Major Factors Explaining Performance Variability of Seal Coat Pavement Rehabilitation Overlays

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A statistical experiment was conducted with the objective of identifying the role of certain factors in explaining the performance variability of seal coat pavement surfaces. Considered factors included the type and properties of the aggregate used in a seal coat surface, the designed construction rate at which the aggregate was spread, and the climatic region in which the highway section was placed. A graphical examination of the effect of each of the considered variables was performed. This examination was followed by statistically testing the significance of the observed effects. A performance model was then formulated, and the usefulness of the model was demonstrated.

This paper reports the results of a statistical experiment conducted as part of a research project undertaken at the Center for Transportation Research, the University of Texas at Austin. The ultimate aim of this research project was to formulate statistical models that can be used for predicting the frictional performance of seal coat pavement overlays. A seal coat overlay is a rehabilitation method for pavements of all classes, used mostly on rural highways. The construction of this method involves the application of asphalt to a road surface, at a range of 1.36 to 3.17 liters/m^2 (0.3 to 0.7 gal/yd^2) of surface, followed by the spreading of cover aggregate, at a range of 77 to 165 m^2 of surface for each cubic meter of material (70 to 150 yd^2/yd^3), to form an overlay about 1 in. thick. Multiple successive layers of asphalt and aggregate may be used to achieve thicker seal coat overlays.

The methodology, reported earlier by Abdul-Malak et al. (*1,2*), involved establishing 59 seal coat test sections in many districts of the state of Texas, including all four environmental regions, and monitoring their performances over time. Many factors, believed to have an influence on performance level and identified in the literature and Texas district surveys (*1*), were considered in this study. These factors included aggregate physical and mineralogical properties, construction variables, traffic variables, and environment and weather variables.

Frictional performance has been measured by a skid trailer and expressed as a friction number (FN). Eight sets of FN measurements, spanned over about 5 years, were used for the analysis of the statistical experiment. Weather data relevant to the period before field testing were also collected.

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The performance data were graphed to detect the sources of performance variability and then grouped according to the different considered variables (*2*). The grouping gave insights into which variables controlled the observed differences in frictional performance. The grouping was followed by extensive statistical modeling that pinpointed the significant variables.

In this paper, the effect of aggregate type, aggregate construction spreading rate, and climatic region on seal coat frictional performance is examined graphically. A statistical experiment that tests for the statistical significance of the considered variables is then analyzed.

BACKGROUND

Parameters of Frictional Resistance

Two components make up the frictional resistance developed between the tire and the pavement surface: adhesion and hysteresis (*3*). Among the many factors that affect the role of these components, the most important are the microtexture and macrotexture of the pavement surface (*4*). The microtexture controls the adhesion component, whereas the macrotexture controls the hysteresis component.

In seal coats, the microtexture is the fine-scaled roughness contributed by individual small asperities on the individual coarse aggregate particles. Ideally, for it to sustain a highly favorable microtexture, the aggregate particle should be composed of hard, coarse, angular minerals well bonded into a softer matrix so that gradual differential wear will occur. The macrotexture is the large-scale texture at the surface caused by the size and shape of and the spacing among the coarse aggregate particles. Appropriate angularity, proper maximum size and gradation, and adequate spreading rate of aggregate particles are essential for achieving adequate macrotexture.

The most commonly used laboratory method is the polish value (PV) test (*5*), in which the friction of the coarse aggregate particles is evaluated with the British portable tester after 9 hr of exposure to accelerated polishing. The four-cycle magnesium sulfate soundness test (*6*) used to judge the soundness of an aggregate when it is subjected to weathering action (freeze and thaw) gives indications of the strength (or softness) of the cementing matrix that holds the individual grains in the aggregate particles. Recent work has shown that aggregate petrographic properties can be very helpful in explaining a considerable portion of the variability observed in the frictional performance of seal coat surfaces (*7*).

Several methods have been developed for evaluating or measuring pavement macrotexture. Of these, the sand patch and silicone putty (volumetric measurements), outflow meter (drainage measurement), and stereo photographic interpretation (topography measurement) methods are most commonly used. Other methods have recently evolved, examples of which are the "Numerisateur," a contactless sensor-based system used in France, and the Transport and Road Research Laboratory Mini-Texture Meter, a laser based monitoring system used in Britain (*8*).

Variability in Frictional Resistance

Two types of seasonally caused variations have been observed: long-term and short-term. Long-term variations are caused by changes in the microtexture of the exposed aggregates brought about by polishing during long dry periods and roughening caused by the rejuvenating effects of long wet periods (*9*). As a result of this mechanism, friction measurements made in the wet periods have been reported to be much higher than those made in the dry periods. Superimposed on these long-term (annual) variations are short-term variations attributable to external factors, such as amount and timing of intermittent rainfall, and possibly to contamination from oily films, drippings, and other deposits on the surface (*10,11*).

Two models, a generalized prediction model and a mechanistic model, were recently developed at Pennsylvania State University (*12*) to predict seasonal variations in the skid resistance of asphalt pavements associated with rainfall conditions, temperature effects, and time of year. It has been suggested that the models be limited to the geographical area within which the investigation was conducted.

METHODOLOGY

Data Collection

Extensive laboratory testing was performed on the aggregate samples obtained from construction sites. Of the numerous tests performed (*2*), the following major tests were used for grouping the various types of aggregates encountered: the polish value and insoluble residue tests for measuring the polish susceptibility; the four-cycle magnesium sulfate soundness and freeze-thaw tests for evaluating the resistance to weathering action in natural and synthetic aggregates, respectively; and the Los Angeles abrasion test for determining the resistance to abrasion and impact actions. Other basic tests were also performed on collected aggregate samples, including the sieve analysis (gradation) and the specific gravity and absorption tests.

For each constructed test section, a survey was made that mainly consisted of information on the coarse aggregate material and asphalt type and the rates at which both materials were to be placed; these were the design distribution rate of asphalt (ASDR) and the spreading rate of aggregate (AGSR). Various aggregate materials and asphalt types were used in the construction of the established sections along with wide ranges of ASDR and AGSR; the AGSR range was from 77 to 142 m^2 of surface for each cubic meter of aggregate (70 to 130 yd^2/yd^3), respectively, corresponding to a range of 52 to 20 kg of aggregate per square meter of surface. Typically, aggregates from Grades 3 and 4 were used, with an aggregate maximum size of 1.6 cm (5/8 in.) and 1.3 cm (1/2 in.), respectively. The annual average daily traffic (ADT) counts varied between 300 and 3,500 vehicles per lane.

The skid resistance test has been conducted twice a year in accordance with ASTM E274. Eight sets of skid resistance measurements were used in the analysis to follow.

Detailed climatological data also have been sought. Specifically, the data have been concerned with the length of the last rainfall period, the number of days between the last rainfall that occurred in that period and the day of field testing, and the total precipitation that fell in that period. Data collection also has involved categorizing the testing seasons into either wet or dry.

Design of Performance Experiment

After extensive graphical data manipulation (*2*), a statistical experiment was designed. It was aimed toward a better understanding of the effects on the performance of seal coat overlays of aggregate properties, aggregate construction spreading rate, and the environment.

The design, shown in Table 1, included the various aggregate groups that were considered (AGGR) and the ranges of the results of the four major laboratory tests obtained for most of the aggregates. Two siliceous gravel aggregates with high percentages of carbonate contents were grouped with the limestone aggregates of the Limestone 2 group. Because the obtained asphalt and aggregate spreading rates were those specified by the highway engineer and to account for the slight expected variations in the actual construction rates, the aggregate spreading rate variable was introduced into this experiment as a three-level variable (LAGSR)—low, medium, and high. With respect to the environment variable, Figure 1 shows a map of the state of Texas with its four climatic regions (I, II, IV, and V) and the districts where test sections were placed. The respective environmental characteristics are wet and no freeze, wet and freeze-thaw cycling, dry and no freeze, and dry and freeze-thaw cycling. However, according to the findings of the graphical data manipulation, only the temperature freeze-thaw division of the climatic regions seemed to matter. Therefore, it was decided to consider two temperature-based classes of region (RGT)—cold and warm—in the experiment. The two classes are delineated by the horizontally dividing line of the map.

The groups of sections with similar characteristics and performance patterns were placed in the appropriate cells of the design. This design represented about three-fourths the total number of friction observations collected for all established sections, amounting to 355 observations. Because of the different number of observations in each cell and because of the presence of empty cells, the design was regarded as unbalanced. Adding more levels of the considered variables, to

TABLE 1 Design of the Experiment for the Environment, Aggregate Type, and Construction Spreading Rate Effects

AGGREGATE GROUPS (AGGR)	AGGREGATE PROPERTIES	LEVELS OF CONSTRUCTION AGSR	REGION (RGT)	
			II & V (COLD)	I & IV (WARM)
LIGHTWEIGHT (A)	PV[a] = 48 to 51 FRTH[b] = 3.00 to 9.53 LA[c] = 18 to 25	77 (LOW)	Group 1 (n=13)	---
		104 to 120 (MED)	Group 3 (n=40)	Group 2 (n=32)
		130 to 142 (HIGH)	---	Group 4 (n=16)
SANDSTONE AND RHYOLITE (B)	PV = 36 to 41 MSS[d] = 0.0 to 15.0 LA = 15 to 28 INRD[e] = 55.00 to 100.00	77	Group 5 (n=8)	---
		104 to 120	Group 6 (n=75)	---
		130 to 142	Group 7 (n=10)	---
LIMESTONE ROCK ASPHALT (C)	PV = 34 to 40 MSS = 7.0 to 14.0 LA = 28 to 34 INRD=1.28 to 14.71	77	---	---
		104 to 120	Group 8 (n=14)	Group 9 (n=27)
		130 to 142	---	Group 10 (n=16)
LIMESTONE 1 (D)	PV = 33 to 37 MSS = 17.1 to 41.0 LA = 26 to 36 INRD=0.41 to 4.24	77	---	---
		104 to 120	Group 11 (n=22)	---
		130 to 142	Group 12 (n=10)	---
LIMESTONE 2 (E)	PV = 25 to 29 MSS = 2.7 to 8.6 LA = 22 to 24 INRD=0.45 to 20.23	77	---	---
		104 to 120	Group 13 (n=18)	Group 15 (n=7)
		130 to 142	Group 14 (n=14)	Group 16 (n=32)

(a: Polish Value; b: FReeze-THaw resistance: c: Los Angeles abrasion; d: Magnesium Sulfate Soundness; e: INsoluble ResiDue)

allow for the inclusion of the remaining one-fourth of the collected observations, only would have augmented the problems that are usually encountered with such designs. Table 1 indicates between parentheses the abbreviations used for the different variables in the statistical analyses. It also shows the number of observations occupying each cell.

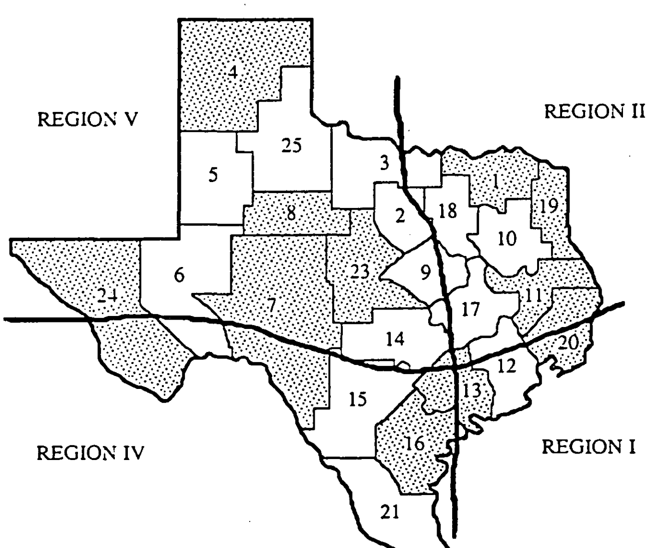

FIGURE 1 Texas map showing the climatic regions and the districts where test sections were placed.

EXAMINATION OF PERFORMANCE VARIABILITY

The performance of each group of sections was judged on the basis of the rate of decrease in FN and the number of accumulated traffic passes withstood by the material before the FNs intercepted with the zone of minimum friction. This zone was assumed to be confining FNs in the range of 30 to 40. The lower boundary, an FN of 30, was that thought by highway engineers to represent the level of friction below which a corrective measure should be considered. The upper boundary was roughly chosen on the basis of a study involving wet-pavement accidents (*13*), in which a significant decrease in the accident rate was revealed when pavement FNs were greater than about 44.

Variability Associated With Aggregate Type and Properties

Figures 2 and 3 depict the performance of various groups of test sections constructed in the cold and warm regions, respectively, with a medium-level aggregate spreading rate. The scatter in the performance of the five groups (Groups 3, 6, 8, 11, and 13) located in the cold region (Figure 2) was found to be wide. However, much of the scatter appeared to be explained by the type and properties of aggregates constituting each group. As expected, the performance of the lightweight aggregate group was seen to be superior. The sandstone aggregates of Group 6 were found to have maintained

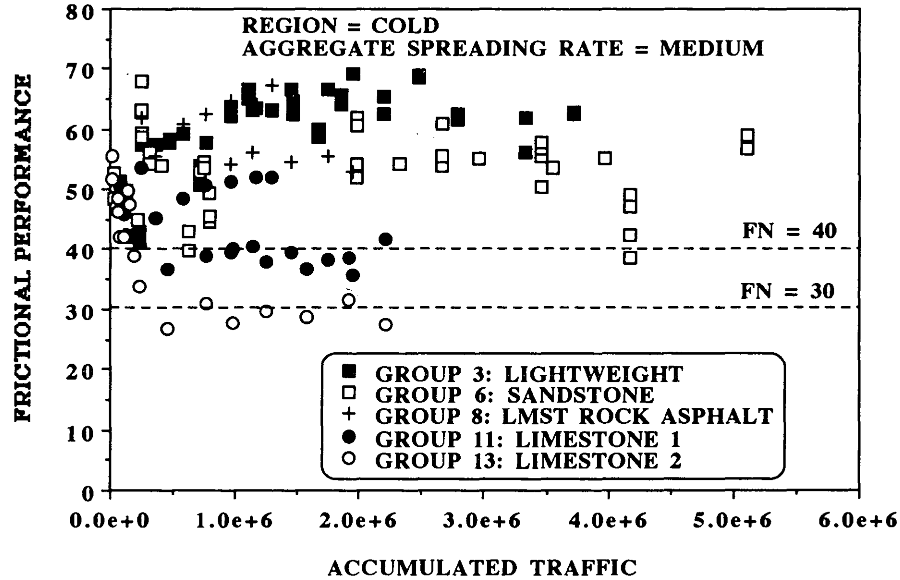

FIGURE 2 Frictional performance of five groups of test sections constructed in the cold region with medium-level aggregate spreading rate—grouped according to aggregate types.

adequate frictional performance. However, the FNs were widely scattered at the early stages of performance, ranging from about 40 to about 70.

Group 8, consisting of a porous limestone rock asphalt aggregate with a PV of 40, showed a steady performance compared with the decrease in performance observed in Group 9 (Figure 3). It is believed that the difference is because the aggregate in Group 8 possesses a constantly rejuvenated microtexture caused by the high number of temperature freeze-thaw cycles that characterize the cold region. Since the aggregate of Group 8 was placed on both the inner and outer lanes of the same highway section, the variability within the performance data of this group is thought to be attributable to the various levels of ADT the aggregate was exposed to on each of the lanes. Although the accumulated traffic was the basis used in performance evaluation, ADT is thought to control the level of particle embedment during the early years of a section's life, thus controlling the level of macrotexture that may be maintained throughout the remaining useful years.

In the limestone groups, the rate of decrease in the FN was seen to be high, particularly for Group 13, with almost all of the sections intercepting with the zone of minimum friction

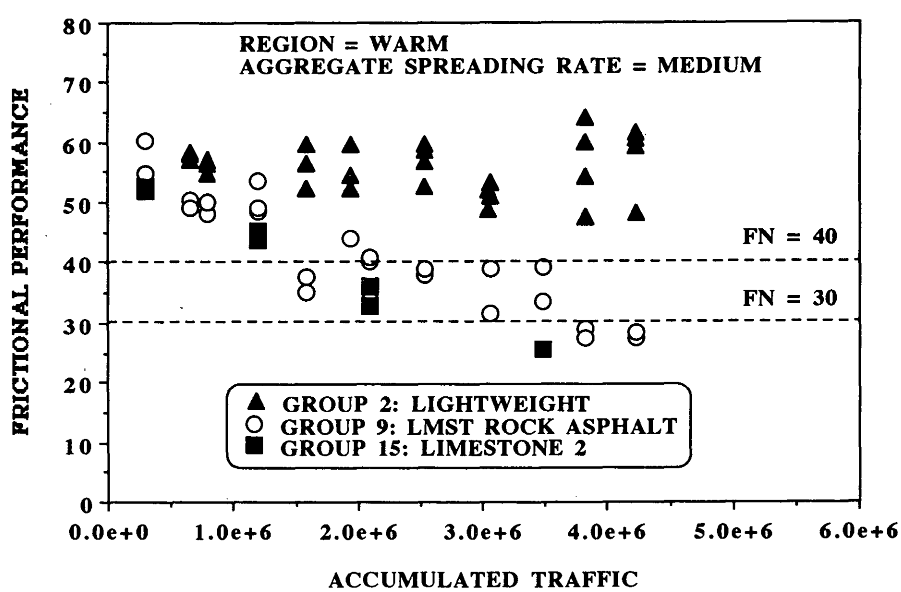

FIGURE 3 Frictional performance of three groups of test sections constructed in the warm region with medium-level aggregate spreading rate—grouped according to aggregate types.

at accumulated traffic of less than 1 million passes. Sections of Group 11 constructed of porous aggregates having higher PVs performed better than those of Group 13 built of dense aggregates having low PVs. However, the data of Group 11 were found to show a considerable variability. The only factor found to explain this variability was the low level of ADT (interacted with the effect of region) on those sections exhibiting a higher level of performance. In the warm region (Figure 3), similar observations could be made about the role that the aggregate type played in explaining performance variability.

Variability Associated with Aggregate Construction Spreading Rate

The clear role of the aggregate construction spreading is illustrated in Figures 4 and 5. The implication was that as the spreading rate increased, the level of frictional performance increased. The phenomenon can be explained as follows. Under the exposure to traffic, the aggregate particles in a seal coat surface are pressed more and more into the asphalt layer, thus displacing some of the asphalt. When the same cubic yard of aggregates is spread over different surface areas, more asphalt will need to be displaced in the smaller areas. The displacement of asphalt results in the asphalt filling much of the volume of the interstices between the aggregate particles. This, in turn, results in a reduction in the macrotexture of the surface that may cause a bleeding distress in the surface. Moreover, when the aggregate particles are spaced so closely that excessive interlocking and overlaying between the particle edges occur, the particles may become crushed. Crushing alters the gradation of the aggregate, thus making the surface unstable and causing bleeding problems.

Variability Associated With Environment

The data included in Figures 6 and 7 were grouped according to the temperature freeze-thaw division of the climatic regions. The effect of region on the performance of Groups 8 and 9 was discussed earlier in this section. The Limestone-2 group consisted of the test sections built with dense aggregates of the poorest polish qualities. As seen in Figure 7, most of its friction data fell within the zone of minimum friction, indicating that its use should not be desirable if other better-quality aggregates can be economically obtained. However, Groups 15 and 16 of the warm region performed much better than Groups 13 and 14 of the cold region. If this performance difference was truly caused by the climatic region variable, the relevant weather components would be moisture and temperature. That is because, in general, chemical decay of minerals in dense rocks is fostered by warm, moist climates (*14*).

STATISTICAL TESTING

Three-Variable General Linear Model

Because of the unbalance of the experimental design presented in Table 1, the general linear model (GLM) procedure, a capability of the statistical analysis system software, was used for testing the significance of the main three variables constituting the design. The first model generated had the FN as the dependent variable and the three variables and their interaction terms as the main predictors. In addition, accumulated traffic, referred to as CUTR in this analysis, and ADT levels were used as covariates in the model. The ADT variable was thought to influence the degree of aggregate embedment in the asphalt film, especially during the early

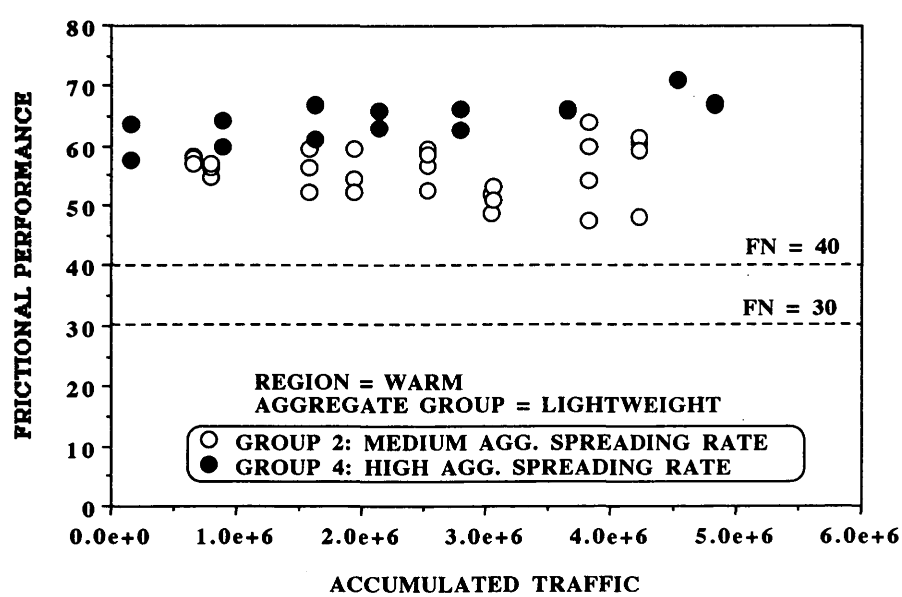

FIGURE 4 Frictional performance of two groups of test sections constructed in the warm region with lightweight aggregates—grouped according to aggregate construction spreading rate.

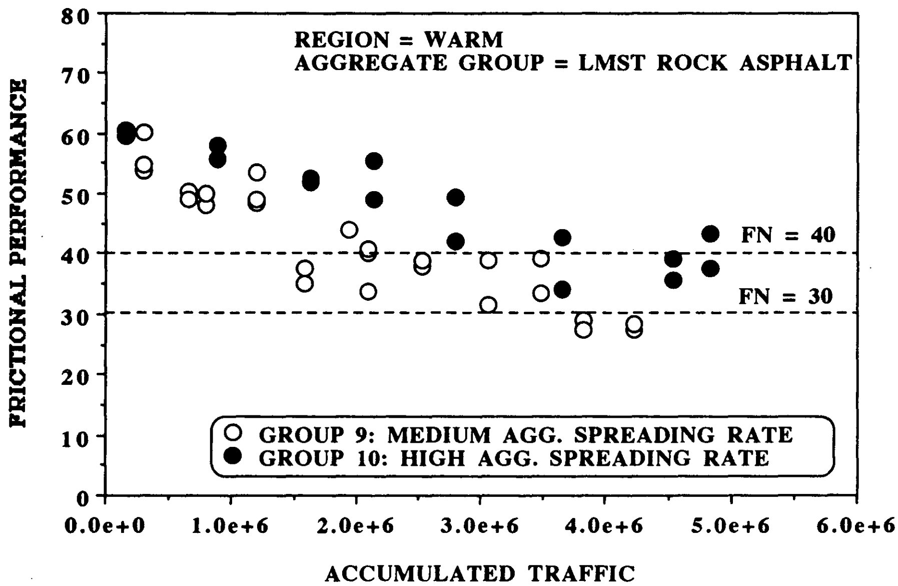

FIGURE 5 Frictional performance of two groups of test sections constructed in the warm region with limestone rock asphalt aggregates—grouped according to aggregate construction spreading rate.

years of a section life, thus affecting the macrotexture depth to be maintained on a seal coat surface. It was also thought to interact with the region variable because both variables control the degree of rejuvenation in the surfaces of aggregate particles. Since the performances of some of the groups were seen to have exhibited logarithmic relationships with traffic, the natural logarithmic function of the CUTR (LGCUTR) was used in this analysis. The model, based on 355 observations, had the following form:

$$FN = AGGR + LGCUTR + (AGGR \times LGCUTR) + RGT + (AGGR \times RGT) + (LGCUTR \times AGGR \times RGT) + LAGSR + (AGGR \times LAGSR) + ADT + (ADT \times AGGR)$$

The summarized statistical results are shown in Table 2. The model had an excellent coefficient of determination (R^2) of

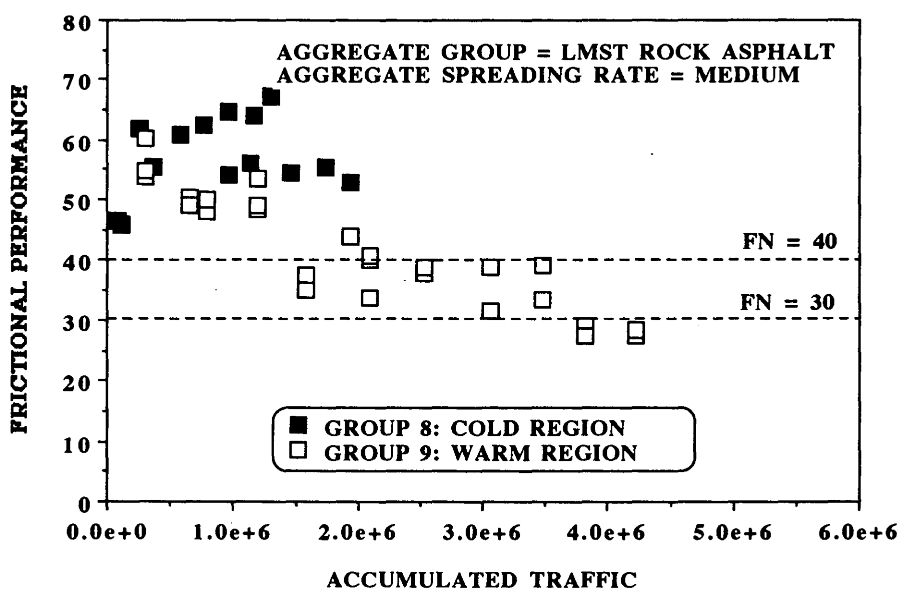

FIGURE 6 Frictional performance of two groups of test sections constructed with limestone rock asphalt aggregates and medium aggregate construction spreading rate—grouped according to region.

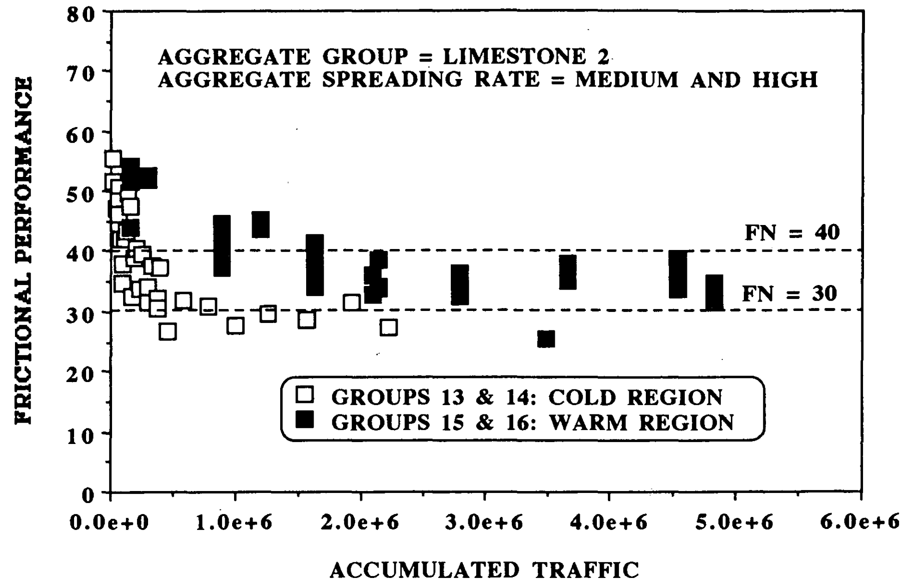

FIGURE 7 Frictional performance of four groups of test sections constructed with limestone aggregates and high and medium aggregate construction spreading rates—grouped according to region.

about 0.84 with each of the considered terms that showed significance at the individual level. Other covariates were then considered in the analysis that included the aggregate sieve analysis results and the asphalt distribution rate as macrotexture parameters and the LRP, DLR, and TPP short-term weather variables. Only the DLR weather variable showed significance at the individual level accompanied by a very slight increase in the model's R^2. However, because it does not serve any design purposes, this variable was omitted from the model.

The GLM solution of the above model indicated that aggregate Groups A and B had friction means that were higher than those of Groups C, D, and E. It also indicated that Groups A, B, and D had different slopes (with traffic) compared with those of Groups C and E. The effect of region was seen to be significant in Groups A and C, particularly in interaction with traffic. In addition, the LAGSR variable was observed to explain some of the variation in Groups A, B, C, and D. Finally, the ADT effects was shown to be significant in Groups B, C, and D. The scatter of the residuals against the predicted response was seen to be normal, requiring no transformation of the response.

One-Way General Linear Model

To ensure that any possible bias in the computed estimates was not wholly the result of empty cells being present in the design (because those affect the number of degrees of freedom of the interaction terms), another general linear model was generated in which the groups filling 16 of the cells were considered as 16 levels of a one-way experiment. To avoid over specification in the model, the ADT variable was left out after a small reduction in the R^2 of the first model, which resulted from this action (R^2 decreased to about 0.825), was observed. Using the GLM procedure, the one-way model had

TABLE 2 Three-Variable General Linear Model

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GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: FN

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	31	30656.11604231	988.90696911	47.92	0.0	0.824122	9.1429
ERROR	317	6542.41924249	20.63854651		ROOT MSE		FN MEAN
CORRECTED TOTAL	348	37198.53528479			4.54296671		49.68836390

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
LGCUTR	1	0.41149891	0.02	0.8878	1	653.51917951	31.66	0.0001
GROUP	15	23867.05988307	77.10	0.0	15	5345.54762448	17.27	0.0001
LGCUTR*GROUP	15	6788.64466032	21.93	0.0001	15	6788.64466032	21.93	0.0001

the form of

$$FN = LGCUTR + GROUP + (LGCUTR \times GROUP)$$

and an R^2 of about 0.825, the same as that of the first model after dropping ADT. The statistical results are shown in Table 3. Any possible bias in the estimates of the solution of the one-way model is primarily the result of unequal numbers of observations in the filled cells.

Regression Model

To get the prediction equation of the one-way model, a regression analysis [in this case, an analysis of variance (ANOVA)] was performed on the 16 groups. The resulted estimates for the groups and their interactions with LGCUTR are summarized in Table 4. The model had a good adjusted R^2 of 0.77. Because the GROUP variable was dummy coded, the estimates of the intercept and LGCUTR applied directly to Group 16. With 90 percent confidence, the intercepts of Groups 2, 7, 11, 12, 13, and 14 were shown to be not statistically significant compared with that of Group 16. Furthermore, the slopes of Groups 11 through 14 were found to be not statistically significant from that of Group 16.

USE OF THE PERFORMANCE MODEL

The regression equation can be used most appropriately for predicting the mean performance of aggregates that are, based on history, to fall in any of the 16 groups constituting the design in Table 1. Further, the prediction model can be incorporated into a pavement management system, as illustrated in Figure 8. Suppose that a seal coat overlay is to be placed with a medium AGSR on a highway, located in the warm region, with an expected ADT of 2,740 vehicles per lane and that no major rehabilitation project is scheduled for this highway within the next 8 years. For the 8-year period, two overlays of a local limestone rock asphalt aggregate are required, as contrasted with only one overlay of a sandstone aggregate. If this sandstone aggregate is not available locally, the extra cost incurred from obtaining and hauling this good-quality aggregate should be weighed against the cost of having to lay down a second overlay with the local material.

CONCLUSIONS

A statistical experiment was conducted with the objective of identifying the role of certain factors in explaining the performance variability of seal coat pavement surfaces. Factors found to be statistically significant included the type and properties of aggregates, the aggregate construction spreading rate, and the climatic region. These class variables, along with a short-term weather covariate—the number of days between last rainfall and day of field testing—and the level of ADT exposure, as well as some interaction terms, were found to explain about 84 percent of the observed performance variability. A prediction equation was formulated to describe the performance of the 16 groups of test sections included in the experiment. The following observations were also drawn from the study:

1. The grouping of some of the data according to the various aggregate materials was found to explain, in broad terms, much of the scatter observed in the data. Superior performance was observed in the lightweight and sandstone groups. The limestone rock asphalt and limestone groups experienced different, noticeable rates of decrease in frictional performance.
2. The level of performance of aggregates with high polish values and high soundness losses (carbonate aggregates) was found to be dependent on the level of ADT because the polishing action of this variable interacted with the degree of rejuvenation caused by weathering action.
3. Porous aggregates, particularly some lightweight and limestone rock asphalt ones, were seen to maintain excellent rejuvenated surfaces in the cold region characterized by temperature freeze-thaw cycling.
4. The level of construction aggregate spreading rate was shown to explain much of the variations among many of the

TABLE 3 One-Way General Linear Model

SAS

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: FN

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	29	31150.44194538	1074.15317053	57.23	0.0	0.836233	8.7116
ERROR	325	6100.46552738	18.77066316		ROOT MSE		FN MEAN
CORRECTED TOTAL	354	37250.90747275			4.33251234		49.73250423

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
AGGR	4	17293.54896334	230.33	0.0	4	1551.68445536	20.67	0.0001
LGCUTR*AGGR	5	4893.57083960	52.14	0.0001	5	2153.45228166	22.94	0.0001
AGGR*RGT	4	2095.10085401	27.90	0.0001	4	1438.11287015	19.15	0.0001
LGCUTR*AGGR*RGT	4	1394.20094170	18.57	0.0001	4	1704.37329012	22.70	0.0001
LAGSR	2	3063.01791495	81.59	0.0001	2	2390.55288756	63.68	0.0001
AGGR*LAGSR	5	1378.77114586	14.69	0.0001	5	1337.36369584	14.25	0.0001
ADT	1	118.81673852	6.33	0.0124	1	639.85718132	34.09	0.0001
ADT*AGGR	4	913.41454740	12.17	0.0001	4	913.41454740	12.17	0.0001

TABLE 4 Regression or ANOVA Equation of the One-Way General Linear Model

SAS

DEP VARIABLE: FN
ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	31	29509.43407	951.91723	39.717	0.0001
ERROR	323	7741.47340	23.96740991		
C TOTAL	354	37250.90747			

ROOT MSE	4.895652	R-SQUARE	0.7922
DEP MEAN	49.7325	ADJ R-SQ	0.7722
C.V.	9.843969		

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR HO: PARAMETER=0	PROB > |T|
INTERCEP	1	101.55039	11.71296926	8.670	0.0001
LGCUTR	1	-4.24198826	0.80939370	-5.241	0.0001
GROUP1	1	-75.89946709	23.87036818	-3.180	0.0016
GROUP2	1	-35.21252122	22.59299120	-1.559	0.1201
GROUP3	1	-119.68286	15.74819426	-7.600	0.0001
GROUP4	1	-69.68385572	20.35115642	-3.424	0.0007
GROUP5	1	-108.47536	26.84568586	-4.041	0.0001
GROUP6	1	-52.94475671	13.77786481	-3.843	0.0001
GROUP7	1	-55.92553587	38.48353356	-1.453	0.1471
GROUP8	1	-88.37051997	21.60586706	-4.090	0.0001
GROUP9	1	84.45210742	20.34597279	4.151	0.0001
GROUP10	1	42.58030511	20.35115642	2.092	0.0372
GROUP11	1	-19.93751604	19.53226906	-1.021	0.3081
GROUP12	1	9.33253706	38.48353356	0.243	0.8085
GROUP13	1	9.22700334	15.15751539	0.609	0.5431
GROUP14	1	5.28029734	28.09984244	0.188	0.8511
GROUP15	1	76.03174979	30.87638883	2.462	0.0143
LGGRP1	1	5.64484886	1.66759373	3.385	0.0008
LGGRP2	1	3.53035553	1.55957045	2.264	0.0243
LGGRP3	1	9.87131565	1.11132988	8.882	0.0001
LGGRP4	1	6.54326212	1.40816492	4.647	0.0001
LGGRP5	1	8.36087896	1.96677630	4.251	0.0001
LGGRP6	1	4.55134506	0.96056646	4.738	0.0001
LGGRP7	1	5.19284977	2.88481095	1.800	0.0728
LGGRP8	1	7.54227463	1.57649801	4.784	0.0001
LGGRP9	1	-5.87541208	1.41790765	-4.144	0.0001
LGGRP10	1	-2.43635841	1.40816492	-1.730	0.0846
LGGRP11	1	1.42080995	1.40901508	1.008	0.3140
LGGRP12	1	-0.47536686	2.88481095	-0.165	0.8692
LGGRP13	1	-1.57202275	1.12112947	-1.402	0.1618
LGGRP14	1	-1.45825924	2.22656057	-0.655	0.5130
LGGRP15	1	-5.56882502	2.20398239	-2.527	0.0120

SAS

VARIABLE	MEAN	VARIANCE
LGCUTR	13.87742571	1.34459076
GROUP1	0.03513514	0.03399253
GROUP2	0.08648649	0.07922068
GROUP3	0.10810811	0.09668205
GROUP4	0.04324324	0.04148539
GROUP5	0.03513514	0.03399253
GROUP6	0.18918919	0.15381235
GROUP7	0.02702703	0.02636783
GROUP8	0.03783784	0.03650480
GROUP9	0.08378378	0.07697209
GROUP10	0.04324324	0.04148539
GROUP11	0.05945946	0.05607559
GROUP12	0.02702703	0.02636783
GROUP13	0.04864865	0.04640738
GROUP14	0.04054054	0.03900242
GROUP15	0.02702703	0.02636783
LGGRP1	0.50979647	7.04757918
LGGRP2	1.27627954	16.93262469
LGGRP3	1.51907548	18.79943111
LGGRP4	0.63487580	8.81553219
LGGRP5	0.29622619	3.92526663
LGGRP6	2.69585683	30.75175868
LGGRP7	0.36438294	4.70853787
LGGRP8	0.51623181	6.69787343
LGGRP9	1.22511119	16.17108453
LGGRP10	0.63487580	8.81553219
LGGRP11	0.81952484	10.48865524
LGGRP12	0.36438294	4.70853787
LGGRP13	0.61050922	7.27357805
LGGRP14	0.50759072	6.00945932
LGGRP15	0.39129151	5.44124143

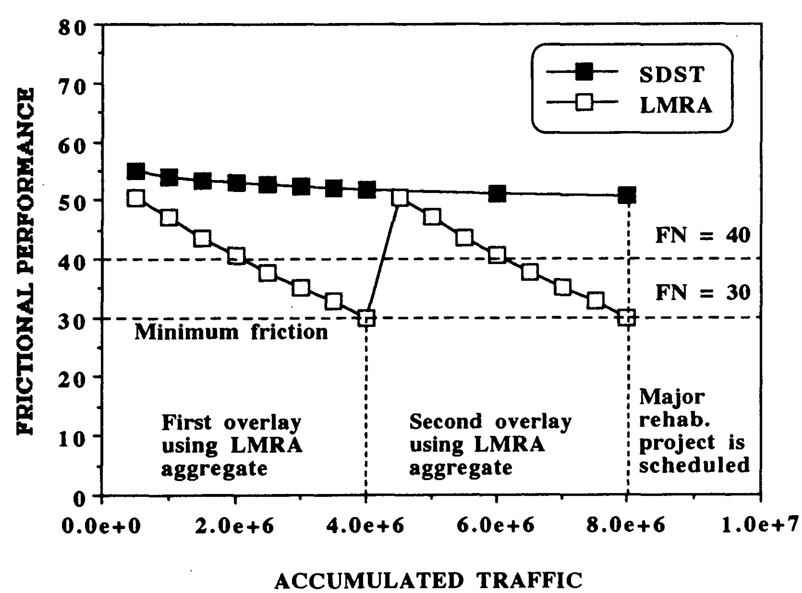

FIGURE 8 Example of how the performance model can be incorporated in a pavement management system.

examined groups. The implication was that as the spreading rate increased, a higher level of frictional performance was achieved.

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REFERENCES

1. M. U. Abdul-Malak, A. H. Meyer, and D. W. Fowler. Research Program for Predicting the Frictional Characteristics of Seal-Coat Pavement Surfaces. In *Transportation Research Record 1217*, TRB, National Research Council, Washington, D.C., 1989, pp. 53–64.
2. M. U. Abdul-Malak. *Implication of Aggregates in the Construction and Performance of Seal Coat Pavement Overlays*. Ph.D. dissertation. The University of Texas at Austin, Austin, 1990.
3. T. D. Gillespie. *Pavement Surface Characteristics and Their Correlation With Skid Resistance*. Report 12, Pennsylvania State University.
4. J. J. Henry and S. H. Dahir. Effects of Textures and the Aggregates That Produce Them on the Performance of Bituminous Surfaces. In *Transportation Research Record 712*, TRB, National Research Council, Washington, D.C., 1979, pp. 44–50.
5. *Manual of Test Methods: Accelerated Polish Test for Coarse Aggregate*. Test Method Tex-438-A-1983. Texas State Department of Highways and Public Transportation, Jan. 1983.
6. *Manual of Test Methods: Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate*. Test Method Tex-411-A-1978. Texas State Department of Highways and Public Transportation, Jan. 1978.
7. M. U. Abdul-Malak, D. W. Fowler, and A. H. Meyer. The Mineralogy of Aggregates in Relation to the Frictional Performance of Seal Coat Pavement Overlays: A Petrographic Study. Presented at the 71st Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1992.
8. Surface Characteristics. Technical Committee Report 1. Presented at 18th World Road Congress, Brussels, Belgium, Sept. 13–19, 1987.
9. S. H. Dahir et al. *Seasonal Skid Resistance Variations*. Report PA 80/75-10. FHWA, U.S. Department of Transportation, 1979.
10. R. R. Hegmon. Seasonal Variations in Pavement Skid Resistance—Are These Real? *Public Roads*, Sept. 1978, pp. 55–62.
11. B. J. Hill and J. J. Henry. Short-Term, Weather-Related Skid Resistance Variations. In *Transportation Research Record 836*, TRB, National Research Council, Washington, D.C., 1981, pp. 76–81.
12. K. Saito and J. J. Henry. Mechanistic Model for Predicting Seasonal Variations in Skid Resistance. In *Transportation Research Record 946*, TRB, National Research Council, Washington, D.C., 1983, pp. 29–37.
13. J. L. Beaton. Providing Skid Resistant Pavements, Skidding Accidents: Pavement Characteristics. In *Transportation Research Record 622*, TRB, National Research Council, Washington, D.C., 1976, pp. 39–50.
14. H. Williams, F. J. Turner, and C. M. Gilbert. *Petrography: An Introduction to the Study of Rocks in Thin Sections*. W. H. Freeman and Company, San Francisco, 1982.

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