FACTORS INFLUENCING AGGREGATE SKID-RESISTANCE PROPERTIES

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Aggregates that had been rated in laboratory paving mixtures for wear and polishing resistance have been examined to determine factors that influenced differences in laboratory skid-resistance properties observed. Aggregates have been examined for physical properties such as specific gravity, absorption, and surface texture; for Los Angeles wear; for acid-insoluble residue percentage and gradation in the case of carbonate aggregates; and petrographically for mineral composition, grain shape, grain size and distribution, and hardness of minerals. An attempt has been made to relate the properties determined to observed laboratory skid-resistance performance. No general correlations were observed between physical properties of aggregates and laboratory skid resistance. Correlations were observed, however, within some petrographic groups. For granite aggregates, higher Los Angeles wear loss indicated higher skid resistance. For synthetic aggregates, high absorption and surface capacity seemed to correlate with higher skid resistance. The acid-insoluble residue percentages for the four carbonate aggregates examined indicated that skid resistance improved with increased residue and that sand-size residue probably is more important than total residue. A general correlation was found between the petrographic properties and the skid resistance of any given aggregate: skid resistance was higher for aggregates having mixed composition of hard and soft minerals than for aggregates consisting predominantly of minerals of the same type having the same hardness.

•THIS paper reports on factors that influence the laboratory skid resistance of paving aggregates. The study is part of an overall research program on laboratory and field determination of wear and polishing properties of aggregates as these properties affect the skid resistance of pavements.

Prior to this study, two laboratory methods had been developed for predetermining skid-resistance properties of aggregates subjected to wear and polishing, the circular track and the jar mill methods (2, 3). Different aggregates were polished to different terminal skid-resistance levels, and there was a linear correlation between methods even though terminal polish levels were not the same for a given aggregated in both methods. All aggregates tested, however, had the same relative rating in both test methods. Skid resistance was measured by using the British portable tester (BPT) and was recorded in British portable numbers (BPN) in accord with ASTM Designation E 303-69.

The purpose of this study was to discover why different aggregates behave differently under the same wear and polishing exposures. Twenty aggregates that had been evaluated by using the circular track and jar mill methods were subjected to test for physical properties, for insoluble residue in the case of carbonate rocks, and for petrographic properties. These various properties have been compared to wear and polish results for possible correlation. Figure 1 shows the steps in the investigation procedure.

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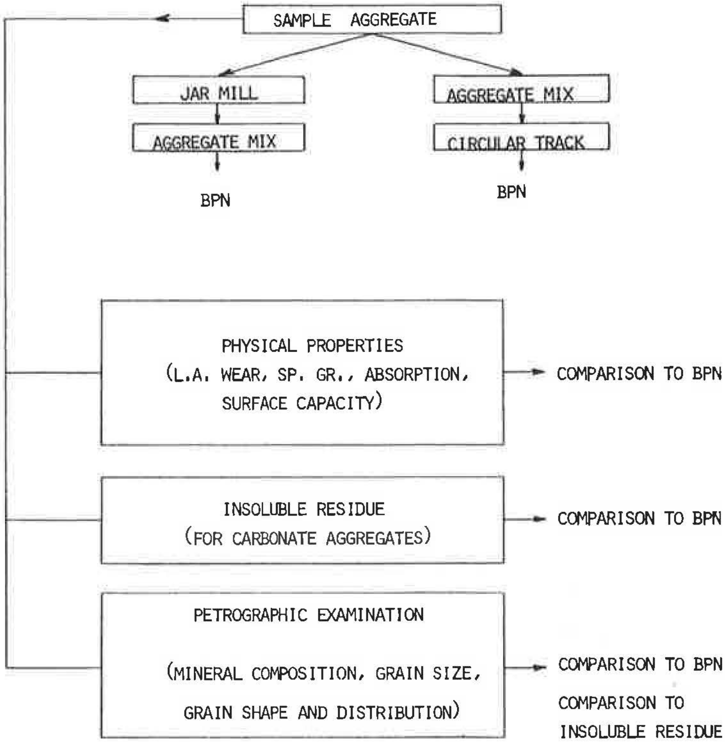

Figure 1. Study procedure.

The major findings of this research involve the hardness of minerals in the various aggregates studied and the mixture of minerals of different hardnesses in the same aggregate. An aggregate containing a mixture of from 50 to 70 percent hard minerals and 30 to 50 percent soft minerals will have a terminal skid resistance after wear that is higher than aggregates containing predominantly soft or hard minerals. Aggregates containing predominantly hard minerals will polish less rapidly than will aggregates containing predominantly soft minerals, but terminal skid-resistance values when reached will be similar. Hardness and percentages of minerals can be determined from petrographic studies of thin sections of aggregates by using the polarizing microscope.

SAMPLE AGGREGATES

Aggregates from 20 sources representative of the range of aggregates used in North Carolina and believed to be fairly representative of those used in other parts of the United States had been previously rated for laboratory skid resistance in tests using the circular track and jar mill methods (1-3). Skid resistance was determined by using the British portable tester in accordance with ASTM Designation E 303-66T(4), and values were recorded as British portable numbers (BPN). Physical properties were obtained by using AASHO and ASTM procedures when applicable (Table 1). Circular track BPN values are given in Table 2.

North Carolina State Highway Commission (NCSHC) No. 13 stone gradation (3) has been used in all of the testing. This is the normal coarse aggregate gradation used in bituminous surface mixes, and the physical properties of this material are given in Table 1. In the jar mill method, aggregate from the No. 13 stone was obtained by sieving the fraction passing the $^3/_8$-in. and retained on the No. 4 sieve.

TABLE 1

PHYSICAL PROPERTIES OF SAMPLE AGGREGATES

Number	General Classification	Grading C Los Angeles Wear Loss[a] (percent)	Bulk Specific Gravity[a]	Water Absorption[a] (percent)	Surface Capacity[b] (percent)	Approximate Asphalt Absorption[b] (percent)
LS-1	Limestone	18.0	2.85	0.30	0.6	0.21
LS-2	Limestone	25.0	2.87	0.40	0.9	0.28
LS-3	Limestone	46.0	2.47	3.35	5.5	2.45
LS-4	Limestone	29.0	2.95	0.30	0.7	0.21
GT-1	Granite	36.0	2.79	0.31	0.6	0.20
GT-2	Granite	63.0	2.67	0.42	1.0	0.29
GT-3	Granite	51.0	2.65	0.50	1.0	0.34
GT-4	Granite	41.0	2.66	0.50	1.0	0.34
GN-1	Granite gneiss	29.0	2.67	0.41	0.8	0.28
GN-2	Granite gneiss	52.0	2.68	0.6	1.1	0.41
GN-3	Granite gneiss	48.0	2.71	0.55	1.0	0.36
GL-1	Gravel	42.0	2.64	0.30	0.5	0.20
GL-2	Gravel	43.0	2.78	1.01	2.1	0.68
SL-1	Slate	17.0	2.78	0.32	0.4	0.21
SL-2	Slate	24.0	2.78	0.33	0.5	0.2
RH-1	Rhyolite	27.0	2.67	0.30	0.6	0.21
TR-1	Traprock (diabase)	15.0	2.77	0.30	0.6	0.20
SS-1	Sandstone (arkose)	N.A.	2.66	2.55	5.5	1.70
SP-1	Expanded glass[c]	23.3	2.05	2.4	5.4	1.60
SO-1	Expanded slate[c]	40.0	1.58	3.5	7.2	2.45

[a]Determined by the Materials Laboratory of the North Carolina State Highway Commission.
[b]Obtained by using Hveem's Method (5, p. 56).
[c]Provided by manufacturer except surface capacity.

MEGASCOPIC AND PETROGRAPHIC STUDY

Thin sections of hard specimens were prepared for all of the mineral aggregates given in Table 1 except for one gravel, GL-1, and the synthetic aggregates, SP-1 and SO-1. These aggregates were not included because sufficiently large pieces were not available. Where an aggregate apparently consisted of more than one rock type or color representative "chunks" were obtained, and thin sections were prepared for each of the variations recognized. A detailed petrographic description of each aggregate is given in other publications (1, 2). Photomicrographs of thin sections obtained from 12 aggregates representative of the aggregate samples are shown in Figure 2. The photomicrographs and the data given in Tables 3 and 4 reveal that aggregates in different classifications as well as some aggregates grouped in the same classification may vary significantly in mineral composition percentage or size and shape of grain or both. Variations of this nature become important when mineral properties of these aggregates are related to their skid-resistance properties.

TABLE 2

RELATIVE RATING OF SKID-RESISTANCE CHARACTERISTICS OF SAMPLE AGGREGATES

Aggregate	BPN Adjusted Value After Exposure		Relative Rating
	8 Hours	16 Hours	
SS-1	61.0	58.5	1
SO-1	52.0	51.0	2
SL-2	46.5	46.0	3
SP-1	46.5	45.0	4
SL-1	46.0	45.0	5
GL-2	45.3	45.0	6
GT-2	45.0	44.5	7
GT-3	45.0	43.5	8
GT-4	44.5	43.0	9
GN-1	44.2	43.0	10
GN-2	43.7	43.0	11
GN-3	43.5	42.5	12
GT-1	43.0	42.0	13
RH-1	43.5	41.5	14
TR-1	43.5	40.5	15
GL-1	42.0	40.0	16
LS-4	41.5	40.0	17
LS-3	41.5	40.0	18
LS-2	[illegible]	[illegible]	19
LS-1	36.0	35.0	20

INSOLUBLE RESIDUE TEST

Four of the aggregate samples included in this study were classified as limestone (Table 1). In some geographical areas this type of aggregate has a reputation for polishing readily under the action of traffic, causing pavement surfaces to become slippery after a relatively short period of time.

Some investigators (6-14) have examined limestones from various sources and have found that they are not all alike in their polishing characteristics. These same investigators generally agree that a limestone having some siliceous material in its composition is less likely to polish and become slippery than is one having only carbonate composition. Agreement is not general, however, as to the percentage of siliceous material and the particle size that must be present in a limestone to make it significantly skid resistant.

A method to determine the amount of siliceous material contained in a carbonate aggregate is the acid-insoluble residue test pioneered by Gray and Renninger (11) and

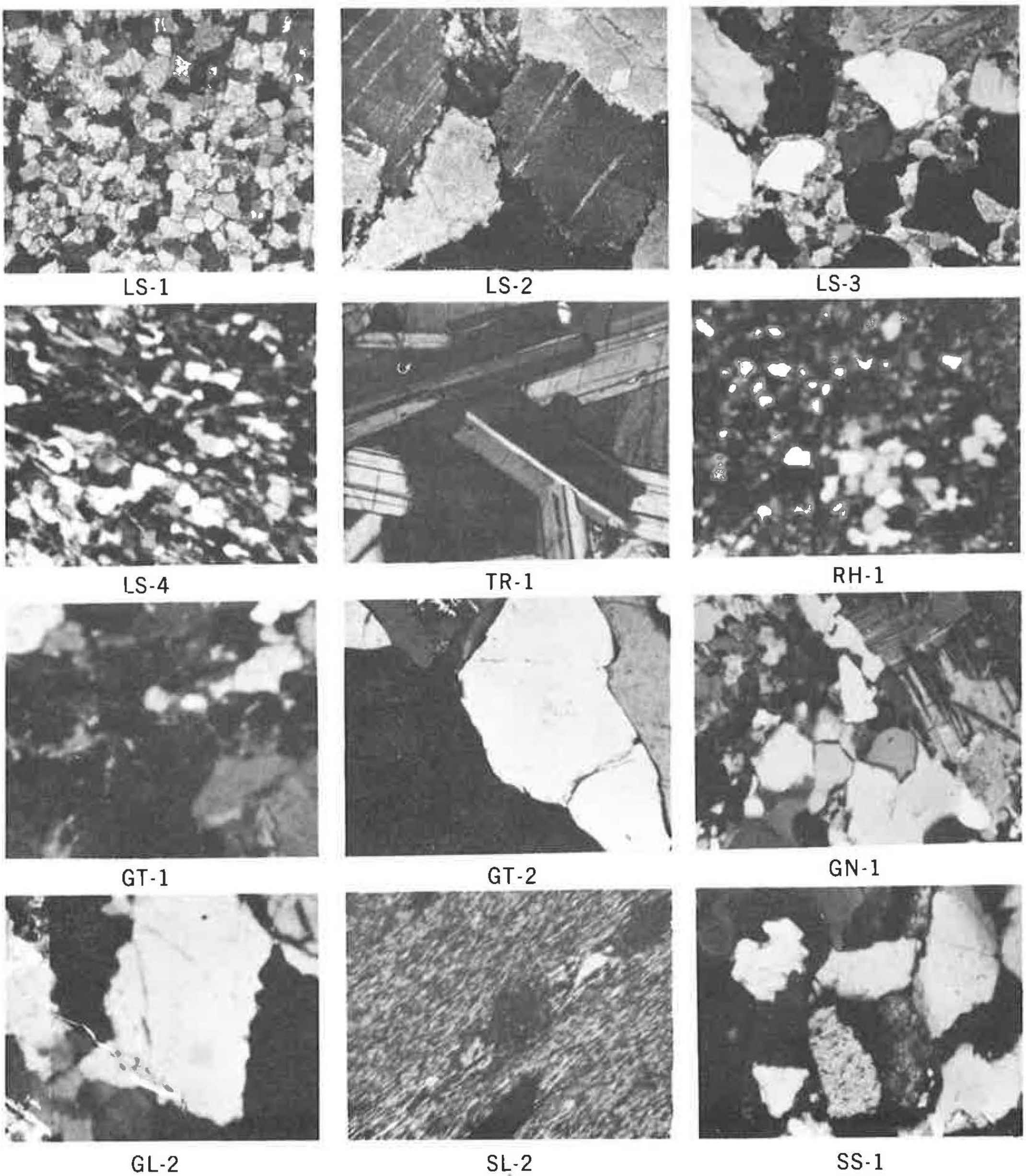

Figure 2. Photomicrographs of 12 selected aggregates under crossed nicols (x35).

modified by others. A modification of the Gray and Renninger method was used to determine the amount of insoluble residue in the four limestone aggregates used in this study.

For each of the four limestone aggregates, three acid-insoluble residue tests were performed by using NCSHC No. 13 stone, and three tests were performed by using only the fraction of material passing the ⅜-in. and retained on the No. 4 sieve. Average gradations indicating percentage and size of residue particles obtained as a result of these tests on each aggregate are given in Table 5.

Some correlation was found between the amount and particle size of insoluble residue and skid-resistance properties of pavement mixes made from carbonate aggregates. Generally, it was found that the higher the amount of insoluble residue was, the higher the skid resistance was.

TABLE 3

MOHS' HARDNESS OF MINERALS IN SAMPLE AGGREGATES

Mineral		Hardness Range
No.	Name	
M-1	Chlorite (sericite or kaolinite)	2 to 2.5
M-2	Mica (biotite or muscovite)	2 to 3
M-3	Calcite	3
M-4	Dolomite	3.5 to 4
M-5	Pyroxene (augite)	5 to 6
M-6	Feldspar (plagioclase or orthoclase)	6
M-7	Hematite or magnetite	6
M-8	Olivine	6.5 to 7
M-9	Quartz	7
M-10	Others (apatite, amphilbole, pyrite, epidote, and zircon)	5 to 7.5

ANALYSIS OF FACTORS AFFECTING POLISHING OF AGGREGATES

Skid Resistance and Physical Properties of Aggregates

A comparison between the physical properties of the 20 sample aggregates given in Table 1 and the skid-resistance characteristics after exposure of the same aggregates given in Table 2 has failed to establish a consistent general relationship between any of

TABLE 4

PERCENTAGE OF MINERAL COMPOSITION OF SAMPLE AGGREGATES

Aggregate	M-1	M-2	M-3	M-4	M-5	M-6	M-7	M-8	M-9	M-10
LS-1			93						5	2
LS-2			65	30					5	
LS-3			50	20			5		25	5
LS-4		5	25	30		5			30	5
GT-1 (light)		10				52[a]			35	3
GT-1 (dark)		12				55[a]			20	13
GT-2 (light)		10				65			20	5
GT-2 (dark		10				70			20	trace
GT-3		10				50			35	5
GT-4	2	8				55			35	
GN-1		10				40			40	10
GN-2	4	10				55			25	6
GN-3		15				60[a]			15	10
GL-1									98	2
GL-2 (granite)	2	10				32			50	6
GL-2 (gneiss)		5			30	32			25	8
SL-1	60					20			20	
SL-2	55					20			15	10
RH-1		5				40	15		40	
TR-1					40	50	5	5		
SS-1						50[a]	10		40	

Note: Percentage of mineral composition is approximate. Names and hardness of minerals are given in Table 3. Aggregate identification and more details are included elsewhere (1, 2).

[a]Chemically altered, in part.

TABLE 5

INSOLUBLE RESIDUE OF FOUR LIMESTONES

Sieve	Accumulative Percent Retained[a]							
	LS-1		LS-2		LS-3		LS-4	
	No. 13 Stone[b]	No. 4 Fraction[c]	No. 13 Stone[b]	No. 4 Fraction[c]	No. 13 Stone[b]	No. 4 Fraction[c]	No. 13 Stone[b]	No. 4 Fraction[c]
3/8 in.	-	-	-	-	-	-	-	-
No. 4	1.3	1.8	0.2	0.7	0.1	0	8.2	22.5
No. 8	2.0	1.9	0.8	1.0	0.1	1	15.8	24.8
No. 16	2.1	1.9	0.9	1.0	0.2	0.1	17.7	25.2
No. 30	2.2	2.3	1.1	1.1	0.7	0.6	17.8	25.3
No. 50	2.2	2.3	1.1	1.2	5.1	6.4	17.8	25.4
No. 100	2.2	2.3	1.3	1.2	23.6	24.6	17.8	25.4
No. 200	2.2	2.4	1.4	1.3	27.7	31.0	17.8	25.4
No. 270	-	2.4	-	1.3	-	31.4	-	25.6
Filter paper (total residue)	7.3	6.7	3.4	33.3	34.1	34.1	44.4	45.4

[a]Each value is average of three tests for 500-gram initial sample.
[b]Gradation given in another paper (3).
[c]Passing 3/8 in. sieve and retained on sieve No. 4.

the physical properties of an aggregate and its skid-resistance characteristics. It had been anticipated intuitively that the rougher the unworn surface texture of an aggregate was, as may be reflected by its absorption or surface capacity and/or specific gravity, the higher its resistance to skidding would be after wear and polishing. Comparisons have revealed that, although this concept may be true for SO-1, SP-1, SS-1, and GL-2 with high absorption, high surface capacity, and high skid resistance, it does not hold true for either LS-3 with high absorption and relatively low skid resistance or, in a reverse manner, SL-1, SL-2, and GT-1 with low absorption and surface capacity and relatively high skid resistance.

A comparison of both Los Angeles and jar mill wear losses of an aggregate to the skid resistance of that aggregate produced no results that could be considered consistent or general. For example, in the case of the four granite aggregates (GT-1 through GT-4), the higher the Los Angeles wear loss was, the higher the skid resistance was; this trend was almost reversed in the case of the limestone aggregates (LS-1 through LS-4).

Skid Resistance of Carbonate Aggregates

All four of the limestone aggregates fall at the lower end of the group of aggregates with respect to skid resistance after exposure (Table 2). LS-3 and LS-4 were about as skid resistant as the lowest of the other aggregates, LS-2 and LS-1 ranged downward, and LS-1 exhibited the lowest skid resistance value of all aggregates included in the research.

Review of the literature on skid-resistance characteristics of limestone aggregates had pointed to the significance of the acid-insoluble residue content of an aggregate in improving the skid-resistance characteristics of that aggregate. By using the polarizing microscope method, we found that the sand-sized (-0.05 mm) insoluble residue that remained from reacting the limestone with hydrochloric acid consisted of hard siliceous particles, mostly quartz. Similar findings have been reported by other investigators (7, 8, 9, 10, 11, 12, 13). Particles smaller than the size of sand included siliceous material and other clay-sized material that was not identified.

An examination of the insoluble residue test data given in Table 5 generally confirms the findings of other investigators that the higher the insoluble residue of a carbonate aggregate is, the better its skid-resistance performance will be. This general statement, however, seems to require some qualification even in the case of this admittedly limited investigation of limestone aggregates.

Low Insoluble Residue Limestones

A comparison of LS-1 and LS-2 reveals that although LS-1 had a more total insoluble residue and more sand-sized residue than did LS-2, the latter showed a significantly higher skid resistance after exposure. Other differences must exist that obscure the differences in percentage of residue.

LS-1 is identified from the petrographic study as a uniform fine-grained limestone composed of about 95 percent subangular calcite (Fig. 2). The presence of about 2.4 percent sand-sized insoluble residue seems to have contributed little to improving skid resistance, and about 5 percent of minus No. 200 residue containing some clayey material may actually have contributed to lower skid resistance. Under exposure, LS-1 polished rapidly to a relatively low-skid-resistance value.

LS-2 contained less sand-sized insoluble residue and less total insoluble residue than did LS-1. An examination of the LS-2 photomicrograph shown in Figure 2 reveals that this aggregate has subangular medium-to-coarse carbonate grains. These grains were estimated to be one-third dolomite (H = 3.5 to 4) or magnesite (H = 3.5 to 5) and two-thirds calcite (H = 3). It is believed that the presence of coarse-grained dolomite or magnesite with slightly higher Mohs' hardness than the calcite ground mass contributed to the improvement of skid-resistance characteristics of LS-2 over LS-1 through differential wear. This belief seems to be reinforced from an examination of worn aggregate particles under a stereoscopic microscope. After wear to terminal polish, LS-2 exhibited greater surface asperity size and roughness than did LS-1.

A more general statement would be that, when the presence of sand-sized insoluble residue is insufficient to influence skid-resistance properties significantly, the presence of any other mineral harder than calcite in a significant percentage may improve the skid-resistance properties of the limestone. Shupe and Lounsbury (8) have reported, in essence, that the higher the calcite content of a limestone is, the more susceptible it is to polishing.

High Insoluble Residue Limestones

The insoluble reside test results of LS-3 and LS-4 (the higher skid-resistant limestones) indicate that amount and gradation of sand-sized residue and amount of total residue should be considered as factors affecting the skid-resistance properties of an aggregate.

LS-3 and LS-4 are equal in skid-resistance properties (Table 2). Both limestones have relatively high insoluble residue percentages but with considerably different particle-size distribution (Table 5). If total residue alone were the determining factor in improved skid resistance, LS-4 would be superior to LS-3. If sand-sized material alone were the determining factor, LS-3 would be superior to LS-4. Neither condition governs, however, and some other explantion must be sought for lack of difference in performance.

Examination of the photomicrographs of LS-3 and LS-4 reveals differences in grain size and size distribution. LS-3 calcite grains form a fine-grained matrix for the larger grains of dolomite, quartz, and other minerals. LS-4 is uniformly fine grained. These grain sizes and grain distribution properties seem to favor LS-3 in resisting polish. Another consideration may be the effect of insoluble residue that passes the No. 200 sieve. It may be that the passing 200 fraction of insoluble residue containing clay minerals is detrimental to skid resistance, and a high percentage of passing No. 200 also may have affected the skid-resistance properties of LS-4 negatively.

It seems clear, however, that the presence of harder impurities mixed with a calcite ground mass does improve the skid-resistance properties of carbonate rocks in some direct relationship to the amount of impurities. Noncarbonate rocks seem to respond to this same general rule involving a mixture of grains having differential hardness.

It is probable that the impurities wear less rapidly than the calcite, leaving surface relief at all times to aid skid resistance. Examination under a stereoscopic microscope of surfaces exposed to wear tends to support this contention.

NONCARBONATE AGGREGATES

Most of the aggregates studied were noncarbonate in mineral composition, and from those aggregates a range of behavior was observed under the wear and polishing exposures. The ratings given in Table 2 reveal that there was a wide range of response within the granites alone. The traprock (TR-1), composed of hard minerals, was low in the ratings, whereas the sandstone (SS-1), composed of about 50 percent hard and 50 percent soft minerals, showed the most favorable response. The photomicrographs (Fig. 2) show wide variations in mineral composition and in grain size, shape, and distribution. The percentages of mineral composition and mineral hardness of all of these aggregates are given in Tables 3 and 4.

From study of the carbonate rocks, it seems that a mixture of hard and soft minerals results in better skid-resistance properties than do soft minerals alone. One possible extrapolation of the carbonate rock observations would be that all hard minerals would be best. This conjecture seems to be refuted when TR-1, a diabase composed of all hard minerals (H = 5.5 to 7), is considered. TR-1 exhibited the lowest skid resistance of the aggregates except for the limestones and GL-1, a quartz gravel (H = 7). It seems reasonable to conclude that the presence of a preponderance of minerals with a small range of hardness is conducive to lower terminal skid-resistance properties, although the harder aggregates will take a longer time than the softer aggregates to reach terminal polish under exposure.

This conclusion suggests that an aggregate composed of both hard and soft minerals would be expected to produce the most desirable skid-resistance characteristics. This concept was suggested several years ago by Maclean and Shergold (15) in England and confirmed by others (8) in the United States. However, not all aggregates with mixed hardness composition are the same, as will be seen in the ensuing discussion, because of other variables involved. A systematic examination of all aggregates was undertaken to determine percentages of minerals and their hardness (Tables 3 and 4) and other features, such as grain size and distribution, for correlation with skid-resistance properties. Hardness data and BPN values are given in Table 6. Grain size and distribution are discussed in subsequent paragraphs.

TABLE 6

BPN AND RANGE OF MINERAL CONTENT WITHIN INDICATED HARDNESS OF SAMPLE AGGREGATES

Aggregate	BPN[a]	Mineral Content[b] (percent)	
		H ≤ 2 to 4	H ≥ 5 to 7.5
SS-1	58.5	30 to 40	60 to 70
SO-1	51.0	N.A.	N.A.
SL-2	46.0	50 to 55	45 to 50
SP-1	45.0	N.A.	N.A.
SL-1	45.0	55 to 60	40 to 45
GL-2	45.0	10 to 15	85 to 90
GT-2	44.5	10 to 12	88 to 90
GT-3	43.5	10 to 12	88 to 90
GT-4	43.0	8 to 10	90 to 92
GN-1	43.0	8 to 10	90 to 92
GN-2	43.0	10 to 15	85 to 90
GN-3	42.5	15 to 20	80 to 85
GT-1	42.0	10 to 15	85 to 90
RH-1	41.5	10 to 12	88 to 90
TR-1	40.5	0 to 2	98 to 100
GL-1	40.0	1 to 3	97 to 99
LS-4	40.0	60 to 70	30 to 40
LS-3	40.0	65 to 75	25 to 35
LS-2	39.0	95 to 97	3 to 5
LS-1	35.0	93 to 95	5 to 7

[a]After 16 hours of circular track exposure.
[b]Details are given in Tables 3 and 4.

The photomicrographs (Fig. 2) of GT-1 and GT-2 granites with different skid-resistance properties reveal approximately the same percentages of hard minerals but markedly different grain size. GT-2 has the larger grain size and exhibits superior skid-resistance properties. Granites characteristically are composed of significant quantities of quartz (H = 7), feldspar (H = 5.5 to 6), and some soft mineral like biotite (H = 2.5 to 3). Feldspar alters chemically to sericite (H = 2 to 2.5), and some alteration is observed for GT-1. Los Angeles wear loss for GT-2 was almost twice that for GT-1, which suggests that GT-2 is less well bound and its surface may tend to remain rougher through loss of grains before polishing has occurred. In general, the characteristics observed seem to favor GT-2 over GT-1 for skid-resistance properties. Aggregate called granitegneiss is closely related to granite both in compositional features and in skid-resistance characteristics. A photomicrograph of GN-1, which was used as a standard aggregate throughout this study, is shown in Figure 2. Although the granite-gneiss aggregates fall in the medium-range

skid-resistance group, they seem to be generally inferior to the granites. This inferiority may, in general terms, be attributed to the more extensive alterations in their compositional minerals, particularly from feldspar to kaolinite or sericite, and to the lesser availability in their composition of the stable harder mineral like quartz.

RH-1 was identified as a rhyolite. The petrographic analysis for this aggregate showed that it had about the same composition as a granite except for the grain size, which was considerably smaller. As shown in the photomicrograph of RH-1, this type of rock has a ground mass of fine subangular grains that result in a dense, relatively nonporous mass susceptible to uniform wearing and polishing except where some crystal phenocrysts interrupt the grain uniformity and help to improve the skid-resistance characteristics of the aggregate. The skid resistance of the rhyolite aggregate was considerably less than that of an unaltered granite having the same composition. This fact seems to confirm the conclusion that grain size is a factor that contributes to the skid-resistance characteristics of an aggregate.

Two crushed gravels, GL-1 and GL-2, were compared. GL-1, a fall-line gravel, is the least skid-resistant noncarbonate aggregate, is 98 percent quartz, and polishes to a low skid-resistance value. GL-2 is a mountain-stream gravel composed of granite and granitegneiss; its skid-resistance characteristics are typical of those aggregates. The photomicrograph of GL-2 (Fig. 2) shows coarse interlocking grains that probably contribute to skid resistance.

An interesting and rather surprising result was obtained when the slates, particularly SL-2, were tested for skid resistance. It had been anticipated that the flakey particle shape and the fine grain size of this type of aggregate would make it susceptible to the development of a relatively well-polished surface under only moderate traffic action. Skid test results have indicated that this is not the case. SL-2 had the highest skid resistance of any of the natural aggregates in this study that actually have been used in North Carolina pavements (Table 2).

The photomicrograph of SL-2 shows a thin section of this aggregate under crossed nicols of the polarizing microscope. The banded, extremely fine grains are composed of only about 45 percent of the naturally hard minerals, but it has been theorized that slates gain a high degree of hardness of grains through metamorphism (16). It is suspected that this type of aggregate derives its high skid-resistance characteristics from the continuous renewal of the sharp-edged, hard, banded, and brittle surface grains that continuously break and "peel off" under the action of traffic, resulting in little or no accumulated polish.

It may be interesting to mention at this point that the synthetic aggregate SO-1, produced from a slate rock, showed high skid-resistance characteristics. These characteristics have been generally attributed to continuous rough surface renewal and to high contact pressure produced between the grain surface and the rubber because of the high porosity of this aggregate, i.e., voids act as soft areas and vesicule walls function as hard areas.

The sandstone (arkose) aggregate SS-1 that was used in this investigation is an excellent example of the type of aggregate that could provide an ideally long-lasting skid-resistant surface. The sandstone specimens produced the highest skid resistance of the aggregates included in this investigation (Table 2).

The composition of this sandstone, shown in Figure 2, is thought to be the primary factor that gives it skid-resistance characteristics. With grain structure of about 50 percent hard, angular to subangular quartz (H = 7) and hematite (H = 6), and 35 to 40 percent kaolinite (H = 2 to 2.5) resulting from the alteration of feldspar, the soft ground mass wears away relatively fast, exposing the hard grains to provide a sandpaper-like surface. Before the asperities of these hard particles have a sufficient wearing action to cause them to polish, the matrix has been worn down to where it can no longer hold the hard particles, allowing them to be dislodged to expose fresh, unpolished particles. This continuous renewal of the pavement surface is believed to give sandstone highly favorable skid-resistance properties.

Our findings regarding the sandstone aggregate are in agreement with those of some investigators (8, 17, 18) who have experimented with sandstone aggregates in the laboratory or have examined actual pavement field test sections and found them to be highly skid resistant.

An important conclusion that may be drawn from the preceding analysis is that those aggregates that are predominantly composed of one type of mineral, or of different minerals with approximately the same hardness, are more susceptible to polishing and becoming nonskid resistant under sustained traffic action than are aggregates composed of different minerals not equal in hardness. Obviously, the aggregates with the softer mineral composition are polished at a faster rate than those with the harder mineral composition. The analysis has confirmed that the presence in the composition of an aggregate of two or more minerals that have significantly different hardness values contributes considerably to giving the aggregate a sustained high skid

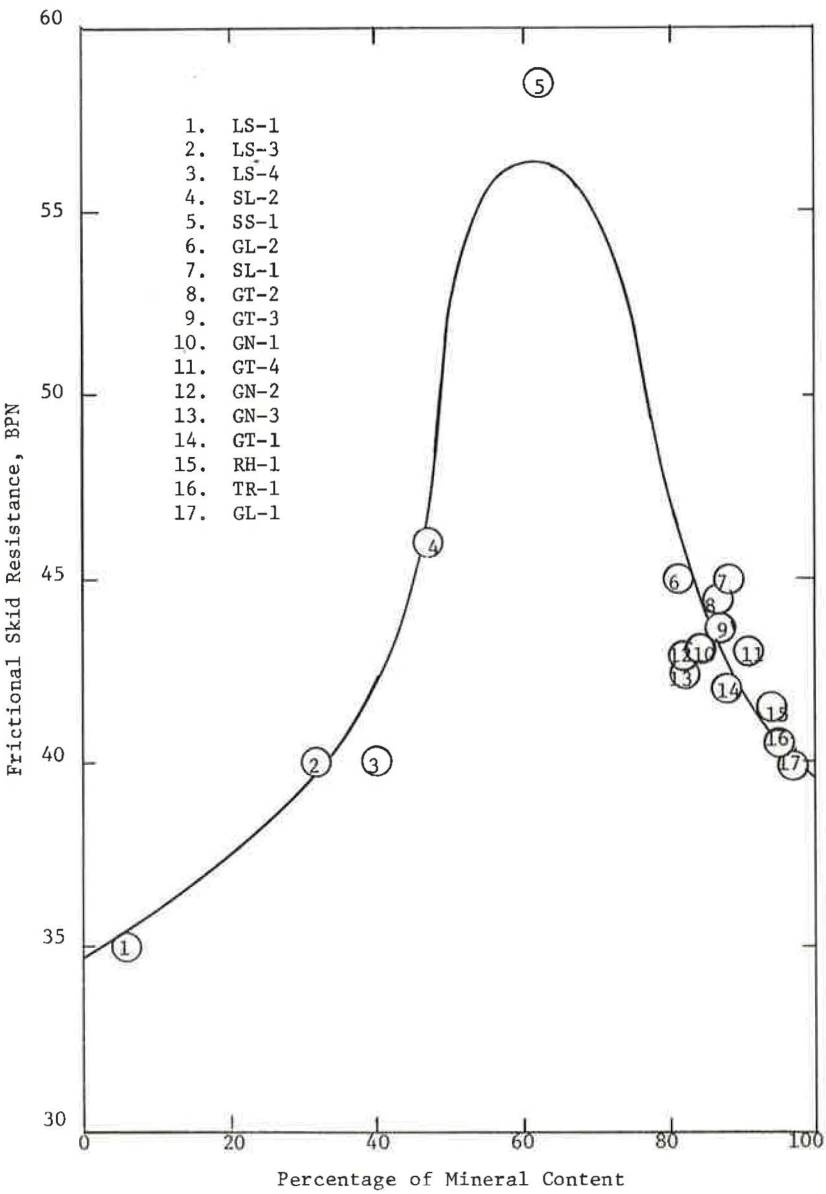

Figure 3. BPN values versus hard mineral content.

resistance under prolonged traffic action; the greater the difference in hardness is, the greater the contribution appears to be. An important observation in this connection is that the proportion of hard to soft minerals appears significant and that there seems to be an optimum proportion that, when exceeded or not attained, results in decreased skid-resistance effectiveness. This concept of optimum proportion of mineral content is shown in Figure 3. The range of values for percentage of mineral content in the sample aggregates is given in Table 6. It is emphasized that the numerical values for mineral content given in Table 6 and shown in Figure 3 are approximate ranges subject to reasonable numerical variation.

Grain size, shape, distribution, and surface capacity seem to contribute significantly to skid-resistance attributes: The larger and the more angular grains, evidently resulting in a coarser and a more textured surface, seem to contribute more effectively to the skid resistance of an aggregate than do grains of smaller size, less angularity, and smoother surface texture. These attributes generally contribute to the modification of the influence of the compositional proportion concept, as was obvious in the case of the fine-grained rhyolite, RH-1, when compared to the coarser-grained granite, although both types of aggregate had similar compositions.

Another factor related to the mineral composition of aggregates in relation to their skid resistance is the distribution of the mineral grains. The more uniform the distribution is of the harder and softer grains, the better the resulting skid resistance is, as in the case of the sandstone aggregate.

SUMMARY AND CONCLUSIONS

The research reported here is part of a broad effort to treat the problem of maintaining an adequate level of pavement skid resistance. This particular portion of the research has been devoted to identification and evaluation of factors that contribute to the skid-resistance properties of aggregates. Previous research has indicated that different aggregates do have different skid-resistance properties and that aggregates may be rated relative to one another through use of wearing and polishing exposures in the laboratory.

The acid-insoluble residue percentages for the four carbonate aggregates examined indicated that skid resistance improved with increased residue and that sand-sized residue probably is more important than total residue.

A general correlation was found between the petrographic properties and the skid resistance of any given aggregate: Aggregates having mixed composition of hard and soft minerals had higher skid resistance than did aggregates consisting predominantly of minerals of the same type or having the same hardness.

The following conclusions seem to be supported by the findings from this research for laboratory skid resistance of aggregates:

1. Pavements made from aggregates composed predominantly of the same mineral or of minerals having a narrow range of hardness, such as most limestones, diabases, and some quartz gravels, will polish to lower levels of skid resistance than will aggregates composed of minerals with a wide range of hardness as measured by Mohs' scale, such as sandstone, granites, gneisses, and slates. Aggregates having softer mineral composition will reach terminal polish levels more rapidly than will aggregates having harder mineral composition.

2. Pavement surfaces made from aggregates having approximately the same mineral composition but with differing grain shape and/or size will produce differing skid-resistance levels. The more angular and the larger are the mineral grains in individual aggregate particles, the higher is the skid resistance of the aggregate particles when incorporated in pavement surfaces.

3. There seems to be an optimum compositional proportion of hard to soft mineral grains in an aggregate for high skid-resistance performance. The optimum seems to fall in the range of proportion of 50 to 70 percent of hard minerals ($H \geq 6$ or 7) to 30 to 50 percent of soft minerals ($H \leq 2$ or 3). The influence of this compositional proportion is apparently modified by the size, shape, and distribution of the mineral grains in the aggregate particles. The larger and the more angular are the hard mineral grains, and

the more uniform their distribution in the softer mineral matrix, the higher is the resulting skid resistance of the aggregate.

4. Generally, carbonate aggregates will polish faster than will other types of aggregates because of the predominance of the soft carbonate minerals in their composition. The higher is the percentage and the harder is the mineral proportion of impurities in a carbonate aggregate, the better will be its skid-resistance performance.

5. The amount of sand-sized insoluble residue, the residue gradation, and the total amount of insoluble residue obtained from a carbonate aggregate should be considered simultaneously in evaluating a carbonate aggregate for skid resistance. The sand-sized portion of insoluble residue seems to have more influence than does total residue on the skid-resistance performance of carbonate aggregates.

6. A long-lasting and highly skid-resistant pavement surface may be obtained by the use of either a natural aggregate or a synthetic aggregate whose sacrificial surfaces are continuously renewed by traffic action.

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