Relation of Asphalt Pavement Variables To Performance

L. C. BRUNSTRUM, L. E. OTT, A. W. SISKO, T. L. SPEER and
R. A. WILKE, Research and Development Department, American
Oil Company, Whiting, Indiana; and
J. V. EVANS, Marketing Technical Service Department, American
Oil Company, Chicago, Illinois

Plastic deformation in asphalt pavements determines the contribution of two important factors, slope variance and rut depth, in the AASHO serviceability equation. Previous research on a laboratory test track showed the dependence of plastic deformation on the viscosity of the asphalt under pavement conditions. This research has now been extended to determine, on 66 pavements, the effect of pavement variables such as asphalt content, fines content and compaction. Factors affecting asphalt viscosity (temperature susceptibility, mixing at high temperature, and aging in the pavements) were also studied.

The contributions and interactions of pavement and asphalt variables were combined in a single equation by means of least squares multiple regression, enabling comparison of the relative effects of common variations in these properties. Results are illustrated by a bar chart. Charts presented relate actual deformation to that predicted by the regression equation. The basic form of the equation should now be tested with data from actual roads in service.

IF THE many factors determining the performance of flexible pavements are not rigidly controlled, roads can undergo changes in thickness and surface profile that, in time, adversely affect the riding quality (1). These changes are the result of plastic deformation and are evident in the development of slope variances along the road and shallow depressions across the road (2). The rate of deformation changes as the bituminous layers compact and as the mechanical properties of the constituents change.

To minimize plastic deformation, a variety of criteria (e.g., asphalt content, aggregate gradation, specific gravity, voids, asphalt grade, thin film oven tests (TFOT), and compressive stabilities of several sorts) are used during design and construction. Collectively, these diverse criteria insure optimum performance. It would be advantageous if the contribution of all factors relating directly to pavement performance could be expressed in common units that would provide means for comparing the relative importance of each factor.

In previous research (phase 1), plastic deformation was studied in terms of the rut depths developed in experimental pavements on a laboratory test track (3). This study showed the significance of asphalt viscosity in the rutting process and led to the equation, $R = k\eta^{-n}$, where R is rate of rutting, η is asphalt viscosity, and k and n are constants. The data strongly indicated that pavement characteristics such as asphalt content and compaction influenced these constants. Thus, if the contribution of composition and construction variables could be quantitatively determined, k and n might be used to characterize a pavement or serve as a basis for design. In addition, these

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constants could provide the desired means for comparing the relative effects of the variables.

Research has been continued in this area to determine the effect of viscosity grading at 140 F and of pavement composition and construction. Two series of pavements (phase 2 and phase 3), comprising about 50 individual pavements, were made with 13 asphalts from eight crude sources. Pavements were subjected to many wheel passes, simulating severe traffic conditions, on the laboratory test track.

EXPERIMENTAL CONSIDERATIONS

All pavements had the same basic design (similar to that of a dense-graded Illinois I-11 specification). In phase 2, pavement composition was constant, but all the asphalts were used. In phase 3, a single asphalt was used throughout, but pavement composition was varied somewhat more than would normally occur in the construction of actual roads. Pavement design and construction and track equipment were substantially as described in phase 1 (3).

Asphalts

The asphalts included domestic and foreign crude sources and were made by several manufacturing methods. All were commercial paving materials but were blended in the laboratory to be in the midpoint of the viscosity study ranges proposed by the Asphalt Institute. As indicated in Table 1, all four grades were represented, although most were either AC-10 or AC-20 grade. Temperature susceptibility was judged by

TABLE 1

ASPHALT CHARACTERISTICS

Asphalt		Asph. Inst. Study Grade	Original Viscosity		TFOT Ratio (140 F)	Walther Slope (140-275 F)	Penetration at 77 F	Sp. Gr. at 60 F	Flash COC
No.	Source		140 F Posises	275 F Centistokes					
1	A	5	530	183	2.9	3.68	108	1.025	500
2	B	10	1,300	377	3.1	3.43	128	1.035	465
3	C	10	1,330	324	2.4	3.57	82	1.017	620
4	D	10	1,400	325	2.7	3.58	85	1.013	595
5	E	10	1,360	304	2.8	3.62	81	1.036	590
6	F	10	1,370	392	2.2	3.41	105	0.999	640
7	G	10	1,420	352	2.7	3.52	83	1.015	615
8	A	20	2,650	339	2.8	3.78	37	1.044	520
9	H	20	2,020	402	4.6	3.55	82	1.019	620
10	E	20	2,590	432	2.8	3.57	51	1.041	660
11	F	20	2,610	498	2.4	3.49	72	0.998	625
12	B	40	4,440	671	3.5	3.43	56	1.045	480
13	F	40	4,540	645	3.2	3.50	53	0.999	680

TABLE 2

AVERAGE AGGREGATE GRADATION

Series	Passing Sieve (%)							
	¾ In.	½ In.	No. 4	No. 10	No. 40	No. 80	No. 200	Fines
(a) Surface								
Design	-	0	36	20	22	7	6	9
Phase 2	-	0	33.9	21.2	22.3	10.2	4.7	7.7
Phase 3	-	0	32.4	22.6	20.2	7.4	8.6	8.8
(b) Binder								
Design	0	25	45	45	30	30	30	30
Phase 2	0	20.7	38.0	10.3	17.5	10.5	1.7	1.3
Phase 3	0	24.1	33.7	10.9	16.5	12.5	1.5	0.8

TABLE 3

PAVEMENT CHARACTERISTICS, PHASE 2

Pavement No.	Asphalt No.	% Asphalt		% Fines, Surface	Mix Ratio
		Surface	Binder		
(a) Pavements Tested at 150 F					
108	10	4.68	4.87	8.4	4.63
109	5	5.19	4.50	6.5	2.97
110	3	4.82	4.73	7.9	2.56
111	8	4.85	4.76	8.3	4.68
112	4	4.86	4.95	8.4	3.33
113	11	5.16	4.45	7.4	3.06
114	2	4.82	5.05	6.7	3.31
115	7	4.86	4.70	8.6	3.01
117	6	4.78	4.84	6.7	4.04
118	1	5.25	5.05	7.7	2.51
119	12	4.57	4.82	7.4	3.51
120	13	4.61	4.65	6.7	4.21
121	1	5.07	5.10	7.5	2.00
122	5	4.66	5.09	8.2	2.44
123	13	5.38	4.34	5.9	2.38
124	9	5.01	4.74	7.1	3.02
(b) Pavements Tested at 110 F					
125	5	4.97	4.66	6.5	2.44
126	5	5.01	4.72	8.0	2.38
127	6	4.96	4.90	6.8	1.97
128	4	5.20	4.90	7.7	2.98
129	3	5.20	4.70	8.2	2.53
130	7	4.80	4.60	6.6	2.25
131	2	4.98	4.69	6.4	2.67
132	11	5.35	4.76	7.3	2.17
133	10	5.04	4.80	7.8	2.74
134	8	4.80	4.80	7.4	3.72
135	13	4.83	4.60	6.7	2.86
136	13	4.66	4.72	7.2	3.44
137	12	4.67	4.50	6.3	3.20
138	9	4.72	4.70	6.8	3.27
139	5	5.00	5.07	7.2	2.48
140	1	4.70	4.80	7.7	2.35

TABLE 4

EXTREMES OF MAJOR VARIABLES IN PAVEMENTS

Variable	Base Case (%)	Max. (%)	Min. (%)
Asphalt in surface	4.75	6.63	3.81
Asphalt in binder	4.95	6.33	4.37
Fines in surface	8.6	11.7	6.6

Walther slopes between 140 and 275 F. The TFOT ratio (see Appendix) was less than 5 in all cases. Penetration, flash, and gravity relate the asphalts to existing practice.

Pavements

The basic design was by Marshall criteria; optimum asphalt content was 4.75 percent.

The phase 2 series consisted of 32 pavements made with asphalts representing all four grades of the study specification. Average aggregate gradation is given in Table 2. Asphalt content of the surface course averaged 4.92 ± 0.38 percent, and that of the binder 4.76 ± 0.33 percent, as indicated in Table 3. The 32 pavements were subjected to several million wheel passes with 16 pavements at 150 F and 16 at 110 F. Replication was provided in pavements containing asphalts 1, 5 and 13; asphalt 5 was replicated at both temperatures.

The phase 3 series consisted of 16 pavements made with asphalt 11. To gain pronounced response in performance, asphalt and fines contents of the surface course were varied above and below the base case, which was the design of phase 2. Because variable amounts of constituents adhere to the pug mill, composition was determined by extraction of the pavements. Extremes of the major variables, none of which occurred in the same pavement, are given in Table 4. Aggregate gradation was similar to phase 2 and is also given in Table 2. Compaction was done at two levels, one normal and one somewhat below normal.

The number of batches at each level was selected from several statistical designs based on the experience of phase 2 and was chosen to provide the optimum opportunity to test the major variables with the 16 track positions available. Replication of the base case provided an opportunity to check possible technique variations from the earlier phases.

Testing in the laboratory track was done at three temperatures in three cycles, the orders being 80, 125, and 100 F; 100, 125, and 80 F; and 80, 125, and 100 F. At each temperature, rut depth was measured at three or four intervals. Duration of the test at each temperature depended on attaining a measurable increase in rut depth. Temperature variation in the pavements was ±1 F all around the track, as measured with four dial thermometers in each pavement.

Determination of Viscosity in Pavement

The viscosity of either the original asphalt or the TFOT residue, measured at the temperature of the track test, was used in $R = k\eta^{-n}$. Either viscosity provides useful

TABLE 5

PAVEMENT CHARACTERISTICS, PHASE 3

Pavement No.	% Asphalt		% Fines, Surface	Mix Ratio	Age Ratio
	Surface	Binder			
147	5.85	4.98	9.7	1.50	1.31
148	5.90	4.58	9.1	1.52	1.29
149	3.81	4.75	10.3	3.47	4.48
150	5.51	4.45	11.7	1.83	1.65
151	4.67	4.72	7.7	2.50	3.17
152	4.79	4.72	7.4	2.58	2.36
153	4.65	4.75	7.5	2.99	2.98
154	4.72	4.69	7.2	2.79	3.38
155	6.63	6.00	9.8	1.16	1.41
156	4.47	6.33	7.4	2.51	3.82
157	4.28	4.37	7.8	3.49	3.30
158	5.80	5.99	7.8	1.58	1.43
159	4.00	4.65	9.4	3.96	5.50
160	5.80	4.58	6.6	1.65	1.51
161	4.11	4.38	6.8	3.72	3.05
162	6.11	6.19	7.8	1.38	1.27
163	3.94	6.22	8.7	5.67	2.98

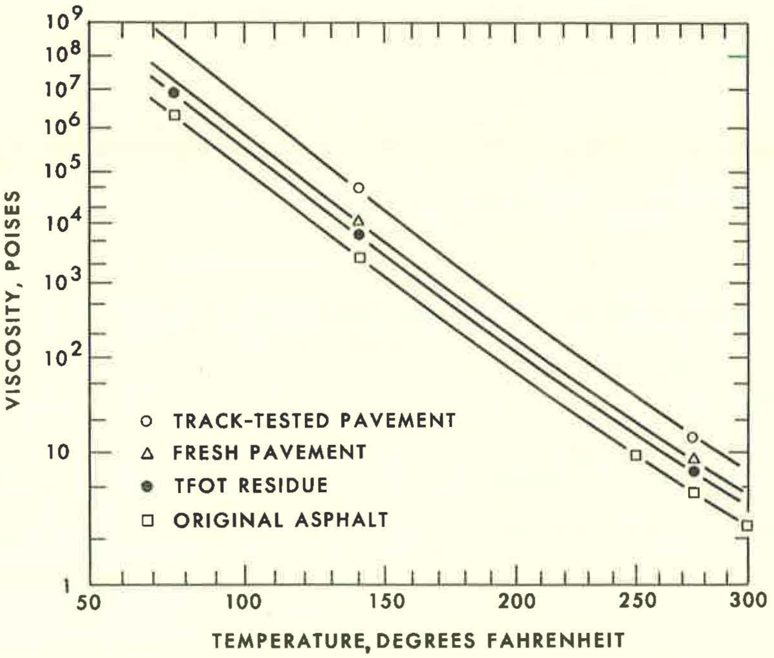

Figure 1. Determination of viscosity in pavement 149.

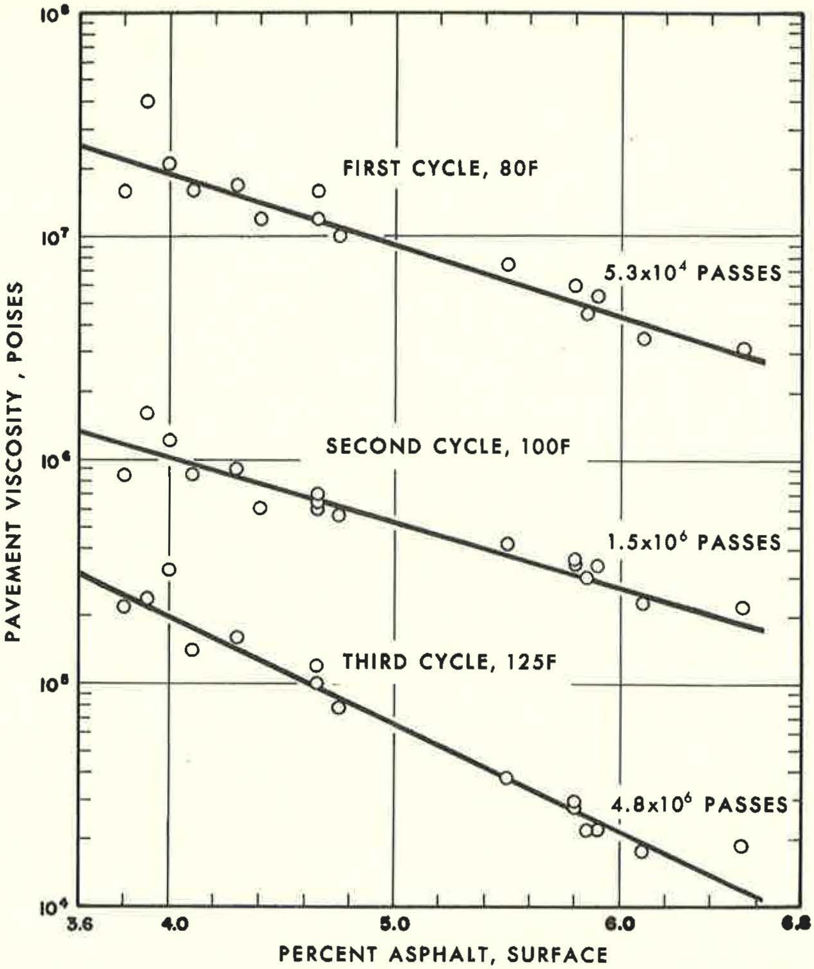

Figure 2. Viscosity of asphalt in pavement.

correlations, but that of the asphalt in the pavement at the temperature and time of the test should provide the best correlation.

The viscosity of an asphalt increases during mixing by a factor called the mix ratio, which is determined by the nature of the asphalt, the mixing time and temperature, and the composition of the pavement. Mix ratios are given in Table 3. Viscosity continues to increase over that in the fresh pavement by a time-dependent factor known as the age ratio. The value given in Table 5 reflects the change that occurred near the end of each test. Some pavements rutted faster than others and were removed from the track before the end of the experiment.

The method of determining viscosity in the pavement is illustrated in Figure 1 by the data on pavement 149. The original viscosity of each asphalt was determined at 77, 140, 250, 275, and 300 F and plotted on the viscosity-temperature chart. Viscosities of the TFOT residues were determined at 77, 140, and 275 F. The plotted data are generally parallel to the original curves. Asphalts extracted from fresh pavements were measured at 140 and 275 F and extrapolated parallel to the original and TFOT curves. Finally, asphalts extracted from tested pavements were measured at 140 and 275 F and similarly extrapolated. For a given temperature level, viscosities were interpolated

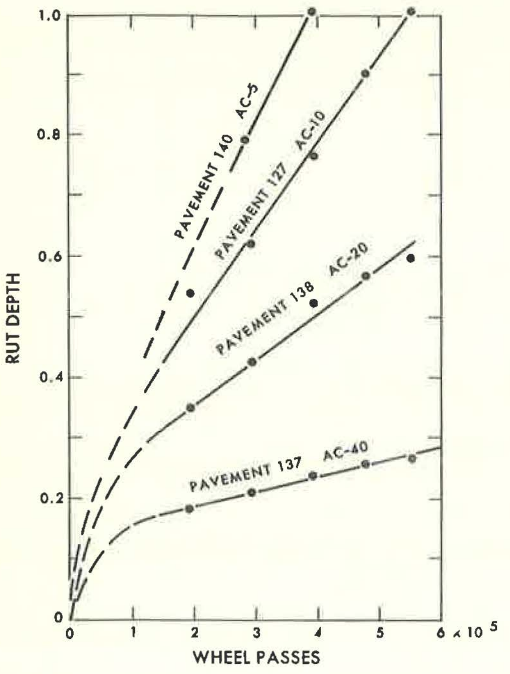

Figure 3. Determination of rut rate.

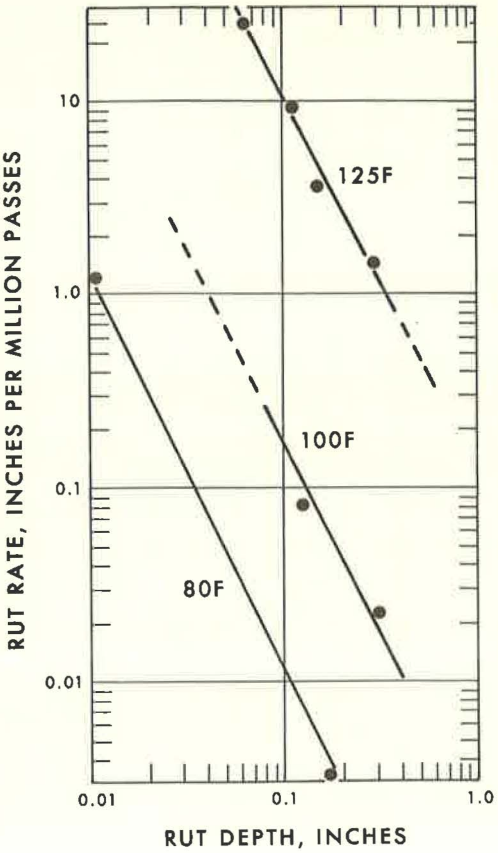

Figure 4. Dependence of rut rate on depth.

linearly between the curves for the fresh pavement and the tested pavement, using the number of wheel passes between the two pavement conditions as the criterion.

Although phase 3 pavements were made with the same asphalt, the viscosities in the pavements differ considerably as a result of testing conditions and asphalt content (Fig. 2). Low asphalt content decreases the asphalt film thickness on the aggregate particles, resulting in higher viscosities and, therefore, higher mix and age ratios.

Determination of Rut Rate

A detailed description of rut measurement has been given (3). Briefly, the track is shut down at intervals and a profilometer with 60 places for a dial indicator is located over each pavement by means of fixed bench marks. The average maximum difference in transverse profiles is taken as the rut depth. Depth is plotted against wheel passes and the rate is calculated in inches per million wheel passes.

The phase 2 pavements were tested at two temperatures and the rate of rutting was determined graphically. Four of the 32 curves obtained are reproduced in Figure 3. Rutting is relatively rapid during the early passes, probably due to compaction and reorientation of the surface particles. The rate soon reduces to a nearly constant level. Correlations between rut rate and viscosity in phase 2 make use of this level. The rate continues to reduce in tests of longer duration; similar rates have been reported for actual roads (1). High rates ended phase 2 too early to determine the full shape of the curves. Also, the need for more frequent rut measurements at the initial stage was indicated.

In phase 3, more attention was given to initial rutting. As in phase 2, plots of rut depth vs wheel passes were prepared. These were not smooth curves but consisted of segments of varying slope, a segment for each temperature in each cycle. Plots of log R vs log D showed a marked dependence of rate on depth as shown in Figure 4 for pave-

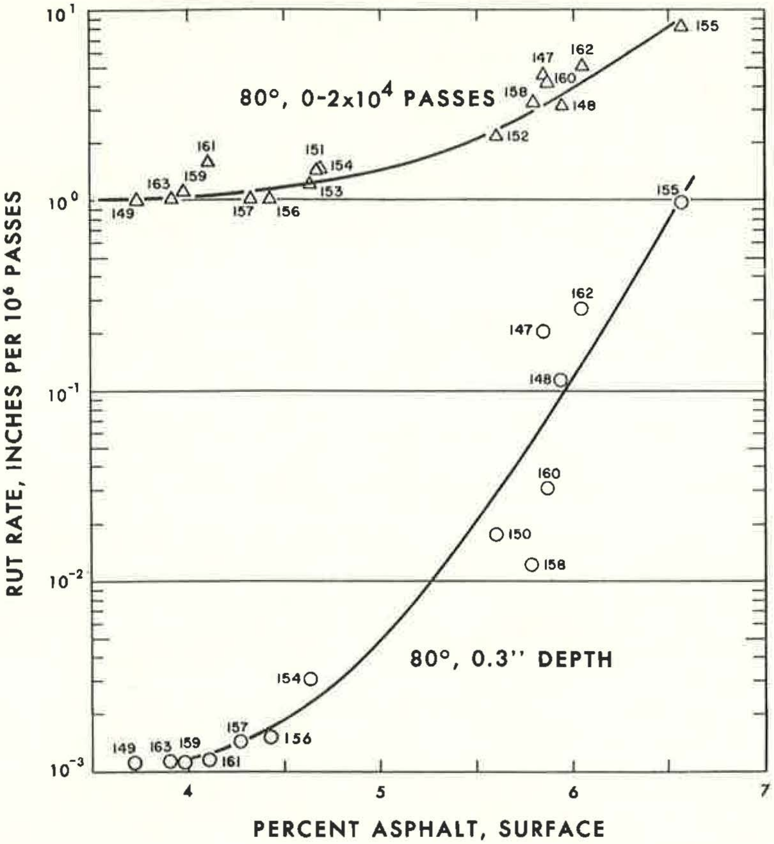

Figure 5. Dependence of rut rate on asphalt content.

ment 149. Similar plots for all pavements showed that the data form a family of parallel straight lines with temperature as a parameter. The family of plots was used to compare the 16 pavements at fixed rut depths and temperatures. A correlation between rut depth and wheel passes was developed from the two plots: $R = dD/dP$ from the depth vs wheel pass plots, and $R = h/D^g$ from the rate vs depth plots.

Equating and integrating these plots yields the following equation:

$$D = \left[(g + 1)\ hP \right]^{\frac{1}{g+1}} \tag{1}$$

where g an h are constants. This equation can be used to reconstruct continuous rut depth-wheel pass curves for each pavement and temperature.

The effect of asphalt content and rut depth is emphasized in Figure 5. The upper curve shows the rate, calculated by the method used in phases 1 and 2, for all pavements during the first cycle on the test track at 80 F. The rates are averages for the first 20,000 passes, during which time the depths became different for each pavement. These initial rates are high, and the apparent effect of the 2.8 percent difference in asphalt content is only tenfold. The lower curve takes cognizance of the effect of rut depth on rate; rate decreases with rut depth much more rapidly for pavements with low asphalt content. By the time each pavement had reached a depth of 0.3 in., the better pavements rut about 1,000 times less than the poorest pavement (155). The two curves show that the most meaningful comparison between pavements must be made at the same rut depth.

REGRESSION ANALYSIS

Other variables affecting the performance of pavements are fines in the surface, asphalt content in the binder, and compaction. No single figure can show the effect of all the variables, much less the interactions between the variables. To resolve these complex actions and interactions, the data were subjected to regression analysis. Data from the two phases were separately analyzed by linear least squares regression. The same model form was used for both phases, but additional terms were used in the models for phase 3 because of the emphasis on pavement variables.

Phase 2 Regression

The data are most conveniently handled as plots of log R vs log η. An adequate regression equation includes both asphalt viscosity in the fresh pavement and asphalt content:

$$\log R = -0.13 - 0.62 \log (\eta \times 10^{-3}) + 0.28 A \qquad (2)$$

It applies at the average rut depths encountered in phase 2, i. e., from zero to approximately 0.5 in.

Observations on phase 2 pavements were adjusted to a common value of A = 5 percent by means of Figure 6, which is a graphical solution to Eq. 2. At the intersection of R and A, for example, R = 9 and A = 5.2, one can follow the viscosity parameter to A = 5 and read R = 7.8. The figure can also be used to predict R for pavements of known η and A. For example, if A is 5.4 percent and η at some temperature is 4×10^4, R is 2.5 in./million wheel passes.

Data adjusted in this way for phase 2 are shown in Figure 7. Deviations from the central line represent minor differences in percent fines, percent asphalt in the binder, and residual errors. At each test temperature, separation of the pavements by grade is evident. Source of the asphalt is of little or no importance except insofar as it determines the viscosity-temperature slope, m. Because 150 F is nearer to the temperature at which the asphalts were graded (140 F) than is 110 F, the data tend to spread more at the lower temperature.

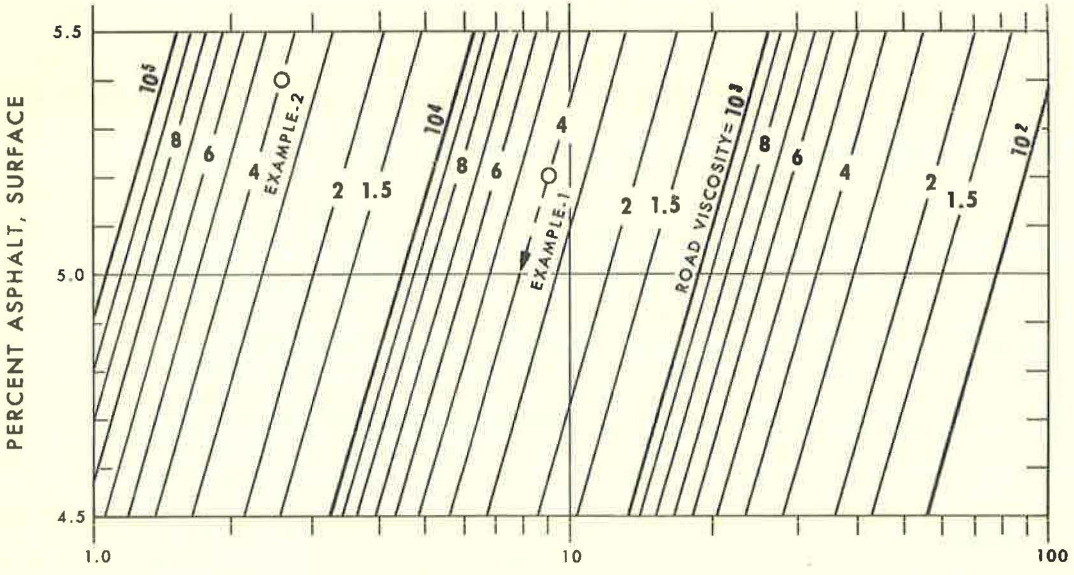

Figure 6. Determining rut rate from η and A, phase 2.

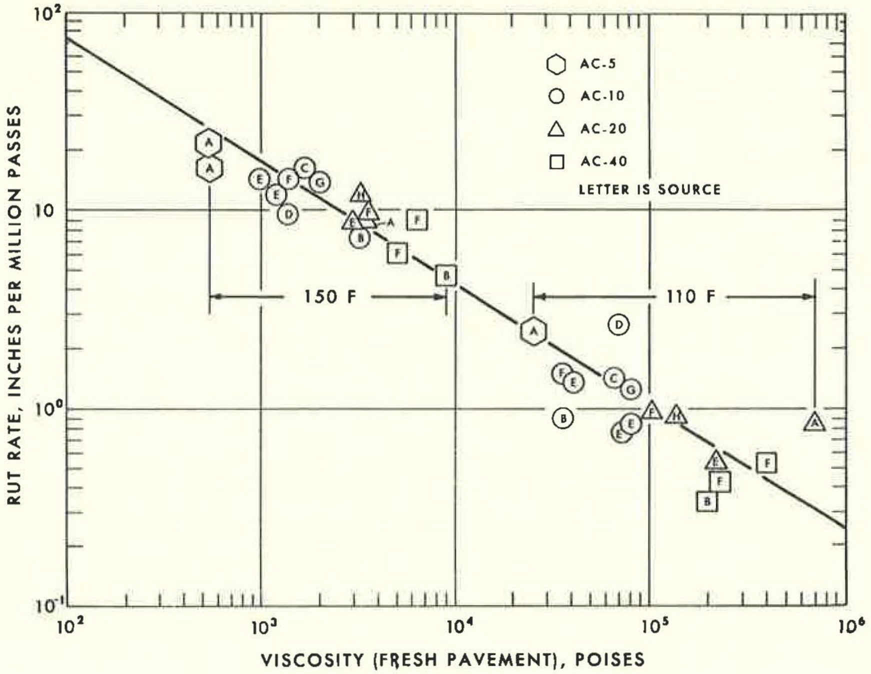

Figure 7. Effect of viscosity on rut rate.

Phase 3 Regression

The results can be expressed in several ways: rut depth vs wheel passes (Eq. 3), wheel passes vs selected rut depths (Eq. 4), or rate of rutting vs viscosity (Eq. 5):

$$D = \left[(1 - B_1)\,10^{B_0}\,P\left(\eta \times 10^{-5}\right)^{B_2 + B_3 \log\left(\eta \times 10^{-5}\right)}\right]^{\frac{1}{1 - B_1}} \qquad (3)$$

$$P = \frac{D^{1-B_1}}{1 - B_1}\left[10^{B_0}\left(\eta \times 10^{-5}\right)^{B_2 + B_3 \log\left(\eta \times 10^{-5}\right)}\right]^{-1} \qquad (4)$$

$$R = \frac{dD}{dP} = 10^{B_0}\,D^{B_1}\left(\eta \times 10^{-5}\right)^{B_2 + B_3 \log\left(\eta \times 10^{-5}\right)} \qquad (5)$$

where

$B_0 = -0.515 + 0.914\,(A - 5) + 0.322\,(F - 8.5) - 0.086\,C - 0.1578\,(F - 8.5)\,C$;

$B_1 = -1.719 + 0.209\,(A - 5) + 0.235\,(F - 8.5) - 0.001\,C - 0.20\,(F - 8.5)\,C$;

$B_2 = -1.149 + 0.143\,(A - 5)$;

$B_3 = -0.0135 - 0.143\,(A - 5)$;

$C = +1$ for normal compaction, -1 for less than normal; and

η = pavement viscosity at the time of measuring D.

Eq. 3 is preferred because these measurements are made on actual roads and because rut depth is a significant factor in the AASHO serviceability index. The equation is conveniently expressed graphically as plots of log D vs log P with the other variables as parameters, as shown in Figure 8 for the case of normal compaction at 7.0 percent F.

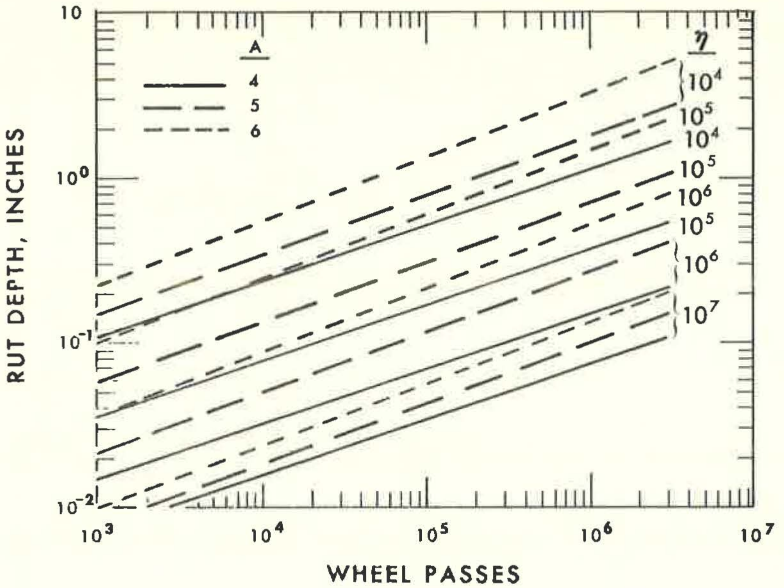

Figure 8. Effect of pavement variables on rut depth.

For a particular pavement, Eq. 3 reduces to

$$D = KP^N \tag{6}$$

where K and N are constants; this equation is similar to Eq. 1. Thus, all of the data may be expressed by this simplified equation and a table relating composition variables to values of K and N. Table 6 lists such values for whole numbers of A, F and η.

The value of K for any value of A and η may be determined from Figure 9. For example, $K = 0.5$ at $A = 5.2$, $F = 9$, and $\eta = 6 \times 10^5$. The corresponding value of N (which does not vary with η) is determined from the equation

$$N = 0.212 + 0.030A + 0.005(F - 7) = 0.378 \tag{7}$$

Observed vs Calculated Rut Rates

The utility of the phase 3 regression equation for predicting plastic deformation from pavement design was judged by comparing the calculated and observed rut rates from all three phases. In each case, the observed rates were compared with the rates calculated by means of the phase 3 equation. The comparison for phase 3 is shown in Figure 10, where the points cluster around the 45° line of perfect correlation through five decades of rut rate. The fit to the central line is good, considering this wide range in rates and the difficulties in making precise observations on so complicated a system.

Comparisons for the earlier phases are shown in Figure 11. The bias in case of phase 1 may be caused by temperature measurement and control and other track technique improvements incorporated in phase 3. Individual pavement thermometers were not used in phases 1 and 2. The comparisons also require considerable extrapolation of phase 3 data with regard to pavement viscosity. Despite these variations, the phase 3 equations adequately predict plastic deformation.

Relative Effect of Pavement Variables

The relative effect of pavement variables may be judged using Eq. 3. Important pavement composition variables include A and F. Pavement temperature is a major

TABLE 6

VALUES OF CONSTANTS FOR NORMAL COMPACTION

Viscosity (poises)	A	4		5		6	
	F	K	N	K	N	K	N
10^4	7	1.110	0.335	1.835	0.361	3.285	0.390
	9	1.430	0.343	2.441	0.370	4.547	0.401
	11	1.866	0.352	3.300	0.380	6.412	0.413
10^5	7	0.370	0.335	0.715	0.361	1.532	0.390
	9	0.464	0.343	0.928	0.370	2.076	0.401
	11	0.589	0.352	1.221	0.380	2.862	0.413
10^6	7	0.151	0.335	0.272	0.361	0.540	0.390
	9	0.185	0.343	0.344	0.370	0.710	0.401
	11	0.230	0.352	0.442	0.380	0.948	0.413
10^7	7	0.075	0.335	0.101	0.361	0.143	0.390
	9	0.091	0.343	0.125	0.370	0.182	0.401
	11	0.110	0.352	0.156	0.380	0.233	0.413

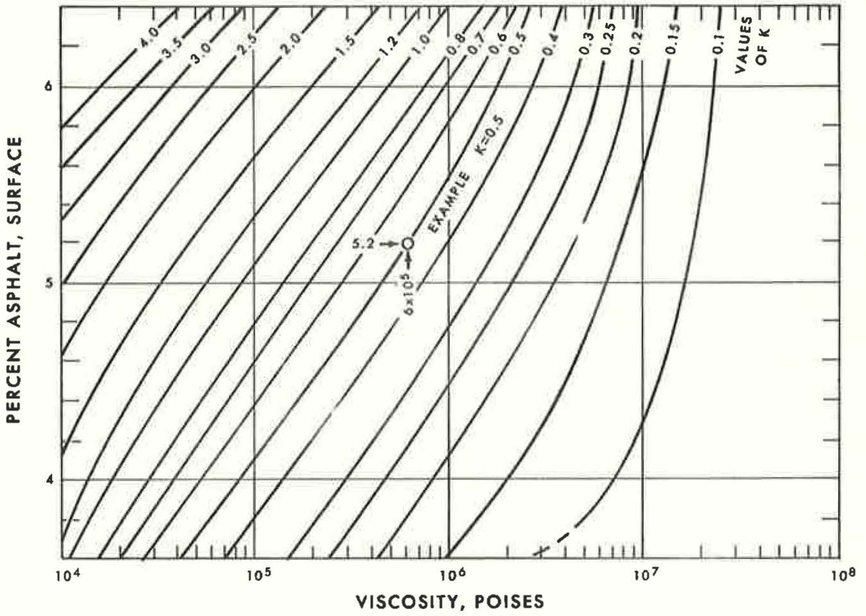

Figure 9. Determining K from A and η (for F = 9, C = +1).

variable in rutting performance. Asphalt properties affecting road viscosity and, consequently, rutting performance include the original viscosity level or grade, a measure of temperature susceptibility (m), mix ratio, and age ratio. Ruts are not as deep for pavements using viscosity graded asphalts when (a) A, F, or pavement temperature are decreased; and (b) compactive effort, mix and age ratios, m, or original asphalt viscosity level are increased.

Since there is a relation between mix and age ratios and asphalt content, the effect of asphalt content is magnified by its additional effect on road viscosity.

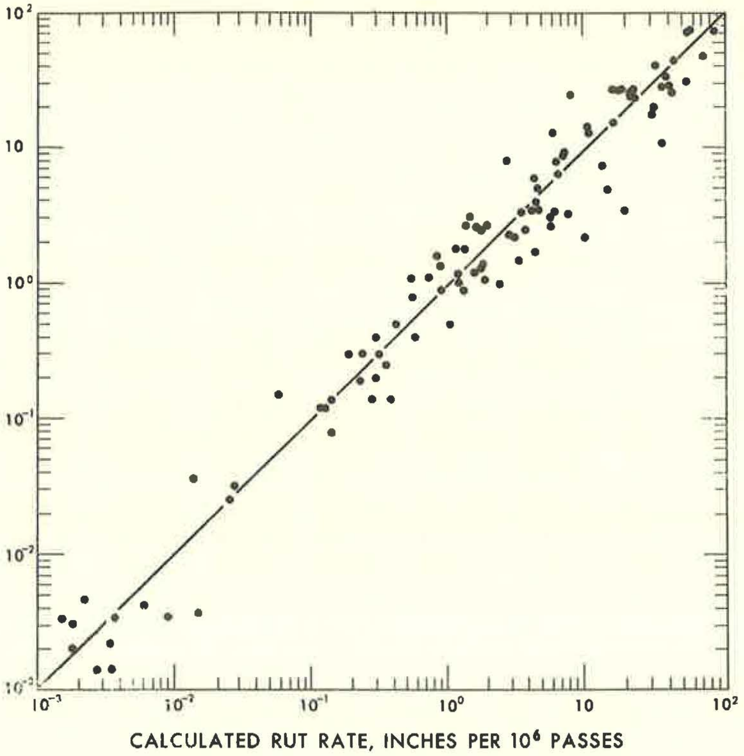

Figure 10. Observed vs calculated rut rate.

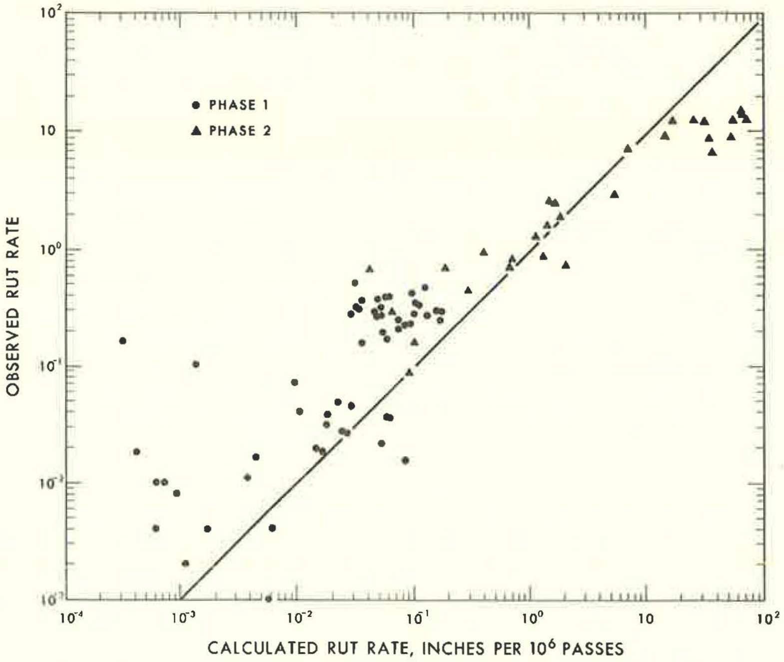

Figure 11. Observed vs calculated rut rate.

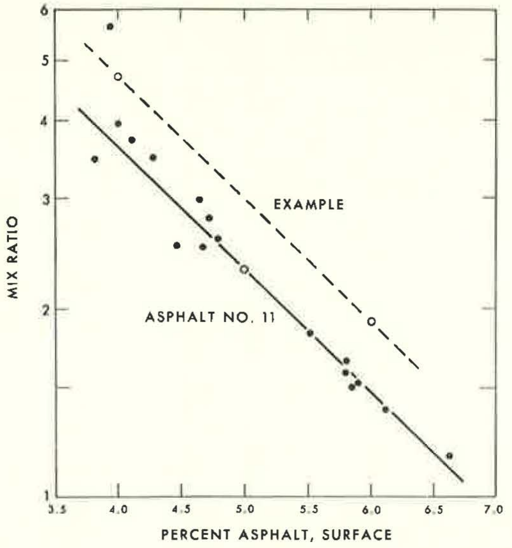

Figure 12. Dependence of mix ratio on asphalt content.

For asphalt 11, the experimental relationship between mix ratio and A is log (mix ratio) = 1.345 - 0.196 A, as shown by the solid line in Figure 12. At A = 5 the mix ratio is 2.3, which agrees well with the TFOT ratio of 2.4. It was assumed that for other asphalts the relationship is parallel, as shown by the dotted line for an asphalt of mix ratio of 3 at A = 5. Here the equation is log (mix ratio) = 1.455 - 0.196 A, which leads to mix ratios of 4.7 at A = 4 and 1.9 at A = 6.

Road viscosity for an average AC-10 asphalt (1,250 poises at 140 F) with a mix ratio of 3.0, age ratio of 3.0, A of 5, and slope of 3.5 at a pavement temperature of 100 F would be 5×10^5 poises, as shown in Figure 13. Lines are also shown for asphalts with slopes of 3 and 4. Applying the mix ratios for A = 4 and 6 leads to viscosities of 16×10^5 and 1.7×10^5, respectively.

Using viscosities so derived, the relative effect of the pavement variables may be judged by the example given in Table 7. The constants for the typical cases, shown at the top of the variables columns, are K = 0.465 and N = 0.370, where K is numerically equal to the rut depth at a million wheel passes. This is equivalent to a rut depth of ½ in. at about 1 ¼ million wheel passes. The values of K and N are the result of varying each property separately (except for asphalt content of which mix ratio and age ratio are a function as determined by experiment). For example, if all the

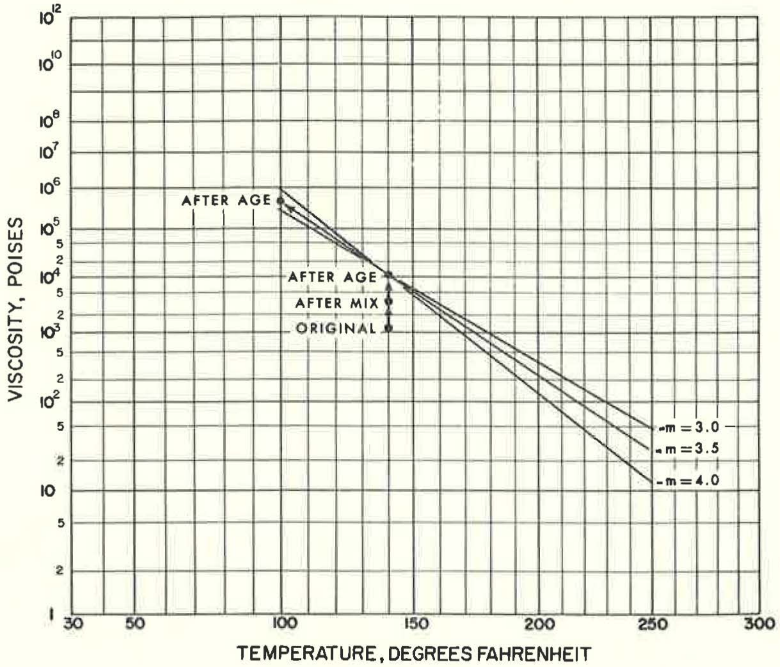

Figure 13. Dependence of road viscosity on asphalt characteristics.

TABLE 7
RELATIVE EFFECT OF PAVEMENT CHARACTERISTICS

% Asphalt, Surface	% Fines, Surface	Temp. (° F)	Grade	Walther Slope	Mix Ratio	Age Ratio	η (poises × 10^{-5})	K	N	P to 0.5-In. D
5[a]	9[a]	100[a]	10[a]	3.5[a]	3[a]	3[a]	5.0	0.465	0.370	1.25
4	-	-	-	-	4.8	4.8	16.0	0.158	0.344	14.6
5	-	-	-	-	3.0	3.0	5.0	0.465	0.370	1.25
6	-	-	-	-	1.9	1.9	1.7	1.665	0.401	0.050
-	7	-	-	-	-	-	5.0	0.365	0.361	2.41
-	9	-	-	-	-	-	5.0	0.465	0.370	1.25
-	11	-	-	-	-	-	5.0	0.601	0.380	0.62
-	-	80	-	-	-	-	50.0	0.170	0.370	18.5
-	-	100	-	-	-	-	5.0	0.465	0.370	1.25
-	-	120	-	-	-	-	0.7	1.080	0.370	0.125
-	-	-	20	-	-	-	13.0	0.307	0.370	3.70
-	-	-	10	-	-	-	5.0	0.465	0.370	1.25
-	-	-	5	-	-	-	2.0	0.690	0.370	0.43
-	-	-	-	4	-	-	10.0	0.345	0.370	2.74
-	-	-	-	3.5	-	-	5.0	0.465	0.370	1.25
-	-	-	-	3	-	-	3.0	0.580	0.370	0.68
-	-	-	-	-	4.5	4.5	15.0	0.291	0.370	4.30
-	-	-	-	-	3.0	3.0	5.0	0.465	0.370	1.25
-	-	-	-	-	1.5	1.5	0.9	0.973	0.370	0.165
4	7	-	-	-	4.8	4.8	16.0	0.130	0.335	55.8
6	11	-	-	-	1.9	1.9	1.7	2.200	0.447	0.036
-	-	-	20	4	4.5	4.5	80.0	0.140	0.370	31.2
-	-	-	5	3	1.5	1.5	0.23	1.730	0.370	0.034

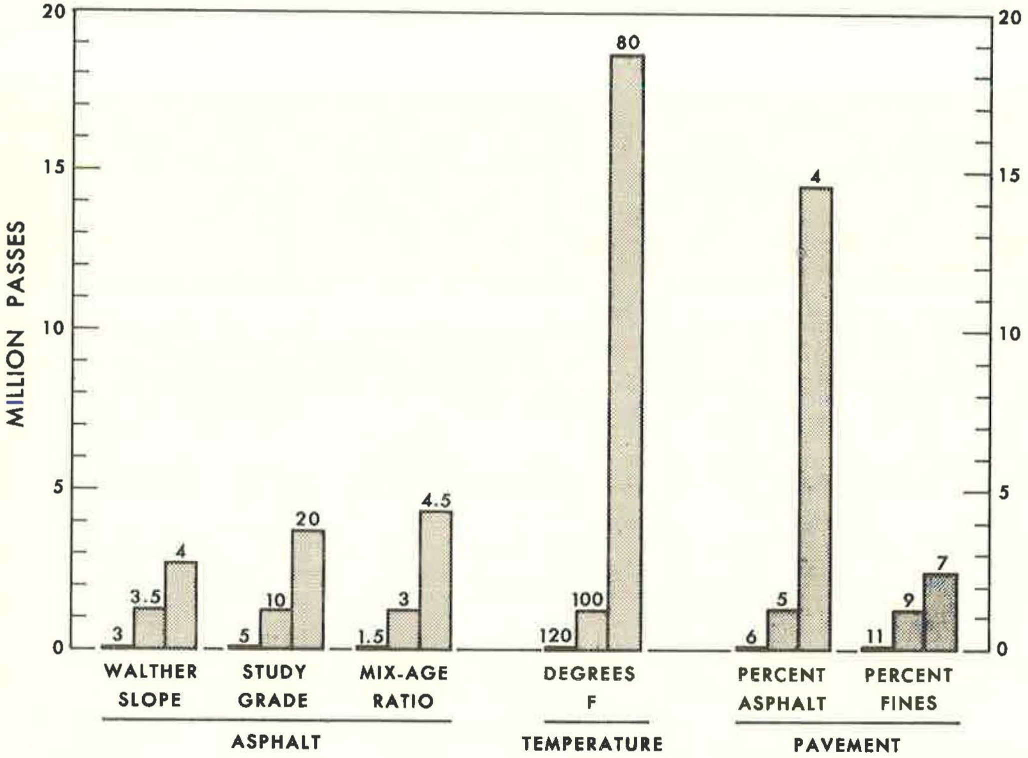

Figure 14. Effect of variables on performance.

properties except asphalt content in the surface course are held at the typical value and A is varied from 4 to 6 percent, K would vary from 0.158 to 1.66; or if the temperature for the typical case is varied from 80 to 120 F, K would vary from 0.17 to 1.08.

The relative effect of the variables can also be expressed as wheel passes to a given rut depth, as in Figure 14, where the typical case is shown at the top of the center bars. Varying one property at a time clearly shows that temperature and asphalt content overshadow the effects of asphalt properties.

The effect of simultaneously varying the pavement parameters A and F compared with simultaneously varying the asphalt parameters is shown at the bottom of Table 7. Possible variations in pavement job-mix parameters for a single construction project introduce greater variations in performance than do asphalt parameters, even when the range is from the center of the AC-5 to the center of the AC-20 grade with values of m and mix ratio selected to encompass the national range of available paving asphalts.

CONCLUSION

The rut depth equation is of practical significance because it quantitatively relates the contribution and interactions of pavement properties to performance. These contributions can be calculated as precisely as current measurement techniques permit, and can make more meaningful mix design feasible. Although the term rut depth has been used, the general phenomenon studied in these experiments has been plastic deformation of pavements. The functional relationships in the rut depth equation should be applicable to the study of changes in surface profile which originate in actual roads under traffic.

The results are sufficiently encouraging to justify further studies on the contributions of aggregate type and gradation and of pavement compaction. Should these also prove successful, it would be reasonable to extend the study to mix design and possibly to structural design. Experiments on actual roads should now be made to verify the relationships found on the laboratory test track.

ACKNOWLEDGMENT

The authors are grateful to Dr. J. W. Gorman for assistance with the statistical design and development of regression equations.

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Appendix

GLOSSARY

Symbols

A = weight percent asphalt in surface course;
B = constant in regression equations;
C = compactive effort;
D = rut depth (in.);
F = weight percent fines, < 200 mesh, in surface course;
K = intercept in log D vs log P plots;
N = slope in log D vs log P plots;

P = wheel passes (million);
R = rut rate (in./million wheel passes);
g = slope in log R vs log D plots;
h = intercept in log R vs log D plots;
k = intercept in log R vs log η plots;
m = slope in walther plots;
n = slope in log R vs log η plots; and
η = asphalt viscosity (poises).

Terms

TFOT ratio—ratio of viscosity of TFOT residue to viscosity of original asphalt, both at 140 F;
Mix ratio—ratio of asphalt viscosity just after mix plant operation to original viscosity, both at 140 F; and
Age ratio—ratio of viscosity after aging in track to viscosity after mix plant operation, both at 140 F.

Discussion

C. R. FOSTER, National Bituminous Concrete Assoc.—This paper has been prepared in the usual excellent manner that characterizes papers from American Oil Company's Research and Development Department and I have no comments on the data contained in the paper or the analysis made of the data. I do think, however, that a comment on the applicability of these findings to real pavements is in order.

In this paper the variables are evaluated in terms of rut depth under traffic. The manner of presentation and references to the AASHO serviceability index imply that a small rut depth, or rather a slow rate of development of rut depth, is desirable. Figure 14 summarizes the effect of the variables in terms of passes required to produce 0.5-in. rut. Applying these findings to real pavements would dictate using: (a) the hardest grade of asphalt available; (b) the asphalt that hardens most in the mixing cycle and fastest on the road; (c) the least asphalt content; and (d) the least filler content. I believe a, b, and c would lead to short lived, raveling pavements.

It hardly seems necessary to remind ourselves that in real performance on the road, rich pavements flush and lean pavements ravel and that our desire is to "put in all the asphalt that traffic will bear." I believe the data would be far more meaningful if information was presented on passes required to produce flushing, and if rut depth analysis was made only of pavements that were not flushed.

L. C. BRUNSTRUM, L. E. OTT, A. W. SISKO, T. L. SPEER, R. A. WILKE, and J. V. EVANS, Closure—The authors appreciate Mr. Foster's perceptive comments concerning pavement design and selection of the most meaningful pavement response. We were exploring the relative effects of variations from optimum Marshall design in terms of resistance of the pavement to plastic deformation. Certainly, there is no substitute for good design in producing durable roads. Furthermore, such a design does not require the hardest grade of asphalt, asphalts that harden rapidly, and low asphalt content. But optimum design may not always be achieved and our experimental design was intended to extend the variables beyond the narrow range of optimum design.

Responses other than plastic deformation were observed during the course of the work, including flushing, densification, aggregate reorientation and asphalt migration. A general correlation between plastic deformation and flushing was noted. However, plastic deformation was considered the primary variable because it appears in the

AASHO equation for serviceability index and because it is measurable. The onset and progress of plastic deformation can be precisely measured on the test track and on actual roads. We have not, as yet, developed means to follow flushing or densification on the track. The rutting vs passes curves (Fig. 3) apparently are determined by two rates: an initial portion controlled primarily by densification or other realignment of the aggregate and asphalt, and a straight-line portion controlled by asphalt viscosity. More detailed studies of the initial portion might be rewarding.

Mr. Foster has alluded to applicability of the findings to real roads. The authors, too, realize the need to test the applicability of the relationships to real roads and encouraged such tests in the conclusion.