Evaluation of Alabama Limestone Aggregates for Asphalt Wearing Courses

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The Alabama Highway Department does not permit the use of limestone coarse aggregate in asphalt wearing courses because of potential long-term skid resistance problems. A laboratory study was undertaken to evaluate 32 sources of limestone aggregates in Alabama for possible use in the wearing courses. Twelve approved sources of gravel aggregate were also evaluated for comparison. The frictional properties of all aggregates were determined using the British pendulum tester (ASTM E303) after 9 hr of accelerated polishing on the British wheel (ASTM D3319). Aggregates were also subjected to petrographic analysis. The percentage of noncarbonate material in limestone aggregates was determined by two methods: percent insoluble residue (ASTM D3042) and percent loss on ignition (Tennessee DOT method). The British pendulum number (BPN) values were found to follow a hyperbolic relationship with polishing time. This relationship can possibly be used to predict the limiting BPN value after infinite polish time. There was a general trend that the value of BPN9 (BPN value after 9 hr of polishing) increased as the percentage of insoluble residue increased or the percentage loss by ignition decreased. On the basis of BPN9 values, limestone aggregates were divided into three categories: potentially low, medium, and high skid-resistance levels. If BPN9 is used as an acceptance criterion, the limestone aggregates of the medium and high categories have the potential to provide skid resistance levels comparable with gravel aggregates used at the present time.

The highway pavement system requires aggregates of multifunctional characteristics to meet various demands. For asphalt wearing courses these characteristics not only include strength and durability but also adequate skid resistance. Aggregates having all these properties are often not locally available and have to be imported, thereby increasing delivered costs.

Limestone aggregates are readily available in northern Alabama. However, their use in asphalt wearing course mixes is not currently permitted by the Alabama Highway Department (AHD) because of potential long-term skid resistance problems. Therefore, the use of crushed gravel, slag, and other types of noncarbonate aggregates is required. However, some siliceous aggregates, particularly gravel, have the following disadvantages: low resistance to water damage (stripping and raveling), high asphalt absorption (high asphalt requirement), and partially crushed nature (low strength and stability). Crushed limestone generally does not exhibit these undesirable characteristics. However, its potential lack of long-term skid resistance must be evaluated before its use in asphalt wearing courses.

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In a recent study sponsored by AHD, limestone aggregates were evaluated in asphalt wearing courses (*1*). Laboratory tests showed that limestone aggregates were beneficial in increasing the stability of the mix and its resistance to moisture damage. In two field evaluations, mixes with approximately 30 percent limestone provided better skid resistance than control mixes with 100 percent siliceous aggregate. Figure 1 is from one of these evaluations after approximately 3,000,000 vehicle passes. It shows how skid resistance of the pavement, as measured with the locked-wheel trailer (SN) and the British pendulum tester (BPN), varied with time. At a third field site there was no discernible difference in skid resistance. It was important, therefore, that additional sources of limestone aggregates be evaluated to determine their possible use in wearing courses to take advantage of their durability and stability.

OBJECTIVES

This study was undertaken to achieve the following objectives:

1. Review available literature pertaining to the use of limestone aggregates in asphalt wearing courses.
2. Conduct a nationwide survey through a questionnaire to obtain information about states' experiences with the use of limestone aggregates in asphalt wearing courses.
3. Fingerprint approved sources of limestone and crushed gravel by running various physical tests and by petrographic examination.
4. Analyze data to determine correlations between British pendulum number (BPN) and other aggregate properties.
5. Classify aggregates into three levels (low, medium, or high) of skid resistance on the basis of laboratory tests.

BACKGROUND AND LITERATURE REVIEW

Skid resistance characteristics of the asphalt wearing course are principally determined by the properties of aggregates used because aggregates constitute more than 90 percent of the asphalt paving mix.

According to Sherwood and Mahone (*2*) and Gandhi et al. (*3*), limestone aggregates tend to polish more readily than other commonly used aggregates. Sherwood and Mahone (*2*) found that the majority of Virginia limestones tested in their study tended to become slick when subjected to heavy traffic. However, it has also been established by other investigators (*4–6*) that many limestones differ significantly in polish sus-

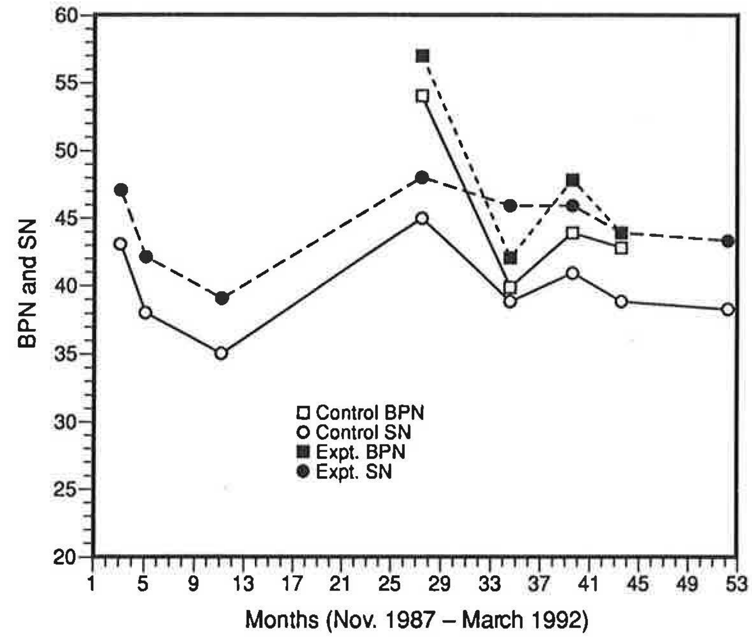

FIGURE 1 Comparison of control and experimental mix frictional performance.

ceptibility. These differences have been attributed primarily to the noncarbonate or acid insoluble constituents in the rock.

Polish susceptibility may be evaluated using a number of different testing techniques. These techniques include (*a*) the British wheel/pendulum method, (*b*) circular track wear method, (*c*) percent acid insoluble residue, (*d*) locked-wheel skid trailer, (*e*) stopping distance on paved surfaces, and (*f*) petrographic analysis.

British Wheel/Pendulum Method

The British wheel/pendulum method (ASTM D3319 and ASTM E303) has been used extensively by researchers including a recent evaluation by Diringer (*7*) in New Jersey. In this method, polish susceptibility is indicated by the so-called polish value (PV), which is a measure of the state of polish reached by a test specimen subjected to accelerated polishing. Diringer's results (*7*) were in agreement with New Jersey's experience from previous studies (*8,9*), where it was documented that crushed gravel mixes yielded superior skid resistance, whereas carbonate rock mixes provided marginal skid resistance over the long term.

Gandhi (*10*) tested various types of aggregates in Puerto Rico for polishing value. He concluded that correlations between the polish value and other aggregate properties such as specific gravity, absorption, abrasion value, initial friction value, percent insoluble residue, and sand size residue were very poor.

Circular Track Wear Method

The circular track wear method (*11*) was used by Dahir and Mullen (*12*). In this method, pavement samples, manufactured from the aggregate to be evaluated, are placed in a circular track and subjected to wear from small-diameter pneumatic tires. Pavement specimens could usually be brought to terminal polish in about 16 hr. Skid resistance values are determined by using the British pendulum tester.

Percent Acid Insoluble Residue Method

Dahir and Mullen (*12*) also used the insoluble residue test (ASTM D3042) in their study of four carbonate aggregates. In this test the insoluble residue reflects the amount of noncarbonate material in limestone (carbonate) aggregates. A large amount of noncarbonate material may indicate higher polish resistance. Dahir and Mullen (*12*) concluded that the acid insoluble residue percentages for the four carbonate aggregates indicated that skid resistance improved with increased residue content and that sand-size residue was probably more important than total residue. Using the polarizing microscope method, the authors found that the sand-sized insoluble residue consisted of hard siliceous particles, mostly quartz. Similar findings have been reported by other investigators (*13–19*). Sherwood (*20*) and Gray and Renninger (*13*) showed that the amount and nature of the acid insoluble mineral grains contained in limestones were primarily responsible for their variable wearing characteristics.

Locked-Wheel Skid Trailer Method

The locked-wheel skid trailer method (ASTM E274) is a field technique that measures the pavement skid resistance. The trailer is usually towed at 40 mph, water is sprayed on the pavement surface, and the trailer wheels are locked to measure skid resistance. When the test wheel is locked, the resistance offered by the pavement surface is measured by a torque-measuring device in the trailer. This resistance is converted into a numerical value called skid number (SN).

Dahir et al. (*21*) used various polishing methods and friction measurement techniques, such as the locked-wheel skid trailer method and the British pendulum tester, to determine the

correlations between laboratory and field skid resistance test results. They found that the general level of skid-resistance characteristics of surface aggregates may be determined in the laboratory and that the aggregates may be ranked similarly by both approaches.

Stopping Distance Method

The stopping distance method (ASTM E445/E445M) is a field technique that characterizes the pavement surface skid resistance by the so-called stopping distance number (SDN). In this method a passenger vehicle with four wheels is used. The pavement in the test lane is wetted. The test vehicle is brought above the desired test speed and is permitted to coast onto the wetted section until the proper speed is attained. The brakes are then promptly and forcefully applied to cause a quick lockup of the wheels and to skid to a stop. The distance required to stop is recorded.

Sherwood and Mahone (*2*) used skid test data and coefficient of friction measurements, measured by different test methods, compiled for 23 years to propose the acid insoluble residue test for differentiation between skid resistance of different aggregates. For the sake of uniformity the authors converted all the skid test data and reported them as 40-mph stopping distance skid numbers using conversion curves developed by Dillard and Allen (*22*). The authors found that a simple relationship existed between the total acid insoluble residue percentages of Virginia limestones and their polish resistance (as indicated by the stopping distance skid number).

Petrographic Analysis Method

Dahir and Mullen (*12*) used the petrographic analysis method to determine the percentages of minerals and their hardness from thin sections of aggregates. The authors concluded that within the various aggregates tested in their study, a mixture of different minerals with different hardness in the same aggregate had a positive influence on skid resistance.

Most carbonate rocks tested by Gandhi et al. (*3*) were pure limestones. Their results showed that polishing of aggregates did not depend entirely on mineral composition. Other factors, such as texture of the rock (grain size, shape, and grain to grain relationship), degree of alteration, cementation, nature of cementating material, nature of impurities present, and porosity, could have considerable influence on polishing.

QUESTIONNAIRE

To obtain information about other states' experiences and current practices with the use of limestone aggregates in asphalt wearing courses, a questionnaire was sent to highway officials in the 50 states and the Canadian provinces.

The detailed results of this questionnaire, based on responses given by 43 states and Ontario, Canada, are given elsewhere (*23*). Figure 2 shows the responses concerning the use of limestone as coarse aggregate in the wearing course.

Seven states responded that they do not use limestone in asphalt wearing course mixes. Limestone aggregate did not meet their specifications or was not available in their region.

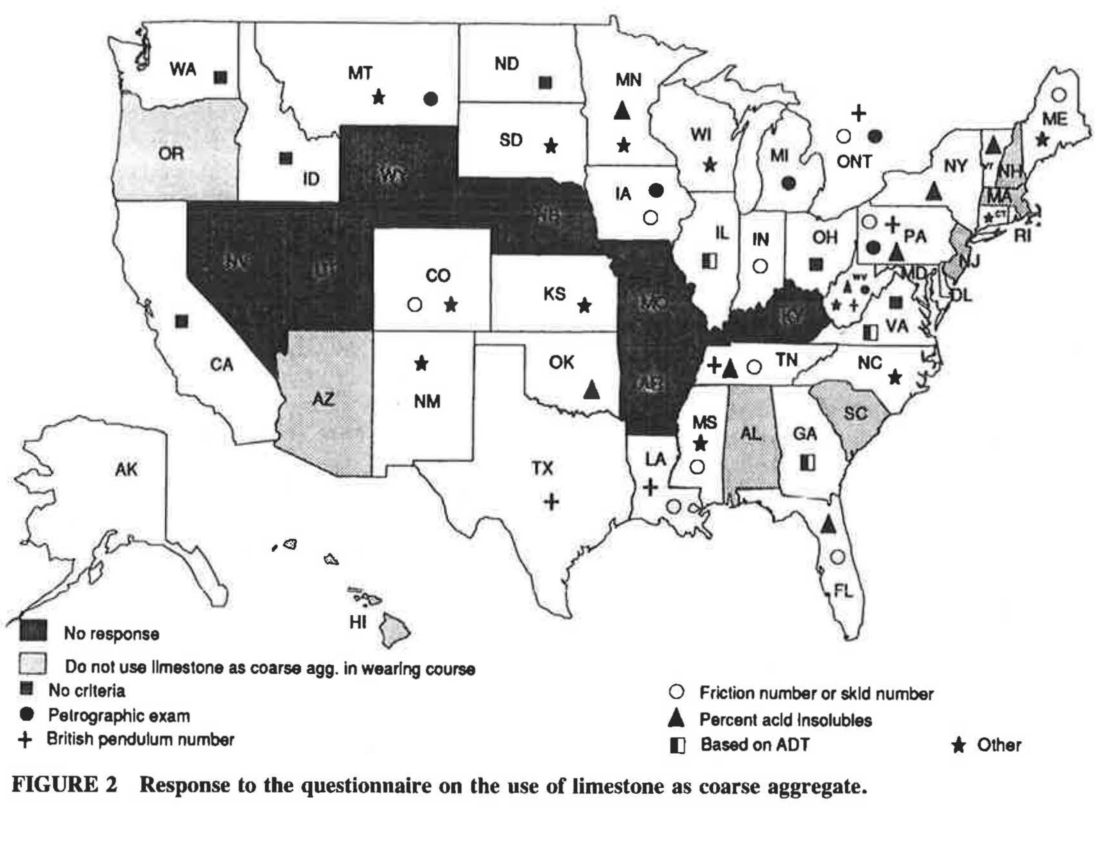

FIGURE 2 Response to the questionnaire on the use of limestone as coarse aggregate.

Eight states use the acid insoluble residue test in evaluating limestone aggregates for polish susceptibility. The skid trailer is used by nine states. Five states use the British pendulum and five states use petrographic analysis. Some states restrict the use of limestone aggregate based on the average daily traffic, and some use more than one criterion as shown in Figure 2.

MATERIALS AND TESTING METHODOLOGY

Materials

Two types of aggregates were used in this study: limestone and gravel. These aggregates were obtained from sources in Alabama approved for use in hot mix asphalt. Physical properties (obtained from AHD) are given in Tables 1 and 2. Thirty-two limestone and 12 gravel aggregates from AHD-approved sources were used. However, there are other approved sources of gravel that are not listed on the approved source list. The limestone aggregate serial number was assigned an A code and the gravel a B code.

Testing Methodology

Aggregate fractions passing the 12.7-mm (½-in.) sieve and retained on the 9.5-mm (⅜-in.) sieve were used for preparing test samples for the British pendulum test. Aggregate fractions passing the 9.5-mm (⅜-in.) sieve and retained on the 4.75-mm (No. 4) sieve were also used for the insoluble residue test and for the loss by ignition test.

The tests conducted are described in the following subsections.

Accelerated Polishing of Aggregates Using the British Wheel (ASTM D3319)

This test method simulates the polishing action of vehicular tires under conditions similar to those occurring on coarse aggregates used in asphalt pavements. A polish value is determined that may be used to classify coarse aggregates by ability to resist polishing under traffic.

Polishing wheel specimens consisting of bare aggregate particles were prepared to fit on the periphery of the accelerated polishing wheel. A rubber-tired wheel rubs against the polishing wheel when both are rotating. Silicon carbide grit and water are fed to accelerate the polishing action. Five replicate samples for each quarry were polished in this manner.

Measurement of Surface Frictional Properties Using the British Pendulum Tester (ASTM E303)

This test method is used to determine the relative effects of the British polishing wheel on coarse aggregates in terms of

TABLE 1 Physical Properties of Limestone Aggregates

SOURCE #	Bulk Specif. Gravity	Absorption %	L.A. Abrasion % Wear	Sod.Sulf. Soundness % Sound
A-1	2.800	0.7	40.0	99.8
A-2	2.600	1.3	24.9	99.7
A-3	2.815	0.5	26.9	99.6
A-4	2.678	0.8	22.8	99.8
A-5	2.565	1.6	27.8	99.7
A-6	2.663	0.9	36.8	97.9
A-7	2.695	0.7	19.8	99.6
A-8	2.672	0.9	20.8	99.1
A-9	2.707	0.8	22.0	98.7
A-10	2.600	1.2	29.0	99.9
A-11	2.729	0.6	28.3	99.7
A-12	2.694	0.5	22.3	99.1
A-13	2.776	0.5	19.5	99.9
A-14	2.703	0.4	24.8	99.8
A-15	2.722	0.4	23.1	99.8
A-16	2.805	0.5	24.5	99.6
A-17	2.629	1.8	22.8	97.4
A-18	2.686	0.6	21.8	99.4
A-19	2.664	1.0	24.2	99.6
A-20	2.804	0.6	17.9	99.1
A-21	2.608	1.0	32.8	98.4
A-22	2.667	0.9	20.0	99.2
A-23	2.647	0.8	25.6	99.7
A-24	2.633	0.8	20.2	99.8
A-25	2.516	2.0	19.1	99.9
A-26	2.654	0.9	27.1	99.6
A-27	2.680	0.7	21.8	99.7
A-28	2.718	0.7	19.6	99.6
A-29	2.707	1.6	22.4	99.6
A-30	2.682	0.6	20.8	99.5
A-31	2.658	0.7	24.0	99.7
A-32	2.808	0.6	21.5	99.8

TABLE 2 Physical Properties of Gravel Aggregates

SOURCE #	Bulk Specific Gravity	Absorption %	L.A. Abrasion % Wear	Sod. Sulf. Soundness % Sound
B-1	2.399	3.7	23.6	99.1
B-2	2.318	4.5	15.5	100.0
B-3	2.330	5.0	16.7	98.9
B-4	2.376	4.1	13.5	99.7
B-5	2.480	2.2	39.0	99.4
B-6	2.444	3.0	15.5	99.3
B-7	2.597	0.6	24.8	99.9
B-8	2.316	4.5	15.5	99.8
B-9	2.567	1.2	36.1	99.0
B-10	2.467	2.7	33.2	98.5
B-11	2.601	0.6	29.4	99.4
B-12	2.342	4.1	17.3	99.1

polish value. A dynamic pendulum impact-type tester was used to measure the energy loss when a rubber slider edge is propelled over a test surface. The test surface is wet before testing to simulate worst conditions and for correlation with field tests such as the locked-wheel skid trailer. BPNs are dimensionless values that represent the frictional properties of the tested surface. BPN values of all test specimens were obtained by removing the specimens from the polishing wheel at set intervals (3, 6, and 9 hr) and testing with the British pendulum. This was done to evaluate the rate of polishing with time.

Percent Insoluble Residue in Carbonate Aggregates (ASTM D3042)

This test gives the percentage of noncarbonate (insoluble) material in carbonate aggregates, which may indicate the polish susceptibility or friction properties of aggregate used in asphalt pavements.

A 500-g sample of aggregate is placed in a glass beaker and is reacted with several increments of hydrochloric acid solution until effervescence is stopped completely. The aggregate residue is washed over a 75-μm (No. 200) sieve, dried, and sieved again. The weight of the plus 75-μm (No. 200) residue is determined and expressed as a percentage of the original sample weight. The gradation of the insoluble residue was not analyzed to determine the sand size fraction, which many believe is critical for skid resistance.

Percent Loss on Ignition of the Mineral Aggregate (Tennessee Department of Transportation Method)

This test gives the percentage of weight loss when aggregates are subjected to a very high ignition temperature. It is an indicator of the relative percentages of carbonate and noncarbonate material in an aggregate.

This test is used by the Tennessee Department of Transportation to restrict the carbonate content of aggregate used in surface mixes. The basic principle of the test is same as that of the acid insoluble residue test. A 300-g sample of aggregate is heated in a muffle furnace at 950°C for a minimum of 8 hr. The samples are weighed before and after heating. The loss in the weight of the sample provides an indication of the carbon dioxide driven from the calcium or magnesium carbonate and is expressed as percent of the original weight.

Petrographic Analysis

This analysis was performed by a geologist in the Geology Department at Auburn University and identifies the constituent minerals of an aggregate and their characteristics. The analysis is done using different approaches for limestone and gravel aggregates. It consists of descriptions of thin sections made from quarry rock samples for limestone aggregates and visual inspection for gravel aggregates. The analysis determines the relative percentage of each mineral type present in an aggregate. The results of petrographic analysis are given elsewhere (*23*).

PRESENTATION AND ANALYSIS OF RESULTS

As mentioned earlier, the BPN is a measure of the frictional characteristics of test specimens subjected to accelerated polishing reported for various polish times. It is reported from an average of three to five specimens depending on the survivability of specimens during polishing. The relationship between the BPN value and polish time follows a hyperbolic function (*1,24*):

$$\mathrm{BPN} = \mathrm{BPN0} - \frac{t}{a + bt} \qquad (1)$$

where BPN is the British pendulum number value at time t (hours), BPN0 = British pendulum number value at time 0 (initial BPN), and a and b are constants calculated from following equations:

$$a = \frac{t1\, t2}{t2 - t1}\left(\frac{1}{\mathrm{dBPN1}} - \frac{1}{\mathrm{dBPN2}}\right) \qquad (2)$$

$$b = \frac{1}{t2 - t1}\left(\frac{t2}{\mathrm{dBPN2}} - \frac{t1}{\mathrm{dBPN1}}\right) \qquad (3)$$

where dBPN1 and dBPN2 are differential BPNs for polish times $t1$ and $t2$, respectively. These values are defined as follows:

$$dBPN1 = BPN1 - BPN0$$

$$dBPN2 = BPN2 - BPN0$$

As the polish time approaches infinity, the BPN value described by Equation 1 approaches the so-called limiting BPN value (BPNL):

$$\lim_{t\to\infty} BPN = BPN0 - \lim_{t\to\infty} \frac{t}{(a + bt)} \quad (4)$$

Hence,

$$BPNL = BPN0 - \frac{1}{b} \quad (5)$$

The limiting BPN value can be estimated from Equation 5 provided both BPN0 and b are known. The former is obtained experimentally and the latter is calculated from Equation 3 and requires measuring BPN values after two polishing intervals.

Results of the average BPN values measured at 0-hr polish time (BPN0) and 9-hr polish time (BPN9) and corresponding estimated limiting BPN values (BPNL) are given in Tables 3 and 4 for limestone and gravel aggregates, respectively. Also included in Table 3 are the values of ΔBPN (BPN0 − BPN9), percent loss by ignition (%LI) and percent insoluble residue (%IR). As shown in Table 3, values of BPN9 for the 32 limestone aggregates tested in this study range from 24 to 36. The range of BPN9 for gravel aggregates (12 sources) is from 27 to 34 (see Table 4). Therefore, values of BPN9 for both limestone and gravel aggregates tested in this study are quite comparable.

Using correlation analysis (SAS program), simple statistics and a correlation matrix among all parameters of the study were developed (see Tables 5 and 6). The top number in each cell is the coefficient of correlation between the two variables defining the cell. The bottom number in each cell is developed from hypothesis testing and indicates the significance of the correlation; lower numbers imply greater significance. The

TABLE 3 Test Results for Limestone Aggregates

SOURCE #	BPNO	BPN9	BPNL	ΔBPN	% LI	% IR
A-1	47	32	29	15	45.68	3.48
A-2	44	33	32	11	34.76	20.51
A-3	43	30	28	13	44.59	0.68
A-4	41	28	27	13	42.29	1.95
A-5	44	33	32	11	37.90	13.04
A-6	43	29	28	14	40.38	1.29
A-7	42	29	28	13	42.36	0.57
A-8	42	31	30	11	39.59	8.79
A-9	44	35	35	9	38.58	6.33
A-10	41	32	29	9	39.18	7.30
A-11	44	27	18	17	44.07	0.27
A-12	38	30	28	8	41.28	2.00
A-13	44	30	26	14	42.68	0.80
A-14	38	28	27	10	38.36	0.85
A-15	40	29	21	11	43.32	2.49
A-16	44	32	30	12	44.45	1.31
A-17	43	31	30	12	38.19	1.57
A-18	42	30	29	12	42.45	0.5
A-19	45	31	30	14	37.00	15.88
A-20	41	27	22	14	41.42	9.73
A-21	46	32	31	14	42.00	0.00
A-22	45	35	32	10	39.14	2.54
A-23	39	29	29	10	39.78	6.8
A-24	43	35	33	8	40.12	7.53
A-25	48	36	34	12	30.72	29.13
A-26	41	29	28	12	41.05	3.50
A-27	46	33	32	13	40.30	3.21
A-28	42	27	24	15	41.66	5.97
A-29	38	26	25	12	46.21	0.83
A-30	45	35	34	10	39.76	0.39
A-31	45	32	26	13	38.52	0.52
A-32	40	24	22	16	42.98	0.01

Notations: BPNO = British pendulum number value at 0 hour
BPN9 = British pendulum number value at 9 hours
BPNL = limiting British pendulum number value
ΔBPN = BPNO - BPN9
% LI = percent loss by ignition
% IR = percent acid insoluble residue (plus No. 200)

TABLE 4 Test Results for Gravel Aggregates

SOURCE #	BPNO	BPN9	BPNL	ΔBPN
B-1	35	30	30	5
B-2	39	30	27	9
B-3	41	30	22	11
B-4	39	32	31	7
B-5	45	34	31	11
B-6	37	27	26	10
B-7	36	29	27	9
B-8	40	29	25	11
B-9	37	29	26	8
B-10	41	32	31	9
B-11	37	33	32	4
B-12	40	31	16	9

numbers are expressions of probability, in decimal form, that the correlations are not significant. For the purpose of this study, the correlation coefficient will be considered low if below 0.50, fair if between 0.50 and 0.80, and good if above 0.80.

In addition to correlations for BPN0, BPN9, ΔBPN, %LI, and %IR, correlations for %SIL, %DOL, %CAL, BSG, and %ABS are shown in Table 5. The terms %SIL, %DOL, and %CAL indicate, respectively, the percentages of silica, dolomite, and calcite determined in the petrographic analysis of the limestone aggregates. The terms BSG and %ABS are, respectively, the aggregate bulk specific gravity and percent absorption. Correlations in Table 6 include the variables %CHERT, %QUARTZ, and %SANDSTONE. These terms indicate, respectively, the percentages of chert, quartz, and sandstone determined in the petrographic analysis of the gravel aggregates.

Relationship Between BPN9 and BPNL

Since polish time of 9 hr was the maximum examined in this study, it was important to determine the correlations between BPN9 and BPNL values for both limestone and gravel aggregates.

Coefficients of correlation between the BPN9 and the BPNL are 0.85 and 0.42 for limestone and gravel aggregates, respectively. This relationship is shown in Figure 3 for limestone

TABLE 5 Correlation Matrix for Limestone Aggregates

	BPNO	BPN9	BPNL	ΔBPN	%LI	%IR	%SIL	%DOL	%CAL	BSG	%ABS
BPNO	1.00000 0.0	0.68086 0.0001	0.47390 0.0061	0.26863 0.1371	-0.32151 0.0728	0.33094 0.0643	0.18528 0.3100	-0.16447 0.3684	0.14727 0.4212	-0.22019 0.2259	0.24363 0.1790
BPN9		1.00000 0.0	0.85382 0.0001	-0.52260 0.0022	-0.55744 0.0009	0.41408 0.0185	0.22777 0.2099	-0.42502 0.0153	0.41040 0.0196	-0.50825 0.0030	0.30436 0.0903
BPNL			1.00000 0.0	-0.57126 0.0006	-0.54913 0.0011	0.38450 0.0298	0.26959 0.1357	-0.46572 0.0072	0.44732 0.0103	-0.53302 0.0017	0.39167 0.0266
ΔBPN				1.00000 0.0	0.35887 0.0437	-0.15934 0.3837	-0.08388 0.6481	0.36752 0.0385	-0.36830 0.0381	0.41212 0.0191	-0.11667 0.5248
%LI					1.00000 0.0	-0.76887 0.0001	-0.55098 0.0011	0.53073 0.0018	-0.48082 0.0053	0.75538 0.0001	-0.54729 0.0012
%IR						1.00000 0.0	0.70531 0.0001	-0.25302 0.1623	0.17667 0.3334	-0.55340 0.0010	0.59373 0.0003
%SIL							1.00000 0.0	-0.30032 0.0949	0.19037 0.2967	-0.56062 0.0008	0.59261 0.0004
%DOL								1.00000 0.0	-0.99357 0.0001	0.80860 0.0001	-0.42818 0.0145
%CAL									1.00000 0.0	-0.76567 0.0001	0.37033 0.0369
BSG										1.00000 0.0	-0.71040 0.0001
%ABS											1.00000 0.0

TABLE 6 Correlation Matrix for Gravel Aggregates

	BPN0	BPN9	BPNL	ΔBPN	%CHERT	%QUARTZ	%SANDSTONE	BSG	%ABS
BPN0	1.00000 0.0	0.56103 0.0577	-0.06461 0.8419	0.70702 0.0101	0.00102 0.9975	0.04598 0.8872	-0.26746 0.4007	-0.32175 0.3078	0.29681 0.3488
BPN9		1.00000 0.0	0.41870 0.1755	-0.18874 0.5569	-0.34461 0.2727	0.32888 0.2966	0.08039 0.8039	0.13735 0.6704	-0.14996 0.6418
BPNL			1.00000 0.0	-0.43435 0.1583	-0.44244 0.1498	0.40696 0.1892	0.19023 0.5537	0.44806 0.1441	-0.41849 0.1758
ΔBPN				1.00000 0.0	0.29562 0.3509	-0.22641 0.4792	-0.38598 0.2153	-0.49904 0.0986	0.48022 0.1141
%CHERT					1.00000 0.0	-0.98450 0.0001	-0.06178 0.8487	-0.87639 0.0002	0.88947 0.0001
%QUARTZITE						1.00000 0.0	-0.11424 0.7237	0.87484 0.0002	-0.89155 0.0001
%SANDSTONE							1.00000 0.0	-0.01129 0.9722	0.03537 0.9131
BULK S.G.								1.00000 0.0	-0.99001 0.0001
%ABS									1.00000 0.0

aggregates. The lower correlation between BPNL and BPN9 in the case of gravel aggregates may be a result of the use of a smaller number of sources compared with limestone aggregates.

Relationship Between BPN9 and BPN0

It was important to evaluate the relationship between the frictional value (BPN) at 9 hr and that at zero time to determine the effect of polishing. As shown in Table 5, the correlation coefficient between BPN9 and BPN0 for limestone is 0.68. The corresponding coefficient for gravel aggregates (Table 6) is 0.56. These results indicate that the BPN value measured at a certain time is partially dependent on the initial BPN value.

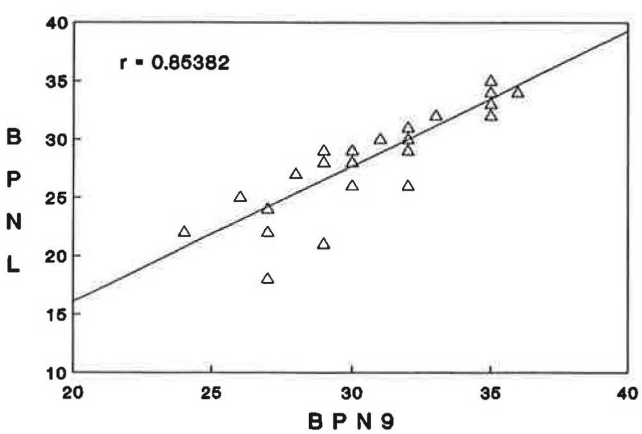

FIGURE 3 BPN9 versus BPNL values for limestone aggregates.

Categorization of BPN9 Values for Both Limestone and Gravel Aggregates

To divide the BPN9 values into low, medium, and high categories, the full range of BPN9 values for both limestone and gravel aggregate sources examined in this study was arbitrarily subdivided into three about equal ranges. This procedure resulted in the following categories and ranges (see Figures 4 and 5): low BPN9, below 28; medium BPN9, 28 to 32; and high BPN9, above 32.

AHD permits the use of all gravel aggregates. The lowest BPN9 for gravel aggregates used in this study is 27. If BPN9 is used as an acceptance criterion, the limestone aggregates with medium and high BPN9 (28 to 32 and 33 to 36, respectively) should also be permitted. However, their performance

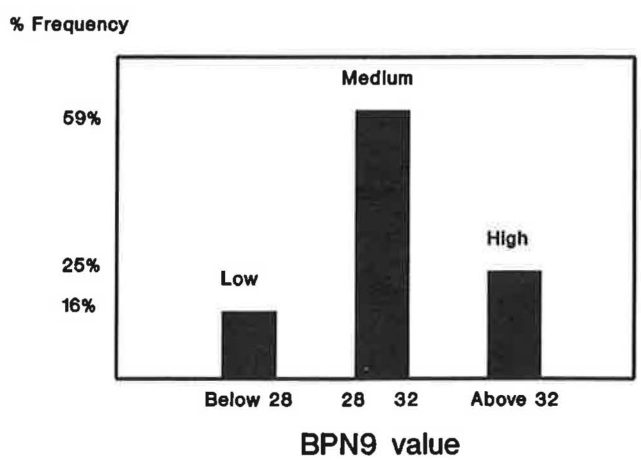

FIGURE 4 Categories of limestone aggregates based on BPN9 values.

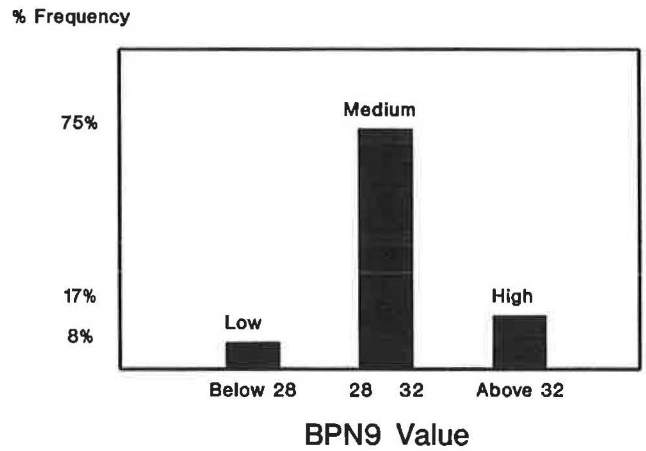

FIGURE 5 Categories of gravel aggregates based on BPN9 values.

should be confirmed in the field. Figure 6 shows the changes in BPN values with respect to time for typical limestone aggregates from low, medium, and high categories. Curves shown in the figures are theoretical plots of the BPN-time relationship based on the hyperbolic function given in Equation 1. There was good agreement between the experimental observations and the theoretical function for both types of aggregates in all these categories. Accordingly, it is expected that the hyperbolic function will provide a good tool for estimating aggregate's BPN value after different polishing times.

Results of Insoluble Residue

Results of the percentage insoluble residue for all the limestone aggregate sources examined in this study are given in Table 3. These values range from 0.00 to 29.13 percent. The correlation coefficient between the percentage insoluble residue (%IR) and other parameters is given in Table 5. A positive correlation coefficient of 0.41 is found between the percentage insoluble residue and the BPN9. The relationship between the two parameters is given by

$$BPN9 = 29.7 + 0.02(\%IR) \quad (6)$$

There is a general trend that as the percentage of insoluble residue increases, the value of BPN9 also increases, but the degree of correlation is poor. This is likely due to variability in the composition and gradation of the residue material: both influence friction.

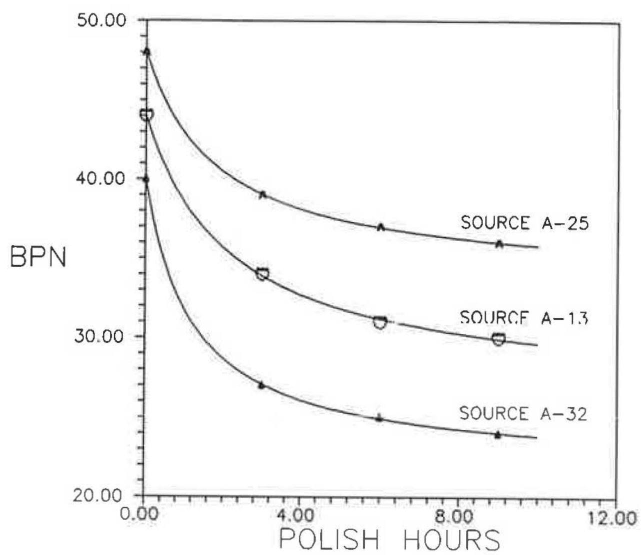

FIGURE 6 Polish hours versus BPN values for three limestone aggregates.

Results of Percentage Loss by Ignition

Results of the percentage loss by ignition for all the limestone aggregate sources examined in this study are given in Table 3. These values range from 30.73 to 46.22 percent. The correlation coefficient between the percentage loss by ignition (%LI) and BPN9 is given in Table 5. A negative correlation coefficient of −0.56 is found between the percentage loss by ignition and the BPN9. The relationship between the two parameters is given by

$$BPN9 = 52.0 - 0.5(\%LI) \quad (7)$$

There is a general trend that as the percentage loss by ignition decreases, the value of BPN9 increases, but there is a relatively low degree of correlation.

The correlation results given in Table 5 also show that a high negative correlation of −0.77 exists between the percentage insoluble residue and the percentage loss by ignition. This high correlation is probably a result of the fact that the two methods use the same concept of measuring the amount of carbonates in the aggregates.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the test data obtained and analyzed in this study the following conclusions are drawn and recommendations made:

1. The BPN or polish values were found to follow a hyperbolic relationship with polishing time. The relationship can possibly be used to predict the ultimate or limiting BPN value (BPNL) at infinite polish time.
2. A wide range of BPN values after 9 hr of polish (BPN9) exists for limestone aggregates (24 to 36). This may be a result of the different constituents of the rocks such as calcite, silica, dolomite, and other minerals. It may also be due to differences in crystalline structure that result in different densities, porosity, fracture shape, surface texture, and so forth.
3. There is a general trend that as the percentage of insoluble residue increases the value of BPN9 also increases. However, the poor degree of correlation obtained suggests that the BPN value cannot be statistically predicted from percent insoluble residue.
4. There is also a general trend that as the percentage loss by ignition decreases the value of BPN9 increases. However, the low correlation obtained suggests that the BPN value

cannot be statistically predicted from the percentage loss by ignition.

5. The coefficient of correlation between values of percentage loss by ignition and those of percentage insoluble residue was determined to be −0.77. This fairly good correlation between the two parameters exists because both measure the amount of carbonates in different ways.

6. The results of this laboratory study have made it possible to establish categories of potentially low, medium, and high skid resistance levels of limestone aggregates for Alabama. On the basis of 9-hr BPN values, these categories have ranges of 24 to 27, 28 to 32, and 33 to 36 for low, medium, and high levels, respectively.

7. AHD permits the use of all gravel aggregates. The lowest BPN9 for gravel aggregates used in this study is 27. If BPN9 is used as an acceptance criterion, the limestone aggregates with medium and high BPN9 (28 to 32 and 32 to 36, respectively) have the potential to provide skid resistance comparable with gravel aggregates used at the present time.

8. A field evaluation of limestone aggregate sources falling into various categories based on 9-hr BPN values (BPN9) is being conducted. Short sections utilizing 75 to 85 percent limestone aggregates are being constructed and will be evaluated periodically with locked-wheel skid trailer. The various sources can then be categorized finally on the basis of field measurements rather than 9-hr BPN values measured in the laboratory.

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