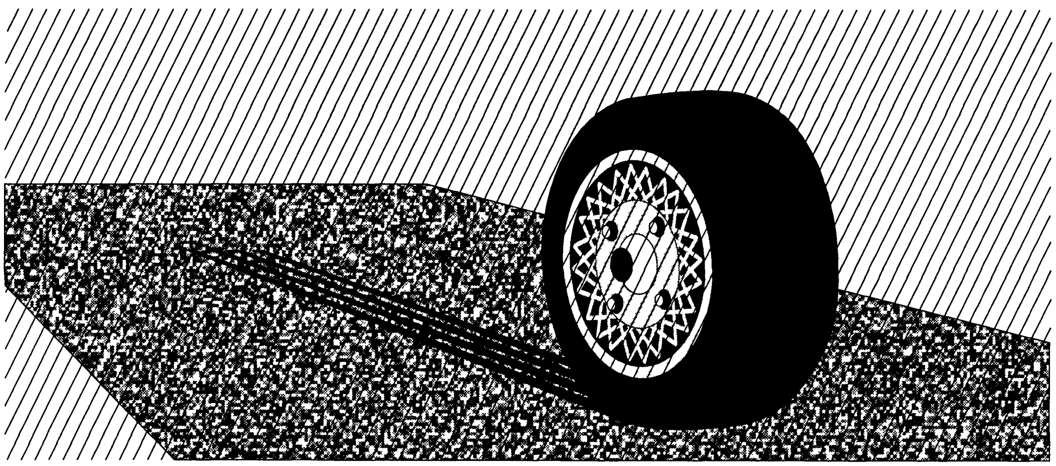
FINAL REPORT

THE EFFECT OF AGGREGATE TYPE AND MIX DESIGN ON THE WET SKID RESISTANCE OF BITUMINOUS PAVEMENT: RECOMMENDATIONS FOR VIRGINIA'S WET ACCIDENT REDUCTION PROGRAM



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16. Abstract

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Fifty-seven sources of nonpolishing aggregates, representing 18 lithologies, were studied. Skid testing of the 18 lithologies was carried out on 1,246 bituminous pavements, using the ASTM E 274-90 procedure. The aggregate groups showing the highest wet friction ranking were Valley Gravel, Fine Grained Granite, Lovingston Granite, Coastal Plain Gravel, and Diabase. Aggregates consistently exhibiting the lowest skid resistance were Aplite, Arch Marble, Slate, and Triassic Hornfels. The BAPM-BPT system showed little correlation with the skid test results.

No significant differences were found between the overall skid numbers generated on I-2 and S-5 asphalt mixes, but two trends were noted: 1) I-2 pavements showed a faster decrease in skid resistance than S-5 pavements as accumulated traffic increased, and 2) where platy aggregates such as Slate and Arch Marble were used, S-5 pavements exhibited consistently higher long-term skid resistance than I-2 pavements. One hundred and five sand patch tests were conducted to measure pavement surface macrotexture during the study. Macrotexture depth showed a higher correlation with skid numbers than any other factor investigated. Mixes exhibiting low skid resistance may do so because of rapid aggregate wear or the tendency of platy aggregate to orient horizontally, which both lower macrotexture depth. A brief survey of the effect of texturing suggests that Virginia's WARP should consider including pavement texturing as an alternative to repaving for wet accident hot spots.

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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INTRODUCTION

Providing skid resistant pavements is a high-priority goal in Virginia's Wet Accident Reduction Program (WARP). Research on pavement friction, begun in Virginia by Shelburne and Sheppe (1948), has continued to the present day. Shelburne and Sheppe mainly researched methods of measuring pavement friction, but noted the role of aggregate type in providing skid resistance. Klein and Brown (1939) and Moyer (1959) also found that aggregate rock type affects pavement friction. Aggregate type affects pavement surface texture, and pavement surface texture is a critical factor in wet skid resistance (Mahone, 1975; Leu and Henry, 1978; Argawal and Henry, 1980; Henry, 1980; Henry and Saito, 1981; Yandell et al., 1982; Wombold et al., 1986; Glendon, 1988).

The early studies found that some aggregates were susceptible to polishing under traffic. Polished aggregates exhibited significantly lower wet skid resistance than those which remained unpolished under traffic wear. Later studies (Nichols, 1959; Sherwood, 1959; Sherwood and Mahone, 1970; Webb, 1970; Stutzenberger and Havens, 1958; Finney and Brown, 1959; Knill, 1959; McLean and Shergold, 1959; Shupe and Lounsbury, 1959; Gray and Renninger, 1960; Stephens and Goetz, 1961; Kummer and Meyer, 1967) ultimately determined that the polish susceptibility of mineral aggregates was related to the mineralogy and texture of the rock.

Based on early research findings and observations by the operating divisions, the Virginia Department of Transportation excluded certain polish-susceptible aggregates from Primary and Interstate roads by 1955. In Virginia, polish-susceptible aggregates are predominately the limestones and dolomites occurring in the Valley and Ridge area in the western part of the state. To date, Virginia is the only state to exclude polish-susceptible limestone aggregates as coarse aggregate in primary and interstate surface mixes.

This report identifies and characterizes Virginia's nonpolishing aggregates in terms of their wet skid resistance, to provide information which can be applied to Virginia's Wet Accident

Reduction Program (WARP). The Virginia *Road and Bridge Specifications* (1991) states, "The term 'non-polishing aggregate' shall mean aggregate that the Department has determined will result in a surface of acceptable skid resistance when it is used and exposed as part of a wearing surface. The Department reserves the right to evaluate and determine the acceptability of polishing characteristics of aggregate proposed for use in pavement surfaces." Most of the "nonpolishing aggregates" produced in Virginia are composed predominately of hard, durable silica or silicate minerals. Selected manufactured materials such as slag and expanded shale have also proved to be nonpolishing. However, several studies (Nichols, Dillard and Alwood, 1956; Webb, 1970; Runkle and Mahone, 1977) together with data from routine skid testing in Virginia have indicated that some nonpolishing aggregates are superior to others in imparting road surface friction. An important objective of this study was to rate the polish-resistance of the state's various nonpolishing aggregates.

Laboratory tests using the British Accelerated Polishing Machine (BAPM) and British Pendulum Tester (BPT) have successfully distinguished polishing from non-polishing aggregate (Mullen, 1974; Zoeppritz, 1976). It was thought possible that these laboratory tests might be able to distinguish the relative skid resistance of various non-polishing aggregates. The results of the field tests using the ASTM E 274-90 procedure were compared to the results of BAPM-BPT testing to determine whether the BAPM-BPT system could be used to pre-test the skid resistance of non-polishing aggregate.

Information on asphalt mix design was included in the database derived from the skid tests in this study, to investigate the influence of mix design on skid resistance.

Some of the earliest reports on skid resistance recognized that surface texture affects pavement friction (Shelburne and Sheppe, 1948; Moyer and Shupe, 1951). Later Stutzenberger and Havens (1958), Kummer and Meyer (1967), and Webb (1970) among others introduced the terms "microtexture" and "macrotexture," the elements of pavement surface texture which most affect skid resistance. Microtexture refers to asperities with wavelengths up to 0.50 mm (0.020 in), while macrotexture describes asperities with wavelengths from 0.50 mm (0.020 in) to 50 mm (2.00 in). Normally, asperity height is approximately one half of the wavelength.

Microtexture, due to its small size, can be produced by any constituent exposed at the pavement surface. The most important microtexture in bituminous pavements is the surface of the coarse aggregate. The nonpolishing aggregates used in Virginia tend to retain their microtexture over the life of the pavement (Webb, 1970). Microtexture is most effective in imparting surface friction under dry conditions or at low vehicle speeds. The effect of microtexture on wet pavement skid resistance declines rapidly as vehicle speeds increase beyond 31 miles per hour (Henry, 1977; Balmer and Hegmon, 1980; Henry and Saito, 1981).

Macrotexture, on the other hand, is controlled mainly by the size, shape, and spacing of the exposed coarse aggregate particles. Macrotexture affects skid resistance by facilitating drainage under the tire (Moore, 1966; Balmer and Hegmon, 1980) and by tire deformation (Kummer, 1966). Macrotexture is the most important element affecting skid resistance at higher speeds or under wet conditions. In this study, sand patch tests were carried out for some aggregate types to further explore the role of aggregate type on macrotexture.

Pavement texturing is widely used to improve skid resistance. Most of this effort has involved portland cement concrete pavements (Mahone et al., 1976). Texturing bituminous concrete pavements to improve skid resistance is a relatively new idea in Virginia. However, some recent highway projects within the state involved milling or grooving the pavement surface to increase macrotexture and improve skid resistance, and data on skid resistance from these sites were also included in the present study.

From the data on: 1) the wet skid resistance of 18 aggregate lithologies, as measured by ASTM E 274-90 skid tests, 2) BAPM-BPT tests of the same aggregates, 3) the mix design of the skid-tested pavements, 4) the surface macrotexture of some of the aggregates tested above, and 5) the effects of milling or grooving bituminous pavements, recommendations for Virginia's Wet Accident Reduction Program were drawn up. These recommendations are presented at the end of the report.

MATERIALS AND METHODS

Identifying and Characterizing Nonpolishing Aggregates

During 1989 and 1990, a total of 57 sources producing nonpolishing aggregates within Virginia were identified and sampled. Material was taken from a minimum of two stockpiles to obtain a representative sample of the rock being mined. A search of the existing literature on Virginia geology, and contacts with geologists at the Virginia Division of Mineral Resources and industry sources, provided geologic information and other data on each aggregate source. Samples from each source were examined using hand specimen and microscopic techniques. The aggregates from the 57 quarries represented eighteen specific rock types. Table 1 provides brief lithologic descriptions and Table 2 summarizes the results of routine VDOT tests run on aggregates representing each rock type.

Table 1. Lithology of Virginia Nonpolishing Aggregate

Brief descriptions of the eighteen rock types recognized as nonpolishing aggregates produced in Virginia. Textural terms: Fine grained = < 1 mm; Medium grained = 1-10 mm. Lithologic terms, with formation or geographic modifiers where needed, are used to identify the different lithologies.

APLITE—White to light gray; fine to medium grained with average grain size of approximately 0.5 mm. Composed of plagioclase feldspar with a granular texture with minor quartz. Although the aggregate industry refers to the material as aplite a more precise geologic term would be anorthosite.

ARCH MARBLE—Blue-gray, fine grained impure, metamorphosed limestone with average grain size of 0.1 - 0.2 mm. The Arch Marble is composed of approximately 78% calcite and 3% quartz. Remaining minerals are mainly micas. Strong foliation or schistosity results in platy aggregate particles.

BASALT—Dark gray to black, with fine grained to microcrystalline texture. However, some basalts exhibit a coarser texture. Essential mineral composition is plagioclase feldspar and pyroxene at approximately 60% and 40% respectively.

(Table 1 Cont'd)

GRAVEL BLENDS—Blends tested in this study were man-made mixtures of Valley Gravels and limestone fines. Valley Gravels are predominately hard, dense quartzites from the Antietam formation. The fine fraction is limestone from various sources located in the Valley and Ridge portion of the state.

COASTAL PLAIN GRAVEL—Alluvial material recovered from river channel, point bar, and flood plain deposits. Size varies from pebbles (>2 mm) to boulders (>256 mm) which require crushing. Most gravels were derived from vein quartz and quartzite, though gravels of other compositions are found.

DIABASE—Mottled gray or dark green to black, fine to medium grained texture. Plagioclase and pyroxene are the dominant minerals.

BIOTITE GRANITES—Medium gray with occasional pink orthoclase and fine to medium texture. Some samples display a gneissic structure. Major minerals are feldspar (both plagioclase and orthoclase), quartz, and biotite.

FINE GRAINED GRANITE—Light gray; fine grained with average grain size of 0.5 mm and a uniform granular texture. Essential minerals are quartz (30.6%), orthoclase (22.3%), microcline (14.4%), plagioclase (23.3%) and biotite (6.7%). Minor foliation is present.

GREENSTONE—Metamorphosed basalt with a green to greenish gray color due to the presence of chlorite, epidote, or actinolite. Fine grained with average grain size of 0.1 - 0.2 mm. Quartz and plagioclase veins, and amygdules filled with quartz or epidote are common.

ANTIETAM QUARTZITE—White to bluish gray; medium grained metamorphosed sandstone with equidimensional quartz grains in a silica cement. Lone Jack Corporation reports the silica content to be 99.3%.

LOVINGSTON GRANITE—Light to dark gray; medium grained with average grain size of 1-2 mm; texture is equigranular to porphyritic with phenocrysts of plagioclase up to 5 mm. Essential mineral composition is feldspar (60%), quartz (30%) and biotite (10%). Some foliation or schistosity is evident.

METAGRAYWACKE—A metamorphosed rock derived from a poorly sorted sandstone which was composed mainly of quartz, feldspar, and lithic fragments. Bluish gray to dark gray; mainly fine grained with a granular texture. Random sample of material from one quarry contained 35% quartz.

METAMORPHICS—A variety of altered rock types are included here. They are predominantly light to dark gray; fine to medium grained with porphyritic texture and are commonly foliated. Phenocrysts of orthoclase or plagioclase agenes found in some samples. Essential minerals are plagioclase, orthoclase, quartz, and biotite. Descriptive terms for these materials include hornblende or biotite gneiss, hornblendite, amphibolite, metapyroxenite, and protomylonite.

METAVOLCANICS—Of volcanic origin, these rocks have been altered by increased temperature and pressure. They are primarily greenish gray and fine to medium grained. Texture ranges from granular to granoblastic with pink orthoclase porphyroblasts up to 7 mm occurring in some samples. Many samples include a conspicuous foliation. Material includes metarhyolite and metadacite. Luck Stone Corporation lists the essential minerals at Rockville as orthoclase (44%), quartz (33%), muscovite (17%), plagioclase (6%), and chlorite (5%).

PETERSBURG GRANITE—Whitish to light gray; medium to coarse grained with average grain size of 1-2 mm. Texture is equigranular to porphyritic. Pink orthoclase phenocrysts commonly as large as 9 mm are found. Essential minerals are orthoclase, quartz, plagioclase, and biotite. The biotite often displays a preferred orientation.

SLATE—Dark blue-gray, crystalline rock with porphyroblasts of magnetite up to 0.2 mm. The rock is composed chiefly of muscovite, chlorite, and quartz. Highly foliated nature of the rock results in platy aggregate particles.

TRIASSIC HORNFELS—Reddish brown to gray, very fine grained rock with uniform texture. Originally a siltstone, altered to hornfels by contact metamorphism. Common in the Triassic-Jurassic age Culpeper Basin.

VALLEY GRAVELS—Alluvial gravels are mined from river channel and flood plain deposits along major rivers in the Valley and Ridge province. Rocks derived mainly from quartzites of the Antietam Formation. Much of the material is cobble and boulder size and requires crushing.

Table 2
VDOT PHYSICAL TEST RESULTS FOR
NONPOLISHING AGGREGATES (JAN. 1990)

Group	# of Producing Quarries	Specific Gravity	Means Test Results: Absorption	Means Test Results: Abrasion Loss (B)
1. Aplite	1	2.78	0.3	18.3
2. Arch Marble	2	2.76	0.2	21.2
3. Basalt	3	2.90	0.73	13.9
4. Gravel Blends (Gravel Portion)	2	2.71	0.15	20.6
5. Biotite Granite	6	2.75	0.18	30.4
6. Coastal Gravel	4	2.59	0.87	35.5
7. Diabase	9	2.94	0.6	14.5
8. Fine Granite	1	2.62	0.8	33.4
9. Greenstone	1	2.96	0.4	14.7
10. Antietam Quartzite	1	2.62	0.3	22.9
11. Lovingston Granite	3	2.75	0.5	27.5
12. Metagraywacke	2	2.74	0.5	17.3
13. Metamorphics	5	2.78	0.66	19.3
14. Metavolcanics	2	2.68	0.5	17.7
15. Petersburg Granite	8	2.66	0.5	28.0
16. Slate	1	2.78	0.2	17.7
17. Triassic Hornfels	1	2.73	1.2	14.9
18. Valley Gravel	2	2.55	1.5	38.9

Virginia's nonpolishing aggregates are mainly igneous and metamorphic in origin. Granites and granite gneisses are the most common rock types represented. Granites and granite gneisses occur throughout the Piedmont, with the greatest concentration in the eastern portion of the area. In this report the term "granite" is used to include both granite and granite gneiss. Diabases and basalts are common in the northern part of the Piedmont and provide the major sources of nonpolishing aggregates in that area. The third most common nonpolishing rock types represented are a series of complex metamorphic lithologies. Three types of metamorphic rocks were recognized and are here designated as metagraywackes, metavolcanics and metamorphics (undifferentiated). The remaining rock types in Tables 1 and 2 are very diverse and are only produced from one or two quarries.

ASTM E 274-90 Skid Tests

Following identification of the 18 types of nonpolishing aggregates produced in Virginia, an intensive program of skid testing was undertaken. The object of the program was to provide enough skid data for each of the 18 aggregate types to evaluate and compare their skid resistance. Table 3 lists the number of sources represented and the number of sites tested for each aggregate type. All testing was conducted on bituminous pavements in the Virginia primary road system during 1989-91. Test sites were limited to segments of highway a minimum of one mile in length, paved under a single contract. The small number of sites tested for materials such as Gravel Blends and Antietam Quartzite reflect the limited availability of these materials in primary roads.

Table 3
NUMBER OF SOURCES AND NUMBER OF SITES SKID TESTED FOR EACH AGGREGATE TYPE

NON-POLISHING AGGREGATE GROUPS		
Rock Type	Number of Quarry Sources Tested	Number of Sites Tested
Aplite	1	28
Arch Marble	2	81
Basalt	3	86
Gravel Blends	2	10
Biotite Granite	2	42
Coastal Plain Gravels	2	18
Diabase	5	148
Fine Grained Granite	1	66
Greenstone	1	39
Antietam Quartzite	1	11
Lovingston Granite	3	71
Metagraywacke	2	77
Metamorphic	3	62
Metavolcanic	2	195
Petersburg Granite	8	191
Slate	1	19
Triassic Hornfels	1	49
Valley Gravels	2	53

All skid tests were run according to the standard ASTM E 274-90 procedure. A total of 1,246 sites were tested. All tests were run at a test speed of 40 mph and are identified in this work as SN40S for the smooth tire test, and SN40R for the ribbed tire test. Initially, 15 tests were run with both ASTM E 524-88 standard smooth and ASTM E 5 01-82 standard ribbed tires at each site. This number was later reduced to 7 tests per site with each type of tire. In addition to aggregate lithology, a number of other parameters for each skid test site were noted. These parameters included: location, mix design, placement date, skid date, lane average vehicle passes per day (LAVD), accumulated traffic (AT), and the ratio of smooth tire to ribbed tire skid test means.

BAPM-BPT Laboratory Tests

As noted previously, 57 producers of nonpolishing stone in Virginia were visited and sampled. Approximately forty pounds of material was taken randomly from existing stockpiles. In the lab the -3/8, +1/4 size fraction was separated, washed with a dispersing agent, rinsed, and dried. Two to four wearing molds were fabricated for each aggregate following ASTM D 3319 guidelines. In a few cases gentle filing or sanding of the epoxy underside of the molds was necessary to ensure a proper fit on the BAPM polishing wheel and the base of the BPT. Prior to any testing, the BPT was calibrated according to ASTM E 303-83. British Pendulum friction numbers (BPN) were measured at 0, 10, 20, 30, 40, 50, 60, 80, 100, and 120 minute intervals of wear. The testers were divided into two teams, Team A and Team B, for further comparison of results.

On the basis of some preliminary tests, it was decided to conduct the BAPM tests with water and grit according to ASTM D 3319-83, and with water only. This variation from normal ASTM test procedures was adopted after it was determined that the test results for the two methods were similar and in some cases the water-only tests yielded slightly greater reductions in BPN values. This reduction in BPN for water-only tests may be due to a lack of the roughening effect of the grit on the worn aggregate surfaces.

Early in the project it was noted that the friction levels of the molded samples as measured by the BPT dropped off rapidly as the test progressed. In most cases, over 50% of the ultimate friction loss was accomplished during the first 30 minutes of wear (Figure 1). This rapid decline and subsequent leveling of the skid numbers led to a decision to shorten the test period from 10 hours as recommended by ASTM D 3319-83 to 2 hours of total wearing time.

Mix Design

A number of different mixes have been used in the surface courses of Virginia's bituminous pavements. However, bituminous concrete mixtures I-2 and S-5 have been specified in over 90% of the bituminous concrete placed in Virginia in the last two decades. The I-2 design generally incorporates significantly coarser aggregates than the S-5. Up to 37% of plus 1/2-in. material is allowed in an I-2 mix, while 100% of the aggregate must pass the 1/2-in. sieve in the S-5 mix (Virginia Department of Transportation Road and Bridge Specifications, 1987).

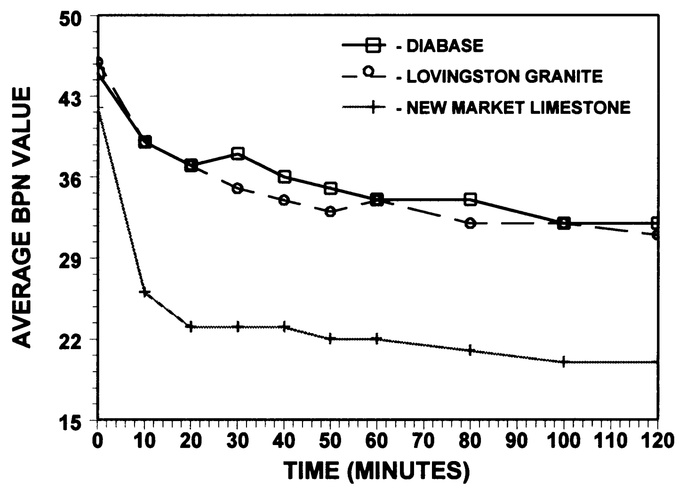

Figure 1. Decrease in BPN with time on the Accelerated Polishing Machine (APM). Diabase and Lovingstone Granite are non-polishing aggregates. New Market Limestone aggregates polish under traffic. Note the rapid decrease in BPN during the early stages of the test.

The mix design for each site tested was included in the data base for this study. Graphs were constructed showing SN40S vs. AT and SN40S vs. LAVD for all of the I-2 and S-5 data. Finally, individual graphs of I-2 and S-5 vs. AT and LAVD for each aggregate were plotted.

Pavement Surface Macrotexture

Data from 105 sand patch measurements of macrotexture (ASTM E 965) were included in the data base. Most of the sand patch tests were conducted in response to a request to investigate specific aggregates. Consequently, data on only 6 of the 18 lithologies were available. Multiple regression was performed on the data from the 105 sites where sand patch measurements of macrotexture were made to determine the effect of macrotexture on skid resistance for those pavements.

Milled or Grooved Pavements

Data were also acquired from a limited number of available sites with mechanically milled or grooved bituminous pavements. SN40S values were compared for two milled sites before, just after, and six months after milling was done. Sand patch tests were also done before and after milling. Also, SN40S values were compared for one longitudinally grooved site before and after grooving and four years after grooving.

RESULTS

Skid test data from the 1,246 sites yielded considerable insight into existing conditions on Virginia's primary road system. As would be expected, traffic volumes for the test sites varied widely. LAVD varied from a low of 425 to a high of 20,936, with a mean of 3,263. AT ranged from 181,496 to 95,488,928 vehicle passes, with a mean of 6,291,494. Using these values for LAVD and AT, a mean age of 5.23 years for the pavements studied is indicated. Eight years is generally considered to be the average life for bituminous pavement surfaces in Virginia (C. S. Hughes, personal communication).

Results of the SN40S tests for the 1,246 sites ranged from 13 to 59 with an overall mean of 36 and a standard error of 7.8, while SN40R tests ranged from 26 to 69 with an overall mean of 47 and a standard error of 5.2 (Figures 2 and 3). Assuming that the test results conform to normal distributions, in the smooth tire tests 16.7% of the pavements should fall below an SN40S of 28 (one standard error below the mean), and 2.5% below an SN40S of 21 (two standard errors below the mean). In the ribbed tire tests, 16.7% of the pavements should fall below an SN40R of 42 (one standard error below the mean), and 2.5% below an SN40R of 37 (two standard errors below the mean).

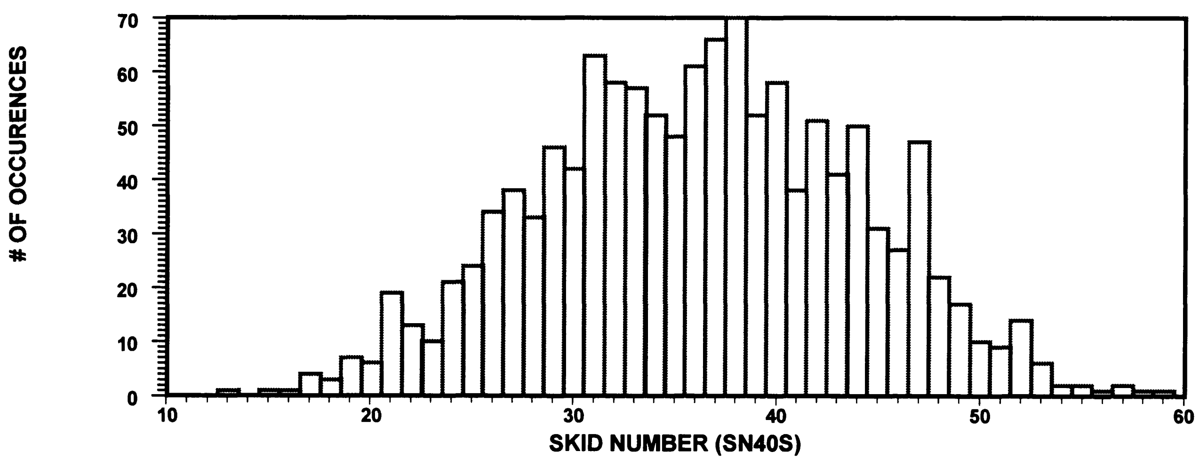

Figure 2. Distribution of skid numbers (SN40S) for tests run with the smooth tire.

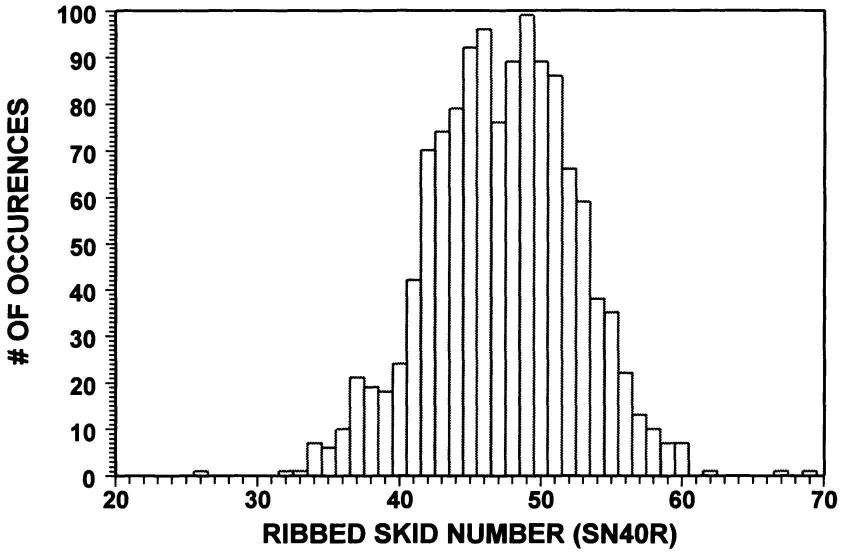

Figure 3. Distribution of skid numbers (SN40R) for tests run with ribbed tires.

The range and standard error values for smooth tires (SN40S) are greater than those for ribbed tires (SN40R). The smaller range for the ribbed tire data has been explained by Henry and Saito (1981) as a function of more effective water removal by ribbed tires, allowing greater tire-to-pavement contact on wet pavements. The greater range in the smooth tire data appears to indicate that smooth tires are more sensitive to small differences in wet pavement friction. This greater sensitivity to wet pavement conditions together with a desire to provide safe pavements under "worst case" conditions has led VDOT to use smooth tire data as a basis for Virginia's wet accident prevention program.

Aggregate Lithologies and SN40S values

As skid test data accumulated from the field it became evident that comparisons of the SN40S values for the different aggregate types would not be a simple matter. Aggregates from different parts of the state were exposed to significantly different volumes of traffic (Table 4). For instance, the LAVD means for the 18 nonpolishing groups ranged from a low of 1,610 for Slate to a high of 6,715 vehicles per day for Diabase. AT means exhibited an equally large range from a low of 2.4 million vehicle passes for Slate to a high of 9.9 million vehicle passes for Diabase. Values for the other 16 aggregate types occupied the broad ranges in between these two.

Table 4
SUMMARY OF LANE AVERAGE VEHICLES PER DAY (LAVD), ACCUMULATED TRAFFIC (AT), AND MEAN STOPPING DISTANCE NUMBERS (SN40S) AND STANDARD ERRORS FOR EACH AGGREGATE TYPE

Aggregate Type	Mean LAVD	Mean AT	Mean SN40S	SN40S Range	Standard Error (σ)	SN40S Mean Minus 2σ
Aplite	1,737	2,611,036	35	21-48	8.45	18
Arch Marble	2,819	8,476,084	33	17-50	8.46	16
Basalt	2,697	4,479,681	37	18-52	7.86	21
Biotite Granite	3,127	5,393,060	34	16-43	5.79	22
Gravel Blends	2,029	5,877,554	38	30-49	5.39	27
Coastal Plain Gravel	1,608	5,444,883	44	31-58	6.50	31
Diabase	6,715	9,906,872	35	18-52	7.19	21
Fine Grained Granite	1,631	5,843,151	42	25-52	5.54	31
Greenstone	4,491	7,570,377	32	18-53	8.49	15
Antietam Quartzite	2,146	5,190,138	38	27-55	8.53	23
Lovingston Granite	2,517	3,112,880	41	19-54	6.86	27
Metagraywacke	2,691	5,965,203	34	15-47	7.15	20
Metamorphics	2,296	5,035,420	37	21-49	7.26	23
Metavolcanic	3,331	7,570,849	34	19-52	6.39	21
Petersburg Granite	3,308	6,044,563	35	17-59	5.84	21
Slate	1,610	2,400,642	32	17-49	6.82	18
Triassic Hornfels	2,618	3,924,126	34	24-52	8.50	17
Valley Gravel	2,505	5,600,897	43	23-57	7.47	29
Mean-All Tests	3,263	6,291,494	36			

Because of these significant differences in exposure to traffic, several techniques were employed to compare and evaluate the relative skid resistance of the aggregate groups. Initially, SN40S means, standard errors, and the means minus two standard errors were computed for each group. The five groups showing the highest values for mean SN40S minus two standard errors were Fine Grained Granite (31), Coastal Plain Gravel (31), Valley Gravel (29), Lovingston Granite (27) and Gravel Blends (27). The five groups projecting the lowest SN40S values were Greenstone (15), Arch Marble (16), Triassic Hornfels (17), Aplite (18) and Metagraywacke (20). Assuming normal distributions apply, 2.5 percent of the SN40S values for each aggregate type should fall below these values. An SN40S of 20 is used in Virginia's Wet Accident Reduction Program as a value below which pavement friction may not be acceptable.

Another common method of evaluating the skid resistance of an aggregate has been to test a number of pavements which have been exposed to a wide range of total vehicle passes, and plot the rate of decrease in SN40 as AT increases (Mahone and Runkle, 1972; Runkle and Mahone, 1977). However, research conducted in Great Britain (Salt, 1976) and elsewhere indicates that LAVD also has a strong influence on skid resistance. In order to test whether AT or LAVD correlated more strongly with SN40 values, correlation coefficients were calculated for SN40S vs. AT and SN40S vs. LAVD for each of the 18 aggregate types.

Correlation coefficients were found to cover a wide range of values (Table 5). Low R^2 values in several situations indicate that increases in AT and LAVD may not be the major causes of decreases in SN40S values. As Table 5 shows, R^2 values are generally higher for SN40S vs. LAVD than for SN40S vs. AT.

Table 5
FIRST AND SECOND ORDER CORRELATION COEFFICIENTS (R^2 VALUES)
FOR SMOOTH TIRE SKID NUMBERS VS ACCUMULATED TRAFFIC (AT)
AND LANE AVERAGE VEHICLES PER DAY (LAVD)

Aggregate Type	R^2 Values SN40S vs. Accumulated Traffic (AT)		R^2 Values SN40S vs. Lane Average Vehicles Per Day (LAVD)	
	1st Order	2nd Order	1st Order	2nd Order
Aplite	0.32	0.35	0.45	0.51
Arch Marble	0.12	0.13	0.25	0.28
Basalt	0.17	0.27	0.18	0.32
Biotite Granite	0.19	0.35	0.10	0.13
Gravel Blends	0.37	0.41	0.16	0.19
Coastal Plain Gravel	0.07	0.25	0.08	0.10
Diabase	0.14	0.15	0.40	0.44
Fine Grain Granite	0.08	0.09	0.31	0.32
Greenstone	0.25	0.31	0.16	0.16
Antietam Quartzite	0.01	0.13	0.01	0.26
Lovingston Granite	0.09	0.26	0.14	0.18
Metagraywacke	0.16	0.28	0.30	0.38
Metamorphics	0.00	0.06	0.04	0.19
Metavolcanics	0.08	0.10	0.18	0.21
Petersburg Granite	0.10	0.14	0.11	0.24
Slate	0.14	0.26	0.54	0.58
Triassic Hornfels	0.18	0.18	0.16	0.16
Valley Gravel	0.02	0.09	0.04	0.15

With these relationships as background, it was decided to utilize SN40S vs. LAVD data as a basis for further aggregate evaluation. SN40S vs. LAVD graphs were plotted for each of the eighteen aggregate types. First order least square curves along with parallel curves at one and two standard errors were computed and plotted. Finally a horizontal line at SN40S = 20 was added. Figures 4, 5, and 6 show three examples of graphs constructed for the eighteen aggregate groups.

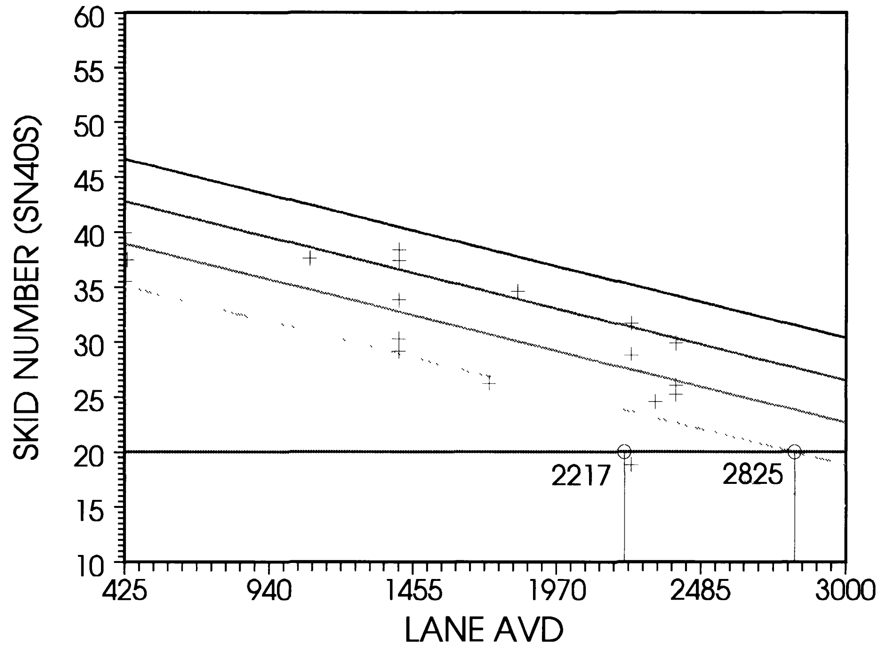

Figure 4. Skid numbers vs. lane average vehicles per day (LAVD) for Slate. Parallel lines at one and two standard errors have been added.

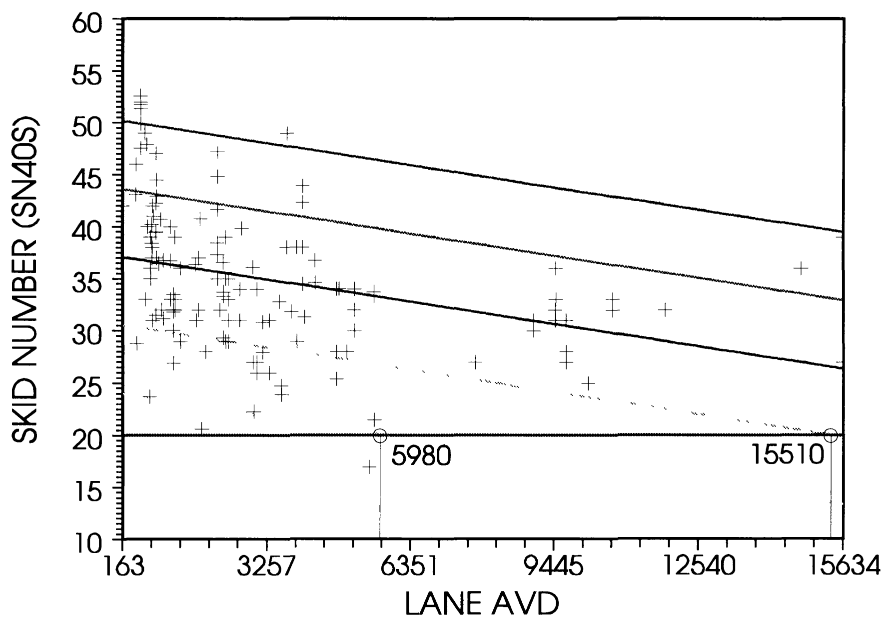

Figure 5. Skid numbers vs. lane average vehicles per day (LAVD) for Petersburg Granite. Parallel lines at one and two standard errors have been added.

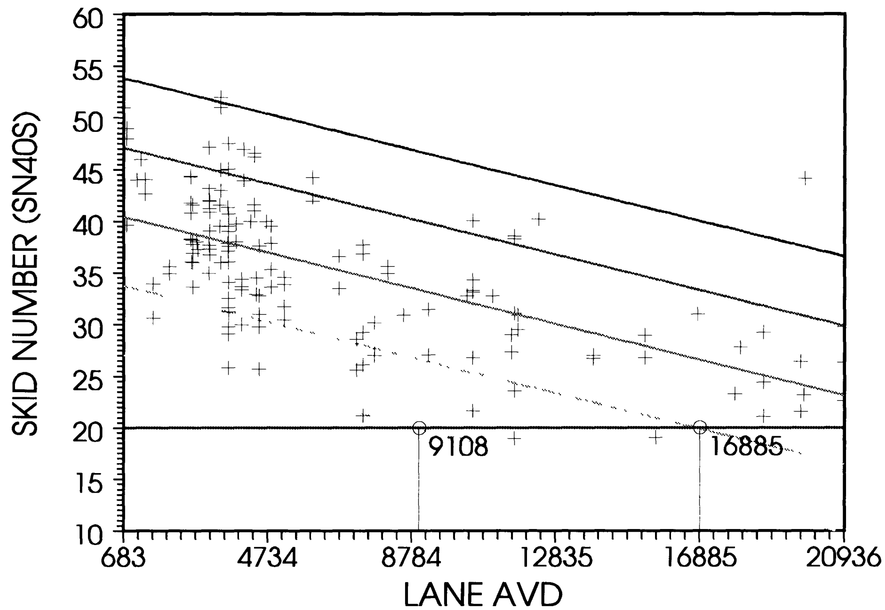

Figure 6. Skid numbers vs. lane average vehicles per day (LAVD) for Diabase. Parallel lines at one and two standard errors have been added.

Figure 4, the data plot for slate, shows that the two-standard-error curve intersects the SN40S = 20 line at a LAVD of 2217 and the one-standard-error line at a LAVD of 2825. Assuming that the sample is representative of the pavements containing Slate aggregates, 2.5% should test below SN40S = 20 at 2,217 LAVD and 16.7% under SN40S = 20 at 2,825 LAVD. Since the skid test population mean LAVD for slate of 1,610 (Table 4) is well below the 2,217 value at two standard errors, it would appear that most of the current Virginia pavements containing slate aggregates would test well above the SN40S value of 20.

Also shown in Figure 4 are the points on the mean and two-standard-error curves at 1,610 LAVD. The SN40S values projected for 1,610 LAVD are 32 and 23 respectively. These values are similar to the 32 and 20 listed in Table 4. According to the projections in Figure 4, only 2.5% of the Slate pavements should fall below an SN40S of 23.

Figure 5 shows SN40S vs. LAVD for Petersburg Granite. The SN40S = 20 line intersects the two-standard-error curve at a LAVD of 5,980, and the one-standard-error curve at a LAVD of 15,510. These values are significantly higher than the mean of 3,308 LAVD listed in Table 4 for the Petersburg Granite skid test sites. Evident too is the relatively high standard error of the SN40S data in Figure 5, possibly due to differences in pavement surface texture. Less variability, resulting in a smaller standard error, would obviously further increase the LAVD considered to be safe for pavements containing Petersburg Granite. At the mean LAVD of 3,308 for Petersburg Granite, the mean and two-standard-error intersections for SN40S are 35 and 22 respectively.

Figure 6 contains the SN40S vs. LAVD graphs for Diabase. The SN40S = 20 curve intersects the two- and one-standard-error lines at 9,108 and 16,885 LAVD respectively. These LAVD values are among the highest in the study, indicating that Diabase maintains SN40S values of greater than 20 even under high volumes of traffic. Again the SN40S values show high variability and relatively large standard errors which lower the LAVD values where the one- and two-standard-error curves reach SN40S = 20. Even so, the mean LAVD of 6,715 for Diabase test sites is well below the 9,108 projected at two standard errors.

Graphs similar to Figures 4, 5, and 6 were constructed for all eighteen aggregate groups. The projected results are shown in Table 6. The five aggregates projecting the highest LAVD values where the mean minus 2σ curve intersected the SN40S = 20 line were Valley Gravel (11,506), Diabase (9,108), Lovingston Granite (9,061), Metavolcanics (7,488), and Greenstone(7,294). Those projecting the lowest LAVD values were Triassic Hornfels (1,916), Arch Marble (1,975), Slate (2,217), and Aplite (2,303). Only one aggregate group, the Arch Marble, showed a mean LAVD for the test population (2,819) to be higher than that projected at the intersection of the SN40S = 20 line and the curve at two standard errors below the mean (1,975).

Table 6
LAVD VALUES AT THE POINT WHERE THE TWO-STANDARD-ERROR LINE, IS PROJECTED TO REACH AN SN40S VALUE OF 20.

LAVD VALUES: -2σ Curve Intersects SN4OS = 20	
Valley Gravel	11,506
Diabase	9,108
Lovingston Granite	9,061
Metavolcanics	7,488
Greenstone	7,294
Fine Grained Granite	6,882
Antietam Qzite	6,872
Petersburg Granite	5,980
Biotite Granite	5,831
Coastal Plain Gravel	5,780
Gravel Blends	5,257
Metagraywacke	4,598
Metamorphics	4,587
Basalt	4,479
Aplite	2,303
Slate	2,217
Arch Marble	1,975
Triassic Hornfels	1,916

Next, multiple regression was performed on the whole test population using SN40S values as the dependent variable. Independent variables were aggregate rock type, LAVD, AT, Mixes I-2 and S-5, and date of placement. The resultant R^2 value was a relatively low 0.33. LAVD showed the strongest negative T value, indicating that high LAVD values correlate with low SN40S values. In order to rank the aggregate types, Basalt was chosen as the comparison group. The choice of Basalt was made because its SN40S value of 37 was closest to the total population mean. Table 7 contains the results of the rankings.

Table 7 shows that the Aggregate Groups testing most positive for T (i.e. projecting higher SN40S values than Basalt) in the regression were Valley Gravel (+6.3), Fine Grained Granite (+3.9), Lovingston Granite (+3.8), and Diabase (+3.1). Aggregate Groups with T values exhibiting the most negative influence were Arch Marble (-3.1), Slate (-3.0), Greenstone (-2.5), Blends (- 2.3) and Metamorphics (-2.3).

Table 7
AGGREGATE RANKING DETERMINED BY T VALUES
GENERATED BY MULTIPLE REGRESSION.
(VALUES ARE RELATIVE TO BASALT AND ARE LISTED FROM THE MOST POSITIVE TO THE MOST NEGATIVE INFLUENCE ON SN40S PERFORMANCE)

Multiple Regression Total Population T Values	
Valley Gravel	6.3
Fine Grained Granite	3.9
Lovingston Granite	3.8
Diabase	3.1
Coastal Gravel	2.3
Antietam Qzite	1.5
Biotite Granite	0.1
Basalt	0.0
Petersburg Granite	-0.6
Metagraywacke	-1.3
Aplite‘	-1.6
Metavolcanics	-2.2
Triassic Hornfels	-2.2
Metamorphics	-2.3
Gravel Blends	-2.3
Greenstone	-2.5
Slate	-3.0
Arch Marble	-3.1

Finally, multiple regression was performed on the data from the 105 sites where sand patch measurements of macrotexture were available. The correlation value increased to R^2 = 0.70 with macrotexture contributing a strongly positive T value of 8.82. These values indicate that macrotexture is a very important element in imparting skid resistance. However, sand patch data were available for only 6 of the 18 aggregate types (Table 8).

Table 8 summarizes the results of the four methods used to evaluate the relative skid resistance of the aggregate groups.

Table 8
SUMMARY OF THE RESULTS OF THE FOUR METHODS USED
TO EVALUATE THE RELATIVE SKID RESISTANCE OF THE AGGREGATE GROUPS.
IN EACH CASE THE COLUMNS REFLECT HIGHEST TO LOWEST SKID RESISTANCE.

SN40S VALUES MEAN - 2 σ		LAVD VALUES: -2σ Curve Intersects SN40S=20		Multiple Regression Total Population T Values		Multiple Regression T Values Using the 105 Sand Patch Locations*	
Fine Grained Granite	31.41	Valley Gravel	11,506	Valley Gravel	6.3	Fine Grained Granite	-2.23
Coastal Gravel	31.26	Diabase	9,108	Fine Grained Granite	3.9	Greenstone	-3.11
Valley Gravel	28.53	Lovingston Granite	9,061	Lovingston Granite	3.8	Biotite Granite	-3.18
Lovingston Granite	27.20	Metavolcanics	7,488	Diabase	3.1	Slate	-3.33
Gravel Blends	26.72	Greenstone	7,294	Coastal Gravel	2.3	Aplite	-3.74
Antietam Qzite	23.24	Fine Grained Granite	6,882	Antietam Qzite	1.5	Arch Marble	-4.40
Metamorphics	22.54	Antietam Qzite	6,872	Biotite Granite	0.1		
Biotite Granite	22.19	Petersburg Granite	5,980	Basalt	0.0		
Metavolcanics	21.23	Biotite Granite	5,831	Petersburg Granite	-0.6		
Petersburg Granite	21.19	Coastal Plain Gravel	5,780	Metagraywacke	-1.3		
Basalt	21.00	Gravel Blends	5,257	Aplite	-1.6		
Diabase	20.98	Metagraywacke	4,598	Metavolcanics	-2.2		
Slate	20.18	Metamorphics	4,587	Triassic Hornfels	-2.2		
Metagraywacke	19.91	Basalt	4,479	Metamorphics	-2.3		
Aplite	18.40	Aplite	2,303	Gravel Blends	-2.3		
Triassic Hornfels	17.10	Slate	2,217	Greenstone	-2.5		
Arch Marble	16.44	Arch Marble	1,975	Slate	-3.0		
Greenstone	15.30	Triassic Hornfels	1,916	Arch Marble	-3.1		

*Sand patch data was available for only six aggregate groups

BAPM-BPT Test Results

Table 9 lists the results of the BAPM-BPT tests. The New Market limestone, a fine grained, high calcium limestone containing approximately 98.5% $CaCO_3$, was included as a standard known to polish readily under traffic. Both the initial and final BPN values for the New Market limestone were significantly lower than all of the other aggregates tested. Aggregates known to polish readily under traffic can be recognized by the BAPM-BPT test using either water and grit or water alone. Table 9 also shows the tests run by each of two testing teams. When duplicate samples were run, Team B results were more variable than Team A results.

Table 9
RESULTS OF ACCELERATED POLISHING MACHINE (APM) AND BRITISH PORTABLE TESTER (BPT) LABORATORY TESTS.
EACH SN IS THE AVERAGE OF TWO MOLDS

			Skid Numbers (SN)		
Aggregate	Operator Teams	Method	Initial	At 120 min.	(Initial) minus 120 min.
Aplite	A	H_20	47	33	14
	A	H_20+Grit	46	30	16
Arch Marble	A	H_20	39	28	11
	A	H_20+Grit	40	31	9
	A	H_20	44	33	11
Basalt	A	H_20	44	30	14
	A	H_20	44	29	15
	A	H_20	41	31	10
Biotite Granite	B	H_20	35	29	6
	B	H_20+Grit	42	30	12
	A	H_20	43	32	11
	A	H_20+Grit	44	32	12
	B	H_20	38	32	6
	B	H_20+Grit	44	30	14
	A	H_20	46	34	12
	B	H_20	39	33	6
	B	H_20+Grit	44	29	15
	B	H_20	42	33	9
	B	H_20+Grit	42	31	11
Coastal Plain Gravel	A	H_20	47	38	9
	A	H_20	34	20	14
	A	H_20	35	24	11
	A	H_20	38	30	8
Fine Grained Granite	B	H_20	37	30	7
	B	H_20+Grit	45	31	14
Diabase	A	H_20	45	32	13
	A	H_20	45	32	13
	A	H_20	45	29	16
	A	H_20	40	29	11
	A	H_20	46	34	12
	A	H_20	46	33	13
	A	H_20	44	31	13
	A	H_20	42	32	10
	A	H_20	48	32	16
Greenstone	A	H_20	47	34	13
	A	H_20+Grit	46	33	13
Quartzite	B	H_20	32	24	13
	B	H_20+Grit	34	23	13
Lovingston Granite	A	H_20	43	33	10
	A	H_20	45	30	15
	A	H_20	50	36	14
	A	H_20+Grit	47	36	11

Table 9
RESULTS OF ACCELERATED POLISHING MACHINE (APM) AND BRITISH PORTABLE TESTER (BPT) LABORATORY TESTS.
EACH SN IS THE AVERAGE OF TWO MOLDS (Continued)

			Skid Numbers (SN)		
Aggregate	Operator Teams	Method	Initial	At 120 min.	(Initial) minus 120 min.
Metagraywacke	A	H_20	49	41	8
	A	H_20	41	39	2
Metamorphics	A	H_20	42	30	12
	A	H_20	47	35	12
	A	H_20	46	32	14
	A	H_20	45	33	12
	A	H_20	45	32	13
Metavolcanics	A	H_20	42	31	11
	A	H_20	45	30	15
Petersburg Granite	A	H_20	44	33	11
	A	H_20	45	31	14
	A	H_20	45	28	17
	B	H_20	39	29	10
	B	H_20+Grit	42	28	14
	A	H_20	44	31	13
	A	H_20	42	30	12
	B	H_20	40	31	9
	B	H_20+Grit	43	30	13
	B	H_20	39	31	8
	B	H_20+Grit	43	28	15
Slate	A	H_20	41	37	4
	A	H_20+Grit	35	33	2
Hornfels	A	H_20	45	32	13
Valley Gravel	A	H_20	52	39	13
	A	H_20	49	43	6
New Market	A	H_20	31	18	13
Limestone	A	H_20+Grit	33	23	10
	B	H_20	42	20	22
	B	H_20	39	20	19
	B	H_20	38	20	18

Table 10 contains a compilation of the mean initial BPN values for each type of aggregate plus the percent of the original BPN value after 10, 20, and 120 minutes with water only on the BAPM. Again, values for the New Market limestone rank significantly below those for the non-polishing aggregates.

Table 10
INITIAL BPN VALUES AND PERCENTAGES OF INITIAL VALUES
AFTER 10, 20, AND 120 MINUTES OF WEAR WITH WATER ON THE APW

	Initial SN	SN at 10 Min (% of initial)	SN at 20 Min (% of initial)	SN at 120 Min (% of initial)
Aplite	47	38(80)	33(71)	33(70)
Arch Marble	43	36(84)	34(79)	31(73)
Basalt	43	36(83)	35(82)	29(67)
Biotite Granite	41	38(92)	35(85)	33(80)
Coastal Gravel	39	34(88)	33(84)	28(72)
Fine Granite	37	36(96)	33(88)	30(81)
Diabase	45	39(87)	37(83)	32(71)
Greenstone	47	41(87)	39(82)	34(72)
Quartzite	32	31(98)	28(89)	24(75)
Lovingston Granite	46	39(84)	37(80)	33(72)
Metagraywacke	45	40(88)	40(88)	38(84)
Metamorphics	45	39(87)	37(83)	32(72)
Metavolcanics	44	37(85)	36(82)	31(71)
Petersburg Granite	42	36(88)	35(83)	30(72)
Slate	41	35(86)	33(81)	37(90)
Hornfels	45	41(91)	38(84)	32(71)
Valley Gravels	51	47(92)	46(90)	42(82)
New Market Limestone	31	21(69)	19(61)	18(58)

Unfortunately, the BPN data contained in Tables 9 and 10 show little correlation with SN40S values measured by the skid trailer (see Table 4). Similar low correlations were found by Dillard and Mahone (1963). Analysis of the data also showed other problems, including high test variability and high operator variability.

Table 11.
MEAN SKID NUMBERS AND TRAFFIC DATA FOR ALL MIXES IN THE TEST POPULATION

	S-3	S-5	I-2	S-6	URBAN[a]	ST[b]	SS[c]	SS/B[d]	LATSU/C[e]
Lane Avd	3,812	3,762	2,778	6,375	3,030	1,306	1,940	1,368	2,568
Accumulated Traffic	6,709,595	8,223,842	4,643,765	7,125,249	2,572,138	2,681,696	3,979,295	3,536,964	154,061
Smooth Mean	30	36	37	36	31	37	38	34	43
Ribbed Mean	45	47	48	44	44	45	47	48	50

a. Urban Mix
b. Surface Treatment
c. Slurry Seal C
d. Slurry Seal B
e. Latex

Mix Design vs. Skid Resistance

Table 11 contains mean skid resistance values for pavements containing all of the mixes found in the skid test data base. Note that the SN40S means computed for the I-2 and S-5 mixes are similar. No significant difference in skid resistance for the two commonest mixtures can be inferred from these data. To investigate further, graphs were constructed showing SN40S vs. AT and SN40S vs. LAVD, each containing all of the I-2 and S-5 data. Again, significant differences could not be identified. Finally, individual graphs of SN40S vs. LAVD for I-2 and S-5 with each aggregate were plotted in the same manner. Figure 7 is one of these graphs.

Graphs similar to Figure 7 were constructed for each aggregate type. While the differences in the Arch Marble curves shown in Figure 7 were the most dramatic, in every case but one the I-2 curve showed a greater downward slope than the S-5 curve. The lone exception was Valley Gravel, where the slope differences were insignificant. Even in cases where the initial I-2 SN40S values at low AT were higher than the S-5 values, the greater slope of the I-2 curve carried it to lower SN40S values as AT increased.

Using all of the individual I-2 and S-5 mix curves plotted for SN40S vs. AT for each aggregate type, SN40S values at 1 million, 4.4 million and 8.8 million vehicle passes were estimated. At one million vehicle passes I-2 mixes projected slightly higher SN40S values than S-5 mixes. As accumulated traffic increased to 4.4 million and 8.8 million, S-5 skid numbers assumed the higher values. These trends appear to indicate that during the early stages, I-2 mixes are more skid resistant than S-5 mixes. However, as the pavement ages beyond one million AT, S-5 mixes project higher skid numbers.

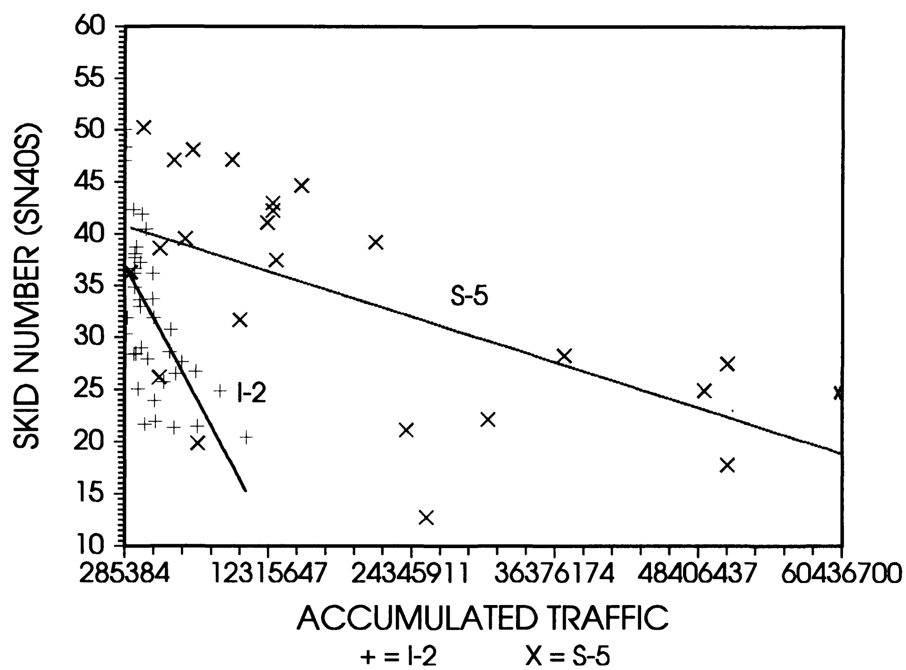

Figure 7. Skid numbers (SN40S) vs. accumulated traffic for I-2 and S-5 mixes containing Arch Marble aggregate.

Pavement Macrotexture as Measured by the Sand Patch Method

Over the course of the study, 105 sand patch tests were conducted, mostly in response to requests to investigate specific aggregates. Six lithologies were tested (Table 8). No claim can be made that these data represent a comprehensive survey of macrotexture depths associated with all 18 aggregate lithologies in Virginia. Macrotexture depths for the 105 tests ranged from 0.23 mm (0.009 in) to 1.07 mm (0.042 in). Most fell into the interval 0.25 mm (0.010 in) to 0.66 mm (0.026 in). For situations requiring a high level of skid resistance, Salt (1976) recommended a minimum macrotexture depth of 1.00 mm (0.039 in).

Table 12 lists the number of sand patch tests performed and the mean macrotexture depth for each aggregate type tested. Mean depths ranged from 0.49 mm (0.019 in) for Slate and Biotite Granite to 0.97 mm (0.038 in) for Fine Grained Granite. Compared to Fine Grained Granite, the macrotextures exhibited by the other five aggregates are relatively low. Three of the five consistently ranked low in skid resistance (Table 8). Figures 8, 9 and 10 show the relationships between macrotexture depth and skid numbers for three of the aggregates listed in Table 12. Each figure contains data points and second order curves for smooth and ribbed tires. Plainly, the difference between the smooth and ribbed SN40 curves decreases as macrotexture depth increases.

Table 12
MEAN MACROTEXTURE DEPTHS OF PAVEMENTS CONTAINING SIX AGGREGATE TYPES

Aggregate	Number of Tests	Mean Macrotexture Depth
Aplite	24	0.56 mm (0.022 in.)
Arch Marble	32	0.49 mm (0.019 in.)
Biotite Granite	26	0.49 mm (0.019 in.)
Lovingston Granite	5	0.58 mm (0.023 in.)
Slate	15	0.49 mm (0.019 in.)
Fine Grained Granite	30	0.97 mm (0.038 in.)

Figure 11 shows mean macrotexture depths by year of placement for the pavements measured by the sand patch method. The lowest depths were found in pavements placed in 1985-1986. Mean macrotexture depths for those years were found to be 0.44 mm (0.0173 in) and 0.40 mm (0.0158 in), compared to a mean depth of 0.50 mm (0.0197 in) for all pavements measured. The low macrotextures of the 1985-86 period were reflected in decreased pavement friction. The lowest mean annual skid values for SN40S were found for pavements placed in those years.

Milled or Grooved Pavements

Texturing bituminous concrete pavements to improve skid resistance is relatively new in Virginia. Tables 13 and 14 contain data on two recent highway projects within the state where milling of pavement surfaces was undertaken to increase macrotexture and improve skid resistance.

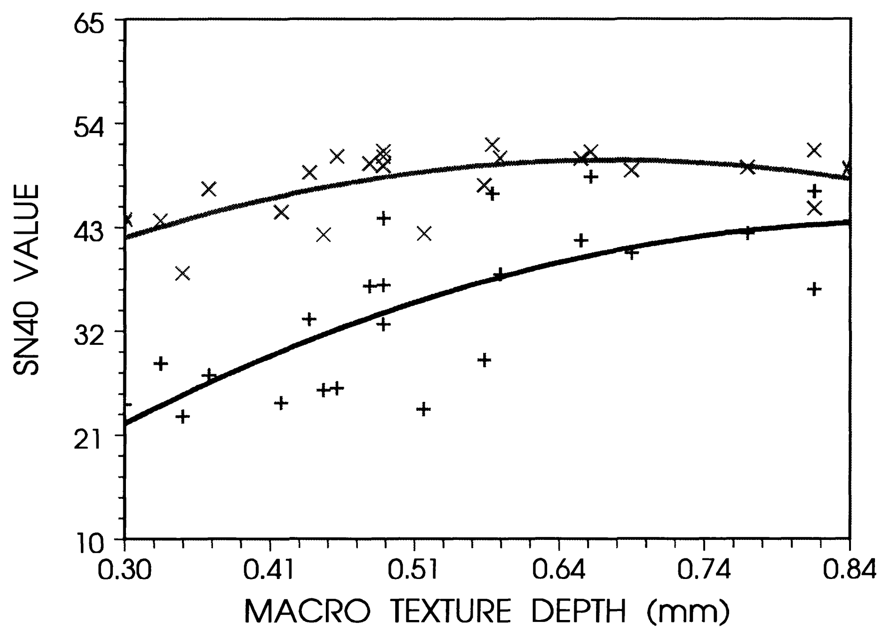

Figure 8. SN40 values vs. macrotexture depth for pavements containing Aplite aggregate. + = smooth tire data. x = ribbed tire data.

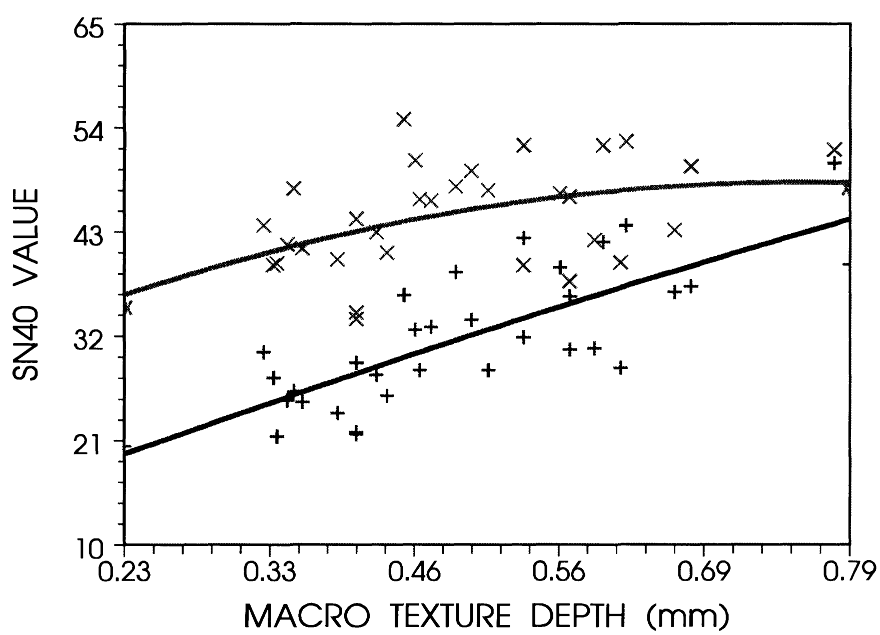

Figure 9. SN40 values vs. macrotexture depth for pavements containing Arch Marble aggregate. + = smooth tire data. x = ribbed tire data.

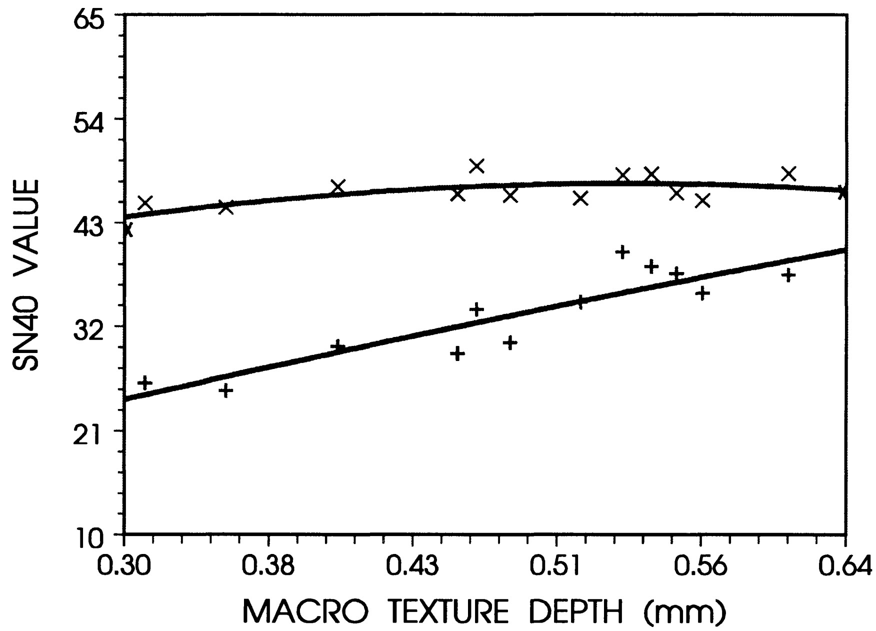

Figure 10. SN40 data vs. macrotexture depth for pavements containing Slate aggregate. + = smooth tire data. x = ribbed tire data.

Table13.
SKID TESTS AND OTHER DATA FROM PAVEMENT TEXTURING CONDUCTED ON RT. 134

Site	Lane	No. of Tests	Variables	Mile Post	Mean Sn40S Before Mill'g 11/28/90	SD	Mean Sn40S After Mill'g 12/11/90	SD	Mean Sn40S After Mill'g 6/11/91	SD
1	WBTL	4	Adjusted Speed	2.13-2.36	14	4.0	40	0.5	17	3.4
2	WBTL	11	Adjusted Speed	1.42-2.13	13	2.1	41	2.5	20	4.6
3	WBTL	1	Changed Teeth	1.17-1.42	15	3.0	44	0.5	23	6.7
4	WBPL	19		1.17-2.36	18	8.3	41	5.0	24	7.5

SAND PATCH TEST

Number of Tests	Variables	Mean Diameter in Inches	Standard Deviation
4	Before Texturing	14.22	0.30
44	Regular Teeth	7.08	0.71
35	After Alternating Teeth	6.03	0.25

Table 14. SKID TESTS AND OTHER DATA FROM PAVEMENT TEXTURING CONDUCTED ON INTERSTATE 95

	Mean SN405 Prior to Texture (5/1/90)			Mean SN405 After Texturing (4/23/91)			Mean SN405 After Texturing (6/18/91)			Mean SN405 After Texturing (9/4/91)		
Lane	No. of Tests	SN405	Std. Dev.	No. of Tests	SN405	Std. Dev.	No. of Tests	SN405	Std. Dev.	No. of Tests	SN405	Std. Dev.
0				15	55	2.3	16	51	2.8	15	52	2.1
1	22	19	1.3	15	49	1.8	17	44	1.9	15	40	2.0
2				15	48	1.4	16	44	1.2	15	39	1.2
3				15	49	1.6	16	48	2.4	15	45	2.3

SAND PATCH TESTING AFTER TEXTURING

Lane	Number of Tests	Mean Diameter in cm	Standard Deviation
0	125	14.6	0.57
1	135	14.6	0.59
2	110	14.4	0.15
3	100	14.6	0.12

DATA FROM EXTRACTED CORES

Densities:	93.6	94.2	95.0	95.4	96.1	$\bar{x}$ = 94.9		Std. Dev. = 0.98	
VTM:	6.4	5.8	5.0	4.6	3.9	$\bar{x}$ = 5.1		Std. Dev. = 0.98	
VMA:	18.6	18.1	17.4	17.1	16.5	$\bar{x}$ = 17.5		Std. Dev. = 0.83	
VFA	65.8	68.2	71.5	73.2	76.5	$\bar{x}$ = 71.0		Std. Dev. = 4.19	
Gradation:	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
% Passing:	100	94.8	60.6	42.6	34.3	25	14.3	9.2	6.9
AC:	5.13%		Average Vehicles Daily: 123,500				Average Tractor Trailers Daily: 9,680		

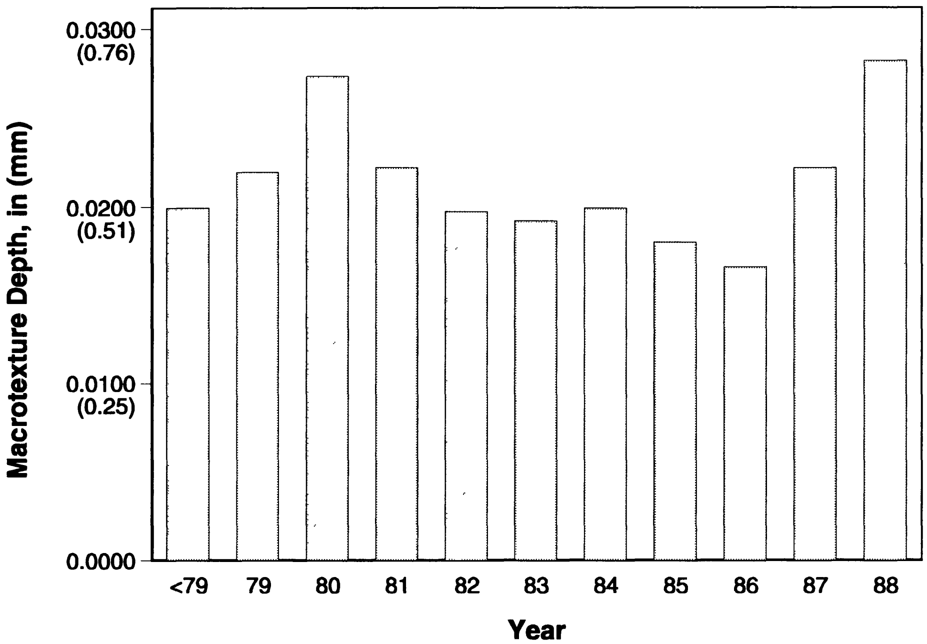

Figure 11. Mean macrotexture depths by year of placement for pavements measured by the sand patch method.

Table 13 shows the results of milling on Route 134, a road carrying moderate levels of traffic. Milling significantly increased macrotexture and skid resistance. However, after six months under traffic, skid resistance declined to values approaching premilled levels. Visually, it was evident that much of the macrotexture had been lost. Table 14 contains similar data for a section of Interstate 95. Despite far greater volumes of traffic, the I-95 section appears to have retained most of its skid resistance even after several months of wear.

Experimental longitudinal grooving has also been conducted on two bituminous pavements in Virginia. Table 15 contains skid data before and after grooving of a high-traffic pavement in eastern Virginia. The pavement was surfaced with an S-5 mix. Similar longitudinal grooving was performed on a slippery section of U.S. Route 29 at Lynchburg, Virginia. While original test results were unavailable, recent testing of the site three years after grooving yielded a mean SN40S value of 34.

DISCUSSION

Skid Resistance of Various Aggregates

Table 8 shows that certain aggregate groups tend to fall near the top of each ranking, indicating high relative skid resistance. Other groups consistently fall near the bottom, indicating relatively low skid resistance. Because of the high variability in the test population, the relative ranking in any one of these columns might be open to serious question. However, some aggregate groups consistently rank high or low.

Aggregates exhibiting generally high rank are Valley Gravel, Fine Grained Granite, Lovingston Granite, Coastal Gravels, and Diabase. Valley and Coastal Gravels are composed of a mixture of crushed and uncrushed quartz and quartzite gravels. The materials are hard and durable, showing little wear even under heavy traffic. While Fine Grained Granite and Lovingston Granite rank highest of the granites, Biotite Granite and Petersburg Granite also project relatively high SN40S values. The mixture of hard granular quartz and softer minerals produces differential wear and surface renewal in granites, which enhances skid resistance (Webb, 1970). Diabase is a very tough rock composed of intergrown feldspars and pyroxenes which resists wear under traffic.

Aggregate groups which consistently rank relatively low in skid resistance are Arch Marble, Triassic Hornfels, Slate, and Aplite. Greenstone is rather inconsistent, falling near the top of two columns and near the bottom of the remaining two columns.

SN40S data on the remaining eight aggregate groups tend to be distributed between the high and low members. These groups consistently exhibit levels of skid resistance near the mean for the whole test population. Included in this middle group are two granites (Biotite Granite and Petersburg Granite), three types of metamorphic rocks (Metavolcanics, Metagraywacke, and Undifferentiated Metamorphics), Gravel Blends, Antietam Quartzite, and Basalt.

The four aggregates projecting the lowest skid resistance exhibit some properties which might logically account for their relatively low tire-pavement friction values. Slate and Arch Marble are strongly foliated rocks, high in micas. Aggregates produced from the crushing of foliated rocks tend to assume flat, platy shapes with smooth, reflective faces. In addition, the Arch Marble contains high levels of calcite, a relatively soft mineral. Why the remaining two aggregates, Triassic Hornfels and Aplite, exhibit only fair skid resistance is less clear. Triassic Hornfels is very fine grained, dense, uniform rock, and Aplite is composed predominately of feldspar. While feldspars are harder than calcite and micas, they are softer than quartz and may cleave under stress. Uniformity of hardness in the minerals of an aggregate, if the minerals are softer than quartz, may not be the optimum condition for maintaining a high level of skid resistance (Webb, 1970). The uniformity of the Aplite and the Triassic Hornfels may preclude surface renewal and make them susceptible to polishing if traffic is sufficiently heavy.

Table 15
SKID TEST RESULTS BEFORE AND AFTER GROOVING OF A 1.3 MILE SECTION OF AN S-5 PAVEMENT ON ROUTE 44 IN EASTERN VIRGINIA

Milepost	SN40S Before Grooving	SN40S After Grooving	SN40S 4 Years After Grooving
0.7			
0.8			
	22		
0.9			
	18		33
1.0			39
		37	
1.1	22		
			35
1.2			
	18	35	
1.3			33
	18		
1.4			29
1.5			36
	17	38	
1.6			37
1.7			
	22	43	
1.8			
		43	
1.9	23		
Mean	20	39	36

It appears that if Virginia is to consistently maintain high levels of wet accident safety in the face of increasing traffic, some LAVD limitations may be required for the use of Arch Marble, Aplite, Slate, and Triassic Hornfels.

BAPM-BPT Tests

Aside from the problems of test and operator variability, other researchers (Webb, 1970; Mullen, 1974; Henry and Dahir, 1979) have found that BPT friction numbers (BPN) seem to be most affected by aggregate and pavement asperities in the microtexture range (wavelengths ≤ 0.5 mm). It is generally accepted (Henry, 1977; Balmer and Hegmon, 1980; Henry and Saito, 1981) that microtexture is most effective in providing wet skid resistance at slow speeds of 30 miles per hour or less, and macrotexture (wavelengths from 0.5 to 50.0 mm) is the more critical element in providing skid resistance in pavements carrying medium to high speed traffic. Given a correlation between macrotexture and skid resistance at medium to high speeds, there may be little reason to expect BPT test results and skid trailer test results to agree.

According to tests performed for this project, the BAPM-BPT system can differentiate between nonpolishing aggregates and highly polish-susceptible aggregates. However, in Virginia this capability appears to be unneeded since simple hand specimen examination is sufficient to differentiate polishing from nonpolishing rock types. Results of the BAPM-BPT tests in this study showed little correlation with the SN40S numbers produced by the skid trailers. Based on the data presented, use of the BAPM-BPT system to pre-evaluate the skid resistance of the various aggregates produced within the state appears to hold little promise.

Mix Design and Pavement Macrotexture

Comparison of the relative skid resistance of I-2 and S-5 mixes showed a more rapid loss of skid resistance for I-2 mixes than for S-5 mixes as accumulated traffic increased, for all aggregate types except Valley Gravel. This was attributed to aggregate wear. In particular, large platy particles of Arch Marble and Slate in I-2 mixes tended to be oriented parallel to the pavement surface, resulting in low aggregate relief and smooth foliation or cleavage planes in the aggregate coming in contact with the tire. The results of these tests suggest that when platy aggregate is used, S-5 mixture would provide better long-term skid resistance than I-2.

Only a limited number of sand patch tests of pavement macrotexture were made, and these tests did not encompass all aggregate types. Consequently, findings from the sand patch tests are not conclusive, but it seems reasonable to hypothesize an association between the low macrotexture depth of Aplite, Arch Marble, Slate and Hornfels and their low skid resistance (Table 8). Again, logical explanations for this effect might be accelerated wear due to high contents of relatively soft minerals, or the preferred flat orientation of platy aggregate particles. Further research is needed to design bituminous pavements to ensure greater macrotexture.

The low macrotexture values for pavements placed in 1985-86, as measured by the sand patch test in this report, may reflect increased asphalt content. Asphalt contents were often increased during this period in order to increase density in the mixes (C. S. Hughes and K. H. McGhee, personal communication). One of the authors (D. C. Mahone) has also observed high rates of flushing for pavements placed during the mid-80s. Both skid numbers and macrotexture depth return to more normal levels after this period, so the problem apparently has been addressed.

Milled and Grooved Pavements

The findings for milled or grooved bituminous pavements suggest that pavement skid resistance can be effectively increased by texturing. However, the results of the milling on Route 134, where skid values reverted to pre-milled levels after six months, suggest that mix design may be critical to the success of textured pavements. High density (97%) and high asphalt content (6.76%) resulting in an unstable mix were suspected as the causes for the rapid reversion. In the I-95 section, lower density (94.9%), lower asphalt content (5.13%) and an adequate void structure may have been important factors in retaining pavement texture and skid resistance. For the experimental longitudinal grooving, retention of relatively high SN40S values after four years under heavy traffic suggests that the mix was stable enough to retain the grooves over an extended period. Additional testing is needed to determine the best asphalt mix for milled bituminous pavements.

CONCLUSIONS

1. On the basis of field observations and laboratory analyses, the aggregates from Virginia's 57 producers of nonpolishing material were found to represent 18 different lithologies.

2. Skid test results for the total test population of 1,242 sites showed a mean SN40 of 36 and a standard error of 7.8 for smooth tires, and a mean SN40 of 47 with a standard error of 5.2 for ribbed tires.

3. Mean values for accumulated traffic (AT) and lane average vehicles per day (LAVD) for the eighteen aggregate groups varied widely. AT ranged from 2.4 million for Slate to 9.9 million for Diabase. LAVD varied from 1,610 for Slate to 6,715 for Diabase. These large differences preclude simple comparisons of mean skid numbers (SN40S) for the different aggregate groups.

4. In an effort to rank the relative skid resistance of the 18 aggregates SN40S data were treated using four different methods. These were: 1) determining the SN40S value at each group mean minus 2 standard errors, 2) determining the LAVD value where a two standard error line projects to an SN40S of 20, 3) ranking the aggregate group T values from most positive to most negative through a multiple regression analysis incorporating the whole test population, and 4) ranking six of the aggregate types by multiple regression analysis where sand patch macrotexture data from 109 test sites were available. Based on these

four methods of data treatment, five aggregate groups, Valley Gravel, Fine Grained Granite, Lovingston Granite, Coastal Plain Gravels, and Diabase, consistently ranked relatively high in skid resistance, while four aggregates, Arch Marble, Triassic Hornfels, Slate, and Aplite, ranked consistently low.

5. Only one aggregate group, the Arch Marble, showed a mean LAVD (2,819) higher than that projected at the intersection of the SN40S = 20 line and the curve at two standard errors below the SN40S mean (1,975). This difference could mean that more than 2.5 percent of the pavements containing Arch Marble would show SN40S values below 20.

6. Extensive tests using the British Accelerated Polishing Machine (BAPM) and the British Pendulum Tester (BPT) indicated that the British Pendulum test Numbers (BPN) produced by the BAPM-BPT system on Virginia's nonpolishing aggregates showed little correlation with the SN40 numbers produced by the skid trailer. Consequently use of the BAPM-BPT system to pre-evaluate the skid resistance of aggregates produced in Virginia appears to hold little promise at this time.

7. The two mix designs, I-2 and S-5, used most extensively in Virginia over the last two decades showed no overall statistical difference in SN40S values when the whole test population was considered.

8. When skid numbers (SN40S) for I-2 and S-5 mixer were plotted vs. accumulated traffic (AT) for each aggregate type, I-2 curves usually started at higher SN40S values than S-5 curves, but showed a greater negative slope. This indicates that the initial skid resistance of I-2 is higher but drops more rapidly as accumulated traffic increases, especially for platy aggregates. Consequently, when platy aggregates are used, S-5 mixtures could be expected to provide a higher level of long-term skid resistance than I-2 mixtures.

9. Macrotexture depth, as measured by the sand patch method, showed a higher correlation with skid number (SN40S) than any other factor investigated.

10. As macrotexture depth increased, the differences between smooth and ribbed tire skid numbers diminished. The finding that smooth tires are more sensitive at low macrotexture depths supports the use of SN40S values as a standard measure of skid resistance. Ribbed tires may show a low sensitivity to potentially hazardous pavements.

11. If a mix possesses adequate volumetric properties, pavement texturing by milling or grooving appears to hold considerable promise as a method of increasing macrotexture and skid resistance of worn or low-friction bituminous pavements.

RECOMMENDATIONS

1. Based on the results of the present study, together with prior research and extensive discussions with the operating divisions, VDOT should continue to use the smooth tire as the standard tire for skid testing. A smooth tire skid number (SN40S) of 20 should be the minimum acceptable wet pavement SN40S value. SN40S values under 20 should be considered unacceptable and require immediate remediation.

2. All nonpolishing aggregates produced in Virginia, with the exception of Aplite, Arch Marble, Slate, and Triassic Hornfels, should be allowed in all pavement surfaces regardless of expected traffic volumes.

3. Aggregates composed of Aplite, Slate, Arch Marble, and Triassic Hornfels should not be allowed in Interstate or other high traffic pavement surfaces until further research is conducted.

4. When platy aggregates such as Slate and Arch Marble are used in bituminous pavement, S-5 rather than I-2 mixes should be used.

5. Since pavement macrotexture depth showed a higher correlation with skid number (SN40S) than any other factor tested, laser methods or other rapid methods of measuring pavement surface macrotexture should be developed. The sand patch method is labor and time intensive, and can be dangerous to perform.

6. Include the option of milling or grooving as an alternative to repaving wet accident hot spots or other locations where skid resistance is found to be low.

7. Research on methods of texturing bituminous pavement to improve skid resistance should be expanded.

8. Methods for increasing the macrotexture of new pavement surfaces should be developed, including design, field placement techniques and roller operations.

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