are shown graphically in Figure 5, confirm known relations of load to life.

Tests for fatigue parameters A and n were also performed at room temperature on samples 5.08 cm (2 in) thick. An original crack of 0.254 cm (0.1 in) was introduced in the specimen before testing. For the specific specimen in question, the c - N data were analyzed by following the procedure described earlier. For a value of n = 2.0, the value of A was 3.4×10^{-7}. These values compare well with those previously obtained by testing, on elastic foundation, beam specimens that had the same asphalt mix properties. Figure 6 shows the graphical analysis of the data.

CONCLUSIONS AND RECOMMENDATIONS

It is obvious that the new method for testing fatigue and fracture toughness is an applicable and feasible one that has certain advantages over the old one. The following conclusions and recommendations can be made:

1. The new method makes it feasible for actual cores taken from highways to be tested for fatigue and fracture in the laboratory, whereas the method that used beams on elastic foundations required a beam cut from the pavement, a task too difficult to be done properly.
2. The theoretical analysis of the specimen geometry and the experimental setup are much simpler in the new method than in the old one. The stress-intensity factor K is independent of the elastic modulus E of the material.

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Petrographic Insights Into the Susceptibility of Aggregates to Wear and Polishing

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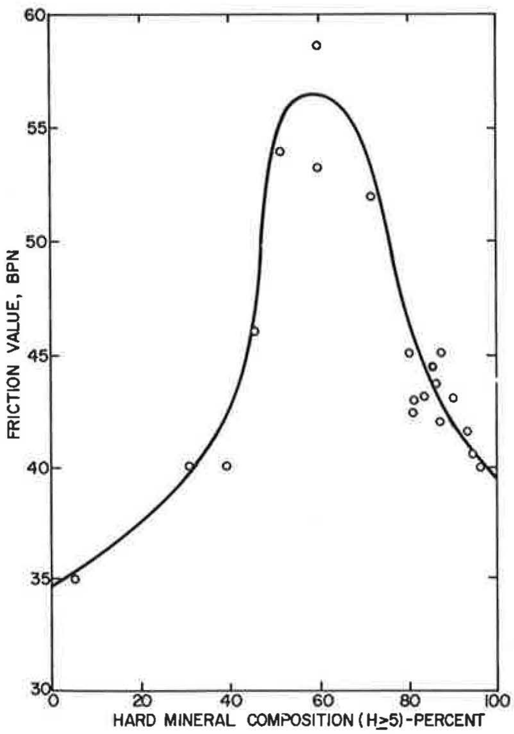
Results from three studies confirm that a strong relation exists between the petrographic properties of an aggregate and its susceptibility to wear and polishing. Constituent mineral composition; hardness; differential hardness; porosity; grain shape, size, and distribution; and bonding between grains or crystals and matrix are all important properties that contribute to aggregate wear resistance and polish resistance. Hard, well-bonded minerals will resist wear but will eventually polish though at a slower rate than softer minerals. Loosely bonded materials will resist polishing but will wear at a rate that may render them not durable. Two subtasks in the studies revealed that an inverse relation exists between the rate of wear of an aggregate and its susceptibility to polishing. To resist both polishing and wear, an aggregate should ideally contain a high percentage of hard, coarse, angular crystals well bonded into a matrix of softer, finer grains, or the hard crystals should be well bonded together in a porous structure so that slow, gradual, irregular fracture of the crystals will occur. Based on the findings from the three studies and other research, a table has been prepared that includes suggestions for aggregate property values that will result in high resistance to both wear and polishing.

It is generally conceded by those concerned with pavement surface skid resistance and wear resistance that these properties are largely a function of aggregate performance, particularly in bituminous surfaces in which the coarse aggregate constitutes the major portion of the surface that comes in contact with vehicle tires. Other factors such as particle size, shape, and gradation; mix design; binder properties; and construction practices are also important, but these factors play a lesser role.

In the past two decades, several studies have been done by concerned agencies and interested researchers to predict the skid-resistance performance of surface aggregates by laboratory tests before the aggregates are used in field construction, particularly in bituminous surfaces. Most of the methods used in these studies were laboratory polishing procedures intended to simulate aggregate polishing by traffic (1, 2, 3, 4). Other studies involved the testing of field installations to obtain a history of skid-resistance performance on the aggregates that were used in these installations (4, 5, 6). Results of both field and laboratory tests often showed significant performance variations, not only between one general group of aggregates and another—for example, between limestone and granite—but also between aggregates of the same group that come from different sources—for example, between one limestone and another or between one granite and another (7, 8, 9, 10). These variations aroused an interest among several researchers in investigating basic factors that influence the skid-resistance performance of various aggregates. Accordingly, several petrographic studies were undertaken

Figure 1. BPN friction values (ASTM E303) versus hard mineral content.



to investigate the intrinsic properties that may control the resistance of aggregates to polishing. Some of these studies were concerned with the investigation of different types of aggregates (9, 10, 11, 12, 13, 14, 15), and others were principally concerned with investigating carbonate aggregates, limestones, and dolomites because they are widely used and because they generally tend to polish faster than most other types of aggregates (7, 8).

INITIAL FINDINGS

Several papers published in the late 1950s and in the 1960s (7, 8, 10, 11, 12) showed that the polish susceptibility of aggregates was associated with the percentage content of soft carbonate minerals, particularly calcite and dolomite in carbonate rocks, and with the fineness and uniformity of grains in other rocks, as in the case of fine-grained serpentines, basalts, and some rhyolites. On the other hand, aggregates composed of minerals that have differential hardness—such as most sandstones, some granites, and some limestones with high silica content—and aggregates that are composed predominantly of one hard mineral but have a porous structure—such as scoria, vesicular slag, expanded shale, clay, or slate—tended to retain polish resistance under prolonged exposure to traffic provided that they could resist premature wear.

RECENT RESEARCH

In the past few years, further work by Dahir and others (9, 13, 14, 15) has confirmed earlier findings that pertain to constituent mineral hardness and to the fineness and uniformity of grains; it has also added some refinements to include the proportion of hard minerals, the degree of differential hardness, crystal size, shape, and distribution in matrix, and the susceptibility of some of the constituent minerals to wear or attrition caused by extreme softness of matrix.

To summarize, it has been found that the optimum hard mineral content that is needed to maintain a high level of long-lasting skid resistance lies in the range of 50 to 70 percent (Figure 1) (9) and that differential hardness between the hard crystals and the softer matrix grains should be at least two numbers on the Mohs hardness scale. Examples of this group include most sandstones and some granites and gneisses. In contrast, some diabase rocks that have not been altered by weathering are composed of minerals that range in hardness from Mohs H = 5 to H = 6, and most dolomitic limestones are composed of minerals that range in hardness from H = 3 to H = 4. Both of these types were found to be more polish susceptible than sandstones and granites (Tables 1 through 3).

Figure 2 shows examples of polish-resistant aggregates and of polish-susceptible aggregates that contain hard minerals. Polish-susceptible aggregates (limestone) that contain soft minerals are not shown because photographs of such material reproduce poorly.

For an aggregate to be both skid resistant and wear resistant, its matrix should consist of minerals that are not so soft and friable as to wear readily or weather easily and thus render the material unusable because of lack of durability. Examples of this type of aggregate include clayey siltstones and some geologically young sandstones (SS-1 in Tables 1 and 3), both of which provide high friction but lack durability. On the other hand, if hard crystals are highly bonded together by a medium of equal hardness or by a strong interlock, they will eventually polish to a smooth surface regardless of their hardness. Examples of this type include high-content quartz aggregate (>90 percent), as in some quartzites and quartz gravels, and some unweathered diabase (Figures 2 and 3 and Tables 1 through 3). Furthermore, to produce and maintain high friction, the hard crystals should be relatively coarse—100 to 250 μm (16)—and have sizes larger than those of grains in the bonding matrix; they should also be of angular shape, neither rounded nor flakey, with protruding asperity angles of 90° or less (17). The hard crystals should have fairly even distribution in the softer matrix and should not occur in concentrations separated by relatively large, smooth matrix patches.

COMPARISON OF RESULTS OF THREE STUDIES

Three independent studies that involve petrographic analysis of aggregates were undertaken at different times. The results of the studies are summarized and compared below.

Study 1

Samples from 20 aggregates were incorporated in 150-mm (6-in) diameter specimens prepared in the laboratory by using an open-graded asphalt mix design (3). The specimens were cured, their surfaces were cleaned with a solvent, and they were then polished dry for 16 h in a circular track apparatus that used four small rotating go-cart pneumatic tires. British pendulum numbers (BPNs), according to ASTM E 303-69, were measured after each 2 h of polishing. Generally, BPNs appeared to reach a stable condition before 16 h of polishing had elapsed. Thin sections were prepared from the aggregates used in the testing, and photomicrographs were made. Tables 1 through

Table 1. Physical properties and skid resistance of sample aggregates.

Study[a]	Aggregate: Symbol	Aggregate: General Classification	Bulk Specific Gravity[b]	Los Angeles Abrasion Loss (%)	Water Absorption (%)	Polishing Passes: Laboratory	Polishing Passes: ADT per Lane[c]	Skid Resistance: BPN[d]	Skid Resistance: SN_{40}
1	LS-1	Limestone	2.85	18	0.30	115 000		35	
	LS-2	Dolomitic limestone	2.87	25	0.40	115 000		39	
	MB	Marble	2.95	29	0.30	115 000		40	
	DB-1	Diabase	2.77	15	0.30	115 000		41	
	RH	Rhyolite	2.67	27	0.30	115 000		42	
	GT	Granite	2.66	41	0.50	115 000		43	
	GN	Gneiss	2.67	29	0.41	115 000		43	
	SL	Slate	2.78	24	0.33	115 000		45	
	SS-1	Arkosic sandstone	2.66	NA	2.55	115 000		59	
2	LS-3	Limestone	2.82	16	0.27	48 000		15	
	LS-4	Dolomitic limestone	2.72	29	0.40	48 000		18	
	DB-2	Diabase	2.78	16	0.30	48 000		21	
	QZ	Quartzite	2.64	36	0.30	48 000		19	
	SS-2	Arkosic sandstone	2.58	20	2.50	48 000		48	
	SS-3	Lithic sandstone	2.65	21	1.20	48 000		34	
3	LS-5	Limestone	2.82	20	0.49		800		36
							7000		35
							2500		40
	LS-6	Limestone	2.72	20	0.27		6500		27
	GL	Gravel (SS)	2.59	24	1.22		2500		63

[a]Study 1 was performed at North Carolina State University, and studies 2 and 3 were performed at Pennsylvania State University.
[b]Physical properties for study 1 were provided by the North Carolina Department of Transportation, and those for study 2 were provided by the Pennsylvania Department of Transportation.
[c]Trucks ranged from 2 to 4 percent on the three pavements of LS-5 and GL; there were no trucks on LS-6.
[d]Measured on laboratory-prepared pavement specimens in study 1 and on ground rock panels in study 2.

Table 2. Mohs hardness of minerals in sample aggregates.

Mineral	Name	Hardness Range
M-1	Chlorite, kaolinite, or sericite	2-2.5
M-2	Mica (biotite or muscovite)	2-3
M-3	Calcite	3
M-4	Dolomite	3.5-4
M-5	Pyroxene (augite)	5-6
M-6	Feldspar (orthoclase or plagioclase)	6
M-7	Limonite, hematite, or magnetite	5-6.5
M-8	Olivine	6.5-7
M-9	Quartz	7
M-10	Others (apatite, amphibole, epidote, pyrite, zircon)	5-7.5

Table 3. Percentage mineral composition, level of bonding, and skid resistance of sample aggregates.

Aggregate	Mineral: M-1	M-2	M-3	M-4	M-5	M-6	M-7	M-8	M-9	M-10	Skid Resistance: BPN[a]	Skid Resistance: SN_{40}	Bonding
LS-1			93						5	2	35		Good, uniform
LS-2			65	30					5		39		Medium to good
MB		5	25	30		5			30	5	40		Medium to good
DB-1					40	50	5	5			41		Highly interlocking laths
RH		5				40	15		40		42		Fine grains, well bonded
GT		10				50			35	5	43		Good, interlocking grains
GN		10				40			40	10	43		Good bonding
SL	55					20			15	10	45		Medium to loose
SS-1	40					10	10		40		59		Loose
LS-3			85	15							15		Good, uniform
LS-4			70	30							18		Good
DB-2		2			45	48	5				21		Highly interlocking laths
QZ									99	1	19		Very well cemented
SS-2	30						10		60		48		Medium to loose
SS-3	20								80		34		Medium to good
LS-5			59	30					10	1		37	Good
LS-6			90	10								27	Good, uniform
GL							30		70			63	Medium to good

[a]Measured on surfaces identified in text and in footnote to Table 1.

3 give pertinent petrographic data and friction data (BPNs) measured after 16 h of polishing. Because of the prolonged polishing, BPNs measured after 16 h were close to SN_{40} (within 5 to 10 numbers) measured with a skid trailer (ASTM E 274) on pavements that incorporate the same aggregates (18). BPNs versus percentage hard mineral content for all 20 aggregates tested are shown in Figure 1. Photomicrographs of representative samples of the aggregates tested are shown in Figure 3.

Study 2

Rock panels 100 by 150 mm (4 by 6 in) were mounted in steel frames, planed by grinding, and then polished with silica abrasive and water by using a reciprocating rubber pad to accelerate the polishing process (19). Eight silica abrasive gradations that ranged in size from 5 to 105 microns were used. Each surface was polished by using 6000 passes of the rubber pad for each abrasive size gradation, starting with the coarsest size and followed successively by the finer sizes. The surface friction of specimens was measured by the British portable tester (BPT) after polishing with each abrasive size. By the end of the polishing cycle, friction appeared to stabilize to a fairly constant state of polish. Friction measurements (BPNs) after the final polishing cycle and corresponding petrographic data are given in Tables 1 through 3. Photomicrographs of thin sections are shown in Figure 3.

Study 3

Five bituminous surfaces in Centre County, Pennsylvania, were designated for routine skid-resistance testing by a full-scale tire skid trailer that conformed to ASTM E 274-70. Representative coarse aggregate particles were taken from each surface. Bihourly skid tests according to ASTM Method E 274 were made in late September for 30 h. The average skid number (SN_{40}) and the petrographic data on the surface aggregates and other pertinent data, including average daily traffic (ADT), are given in Tables 1 through 3. Corresponding photomicrographs of thin sections of the coarse aggregates used in the surfaces are shown in Figure 3.

Figure 2. Aggregates of varying polish susceptibility.

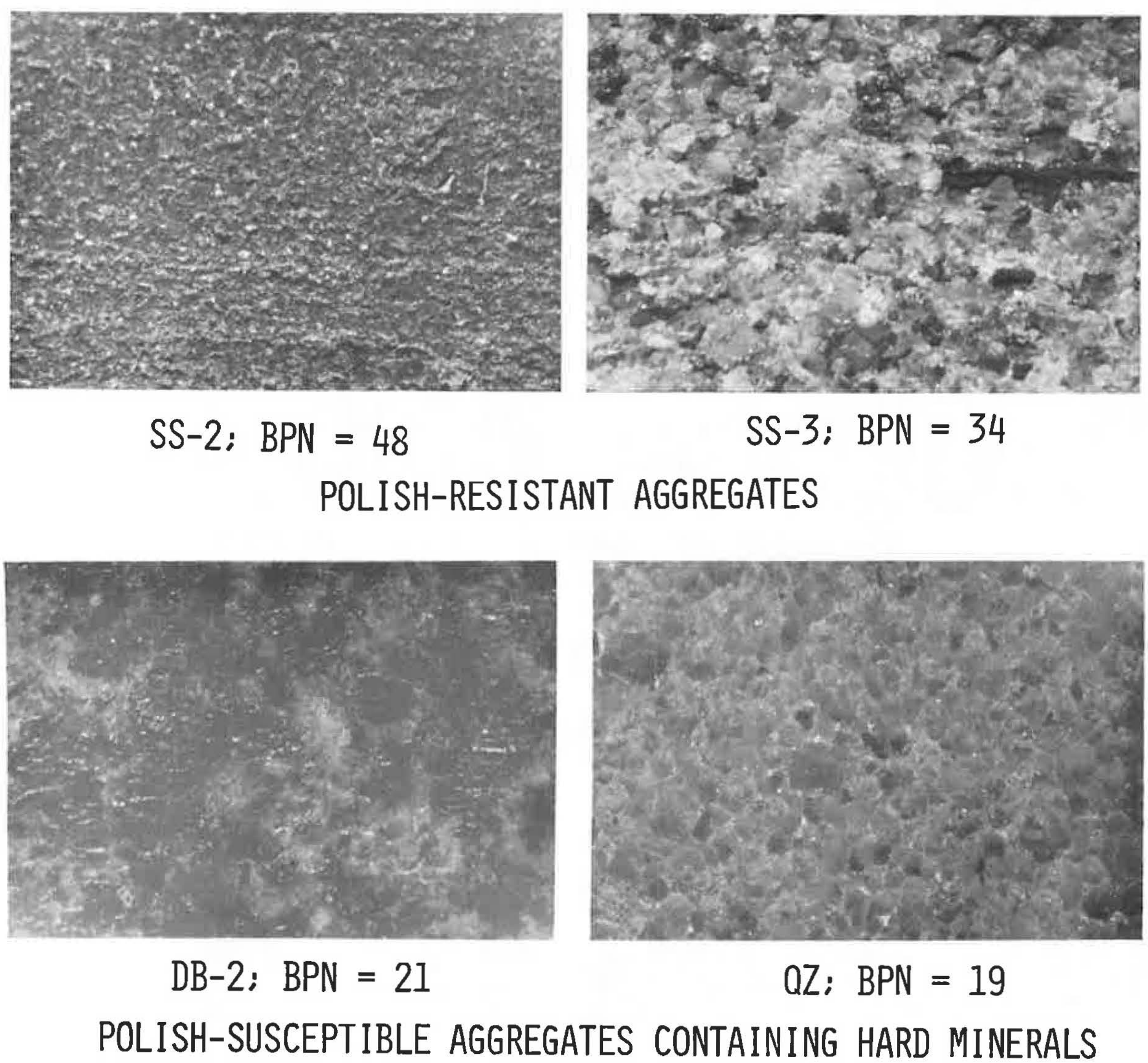
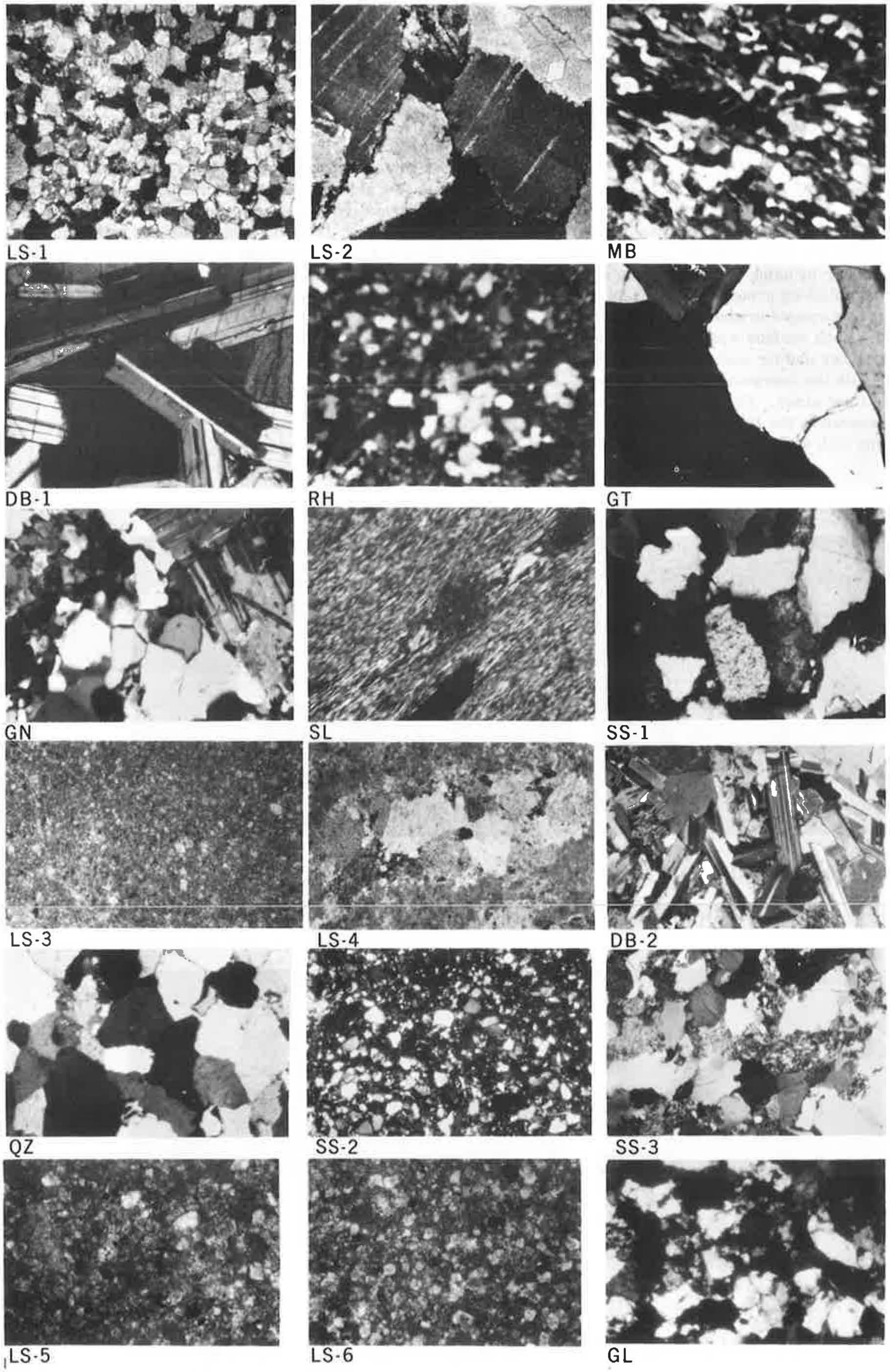


Figure 3. Thin-section photomicrographs of the sample aggregates under crossed nicols (22.4x).



DISCUSSION OF RESULTS

Data in Tables 1 through 3 and Figures 1 through 3 show that a strong relation exists between the petrographic properties of an aggregate and its susceptibility to polishing. Constituent mineral composition; hardness; differential hardness; porosity; grain shape, size, and distribution; and bonding between grains or crystals and matrix are all important properties that contribute to the friction performance an aggregate will exhibit in service.

To provide and maintain a high friction level while enduring the effect of traffic and environmental influences through the expected pavement surface life, an ideal aggregate should have a high composition (50 to 70 percent) of coarse, sharp, hard mineral crystals well distributed and strongly bonded into a matrix of softer mineral(s) of finer grains. Alternatively, the crystals should be well bonded together in a porous structure and optimally have a porosity in the range of 25 to 35 percent (20) so that gradual, irregular fracture of the crystals will occur at a rate sufficiently slow that it will not cause undue surface wear. Table 4 includes suggested target properties for an ideally skid- and wear-resistant aggregate. It is realized that such an aggregate hardly exists in nature and may not be feasible or economical to manufacture with currently known technology. However, this fact does not preclude possible future developments for which the target values in Table 4 or similar values may be used. In the meantime, the closer the properties of an aggregate come to these target values, the better the aggregate will be expected to perform as a pavement surface aggregate.

Obviously, as established in the specifications of the Pennsylvania Department of Transportation (21, 22), the skid-resistance requirements of pavement surfaces that have different levels of traffic and different environmental conditions may be satisfied by aggregates of varying properties. But the data given in Table 4 may serve as a reference and do point to the important properties expected in an aggregate intended for use in a pavement surface, particularly in a bituminous pavement. It is hoped that more attention will be directed by concerned and interested agencies and researchers to investigating the petrographic properties of surface aggregates and that sufficient quantitative data will be generated to permit the development of a specification for surface aggregate based on the study of aggregate petrography.

Table 4. Target values for properties that would enhance skid resistance and wear resistance of aggregates.

Property	Value Range	Reference
Mohs hardness of hard fraction	8-9	(16, 23, 25)
Mohs hardness of soft fraction	6-7	(16, 23)
Differential hardness, min	2-3	(7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 23)
Percentage of hard fraction		
Natural aggregate	50-70	(9)
Artificial aggregate	20-40	(24)
Hard grain or crystal size	150-300 μm, average 200	(24, 25)
Hard grain or crystal shape	Angular tips (≤90°)	(9, 17, 24)
Percentage porosity (vesicularity)	25-35	(20, 25)
Pore size, optimum	125 μm	(25)
Aggregate particle size range	3-13 mm	(6)
Aggregate particle shape	Conical, angular (≤90°)	(17, 25)
Los Angeles abrasion, percent	≤20	(9, 21)
Aggregate abrasion value, percent[a]	≤8	(15, 16, 23, 25)
Aggregate impact value, percent[a]	≤20	(15, 23, 24)
Polished stone value, BPN[b]	≥75	(15, 16, 23, 25)

[a]According to British Standards Institution BS812:75.
[b]According to BS812:75 or ASTM D3319-74T and E303.

COROLLARY TO THE STUDY

To illustrate the dilemma that the highway engineer must face, tests were made to investigate whether a relation exists between aggregate skid resistance and aggregate wear by abrasion. In study 1 (3), 1000-g samples between 9.5 and 4.75 mm (passing the 3/8-in sieve and retained on the no. 4 sieve) in size from each of eight aggregates were abraded by tumbling them dry in a rotating jar-mill for 120 h; 19-mm (0.75-in) hard flint pebbles were used as abrasive. The abraded aggregate particles were then glued in a 150-mm (6-in) diameter frame and tested with the BPT (ASTM E 303-69). Wear as percentage loss and friction in BPN measurements are given in Table 5, and a correlation is shown in Figure 4. The high coefficient of correlation indicates that some relation exists between wear and the friction performance of an aggregate: High friction is associated with a high rate of wear. This relation was not found to be generally true when Los Angeles abrasion test results (ASTM C 131) were correlated with BPN. However, it did hold true for aggregates that were of the same type but came from different sources, as in the case of four granite samples tested in study 1 (9).

A recent limited study at Pennsylvania State University appears to confirm the finding that high friction is associated with high rate of wear. Ten individual particles 12.7 to 9.5 mm (0.5 to 0.375 in) in diameter from each of seven aggregate samples were weighed, mounted in steel holders, reweighed, and then polished for 30 min in a small, rubber-covered drum machine that rotated at 110 revolutions/min (4). A slurry of silica abrasive and water was used to aid the polishing. Friction force was measured by an electronic force cell, and the instantaneous average friction was recorded as a continuous trace by an oscillograph recorder. Initial and final friction forces were read and recorded, and the specimens were reweighed after polishing. A decrease in friction attributable to aggregate polishing

Table 5. Wear, friction, and other physical properties of eight typical paving aggregates.

Aggregate	Symbol	Bulk Specific Gravity	Water Absorption (%)	Los Angeles Abrasion Loss[a] (%)	120-h Jar-Mill Wear Loss (%)	BPN
Arkosic sandstone	SS-1	2.66	2.55	NA	40.2	62.0
Expanded slate	SO-1	1.58	3.50	40	31.1	60.0
Granite gneiss	GN-1	2.67	0.41	29	22.8	54.0
Slate	SL-2	2.78	0.33	24	21.2	54.0
Limestone	LS-1	2.85	0.30	18	14.5	48.5
Granite	GT-1	2.79	0.31	36	13.0	54.0
Dolomitic limestone	LS-2	2.87	0.40	25	10.9	47.5
Expanded glass	SP-1	2.05	2.40	23	7.8	45.0

[a]ASTM C 131.

Table 6. Results of wear and polishing of seven aggregates in Pennsylvania State University small-drum machine.

Aggregate	Initial Weight (g)	Final Weight (g)	Weight Loss (%)	Friction Force (N) Initial	Final	Drop
Juniata, Pennsylvania, red bed	20.8	17.8	14.4	75.58	55.87	19.71
Maryland granite	19.8	18.3	7.6	44.35	25.49	18.86
Texas red rock	17.0	16.5	2.9	70.64	49.29	21.35
Connecticut traprock	18.8	18.5	1.6	87.10	34.52	52.58
Expanded shale	22.6	17.8	21.2	90.39	90.30	0.09
Blast furnace slag	16.4	16.1	1.8	82.16	39.46	42.70
Fused refuse	18.6	18.2	2.2	64.90	34.52	30.38

Note: 1 N = 0.2248 lbf.

Figure 4. Jar-mill wear versus friction number.

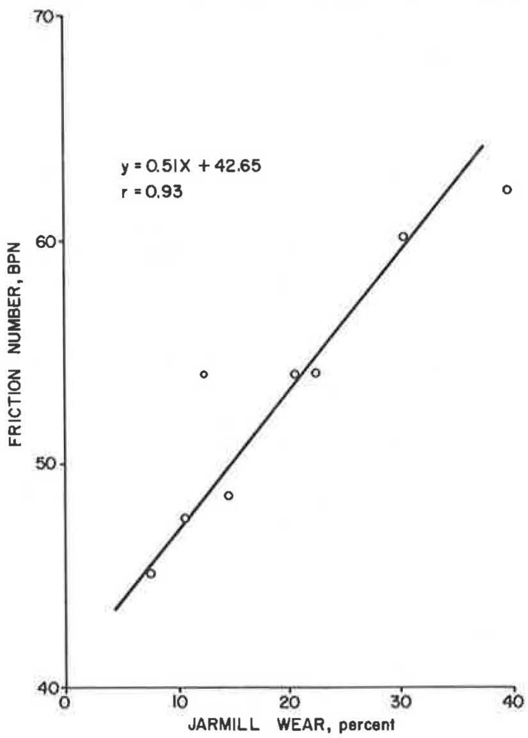
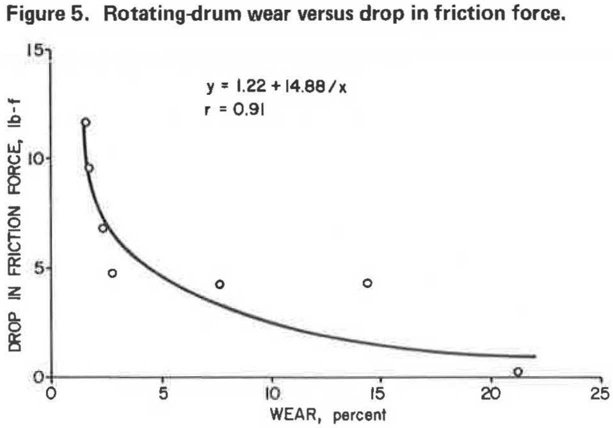


Figure 5. Rotating-drum wear versus drop in friction force.



was indicated by the drop in friction force from initial to final: High polishing is associated with a high drop in friction and vice versa.

The testing results are summarized in Table 6, and drop in friction force versus percentage of wear is shown in Figure 5. Although it is nonlinear, the good correlation confirms that an adverse relation exists between the rate of wear and the friction properties of an aggregate, a fact that poses a dilemma for the highway engineer and requires attainment of a balance between the two parameters—polish resistance and wear resistance—until some aggregate can be economically manufactured to optimize both. Thus far, high resistance to both wear and polishing has been reported only in the production of some relatively expensive synthetic aggregates in Britain (23, 24, 25).

CONCLUSIONS

Three studies by Dahir have indicated that aggregate wear and polish susceptibility may be determined in the laboratory by using petrographic analyses. Constituent mineral properties and bonding largely determine aggregate performance. Hard, well-bonded minerals will resist wear but will eventually polish, though at a slower rate than softer minerals. Loosely bonded, coarse-grained, hard minerals will resist polishing but will wear at a rate that may render them not durable. To resist both wear and polishing, an aggregate should ideally contain a high percentage of hard, coarse, angular crystals that are well bonded into a matrix of softer, finer grains, or the hard crystals should be well bonded together in a porous structure in such a way that slow, gradual, irregular fracture of the crystals will occur. Since an ideal surface aggregate is currently hardly attainable, compromises must be made in the selection of aggregates for practical applications.

Much basic, useful information about the relations between aggregate petrography and the wear and polish susceptibility of aggregates is already known, but more quantitative data are needed to make possible the development of a model or a standard specification that can be used to predetermine the expected skid resistance and wear resistance of an aggregate from petrographic analysis alone.

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The contents of this paper reflect my views, and I am responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the offi-

cial views or policies of the Pennsylvania Department of Transportation, the North Carolina Department of Transportation, or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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