 100g 5 sec (.1 mm)	40°F 200g 60 sec (.1 mm)		
1	577	3325	57	26	1.061	5.71
2	*	*	*	*	*	*
3	*	*	*	*	*	*
4	491	4878	so	29	1.029	5.60
5	*	*	*	*	*	*
6	1173	29427	21	9	1.0:7	4.81
7	695	8699	29	19	1.040	5.28
8	633	6097	46	26	1.010	4.48
9	428	3387	36	20	1.024	7.06
10	566	9663	34	27	1.025	6.79
11	548	4598	46	25	1.025	6.32
12	1308	8728	27	34	1.023	6.53
13	1159	7737	38	38	1.025	6.17
14	548	3591	57	24	1.037	5.15
15	788	13383	35	29	1.030	6-33
16	591	4637	88	30	1.030	6.58
17	563	5430	36	22	1.030	6.19
18	648	5867	51	34	1.042	4.31
19	341	1990	41	19	1.020	5.71
20	312	2347	38	24	1.010	5.56
21	649	7710	39	33	1.022	6.16
22	570	6146	40	21	1.050	5.25
23	576	5328	40	22	1.031	4.99
24	454	3987	35	18	1.019	631
26	609	6515	28	14	1.035	8.09
27	10215	79042	26	12	1.045	4.81
28	724	7336	35	22	1.046	5.57
29	911	9853	23	17	1.036	4.78
30	696	7134	39	27	1.032	6.%
31	745	8067	24	17	1.036	5.29
32	277	910	75	28	1.077	539
33	275	602	118	38	1.033	5.15
34	281	1043	86	40	1.074	4.96
35	344	1826	150+	150+	1.043	5.26
36	348	1635	76	30	1.009	5.83
38	385	2407	66	46	1.019	5.45
39	1524	50112	21	11	1.060	6.30
40	777	7746	40	25	1.047	5.90
41	542	3892	63	39	1.031	7.80
42	+ +	8378	37	+ +	1.030	5.65

* Not Enough Material to Test; + + Data Not Available

Table 9. Summary of Recompacted Mix Properties of Top Layer For 75 Blow Manual Marshall Hammer

Site	Bulk Specific Gravity	Voids Total Mix (%)	Voids Mineral Agg. (%)	Voids Filled (%)	Marshall	
					Stab. (lbs.)	Flow (.01 in)
1	2.392	1.58	14.45	89.09	3061	18.0
2	*	*	*	*	*	*
3	*	*	*	*	*	*
4	2.341	3.75	16.49	77.24	5338	15.0
5	*	*	*	*	*	*
6	2.383	2.85	13.79	79.39	5679	14.0
7	2.386	2.22	14.34	84.49	3268	12.0
8	2.412	2.68	13.37	80.06	4143	12.3
9	2.411	0.60	17.22	96.54	2617	21.7
10	2.239	6.00	20.83	71.19	3072	12.0
11	2.370	2.58	17.19	85.03	3000	18.5
12	2.347	1.13	16.12	92.97	3002	19.0
13	2.424	1.85	16.43	88.77	2442	10.7
14	2.509	1.81	14.26	87.43	4233	15.7
15	2.328	3.21	17.52	81.68	3888	16.7
16	2.358	2.00	17.06	88.27	3164	17.7
17	2.330	2.24	16.24	86.26	3888	12.0
18	*	*	*	*	*	*
19	2.440	0.65	14.31	95.45	3339	16.5
20	*	*	*	*	*	*
21	2.422	1.14	15.72	92.78	3234	15.7
22	2.509	1.30	13.83	90.63	3484	14.0
23	2.452	1.81	13.68	86.77	4187	17.7
24	2.583	1.33	17.31	92.31	3514	14.0
26	2.281	2.55	20.38	87.50	2603	16.0
27	2.290	9.00	19-54	53.96	4976	16.0
28	2.320	2.97	15.32	80.64	2848	13.0
29	2.327	3.85	14.59	73.61	4953	12.0
30	2.303	1.93	17.46	88.93	3918	14.0
31	2.391	2.14	14.35	85.12	4840	19.8
32	2.435	3.10	15.29	79.72	2936	10.8
33	2.453	1.81	14-03	87.14	3900	14.0
34	2.410	1.25	12.39	89.92	2686	13.8
35	2.400	2.04	14.14	85.63	+	+
36	2.348	1.68	15.87	89.41	3867	21.0
38	2.346	2.07	13.99	85.23	3800	15.2
39	2.243	5.71	19.04	70.02	7401	15.0
40	2.370	1.47	14.83	90.09	2033	19.5
41	2.387	1.03	19.09	94.60	2715	28.0
42	2.431	1.96	15.30	87.19	4245	17.0

* Not Enough Material to Test; + Data Not Available

Table 10. Summary of Top Layer GTM Recompacted Mix Properties for GTM, 300 Revolutions, 120 psi, 1 Degree Angle

Site	Bulk Specific Gravity	VTM (%)	VMA (%)	VF (%)	Marshall		GSI	GEPI	Shear Strength (psi)
					Stab. (lbs.)	Flow (.01 in)			
1	2.421	0.4	13.4	97.1	1635	27.0	1.61	2.10	3.1
2	*	*	*	*	*	*	*	*	*
3	*	*	*	*	*	*	*	*	*
4	2.361	2.9	15.8	81.4	4563	16.0	1.04	1.20	47.1
5	*	*	*	*	*	*	*	*	*
6	2.378	2.9	13.8	793	4593	14.7	1.08	1.25	42.6
7	2.388	2.1	14.2	85.2	2M9	113	1.04	130	38.8
8	2.422	23	13.1	82.1	2999	11.7	1.07	1.22	363
9	2.414	0.6	17.2	96.5	2175	21.7	1.69	1.28	26.6
10	2.245	5.7	20.6	72.2	2508	12.5	1.00	1.15	41.7
11	2.374	2.4	17.1	85.7	2788	16.5	1.37	1.2S	413
12	2.351	1.0	16.0	93.9	2670	21.0	1.63	1.27	12.0
13	2.423	1.9	16.5	88.5	2252	13.7	1.43	1.25	29.5
14	2.502	2.1	14.5	85.7	3647	15.0	1.29	1.20	34.3
15	2.339	2.7	17.1	84.0	3544	21.3	1.28	1.13	38.4
16	2.369	1.5	16.7	90.8	3081	18.7	1.40	1.17	32-3
17	2.333	2.1	16.1	87.0	3165	13.5	1.20	1.15	36.8
18	2.180	10.5	19.5	46.3	1290	12.0	1.00	1.10	50.2
19	2.428	1.1	14.7	92.5	2973	14.3	1.36	1.06	24.1
20	2.199	9.6	21.7	55.9	1259	14.0	1.00	1.18	50-3
21	2.432	0.7	15.4	953	2627	13.0	1.50	1.20	25.5
22	2.508	1.3	13.9	90.6	2875	14.7	1.47	1.15	38.5
23	2.456	1.7	13.5	87.8	3155	18.0	1.41	1.18	41.9
24	2.571	1.8	17.7	89.6	3326	14.7	1.53	1.15	25.9
26	2.263	33	21.0	84.2	2333	16.7	1.00	1.08	35.8
27	2.279	9.5	20.0	52.6	5220	19.0	0.93	1.03	52.7
28	2.336	23	14.7	84.5	2458	13.3	1.10	1.20	34.1
29	2.347	3.0	13.8	78.4	3208	12.3	1.02	1.20	42.9
30	2.304	1.9	17.4	89.2	2868	13.5	1.09	1.20	38.2
31	2359	3.5	15.5	77.8	4141	16.8	1.12	1.20	36.7
32	2.436	3.1	15.3	79.7	3040	11.0	1.04	1.27	34.0
33	2.459	1.8	14.0	87.2	3602	12.8	1.14	1.25	29.5
34	2.418	1.1	12.3	90.9	2190	11.3	1.29	1.22	31.1
35	2.401	2.0	14.1	85.8	+	+	1.11	1.21	28.6
36	2365	1.0	15.3	93.6	2828	27.3	1.53	1.28	17.3
38	2.319	3.2	15.0	79.2	2700	19.8	1.63	1.18	23.1
39	2.248	5.5	18.9	70.8	5304	11.5	1.00	1.2	52.4
40	2.367	1.6	14.9	89.4	1845	17.5	1.39	1.35	30.1
41	2.379	1.4	19.4	93.0	2257	24.5	1.80	1.35	25.7
42	2.415	2.6	15.9	83.5	3293	18.5	1.33	1.05	33.5

* Not Enough Material to Test; + Data Not Available

Rut depth measurements were obtained for each of the pavements evaluated and the maximum rut depths are shown in Table 2. The measured rut depths ranged from a low of 0.04 inches at site 42 to a high of 1.65 inches at site 13. The maximum rut depth on a pavement identified as good performing by the states was 0.51 inches and the minimum rut depth for a rutted pavement was 0.30 inches. There was overlap in the rut depth measurements between observed good and rutted pavements and a single rut depth could not be identified as delineating between good and rutted.

Evaluation of Rut Depth Data

Each of the 42 pavements were selected by State DOT personnel as either good or rutted based on a subjective analysis of the rut depth and the age of the pavement. From the data it was decided to represent rate of rutting as the maximum rut depth at the surface in inches divided by the square root of the total traffic in ESALs. A linear relationship for rate of rutting was found to provide high estimates for older pavements, a log function was found to provide low estimates for older pavements, and the square root function appeared to fit all the data better. The chosen expression for rate of rutting agrees with rates of rutting utilized in other work (*6*, *7*).

Rut depth measurements were obtained for each of the pavements evaluated and the maximum rut depths are shown in Table 2. The measured rut depths ranged from a low of 0.04 inches at site 42 to a high of 1.65 inches at site 13. The maximum rut depth on a pavement identified as good performing by the states was 0.51 inches and the minimum rut depth for a rutted pavement was 0.30 inches. There was overlap in the rut depth measurements between observed good and rutted pavements and a single rut depth could not be identified as delineating between good and rutted.

Figure 4 shows the rate of rutting for the 30 sites having the lowest rate of rutting and the rating given each pavement by the various participating states. The separation between good and rutted pavements when rated subjectively appears to occur between 0.00020 and 0.00025 inches per square root ESALS. Only one of the good pavements had a rate of rutting greater than 0.00023 and two of the rutted pavements had a rate lower than 0.00023. Site 3 was one of the rutted pavements with a rate of rutting higher than 0.00023, however, the primary mode of distress at this site was raveling, caused by stripping, and not rutting. Therefore 0.00023 inches of rut depth per square root ESALS was identified as delineating between good and rutted pavements. This rate of rutting agrees closely with that identified by Kandhal et.al. (*6*) and Parker and Brown (*7*) in field studies of rutted pavements.

Location of Rutting

An attempt was made to quantify where in the pavement structure the rutting was occurring. When possible, trench cuts were made and the rutted pavements examined. From visual observations it was determined that the majority of the rutting was occurring in the top 3 to 4 inches of the pavements. In every case but one the amount of rutting in the base course was insufficient to measure.

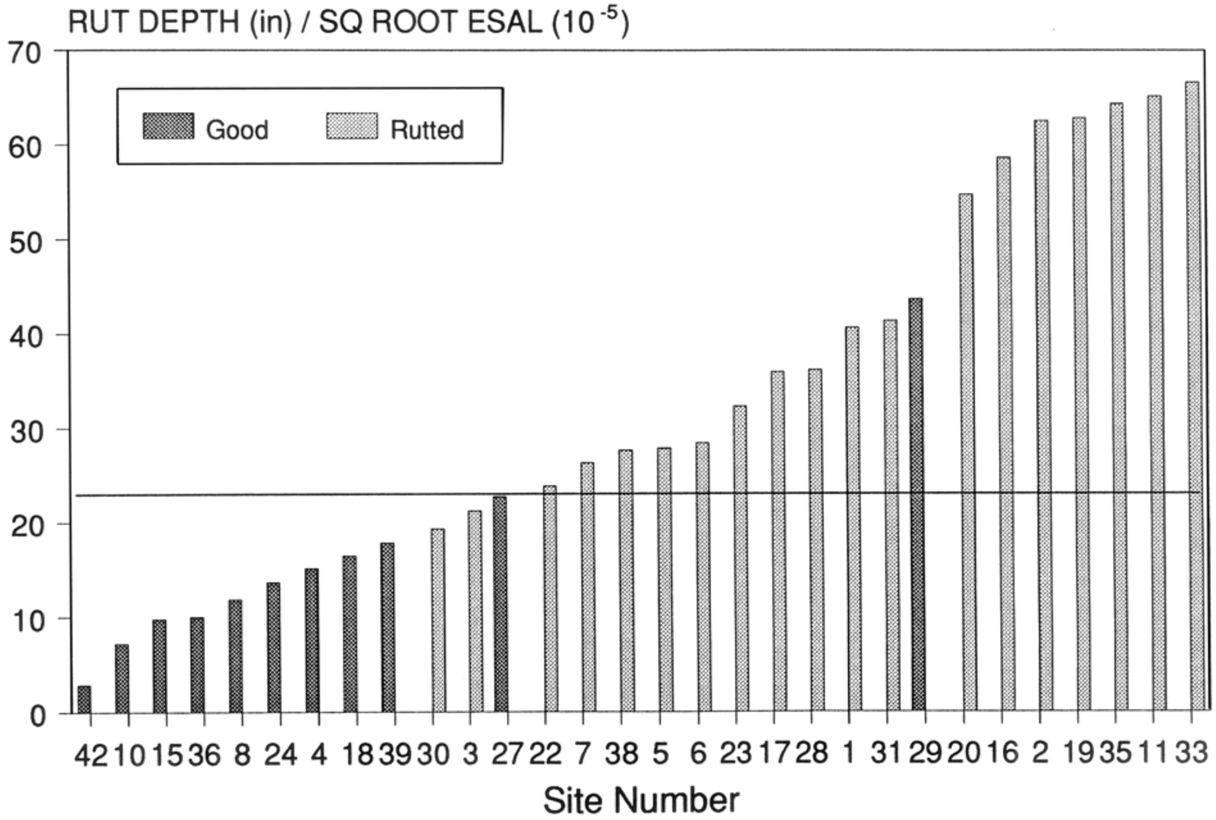

Figure 4. Subjective Performance Rating vs. Rate of Rutting

Mix Design Parameters

The mix design parameters evaluated were asphalt content, voids total mix (VTM), voids in the mineral aggregate (VMA), voids filled with asphalt cement (VFA), and Marshall stability and flow (Tables 3 and 4). Ten of the sites utilized a 75-blow Marshall mix design for the surface mix and 22 of the sites used 50-blow Marshall mixes.

Table 11 shows the correlation coefficients for the rate of rutting and the mix design properties of the top layer. The table shows the correlation coefficients for both 50 and 75 blow mixes together and separately. None of the mix properties evaluated had a good correlation with rate of rutting.

Table 11. Summary of Correlations for Mix Design Variables

	Correlation with Rate of Rutting					
	All		50 Blow		75 Blow	
Variable	**R-Value**	**n**	**R-Value**	**n**	**R-Value**	**n**
Voids Total Mix	-0.36	27	-0.30	18	-0.55	10
Voids Mineral Aggregate	-0.16	27	-0.13	18	-0.12	10
Voids Filled Asphalt	0.32	27	0.27	18	0.48	10
Marshall Stability	-0.30	24	-0.35	16	-0.29	9
Marshall Flow	0.14	23	-0.15	14	0.28	9

Stronger relationships were found between mix properties and rate of rutting when only the 75-blow mixes were evaluated. The best relationships were found between mix design VTM and mix design VFA. The relationship between VTM and rate of rutting has an R-square of 0.30 for all the data and 0.66 for the 75-blow mixes. The relationship is shown in Figure 5. There was no relationship found for the 50-blow mixes and that was expected since a 50 blow compactive effort is not sufficient for heavy duty pavements. Figure 6 shows the relationship between mix design VFA and rate of rutting ($R^2 = 0.23$) for 75-blow mixes.

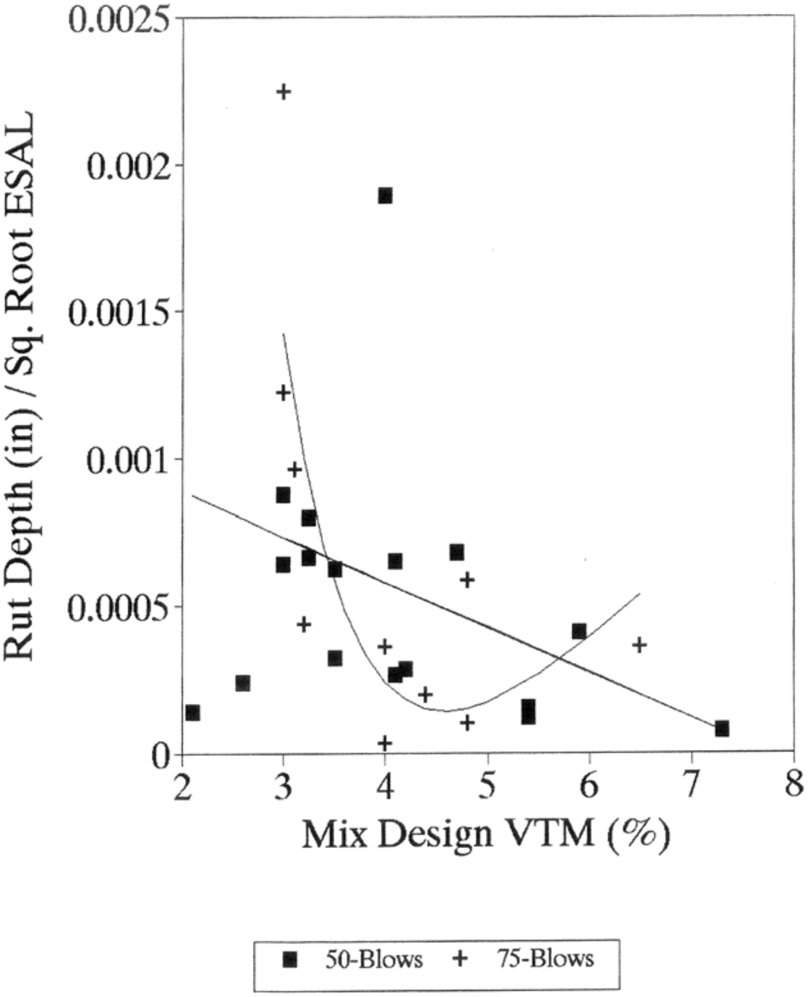

Figure 5. Mix Design Voids Total Mix vs. Rate of Rutting

All of the pavements evaluated were carrying heavy truck traffic and as previously reported (*13*) should have been designed utilizing a 75-blow mix. Utilizing a 50-blow mix design would allow for excessive asphalt content therefore causing the voids in-place to be too low after densification by traffic. Most states participating in this study have increased their mix design compactive effort to 75 blows.

Table 12 shows the means and standard deviations for the mix design parameters compared to performance. The data shows that good performing pavements had higher design VTM, higher VMA, lower VFA, and higher stability. This information is provided to show trends in performance and these numbers in Table 12 should not be used to set specification requirements.

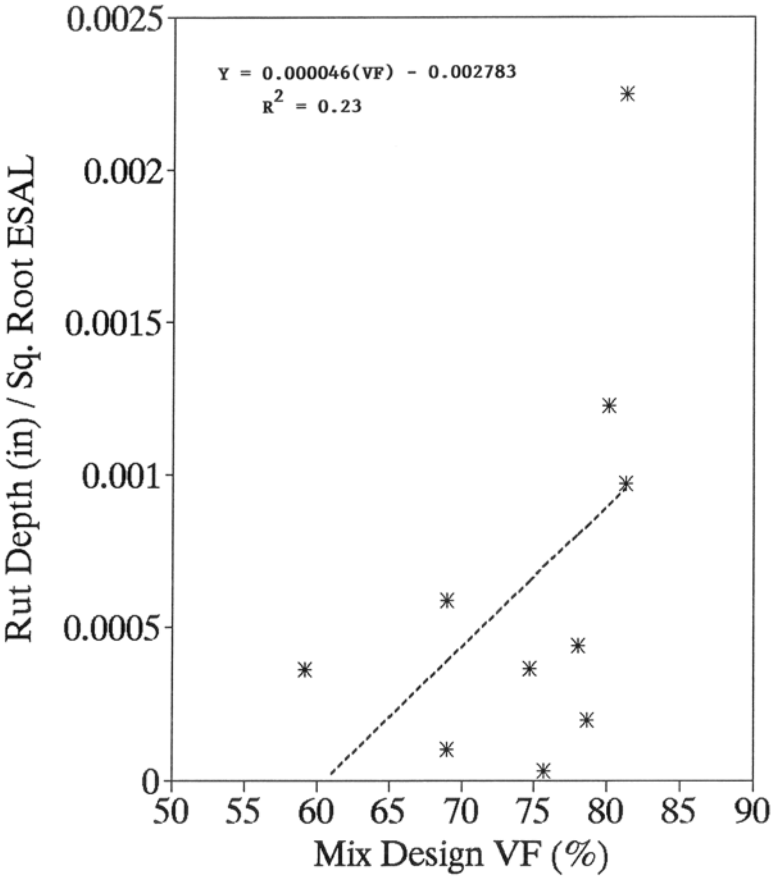

Figure 6. 75-Blow Mix Design Voids Filled with Asphalt vs. Rate of Rutting

Table 12. Summary of Mix Design Parameters Compared to Performance

	Good		Rutted	
Variable	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Voids Total Mix (%)	5.01	1.62	3.83	1.02
Voids Mineral Aggregate	18.20	2.28	16.58	1.79
Voids Filled (%)	72.31	8.78	76.85	5.79
Marshall Stability (lbs)	2311	586	2100	387
Marshall Flow (0.01 in)	10.2	2.86	9.7	1.49

These correlations developed for mix design properties have little practical meaning since mix properties produced during plant production likely deviate from mix design properties. Nevertheless these relationships were developed to determine if a relationship exists between mix design properties and rutting and the results do follow the expected trend.

Construction Data

The quality control or construction data summarized in Tables 5 and 6 show that some construction data were available for 32 of the 42 sites. The construction data represent the mix properties immediately after construction prior to densification by traffic. For analysis, the data was separated into three areas. These three areas are data from pavement cores, lab compacted data from plant produced material and asphalt content and gradation analysis. Data from pavement cores consisted of voids total mix and unit weight to check initial compaction. Properties measured for lab compacted samples consisted of voids total mix, unit weight, and Marshall stability and flow. Lab compacted samples are used to evaluate and verify the mix design “as produced.”

One of the most important observations that was made with regards to construction testing is the lack of data. Construction history data from asphalt cores was available from 20 of 42 sites, however this data is incomplete for many of the sites.

Probably the most important test that can be conducted during QC/QA is to compact plant produced material in the laboratory and to evaluate the air voids of these laboratory compacted samples. Satisfactory compactive effort must be used for this test. Only 13 of 42 sites (31%) utilized laboratory compacted samples as a part of QA/QC procedures. Verification of mixture properties from laboratory compacted samples during construction is essential to ensure that a satisfactory pavement is constructed. More states are beginning to compact samples in the laboratory during construction due to work performed by the FHWA field laboratory and due to increased awareness by state DOTs. Measurement of the VTM in laboratory compacted mixtures is the most important test that can be conducted to evaluate expected performance.

Correlation coefficients for the construction mix properties, lab compacted mix properties, and rate of rutting for all sites were determined. The correlations were not highly significant because of the low number of 75-blow projects and insufficient data for some mix properties and therefore the results are not presented here.

Mix Design Compactive Effort

Design of asphalt mixtures by the Marshall method is based on the assumption that the laboratory compacted test samples will have a density approximately equal to the density of the mixture in service after several years of traffic. Selection of the proper compaction level during the mix design phase is critical for proper pavement performance. If the mix design compactive effort is too low, excessive asphalt contents will be designed and rutting could develop as a result of low in-place air voids due to a higher density in-place after traffic than achieved in the mix design.

To evaluate the adequacy of the mix design compactive effort the mix design unit weights were compared to the in-place unit weight. If the mix design compactive effort is adequate the unit weight in-place after traffic should be similar to the mix design unit weight.

Twenty-two of the layer 1 mixes were 50-blow mixes and 10 were 75-blow mixes. Figure 7 shows the difference in pounds between the in-place unit weight and the mix design unit weight for the 50-blow mixes. The in-place unit weight exceeded the mix design unit weight in 18 of 22 sites or 82% of the time. Only four sites were below the mix design unit weight. Fifteen sites exceeded the mix design unit weight by over 2 pounds per cubic foot (approximately one standard deviation). Only five of 20 sites had in-place unit weight within plus or minus 2 pounds of the 50-blow mix design unit weight.

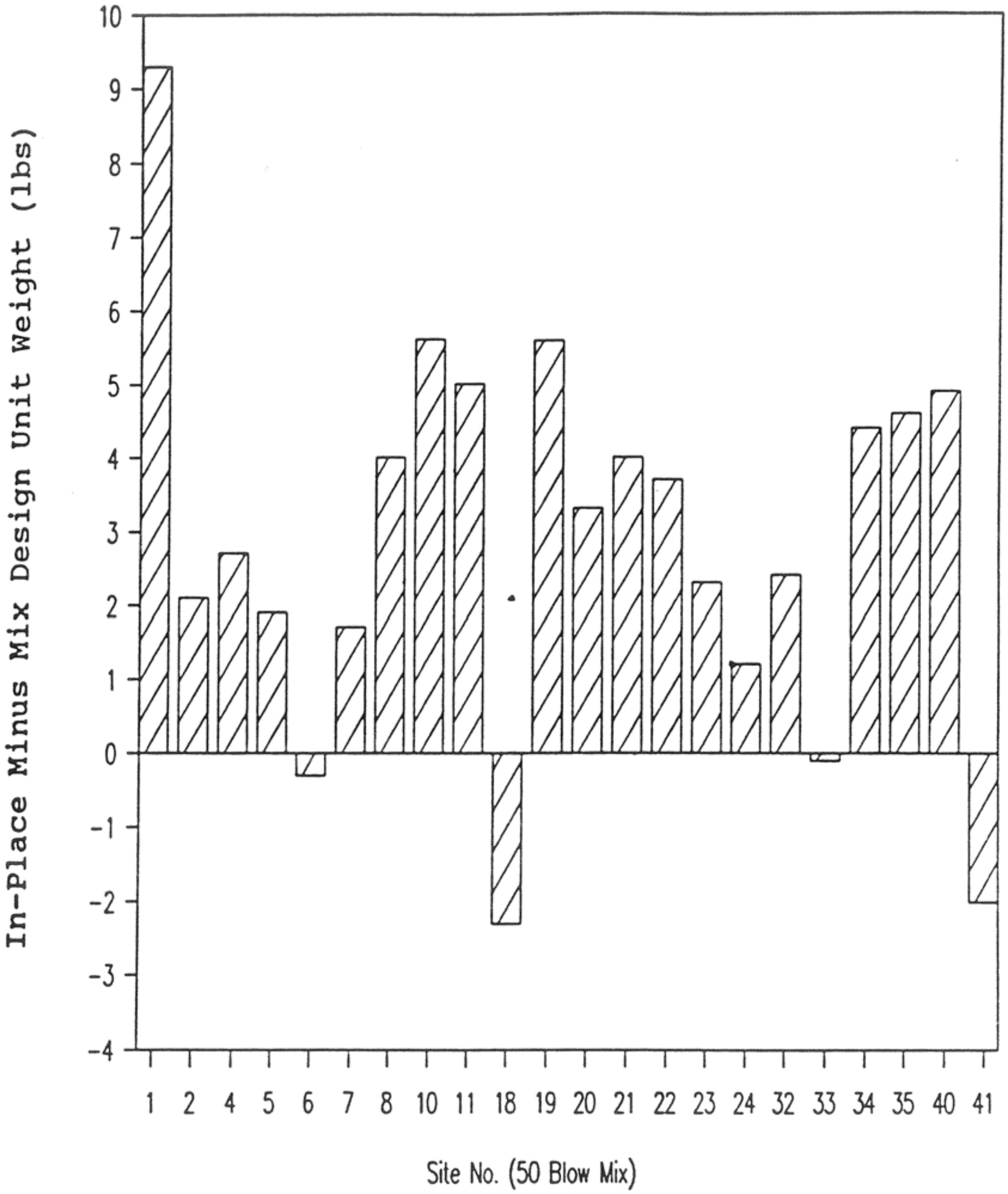

Figure 7. Difference in Pounds Between 80th Percentile In-Place Unit Weight and Mix Design Unit Weight for 50-Blow Marshall Mix Designs

The 75-blow mixes are shown in Figure 8. Seven of 10 sites were over the mix design unit weight, but only three of ten by over 2 pounds per cubic foot. Seven of 10 sites were within plus or minus 2 pounds per cubic foot of the mix design unit weight.

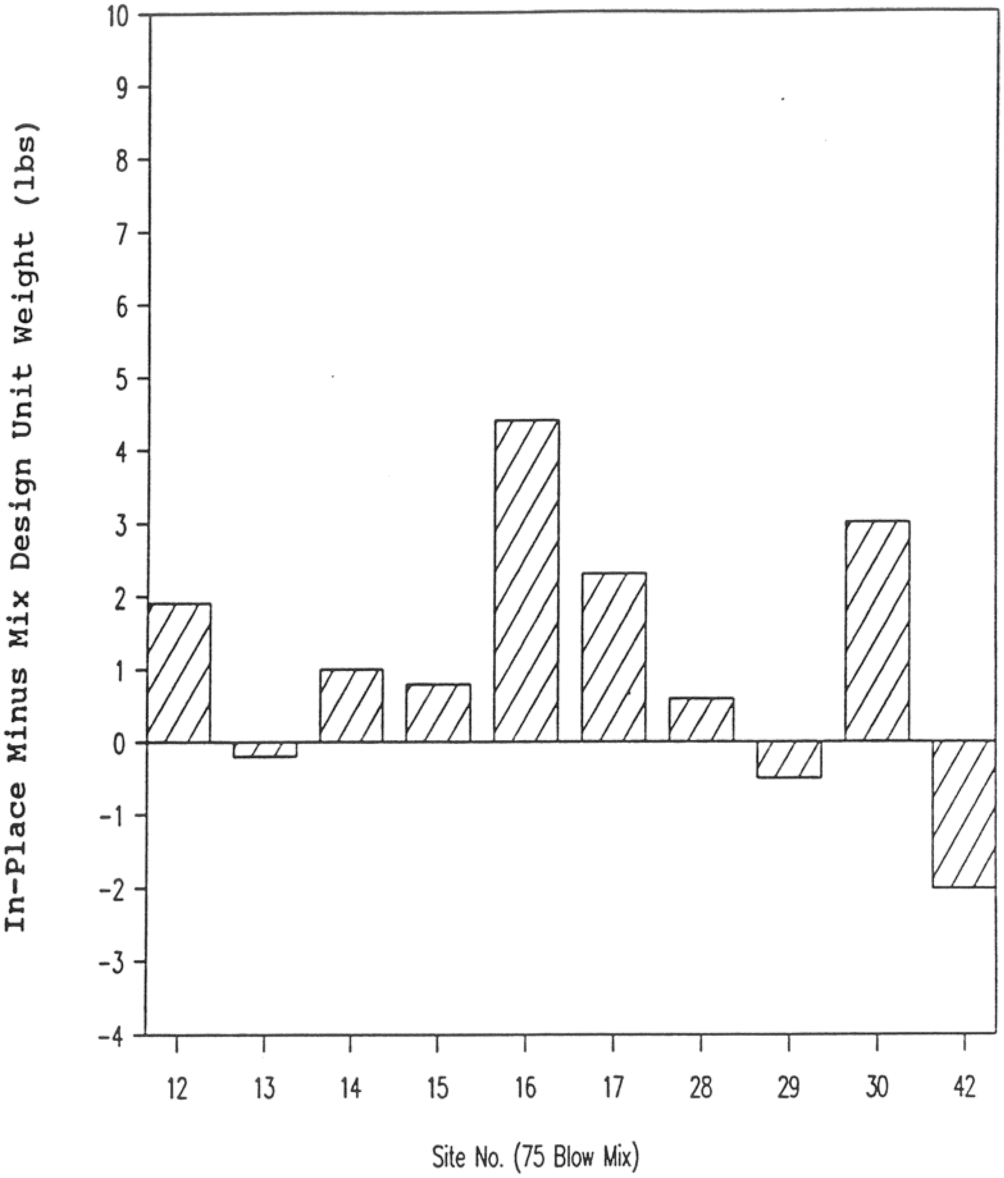

Figure 8. Difference in Pounds Between 80th Percentile In-Place Unit Weight and Mix Design Unit Weight for 75-Blow Marshall Mix Designs

All of the pavements evaluated carried high volumes of heavy truck traffic. Neither the 50-blow nor 75-blow mixes had in-place weights within 2 pounds of the mix design unit weight in every case. However, the 75-blow mixes had a much higher percentage within 2 pounds (70%) than the 50-blow mixes (25%). It is obvious from these data that 50 blows per side is not an adequate compactive effort for mixes subjected to heavy truck traffic and that mixes subjected to heavy truck traffic should be designed using 75-blow compactive effort.

Data From Recompacted Samples

There is always a difference in the properties of a mix during mix design and during plant production. This difference at least partially accounts for the poor correlations between mix design parameters and performance. By evaluating the aggregate, asphalt content and gradation from cores and mix properties from recompacted material, the material and volumetric properties of the mix "as-placed" can be estimated. Ideally this information should be obtained during mix production but this information was generally not available. The estimated mixture and materials properties can then be utilized to determine the mixture properties that affect rutting.

Air Voids

It is well established in the literature that low air voids (usually lower than 3% as determined from bulk specific gravity and Rice specific gravity of the mixture) cause rutting (5, 6, 7, 8, 10, 13). Excluding the 5 OGFCs, the relationship between the rate of rutting and the 20th percentile in-place air void content is shown in Figure 9. The relationship has a very low R-square, 0.09. However, the data does show that if the in-place voids drop below 3.0 to 4.0% the probability of experiencing unacceptable rates of rutting increases. Of the layer 1 pavements with voids below 3.0%, 17 of 21 or 81% had rates of rutting above 0.00023 inches per square root ESALs and above 3.0% voids only 6 of 13 or 46% had unacceptable rates of rutting. If the voids stayed at 4.0% or above, only one of seven or 14% had unacceptable rates of rutting.

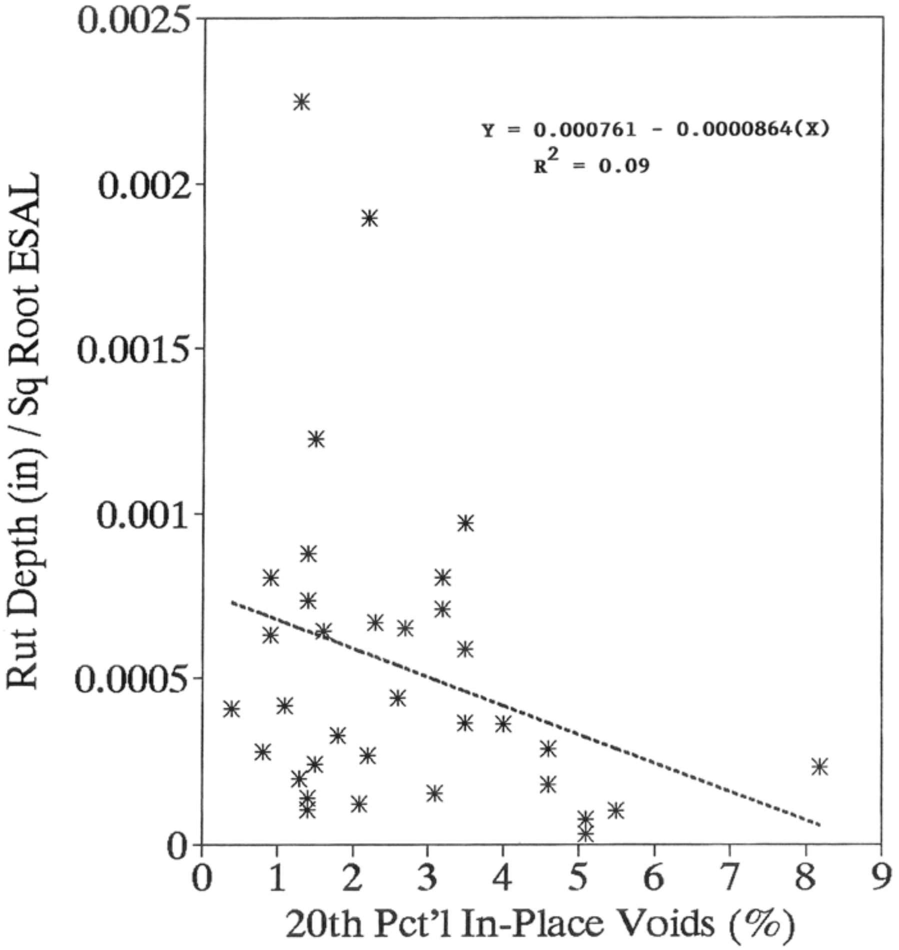

Figure 9. 20th Percentile In-Place Voids vs. Rate of Rutting

The amount of rutting is also a function of voids in the recompacted mix. Voids in the recompacted mixes are an estimate of the mix design void content. The broken up mix is reheated to a temperature that provides a satisfactory viscosity for compaction and the resulting density should therefore be very close to the initial mix design density. Excluding OGFCs, 21 of 28 or 75 % of the layer 1 mixes (Figure 10) had unacceptable rates of rutting when the voids were below 3.0% for GTM recompacted samples. When the voids were above 3.0%, four of seven or 57% of the mixes had unacceptable rates of rutting. If the voids stayed above 4.0%, none of the mixes had unacceptable rates of rutting.

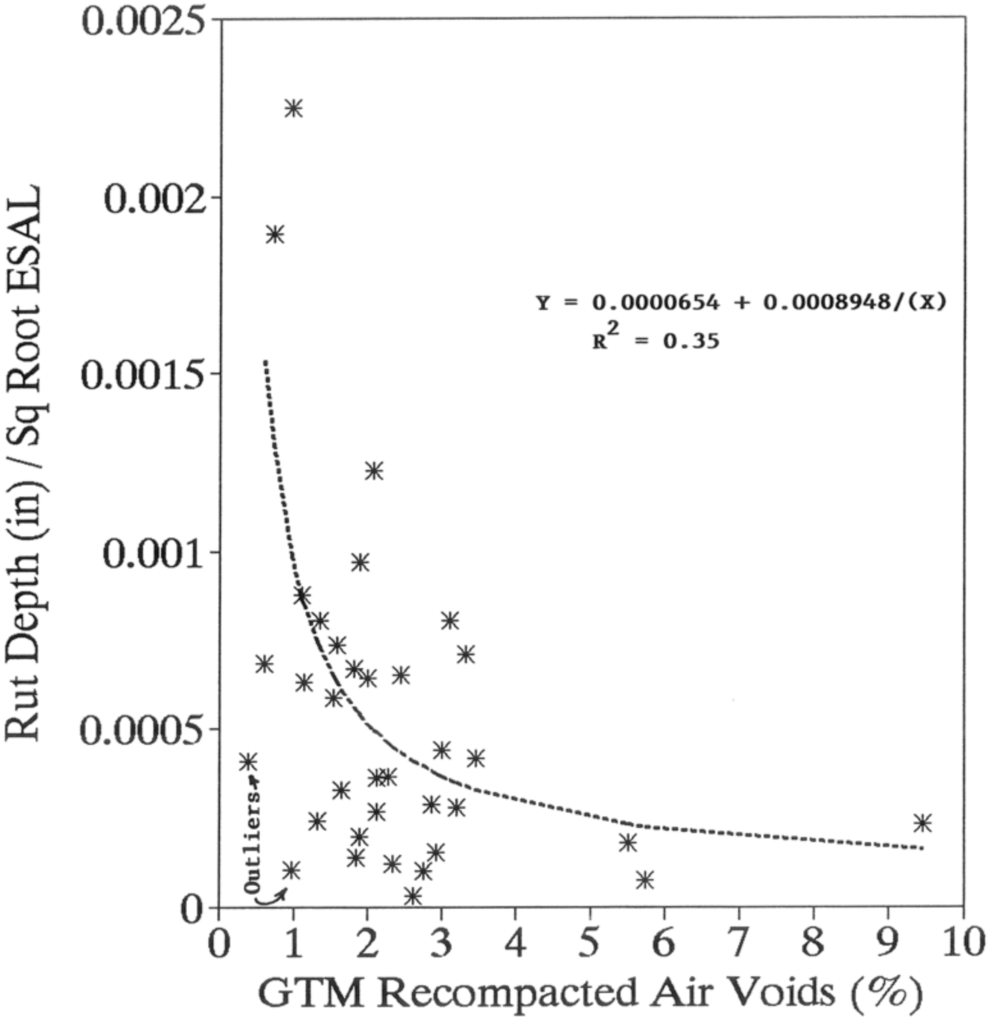

Figure 10. GTM Voids, Recompacted to 300 Revolutions at 120 psi, 1 Degree Gyration Angle vs. Rate of Rutting

The same is true of the 75-blow Marshall recompacted samples. The results are shown in Figure 11. Excluding OGFCs, when the voids were below 3.0%, 23 of 28 or 82% of the layer 1 mixes had unacceptable rates of rutting and above 3.0%, two of seven or 29% had unacceptable rates of rutting. When the voids stayed above 4.0%, none of the mixes had unacceptable rates of rutting.

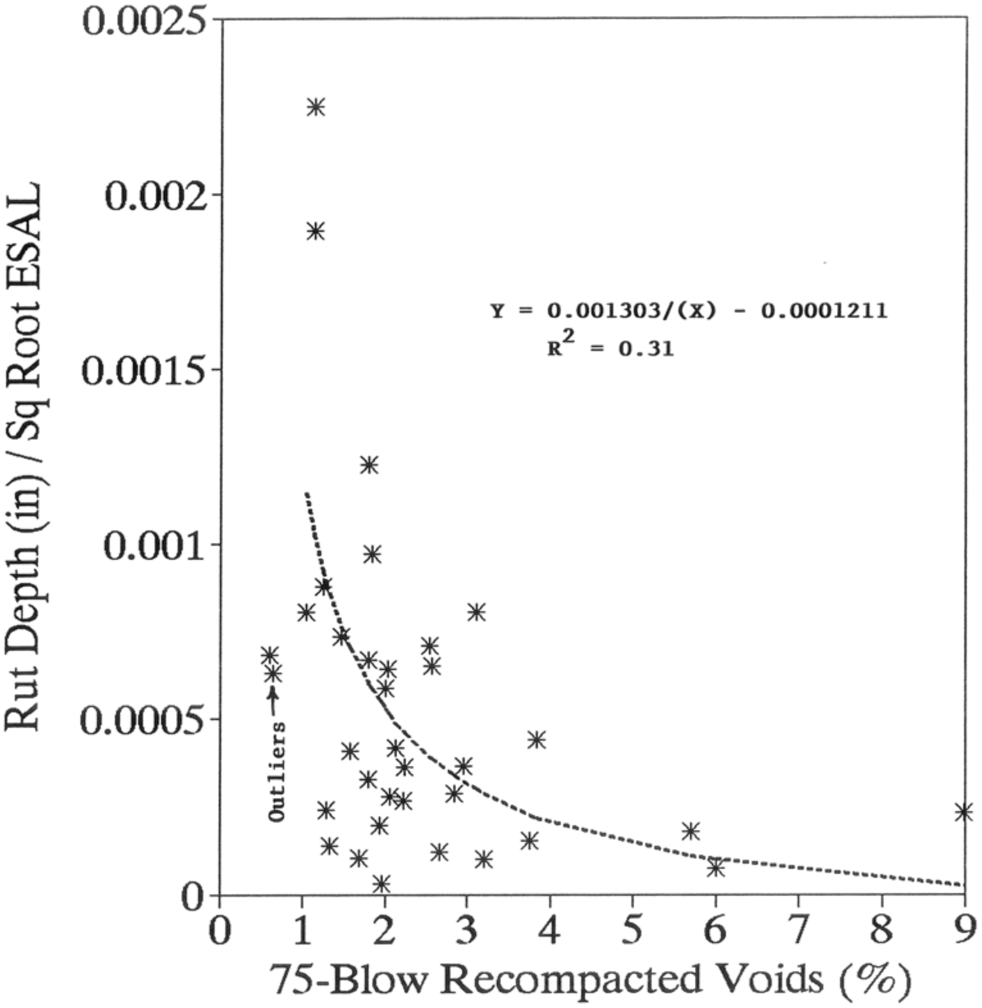

Figure 11. 75- Blow Marshall Recompacted Voids vs. Rate of Rutting

Voids have a significant effect on performance. It is evident from this study that when the voids drop below 3.0% to 3.5% in-place the probability of rutting increases significantly. These low voids are usually the result of low compactive effort in the laboratory (for example 50-blows) or failure to control the mix at the proper void content (as measured in laboratory compacted samples) during construction.

Aggregate Properties

The results of the tests on the aggregate properties were previously reported by the authors (12). The significant findings reported were that when the air voids are low rutting is likely to occur regardless of aggregate properties. To analyze the effect of aggregate properties only mixes having in-place voids above 2.5% were used. There were insufficient numbers of pavements with voids above 3.0%, hence the limit was decreased to 2.5% to provide enough data for analysis. Below 2.5% the aggregate properties seemed to have little effect on rutting. The results (12) showed that angular, crushed rough textured aggregates would control rutting when the voids were above 2.5% in-place. Aggregate particles were considered crushed when they had two or more fractured faces. A fracture had to be equal to at least one half the cross sectional area to be counted. The results are shown in Figures 12 and 13.

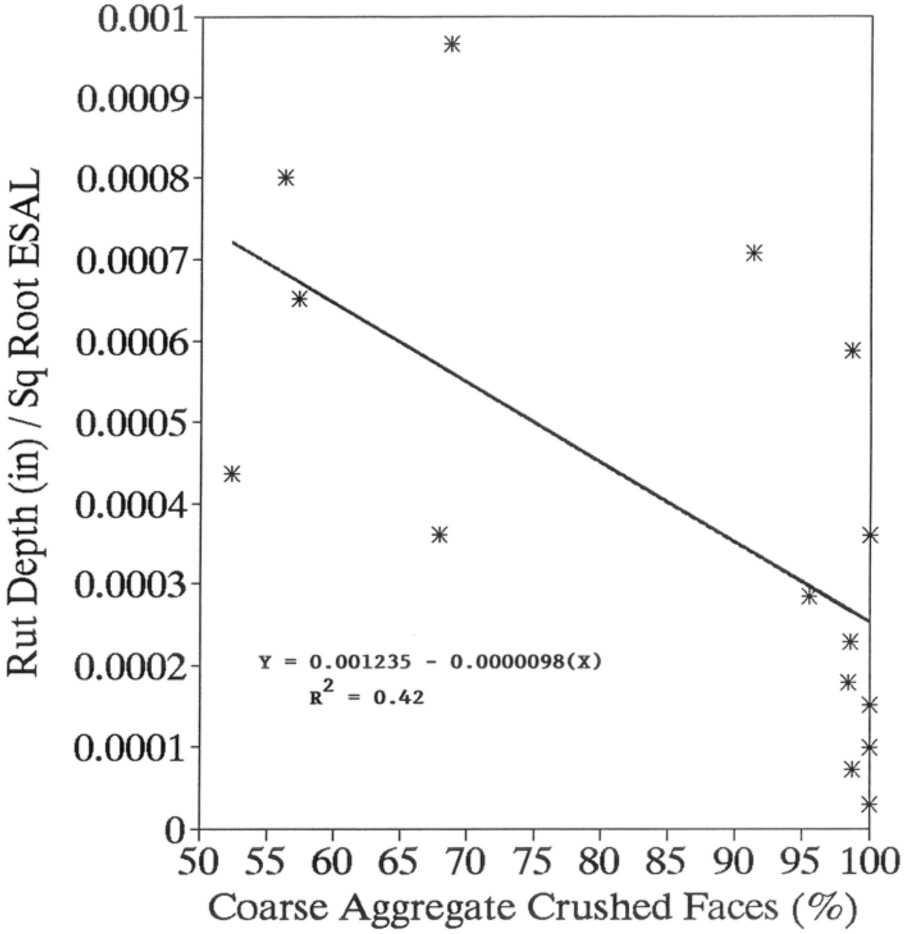

Figure 12. Coarse Aggregate (Plus No. 4) Two or More Crushed Faces vs. Rate of Rutting for Mixes with 20th Percentile In-Place Voids Greater Than 2.5 Percent

Asphalt Cement Properties

The asphalt cements were recovered from the in-place cores to determine their properties. The asphalt cement properties evaluated were viscosity at 140 and 275°F, penetration at 77 and 40°F and asphalt content. The results of the correlation analysis are shown in Table 13.

None of the asphalt cement properties alone had a good correlation with rate of rutting. The correlation improved when only those mixes with more than 2.5% in-place voids were analyzed. The best correlation with rutting was for penetration at 77°F with mixes above 2.5% voids in-place. So it appears that aggregate properties are important for controlling rutting but asphalt cement properties are not so important. The amount of asphalt cement, however, is extremely important.

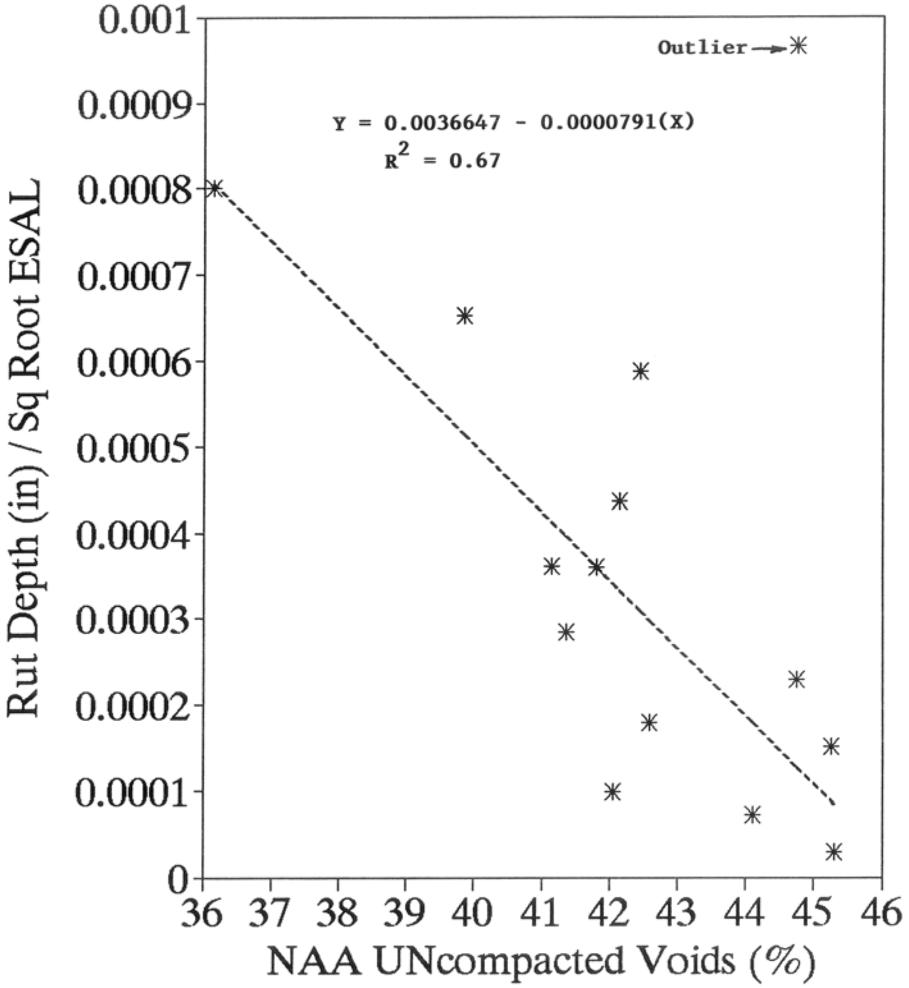

Figure 13. NAA Uncompacted Voids vs. Rate of Rutting for Mixes with 20th Percentile In-Place Voids Greater Than 2.5 Percent

Table 13. Summary of Correlations for Recovered Asphalt Cement

	Correlation with Rate of Rutting			
	All		**>25% VTM**	
Variable	**R-Value**	**n**	**R-Value**	**n**
Viscosity 275°F	-0.09	34	-0.22	14
Viscosity 140°F	-0.19	35	-0.34	15
Penetration 77°F	0.09	35	0.39	15
Penetration 40°F	0.35	33	0.35	14

Correlations with Recompacted Samples

Samples of the mixes were recompacted on both the GTM and with 75-blows per side with the manual Marshall hammer. The results of the correlation analysis for mix properties using both compactive efforts are shown in Table 14.

Table 14. Summary of GTM and 75-Blow Marshall

	GTM		**75-Blow**	
Variable	**R-Value**	**n**	**R-Value**	**n**
Voids Total Mix	-0.36	35	-0.37	35
Voids Mineral Agg.	-0.08	35	-0.09	35
Voids Filled Asphalt	0.40	35	0.41	35
Marshall Stability	-0.31	34	-0.39	34
Marshall Flow	0.01	34	0.18	34
GSI	0.36	35	N/A	N/A
GEPI	0.09	35	N/A	N/A
Shear Strength	-0.43	35	N/A	N/A

N/A = Not Applicable

The GTM mix parameters of shear strength and GSI had higher correlations with rutting than the normal Marshall design parameters of stability and flow. The best relationship found with rutting was GTM shear strength. The relationship is shown in Figure 14 and has an R-square of 0.52. As the shear strength decreases the rate of rutting increases. The relationship between GSI and rate of rutting is shown in Figure 15. The relationship has an R-square of 0.13 which is not high for prediction of rut depth but shows that as the GSI or plasticity of the mix increases the rate of rutting increases.

The Marshall recompacted mix properties did not correlate well with rate of rutting. The correlation coefficients are shown in Table 14. This data shows that VTM and VF are the best two mixture properties determined as part of the Marshall test that correlate with rutting.

Table 15 shows the means of the GTM recompacted parameters compared with performance. The results show that mixes with higher recompacted voids, higher stability, higher GTM shear strength and higher VMA perform better. Mixes with lower voids filled and lower GEPI perform better. It is likely that the high stability for good performing mixes was caused by the high voids and increased oxidation and hence using stability of aged pavements to predict rutting is likely to be misleading.

Table 16 shows the means of the Marshall recompacted parameters compared with performance. The results show that mixes with higher recompacted voids, higher VMA and higher stability perform better. Mixes with lower voids filled also perform better. Again, the measured high stability for good performing mixes was caused by the high voids and high rate of oxidation and cannot be used to predict rutting because the Marshall stability values from laboratory compacted samples during construction will be lower than that for aged mixes.

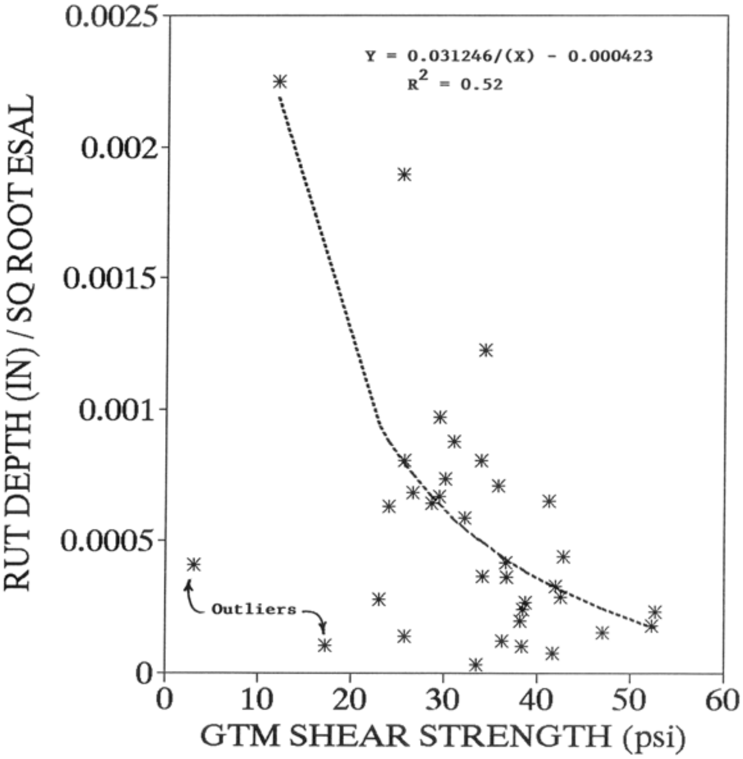

Figure 14. GTM Recompacted Shear Strength vs. Rate of Rutting

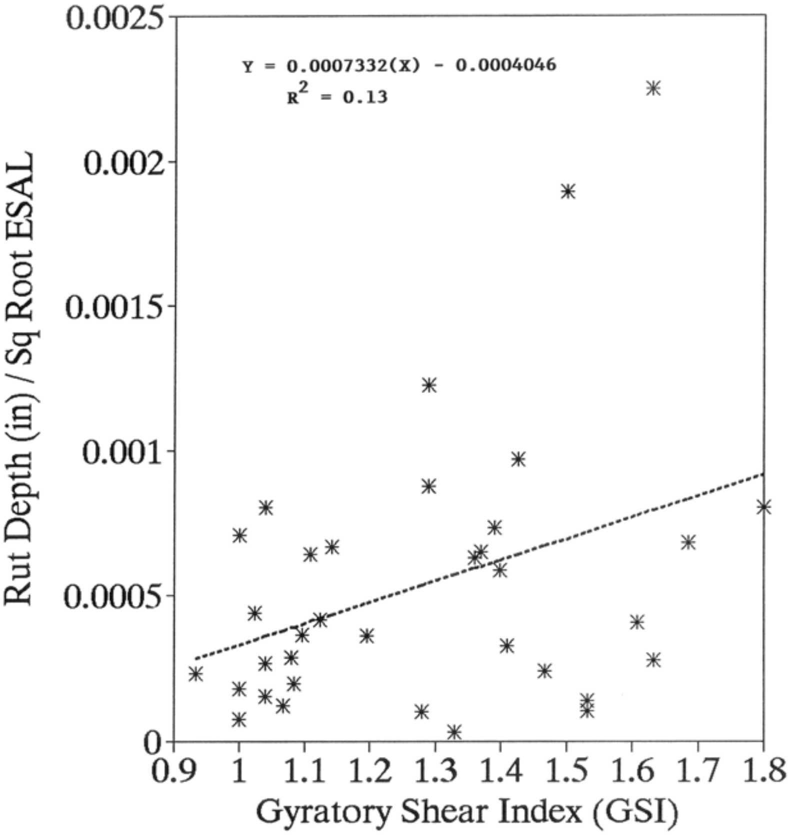

Figure 15. GTM Recompacted Gyratory Shear Index (GSI) vs. Rate of Rutting

Table 15. Summary of GTM and 75-Blow Marshall Recompacted

		GTM		75-Blow	
Variable		**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Voids Total Mix	Good	4.68	3.42	3.76	2.46
	Rutted	1.92	0.88	1.92	0.78
Voids Mineral Aggregate	Good	17.74	2.51	17.23	2.18
	Rutted	15.32	1.92	15.32	1.82
Voids Filled Asphalt (%)	Good	75.10	15.75	79.20	11.69
	Rutted	87.44	5.68	87.32	5.31
Marshall Stability (lbs)	Good	3250	1302	4436	1230
	Rutted	2846	690	3413	878
Marshall Flow (0.01 in)	Good	16.0	4.77	15.3	2.61
	Rutted	16.2	4.21	16.1	3.95
GSI	Good	1.15	0.21	N/A	N/A
	Rutted	1.32	0.23		
GEPI	Good	1.16	0.07	N/A	N/A
	Rutted	1.25	0.19		
Shear Strength (psi)	Good	38.35	11.14	N/A	N/A
	Rutted	31.16	9.31		

N/A = Not Applicable

Table 16.

Rutting Models

From the information presented it is evident that there is no one parameter that can predict the rate of rutting with any high degree of confidence. Therefore, it would be helpful if a model could be developed utilizing material parameters that would be available to the designer that could predict rutting.

The available data was investigated to determine if three to four independent variables could be used to predict rutting. The parameters selected for inclusion in the data base were mix properties, aggregate gradation, aggregate properties, and asphalt cement properties that had previously shown some correlation with rutting.

75-Blow Marshall Model

The best multiple variable model determined for the 75-blow Marshall, aggregate and asphalt cement parameters contained the variables recompacted voids and NAA uncompacted voids. Sites 12, 13, 14 and 21 appear to be outliers. Utilizing them as such, the relationship has an R-square of 0.54 and is shown in Figure 16. The equation has the following form:

$$P = 0.002876 - 0.00006(NAA) + \left(\frac{0.000382}{VTM}\right)$$

Where,

P = Predicted Rate of Rutting (in./Square Root ESALs)
NAA = NAA Uncompacted Voids, Method A, %, (individual test result)
VTM = Marshall Recompacted Voids, %, (average of three samples)

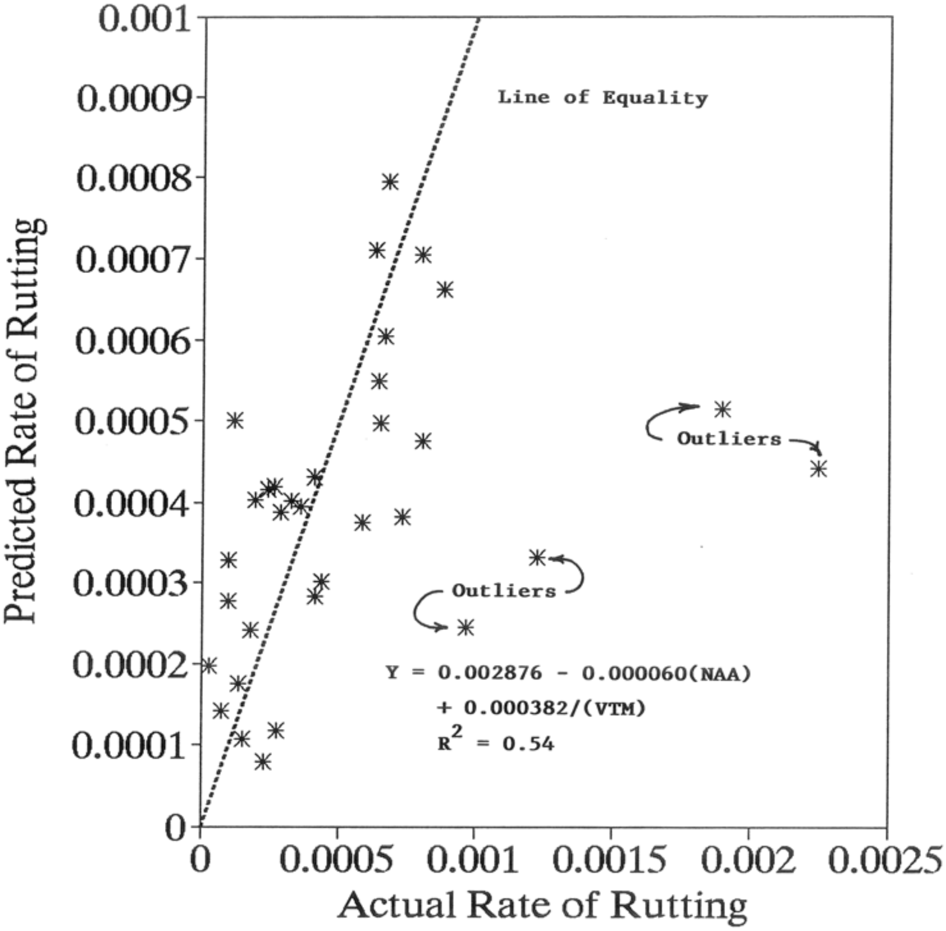

Figure 16. Predicted Rate of Rutting (P) vs. Actual Rate of Rutting from 75-Blow Marshall Recompacted Voids (VTM) and NAA Uncompacted Voids (NAA)

GTM Model

The best multiple variable model that could be found for the GTM, aggregate and asphalt cement parameters contained the variables GTM recompacted voids, GTM shear strength and NAA uncompacted void content. Sites 1 and 36 were identified as outliers for voids and shear strength and utilizing them as such, the relationship has an R-square of 0.64 and is shown in Figure 17. Site 36 is identified on the plot as an outlier, however, site 1 which had a predicted rate of rutting of over 0.008, is not shown on the plot. The equation has the following form:

$$P = 0.00150 - 0.0000474(NAA) + \left(\frac{0.000212}{VTM}\right) + \left(\frac{0.02661}{S}\right)$$

Where,

P = Predicted Rate of Rutting (in./Square Root ESALs)
NAA = NAA Uncompacted Voids, Method A, % (individual test result)
VTM = GTM Recompacted Voids, % (average of three samples)
S = Shear Stress to Produce 1 Degree Angle, psi (average of three samples)

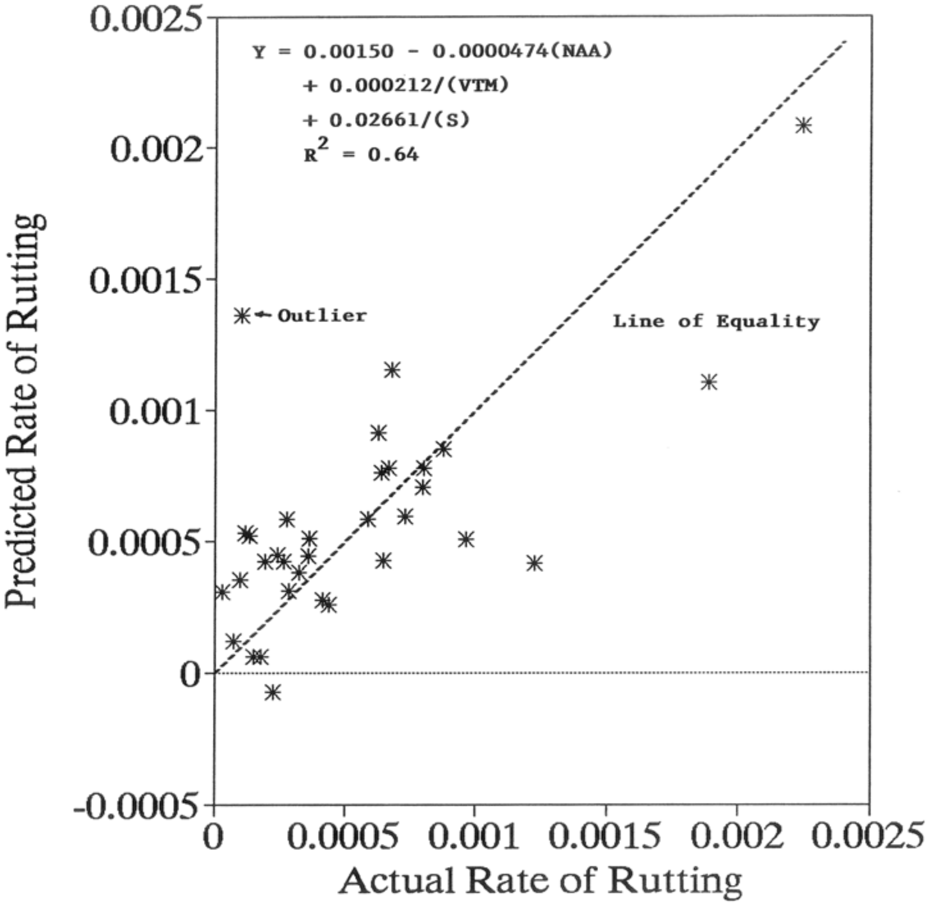

Figure 17. Predicted Rate of Rutting (P) vs. Actual Rate of Rutting from GTM Recompacted Voids (VTM), GTM Shear Strength at 300 Revolutions (S), and NAA Uncompacted Voids (NAA)

The above analysis shows that the GTM parameters can do a better job of predicting rutting than the Marshall parameters.

Aggregate Model

It was previously shown by the authors (*12*) that when the in-place voids of the mix dropped below 2.5%, the aggregate properties had little effect on rate of rutting. Therefore, to determine the effect aggregate properties had on rutting, it was necessary to evaluate mixes with high air voids. Based on all of the data the best method to control rutting is to insure quality of coarse and fine aggregate and to keep the voids above a minimum value. The best model reported by the authors (*12*) for predicting rate of rutting from aggregate properties when the in-place voids were greater than 2.5% included the percent of aggregate with 2 or more crushed faces for coarse aggregate (plus No. 4) and NAA Uncompacted voids. The plot is shown in Figure 18. Site 13 appears as an outlier. Utilizing site 13 as such, the relationship has an R-square of 0.72. The relationship has the following form:

$$P = 0.0031515 - 0.0000035(CF) - 0.0005968\ (NAA)$$

where,

P = Predicted Rate of Rutting (in./square root ESALs)
CF = Percent of Coarse Aggregate with 2 or more crushed faces (individual test result)
NAA = NAA Uncompacted Voids, Method A, % (individual test result)

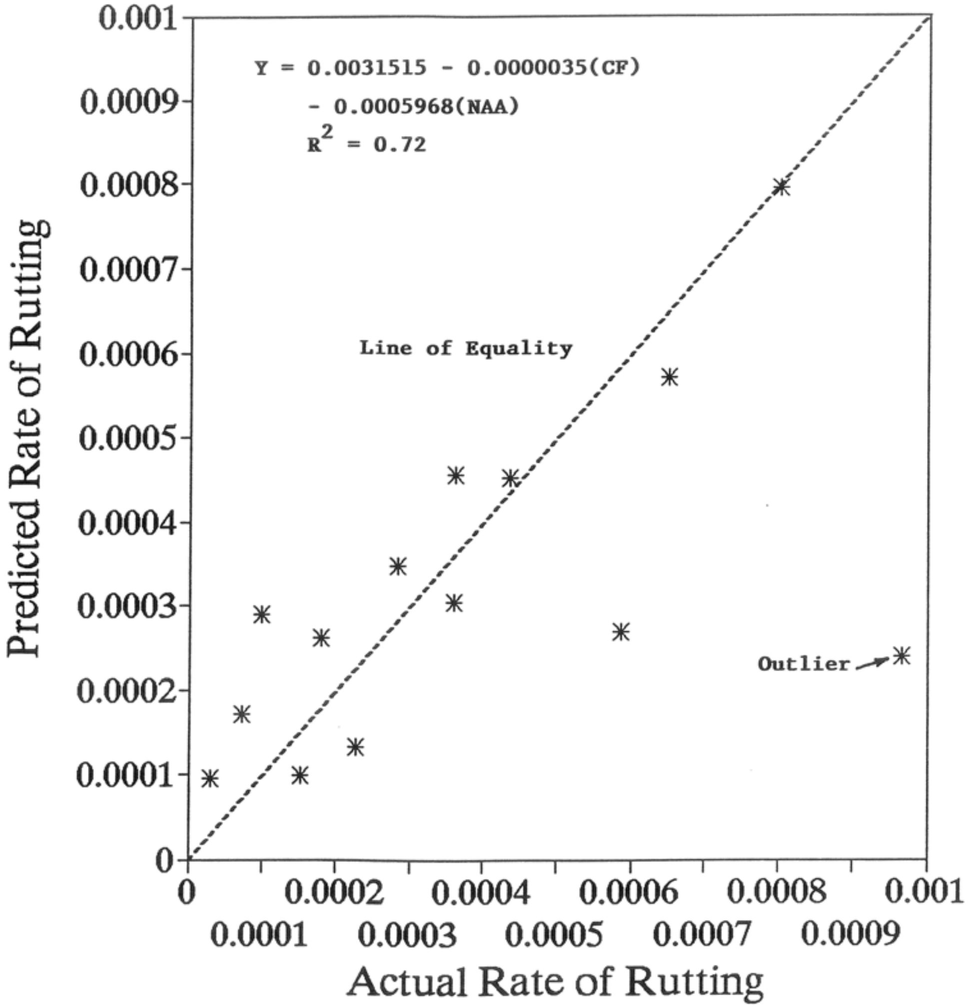

Figure 18. Predicted Rate of Rutting (P) vs. Actual Rate of Rutting for Percent Coarse Aggregate with Two or More Crushed Faces (CF), and NAA Uncompacted Voids (NAA) with In-Place VTM Greater Than 2.5%

Model Combining Layer 1 and Layer 2 Properties

All of the above models have used the properties from the top layer to predict the rate of rutting. It is obvious that the properties from the second layer and lower layers in the pavement structure affect the amount of rutting and this was seen in many of the trenches. An attempt was made to combine the properties of the first two layers to predict rutting. Several models were attempted including averaging the properties of the two layers, using a weighted average based on the average shearing stress in each layer, and entering each property of each layer separately. The analysis was unsuccessful in developing a more statistically significant model than the models developed utilizing the material properties of the top layer only.

CONCLUSIONS

Based on the data obtained in this study the following conclusions are warranted.

1. Sixty-nine percent of the pavements evaluated that were designed with the Marshall method utilized a 50-blow compactive effort. This resulted in high asphalt content and led to low in-place voids after traffic and subsequently rutting.
2. Construction quality control documentation was not adequate for the paving projects studied herein. Thirty-three percent of the sites had no construction history available. Only 38% of the sites utilized laboratory compacted samples of the asphalt mixtures from the mixing plant during construction to verify that the air voids were within an acceptable range. Fifty-three percent of the sites that measured voids in laboratory compacted samples had voids less than 3%.
3. Most of the rutting observed from trench cuts of rutted pavements occurred in the top 3-4 inches of the HMA. Hence, high quality mixtures should be required in the top two layers.
4. In-place air void contents above approximately 3.0% are needed to decrease the probability of premature rutting throughout the life of the pavement. In-place air void contents below approximately 3.0% greatly increase the probability of premature rutting. The asphalt mixture must be placed with a void content significantly above 3.0% (usually 5-7%) using a reasonably high compactive effort to insure that the voids in the mix stay above 3.0% during traffic.
5. The shear strength of the recompacted mix as indicated by the GTM roller pressure had the best correlation with rutting of any single factor.
6. If the in-place air voids are above 2.5% the angularity of the aggregate as measured by percent of coarse aggregate (plus No.4) with 2 or more crushed faces and NAA Uncompacted Voids for the fine aggregate (passing No.4) are highly correlated to rate of rutting.
7. The properties of the asphalt cements extracted from the mixtures are not closely related to rutting. The amount of asphalt cement is of primary importance but the properties of the asphalt cement are of secondary importance.
8. A rate of rutting of 0.00023 inches per square root ESALS delineated between good and rutted pavements for the pavements evaluated.
9. Rutting on high volume roadways can be prevented if angular coarse and fine aggregates are used and if the air voids in the mixture do not fall below approximately 3.0%.

RECOMMENDATIONS

Based on the data obtained in this study the following recommendations are made.

1. Pavements for heavy truck trafficked pavements should be designed utilizing a 75-blow manual Marshall mix design or equivalent and the optimum asphalt cement content selected to give 4.0% VTM if the Marshall method is used.
2. Pavements and mix design compactive effort should be evaluated to ensure that the mix design unit weight is approximately equal to the in-place density after at least two to three years of traffic. If not the mix design compactive effort should be modified.
3. The aggregate gradation deviates from the mix design during the construction process. Therefore, samples of the asphalt mixtures from the mixing plant should be compacted in the laboratory, utilizing the proper compactive effort, during construction to verify that the air voids are within an acceptable range. If the air voids are not within an acceptable range adjustments to the mix should be made.
4. Mixtures for heavy truck trafficked pavements are best evaluated on the GTM at 300 revolutions, 1 degree gyration angle and 120 psi to determine the susceptibility for rutting.
5. Pavements should be designed with rough textured angular aggregates to minimize rutting. Aggregate properties should be selected based on the model shown to provide desired performance.

REFERENCES

1. Middleton, D.R., F.L. Roberts, and T. Chira-Chavala, “Measurements and Analysis of Truck Tire Pressures on Texas Highways,” Transportation Research Record 1070, Transportation Research Board, Washington, D.C., 1986, pp. 1-8.
2. Kim,O. and C.A.Bell, “Measurement and Analysis of Truck Tire Pressures in Oregon,’Transportation Research Record 1207, Transportation Research Board, Washington, D.C., 1988, pp. 100-110.
3. Hudson,S.W and S.B. Seeds, “Evaluation of Increased Pavement Loading and Tire Pressures,” Transportation Research Record 1207, Transportation Research Board, Washington, D.C., 1988, pp. 197-206.
4. ____________, “Proceedings, A Symposium/Workshop on High Pressure Truck Tires,” American Association of State Highway and Transportation Officials and Federal Highway Administration, Austin, Texas, February 1987.
5. Ford, Miller C., “Development of a Rational Mix Design Method for Asphalt Bases and Characteristics of Arkansas Asphalt Mixtures,” FHWA Report No. FHWA/AR-85/004, Arkansas Highway and Transportation Department, July 1985.
6. Kandhal, Prithvi, Stephen A. Cross, and E.R. Brown, “Evaluation of Bituminous Pavements for High Pressure Truck Tires,” FHWA Report No. FHWA-PA-90-008+87-01, Pennsylvania Department of Transportation, December 1990.
7. Parker, Frazier and E.R. Brown, “Effects of Aggregate Properties on Flexible Pavement Rutting in Alabama,” Effects of Aggregate and Mineral Fillers on Asphalt Performance, ASTM STP 1147, Richard C. Meininger, Ed., American Society for Testing and Materials, Philadelphia, PA 1992.
8. Huber, G.A. and G.H. Heiman, “Effects of Asphalt Concrete Parameter on Rutting Performance: A Field Investigation,” Proceedings, Association of Asphalt Paving Technologists, Volume 56, 1987, pp. 33-61.
9. Cross, Stephen A. and E. Ray Brown, “A National Study of Rutting in Asphalt Pavements,” NCAT Draft Report No. 91-8, National Center for Asphalt Technology, Auburn University, Alabama, 1991.
10. Brown, E.R. and Stephen A. Cross, “A Study of In-Place Rutting of Asphalt Pavements,” Proceedings, The Association of Asphalt Paving Technologists, Volume 59, 1990.
11. Meininger, Richard C., “Proposed Method of Test for Particle Shape and Texture of Fine Aggregate Using Uncompacted Void Content,” The National Aggregate Association, Silver Springs, MD, March 1989.
12. Cross, Stephen A. and E.R. Brown, “Selection of Aggregate Properties to Minimize Rutting of Heavy Duty Pavements,” Effects of Aggregate and Mineral Fillers on Asphalt Performance, ASTM STP 1147, Richard C. Meininger, Ed., American Society for Testing and Materials, Philadelphia, PA 1992.
13. Brown, E.R. and Stephen A. Cross, “Comparison of Laboratory and Field Density of Asphalt Mixtures,” TRR 1300, Transportation Research Board, Washington, D.C., 1991.