performed by Schweyer, Ruth, and Potts on the six asphalt cements used on this project. This is a significant contribution toward understanding the complex behavior of paving asphalts.

It has been noted that the softening points of all asphalt cements fall in a narrow range of 48.9-51.1°C (120-124°F) and thus have a low sensitivity in connection with the temperature susceptibility. However, the softening points should be evaluated in conjunction with the penetrations at 25°C (77°F), which vary from 4.2 to 8.0 mm, in order to determine the relative differences in temperature susceptibility.

Regarding the ductility test at low temperature, the TFOT ductility results (Table 2) did not predict the low-temperature cracking. However, it is interesting to note the ductility values at 4°C (39.2°F) run on the asphalt cements recovered from the project just after construction (Table 3), which indicate very low ductility values for T-1 and T-5 asphalt cements.

It would be interesting to follow up this study to ascertain which of the remaining four asphalt cements develops low-temperature cracking first.

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Seasonal Variation in Skid Resistance of Bituminous Surfaces in Indiana

B. L. ELKIN, K. J. KERCHER, AND S. GULEN

Results are reported of repetitive testing of 15 individual bituminous sections at speeds of 40, 50, and 60 miles/h by means of a skid-resistance measuring system as described by ASTM E274 to identify the surface types that provide and maintain satisfactory skid resistance independent of speed, seasonal changes, and climatic factors such as rainfall and temperature. The bituminous test sections represent surface types commonly used in Indiana, an experimental open-graded friction course, and conventional mixes modified by the substitution of slag for some or all of the conventional aggregate portion. A complete petrographic analysis that concentrated on the carbonates of the coarsest fraction was performed on individual pieces of aggregate extracted from a series of cores taken from the test sections. The report also briefly describes the calibration and standardization of Indiana's skid-resistance measurement system. The cyclic nature of skid resistance relative to season is very apparent for all of the surface types included in the study. With one exception, the skid resistance was highest in the spring, dropped off noticeably during the summer, and began to recover in late fall. Average skid values at 40 miles/h for all the test sections ranged from a high of 61.8 to a low of 23.8. Speed gradients were calculated and compared to provide an indication of seasonal sensitivity. Information obtained from the petrographic analysis and accelerated wear rates determined by means of the British polishing wheel in the laboratory revealed that slag has a greater potential for polishing than the aggregates, which are predominantly limestone. However, skid test results show that the addition of slag improves the frictional characteristics of the pavement. Dolomite appears to be more susceptible to polishing than limestone but is not as susceptible as the slag.

This report was prepared to provide for the early dissemination of information obtained midstream in a study that received Federal Highway Administration (FHWA) approval in December 1976. A sizable quantity of information has been gathered in a program of replicate sampling and testing of 15 selected test sections distributed throughout the state of Indiana. All of the routinely used conventional bituminous surface types are included, as well as some that are experimental because of modification of the mix design, aggregate type, or aggregate gradation. Field testing is to continue through the fall of 1980.

All states are required to perform pavement skid-resistance tests and to develop and provide an inventory of skid resistance for traffic safety purposes (1). Furthermore, most states obtain this information by the use of a skid-test measurement system (SMS) as described by ASTM E274. Once the measurements are obtained, the data may or may not be distributed in some fashion to maintenance, traffic, or traffic safety departments to provide a data base for future analysis or to identify those areas that appear to require immediate attention because they have low skid-resistance values and are high-accident-rate locations.

An inventory system has been established, much testing has been accomplished, and a system of reporting and follow-up has been implemented and is working; however, certain questions need to be answered. More information is needed to allow for the accurate analysis of the data obtained: Are individual test values valid? How many tests are needed to give a true indication of the surface friction under traffic? What factors affect skid-resistance values? What does it mean if there is some disparity between values obtained on what appears to be the same type of surface for the same conditions? How much disparity is normal or acceptable? Why does temperature seem to affect the skid resistance of some pavement types at some times and not at others? In short, the objective is a better understanding of the meaning of pavement skid resistance as measured by a towed trailer system. Therefore, the variability of the skid system itself must be considered. In addition, the effect of the weather, seasons, climate, pavement type and condition, and speed of the vehicle traveling on the roads must be determined. Traffic volumes obviously affect the wear rate of certain pavement types more than others, as do the type and condition of the coarse aggregate fraction incorporated in the pavement surface.

This report describes and documents the preliminary activities and initial analysis of the data collected to date on 15 bituminous sections. This information should be considered at this stage as the foundation for the development of a relationship between pavement skid resistance and seasonal changes, mix design, surface texture, and pavement wear rates that can be used to answer the questions posed earlier.

TECHNICAL APPROACH

Skid Measurement

The SMS is used to determine a skid number that can be thought of as the coefficient of friction of the pavement surface multiplied by 100. The frictional coefficient of the pavement is determined from the torsional force on a transducer that is an integral part of the axle assembly and is produced by dragging a locked wheel that has a special test tire at 40 miles/h across the wetted surface.

The SMS used in this study (in accordance with ASTM E274) is a two-wheeled towed-trailer system that uses a strain-gauge-instrumented torque tube to produce an analog signal during wheel lockup. The analog signal is digitized, processed, and converted to a skid number on board the system. Indiana's SMS is depicted in Figure 1.

Routine Evaluation of the SMS

The physical and operational characteristics of the system were initially evaluated and standardized in accordance with the requirements of ASTM E274 at the Field Test and Evaluation Center for Eastern States in East Liberty, Ohio, in August 1976 (2). Test results with the adjusted and calibrated system on the standard test surfaces at East Liberty produced a pooled standard deviation (SD) of 2.3 skid numbers for test speeds from 40 to 60 miles/h.

Special Evaluation for the Study

Sections of four different roads located close to the Research and Training Center (West Lafayette, Indiana) were selected, somewhat at random, to determine the normality and homogeneity of the skid numbers produced by the SMS. The criteria for selection after the location requirement were simple: The sections had to include a range of pavement surface types and provide a range of skid resistance, and the surface of each of the test sections had to be uniform in texture and free from defects.

Twenty tests were performed on each of the four sections within a two-day period. The tests were performed virtually at the same spot to cancel any significant variability of the pavement surface.

The Shapiro-Wilk method was used to check the normality of the skid numbers obtained on each of the four sections. Bartlett's test and the Burr-Foster Q test were used to check the homogeneity of variance (3). The distribution of skid numbers produced by the SMS was found to be normal at the 0.05 percent level for three of the special sites and normal at the 0.04 percent level for the fourth site. Results of both methods of analysis to determine the homogeneity of variances of all four sites is positive; in other words, the differences of the variances obtained on the four test sections were not found to be significant. It was inferred from this that the SMS is capable of producing skid numbers on in-service pavements that are within acceptable limits for accurate replicate testing and are not affected by pavement type and level of skid resistance.

The SMS was reevaluated at the East Liberty test center in July 1978 (4). The SD at that time was found to be 1.7 skid numbers, which is less than the initial evaluation value of 2.3. This information reinforced confidence in the system.

Selection of Study Test Sections

A preliminary list of many and various surface types that had been recently constructed was prepared late in 1976. An initial selection of 40 permanent study sections was made from this list. This list was later revised to a number of sections that could be properly and sufficiently tested with an established frequency throughout three complete annual cycles and in accordance with criteria suggested by FHWA in its review of the study plan--namely, age, traffic volume, and the guidelines set out by FHWA (5). The final list includes 15 bituminous test sections distributed about the state. Specifics of each section are summarized in Table 1. Each surface-type designation is fully described in the Indiana State Highway Standard Specifications except for the open-graded friction course (6). Briefly, however, HAE designates a hot emulsified asphaltic mixture and HAC designates a hot asphaltic concrete. The type designation refers to the maximum aggregate size fraction and gradation. Both the HAC type A and the HAE type II mixes of this study call for aggregate gradations that have 100 percent passing the 0.75-in sieve. Type B and type III are both made with aggregate that passes the 0.5-in sieve, and the type D and type IV mixes are made with aggregate that passes the no. 4 sieve. The mix design for the open-graded surface calls for a gradation that has 100 percent passing the 0.5-in sieve, 30 percent

Figure 1. Indiana's skid-test measurement system.

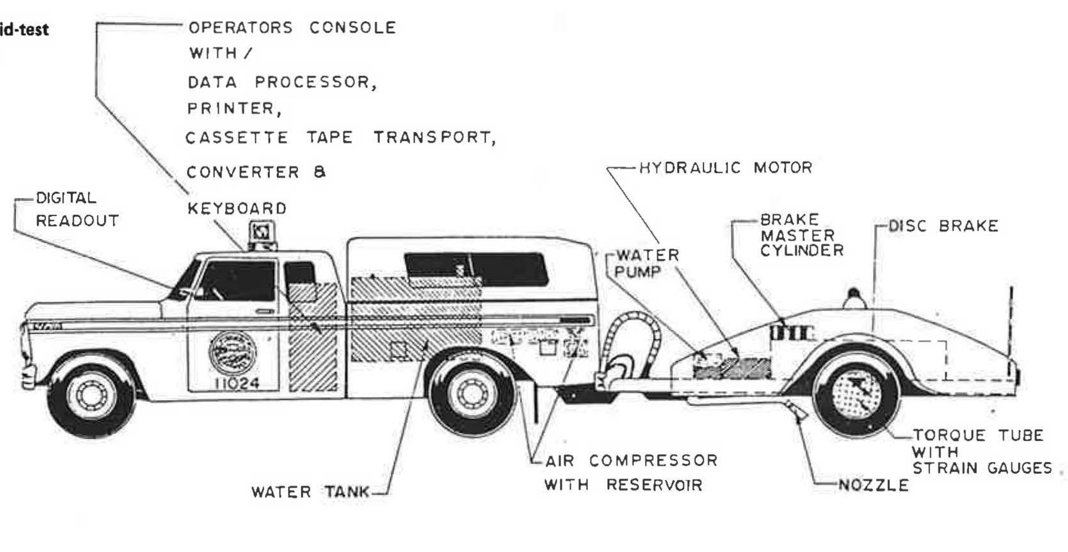

Table 1. Summary of data on bituminous test sections.

Road	Contract	No. of Lanes	Length (miles)	Surface Type	ADT per Test Lane[a]	Date Opened to Traffic
IN-26	RS-10177	2	5.0	HAE-II, no. 9 gravel	1800	9/75
IN 3	RS 9781	2	5.0	HAE II, no. 9 stone	2000	8/74
IN-9	RS-10065	4	4.7	HAE-III, no. 11 gravel	4900	7/75
US-24	RS-9592	2	5.0	HAE-III, no. 11 stone	1700	7/74
US-30	M-9314	4	6.0	HAE-III, no. 11 slag	6000	9/73
I-65	R-10209	4	5.0	HAE-IV, natural sand	8700	11/75
I-64	R-9967	4	3.5	HAE-IV, natural sand	2600	11/75
US-20	RS-10365	4	5.83	HAE-IV, slag	2800	8/76
IN-29	RS-10356	2	2.5	HAC-A, no. 9 gravel	1350	6/76
IN-14	RS-10047	2	1.5	HAC-A, no. 9 stone	1200	7/75
US-41	RS-10058	4	5.05	HAC-A[b], no. 9 stone	2100	10/75
IN-37N	R-9506	4	3.24	HAC-B, gravel	5500	10/74
IN-37S	R-9495	4	2.7	HAC-B, stone	5200	11/74
IN-2	RS-10364	2	5.5	HAC-B, slag	1500	5/76
I-64	R-9967	4	2.2	Open-graded friction course, crushed gravel	2600	11/75

[a] ADT = average daily traffic; figures are approximate. [b] US-41 used a blend of petroleum asphalt and Trinidad asphalt.

passing the no. 4 sieve, and 15 percent passing the no. 8 sieve and has a bitumen content of 6.2 percent.

In the final analysis, the permanent sections are composed of all major aggregate types--gravel, crushed stone, and slag. Surface texture includes both coarse- and fine-textured emulsified asphalt mixes, both coarse- and fine-textured hot asphaltic concretes, and an open-graded hot asphaltic friction course.

A history of each test section was compiled to include mix design, material sources, and a check for unusual occurrences during the placement of the material. As a part of this investigation, an initial material sample was obtained from each test section to verify mix properties and to determine degree of deterioration of the materials that may have occurred prior to any field testing for this study.

All test locations were initially visited to determine any unsafe areas for skid testing. After dangerous curves, hills, and residential areas had been eliminated, the remaining mileage was divided into 0.25-mile-long subsections. The subsections were consecutively numbered in each direction of travel, and a table of random numbers was employed to select three subsections in each test lane. A few of the final sections are tested in one direction only because all six subsections are in the same direction of travel. All subsections were permanently marked.

Development of the Testing Program for the Permanent Sites

SMS Testing

The following control values were used throughout the data analysis.

1. The value of α, the probability of making a type 1 error (rejecting the true hypothesis), was set at 0.05.
2. The value of β, the probability of making a type 2 error (accepting the false hypothesis), was set at 0.10.

Once these values were established, the next step was to determine the number of tests necessary to satisfy accepted statistical requirements (7). The size of a population sample is a function of (a) the value of α, (b) the value of β, (c) the SD of the population (σ), and (d) the allowable error, or tolerance (δ).

The value of σ was estimated from the results of the skid tests performed on the four special test sites as follows [average weighted SD = ±0.95 (estimation of σ)].

Road	SD	Sample Size	Road	SD	Sample Size
IN-25	±0.99	20	IN-26	±1.17	19
US-231	±0.62	20	US-41	±1.03	20

The following statistical hypotheses were used to determine the sample size:

$$H_0: \mu = \mu_0 \quad (1)$$

$$H_1: \mu \neq \mu_0 \text{ at the 5 percent significance level} \quad (2)$$

where μ_0 = mean of random sample from a normal population and μ = mean of the normal population.

When σ is estimated to be ±0.95 and the allowable difference $\delta = |\mu - \mu_0| = 2.0$ skid numbers, it is found that n = 5 is the minimum number of skid tests per site to satisfy the statistical controls and account for the inherent variability of the skid system. The skid testing program was finalized once this value was established; this required five skid-test measurements in each of the six subsections at 40 miles/h, five tests at 50 miles/h, and five tests at 60 miles/h.

It was originally intended to test each of the permanent sections at least once during each season except during winter, which is too unpredictable. However, since October 1977, when skid testing began, machine downtime and weather conditions have caused major interruptions to the established schedule. Sections close to the research facility have averaged two visits per season, whereas those at some distance average only one visit per season.

Determination of Traffic Use

Traffic use in Indiana ranges from very high volumes in the Gary and Indianapolis areas to very low volumes in the widespread rural areas found throughout most of the state. Test sections for this project reflect this diversity of traffic use.

Traffic volumes are determined by means of pressure-tube-type traffic counters placed at three or four test sites within each test section. These counts are made twice yearly for one-week periods in the spring and fall. The volumes collected are adjusted for traffic mix by 8-h traffic classification counts taken while the counter is in place. The volumes are further adjusted by a monthly factor obtained from permanent recording sites that exhibit similar traffic patterns and are monitored by the Indiana State Highway Commission Division of Planning.

Climatological Information

Permanent weather stations are maintained throughout the state under the auspices of the National Climatic Center. A copy of the monthly bulletins that summarize weather conditions at these stations is used to determine daily high, low, and average temperatures; precipitation; sky cover; humidity; and wind direction information for reporting stations near the test sites. Information is compiled for each of the seven days previous to each skid-test date by using the weather station nearest a test section. Pavement temperatures are recorded during each test by using an infrared heat sensor mounted in the floor of the tow vehicle's cab and centered over the left wheelpath.

Field Sampling and Testing

All field sampling and testing accomplished to date in each 0.25-mile subsite was done in the left wheelpath approximately 500 ft beyond the end of the skid-testing area in the following sequence. First, three 6-in-diameter cores were taken from a 10-ft strip within the wheelpath for subsequent laboratory testing. Next, five British pendulum number (BPN) values were obtained by means of the portable skid-test apparatus described in ASTM E303-74 at a convenient distance from the coring locations. These tests were performed at two setups approximately 15 ft apart. A dial-type surface thermometer was used to measure the pavement surface temperature. Finally, the sand-patch test (8) was performed at still another location beyond the portable skid-test area to provide information relative to the surface texture. Three tests were made at three different locations within 10 ft of each other.

Laboratory Testing

Laboratory testing began with the preparation of the three 6-in cores taken in the field. The surface is separated from the core by a wet cut with a diamond blade.

A determination of bulk specific gravity was performed on one of the prepared specimens (in accordance with ASTM D1188) to determine the percentage of voids in the compacted mix.

A reflux extraction test (as described by ASTM D2172) was run on the remaining samples to separate the bitumen and the aggregate. The percentage of bitumen content was calculated from this information. A sieve analysis similar to that of ASTM C136 was performed to determine the gradation of the extracted aggregate.

The extracted bitumen was recovered by the Abson method (ASTM D1856), and both kinematic viscosity (ASTM D2170) and penetration tests (ASTM D5) were performed on the recovered asphalt.

The aggregate fraction between the 0.5-in and no. 4 sieves was sent to the Division of Materials and Tests for evaluation of its polishing characteristics by using the British polishing wheel. A detailed petrographic analysis of both the coarse and fine aggregate fractions from each test site was performed by Purdue University (9).

The procedure adopted for the detailed petrographic examination began with the separation of the aggregate samples into size fractions. The percentage of each constituent was determined. A brief general description of each rock type was prepared that included grain size, particle shape, amount of weathering, cementing material, and impurities. Particle shape was described separately for each size fraction.

The distinction between limestone and dolomite for individual pieces between the 0.75-in and no. 8 sieves was made by using a 10 percent HCl solution. Brisk effervescence was taken to indicate the presence of limestone; pieces that showed slow effervescence (or produced effervescence only when scratched) were considered to be dolomite.

Fractions from the no. 30 to no. 100 sieves were examined under the binocular microscope, and it was observed in all cases that the amount of quartz increased with decreasing grain size.

Thin sections were made for the coarsest size fraction of limestone and dolomite for each sample. The sections were studied microscopically to determine the texture and mineralogy of the carbonate fraction. Carbonates were chosen for the microscopic study because they formed the main portion of each size fraction (generally more than 50 percent).

TEST RESULTS AND DATA ANALYSIS

Skid-Test Data

The results of seasonal testing for each of the sections by means of the SMS is contained in Table 2. The mean SN_{40} is the overall average skid number (SN) of the section that is the average of the five individual tests in each of the six subsites for each date at a test speed of 40 miles/h. The overall speed gradient, G_{40-60}, is defined as

$$G_{40-60} = (SN_{40} - SN_{60})/20 \quad (3)$$

The test speeds specified by ASTM E274 are 30, 40, and 50 miles/h. The test speeds selected to achieve the objectives of this study are 40, 50, and 60 miles/h for two reasons. First, evaluations at the Field Test Center showed that the system was less stable at the lower speeds. Second, the 60-miles/h tests were needed to bracket the posted speed limit of 55 miles/h. The July-September 1978 quarterly Traffic Speed Report (10) for sites in Indiana shows that the average speed for all passenger vehicles ranged from 56.4 to 59.2 miles/h, depending on highway type, and ranged from 55.2 to 59.0 miles/h for all trucks. Information for 1977 ranged from 55.9 to 60.1 miles/h for all passenger cars and 54.2 to 59.3 miles/h for all trucks. The average skid numbers at 40 miles/h (ASN_{40}) for each of the subsites were compared by using analysis of variance (ANOVA) to determine whether any of the subsites were significantly different from the group. The overall average SN_{40} and SDs shown in the tables were calculated by using only those subsites that were similar according to the ANOVA results.

The speed gradients of each subsite were also averaged for each test date. These averages and their respective SDs were also analyzed by ANOVA to determine which sites, if any, produced significantly different skid-speed gradients on any test date.

Skid Data Analysis

A linear regression analysis of skid number and corresponding speed was performed for each test section from the average skid numbers of the six subsites at the three test speeds (40, 50, and 60 miles/h). Correlation coefficients were then calculated to verify the linear relationship that apparently existed between skid number and speed. Almost all of the correlation coefficients were

Table 2. Skid results by season.

Road	Test Date	SN_{40}				Average Surface Temperature (°F)	Speed Gradient (G_{40-60})
		Mean	SD	Maximum	Minimum		
IN-26	10/27/77	47.9	±0.39	49.7	45.8	71	0.221
	4/7/78	50.9	±0.96	52.0	49.5	87	0.234
	5/11/78	49.8	±0.91	52.9	45.8	69	0.287
	7/18/78	45.3	±0.96	46.9	41.5	115	0.239
	9/28/78	44.5	±0.72	47.9	42.6	87	0.267
	10/30/78	46.0	±0.64	46.9	42.3	69	0.306
	5/23/79	45.5	±1.18	46.8	40.6	105	0.278
	8/22/79	50.4	±0.86	51.2	47.3	110	0.219
IN-3	10/25/77	41.1	±0.48	42.6	35.4	64	0.149
	4/24/78	47.1	±0.38	47.4	44.8	75	0.141
	5/23/78	44.2	±1.75	46.3	41.8	65	0.204
	8/31/78	36.2	±0.29	40.8	35.8	86	0.209
	8/1/79	41.6	±0.81	46.0	40.8	86	0.258
IN-9	11/1/77	42.0	±0.83	44.3	37.7	72	0.327
	4/14/78	44.9	±0.57	49.1	40.6	68	0.284
	7/31/78	36.9	±0.67	39.9	30.6	107	0.350
	9/27/78	33.7	±1.18	37.6	28.7	92	0.340
	8/7/79	45.0	±1.49	47.0	33.9	142	0.397
US-24	10/26/77	45.1	±0.45	47.7	43.0	65	0.271
	4/25/78	46.6	±0.15	49.9	46.5	73	0.145
	5/27/78	46.3	±1.01	49.7	45.2	72	0.188
	9/1/78	41.5	±0.95	42.2	39.9	99	0.250
	8/1/79	38.2	±1.17	42.3	35.0	118	0.189
US-30	10/11/77	49.3	±0.45	49.8	44.2	64	0.223
	11/17/77	49.8	±0.83	52.3	46.4	54	0.317
	5/5/78	57.2	±0.86	58.0	50.8	76	0.280
	6/8/78	60.4	±0.42	60.9	52.7	89	0.387
	9/11/78	41.6	±0.25	45.2	37.4	110	0.327
	11/2/78	43.6	±0.84	47.6	40.5	75	0.324
	7/19/79	49.9	±1.18	55.6	48.4	117	0.275
I-65	10/5/77	32.9	±0.71	33.7	31.9	79	0.417
	11/4/77	32.3	±0.77	35.0	31.1	69	0.457
	4/5/78	36.6	±0.25	39.0	36.2	77	0.381
	5/10/78	32.9	±0.93	34.3	32.0	91	0.452
	7/17/78	24.9	±0.85	28.9	23.8	113	0.411
	9/7/78	28.5	±1.05	30.1	27.1	106	0.497
	10/3/78	30.5	±0.60	30.1	29.6	73	0.546
	11/1/78	31.1	±0.43	31.7	29.1	76	0.457
	5/7/79	28.4	±1.25	29.7	26.5	100	0.337
	8/9/79	32.3	±0.86	33.3	31.3	138	0.565
I-64[a]	10/18/77	49.5	±0.93	53.3	48.9	65	0.220
	4/11/78	54.8	±0.34	56.6	53.0	69	0.278
	5/16/78	54.7	±1.39	58.4	53.1	65	0.283
	8/17/78	49.2	±0.58	49.8	46.4	97	0.382
	11/9/78	48.7	±0.70	49.6	44.6	55	0.339
	8/14/79	58.9	±1.17	60.2	54.7	90	0.575
US-20	10/12/77	54.2	±0.78	56.5	50.5	51	0.195
	11/18/77	55.3	±1.19	56.9	51.3	42	0.269
	5/9/78	59.4	±1.40	60.8	54.6	72	0.320
	9/12/78	53.1	±0.76	53.9	47.6	75	0.385
	11/3/78	51.5	±1.41	55.0	47.6	67	0.387
	5/21/79	51.1	±0.40	54.6	50.7	95	0.217
	8/23/79	60.0	±0.83	61.1	56.8	122	0.412
IN-29	4/27/78	45.8	±0.23	47.9	45.5	83	0.322
	5/19/78	44.5	±0.93	45.8	43.0	98	0.328
	8/1/78	41.9	±0.74	42.7	39.9	96	0.426
	9/25/78	41.0	±0.59	43.4	40.4	86	0.477
	10/26/78	41.6	±0.47	42.1	39.5	53	0.361
	8/3/79	39.8	±0.98	46.3	39.0	108	0.409
IN-14	4/26/78	50.1	±0.53	50.5	44.1	63	0.211
	5/22/78	48.1	±0.87	50.3	41.6	77	0.251
	8/3/78	41.9	±0.66	43.6	38.7	92	0.237
	8/1/79	50.0	±1.06	51.0	43.3	88	
US-41	10/3/77	46.0	±1.38	47.4	44.4	79	0.135
	11/2/77	44.1	±0.93	45.4	40.7	78	0.186
	8/6/79	47.6	±0.94	48.4	43.9	122	0.298
IN-37 N	10/20/77	36.4	±1.36	41.0	30.0	72	0.267
	4/4/78	45.1	±1.26	46.8	38.2	66	0.328
	8/29/78	35.8	±0.94	37.2	33.8	96	0.379
	10/6/78	31.0	±1.20	37.0	29.8	58	0.412
	7/23/79	39.5	±1.30	40.5	34.4	127	0.540
IN-37 S	10/31/77	33.5	±1.17	34.8	32.4	63	0.243
	4/28/78	40.3	±0.95	43.7	39.0	94	0.234
	7/11/78	31.5	±0.86	32.7	30.5	103	0.284
	9/26/78	30.5	±0.73	32.5	29.5	91	0.227
	7/24/79	40.3	±1.06	42.5	39.0	111	0.358
IN-2	10/6/77	54.1	±1.57	56.3	52.2	60	0.238
	11/15/77	52.5	±0.92	53.5	51.4	62	0.228
	4/3/78	57.0	±1.43	58.7	55.3	78	0.292
	6/7/78	55.5	±1.91	61.2	53.6	105	0.261
	7/10/78	49.3	±0.58	50.0	46.3	102	0.322
	9/8/78	47.4	±0.87	49.2	46.2	119	0.288
	10/2/78	51.1	±0.91	53.3	49.8	91	0.294
	11/16/78	50.7	±0.89	51.7	47.7	46	0.332
I-64[b]	10/18/77	38.7	±0.98	39.7	36.0	69	0.189
	4/11/78	42.4	±0.93	43.7	39.2	81	0.244
	5/16/78	43.3	±1.07	44.2	37.8	68	0.361
	8/17/78	35.4	±1.01	36.6	32.3	106	0.450
	11/9/78	32.9	±0.36	33.4	29.5	55	0.375
	8/14/79	37.3	±0.38	42.9	36.9	88	0.570

[a]HAE-IV. [b]Open-graded friction course.

found to be greater than 0.900; many were in the range from 0.970 to 0.999. This indicates that there is a significant linear correlation between skid number and speed. Therefore, the speed gradient as defined in this report is valid because the slope of the regression line is constant between test speeds of 40 and 60 miles/h.

As a further step in the analysis of the speed gradients, the overall average speed gradient for skid tests obtained during each visit was calculated as shown in Table 2. These overall speed gradients were then compared by ANOVA at the 0.05 level to see whether they were significantly different from visit to visit.

Results of laboratory and field testing are presented in Tables 3 and 4. Table 3 lists the polishing data obtained from tests performed on the aggregate fraction that passed the 0.5-in to no. 4 sieves by personnel at the Division of Materials and Tests by using the British polishing wheel. Also shown are data on aggregate type from the petrographic analysis by Purdue University (9). Samples from each of the six subsites were analyzed independently. Some sections, especially those of HAE type IV, show a great variety of aggregate types. In many of the sections one type may be predominant in the sampling of one of the subsites and not in one or more of the other subsites. Because of this variability, percentages are not given. Instead, the aggregate types are listed in the order of their apparent predominance. The polishing index given in the table is the difference between the average initial BPN and the average final BPN of aggregate samples from each of the subsites.

The percentage of bitumen, penetration of recovered asphalt, percentage of voids in the compacted mix, and the sand-patch texture values of Table 4 are averages of the results of tests performed in 1977 and 1978 on sample specimens and test sites from all of the subsites within the test sections. The BPN values shown in Table 4 are the highest and the lowest of the 60 readings obtained each year for each test section in the field.

DISCUSSION OF RESULTS

Level of Skid Resistance

The test sections selected for this study exhibited a range of pavement skid numbers from 23.8 to 61.8. Three of the sections--IN-2, US-20, and I-64 (HAE type IV)--produced skid numbers that were consistently at or above 50 whereas three others--I-65, IN-37S, and I-64 (open-graded friction course)--produced skid numbers in the low 30s and even into the 20s. This situation occurs almost independently of season with few exceptions. There was noticeable improvement of the low values in the spring 1978 results, which greatly reduced the spread (except for the I-65 section). Even though there was a significant improvement in the April 1978 results over the initial values of October 1977 by an average of 4 skid numbers, the outcome of tests in May 1978, only one month later, showed a loss of the improvement, so that the average value equaled the October 1977 value of 32.9.

The HAE type IV surface on I-65 consistently produced the lowest skid numbers of all of the bituminous test sections. It should be noted that consistently low skid numbers are not typical for this type of mix. In fact, it was later found that this section was "bleeding" as a result of construction problems. An obvious factor contributing to this outcome is the very high directional average daily traffic (ADT) of 8700 vehicles, which is 1.5-7 times greater than that for any of the other sections. Results found in Table 4 reveal a bitumen content that may be too high for the traffic volume, coupled with a percentage of voids in the compacted mix that is too low. The best overall average SN_{40} for this section was 36.6 (obtained in April 1978). However, the expected average SN_{40} from season to season for this particular section appears to be more in the range of 28-32.

Another section that produced low skid numbers is IN-37S, which is an HAC type B surface with stone as the coarse aggregate. The ADT across this section is approximately 5200, which ranks it as the fourth-busiest section in the study. The coarse aggregate was identified from the petrographic analysis as a pure limestone. The section showed improvement in the spring test results, but the overall average SN_{40} is more probably 31-34, especially during the critical summer season, when pavement temperature is high and traffic is heavy.

The experimental open-graded friction course section of I-64 is producing relatively low skid numbers and appears to be sensitive to seasonal changes. These results do not compare favorably with the experience reported by other states. Results of gradation tests performed on aggregate extracted from pavement core samples reveals that the fraction that passes the 0.38-in sieve is too fine and too densely graded.

A closer inspection of the sections that have produced high average skid-resistance values reveals some significant indications. First, three of the sections are experimental mixes in which slag has been substituted for gravel or stone as the coarse aggregate fraction--namely, IN-2, US-20, and US-30. In fact, all three of the slag-modified mixes have produced high skid numbers, if not the highest, in all seasons. The HAE-IV surface on I-64 also produced high skid resistance. Another significant point to consider is that three different surface types are represented by the four sections that produced the highest skid numbers in all seasons over a two-year period. In other words, it does not appear from the information available so far that mix design by itself is responsible for high skid resistance. There are many other factors such as age and ADT that must be considered that confuse the analysis. When age and ADT are taken into account,

Table 3. BPNs and polishing indices from accelerated laboratory tests.

Road	Predominant Aggregate Type	Mean Laboratory BPN Initial	Mean Laboratory BPN Final	Polishing Index
IN-3	Dolomite, limestone	37.0	28.8	8.2
IN-26	Information not available	37.0	28.0	9.0
IN-9	Limestone	34.0	30.8	3.2
US-24	Limestone, dolomite, dolomitic-limestone	38.2	29.7	8.5
US-30	Slag	42.2	30.0	12.2
I-65	Limestone, dolomite, quartzite, siltstone, sandstone, chert, granite	31.0	26.8	4.2
I-64[a]	Information not available	36.2	27.0	9.2
US-20	Slag, dolomite, limestone, schist, sandstone, granite, chert	39.2	24.8	14.4
IN-37N	Limestone, dolomite, quartzite, chert, sandstone	31.7	28.8	2.9
IN-37S	Pure limestone	36.7	29.0	7.7
IN-2	Slag	38.8	28.5	10.3
I-64[b]	Information not available	34.7	26.3	8.4

[a]HAE-IV. [b]Open-graded friction course.

Table 4. Results of laboratory and field tests.

Road	Percentage of Bitumen		Penetration of Recovered Asphalt		Percentage of Voids in Compacted Mix		Field BPN Values, Maximum-Minimum		Sand-Patch Texture (mm)	
	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978
IN-3	5.28	4.92	24	23	10.63	7.53	55-44	54-42	0.53	0.56
IN-26	4.20	4.60	27	28	9.67	10.10	63-46	59-42	0.41	0.49
IN-9	5.48	5.37	32	32	6.21	5.22	60-46	54-39	–	0.40
US-24	5.02	5.32	22	21	10.80	9.90	62-49	60-44	0.55	0.73
US-30	5.85	6.30	22	18	5.80	6.50	67-52	70-52	0.38	0.41
I-65	6.98	7.55	38	44	3.90	4.72	81-55	64-53	0.10	0.11
I-64[a]	6.97	7.00	22	19	7.77	8.86	72-57	68-55	0.23	0.30
US-20	5.37	6.67	14	11	10.03	10.77	65-59	65-57	0.30	0.40
IN-29	–	5.47	–	34	–	2.67	–	57.44	–	0.29
IN-14	–	5.57	–	26	–	3.17	–	59-47	–	0.63
IN-37N	5.53	5.20	35	31	4.56	4.30	58-50	59-47	0.27	0.27
IN-37S	5.35	5.80	26	28	5.34	3.70	57-40	54-37	0.31	0.41
IN-2	6.16	6.16	26	25	6.19	5.58	65-51	67-52	0.39	0.46
I-64[b]	6.22	6.12	34	33	7.51	6.22	59-39	57-41	0.51	0.34

Note: Values are averages of all subsites unless otherwise noted.
[a]HAE-IV. [b]Open-graded friction course.

US-30 is readily seen as the top performer. This section has been open to traffic almost six full years and has an ADT of approximately 6000 vehicles. It is the oldest section in the study and has the second-largest ADT (after that of I-65). The only drawback to US-30 is that it also produced the broadest range of overall average skid numbers through the seasons, from 41.6 to 60.4--an indication of seasonal sensitivity.

There is an indication that the coarser surface mixes are less sensitive to seasonal changes, since both the HAC type A and the HAE type II mixes, which have the coarsest aggregate gradation, exhibited a narrow range of average skid values throughout the seasons. The open-graded friction course has a broader range of skid numbers than the HAE-II or the HAC type A, but its level of skid resistance is low in relation to the other mix types.

Pavement Temperature and Skid Resistance

A definite relationship between pavement temperature and pavement skid resistance is apparent in almost all of the test sections. However, a number of the sections show what might be considered as the classic relationship. This relationship is especially noted if one plots skid number and pavement temperature as a function of time for IN-29 (HAC type A, gravel), US-30 (slag-modified HAE type III), I-65 (HAE type IV), IN-2 (slag-modified HAC type B), and IN-26 (HAE type II, gravel). These roads are very good examples of the loss of skid resistance as pavement surface temperature increases beyond 90°F and especially above 100°F. This situation does not appear to be dependent on pavement surface type, since all mix types are included in the examples cited. As more information becomes available, it may be possible to define this relationship more precisely.

Polishing Index and Field BPN Values

Results of the accelerated polishing tests performed in the laboratory with the British polishing wheel are given in Table 3. Laboratory polishing-index information was available for only 12 of the sections. Polishing indices for the aggregates of 3 of the sections are significantly lower than the rest (2.9, 3.2, and 4.2). The predominant aggregate type of all three is limestone. On the other hand, the polishing indices of the aggregates tested from 3 other sections are significantly high (10.3, 12.2, and 14.4). The predominant aggregate type of these sections is slag. The remaining 6 sections produced values from 7.7 to 9.2.

The field BPN values are much higher than the laboratory values. The lowest field value is 7-10 numbers greater than the initial laboratory value. The field values also appear to be quite variable; however, the variability of the field values does not appear to be directly related to a particular aggregate type or mix type. A difference in maximum and minimum values of 11-26 numbers is seen in all but two of the test sections for both years; the slag-modified HAE type IV surface on US-20 (a difference of 6-8 numbers) and the HAC type B surface with gravel coarse aggregate on IN-37 (a difference of 8-12 numbers) produced the most uniform field BPN values of the sections.

A direct comparison of the 1977 and 1978 field BPN values of all sections reveals no significant difference from year to year except for the I-65 section; however, the 81 value is not felt to be representative. It is pointed out that the mean initial laboratory value for the aggregate from this section is 31.0, which is the lowest of all the initial laboratory values. The 1979 polishing data will be compared with the 1977 and 1978 values to see whether BPN values can be used with confidence to predict pavement durability in relation to skid resistance.

An interesting observation is that those sections that had the highest average skid numbers also had the highest polishing indices, and those that had low average skid resistance had low indices. It appears that those sections that possessed the capacity to lose skid numbers (the ones with the high numbers) contain coarse aggregate that has the potential to polish. Although this may be evident from the results of accelerated polishing tests performed in the laboratory, results of skid tests, which are short term, show otherwise, as expected.

A comparison of the two HAC type B sections on IN-37 reveals that the mix that incorporates the stone as the coarse aggregate is not as variable as the section that has gravel coarse aggregate in the mix. The range of average SN_{40} on three visits to the IN-37 section that has the gravel aggregate is 8-10 skid numbers, whereas the section that incorporates the stone produced a range of 2-4 numbers. Since most of the other variables such as ADT, pavement temperature, mix type, rainfall, climate, and age are very similar, the difference of aggregate type must be considered to be the probable cause of the skid variability. The surface-texture information shows the mix that incorporates stone coarse aggregate to have more texture than the mix surface that has the gravel aggregate.

The slag-modified mixes produced a noticeably larger difference of skid numbers on most test dates. The skid values for the modified HAC type B on IN-2 are less variable than the HAE type III or type IV; however, the apparent loss of pavement skid resistance from spring to summer on IN-2, which has a low ADT, is quite dramatic.

Significant loss of skid resistance from spring through summer is found in 9 of the 15 sections. This phenomenon apparently occurs independently of mix type and is to be expected. Additional testing is needed to show the extent of recovery and to verify the relationship of skid resistance and season. The level of skid resistance remained more constant from spring through summer for 5 of the sections.

A few observations from information contained in Table 4 are worthy of mention. First of all, there is evidence that may explain the occurrence of low skid resistance on I-65. The pavement-surface texture of the I-65 section as determined by the sand-patch method in both 1977 and 1978 is only 0.0040 in (0.1 mm). Compared with the other test sections, this is a very low value. Also, the percentage of voids of the compacted mix for the I-65 sections appears to be very low in relation to the other HAE type IV sections. Second, the texture values remained the same or increased for all sections except for the open-graded friction course on I-64.

Speed Gradient

The speed gradients for most of the sections remained well under the (generally accepted) limit of 0.500. Four of the surfaces produced initial speed gradients that were less than 0.200. Six other sections exhibited initial gradients of less than 0.250. One section had an initial gradient of 0.417, and four of the sections exhibited gradients of 0.540-0.575.

The HAE type IV surface on I-64 produced a very respectable initial speed gradient of 0.220 in October 1977. The section was tested five additional times and, with the exception of November 1978, the gradient increased to a value of 0.575. The open-graded friction course on I-64 produced an even better initial speed gradient of 0.189 in October 1977. Again, the speed gradient increased on all succeeding visits except for one (November 1978) to a value of 0.570. The HAC type B surface with gravel on IN-37N started at 0.267 and continually increased to 0.540 over five visits. The HAE type IV surface on I-65 had an initial value of 0.417. This section produced varied speed gradients over 10 visits. The lowest speed gradient was a 0.337 in May 1979. A 0.546 was calculated from the October 1978 tests, and the highest gradient for the section was 0.565, achieved in August 1979.

Two of the sections produced very uniform speed gradients over the testing period. The HAC type A surface on IN-14 and the HAE type II surface on IN-26 had similar initial values. The maximum differences between their highest and lowest average speed gradients were 0.040 and 0.087, respectively.

Many sections produced improved speed gradients in the spring, and some showed improvement in the fall. The ANOVA of the speed gradients was used to see whether the average speed gradients from each set of tests were statistically similar or significantly different from visit to visit. A significant difference in G_{40-60} could imply that the surface was sensitive to seasonal changes. The following summarizes the results of the analysis of the speed gradients:

1. All three of the HAE type III surfaces produced speed gradients that did not vary significantly from season to season.
2. All three of the HAE type IV surfaces produced speed gradients that were significantly different from season to season.
3. Two of the three HAC type B surfaces exhibited speed gradients that did not vary significantly with season; only the section that contained the gravel was significantly different from season to season.
4. Of the two HAC type A surfaces, the section that contained stone showed no significant difference, but the section that had gravel was found to have speed gradients that were different from season to season.
5. Of the two HAE type II surfaces, the section that had gravel produced speed gradients that were not significantly different from season to season, but the speed gradients of the section that contained stone were found to vary significantly from season to season.
6. The speed gradients of the open-graded friction course were found to vary significantly with season.

SUMMARY OF RESULTS

It is felt that conclusions at this time would be premature. Trends are apparent from the data obtained so far. A lot of factors are involved. Additional data and further evaluation and analysis will definitely help to define and refine the relationship of the many factors involved in pavement skid resistance.

The following statements summarize the major results of the initial analysis of data that have been obtained halfway through the study:

1. It was found that five tests at each test speed are necessary to give a reliable estimate of the true average skid number of a pavement surface because of the inherent variability of the SMS.
2. The 15 bituminous test sections, representing six different mix designs and incorporating gravel, stone, or slag as the coarse aggregate fraction, produced skid numbers as high as 61.8 and as low as 23.8 between October 1977 and July 1979.
3. A high linear correlation between skid resistance and speed was found between test speeds of 40 and 60 miles/h; all but a very few of the correlation coefficients were greater than 0.900.
4. It does not appear from the available data that skid resistance is a function of mix design alone.
5. Skid resistance is improved when slag is the predominant aggregate type, regardless of mix design.
6. With few exceptions, skid resistance is highest in the spring and lowest in the summer, irrespective of mix design and aggregate type.
7. Skid resistance appears to be a function of the temperature of the pavement surface, but the exact relationship remains undefined.
8. The skid resistance of bituminous surfaces appears to be less susceptible to short-term temperature changes in the summer than in the spring and fall.
9. Results of the laboratory-accelerated polishing test indicate that slag has a greater potential for polishing than either limestone or dolomite and that limestone has the least polishing potential of the three.
10. The significant variability of the speed gradients from season to season for all of the sections of a certain type of surface and the uniformity of the speed gradients of all of the sections of another type of surface might be used to show that certain surface types are sensitive to seasonal changes.
11. It should be realized that the very small number of sections selected in this study to represent bituminous surface types common to Indiana may not, in fact, be representative or typical.

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The contents of this report reflect our views, and we are responsible for the facts and accuracy of the data presented herein.

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Wet-Pavement Friction of Pavement-Marking Materials

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A total of 39 formulations of 11 types of marking materials were studied in the laboratory and in the field. Field skid number measurements were made at three sites by using the Pennsylvania Transportation Institute Pavement Friction Tester. Laboratory and field measurements were taken to determine British pendulum numbers, microtexture, macrotexture, and static coefficient of friction. Laboratory polishing and accelerated exposure testing were also performed. A wet-friction data bank for typical pavement-marking materials was established. Based on an analysis of these data, it was found that wet friction can vary dramatically for different marking materials. The texture of the underlying pavement affects the friction of thinner marking materials (paints), but the wet-friction resistance of the thicker marking materials is unaffected by the texture of the underlying pavement. Reductions in skid resistance from the paints can persist even after the aggregate surface is exposed from wear. The wet friction of marking materials exhibits a daily and seasonal variability much like that of the pavement itself, and the variability must be accounted for when skid-resistance measurements are made.

Many types of materials are used for pavement-marking purposes. Although these materials are routinely specified and tested in order to control their durability and visibility, little is known about their friction properties. The friction, or skidding resistance, of pavement surfaces has received considerable attention in recent years; this has resulted in improved test procedures and in surfaces that are more skid resistant. Well-marked pavements and highly skid-resistant pavement surfaces are both important safety features. However, the differential skid resistance that can develop between marked and unmarked pavement surfaces may, in certain circumstances, be a potential safety hazard.

The purpose of this paper is to report on the results of an extensive study of the wet-pavement friction of all types of pavement-marking materials. Both laboratory and field data are presented for a variety of pavement surfaces. The results are discussed in terms of the different levels of friction that can be developed by the different marking materials and the implications of these differences.

WET-PAVEMENT FRICTION

The texture of a road surface is the most important characteristic that provides resistance to skidding in wet weather (1). For the purpose of designing surfaces for good skid resistance, it is convenient to define two texture classifications: macrotexture, which is related to the gradation of the coarse aggregate, and microtexture, which is determined by the surface characteristics of the exposed aggregate particles. It has been shown (2) that, for skid-resistance considerations, microtexture consists of that portion of the surface spectrum that has surface asperities <0.5 mm (0.02 in) and macrotexture consists of the portion that has surface asperities >0.5 mm.

Pavement skid resistance is quantified by its skid number (SN), which is defined as the ratio of the friction force and the vertical load that results when a locked wheel slides along a wetted pavement at a velocity V. The procedure for measuring the SN is specified by ASTM E274. For pavements it has been shown that the skid resistance decreases with speed according to the following relationship (3):

$$SN = SN_0 \exp[-(PNG/100)V] \quad (1)$$

where SN_0 is the zero speed intercept and PNG is the percentage of the normalized gradient, which is defined as

$$PNG = -(100/SN)/(dSN/dV) \quad (2)$$

It has also been shown that SN_0 can be predicted by microtexture or British pendulum number (BPN) measurements as specified in ASTM E303. The value of PNG, which determines the rate at which skid resistance decreases with speed, is determined by the macrotexture of the pavement as measured by profile analysis or by the sand-patch method (4).

EFFECTS OF MARKING MATERIALS ON SKID RESISTANCE

Pavement texture is altered at those locations where pavement marking materials are applied. As a result, there will be a difference in skid resistances between the marked and the unmarked areas of the pavement. Problems may arise when the friction forces available to all tires on a vehicle are not equal. If emergency stops, or other maneuvers, are attempted when the friction forces are significantly different at one or more of the tires, the directional control of the vehicle may be lost.

Marking materials of various types are applied in thicknesses ranging from 0.4 to 3 mm (0.016-0.125 in). Thinner applications, typical of traffic paints, permit the macrotexture to continue to show through to some extent but may alter the microtexture significantly. A surface dressing of glass spheres added for reflective purposes may also provide some texture until the spheres are worn away. At the other extreme, the thick materials such as the thermoplastics obliterate the pavement microtexture and macrotexture completely. After the surface dressing of glass spheres on thermoplastics has worn away, little texture remains, except for