A STUDY OF RUTTING OF ALABAMA ASPHALT PAVEMENTS

Summary Report
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by

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ABSTRACT

Pavement rutting is the accumulation of permanent deformation in all or a portion of the layers in a pavement structure that results in a distorted pavement surface. The overall objective of this study was to develop recommendations for more rut resistant asphalt concrete mixtures which comprise the uppermost layers of flexible pavements. To accomplish project objectives a plan of study was conducted that included 1) an analysis of rutting data from the Alabama Highway Departments pavement condition data base, 2) a field evaluation and sampling program at thirteen test sites, 3) a laboratory testing program, and 4) analyses of data from the field and laboratory testing programs.

The analysis of the pavement condition data base indicated that rutting is increasing and that rutting susceptibility varies geographically because of the variable quality of locally available aggregate. Careful control of crushing of gravel and the development of a test to quantify and limit particle shape and texture of fine aggregate were identified as means for improving aggregate quality.

In most cases permanent deformation appeared to be confined to the top three or four inches of asphalt aggregate layers, thereby, implicating high tire pressures as the primary causative factor. A rate of rutting of 2×10^{-4} in/$\sqrt{ESAL}$ or 1.0×10^{-7}in/ESAL delineated good and poor performing pavements.

Mix and aggregate properties that appeared to be related to rutting include: layer thickness, voids, GSI, gyratory roller pressure, percent fractured faces, percent passing No. 200 sieve and creep strain. The correlation of these properties was not very strong, but in almost every case was caused by one or two points far outside the range of the bulk of the data. This illustrates the complexity of the rutting process and the necessity of considering a number of properties during material selection and mix design.

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INTRODUCTION

Pavement rutting is the accumulation of permanent deformation in all or a portion of the layers in a pavement structure that results in a distorted pavement surface. Longitudinal variability in the magnitude of rutting causes roughness. Water may become trapped in ruts resulting in reduced skid resistance, increased potential for hydroplaning and spray that reduces visibility. Progression of rutting can lead to cracking and eventually complete disintegration.

Flexible pavement rutting is not a new problem. As long as flexible pavements have been used, rutting has been recognized as a primary distress mechanism and a primary design consideration. What is new regarding flexible pavement rutting is the awareness that permanent deformation in the high quality asphalt layers (surface, binder and base) has become a significant contributor to pavement rutting.

Repetitive applications of heavy trucks with increasingly high pressure tires drives rut formation in high quality asphalt layers. The stresses induced in near surface layers by the high pressure tires exceed the ability of the materials to resist densification below critical voids (4%) and subsequent plastic flow.

Recent studies (1-5) have shown that truck tire inflation pressures, and therefore contact pressures, have increased dramatically from 80 psi on which design procedures are commonly based. Average truck tire inflation pressures for radial tires are now around 100 psi. This means that a significant portion of truck tires have inflation pressures higher than 100 psi, often in the 130 to 140 psi range.

Extraordinarily high tire pressures mean that asphalt concrete layers which are of the highest quality but nearest to the surface in a pavement structure are not immune to rutting. Although recent modifications such as asphalt content selection based on 75 blow Marshall compaction have increased rutting resistance, material quality provided by existing specification occasionally is insufficient to meet the demands of today's traffic.

OBJECTIVES

The overall objective of this study was to develop recommendations for more rut resistant asphalt concrete mixtures. To accomplish this overall objective the following five sub-objectives were:

To determine the nature and extent of rutting on Alabama Highways,

To conduct testing and evaluation of typical asphalt concrete mixtures,

To characterize mixtures that are susceptible to rutting and those that are not susceptible to rutting,

To review Alabama Highway Department (AHD) material selection and asphalt concrete mix design procedures, and

To formulate recommended modifications to current practices to enhance resistance of asphalt concrete mixes to permanent deformation.

PLAN OF STUDY

To accomplish project objectives a three (3) phase study was executed. The three phases consisted of 1) an analysis of rutting data from the Alabama Highway Department's pavement condition data base, 2) field evaluation and sampling at thirteen test sites, and 3) a program of laboratory testing. Data from these studies was analyzed to develop a model for describing the rutting process and to formulate recommendations for improving the rutting resistance of asphalt concrete mixes.

The assessment of the nature and extent of rutting of asphalt pavements was limited to an analysis of data from the 1984, 86, and 88 Alabama Highway

Department pavement condition data bases. Testing and sampling was conducted at thirteen (13) test sites. Sites were selected to provide materials with a range of rutting resistance. Test pits were dug through and cores taken of all asphalt-bound layers. Laboratory testing of materials from the cores measured properties to characterize in-situ mix, recompacted mix, recovered aggregate and recovered asphalt cement.

Efforts to improve rutting performance of Alabama asphalt pavements were focused on consistant material selection and mix design for asphalt concrete. Consideration of structural pavement thickness design and construction aspects were beyond the scope of the study.

PRESENTATION AND ANALYSIS OF RESULTS

Data and analyses of these data from the three phases of the study described in the preceding section are presented individually in this section. These analyses are then combined and a model proposed for describing rutting of asphalt-bound layers of flexible highway pavements.

Analysis of Rutting Data from Pavement Condition Database.

The rutting data in the 1984, 1986, and 1988 pavement condition data bases were analyzed to assess the nature and extent of the rutting problem in Alabama. As noted earlier, the data will be grouped and compared to isolate the effects of various parameters.

Combined Data. Figure 1 summarizes data from the 1984, 1986, and 1988 databases. The data is grouped according to roadway type (state routes, interstate routes and combined). From this figure the following observations can be made:

- Mean rut depths are larger on interstate routes than on state routes. This is likely due to the larger traffic volumes on interstate routes.

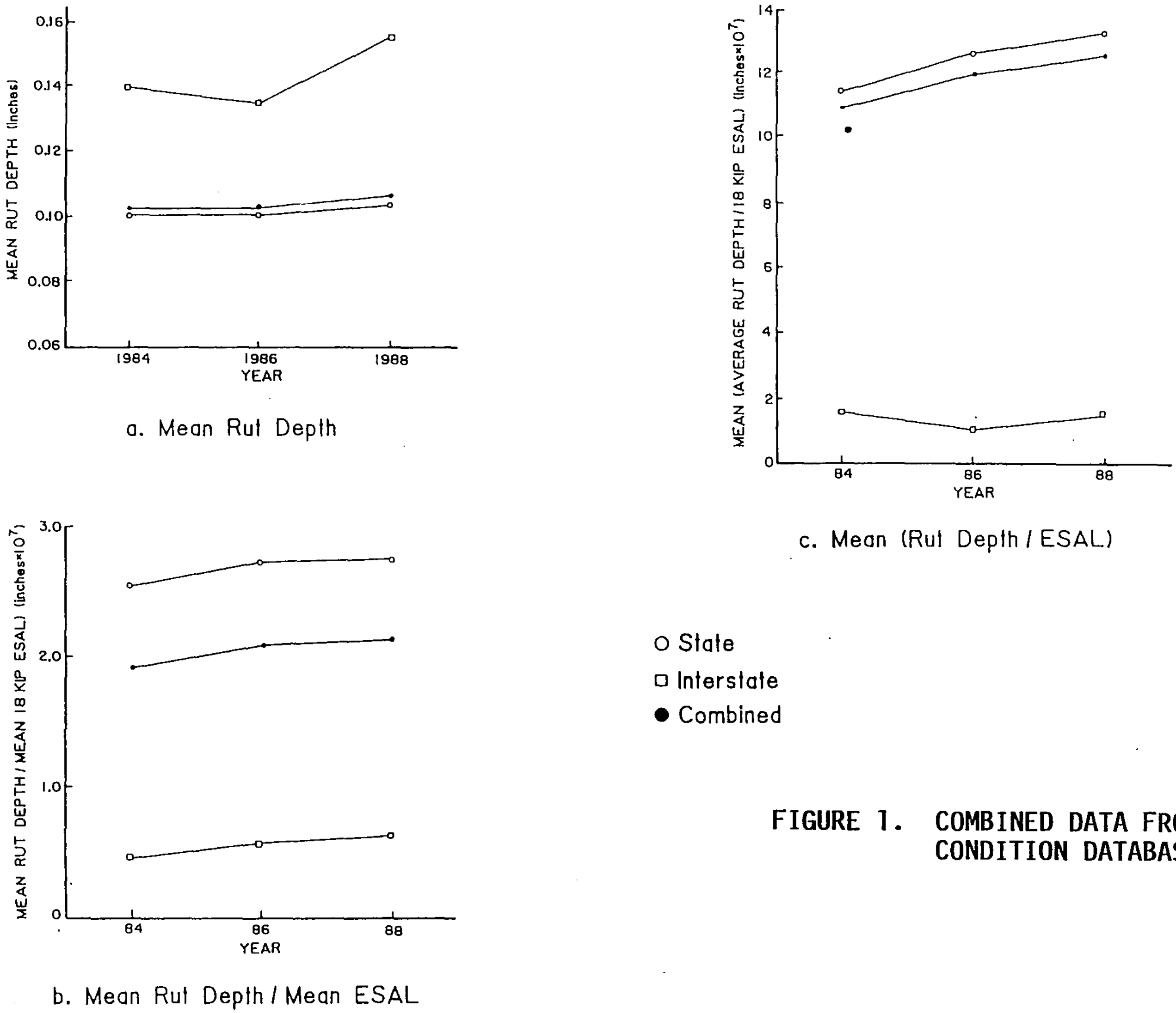

FIGURE 1. COMBINED DATA FROM PAVEMENT CONDITION DATABASES.

- The average rut depth has increased from 1984 to 1988.
- The average rut depth increase, from 1984 to 1988, is larger for interstate routes (0.01494 in.) than state routes (0.0036 in.).
- Values of the ratios of the means (b) are considerably different than values of means of the ratios (c). This is due to the large numeric differences between numerators (average rut depth) and denominators (ESAL) and the wide range of ESAL values. Values shown for both parameters are ratios multiplied by 10^7.
- Because of the large influence of extreme values of ESAL's, the ratio of the means is considered a better indicator of rate of rut development.
- Both ratios indicate that the rate of rut development is increasing.
- Both ratios indicate that the rate of rut development is much greater on state routes than interstate routes. This is likely due to higher quality pavements (including quality of asphalt bound materials) on the interstate system.

All but one of the parameters examined indicated that rutting is increasing. For rut depth this could be caused by an increase in pavement rutting susceptibility, an increase in traffic volume or an increase in loading severity (truck weight and/or tire pressure). For rate of rut development, possible causes would be restricted to rutting susceptibility and loading severity.

Highway Department Division. Comparisons by Highway Department Divisions were made for mean rut depth, the ratio of mean rut depth to ESAL's and the mean of the ratio of average rut depth to ESAL's. These comparisons were made to determine if geographical variations in rutting exists and to examine possible reasons for these variations. Speculation was that geology and, thus, the availability of variable quality aggregates might be a factor. Divisions 1, 3 and 4 are predominately in the Piedmont and Appalachian Plateau geologic provinces. Rock deposits in these areas are used for crushed stone and are the source of sand and gravel materials. Division 2 is divided between the Appalachian Plateau and the Coastal Plain region. Divisions 5-9 lie below the Fall Line in the Coastal Plain region. Natural sands and gravels are available and are the predominate aggregate materials used in this region.

If indeed geology and, thus, geography is a factor, rutting susceptibility should be less in Divisions 1-4 than in Divisions 7-9. Divisions 5 and 6 should be intermediate. Table 1 contains averages for rut depth, the ratio of mean rut depth to mean ESAL's, and the mean of the ratio of rut depth to ESAL's sorted by division. These averages indicate that pavements in Divisions 5-9 are more susceptible to rutting than those in Divisions 1-4.

The most consistant indicator of this trend is the ratio of means which is an indicator of rate of rut development. Rut depth and the mean of the ratio of rut depth to ESAL's is more sensitive to pavement age. Between 1986 and 1988 the relationship between average rut depth and the mean of the ratio for combined and state route data reversed.

As can be seen in Table 1, the average 1988 rut depths on state and combined routes for Divisions 1-4 are about equal those in Divisions 5-9. The means of the ratios for 1988 become larger in Divisions 1-4. This reversal in trend is thought to be primarily due to a reversal in values for Divisions 4 and 5. In 1986 the average number of ESAL's on combined state and interstate routes in Division 4 was 306,000 and in 1988, 365,000. The trend in Division 5 was just the opposite, with applied ESAL's going from 450,000 in 1986 to 384,000 in 1988. This reversal in applied traffic (average pavement age) for Divisions 4 and 5 is thought to be primarily responsible for the reversal in trends.

Despite the exceptions noted above, the analyses of the data support the contention that rutting susceptibility is related to geographic location. In

TABLE 1. SUMMARY OF RUTTING SUSCEPTIBILITY BY AHD DIVISION

Routes	Divisions	Database Year 1984	1986	1988
		Average Rut Depth (inches)		
State & Interstate	1 - 4	0.07380	0.08491	0.10572
	5 - 9	0.12759	0.11615	0.10756
State	1 - 4	0.07368	0.08568	0.10513
	5 - 9	0.12464	0.11197	0.10104
Interstate	1 - 4	0.10006	0.09128	0.11099
	5 - 9	0.18646	0.18685	0.17707
		Mean Rut Depth/Mean ESAL (inch x 10^{-7})		
State & Interstate	1 - 4	1.286	1.560	2.145
	5 - 9	2.750	2.751	2.480
State	1 - 4	1.690	2.018	2.595
	5 - 9	3.628	3.424	3.000
Interstate	1 - 4	2.396	2.639	3.908
	5 - 9	6.616	7.708	8.470
		Mean (Average Rut Depth/ESAL) (inch x 10^{-7})		
State & Interstate	1 - 4	8.510	11.073	15.095
	5 - 9	13.656	12.730	10.465
State	1 - 4	8.822	11.636	15.095
	5 - 9	14.536	13.452	10.872
Interstate	1 - 4	0.660	0.373	1.354
	5 - 9	1.585	1.383	1.500

addition, geology and, thus, properties of available aggregate provide a logical explanation for the observed relationship between rutting susceptibility and geographic location.

Analysis of Field Data.

Data from thirteen (13) field sites was analyzed to determine where in the pavement structure permanent deformation was developing and the relationship between rut development and traffic. The profiles of the asphalt bound layers were analyzed to determine where rutting was developing. When trenches were opened, stringlines were stretched along layer interfaces to defect depressions in the lower layer surface. These depressions would be indicative of permanent deformation in the layer itself or lower layers. Measurements in the trenches indicated that permanent deformation was primarily confined to near surface (approximately 4 inch depth) asphalt bound layers. In most pavements this limited permanent deformation to surface and binder layers. The interface between binder and black base layers were usually relatively depression free.

At only Site 9 was there evidence of rutting in base or subbase layers below asphalt bound layers. There was evidence of rutting in or below a sand-clay-shell base at this site. At only Site 2 was there evidence that stripping may have contributed to rutting. At this site several cores in wheel paths disintegrated and could not be completely recovered. Stripping was confined to the original binder and base layer.

Rut depths are tabulated in Table 2. Also shown in Table 2 are rut depths for projects in which the test sites were located compiled from the 1988 pavement condition database. While rut depth is an indicator of performance, it is influenced by traffic (volume and load) which must be considered when assessing rutting susceptibility. Traffic applied to the pavements at the test sites was converted to 18 kip equivalent single axle loads (ESAL). Ratios of rut

TABLE 2. TEST SITE RUTTING ANALYSIS DATA.

Site	18kip ESAL	Rut Depth		RD/ESAL		RD/√ESAL
		Test• Site (in)	1988+ DB (in)	Test Site (in)	1988 DB (in)	Test Site (in)
1*	$6.6x10^6$	0.48	0.38	$0.73x10^{-7}$	$0.58x10^{-7}$	$18.7x10^{-5}$
2	$2.6x10^6$	0.45	0.30	$1.73x10^{-7}$	$1.15x10^{-7}$	$27.9x10^{-5}$
3	$2.9x10^6$	0.47	0.41	$1.62x10^{-7}$	$1.41x10^{-7}$	$27.6x10^{-5}$
4*	$4.3x10^6$	0.30	0.20	$0.70x10^{-7}$	$0.47x10^{-7}$	$14.5x10^{-5}$
5	$2.0x10^6$	1.09	0.35	$5.45x10^{-7}$	$1.75x10^{-7}$	$77.1x10^{-5}$
6	$3.7x10^6$	0.84	0.43	$2.27x10^{-7}$	$1.16x10^{-7}$	$43.7x10^{-5}$
7*	$3.6x10^6$	0.22	0.13	$0.61x10^{-7}$	$0.36x10^{-7}$	$11.6x10^{-5}$
8	$0.5x10^6$	0.56	0.20	$11.20x10^{-7}$	$4.00x10^{-7}$	$79.2x10^{-5}$
9	$1.6x10^6$	0.66	0.39	$4.12x10^{-7}$	$2.44x10^{-7}$	$52.2x10^{-5}$
10	$2.0x10^6$	0.53	0.28	$2.65x10^{-7}$	$1.40x10^{-7}$	$37.5x10^{-5}$
11*	$5.9x10^6$	0.35	0.18	$0.59x10^{-7}$	$0.30x10^{-7}$	$14.4x10^{-5}$
12	$0.3x10^6$	0.14	0.02	$4.67x10^{-7}$	$0.67x10^{-7}$	$25.6x10^{-5}$
13*	$1.5x10^6$	0.26	0.16	$1.73x10^{-7}$	$1.07x10^{-7}$	$21.2x10^{-5}$

*Sites selected for good rutting performance.

•Rut depth measured with 12 foot straight edge across lane.

+Rut depth measured with 4 foot straight edge across wheel path. Average of 8 measurements per mile for entire design section in which test site located.

depth to ESAL's and rut depth to square root of ESAL's were computed and tabulated in Table 2.

Histograms of rut depth and the ratios were plotted, as illustrated by the ratio of rut depth to square root of ESAL's in Figure 2. Rut depth provided a reasonable good separation of good and poor performing pavements, with those performing poorly having rut depths greater than 0.4 inches when measured with a 12-foot straight edge. The ratios that provide an indication of the rate of rutting and a clear delineation between good and poor performing pavements. A 1.0×10^{-7} in./ESAL or 2.0×10^{-4} in./$\sqrt{\text{ESAL}}$ criteria separates rutting and nonrutting pavement.

Analysis of Laboratory Data.

After completion of all laboratory testing a detailed statistical analysis using SAS program was performed to determine those properties that are related to rutting. In-place mix properties included asphalt content, voids, resilient modulus and creep strain. Properties of recompacted mix included voids, stability and flow of samples compacted with a manual Marshall hammer and with a gyratory testing machine. During compaction in the gyratory, roller pressure was measured and gyratory shear index (GSI) was computed. Properties of recovered asphalt included penetration and viscosity. Properties of recovered aggregate included gradation, fractured face counts on coarse aggregate particles, and uncompacted voids and flow time for fine aggregate fractions.

To be useful a model must include rut depth and traffic. Three relationships were considered: (Rut Depth)/ESAL, (Rut Depth)/$\sqrt{\text{ESAL}}$, and (Rut Depth)/ln ESAL. It was determined that (Rut Depth)/$\sqrt{\text{ESAL}}$ was the parameter that correlated best with laboratory properties. Correlation coefficients from the linear regression between (Rut Depth)/$\sqrt{\text{ESAL}}$ and various parameters are tabulated in Table 3. A correlation coefficient close to 1 indicates a good

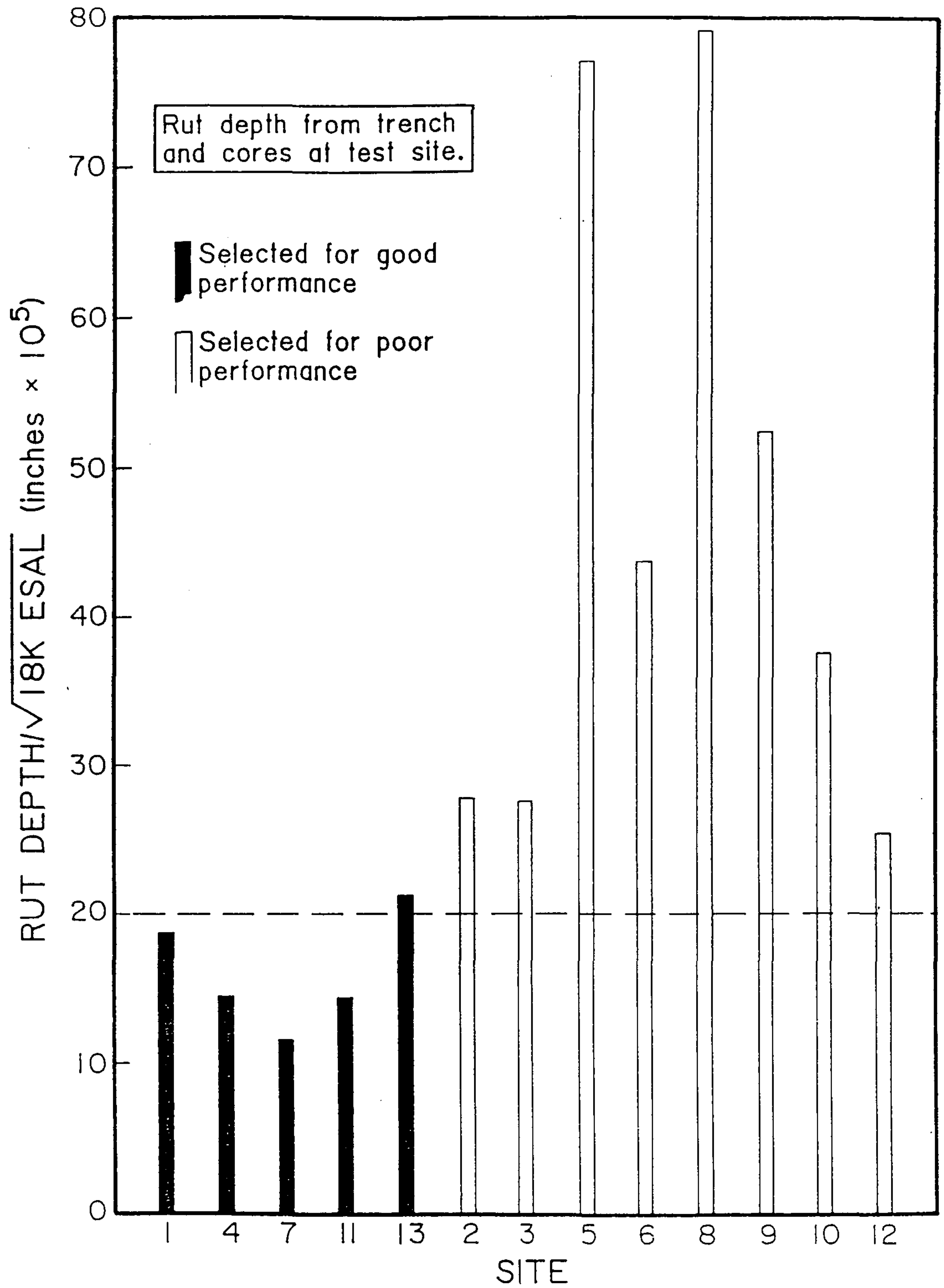

FIGURE 2. (RUT DEPTH)/$\sqrt{ESAL}$ AT TEST SITES.

TABLE 3. CORRELATION COEFFICIENTS BETWEEN RUT DEPTH/$\sqrt{ESAL}$ AND VARIOUS MIX PROPERTIES.

Property	Correlation Coefficient
Thickness, inches	0.59
Voids (In-Place), %	-0.66
Resilient Modulus, psi	-0.65
Creep Strain, %	0.45
Recompacted Voids (Hand), %	-0.47
Recompacted Voids (Gyratory), %	-0.57
Marshall Stability, lbs	-0.74
Gyratory Stability, lbs	-0.66
Marshall Flow, .01 inches	0.50
Gyratory Flow, .01 inches	0.41
GSI	0.64
Gyratory Roller Pressure, psi	-0.61
Passing 3/8 inch, %	-0.47
Passing No. 50, %	0.17
Passing No. 200, %	0.37
Fractured Faces, %	-0.13
NAA Voids, %	0.15
Flow Time, sec	0.05
Asphalt Penetration (77°F)	0.46
Asphalt Viscosity (140°F)	-0.50

correlation and a correlation coefficient close to a 0 indicates a poor correlation. Since most of the rutting that was observed occurred in the top four inches and generally in the top layer, the analysis was made considering only the properties of the top layer.

In-Place Voids. It has been known that rutting is a function of in-place voids. Brown and Cross (9), Ford (10), and Huber and Herman (11) showed that once in-place voids drop below approximately 3 percent rutting is likely to occur. Table 3 shows that the correlation coefficient for in-place voids and (Rut Depth)/$\sqrt{ESAL}$ is -0.66.

Six pavements had in-place voids below 3 percent in the top layer. These pavements were at sites 2, 3, 5, 6, 8, and 9. These six sites along with site 10 had the highest (Rud Depth)/$\sqrt{ESAL}$ values and hence rut at a faster rate. Site 10 had very low in-place voids (1.6 percent) in the second layer which likely explains why it had a high rate of rutting. In place voids near four percent and higher typically result in a (Rut Depth)/$\sqrt{ESAL}$ of approximately .0002 or less. This means that the expected rut depth for these mixes after 1 million ESALs would be no more than 0.2 inches and after 4 million ESALs, it would be no more than 0.4 inches.

Resilient Modulus (M_R). The correlation coefficient between M_R and (Rut Depth/$\sqrt{ESAL}$ was determined to be -0.65. This is a relatively high correlation and shows that an increase in M_R should result in a decrease in rut depth. Since the M_R was conducted on field samples, it is likely that the mixes with higher voids aged more rapidly than other mixes and thus, resulted in higher M_R values. Since M_R changes with age of the asphalt mix, it would be impossible from this study to determine minimum M_R values to specify for new construction.

Creep. The correlation coefficient between creep strain and (Rut

Depth)/$\sqrt{ESAL}$ was determined to be 0.45. There was a definite trend in creep strain values. Seven of the mixes had low creep strain values. Five of the six values with high creep strain had (Rut Depth)/$\sqrt{ESAL}$ greter than 0.0002. Four of the seven values with low creep strain had (Rut Depth)/$\sqrt{ESAL}$ greater than 0.0002.

Recompacted Voids (Hand Hammer). Some of the mix taken from the in-place pavement was heated, broken up and recompacted using 75 blows with the Marshall hand hammer. This process should provide an estimate of the original laboratory compacted mix properties. Table 3 shows that the correlation coefficient between recompacted voids and (Rut Depth)/$\sqrt{ESAL}$ is -0.47.

While recompacted voids do not relate as well with rutting as in-place voids, it does relate well enough to be effective in minimizing rutting. If laboratory voids are four percent or higher, rutting should not be a major problem provided all other properties are acceptable.

Recompacted Voids (Gyratory Testing Machine). Samples recompacted in the gyratory provide similar results as those recompacted with hand hammer. The correlation coefficient for samples compacted in the GTM is -0.57 which is slightly better than that for hand hammer.

Marshall Stability (Recompacted with Hand Hammer). The correlation between (Rut Depth)/$\sqrt{ESAL}$ and Marshall stability of samples recompacted with a hand hammer is very high (correlation coefficient = -0.74). This indicates that an increase in stability will result in a decrease in rutting. This correlation is somewhat surprising since most pavement engineers believe that Marshall stability is not related to rutting.

The actual Marshall stability values measured are generally very high since the asphalt has oxidized and stiffened. Even if Marshall stability is closely related to rutting it would be difficult to establish stability requirements from the data in this report since the stability values reported are much higher than that which would be expected for new mix.

Marshall Stability (Recompacted with Gyratory). The correlation coefficient between the stability (gyratory compacted) and (Rut Depth)/$\sqrt{ESAL}$ is -0.66. Again this is a high degree of correlation. The explanation provided for stability (hand hammer compaction) also applies to the stability measured here.

Marshall Flow (Hand Compacted). Flow is considered a reasonably good indicator of rutting. The correlation coefficient between Marshall flow (hand compacted) and rutting for this study was measured to be 0.50. A flow of 16 is specified by most agencies as the maximum allowable flow. Four of the five mixes with a flow above 16 had (Rut Depth/$\sqrt{ESAL}$ greater than 0.0002. Four of the eight mixes with flow 16 or less had (Rut Depth)/$\sqrt{ESAL}$ greater than 0.0002. Again, there is a trend which indicates that mixes with a flow above 16 are more likely to rut.

Marshall Flow (Gyratory Compacted). The correlation coefficient between Rut Depth/$\sqrt{ESAL}$ and Marshall Flow (Gyratory Compacted) is 0.41. Four of the five mixes with a flow greater than 16 have a (Rut Depth)/$\sqrt{ESAL}$ greater than 0.0002. Only four of eight mixes with flow less than sixteen have (Rut Depth)/$\sqrt{ESAL}$ greater than 0.0002.

Gyratory Shear Index (GSI). The GSI has been shown to be a good indicator of rutting (6). As shown in Table 3 the correlation coefficient between GSI and Rut Depth/$\sqrt{ESAL}$ was 0.64. There was significant scatter about the best fit line, but the data that ploted well above the best fit line generally had low fractured face count and the data below the line generally had a high fractured face count. Much data was grouped at GSI = 1.0 since this is the lowest value that a mix can have. Previous studies have shown that mixes with a GSI greater than 1.3 are expected to exhibit severe rutting (9). The data shows that 4 of the 5 mixes with GSI above 1.3 had experienced a Rut Depth/$\sqrt{ESAL}$ greater than .0002.

Gyratory Roller Pressure. The correlation coefficient between roller pressure and (Rut Depth)/$\sqrt{ESAL}$ is -0.61. The roller pressure is that force required to produce a 1 degree gyration angle in the asphalt mix. A mix that is more resistant to deformation should require a higher pressure to deform it during the compaction progress. Seven of the eight mixes with a roller pressure of 14 psi or less had Rut Depth/$\sqrt{ESAL}$ greater than 0.0002. Three of the five mixes with a roller pressure greater than 14 psi had Rut Depth/$\sqrt{ESAL}$ less than 0.0002.

Aggregate Gradation. The aggregate gradation definitely affects the rutting resistance of an asphalt mixture but this is a difficult property to analyze. Studies have shown that the maximum aggregate size is important as well as percent passing No. 200 sieve are important (9,10). However, the overall evaluation of individual gradations is difficult. For this project the percent passing 3/8 inch sieve, percent passing No. 50, and percent passing No. 200 sieve were analyzed to determine their affect on rutting. The correlation coefficient between Rut Depth/$\sqrt{ESAL}$ and percent passing the 3/8 inch sieve is -0.47. This indicates that an increase in percent passing the 3/8 inch sieve will decrease rutting. This is opposite from the expected trend. The high correlation coefficient was basically the result of one data point that has a very low percent passing the 3/8 inch sieve and very high rutting. Based on the findings by others and the data scatter it is concluded that clear trend between Rut Depth/$\sqrt{ESAL}$ and percent passing the 3/8 inch sieve is not shown in this study.

The second sieve size that was investigated was the percent passing the

No. 50 sieve. The correlation coefficient of 0.17 indicates very little trend between Rut Depth/$\sqrt{ESAL}$ and percent passing No. 50 sieve. The correlation coefficient of 0.37 indicate a better but still poor correlation between (Rut Depth)/$\sqrt{ESAL}$ and percent passing the No. 200 sieve. However, the two most severely rutted pavements had more than seven percent passing the No. 200 sieve.

Fractured Faces. The fractured face count of an aggregate should affect its ability to resist rutting. Some percentage of fractured aggregate is almost always specified for high volume roads but there is very little field data to support or contradict this type specification. The correlation coefficient between fractured face count and (Rut Depth)/ $\sqrt{ESAL}$ for the study was -0.13 (Table 3). This is a very low correlation that shows a slight trend toward less rutting for higher fractured face count.

The correlation appears to be much better than this after detailed review of the data. The two mixes with highest (Rut Depth)/$\sqrt{ESAL}$ (Site 5 = 77.1 x 10^{-5} and Site 8 = 79.2 x 10^{-5}) also had high fractured face counts (Site 5 = 81.0% and Site 8 = 98.1%). These mixes had low in-place voids (Site 5 = 2.3% and Site 8 = 0.6%). Site 5 was the most severely rutted site studied (Rut Depth = 1.09 inches) with rutting well into plastic flow. Plastic flow had not started at Site 8, but the mix was characterized by very high asphalt content (7.8%) and very low in-place voids (0.6%). If the data for Site 8 is eliminated, for unrealistically high asphalt content, the correlation coefficient becomes -0.41 indicating a much stronger trend.

The data shows that all six mixes with fractured face percentages of 80 or less had a (Rut Depth/ $\sqrt{ESAL}$ greater than .0002. The data also shows that four out of seven mixes with a fractured face count greater than 80 had (Rut Depth/ $\sqrt{ESAL}$ less than .0002, including the two mixes discussed above.

Fine Aggregate Shape & Texture. Uncompacted voids from the NAA flow test (11) and time from the modified test measure particle angularity and texture. Higher voids and flow times indicate rougher textured and more angular particles. The correlation coefficients in Table 3 shows that flow time from the modified NAA test has very little correlation (0.05). Uncompacted voids from the NAA test have better (0.15), but still very poor correlation.

The positive correlation coefficient indicates that an increase in voids will result in an increase in rutting. This is opposite of the expected trend. However, a detailed review of the data reveals stronger correlation. Sites 5 and 8, which have the two highest rates of rutting, do not follow the pattern of the data at other sites. If the data point for Site 8 (45.9, 79.2 x 10^{-5}) is omitted, for unrealistically high asphalt content, the correlation coefficient becomes -0.25 indicating a stronger trend. More importantly the sign of the correlation coefficient is reversed and indicates, as expected, that rate of rutting decreases as uncompacted voids increases.

Again, if the data point for Site 8 (23.9, 79.2 x 10^{-5}) is omitted, the correlation coefficient for flow time becomes - 0.37. This not only represents a dramatic increase in magnitude, but the change in sign means that the trend is in the expected direction, i.e., rate of rutting decreases as flow time increases. The performance of the mix at Site 8 demonstrates the multiplicity of factors that can influence rutting performance, and the importance of both aggregate properties and asphalt content during material selection and mix design.

Asphalt Penetration. The data in Table 3 shows that the correlation coefficient between (Rut Depth/$\sqrt{\text{ESAL}}$ and penetration is 0.46. The data shows an obvious trend indicating an increase in penetration would result in an increase in rutting. Since most asphalt pavements in Alabama begin with similar penetration, it is not clear what this trend indicates. As before, it may be that larger voids result in more oxidation of the asphalt and better resistance to rutting. At any rate it is reasonable to expect more rutting when using an asphalt with higher penetration.

Viscosity. The correlation coefficient between (Rut Depth)/$\sqrt{ESAL}$ and viscosity is -0.50 as shown in Table 3. This indicates that an increase in viscosity would result in a decrease in Rutting. The discussion under asphalt penetration will also be true for viscosity.

CONCLUSIONS AND RECOMMENDATIONS

Analyses of the Department's pavement condition database indicate that rutting in Alabama is increasing, and that this increase is attributible to either increased loading intensity or increased asphalt concrete rutting susceptibility. The analyses also indicate that rutting varies geographically and that this variation can be explained by quality of locally available aggregate. Those areas with crushed stone and angular natural sands are less susceptible to rutting.

Analyses of data from field test sites indicate that permanent deformation causing rutting is generally confined to the top 3 to 4 inches (surface and binder courses). There was little evidence that lower base/subbase courses or subgrade were significant contributors to rutting. At only one site was there evidence that stripping may have contributed to rutting. There was some evidence that surface treatment layers used in conjunction with thin overlays may have contributed to rutting susceptibility. A rate of rutting of 2×10^{-4} in/$\sqrt{ESAL}$ or 1.0×10^{-7} in/ESAL delineated good and poor performing pavements.

The properties measured in this study that appear to be useful in minimizing rutting include: layer thickness, voids, GSI, Gyratory roller pressure, percent of fractured faces, percent passing No. 200 sieve, Marshall flow, and creep strain. The correlation coefficients for most of these properties were low, however, there appeared to be a definite trend shown in the figures. The low correlation coefficients in almost every case was caused by one or two of the data points being far outside the range of the other data. This shows that rutting is a very complicated process and is affected by a large number of factors and hence, to use only a small number of properties to accurately predict rutting is impossible.

The crushing of gravel should be more carefully controlled to insure that the 80% requirement for particles with two fully fractured faces is met. This may require limitations on minimum particle size for crushing. On heavily traveled roadways (state primary and interstate routes) crushed particle requirements for binder mixes should be the same as surface mixes. The use of a test, such as the National Aggregate Association's uncompacted voids method, to quantify and limit particle shape and texture of fine aggregate should recieve additional study but this study showed no correlation.

The use of surface treatment interlayers, particularly in conjunction with thin overlays, should receive further study. This study should focus 1) on identifying conditions where surface treatment interlayers should and should not be used, and 2) on construction control procedures that will prevent excess asphalt cement that could soften the overlay and increase rutting susceptibility.

Procedures should be adopted for better control of asphalt content during construction. Target job mix formula asphalt content should not be changed without sufficient test results to justify changes.

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