Comparison of Laboratory and Field Density of Asphalt Mixtures

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The objective of this paper is to investigate the relationships among the measured density of an asphalt mixture in the mix design, during quality control (QC) of the mixture (laboratory compaction of a field-produced mix), after initial compaction (after construction and before traffic), after densification by traffic (ultimate density), and after recompaction. Of primary concern is the relationship among density after traffic, mix-design density, and density of laboratory-compacted samples during construction. Eighteen different pavements from six states were sampled. Thirteen were rutting prematurely; five were performing satisfactorily. Construction history, including mix-design data, QC or quality assurance data or both, traffic data, and laboratory data of the physical properties of the pavement cores were analyzed from each site. The results show that in-place air-void contents below 3 percent greatly increase the probability of premature rutting and that the in-place unit weights of the pavements after traffic usually exceed the mix-design unit weight, resulting in low air voids and hence premature rutting.

Density, or in-place unit weight, is an important component of a properly designed and constructed asphalt pavement. Selection of the proper compaction level during the mix-design phase is critical for proper pavement performance. The Asphalt Institute (1) recommends that the mix-design density closely approach the maximum density of the pavement under traffic. The Marshall mix-design method as originally developed by the U.S. Army Corps of Engineers at the Waterways Experiment Station (2) in the late 1940s was based on the evaluation of samples compacted to a relative density that approximated the density developed by a number of repetitions of a selected aircraft. The original method called for compacting samples to 50 blows per side for tire pressures up to 100 psi and 75 blows per side for pressures greater than 100 psi. The Marshall method has been adapted to highway use with 50 blows per side for medium traffic and 75 blows per side for heavy traffic (1).

In recent years, studies have shown that typical truck tire pressures are approaching 120 psi (3) and that higher truck tire pressures and increased truck traffic have led to an increase in premature rutting (4). The problem could very well be that the mix-design density is being exceeded by the in-place density. This excess density in the field results in low in-place air voids. The relationship between low air voids and rutting is well established in the literature (5–7).

The objective of this paper is to investigate the relationships among the measured density of the mixture in the mix design, during quality control (QC) of the mixture (laboratory compaction of a field-produced mix), after initial compaction (after construction and before traffic), after densification by traffic (ultimate density), and after recompaction. Of primary concern is the relationship among density after traffic, mix-design density, and density of laboratory-compacted samples during construction.

Eighteen of the 30 pavements sampled in a National Center for Asphalt Technology (NCAT) rutting study were selected for study. The 18 pavements were those for which traffic data, mix-design data, and QC or quality assurance (QA) data or both were available. Thirteen had rutted prematurely. The ages of these rutted pavements ranged from 1 to 6 years at the time of sampling. Five of the 18 pavements were identified by the various states as performing satisfactorily (Sites 4, 8, 10, 18, and 24). These five pavements ranged in age from 5 to 16 years at the time of sampling.

TEST PLAN

The test plan for the rutting study is shown in Figure 1. A complete listing of the overall test plan can be found elsewhere (5). The field testing consisted of obtaining 4- and 6-in.-diameter cores, measuring rut depths, and, in a majority of the rutted pavements, viewing the pavement layers in a trench cut across the traffic lane. In general, 11 to 12 cores were obtained on 1-ft intervals across the traffic lane at each site. The 4-in. cores were saved for further testing. The 6-in. cores were tested, and the relevant results are reported herein.

Rut-depth measurements were obtained using a 12-ft 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 in. at 1-ft intervals over the core locations. Rut-depth measurements at each core location and measurements of each core allowed the determination of the relative elevation of each pavement layer. 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 near the middle of the rut. Rut depths and the traffic information are presented in Table 1.

Laboratory tests were conducted to characterize the material and mixture properties. The 6-in. cores were first measured to determine the layer thickness of each core. Next, the cores were sawed into their respective pavement layers, and the bulk specific gravity was determined (ASTM D2726) for each layer. The bulk specific gravities were evaluated across the pavement lane for each layer to determine the average in-place unit weight and the standard deviation of the
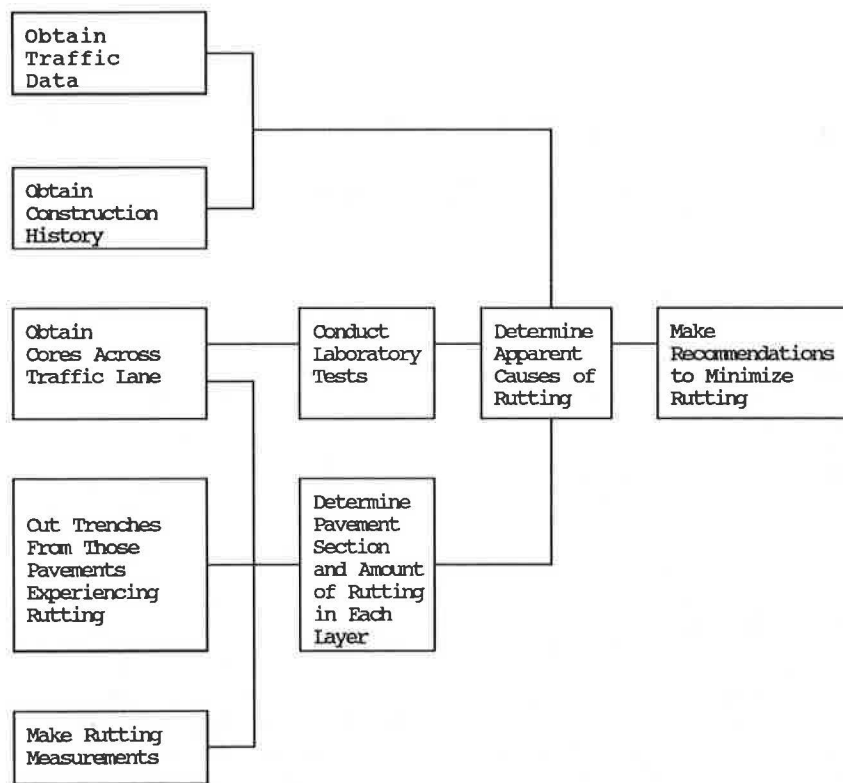
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┌──────────────┐
│ Obtain       │───────┐
│ Traffic      │       │
│ Data         │       │
└──────────────┘       │
                       │
                       │
┌──────────────┐       │
│ Obtain       │───────┤
│ Construction │       │
│ History      │       │
└──────────────┘       │
                       │
┌──────────────┐   ┌──────────────┐   ┌──────────────┐   ┌──────────────┐
│ Obtain       │   │ Conduct      │   │ Determine    │   │ Make         │
│ Cores Across │───│ Laboratory   │───│ Apparent     │───│ Recommendations │
│ Traffic Lane │   │ Tests        │   │ Causes of    │   │ to Minimize  │
└──────────────┘   └──────────────┘   │ Rutting      │   │ Rutting      │
                                      └──────────────┘   └──────────────┘
                   ┌──────────────┐
┌──────────────┐   │ Determine    │
│ Cut Trenches │   │ Pavement     │
│ From Those   │   │ Section      │
│ Pavements    │───│ and Amount   │
│ Experiencing │   │ of Rutting   │
│ Rutting      │   │ in Each      │
└──────────────┘   │ Layer        │
                   └──────────────┘
┌──────────────┐
│ Make Rutting │
│ Measurements │
└──────────────┘
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FIGURE 1   Test plan.

measured unit weights. These data were used to determine the 80th-percentile in-place density. Two cores were then selected, and the maximum theoretical specific gravity was determined (ASTM D2041). From the average maximum theoretical specific gravity, the average and 20th-percentile in-place air-void contents were determined. Previous research at NCAT (5) showed the 20th and 80th percentiles to be reasonable to use for comparison of in-place air voids and density after traffic with air voids and density of recompacted samples. The two cores were then extracted to determine the asphalt content (ASTM D2172).

The remaining 6-in. cores were reheated, broken up, and recompacted using two compactive efforts: 75 blows per side with the manual Marshall hammer (standard compactive effort) and 300 revolutions on the Gyratory Testing Machine (GTM) at 120 psi and a 1-degree angle. The processes produce samples that have densities approximately equal to the mix after several years of heavy traffic. Hence recompacted densities are approximately equal to mix-design densities if the materials are the same and the proper procedures are used. The recompacted samples were tested for unit weight, air-void content, Marshall stability, and flow. The average results of the tests performed on the 6-in. cores are presented in Table 2; the average results of the recompaction analysis are presented in Table 3.

Construction history and mix-design information for the pavements evaluated were provided by the various states. The data reported are all of the data available to NCAT at the time this report was prepared. The mix-design information relevant to this study is summarized in Table 4; the construction history data are presented in Table 5.

ANALYSIS OF TEST RESULTS

Design of asphalt mixtures by the Marshall method is based on the assumption that the laboratory-compacted test samples will approximate the density of the mixture in service after several years of traffic. If the mix-design density is too low, rutting could develop as a result of low air voids caused by pavement densification under traffic. The purpose of this study is to evaluate the physical characteristics of asphalt pavements, mainly density and air voids, during the various stages of the pavement's life and relate those characteristics to rutting. The stages investigated were mix design, construction, after construction and before traffic, after traffic, and laboratory recompaction.

An attempt was made to relate the rut depth of the pavement to the density and void properties of the mixtures. However, some scatter, which is caused by several factors, exists in the data. Some of the major factors contributing to the scatter include varying amounts of traffic, different aggregate properties of the mixtures, and the temperature of the pavement surface when traffic was first applied. These factors are not addressed in this report. To help alleviate the problem of different traffic loadings on the various layers of pavements, the analysis was performed on mixtures of the same layer in the pavement structure. In addition, only data from original pavement layers or the latest overlays were used in the analysis. This was done to remove the effects of various surface preparation techniques, such as milling before overlaying, on the relationship between rut depth and mixture properties. Open graded friction courses were present on 5 of the 18 pavements selected for analysis (Sites 2, 3, 5, 18, and 20).

TABLE 1 SUMMARY OF RUT-DEPTH CALCULATIONS AND TRAFFIC

SITE	LAYER	MIX TYPE	AVERAGE LAYER THICKNESS (in)	MAXIMUM SURFACE RUT DEPTH (in)	MAXIMUM RUT IN EACH LAYER (in)	TOTAL 18-kip ESAL's (millions)	TRUCK TRAFFIC (%)
1	1	SURFACE	2.4318	1.5000	1.0000	11.80	50
1	2	BINDER	2.0682	1.5000	0.0000	11.80	50
1	3	SAND	7.9659	1.5000	0.5000	11.80	50
2	N/T	OGFC	0.8000	0.8958	0.1667	2.05	20
2	1	SURFACE	1.2750	0.8958	0.4583	2.05	20
2	N/T	OLD PVM'T	14.2750	0.8958	0.2708	2.05	20
3	N/T	OGFC	0.6932	0.3750	0.1250	3.12	22
3	1	SURFACE	1.5682	0.3750	0.2500	3.12	22
3	2	BINDER	2.4306	0.3750	0.0000	3.12	22
4	1	SURFACE	1.1818	0.2500	0.0000	2.74	12
4	2	BINDER	2.2045	0.2500	0.1000	2.74	12
4	3	BINDER	2.5000	0.2500	0.0000	2.74	12
4	4	BASE	2.2614	0.2500	0.0250	2.74	12
4	5	BASE	4.8068	0.2500	0.1250	2.74	12
5	N/T	OGFC	0.7676	0.6250	0.1250	5.25	41
5	1	SURFACE	1.2045	0.6250	0.3125	5.25	41
5	2	BINDER	1.5511	0.6250	0.1250	5.25	41
5	N/T	OLD PVM'T	9.0057	0.6250	0.0000	5.25	41
6	1	SURFACE	1.4271	0.5750	0.2000	2.00	23
6	2	BINDER	1.9115	0.5750	0.3750	2.00	23
7	1	SURFACE	1.5710	0.3439	0.1563	4.81	34
7	2	BINDER	1.6080	0.3439	0.1563	4.81	34
7	3	LEVEL	1.1534	0.3439	0.0313	4.81	34
8	1	SURFACE	1.2500	0.4000	0.2000	13.34	34
8	2	BINDER	1.8177	0.4000	0.2000	13.34	34
10	1	SURFACE	0.7955	0.1250	0.0125	2.72	21
10	2	BINDER	1.7216	0.1250	0.0000	2.72	21
10	3	BASE	2.4773	0.1250	0.0000	2.72	21
10	4	BASE	1.2102	0.1250	0.1125	2.72	21
11	1	SURFACE	1.0966	0.5500	0.2500	0.68	16
11	2	BINDER	1.3523	0.5500	0.1250	0.68	16
11	3	BINDER	2.5739	0.5500	0.1125	0.68	16
11	4	BASE	3.3693	0.5500	0.0250	0.68	16
11	5	BASE	3.2443	0.5500	0.0375	0.68	16
12	1	SURFACE	1.7212	1.4500	0.5000	0.31	5
12	2	BINDER	3.0192	1.4500	0.9500	0.31	5
12	3	LEVEL	1.0139	1.4500	0.0000	0.31	5
13	1	SURFACE	1.5962	1.6563	0.8125	0.30	12
13	2	BINDER	2.4896	1.6563	0.8438	0.30	12
18	N/T	OGFC	0.8580	0.2000	0.0000	1.55	21
18	1	SURFACE	1.7898	0.2000	0.1500	1.55	21
18	2	SURFACE	2.1136	0.2000	0.0500	1.55	21
18	N/T	OLD SUR	1.8281	0.2000	0.0000	1.55	21
19	1	SURFACE	1.5280	0.3900	0.2250	0.26	3
19	2	SURFACE	1.7216	0.3900	0.0125	0.26	3
19	3	BINDER	2.7500	0.3900	0.1525	0.26	3
20	N/T	OGFC	0.8409	0.3167	0.0417	0.38	19
20	1	SURFACE	1.4091	0.3167	0.0000	0.38	19
20	2	SURFACE	2.1932	0.3167	0.2750	0.38	19
20	N/T	OLD SUR	5.7273	0.3167	0.0000	0.38	19
22	1	SURFACE	2.0375	0.5000	0.3250	4.40	50
22	2	BINDER	2.7938	0.5000	0.1750	4.40	50
23	1	SURFACE	1.4205	0.5858	0.3024	3.30	40
23	2	BINDER	1.4432	0.5858	0.1667	3.30	40
23	N/T	OLD SUR	2.0208	0.5858	0.1167	3.30	40
24	1	SURFACE	1.2750	0.3150	0.0712	5.30	9
24	2	BINDER	2.6438	0.3150	0.2437	5.30	9

N/T = Not Tested

TABLE 2   IN-PLACE DATA (NCAT CORES)

SITE	LAYER	ASPHALT CONTENT (%)	VTM AVG (%)	VTM 20th PCT'L (%)	UNIT WEIGHT AVG (pcf)	UNIT WEIGHT 80th PCT'L (%)
1	1	7.8	1.5	0.7	150.1	151.2
1	2	4.0	2.3	0.9	151.1	153.2
2	1	6.0	4.0	3.6	144.9	145.6
3	1	5.2	6.3	5.7	142.9	143.9
3	2	4.8	3.9	3.3	147.0	148.0
4	1	5.6	4.3	3.1	145.3	147.1
4	2	4.3	3.6	3.2	148.1	148.8
5	1	6.8	3.8	3.1	146.6	147.7
5	2	6.5	3.6	2.8	147.6	148.8
6	1	4.8	5.4	4.6	144.7	146.0
6	2	5.4	4.0	3.4	146.4	147.3
7	1	5.3	3.2	2.2	147.3	148.9
7	2	4.7	3.8	3.1	148.1	149.1
8	1	4.5	3.2	2.1	149.7	151.4
8	2	4.2	4.0	3.0	151.4	153.1
10	1	6.8	6.1	5.1	139.5	141.0
10	2	4.3	11.6	10.9	137.2	138.2
10	3	4.5	13.0	12.5	134.7	135.5
11	1	6.3	4.1	2.7	145.6	147.7
11	2	5.2	4.1	2.4	147.0	149.6
11	3	4.4	10.0	8.5	139.2	141.4
12	1	6.5	1.9	1.3	145.3	146.2
12	2	5.0	4.7	3.6	147.4	149.0
13	1	6.2	4.9	3.5	146.6	148.7
13	2	4.1	8.3	6.4	148.7	151.9
18	1	4.3	6.9	5.2	142.8	145.5
18	2	4.7	5.2	4.0	144.2	146.0
19	1	5.7	1.4	0.9	151.1	151.9
19	2	5.3	3.7	4.2	146.8	147.6
19	3	5.1	6.0	6.9	142.7	144.0
20	1	5.6	2.1	1.8	149.3	149.7
20	2	5.2	3.6	2.5	148.1	149.7
22	1	5.2	2.0	1.5	155.4	156.2
22	2	5.9	2.2	1.9	151.8	152.3
23	1	5.0	2.7	1.8	151.6	153.0
23	2	5.0	4.3	3.7	149.5	150.4
24	1	6.3	2.8	1.4	158.8	161.1
24	2	4.5	2.0	1.5	156.7	157.5

The friction courses were not evaluated because of their porous nature and their small effect on rutting.

Air Voids and Rutting

Figure 2 shows the relationship between air voids recompacted to 75 blows per side with the manual Marshall hammer and the total rut depth at the surface expressed as rut depth per the square root of traffic in million equivalent 18-kip single axle loads (ESALs) for the mixtures in Layer 1. An analysis

of rutted pavements has shown that rut depth divided by the square root of million ESALs is a good way to quantify rate of rutting. A rate of rutting of less than 2×10^{-4} in. per square root of total ESALs has been shown as a good separation between good and poor performing pavements (8). There is enough scatter in the data to make the correlations poor (R-square = 0.12). However, the correlation does show a trend of lower recompacted air voids associated with higher rut depths and higher traffic. The same plot is shown in Figure 3 for the Layer 1 mixtures recompacted on the GTM. The R-square value is nearly identical to the 75-blow samples, and

TABLE 3 RECOMPACTION DATA

SITE	LAYER	GTM 300 VTM (%)	GTM 300 UNIT WEIGHT (pcf)	GSI	75 BLOWS VTM (%)	75 BLOWS UNIT WEIGHT (pcf)
1	1	0.6	151.1	1.37	1.8	149.3
1	2	3.2	149.7	1.01	5.6	146.0
2	1	2.4	147.4	1.29	3.1	146.3
3	1	6.1	143.3	1.00	6.1	143.2
3	2	2.1	149.5	1.07	3.1	148.0
4	1	2.9	147.3	1.04	3.7	146.1
4	2	2.2	150.3	1.13	2.8	149.3
5	1	2.3	148.9	1.27	1.7	149.8
5	2	1.1	151.4	1.37	1.2	151.3
6	1	2.9	148.4	1.08	2.8	148.7
6	2	1.8	149.8	1.43	1.6	150.0
7	1	2.1	149.0	1.04	2.2	148.9
7	2	1.3	151.9	1.39	1.8	151.1
8	1	2.3	151.1	1.07	2.7	150.5
8	2	3.2	152.7	1.12	3.7	152.0
10	1	5.7	140.1	1.00	6.0	139.7
10	2	8.9	141.3	1.00	9.1	141.0
10	3	9.3	140.5	1.00	9.6	140.1
11	1	2.4	148.1	1.37	2.6	147.9
11	2	2.2	149.9	1.28	1.9	150.4
11	3	4.1	148.3	1.03	3.6	149.1
12	1	1.0	146.7	1.63	1.1	146.5
12	2	1.6	152.1	1.53	2.2	151.2
13	1	1.9	151.2	1.43	1.8	151.2
13	2	2.8	157.6	1.33	2.8	157.6
18	1	4.3	146.7	1.02	4.1	147.1
18	2	1.7	149.7	1.50	1.6	149.7
19	1	1.2	151.5	1.36	0.7	152.3
19	2	2.5	149.5	1.50	2.4	149.6
19	3	2.8	149.0	1.25	2.5	149.4
20	1	0.8	151.4	1.53	1.5	150.3
20	2	1.4	151.4	1.44	1.9	150.6
22	1	1.3	157.2	1.47	1.3	156.6
22	2	0.8	153.9	1.72	0.6	154.3
23	1	1.7	153.3	1.41	1.8	153.0
23	2	2.4	152.5	1.32	2.5	152.4
24	1	1.8	160.4	1.53	1.3	161.2
24	2	1.2	157.9	1.67	0.8	158.6

the same trend is evident. It can be seen that the rut depth generally increases with a decrease in recompacted air-void content. The relationship between air voids and rutting is well documented in the literature (5–7).

Figures 2 and 3 show an important relationship between recompacted air-void content and the probability of rutting. For the Layer 1 mixtures shown in Figure 2, the chance of having a rate of rutting greater than 0.20 in. per square root of million ESALs is 69 percent (9 of 13) if the 75-blow recompacted air-void content is 3 percent. Only 1 of the 5 sites with air voids greater than 3 percent had a rate of rutting significantly above 0.2; its recompacted air-void content was only slightly greater than 3 percent. The Layer 1 mixtures recompacted in the GTM show similar results: 67 percent (10 of 15) of the sites had rut depths greater than 0.20 in. per square root of million ESALs with less than 3 percent air voids, and none of the sites had a rutting rate significantly greater than 0.2 with recompacted air voids greater than 3 percent. From these data it can be seen that mixtures should be designed to have air-void contents greater than 3 percent, preferably around 4 percent.

Pavement Densification and Traffic

Figures 4 and 5 show the relationship between traffic, expressed as total equivalent 18-kip single axle loads in millions,

TABLE 4 MIX-DESIGN DATA

SITE	LAYER	ASPHALT CONTENT (%)	VTM (%)	UNIT WEIGHT (pcf)	BLOWS PER SIDE	3/4	1/2	3/8	#4	#8	#16	#30	#50	#100	#200
											(Percent Passing)				
1	1	6.3	6.0	141.1	50	100	97	90	67	56	--	35	--	14	6.0
2	1	5.8	5.4	143.7	50	100	98	93	68	57	--	34	--	10	5.0
3	1	5.4	3.9	145.5	50	100	98	93	70	52	--	35	--	7	4.0
3	2	4.2	--	--	50	96	78	--	41	32	--	--	--	--	--
4	1	6.0	5.4	144.4	50	100	98	90	68	56	--	29	--	11	6.0
4	2	4.8	3.2	150.5	50	85	68	--	43	35	--	--	--	--	--
5	1	6.2	3.8	145.8	50	100	98	94	68	54	--	33	--	13	6.0
5	2	5.2	3.6	149.8	50	95	70	--	40	32	--	--	--	--	--
6	1	4.8	4.2	146.3	50	100	99	90	60	44	34	25	10	7	5.6
6	2	5.3	3.2	147.3	50	100	99	84	57	41	32	24	9	6	5.0
7	1	5.0	4.1	147.2	50	100	99	89	70	58	48	36	18	8	6.0
7	2	4.8	3.5	148.1	50	100	95	90	67	49	37	28	13	6	4.7
8	1	4.8	5.4	147.4	50	100	99	88	60	45	36	23	13	8	5.8
8	2	4.3	6.8	148.3	50	100	98	90	78	61	51	40	26	14	8.6
10	1	7.0	7.3	135.4	50	100	100	99	73	63	49	33	19	10	2.0
10	2	6.5	5.9	139.9	50	100	90	84	69	52	33	17	8	5	3.0
11	1	6.5	4.1	142.7	50	100	100	96	71	53	40	24	16	11	8.0
11	2	4.4	7.4	142.9	50	100	96	87	67	52	34	24	16	10	6.0
11	3	3.5	5.1	142.9	50	98	90	84	71	58	41	27	18	12	8.0
12	1	6.5	3.0	144.3	75	100	100	92	62	42	31	25	17	9	5.0
12	2	4.8	3.2	150.4	75	77	64	53	37	25	20	18	12	6	4.0
13	1	6.4	3.1	148.9	75	100	100	92	65	45	26	16	10	9	5.0
13	2	4.3	3.8	153.2	75	73	63	54	44	30	17	10	7	5	4.0
18	1	5.8	3.5	147.7	50	100	93	79	53	39	28	22	14	9	6.1
18	2	5.8	3.5	147.7	50	100	93	79	53	39	28	22	14	9	6.1
19	1	6.4	3.5	146.3	50	100	88	78	55	38	27	21	14	10	6.2
19	2	6.0	4.8	145.0	50	100	84	72	54	44	35	28	19	10	5.2
20	1	5.8	3.6	146.4	50	100	89	75	53	38	28	21	14	10	5.9
20	2	5.8	3.6	146.4	50	100	89	75	53	38	28	21	14	10	5.9
22	1	5.8	2.6	152.6	50	100	97	84	55	42	--	--	19	--	7.6
22	2	6.7	2.7	151.1	50	100	98	88	61	46	--	--	15	--	6.9
23	1	5.3	3.5	150.8	50	100	97	81	51	37	--	--	18	--	7.9
23	2	6.0	2.6	150.7	50	99	--	68	--	47	--	--	16	--	6.9
24	1	6.7	2.1	159.9	50	100	100	100	99	80	54	36	26	20	15.2
24	2	4.5	2.4	156.4	50	--	84	--	53	40	--	--	16	--	9.8

"--" = Data Not Available

and pavement densification, expressed in air voids. The air-void content is the 20th-percentile in-place air-void content of the pavement at the time of sampling. The traffic is the total estimated equivalent 18-kip wheel loads applied to the original pavement or the last overlay for overlaid pavements. The figures show a reduction in air voids, or pavement densification, with an increase in traffic.

A straight-line regression analysis was used to develop the correlations between densification and traffic. The relationship is poor, with an R-square of 0.08 for Layer 1 and 0.11 for Layer 2 (Figures 4 and 5). A good correlation, however, would mean that traffic alone and not mix properties controlled rutting.

A somewhat more useful methodology for investigating the relationship between traffic and pavement densification is to use both the in-place data and the recompaction data. By dividing the in-place unit weight by the recompacted unit weight, an idea of the relative amount of densification obtained for a particular mixture can be established. By plotting this value against the traffic, an estimate of the amount of traffic necessary to reach the recompacted density can be made. The pavement layers were recompacted using both the GTM and the manual Marshall hammer with 75 blows per side. The data show that 75-blow compaction (for recompacted samples) produces a density equal to that expected after 5.4 million ESALs for the top layer and equal to that

TABLE 5   QC DATA

SITE	LAYER	ASPHALT CONTENT AVG (%)	INITIAL IN-PLACE VTM AVG (%)	INITIAL IN-PLACE AVG UNIT WEIGHT (pcf)	LAB COMPACTED VTM AVG (%)	LAB COMPACTED AVG UNIT WEIGHT (pcf)
1	1	6.1	---	---	---	---
1	2	---	---	---	---	---
2	1	5.8	---	---	3.6	---
3	1	5.4	---	---	4.5	144.9
3	2	---	---	---	---	---
4	1	6.0	---	---	---	---
4	2	4.8	---	---	---	---
5	1	6.2	---	---	3.8	145.1
5	2	5.2	---	---	---	---
6	1	5.2	8.0	141.6	---	---
6	2	5.3	5.8	144.1	---	---
7	1	5.2	6.9	142.2	---	---
7	2	4.7	6.4	142.7	---	---
8	1	4.8	---	---	---	---
8	2	---	---	---	---	---
10	1	---	---	---	---	---
10	2	---	---	---	---	---
10	3	---	---	---	---	---
11	1	5.5	---	---	1.3	149.1
11	2	5.5	---	---	3.6	147.7
11	3	---	---	---	---	---
12	1	6.4	4.7	141.4	---	---
12	2	4.7	4.7	149.0	---	---
13	1	6.1	6.1	143.8	---	---
13	2	4.3	4.5	152.1	---	---
18	1	5.8	5.6	144.3	3.53	147.7
18	2	6.1	5.6	144.3	3.48	147.70
19	1	---	6.7	143.0	---	---
19	2	---	7.4	142.3	---	---
19	3	---	7.4	142.3	---	---
20	1	5.7	3.7	146.7	2.56	148.88
20	2	5.8	3.7	146.7	2.48	148.69
22	1	---	---	---	---	---
22	2	---	---	---	---	---
23	1	---	---	---	---	---
23	2	---	---	---	---	---
24	1	---	---	---	---	---
24	2	---	---	---	---	---

"---" = Data not Available

expected after 6.3 million ESALs for the second layer. The data also show that the GTM compaction produces a density equal to that expected after 9.1 million ESALs for the top layer and after 8.63 million ESALs for the second layer. The data for both the GTM and 75-blow recompacted samples are presented in Table 3, and the results of the plots are shown in Figures 6–9.

Mix Design, In-Place, and QC/QA Mix Properties

The relevant mix-design information for the pavements evaluated in this study are presented in Table 4. Of the 18 sites

investigated in this study, 16 were designed using a 50-blow Marshall mix design. A 75-blow Marshall mix design was used in two sites. Most of the pavements investigated were high-volume roads, for which a 75-blow Marshall mix design should be used. The use of 50-blow mix designs on the majority of these pavements could be a major cause of the rutting that has been observed. The 2 sites in this study for which the 75-blow mixes were used rutted severely (approximately 1.5 in.). The poor performance of these 75-blow mixes could be related to the high Gyratory Shear Index (greater than 1.3), low recompacted air voids (1.0 to 2.8 percent), and low mix-design
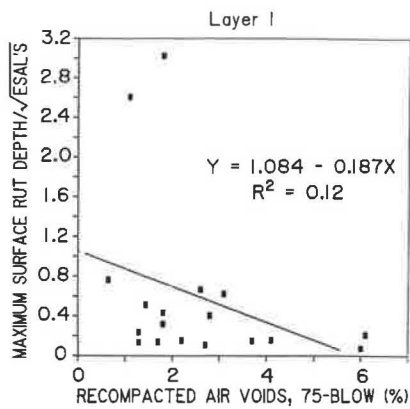
FIGURE 2 75-blow recompacted air-void content versus maximum surface rut depth divided by the square root of traffic in million ESALs.

FIGURE 3 GTM recompacted air-void content versus maximum surface rut depth divided by the square root of traffic in million ESALs.
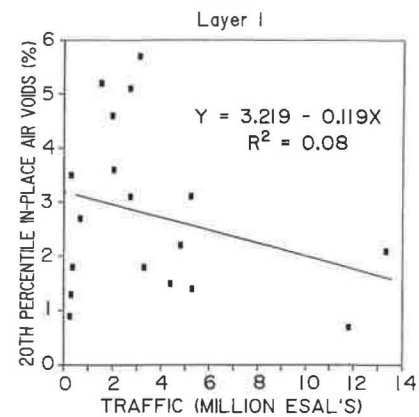

FIGURE 4 Traffic versus 20th percentile in-place air-void content for Layer 1 mixtures.
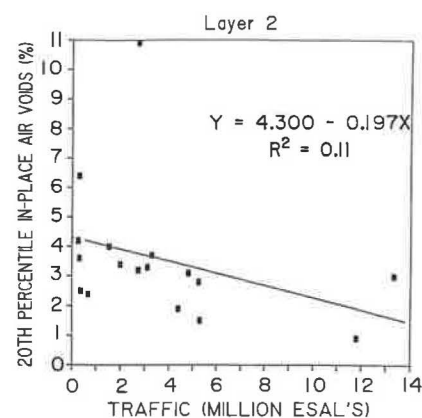
FIGURE 5 Traffic versus 20th percentile in-place air-void content for Layer 2 mixtures.

air-void contents (3.0 to 3.8 percent). The mix-design air-void contents for the mixes in Layer 1 ranged from a high of 7.3 percent to a low of 2.1 percent (Table 4). Two of the Layer 1 mixes were designed with an air-void content of less than 3 percent with 50-blow compaction, and two were designed with an air-void content of 3.0 and 3.1 percent with 75-blow compaction. The design air-void contents for the Layer 2 mixes ranged from 7.4 to 2.4 percent. Three of the Layer 2 mixes were designed with air-void contents of less than 3 percent with 50-blow compaction.

The QC data supplied by the various states are summarized in Table 5. QC data were available for 15 of the sites. At the time of preparation of this report, the mix-design information from Sites 22–24 was available; however, the construction data were not available. The laboratory-compacted data represent testing performed on samples of the mix that were obtained from either the plant or the roadway, returned to the laboratory, and compacted to duplicate the mix design.

One of the most important observations that can be made with regard to construction testing is the lack of data. Construction history data from asphalt cores were available from 14 of 15 sites, but these data are incomplete for many of the sites and pavement layers. The data from the asphalt cores

represented extractions for asphalt content, gradation analysis, and unit weights to check initial compaction. Of the 14 sites with in-place density data, 6 contained extraction and gradation analysis data only, 6 contained both extraction and gradation analysis data and unit weight and air-void data, and 2 contained only unit weight and air-void data. Laboratory-compacted samples as a part of QC/QA procedures were used for only 5 of the 15 sites; this represented only 8 of 32 mixtures evaluated. Additional information was either not obtained or not available in the project files. Probably the most important test that can be conducted during QC/QA is to compact plant-mixed material in the laboratory and determine and evaluate the air voids of the laboratory-compacted mixture.

The results of the testing performed on the 6-in. cores from each project are summarized in Tables 2 and 3. The results of the testing performed on the pavement cores after traffic loadings, referred to as in-place data, are presented in Table 2. The results of the recompaction analysis performed on the cores from each site are presented in Table 3. The in-place cores (Table 2) show 16 of the 38 mixtures with in-place air voids below 3 percent with 10 of the low air-void contents occurring in Layer 1. This indicates that the in-place density was higher than the mix-design density or that something in
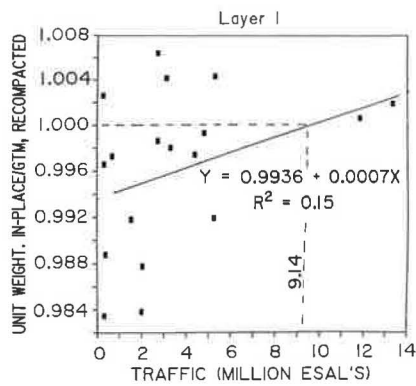
FIGURE 6   Traffic versus ratio of in-place to GTM-recompacted unit weight for Layer 1 mixtures.
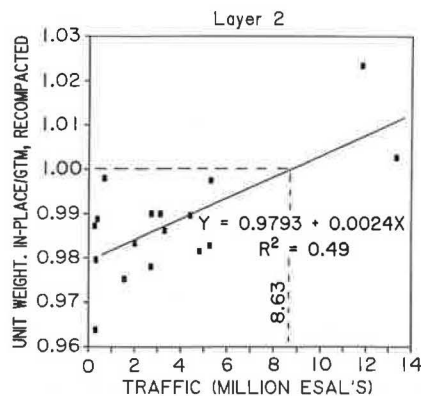

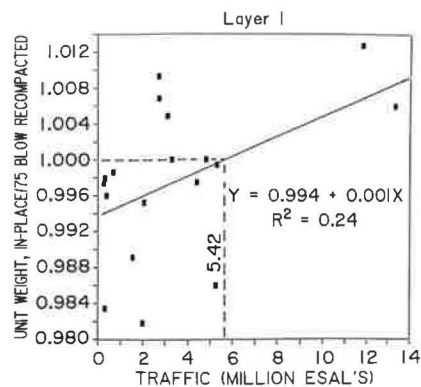**FIGURE 7   Traffic versus ratio of in-place to GTM-recompacted unit weight for Layer 2 mixtures.**

FIGURE 8   Traffic versus ratio of in-place to 75-blow-recompacted unit weight for Layer 1 mixtures.
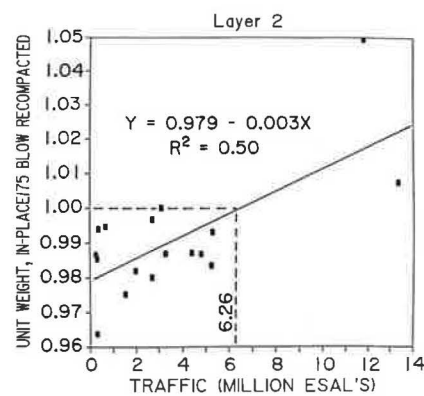

FIGURE 9   Traffic versus ratio of in-place to 75-blow-recompacted unit weight for Layer 2 mixtures.
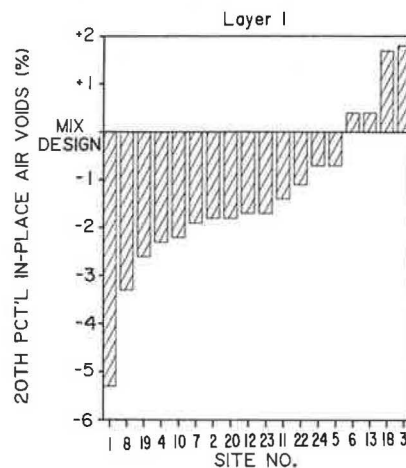
FIGURE 10   Comparison of 20th-percentile in-place air-void contents with their mix-design air-void contents for Layer 1 mixture.
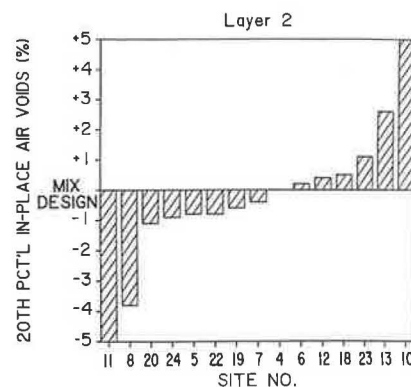
FIGURE 11   Comparison of 20th-percentile in-place air-void contents with their mix-design air-void contents for Layer 2 mixtures.

the mix had changed. Thus the mix-design compactive effort was likely too low, probably because of 50-blow compaction or other causes, or because something in the mix, such as the amount of fines, had changed after its design.

The recompaction data include data from both the 75-blow Marshall hammer and the GTM. For the GTM, 30 of 38 mixtures and for the Marshall hammer, 27 of 38 mixtures had air-void contents below 3 percent. These low voids are typical for rutted pavements. The above data show that mixtures exceed the mix-design densities after traffic and that these high densities and low air voids lead to premature rutting.

The differences between the in-place air-void contents at the 20th percentile and the mix-design air-void content are shown in Figures 10 and 11 for Layers 1 and 2, respectively. Fourteen of 18 mixtures (78 percent) for Layer 1 and 8 of 15 (53 percent) for Layer 2 showed the in-place air-void content to be lower than the mix-design air-void content. The same

was true for the unit weight at the 80th percentile (Figures 12 and 13), with 78 percent of the mixtures from Layer 1 and 53 percent of the mixtures from Layer 2 exceeding the mix-design unit weight. This indicates that the mix-design compactive effort, especially for the near surface mixtures, is too low for the current level of traffic. In many cases the in-place air voids are 1 to 3 percent lower than the mix-design air voids. Because mixes are typically designed to have 4 percent air voids and rutting is expected to be a problem at 3 percent air voids, these lower in-place air voids are a major problem.

The data show that the in-place unit weight exceeds the mix-design unit weight and that the in-place void content is below the mix-design content. In an attempt to verify that the mix-design compactive effort is indeed low and that the voids are not being overfilled by adding asphalt cement to facilitate compaction, an analysis of variance (ANOVA) was performed on the asphalt contents reported in the mix design, in the QC data, and from extractions performed on the 6-in. cores (in-place) from each site. The results of the ANOVA are presented in Table 6. The analysis showed no significant difference among the means of the asphalt contents of the mix design, QC, and in-place values with a confidence interval of 75 percent.
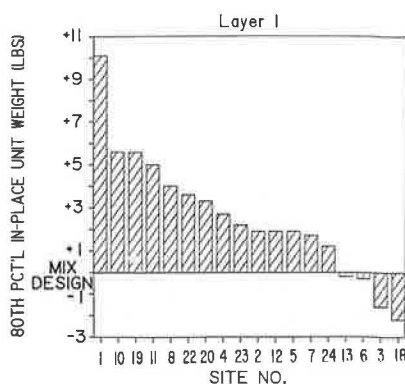
TABLE 6 RESULTS OF ONE-WAY ANOVA ON ASPHALT CONTENT

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-VALUE
Total	93	13.0462		
Model	2	0.5790	0.2895	2.11
Error	91	12.4672	0.1370	

To statistically show that the mix-design density is exceeded by the in-place density, an ANOVA was performed on the unit weights obtained from the mix design, the in-place data, and the recompaction (GTM and 75-blow) data. The results are presented in Table 7. The ANOVA showed a significant difference at the 95-percent confidence level in the means of the unit weights from the above data sets. Duncan's multiple range test was performed with alpha = 0.05 to determine the rank and significant differences between the means; the results are presented in Table 8. Duncan's test ranked the means from highest to lowest as GTM, 75-blow, in-place after traffic, and mix design with a significant difference between each group of means except GTM and 75-blow recompacted.

The difference between the initial in-place air-void content and the mix-design air-void contents for Layers 1 and 2 are shown in Figures 14 and 15. All of the initial in-place air-void contents were above the mix-design void content as they should be. However, data from Site 20 indicates the initial in-place density to be very close to the mix-design density, which results in low in-place air voids after traffic. Figure 10 shows that for Site 20 the in-place air-void content after traffic is

FIGURE 12 Comparison of 80th-percentile unit weights with their mix-design unit weights for Layer 1 mixtures.
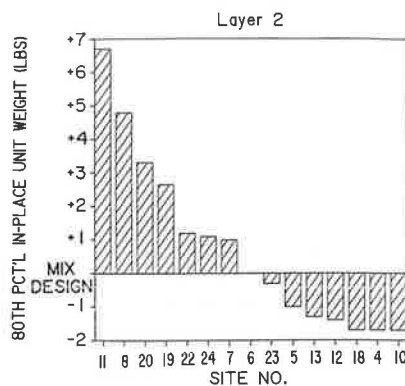

FIGURE 13 Comparison of 80th percentile in-place unit weights with their mix-design unit weights for Layer 2 mixtures.

TABLE 7 RESULTS OF ONE-WAY ANOVA ON UNIT WEIGHT

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-VALUE
Total	145	476.9889		
Model	3	213.3884	71.1295	38.32
Error	142	263.6005	1.8563	

TABLE 8 RESULTS OF DUNCAN'S MULTIPLE RANGE TEST

Model	Duncan's* Grouping	Mean	Number Observations
GTM	A	1.186	37
75 Blow	A A	0.881	37
In-Place	B	-0.241	37
Mix Design	C	-1.931	35

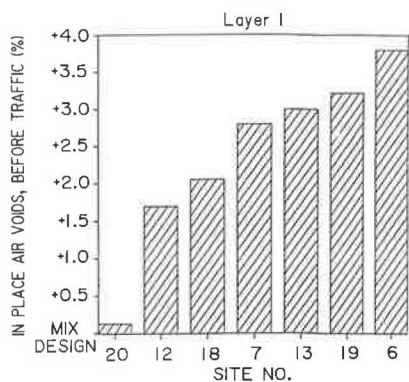* Means with the same letter are not significantly different.

FIGURE 14 Comparison of QC air-void contents before traffic with their mix-design air-void contents for Layer 1 mixtures.
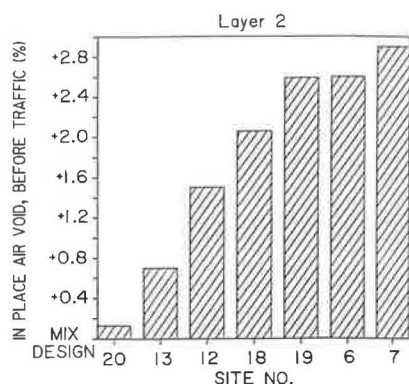

FIGURE 15 Comparison of QC air-void contents before traffic with their mix-design air-void contents for Layer 2 mixtures.
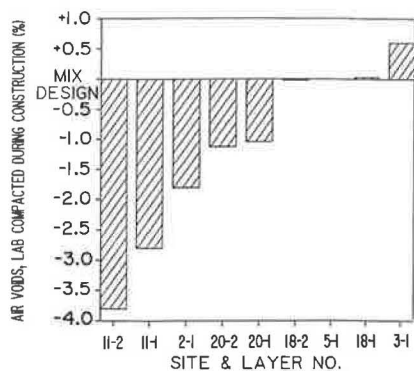

FIGURE 16 Comparison of laboratory-compacted air-void contents with their mix-design air-void contents.

indeed approximately 2 percent lower than the mix-design value. The rut depth at Site 20 was only 5/16 in., due in part to the low level of traffic (0.38 million ESALs). The results of the limited data available on the QC laboratory-compacted samples are shown in Figure 16. Five of the 9 mixtures had air-void contents significantly below the mix-design value, and 4 were within 0.5 percent of the mix-design value. From this

information it can be seen that five of the mixtures should have been modified to raise the air-void content in order to minimize rutting.

CONCLUSIONS

On the basis of the data obtained in this study the following conclusions are warranted.

1. In-place air-void contents greater than 3 percent are necessary to decrease the probability of premature rutting throughout the life of the pavement. The voids in laboratory-compacted samples are used to estimate the ultimate void content of the mixture.

2. An in-place air-void content of less than 3 percent greatly increases the probability of premature rutting.

3. Compaction using 300 revolutions of the GTM set at 120 psi and a 1-degree angle gives sufficient design density and void content for up to 9 million ESALs.

4. Compaction using 75 blows per side with the manual Marshall hammer gives sufficient design density and void content for up to 6 million ESALs.

5. Construction QC documentation is not adequate on many paving projects. Samples of asphalt mixtures from the mixing plant should be compacted in the laboratory during construction to verify that the air voids are within an acceptable range. If they are not within an acceptable range, adjustments to the mix should be made.

6. A 50-blow Marshall mix design was used for most of the pavements evaluated in this study. A 75-blow Marshall mix design should be used for mixtures to be exposed to high traffic volumes to ensure adequate voids throughout the life of the pavement.

7. The in-place unit weight of the pavement after traffic usually exceeded the mix-design unit weight, resulting in low air voids and hence premature rutting.

RECOMMENDATIONS

On the basis of the data obtained from this study the following recommendations are made.

1. Samples of the field-produced mixture should be compacted using the specified mix-design compactive effort to ensure that the mix has acceptable air voids and other properties. If there is a significant difference between the field-produced samples and the mix design, modifications to the field-produced mix must be made.

2. Efforts must be made to ensure that the mix design produces a density approximately equal to the in-place density after several years of traffic. The results of this study show that this is not the case. For heavy-duty pavements with significant truck traffic, such as most Interstate highways, it is recommended that either a 75-blow Marshall mix design or the GTM be used. For the Marshall mix design, compaction should be performed with either the manual Marshall hammer or another hammer calibrated to give the same density as the manual hammer.

3. Pavements should be designed to ensure 4 percent air voids in-place after several years of traffic to help prevent premature rutting. Mixes with design air voids much less than 4 percent are likely to rut.

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