Evaluation of Limestone Aggregates in Asphalt Wearing Courses

Phase II

by

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ABSTRACT

Skid resistance is a major factor in highway construction and maintenance. Limestone is not used in asphalt wearing course in Alabama due to its potential low skid resistance. This study was conducted to evaluate different sources of limestone, approved by Alabama Highway Department, and gravel aggregates available in Alabama. Thirty-two limestone and twelve gravel aggregates obtained from different sources were evaluated by British Wheel/Pendulum test, acid insoluble residue test, and loss by ignition test. The purpose of using different testing techniques was to evaluate possible correlations between results obtained by these techniques and to determine which test best characterizes the limestone skid resistance. Results of this study showed that limiting British pendulum numbers (estimated British pendulum numbers at infinite time) had a good correlation of 0.85 with British pendulum numbers at nine hours (BPN9). Loss by ignition of limestone aggregates had a fair, negative correlation coefficient of 0.56 with British pendulum numbers at nine hours. Bulk specific gravity of limestone aggregates was also found to have a fair, negative correlation coefficient of 0.51 with British pendulum numbers at nine hours.

Limestone and gravel aggregates were classified into three potential levels of low, medium and high skid resistance. This classification was based on British pendulum numbers at nine hours determined by the British Wheel/Pendulum tester. Ranges for the low, medium, and high BPN values of both aggregates were established as less than 28, 28 to 32, and above 32, respectively. Results of this classification of limestone aggregates based on BPN values will be used to provide recommendations for selecting one source of limestone from each class to build field test sections as the next phase of this study.

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I. INTRODUCTION

The ever increasing highway pavement system requires aggregates of multifunctional characteristics to meet various demands. These characteristics include strength, durability and skid resistance. Aggregates having all these properties are often not locally available and have to be imported. When this situation exists, hauling costs increase highway construction costs.

Limestone aggregates are readily available in North 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 like gravel have the following disadvantages:

a) low resistance to water damage (stripping and ravelling),
b) high asphalt absorption (high asphalt requirement), and
c) partially crushed nature (low strength and stability).

Limestone do not exhibit these undesirable characteristics.

However, their potential lack of long-term skid resistance must be evaluated prior to their use in asphalt wearing courses.

In a recent study sponsored by the Alabama Highway Department, limestone aggregates were evaluated in asphalt wearing courses (1). Three field sites were evaluated and showed that limestone aggregates were beneficial in increasing the stability of the mix and its resistance to moisture damage. In addition, laboratory frictional resistance of some limestone aggregates was comparable to gravel aggregates. These results were confirmed on two field sites while the third site did not show any improvement in the properties just cited. It was important, therefore, that additional sources of limestone aggregates be categorized and evaluated to determine their possible use in wearing courses to take advantage of their durability and stability.

The purpose of the present study is to evaluate a wide range of limestone aggregate sources which have been approved by the Alabama Highway Department for applications other than asphalt wearing courses. Results of this evaluation will assist in formulating recommendations for constructing three field projects incorporating limestone aggregates of low, medium, and high skid resistance so that additional field evaluation can be made. Future merits of this study will include providing data to AHD to support discriminatory use of limestone coarse and fine aggregates in asphalt wearing course mixes.

II. RESEARCH OBJECTIVES

The objective of this study was to evaluate potential long term skid resistance of a wide range of limestone aggregate sources in Alabama through laboratory tests. Results of this evaluation will be used in formulating recommendations for constructing three field projects incorporating limestone aggregates of low, medium, and high categories of skid resistance.

In order to achieve these objectives the work was divided into three phases:

Phase A: Background And Surveying

The following two tasks were accomplished in this phase:

[1] Review of available literature pertaining to the use of limestone aggregates (both coarse and fine) in asphalt wearing courses.

[2] Conduct a nation-wide survey through a questionnaire to obtain information about states' experiences with the use of limestone aggregates in asphalt wearing courses.

Phase B: Experimental Work And Data Analysis

This phase involved the following three tasks:

[1] Finger-printing all approved sources of limestone and crushed gravel by running the following tests:

a. British Wheel/Pendulum.

b. Percent insoluble residue.

c. Percent loss by ignition.

d. Petrographic examination.

[2] Analyzing data obtained from this study, and the data provided by AHD (which cover other characteristics of limestone aggregates) to determine correlations between British pendulum number values (BPN) and other aggregates properties.

[3] Classifying all limestone aggregates into three levels (low, medium and high) of skid resistance based on laboratory tests.

Phase C: Recommendations

In this phase, sources of limestone aggregates and general locations of field test sites were selected for future field experiments.

III. BACKGROUND AND LITERATURE REVIEW

Asphalt wearing courses should exhibit a number of critical characteristics including skid resistance, structural capacity, and ridability. Skid resistance characteristics of the pavement surface are principally determined by the properties of aggregates used because aggregates constitute more than 90% of the pavement structure.

According to Sherwood and Mahone (2), and Gandhi and Colucci (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 (4,5,6) that many limestones differ significantly in polish susceptibility. These differences have been attributed primarily to the noncarbonated or acid insoluble constituents in the rock.

Polish susceptibility may be evaluated using a number of different testing techniques. These techniques include [1] the British Wheel/Pendulum method, [2] circular track wear method, [3] percent acid insoluble residue, [4] locked wheel skid trailer, [5] stopping distance on paved surfaces, and [6] petrographic analysis.

British Wheel/Pendulum method

The British Wheel/Pendulum method [ASTM D3319-83, and E303-83] has been used extensively by researchers including a recent evaluation by Diringer (7). 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. In Diringer's study in New Jersey, five types of aggregate were tested for polishing value (PV). Results indicated that considerable variability of polish resistance can be expected for a given aggregate type. Results from Diringer's study summarized in Table 1 and illustrated in Figure 1. Aggregates were divided into three categories with respect to their polish values. These categories are given in Table 2 and illustrated in Figure 1. These results 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, while carbonate rock mixes provided marginal skid resistance over the long term.

TABLE 1 PV READINGS OF FIVE AGGREGATES [DIRINGER, 7]

AGGREGATE TYPE	PV RANGE
Carbonate rock	20 - 28
Traprock	25 - 34
Gneiss	27 - 36
Argillite	30 - 37
Crushed Gravel	30 - 43

TABLE 2 AGGREGATES CATEGORIES [DIRINGER, 7]

Minimum PV	Quality
24 or less	Poor
25 to 30	Marginal
31 or more	Good

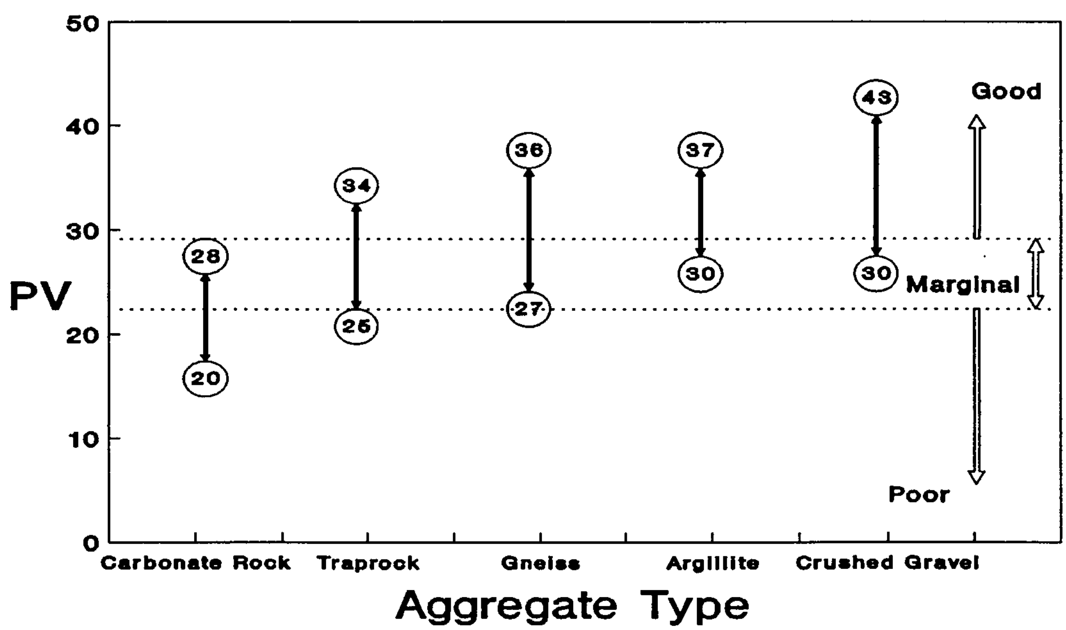


FIGURE 1 PV readings of different types of aggregates [Diringer 7]

Gandhi (10) tested three types of aggregates for polishing value. Results are given in Table 3 and illustrated in Figure 2. The author concluded that correlations between the polish value and other aggregates properties such as specific gravity, absorption, abrasion value, initial friction value, percent insoluble residue and sand size residue were very poor.

TABLE 3 PV RANGES AT 16 POLISH HOURS OF THREE TYPES OF LIMESTONE AGGREGATES [GANDHI 10]

AGGREGATE TYPE	PV RANGE
Carbonate rocks	39 - 59
Noncarbonate rocks	41 - 56
River Gravels	41 - 55

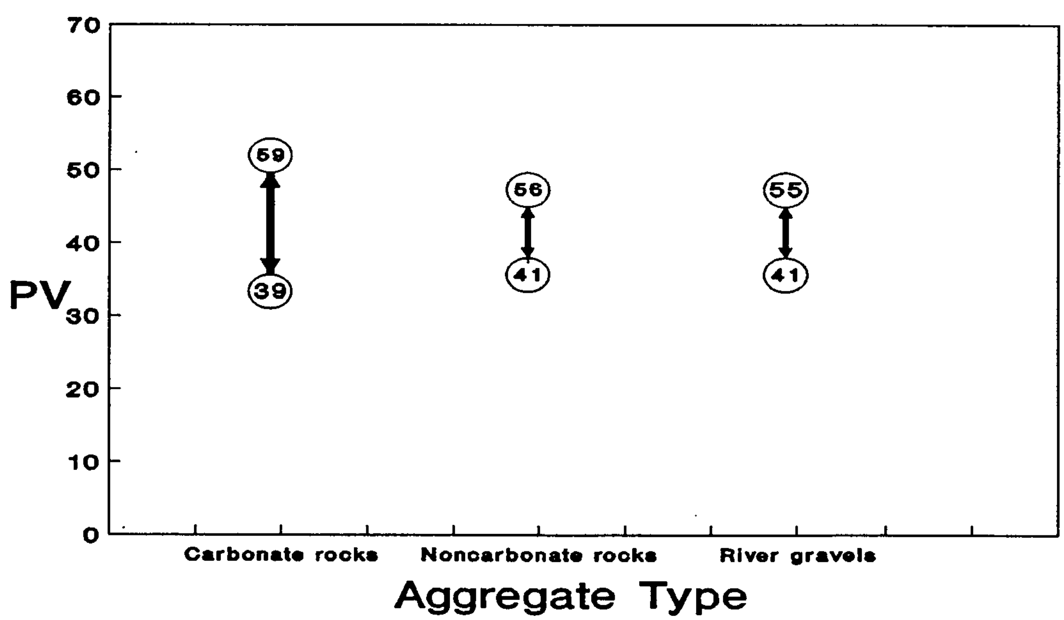


FIGURE 2 PV ranges of different types of limestone aggregates [Gandhi, 10]

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 hours. Skid resistance values were determined by using the British Pendulum tester. Using the circular track method, Dahir and Mullen examined four types of aggregates for their polishing susceptibility. Ranges of polish values obtained after 16 hours of polish for different types of aggregates are given in Table 4.

TABLE 4 PV RANGES AT 16 HOURS FOR FOUR TYPES OF AGGREGATES [DAHIR AND MULLEN,12]

Aggregate type	PV
Limestone	35 - 40
Gravel	40 - 45
Granite	42 - 44.5
Sandstone	58.5

Percent acid insoluble residue method

Dahir and Mullen (12) also used the insoluble residue test [ASTM D 3042-86] in their study. 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. Four carbonate aggregates were examined in their study. The authors 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 (13,14,15,16,17,18,19).

Insoluble residue test results obtained by several investigators were used by Sherwood and Mahone (2) to provide tentative guidelines for future studies dealing with the polish resistance of limestone aggregates. The authors indicated that a relationship appeared to exist between coarseness of insoluble particles and coefficient of friction. In addition, they suggested that an even better relationship may exist between total insoluble particles and coefficient of friction. However, the extent of this relationship will depend on the type of limestone examined. Sherwood (20), and Gray and Reninger (13) showed that the amount and nature of the acid insoluble mineral grains contained in limestones were primarily responsible for their variable wearing characteristics. However, all carbonate rocks tested by Gandhi (10) had very low percent insoluble residue, but they showed a wide range (39-59) of polish values as shown in Table 3. Gandhi concluded that although the limestone aggregates as a group had low polish values, some light-weight, porous limestones showed high polish values in the laboratory. However, they might wear out quickly under traffic.

Locked-wheel skid trailer method

The locked-wheel skid trailer method [ASTM E274-85], is a field technique which measures the pavement skid resistance. In this method, a locked-wheel skid trailer is used (see Figure 3). The trailer is usually towed at 40 mph and its wheel is locked to measure the skid resistance of the pavement surface. When the test wheel is locked, the trailer is dragged by the truck. 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).

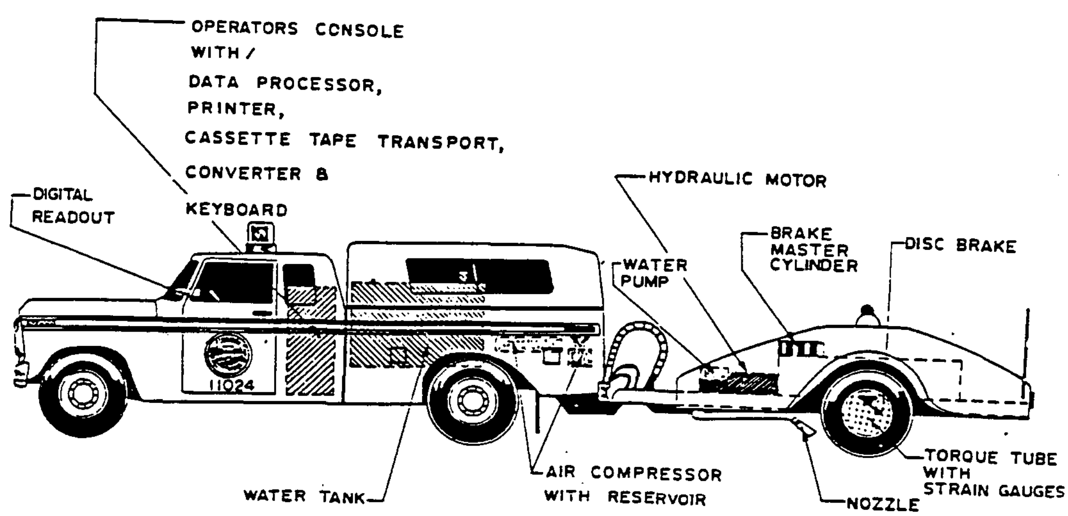


FIGURE 3 Typical locked wheel skid trailer

Dahir, Meyer and Hegmon (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 tests 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-88] is a field technique which 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 resulting distance required to stop is then 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 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). Ranges of average values of stopping distance skid numbers (SDN_{40}) and average values of total percent insoluble provided by Sherwood and Mahone are given in Table 5. The authors rated limestones according to stopping distance skid number.

TABLE 5 SUMMARY OF STOPPING DISTANCE SKID NUMBER AND AVERAGE INSOLUBLE RESIDUE FOR VIRGINIA LIMESTONES (2)

Rating	Range of SDN*	Average insoluble %
Good	53	37
Fair	44 - 43	13
Poor	42 - 40	10
Unacceptable	39 - 36	8
Critical	34 - 31	5

* These values represent ranges of average Stopping Distance Skid Numbers at 40 mph for a number of limestone sources.

Petrographic analysis method

Dahir and Mullen (12) used the petrographic analysis 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.

An aggregate containing a mixture of 50 to 70 % hard minerals and 30 to 50 % soft minerals will have a terminal skid resistance after wear that is higher than aggregates containing predominantly hard or soft minerals. Aggregates containing predominantly hard minerals polished less rapidly than aggregates containing predominantly soft minerals, but terminal skid resistance values when reached were similar.

Most carbonate rocks tested by Gandhi and Colucci (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. However there was a wide variation in their nature of polishing. Dense limestones showed low polish values whereas porous limestones generally showed higher values.

IV. QUESTIONNAIRE

In order to obtain information about other states' experiences and current practices with the use of limestone aggregates, a questionnaire (Appendix A) was sent to highway officials in 50 states and Canadian provinces.

The results of this questionnaire based on responses given by forty-three states and Ontario, Canada are shown in Figures 4, 5 and 6. A brief discussion follows.

Seven states responded that they do not use limestone in asphalt wearing courses mixes (see Figure 4). Either limestone aggregate did not meet their specifications or it was not available in their region.

Thirty five states and Ontario use limestone as coarse and fine aggregates (see Figures 5 & 6). Alabama uses limestone as fine aggregate but not 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.

In summary, a majority of states use limestone in asphalt wearing courses in addition to other aggregates with different criteria and restrictions.

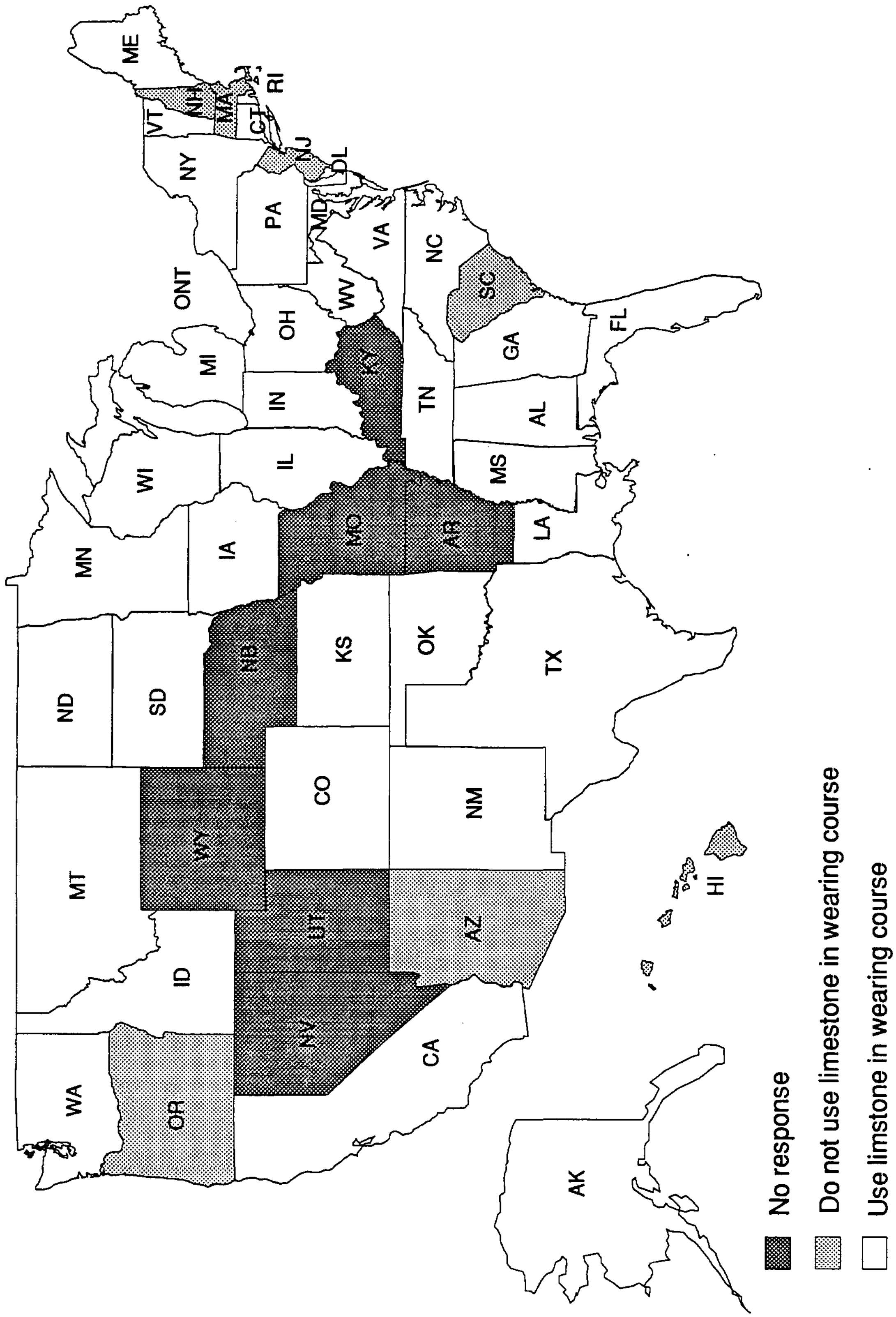


FIGURE 4 Use of limestone aggregates in wearing course by various states

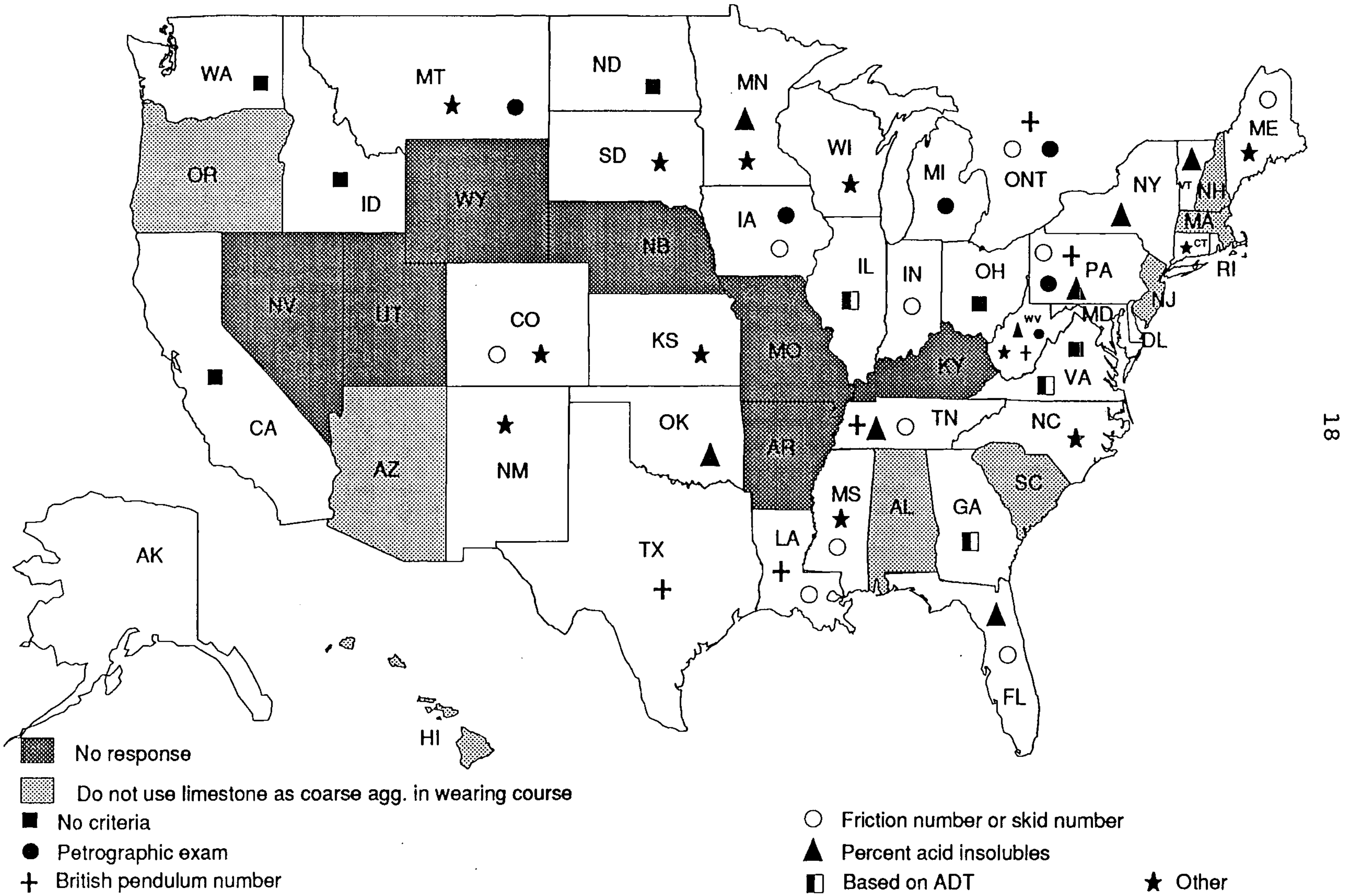


FIGURE 5 Response to the use of limestone as coarse aggregate

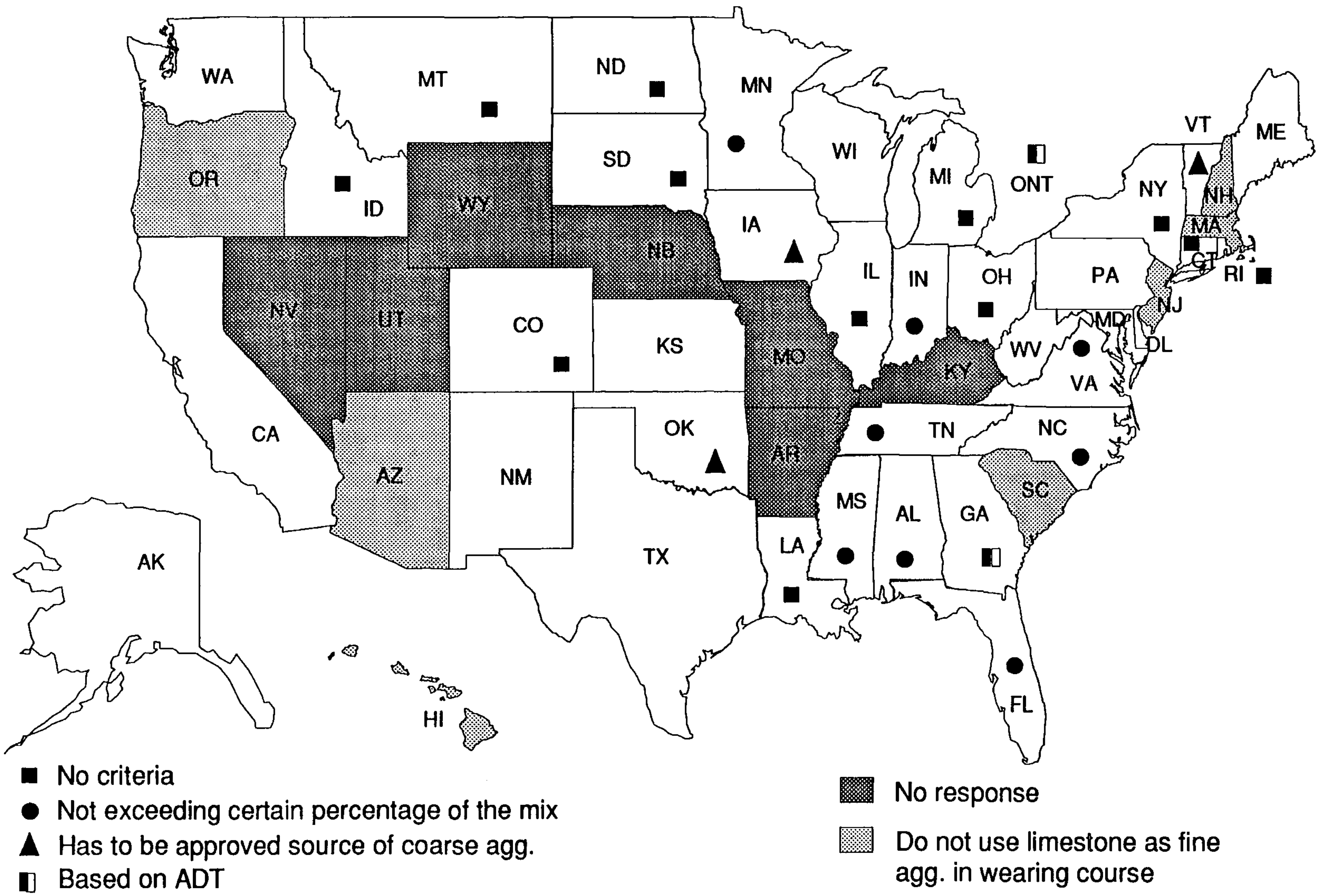


FIGURE 6 Response to the use of limestone as fine aggregate

With regard to techniques for evaluating polish susceptibility, a number of test methods: percent insoluble residue, skid trailer, British pendulum number and petrographic analysis, are used. However, the most widely used are the acid insoluble residue and skid trailer as shown in Table 6.

TABLE 6 SUMMARY OF THE RESPONSES TO THE QUESTIONNAIRE FROM THE UNITED STATES

Item	Number of states
Responses received	43
No response	7
States using limestone as coarse and fine aggregate	35
States using limestone only as fine aggregate	1
States not using limestone	7
States using friction number or skid number	9
States using acid insoluble residue	8
States using BPN	5
States using petrographic analysis	5

V. MATERIALS AND TESTING METHODOLOGY

Materials

Two types of aggregates were used in this study: limestone and gravel. These aggregates were obtained from approved sources in the state of Alabama. Source designation, county and division for limestone and gravel aggregates used in this study are listed in Table 7 and shown on Alabama map Figure 7. Physical properties (obtained from AHD) are listed in Tables 8 and 9. Thirty two types of limestone and 12 types of 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 samples were received from AHD in 100-lb bags. They were sieved in order to produce specific sizes needed for performing tests. Aggregate fractions passing 1/2" sieve and retained on 3/8" sieve were collected, washed, dried in an oven at $230 \pm 9^\circ$ F and stocked in one-gallon cans, for preparing test samples for the British Pendulum test. Aggregate fractions passing 3/8" sieve and retained on # 4 sieve were also collected. Half were washed, dried in oven at 230 $\pm$ 9° F, and stocked in quart cans for the insoluble residue test. The other half were stocked directly, without washing, in quart cans for the Loss by Ignition test.

TABLE 7 LIMESTONE AND GRAVEL SOURCES DESIGNATION COUNTY AND DIVISION

SOURCE #	COUNTY	DIVISION
A-1	Lee	4
A-2	Colbert	2
A-3	Shelby	3
A-4	Madison	1
A-5	Colbert	2
A-6	Jackson	1
A-7	Marshall	1
A-8	Marshall	1
A-9	Blount	3
A-10	Colbert	2
A-11	Shelby	3
A-12	Jefferson	3
A-13	Shelby	3
A-14	Talladega	4
A-15	Etowah	3
A-16	Shelby	3
A-17	Madison	1
A-18	Morgan	1
A-19	Madison	1
A-20	Calhoun	4
A-21	Franklin	2
A-22	Jackson	1
A-23	Morgan	1
A-24	Colbert	2
A-25	Colbert	2
A-26	Madison	1
A-27	Jackson	1
A-28	Jackson	1
A-29	Jefferson	3
A-30	Dekalb	1
A-31	Lawrence	2
A-32	Talladega	4
B-1	Madison	1
B-2	Madison	1
B-3	Madison	1
B-4	Pickens	5
B-5	Calhoun	4
B-6	Fayette	5
B-7	Shelby	3
B-8	Madison	1
B-9	Conecuh	9
B-10	Etowah	3
B-11	Chilton	5
B-12	Lauderdale	2

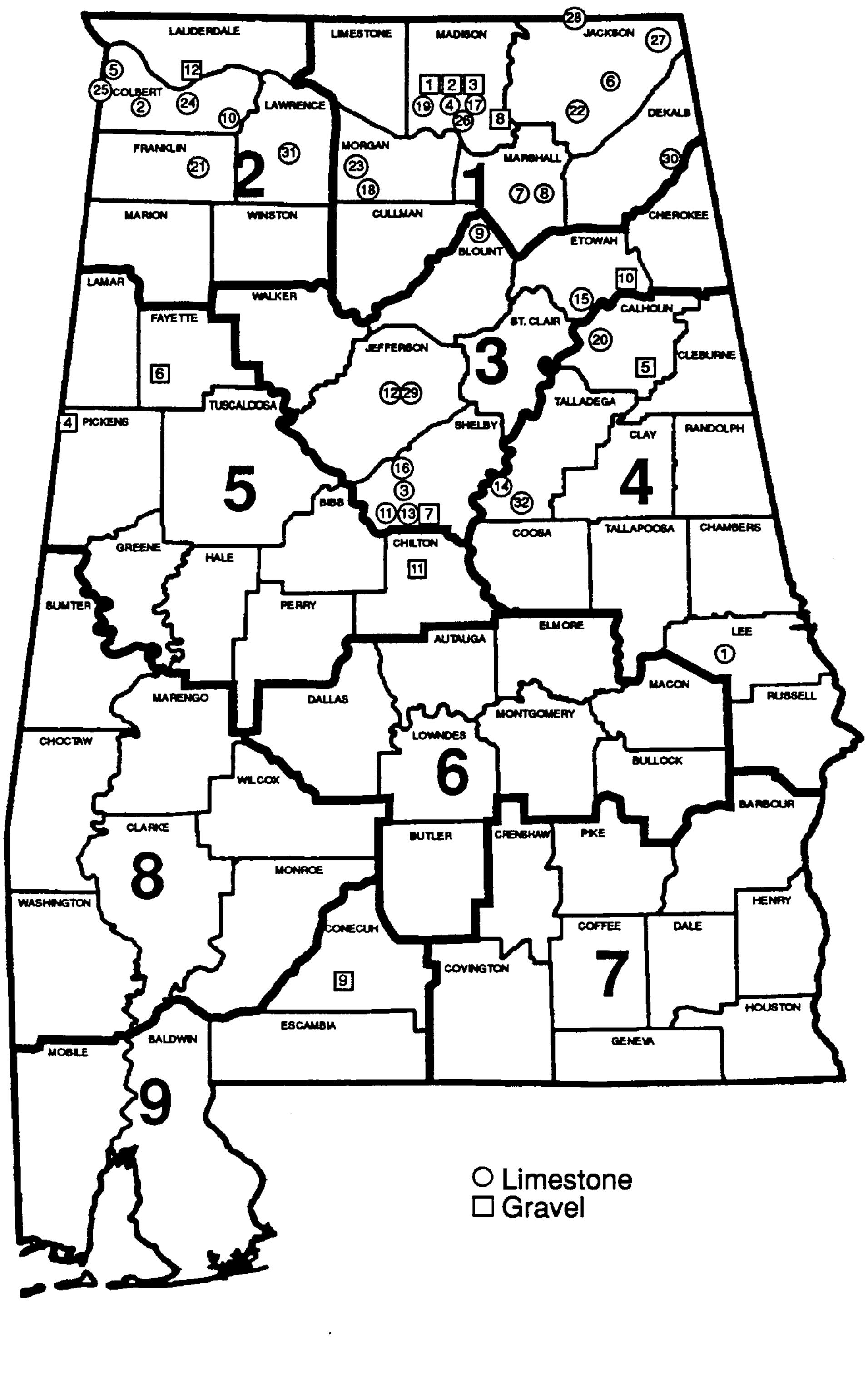


FIGURE 7 Location of aggregates sources

TABLE 8 PHYSICAL PROPERTIES OF LIMESTONE AGGREGATES OBTAINED FROM AHD

SOURCE #	Bulk Specif. Gravity	Absorption %	L.A. Abrasion % Wear	Sod.Sulf. Soundness % Sound	% Silica
A-1	2.800	0.7	40.0	99.8	5.3
A-2	2.600	1.3	24.9	99.7	4.7
A-3	2.815	0.5	26.9	99.6	3.7
A-4	2.678	0.8	22.8	99.8	6.5
A-5	2.565	1.6	27.8	99.7	2.3
A-6	2.663	0.9	36.8	97.9	7.1
A-7	2.695	0.7	19.8	99.6	6.6
A-8	2.672	0.9	20.8	99.1	8.0
A-9	2.707	0.8	22.0	98.7	8.0
A-10	2.600	1.2	29.0	99.9	7.1
A-11	2.729	0.6	28.3	99.7	5.2
A-12	2.694	0.5	22.3	99.1	6.6
A-13	2.776	0.5	19.5	99.9	6.6
A-14	2.703	0.4	24.8	99.8	5.8
A-15	2.722	0.4	23.1	99.8	4.5
A-16	2.805	0.5	24.5	99.6	1.8
A-17	2.629	1.8	22.8	97.4	5.2
A-18	2.686	0.6	21.8	99.4	4.6
A-19	2.664	1.0	24.2	99.6	7.9
A-20	2.804	0.6	17.9	99.1	4.1
A-21	2.608	1.0	32.8	98.4	4.9
A-22	2.667	0.9	20.0	99.2	4.2
A-23	2.647	0.8	25.6	99.7	7.0
A-24	2.633	0.8	20.2	99.8	8.0
A-25	2.516	2.0	19.1	99.9	11.3
A-26	2.654	0.9	27.1	99.6	4.6
A-27	2.680	0.7	21.8	99.7	4.2
A-28	2.718	0.7	19.6	99.6	6.2
A-29	2.707	1.6	22.4	99.6	7.0
A-30	2.682	0.6	20.8	99.5	6.5
A-31	2.658	0.7	24.0	99.7	4.4
A-32	2.808	0.6	21.5	99.8	1.4

TABLE 9 PHYSICAL PROPERTIES OF GRAVEL AGGREGATES OBTAINED FROM AHD

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

The following is a listing and brief description of tests run:

A) Accelerated Polishing of Aggregates Using the British Wheel (ASTM D3319 - 83)

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 for their ability to resist polishing under traffic.

Polishing wheel specimens were prepared to fit around the periphery of the accelerated polishing wheel. The molds sides were precoated with wax, then wiped so as not to contaminate the aggregates. A single layer of dry aggregate was placed by hand into each mold, leaving as few gaps as possible between the aggregates. The gaps were filled with sand to avoid the bonding agent to project at the top of the specimen. The bonding agent was then spread over the aggregates, filling the mold. When the bonding agent was cured (6-8 hours) the specimen is stripped from the mold and edges are dressed with a belt sander. Five replicate samples for each quarry were prepared in this manner. Two sets of five samples and one set of four samples were polished at a time on the wheel. During polishing No. 150 silicon carbide grit is fed at a rate of 6 ± 2 g/min, and water at the rate of 50 to 75 ml/min.

B) Measuring Surface Frictional Properties Using the British Pendulum Tester (ASTM E303 - 83)

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

First, the friction value of the original sample (before polishing) was determined, using the British pendulum tester. The pendulum tester was leveled and zeroed, the height of the pendulum was adjusted so as to impact the same area of the test specimen at each test, and a thin film of water was applied to the specimen surface. The pendulum was then released. The value obtained from the first swing was not recorded so as to allow the slider to self-adjust to the surface of the specimen. Four swings were then made, and their values were recorded. An average of all these values was calculated to give the British Pendulum Number value at time zero (BPN0). Readings were also taken with the British pendulum tester by removing the specimens from the polishing wheel at set intervals (3, 6 and 9 hours). After removal from the polishing wheel, each test specimen was washed off all grit, locked into the specimen base and BPN value was determined.

British pendulum numbers are basically a measure of frictional resistance. Higher values indicate higher frictional resistance and imply greater skid resistance. As specimens are polished, maintenance or smaller reductions in frictional resistance indicates greater resistance to polishing.

C) Percent Insoluble Residue in Carbonate Aggregates (ASTM D3042 - 86)

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.

The sample, 500 gms of aggregate retained on #4 sieve, was put in a glass beaker and 1000 milliliter of hydrochloric acid solution added. The mixture of sample and acid was agitated until effervescence stopped. An additional 300 milliliters of acid was added and the same procedure repeated until effervescence stopped completely. Next, the beaker with the aggregate residue was heated to 230° F, and new acid added in increments until effervescence stopped completely. The aggregate residue was washed over a # 200 sieve, dried and sieved again. The weight of the plus # 200 residue was determined and expressed as a percentage of the original sample weight.

D) 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 Highway Department 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.

In this test samples, 300 gms of aggregate retained on #4 sieve, were heated in the muffle furnace at 950° C for a minimum of 8 hours. The samples were weighed before and after heating. The loss in the weight of the sample provided an indication of the carbon dioxide driven from the calcium or magnesium carbonate, and was expressed as percent of the original weight.

E) Petrographic Analysis

This analysis was performed by a geologist in the Geology Department at Auburn University and identifies the constituent minerals, and their characteristics, present in an aggregate.

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. In order to get the most precise description of the tested rocks, it has been recommended that future petrographic work be done on thin sections of aggregates used in the British Pendulum Wheel specimens.

Carbonate Aggregates (limestones)

After washing the aggregates to remove fine dust, each carbonate aggregate is sorted on the basis of general clast composition and texture. Dolomite and limestone clasts are distinguished on the basis of degree of effervescence in 10% hydrochloric acid. Cherts/siliceous limestones are identified on the basis of clast hardness relative to steel. Where possible and appropriate, these three groups are subdivided further on the basis of general textures-- e.g., recrystallization fabrics, presence or absence, abundance and/or size of visible sand-sized carbonate grains, and abundance of fine-grained carbonate mud (micrite).

After gross sorting, representative clasts from each grouping are collected for thin section preparation. Standard-sized grain-mount thin sections are commercially prepared for each sample and stained to facilitate identification of carbonate minerals (calcite, dolomite,, ferroan dolomite). These small thin sections accommodated between 3 to 5 selected clasts.

Thin sections are scrutinized under a transmitted-light petrographic microscope. Observations made for each clast included (1) the relative abundance of calcitic, dolomitic, and siliceous (chert and/or clastic quartz grains) components, (2) degree of recrystallization and crystal sizes, and, where original sedimentary textures are not destroyed by recrystallization, (3) the presence or absence, origin (fossil fragments, oolites, peloids), and mineralogy of sand-sized carbonate grains, (4) the presence or absence , abundance, and size of fine-grained carbonate mud and/or crystalline cement (spar). Based on (3) and (4), clast lithologies are classified using the Folk classification scheme.

For several samples, the variability in textures/ compositions observed in the thin sections was greater than that observed during initial aggregate sorting. Hence, there is some uncertainty regarding how representative the selected clasts are of the bulk aggregate. In these cases, estimates of relative percentages are reported over a considerable range. In the future, representative sampling problems can be alleviated by modifying thin section preparation procedures:

1] Oversized thin sections should be prepared from a larger randomly selected portion of each aggregate.

2] If possible, oversized thin sections should be prepared from the impregnated, skid resistance specimens after polishing is completed.

Siliceous Aggregates (gravels)

Each aggregate sample is sorted on the basis of general clast lithology. The relative percentages of clast types are evaluated by visual estimation and/or by clast counting. Major lithologic components (chert, quartz/quartzite, and quartz sandstone) are relatively easy to identify (only an occasional weathered clast required splitting to confirm identification).

Chert, derived from sedimentary source rocks, is distinguished on the basis of its very fine-grained (microcrystalline) textures and typically conchoidal fracture. Quartz/quartzite, derived from metamorphic source areas, is identified on the basis of its coarse to extremely coarse interlocking or sutured crystals (the product of recrystallization). Quartz sandstones are distinguished on the basis of their fine to coarse, rounded to subrounded grains, and iron-oxide or silica cements. When fractured, quartz cemented sandstones generally break along grain-cement boundaries and not across grains. Minor mineralogic components within quartz sandstones can not be assessed without thin section studies.

Minor components of aggregates included shell fragments, unidentifiable rock fragments, and dolomite clasts. The latter are identified on the basis of color, texture, and degree of effervescence in dilute 10% hydrochloric acid.

VI. 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 [1,23]:

$$BPN = BPN0 + t/(a+bt) \qquad (1)$$

where BPN = 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:

$$a = \frac{t1\ t2}{t1 - t2}(1/dBPN1 - 1/dBPN2) \qquad (2)$$

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

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):

$$\lim_{t\to\infty} BPN = BPN0 + \lim_{t\to\infty} t/(a+bt)$$

Hence,

$$BPNL = BPN0 + 1/b \qquad (4)$$

The limiting BPN value can be estimated from equation 4, 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 hour polish time (BPN0) and 9 hours polish time (BPN9) and corresponding estimated limiting BPN values (BPNL) are given in Tables 10 and 11 for limestone and gravel aggregates, respectively. Also included in Table 10 are the values of ΔBPN (BPN0-BPN9), percent loss by ignition and percent insoluble residue. As shown in Table 10, 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 11). Therefore, values of BPN9 for both limestone and gravel aggregates tested in this study are quite comparable. Since polish time of 9 hours was the maximum time examined in this study, it was important to determine the correlations between BPN9 and BPNL values for both limestone and gravel aggregates.

TABLE 10 TEST RESULTS FOR LIMESTONE AGGREGATES

SOURCE #	BPN0	BPN9	BPNL	ΔBPN	% LI	% IR
A-1	47	32	29	15	45.68	3.4866
A-2	44	33	32	11	34.7618	20.51
A-3	43	30	28	13	44.5954	0.6895
A-4	41	28	27	13	42.2905	1.9533
A-5	44	33	32	11	37.9081	13.046
A-6	43	29	28	14	40.3806	1.292
A-7	42	29	28	13	42.3667	0.572
A-8	42	31	30	11	39.5973	8.79
A-9	44	35	35	9	38.5836	6.33
A-10	41	32	29	9	39.1899	7.304
A-11	44	27	18	17	44.0792	0.276
A-12	38	30	28	8	41.2898	2.004
A-13	44	30	26	14	42.6857	0.808
A-14	38	28	27	10	38.3642	0.856
A-15	40	29	21	11	43.3299	2.498
A-16	44	32	30	12	44.4518	1.316
A-17	43	31	30	12	38.1986	1.572
A-18	42	30	29	12	42.4521	0.5
A-19	45	31	30	14	37.0084	15.888
A-20	41	27	22	14	41.425	9.732
A-21	46	32	31	14	42.0098	0.0008
A-22	45	35	32	10	39.1488	2.54
A-23	39	29	29	10	39.7839	6.8
A-24	43	35	33	8	40.1233	7.538
A-25	48	36	34	12	30.7293	29.132
A-26	41	29	28	12	41.0561	3.508
A-27	46	33	32	13	40.3071	3.21
A-28	42	27	24	15	41.6694	5.976
A-29	38	26	25	12	46.2189	0.838
A-30	45	35	34	10	39.7656	0.394
A-31	45	32	26	13	38.5257	0.528
A-32	40	24	22	16	42.9879	0.016

Notations: BPN0 = British pendulum number value at 0 hour
BPN9 = British pendulum number value at 9 hours
BPNL = limiting British pendulum number value
ΔBPN = BPN0 - BPN9
% LI = percent loss by ignition
% IR = percent acid insoluble residue

TABLE 11 TEST RESULTS FOR GRAVEL AGGREGATES

SOURCE #	BPN0	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

Results of the petrographic analysis are given in Tables 12 an 13 for limestone and gravel aggregates, respectively.

Using correlation analysis [SAS program], simple statistics and a correlation matrix among all parameters of the study was developed [see Tables 14, 15, 16 and 17]. 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.

Relationship between BPN9 and BPNL :

Coefficients of correlation between the BPN9 and the BPNL are 0.85 and 0.42 for limestone and gravel aggregates, respectively. These relationships are illustrated in Figures 8 and 9 for limestone and gravel aggregates, respectively. The lower correlation between BPNL and BPN9 in case of gravel aggregates may be a result of the use of smaller number of sources compared to limestone aggregates.

TABLE 12 ESTIMATED PERCENTAGES OF COMPOSITION OF LIMESTONE SAMPLE AGGREGATES FROM PETROGRAPHIC ANALYSIS

SOURCE #	% SILICA*	% DOLOMITE	% CALCITE
A-1	-	100	-
A-2	5	-	95
A-3	-	-	100
A-4	3	1-3	94-96
A-5	20	1	79
A-6	<1 (qg	16	84
A-7	-	20-30	70-80
A-8	2-3	48	49-50
A-9	1 (qg	75	24
A-10	5	-	95
A-11	1 (qg	51	48
A-12	-	1	99
A-13	2 (qg	85	13
A-14	-	95	5
A-15	1	99	-
A-16	-	100	-
A-17	3	-	97
A-18	-	-	100
A-19	15	50	35
A-20	3	95	2
A-21	-	-	100**
A-22	2-3	45	52-53
A-23	4-8	-	92-96
A-24	3-4	-	96-97
A-25	13	-	87
A-26	10	21	69
A-27	-	50	50
A-28	5-6	94-95	-
A-29	2	98	-
A-30	1-2	10	88-89
A-31	-	2	98
A-32	-	100	-

Notations:
* = silica is mostly chert
** = no thin section for this source
qg = quartz grains (not chert)

TABLE 13 ESTIMATED PERCENTAGES OF COMPOSITION OF GRAVEL SAMPLE AGGREGATES FROM PETROGRAPHIC ANALYSIS*

SOURCE #	% CHERT	% QUARTZITE	% SANDSTONE
B-1	67	12	21
B-2	95	-	5
B-3	95	2	3
B-4	100	-	-
B-5	4	96	-
B-6	97	3	-
B-7	7	86	7
B-8	92	8	-
B-9	9	91	-
B-10	42	40	18
B-11	21	76	3
B-12	94	-	6

*Minor lithologic components (totals never exceed 3%) have been omitted. Values are normalized to 100%

Correlation Analysis for Sample Aggregates

TABLE 14 SIMPLE STATISTICS FOR LIMESTONE AGGREGATES

Variable	N	Mean	Std Dev	Minimum	Maximum
BPN0	32	42.75000	2.59030	38.0000	48.0000
BPN9	32	30.62500	2.92652	24.0000	36.0000
BPNL	32	28.40625	3.97459	18.0000	35.0000
ΔBPN	32	12.12500	2.22522	8.0000	17.0000
%LI	32	40.65514	3.15826	30.7293	46.2189
%IR	32	4.99701	6.62814	0.0008	29.1320
%SILICA	32	3.25000	4.83935	0	20.0000
%DOLOMITE	32	42.62500	41.94909	0	100.0000
%CALCITE	32	54.12500	40.75794	0	100.0000
BULK SPEC GRAVITY	32	2.68703	0.07221	2.5160	2.8150
%ABS	32	0.86250	0.40381	0.4000	2.0000

TABLE 15 SIMPLE STATISTICS FOR GRAVEL AGGREGATES

Variable	N	Mean	Std Dev	Minimum	Maximum
BPN0	12	38.91666	2.74552	35.0000	45.0000
BPN9	12	30.50000	1.97714	27.0000	34.0000
BPNL	12	27.00000	4.61224	16.0000	32.0000
ΔBPN	12	8.41667	2.31432	4.0000	11.0000
%CHERT	12	60.25000	40.49495	4.0000	100.0000
%QUARTZITE	12	34.50000	40.68393	0.0000	96.0000
%SANDSTONE	12	5.25000	7.14938	0.0000	21.0000
BULK SPEC. GRAVITY	12	2.43642	0.10729	2.3160	2.6010
%ABS	12	3.01667	1.56370	0.6000	5.0000

TABLE 16 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

Notation: Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 32

TABLE 17 CORRELATION MATRIX FOR GRAVEL AGGREGATES

	BPNO	BPN9	BPNL	ΔBPN	%CHERT	%QUARTZ	%SANDSTON	BSG	%ABS
BPNO	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

Notation: Pearson Correlation Coefficients / Prob > |R| under o: Rho=0 / N = 12

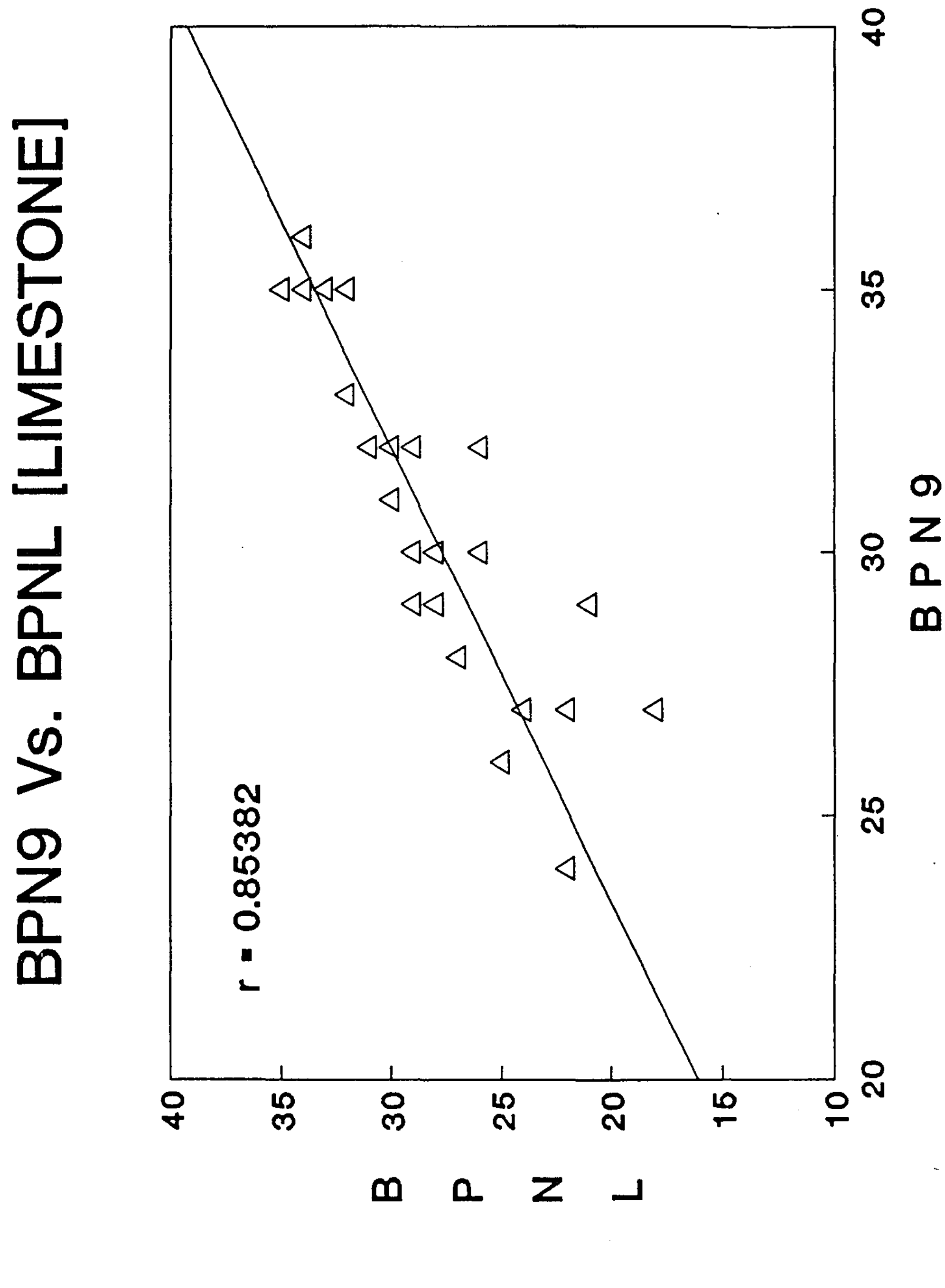


FIGURE 8 BPN9 versus BPNL values for limestone aggregates

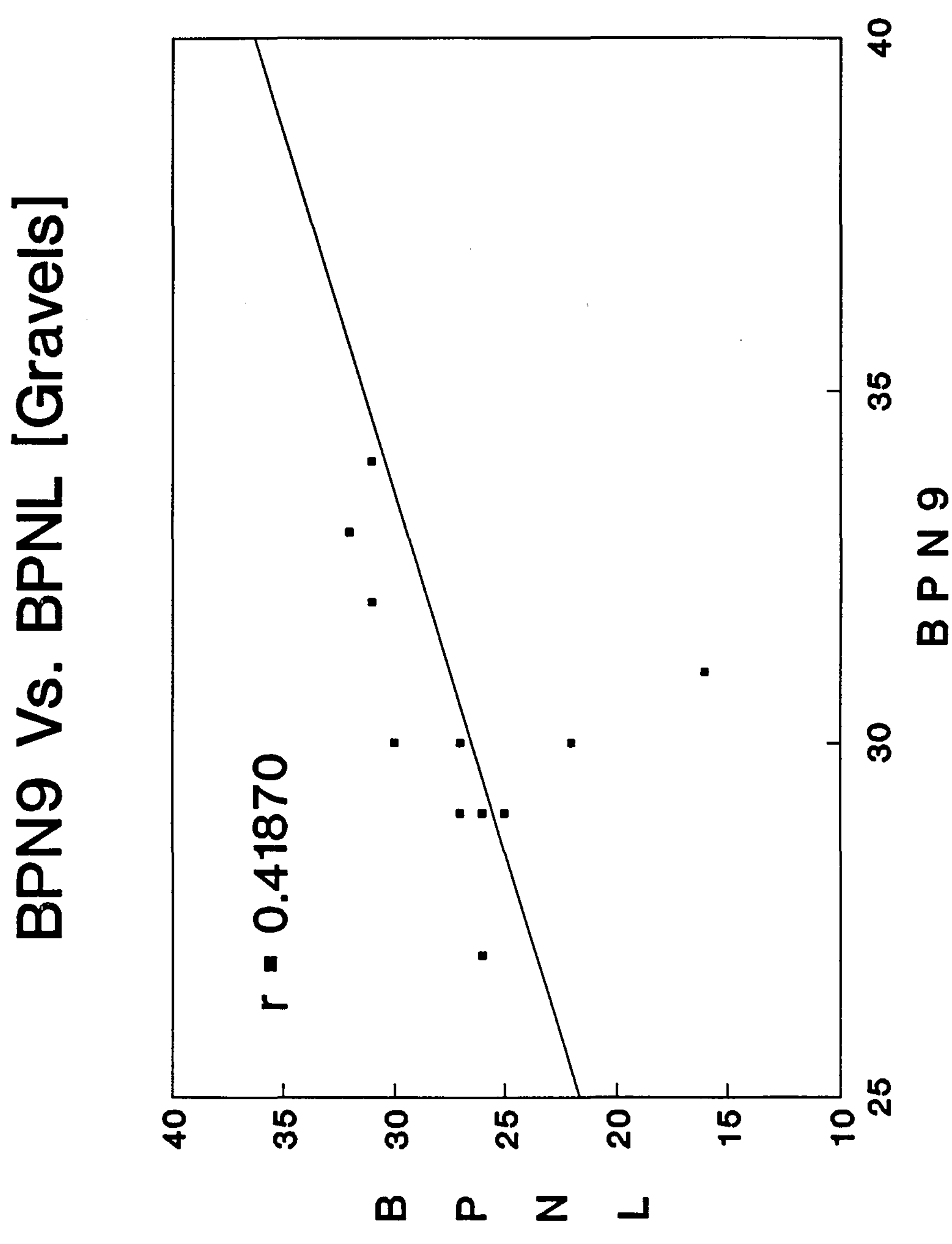


FIGURE 9 BPN9 versus BPNL values for gravel aggregates

Relationship between BPN9 and BPN0

It was important, to evaluate the relationship between the frictional value (BPN) at 9 hours and that at zero time to determine the effect of polishing. As shown in Table 16, and Figure 10, the correlation coefficient between BPN9 and BPN0 for limestone is 0.68. Corresponding coefficient for gravel aggregates (Table 17, and Figure 11) is 0.56. These results indicate that the BPN value measured at a certain time is partially dependent on the initial BPN value.

Categorization of BPN9 values for both limestone and gravel aggregates

In order to divide the BPN9 values into three categories; low, medium, and high, the full range of BPN9 values for both limestone and gravel aggregate sources examined in this study was subdivided into three about equal ranges. This procedure resulted in the following categories and ranges: (see Figures 12 and 13)

Low BPN9 = below 28

Medium BPN9 = 28 - 32

High BPN9 = above 32

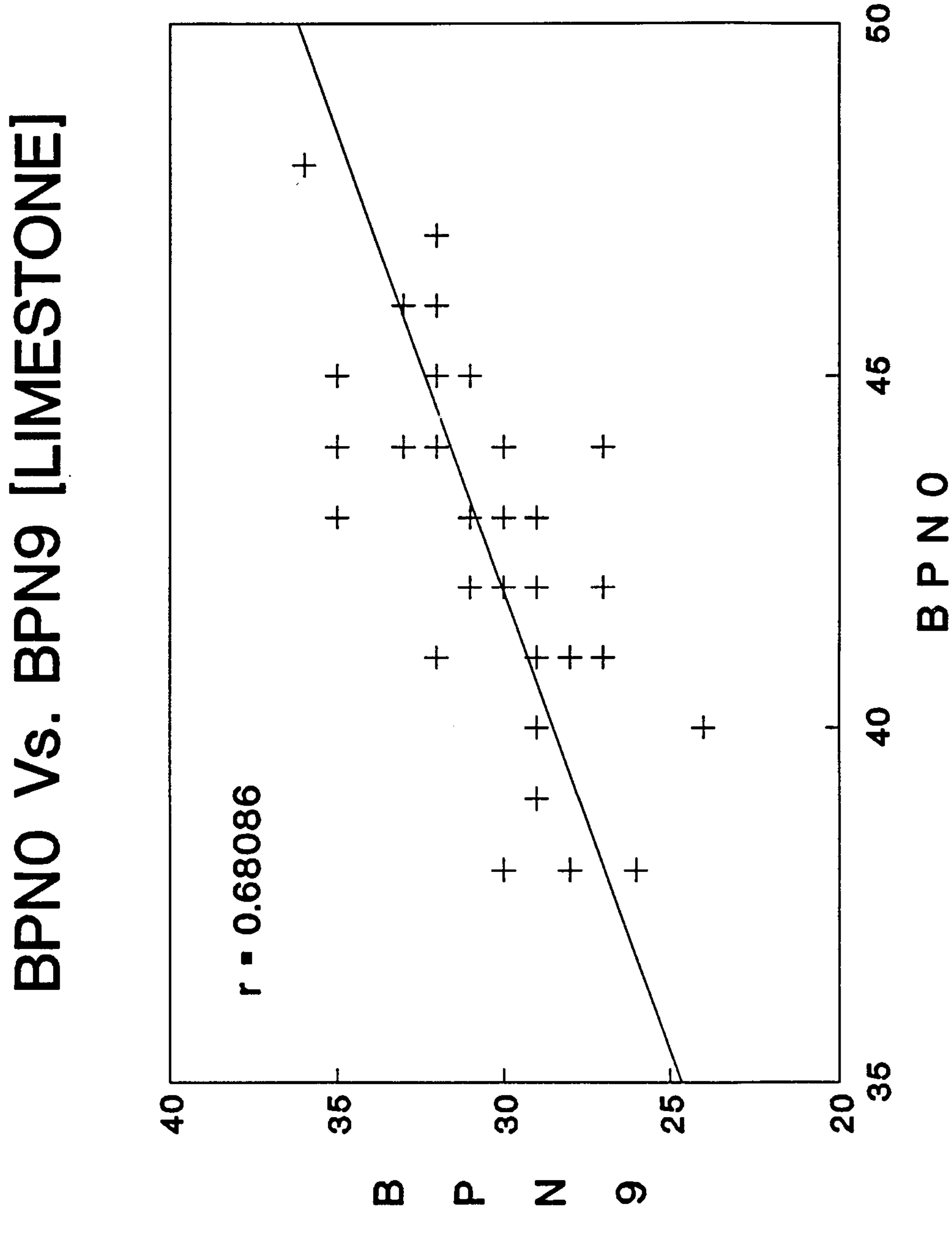


FIGURE 10 BPN0 versus BPN9 values for limestone aggregates

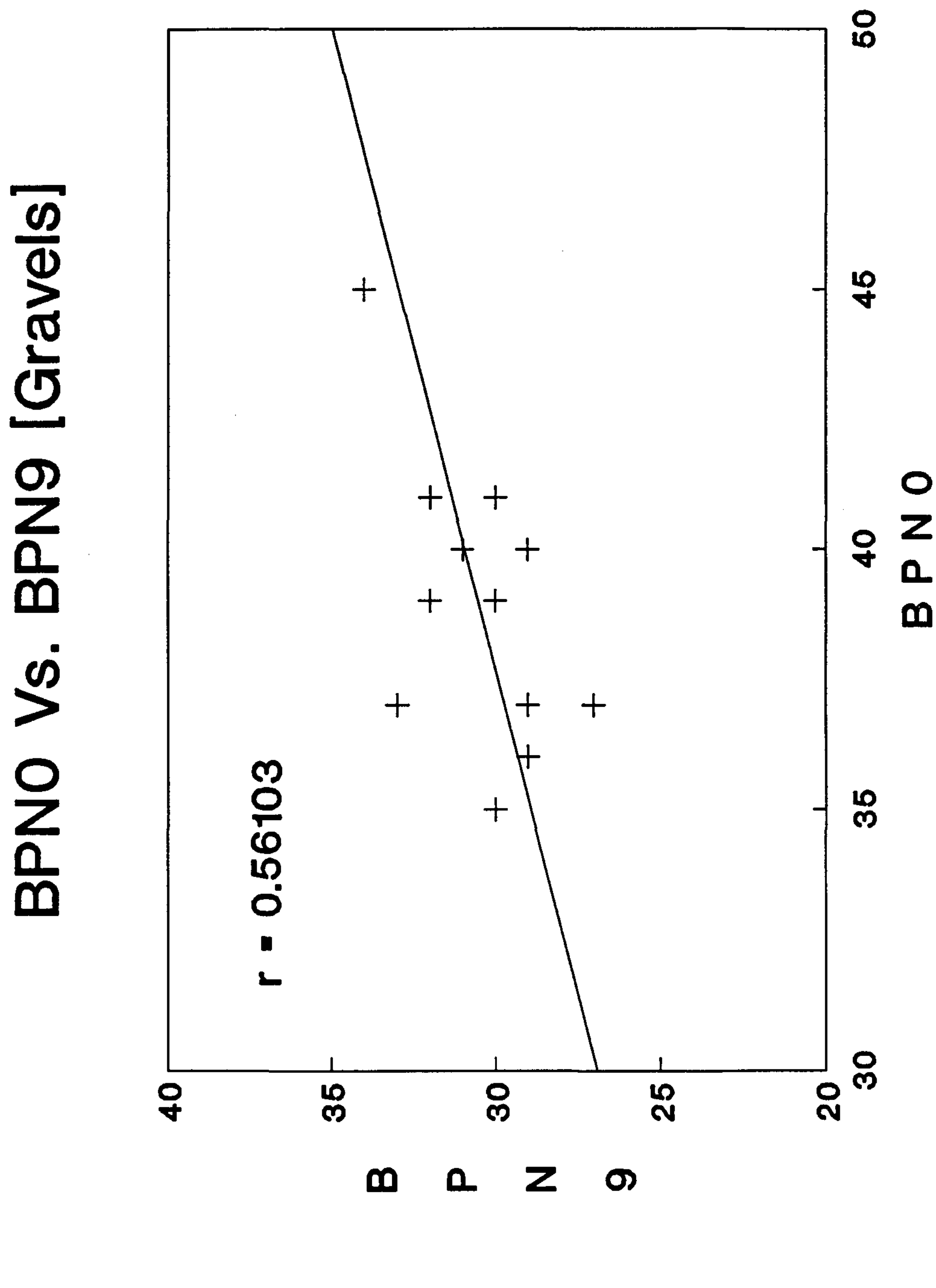


FIGURE 11 BPN0 versus BPN9 values for gravel aggregates

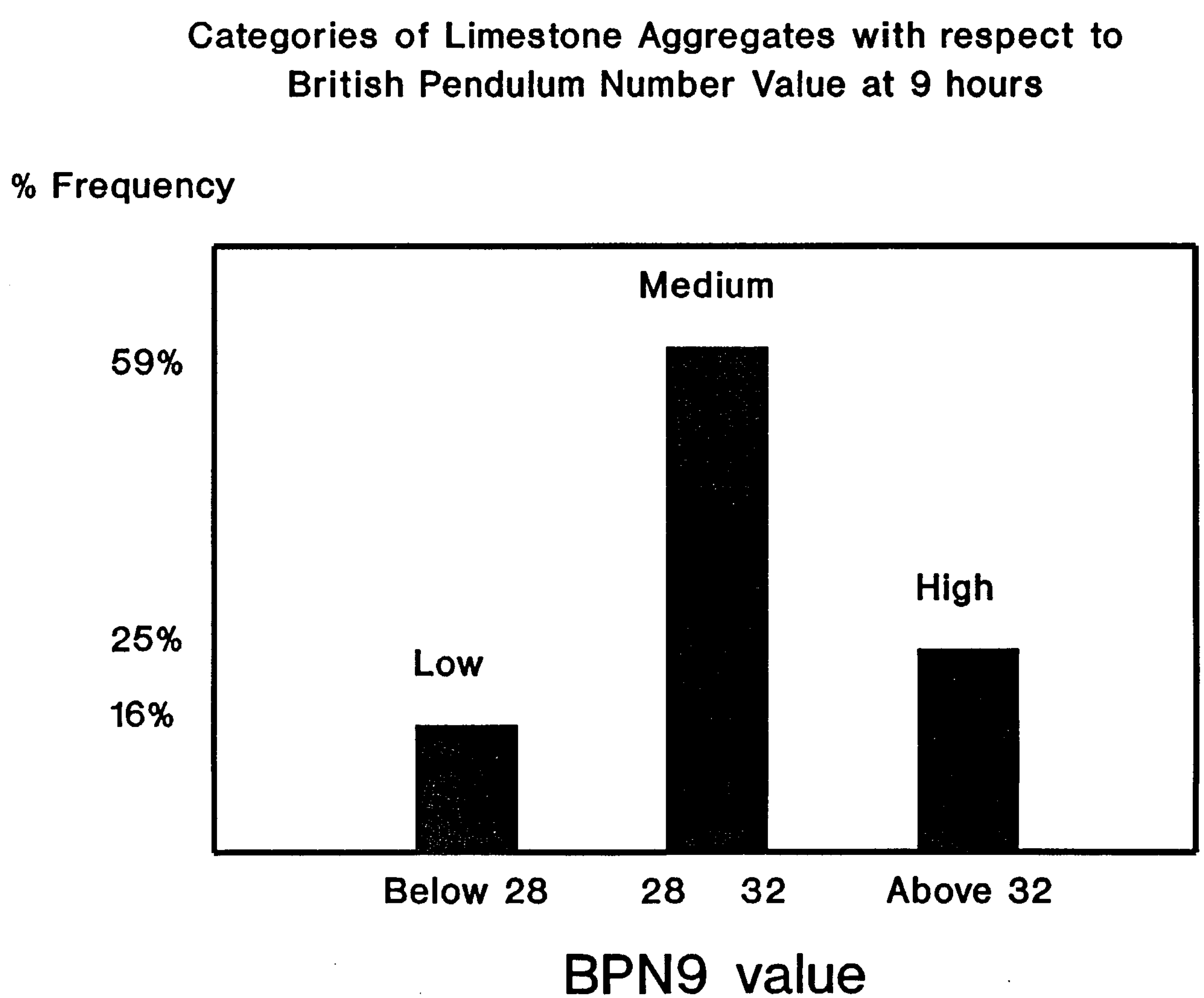
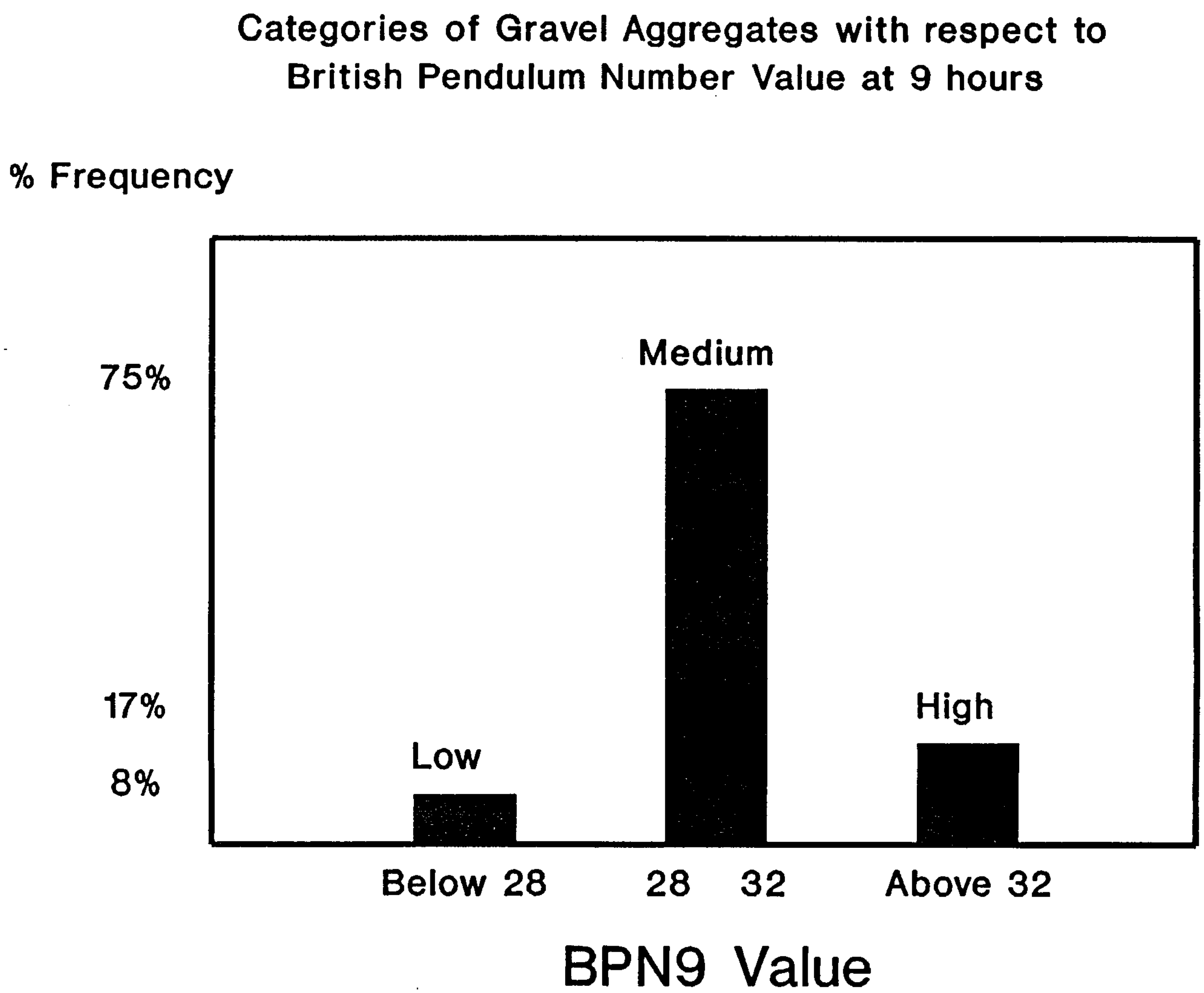


FIGURE 12 Categories of limestone aggregates based on BPN9 values

FIGURE 13 Categories of gravel aggregates based on BPN9 values



Categorized values of BPN9 for both limestone and gravel aggregates with their corresponding sources are shown in Tables 18, 19, 20 and 21 and illustrated on the Alabama map (see Figure 14). Alabama Highway Department 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 criteria then the limestone aggregates with medium and high BPN9, (28-32) and (33-36), respectively, should also be permitted. However, their performance should be confirmed in the field. Figures 15 and 16 illustrate the changes in BPN values with respect to time for typical limestone and gravel aggregates, respectively, 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 earlier. There is a 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.

TABLE 18 SORTING OF LIMESTONE AGGREGATES BY BPN9

SOURCE #	BPN9	%LI	%I R	%SIL	%DOL	%CAL
A-32	24	42.9879	0.016	0	100	0
A-29	26	46.2189	0.838	2	98	0
A-11	27	44.0792	0.276	1	51	48
A-20	27	41.425	9.732	3	95	2
A-28	27	41.6694	5.976	5	95	0
A-4	28	42.2905	1.9533	3	2	95
A-14	28	38.3642	0.856	0	95	5
A-6	29	40.3806	1.292	0	16	84
A-7	29	42.3667	0.572	0	25	75
A-15	29	43.3299	2.498	1	99	0
A-23	29	39.7839	6.8	6	0	94
A-26	29	41.0561	3.508	10	21	69
A-3	30	44.5954	0.6895	0	100	0
A-12	30	41.2898	2.004	0	1	99
A-13	30	42.6857	0.808	2	85	13
A-18	30	42.4521	0.5	0	0	100
A-8	31	39.5973	8.79	2	48	50
A-17	31	38.1986	1.572	3	0	97
A-19	31	37.0084	15.888	15	50	35
A-1	32	45.68	3.4866	0	100	0
A-10	32	39.1899	7.304	5	0	95
A-16	32	44.4518	1.316	0	100	0
A-21	32	42.0098	0.0008	0	0	100
A-31	32	38.5257	0.528	0	2	98
A-2	33	34.7618	20.51	5	0	95
A-5	33	37.9081	13.046	20	1	79
A-27	33	40.3071	3.21	0	50	50
A-9	35	38.5836	6.33	1	75	24
A-22	35	39.1488	2.54	2	45	53
A-24	35	40.1233	7.538	3	0	97
A-30	35	39.7656	0.394	2	10	88
A-25	36	30.7293	29.132	13	0	87

TABLE 19 LIMESTONE SOURCES CATEGORIZED BASED ON BPN9

SOURCE #	COUNTY	DIVISION	BPN9	CATEGORY
A-32	Taladega	4	24	L
A-29	Jefferson	3	26	L
A-11	Shelby	3	27	L
A-20	Calhoun	4	27	L
A-28	Jackson	1	27	L
A-4	Madison	1	28	M
A-14	Talladega	4	28	M
A-6	Jackson	1	29	M
A-7	Marshall	1	29	M
A-15	Etowah	3	29	M
A-23	Morgan	1	29	M
A-26	Madison	1	29	M
A-3	Shelby	3	30	M
A-12	Jefferson	3	30	M
A-13	Shelby	3	30	M
A-18	Morgan	1	30	M
A-8	Marshall	1	31	M
A-17	Madison	1	31	M
A-19	Madison	1	31	M
A-1	Lee	4	32	M
A-10	Colbert	2	32	M
A-16	Shelby	3	32	M
A-21	Franklin	2	32	M
A-31	Lawrence	2	32	M
A-2	Colbert	2	33	H
A-5	Colbert	2	33	H
A-27	Jackson	1	33	H
A-9	Blount	3	35	H
A-22	Jackson	1	35	H
A-24	Colbert	2	35	H
A-30	Dekalb	1	35	H
A-25	Colbert	2	36	H

TABLE 20 SORTING OF GRAVEL AGGREGATES BY BPN9

SOURCE #	BPN9	% CHERT	% QUARTZITE	% SANDSTONE
B-6	27	97	3	-
B-7	29	7	86	7
B-8	29	92	8	-
B-9	29	9	91	-
B-1	30	67	12	21
B-2	30	95	-	5
B-3	30	95	2	3
B-12	31	94	-	6
B-4	32	100	-	-
B-10	32	42	40	18
B-11	33	21	76	3
B-5	34	4	96	-

TABLE 21 GRAVEL SOURCES CATEGORIZED BASED ON BPN9

SOURCE #	COUNTY	DIVISION	BPN9	CATEGORY
B-6	Fayette	5	27	L
B-7	Shelby	3	29	L
B-8	Madison	1	29	L
B-9	Conecuh	9	29	L
B-1	Madison	1	30	M
B-2	Madison	1	30	M
B-3	Madison	1	30	M
B-12	Lauderdale	2	31	M
B-4	Pickens	5	32	H
B-10	Etowah	3	32	H
B-11	Chilton	5	33	H
B-5	Calhoun	4	34	H

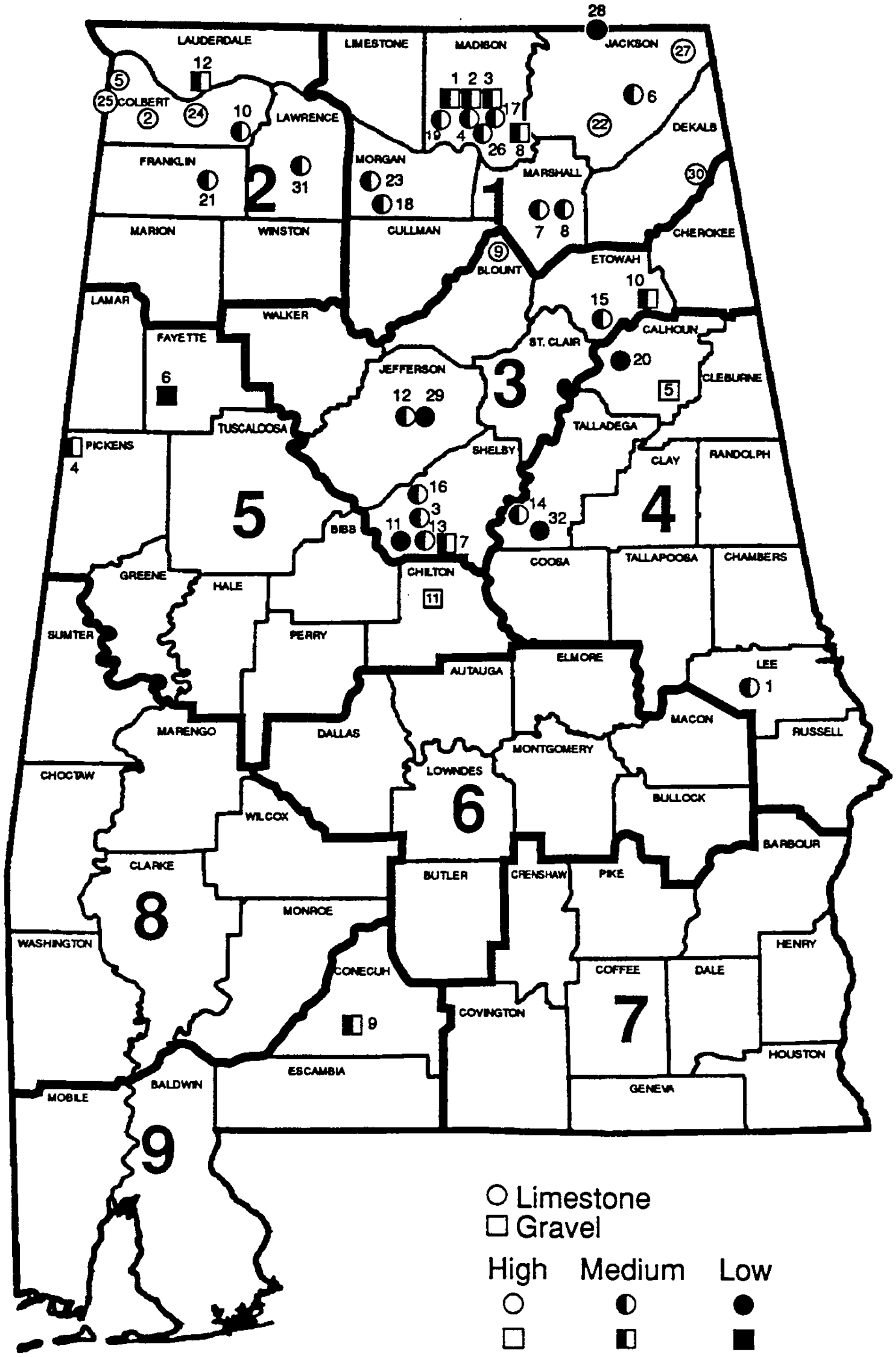


FIGURE 14 Location of the different categories of limestone and gravel aggregates sources

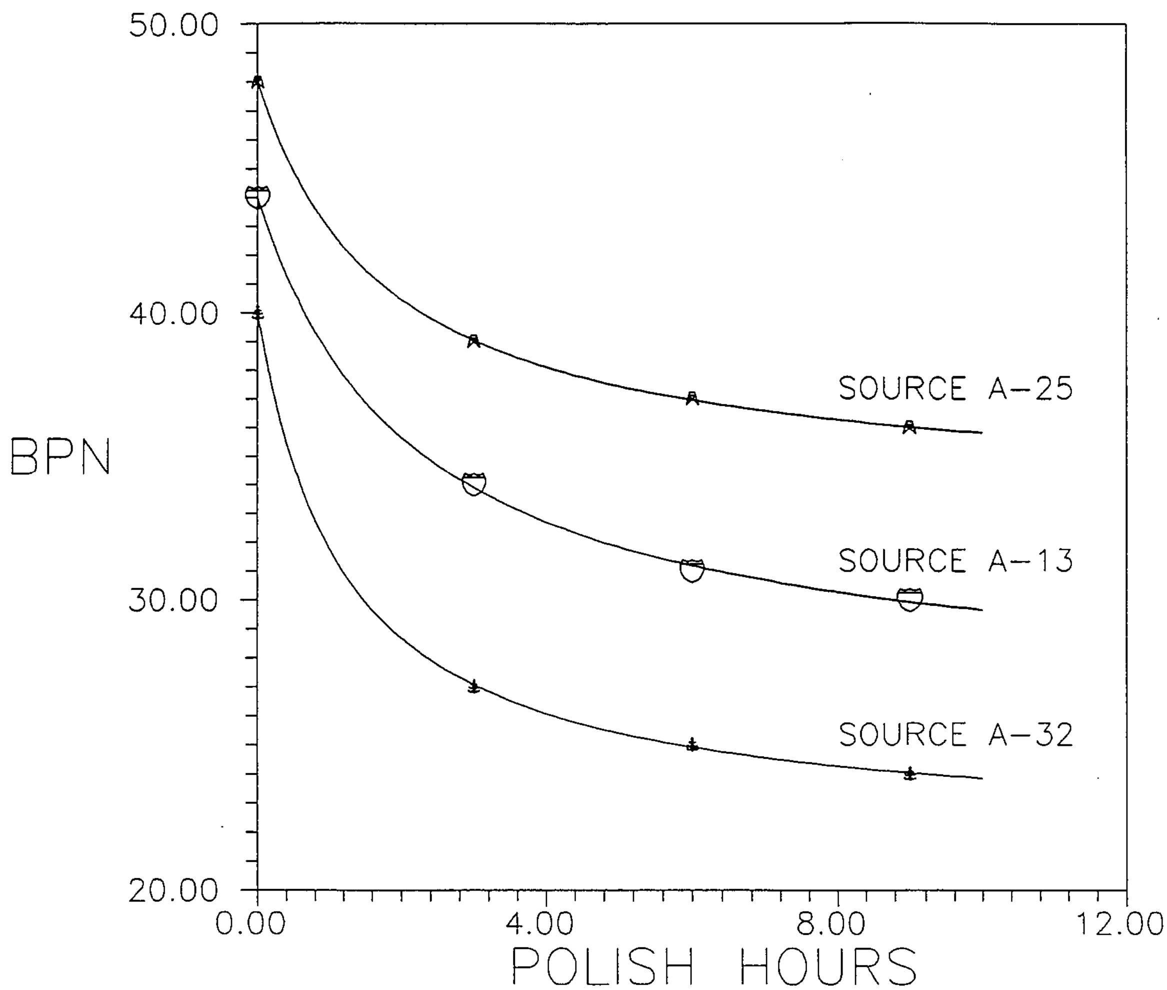


FIGURE 15 Polish hours versus BPN values for limestone aggregates

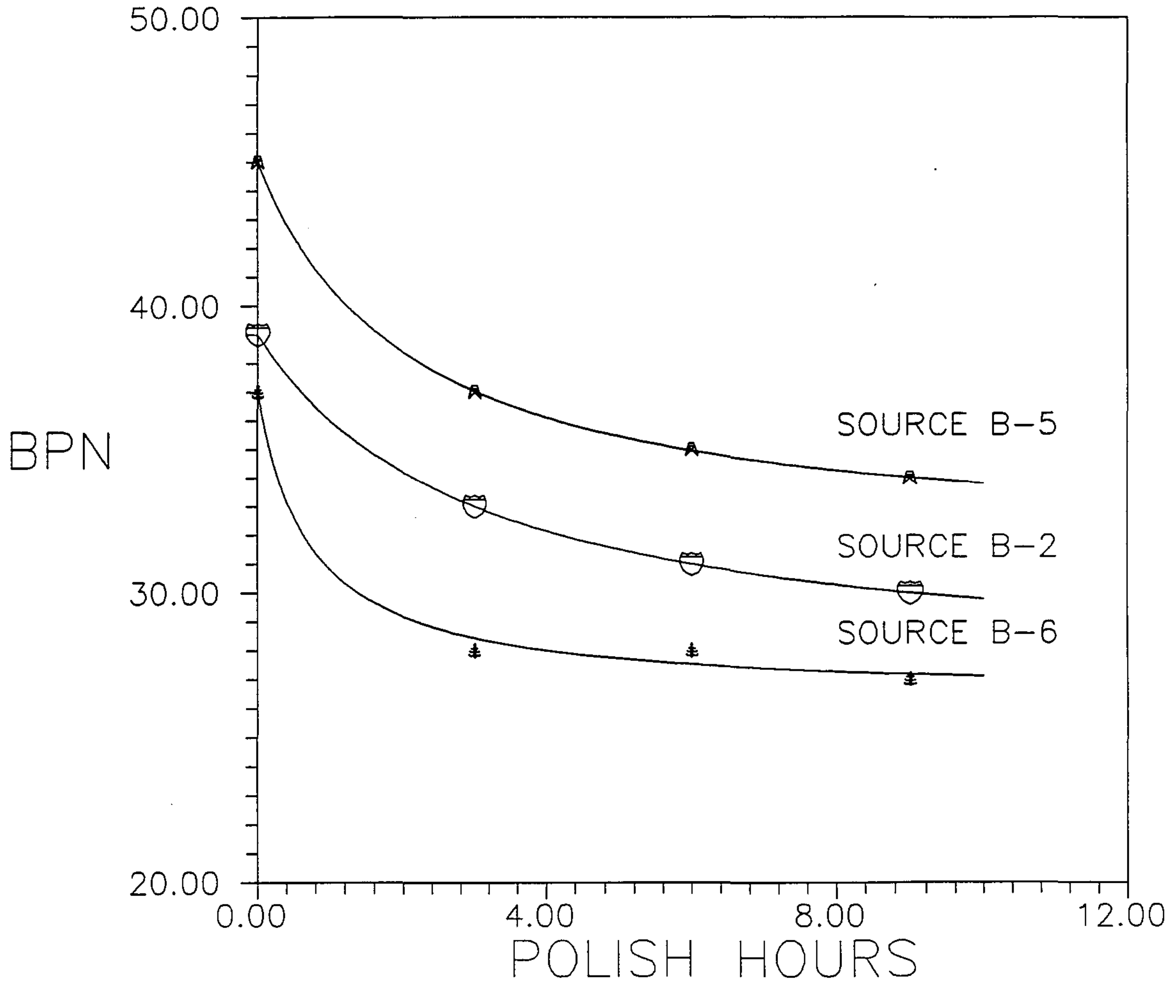


FIGURE 16 Polish hours versus BPN values for gravel aggregates

Results of Insoluble Residue

Results of the percentage insoluble residue for all the limestone aggregate sources examined in this study are given in Table 10. These values range from 0.0008% to 29.132%. The correlation coefficient between the percentage insoluble residue (%IR) and other parameters is shown in Table 16. A positive correlation of 0.41 is found between the percentage insoluble residue and the BPN9. The relationship between the two parameters is shown in Figure 17. There is a general trend that as the percentage of insoluble residue increases the value of BPN9 also increases. However, a minimum insoluble residue content cannot be used as a specification requirement (as used by some states) because of unacceptable (poor) degree of correlation.

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 10. These values range from 30.73% to 46.22%.
The correlation coefficient between the percentage loss by ignition (%LI) and BPN9 is shown in Table 16. A negative correlation of -0.56 is found between the percentage loss by ignition and the BPN9. The relationship between the two parameters is shown in Figure 18. There is a general trend that as the percentage loss by ignition decreases the value of BPN9 increases.

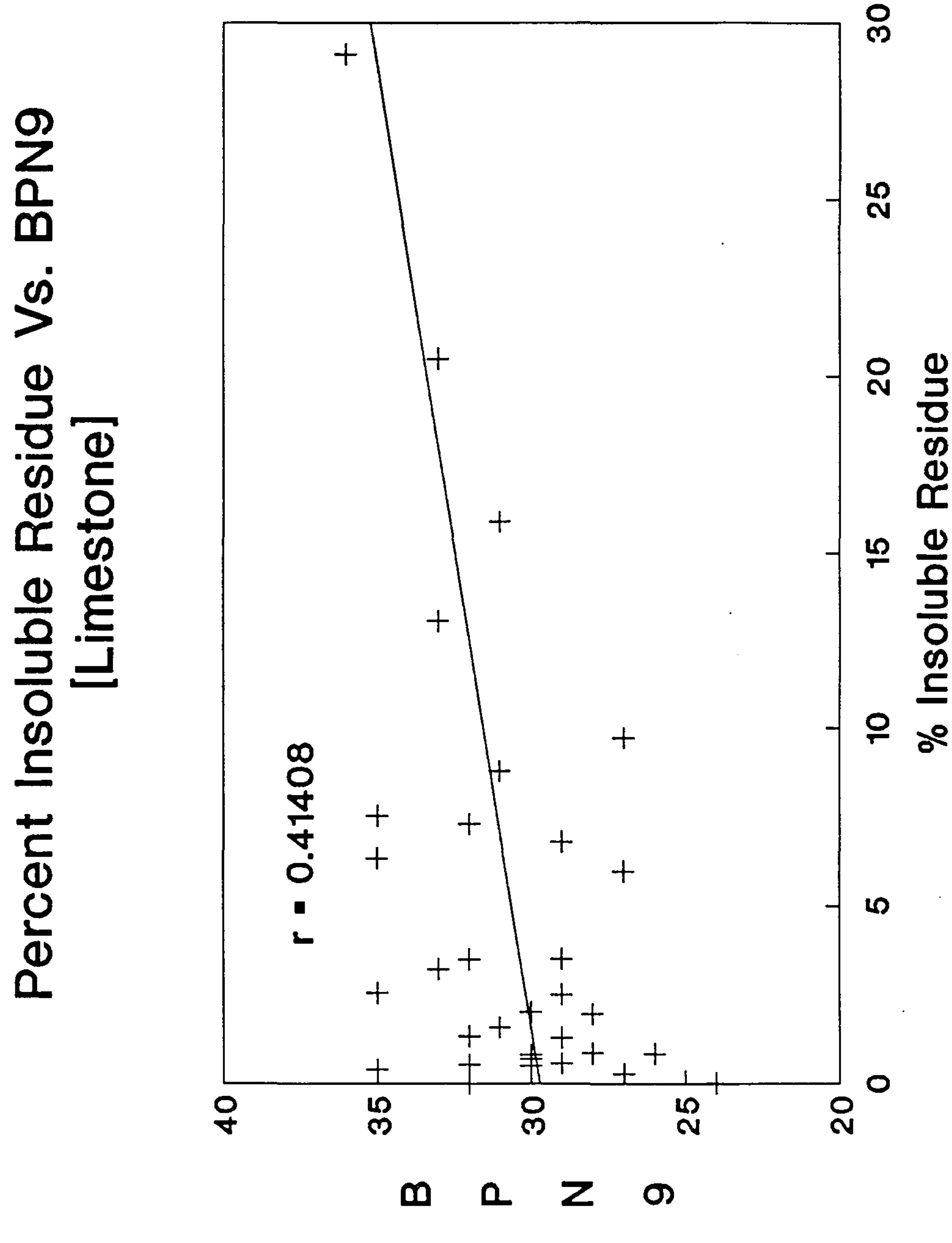


FIGURE 17 Percent loss by ignition values versus BPN9 values for limestone aggregates

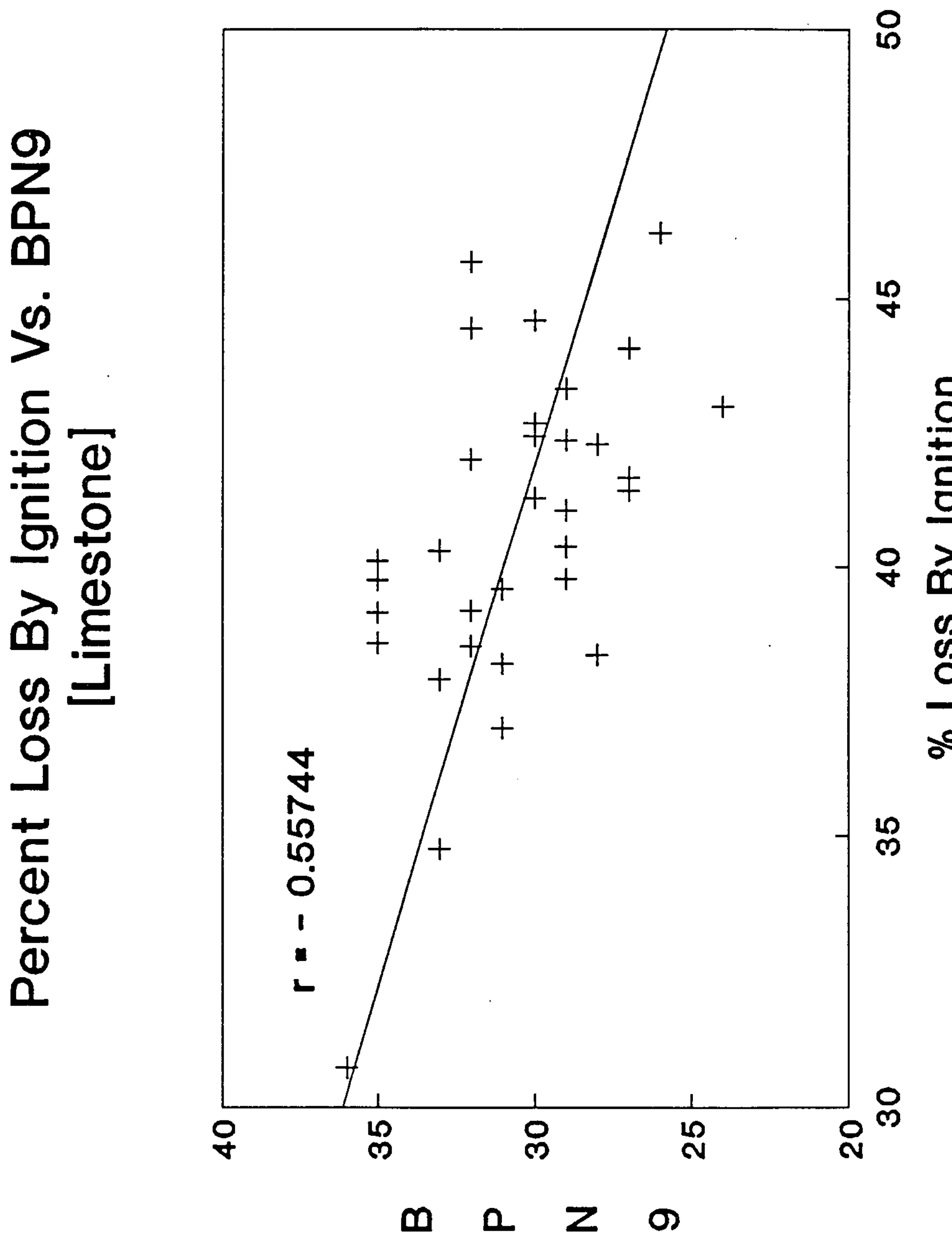


FIGURE 18 Percent loss by ignition values versus BPN9 values for limestone aggregates

However, a minimum loss by ignition content cannot be used as the only specification requirement because of the relatively low degree of correlation.

The correlation results given in Table 16 also show that a high negative correlation of - 0.77 exists between the percentage insoluble residue and the percentage loss by ignition [also, see Figure 19]. This high correlation is probably a result of the fact that the two methods utilize the same concept of measuring the amount of carbonates in the aggregates. The reason for the increase of the insoluble residue as the loss by ignition decreases is that the insoluble residue is a measure of the remaining material after reaction with acid while the loss by ignition is a measure of the amount of material lost by ignition.

Table 22 shows the average values of loss by ignition and insoluble residue for the group of limestone aggregates in each category. Despite the low linear correlation between BPN values and values of loss by ignition, it is found that limestone aggregates of low, medium, and high categories determined on the basis of BPN values exhibited average percentages loss by ignition of high, medium, and low values, respectively.

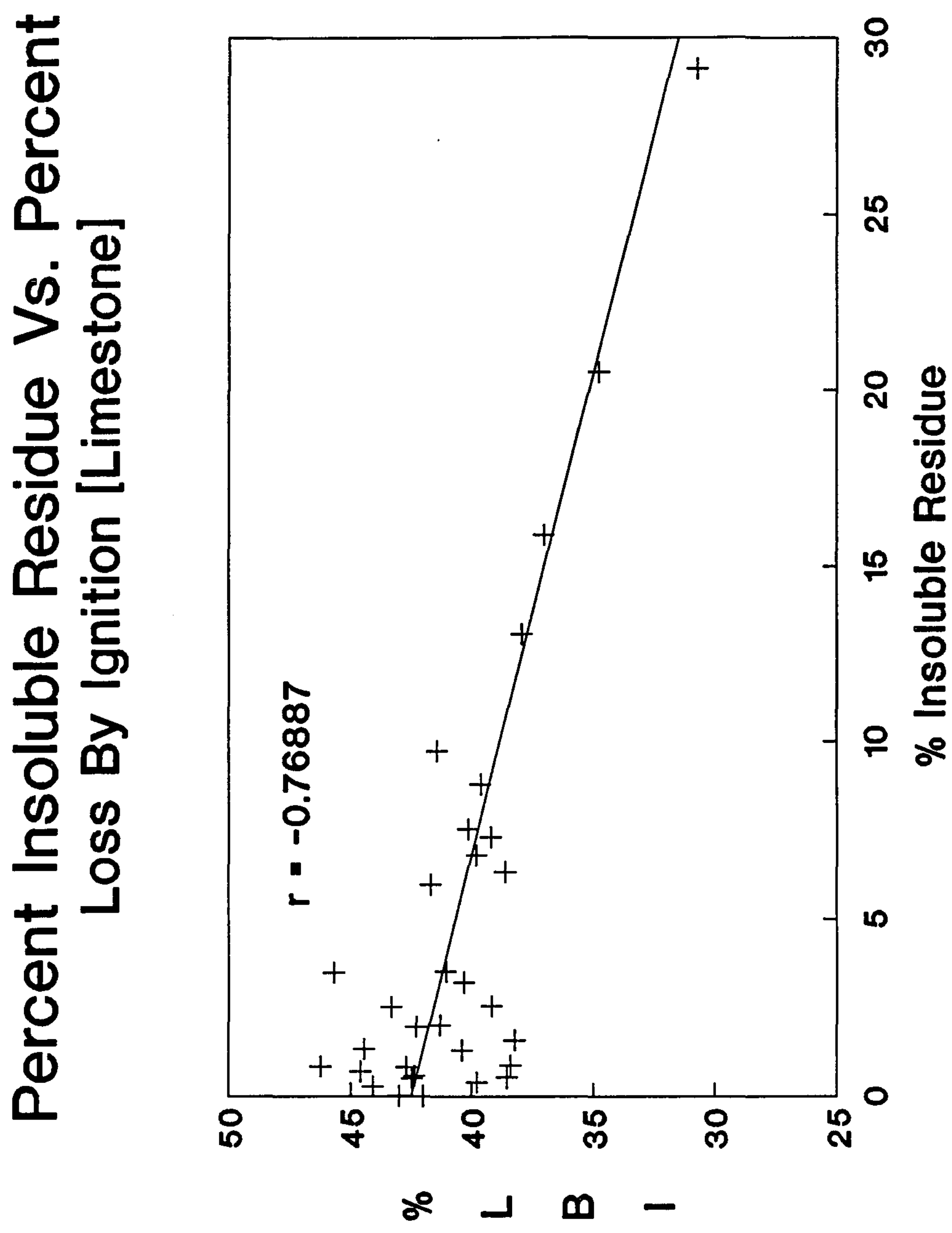


FIGURE 19 Percent insoluble residue versus percent loss by ignition for limestone aggregates

TABLE 22 BPN9 RANGES AND CORRESPONDING AVERAGES OF DIFFERENT PARAMETERS (LIMESTONE AGGREGATES)

BPN9 ranges	Average BPN0	Average BPN9	Average ΔBPN	Average %LI	Average %IR
24 - 27	41	26	15	43.28	3.37
28 - 32	42	30	12	41.22	3.18
32 - 36	45	34	11	37.67	10.21

Bulk specific gravity versus BPN9

Linear correlation analysis yields a negative correlation of -0.51 between the bulk specific gravity and BPN values at 9 hours of limestone aggregates [see Figure 20] which indicates that the two parameters exhibit opposite trends. This trend may probably be explained partly on the ground that aggregates of low bulk specific gravity, possibly contain more voids and thus have coarser microtexture leading to higher BPN9 values. However a better possible explanation can be based on specific gravity and hardness of the mineral constituents in the limestone aggregates. Alabama has dense dolomitic limestone with low impurity (quartz) in Birmingham - Gadsden area. The specific gravity of this dolomitic limestone is about 2.8. Lighter high calcium limestone with high impurity (quartz) is found across northern end of Alabama (Huntsville - Florence area) and its specific gravity ranges from 2.6 to 2.7. Different mineral constituents provide differential wear (because of different hardness) and specific gravity of limestone aggregate as illustrated below in Table 23:

TABLE 23 TYPICAL PROPERTIES OF THE CONSTITUENTS OF LIMESTONE AGGREGATES

Mineral	Specific gravity	Hardness
Quartz	2.6	7
Calcite	2.7	3
Dolomite	3.5 - 4	3.9 - 4.2

The preceding geographical and geological trend can be seen in Figure 14. The category of limestone generally changes from low to medium to high when one moves toward north-northwest.

The corresponding correlation between these two parameters for gravel aggregates was 0.14 which is insignificant.

As shown in Table 16, a significant and positive correlation of 0.76 between the bulk specific gravity and percentage loss by ignition of limestone aggregates [see Figure 21]. Again this trend could be because of the different mineral constituents present in the limestone aggregate. For example, more calcite and dolomite and less quartz would give higher specific gravity and high loss by ignition.

Percentage absorption versus BPN9

The correlation between these two parameters were 0.30 for limestone and -0.15 for gravel which is insignificant in both cases.

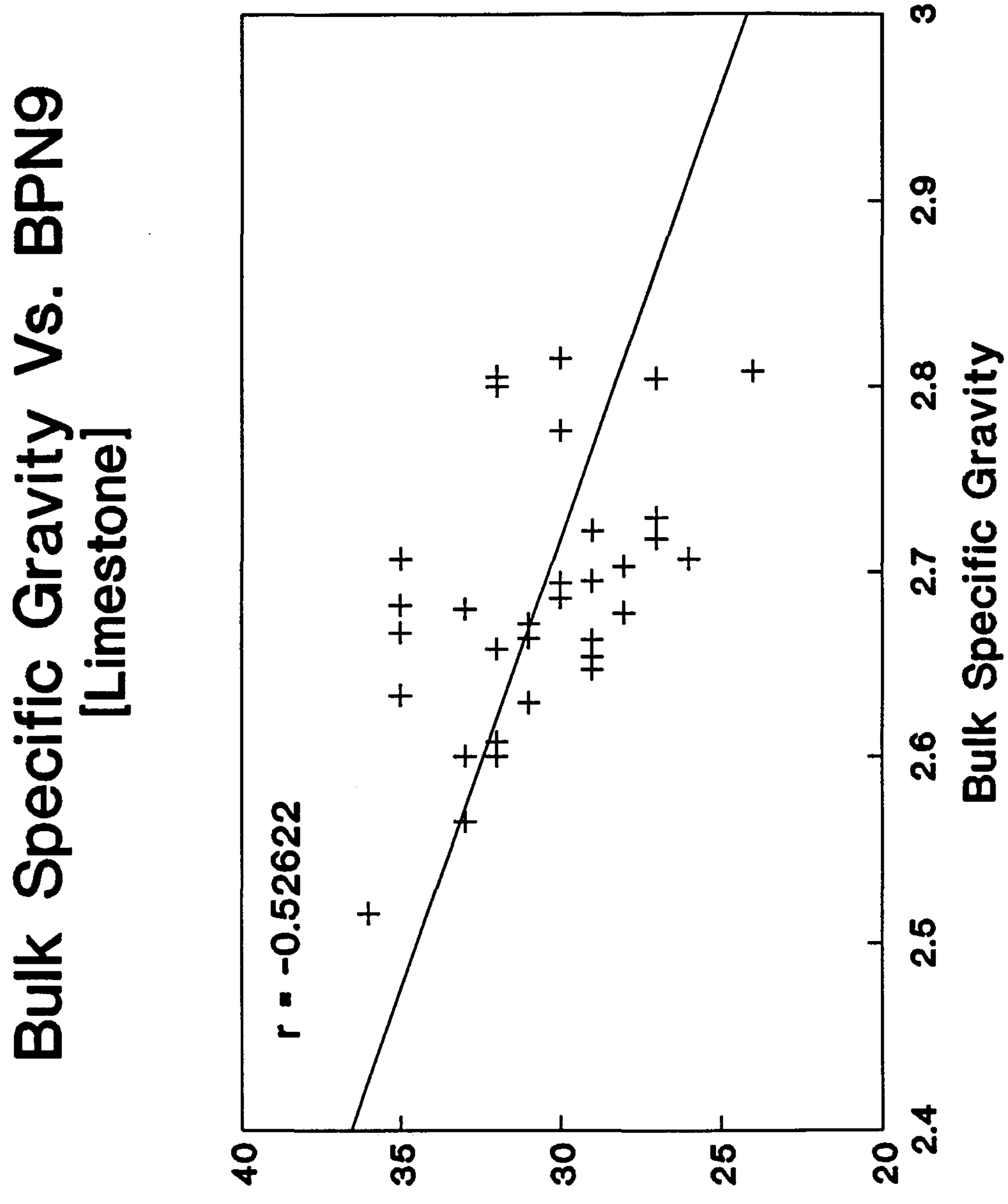


FIGURE 20 Bulk specific gravity versus BPN9 values for limestone aggregates

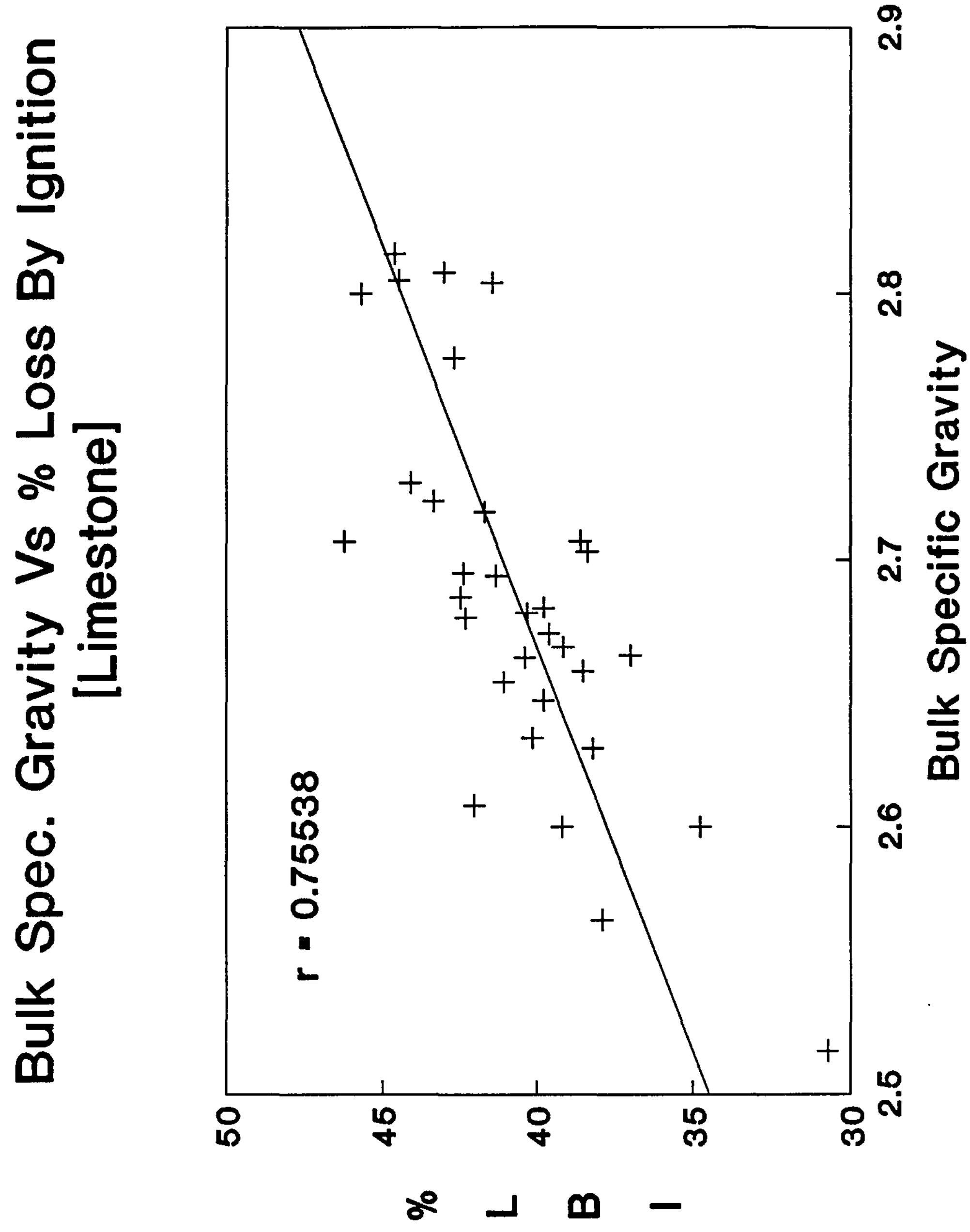


FIGURE 21 Bulk specific gravity versus percent loss by ignition for limestone aggregates

VII. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

In this study, tests were conducted to evaluate two different types of aggregates, namely; limestone and gravels with respect to their polishing characteristics and potential use in asphalt wearing courses. Tests used were the British wheel/pendulum test, acid insoluble residue test and loss by ignition test. Based on the test data obtained and analyzed in this study the following conclusions are drawn and recommendations made:

1) A wide range of BPN values after 9 hours of polish (BPN9) exists for limestone aggregates (24-36). This may be a result of the different constituents in 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, etc..

2) There is a general trend that as the percentage of insoluble residue increases the value of BPN9 also increases. However, a minimum insoluble residue content cannot be used as a specification requirement (as used by some states) because of poor degree correlation.

3) Linear correlation analysis yields a negative correlation of 0.56 between the percentage loss by ignition of limestone aggregates and their BPN values at 9 hours (BPN9) polish testing period. In other words, as the percentage loss by ignition decreases the value of BPN9 increases. The low correlation obtained suggests that the BPN value can not be statistically predicted from the percentage loss by ignition. Accordingly, minimum loss by ignition content cannot be used as the only specification requirement. Despite the low linear correlation between BPN values and values of loss by ignition, it was found that limestone aggregates of low, medium, and high categories determined on the basis of BPN values exhibited average percentages loss by ignition of high, medium, and low values, respectively.

4) Linear correlation analysis yields a negative correlation of 0.51 between the bulk specific gravity and BPN values of limestone aggregates which indicates that the two parameters exhibit opposite trends. The corresponding correlation between these two parameters for gravel aggregates was insignificant. This trend may possibly be explained partly on the ground that aggregates of low bulk specific gravity contain more voids leading to coarser microtexture and thus higher BPN9 values. However, the presence of mineral constituents of different specific gravity and hardness values is believed to be the primary factor.

5) Linear correlation analysis yields a positive correlation of 0.76 between the bulk specific gravity and percentage loss by ignition of limestone aggregates.

6) Correlation between values of percentage loss by ignition and those of percentage insoluble residue is -0.77. This fairly good correlation between the two parameters exists because both measure the amount of carbonates in different ways.

7) The results of this laboratory study has 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-hours BPN values, these categories have ranges of 24-27, 28-32, and 33-36 for low, medium, and high levels, respectively. Table 19 shows the limestone sources which belong to these three categories.

RECOMMENDATIONS

The results and conclusions of this study warrant the following recommendations for consideration:

1) In order to conduct a field study on the performance of limestone aggregates in asphalt wearing courses, it is recommended to use limestone sources representing low, medium, and high categories of skid resistance.

These recommended sources are shown on Alabama map [see Figure 14]. It appears that divisions 1, 2, 3 and 4 will be suited to construct the field projects utilizing limestone aggregate from these sources. At least three field projects incorporating limestone aggregate of potential low, medium and high skid resistance should be constructed. Each field project should have three test sections as follows:

a) 100% gravel aggregates (control)

b) Substitute limestone fine aggregate in (a) above

c) 100% limestone aggregates (both coarse and fine)

Sections (b) and (c) should be limited to about half-mile length and should preferably be on a tangent section. Source A-32 (Division 4) should be used for low category. Sources A-3, A-12, A-13 or A-18 (Divisions 1 and 3) can be used for medium category. Sources A-25, A-30, A-24, A-22 or A-9 can be used for high category.

2) A program for field testing using British pendulum tester and locked wheel skid trailer should be performed so that field results can be compared with laboratory results. Field testing should be conducting twice annually (summer and winter)

3) A state-wide field evaluation of all limestone aggregate sources falling into preliminary medium and high categories based on 9-hours BPN values (BPN9) should also be considered. These sources are shown on Alabama map Figure 22. Short sections utilizing 100% limestone aggregates from these sources can be constructed on low volume roads and evaluated periodically with locked wheel skid trailer. These sources can then be categorized finally based on field

measurements rather than 9-hours BPN values measured in the laboratory.

Alabama Highway Department 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 criteria then the limestone aggregates with medium and high BPN9 (28-32) and (32-36) respectively, should also be permitted. However, this performance should be confirmed in the field as mentioned earlier.

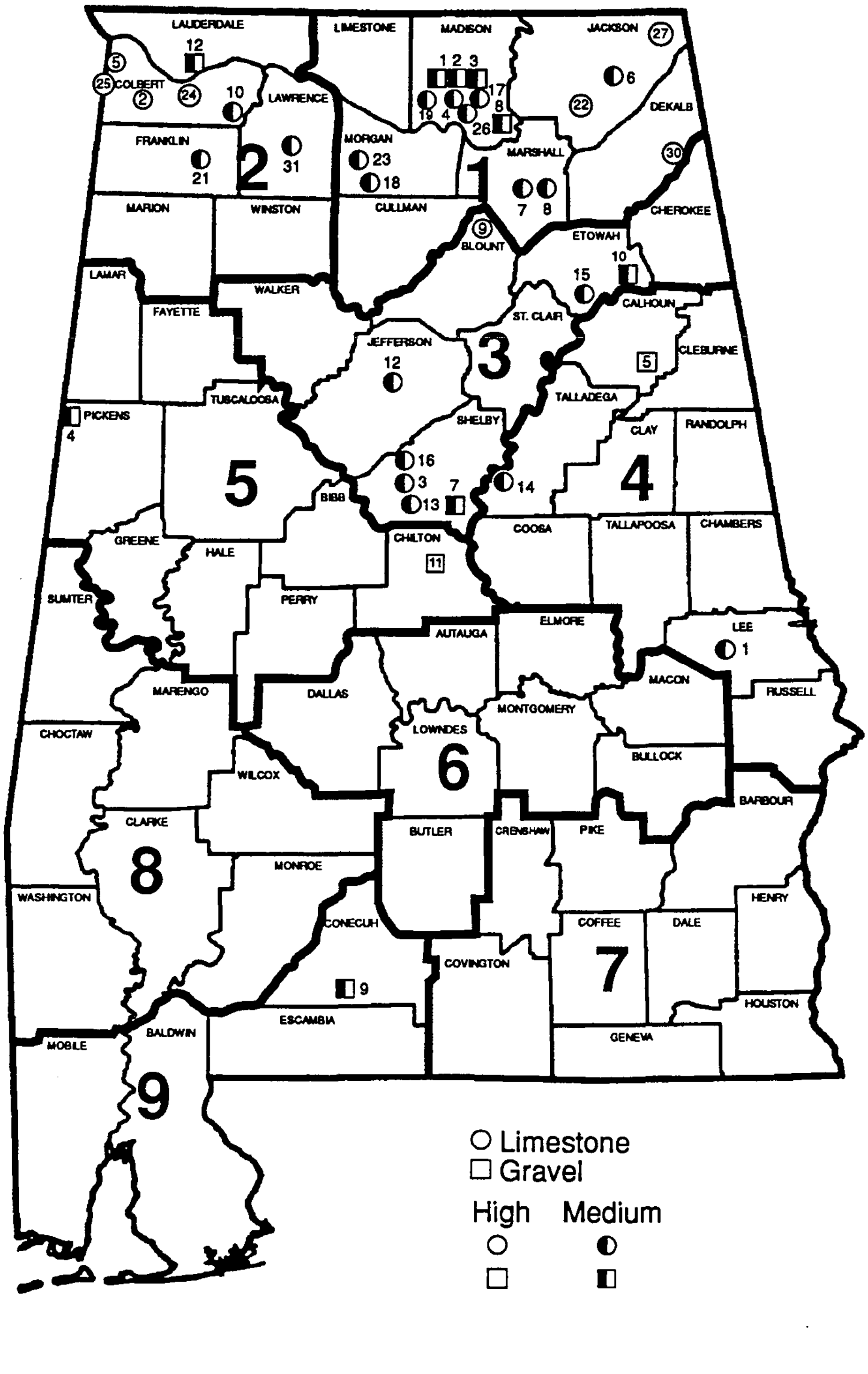


FIGURE 22 Location of the medium and high categories of limestone aggregates sources

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APPENDIX

QUESTIONNAIRE ON USE OF LIMESTONE AGGREGATES IN ASPHALT WEARING COURSES

QUESTIONNAIRE ON
USE OF LIMESTONE AGGREGATES IN ASPHALT WEARING COURSES

Name____________________________ State________________________

1. Do you permit the use of limestone <u>coarse</u> aggregate in asphalt wearing courses?

   ☐ Yes ☐ No

2. If yes, what is your criteria for permitting such usage?

   ☐ No Criteria

   ☐ British Pendulum Number (BPN) or Polished Stone Value (PSV)

   ☐ Loss by ignition

   ☐ Percent acid insolubles

   ☐ Petrographic exam

   ☐ Friction numbers (FN) or Skid numbers (SN) obtained in field

   ☐ Other ____ (specify)

3. Do you permit the use of limestone <u>fine</u> aggregate in apshalt wearing courses?

   ☐ Yes ☐ No

4. If yes, what is your criteria for permitting such usage?

5. Please attach a copy of your aggregate and/or asphalt concrete specifications and test methods if you have responded to Questions 2 and 4. That will help us understand your criteria and corresponding limits.

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