Pavement Densification Related to Asphalt Mix Characteristics

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The primary purpose of this paper is to present the relationship between the characteristics of asphalt pavement mixtures and their Marshall job mix design values and pavement rutting or densification. Characteristics of cores taken from 24 test sites, along with their Marshall job mix design values, were correlated with the measured rut depths of the pavement. All of the pavements under study were high-type asphalt concrete with 12-ft lanes, sealed shoulders, and good drainage. The traffic load ranged from light to heavy. The pavement ages ranged from 3 to 22 yr. Relationships were established between asphalt pavement rutting and physical characteristics of the pavement core, including the voids filled, air voids, Marshall stability, and hump in the aggregate grading curve. The Marshall laboratory job mix design values of stability and flow were used to calculate a Marshall modulus. This modulus was found to relate to the rutting potential of the mixtures based on the measured pavement rut depth of the pavements at the study sites. The results presented will enable the design engineer to analyze pavement mixtures designed by the Marshall method and to predict pavement rutting based on the standard Marshall test. The results and discussion in this paper also provide insight into the relationship between mixture characteristics and the development of ruts in pavements.

In recent years Arkansas has experienced some variation in the level of performance obtained from asphalt concrete pavements. Variations are considered to be the result of a number of factors, including asphalt and aggregate characteristics, construction techniques, and traffic and environmental conditions. These variations of pavement performance have shown a need to evaluate the physical characteristics of the asphalt concrete pavement and to relate these physical properties to pavement performance. The primary purpose of this paper is to present the relationship between the characteristics of asphalt pavement mixtures and their Marshall job mix design (JMD) values with the measured pavement densification or rutting.

The data in this paper are taken from a study conducted by the author for the Arkansas State Highway and Transportation Department (AHTD) (*1*). This investigation of Arkansas asphalt pavements was designed to evaluate the characteristics of the in situ asphalt pavement mixtures and to relate them to pavement performance. Pavement performance is reduced because of the effects of traffic and the environment. The amount of pavement rutting and cracking is proportional to the decrease in pavement smoothness and directly affects ease of movement by the traveling public. Thirty-eight sites were investigated. The locations of these study sites were selected to provide pavements of varying ages, mineral aggregate compositions, traffic levels, and types of design.

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Rutting may be caused by several factors that occur both separately and in combination. These factors include tender asphalt mixtures, loss of stability in the underlying layers because of stripping, high shear stresses from traffic or loss of subgrade support, and the resultant pavement distress, densification of the pavement structure in the wheelpaths, or loss of asphalt mixture because of attrition by the action of traffic.

Laboratory tests performed on the pavement cores included resilient modulus, Marshall stability and flow, bulk specific gravity, maximum specific gravity, asphalt content, and extracted aggregate gradation. Pavement performance was evaluated from condition surveys and rut, crack, skid, and roughness measurements. Described in this paper are the characteristics of asphalt pavement mixtures and their Marshall job mix designs (JMD) for 24 sites and the rutting propensity of the pavement at these sites.

REVIEW OF LITERATURE

The use of asphalt concrete that is properly designed, manufactured, and placed on a well-constructed roadbed will provide an excellent pavement to serve the traveling public. The performance of asphalt concrete pavement is dependent on the many possible combinations of aggregates, asphalt cements, construction practices, road beds, traffic densities, and environmental conditions.

Asphalt Mixture Design and Criteria

The proper combination of different types and gradations of aggregate with varying quantities of asphalt cement to yield a satisfactory asphalt pavement is known as mix design. The discussion of asphalt mixture characteristics is based on the Marshall method because this is the procedure used in Arkansas. Marshall mix design parameters usually include aggregate gradation limits, stability, flow, air voids, voids in the mineral aggregate, and water-susceptibility criteria. The level of traffic determines the specific design criteria to be followed. There are no criteria in the job mix procedure on design to reduce rutting.

The initial criteria for a satisfactory mix by the Marshall method included the requirements for minimum stability, flow, and density (air voids). The air voids were calculated on the basis of apparent specific gravity of the mineral aggregate. The importance of voids in the mineral aggregate was presented in the Marshall test manual (*3*).

Goode and Lufsey (*3*) reported the results of a study that included the relationship between air voids, film thickness, and asphalt hardening. Marshall specimens were used in this work. The film thickness of asphalt coating was calculated using the effective asphalt content of the mix and the aggregate surface area. Detailed procedures were presented for calculating the surface area and film thickness. A definite trend was noted for asphalt hardening to increase as the film thickness decreased and the air voids increased. An asphalt mixture having film thickness of 6 microns and air voids of 4 to 5 percent showed good resistance to hardening.

Guidelines for the design of pavement structures are given in the AASHTO manual (*4*). Also presented in this manual are typical criteria for the design of asphalt mixtures. The desired properties of the asphalt mixtures are based on the level of traffic for a 20-yr traffic analysis period. Three levels of traffic, based on an equivalent daily 18-kip axle load, are 1 to 50, 50 to 500, and 500 to 3,000. The compactive effort used in the Marshall method of design for these levels of traffic is for 35 blows, 50 blows, and 75 blows to each end of the test specimens. Recommended in the AASHTO manual are design values of Marshall stability and flow, total voids, and voids filled for surface, binder, and base mixtures. It is of interest to note that no criteria are given for voids in mineral aggregate (VMA) in these mixtures.

Design To Limit Rutting and Cracking

Current mix design procedures were assessed by Finn et al. (*5*). This report presented two case studies in which pavements designed in accordance with the Marshall procedure had experienced premature failure by rutting and cracking. Finn et al. investigated the failures and performed Hveem stability tests and a creep test to modify the mix designs to obtain a more durable pavement. The creep test was performed on 4-in.-diameter by 8-in.-high specimens with an MTS device to estimate permanent pavement deformation. The results yielded a creep modulus, which was used to predict an acceptable asphalt content for the asphalt mixtures. N. W. McLeod, in his discussion of the report, indicated that, in his experience, in most cases where rutting has occurred it has been caused by a combination of very low percent air voids and a high Marshall flow index. McLeod also noted that the Marshall flow index has been an effective creep test for a long time.

The use of elastic layer theory and fatigue tests to predict pavement resistance to cracking and subsequent failure is well documented in the literature. The development and improvement of test equipment to measure the elastic characteristics of asphalt mixtures, such as the resilient modulus equipment reported by Schmidt (*6*), have greatly facilitated this area of analysis. The addition of maximum and minimum resilient modulus values to the JMD criteria may provide asphalt mixtures with improved performance capability. The criteria for asphalt pavement design continue to change as more information on asphalt mixture characteristics and performance becomes available.

PAVEMENT TEST SITES AND TEST METHODS

Pavement test sites were selected to represent the various types of asphalt concrete hot mix (ACHM) pavements that have been constructed during the past 25 yr in Arkansas. In general, the pavement lanes were 12 ft wide with sealed shoulders and good drainage. The sites were usually on tangents with level grades and good sight distance to permit safe field operations.

Field Tests

A sample of the total asphalt layer at each site was obtained using a 4-in. diamond-studded core barrel attached to a vertical-shaft, water-cooled coring machine. Nine cores were secured at each test site. Rut depths were measured at the same time that core samples were taken.

Field evaluation of the pavement test site included coring, dynaflect measurements, rut depth measurement, and visual estimation of pavement conditions. In addition, the pavement roughness and skid number were determined in the vicinity of each test site.

Laboratory Tests

Laboratory tests of pavement cores included layer thickness, bulk density, resilient modulus, maximum mixture specific gravity, Marshall stability and flow, asphalt content, and gradation. The layer thickness and the overall core height were measured. The core was then sawed into layers at the layer interface and air dried until a constant weight was obtained. The height and diameter of each core layer was measured using a 0.001-in. dial gauge device.

Next the resilient modulus of each core layer was measured at 77°F using the Retsina Mark IV device. The bulk specific gravities of the surface layers were measured in accordance with ASTM Method D 2726 (*7*). The weight of the sample in air, in water (at 77°F), and saturated surface dry were obtained using a Mettler digital readout automatic balance.

The Marshall stability (lb) and flow (0.01 in.) were determined in accordance with ASTM Method D 1559 (*7*). The maximum stability was converted to stress in lb/in.^{2} (psi) as follows. The stress value was taken to be equal to the Marshall stability divided by the cross-sectional area of the specimen. The Marshall stability values were not reported in pounds because the core test specimens were of varying thicknesses that were sometimes outside the range of the stability correlation ratios given in ASTM Method D 1559. It is noted that the flow was taken to be at the point of maximum load as determined from the strip chart recorder printout from the Marshall test apparatus.

Next, the core specimens were heated to 250°F until soft enough to break apart with a trowel. The loose asphalt mixture was then tested for its maximum specific gravity in accordance with ASTM Method D 2041 (*7*), except as noted in the following. The ASTM procedure was modified by using a wetting agent, Aersol OT, in the deaired distilled water. The asphalt mixture was covered with water in a one-half gallon glass pycnometer and deaired for 15 min using a water aspirator at a vacuum of approximately 26 in. of mercury. Care was exercised in removing all of the air bubbles from inside the pycnometer before taking the final weight of the asphalt mixture in water. A water temperature of 77°F was maintained during this test.

The asphalt mixture was then placed in a pan and the excess water removed. The mixture was dried to a constant weight at 212°F before starting the extraction test. The amount of asphalt in each core specimen was determined by extraction in accordance with ASTM Method D 2172 (*7*). A mechanical analysis of the extracted aggregate was performed in accordance with AASHTO Method T30 (*8*).

A voids analysis for each core layer tested was performed. The amount of air voids, voids in the mineral aggregate, and voids filled with asphalt was calculated on the basis of aggregate effective specific gravity. In accordance with the historical asphalt specific gravity, as used in the JMD calculations, the asphalt cement specific gravity was assumed to be 1.020 for this calculation. Otherwise the procedure of the Asphalt Institute MS-2 (*9*) was followed.

TEST RESULTS AND DISCUSSION

The characteristics of the pavement at the 24 test sites are shown in Table 1. These 24 sites were selected for analysis because of the availability of the original AHTD Marshall JMDs. Initial field density test results were not available for these 24 test sites. The pavement age ranged from 3.0 to 22.7 yr at the time of coring. Traffic data include the daily number of 18K equivalent axle loads (DEAL) and the accumulated total number of 18K equivalent axle loads (AEAL) experienced by the pavement surface since construction. Daily traffic ranged from 66 to 807 equivalent axle loads (EAL), and the AEAL values ranged from 110,000 passes at Site 16 to 3,064,000 wheel passes at Site 2.

Measured pavement parameters reported in Table 1 include the pavement roughness as measured by a Mays meter, crack index, and rut depths. Also shown in Table 1 are the grade of asphalt used in each mixture and the air voids measured in the wheelpath (WAV) and between the wheelpath (BAV).

Pavement Performance Evaluation

Pavement roughness measured by the Mays meter ranged from 22 percent at Site 3 to 90 percent at Sites 5, 14, 18, and 20. A Mays ride rating in percentage was obtained by the AHTD Pavement Management section by converting the Mays count, using a calibration factor obtained in April and October of each year. The Mays count is multiplied by the calibration factor and divided by the length of pavement evaluated; the product is subtracted from 100 to obtain the Mays ride rating. The Mays ride reading of 100 percent indicates a perfectly smooth pavement.

The degree of cracking shown in Table 1 was based on the AASHO Road Test (*10, 11*) classification system. Time did not permit the measurement of the amount of cracking, and the classifications are, therefore, based on the visual appearance of the pavement in the test site area. The most severe cracking was observed at Sites 6, 8, 9, 15, 16, and 21. No cracking was observed at Sites 1, 3, 5, 23, and 24. A value of 0.1 for the crack index was assigned to these sites for regression analysis purposes. In general, the greatest cracking occurred at sites with high air voids and small ruts.

The most obvious factors thought to affect the pavement performance, including age, DEAL, and AEAL, were evaluated by regression analysis. The coefficient of correlation of rut depth and crack index with these factors gave the following values, respectively: age, 0.109 and 0.458; DEAL, 0.172 and 0.350; and AEAL, 0.172 and 0.350. In addition to the previously discussed factors affecting pavement performance, other factors inherent in pavement design and

TABLE 1 PAVEMENT CHARACTERISTICS

Site No.	Age (yr)	DEAL No.	AEAL $\times 10^{-6}$	Mays (%)	CI (degree)	Rut 1/32 in.	AC Grade	WAV (%)	BAV (%)
1	3.7	746	1,008	60	0.1	14	AC	1.3	1.8
2	10.4	807	3,064	87	1.8	7	60-70	2.1	4.3
3	5.0	286	523	22	0.1	36	AC-20	0.2	2.2
4	15.3	258	1,439	63	0.4	9	60-70	0.6	3.0
5	3.4	288	357	90	0.1	7	60-70	2.0	2.8
6	12.5	130	594	44	2.0	11	60-70	1.0	2.8
7	18.8	231	1,582	63	1.8	9	60-70	0.2	3.4
8	18.8	213	1,460	47	2.8	7	60-70	4.0	9.6
9	18.0	223	1,468	50	2.2	8	60-70	4.3	5.7
10	6.6	227	548	75	1.8	8	60-70	3.1	4.4
11	9.9	330	1,192	71	1.0	11	60-70	0.5	1.4
12	5.0	162	296	73	1.6	12	AC-20	1.1	3.2
13	13.7	258	1,290	80	1.8	12	60-70	1.1	1.8
14	4.0	319	466	90	0.2	8	AC-20	1.2	2.0
15	22.7	231	1,916	80	2.4	9	60-70	2.1	4.6
16	4.6	66	110	76	2.0	4	AC-20	4.5	6.8
17	3.0	219	240	86	1.4	2	AC-40	2.2	5.3
18	3.9	324	319	90	1.0	9	AC-20	1.7	2.4
19	17.0	61	380	88	1.6	9	60-70	1.6	2.8
20	3.3	303	365	90	1.4	5	AC-30	2.5	2.7
21	3.3	250	301	82	2.4	4	AC-30	2.1	3.2
22	17.0	163	1,010	84	0.6	7	60-70	2.0	4.9
23	5.8	410	868	75	0.1	17	AC-20	1.6	2.5
24	6.0	384	842	72	0.1	18	AC-20	1.0	1.1
Average	9.6	287	688	72	1.3	10	–	1.8	3.5

construction may influence collection of representative pavement samples and could contribute to these low individual correlations. These factors may include construction at different times of the year, different material suppliers, different contractors and equipment, changing mix design procedures, or different inspection personnel.

Despite the low correlation of traffic and age factors with pavement performance factors, the primary cause of pavement rutting is repeated heavy wheel loads. When these wheel loads are channelized and slow moving, rutting may occur in some asphalt mixtures under certain environmental conditions.

Asphalt mixtures proposed for use should provide adequate resistance to pavement distress caused by rutting. The evaluation of the relationship between asphalt mixture characteristics and pavement rutting will be useful in selecting the job mix design most resistant to this type of distress.

Core and Laboratory Mixture Characteristics

The results of the laboratory tests on the asphalt mixture surface layer are shown in Table 2. The characteristics of the field cores include resilient modulus (MR) at 77°F in ksi, Marshall stability (STAB) in 100 lb, Marshall flow (FL) in 0.01 in., average air voids (AAV), voids in the mineral aggregate (VMA), voids filled with asphalt (VF), and asphalt content (PAC).

The average air voids are based on tests from cores taken from both wheelpaths and between the wheelpaths. The VMA and VF are calculated for the AAV condition. The Marshall job mix design (JMD) values are also shown in Table 2. These tabulated values were obtained from the JMD graphs using the asphalt content of the cores. Air voids outside the desired range of 3 to 5 percent occurred at some sites because construction specifications permit the asphalt content of the mixture to vary plus or minus 0.4 percent from the JMD optimum value.

The gradation of the extracted aggregate is shown in Table 3. There were 15 Arkansas ACHM SC Type II (minus 3/4-in. top size) mixes. The remaining 9 sites were Arkansas ACHM SC Type III (minus 1/2-in. top size) mixes. The JMD gradations are not included in this paper because the core gradations were very similar to the design gradations.

The D40 column in Table 3 is the "hump" in the grading curve at the No. 40 sieve. The value is determined on a plot of the gradation on the 0.45 power paper as indicated by Carpenter and Enockson (*12*). A line is extended from the origin to the No. 4 sieve data point. The difference in percentage between the straight line and the gradation at the No. 40 sieve is the hump.

Rutting Related to Core Properties

Regression analysis to determine the more significant relationships between the pavement ruts and mixture of physical measurements was performed on the data presented in this paper. The data analysis was performed on an IBM 360/370 computer at the University of Arkansas using the CMS/SAS system.

The pavement mixture characteristics found to have an appreciable coefficient of correlation with rutting or the

TABLE 2 MIXTURE CHARACTERISTICS

	Pavement Core							Job Mix Design		
Site No.	STAB (100 lb)	FL (0.01 in.)	MR (ksi)	VMA (%)	AAV (%)	VF (%)	PAC (%)	LSTAB (100 lb)	LFL (0.01 in.)	LAV (%)
1	139	8	310	14.0	1.5	89.4	5.4	92	10	3.3
2	283	12	530	15.6	3.1	80.6	5.6	181	11	3.3
3	131	12	250	13.1	0.9	93.3	5.1	112	11	4.3
4	209	9	370	13.9	1.6	88.8	5.2	156	11	4.6
5	176	10	350	13.5	2.4	82.4	4.7	145	9	3.7
6	224	12	440	13.9	2.0	85.6	5.2	159	11	3.9
7	170	12	290	15.8	2.1	86.8	6.0	118	11	6.1
8	199	14	420	19.8	7.2	64.5	5.8	112	11	6.9
9	210	13	420	18.2	5.0	72.8	6.0	116	12	6.1
10	290	14	490	14.4	3.7	74.7	4.7	104	11	4.2
11	225	12	300	12.5	0.8	93.8	5.0	104	10	4.9
12	232	12	370	14.2	1.8	87.6	5.4	88	10	4.8
13	181	11	340	13.9	1.3	89.6	5.5	129	12	4.8
14	125	8	250	13.8	1.7	88.1	5.2	131	9	3.5
15	165	10	500	17.8	3.0	83.5	6.6	138	11	4.8
16	244	15	490	19.0	5.8	69.0	6.1	207	11	3.1
17	250	12	600	13.3	3.5	74.6	4.4	206	9	3.8
18	108	11	330	15.6	2.1	86.7	6.0	104	12	1.6
19	201	12	520	15.6	2.2	86.0	5.6	149	11	3.4
20	159	9	280	15.6	2.6	83.5	5.8	142	12	1.5
21	214	12	470	14.8	3.0	79.7	5.2	148	9	3.0
22	235	14	580	15.8	3.5	78.2	5.1	174	10	4.3
23	172	11	380	13.5	1.9	85.8	5.0	87	9	6.8
24	170	14	200	12.7	1.1	91.6	5.3	96	10	6.0
Average	196	12	395	15.0	2.6	83.2	5.4	133	10	4.3

TABLE 3 EXTRACTED AGGREGATE GRADATION

Site No.	Total Percent Passing Sieve Size Number									D40
	0.75	0.50	0.38	4	10	20	40	80	200	
1	100	94	85	62	47	38	29	15.0	7.2	8
2	100	92	82	62	44	33	26	15.0	9.0	5
3	100	91	77	56	41	32	27	15.0	9.5	8
4	100	94	86	65	46	35	29	17.0	10.0	7
5	100	94	86	66	49	38	30	13.8	7.5	7
6	–	100	96	70	45	35	27	17.0	11.0	1
7	–	100	97	76	52	36	27	15.0	10.3	1
8	–	100	97	77	53	35	25	14.0	8.1	1
9	–	100	98	81	59	42	31	12.2	8.0	1
10	100	90	82	66	42	32	23	12.0	6.5	1
11	100	89	75	55	40	31	24	14.0	5.5	5
12	100	93	77	54	40	30	23	10.0	5.5	4
13	–	100	97	75	39	33	27	18.0	10.2	1
14	100	88	77	56	41	32	24	14.0	6.5	1
15	–	100	97	75	49	32	22	11.0	7.7	4
16	100	97	86	59	41	33	30	22.0	12.1	9
17	–	100	97	64	43	32	21	14.0	9.5	1
18	100	93	84	67	52	41	26	14.0	7.1	3
19	–	100	97	67	46	34	26	14.0	8.2	3
20	100	95	82	61	43	34	22	10.0	5.4	1
21	100	94	83	62	46	38	25	13.0	7.8	4
22	–	100	97	70	48	36	31	16.0	12.4	7
23	100	89	79	59	43	35	30	13.0	6.9	10
24	100	95	87	64	42	30	25	18.0	10.0	4

logarithm of rutting include, respectively, air voids, 0.674; voids filled, 0.658; and resilient modulus, 0.602. The effect of the amount and type of asphalt and the aggregate character may be reflected in the above factors.

Stepwise linear regression was used to determine the best-fitted equation for each dependent variable and its relationship to other mix characteristics. One best-fitted equation that illustrates the relationship between rutting and the mixture properties is the following:

$$RUT = -73.8 + 0.937\ VF + 0.582\ D40 + 2.33\ BAV - 0.0236\ STAB \quad (1)$$

where

RUT = rut depth, 1/32 in.;
VF = voids filled (percent);
D40 = hump in grading curve (percent);
BAV = air voids between wheelpath (percent); and
STAB = Marshall stability (psi).

The coefficient of determination (R^2) value is 0.495 for this equation with a high confidence level. This indicates that only about 50 percent of the rutting is explained by this equation. Additional factors to be considered in design that affects rutting include traffic speed and character, environmental conditions, and support from the underlying pavement structure and subgrade. These factors were not part of this analysis. Their evaluation would increase the understanding of the rutting problem.

Using Equation 1 and the data from Site 1, a rut depth of 22/32 in. is predicted. With the data from Site 2, the equation predicts a rut depth of 8/32 in. In this equation, an increase in VF, BAV, and D40 values increases the amount of rutting, whereas an increase in stability of the mix decreases the rutting. The change in air voids will control the value of voids filled and with an increase in air voids the amount of rutting will decrease. This is illustrated later in this paper.

A plot of the relationship between rut depth and average air voids is given in Figure 1. A log-log relationship gave the best-fitted equation with a coefficient of determination of 0.456. The equation for this curve is given as follows:

$$\log RUT = 1.188 - 0.695 \log AAV \quad (2)$$

where RUT equals rut depth, 1/32 in., and AAV equals average air voids (percent).

The rut depth increases with a decrease in air voids, as indicated in Figure 1. Air voids of 1.4 percent in the mixture will have a rut depth of about 12/32 in. The equation will predict a rut depth of 8/32 in. with air voids of 2.5 percent. A mixture with air voids of 0.1 percent would indicate a rut depth of 76/32 in.

The data also indicate that crack index has a semi-logarithmic relationship with the rut depth, the pavement crack index increasing as the rut depth decreases. The field observations confirm the computer correlation, because more cracks are visible when the rut depth decreases.

The best-fitted equation relating air voids and voids in the mineral aggregate to pavement rutting was determined by stepwise linear regression. This relationship is shown as follows:

$$\log RUT = 0.293 - 1.17 \log AAV + 0.071\ VMA \quad (3)$$

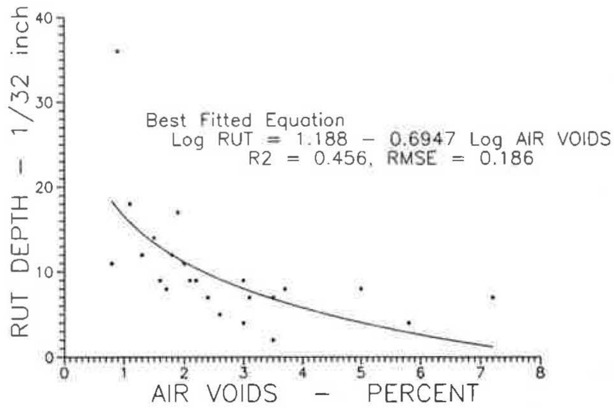

FIGURE 1 Relationship between rut depth and air voids.

where

RUT	=	rut depth, 1/32 in.;
VMA	=	voids in mineral aggregate (percent); and
AAV	=	average air voids (percent).

The R^2 value equals 0.564 for this equation, with a significant level of confidence. For a mixture with a VMA of 14 percent and air voids of 1.4 percent, a rut depth of 13/32 in. would be indicated. With air voids of 2.5 percent and a VMA of 14, the predicted rut depth would be 7/32 in.

Rutting Related to JMD Values

Regression analysis of rut depths correlated with JMD values of Marshall stability and flow and air voids indicated a fairly good relationship between pavement rutting and Marshall stability. The best-fitted equation is the following:

$$\log \text{RUT} = 1.598 - 0.00496 \text{ LSTAB} \quad (4)$$

where RUT equals rut depth, 1/32 in., and LSTAB equals JMD Marshall stability (psi). The R^2 value for this equation is 0.490. The plot of these data is shown in Figure 2. A definite trend is shown that indicates a decrease in rut depth with an increase in JMD Marshall stability.

The data point for Site 3 (with a rut depth of 36/32 in.) appears to be in error and should possibly be deleted from the regression analysis. The curve shown on Figure 2 indicates a rut depth of about 16/32 in., appropriate for Site 3, which had a Marshall stability of 1,120 lb. This site is on a major city route (alternate US-71) and is located where traffic speeds vary from 5 to 30 mph, with traffic mostly channelized. The portland cement concrete had previously been overlaid twice and reflective cracking was a problem. The binder course under this surface layer also appeared to have been partly consolidated into the open-graded crack relief layer that was placed over the old portland cement concrete overlay to reduce reflective cracking. Thus the deep ruts at this site resulted from the slow-moving channelized traffic, consolidation of the binder layer into the base, and the surface mix that became plastic with 0.2 percent air voids.

The JMD factors of air voids and Marshall flow did not indicate any significant relationships with rutting. The Arkansas JMD procedure has changed over the span of 20 or more years, covered by the data in Table 2. In particular, there have been changes in the method of determining air voids of the laboratory mixture. In some JMDs, voids were determined on the basis of aggregate bulk and apparent specific gravity, whereas more recent mix designs are based on the aggregate effective specific gravity. The design air voids in Table 2 did not indicate any significant relation with pavement rut depth, probably because of the lack of a common basis for air void determination.

The relationship between pavement rutting and Marshall flow values was evaluated by regression analysis. The coefficient of correlation between these two variables was about 0.141. However, in view of the previously quoted remarks by McLeod on the topic of premature rutting and Marshall flow, additional analysis was performed. The Marshall modulus (EM) was calculated by dividing the JMD maximum stress by the JMD strain at that stress. To obtain the value for EM, the stability is divided by the product of the flow (× 0.01) and specimen thickness. For example, with a 2.5-in.-high specimen having a Marshall stability of 1,560 lb and a flow of 11, the EM value is 5,670 psi.

The measured rut depths were plotted in relation to the calculated Marshall modulus, as shown in Figure 3. The

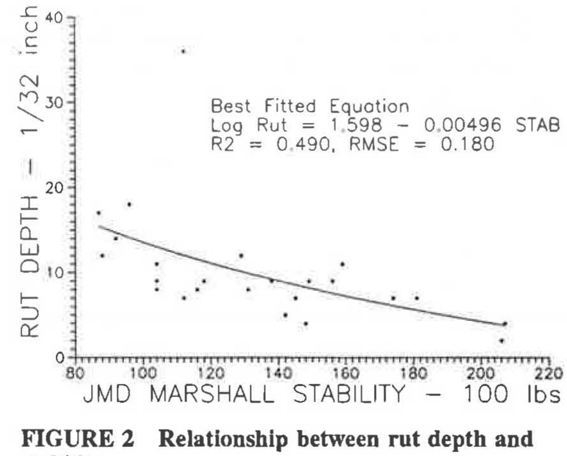

FIGURE 2 Relationship between rut depth and stability.

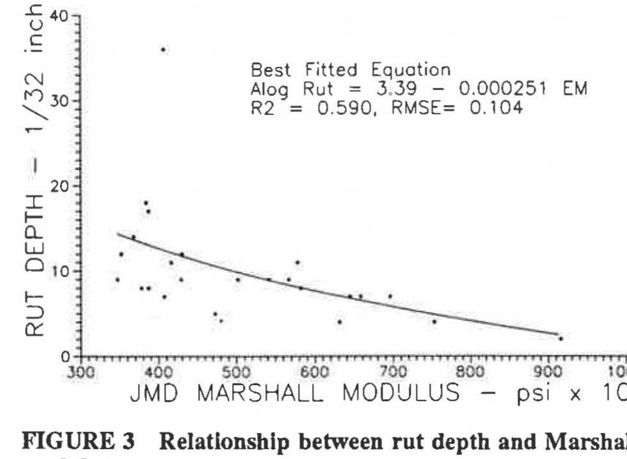

FIGURE 3 Relationship between rut depth and Marshall modulus.

best-fitted equation for this relationship was determined by regression analysis and is shown as follows:

$$\text{Alog RUT} = 3.39 - 0.000251\ \text{EM} \qquad (5)$$

where Alog RUT equals the natural log of RUT, 1/32 in., and EM equals the JMD Marshall modulus (psi).

The R^2 value was 0.590 for this relationship. The equation uses the combination of Marshall stability and flow as the Marshall modulus to provide an effective method of estimating the amount of ruts that may occur with a given JMD. Based on an asphalt mixture with a Marshall modulus between 4,000 to 7,000 psi, ruts would be predicted to be between 5/32 and 10/32 in.

Rutting Related to Pavement Densification

Densification of the pavement because of traffic occurs in the wheelpaths in asphalt pavement. The average rut depth was 10/32 in. for the 24 test sites, as shown in Table 1. The average air voids in the wheelpath were 1.8 percent and between the wheelpath they were 3.5 percent.

For a 2-in.-thick surface layer, this reduction in air voids of 1.7 percent is about equal to 2/32 in. consolidation of the surface layer. The other 8/32-in. rut is attributed to densification in the underlying pavement support structure or heaving of the surface layer adjacent to the wheelpaths. The characteristics of the asphalt mixture along with the total pavement structure control the total rut depth, as has been shown in the previous discussion.

The test sites for this study included conventional designs of asphalt concrete over granular bases, asphalt concrete over black bases, and asphalt concrete overlays of portland cement concrete pavement. All of the pavement sections were well designed and constructed. It was observed that the rut depth was the greatest in the inner wheelpath for the pavements with black bases. The rut depths were equal in both wheelpaths for pavements over portland cement concrete. The rut depths were greater in the outer wheelpath for some of the conventional designs of asphalt concrete over granular bases.

The findings of this paper are based on the statistical analysis of data obtained from 24 pavement test sites and laboratory job mix designs in Arkansas.

CONCLUSIONS

On the basis of the experimental work covered by this report and within the limitations of the test procedures, materials, and conditions used in this investigation, the following conclusions are warranted:

1. The Marshall modulus may be used in the job mix design procedure to evaluate the rutting tendency of the proposed mixture. A Marshall modulus of between 4,000 and 7,000 psi would indicate a predicted rut depth of 5/32 to 10/32 in.

2. The air voids in the pavement are indicative of the measured rut depth. Air voids over 2.5 percent were associated with rut depths of 10/32 in. or less. The results of this study indicate that mixture air voids of 2.5 to 5 percent will provide asphalt mixtures that have an acceptable level of rutting.

3. Deep ruts are associated with pavements having air voids of less than 1.0 percent and with traffic that is slow moving and channelized.

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REFERENCES

1. M. C. Ford, Jr. *Development of a Rational Mix Design Method for Asphalt Bases and Characteristics of Arkansas Asphalt Mixtures.* Report FHWA/AR/004, FHWA, U.S. Department of Transportation, July, 1985.
2. *The Marshall Method for the Design and Control of Bituminous Paving Mixtures.* Marshall Consulting and Testing Laboratory, Jackson, Miss., 1949.
3. J. F. Goode and L. A. Lufsey. Voids, Permeability, Film Thickness Versus Asphalt Hardening. In *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 34, 1965.
4. *AASHTO Interim Guide for Design of Pavement Structures.* Chapter III, 1972, revised 1981, American Association of State Highway and Transportation Officials, 1981.
5. F. N. Finn, C. L. Monismith, and N. J. Markevich. Pavement Performance and Asphalt Concrete Mix Design. In *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 52, 1983.
6. R. J. Schmidt. A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes. In *Highway Research Record 404*, HRB, National Research Council, Washington, D.C., 1972, pp. 22–32.
7. *1982 Annual Book Of ASTM Standards*, Part 15, American Society for Testing and Materials, Philadelphia, Pa., 1982.
8. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing.* Part III, American Association of State Highway and Transportation Officials, 1978.
9. *Mix Design Methods for Asphalt Concrete.* Manual Series No. 2, Asphalt Institute, March 1979.
10. *Special Report 61A: The AASHO Road Test, Report 1—History and Description of Project.* HRB, National Research Council, Washington, D.C., 1961.
11. *Special Report 61E: The AASHO Road Test, Report 5—Pavement Research.* HRB, National Research Council, Washington, D. C., 1961.
12. S. H. Carpenter and L. Enockson. Field Analysis of Rutting in Overlays of Concrete Interstate Pavements in Illinois. In *Transportation Research Record 1136*, TRB, National Research Council, Washington, D.C., 1987, pp. 46–56.

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