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Abstract

The objectives of the study were 1) to identify sources of native aggregates with varying histories of skid resistance performance; 2) to evaluate and correlate native aggregate characteristics, processing techniques, and other factors with skid resistance and surface mixture performance; and 3) to provide guidelines for implementation of research findings. Limestone, sandstone, river gravel, and control aggregates (granite, traprock, and slags) were subjected to a battery of tests to determine physical relationships between aggregate type and skid resistance.

Laboratory results were analyzed for correlations among themselves and for correlations with skid number data obtained from pavements containing aggregates involved in the study. No significant correlation could be found between any of the laboratory results and field skid numbers. This was particularly disturbing with reference to the KTRP test. It was thought that it could be used to adequately predict field skid performance. However, preliminary findings have shown no such relationship. It is recommended that the KTRP test be amended to provide a more defined weight loss over time to attempt to explain the behavior of an aggregate's skid resistance over time.

Key Words: Skid resistance, Native aggregates, Abrasiveness, Polishing, Skid number	18. Distribution Statement: Unlimited with approval of Kentucky Transportation Cabinet

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Research Report
UKTRP-87-33

NATIVE AGGREGATES FOR SKID RESISTANCE

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and

Federal Highway Administration
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November 1987

Mr. Robert E. Johnson
Division Administrator
Federal Highway Administration
330 West Broadway
Frankfort, Kentucky 40602

Dear Mr. Johnson:

SUBJECT: IMPLEMENTATION STATEMENT
KYHPR 84-98 - Native Aggregates for Skid Resistance

The KTRP Abrasion Test has been demonstrated as a method to determine aggregate abbrasiveness. The KTRP percent loss results used in conjunction with the area between gradation curves is believed to indicate relative abrasiveness of a group of different aggregate sources.

Combining results from the KTRP Abrasion Test with those of the Los Angeles Abrasion Test and the insoluble residue test permits an assessment of performance in skid resistant mixes.

A correlation between KTRP percent loss and initial skid number could not be determined at this time. Research staff is of the opinion a correlation may be found between these two variables by using the terminal skid number instead of the initial skid resistance value. Therefore, continued monitoring of selected sections on a long term basis is recommended.

The Division of Materials shall implement the plan with the aid of KTRP staff, who will provide training and assistance as needed. Long-term monitoring will be cooperative effort between KTRP, Pavement Management, and Materials Divisions. All field data from monitoring shall be given to KTRP for evaluation.

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EXECUTIVE SUMMARY

Maintaining adequate skid resistance of pavement surfaces is a concern of highway and transportation officials. Unfortunately, Kentucky aggregates, as a whole, do not exhibit desirable long-term skid resistant qualities. Hence, high quality aggregates have been imported from outside the state, introducing excessive transportation costs.

Objectives of this study were 1) to identify active sources of native aggregates with varying histories of skid resistance performance; 2) to evaluate and correlate native aggregate characteristics, processing techniques, and other factors with skid resistance and surface mixture performance; and 3) to provide guidelines for implementation of research findings.

Fifty-five aggregate sources were studied. Limestone, sandstone, river gravel, and control aggregates (granite, traprock, and slag sources) made up the population of test materials.

Laboratory testing included specific gravity and absorption tests, Los Angeles Abrasion Tests, and the Kentucky Transportation Research Program Abrasion Test. The KTRP test measures the abrasiveness of an aggregate by totaling the weight loss a plastic cylinder incurs over time when placed in a container that has a small charge of the aggregate being evaluated.

Laboratory results were analyzed for correlations among themselves and for correlations with skid number data obtained from pavements containing aggregates involved in the study. No significant correlation could be found between any of the laboratory results and field skid numbers. This was particularly disturbing with reference to the KTRP test. It was thought that it could be used to adequately predict field skid performance. However, preliminary findings have shown no such relationship. It is recommended that the KTRP test be amended to provide a more defined weight loss over time to attempt to explain the behavior of an aggregate's skid resistance over time.

The KTRP test does yield two bits of valuable information. When fitting test data by means of a least squares approximation, a cumulative weight loss versus time curve is created. Taking the first derivative of the curve gives the time at which an aggregate begins to lose its abrasive qualities. The second derivative of the curve yields the rate of weight loss over time. This depicts a similar change in skid resistance associated with changing material characteristics. These results may be used to compare abrasive behavior of one aggregate to that of another.

INTRODUCTION

Limestone aggregates are abundant in Kentucky. Some problems have been encountered with the use of limestones in asphaltic concrete surfaces due to polishing of the aggregates. Considerable history has been developed that relates skid resistant characteristics of asphaltic concrete surfaces with age and/or the accumulation of traffic (1). In many situations, the performance has not been entirely satisfactory, and as a result, aggregates have been imported for use in skid resistant surface mixtures. Imported aggregates used with some degree of success include:

a) Iron Mountain Traprock,
b) Blast Furnace Slag, and
c) Granite.

These three aggregates have demonstrated satisfactory skid resistant histories during the course of their application and are accepted for use in Kentucky. Importation of aggregates has created some concern among transportation officials and generated renewed interest in utilization of native Kentucky aggregates for skid resistant surfaces.

Current procedures to evaluate skid resistant surfaces in Kentucky have involved the use of the locked-wheel trailer method (ASTM E 274) (2). This method of testing has been used successfully to evaluate skid resistance of in-service pavements. Unfortunately, this approach requires construction of pavement sections for each variable being evaluated. As a result, experimentation with native aggregates for skid resistant mixtures has been limited because of the availability of projects and the costs and liabilities associated with field experimentation. There is renewed interest in development of laboratory testing of aggregates and/or mixtures for evaluation of skid resistance performance and this study was conceived with the following general objectives:

(1) to identify and tabulate active sources of native aggregates with varying historical skid resistance performance;
(2) to evaluate and correlate native aggregate characteristics, processing techniques, and other factors with skid resistance and surface mixture performance; and
(3) to provide guidelines for implementation of research findings.

Forty-eight sources of aggregates considered to have potential applications as skid resistant mixtures were identified. Those materials were compared to seven sources used as control. Of the 55 sources, 45 were Kentucky aggregates and the remaining ten were imported (see Table 1). Laboratory evaluations of samples from those sources included specific gravity, absorption, Los Angeles abrasion, and a modified abrasion test referred to as the KTRP abrasion test (see Appendix A). A comprehensive literature review also was conducted to provide background information (see Appendix B).

LABORATORY TESTING

Fifty-five aggregate samples were included for testing. Aggregates tested, as shown in Table 1, included 31 limestones, 12 river gravels, 5 slags, 4 sandstones, and one sample each of granite, traprock, and expanded shale. Forty-five of the aggregate samples were from Kentucky quarries and the remaining were from out-of-state sources.

Samples were obtained by the Kentucky Department of Highways, Division of Materials, and delivered to the Kentucky Transportation Research Program (KTRP) in 80- to 100-pound bags. A dry sieve analysis was performed on each sample. Different size fractions were then used to reconstitute specimens to the proper size and gradation for tests to be performed. The tests included specific gravity and absorption, Los Angeles Abrasion, and the KTRP Abrasion Test. Insoluble residue tests were performed by the Division of Materials.

Specific gravity and absorption testing of coarse and fine aggregates were performed in accordance with Kentucky Methods KM 64-607 and KM 64-605, respectively. Results are summarized in Table 2. The Los Angeles Abrasion Test was performed in accordance with ASTM C-131, "Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine" (3). Results of this testing activity are contained in Table 4.

The KTRP Abrasion Test was conceived to assess an aggregate's abrasive and degradation characteristics due to mechanical handling. Results of the KTRP abrasion tests are contained in Table 4. The testing procedure is briefly described in the following paragraphs.

A 2,000-gram sample obtained in accordance with Kentucky Method KM 64-601, "Sampling of Aggregates for Use as Highway Materials", is placed

TABLE 1. IDENTIFICATION OF AGGREGATE SOURCES

SAMPLE NUMBER	QUARRY NAME	LOCATION	MATERIAL TYPE
1	MAYSVILLE MATERIALS	MAYSVILLE	RIVER GRAVEL
2	LAKE CITY MINING	LAKE CITY	RIVER GRAVEL
3*	AMERICAN MATERIAL	NEW MIAMI, OH	SLAG
4	KEN-TENN (LEONARD)	HICKORY	RIVER GRAVEL
5	HARROD CONCRETE AND STONE	FRANKFORT	LIMESTONE
6	REED CRUSHED STONE	GILBERTSVILLE	LIMESTONE (FLINTY)
7	MAYSVILLE MATERIAL	MAYSVILLE	RIVER GRAVEL
8	COLUMBUS SAND AND GRAVEL	COLUMBUS	RIVER GRAVEL
9	CUMBERLAND RIVER QUARRY	SMITHLAND	SANDSTONE
10*	AMERICAN MATERIALS	MIDDLETOWN, OH	SLAG
11	KEN MOR STONE, INC. (V)	OLIVE HILL	LIMESTONE (LEDGE #8)
12	ACME STONE CO.	OLIVE HILL	LIMESTONE (LEDGE #9)
13	ACME STONE CO.	OLIVE HILL	LIMESTONE (LEDGE #10)
14	HENDERSON SAND AND GRAVEL	HENDERSON	RIVER GRAVEL
15*	IRON MOUNTAIN TRAP ROCK	IRON MOUNTAIN, MO	TRAP ROCK
16	J. F. PACE CONSTRUCTION COMPANY	GLASGOW	LIMESTONE (LEDGE #3b)
17	MEDUSA AGGREGATES	BARDSTOWN	LIMESTONE
18	VULCAN MATERIALS	ELIZABETHTOWN	LIMESTONE (LEDGE #6)
19*	SOUTHERN STONE COMPANY	GODWIN, TN	SLAG
20*	HECKETT SLAG PRODUCTS	ASHLAND	SLAG
21	J. F. PACE CONSTRUCTION COMPANY	GLASGOW	LIMESTONE (LEDGE #2b)
22	J. F. PACE CONSTRUCTION COMPANY	GLASGOW	LIMESTONE (LEDGE #1b)
23*	VULCAN MATERIALS	ENKA, NC	GRANITE
24	TRI-COUNTY STONE, INC.	TOMKINSVILLE	LIMESTONE (LEDGE #1a)
25	MONTGOMERY AND COMPANY	KNOB LICK	LIMESTONE
26	GRAYSON COAL AND STONE	WATER GAP	SANDSTONE (BROWN)
27	GRAYSON COAL AND STONE	WATER GAP	SANDSTONE (GRAY)
28	WALKER CONSTRUCTION CO.	MT. STERLING	LIMESTONE
29	TRI-COUNTY SAND AND GRAVEL	JONESVILLE	RIVER GRAVEL
30*	INTERNATIONAL MILL SERVICE	MONROE, OH	SLAG
31	KENTUCKY SOLITE CORPORATION	BROOKS	EXPANDED SHALE
32	HOPKINSVILLE STONE CO.	HOPKINSVILLE	LIMESTONE (LEDGE #8abx)
33	HOPKINSVILLE STONE CO.	HOPKINSVILLE	LIMESTONE (CLASS K)
34	MAYSVILLE DREDGING	MAYSVILLE	RIVER GRAVEL (OPEN GRADE)
35	DRAVO CORPORATION	GEORGETOWN, PA	RIVER GRAVEL

TABLE 1. CONTINUED

SAMPLE NUMBER	QUARRY NAME	LOCATION	MATERIAL TYPE
36	ROGERS GROUP INC.	CUMBERLAND GAP, TN	LIMESTONE
37	KENTUCKY STONE CO.	FRANKLIN	LIMESTONE
38	PORTER BROWN LIMESTONE CO.	SPRINGFIELD, TN	LIMESTONE
39	ELKHORN STONE CO.	ELKHORN CITY	LIMESTONE
40	BULLITT COUNTY STONE CO.	SHEPHERDSVILLE	LIMESTONE
41	KENTUCKY STONE CO.	FLEMINGSBURG	LIMESTONE
42	MARTIN-MARIETTA	LOUISVILLE	RIVER GRAVEL
43	BOONESBORO QUARRIES	BOONESBORO	LIMESTONE
44	REED CRUSHED STONE CO.	GILBERTSVILLE	LIMESTONE (NON-FLINTY)
45	CUMBERLAND RIVER QUARRY	SMITHLAND	SANDSTONE
46	BOONE COUNTY SAND AND GRAVEL	BELLEVIEW	RIVER GRAVEL
47	WARD AND MONTGOMERY	LEBANON	LIMESTONE
48	KENTUCKY STONE COMPANY	CANTON	LIMESTONE (LEDGE #8)
49	KENTUCKY STONE COMPANY	CANTON	LIMESTONE (LEDGE #13)
50	KENTUCKY STONE COMPANY	CANTON	LIMESTONE (LEDGE #6)
51	M & M CONSTRUCTION CO.	NEW ALBANY, IN	RIVER GRAVEL
52	STANDARD SLAG COMPANY	CARTER CITY	LIMESTONE
53	MEDUSA AGGREGATES	PARK CITY	LIMESTONE (LEDGE #4)
54	KENTUCKY STONE COMPANY	BEATTYVILLE	LIMESTONE (LEDGE #6)
55	ELKHORN STONE COMPANY	ELKHORN CITY	LIMESTONE (LEDGE #21)

NOTE: *CONTROL AGGREGATES

in a cylindrical metal jar. A section of plastic pipe, for which the initial weight has been obtained, is placed in the metal jar with the aggregate. The jar is then rotated on a jar mill for 1 hour. Thereafter, the plastic pipe is removed from the jar, thoroughly cleaned and weighed. The plastic pipe is returned to the metal jar and the procedure is repeated again for another 1-hour cycle, a 2-hour cycle, another 2-hour cycle, and a 14-hour cycle. The plastic pipe is removed from the metal jar the end of each cycle, thoroughly cleaned, and weighed. At the end of the last cycle, the aggregate is removed from the metal jar at, wet sieved, and dried to a constant weight. The weight retained on each sieve is recorded to the nearest gram. The procedure for the Test of Aggregate Abrasiveness and Degradation (KTRP Abrasion Test) is outlined in Appendix B.

TABLE 2. SPECIFIC GRAVITY AND ABSORPTION RESULTS

TYPE OF MATERIAL	COARSE AGGREGATE				FINE AGGREGATE			
	SSD	OD	ASG	ABS	SSD	OD	ASG	ABS
1-R GRAV	2.58	2.54	2.65	1.7	2.49	2.41	2.62	3.3
2-R GRAV	2.24	2.08	2.49	7.9	2.29	2.11	2.58	8.7
3-SLAG	2.44	2.36	2.56	3.2	2.58	2.53	2.68	2.2
4-R GRAV	2.40	2.28	2.59	5.2	2.43	2.32	2.62	5.0
5-LSTONE	2.69	2.68	2.72	0.5	2.69	2.68	2.70	0.3
6-LSTONE	2.67	2.67	2.69	0.3	2.64	2.63	2.66	0.5
7-R GRAV	2.58	2.54	2.64	1.4	2.58	2.55	2.63	1.2
8-R GRAV	2.49	2.42	2.59	2.8	2.51	2.45	2.60	2.5
9-SSTONE	2.50	2.46	2.56	1.6	2.55	2.53	2.58	0.8
10-SLAG	2.36	2.25	2.54	5.0	2.55	2.47	2.69	3.4
11-LSTONE	2.69	2.68	2.71	0.5	2.69	2.67	2.71	0.5
12-LSTONE	2.69	2.67	2.71	0.4	2.68	2.68	2.69	0.2
13-LSTONE	2.67	2.66	2.70	0.7	2.67	2.65	2.70	0.8
14-R GRAV	2.55	2.52	2.60	1.2	2.70	2.65	2.79	1.8
15-T ROCK	2.89	2.88	2.92	0.5	2.87	2.80	3.00	2.5
16-LSTONE	2.66	2.65	2.68	0.5	2.63	2.58	2.71	1.8
17-LSTONE	2.69	2.65	2.78	1.8	2.73	2.70	2.80	1.3
18-LSTONE	2.57	2.49	2.72	3.4	2.58	2.51	2.71	2.9
19-SLAG	2.28	2.20	2.40	3.8	2.65	2.56	2.79	3.2
20-SLAG	2.50	2.46	2.56	1.6	2.59	2.53	2.70	2.6
21-LSTONE	2.45	2.31	2.67	5.7	2.45	2.30	2.72	6.7
22-LSTONE	2.52	2.42	2.69	4.3	2.70	2.60	2.88	3.7
23-GRANIT	2.70	2.69	2.71	0.4	2.69	2.69	2.71	0.4
24-LSTONE	2.66	2.59	2.78	2.7	2.80	2.74	2.91	2.1
25-LSTONE	2.67	2.66	2.70	0.5	2.67	2.66	2.68	0.3
26-SSTONE	2.41	2.28	2.61	5.5	2.54	2.47	2.64	2.6
27-SSTONE	2.37	2.21	2.61	6.9	2.63	2.56	2.75	2.7
28-LSTONE	2.64	2.61	2.69	1.1	2.66	2.64	2.70	0.9
29-R GRAV	2.60	2.59	2.62	0.5	2.58	2.57	2.59	0.4
30-SLAG	3.35	3.29	3.51	1.9	3.52	3.48	3.63	1.2
31-XSHALE	1.49	1.34	1.58	11.0	1.72	1.53	1.87	11.9
32-LSTONE	2.40	2.26	2.63	6.2	2.45	2.30	2.70	6.4
33-LSTONE	2.69	2.68	2.70	0.3	2.65	2.58	2.79	3.0
34-R GRAV	2.58	2.53	2.67	2.0	2.49	2.40	2.64	3.8
35-R GRAV	2.55	2.47	2.68	3.1	2.42	2.28	2.65	6.2
36-LSTONE	2.70	2.68	2.73	0.7	2.72	2.69	2.77	1.0
37-LSTONE	2.67	2.65	2.72	1.0	2.65	2.61	2.72	1.5
38-LSTONE	2.62	2.58	2.70	1.7	2.57	2.53	2.64	1.5
39-LSTONE	2.63	2.61	2.67	0.8	2.65	2.63	2.70	1.0
40-LSTONE	2.67	2.61	2.77	2.2	2.70	2.60	2.87	3.5
41-LSTONE	2.67	2.64	2.72	1.1	2.68	2.65	2.73	1.1
42-R GRAV	2.65	2.60	2.73	1.8	2.65	2.61	2.72	1.5
43-LSTONE	2.71	2.69	2.75	0.8	2.72	2.69	2.77	1.0
44-LSTONE	2.66	2.64	2.70	0.8	2.65	2.63	2.70	1.0
45-SSTONE	2.49	2.45	2.55	1.6	2.49	2.46	2.55	1.4
46-R GRAV	2.63	2.56	2.77	3.0	2.69	2.65	2.75	1.3

TABLE 2. CONTINUED

TYPE OF MATERIAL	COARSE AGGREGATE SSD	OD	ASG	ABS	FINE AGGREGATE SSD	OD	ASG	ABS
47-LSTONE	2.67	2.64	2.73	1.3	2.57	2.54	2.62	1.1
48-LSTONE	2.68	2.67	2.70	0.4	2.67	2.65	2.71	0.8
49-LSTONE	2.68	2.66	2.70	0.6	2.65	2.64	2.68	0.5
50-LSTONE	2.68	2.66	2.71	0.6	2.66	2.64	2.69	0.6
51-R GRAV	2.67	2.63	2.74	1.5	2.68	2.64	2.76	1.6
52-LSTONE	2.64	2.61	2.69	1.1	2.62	2.57	2.71	1.9
53-LSTONE	2.64	2.62	2.67	0.7	2.70	2.67	2.76	1.3
54-LSTONE	2.65	2.64	2.67	0.4	2.67	2.66	2.70	0.5
55-LSTONE	2.67	2.66	2.68	0.3	2.67	2.66	2.70	0.6

KEY TO ABBREVIATIONS

AGGREGATES

R GRAV -- RIVER GRAVEL
SLAG -- SLAG
LSTONE -- LIMESTONE
SSTONE -- SANDSTONE
T ROCK -- TRAPROCK
GRANIT -- GRANITE
XSHALE -- EXPANDED SHALE

SPECIFIC GRAVITY AND ABSORPTION TESTS

SSD -- SATURATED SURFACE DRY
OD -- OVEN DRY
ASG -- APPARENT SPECIFIC GRAVITY
ABS -- PERCENT ABSORPTION

The percent weight loss of the plastic pipe (KTRP Percent Loss) is determined by subtracting the final weight of the plastic pipe from the initial weight, dividing by the initial weight, and multiplying by 100. The KTRP Percent Loss is an indicator of an aggregate's abrasiveness.

Gradations of the aggregate sample before and after the test are plotted on the same gradation chart. The area between the two curves is an indication of the aggregate's susceptibility to mechanical breakdown (the larger the area, the more breakdown).

The cumulative weight loss of the plastic pipe at each phase of the test is plotted as a function of time. The rate of change of aggregate polishing and the time at which maximum polishing is expected to occur may be calculated by fitting a quadratic curve through the data points and taking the first and second derivatives of that equation. The area under the fitted loss curve also is an indication of the aggregate's abrasiveness (the larger the area, the more abrasive the aggregate).

Insoluble residue test results were obtained from the Division of Materials for each of the samples for correlation with results of the other tests. The insoluble residue test is an indicator of an aggregate's resistance to polishing and is used by some agencies for acceptance purposes.

TEST RESULTS AND DISCUSSION

SPECIFIC GRAVITY AND ABSORPTION

All samples were tested in accordance with KM 64-605-85 (Specific Gravity and Absorption of Fine Aggregate) and KM 64-607-79 (Specific Gravity and Absorption of Coarse Aggregates). Results are summarized in Tables 2 and 3, respectively. No relationships appear to exist between apparent specific gravity and absorption. On the average, control samples (slags, traprock, and granite) had the highest apparent specific gravity and the sandstones had the lowest apparent specific gravities. Absorption characteristics were not as consistent. Limestones exhibited the lowest absorption values for both fine and coarse aggregates. Sandstones had the highest absorptive readings of the coarse aggregates tested. River gravels had the highest absorptions for the fine aggregates.

LOS ANGELES ABRASION TEST

The Los Angeles Abrasion Test was performed on all samples to determine how well the aggregates resist a repetitive destructive charge. Limestones, as a group, yielded the lowest average percent loss (24.9 ± 9.3% loss). Sandstones, as would be expected, had the highest average percent loss (69.4 ± 33.2% loss). The average percent losses for river gravels and controls were slightly greater than for limestones. Results of all tests and a breakdown by aggregate type are contained in Tables 4 and 5, respectively.

KTRP ABRASION TEST

Percent Loss

The KTRP Abrasion Test Percent Loss is an indicator of the abrasiveness of an aggregate. The percent loss is expressed as the difference between the initial weight of a plastic cylindrical specimen minus its weight after the test, divided by its initial weight, and multiplied by 100. The higher the percent loss, the more abrasive the aggregate and the better its skid resistance potential. Limestones, as a whole, had the highest KTRP Abrasion Test Percent Loss (2.96 ± 0.86%), while the control aggregates had lower values (1.64 ± 1.09%). Results for the entire data set as well as a breakdown by aggregate type are summarized in Tables 4 and 6, respectively.

Area between Gradation Curves

The area between the gradation curves (the initial and final gradation curves) is a measure of the susceptibility of an aggregate to degradation. A large value suggests the aggregate is susceptible to large degradations of its mineral macrostructure and thus would not be considered a good aggregate for use in skid resistant surfaces because of this breakdown. Areas under the curves were estimated by the Simpson approximation.

TABLE 3. SPECIFIC GRAVITY AND ABSORPTION: GROUPING BY AGGREGATE TYPE

AGGREGATE TYPE			COARSE AGGREGATE	FINE AGGREGATE
RIVER GRAVELS	APPARENT SPECIFIC GRAVITY	RANGE	2.49 TO 2.77	2.58 TO 2.79
		MEAN ± SDEV	2.65 ± 0.08	2.66 ± 0.07
	PERCENT ABSORPTION	RANGE	0.5 TO 7.9	0.4 TO 8.7
		MEAN ± SDEV	2.7 ± 2.0	3.1 ± 2.5
LIMESTONES	APPARENT SPECIFIC GRAVITY	RANGE	2.63 TO 2.78	2.62 TO 2.91
		MEAN ± SDEV	2.71 ± 0.03	2.73 ± 0.07
	PERCENT ABSORPTION	RANGE	0.3 TO 6.2	0.2 TO 6.7
		MEAN ± SDEV	1.4 ± 1.4	1.6 ± 1.6
SANDSTONES	APPARENT SPECIFIC GRAVITY	RANGE	2.55 TO 2.61	2.55 TO 2.75
		MEAN ± SDEV	2.58 ± 0.03	2.63 ± 0.09
	PERCENT ABSORPTION	RANGE	1.6 TO 6.9	0.8 TO 2.7
		MEAN ± SDEV	3.9 ± 2.7	1.9 ± 0.9
CONTROLS	APPARENT SPECIFIC GRAVITY	RANGE	2.40 TO 3.51	2.68 TO 3.63
		MEAN ± SDEV	2.74 ± 0.38	2.89 ± 0.35
	PERCENT ABSORPTION	RANGE	0.4 TO 5.0	0.4 TO 3.4
		MEAN ± SDEV	2.3 ± 1.7	2.2 ± 1.1

TABLE 4. ABRASION TEST RESULTS

TYPE OF MATERIAL*	LOS ANGELES ABRASION TEST (% LOSS)	KTRP ABRASION TEST (% LOSS)	AREA BETWEEN GRADATION CURVES	SKID NUMBER	ADJUSTED SKID ** NUMBER
1-R GRAV	24.6	1.37	21.9	46	66
2-R GRAV	17.0	2.39	33.5	43	39
3-SLAG	39.6	1.15	45.0		
4-R GRAV	19.8	3.62	16.6	42	49
5-LSTONE	20.4	3.18	20.7	43	61
6-LSTONE	16.0	3.68	27.1	43	39
7-R GRAV	19.2	3.24	10.7		
8-R GRAV	18.1	2.41	8.6		
9-SSTONE	40.3	1.17	41.6		
10-SLAG	39.6	0.50	113.3	44	48
11-LSTONE	28.2	1.73	26.9		
12-LSTONE	23.0	1.95	40.2		
13-LSTONE	29.7	3.34	35.8		
14-R GRAV	16.6	3.12	5.2	39	31
15-T ROCK	14.9	3.77	22.7	41	43
16-LSTONE	19.5	2.98	24.5		
17-LSTONE	26.2	4.08	40.4	40	35
18-LSTONE	25.5	2.11	34.2		
19-SLAG	37.5	1.70	71.5	39	37
20-SLAG	31.8	0.98	34.0	40	39
21-LSTONE	37.7	1.44	62.1		
22-LSTONE	26.7	4.03	53.1		
23-GRANIT	29.6	1.16	46.6	47	47
24-LSTONE	19.9	2.77	39.3		
25-LSTONE	19.9	3.48	37.0		
26-SSTONE	97.5	2.07	180.7		
27-SSTONE	98.9	1.79	212.8		
28-LSTONE	30.1	2.75	40.1	47	47
29-R GRAV	30.5	1.30	19.8	45	45
30-SLAG	16.4	2.24	18.2		
31-XSHALE	21.4	1.14	33.7		
32-LSTONE	64.5	0.92	133.4	39	48
33-LSTONE	18.6	3.76	12.8	39	20
34-R GRAV	62.5	1.43	11.3		
35-R GRAV	28.6	1.55	18.7		
36-LSTONE	21.6	3.54	78.2		
37-LSTONE	27.4	3.70	32.8		
38-LSTONE	14.4	2.30	16.3		
39-LSTONE	19.8	3.01	18.4		
40-LSTONE	24.3	2.49	27.5		
41-LSTONE	31.5	2.58	45.7		
42-R GRAV	20.0	2.74	43.0	45	49
43-LSTONE	19.8	2.54	21.2	52	57
44-LSTONE	32.6	2.58	35.1		
45-SSTONE	41.0	1.58	12.4		
46-R GRAV	25.6	1.06	66.5		
47-LSTONE	29.0	2.45	61.2		

TABLE 4. CONTINUED

TYPE OF MATERIAL*	LOS ANGELES ABRASION TEST (% LOSS)	KTRP ABRASION TEST (% LOSS)	AREA BETWEEN GRADATION CURVES	SKID NUMBER	ADJUSTED SKID ** NUMBER
48-LSTONE	14.5	1.80	7.0		
49-LSTONE	19.7	4.12	16.3		
50-LSTONE	17.9	3.11	15.0		
51-R GRAV	21.7	4.38	41.1		
52-LSTONE	27.8	4.26	41.5		
53-LSTONE	27.0	3.76	22.2		
54-LSTONE	21.4	3.53	15.2		
55-LSTONE	17.8	3.80	11.2		

NOTE: * R GRAV — RIVER GRAVEL
SLAG — SLAG
LSTONE — LIMESTONE
SSTONE — SANDSTONE
T ROCK — TRAPROCK
GRANIT — GRANITE
XSHALE — EXPANDED SHALE

River gravels exhibited the lowest values (24.7 ± 18.0) while the sandstones had the highest average area (111.9 ± 99.6). Sandstones have large grain sizes, and when individual grains are eroded from the sandstone particle, the individual particles continue to abrade. Thus, the area between curves for sandstones is not an indicator of how abrasive the aggregate is. Results of the entire data set along with a breakdown by aggregate type are available in Tables 4 and 6, respectively.

Derivatives of Percent Loss Curves

Smooth curves were constructed to produce a more complete description of the abrasive characteristics of the aggregates. The first derivative of the loss curve was set equal to zero to compute the theoretical time at which the plastic cylinder used in the test would be worn away or the time the aggregate becomes polished to the extent it no longer abrades the cylinder. A short time period indicates the aggregate is very abrasive, or the aggregate has polished quickly and no longer abrades the cylinder. When studying the first derivative, some judgment must be used. A short time period for a chert would indicate rapid polishing of the aggregate. For a sandstone, rapid abrasion of the

TABLE 5. LOS ANGELES ABRASION TEST:
GROUPING BY AGGREGATE TYPE

AGGREGATE TYPE		PERCENT LOSS
RIVER GRAVELS	RANGE	16.6 TO 62.5
	MEAN ± SDEV	25.3 ± 12.5
LIMESTONES	RANGE	14.4 TO 64.5
	MEAN ± SDEV	24.9 ± 9.3
SANDSTONES	RANGE	40.3 TO 98.9
	MEAN ± SDEV	69.4 ± 33.2
CONTROLS	RANGE	14.9 TO 39.6
	MEAN ± SDEV	29.9 ± 10.4

TABLE 6. KTRP ABRASION TEST:
GROUPING BY AGGREGATE TYPE

AGGREGATE TYPE		PERCENT LOSS	AREA BETWEEN GRADATION CURVES
RIVER GRAVELS	RANGE	1.06 TO 4.38	5.2 TO 66.5
	MEAN ± SDEV	2.38 ± 1.06	24.7 ± 18.0
LIMESTONES	RANGE	0.92 TO 4.26	7.0 TO 133.4
	MEAN ± SDEV	2.96 ± 0.86	35.2 ± 24.5
SANDSTONES	RANGE	1.17 TO 2.07	12.4 TO 212.8
	MEAN ± SDEV	1.65 ± 0.38	111.9 ± 99.6
CONTROLS	RANGE	0.50 TO 3.77	18.2 TO 113.3
	MEAN ± SDEV	1.64 ± 1.09	50.2 ± 32.9

cylinder (a short time period for the first derivative) indicates the aggregate is no longer skid resistant.

Three samples yielded very large times in comparison to those of the other 52 samples. Those three sources were all limestones. Average values for the first derivative and second derivative were computed with and without the three limestones for the limestone group only and for the overall data set. Sandstones displayed the shortest average time (24.7 ± 7.0 hours) and the limestones with and without the three outliers had the longest times (195.2 ± 350.8 hours and 48.8 ± 5.6 hours, respectively). Tables 7 and 8 include results of the entire data set and group by aggregate type.

The second derivative of the loss curve is an indicator of the rate of change of percent loss with time. It also may predict a similar change in skid resistance under traffic. A large number indicates rapid wear of the plastic cylinder. As noted previously, samples from three limestone sources had results which were quite different from the remaining data. Average values with and without the three outliers were computed. The sandstones, as a group, exhibited the highest average change in wear rate (-33.6 ± -11.0) while the control aggregates had the lowest average change in rate (-18.6 ± -10.3). Tables 7 and 8 include results of individual aggregates as well as a breakdown by aggregate type.

The interpretation of the derivatives is very important. A second degree polynomial was used to describe the percent-loss curves:

$$\text{Percent Loss} = Ax^2 + Bx + C, \tag{1}$$

where A, B, and C are constants of regression. The first derivative is

$$d(\text{percent loss})'/dx' = 2Ax + B. \tag{2}$$

The second derivative is of the following form:

$$d(\text{percent loss})''/dx'' = 2A. \tag{3}$$

A large positive value of B indicates the material is very abrasive. A large negative value of A indicates the material may not remain abrasive very long. This may be true for limestones, cherts, and high silica gravels. For sandstones, it would mean the cylinder is wearing away rapidly. A large value for B and a small negative value for A means the material is very abrasive and will remain abrasive for a long time.

A low value of B means the material is not very abrasive. A large positive value of B indicates an abrasive material. A small negative value of A would mean the material would maintain this value of abrasiveness for a longer time.

TABLE 7. EQUATIONS OF PERCENT LOSS CURVES

SAMPLE NUMBER	TYPE OF MATERIAL	EQUATION OF FITTED LOSS CURVE*	X:Y'(X)=0 (HRS)	Y"*10^4 (G/HR)
1	RIVER GRAVEL	$Y = -0.00063617X^2 + 0.05246045X - 60.00196085$	41.2	-12.7
2	RIVER GRAVEL	$Y = 0.00036505X^2 + 0.03703106X - 0.01382725$	NPP	NPP
3	SLAG	$Y = -0.00092839X^2 + 0.05286077X - 0.01411753$	28.5	-18.6
4	RIVER GRAVEL	$Y = -0.00073066X^2 + 0.08150088X - 0.02494597$	55.8	-14.6
5	LIMESTONE	$Y = 0.00101644X^2 + 0.07623620X - 0.00947962$	NPP	NPP
6	LIMESTONE	$Y = -0.00109474X^2 + 0.08827438X - 0.01695812$	40.3	-21.9
7	RIVER GRAVEL	$Y = -0.00122456X^2 + 0.08312619X - 0.01588031$	33.9	-24.5
8	RIVER GRAVEL	$Y = -0.00152293X^2 + 0.07512600X - 0.01912777$	24.7	-30.5
9	SANDSTONE	$Y = -0.00241186X^2 + 0.08390784X + 0.00085591$	17.4	-48.2
10	SLAG	$Y = -0.00143995X^2 + 0.04383166X - 0.00962749$	15.2	-28.8
11	LIMESTONE	$Y = -0.00028926X^2 + 0.05616188X + 0.00350149$	97.1	-5.8
12	LIMESTONE	$Y = -0.00073756X^2 + 0.07143011X + 0.00638015$	48.4	-14.8
13	LIMESTONE	$Y = -0.00338347X^2 + 0.16170345X + 0.09768978$	23.9	-67.7
14	RIVER GRAVEL	$Y = -0.00093016X^2 + 0.07594995X - 0.02122977$	40.8	-18.6
15	TRAPROCK	$Y = -0.00096435X^2 + 0.08789721X - 0.02238848$	45.6	-19.3
16	LIMESTONE	$Y = 0.00333065X^2 + 0.00232974X + 0.05698792$	NPP	NPP
17	LIMESTONE	$Y = -0.00008276X^2 + 0.12175503X + 0.00725166$	735.6	-1.7
18	LIMESTONE	$Y = 0.00046962X^2 + 0.05244836X + 0.00773681$	NPP	NPP
19	SLAG	$Y = -0.00166566X^2 + 0.08155479X - 0.01040734$	24.5	-33.3
20	SLAG	$Y = -0.00021514X^2 + 0.03159642X - 0.00360575$	73.4	-4.3
21	LIMESTONE	$Y = -0.00098076X^2 + 0.05965509X + 0.01316258$	30.4	-19.6
22	LIMESTONE	$Y = 0.00038688X^2 + 0.10083131X + 0.00347571$	NPP	NPP
23	GRANITE	$Y = -0.00087778X^2 + 0.04909824X + 0.00279862$	28.0	-17.6
24	LIMESTONE	$Y = -0.00028900X^2 + 0.05618769X - 0.01617386$	97.2	-5.8
25	LIMESTONE	$Y = 0.00059458X^2 + 0.05324858X - 0.02702280$	NPP	NPP
26	SANDSTONE	$Y = -0.00137611X^2 + 0.08384178X + 0.01828270$	30.5	-27.5
27	SANDSTONE	$Y = -0.00116561X^2 + 0.07227703X + 0.02126851$	31.0	-23.3
28	LIMESTONE	$Y = 0.00221546X^2 + 0.03065659X + 0.00773291$	NPP	NPP
29	RIVER GRAVEL	$Y = -0.00100991X^2 + 0.05587482X + 0.00971006$	27.7	-20.2
30	SLAG	$Y = -0.00040796X^2 + 0.04936158X - 0.01725627$	60.5	-8.2
31	EXPANDED SHALE	$Y = 0.00038708X^2 + 0.02739562X - 0.01926843$	NPP	NPP
32	LIMESTONE	$Y = -0.00171924X^2 + 0.05695618X + 0.00591630$	16.6	-34.4
33	LIMESTONE	$Y = 0.00066128X^2 + 0.08202999X + 0.00445847$	NPP	NPP
34	RIVER GRAVEL	$Y = -0.00135407X^2 + 0.06076252X + 0.02059481$	22.4	-27.1
35	RIVER GRAVEL	$Y = -0.00098506X^2 + 0.05948125X + 0.00086368$	30.2	-19.7
36	LIMESTONE	$Y = -0.00008769X^2 + 0.08139499X + 0.00773048$	464.1	-1.8

TABLE 7. CONTINUED

SAMPLE NUMBER	TYPE OF MATERIAL	EQUATION OF FITTED LOSS CURVE*	X:Y'(X)=0 (HRS)	Y"*10^4 (G/HR)
37	LIMESTONE	$Y = 0.00085915X^2 + 0.08193729X + 0.00097862$	NPP	NPP
38	LIMESTONE	$Y = -0.00154719X^2 + 0.09448306X - 0.00021520$	30.5	-30.9
39	LIMESTONE	$Y = 0.00053186X^2 + 0.06892125X + 0.01748239$	NPP	NPP
40	LIMESTONE	$Y = -0.00134755X^2 + 0.0944696X + 0.01322762$	35.1	-27.0
41	LIMESTONE	$Y = 0.00112514X^2 + 0.04655301X + 0.00021740$	NPP	NPP
42	RIVER GRAVEL	$Y = 0.00002149X^2 + 0.07651832X - 0.0155485$	NPP	NPP
43	LIMESTONE	$Y = -0.00100943X^2 + 0.09225463X + 0.01711877$	45.7	-20.2
44	LIMESTONE	$Y = 0.00170818X^2 + 0.03817527X + 0.00456442$	NPP	NPP
45	SANDSTONE	$Y = -0.00177491X^2 + 0.07148274X + 0.00864036$	20.1	-35.5
46	RIVER GRAVEL	$Y = 0.00074668X^2 + 0.01182070X - 0.00124192$	NPP	NPP
47	LIMESTONE	$Y = 0.00140858X^2 + 0.03531642X + 0.01294888$	NPP	NPP
48	LIMESTONE	$Y = -0.00066648X^2 + 0.05716963X + 0.00568197$	42.9	-13.3
49	LIMESTONE	$Y = 0.00032889X^2 + 0.09840105X - 0.00089793$	NPP	NPP
50	LIMESTONE	$Y = -0.00089244X^2 + 0.09762832X + 0.00053021$	54.7	-17.9
51	RIVER GRAVEL	$Y = 0.00046667X^2 + 0.09620806X - 0.00605746$	NPP	NPP
52	LIMESTONE	$Y = 0.00036061X^2 + 0.09898605X + 0.01053189$	NPP	NPP
53	LIMESTONE	$Y = -0.00081763X^2 + 0.11803096X + 0.00277717$	72.2	-16.4
54	LIMESTONE	$Y = -0.00003714X^2 + 0.09573341X - 0.00191356$	1288.8	-0.7
55	LIMESTONE	$Y = 0.00036664X^2 + 0.09054403X + 0.01089090$	NPP	NPP

NOTE: * X - TIME AT WHICH MAXIMUM POLISHING OF THE PLASTIC CYLINDER OCCURS (HOURS)

X:Y'(X)=0 - TIME FOR FIRST DERIVATIVE EQUAL TO ZERO (HOURS)

Y - WEIGHT LOSS OF THE PLASTIC CYLINDER (GRAMS)

Y"*10^4 - RATE OF CHANGE OF PERCENT WEIGHT LOSS OF THE PLASTIC CYLINDER WITH TIME (GRAMS PER HOUR)

NPP - RESULT NOT PHYSICALLY POSSIBLE

INSOLUBLE RESIDUE

Insoluble residue tests were performed on all 55 samples in accordance with KM-64-223-86 (Insoluble Residue in Carbonate Aggregates). According to these tests, the river gravel group, on the average, had the best results (85 ± 26%) and the limestone group had the worst results (15 ± 15%).

TABLE 8. CHARACTERISTICS OF LOSS CURVES:
GROUPING BY AGGREGATE TYPE

AGGREGATE TYPE		X:Y'(X)=0 (HRS)	Y"*10^4 (G/HR)
RIVER GRAVELS	RANGE	22.4 TO 55.8	-12.7 TO -30.5
	MEAN ± SDEV	34.6 ± 11.8	-21.0 ± -6.1
LIMESTONES	RANGE	16.5 TO 1288.8	-0.7 TO -67.7
	MEAN ± SDEV	195.2 ± 350.9	-18.7 ± -16.7
LIMESTONES [1]	RANGE	16.6 TO 97.2	-5.8 TO -67.7
	MEAN ± SDEV	48.8 ± 25.7	-22.7 ± -15.9
SANDSTONES	RANGE	17.4 TO 31.0	-23.3 TO -48.2
	MEAN ± SDEV	24.8 ± 7.0	-33.6 ± -11.0
CONTROLS	RANGE	15.2 TO 73.4	-4.3 TO -33.3
	MEAN ± SDEV	39.4 ± 21.2	-18.6 ± -10.3

NOTE: X:Y'(X)=0 - TIME FOR FIRST DERIVATIVE EQUAL TO ZERO (HOURS)

Y"*10^4 - RATE OF CHANGE OF PERCENT WEIGHT LOSS OF THE PLASTIC PIPE WITH TIME (GRAMS PER HOUR)

[1] - THREE LIMESTONE DATA POINTS WERE OMITTED

This test is performed to determine the amount of insoluble noncarbonate material in a carbonate aggregate. The insoluble residue materials created from these tests were not sized or examined petrographically. Results for individual samples as well as a breakdown by aggregate type are contained in Tables 9 and 10, respectively.

CORRELATIONS

A large number of correlations were performed. Linear, quadratic, and cubic models of analyses were used to obtain the best correlation of the data set. A complete listing of all correlations that were performed along with regression coefficients is contained in Table 11.

Correlations have been grouped into three categories: 1) Los Angeles Abrasion Test results versus KTRP Abrasion Test results (for example, KTRP Percent Loss versus Area between Gradation Curves), 2) KTRP Abrasion Test results versus skid number (Figure 1), and 3) KTRP Abrasion Test results versus skid number adjusted for pavement age and traffic accumulation (Figure 2).

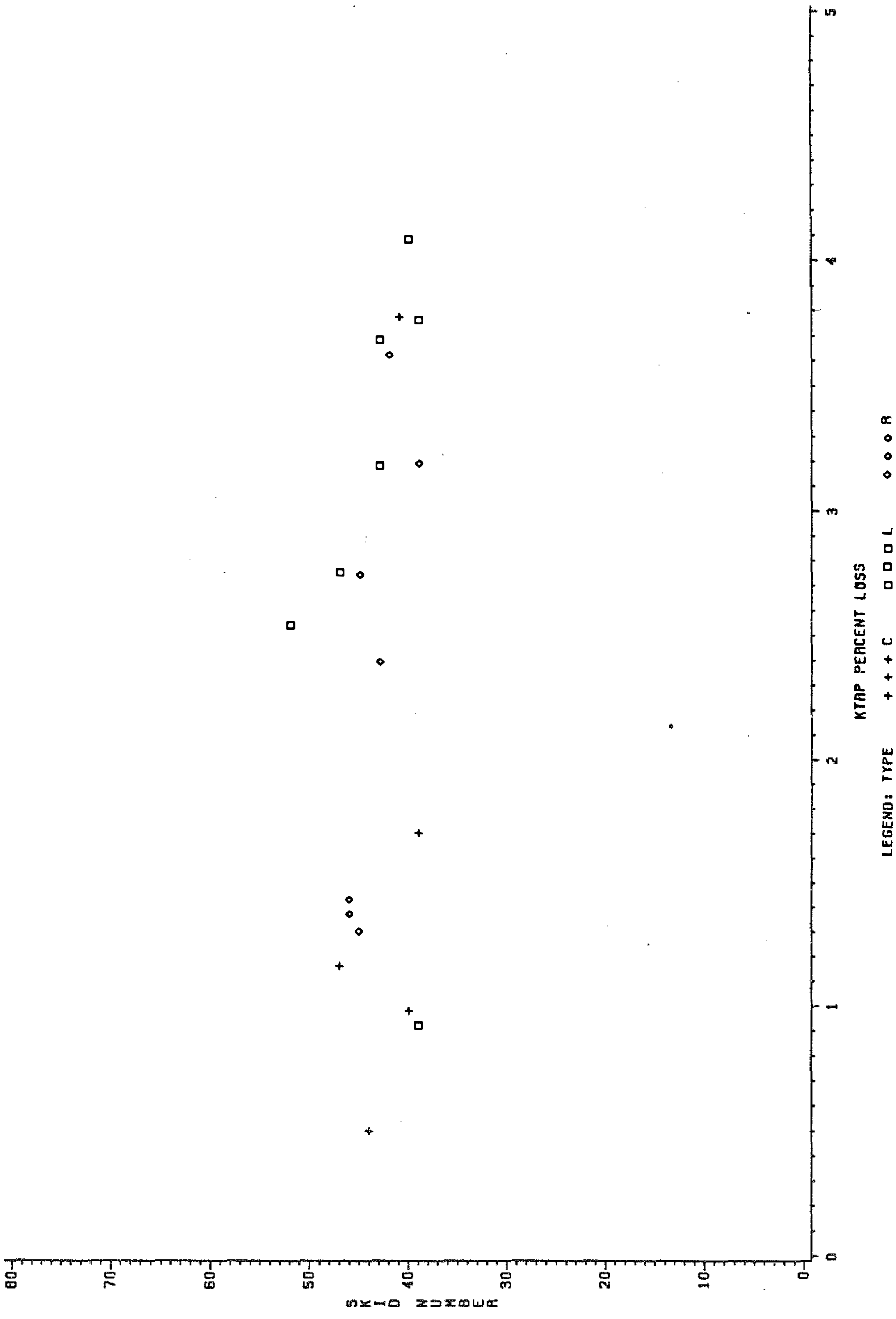

Figure 1. Skid Number versus KTRP Percent Loss

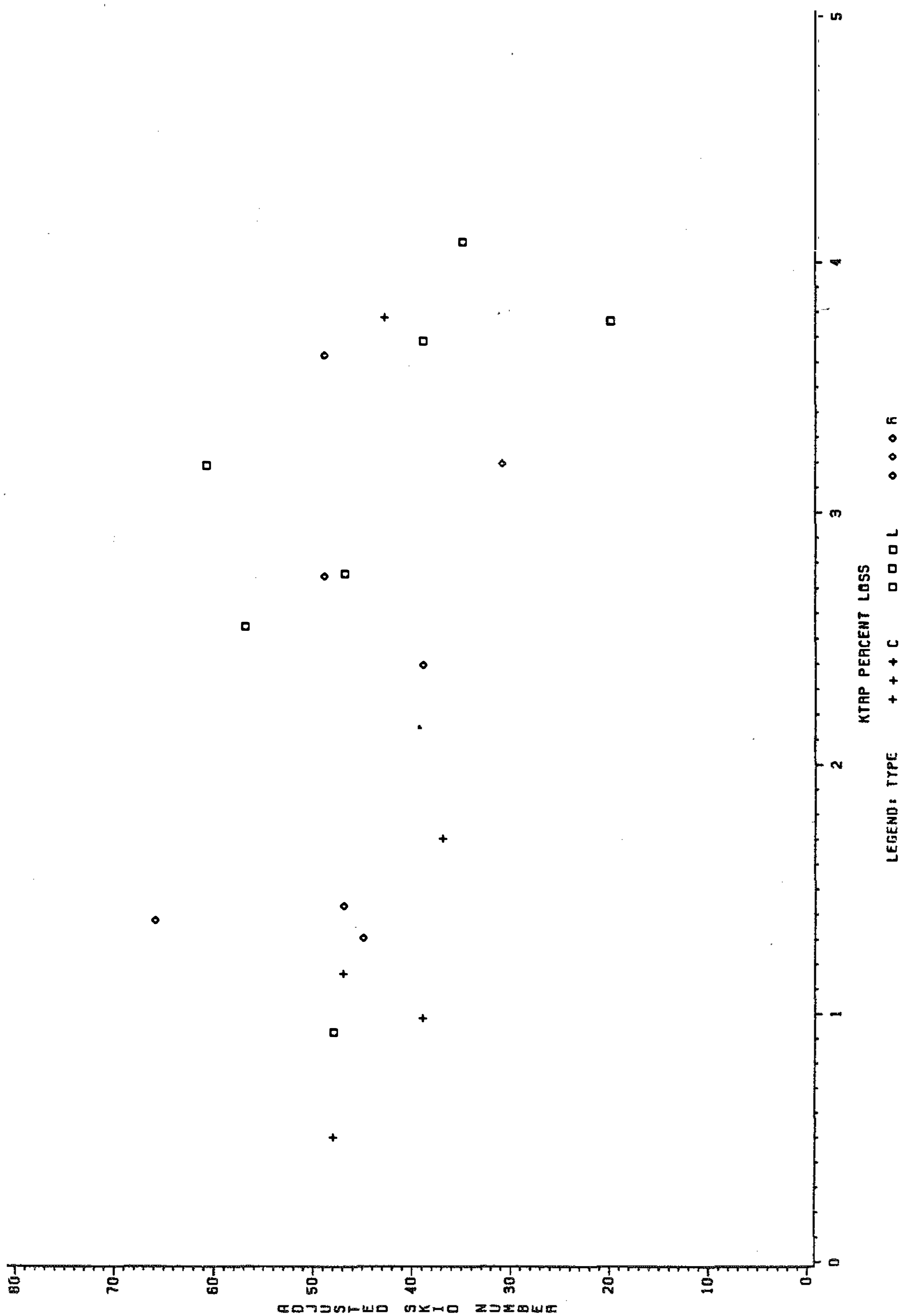

Figure 2. Adjusted Skid Number versus KTRP Percent Loss

TABLE 9. INSOLUBLE RESIDUE RESULTS

TYPE OF MATERIAL*	INSOLUBLE RESIDUE (PERCENT)	SKID NUMBER	ADJUSTED SKID NUMBER	TYPE OF MATERIAL*	INSOLUBLE RESIDUE (PERCENT)	SKID NUMBER	ADJUSTED SKID NUMBER
1-R GRAV	96	46	66	29-R GRAV	100	45	45
2-R GRAV	100	43	39	30-SLAG	45		
3-SLAG	41			31-XSHALE	98		
4-R GRAV	95	42	49	32-LSTONE	15	39	48
5-LSTONE	2	43	61	33-LSTONE	10	39	20
6-LSTONE	22	43	39	34-R GRAV	97		
7-R GRAV	96			35-R GRAV	88		
8-R GRAV	96			36-LSTONE	3		
9-SSTONE	99			37-LSTONE	1		
10-SLAG	39	44	48	38-LSTONE	71		
11-LSTONE	14			39-LSTONE	10		
12-LSTONE	8			40-LSTONE	7		
13-LSTONE	27			41-LSTONE	1		
14-R GRAV	94	39	31	42-R GRAV	33	45	49
15-T ROCK	83	41	43	43-LSTONE	10	52	57
16-LSTONE	23			44-LSTONE	8		
17-LSTONE	0	40	35	45-SSTONE	99		
18-LSTONE	47			46-R GRAV	27		
19-SLAG	57	39	37	47-LSTONE	15		
20-SLAG	54	40	39	48-LSTONE	19		
21-LSTONE	23			49-LSTONE	14		
22-LSTONE	23			50-LSTONE	16		
23-GRANIT	94	47	47	51-R GRAV	93		
24-LSTONE	32			52-LSTONE	9		
25-LSTONE	8			53-LSTONE	14		
26-SSTONE	97			54-LSTONE	6		
27-SSTONE	13			55-LSTONE	19		
28-LSTONE	1	47	47				

NOTE: *R GRAV — RIVER GRAVEL
SLAG — SLAG
LSTONE — LIMESTONE
SSTONE — SANDSTONE
T ROCK — TRAPROCK
GRANIT — GRANITE
XSHALE — EXPANDED SHALE

** Skid numbers adjusted for age of pavement (Figure 6, Pg 9, "Skid Resistance Studies in Kentucky (An Overview - 1974)," Research Report 399, Division of Research, Kentucky Department of Transportation, September 1974.

Linear, quadratic, and cubic models of fit were applied in all correlation analyses. Other models such as semi-log and log-log also were used. In those trials, however, correlation coefficients produced were lower than their previous counterparts. Results of semi-log and log-log fittings have not been tabulated.

TABLE 10. INSOLUBLE RESIDUE:
GROUPING BY AGGREGATE TYPE

AGGREGATE TYPE		INSOLUBLE RESIDUE (PERCENT)
RIVER GRAVELS	RANGE	27 TO 100
	MEAN ± SDEV	85 ± 26
LIMESTONES	RANGE	0 TO 71
	MEAN ± SDEV	15 ± 15
SANDSTONES	RANGE	13 TO 99
	MEAN ± SDEV	77 ± 42
CONTROLS	RANGE	39 TO 94
	MEAN ± SDEV	59 ± 21

The correlations indicated little if any evidence of a relationship between 1) abrasion varibles, 2) abrasion varibles and skid number, and 3) abrasion varibles and adjusted skid number. There are many factors that may explain the lack of evident relationships:

1) inadequate number of sources for each aggregate group,
2) too few variables taken into account to adequately describe the aggregates' physical characteristics,
3) only 19 skid test sections matched the 55 aggregate sources used in the study,
4) test sections had similar skid numbers,
5) all test sections were relatively new chronologically but have variable levels of traffic accumulation,
6) an absence of a skid history for the test sections, and
7) variable mixture designs.

Four types of aggregate were tested as part of this study. There were 31 limestone sources, 12 river gravel sources, 7 control sources (consisting of 5 slag sources, 1 traprock source, and 1 granite sources), and 4 sandstone sources. With the possible exception of the limestone group, there were not sufficient samples in any group to provide an indication of a relationship between varibles.

TABLE 11. CORRELATION MATRIX

CORRELATION VARIABLES	MODEL OF FIT	ENTIRE DATA SET	RIVER GRAVELS	LIMESTONES	SANDSTONES	CONTROLS
KTRP ABRASION (% LOSS)	LINEAR	0.166486	0.236605	0.207830	0.710809	0.683741
vs LOS ANGELES ABRASION	QUADRATIC	0.300196	0.445724	0.252235	0.927772	0.778774
(% LOSS)	CUBIC	0.309110	0.514511	0.380126	NED*	0.932414
AREA UNDER LOSS CURVE	LINEAR	0.742128	0.822299	0.649213	0.662199	0.814712
vs KTRP ABRASION (% LOSS)	QUADRATIC	0.745489	0.833033	0.658505	0.929763	0.815379
	CUBIC	0.752031	0.883236	0.662842	NED	0.853841
KTRP ABRASION (% LOSS) vs	LINEAR	0.088920	0.016025	0.140357	0.546309	0.385463
AREA BETWEEN GRADATION	QUADRATIC	0.101898	0.063982	0.191171	0.550166	0.458611
CURVES	CUBIC	0.124247	0.441486	0.193284	NED	0.628072
LOS ANGELES ABRASION	LINEAR	0.685515	0.019081	0.703534	0.970723	0.553026
(% LOSS) vs AREA BETWEEN	QUADRATIC	0.745372	0.024822	0.729821	0.970726	0.814402
GRADATION CURVES	CUBIC	0.748063	0.113753	0.805589	NED	0.866765
AREA UNDER LOSS CURVE	LINEAR	0.033995	0.017115	0.117610	0.713492	0.161516
vs AREA BETWEEN GRADATION	QUADRATIC	0.045887	0.179857	0.131560	0.896303	0.165125
CURVES	CUBIC	0.069580	0.574681	0.131565	NED	0.420502
KTRP ABRASION (% LOSS)	LINEAR	0.117693	0.041881	0.066436	0.068015	0.188667
vs INSOLUBLE RESIDUE	QUADRATIC	0.175842	0.167243	0.068966	0.805113	0.362381
	CUBIC	0.190566	0.180310	0.069905	NED	0.651499
SKID NUMBER vs AREA	LINEAR	0.037351	0.160433	0.135753	NED	0.042009
BETWEEN GRADATION CURVES	QUADRATIC	0.077981	0.361185	0.171047	NED	0.045836
	CUBIC	0.095212	0.600550	0.378111	NED	0.460836
SKID NUMBER vs	LINEAR	0.055661	0.287964	0.134104	NED	0.195425
Y'(X) = 0	QUADRATIC	0.057476	0.331661	0.750652	NED	0.195519
	CUBIC	0.163114	0.331683	NED	NED	0.200948
LOS ANGELES ABRASION	LINEAR	0.009462	0.009989	0.028783	0.371305	0.183808
(% LOSS) vs INSOLUBLE	QUADRATIC	0.013508	0.021745	0.040661	0.999938	0.229240
RESIDUE	CUBIC	0.032736	0.024109	0.044839	NED	0.286151
AREA UNDER LOSS CURVE	LINEAR	0.154699	0.029700	0.025299	0.039030	0.209718
vs INSOLUBLE RESIDUE	QUADRATIC	0.205561	0.283961	0.038964	0.975773	0.422401
	CUBIC	0.219292	0.371408	0.038976	NED	0.711317
AREA BETWEEN GRADATION	LINEAR	0.011207	0.609447	0.011518	0.478264	0.120580
CURVES vs INSOLUBLE	QUADRATIC	0.023085	0.657409	0.016366	0.985692	0.226303
RESIDUE	CUBIC	0.027769	0.675276	0.027116	NED	0.236587
Y'(X) = 0 vs INSOLUBLE	LINEAR	0.140449	0.021308	0.052960	0.375304	0.000007
RESIDUE	QUADRATIC	0.289537	0.243729	0.082834	0.974446	0.269180
	CUBIC	0.425517	0.482973	0.126800	NED	0.312421

TABLE 11. CONTINUED

CORRELATION VARIABLES	MODEL OF FIT	ENTIRE DATA SET	RIVER GRAVELS	LIMESTONES	SANDSTONES	CONTROLS
Y"(X) * 10^4 vs INSOLUBLE RESIDUE	LINEAR	0.080195	0.028411	0.120527	0.411663	0.000710
	QUADRATIC	0.097707	0.028802	0.167228	0.774997	0.007563
	CUBIC	0.201927	0.226155	0.172305	NED	0.104930
SKID NUMBER vs KTRP ABRASION (% LOSS)	LINEAR	0.046686	0.589013	0.010057	NED	0.114749
	QUADRATIC	0.227541	0.590102	0.735169	NED	0.194454
	CUBIC	0.235632	0.683380	0.900445	NED	0.297145
ADJUSTED SKID NUMBER vs KTRP ABRASION (% LOSS)	LINEAR	0.109149	0.187308	0.236061	NED	0.047560
	QUADRATIC	0.178743	0.309853	0.542390	NED	0.486497
	CUBIC	0.194412	0.376861	0.547869	NED	0.501018
SKID NUMBER vs LOS ANGELES ABRASION (% LOSS)	LINEAR	0.001768	0.312396	0.120999	NED	0.001796
	QUADRATIC	0.028941	0.582208	0.164460	NED	0.081119
	CUBIC	0.075754	0.735963	0.166108	NED	0.954370
ADJUSTED SKID NUMBER vs LOS ANGELES ABRASION (% LOSS)	LINEAR	0.016245	0.025342	0.024110	NED	0.000762
	QUADRATIC	0.023740	0.320901	0.030783	NED	0.014173
	CUBIC	0.128538	0.905181	0.077168	NED	0.999889
ADJUSTED SKID NUMBER vs AREA BETWEEN GRADATION CURVES	LINEAR	0.007364	0.062968	0.022407	NED	0.124672
	QUADRATIC	0.007677	0.356057	0.034306	NED	0.331874
	CUBIC	0.079535	0.572691	0.527117	NED	0.555343
SKID NUMBER vs INSOLUBLE RESIDUE	LINEAR	0.000719	0.030512	0.009750	NED	0.167797
	QUADRATIC	0.067638	0.258766	0.023656	NED	0.974927
	CUBIC	0.132500	0.912873	0.241104	NED	0.997977
ADJUSTED SKID NUMBER vs INSOLUBLE RESIDUE	LINEAR	0.002812	0.010502	0.028122	NED	0.032705
	QUADRATIC	0.021937	0.012313	0.028375	NED	0.928948
	CUBIC	0.024198	0.574837	0.042525	NED	0.989699
Y'(X) = 0 vs INSOLUBLE RESIDUE [1]	LINEAR	0.119137	0.021308	0.017190	0.375304	0.000007
	QUADRATIC	0.127883	0.243729	0.047601	0.974446	0.269180
	CUBIC	0.131091	0.482973	0.083981	NED	0.312421
Y"(X) * 10^4 vs INSOLUBLE RESIDUE [1]	LINEAR	0.017145	0.028411	0.048011	0.411663	0.000710
	QUADRATIC	0.022093	0.028802	0.058423	0.774997	0.007563
	CUBIC	0.051930	0.226155	0.059800	NED	0.104930
Y'(X) = 0 vs Y"(X) * 10^4	LINEAR	0.214226	0.611987	0.257354	0.875088	0.779766
	QUADRATIC	0.317948	0.635802	0.547525	0.928731	0.884267
	CUBIC	0.495650	0.657076	0.713130	NED	0.888309
Y'(X) = 0 vs Y"(X) * 10^4 [1]	LINEAR	0.478878	0.611987	0.477256	0.875088	0.779766
	QUADRATIC	0.549451	0.635802	0.832407	0.928731	0.884267
	CUBIC	0.555082	0.657076	0.850586	NED	0.888309

TABLE 11. CONTINUED

CORRELATION VARIABLES	MODEL OF FIT	ENTIRE DATA SET	GRAVELS	LIMESTONES	SANDSTONES	CONTROLS
LOS ANGELES ABRASION (% LOSS) vs Y'(X) = 0	LINEAR	0.022933	0.272683	0.013244	0.976670	0.328084
	QUADRATIC	0.039235	0.461004	0.018527	0.998026	0.697994
	CUBIC	0.111578	0.588314	0.101174	NED	0.894469
LOS ANGELES ABRASION (% LOSS) vs Y'(X) = 0 [1]	LINEAR	0.120054	0.272683	0.106999	0.976670	0.328084
	QUADRATIC	0.202558	0.461004	0.524324	0.998026	0.697994
	CUBIC	0.203584	0.588314	0.780321	NED	0.894469
LOS ANGELES ABRASION (% LOSS) vs Y"(X) * 10^4	LINEAR	0.076900	0.089874	0.085149	0.761445	0.236121
	QUADRATIC	0.120561	0.104807	0.093259	0.884497	0.295997
	CUBIC	0.152890	0.375812	0.275132	NED	0.423591
LOS ANGELES ABRASION (% LOSS) vs Y"(X) * 10^4 [1]	LINEAR	0.060416	0.089874	0.081220	0.761445	0.236121
	QUADRATIC	0.120816	0.104807	0.113269	0.884497	0.295997
	CUBIC	0.138386	0.375812	0.310131	NED	0.423591
ADJUSTED SKID NUMBER vs Y'(X) = 0	LINEAR	0.105281	0.012750	0.432205	NED	0.236432
	QUADRATIC	0.106052	0.012780	0.454378	NED	0.240699
	CUBIC	0.126888	0.028417	NED	NED	0.378396
SKID NUMBER vs Y"(X) * 10^4	LINEAR	0.000095	0.047479	0.000000	NED	0.000446
	QUADRATIC	0.315864	0.437384	0.647189	NED	0.479618
	CUBIC	0.353418	0.787574	NED	NED	0.500000
ADJUSTED SKID NUMBER vs Y"(X) * 10^4	LINEAR	0.014870	0.194380	0.298645	NED	0.006740
	QUADRATIC	0.079567	0.752707	0.411853	NED	0.555358
	CUBIC	0.142407	0.902861	NED	NED	0.809262
SKID NUMBER vs Y'(X) = 0 [2]	LINEAR	0.005415	0.287964	0.710853	NED	0.195425
	QUADRATIC	0.115653	0.331661	1.000000	NED	0.195519
	CUBIC	0.116951	0.331683	NED	NED	0.200948
ADJUSTED SKID NUMBER vs Y'(X) = 0 [2]	LINEAR	0.003940	0.012750	0.030100	NED	0.236432
	QUADRATIC	0.028692	0.012780	1.000000	NED	0.240699
	CUBIC	0.116814	0.028417	NED	NED	0.378396
SKID NUMBER vs Y"(X) * 10^4 [2]	LINEAR	0.019759	0.047479	0.651174	NED	0.000446
	QUADRATIC	0.289489	0.437384	1.000000	NED	0.479618
	CUBIC	0.317129	0.787574	NED	NED	0.500000
ADJUSTED SKID NUMBER vs Y"(X) * 10^4 [2]	LINEAR	0.002252	0.194380	0.012115	NED	0.006740
	QUADRATIC	0.014774	0.752707	1.000000	NED	0.555358
	CUBIC	0.060140	0.902861	NED	NED	0.809262

NOTE: *NED - INSUFFICIENT DATA TO PERFORM CORRELATION

(1) - THREE LIMESTONE DATA POINTS WERE EXCLUDED FROM THE CORRELATION

(2) - ONE LIMESTONE DATA POINT WAS EXCLUDED FROM THE CORRELATION

Physical characteristics such as grain size, pore size, and permeability were not considered when attempting to find a relationship between aggregate type and skid resistance. These were not considered because tests for those three parameters were not performed.

Skid data were available for only 19 sections. Correlations cannot be considered to provide an adequate characterization of how various abrasion varibles relate to skid number. Most test sections had similar skid numbers, and in the absence of variability in skid numbers, there is little chance to detect a meaningful correlation coefficient.

DISCUSSION

Data obtained during this study could best be used to compare the abrasive behavior of one aggregate relative to another. All aggregates that are tested could be compared to a control aggregate (granite, for example). However, the different types of aggregates behave very differently and comparing all aggregates to one control may not yield significantly meaningful information. It is suggested that performance of each aggregate within an aggregate group be compared to performances of other aggregates within that same group or a control within that group. For example, compare the behavior of all sandstones to a "control" sandstone. The "control" aggregate would be one in which experience has indicated field performance to be good.

The weight-loss curve from the KTRP Abrasion Test is the best tool to use in comparing aggregates. There are two numbers that may be obtained from that curve that are useful in making this comparison. The first number is the percent weight loss at the end of the test. This may be used to compare one aggregate to another.

The second number is the first derivative of the weight loss curve as defined by Equation 2. When this equation is set equal to zero and X (in hours) is determined, this is the time (theoretically) at which the aggregate is no longer abrading the cylinder (i.e., the aggregate is completely polished). This number could be converted to number of theoretical wheel passes in the field that would cause polishing of the aggregate to such an extent it would be void of skid resistant attributes. If an average speed and an average tire print length were assumed, the amount of time each wheel is on the pavement could be calculated. That time divided into X, would yield the expected number of wheel passes wherein complete polishing of the aggregate would be expected. Equation 4 describes this relationship:

$$WP = X/(1.467S/L) \qquad (4)$$

where WP = expected wheel passes to maximum polishing,
X = time in hours at which the first derivative of Equation 2 equals zero,
S = assumed average traffic speed in miles per hour, and
L = assumed length of tire print in feet.

Therefore, an estimate of the skid-resistant life of an aggregate may be made in terms of wheel passes.

CONCLUSIONS AND RECOMMENDATIONS

Test data indicated considerable variability between samples. Further analyses indicated variability existed to a similar degree within each specific aggregate category: limestones, sandstones, traprocks, granites, and river gravels. This observation was generally consistent for all tests but was particularly apparent for the two abrasion tests (KTRP and Los Angeles). It was concluded that results of abrasion tests cannot be directly related to aggregate type. It was speculated that the KTRP Abrasion Test may have provided better results had the period of testing been extended beyond the 20 hours used in this study. A testing period of 48 hours would have provided more definitive information relative to abrasion characteristics and aggregate type. One additional reading between 4 and 20 hours also should have been obtained to better define the shape of the curve. Correlations also were attempted to relate ASTM E 274 skid numbers with results of laboratory analyses. In summary, there does not appear to be a significant correlation of skid number versus abrasion for any of the aggregates tested. This includes correlations for control samples, which have been providing satisfactory skid resistance performance. It is generally concluded that other variables such as density of the mixture, asphalt content, surface texture, and aggregate gradation may have as significant an influence on skid resistance performance as abrasion characteristics of the aggregates used in the mixture. Another interesting observation relates to the correlations of skid number versus age and/or total number of vehicle passes. Experience (1) indicates the existence of such relationships. This could not be resolved; however, it was noted that ages were similar for those projects where aggregate data and field skid resistance data were available. It is speculated that additional skid testing of those projects may provide additional information that could ultimately lead to a correlation between skid number and aggregate abrasion characteristics.

Finally, it was concluded that, while the KTRP Abrasion Test did not provide a definitive correlation between skid number and aggregate type, the KTRP test was a good referee test for comparison of aggregate sources in terms of relative abrasiveness. The area between gradation curves appears to be more indicative of an aggregates absolute abrasion resistance than the KTRP Percent Loss. It appeared the KTRP Abrasion Test was more indicative of the abrasive effects of the aggregate on an object; the Los Angeles Abrasion Test was more indicative of an aggregates impact resistance. It therefore is recommended that the KTRP Abrasion Test be included in the aggregate testing program for the Division of Materials. The KTRP Abrasion Test results could provide an additional index for aggregate quality.

Continued monitoring of field sections where aggregates from this study have been used is recommended. This effort should be coordinated by KTRP, Division of Materials, and Pavement Management staffs. It is anticipated long-term monitoring may provide information concerning mature skid numbers that may relate more appropriately with the KTRP Abrasion Test results than the skid numbers for earlier test periods that have been used in this study.

It is disappointing that definitive correlations could not be developed. Intuitively, it is opined that continued monitoring of the test sections may eventually provide insight into some of the observed inconsistencies. It should be noted that problems associated with the correlations of aggregate properties with skid numbers prevented expansion of this study to address the abrasion characteristics of mixtures. Additionally, testing of surface mixtures using a British Portable Tester and/or a modified shear box was abandoned because of the lack of good correlations between KTRP Abrasion Test results and skid numbers.

REFERENCES

1. Havens, J. H.; Burchett, J. L.; and Rizenbergs, R. L.; "Skid Resistance Studies in Kentucky (An Overview - 1974)," Research Report 399, Division of Research, Kentucky Department of Transportation, September 1974.

2. Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-scale Tire. Annual Book of ASTM Standards, 4.03 (E 274-85), pp. 755-762, American Society Testing and Materials, 1987.

3. Standard Test Method for Resistance to Degradation of Small-size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. Annual Book of ASTM Standards, 4.03 (C 131-81), pp. 38-39, American Society for Testing and Materials, 1987.

APPENDIX A

PROPOSED
TEST OF AGGREGATE ABRASIVENESS AND DEGRADATION

PROPOSED
Kentucky Method

TEST OF AGGREGATE ABRASIVENESS AND DEGRADATION

1. SCOPE

1.1 This method covers determination of the abrasiveness of an aggregate and the degradation of an aggregate due to mechanical handling.

2. APPARATUS

2.1 Sieves - A nest of six sieves and pan (1/2 inch, 3/8 inch, No. 4, No. 8, No. 16, and No. 200) conforming to AASHTO M92.

2.2 Plastic Pipe - A plastic pipe conforming to Slope Indicator, Inc. Catalog Number P/N 51101100 having a length equal to 2.5 inches and an external diameter of 2.75 inches. The plastic pipe shall have rough edges sanded and be thoroughly cleaned.

2.3 Scales or Balances - One scale having a 100-gram capacity and resolution of 0.0001 gram. Another scale (for aggregate) having a 3,000-gram capacity and resolution of 1 gram.

2.4 Cast Metal Cylindrical Jar - Jar is to be open at one end, 1.35 feet in height and having an outside diameter of 8.65 inches. The wall thickness of the jar shall be approximately 0.30 inch. A lid shall be provided for the jar and a positive seal between the jar and lid shall be obtained by use of a rubber gasket.

2.5 Jar Mill - The jar mill shall consist of horizontal, rubber encased rods spaced laterally to support and rotate the jar. The jar mill shall be geared or driven to rotate the jar at 72 +/- 2 RPM.

2.6 Drying Stove or Oven - An oven capable of maintaining a constant temperature of 230 +/- 9^{o}F (110 +/- 5^{o}C).

2.7 Mechanical Shaker - Gilson and Rotap shakers are satisfactory.

2.8 Sample Splitter

3. SAMPLE

3.1 Samples shall be obtained in accordance with Kentucky Method 64-601. Using the sieves designated under 2.1, perform a dry sieve analysis in accordance with Kentucky Method 64-602. The minimum sample weight shall be 2,000 grams.

4. PROCEDURE

4.1 Wash the aggregate retained on the No.-16 through the 1/2-inch sieves. Dry the aggregate to a constant weight. Weigh the material retained on each sieve and record the weight to the nearest gram.

4.2 Weigh the 2.75-inch plastic pipe section to the nearest 0.0001 gram. The pipe must be clean at the time of weighing. Cleaning is to be accomplished using soap and water only. After cleaning, do not handle the pipe with bare hands -- use clean plastic or rubber gloves or clean metal tongs.

4.3 Clean the inside of the cylindrical metal jar and check the rubber gasket to be sure it is in good condition and will provide a positive seal.

4.4 With the jar in an upright position, insert the pipe section into the jar.

4.5 Place the washed aggregate retained on the No.-16 through the 1/2-inch sieves and the material retained on the No.-200 sieve into the jar. Check to make sure that all weights have been recorded.

4.6 Place the rubber gasket on the jar, cover with the lid, and secure tightly. Check to make sure the jar is leakproof.

4.7 Place the jar on the jar mill and rotate for 1 hour. At the end of 1 hour of rotation, turn the jar mill off, remove the lid from the jar with the jar in an upright position. Remove the plastic pipe from the jar, tapping the pipe to be sure aggregate particles and/or debris remain in the jar and are not removed with the plastic pipe.

4.8 Clean the pipe as designated in 4.2 and weigh to nearest 0.0001 gram.

4.9 Repeat steps 4.4, 4.6, 4.7, and 4.8. A repeat of 4.5 is not indicated since the aggregate was not removed during the initial step 4.7.

4.10 Repeat steps 4.4, 4.6, 4.7, and 4.8; except this time allow jar mill to run for 2 hours.

4.11 Repeat step 4.10.

4.12 Repeat step 4.10, except allow jar mill to run for 6 hours.

4.13 Repeat step 4.12.

4.14 Repeat step 4.13, except allow jar mill to run for 30 hours.

4.15 Remove the aggregate from the jar and place in the nest of sieves designated under 2.1. Place the sieves in the mechanical shaker. A minimum of 5 minutes shall be required for mechanical sieving. Remove the sieves from the mechanical shaker at the end of that period.

4.16 The inside of the jar shall be thoroughly washed. The aggregate shall be wet washed after the remnants of the jar are poured over into the nest of sieves.

4.17 Dry the aggregate retained on each sieve to a constant weight. Record the weight of the aggregate retained on each sieve to the nearest gram. If there is any difference in the total sample weight before and after the test, it shall be assumed to be minus-200 material and recorded as such.

5. PLOTS

5.1 Plot the gradations before and after the test on the same chart. The area between the two curves is an indication of the susceptibility of the aggregate to mechanical breakdown (the larger the area, the more breakdown).

5.2 By plotting the cumulative weight loss of the plastic pipe at each phase of the test, a cumulative weight loss curve may be derived. From this curve, the rate of polishing and the time at which the maximum polishing occurs may be calculated from a fitted quadratic curve using data from the test.

6. CALCULATIONS

6.1 The percent weight loss of the plastic pipe is called the Percent Loss. It is calculated as

$$\text{Percent Loss} = \frac{\text{initial weight} - \text{final weight}}{\text{initial weight}} \times 100.$$

6.2 The area between the two gradation curves may be determined by use of a planimeter.

6.3 To determine the first derivative of the cumulative weight loss curve, an equation that describes the curve must be obtained using polynomial regression techniques, which may be obtained from a statistics handbook. Once this equation is derived, the first derivative of the curve may be computed calculus.

6.4 The second derivative is determined by taking the derivative of the first derivative.

7. PRECAUTIONS

7.1 Be sure to never handle the cleaned pipe with bare hands -- use rubber or plastic gloves or clean metal tongs.

8. REPORT

8.1 Report percent loss to the nearest hundredth of a percent.

8.2 Report the area between the gradation curves as a dimensionless unit to the nearest tenth.

8.3 Report the time at which the maximum polishing of the aggregate occurs (i.e., the first derivative of the fitted curve set equal to zero) to the nearest hundredth of an hour.

8.4 Report the rate of change of polishing (i.e., the second derivative of the fitted curve) to the nearest tenth of a gram per hour.

APPROVED ______________________
Director
Division of Materials

DATE ___________

APPENDIX B

ANNOTATIVE BIBLIOGRAPHY

"TWO LABORATORY METHODS FOR EVALUATING SKID RESISTANCE PROPERTIES OF AGGREGATES"
Mullin, W. G.; Dahir, S. H. M.; and Barnes, B. D.; Research Record 376, Highway Research Board, Washington, D.C.; 1971.

Circular Track Method: Pavement samples are placed in a circular track and subjected to wear from small-diameter pneumatic tires. No abrasive or water is used. Skid resistance values were determined by BPT.

Jar Mill Method: Coarse aggregates were polished in a jar mill with a charge of flint pebbles. Pavement samples made of the polished aggregate were tested by exposing a number of samples of the same aggregate for different amounts of time to estimate a wear-time curve.

Results: For the eight aggregates being compared, both the jar mill method and circular track method produced the same rating of aggregate for skid resistance characteristics. BPN values of worn aggregate were higher for the jar mill method than for circular track method. However, there were no correlations between percentage wear loss and terminal skid resistance after wear. The lack of these correlations seems to eliminate the possibility of using a wear loss test as a means of pre-evaluating aggregates for skid resistance.

"SEASONAL VARIATIONS IN THE SKID RESISTANCE OF PAVEMENTS IN KENTUCKY"
Burchett, J. L.; and Rizenbergs, R. L.; Research Report 532, Division of Research, Kentucky Department of Transportation, Lexington, Kentucky; November 1979.

Frequent measurements of skid resistance were made on 20 pavements in Kentucky. Principal analyses involved relating changes in skid resistance to time and relating skid resistance to temperature, average antecedent temperatures, and average rainfall.

When test sections at the same location were compared, the magnitude of the annual variation in skid resistance was strongly associated with volume of traffic. The lowest skid numbers during the year for portland cement concrete and sand-asphalt pavements occurred in early to mid-August. The lower skid number for Class I surfaces occurred in late August to early September. Similarity of the annual precipitation and temperature cycle with the annual variations in skid resistance of pavements suggested that both precipitation and temperature affected skid resistance. Correlations between changes in skid number and temperature suggested that the annual changes in skid resistance resulted from a reaction of the surface to temperature over a few weeks. Measurements of skid resistance in Kentucky should be obtained between the first of July and the middle of November because measurements obtained within that period will not differ by more than than 4 SN.

"SKID NUMBER AND SPEED GRADIENTS ON HIGHWAY SURFACES"
Mahone, D. C.; Research Record 602, Transportation Research Board, Washington, D.C.; 1976.

Three major factors that influence the skid number (SN) and speed gradient (G) were studied: tire tread depth, water film, and pavement surface texture.

Tread depths of 0.87, 0.71, 0.56, 0.40, 0.24 cm, and bald, along with water film thicknesses of 0.04, 0.05, 0.08, and 0.10 cm were tested at speeds of 48.3, 64.4, 80.5, 96.6, and 112.6 km/h. For each combination of conditions, five skid resistance measurements were made at each site for each speed. The author feels the data show the same general trends that would be expected with treaded tires and the normal water output required by ASTM E 274-70.

"SKID RESISTANCE OF BITUMINOUS-PAVEMENT TEST SECTIONS: TORONTO BY-PASS PROJECT"
Ryell, J.; Corkill, J. T.; and Musgrove, G. R.; Research Record 712, Transportation Research Board, Washington, D.C.; 1979.

The objective of the project was to determine the most suitable bituminous surface-course mixture for future short- and long-term programs to improve the driving quality, and especially skid resistance, of the pavement. In the first phase of pavement improvement on the Toronto By-Pass, an open-graded bituminous surface-course mixture was used that contained traprock aggregates. Skid-resistance measurements and noise characteristics of this mixture are included in the report. Seventeen mixtures were evaluated in single-course thicknesses of 25 or 38 mm. Six test sections consisted of HL1 mixtures in which the coarse aggregate content was progressively increased to obtain a greater density of stone particles at the surface. Four test sections contained modified HL1 mixtures, since slag coarse aggregates were used in place of the traprock. Two sections were described as sand-asphalt mixtures that used traprock screenings as the fine aggregate. Four sections consisted of open-graded mixtures designed for high permeability to facilitate rapid drainage of surface water into, and laterally through, the surface-course layer. A final test section consisted of a mastic-type mixture based on the German Gussasphalt technology and modified so the material could be mixed and placed by conventional hot-mix plant and paving equipment.

*Almost all the bituminous mixtures tested had better skid resistance than the existing smooth, polished concrete.
*Initial target skid numbers need to be raised because all mixes were characterized by a decline in skid resistance during the first four years.
*This decline was caused by the coarse-aggregate particles being pressed into the matrix under wheel loads.
*In the driving lane, the bituminous mixtures that provided recommended skid values were dense-graded mixtures with both coarse and fine aggregates that consisted of traprock, steel slag, or blast furnace slag, and open-graded mixtures that contained coarse and fine traprock aggregates with high stone contents.
*For passing lanes, most bituminous mixtures are adequate.
*Sand mixtures are good only for low-speed traffic.
*Blast furnace and steel slag provide better skid resistance in dense-graded bituminous mixtures than traprock aggregate.

*Open-graded surface-course mixtures are quieter than adjacent sections of smooth, polished concrete.
*This test was geared toward heavy traffic volumes. The performance of bituminous mixtures may lead to different results on highways with less traffic or lower maximum speed limits.

"SYNTHETIC AGGREGATES FOR SKID-RESISTANT SURFACE COURSES"
Anderson, D. A.; Henry, J. J.; Research Record, Transportation Research Board, Washington, D.C.; 1979.

Skid resistance is controlled by both the microtexture and the macrotexture of the pavement surface. Macrotexture is controlled principally by the gradation of the aggregate, whereas microtexture is controlled by the properties of the individual aggregate particles. The combined effect of macrotexture and microtexture in determining the skid number at any speed has been defined in previous research and may be used to estimate the potential skid resistance of new or untried aggregates before their design or manufacture. Skid resistant aggregates also must be resistant to wear and polishing. This may be done by a variety of ways listed in the report.

"PREDICTION OF PAVEMENT SKID RESISTANCE FROM LABORATORY TESTS"
Mullen, W. G.; Research Record 523, Transportation Research Board, Washington, D.C.; 1974.

Laboratory test used on mixes: North Carolina State small wheel circular track
Laboratory test for friction: British portable tester ASTM 303

Good correlation between BPT and skid trailer both in field and laboratory. Allows translation of laboratory friction measurements into skid trailer skid numbers at velocities from 20 to 50 mph.

From field-laboratory wear correlation studies, a method was developed whereby an upper limit on field polish may be predicted for dense- and open-graded mixtures based on circular track results. This prediction method allows for the pre-evaluation of mixes for field polish resistance adequacy before construction.

"DESIGN, CONSTRUCTION, AND PERFORMANCE OF ASPHALT FRICTION COURSES"
Kandhal, P. S.; Brunner, R. J.; and Nichols, T. H.; Research Record 659, Transportation Research Board, Washington, D.C.; 1977.

During 1969-1971, eight test pavements of open-graded asphalt friction courses were constructed in Pennsylvania. Details of design, construction, and performance of these pavements are discussed. Four test pavements incorporating two aggregate types and control sections of dense-graded bituminous surface were constructed in 1974. The asphalt friction courses were designed according to FHWA procedure modified in terms of asphalt mixing viscosities. Interim data obtained suggest a minimum air void content of 25 percent is necessary to maintain the desired permeability after a decrease in most pavements from traffic action and clogging by debris. A highly skid resistant gravel aggregate was used in the asphalt friction course and in the dense-graded surface course. After 1.5 years, the skid speed gradient of both pavements is almost equal and approaches 0.45. In the case of dolomite aggregate (medium skid resistance), the asphalt friction course had a substantially lower speed gradient compared to the dense-graded surface course.

"SKID RESISTANCE OF PAVEMENTS"
Rizenbergs, R. L.; Burchett, J. L.; and Napier, C. T.; Research Report 347, Division of Research, Department of Highways, September 1974.

Standard pavement types and experimental surfaces on roads throughout Kentucky were evaluated in terms of skid resistance and effects of traffic, wear, and polishing. Friction verses speed gradients and the relationships between locked wheel and incipient friction were determined.

Asphaltic concrete was significantly more skid resistant on interstates and parkways than on two-lane roads. Roadway geometrics, traffic characteristics, and construction practices were thought to be contributing factors.

Portland cement concrete pavements retained high skid resistance during early life to about two million vehicle passes. Loss of texture accelerated by studded tires, exposed coarse aggregates that polish more readily than the sand-cement matrix. PCC pavements containing dolomitic glacial gravel were more slippery than pavements containing a variety of limestones.

Sand-asphalt surfaces, composed of not less than 50 percent quartz and a significant percentage of limestone sand, did not exhibit the desired level of friction. Several experimental sand-asphalts without limestone sand showed improved skid resistance, but were judged not to be suitable for deslicking purposes on roadways carrying high-speed traffic. Further development of thin-layered asphalt surfaces containing hard, angular silica sands and other aggregate types recognized for their high skid resistance properties hold promise.

"SKID RESISTANCE GUIDELINES FOR SURFACE IMPROVEMENTS ON TEXAS HIGHWAYS"

McCullough, B. F.; and Hankins, K. D.; Research Record 131, Highway Research Board, Washington, D.C.; 1966.

This report by the Texas Highway Department addresses skid resistance values as minimum safety values and goals for highway safety. The data were from 517 rural sections of randomly selected highways. The study, which began in 1963, led to selections of skid numbers of 0.4 and 0.3 for testing velocities of 20 and 50 mph, respectively, for guidelines for considering surface improvements. Skid resistance values of 0.31 and 0.24 at 20 and 50 mph, respectively, were recommended as minimum values.