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DEVELOPMENT OF A PROCEDURE TO IDENTIFY AGGREGATES FOR BITUMINOUS SURFACES IN INDIANA

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16. Abstract

Adequate friction resistance is needed to prevent pavement slipperiness allowing vehicles to stop in a reasonable distance. For stone mastic asphalt surfaces, friction resistance is mainly a function of the interaction between the aggregates exposed at the road surface and vehicle tires. Aggregate performance is reduced with time by wear and polishing as a consequence of vehicular traffic. In this research a method to investigate performance based on physical, chemical and petrographic factors has been evaluated. The objective was to develop a laboratory method to test Indiana dolomite, limestone, sandstone, and gravel aggregates to predict friction resistance in the field and determine causes for the range of values among these aggregates. Assessment of gravel sources was based on individual rock types and their proportions comprising the gravel. Initial friction Values (IFV) and Polished Values (PV) were determined in the laboratory with the British Wheel and Pendulum test and field values obtained from the towed friction trailer. For two laboratories involved a significant difference in IFV and PV was obtained so that further verification is required. Correlations between parameters were established which provide predictions of friction resistance based on laboratory specimens. A database of physical and chemical properties should be collected on aggregates used or considered for bituminous wearing courses. This includes the testing required for Class A aggregates plus elemental Mg and elemental Ca content.

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Development of a Procedure to Identify Aggregates for Bituminous Surfaces in Indiana

Introduction

Adequate friction resistance is needed to prevent pavement slipperiness allowing vehicles to stop in a reasonable distance. For stone mastic asphalt surfaces, friction resistance is mainly a function of the interaction between the aggregates exposed at the road surface and vehicle tires. Aggregate performance is reduced with time by wear and polishing as a consequence of vehicular traffic. In this research a method to investigate performance based on physical, chemical and petrographic factors has been evaluated. The objective was to develop a laboratory method to test Indiana dolomite, limestone, sandstone, and gravel aggregates to predict friction resistance in the field and determine causes for the range of values among these aggregates. Assessment of gravel sources was based on individual rock types and their proportions comprising the gravel. Initial friction Values (IFV) and Polished Values (PV) were determined in the laboratory with the British Wheel and Pendulum test and field values obtained from the towed friction trailer. For two laboratories involved a significant difference in IFV and PV was obtained so that further verification is required. Correlations between parameters were established which provide predictions of friction resistance based on laboratory specimens. A data base of physical and chemical properties should be collected on aggregates used or considered for bituminous wearing courses. This includes the testing required for Class A aggregates plus elemental Mg and elemental Ca content.

Findings

This study was a continuation of previous work by Bruner, Choi and West, 1995, FHWA/IN/JHRP 95/11, which focused primarily on dolomite aggregates (19 sources). In the current study, 21 limestone sources, three sandstones and six gravel sources were added. Data from both studies were evaluated to provide an overall conclusion. Frictional performance is determined by polishing aggregate coupons with the British Wheel machine and measuring friction values with the British Pendulum tester. This provides the IFV (initial friction value), PV (polished value or BPN at 10 hours) and the difference between IFV and PV, WI, wear index.

Following aggregate collection, megascopic and microscopic evaluation of the aggregate samples was accomplished. Twenty-four additional rock thin sections were examined to extend those from the first study. Laboratory tests included acid insoluble residue (ASTM, D3042), size distribution of acid insoluble residue, elemental Mg content (ASTM, C602), Los Angeles abrasion (ASTM, C131), sulfate soundness (ASTM, C88), freeze-thaw loss in water and in brine solution (AASHTO, T103, Procedure A), absorption and specific gravity (ASTM, C127). These were conducted at INDOT, Division of Materials and Tests, and at Purdue University.

Aggregate coupons of limestones, sandstones and gravels were made for the British Wheel test and British Pendulum test (ASTM, D3319, E303). The coarest portion of the No. 11 INDOT gradation, 12.5 mm to 9.5 mm in size, was used. To construct the coupons, aggregates were embedded in epoxy resin and a hardener component added. The epoxy was different from that used in the 1995 study (Bruner, Choi and West). Coupons were polished using the British Wheel machine and measured with the British Pendulum tester after zero hours (IFV), 1 hour, 3 hours, 6 hours and 10 hours (Polished value, PV or BPN_{10}). These data were added to the existing information from the previous dolomite study (Bruner, Choi and West, 1995, FHWA/IN/JHRP 95/11).

Finally, analysis of all data from the current and the 1995 study were combined and a statistical evaluation performed. Results were compared to those from other states. Based on this, PV of dolomites and limestones required for bituminous surface courses can be recommended. Results can be used to develop specifications to evaluate additional sources for medium and high vehicular traffic pavements having bituminous overlays in Indiana.

Gravels consisted primarily of limestones and dolomites. The weighted PV ranged from 22.6 to 26.3 and PV correlates best with freeze-thaw loss. Other important factors are absorption, percent of crushed gravel pieces and percent of metamorphic rocks. Crushed gravels showed PN values greater than some crushed dolomites and crushed limestones. Crushed gravel sources should be considered for bituminous surface courses if they meet the standard requirements for Class A stone.

For carbonate aggregates, the difference in mineral hardness within an aggregate piece has a significant effect on friction resistance. Uneven texture after polishing yields a high PV. Materials that yield a contrast in hardness are: quartz vs. calcite, calcite vs. insoluble materials, dolomite vs. calcite, impure dolomite and impure limestone.

Certain geologic formations yield impure aggregate sources. The Kokomo Member and Mississinewa Member are impure carbonates with higher friction values. The Huntington Dolomite and Brassfield Limestone possessing high carbonate purity, showed lower friction values.

Factors greatly affecting PV for dolomite aggregates are IFV, absorption, specific gravity, sodium sulfate loss, elemental Mg content, and percentage of insoluble residue, minus #200 sieve size. The most influential independent variables for dolomite are absorption and elemental Mg content.

The important factors affecting PV for limestone aggregates are total insoluble residue and percent insoluble residue, minus #200 sieve size. In all, the most influential independent variable is the total insoluble residue content.

Considering dolomite and limestone aggregates collectively, the most important variables are absorption, elemental Mg content and total insoluble residue.

Multiple linear regression equations were developed which can be used to predict PV. These are provided in the report.

As a starting point for further research using the British Polishing Wheel and Pendulum test the following is proposed:

Minimum Polish Value	Frictional Resistance of Bituminous Surface
24 or less	Poor
25 to 30	Marginal
31 or more	Good

For the calcareous sandstones studied, as total insoluble residue content increases (quartz, clay), PV also increases. With an increase in the ratio of plus #200 to minus #200 size insoluble residue, PV also increases.

Sandstones in the study showed a higher average PV (33.61) than did carbonate aggregate (PV=28.50 for dolomite and PV=24.77 for limestone) because of the heterogeneity of the calcareous sandstones. Quartz, calcite and clay provide this varied composition.

Implementation

Higher elemental Mg values for dolomite aggregates indicate a greater presence of dolomite mineral. Such aggregates experience a lower PV. For the INDOT specifications, a minimum 10.3 % elemental Mg is required for carbonate aggregates when used in surface courses with intermediate traffic requirements. Based on results of this study, dolomites with less than 10.3 % elemental Mg should be considered for aggregate use if other requirements such as absorption and soundness are met. Impure limestones, containing clay, quartz or dolomite should also be considered if they meet those same requirements.

Carbonates with higher insoluble residue contents show a higher friction resistance than do purer carbonates with their low insoluble residue values. Data on insoluble residue content including grain size evaluation (+#200 size fraction vs - #200 size fraction) should also be determined. A data base for aggregates used in bituminous wearing courses should be compiled by INDOT which includes the insoluble residue content and absorption. Elemental Mg and Elemental Cu should also be determined.

A discrepancy in PV was observed between two pieces of test equipment for the British Pendulum test (Purdue University equipment vs Alabama DOT equipment). Before BPN is selected as a standard criterion for evaluating aggregate quality in Indiana, the standard method must be developed using new equipment and a detailed evaluation of inherent variations. PVs need to be evaluated on a continuing basis because PV can vary even within the same aggregate source.

Some impure limestones with a higher frictional value should be considered as a source for bituminous overlays, but field performance of these limestones must be verified through field and laboratory evaluation prior to their use as overlays.

Additional testing using new Polishing Wheel and Pendulum test equipment should be conducted on Indiana aggregates to verify these results. INDOT studies assisted by research perfomed at Purdue University should address this objective.

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List of Abbreviation

AASHTO -- American Association of State Highway and Transportation Officials

AB -- Absorption

AFN -- Average Friction Number

ASTM -- American Society for Testing and Materials

BPN -- British Pendulum Number

DOL -- Dolomite

FNR -- Friction Number Ribbed

FNS -- Friction Number Smooth

F-T -- Freeze-Thaw Loss

IFV -- Initial Friction Value

IG – Igneous Rock

INDOT -- Indiana Department of Transportation

ITM -- Indiana Test Method

ISM -- Indiana Standard Method

LA -- Los Angeles Abrasion Loss

LS -- Limestone

META -- Metamorphic Rock

MG -- Elemental Mg Content

MgO -- Magnesium Oxide

M_200 – Insoluble Residue < # 200 sieve

OS -- Other Sedimentary Rock

P_200 -- Insoluble Residue > # 200 sieve

PV -- Polished Value

SPG -- Specific Gravity

SUL – Sulphate Soundness Loss

T_ACID -- Total Acid Insoluble Residue

WI -- Wear Index

1. INTRODUCTION

The goal of this project is to extend the knowledge obtained from the 1995 JTRP study directed by T.R. West (Bruner, Choi and West, 1995) which focused mostly on dolomite aggregate sources to additional aggregate types, such as limestones, gravels and selected sandstones. Dolomite was the focus of the 1995 study because of its prevalent use in bituminous surface pavements for medium and high vehicular traffic roads.

Bituminous courses are placed over concrete pavements after the concrete has experienced years of wear from highway traffic. The coarse aggregate in the bituminous overlay must supply the primary roughness to yield needed resistance for braking. Although most coarse aggregate types in new bituminous pavements initially provide high friction values, polishing of the coarse aggregate to an equilibrium level eventually occurs. The extent of polishing an aggregate will experience is a function of rock type and gradation, as well as its physical and chemical properties.

For high vehicular traffic roads, equal amounts of dolomite and blast furnace slag are used as the coarse aggregate in bituminous surfaces. A minimum value of 10.3 % elemental Mg (78.1 % dolomite) is required for aggregates to qualify as an acceptable dolomite material. As high purity dolomites occur in only certain geologic formations in Indiana and therefore, in only certain locations, high purity dolomite aggregate must be shipped long distances to produce the bituminous surfaces for paving projects on Interstate highways. These greater transportation distances greatly increase the cost of construction.

The results of the study by Bruner, Choi and West (1995) suggest that some limestones may provide equal or better frictional resistance than do some dolomites that qualify because of their elemental Mg content. Difficulties can arise when attempting to isolate the major factors influencing polish and friction properties, and prioritizing those parameters because of their indeterminate and interrelated nature. The frictional resistance of the limestone and dolomite aggregates is controlled by their physical and chemical properties.

A detailed petrographic examination is necessary to determine the texture and composition of aggregates. The two most important, direct textural parameters affecting frictional properties are grain size and shape. Angular grains, at least initially, have a tendency to develop harshly textured surfaces and provide a greater degree of resistance as compared to rocks containing smooth grains. Dierstein and LaCroix (1984) reported that resistance to polishing effects of aggregates is related to grain size, hardness and durability. Larger and harder grains generally provide greater friction values. As an example to illustrate this relationship, Dierstien and LaCroix compared dolomite and limestone sources. Dolomites with generally larger and harder grains, proved superior to limestones. Shupe (1960) noted that particle-by-particle type of wear in rocks such as sandstone consisting of hard quartz and weak calcite matrix was related with high friction values. In a study by Shakoor and West (1979), grain size and particle shape were found to affect polish and thus friction properties; however, they contributed to a lesser degree than did composition. According to the 1995 JTRP study (Bruner, Choi and West, 1995), texture of dolomite aggregates such as grain shape and grain size did not relate well with frictional resistance. Only median grain size showed a high correlation to Polished Values.

Therefore, in this study, the major consideration is given to the compositional properties of dolomite and limestone aggregates to find the critical factors that provide some limestones with a better performance in skid resistance.

As mentioned previously, composition has been found to be a principal factor influencing aggregate performance. Review of the study by Russell (1972), provides the reason why magnesium content was selected as the criterion for acceptance of dolomite aggregates in Indiana. A high percentage of MgO corresponds directly with a high dolomite concentration. Russell's study of Illinois aggregates showed that percent MgO had a positive correlation with friction value, that is, greater friction values occurred with increases in MgO content. In this study Russell considered dolomite aggregate to consist of >50% dolomite mineral or 10.9% MgO. However, in a study on dolomite aggregates by Bruner, Choi and West (1995), the higher elemental Mg content of dolomite correlates with smaller PV (Polished Value) and higher WI (Wear Index). This means that dolomites with a high elemental Mg content polish easier under traffic conditions.

The amount of dolomite can be calculated from the percent of elemental Mg or from the percent of MgO in the following way.

$$\text{a) } Mg\ in\ Dolomite = \frac{Molecular\ Weight\ of\ Mg}{Molecular\ Weight\ of\ (CaMg)(CO_3)_2} = \frac{24.31g}{184.4g} = 0.1318$$

$$\%\ Dolomite = \frac{\%\ Elemental\ Mg}{0.1318}$$

Therefore 10.3% elemental magnesium corresponds to 78.1% dolomite, whereas 13.2% corresponds to 100% dolomite and 50% dolomite corresponds to 6.6% Mg.

$$\text{b) } MgO\ in\ Dolomite = \frac{Molecular\ Weight\ of\ MgO}{Molecular\ Weight\ of\ (CaMg)(CO_3)_2} = \frac{40.32g}{184.4g} = 0.2186$$

$$\%\ Dolomite = \frac{\%\ MgO}{0.2186}$$

Therefore 10.93% MgO corresponds to 50% dolomite whereas 21.865 MgO corresponds to 100% dolomite and 78.1% dolomite corresponds to 17.07% MgO.

A comparison of the representation of Mg and MgO in dolomite is illustrated in Figure 1-1. As shown in this figure, acceptable dolomite amount for Illinois DOT use ranges from 50 to 100% dolomite (10.93 to 21.86% MgO) whereas for INDOT, acceptable dolomite amounts ranges from 78.1 to 100% dolomite (10.3 to 13.19% Mg).

In a study performed by Shupe (1958), an increase in magnesium content for Indiana limestone sources showed an increase in friction properties. In other words, the less pure limestones having greater magnesium content and thus greater mineral diversity were better aggregates with regard to frictional resistance.

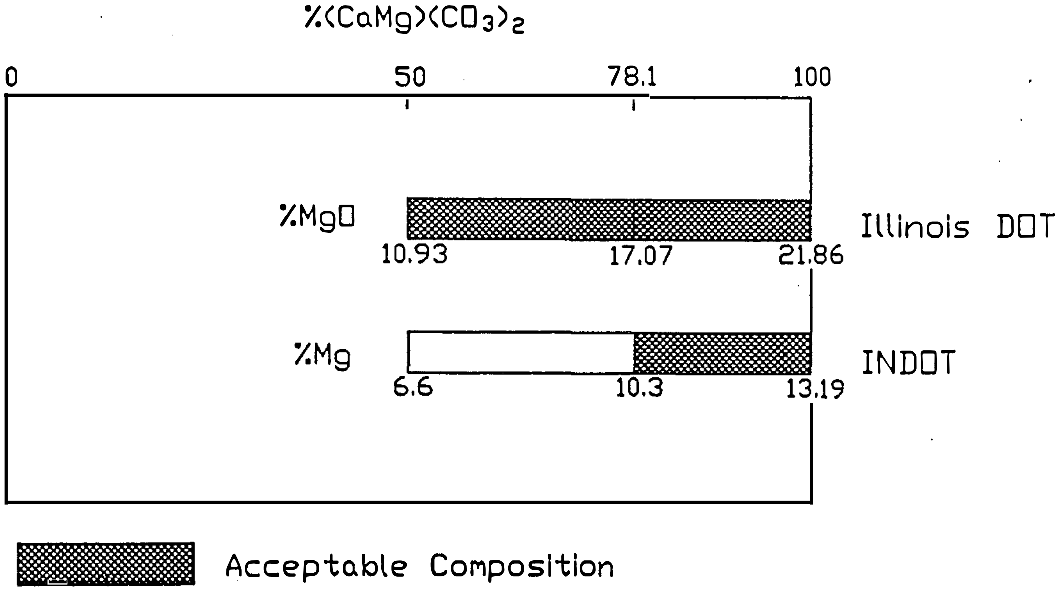


Figure 1-1. Percent dolomite in carbonate aggregates related to percent MgO and Mg content for bituminous surface courses

Russell also observed a negative correlation between friction value and quartz content for these dolomite sources. A general decrease in friction value was also observed with an increase in the calcite concentration.

Russell's study of carbonate aggregates, and that by Cummings (1976) focused on acid-insoluble residue content. Russell's study included carbonate aggregates containing less than 12 percent insoluble residue. A positive correlation was found between acid-insoluble residues >75 microns in size and friction values for the dolomite aggregates; however, little correlation was found between these factors for carbonate aggregates in general. Cummings analyzed aggregates containing up to 25 percent acid-insoluble residue. He found a positive correlation with friction value for dolomite aggregates containing insoluble-residue retained on the No. 200 sieve, as well as with the ratio between the No. 30 and No. 200 sieves. In essence, regarding those aggregates with greater than 70 percent insoluble material retained on the No. 30 sieve, they show poor results in terms of friction values as compared to samples whose majority of insoluble material occurred on the No. 200 sieve.

Dierstein and LaCroix (1984) also indicated a relationship between acid-insoluble residue and friction values. They concluded that grain size was the primary mechanism affecting variation in friction values for carbonates containing less than 10 percent insoluble content. At greater than 25 percent, the sand size acid-insoluble residue generally accounts for higher friction values.

Dahir and Mullen (1971) observed that skid resistance increases with an increase in the amount of insoluble residue, sand size residue probably is more important than total residue and the presence of clay generally contributes to lower frictional resistance. They also mentioned that skid resistance was higher for aggregate having mixed composition of hard and soft minerals than for aggregate consisting predominantly of minerals of the same type with the same hardness.

Sherwood and Mahone (1970) mentioned the positive relationship between the amount of acid insoluble residue and frictional values of carbonate rocks. Also they noticed that size distribution of the insoluble fraction affects pavement friction values. The better relationship may exist between total insoluble residue and friction coefficient.

In the study by Bruner, Choi and West (1995), involving dolomite aggregates, insoluble residue does not correlate with WI (Wear Index). However, dolomite aggregates containing greater amounts of insoluble residue less than #200 size show a higher PV (Polished Value).

The common physical tests considered to have major influence on aggregate performance are absorption, soundness, abrasion and specific gravity. Senior and Rogers (1991) provided a thorough overview of the first three of these parameters and their significance in evaluating highway aggregates. They indicated that the abrasion loss was increased nine units with additional moisture content of 5 percent. Aggregate type also influences the test results. Generally, weaker argillaceous rocks have a tendency to absorb the impact of the steel balls, whereas coarse-grained crystalline materials do not and they experience higher losses.

The sodium sulfate soundness test is a measure of an aggregate's durability and thus, its resistance to weathering. For INDOT, sodium sulfate testing was previously used to determine aggregate soundness but currently it is performed only occasionally. Because of problems obtaining reproducible results for sodium sulfate testing, unconfined freeze-thaw testing is now used as a replacement.

A relationship between absorption and freeze-thaw resistance is known to exist. Although there are exceptions, aggregates with high absorption generally have lower freeze-thaw resistance. Senior and Rogers (1991) concluded that the following combinations of tests; Los Angeles abrasion loss, sodium sulfate loss, and absorption; can be used to differentiate between good and poor aggregates. However, these tests are not particularly accurate in predicting the performance of marginal aggregates. Therefore, as indicated above, these physical tests have some shortcomings regarding the prediction of field performance for frictional resistance.

Specific gravity is related to composition and absorption. Variations in composition within an aggregate source increase with differential polishing. The presence of compositional variation has been shown to reduce the effects of polishing by vehicular traffic.

In a study by Bruner, Choi and West (1995), for dolomite aggregates, Los Angeles abrasion did not show a correlation with either WI or PV. However, dolomites with higher absorption values show lower WI and higher PV. Also higher specific gravities correlated with lower PV and higher WI. The dolomites showing higher sulfate soundness also show a higher PV and lower WI. However, the correlation between the Los Angeles abrasion loss and frictional resistance was not significant.

2. PROBLEM STATEMENT

The highway pavement system requires aggregates of multifunctional characteristics to meet various demands. For bituminous wearing courses these characteristics not only include strength and durability but also adequate frictional resistance. Aggregate having all these properties frequently are not locally available and have to be imported which thereby increases transportation costs.

Natural aggregates used in highway construction in Indiana are crushed carbonate rocks and glacial river gravels. This includes both base courses and aggregates for the pavement itself. Historically, dolomites have been specified for use in surface courses for medium volume roads and a combination of dolomite and blast furnace slag used for surface courses of high volume roads.

Following pavement construction, the frictional resistance of pavement is monitored after specific time intervals using the ASTM procedure, "Towed Friction Trailer" (ASTM Standard E-274). When the FNS (Friction Number Smooth) or FNR (Friction Number Ribbed) fall below a critical value, replacement of the overlay is considered.

In 1995 a 2-1/2 year JHRP study on the contribution of aggregates to frictional resistance of bituminous surfaces was completed under the direction of T.R. West (Bruner, Choi and West, 1995). In this study coupon samples of aggregates were evaluated using the British Polishing Wheel and the British Pendulum Tester. Also a comparison was made to the frictional resistance of pavements as measured by the skid trailer.

Detailed petrographic evaluation and compilation of laboratory data allowed for the correlation of frictional resistance measurements. Because of its prevalent use in medium and high vehicular traffic roads, dolomite was the primary aggregate type studied, along with selected examples of crushed stream gravels. Low volume vehicular traffic roads are those with less than 1 million ESALs, or Equivalent Single Axel Loads, whereas medium volume roads have from 1 to 3 million ESALs. Limestones, because of their limited use in medium and high vehicular traffic roads, were represented by only two examples in this study. This did not adequately depict the range of characteristics shown by limestone aggregates. Despite this limited number of samples, these limestones performed better in the British Pendulum Tester than did some of the dolomite samples from approved sources.

For high vehicular traffic roads, equal amounts of dolomite and blast furnace slag are used as the coarse aggregate in bituminous surfaces. This is to provide a greater frictional resistance for the pavement surface. Based on past research on carbonate rocks it had been concluded that high purity dolomites provide a better frictional resistance in pavements than do limestones. However, the study by Bruner, Choi and West (1995) noted that impure dolomites having low elemental Mg content provided better frictional resistance. Elemental magnesium is used as an indication of dolomite content as dolomite has the composition $CaMg(CO_3)_2$. A minimum value of 10.3 % Mg is required for aggregates to qualify as an acceptable dolomite material, which corresponds to 78.1% dolomite (INDOT Specifications, 1999). As high quality dolomites occur in only certain geologic formations in Indiana and therefore, in only certain locations, high quality dolomite aggregates are commonly shipped long distances to produce the bituminous surfaces for paving projects on Interstate highways. These greater transportation distances greatly increase the cost of construction.

Results of the study by Bruner, Choi and West (1995) suggest that some limestones may provide equal or better frictional resistance than do some dolomites that qualify because of their elemental Mg content. In the current study, in order to determine factors other than elemental Mg content that affect high quality limestone performance, various limestone aggregates were evaluated to determine their frictional resistance based on the British Polishing Wheel and Pendulum Tester. Acid insoluble residue and Mg content of carbonates showed considerable promise in the previous study, and therefore would be conducted on the limestone samples as well.

3. OBJECTIVES

The objectives of this study were to 1) Extend the knowledge obtained from FHWA/IN/JHRP-95/11 (Bruner, Choi and West, 1995) by evaluating gravels, limestones and sandstones, and expanding the base of dolomites. 2) Find factors that gave some limestones a higher frictional resistance on bituminous pavement, and 3) Develop specifications, if possible, to allow certain limestones and crushed gravels to be used in medium and high vehicular traffic roads.. To accomplish this, additional aggregate types, such as limestones, gravels and selected sandstones would be evaluated. Dolomite had been the focus of the 1995 study because of its prevalent use in surface pavement for medium and high vehicular traffic roads.

For high vehicular traffic roads equal amounts of dolomite and blast furnace slag are used as the coarse aggregate in the bituminous surface. A minimum value of 10.3% elemental Mg is required for aggregates to qualify as an acceptable dolomite material, which corresponds to 78.1% dolomite in the sample. As high quality dolomites occur in only certain geologic formations in Indiana and therefore, in only certain locations, high quality dolomite aggregates are commonly shipped long distances to produce the bituminous surfaces for paving projects on interstate highways. These greater transportation distances significantly increase the cost of construction.

Therefore, this study focuses on high quality limestones. These aggregates were sampled and analyzed in order to find the factors that give limestone higher frictional resistance for bituminous pavement. Results of this study will be used to evaluate frictional resistance provided by various aggregate types. Development of specifications that allow certain limestones and crushed gravels to be used in high vehicular traffic roads is a stated objective. The outcome would be a reduction in cost of materials for road construction or resurfacing of medium and high vehicular traffic projects including interstate highway projects.

4. WORK PLAN

The work plan builds on the results obtained in the previous JTRP study directed by T.R. West (Bruner, Choi and West, 1995). Predominantly, dolomite sources were included in that study. In the current study, additional rock types including limestones, crushed gravels and selected sandstones were chosen from those specifically addressed under the INDOT Specification.

First, through a meeting with SAC members, the aggregate sources including limestones, crushed gravels and sandstones were selected for study. Input from INDOT (Division of Materials and Tests), FHWA and industry (Indiana Mineral Aggregates Association and representatives of aggregate suppliers) was obtained.

A total of 21 sources of limestone aggregates, 3 sources of sandstones and 6 sources of crushed gravels were collected based on bedrock formation, rock types, texture, composition and geographic location (ASTM Standard C702, D75).

Following aggregate collection, megascopic and microscopic observations on the aggregate sources were accomplished. A total of 24 rock thin sections were made for the limestone and sandstone sources.

Also, laboratory tests including acid insoluble residue (ASTM Standard D3042), size distribution of the acid insoluble residue, elemental Mg content (ASTM Standard C602 and Atomic Absorption Method), Los Angels abrasion (ASTM Standard C131), sulfate soundness (ASTM Standard C88), freeze-thaw loss in water and brine solution (AASHTO Standard Specification, T103 Procedure A), absorption and specific gravity (ASTM Standard C127) were conducted at the INDOT Division of Materials and Tests and at Purdue University. In particular, the acid insoluble residue and Mg content were used for the identifications of quality limestones.

Aggregate coupons of limestones, sandstones and crushed gravels were made for the British Wheel test and British Pendulum test (ASTM Standard D3319, E303). In order to make aggregate coupons, the largest pieces of crushed stone comprising the No.11 INDOT gradation, 12.5mm to 9.5mm in size, were selected. To construct the coupons the aggregates are embedded in epoxy that has a resin component and a hardener component mixed in a one to one ratio by volume. The aggregate coupons were polished with British Wheel machine and frictional resistance measured with British Pendulum Tester after 0 (Initial Friction Value, IFV), 1 hour, 3 hour, 6 hour and 10 hour (Polish Value, PV) during the polishing process. These data were added to the list of existing information of a similar nature on dolomites from the 1995 study directed by T.R. West (Bruner, Choi and West, 1995).

Finally, analysis of all data to provide results and conclusions relating information from the various tasks was accomplished. Results of this study were compared to those from other states. From this the PV of dolomite and limestone for bituminous surface pavement required for pavement surfaces can be recommended. Also, results can be used to develop specifications yielding the approval of additional aggregate sources for medium and high vehicular traffic bituminous surface pavements in Indiana.

5. ANALYSIS OF DATA

5.1 Gravel Study

Six gravel sources were selected for this study (Figure 5-1). For these samples a megascopic, petrographic examination was performed and the Initial Friction Value (IFV) and Polish Value (PV) were determined on coupons made from these gravels.

The objective of the petrographic examination for the gravel samples was to describe and classify constituents and determine the relative amounts of these different materials. This method is based on ASTM Standard C295.

The major gravel resources in Indiana are found in landforms deposited directly by glacial melt-water runoff during continental glaciation. At first glance, the composition of the Indiana gravels seems to be a bewildering array of rock and mineral types, and in many samples 10 to 20 varieties of rocks can be found (Carr and Webb, 1970). Included are carbonates, sandstone, siltstone, chert, shale, iron concretion, gneiss, schist, quartzite, granite, granodiorite, diorite, gabbro, andesite, basalt, gabbro, syenite, dacite, rhyolite, amphibolite, and quartz (Shakoor and West, 1979, McGregor, 1960).

5.1.1. Selection of Samples for Examination

Approximately 2.5 kg of a gravel sample were prepared for sieve analysis by reducing the sample material to the required quantity according to ASTM Standard C 702. From this, by sample splitting, 300 representative particles were selected and subsequently examined.

The size ranging from 9.5mm to No. 4 (4.75mm) was chosen and fractions smaller than the No. 4 were not included in the analysis. This is because it is generally accepted that the coarse aggregate portion largely determines the skid resistance for bituminous pavements, and the finer portion represents only ten to thirty percent of the total No. 11 size sample used for bituminous surface aggregate. All particles present in the size fraction were examined if they numbered fewer than 300 particles.

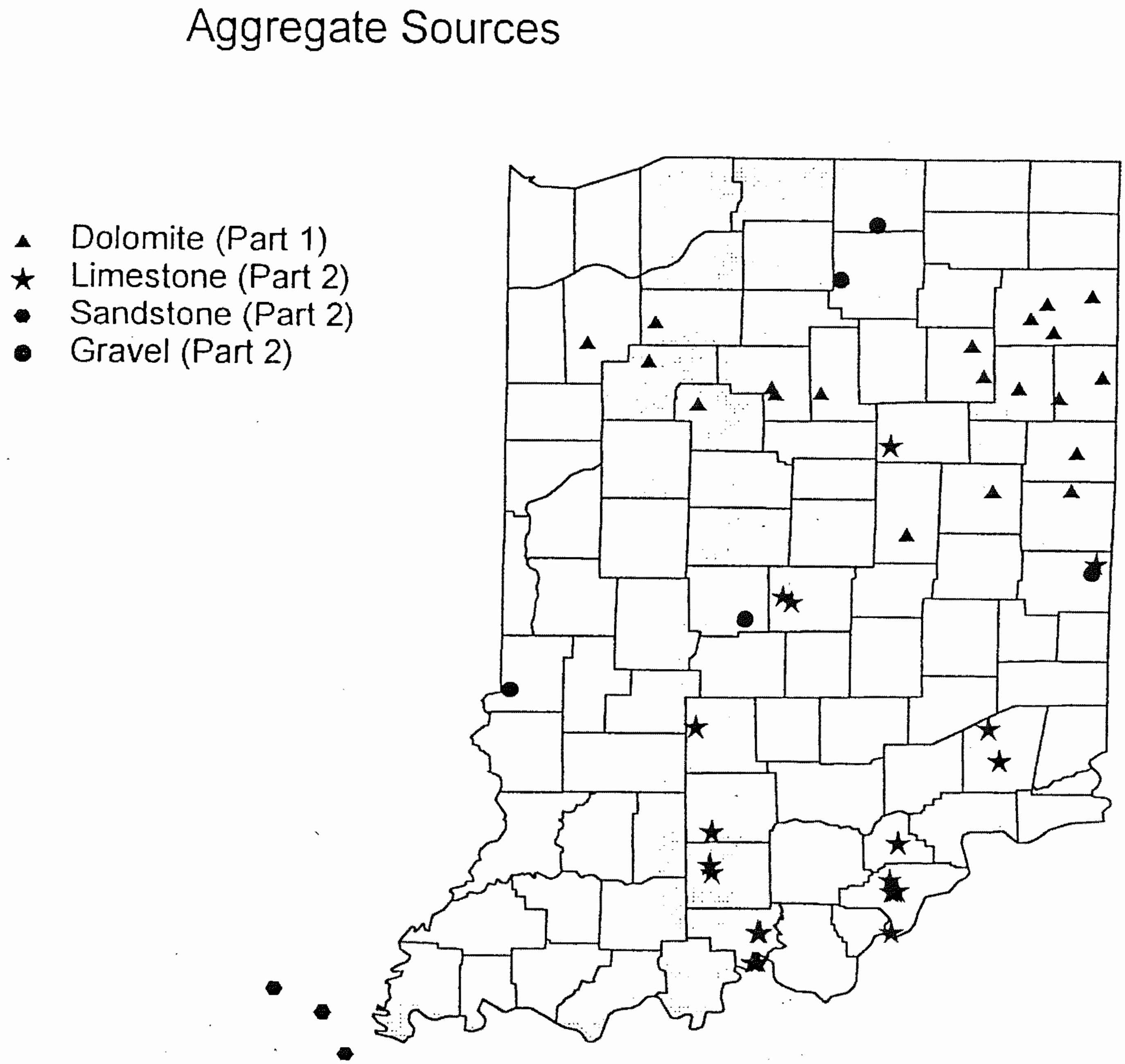


Figure 5-1. Location map of aggregate sources

5.1.2 Examination of Gravels

Rock particles were identified in a wet surface condition that enhances the color and structure of the particles. Hand lens and binocular microscope were used to identify individual rock constituents. Following this, 0.1 N HCl was applied on soft rocks to differentiate carbonates from other constituents. Limestones produced a brisk effervescence whereas dolomite showed slow effervescence or produced effervescence only when scratched. Ten rock types were chosen according to their frequency in the sample. If particles of indeterminate type were encountered in the samples, they were included with known types having similar texture and hardness. The ten rock categories selected are limestone, sandstone, siltstone, shale, chert, granite, diorite, felsite, gneiss, and quartzite.

The percentage of crushed particles was determined according to the definition of a fractured face in the Indiana Test Method (ITM) 204. It reads as follows: Fractured surface: A broken surface constituting an area of at least 25% of the largest cross sectional area of the particle. A fractured particle is defined as one being fractured either by mechanical means or by nature. Natural fractures must be similar to those fractures produced by a crusher.

The ten rock types were collected into five major rock types, that is, igneous, metamorphic, limestone, dolomite and other sedimentary rocks. The petrographic analyses for the gravels are summarized in Table 5-1.

Results show that gravel samples examined consist mainly of carbonates (limestone and dolomite) ranging from 6.6 percent to 56.3 percent. Igneous rock is the second most abundant constituent of the gravel, ranging from 9.0 percent to 49.2 percent, followed next by other sedimentary rocks ranging from 16.0 percent to 46.9 percent. Metamorphic rocks consist of a portion ranging between 3.6 percent and 18.7 percent of gravel samples (Figure 5-2).

5.1.3 Physical Properties of Gravels

The physical test results for gravel samples were obtained from INDOT. These test results are listed in Table 5-2.

According to results of the physical properties of the gravels, absorption ranges from 1.21 % to 3.21 %, specific gravity from 2.509 to 2.676, Los Angeles abrasion loss from 22.64 % to 28.00 % and the freeze and thaw loss in brine solution from 4.49 to 9.18. For sample GR-6 the freeze and thaw loss in water was performed instead, resulting in 2.06 % loss.

5.1.4 Estimation of IFV and PV for Gravel Samples

The aggregate coupons for gravel samples were made using single individual rock types. The Initial Friction Value (IFV) and Polished Value (PV) were measured using the British Pendulum tester. The IFV and PV for gravel aggregates are listed in Table 5-3. According to the results of the British Pendulum test, igneous rocks in gravels have an IFV ranging from 32.2 to 45.6 and a PV ranging from 21.0 to 29.9. Aggregate coupons of metamorphic rocks were made only from GR-1 and GR-6 gravels because not enough metamorphic rock pieces in other gravel sources were present. The metamorphic rocks in gravels show IFV ranging from 39.6 to 43.3 and PV ranging from 27.5 to 28.3. The limestone in gravels show IFV ranging from 33.2 to 46.6 and PV ranging from 18.6 to 31.4. The dolomite in gravels show IFV ranging from 40.2 to 46.7 and PV ranging from 24.5 to 27.3. The other sedimentary rocks such as sandstone, shale, siltstone and chert show IFV ranging from 35.2 to 43.7 and PV ranging from 21.6 to 25.3.

As indicated in Table 5-3, it is noted that on average dolomites show higher IFV and PV values than do limestones. Weighted averages of IFV and PV for each gravel sample based on their percentage of rock compositions are summarized in Table 5-4.

As indicated in Figures 5-3 and 5-4, as the percentage of crushed faces of gravel increases, both IFV and PV also increase. In Table 5-5, the percent of crushed gravel faces is more highly correlated with IFV (R=0.890) than with PV (R=0.804). IFV depends more on the percent of the crushed gravel than it does on PV. This shows that the influence of the amount of crushed gravel faces is diminished as the gravels are polished.

Table 5-1. Rock type distribution in gravel samples

Id. No.	Igneous Rock	Metamorphic Rock	Limestone	Dolomite	Other Sedimentary Rock	Remarks
GR-1	27.5	11.1	19.5	20.8	21.1	99% crushed
GR-2	35.8	3.6	20.8	21.5	18.3	30% crushed
GR-3	29.7	6.8	14.1	14.7	34.7	10% crushed
GR-4	49.2	8.7	17.5	8.6	16.0	78% crushed
GR-5	9.0	3.7	15.9	40.4	31.0	57% crushed
GR-6	27.8	18.7	6.2	0.4	46.9	93% crushed
Average	29.8	8.8	15.7	17.7	28.0	61% crushed

Table 5-2. Physical properties of gravel samples

Id. No.	Absorption	Specific Gravity	L.A. Abrasion Loss	Freeze/Thaw Loss in Brine
GR-1	3.21%	2.590	27.99%	9.18%
GR-2	1.42%	2.593	26.26%	4.49%
GR-3	1.21%	2.676	22.64%	5.67%
GR-4	1.33%	2.638	24.22%	4.64%
GR-5	1.57%	2.645	23.19%	5.77%
GR-6	2.03%	2.509	28.00%	*2.06%
Average	1.80%	2.609	25.38%	5.95%

- *: Freeze - thaw loss in water

Table 5-3. IFV and PV for rock constituents in gravel samples

Id. No.	Igneous Rock		Metamorphic Rock		Limestone		Dolomite		Other Sedimentary Rock	
	IFV	PV	IFV	PV	IFV	PV	IFV	PV	IFV	PV
GR-1	43.3	26.3	43.3	28.3	43.3	25.3	46.7	27.3	43.7	25.3
GR-2	32.2	21.0	-	-	33.2	23.1	41.7	24.6	36.6	23.1
GR-3	34.2	21.0	-	-	34.2	24.1	40.2	26.9	35.2	24.1
GR-4	40.3	23.7	-	-	36.3	25.3	42.3	25.3	35.3	23.6
GR-5	40.3	24.3	-	-	35.7	18.6	41.6	24.5	37.2	22.6
GR-6	45.6	29.9	39.6	27.5	46.6	31.4	-	-	35.7	21.6
Average	39.3	24.4	41.5	27.9	38.2	24.6	42.5	25.7	37.3	23.4

Table 5-4. Weighted average of IFV and PV for gravel samples

Identification No.	IFV	PV	Remark
GR-1	44.1	26.3	99% crushed
GR-2	35.3	22.6	30% crushed
GR-3	35.6	23.5	10% crushed
GR-4	39.0	24.1	78% crushed
GR-5	39.1	22.9	57% crushed
GR-6	39.9	25.6	93% crushed
Average	38.8	24.2	61% crushed

* Example (GR-1):

IFV = 43.3(0.275)+43.3(0.111)+43.3(0.195)+46.7(0.208)+43.7(0.211)=44.1

PV= 26.3(0.275)+28.3(0.111)+25.3(0.195)+27.3(0.208)+25.3(0.211)=26.3

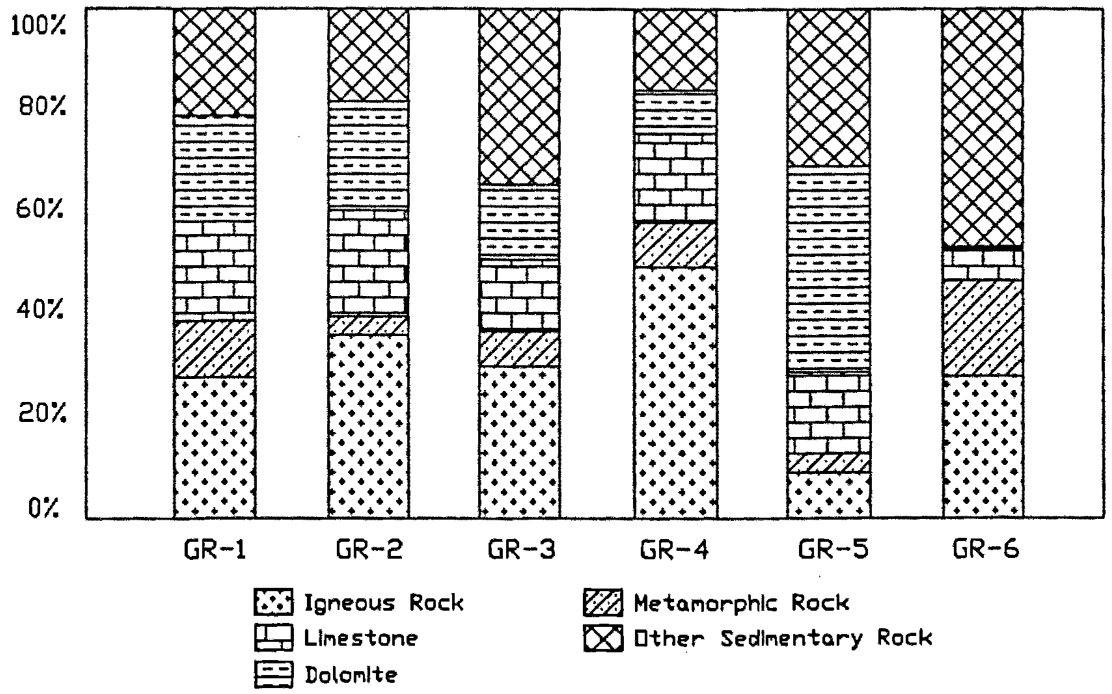


Figure 5-2. Rock type distribution of gravel samples

5.1.5 Correlation of Frictional Properties for Gravel Samples

In order to find the most critical factor for frictional properties of gravels, data analyses for correlations between British Pendulum Number (BPN) and other aggregate properties were performed. Using a correlation analysis (SAS program), the statistics and correlation matrix for all parameters of the gravels were developed as shown in Table 5-5. The top number (R-value) in each cell is the coefficient of correlation between two variables defining the cell. R-value measures the degree of linear relationship among variables. The middle number (P-value) in each cell is developed from hypothesis testing and indicates the significance of the correlation; lower P-values imply greater significance. The bottom number in each cell is the number of data used for correlation analysis. For the purpose of this study, the correlation coefficient (R-value) is considered to be low if it falls below 0.50, fair if between 0.50 and 0.80, and good if above 0.80 (Kandhal et al., 1993).

5.2. Carbonate Rock Study

Results of the current research on limestone aggregates along with those on dolomite aggregates by Bruner, Choi and West (1995) were analyzed collectively. The total number of samples was 21 limestone sources and 20 dolomite sources. The bedrock distribution of principal carbonate rocks and their columnar sections are shown in Figures 5-5 and 5-6, respectively. The lithology of the geologic formations of the carbonate aggregates is described below based on the Indiana Geological Survey Bulletin 59, 1986 and Bulletin 42H, 1971, extending from oldest to youngest rocks.

[Silurian Period]

- Brassfield Limestone
    - Reddish brown and gray coarsely crystalline limestone.
    - Total, 1 source: L006
- Salamonie Dolomite
    - White to tan porous, fossil-fragmental dolomite. In some places this dolomite grades in two units: an upper cherty limestone and dolomite unit (Laurel Member) and a lower argillaceous dolomitic limestone unit (Osgood Member).
    - Total, 8 sources: D002, D010, D011, D012, L003, L009, L010, L011.
- Louisville Limestone
    - Bluish-gray silty dolomitic limestones that contain varying amounts of shale. In some areas, this rock is a blue and gray mottled dolomite.
    - Total, 3 sources: D008, L008, L012
- Pleasant Mills Formation
    - Tan to brown micritic to fine-grained and sugary dolomite that on outcrop appears thin to rather massively bedded but that is also color banded and faintly laminated. Oolites are abundant.
    - Total, 3 sources: D007, D009, D020.

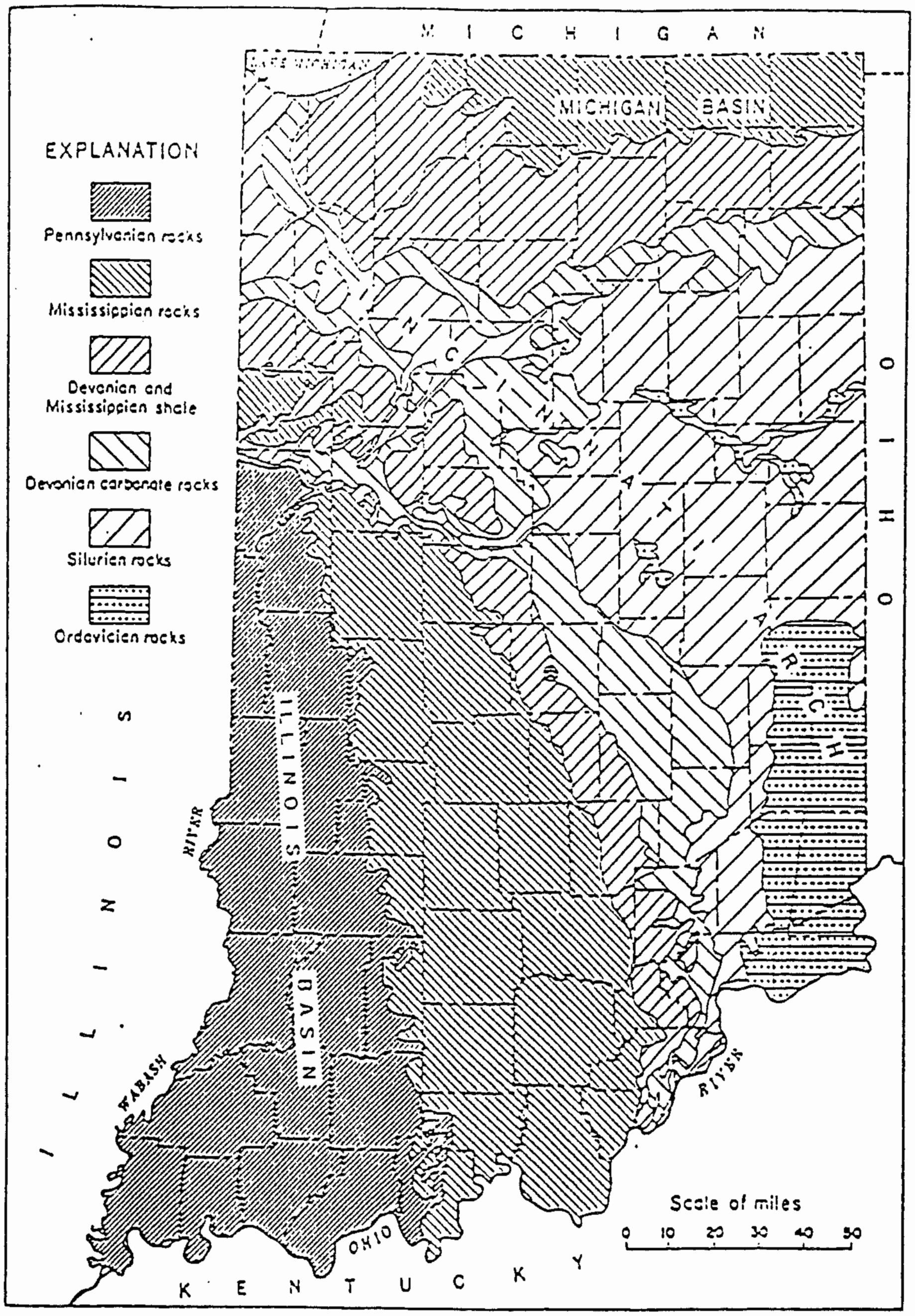


Figure 5-5. Generalized bedrock map of Indiana (Dawson and Carpenter, 1963)

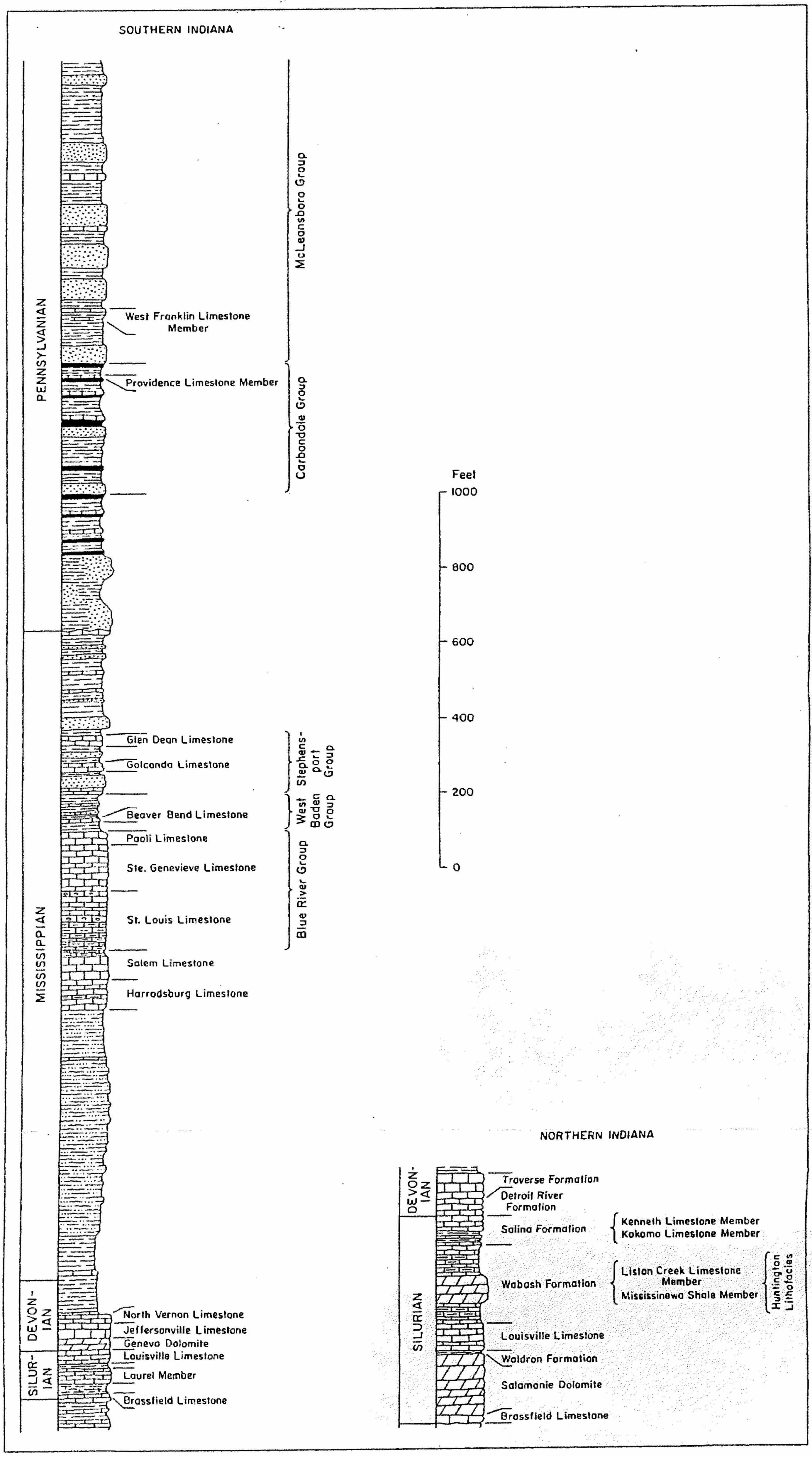


Figure 5-6. Generalized columnar sections showing rock units, except Ordovician, quarried for crushed stone in Indiana (D. D. Carr et al, 1971)

- Wabash Formation
    - Kenneth Member: light-colored dense to fine-grained bedded to massive cherty limestone.
    - Kokomo Member: strikingly banded tan and gray micritic to very fine grained, thinly laminated and dolomitic limestone.
    - Mississinewa member: argillaceous dolomitic siltstone and silty dolomite, fairly calcareous in places, that is in various shades of gray and is dense to fine grained and massive appearing in un-weathered exposures.
    - Huntington dolomite: reef, bank, and biohermal deposits of coarse-grained porous dolomite.
    - Total, 10 sources: D001, D004, D005, D013, D014, D015, D016, D017, L001, L004.

[Devonian Period]

- Jeffersonville Limestone
    - Grayish-brown carbonaceous limestone or dolomitic limestones. Three fauna zones are present in the formation: the middle and upper zones contain very thin argillaceous and pyretic laminae in places. The lower zone generally does not contain the argillaceous and pyretic laminae.
    - Total, 2 sources: L007, L013.
- North Vernon Limestone
    - Gray dense massive argillaceous limestone (Silver Creek Member)
    - Gray granular to shaly thin-bedded very fossiliferous limestone (Speed Member)
    - Gray and dark gray medium-grained and very coarse-grained crinoidal limestone (Beechwood Member)
    - Total, 1 source: L002 (mixed with Jeffersonville Limestone).
- Detroit River Formation
    - Brownish-gray fine- to coarse-grained limestones and dolomites.
    - Total, 3 sources: D003, D018, D019 (mixed with Traverse Formation, Wabash Formation or Louisville Limestone)

- Traverse Formation
  - Brownish-gray calcareous dolomites and dolomitic limestones that contain a few scattered chert bands and shaly layers near the base.
  - Total, 3 sources: D003, D018, D019 (mixed with Detroit River Formation, Wabash Formation or Louisville Limestone)

[Mississippian period]

- St. Louis Limestone
  - Gray to light brown thin-bedded micritic limestone. Contains small amounts of shale and chert (Upper unit)
  - Gray to brown thin-bedded dolomitic limestone interbedded with calcareous shale (Lower unit)
  - Total, 1 source: L005 (mixed with Ste. Genevieve limestone)
- Ste. Genevieve Limestone
  - Fredonia member: dominantly an oolitic limestone that is from light gray to gray, medium grained.
  - Rosiclare member: gray, fine- to medium-grained, crystalline, oolitic limestone, which is locally argillaceous, arenaceous, or conglomeratic. May contain beds of calcareous shale and sandstone.
  - Levias Member: light-gray, thin-bedded to massive, crystalline, oolitic limestone
  - Total, 2 sources: L015, L016.
- Beaver Bend Limestone
  - White to light gray, highly oolitic, thick-bedded to massive limestone.
  - Total, 5 sources: L017, L018, L019, L020, L021.
- Haney Limestone
  - Dominantly biomicritic and includes skeletal limestone and micritic dolomite with minor shale.
  - Total, 1 source: L014

Table 5-6 BPN and Physical Properties, Mg contents and Insoluble residues

A. Limestone

Id. No.	IFV	PV	WI	Absorption	Sp. Gravity	LA Abrasion	F-T	Mg (%)	Insol (Total)	>#200	<#200
L-001	38.60	28.14	10.46	2.170	2.591	28.500		5.40	12.72	2.40	10.32
L-002	40.20	24.72	15.48	1.780	2.586	27.000	22.250	0.70	5.76	3.64	2.12
L-003	44.38	22.69	21.69	2.000	2.604	21.370	7.980	9.50	4.09	2.04	2.05
L-004	43.14	23.49	19.65	1.030	2.633	32.090		3.60	3.37	0.24	3.13
L-005	39.48	21.67	17.81	0.930	2.652	28.600		2.20	4.96	1.53	3.43
L-006	43.00	20.87	22.13	1.350	2.631	37.230	10.920	0.60	1.97	0.15	1.82
L-007	41.13	25.50	15.63	1.260	2.624		16.620	0.90	4.54	2.36	2.18
L-008	41.76	24.97	16.79	1.150	2.653	26.490	27.460	2.50	6.00	0.70	5.30
L-009	42.26	27.40	14.86	2.065	2.642	25.935	15.430	9.05	6.38	0.30	6.08
L-010	45.30	25.39	19.91	2.330	2.621	23.030	19.470	10.00	6.17	1.80	4.37
L-011	43.68	25.39	18.29	0.780	2.698	32.240	7.460	4.60	5.14	0.86	4.28
L-012	46.69	27.51	19.18	1.005	2.670	25.730		2.30	6.04	0.60	5.44
L-013	48.87	29.24	19.63	1.050	2.639	27.720		1.90	11.21	4.83	6.38
L-014	44.10	25.00	19.10	1.530	2.626	28.490	8.060	1.60	4.13	1.43	2.70
L-015	43.21	27.12	16.09	0.880	2.638	22.400		1.10	4.41	1.86	2.55
L-016	41.02	24.72	16.30					1.10	4.59	1.16	3.43
L-017	47.85	25.73	22.12	2.470	2.517	38.170	3.010	0.50	1.41	0.14	1.27
L-018	44.69	22.55	22.14	1.970	2.592	34.760		0.70	2.28	0.12	2.16
L-019	42.37	23.95	18.42	1.320	2.634	24.790	11.300	0.70	4.01	0.64	3.37
L-020	40.10	22.05	18.05	1.150	2.689	24.390		1.20	3.61	0.47	3.14
L-021	42.50	22.01	20.49	1.690	2.639	26.705	5.380	1.00	3.60	0.16	3.44
Average	43.06	24.77	18.30	1.496	2.629	28.192	12.945	2.91	5.07	1.31	3.76

B. Dolomite

Id. No.	IFV	PV	WI	Absorption	Sp. Gravity	LA Abrasion	Sulfate	Mg (%)	Insol (Total)	>#200	<#200
D-001	40.00	24.90	15.10	0.79	2.732	25.53	0.36	12.40	1.70	1.23	0.48
D-002	43.30	25.00	18.30	2.39	2.599	28.59		12.90	0.71	0.02	0.69
D-003	41.80	27.30	14.50	2.64	2.605	27.05	9.57	11.30	3.13	2.07	1.06
D-004	46.90	35.30	11.60	6.25	2.390	29.36	9.86	11.30	2.11	0.11	2.00
D-005	44.00	27.70	16.30	2.02	2.616	29.19	7.30	11.60	9.82	3.55	6.28
D-006	42.70	26.80	15.90	1.56	2.626	26.62	2.24	12.40	5.29	1.79	3.50
D-007	44.00	28.80	15.20	3.05	2.583	32.43	4.79	12.90	1.34	0.21	1.13
D-008	44.60	28.70	15.90	2.38	2.594	31.73	0.76	13.10	0.22	0.03	0.20
D-009	44.80	31.00	13.80	1.21	2.671	22.47	5.59	10.70	7.42	4.40	3.02
D-010	45.90	31.30	14.60	3.76	2.489	36.98	3.29	12.60	4.16	1.81	2.35
D-011	46.20	30.00	16.20	2.02	2.632	24.75	5.99	12.20	6.31	2.71	3.59
D-012	47.60	31.30	16.30	2.74	2.588	29.50	2.24	11.90	7.65	3.39	4.26
D-013	43.50	32.70	10.80					10.10	5.56	0.78	4.78
D-014	46.70	32.00	14.70	4.00	2.480	30.28	13.18	11.20	5.27	0.71	4.55
D-015	40.50	24.10	16.40	1.03	2.669	29.76	2.56	12.80	0.50	0.27	0.22
D-016	40.10	23.60	16.50	1.86	2.614	32.62	0.55	12.90	0.08	0.02	0.06
D-017	41.30	24.90	16.40	1.00	2.718	25.69	0.31	12.90	0.35	0.03	0.32
D-018	43.60	28.40	15.20	2.48	2.619	27.25	3.62		2.15	0.94	1.21
D-019	41.60	28.00	13.60	1.59	2.648	30.75	6.45		6.66	4.45	2.21
D-020	41.90	28.10	13.80	2.95	2.590	28.54	5.33		5.90	3.14	2.76
Average	43.55	28.50	15.06	2.41	2.60	28.90	4.67	12.07	3.82	1.58	2.23

5.2.1 Aggregate Lithology and Friction Resistance Properties

Friction resistance and other aggregate properties for limestone and dolomite samples are listed in Table 5-6. In order to determine how a specific geological formation relates to fictional properties, aggregate sources sampled from only one geological formation were used in the correlation analysis. The IFV and PV for each geological formation are shown in Table 5-7.

The Wabash Formation is divided into four members these being the Kenneth, Kokomo, Mississinewa and Huntington. Of the samples obtained from the Wabash Formation, L004 and D016 were excluded from consideration because these two samples were so difficult to assign to specific rock members.

As shown in Table 5-7, for the dolomite aggregates, the Kokomo Member (Upper Silurian) shows the highest PV (average 33.3) and the Huntington Dolomite (Upper Silurian) shows the lowest PV (average 25.6). For the limestone aggregates, Mississinewa Member (Upper Silurian) shows the highest PV (28.1) and Brassfield Limestone (Lower Silurian) shows the lowest PV (20.9).

In order to determine the factors affecting the frictional properties of dolomite and limestone aggregates, elemental magnesium content and acid insoluble residue value for the geological formations were determined. This was because INDOT currently uses the elemental magnesium content analysis as the acceptance criteria for dolomite sources with the minimum level set at 10.3%. Also impure dolomite and impure limestone have been known to be quality aggregate sources.

Elemental magnesium contents and acid insoluble residues for the various geological formations are provided in Table 5-8.

As presented in Table 5-8, considering elemental Mg content, for dolomite aggregates, Louisville Limestone (Middle Silurian) shows the highest elemental Mg content (13.1%) and the Kokomo Member, which has the highest PV, shows the lowest elemental Mg content (10.9%).

Table 5-7. Friction resistance properties of carbonate aggregate samples.

Formation		Dolomite			Limestone			Remark
		IFV	PV	WI	IFV	PV	WI	
Wabash Fm	Kokomo Mbr.	43.5-46.9 (45.7)	32.0-35.3 (33.3)	10.8-14.7 (12.4)	-	-	-	D004, D013 D014
	Mississinewa Mbr.	-	-	-	38.6	28.1	10.5	L001
	Huntington Dol.	40.0-44.0 (41.5)	24.1-27.7 (25.4)	15.1-16.4 (16.1)	-	-	-	D001, D005 D015, D017
Salamonie Dolomite		43.0-47.6 (45.7)	25.0-31.3 (29.4)	14.6-18.3 (16.4)	42.3-45.3 (43.9)	22.7-27.4 (25.2)	14.9-21.7 (18.7)	L003, L009 L010, L011 D002, D010 D011, D012
Brassfield Limestone		-	-	-	43.0	20.9	22.1	L006
Jeffersonville Limestone		-	-	-	41.1-48.9 (45.0)	25.5-29.2 (27.4)	15.6-19.6 (17.6)	L007, L013
Louisville Limestone		44.6	28.7	15.9	41.8-46.7 (44.2)	25.0-27.5 (26.2)	16.8-19.2 (18.0)	L008, L012 D008
Haney Limestone		-	-	-	44.1	25.0	19.1	L014
Ste. Genevieve Limestone		-	-	-	41.0-43.2 (42.1)	24.7-27.1 (25.9)	16.1-16.3 (16.2)	L015, L016
Beaver Bend Limestone		-	-	-	40.1-47.9 (43.5)	22.0-25.7 (23.3)	18.1-22.1 (20.2)	L017, L018 L019, L020 L021
Pleasant Mills Formation		41.9-44.8 (43.6)	28.1-31.0 (29.3)	13.8-15.2 (14.3)	-	-	-	D007, D009 D020

For limestone aggregates, Salamonie Dolomite (Lower Silurian) shows the highest elemental Mg content (8.29%) and Brassfield Limestone with the lowest PV shows the lowest elemental Mg content (0.6%).

It is important to consider the following:

For dolomite aggregates:

- The lower the elemental Mg content, the more impure is the dolomite
- The lower the elemental Mg content, the higher is the PV (Figure 5-7).

higher the elemental Mg content, the more impure is the limestone

- The higher the elemental Mg content, the higher is the PV (Figure 5-8).

Considering acid insoluble residue, for dolomite aggregates, the Pleasant Mills Formation (Middle Silurian) has the highest acid insoluble residue (4.89%) and Louisville Limestone (Middle Silurian) has the lowest insoluble residue (0.22%).

For limestone aggregates, the Mississinewa Member (Upper Silurian) has the highest PV but also indicates the highest insoluble residue (12.72%). Brassfield Limestone (Lower Silurian) has the lowest PV and also has the lowest insoluble residue (1.97%).

It is also important to consider that:

For both dolomite and limestone aggregates:

- The higher the acid insoluble residue (fine quartz and clay), the more impure are the dolomites and limestones
- The higher the acid insoluble residue, the higher the PV (Figures 5-9 and 5-10).

As shown in Figures 5-9 and 5-10, for the dolomite case, the PV is correlated more highly with elemental Mg content ($R=0.707$, $R^2=0.50$) than is the acid insoluble residue ($R=0.318$). Unlike dolomite, in the case of limestone, PV is more highly correlated with acid insoluble residue ($R=0.853$, $R^2=0.73$) than with elemental Mg content ($R=0.376$, $R^2=0.14$).

Table 5-8. Elemental Mg content of carbonate aggregate samples.

Formation		Dolomite		Limestone		Remark
		Elemental Mg Content (%)	Acid Insoluble Residue (%)	Elemental Mg Content (%)	Acid Insoluble Residue (%)	
Wabash Fm	Kokomo Mbr	10.1-11.3 (10.9)	2.11-5.56 (4.31)	-	-	D004, D013 D014
	Mississinewa Mbr.	-	-	5.40	12.72	L001
	Huntington Dol.	11.6-12.9 (12.4)	0.35-9.82 (3.09)	-	-	D001, D005 D015, D017
Salamonie Dolomite		11.9-12.9 (12.4)	0.71-7.65 (4.71)	4.60-10.00 (8.29)	4.09-6.38 (5.45)	L003, L009 L010, L011 D002, D010 D011, D012
Brassfield Limestone		-	-	0.6	1.97	L006
Jeffersonville Limestone		-	-	0.9-1.9 (1.4)	4.54-11.21 (7.88)	L007, L013
Louisville Limestone		13.1	0.22	2.3-2.5 (2.4)	6.00-6.04 (6.02)	L008, L012 D008
Haney Limestone		-	-	1.6	4.13	L014
Ste. Genevieve Limestone		-	-	1.1 (1.1)	4.41-4.59 (4.50)	L015, L016
Beaver Bend Limestone		-	-	0.5-1.2 (0.82)	1.41-4.01 (2.98)	L017, L018 L019, L020 L021
Pleasant Mills Formation		10.7-12.9 (11.8)	1.34-7.42 (4.89)	-	-	D007, D009 D020

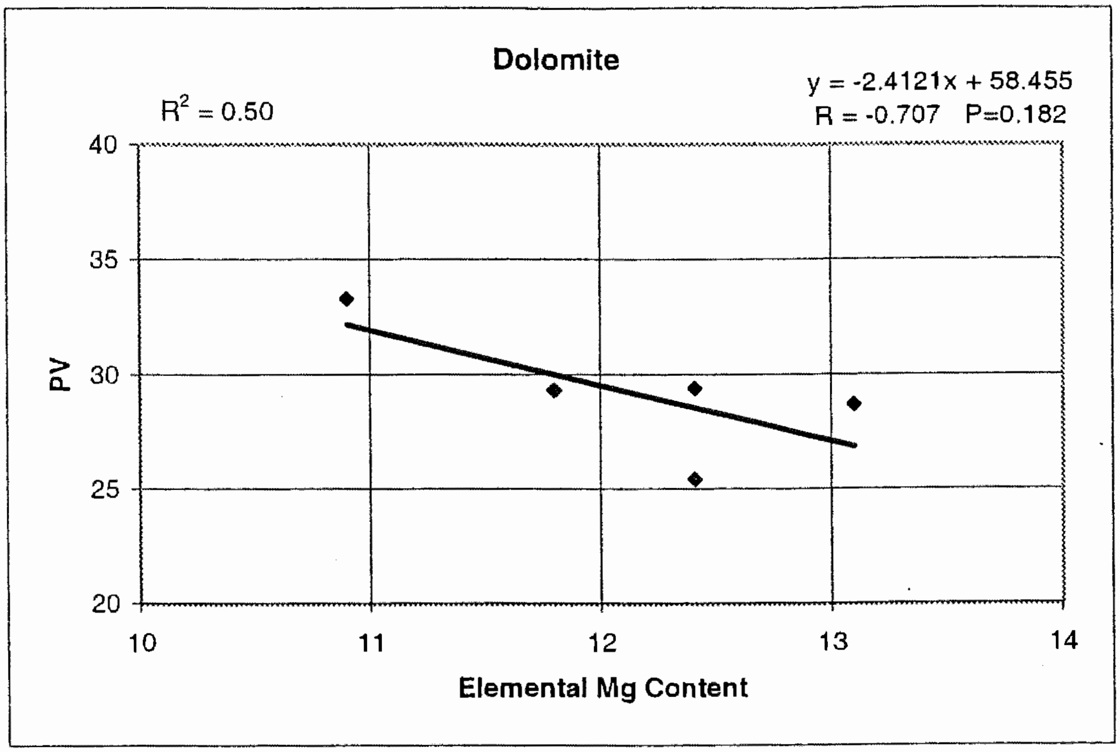


Figure 5-7. Elemental Mg content of dolomite samples

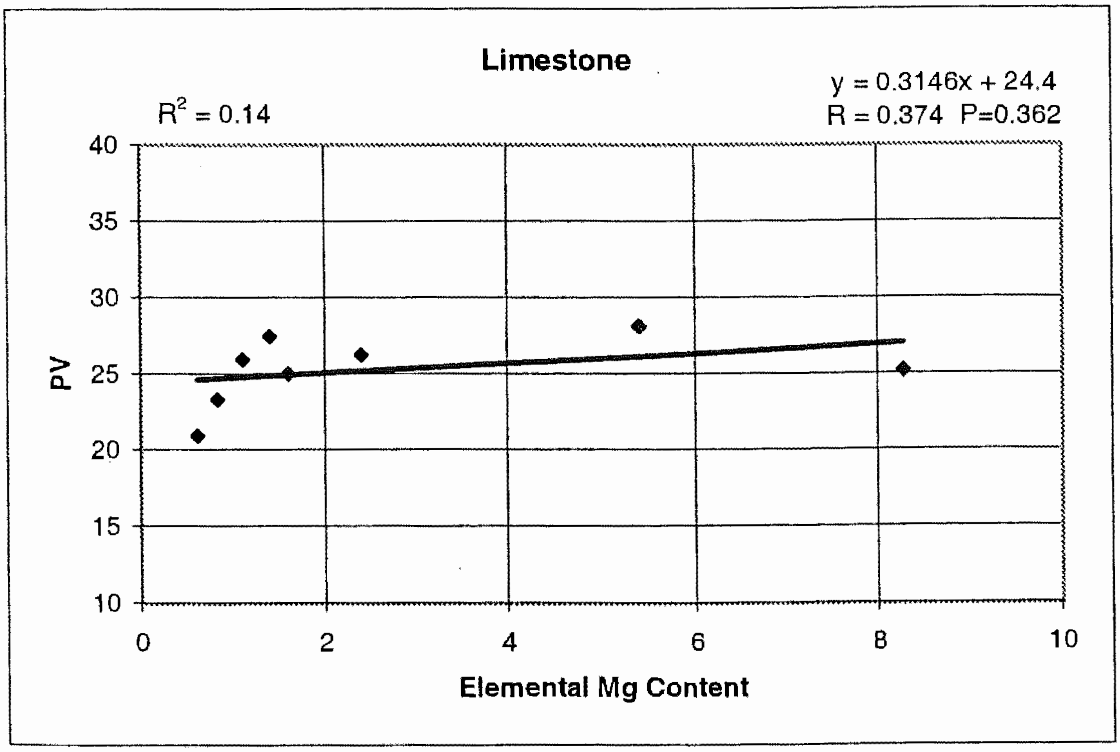


Figure 5-8. Elemental Mg content of limestone samples

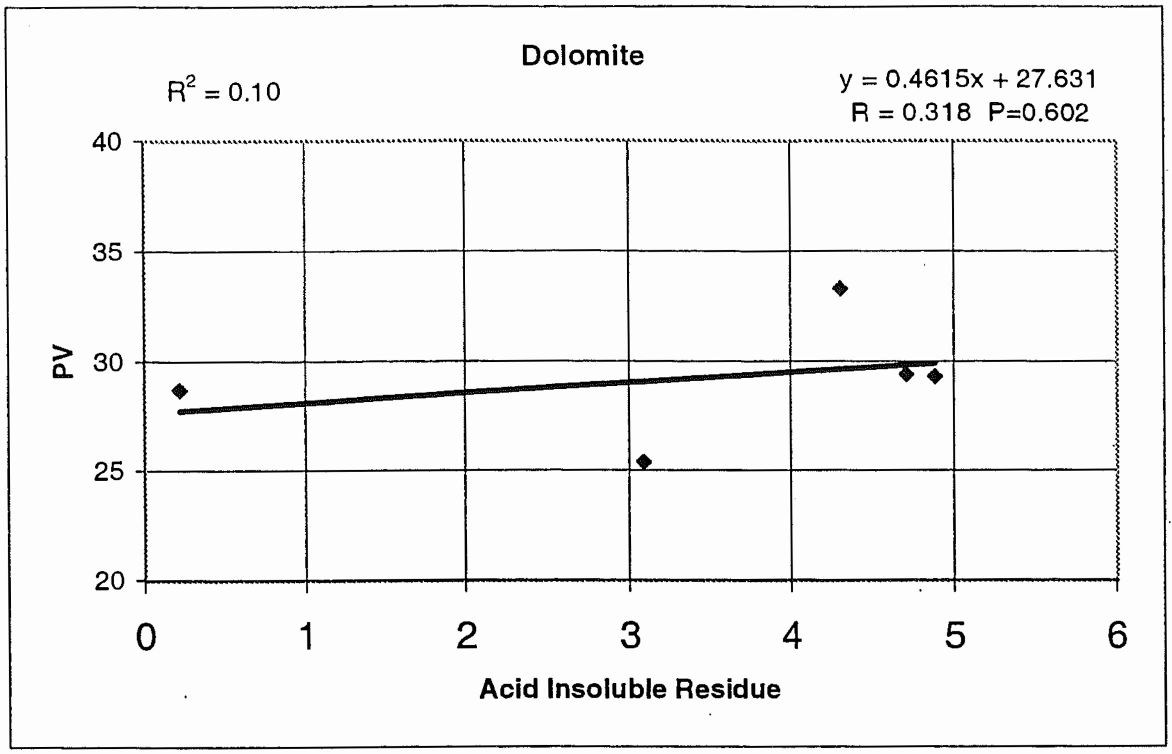


Figure 5-9. Acid insoluble residue of dolomite samples

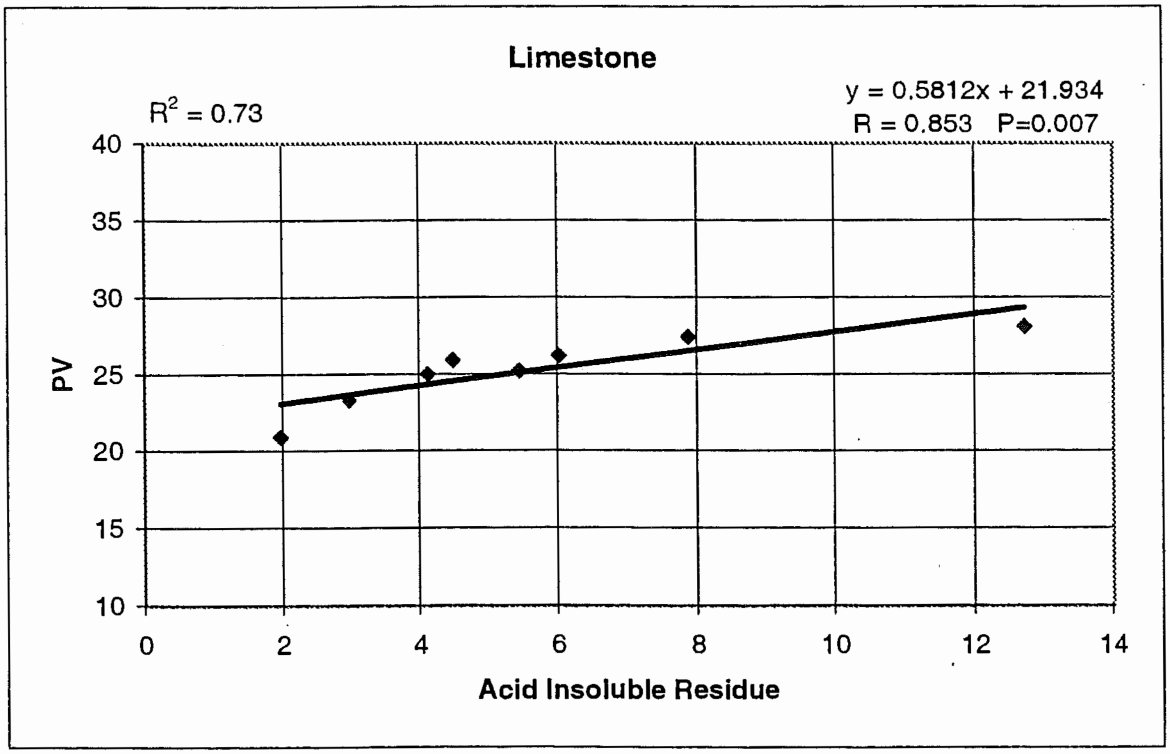


Figure 5-10. Acid insoluble residue of limestone samples

5.2.2 Physical and Frictional Resistance Properties of Carbonate Aggregates

Data on the physical properties for representative samples of dolomite and limestone were obtained from INDOT.

For the dolomite study (Bruner, Choi and West, 1995), sulfate soundness results were used for correlation with frictional properties but in the subsequent limestone study, freeze-thaw data were used as a replacement for sulfate soundness data. In the time between the two studies, INDOT changed its standard testing from the sodium sulfate to the freeze and thaw test.

Among the physical tests, specific gravity, absorption and sodium sulfate soundness, correlated best with the PV and WI for dolomite. However, for limestone only freeze-thaw correlated with WI. Los Angeles abrasion did not correlate with IFV or PV at a significant probability level for either dolomite or limestone. The physical tests are summarized in Table 5-6.

5.2.2.1 Specific Gravity

Specific gravity can be considered as a measure of mineral purity of a sample. As a consequence of large amounts of impurities, the specific gravity will be reduced from that of a more pure sample. As mentioned in a previous section, the more impure samples provided greater polish resistance. The specific gravity for dolomites generally ranges from 2.86 to 3.10. Dolomites in the previous study ranged from 2.390 to 2.732, with an average of 2.60. Specific gravity for limestones generally ranges from 2.71 to 2.83. Limestone in this study ranged from 2.519 to 2.698 with an average of 2.63.

As can be observed in Figures 5-11 and 5.12, for dolomite, PV decreases with increasing specific gravity (R=-0.745, R^2=0.56 and P=0.000) and WI increases with increasing specific gravity (R=0.462, R^2=0.21 and P=0.046). Therefore, PV is increased for samples with a lower specific gravity, thus indicating greater polish resistance with increasing impurity and decreasing specific gravity.

As shown in Figures 5-13 and 5-14, for limestone samples, PV and WI do not correlate with the specific gravity, having R=-0.073 and P=0.761 for PV and R=-0.127 and P=0.593 for WI.

5.2.2.2 Absorption

Materials with a high absorptive capacity are generally weaker aggregates. However, regarding frictional resistance, a weaker fraction yields a rougher surface during polishing. For dolomites, as absorptive capacity increases, PV increases (R=0.765, R^2=0.59 and P=0.000) and WI decreases (R=-0.538, R^2=0.29 and P=0.018) as shown in Figures 5-15 and 5-16.

For limestones, PV and WI do not correlate with absorption as indicated in Figures 5-17 and 5-18. For dolomite, the presence of weaker material aids in the reduction of the polishing effect. This is because the weaker materials easily absorb water and increase micro-texture on aggregate surface causing an increase in PV. However, this phenomenon is not significant for the limestone samples.

5.2.2.3 Sodium Sulfate Soundness

This test is a measure of aggregate durability and is related to absorption. As shown in Figures 5-19 and Figure 5-20, for dolomites, as sulfate soundness loss increases, PV increases (R=0.603, R^2=0.36 and P=0.008) and WI decreases (R=-0.567, R^2=0.32 and P=0.014).

For limestones, the sulfate soundness loss data were too few in number to provide a meaningful analysis. Therefore, freeze-thaw data were used for the comparison with PV and WI instead of with sulfate soundness data.

5.2.2.4 Freeze and Thaw Loss

In the Indiana specification, 50 cycles of freezing and thawing can be used for aggregate verification instead of the sodium sulfate soundness test. For the limestone aggregate study freeze and thaw loss results were used instead of those for the sulfate soundness test.

As shown in Figures 5-21 and 5-22, PV of the limestone samples does not correlate well with freeze and thaw loss (R=0.286, R^2=0.08 and P=0.367). However, WI decreases as the freeze and thaw loss increases (R=-0.653, R^2=0.34 and P=0.021) indicating a lower polishing susceptibility with higher freeze and thaw loss.

5.2.2.5 Los Angeles Abrasion Loss

As shown in Figures 5-23 and 5-24, the PV and WI of the dolomite samples do not correlate well with freeze and thaw loss, having R=0.107 and P=0.662 for PV and R=-0.008 and P=0.973. The PV and WI of the limestone samples in Figures 5-25 and 5-26 do not correlate well with the freeze and thaw loss, having R=-0.210, =0.04 and P=0.388 for PV and R= 0.359, R^2=0.13 and P=0.131 for WI.

5.2.3 Magnesium Content and Frictional Properties of Carbonate Aggregates

Data acquired from the magnesium analysis, based on 17 samples for dolomites and 21 samples for limestone, were analyzed to find the relationship between elemental Mg content and frictional resistance. The elemental magnesium contents range from 10.1% to 13.1% for the dolomite samples and 0.5% to 10% for the limestone samples.

As shown in Figures 5-27 and 5-28, for dolomites, elemental Mg contents correlate with PV (R=-0.653, R^2=0.43 and P=0.005) and WI (R=0.756, R^2=0.57 and P=0.000). This indicates that purer dolomites with higher elemental Mg values show lower PV and higher WI. Therefore, impure dolomite (lower elemental Mg content) is a potentially acceptable aggregate for bituminous surface pavements.

As shown in Figures 5-29 and 5-30, for limestone samples, elemental Mg contents do not correlate with either PV (R=0.205, R^2=0.04 and P=0.373) or WI (R=-0.109, R^2=0.01 and P=0.639).

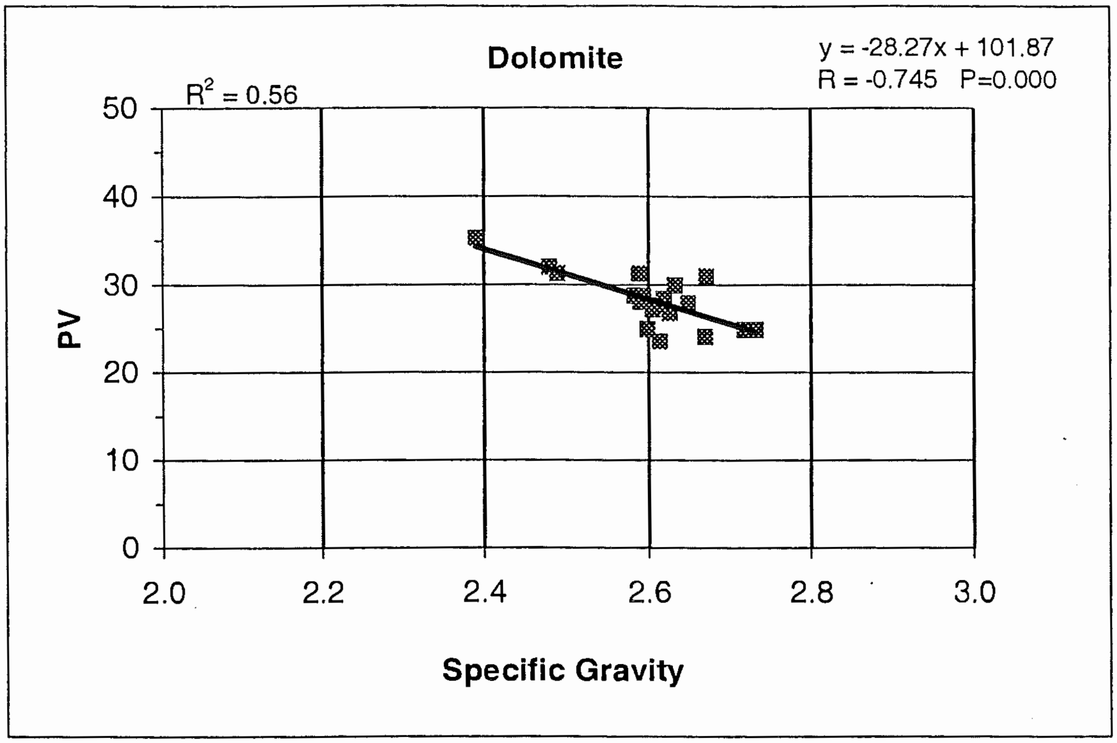


Figure 5-11. Correlation of Polished Value and Specific Gravity in dolomite samples

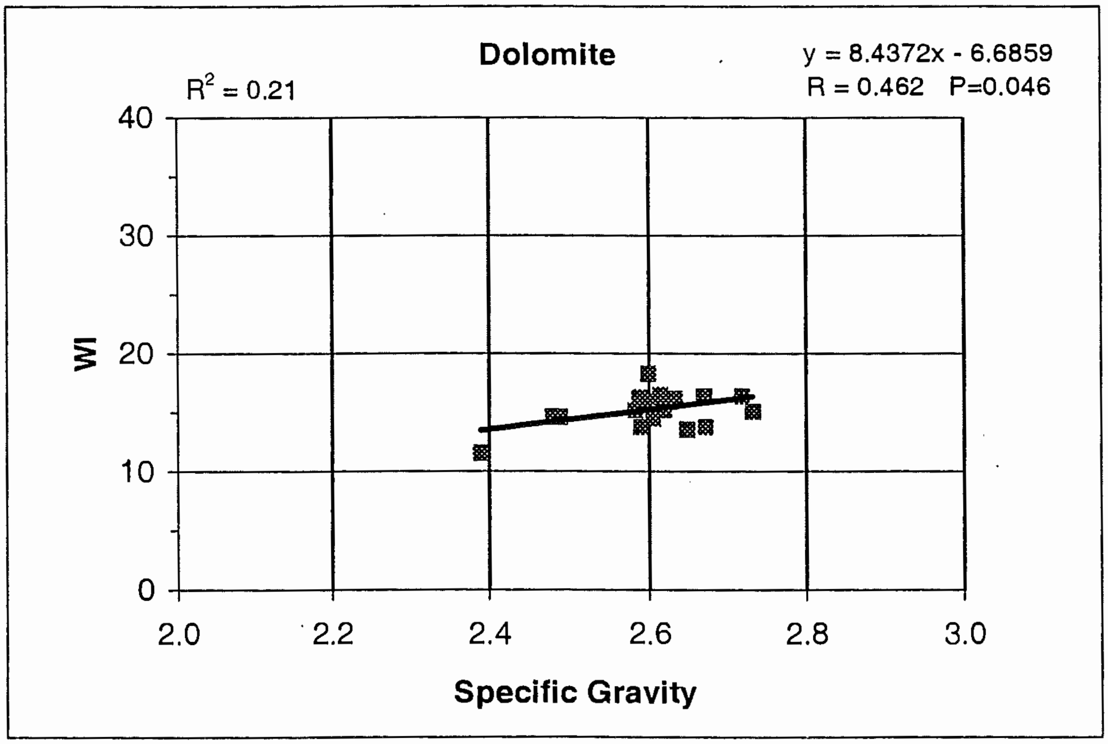


Figure 5-12. Correlation of Wear Index and Specific Gravity in dolomite samples

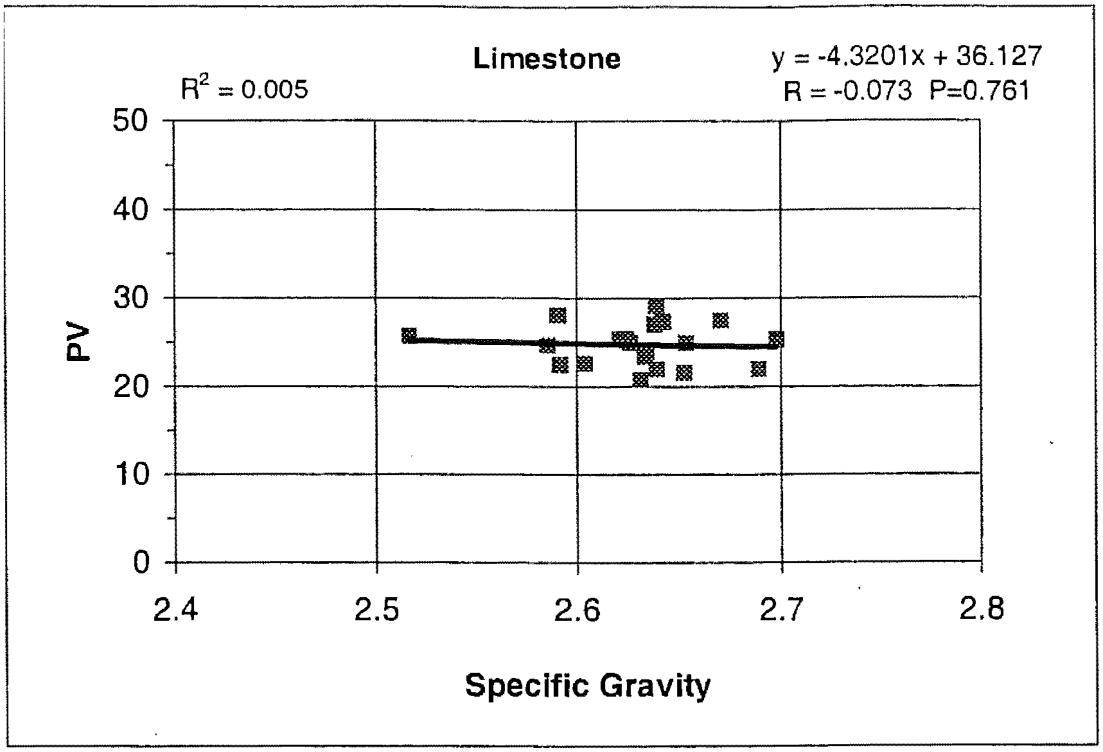


Figure 5-13. Correlation of Polished Value and Specific Gravity in limestone samples

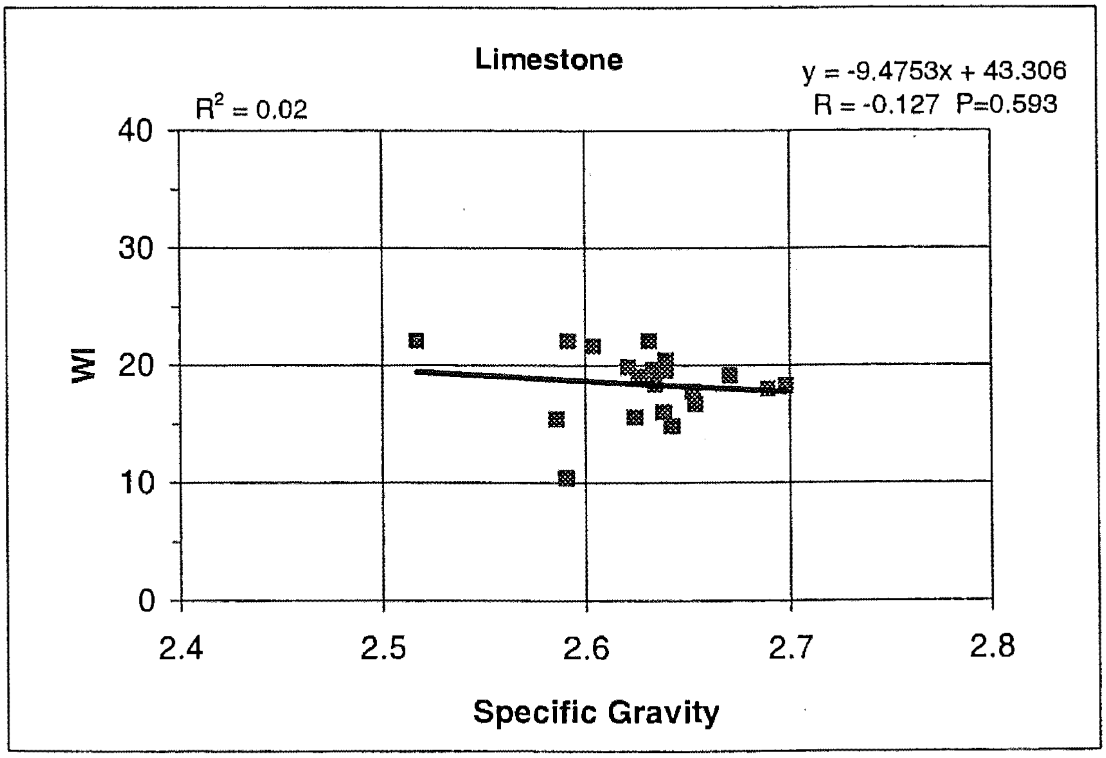


Figure 5-14. Correlation of Wear Index and Specific Gravity in limestone samples

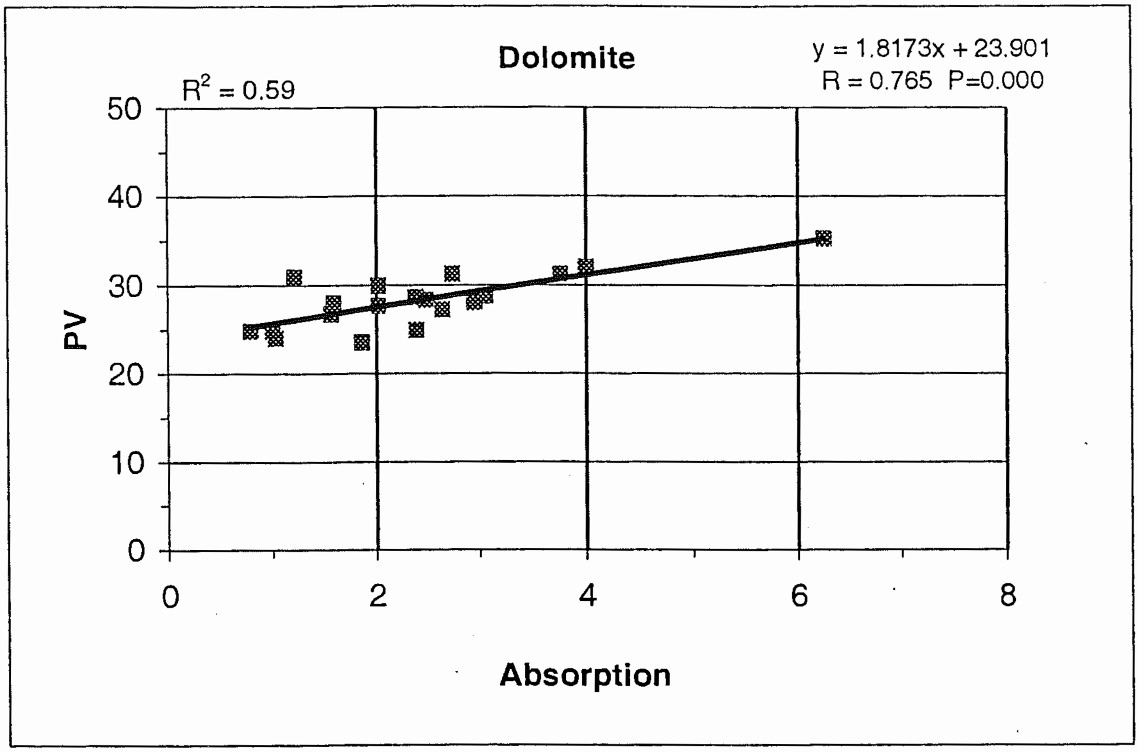


Figure 5-15. Correlation of Polished Value and Absorption in dolomite samples

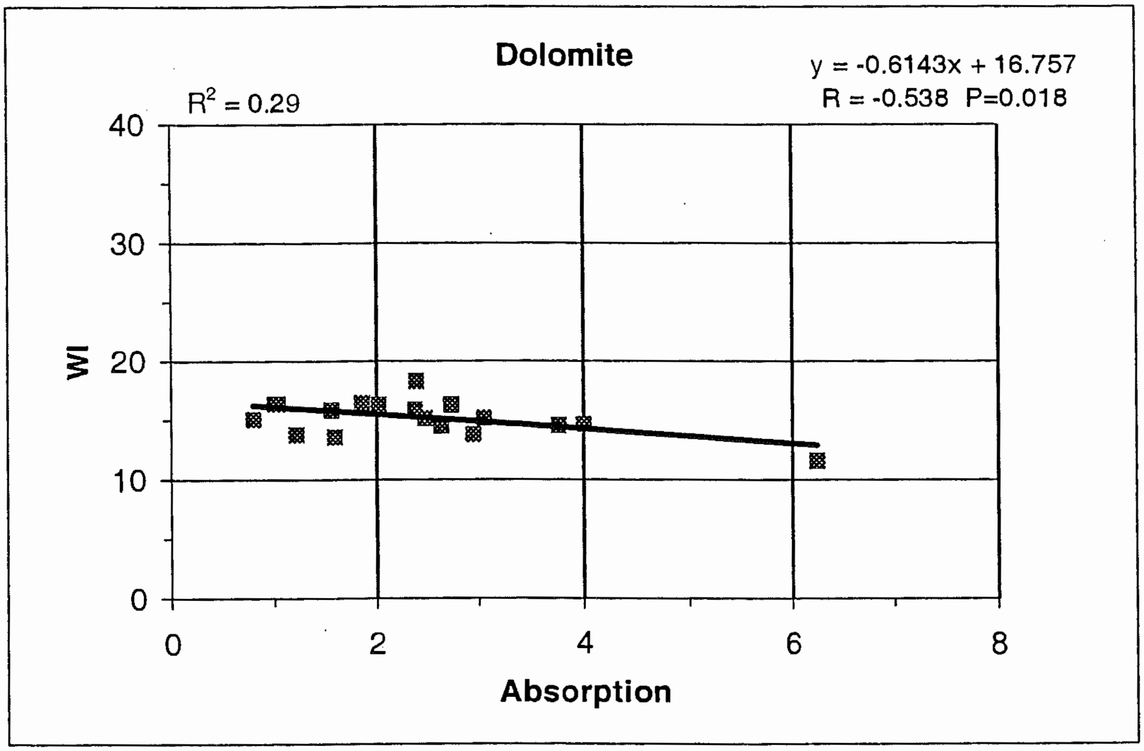


Figure 5-16. Correlation of Wear Index and Absorption in dolomite samples

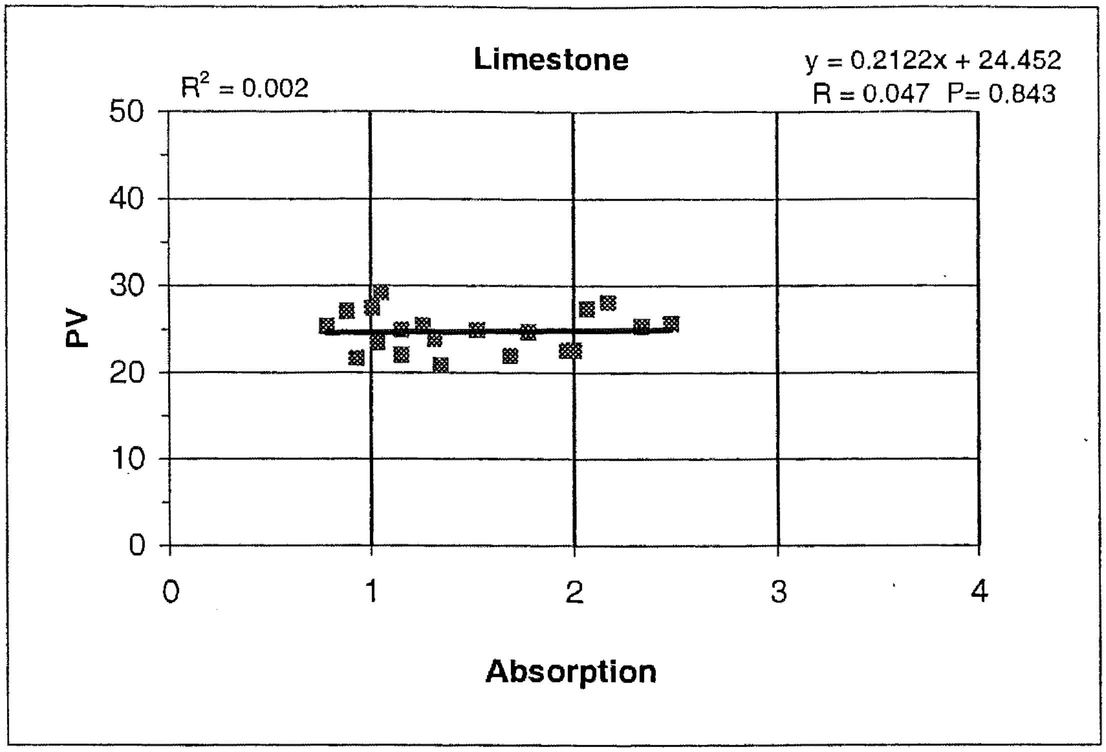


Figure 5-17. Correlation of Polished Value and Absorption in limestone samples

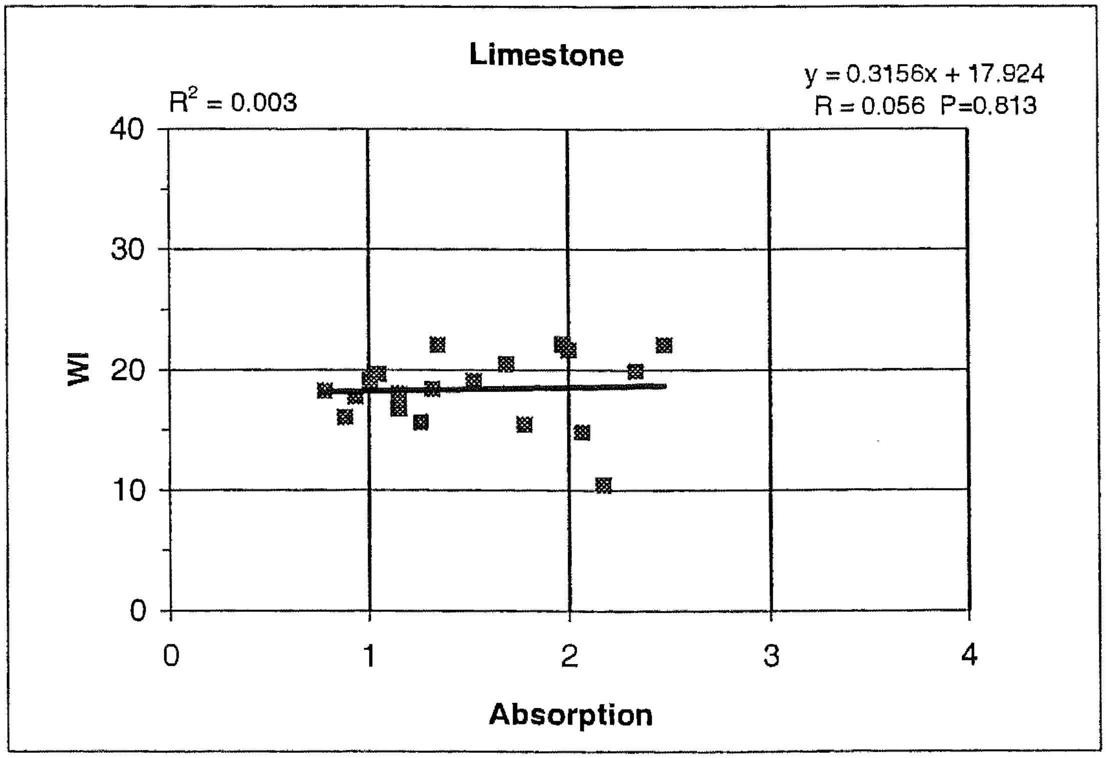


Figure 5-18. Correlation of Wear Index and Absorption in limestone samples

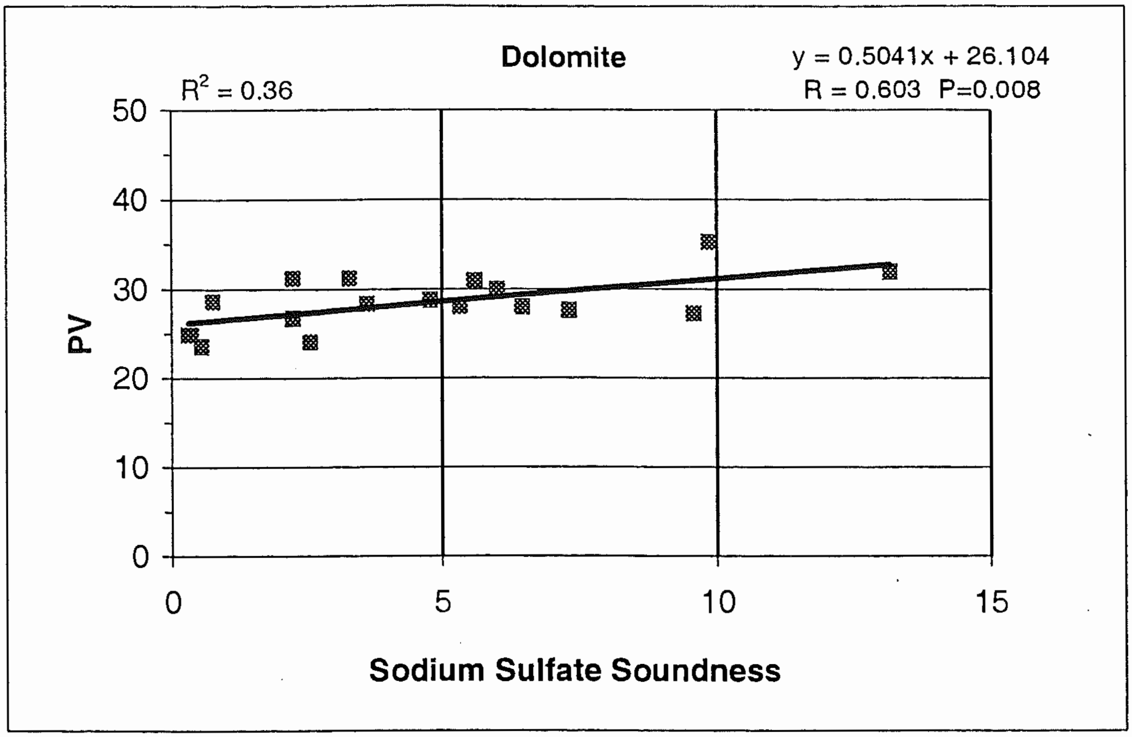


Figure 5-19. Correlation of Polished Value and Sodium sulfate soundness in dolomite samples

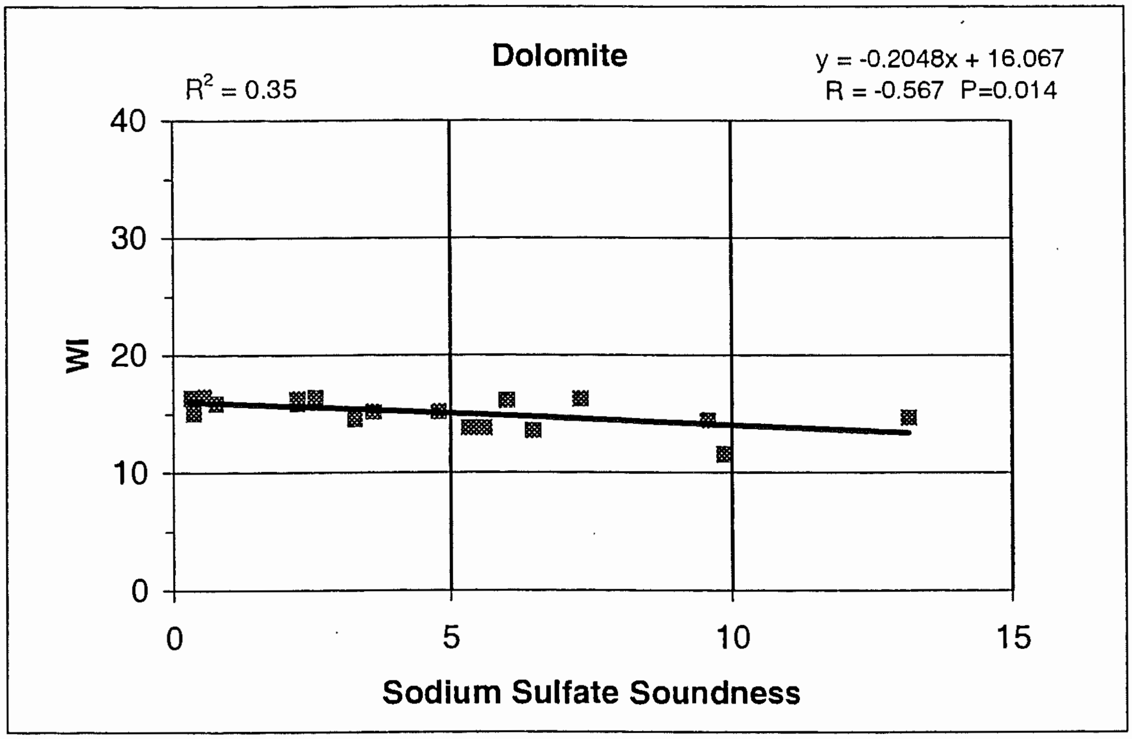


Figure 5-20. Correlation of Wear Index and Sodium sulfate soundness in dolomite samples

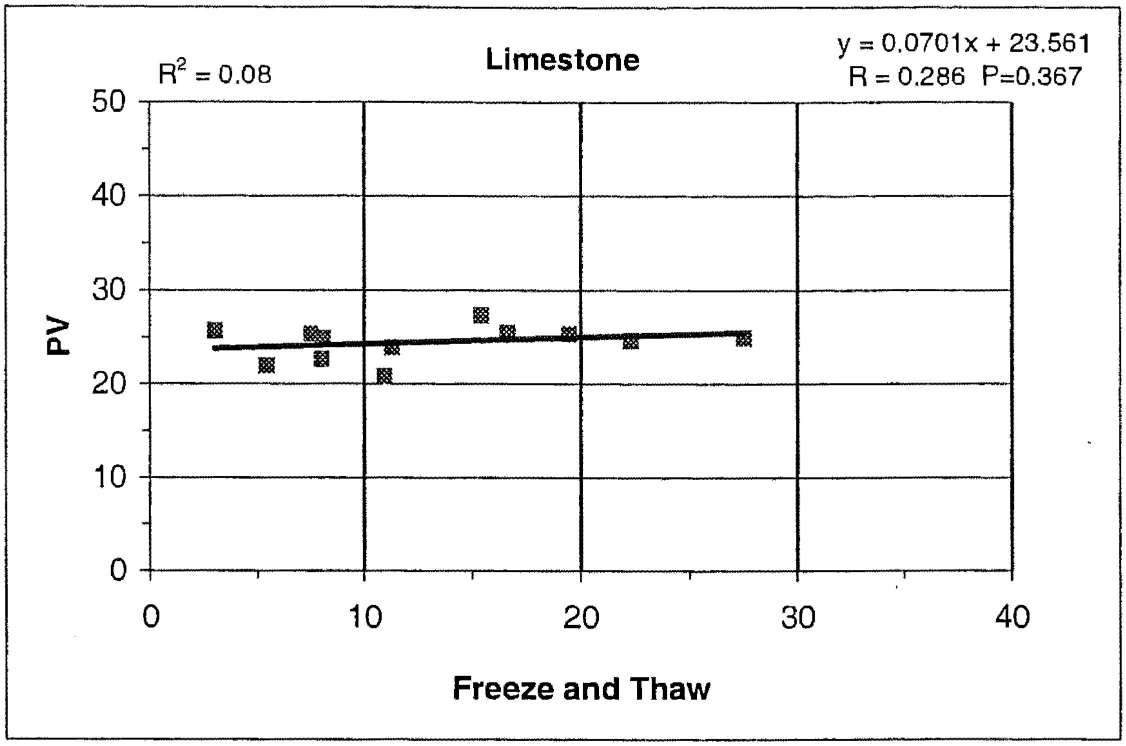


Figure 5-21. Correlation of Polished Value and Sodium sulfate soundness in limestone samples

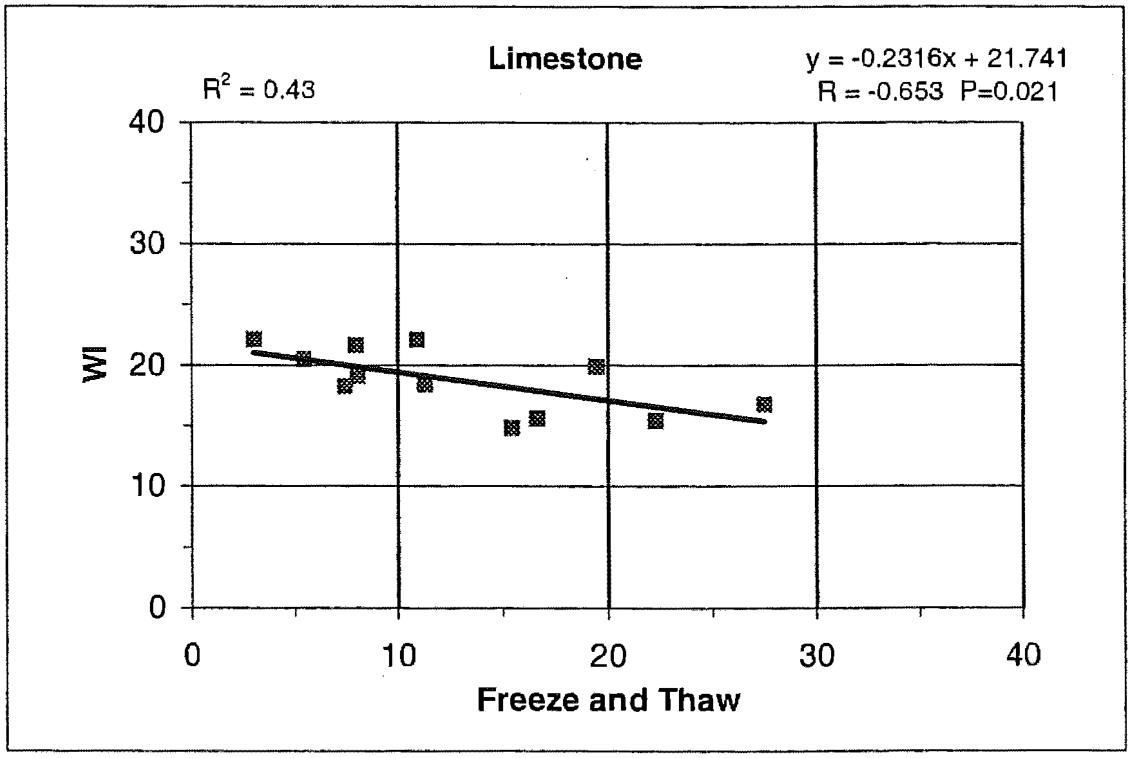


Figure 5-22. Correlation of Wear Index and Sodium sulfate soundness in limestone samples

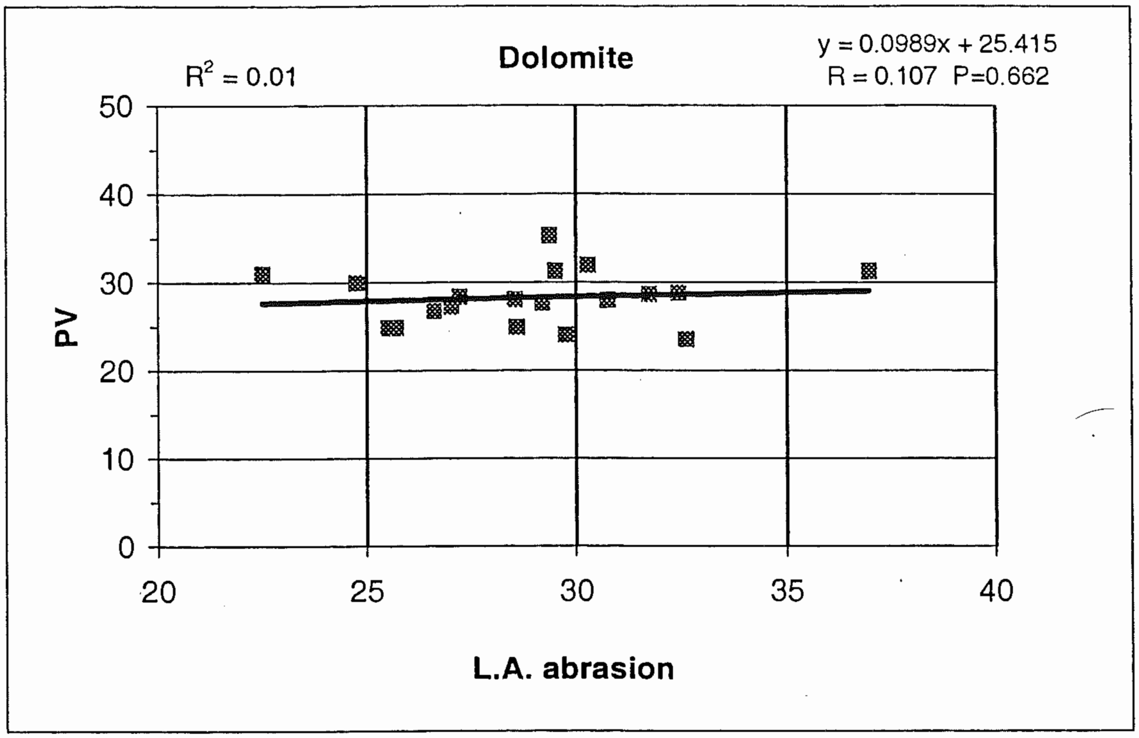


Figure 5-23. Correlation of Polished Value and L.A. Abrasion in dolomite samples

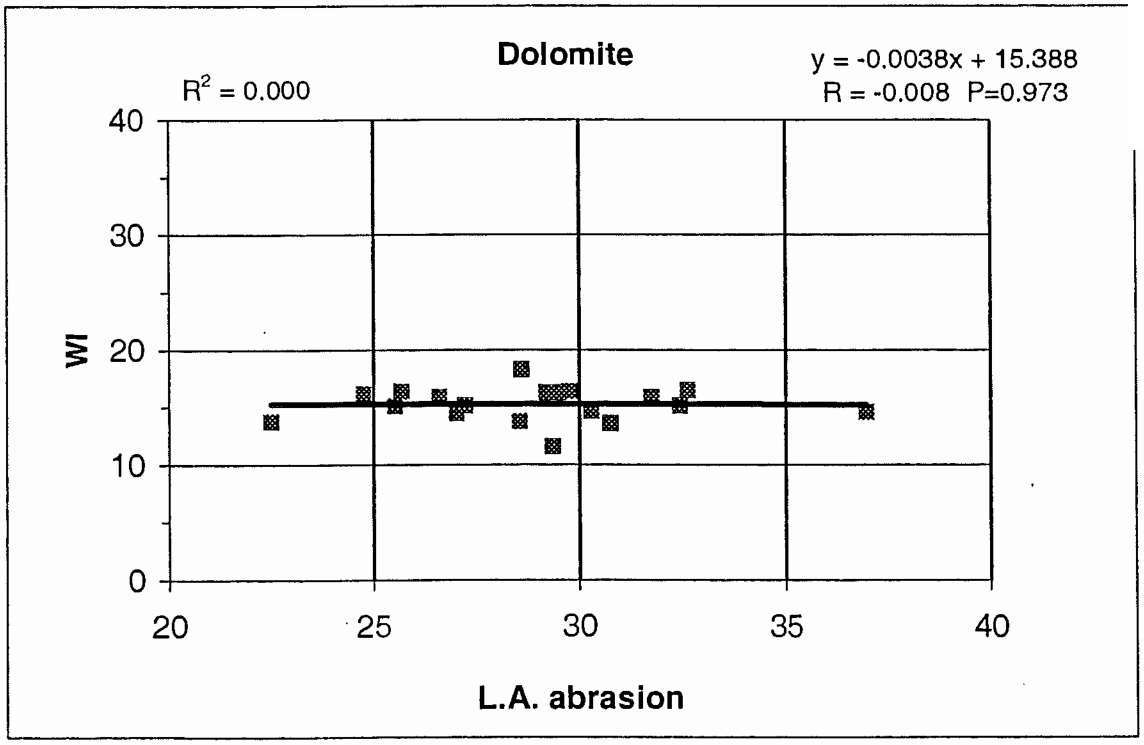


Figure 5-24. Correlation of Wear Index and L.A. Abrasion in dolomite samples

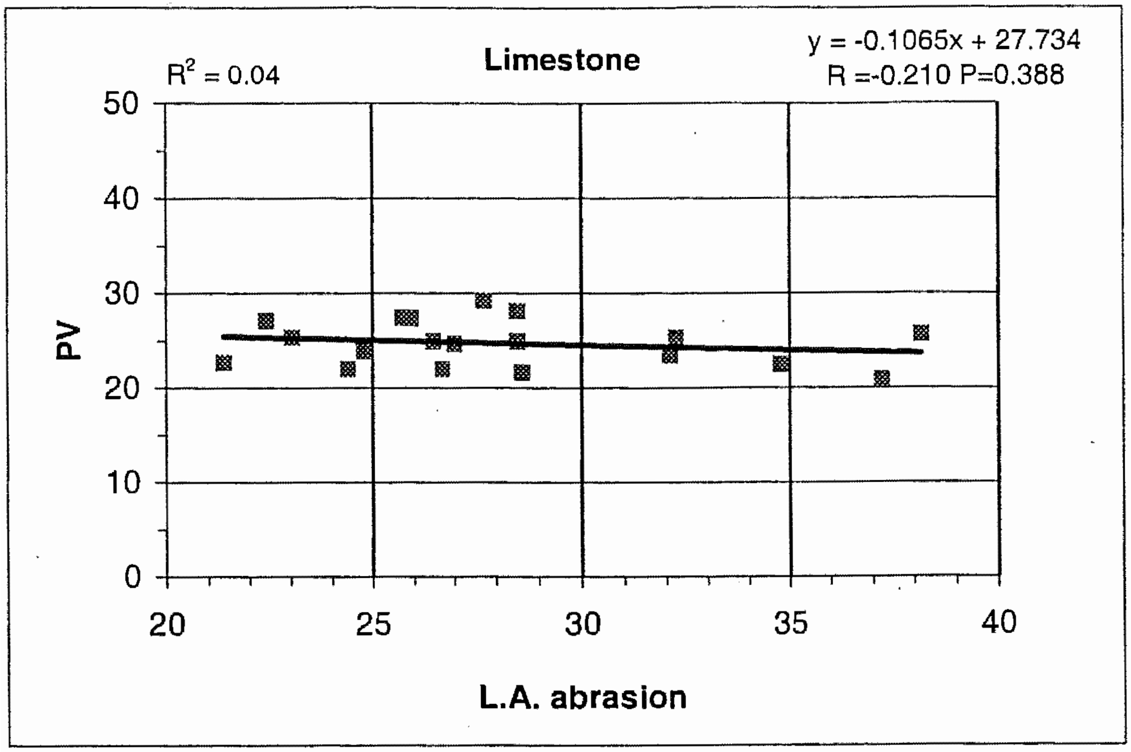


Figure 5-25. Correlation of Polished Value and L.A. Abrasion in limestone samples

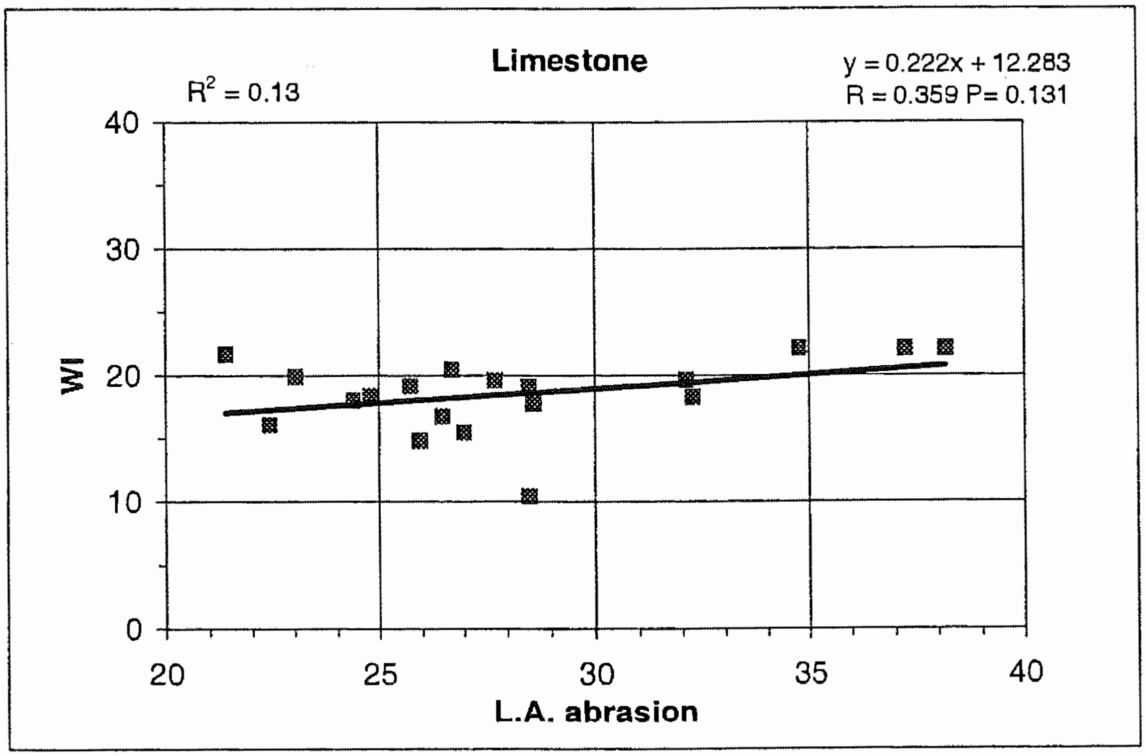


Figure 5-26. Correlation of Wear Index and L.A. Abrasion in limestone samples

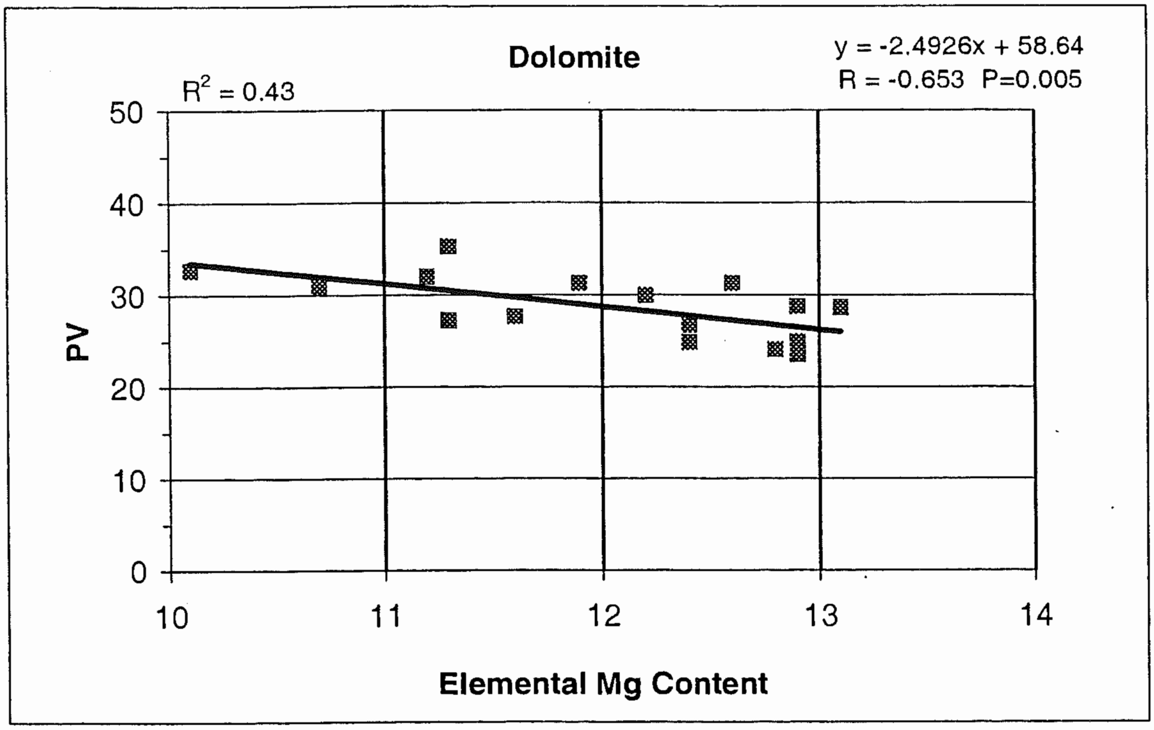


Figure 5-27. Correlation of Polished Value and Mg content in dolomite samples

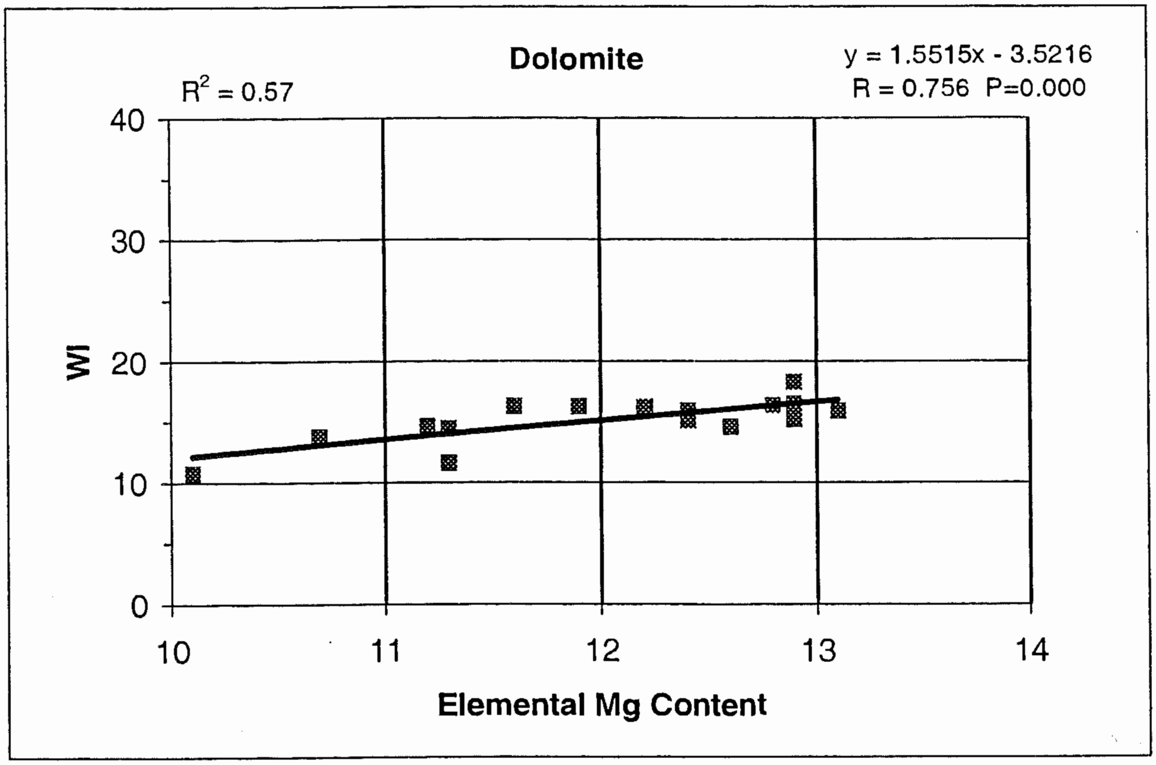


Figure 5-28. Correlation of Wear Index and Mg content in dolomite samples

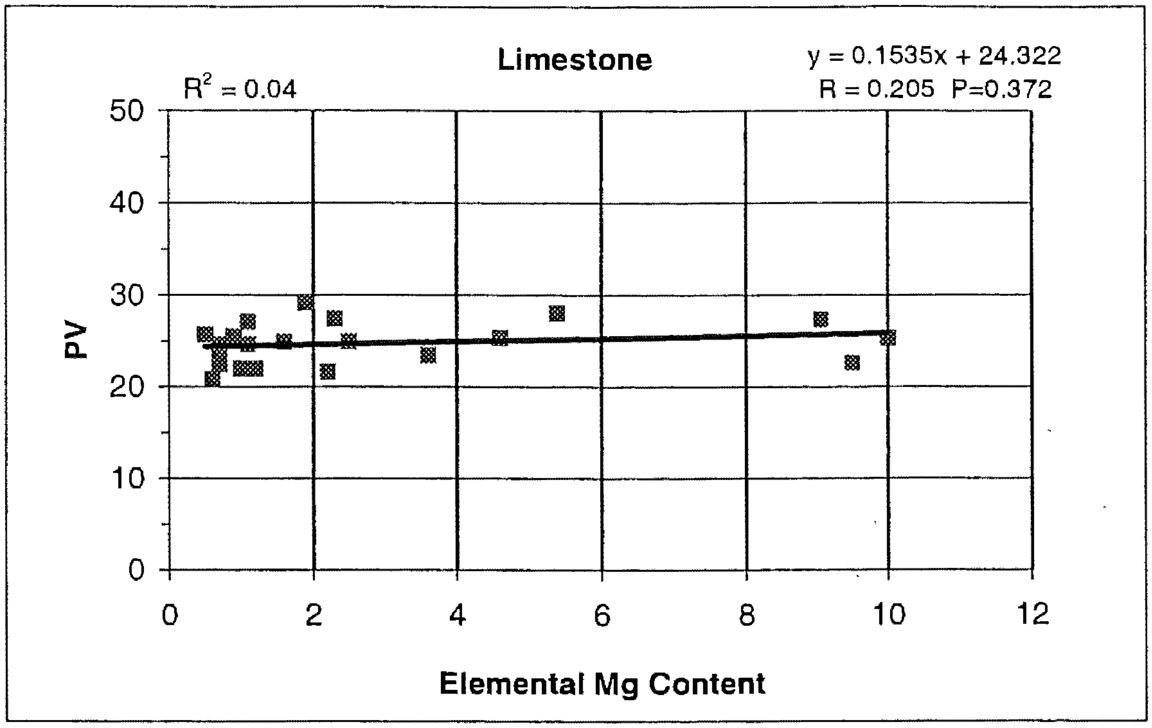


Figure 5-29. Correlation of Polished Value and Mg content in limestone samples

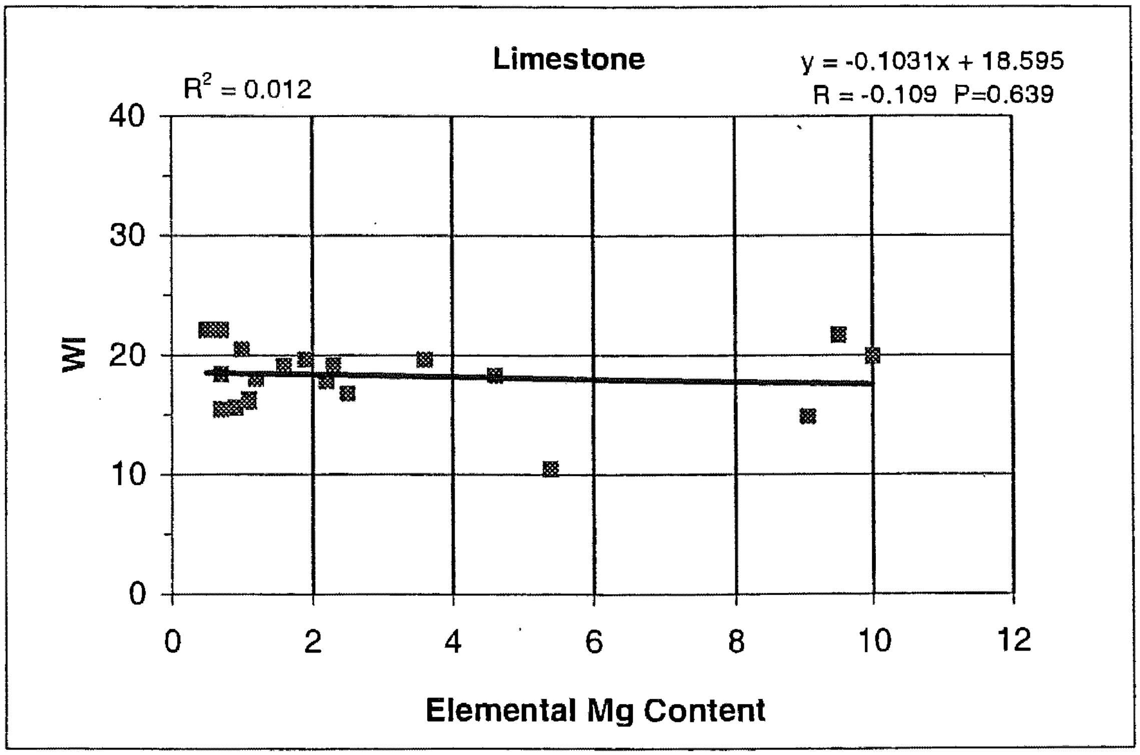


Figure 5-30. Correlation of Wear Index and Mg content in limestone samples

5.2.4 Acid Insoluble Residue and Frictional Properties of Carbonate Aggregates

The data evaluated on the acid-insoluble residue test were divided into three groups. These consisted of 1) total acid-insoluble residue, 2) percent residue greater than #200 sieve (75 microns) and 3) percent residue smaller than #200 sieve (75 microns).

Based on the results of the comparison between PV and WI and acid-insoluble residues, both PV and WI correlate well with total acid-insoluble residue. The PV and WI are least correlated with the percent material greater than #200. This indicates the percent amounts of smaller than #200 has a positive effect on frictional resistance.

As shown in Figures 5-31 and 5-32, total acid-insoluble residue in the dolomite samples correlate poorly with PV (R=0.448, R^2=0.20 and P=0.048) and WI (R=-0.255, R^2=0.07 and P=0.277). However, as shown in Figures 5-33 and 5-34, total acid-insoluble residue for limestone samples correlates strongly with PV (0.703, R^2=0.49 and P=0.000) and WI (R=-0.639, R^2=0.41 and P=0.002). For both dolomite and limestone, as the acid-insoluble residue increases, the polished value (PV) increases and polishing susceptibility (WI) decreases.

The total acid-insoluble residue may be the most critical factor for the evaluation of limestone as a source for bituminous pavement surfaces than it is in the evaluation of dolomite because of the higher correlation of limestone PV with total acid-insoluble residue.

As shown in Figures 5-35 through 5-38, regarding percent insoluble materials greater than #200 in dolomite samples, acid-insoluble residues do not correlate well with PV or WI. But the limestone shows a slight correlation between PV and WI and percent insoluble materials greater than #200.

As shown in Figures 5-39 through 5-42, in the case of percent insoluble materials smaller than #200 in dolomite, the acid-insoluble residue shows a moderate correlation with PV (R=0.560, R^2=0.26 and P=0.010) and WI (R=-0.286, R^2=0.08 and P=0.222). The acid-insoluble residue of limestones is well correlated with PV (R=0.616, R^2=0.38 and P=0.003) and WI (R=-0.623, R^2=0.39 and P=0.003).

As shown in Figures 5-43 through 5-46, the ratio of percent insoluble residue greater than #200 to percent insoluble residue smaller than #200 does not correlate well with PV or WI.

From the above results for both dolomite and limestone, it is important to note that as the acid-insoluble residues increase, the polished values increase and polishing susceptibility decreases. Particularly for the total acid-insoluble residue, there is a strong correlation for limestone aggregates.

5.2.5 Field and Laboratory Testing

The frictional resistance of aggregates can be evaluated using field tests. In this method the level of friction is measured on traveled sections of selected highways using the towed friction trailer (ASTM Standard E274). Recorded friction values for a given road surface are known as Average Friction Numbers (AFN). Typically both the Average Friction Numbers from the smooth and from ribbed tires are reported (Friction Number Smooth (FNS) and Friction Number Ribbed (FNR)).

An AFN of 20 for the FNS and of 30 for FNR are values of concern used by INDOT to indicate the need for follow-up evaluations to determine if corrective action or the pavement may be required.

After the field test was performed with towed trailers on the highway, 8-in cores were obtained and brought to INDOT lab. Then the aggregate was extracted from the cores. Fresh pieces of +9.5mm size were used to construct coupons. Coupons were measured using the British Pendulum before and after polishing by the British Wheel test

Following extraction of aggregates from core samples, coupons were prepared and tested in the same way as that used for quarried aggregates. This allowed for a direct comparison between laboratory friction values and those obtained in the field.

Correlation analysis between BPN and AFN was performed on the carbonate aggregates. As shown in Figures 5-47 and 5-48, the FNR and FNS are more highly correlated with IFV than with PV. Using these correlations, the FNR=30 corresponds to PV=24.7 and IFV=36.9. The FNS=20 corresponds to PV=19.2 and IFV=30.5. In all, a PV of 25 may be considered as a minimum, acceptable friction value. The PV=25 corresponds to FNS=27.7 and FNR=30.7. However, these correlations were performed using only 6 data points, but showed a high significance level (P=0.067-0.106) for PV.

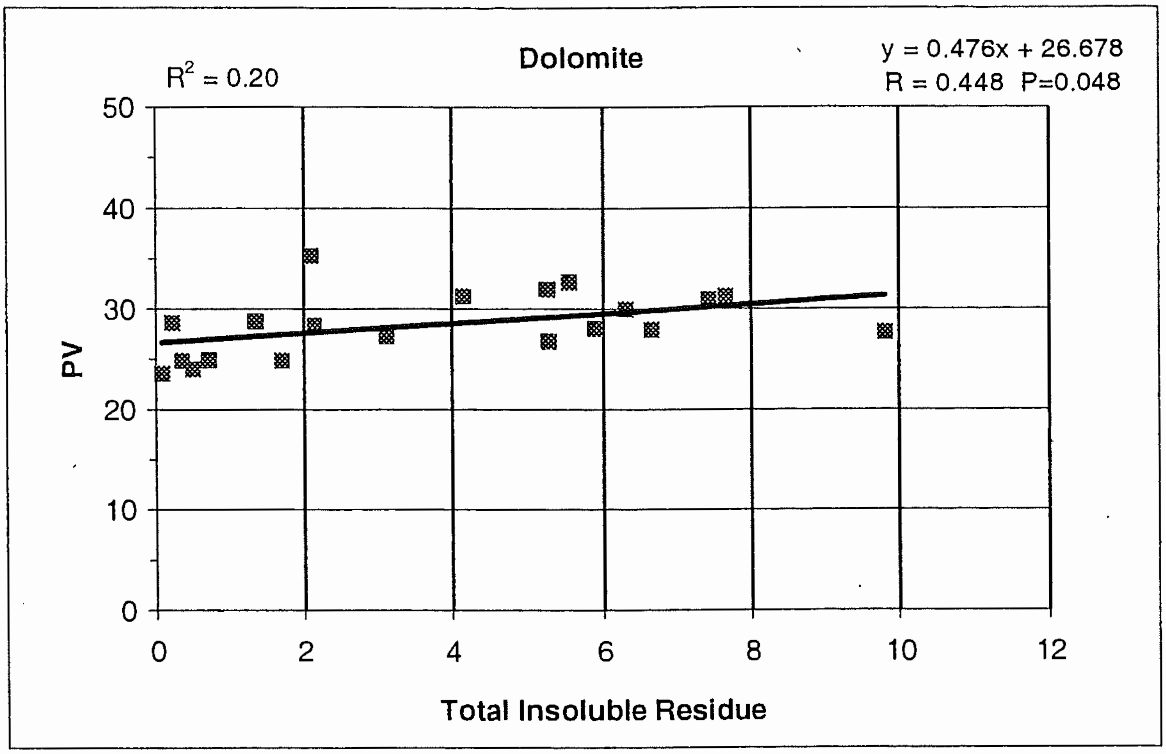


Figure 5-31. Correlation of Polished Value and Total insoluble residue in dolomite samples

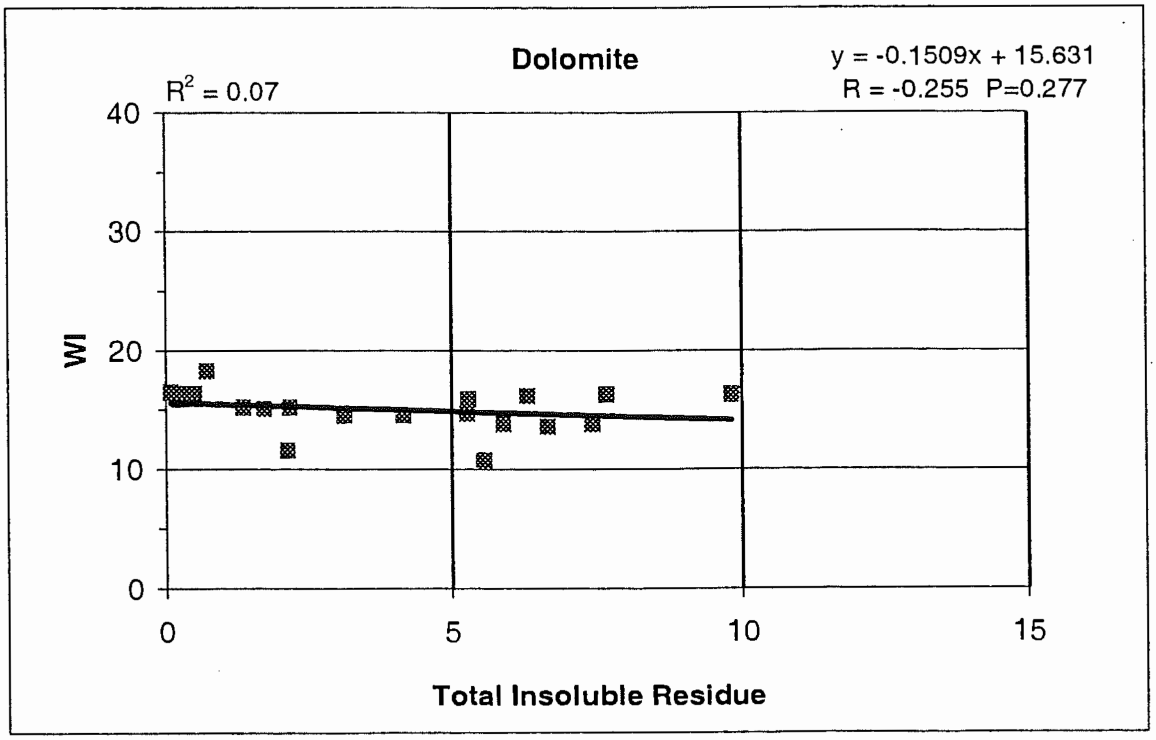


Figure 5-32. Correlation ofWear Index and Total insoluble residue in dolomite samples

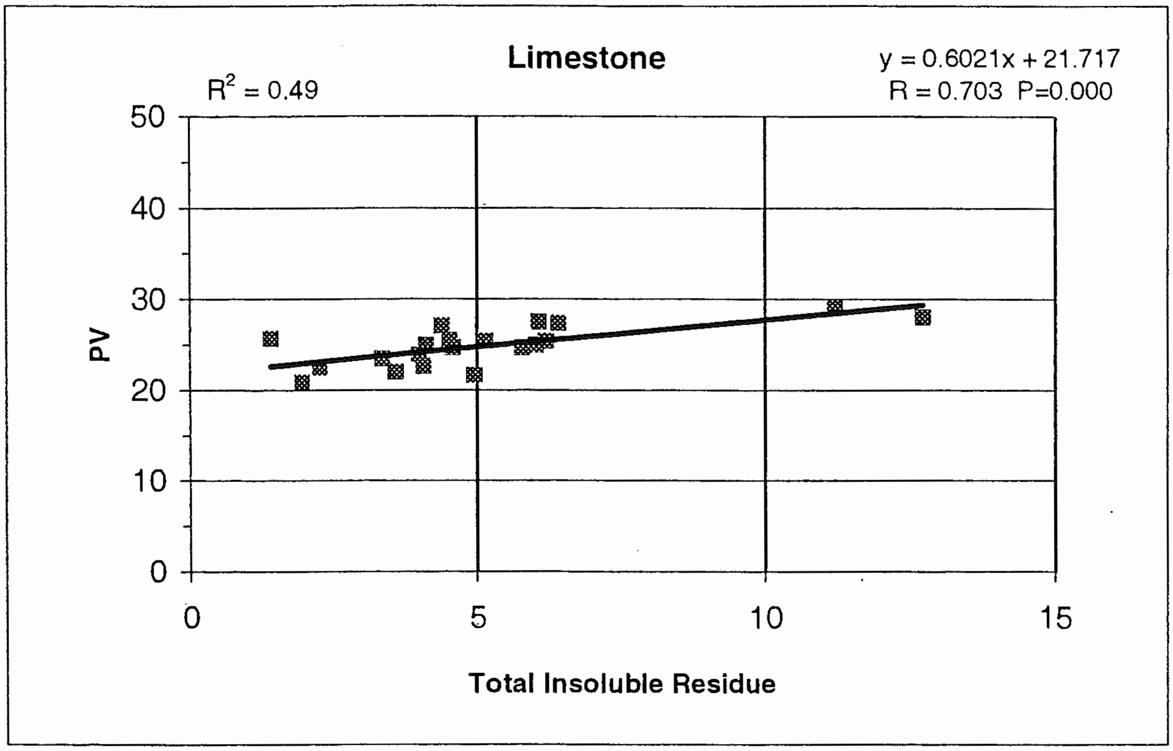


Figure 5-33. Correlation of Polished Value and Total insoluble residue in limestone samples

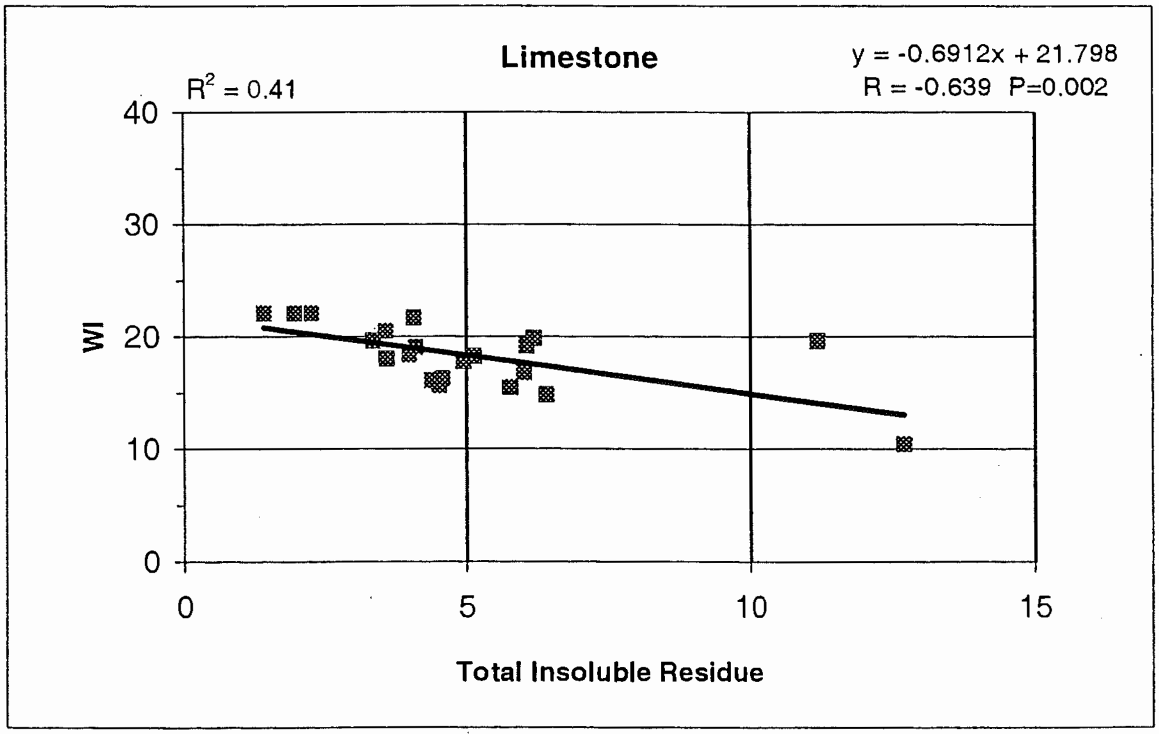


Figure 5-34. Correlation ofWear Index and Total insoluble residue in limestone samples

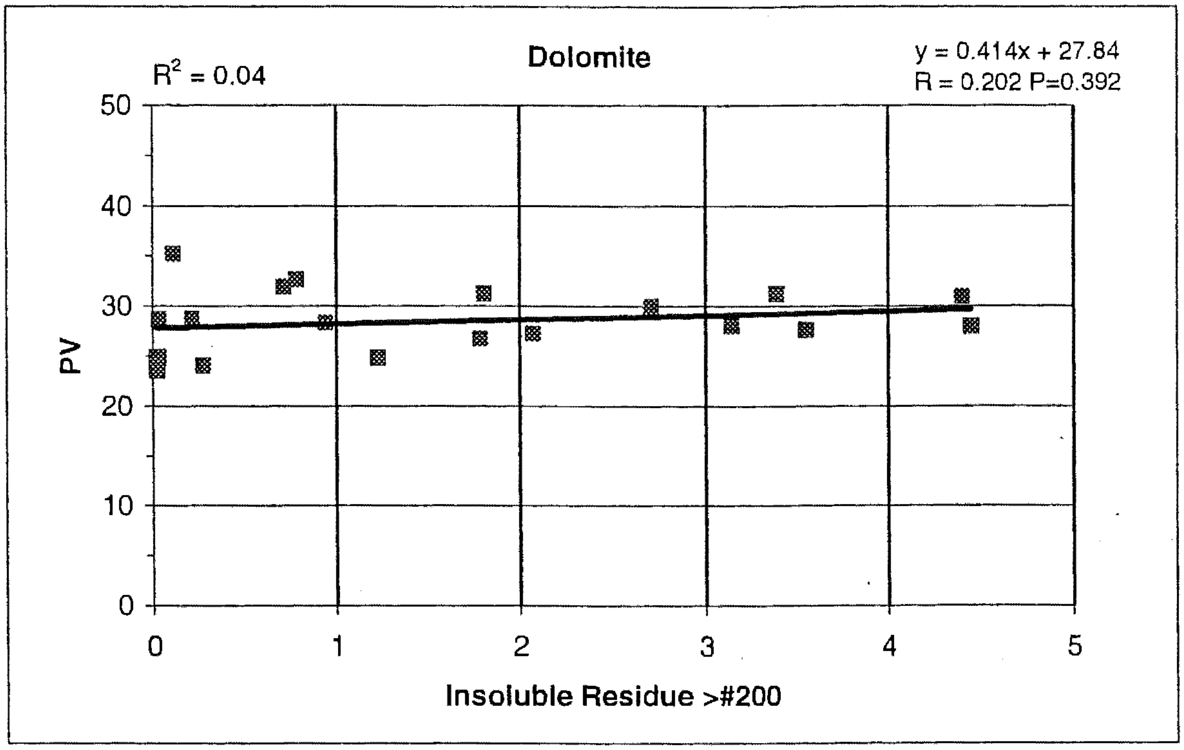


Figure 5-35. Correlation of Polished Value and insoluble residue >#200 in dolomite samples

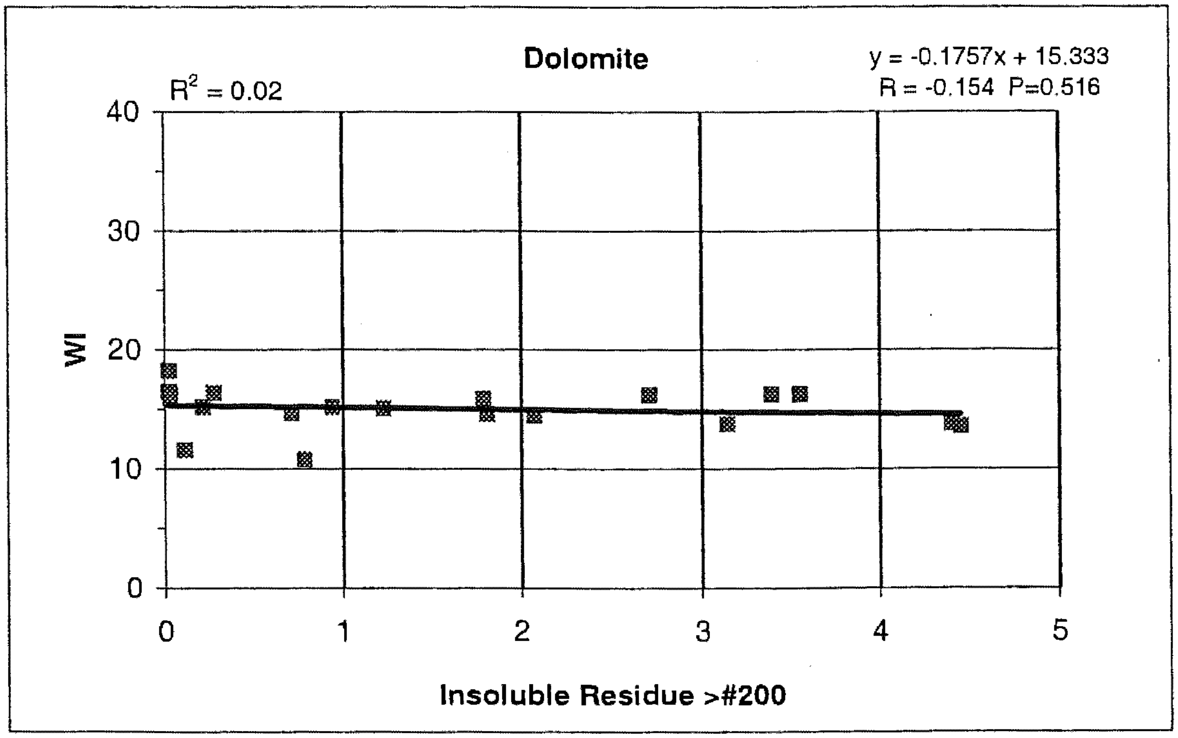
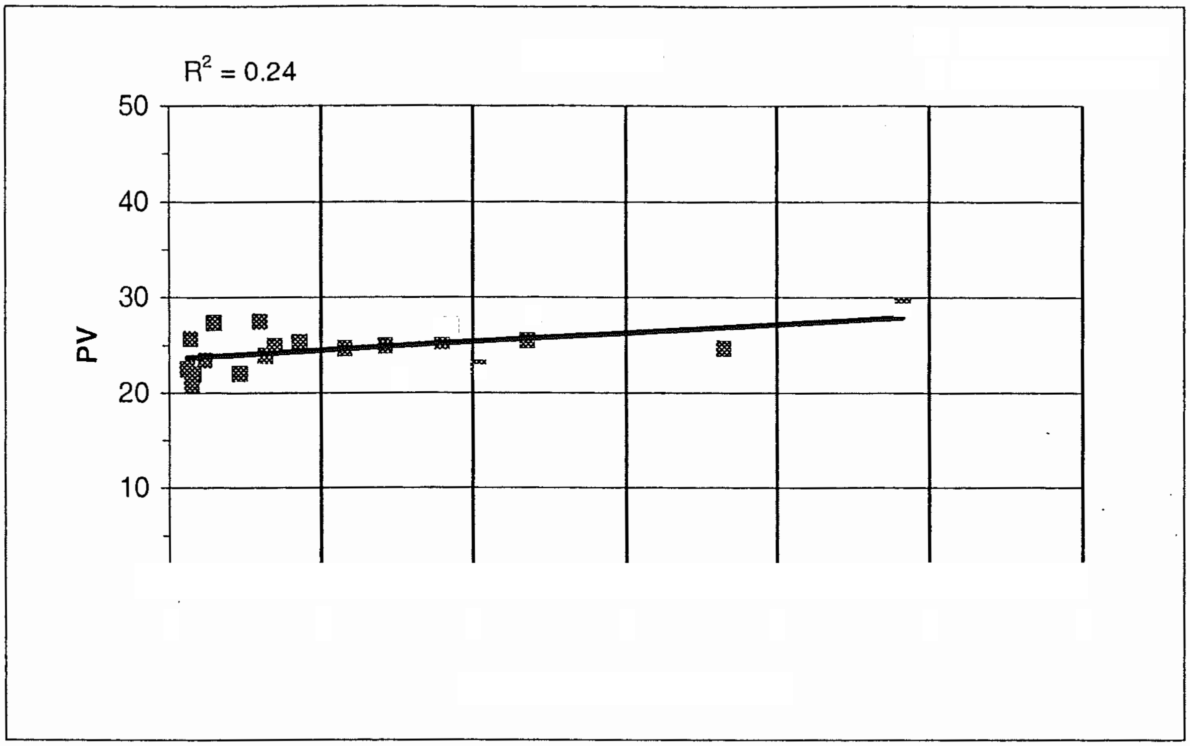
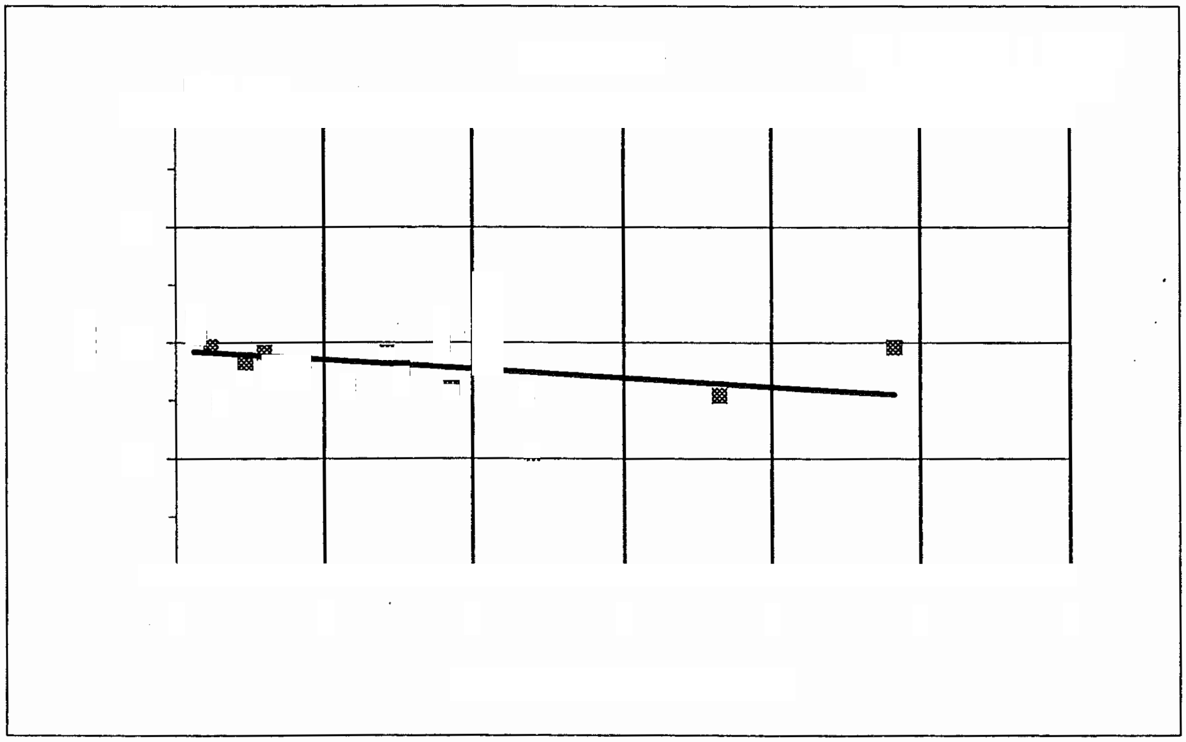


Figure 5-36. Correlation ofWear Index and insoluble residue >#200 in dolomite samples


R^2 = 0.24
50
40
30
20
10
PV



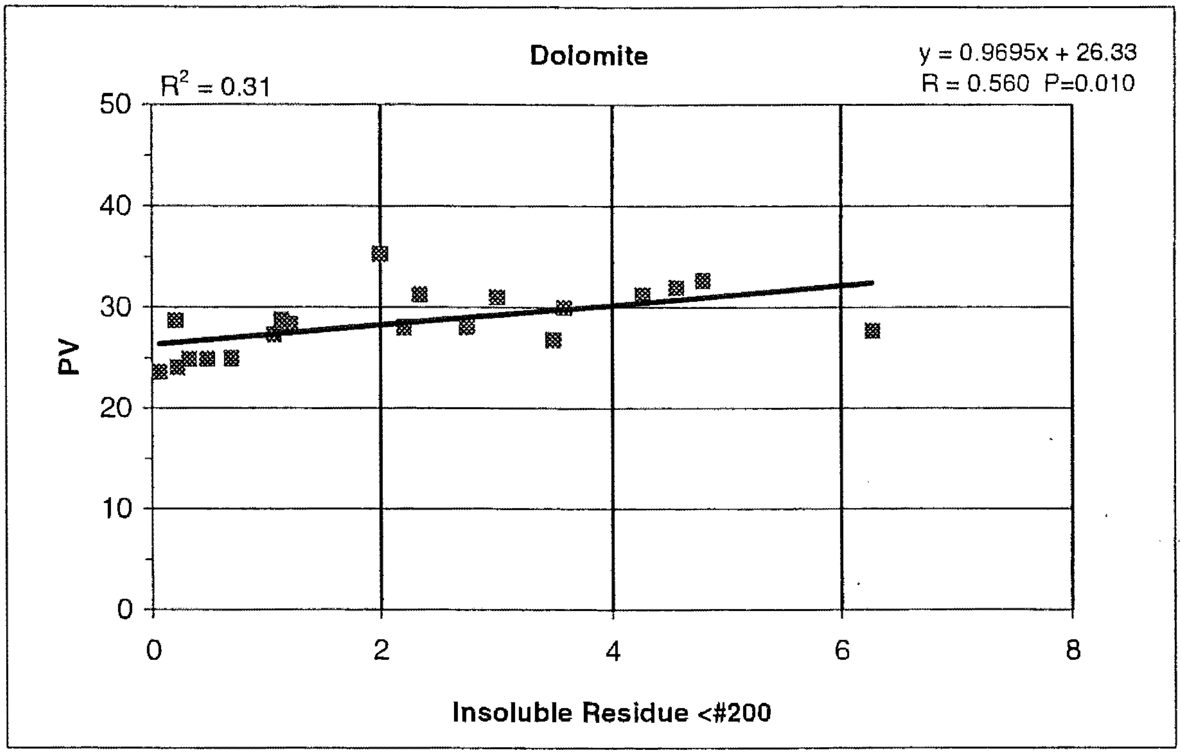


Figure 5-39. Correlation of Polished Value and insoluble residue <#200 in dolomite samples

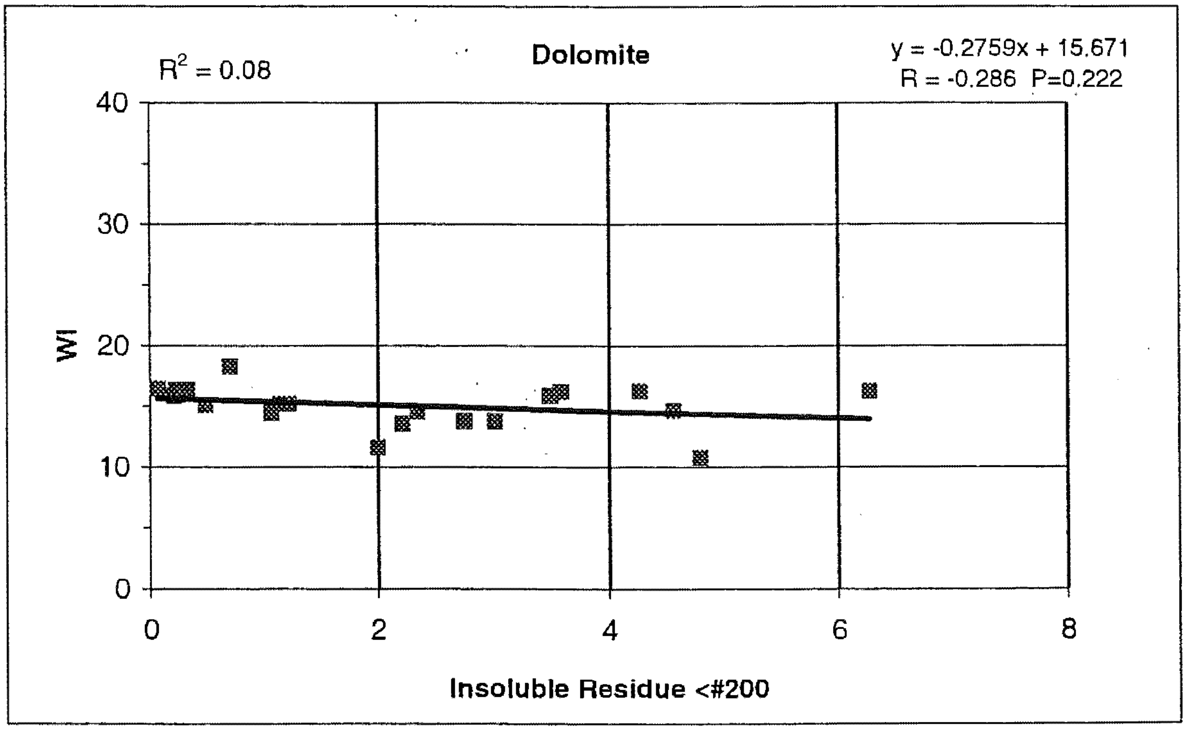


Figure 5-40. Correlation ofWear Index and Total insoluble residue in dolomite samples

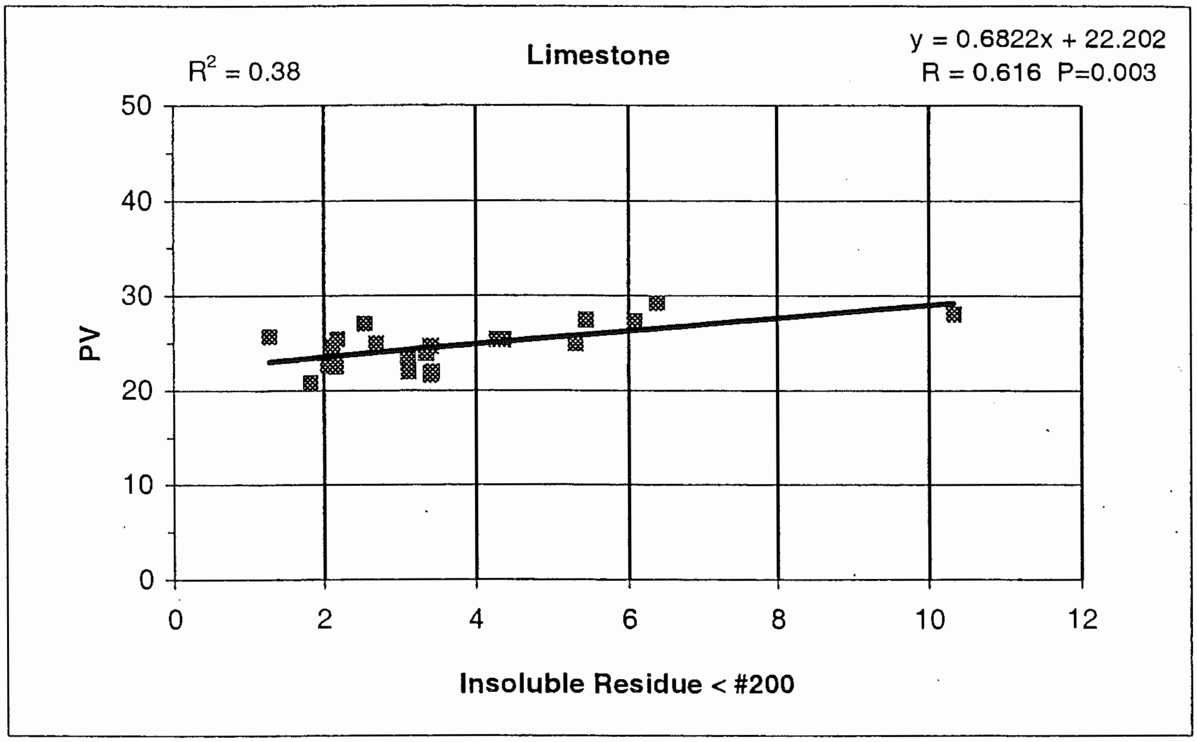


Figure 5-41. Correlation of Polished Value and insoluble residue <#200 in limestone samples

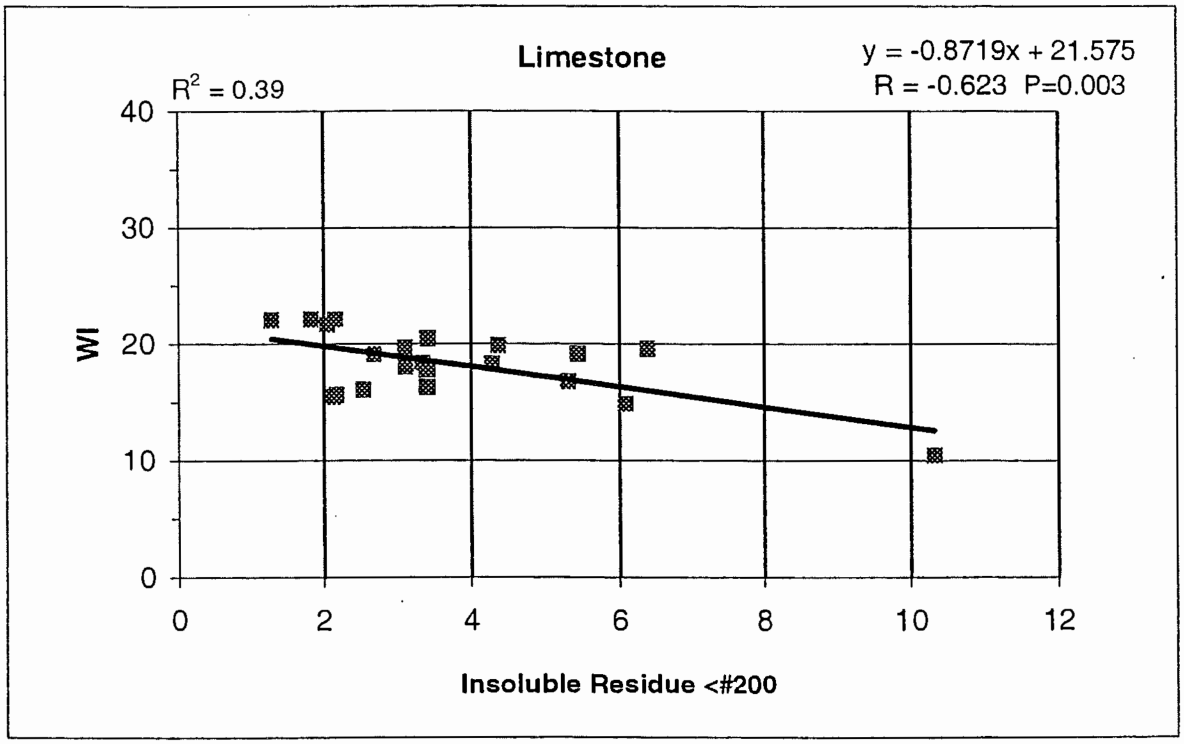


Figure 5-42. Correlation of Wear Index and insoluble residue <#200 in limestone samples

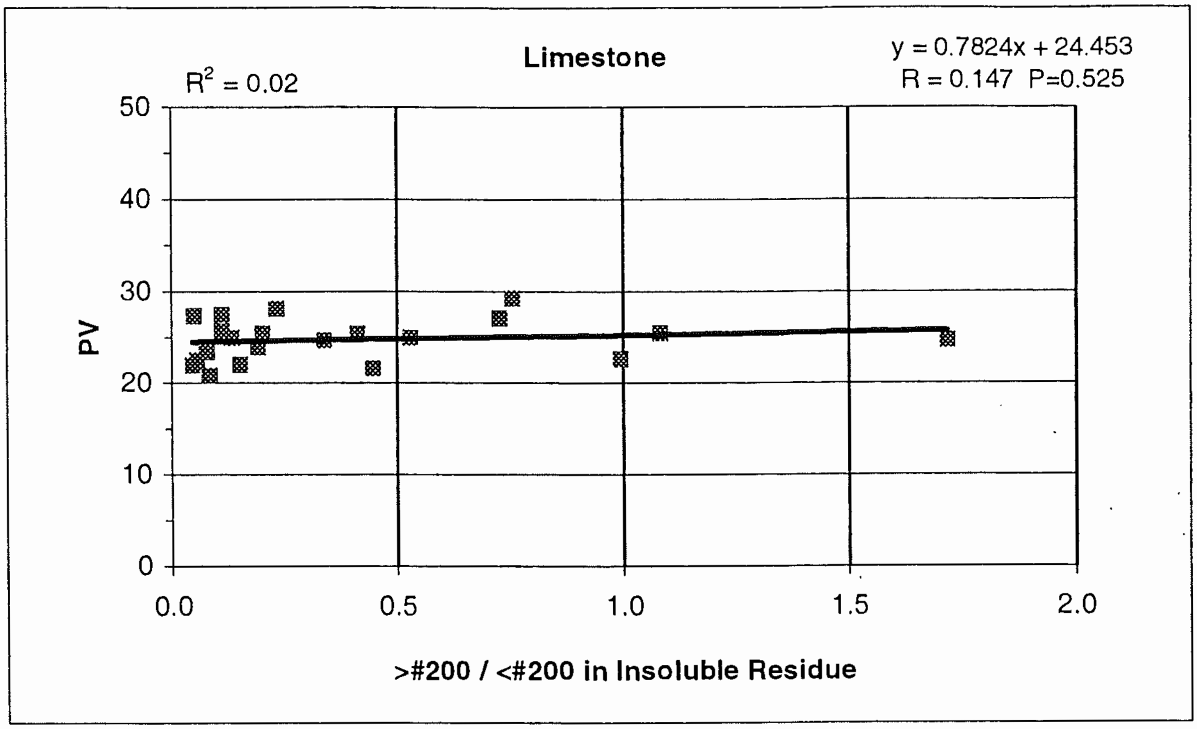


Figure 5-43. Correlation of Polished Value and the ratio of >#200 / <#200 in insoluble residue in limestone samples

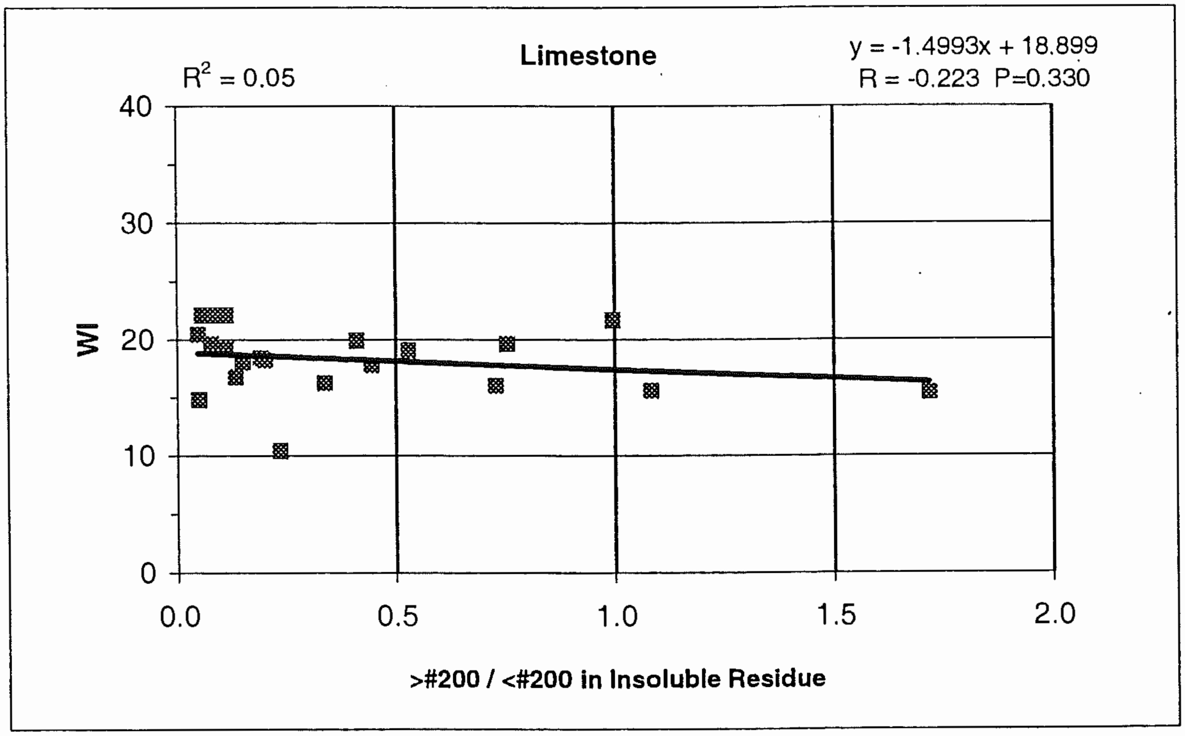


Figure 5-44. Correlation of Wear Index and the ratio of >#200 / <#200 in insoluble residue in limestone samples

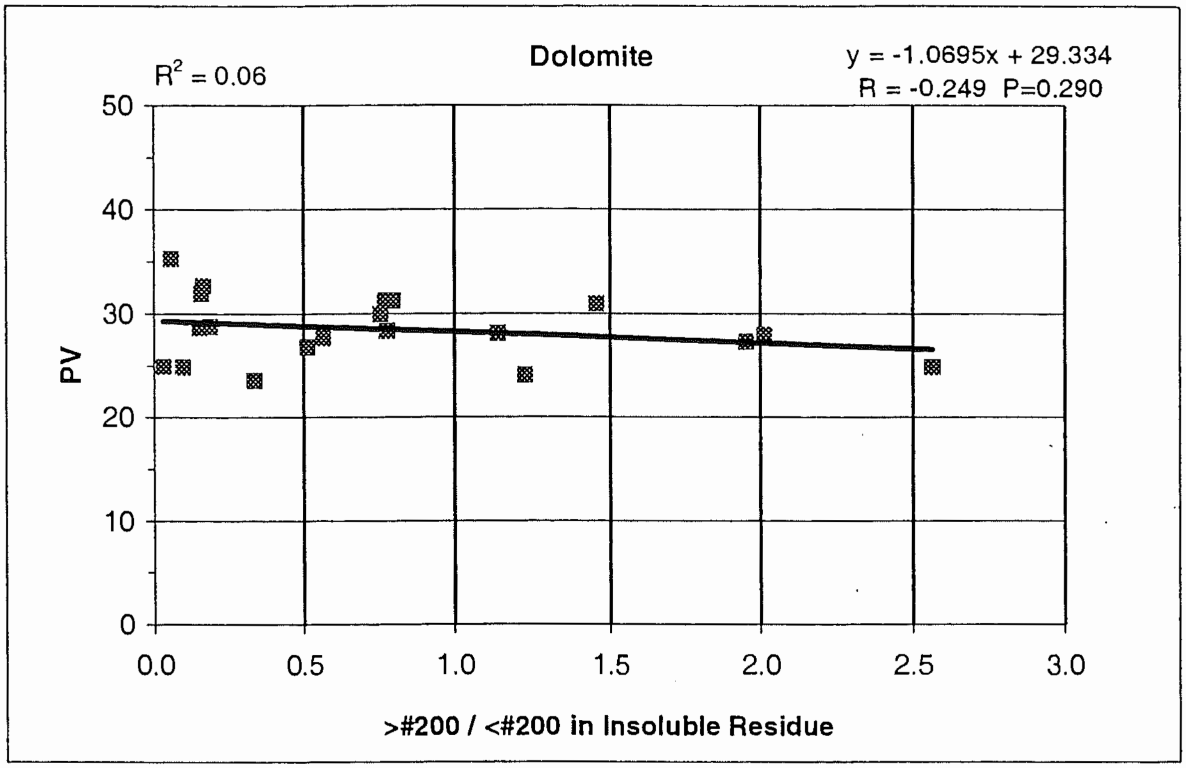


Figure 5-45. Correlation of Polished Value and the ratio of >#200 / <#200 in insoluble residue in dolomite samples

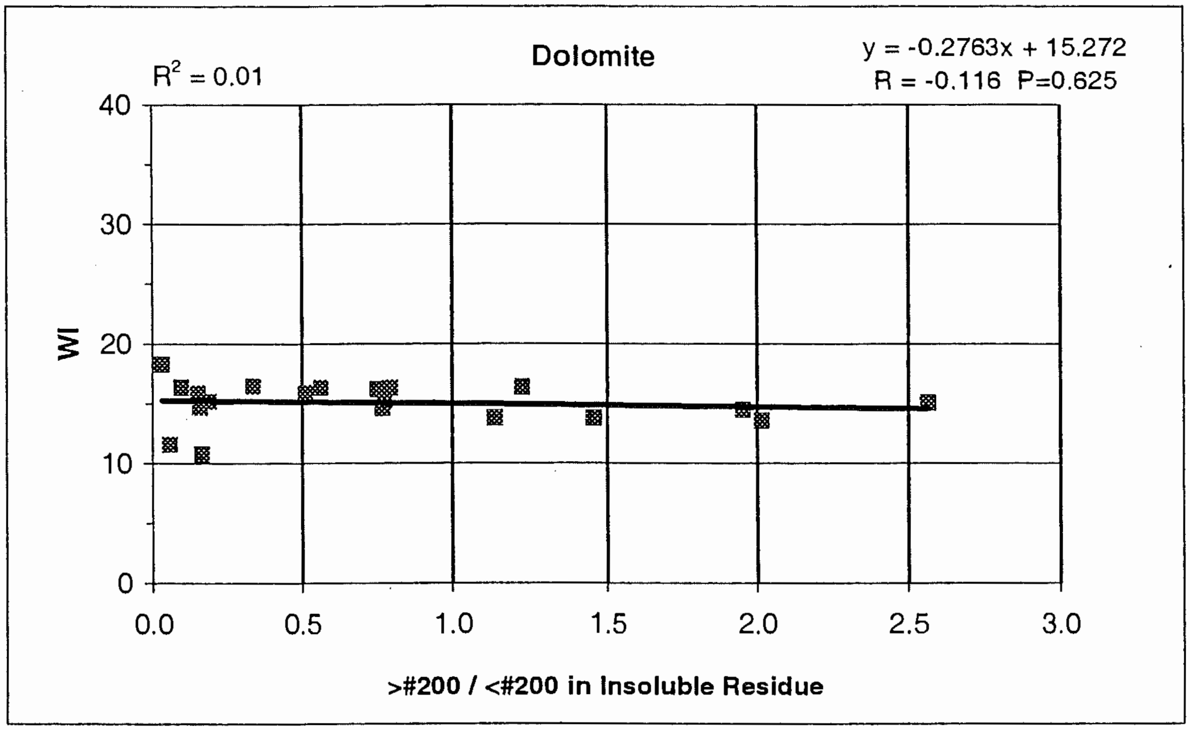


Figure 5-46. Correlation of Wear Index and the ratio of >#200 / <#200 in insoluble residue in dolomite samples

Table 5-9. Correlation matrix for carbonate aggregates

A. Limestone

	IFV	PV	WI	AB	SPG	LA	F-T	MG	T_ACID	P_200	M_200	RATIO
IFV	1	0.32288	0.6628	0.10318	-0.20263	0.20225	-0.58439	0.05871	-0.08972	0.05221	-0.14758	-0.11676
	0	0.1534	0.0011	0.6651	0.3916	0.4063	0.046	0.8004	0.699	0.8222	0.5232	0.6142
	21	21	21	20	20	19	12	21	21	21	21	21
PV	0.32288	1	-0.49469	0.0474	-0.0725	-0.21025	0.28632	0.20545	0.70343	0.48816	0.61593	0.1469
	0.1534	0	0.0226	0.8427	0.7613	0.3876	0.3669	0.3716	0.0004	0.0248	0.003	0.5252
	21	21	21	20	20	19	12	21	21	21	21	21
WI	0.6628	-0.49469	1	0.05648	-0.1274	0.35913	-0.6528	-0.10864	-0.63892	-0.33827	-0.62283	-0.22344
	0.0011	0.0226	0	0.813	0.5925	0.131	0.0214	0.6392	0.0018	0.1336	0.0026	0.3302
	21	21	21	20	20	19	12	21	21	21	21	21
AB	0.10318	0.0474	0.05648	1	-0.75713	0.10063	-0.13827	0.40689	0.00952	-0.05069	0.04289	0.00236
	0.6651	0.8427	0.813	0	0.0001	0.6819	0.6683	0.075	0.9682	0.8319	0.8575	0.9921
	20	20	20	20	20	19	12	20	20	20	20	20
SPG	-0.20263	-0.0725	-0.1274	-0.75713	1	-0.36788	0.19899	0.05525	0.11193	-0.11354	0.21331	-0.22235
	0.3916	0.7613	0.5925	0.0001	0	0.1212	0.5353	0.817	0.6385	0.6336	0.3665	0.3461
	20	20	20	20	20	19	12	20	20	20	20	20
LA	0.20225	-0.21025	0.35913	0.10063	-0.36788	1	-0.39756	-0.41644	-0.33871	-0.34775	-0.23565	-0.37292
	0.4063	0.3876	0.131	0.6819	0.1212	0	0.226	0.0761	0.156	0.1446	0.3314	0.1158
	19	19	19	19	19	19	11	19	19	19	19	19
F-T	-0.58439	0.28632	-0.6528	-0.13827	0.19899	-0.39756	1	0.12455	0.71913	0.44226	0.43973	0.32463
	0.046	0.3669	0.0214	0.6683	0.5353	0.226	0	0.6997	0.0084	0.15	0.1526	0.3032
	12	12	12	12	12	11	12	12	12	12	12	12
MG	0.05871	0.20545	-0.10864	0.40689	0.05525	-0.41644	0.12455	1	0.32261	0.0703	0.37509	-0.01538
	0.8004	0.3716	0.6392	0.075	0.817	0.0761	0.6997	0	0.1538	0.762	0.0938	0.9472
	21	21	21	20	20	19	12	21	21	21	21	21
T_ACID	-0.08972	0.70343	-0.63892	0.00952	0.11193	-0.33871	0.71913	0.32261	1	0.66525	0.89292	0.1802
	0.699	0.0004	0.0018	0.9682	0.6385	0.156	0.0084	0.1538	0	0.001	0.0001	0.4344
	21	21	21	20	20	19	12	21	21	21	21	21
P_200	0.05221	0.48816	-0.33827	-0.05069	-0.11354	-0.34775	0.44226	0.0703	0.66525	1	0.25789	0.78597
	0.8222	0.0248	0.1336	0.8319	0.6336	0.1446	0.15	0.762	0.001	0	0.2591	0.0001
	21	21	21	20	20	19	12	21	21	21	21	21
M_200	-0.14758	0.61593	-0.62283	0.04289	0.21331	-0.23565	0.43973	0.37509	0.89292	0.25789	1	-0.24075
	0.5232	0.003	0.0026	0.8575	0.3665	0.3314	0.1526	0.0938	0.0001	0.2591	0	0.2931
	21	21	21	20	20	19	12	21	21	21	21	21
RATIO	-0.11676	0.1469	-0.22344	0.00236	-0.22235	-0.37292	0.32463	-0.01538	0.1802	0.78597	-0.24075	1
	0.6142	0.5252	0.3302	0.9921	0.3461	0.1158	0.3032	0.9472	0.4344	0.0001	0.2931	0
	21	21	21	20	20	19	12	21	21	21	21	21

B. Dolomite

	IFV	PV	WI	AB	SPG	LA	SUL	MG	T_ACID	P_200	M_200	RATIO
IFV	1	0.83636	-0.17435	0.65025	-0.67087	0.13232	0.44441	-0.3454	0.41405	0.15757	0.54152	-0.42429
	0	0.0001	0.4622	0.0026	0.0017	0.5892	0.0646	0.1745	0.0695	0.507	0.0137	0.0623
	20	20	20	19	19	19	18	17	20	20	20	20
PV	0.83636	1	-0.6856	0.76523	-0.74493	0.10716	0.6034	-0.6527	0.44825	0.20234	0.55958	-0.24888
	0.0001	0	0.0008	0.0001	0.0003	0.6624	0.008	0.0045	0.0475	0.3923	0.0103	0.29
	20	20	20	19	19	19	18	17	20	20	20	20
WI	-0.17435	-0.6856	1	-0.53805	0.4624	-0.00849	-0.56742	0.75604	-0.25533	-0.1542	-0.28601	-0.11639
	0.4622	0.0008	0	0.0175	0.0462	0.9725	0.014	0.0004	0.2773	0.5163	0.2215	0.6251
	20	20	20	19	19	19	18	17	20	20	20	20
AB	0.65025	0.76523	-0.53805	1	-0.96817	0.42739	0.59233	-0.31927	0.0092	-0.21238	0.20439	-0.43279
	0.0026	0.0001	0.0175	0	0.0001	0.068	0.0096	0.2281	0.9702	0.3827	0.4013	0.0642
	19	19	19	19	19	19	18	16	19	19	19	19
SPG	-0.67087	-0.74493	0.4624	-0.96817	1	-0.5287	-0.58818	0.29564	-0.05644	0.19434	-0.26904	0.48014
	0.0017	0.0003	0.0462	0.0001	0	0.02	0.0102	0.2663	0.8185	0.4253	0.2654	0.0375
	19	19	19	19	19	19	18	16	19	19	19	19
LA	0.13232	0.10716	-0.00849	0.42739	-0.5287	1	-0.03362	0.41488	-0.2046	-0.28123	-0.09973	-0.30987
	0.5892	0.6624	0.9725	0.068	0.02	0	0.8946	0.1101	0.4008	0.2435	0.6846	0.1967
	19	19	19	19	19	19	18	16	19	19	19	19
SUL	0.44441	0.6034	-0.56742	0.59233	-0.58818	-0.03362	1	-0.76433	0.41806	0.22345	0.51016	-0.03427
	0.0646	0.008	0.014	0.0096	0.0102	0.8946	0	0.0009	0.0843	0.3728	0.0305	0.8926
	18	18	18	18	18	18	18	15	18	18	18	18
MG	-0.3454	-0.6527	0.75604	-0.31927	0.29564	0.41488	-0.76433	1	-0.63132	-0.45573	-0.65587	-0.12587
	0.1745	0.0045	0.0004	0.2281	0.2663	0.1101	0.0009	0	0.0066	0.066	0.0043	0.6303
	17	17	17	16	16	16	15	17	17	17	17	17
T_ACID	0.41405	0.44825	-0.25533	0.0092	-0.05644	-0.2046	0.41806	-0.63132	1	0.86083	0.90262	0.20251
	0.0695	0.0475	0.2773	0.9702	0.8185	0.4008	0.0843	0.0066	0	0.0001	0.0001	0.3918
	20	20	20	19	19	19	18	17	20	20	20	20
P_200	0.15757	0.20234	-0.1542	-0.21238	0.19434	-0.28123	0.22345	-0.45573	0.86083	1	0.55796	0.54759
	0.507	0.3923	0.5163	0.3827	0.4253	0.2435	0.3728	0.066	0.0001	0	0.0106	0.0124
	20	20	20	19	19	19	18	17	20	20	20	20
M_200	0.54152	0.55958	-0.28601	0.20439	-0.26904	-0.09973	0.51016	-0.65587	0.90262	0.55796	1	-0.1328
	0.0137	0.0103	0.2215	0.4013	0.2654	0.6846	0.0305	0.0043	0.0001	0.0106	0	0.5767
	20	20	20	19	19	19	18	17	20	20	20	20
RATIO	-0.42429	-0.24888	-0.11639	-0.43279	0.48014	-0.30987	-0.03427	-0.12587	0.20251	0.54759	-0.1328	1
	0.0623	0.29	0.6251	0.0642	0.0375	0.1967	0.8926	0.6303	0.3918	0.0124	0.5767	0
	20	20	20	19	19	19	18	17	20	20	20	20

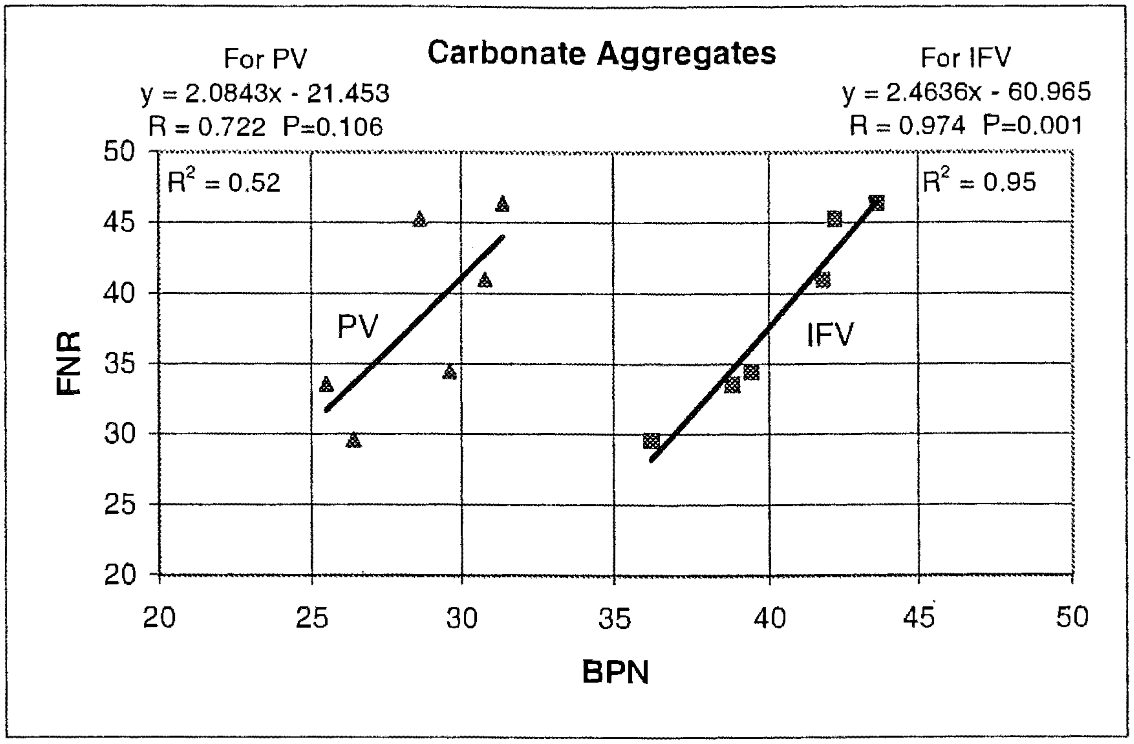


Figure 5-47. Correlation of Average Friction Number from ribbed trailer tire to IFV and PV determined from coupons composed of extracted core aggregates.

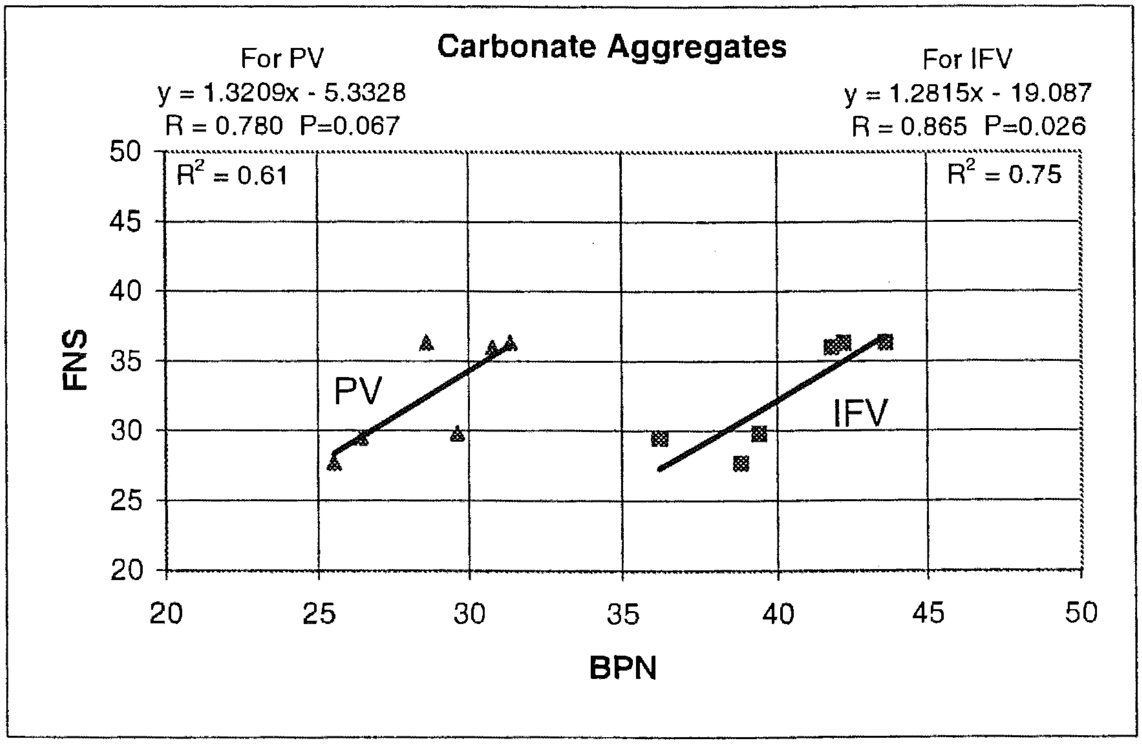


Figure 5-48. Correlation of Average Friction Number from smooth trailer tire to IFV and PV determined from coupons composed of extracted core aggregates.

5.3 Categorization of Carbonate Aggregates

5.3.1 Selection of critical parameters

For bituminous wearing courses, aggregates are required to meet various demands such as strength, durability and skid resistance. For INDOT Specifications (1999), the strength and durability requirements are designated for aggregate samples used as pavement materials. In the current study, the frictional resistance capability of aggregate sources is indicated based on the correlation analysis between PV and other parameters.

For dolomite aggregates, from results of the correlation analysis (Tables 5-9A and 5-9B) and confidence interval (Appendix 1) between polished value (PV) and other aggregate properties, the parameters having $R > 0.50$ are initial friction value (IFV) ($R=0.836$, $0.625 \leq \rho \leq 0.933$, $R^2 = 0.70$), absorption ($R=0.765$, $0.476 \leq \rho \leq 0.905$, $R^2 = 0.59$), specific gravity ($R=-0.745$, $0.896 \leq \rho \leq 0.440$, $R^2 = 0.56$), sulfate soundness loss ($R=0.603$, $0.189 \leq \rho \leq 0.835$, $R^2 = 0.36$), elemental Mg content ($R=-0.653$, $0.863 \leq \rho \leq 0.251$, $R^2 = 0.43$) and percent of acid insoluble residue smaller than #200 ($R=0.560$, $0.156 \leq \rho \leq 0.803$, $R^2 = 0.31$) for dolomite aggregates.

For limestone aggregates, the parameters having $R > 0.50$ are total acid-insoluble residue ($R=0.703$, $0.390 \leq \rho \leq 0.871$, $R^2 = 0.49$) and percent residue less than #200 ($R=0.616$, $0.251 \leq \rho \leq 0.828$, $R^2 = 0.38$).

Some physical properties of aggregates are interrelated. For dolomite aggregates, absorption is highly correlated with specific gravity (R=-0.968) and sulfate soundness loss (R=0.592). Elemental Mg content is well correlated with sulfate soundness loss (R= -0.764) and percent of acid insoluble residue smaller than #200 (R=-0.656).

For limestone aggregates, only absorption among physical properties is well correlated with specific gravity (R=-0.757). In the regression analysis, the dependant variables are IFV and PV, and independent variables are physical properties, elemental Mg content and acid insoluble residue. The independent variables should be independent of each other.

5.3.2 Regression Analysis of Laboratory Data

In this research, a large quantity of data was generated based on laboratory analysis, INDOT records and the 1995 JTRP study. The goal of the statistical analysis was to determine aggregate properties that predict the performance of aggregates during in-service conditions with regard to skid resistance. Relevance of data was determined through correlation analysis, stepwise regression and multiple linear regression analyses.

PV was selected as the dependant variable and other laboratory data values were set as independent variables. Regression analysis was accomplished in three steps: First, the variables showing higher correlation were forced into regression and the relationship between PV and these laboratory variables were formulated separately for dolomite and limestone aggregates. Second, regression was conducted by stepwise method of the SAS program. PV and strongly related laboratory variables were chosen. Equations among these variables were generated separately for dolomite and limestone aggregates. Third, the dolomite and limestone data were combined into carbonate aggregates and analyzed collectively.

5.3.2.1 Dolomite Aggregates

Among the laboratory variables for dolomite aggregates, absorption, elemental Mg content and acid insoluble residue <#200 were selected as independent variables. Using multiple linear-regression, the relationship between PV and these variables was developed:

$$\begin{aligned} PV\ (1) = {} & 38.0232 + 1.5568\ (\text{Absorption}) - 1.1750\ (\text{Mg content}) \\ & + 0.3950\ (\text{Insoluble residue} <\#200) \\ & (R^2 = 0.779,\ P < 21.19\%) \end{aligned}$$

Next, elemental Mg content was correlated with percent of acid insoluble residue less than #200. The above equation after removal of acid insoluble residue is as follows:

$$PV\ (2) = 46.0331 + 1.5645\ (\text{Absorption}) - 1.7651\ (\text{Mg content})$$
$$(R^2 = 0.747,\ P < 1.75\%)$$

Based on 5% significance level, PV (2) was selected as the appropriate equation for dolomite aggregates. Considering the average 2.406% for absorption values in dolomite samples and the 25 of PV for the quality aggregates, the elemental Mg content corresponds to 14.1%. This result indicates all ranges of dolomite (6.6% to 13.2% elemental Mg) have frictional resistance greater than PV=25, with minimum 1.45% absorption.

For dolomite aggregates, the higher elemental Mg values correspond with the purer dolomite aggregates. The higher purity dolomites are poorer performer with regard to skid resistance. In the Indiana specifications (INDOT, 1999), a minimum 10.3% elemental Mg content is required for carbonate aggregate sources based on a study performed in Illinois (Dierstein and LaCroix, 1984, 1990). It states: "The higher percentage of MgO corresponds with the higher frictional values". However, in the current study, the lower elemental Mg content corresponded with higher frictional values. Therefore, dolomites with less than 10.3% Mg should be considered as an acceptable aggregate source if they pass the other specifications such as absorption and sulfate soundness loss. This is also consistent with elemental Mg content being inversely correlated with sulfate soundness loss ($R=-0.764$, $R^2=058$). From Figure 5-49, PV can be estimated using measured absorption and elemental Mg content data.

5.3.2.2 Limestone Aggregates

From the laboratory test variables of limestone aggregates, absorption, elemental Mg content and total insoluble residue were selected as independent variables. Using multiple linear-regression, the relationship between PV and these variables is as follows:

$$PV\ (1) = 21.3374 + 0.2733\ (\text{Absorption}) - 0.0376\ (\text{Mg content})$$
$$+ 0.6161\ (\text{Total insoluble residue})$$
$$(R^2 = 0.499,\ P < 81.35\%)$$

Next, only total insoluble residue was considered as an independent variable because absorption and Mg content do not correlate well with PV. The relationship between PV and total insoluble residue is as follows:

$$PV\ (2) = 21.7006 + 0.6029\ (\text{Total insoluble residue})$$
$$(R^2 = 0.495,\ P < 0.05\%)$$

Using 5% significance level, PV (2) was selected as the appropriate equation for limestone aggregates. Considering the value of 25 for PV, the minimum required value yields a total insoluble residue of limestone aggregates equal to 5.47%.

5.3.2.3 Integration of dolomite and limestone data

IFV and PV values and laboratory data for dolomite and limestone were analyzed collectively to predict the performance of carbonate aggregates in frictional resistance. Absorption, elemental Mg content and total insoluble residue were selected as independent variables by stepwise regression. The relationship between PV and these variables is as follows:

$$PV\ (3) = 19.4659 + 1.7212(\text{Absorption}) + 0.2105\ (\text{Mg content})$$
$$+ 0.47863(\text{Total insoluble residue})$$
$$(R^2 = 0.675,\ P < 0.61\%)$$

However, based on the distribution of elemental Mg content in carbonate aggregates, PV is more highly correlated with elemental Mg content by the 2nd degree polynomial equation (Figure 5-50) than by the linear equation. The equation is as follows:

$$PV\ (4) = 19.5464 + 1.7129\ (\text{Absorption}) + 0.0164\ (\text{Mg content})^2$$
$$+ 0.5189\ (\text{Total insoluble residue})$$
$$(R^2 = 0.683,\ P < 0.39\%)$$

The measured PV is compared with predicted equations PV (1), PV (2), PV (3) and PV (4) as shown in Tables 5-10A and 5-10B. According to the comparison of the squares of residuals, the squared values of residuals are similar for PV (1) through PV (4).

5.3.3 Categorization of Polished Values

According to historical perspectives, the tentative acceptance criteria for the minimum polished value permitted for surface course mixes is as follows. These limits are considered as a starting point for future refinement (Dierstein and LaCroix, 1990).

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

According to the study on Alabama limestone and gravel aggregates as an asphalt wearing course, BPN9 values were divided into 3 categories as following (Kandhal et al., 1993):

BPN9 Values	Categories
Below 28	Low
28 to 32	Medium
32 or more	High

Also those authors noted that a general trend shows that as the insoluble residue percent (IR) increases the value of BPN9 also increases (R=0.414). The relationship between two parameters was given by:

$$\mathrm{BPN9} = 29.7 + 0.02 * (\%\ \mathrm{IR}).$$

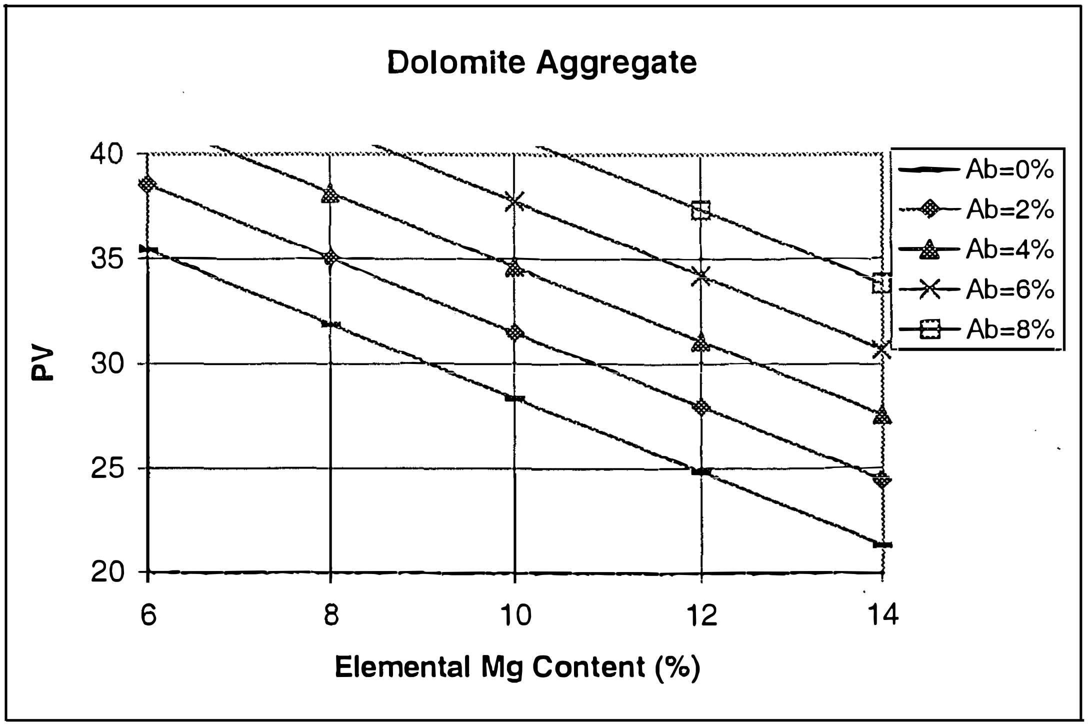


Figure 5-49. Prediction of polished value by absorption and elemental Mg content in dolomite aggregates

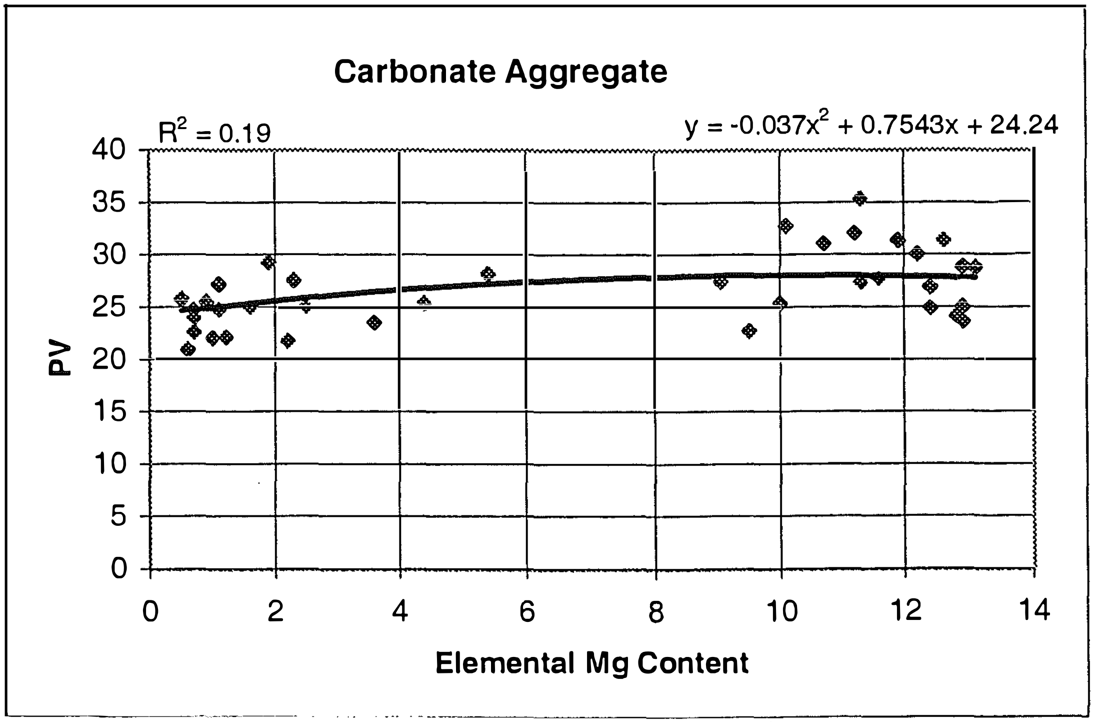


Figure 5-50. Non-linear relationship between polished value and elemental Mg content in carbonate Aggregates.

										24.90	-0.13	4.25

B. Dolomite

Id. No.	Measured PV	Pre. PV(1)	Res.(1)	SQ	Pre. PV (2)	Res.(2)	SQ	Pre. PV (3)	Res.(3)	SQ	Pre. PV (4)	Res.(4)	SQ
D-001	24.90	24.87	0.03	0.00	25.38	-0.48	0.23	24.25	0.65	0.42	24.30	0.60	0.36
D-002	25.00	26.86	-1.86	3.46	27.00	-2.00	4.01	26.63	-1.63	2.67	26.73	-1.73	2.99
D-003	27.30	29.27	-1.97	3.90	30.22	-2.92	8.51	27.89	-0.59	0.34	27.78	-0.48	0.23
D-004	35.30	35.27	0.03	0.00	35.87	-0.57	0.32	33.61	1.69	2.85	33.44	1.86	3.48
D-005	27.70	30.02	-2.32	5.38	28.72	-1.02	1.04	30.08	-2.38	5.69	30.30	-2.60	6.77
D-006	26.80	27.26	-0.46	0.22	26.59	0.21	0.05	27.29	-0.49	0.24	27.48	-0.68	0.46
D-007	28.80	28.06	0.74	0.55	28.03	0.77	0.59	28.07	0.73	0.53	28.19	0.61	0.37
D-008	28.70	26.42	2.28	5.22	26.63	2.07	4.27	26.43	2.27	5.17	26.54	2.16	4.65
D-009	31.00	28.53	2.47	6.11	29.04	1.96	3.84	27.35	3.65	13.31	27.34	3.66	13.38
D-010	31.30	30.00	1.30	1.69	29.68	1.62	2.64	30.58	0.72	0.52	30.74	0.56	0.31
D-011	30.00	28.25	1.75	3.06	27.66	2.34	5.48	28.53	1.47	2.16	28.72	1.28	1.65
D-012	31.30	29.99	1.31	1.72	29.31	1.99	3.94	30.35	0.95	0.91	30.53	0.77	0.60
D-013	32.70												
D-014	32.00	32.89	-0.89	0.79	32.52	-0.52	0.27	31.23	0.77	0.59	31.18	0.82	0.67
D-015	24.10	24.67	-0.57	0.33	25.05	-0.95	0.90	24.17	-0.07	0.01	24.25	-0.15	0.02
D-016	23.60	25.79	-2.19	4.78	26.17	-2.57	6.62	25.42	-1.82	3.32	25.50	-1.90	3.59
D-017	24.90	24.55	0.35	0.12	24.83	0.07	0.01	24.07	0.83	0.69	24.16	0.74	0.54
D-018	28.40												
D-019	28.00												
D-020	28.10												
Average	28.50	28.29	0.00	2.33	28.29	0.00	2.67	27.87	0.42	2.46	27.95	0.35	2.51

In the current study on Indiana limestones and the previous study on Indiana dolomites (Bruner, Choi and West, 1995), the BPN10 was used as the polished value. By the comparison between laboratory BPN and in-field AFN (Figures 5-47 and 5-48), PV=25 may be considered as a minimum acceptable friction value for bituminous pavement aggregates. Carbonate aggregates (dolomite and limestone) are categorized into three groups as following:

Polished Values	Categories
24 or less	Low
25 to 30	Medium
31 or more	High

5.4 Sandstone Study

5.4.1 Selection of Sandstone Samples

Samples were obtained from three sandstone sources in Illinois. They were designated as "S-001" and "S-002" obtained from the Aux Vases Sandstone that is predominantly a well sorted, calcareous, and very fine-grained quartz sandstone. The sample designated "S-003" is from the Rosiclare Sandstone. Rosiclare Sandstone is also calcareous sandstone and is considered as a member of the Aux Vases Sandstone.

The petrographic description for the calcareous sandstone is as follows (Hockett, 1987):

"A calcareous sandstone in which the clastic quartz grains are bound in a matrix of calcite. The angular to subangular quartz grains are from 0.1 to 0.5mm in length and constitute about 60 percent of the material. The remainder is primarily a calcite cement, with grains 0.1 to 0.3mm in length, with a trace of microcline, plagioclase, quartzite or chert, and dark carbonaceous matter."

5.4.2 Physical Properties of Sandstone Samples

The physical test data for sandstone samples were obtained from INDOT and the data are listed in Table 5-11.

According to the results of the physical properties of the sandstone, absorption ranges from 1.12 % to 1.70 %, the specific gravity ranges from 2.584 to 2.624 and Los Angeles abrasion losses range from 26.24 % to 28.66 %. Freeze and thaw loss in brine is 30.28% for S-001 and the freeze and thaw loss in water ranges from 0.72 to 8.12% for S-002 and S-003.

5.4.3 Magnesium Content and Acid-insoluble Residue of Sandstone Samples

The elemental Mg content and the acid-insoluble residue of sandstone samples are listed in Table 5-12.

Table 5-11. Physical properties of sandstone samples

Id. No.	Absorption	Specific Gravity	L.A. Abrasion Loss	Freeze/Thaw Loss in water
S-001	-	-	-	*30.28%
S-002	1.70%	2.584	28.66%	8.12%
S-003	1.12%	2.624	26.24%	0.72%
Average	1.41%	2.604	27.45%	4.42%

- *: Freeze - thaw loss in brine.

Table 5-12. Elemental Mg content and acid-insoluble residue of sandstone samples

Unit: %

Id. No.	Elemental Mg Content	Dolomite Content	Calcite Content	Acid-insoluble Residue			
				Total	> #200	< #200	>#200 / <#200
S-001	2.5	7.94	75.5	16.60	9.40	7.20	1.31
S-002	0.4	1.27	39.8	58.94	56.91	1.98	28.7
S-003	0.4	1.27	35.4	63.36	63.06	0.30	210.0
Average	1.1	3.49	50.2	46.30	43.12	3.16	80.0

Table 5-13. IFV, PV and WI for sandstone samples

Id. No.	IFV	PV	WI
S-001	45.59	26.11	19.48
S-002	50.08	36.42	13.66
S-003	51.45	38.30	13.15
Average	49.04	33.61	15.43

Total acid-insoluble residue of sandstone samples ranged from 16.00 to 63.36%. For percent of insoluble greater than #200, it ranged from 9.40 to 63.06% and for materials smaller than #200 it ranged from 0.30 to 7.20%. The ratio of percent material > #200 to percent material < #200 ranged from 1.31 to 210.0. Based on the petrographic analysis, S-001 is considered to be significantly more calcareous than the other two sandstone samples.

5.4.4 Frictional Resistance Properties of Sandstone Samples

Initial Friction Value (IFV) and Polished Value (PV) were measured on sandstone coupons using the British Pendulum tester. The IFV and PV for sandstone samples are listed in Table 5-13.

As shown in Tables 5-12 and 5-13, as the total insoluble residue increases, IFV and PV also increase but WI decreases. Also, as the ratio of percent material > #200 to percent material < #200 increases, IFV and PV also increase but WI decreases. The reason that S-001 shows a lower PV than the other sandstones is that S-001 is more properly described as a quartzose limestone. Also, as shown in Table 5-11, S-001 has higher elemental Mg content and a lower acid insoluble residue than do S-002 and S-003.

5.5 Variation of Frictional Resistance Values

To evaluate the variation in frictional values between different test equipments in the current study, Polished Values were obtained from two different British Pendulum Testers: BPT1 (Purdue University equipment) and BPT2 (Alabama DOT equipment). The results are tabulated in Table 5-14 to Table 5-17 based on the various types of aggregate.

Table 5-14. Comparison of Polished Values of gravel aggregates obtained from BPT1 and BPT2.

Id. No.	BPT1	BPT2	Difference (BPT1-BPT2)
GR-1	26.29	25.94	0.35
GR-2	22.58	24.63	-2.05
GR-3	23.47	25.97	-2.50
GR-4	24.12	24.52	-0.40
GR-5	22.94	25.44	-2.50
GR-6	25.63	25.52	0.38
Average	24.17	25.29	-1.12

As shown in Table 5-14, on average, the PV from BPT2 are slightly greater than those from BPT1.

Referring to Table 5-15 for limestone aggregates, the PV from BPT 1 and BPT2 showed some discrepancies between the two PVs. On average, the PV from BPT2 is slightly higher than from BPT1.

Table 5-15. Polished Values of limestone aggregates from BPT1 and BPT2.

Id. No.	BPT1	BPT2	Difference (BPT1-BPT2)
L-001	28.14	26.03	2.11
L-002	24.72	26.83	-2.11
L-003	22.69	24.12	-1.43
L-004	23.49	25.28	-1.79
L-005	21.67	23.95	-2.28
L-006	20.87	21.63	-0.76
L-007	25.50	25.50	0.00
L-008	24.97	28.56	-3.59
L-009	27.40	26.50	0.90
L-010	25.39	22.22	3.17
L-011	25.39	26.04	-0.65
L-012	27.51	20.75	6.76
L-013	29.24	25.81	3.43
L-014	25.00	26.03	-1.03
L-015	27.12	26.98	0.14
L-016	24.72	27.14	-2.42
L-017	25.73	29.94	-4.21
L-018	22.55	27.51	-4.96
L-019	23.95	22.13	1.82
L-020	22.05	26.24	-4.19
L-021	22.01	20.87	1.14
Average	24.77	25.24	-0.47

As shown in Table 5-16, PVs for dolomite aggregates measured by BPT1 and BPT2 typically show sizable differences. The first five listed (D-001B, D-003, D-007, D-011 and D-020) are from the current study, evaluated at Purdue University (BPT1) and Alabama DOT (BPT2). The last two (D-001A and D-001C) are of a different nature.

Table 5-16. Polished Values of dolomite aggregates from BPT1 and BPT2.

Id. No.	BPT1	BPT2	Difference (BPT1-BPT2)
D-001B	20.67	21.50	-0.83
D-003	27.30	25.17	2.13
D-007	28.80	27.38	1.42
D-011	30.00	30.00	0.00
D-020	28.10	23.63	4.47
D-001A	24.90	21.83	3.07
D-001C	22.77	22.17	0.60
Average	26.87	25.34	1.53

D-001A is a dolomite coupon from the 1995 JTRP study and D-001C is from the current study with new epoxy material and the 1995 JTRP aggregate sample. There is a considerable discrepancy between these results for the same source. Factors involved are 1) a different location in the same aggregate quarry, 2) different epoxy materials used, and 3) a different technician conducting the test.

It is observed that PVs of BPT1 and BPT2 for D-001B and D-001C are more consistent than are those for D-001A.

The PVs for sandstone aggregates involving BPT1 and BPT2 are shown in Table 5-17. There is an average discrepancy between BPT1 and BPT2 of about 1.5 units.

Table 5-17. Polished Values of sandstone aggregates from BPT1 and BPT2.

Id. No.	BPT1	BPT2	Difference (BPT1-BPT2)
S-001	26.11	25.35	0.76
S-002	36.42	34.08	2.34
S-003	38.30	36.81	1.49
Average	33.61	32.08	

with R=0.76 as shown in Figure 5-51.

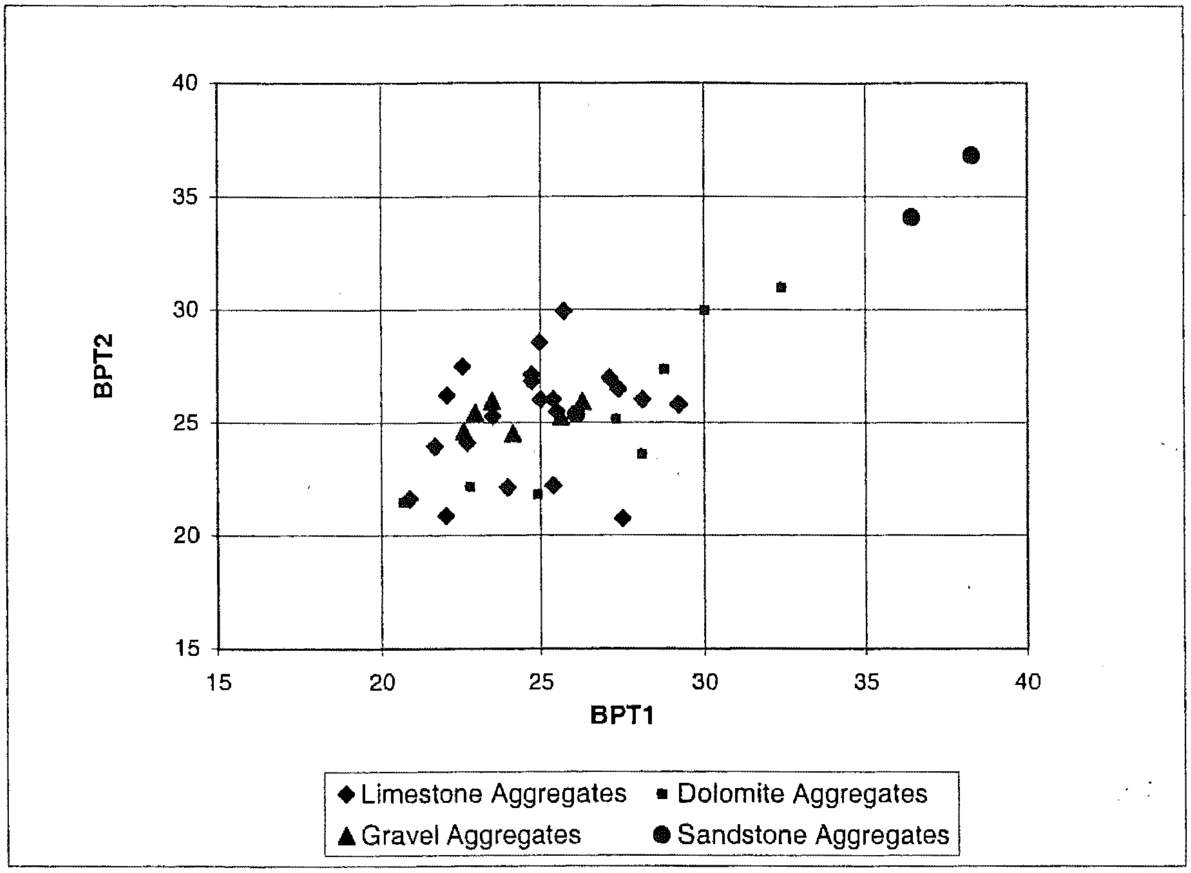


Figure 5-51. Comparison of Polished Values from BPT1 and BPT2 according to aggregate types

6. CONCLUSIONS

The research results for this study, Project SPR-2206, "Development of a Procedure to Identify Aggregates for Bituminous Surfaces in Indiana," proved to be quite significant. Results of this study are combined with those of 1995 JTRP on dolomite aggregates. The conclusions of this combined study are presented below:

1. Gravel Aggregates

- Gravels in this study consisted primarily of sedimentary rocks including limestones and dolomites. The weighted PV of gravel samples ranged from 22.6 to 26.3. PV correlates best with freeze-thaw loss ($R=0.868$, $R^2 = 0.75$). The other variables affecting the performance of gravel aggregates are absorption ($R=0.832$, $R^2 = 0.69$), percentage of crushed gravel pieces ($R=0.804$, $R^2 = 0.65$) and the percentage of metamorphic rocks present ($R=0.830$, $R^2 = 0.69$).
- Higher percentages of crushed gravel pieces show higher frictional resistance.

2 Carbonate Aggregates

- The acid insoluble residue results provide valuable data related to frictional resistance of carbonate aggregates. This test should be performed on aggregates used in bituminous surface courses.
- The difference in mineral hardness within a rock piece yielding an uneven texture during polishing, has a major influence on aggregate performance. For example, quartz and calcite in a calcareous sandstone, calcite and insoluble residue (fine quartz and clay) in limestone, dolomite and calcite in a dolomitic limestone or calcareous dolomite, and an impure dolomite and impure limestone.
- Regarding geologic strata, for dolomite aggregates, the Kokomo Member shows the highest PV=33.3, as the Kokomo Member is impure (10.3% Mg and 4.31% insoluble residue). By contrast, the Huntington Dolomite shows the lowest PV=25.4 because

Huntington Dolomite is very pure (12.4% Mg and a lower 3.09% insoluble residue). Among limestone aggregates, the Mississinewa Member shows the highest PV=28.1 because the Mississinewa Member is very impure (5.40% Mg and 12.72% insoluble residue). By contrast, the Brassfield Limestone shows the lowest PV=20.9 because of its purity (0.6% Mg and 1.97% insoluble residue). The higher friction values in comparable dolomite aggregates may be due to dolomite's greater hardness.

- The important factors affecting the PV of dolomite aggregates are IFV (R=0.836, $R^2 = 0.70$), absorption (R=0.765, $R^2 = 0.59$), specific gravity (R=-0.745, $R^2 = 0.56$), sulfate soundness loss (R=0.603, $R^2 = 0.36$), elemental Mg content (R=-0.653; $R^2 = 0.43$) and percentage of insoluble residue smaller than #200 (R=0.560, $R^2 = 0.31$).. Among the variables, IFV and PV, absorption, specific gravity and sulfate soundness loss, and the elemental Mg content and the percentage of insoluble residue are intercorrelated with each other. Therefore the most effective independent variables for dolomite aggregate performance are absorption and elemental Mg content.
- The important factors affecting the PV of the limestone aggregates are total insoluble residue (R=0.703, $R^2 = 0.49$) and percent residue smaller than #200 (R=0.616, $R^2 = 0.38$). Both of these, insoluble residue and percent residue smaller than #200, are intercorrelated with each other. Therefore the most effective independent factor for limestone aggregates is the total insoluble residue as it has the higher R-value.
- Considering dolomite and limestone aggregates collectively as carbonate aggregates, the important factors affecting the performance of these carbonate aggregates are absorption (R=0.664, $R^2 = 0.44$), specific gravity (R=-0.556, $R^2 = 0.31$), and elemental Mg content (R=0.497, $R^2 = 0.25$). Absorption and specific gravity are highly dependant on each other. The total acid insoluble residue correlates well with both the percentage of insoluble residue <#200 and the percentage >#200. Therefore, the most effective variables for carbonate aggregates collectively are absorption, elemental Mg content and total insoluble residue.
- Multiple linear regression proved satisfactory in determining interactions between laboratory tests performed on dolomites and limestones in regard to friction values.

Empirical equations were developed providing reasonable probability for estimating the laboratory friction values. These equations are as follows:

For dolomite aggregate at the 5% significance level,

$$PV = 46.0331 + 1.5645\ (\text{Absorption}) - 1.7651\ (\text{Mg content})$$

For limestone aggregates at the 5% significance level,

$$PV = 21.7006 + 0.6029\ (\text{Total insoluble residue})$$

For carbonate aggregates at the 5% significance level,

$$PV = 19.5464 + 1.7129\ (\text{Absorption}) + 0.0164\ (\text{Mg content})^2 + 0.5189\ (\text{Total insoluble residue})$$

- For dolomite aggregates, the higher elemental Mg values relate to higher purity dolomite materials. These dolomites have a lower friction resistance. Regarding INDOT specifications, a minimum 10.3% elemental Mg content is required for carbonate aggregates used for surface courses with intermediate traffic requirements. This is a consequence of the study of Illinois aggregates, which stated, "The higher percentage of MgO corresponds with the higher frictional values". However, in the current study, lower elemental Mg content values correspond to higher frictional values. Therefore dolomite aggregates with less than 10.3% elemental Mg should be considered as potential aggregate sources if these aggregates pass the other specifications such as absorption and soundness loss.
- For Class A aggregate (INDOT Standard Specifications, 1999) carbonate aggregates show an increase in frictional resistance with increasing absorption percentage. However, aggregates with greater than 5% absorption do not qualify as Class A aggregates and there is no indication that aggregates with greater than 5% absorption would have good friction values. Strength and durability problems are likely to occur above the 5% level.

3. Sandstone Aggregates

- Based on the study of calcareous sandstones, as total insoluble residue (quartz, clay) increases, PV increases. Also, as the ratio of +#200 to -#200 size insoluble residue increases, PV also increases
- Sandstone aggregates showed a higher average frictional resistance PV=33.61 than did carbonate aggregates (average PV=28.50 for dolomite and average PV=24.77 for limestone) because of the heterogeneity of calcareous sandstones. Quartz, calcite and clay provide this heterogeneity.

7. RECOMMENDATIONS

Some recommendations on a procedure to identify a quality aggregates were made based on the overall results of the 1995 JTRP, SPR-2206 (Bruner, Choi and West, 1995) study and the current study.

- Crushed gravel aggregates and heterogeneous sandstone aggregates performed better in bituminous surface courses than did some crushed carbonate aggregates. These gravel and sandstone aggregates should be considered for use in a wearing course of bituminous pavements.
- Both impure limestones and impure dolomites performed better as bituminous surface courses than did either pure limestones or pure dolomites. These impure carbonates should be considered for use in wearing courses of bituminous pavements.
- Frictional resistance of dolomite aggregates can be predicted based on absorption and elemental Mg content. Frictional resistance of limestone aggregates can be also predicted from acid insoluble residue values. It is recommended, however, that the aggregates used must satisfy other aggregate specifications such as soundness loss (or freeze thaw) and maximum allowable absorption for Class A stone.
- The higher purity dolomites showed a lower friction resistance in the current study. Regarding INDOT specifications, a minimum 10.3% elemental Mg content is required for carbonate aggregates for bituminous surface courses with intermediate traffic requirements. However, based on the current study, dolomites with less than 10.3% elemental Mg should be considered for use in surface courses if these aggregates pass the other specifications such as absorption and soundness loss. Candidates should qualify as Class A materials, as high absorption and soundness loss may give rise to a strength or durability problem. Absorption values for Class A stone should be evaluated to select potential aggregates containing less than 10.3% Mg, for possible use in bituminous overlays.
- Limited data on field and laboratory measurements (AFN and BPN) from the 1995 JTRP study suggest that a PV of 25 be considered as a minimum acceptable friction value for bituminous pavement aggregates with intermediate traffic requirements. It is

recommended that some limestones be considered for bituminous surface courses, but the field performance of these limestones should to be verified.

- A discrepancy in PV values was observed between the two pieces of equipment used for British Pendulum testing. Before BPN is selected as a standard criterion for evaluating aggregate quality in Indiana, this standard method must be verified using new equipment and a detailed evaluation of inherent variations. PVs need to be evaluated on a continuing basis as PV can vary to some extent within the same aggregate source.

8. IMPLEMENTATION SUGGESTIONS

Based on the current study high purity dolomites show a lower friction resistance, or, impure dolomites (low Mg) show a higher frictional value. Based on INDOT specifications, a minimum 10.3% elemental Mg content is required for carbonate aggregates when used for surface courses with intermediate traffic requirements. Therefore dolomites with less than 10.3% elemental Mg should be considered for bituminous surface courses with intermediate traffic requirements if these aggregates pass the other specifications such as absorption and soundness loss.

Carbonates with higher insoluble residue contents show a higher friction resistance than do purer carbonates with their low insoluble residue values. Data on insoluble residue content including grain size evaluation (+#200 size fraction vs. - #200 size fraction) should also be determined. A data base for aggregates used in bituminous wearing courses should be compiled by INDOT which includes the insoluble residue content and absorption values. Elemental Mg and elemental Ca should also be determined.

A discrepancy in PV was observed between different pieces of test equipment for the British Pendulum test (Purdue University equipment vs. Alabama DOT equipment). Before BPN is selected as a standard criterion for evaluating aggregate quality in Indiana, the standard method must be developed using new equipment and a detailed evaluation of inherent variations. PVs need to be evaluated on a continuing basis because PV can vary even within the same aggregate source.

Some impure limestones with a higher frictional value should be considered for surface courses of bituminous overlays. However, field performance of these limestones must be verified through field and laboratory evaluation prior to their use as overlays.

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APPENDICIES

Appendix 1. Confidence Interval for R-value (Fisher's Transformation)

A. Limestone

Variables	R-value	z'	n	$\sigma(z')$	$u_{z'}$(min.)	$u_{z'}$(max.)	ρ(min.)	ρ(max.)
IFV - PV	0.323	0.335	21	0.236	-0.127	0.797	-0.126	0.662
IFV - WI	0.663	0.798	21	0.236	0.336	1.260	0.324	0.851
IFV - AB	0.103	0.103	20	0.243	-0.372	0.579	-0.356	0.522
IFV - SPG	-0.203	-0.206	20	0.243	-0.681	0.270	-0.592	0.263
IFV - LA	0.202	0.205	19	0.250	-0.285	0.695	-0.278	0.601
IFV - F-T	-0.584	-0.669	12	0.333	-1.322	-0.015	-0.867	-0.015
IFV - MG	0.059	0.059	21	0.236	-0.403	0.521	-0.382	0.479
IFV - T_ACID	-0.090	-0.090	21	0.236	-0.552	0.372	-0.502	0.356
IFV - P_200	0.052	0.052	21	0.236	-0.410	0.514	-0.388	0.473
IFV - M_200	-0.148	-0.149	21	0.236	-0.611	0.313	-0.545	0.303
IFV - RATIO	-0.117	-0.118	21	0.236	-0.580	0.344	-0.522	0.331
PV - WI	-0.495	-0.543	21	0.236	-1.005	-0.081	-0.764	-0.081
PV - AB	0.047	0.047	20	0.243	-0.428	0.522	-0.404	0.480
PV - SPG	-0.073	-0.073	20	0.243	-0.548	0.402	-0.499	0.382
PV - LA	-0.210	-0.213	19	0.250	-0.703	0.277	-0.606	0.270
PV - F-T	0.286	0.294	12	0.333	-0.359	0.948	-0.344	0.739
PV - MG	0.205	0.208	21	0.236	-0.254	0.670	-0.249	0.585
PV - T_ACID	0.703	0.873	21	0.236	0.411	1.335	0.390	0.871
PV - P_200	0.488	0.533	21	0.236	0.071	0.995	0.071	0.760
PV - M_200	0.616	0.719	21	0.236	0.257	1.181	0.251	0.828
PV - RATIO	0.147	0.148	21	0.236	-0.314	0.610	-0.304	0.544
WI - AB	0.056	0.056	20	0.243	-0.419	0.531	-0.396	0.486
WI - SPG	-0.127	-0.128	20	0.243	-0.603	0.348	-0.539	0.334
WI - LA	0.359	0.376	19	0.250	-0.114	0.866	-0.114	0.699
WI - F-T	-0.653	-0.781	12	0.333	-1.434	-0.127	-0.892	-0.126
WI - MG	-0.109	-0.109	21	0.236	-0.571	0.353	-0.516	0.339
WI - T_ACID	-0.639	-0.756	21	0.236	-1.218	-0.295	-0.839	-0.286
WI - P_200	-0.338	-0.352	21	0.236	-0.814	0.110	-0.672	0.110
WI - M_200	-0.623	-0.730	21	0.236	-1.192	-0.268	-0.831	-0.262
WI - RATIO	-0.223	-0.227	21	0.236	-0.689	0.235	-0.597	0.231

$z' = 0.5*\ln[(1+R)/(1-R)]$

$\sigma(z') = 1/\mathrm{sqrt}(n-3)$ n = number of samples

$u_{z'} = z' +/- z_{(0.5\alpha)}*\sigma(z')$ $z_{(0.5\alpha)} = 1.96$ for 95% confidence interval

B. Dolomite

Variables	r-value	z'	n	$\sigma(z')$	$u_{z'}$(min.)	$u_{z'}$(max.)	ρ(min.)	ρ(max.)
IFV - PV	0.836	1.208	20	0.243	0.732	1.683	0.625	0.933
IFV - WI	-0.174	-0.176	20	0.243	-0.651	0.300	-0.572	0.291
IFV - AB	0.650	0.775	19	0.250	0.285	1.265	0.278	0.853
IFV - SPG	-0.671	-0.813	19	0.250	-1.303	-0.323	-0.862	-0.312
IFV - LA	0.132	0.133	19	0.250	-0.357	0.623	-0.343	0.553
IFV - SUL	0.444	0.477	18	0.258	-0.029	0.983	-0.029	0.754
IFV - MG	-0.345	-0.360	17	0.267	-0.884	0.164	-0.708	0.163
IFV - T_ACID	0.414	0.440	20	0.243	-0.035	0.916	-0.035	0.724
IFV - P_200	0.158	0.159	20	0.243	-0.316	0.635	-0.306	0.561
IFV - M_200	0.542	0.607	20	0.243	0.132	1.082	0.131	0.794
IFV - RATIO	-0.424	-0.453	20	0.243	-0.928	0.023	-0.730	0.023
PV - WI	-0.686	-0.840	20	0.243	-1.316	-0.365	-0.866	-0.350
PV - AB	0.765	1.008	19	0.250	0.518	1.498	0.476	0.905
PV - SPG	-0.745	-0.962	19	0.250	-1.452	-0.472	-0.896	-0.440
PV - LA	0.107	0.107	19	0.250	-0.383	0.597	-0.365	0.535
PV - SUL	0.603	0.698	18	0.258	0.192	1.204	0.189	0.835
PV - MG	-0.653	-0.781	17	0.267	-1.304	-0.257	-0.863	-0.251
PV - T_ACID	0.448	0.482	20	0.243	0.007	0.958	0.007	0.743
PV - P_200	0.202	0.205	20	0.243	-0.271	0.680	-0.264	0.592
PV - M_200	0.560	0.633	20	0.243	0.157	1.108	0.156	0.803
PV - RATIO	-0.249	-0.254	20	0.243	-0.730	0.221	-0.623	0.217
WI - AB	-0.538	-0.601	19	0.250	-1.091	-0.111	-0.797	-0.111
WI - SPG	0.462	0.500	19	0.250	0.010	0.990	0.010	0.757
WI - LA	-0.008	-0.008	19	0.250	-0.498	0.482	-0.461	0.448
WI - SUL	-0.567	-0.643	18	0.258	-1.149	-0.137	-0.817	-0.136
WI - MG	0.756	0.987	17	0.267	0.463	1.511	0.433	0.907
WI - T_ACID	-0.255	-0.261	20	0.243	-0.736	0.215	-0.627	0.211
WI - P_200	-0.154	-0.155	20	0.243	-0.631	0.320	-0.558	0.310
WI - M_200	-0.286	-0.294	20	0.243	-0.770	0.181	-0.647	0.179
WI - RATIO	-0.116	-0.117	20	0.243	-0.592	0.359	-0.531	0.344

C. Gravel

Variables	r-value	z'	n	$\sigma(z')$	$u_{z'}$(min.)	$u_{z'}$(max.)	ρ(min.)	ρ(max.)
IFV - PV	0.837	1.211	6	0.577	0.079	2.343	0.079	0.982
IFV - WI	0.924	1.616	6	0.577	0.484	2.747	0.450	0.992
IFV - AB	0.893	1.437	6	0.577	0.305	2.568	0.296	0.988
IFV - SPG	-0.372	-0.391	6	0.577	-1.522	0.741	-0.909	0.630
IFV - LA	0.563	0.637	6	0.577	-0.494	1.769	-0.458	0.943
IFV - F-T	0.846	1.242	6	0.577	0.110	2.374	0.110	0.983
IFV - IG%	-0.178	-0.180	6	0.577	-1.312	0.952	-0.865	0.741
IFV - META%	0.506	0.557	6	0.577	-0.574	1.689	-0.518	0.934
IFV - LS%	-0.031	-0.031	6	0.577	-1.163	1.101	-0.822	0.801
IFV - DOL%	-0.006	-0.006	6	0.577	-1.138	1.126	-0.814	0.810
IFV - OS%	-0.025	-0.025	6	0.577	-1.157	1.107	-0.820	0.803
IFV - CRUSH%	0.890	1.422	6	0.577	0.290	2.554	0.282	0.988
PV - WI	0.565	0.640	6	0.577	-0.491	1.772	-0.455	0.944
PV - AB	0.832	1.195	6	0.577	0.063	2.326	0.063	0.981
PV - SPG	-0.573	-0.652	6	0.577	-1.784	0.480	-0.945	0.446
PV - LA	0.714	0.895	6	0.577	-0.236	2.027	-0.232	0.966
PV - F-T	0.868	1.325	6	0.577	0.193	2.457	0.191	0.985
PV - IG%	0.082	0.082	6	0.577	-1.049	1.214	-0.782	0.838
PV - META%	0.830	1.188	6	0.577	0.057	2.320	0.056	0.981
PV - LS%	-0.329	-0.342	6	0.577	-1.473	0.790	-0.900	0.658
PV - DOL%	-0.494	-0.541	6	0.577	-1.673	0.590	-0.932	0.530
PV - OS%	0.228	0.232	6	0.577	-0.900	1.364	-0.716	0.877
PV - CRUSH%	0.804	1.110	6	0.577	-0.022	2.241	-0.022	0.978
WI - AB	0.766	1.011	6	0.577	-0.121	2.142	-0.120	0.973
WI - SPG	-0.162	-0.163	6	0.577	-1.295	0.968	-0.860	0.748
WI - LA	0.351	0.367	6	0.577	-0.765	1.498	-0.644	0.905
WI - F-T	0.727	0.922	6	0.577	-0.209	2.054	-0.206	0.968
WI - IG%	-0.325	-0.337	6	0.577	-1.469	0.794	-0.899	0.661
WI - META%	0.183	0.185	6	0.577	-0.947	1.317	-0.738	0.866
WI - LS%	0.183	0.185	6	0.577	-0.947	1.317	-0.738	0.866
WI - DOL%	0.336	0.350	6	0.577	-0.782	1.481	-0.654	0.902
WI - OS%	-0.197	-0.200	6	0.577	-1.331	0.932	-0.870	0.732
WI - CRUSH%	0.781	1.048	6	0.577	-0.084	2.180	-0.083	0.975

Appendix 2. Correlation Analysis

A. Limestone

```
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                                             Correlation Analysis

 12 'VAR' Variables:  IFV       PV        WI        AB        SPG       LA        SUL       MG
                      T_ACID    P_200     M_200     RATIO

                                              Simple Statistics

 Variable                N          Mean       Std Dev           Sum       Minimum       Maximum
 IFV                    21     43.063333      2.659395    904.330000     38.600000     48.870000
 PV                     21     24.767143      2.291369    520.110000     20.870000     29.240000
 WI                     21     18.296190      2.896157    384.220000     10.460000     22.140000
 AB                     20      1.495500      0.525029     29.910000      0.780000      2.470000
 SPG                    20      2.628950      0.039451     52.579000      2.517000      2.698000
 LA                     19     28.191579      4.755024    535.640000     21.370000     38.170000
 SUL                    12     12.945000      7.390808    155.340000      3.010000     27.460000
 MG                     21      2.911905      3.063246     61.150000      0.500000     10.000000
 T_ACID                 21      5.066190      2.677065    106.390000      1.410000     12.720000
 P_200                  21      1.306190      1.247431     27.430000      0.120000      4.830000
 M_200                  21      3.760000      2.068719     78.960000      1.270000     10.320000
 RATIO                  21      0.402857      0.436362      8.460000      0.050000      1.720000
                                                The SAS System          11:42 Monday, July 17, 2000   2
                                             Correlation Analysis
   Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                    IFV            PV            WI            AB           SPG            LA

IFV             1.00000       0.32288       0.66280       0.10318      -0.20263       0.20225
                 0.0           0.1534        0.0011        0.6651        0.3916        0.4063
                     21            21            21            20            20            19
PV              0.32288       1.00000      -0.49469       0.04740      -0.07250      -0.21025
                 0.1534        0.0           0.0226        0.8427        0.7613        0.3876
                     21            21            21            20            20            19
WI              0.66280      -0.49469       1.00000       0.05648      -0.12740       0.35913
                 0.0011        0.0226        0.0           0.8130        0.5925        0.1310
                     21            21            21            20            20            19
AB              0.10318       0.04740       0.05648       1.00000      -0.75713       0.10063
                 0.6651        0.8427        0.8130        0.0           0.0001        0.6819
                     20            20            20            20            20            19
```

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SPG          -0.20263     -0.07250     -0.12740     -0.75713      1.00000     -0.36788
               0.3916       0.7613       0.5925       0.0001      0.0           0.1212
                   20           20           20           20           20           19
LA            0.20225     -0.21025      0.35913      0.10063     -0.36788      1.00000
               0.4063       0.3876       0.1310       0.6819       0.1212      0.0
                   19           19           19           19           19           19
SUL          -0.58439      0.28632     -0.65280     -0.13827      0.19899     -0.39756
               0.0460       0.3669       0.0214       0.6683       0.5353       0.2260
                   12           12           12           12           12           11
MG            0.05871      0.20545     -0.10864      0.40689      0.05525     -0.41644
               0.8004       0.3716       0.6392       0.0750       0.8170       0.0761
                   21           21           21           20           20           19
T_ACID       -0.08972      0.70343     -0.63892      0.00952      0.11193     -0.33871
               0.6990       0.0004       0.0018       0.9682       0.6385       0.1560
                   21           21           21           20           20           19
P_200         0.05221      0.48816     -0.33827     -0.05069     -0.11354     -0.34775
               0.8222       0.0248       0.1336       0.8319       0.6336       0.1446
                   21           21           21           20           20           19
M_200        -0.14758      0.61593     -0.62283      0.04289      0.21331     -0.23565
               0.5232       0.0030       0.0026       0.8575       0.3665       0.3314
                   21           21           21           20           20           19

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                                    Correlation Analysis
      Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                      IFV           PV           WI           AB          SPG           LA

RATIO        -0.11676      0.14690     -0.22344      0.00236     -0.22235     -0.37292
               0.6142       0.5252       0.3302       0.9921       0.3461       0.1158
                   21           21           21           20           20           19
                                      The SAS System         11:42 Monday, July 17, 2000   4
                                    Correlation Analysis

      Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                      SUL           MG       T_ACID        P_200        M_200        RATIO

IFV          -0.58439      0.05871     -0.08972      0.05221     -0.14758     -0.11676
               0.0460       0.8004       0.6990       0.8222       0.5232       0.6142
                   12           21           21           21           21           21
PV            0.28632      0.20545      0.70343      0.48816      0.61593      0.14690
               0.3669       0.3716       0.0004       0.0248       0.0030       0.5252
```

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                   12             21             21             21             21             21
WI           -0.65280       -0.10864       -0.63892       -0.33827       -0.62283       -0.22344
               0.0214         0.6392         0.0018         0.1336         0.0026         0.3302
                   12             21             21             21             21             21
AB           -0.13827        0.40689        0.00952       -0.05069        0.04289        0.00236
               0.6683         0.0750         0.9682         0.8319         0.8575         0.9921
                   12             20             20             20             20             20
SPG           0.19899        0.05525        0.11193       -0.11354        0.21331       -0.22235
               0.5353         0.8170         0.6385         0.6336         0.3665         0.3461
                   12             20             20             20             20             20
LA           -0.39756       -0.41644       -0.33871       -0.34775       -0.23565       -0.37292
               0.2260         0.0761         0.1560         0.1446         0.3314         0.1158
                   11             19             19             19             19             19
SUL           1.00000        0.12455        0.71913        0.44226        0.43973        0.32463
               0.0            0.6997         0.0084         0.1500         0.1526         0.3032
                   12             12             12             12             12             12
MG            0.12455        1.00000        0.32261        0.07030        0.37509       -0.01538
               0.6997         0.0            0.1538         0.7620         0.0938         0.9472
                   12             21             21             21             21             21
T_ACID        0.71913        0.32261        1.00000        0.66525        0.89292        0.18020
               0.0084         0.1538         0.0            0.0010         0.0001         0.4344
                   12             21             21             21             21             21
P_200         0.44226        0.07030        0.66525        1.00000        0.25789        0.78597
               0.1500         0.7620         0.0010         0.0            0.2591         0.0001
                   12             21             21             21             21             21
M_200         0.43973        0.37509        0.89292        0.25789        1.00000       -0.24075
               0.1526         0.0938         0.0001         0.2591         0.0            0.2931
                   12             21             21             21             21             21


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                                     Correlation Analysis

    Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                  SUL             MG         T_ACID          P_200          M_200          RATIO

RATIO         0.32463       -0.01538        0.18020        0.78597       -0.24075        1.00000
               0.3032         0.9472         0.4344         0.0001         0.2931         0.0
                   12             21             21             21             21             21
```

B. Dolomite

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                                 Correlation Analysis

12 'VAR' Variables:  IFV      PV       WI       AB       SPG      LA       SUL      MG
                     T_ACID   P_200    M_200    RATIO

                                  Simple Statistics

Variable            N        Mean      Std Dev          Sum      Minimum      Maximum

IFV                20   43.550000     2.321637   871.000000    40.000000    47.600000
PV                 20   28.495000     3.140311   569.900000    23.600000    35.300000
WI                 20   15.055000     1.748225   301.100000    10.800000    18.300000
AB                 19    2.406316     1.289350    45.720000     0.790000     6.250000
SPG                19    2.603316     0.080683    49.463000     2.390000     2.732000
LA                 19   28.899474     3.317582   549.090000    22.470000    36.980000
SUL                18    4.666111     3.642939    83.990000     0.310000    13.180000
MG                 17   12.070588     0.894961   205.200000    10.100000    13.100000
T_ACID             20    3.816500     2.957099    76.330000     0.080000     9.820000
P_200              20    1.583000     1.534666    31.660000     0.020000     4.450000
M_200              20    2.233500     1.812452    44.670000     0.060000     6.280000
RATIO              20    0.785000     0.733983    15.700000     0.030000     2.560000
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                                 Correlation Analysis

  Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                    IFV          PV          WI          AB         SPG          LA

IFV             1.00000     0.83636    -0.17435     0.65025    -0.67087     0.13232
                 0.0         0.0001      0.4622      0.0026      0.0017      0.5892
                     20          20          20          19          19          19
PV              0.83636     1.00000    -0.68560     0.76523    -0.74493     0.10716
                 0.0001      0.0         0.0008      0.0001      0.0003      0.6624
                     20          20          20          19          19          19
WI             -0.17435    -0.68560     1.00000    -0.53805     0.46240    -0.00849
                 0.4622      0.0008      0.0         0.0175      0.0462      0.9725
                     20          20          20          19          19          19
AB              0.65025     0.76523    -0.53805     1.00000    -0.96817     0.42739
                 0.0026      0.0001      0.0175      0.0         0.0001      0.0680
                     19          19          19          19          19          19
SPG            -0.67087    -0.74493     0.46240    -0.96817     1.00000    -0.52870
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              0.0017        0.0003        0.0462        0.0001        0.0           0.0200
                  19            19            19            19            19            19
LA           0.13232       0.10716      -0.00849       0.42739      -0.52870       1.00000
              0.5892        0.6624        0.9725        0.0680        0.0200        0.0
                  19            19            19            19            19            19
SUL          0.44441       0.60340      -0.56742       0.59233      -0.58818      -0.03362
              0.0646        0.0080        0.0140        0.0096        0.0102        0.8946
                  18            18            18            18            18            18
MG          -0.34540      -0.65270       0.75604      -0.31927       0.29564       0.41488
              0.1745        0.0045        0.0004        0.2281        0.2663        0.1101
                  17            17            17            16            16            16
T_ACID       0.41405       0.44825      -0.25533       0.00920      -0.05644      -0.20460
              0.0695        0.0475        0.2773        0.9702        0.8185        0.4008
                  20            20            20            19            19            19
P_200        0.15757       0.20234      -0.15420      -0.21238       0.19434      -0.28123
              0.5070        0.3923        0.5163        0.3827        0.4253        0.2435
                  20            20            20            19            19            19
M_200        0.54152       0.55958      -0.28601       0.20439      -0.26904      -0.09973
              0.0137        0.0103        0.2215        0.4013        0.2654        0.6846
                  20            20            20            19            19            19


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                                    Correlation Analysis
    Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                 IFV            PV            WI            AB           SPG            LA

RATIO       -0.42429      -0.24888      -0.11639      -0.43279       0.48014      -0.30987
              0.0623        0.2900        0.6251        0.0642        0.0375        0.1967
                  20            20            20            19            19            19
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                                    Correlation Analysis
    Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                 SUL            MG        T_ACID         P_200         M_200         RATIO

IFV          0.44441      -0.34540       0.41405       0.15757       0.54152      -0.42429
              0.0646        0.1745        0.0695        0.5070        0.0137        0.0623
                  18            17            20            20            20            20
PV           0.60340      -0.65270       0.44825       0.20234       0.55958      -0.24888
              0.0080        0.0045        0.0475        0.3923        0.0103        0.2900
                  18            17            20            20            20            20
WI          -0.56742       0.75604      -0.25533      -0.15420      -0.28601      -0.11639
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               0.0140       0.0004       0.2773       0.5163       0.2215       0.6251
                   18           17           20           20           20           20
AB            0.59233     -0.31927      0.00920     -0.21238      0.20439     -0.43279
               0.0096       0.2281       0.9702       0.3827       0.4013       0.0642
                   18           16           19           19           19           19
SPG          -0.58818      0.29564     -0.05644      0.19434     -0.26904      0.48014
               0.0102       0.2663       0.8185       0.4253       0.2654       0.0375
                   18           16           19           19           19           19
LA           -0.03362      0.41488     -0.20460     -0.28123     -0.09973     -0.30987
               0.8946       0.1101       0.4008       0.2435       0.6846       0.1967
                   18           16           19           19           19           19
SUL           1.00000     -0.76433      0.41806      0.22345      0.51016     -0.03427
               0.0          0.0009       0.0843       0.3728       0.0305       0.8926
                   18           15           18           18           18           18
MG           -0.76433      1.00000     -0.63132     -0.45573     -0.65587     -0.12587
               0.0009       0.0          0.0066       0.0660       0.0043       0.6303
                   15           17           17           17           17           17
T_ACID        0.41806     -0.63132      1.00000      0.86083      0.90262      0.20251
               0.0843       0.0066       0.0          0.0001       0.0001       0.3918
                   18           17           20           20           20           20
P_200         0.22345     -0.45573      0.86083      1.00000      0.55796      0.54759
               0.3728       0.0660       0.0001       0.0          0.0106       0.0124
                   18           17           20           20           20           20
M_200         0.51016     -0.65587      0.90262      0.55796      1.00000     -0.13280
               0.0305       0.0043       0.0001       0.0106       0.0          0.5767
                   18           17           20           20           20           20

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                                   Correlation Analysis
      Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                  SUL           MG       T_ACID        P_200        M_200        RATIO

RATIO        -0.03427     -0.12587      0.20251      0.54759

                                                                       20           20
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C. Gravel
                              The SAS System       16:58 Saturday, July 15, 2000   1

                            Correlation Analysis

13 'VAR' Variables:  IFV     PV      WI      AB      SPG     LA      FH      IG
                     META    LS      DOL     OS      CRUSH

                             Simple Statistics

Variable             N        Mean     Std Dev         Sum     Minimum     Maximum

IFV                  6   38.833333    3.222215  233.000000   35.300000   44.100000
PV                   6   24.166667    1.490861  145.000000   22.600000   26.300000
WI                   6   14.666667    2.136040   88.000000   12.100000   17.800000
AB                   6    1.795000    0.749286   10.770000    1.210000    3.210000
SPG                  6    2.608500    0.058722   15.651000    2.509000    2.676000
LA                   6   25.383333    2.370660  152.300000   22.640000   28.000000
FH                   5    5.950000    1.896800   29.750000    4.490000    9.180000
IG                   6   29.833333   13.071292  179.000000    9.000000   49.200000
META                 6    8.766667    5.663097   52.600000    3.600000   18.700000
LS                   6   15.666667    5.225578   94.000000    6.200000   20.800000
DOL                  6   17.733333   13.641359  106.400000    0.400000   40.400000
OS                   6   28.000000   11.805084  168.000000   16.000000   46.900000
CRUSH                6   61.166667   35.594475  367.000000   10.000000   99.000000

                              The SAS System       16:58 Saturday, July 15, 2000   2
                            Correlation Analysis
  Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

              IFV          PV          WI          AB         SPG          LA          FH

IFV       1.00000     0.83710     0.92424     0.89316    -0.37249     0.56327     0.84567
            0.0        0.0376      0.0084      0.0165      0.4671      0.2445      0.0711
                6           6           6           6           6           6           5
PV        0.83710     1.00000     0.56481     0.83235    -0.57341     0.71429     0.86769
           0.0376      0.0         0.2429      0.0398      0.2342      0.1108      0.0566
                6           6           6           6           6           6           5
WI        0.92424     0.56481     1.00000     0.76638    -0.16168     0.35114     0.72715
           0.0084      0.2429      0.0         0.0755      0.7596      0.4949      0.1639
                6           6           6           6           6           6           5
AB        0.89316     0.83235     0.76638     1.00000    -0.47803     0.74468     0.94441
           0.0165      0.0398      0.0755      0.0         0.3376      0.0895      0.0156
                6           6           6           6           6           6           5
```

```
SPG       -0.37249     -0.57341     -0.16168     -0.47803      1.00000     -0.89321     -0.36448
            0.4671       0.2342       0.7596       0.3376      0.0           0.0165       0.5464
                 6            6            6            6            6            6            5
LA         0.56327      0.71429      0.35114      0.74468     -0.89321      1.00000      0.58090
            0.2445       0.1108       0.4949       0.0895       0.0165      0.0          0.3044
                 6            6            6            6            6            6            5
FH         0.84567      0.86769      0.72715      0.94441     -0.36448      0.58090      1.00000
            0.0711       0.0566       0.1639       0.0156       0.5464       0.3044      0.0
                 5            5            5            5            5            5            5
IG        -0.17777      0.08156     -0.32509     -0.20945     -0.01175      0.11203     -0.34218
            0.7362       0.8779       0.5295       0.6904       0.9824       0.8327       0.5730
                 6            6            6            6            6            6            5
META       0.50567      0.83013      0.18341      0.46638     -0.76446      0.65743      0.67684
            0.3061       0.0408       0.7280       0.3511       0.0767       0.1559       0.2095
                 6            6            6            6            6            6            5
LS        -0.03104     -0.32877      0.18264      0.06569      0.48772     -0.13925      0.14109
            0.9535       0.5246       0.7291       0.9016       0.3264       0.7925       0.8210
                 6            6            6            6            6            6            5
DOL       -0.00599     -0.49449      0.33610     -0.00440      0.49003     -0.40093      0.14509
            0.9910       0.3187       0.5148       0.9934       0.3238       0.4308       0.8159
                 6            6            6            6            6            6            5

                                    The SAS System        16:58 Saturday, July 15, 2000    3
                                  Correlation Analysis
     Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                   IFV           PV           WI           AB          SPG           LA           FH

OS        -0.02508      0.22841     -0.19725     -0.01580     -0.40241      0.08551      0.08337
            0.9624       0.6633       0.7080       0.9763       0.4290       0.8721       0.8940
                 6            6            6            6            6            6            5
CRUSH      0.89014      0.80440      0.78135      0.71799     -0.62133      0.67435      0.59219
            0.0174       0.0536       0.0665       0.1081       0.1879       0.1418       0.2927
                 6            6            6            6            6            6            5

                                    The SAS System        16:58 Saturday, July 15, 2000    4
                                  Correlation Analysis
     Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                    IG         META           LS          DOL           OS        CRUSH

IFV       -0.17777      0.50567     -0.03104     -0.00599     -0.02508      0.89014
            0.7362       0.3061       0.9535       0.9910       0.9624       0.0174
                 6            6            6            6            6            6
```

```
PV            0.08156      0.83013     -0.32877     -0.49449      0.22841      0.80440
               0.8779       0.0408       0.5246       0.3187       0.6633       0.0536
                    6            6            6            6            6            6
WI           -0.32509      0.18341      0.18264      0.33610     -0.19725      0.78135
               0.5295       0.7280       0.7291       0.5148       0.7080       0.0665
                    6            6            6            6            6            6
AB           -0.20945      0.46638      0.06569     -0.00440     -0.01580      0.71799
               0.6904       0.3511       0.9016       0.9934       0.9763       0.1081
                    6            6            6            6            6            6
SPG          -0.01175     -0.76446      0.48772      0.49003     -0.40241     -0.62133
               0.9824       0.0767       0.3264       0.3238       0.4290       0.1879
                    6            6            6            6            6            6
LA            0.11203      0.65743     -0.13925     -0.40093      0.08551      0.67435
               0.8327       0.1559       0.7925       0.4308       0.8721       0.1418
                    6            6            6            6            6            6
FH           -0.34218      0.67684      0.14109      0.14509      0.08337      0.59219
               0.5730       0.2095       0.8210       0.8159       0.8940       0.2927
                    5            5            5            5            5            5
IG            1.00000      0.12984      0.21019     -0.67089     -0.48734      0.03468
               0.0          0.8063       0.6894       0.1446       0.3269       0.9480
                    6            6            6            6            6            6
META          0.12984      1.00000     -0.74232     -0.75791      0.58091      0.68077
               0.8063       0.0          0.0910       0.0808       0.2266       0.1366
                    6            6            6            6            6            6
LS            0.21019     -0.74232      1.00000      0.52881     -0.93035     -0.22179
               0.6894       0.0910       0.0          0.2807       0.0071       0.6728
                    6            6            6            6            6            6
DOL          -0.67089     -0.75791      0.52881      1.00000     -0.28319     -0.26614
               0.1446       0.0808       0.2807       0.0          0.5866       0.6102
                    6            6            6            6            6            6

                                 The SAS System       16:58 Saturday, July 15, 2000   5
                               Correlation Analysis
    Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

                       IG         META           LS          DOL           OS        CRUSH

OS           -0.48734      0.58091     -0.93035     -0.28319      1.00000      0.04074
               0.3269       0.2266       0.0071       0.5866       0.0          0.9389
                    6            6            6            6            6            6
CRUSH         0.03468      0.68077     -0.22179     -0.26614      0.04074      1.00000
               0.9480       0.1366       0.6728       0.6102       0.9389       0.0
                    6            6            6            6            6            6
```

```
D. Carbonate (Limestone + Dolomite)
                                     The SAS System         11:01 Friday, May 25, 2001   4

                                   The CORR Procedure

11  Variables:     IFV      PV       WI       Ab       SpG      LA       Mg       T_acid
                   P_200    M_200    ratio

                                   Simple Statistics

Variable           N         Mean      Std Dev          Sum      Minimum      Maximum

IFV               41     43.30073      2.48135         1775     38.60000     48.87000
PV                41     26.58561      3.29672         1090     20.87000     35.30000
WI                41     16.71512      2.88721    685.32000     10.46000     22.14000
Ab                39      1.93923      1.06677     75.63000      0.78000      6.25000
SpG               39      2.61646      0.06348    102.04200      2.39000      2.73200
LA                38     28.54553      4.05989         1085     21.37000     38.17000
Mg                38      7.00395      5.17147    266.15000      0.50000     13.10000
T_acid            41      4.45659      2.85252    182.72000      0.08000     12.72000
P_200             41      1.44122      1.38434     59.09000      0.02000      4.83000
M_200             41      3.01537      2.07290    123.63000      0.06000     10.32000
ratio             41      0.58927      0.62330     24.16000      0.03000      2.56000

                           Pearson Correlation Coefficients
                             Prob > |r| under H0: Rho=0
                               Number of Observations

                     IFV           PV           WI           Ab          SpG           LA

IFV              1.00000      0.53112      0.25297      0.41339     -0.46565      0.17859
                              0.0004       0.1105       0.0089       0.0028       0.2834
                      41           41           41           39           39           38
PV               0.53112      1.00000     -0.68538      0.66386     -0.55598      0.00014
                  0.0004                   <.0001       <.0001       0.0002       0.9993
                      41           41           41           39           39           38
WI               0.25297     -0.68538      1.00000     -0.39155      0.22039      0.15935
                  0.1105       <.0001                    0.0137       0.1776       0.3393
                      41           41           41           39           39           38
Ab               0.41339      0.66386     -0.39155      1.00000     -0.90864      0.26977
                  0.0089       <.0001       0.0137                    <.0001       0.1014
                      39           39           39           39           39           38
SpG             -0.46565     -0.55598      0.22039     -0.90864      1.00000     -0.41367
                  0.0028       0.0002       0.1776       <.0001                    0.0098
```

```
                        39          39          39          39          39          38
LA                 0.17859     0.00014     0.15935     0.26977    -0.41367     1.00000
                    0.2834      0.9993      0.3393      0.1014      0.0098
                        38          38          38          38          38          38

                                   The SAS System          11:01 Friday, May 25, 2001   5
                                  The CORR Procedure
                            Pearson Correlation Coefficients
                               Prob > |r| under H0: Rho=0
                                 Number of Observations

                       IFV          PV          WI          Ab         SpG          LA

Mg                 0.11727     0.49694    -0.47838     0.41896    -0.16108    -0.05381
                    0.4832      0.0015      0.0024      0.0110      0.3480      0.7588
                        38          38          38          36          36          35
T_acid             0.12364     0.31281    -0.25092    -0.09470     0.04607    -0.28739
                    0.4412      0.0465      0.1136      0.5663      0.7806      0.0802
                        41          41          41          39          39          38
P_200              0.11289     0.31226    -0.25954    -0.09748     0.07465    -0.29027
                    0.4822      0.0469      0.1013      0.5549      0.6515      0.0771
                        41          41          41          39          39          38
M_200              0.09451     0.22174    -0.17196    -0.06607     0.01405    -0.20493
                    0.5567      0.1635      0.2823      0.6894      0.9324      0.2171
                        41          41          41          39          39          38
ratio             -0.23506     0.08068    -0.29414    -0.14606     0.22075    -0.25449
                    0.1390      0.6161      0.0619      0.3749      0.1769      0.1231
                        41          41          41          39          39          38

                            Pearson Correlation Coefficients
                               Prob > |r| under H0: Rho=0
                                 Number of Observations

                             Mg      T_acid       P_200       M_200       ratio

      IFV               0.11727     0.12364     0.11289     0.09451    -0.23506
                         0.4832      0.4412      0.4822      0.5567      0.1390
                             38          41          41          41          41
      PV                0.49694     0.31281     0.31226     0.22174     0.08068
                         0.0015      0.0465      0.0469      0.1635      0.6161
                             38          41          41          41          41
      WI               -0.47838    -0.25092    -0.25954    -0.17196    -0.29414
                         0.0024      0.1136      0.1013      0.2823      0.0619
                             38          41          41          41          41
```

```
Ab                0.41896      -0.09470      -0.09748      -0.06607      -0.14606
                   0.0110        0.5663        0.5549        0.6894        0.3749
                       36            39            39            39            39

                         The SAS System          11:01 Friday, May 25, 2001   6
                       The CORR Procedure
                Pearson Correlation Coefficients
                   Prob > |r| under H0: Rho=0
                     Number of Observations

                       Mg        T_acid         P_200         M_200         ratio

SpG              -0.16108       0.04607       0.07465       0.01405       0.22075
                   0.3480        0.7806        0.6515        0.9324        0.1769
                       36            39            39            39            39
LA               -0.05381      -0.28739      -0.29027      -0.20493      -0.25449
                   0.7588        0.0802        0.0771        0.2171        0.1231
                       35            38            38            38            38
Mg                1.00000      -0.17779       0.00316      -0.24490       0.20456
                                 0.2856        0.9850        0.1384        0.2180
                       38            38            38            38            38
T_acid           -0.17779       1.00000       0.72877       0.88939       0.10784
                   0.2856                      <.0001        <.0001        0.5021
                       38            41            41            41            41

P_200             0.00316       0.72877       1.00000       0.33514       0.61886
                   0.9850        <.0001                      0.0322        <.0001
                       38            41            41            41            41
M_200            -0.24490       0.88939       0.33514       1.00000      -0.26468
                   0.1384        <.0001        0.0322                      0.0945
                       38            41            41            41            41
ratio             0.20456       0.10784       0.61886      -0.26468       1.00000
                   0.2180        0.5021        <.0001        0.0945
                       38            41            41            41            41
```

Appendix 3. Multiple Regression Analysis

A. Limestone

```
                                        The SAS System           09:51 Friday, May 25, 2001   8

                                       The REG Procedure
                                         Model: MODEL1
                                    Dependent Variable: PV

                                   Stepwise Selection: Step 1

                  Variable tacid Entered: R-Square = 0.4954 and C(p) = 0.1066

                                      Analysis of Variance

                                             Sum of           Mean
         Source                   DF        Squares         Square    F Value    Pr > F

         Model                     1       52.01760       52.01760      17.67    0.0005
         Error                    18       52.98750        2.94375
         Corrected Total          19      105.00510


                            Parameter     Standard
               Variable      Estimate        Error   Type II SS  F Value  Pr > F

               Intercept     21.70062      0.82472   2038.11814   692.35  <.0001
               tacid          0.60292      0.14343     52.01760    17.67  0.0005

                                Bounds on condition number: 1, 1
------------------------------------------------------------------------------------------------

              All variables left in the model are significant at the 0.1500 level.
                                         The SAS System           09:51 Friday, May 25, 2001  10
                                       The REG Procedure
                                         Model: MODEL1
                                    Dependent Variable: PV

                                   Stepwise Selection: Step 1

                  Variable tacid Entered: R-Square = 0.4954 and C(p) = 0.1066

                                      Analysis of Variance
```

```
                                        Sum of           Mean
Source                    DF           Squares          Square    F Value    Pr > F

Model                      1          52.01760        52.01760      17.67    0.0005
Error                     18          52.98750         2.94375
Corrected Total           19         105.00510


                    Parameter      Standard
      Variable       Estimate         Error    Type II SS   F Value   Pr > F

      Intercept      21.70062       0.82472    2038.11814    692.35   <.0001
      tacid           0.60292       0.14343      52.01760     17.67   0.0005

                         Bounds on condition number: 1, 1
----------------------------------------------------------------------------------------------------
              All variables left in the model are significant at the 0.1500 level.

         No other variable met the 0.1500 significance level for entry into the model.

                             Summary of Stepwise Selection

       Variable     Variable     Number     Partial     Model
Step   Entered      Removed      Vars In    R-Square    R-Square      C(p)      F Value    Pr > F

  1    tacid                           1      0.4954      0.4954      0.1066      17.67    0.0005
                                           The SAS System          09:51 Friday, May 25, 2001  11

 Obs   IFV     PV      WI      ab      spg      la      sul      mg    tacid   p200    m200   ratio

   1  38.60  28.14  10.46  2.170  2.591  28.500      .      5.40  12.72  2.40   10.32   0.23
   2  40.20  24.72  15.48  1.780  2.586  27.000   22.25    0.70   5.76  3.64    2.12   1.72
   3  44.38  22.69  21.69  2.000  2.604  21.370    7.98    9.50   4.09  2.04    2.05   1.00
   4  43.14  23.49  19.65  1.030  2.633  32.090      .      3.60   3.37  0.24    3.13   0.08
   5  39.48  21.67  17.81  0.930  2.652  28.600      .      2.20   4.96  1.53    3.43   0.45
   6  43.00  20.87  22.13  1.350  2.631  37.230   10.92    0.60   1.97  0.15    1.82   0.08
   7  41.13  25.50  15.63  1.260  2.624     .     16.62    0.90   4.54  2.36    2.18   1.08
   8  41.76  24.97  16.79  1.150  2.653  26.490   27.46    2.50   6.00  0.70    5.30   0.13
   9  42.26  27.40  14.86  2.065  2.642  25.935   15.43    9.05   6.38  0.30    6.08   0.05
  10  45.30  25.39  19.91  2.330  2.621  23.030   19.47   10.00   6.17  1.80    4.37   0.41
  11  43.68  25.39  18.29  0.780  2.698  32.240    7.46    4.60   5.14  0.86    4.28   0.20
  12  46.69  27.51  19.18  1.005  2.670  25.730      .      2.30   6.04  0.60    5.44   0.11
  13  48.87  29.24  19.63  1.050  2.639  27.720      .      1.90  11.21  4.83    6.38   0.76
```

```
14  44.10  25.00  19.10  1.530  2.626  28.490   8.06   1.60   4.13  1.43   2.70   0.53
15  43.21  27.12  16.09  0.880  2.638  22.400    .     1.10   4.41  1.86   2.55   0.73
16  41.02  24.72  16.30    .      .       .      .     1.10   4.59  1.16   3.43   0.34
17  47.85  25.73  22.12  2.470  2.517  38.170   3.01   0.50   1.41  0.14   1.27   0.11
18  44.69  22.55  22.14  1.970  2.592  34.760    .     0.70   2.28  0.12   2.16   0.06
19  42.37  23.95  18.42  1.320  2.634  24.790  11.30   0.70   4.01  0.64   3.37   0.19
20  40.10  22.05  18.05  1.150  2.689  24.390    .     1.20   3.61  0.47   3.14   0.15
21  42.50  22.01  20.49  1.690  2.639  26.705   5.38   1.00   3.60  0.16   3.44   0.05
```

```
                     Stepwise Procedure for Dependent Variable PV

     The first 3 variables are forced into the model because of the INCLUDE= option.

     Step 0   The First  3 Vars Entered   R-square = 0.49883949   C(p) =  4.00000000

                         DF        Sum of Squares      Mean Square          F    Prob>F

        Regression        3           52.38068754      17.46022918       5.31    0.0099
        Error            16           52.62440746       3.28902547
        Total            19          105.00509500

                         Parameter        Standard          Type II
        Variable          Estimate           Error   Sum of Squares          F    Prob>F

        INTERCEP       21.33741392      1.51508421     652.34487988     198.34    0.0001
        AB              0.27327327      0.87869865       0.31811314       0.10    0.7598
        MG             -0.03757113      0.15667370       0.18914010       0.06    0.8135
        TACID           0.61607810      0.16170862      47.73890224      14.51    0.0015

     Bounds on condition number:     1.370403,     11.21282
     ----------------------------------------------------------------------------------------

     All variables left in the model are required or significant at the 0.1500 level.
     No other variable met the 0.0500 significance level for entry into the model.
```

B. Dolomite

```
                         The SAS System          10:41 Friday, May 25, 2001   4

                        The REG Procedure
                          Model: MODEL1
                     Dependent Variable: PV

                    Stepwise Selection: Step 1

       Variable ab Entered: R-Square = 0.6025 and C(p) = 9.5580

                       Analysis of Variance

                                   Sum of           Mean
Source                    DF      Squares         Square    F Value    Pr > F

Model                      1    101.59776      101.59776      21.22    0.0004
Error                     14     67.03162        4.78797
Corrected Total           15    168.62937


                  Parameter     Standard
      Variable     Estimate        Error   Type II SS  F Value  Pr > F

      Intercept    23.76289      1.12548   2134.40654   445.79  <.0001
      ab            1.87322      0.40665    101.59776    21.22  0.0004

                 Bounds on condition number: 1, 1
------------------------------------------------------------------------------------------------

                    Stepwise Selection: Step 2

       Variable mg Entered: R-Square = 0.7467 and C(p) = 3.7385

                       Analysis of Variance

                                   Sum of           Mean
Source                    DF      Squares         Square    F Value    Pr > F

Model                      2    125.91126       62.95563      19.16    0.0001
Error                     13     42.71812        3.28601
Corrected Total           15    168.62937
```

```
                          The REG Procedure
                           Model: MODEL1
                       Dependent Variable: PV

                     Stepwise Selection: Step 2

                    Parameter     Standard
    Variable         Estimate        Error   Type II SS  F Value  Pr > F

    Intercept        46.03310      8.24011    102.55174    31.21  <.0001
    ab                1.56450      0.35549     63.64479    19.37  0.0007
    mg               -1.76512      0.64891     24.31350     7.40  0.0175

                Bounds on condition number: 1.1135, 4.454
--------------------------------------------------------------------------------
   All variables left in the model are significant at the 0.1500 level.

 No other variable met the 0.1500 significance level for entry into the model.

                     Summary of Stepwise Selection

       Variable   Variable   Number    Partial    Model
 Step  Entered    Removed    Vars In   R-Square   R-Square     C(p)    F Value   Pr > F

   1   ab                       1       0.6025     0.6025     9.5580    21.22   0.0004
   2   mg                       2       0.1442     0.7467     3.7385     7.40   0.0175
```

```
 Obs   IFV    PV     WI     ab     spg     la     sul    mg   tacid  p200  m200  ratio

   1  40.0   24.9   15.1   0.79   2.732  25.53   0.36  12.4   1.70  1.23  0.48   2.56
   2  43.3   25.0   18.3   2.39   2.599  28.59    .    12.9   0.71  0.02  0.69   0.03
   3  41.8   27.3   14.5   2.64   2.605  27.05   9.57  11.3   3.13  2.07  1.06   1.95
   4  46.9   35.3   11.6   6.25   2.390  29.36   9.86  11.3   2.11  0.11  2.00   0.06
   5  44.0   27.7   16.3   2.02   2.616  29.19   7.30  11.6   9.82  3.55  6.28   0.57
   6  42.7   26.8   15.9   1.56   2.626  26.62   2.24  12.4   5.29  1.79  3.50   0.51
   7  44.0   28.8   15.2   3.05   2.583  32.43   4.79  12.9   1.34  0.21  1.13   0.19
   8  44.6   28.7   15.9   2.38   2.594  31.73   0.76  13.1   0.22  0.03  0.20   0.15
   9  44.8   31.0   13.8   1.21   2.671  22.47   5.59  10.7   7.42  4.40  3.02   1.46
  10  45.9   31.3   14.6   3.76   2.489  36.98   3.29  12.6   4.16  1.81  2.35   0.77
  11  46.2   30.0   16.2   2.02   2.632  24.75   5.99  12.2   6.31  2.71  3.59   0.75
  12  47.6   31.3   16.3   2.74   2.588  29.50   2.24  11.9   7.65  3.39  4.26   0.80
```

```
13   43.5   32.7   10.8     .       .        .       .     10.1    5.56   0.78   4.78    0.16
14   46.7   32.0   14.7   4.00   2.480   30.28   13.18   11.2    5.27   0.71   4.55    0.16
15   40.5   24.1   16.4   1.03   2.669   29.76    2.56   12.8    0.50   0.27   0.22    1.23
16   40.1   23.6   16.5   1.86   2.614   32.62    0.55   12.9    0.08   0.02   0.06    0.33
17   41.3   24.9   16.4   1.00   2.718   25.69    0.31   12.9    0.35   0.03   0.32    0.09
18   43.6   28.4   15.2   2.48   2.619   27.25    3.62     .     2.15   0.94   1.21    0.78
19   41.6   28.0   13.6   1.59   2.648   30.75    6.45     .     6.66   4.45   2.21    2.01
20   41.9   28.1   13.8   2.95   2.590   28.54    5.33     .     5.90   3.14   2.76    1.14
```

```
                  Stepwise Procedure for Dependent Variable PV

     The first 3 variables are forced into the model because of the INCLUDE= option.

     Step 0   The First  3 Vars Entered   R-square = 0.77873139   C(p) =  4.00000000

                          DF         Sum of Squares       Mean Square          F    Prob>F

         Regression        3        131.31698690       43.77232897      14.08    0.0003
         Error            12         37.31238810        3.10936568
         Total            15        168.62937500

                          Parameter          Standard          Type II
         Variable          Estimate             Error    Sum of Squares          F    Prob>F

         INTERCEP       38.02318391       10.05750671       44.44143753      14.29    0.0026
         AB              1.55678486        0.34585261       63.00092053      20.26    0.0007
         MG             -1.17495766        0.77381513        7.16872294       2.31    0.1548
         M200            0.39500808        0.29958135        5.40572821       1.74    0.2119

     Bounds on condition number:      1.673367,      13.06769
     ------------------------------------------------------------------------------------------

     All variables left in the model are required or significant at the 0.1500 level.
     No other             the 0.0500 significance level for entry into the model.
```

C. Carbonate (Limestone + Dolomite)

```
                                   The SAS System          09:51 Friday, May 25, 2001   4

                                  The REG Procedure
                                   Model: MODEL1
                               Dependent Variable: PV

                              Stepwise Selection: Step 1

              Variable ab Entered: R-Square = 0.4427 and C(p) = 23.2884

                                Analysis of Variance

                                          Sum of           Mean
     Source                   DF         Squares         Square    F Value    Pr > F

     Model                     1       170.02372      170.02372      27.01    <.0001
     Error                    34       214.01375        6.29452
     Corrected Total          35       384.03747


                       Parameter     Standard
         Variable       Estimate        Error   Type II SS  F Value  Pr > F

         Intercept      22.49064      0.84984   4408.51711   700.37  <.0001
         ab              2.01759      0.38820    170.02372    27.01  <.0001

                         Bounds on condition number: 1, 1
--------------------------------------------------------------------------------------------

                              Stepwise Selection: Step 2

             Variable tacid Entered: R-Square = 0.5875 and C(p) = 10.9254

                                Analysis of Variance

                                          Sum of           Mean
     Source                   DF         Squares         Square    F Value    Pr > F

     Model                     2       225.62107      112.81054      23.50    <.0001
     Error                    33       158.41640        4.80050
     Corrected Total          35       384.03747
```

```
                          The REG Procedure
                            Model: MODEL1
                        Dependent Variable: PV

                       Stepwise Selection: Step 2

               Parameter     Standard
  Variable      Estimate        Error    Type II SS  F Value  Pr > F

  Intercept     20.42284      0.95916    2176.36962   453.36  <.0001
  ab             2.12667      0.34053     187.23176    39.00  <.0001
  tacid          0.42415      0.12463      55.59735    11.58  0.0018

              Bounds on condition number: 1.0089, 4.0358
------------------------------------------------------------------------------------------------

                       Stepwise Selection: Step 3
        Variable mg2 Entered: R-Square = 0.6831 and C(p) = 3.4406

                         Analysis of Variance

                                      Sum of           Mean
Source                     DF        Squares         Square    F Value    Pr > F

Model                       3      262.33526       87.44509      22.99    <.0001
Error                      32      121.70222        3.80319
Corrected Total            35      384.03747

               Parameter     Standard
  Variable      Estimate        Error    Type II SS  F Value  Pr > F

  Intercept     19.54640      0.89913    1797.35912   472.59  <.0001
  ab             1.71285      0.33107     101.79938    26.77  <.0001
  mg2            0.01636      0.00526      36.71418     9.65  0.0039
  tacid          0.51888      0.11505      77.36076    20.34  <.0001

              Bounds on condition number: 1.294, 10.749
------------------------------------------------------------------------------------------------

    All variables left in the model are significant at the 0.1500 level.

No other variable met the 0.1500 significance level for entry into the model.
```

```
                                                                  25, 2001   6

                                The REG Procedure
                                 Model: MODEL1
                             Dependent Variable: PV

                          Summary of Stepwise Selection

        Variable    Variable    Number   Partial    Model
   Step Entered     Removed     Vars In  R-Square   R-Square    C(p)     F Value   Pr > F

     1  ab                         1     0.4427     0.4427    23.2884     27.01   <.0001
     2  tacid                      2     0.1448     0.5875    10.9254     11.58   0.0018
     3  mg2                        3     0.0956     0.6831     3.4406      9.65   0.0039
                                 The SAS System               09:51 Friday, May 25, 2001   7

 Obs   IFV     PV     WI      ab     spg     la      sul     mg      mg2   tacid  p200   m200  ratio

   1  40.00  24.90  15.10  0.790  2.732  25.530   0.36  12.40  153.76   1.70  1.23   0.48   2.56
   2  43.30  25.00  18.30  2.390  2.599  28.590    .    12.90  166.41   0.71  0.02   0.69   0.03
   3  41.80  27.30  14.50  2.640  2.605  27.050   9.57  11.30  127.69   3.13  2.07   1.06   1.95
   4  46.90  35.30  11.60  6.250  2.390  29.360   9.86  11.30  127.69   2.11  0.11   2.00   0.06
   5  44.00  27.70  16.30  2.020  2.616  29.190   7.30  11.60  134.56   9.82  3.55   6.28   0.57
   6  42.70  26.80  15.90  1.560  2.626  26.620   2.24  12.40  153.76   5.29  1.79   3.50   0.51
   7  44.00  28.80  15.20  3.050  2.583  32.430   4.79  12.90  166.41   1.34  0.21   1.13   0.19
   8  44.60  28.70  15.90  2.380  2.594  31.730   0.76  13.10  171.61   0.22  0.03   0.20   0.15
   9  44.80  31.00  13.80  1.210  2.671  22.470   5.59  10.70  114.49   7.42  4.40   3.02   1.46
  10  45.90  31.30  14.60  3.760  2.489  36.980   3.29  12.60  158.76   4.16  1.81   2.35   0.77
  11  46.20  30.00  16.20  2.020  2.632  24.750   5.99  12.20  148.84   6.31  2.71   3.59   0.75
  12  47.60  31.30  16.30  2.740  2.588  29.500   2.24  11.90  141.61   7.65  3.39   4.26   0.80
  13  43.50  32.70  10.80    .      .       .      .    10.10  102.01   5.56  0.78   4.78   0.16
  14  46.70  32.00  14.70  4.000  2.480  30.280  13.18  11.20  125.44   5.27  0.71   4.55   0.16
  15  40.50  24.10  16.40  1.030  2.669  29.760   2.56  12.80  163.84   0.50  0.27   0.22   1.23
  16  40.10  23.60  16.50  1.860  2.614  32.620   0.55  12.90  166.41   0.08  0.02   0.06   0.33
  17  41.30  24.90  16.40  1.000  2.718  25.690   0.31  12.90  166.41   0.35  0.03   0.32   0.09
  18  43.60  28.40  15.20  2.480  2.619  27.250   3.62    .       .     2.15  0.94   1.21   0.78
  19  41.60  28.00  13.60  1.590  2.648  30.750   6.45    .       .     6.66  4.45   2.21   2.01
  20  41.90  28.10  13.80  2.950  2.590  28.540   5.33    .       .     5.90  3.14   2.76   1.14
  21  38.60  28.14  10.46  2.170  2.591  28.500    .     5.40   29.16  12.72  2.40  10.32   0.23
  22  40.20  24.72  15.48  1.780  2.586  27.000  22.25   0.70    0.49   5.76  3.64   2.12   1.72
  23  44.38  22.69  21.69  2.000  2.604  21.370   7.98   9.50   90.25   4.09  2.04   2.05   1.00
  24  43.14  23.49  19.65  1.030  2.633  32.090    .     3.60   12.96   3.37  0.24   3.13   0.08
  25  39.48  21.67  17.81  0.930  2.652  28.600    .     2.20    4.84   4.96  1.53   3.43   0.45
  26  43.00  20.87  22.13  1.350  2.631  37.230  10.92   0.60    0.36   1.97  0.15   1.82   0.08
```

27	41.13	25.50	15.63	1.260	2.624	.	16.62	0.90	0.81	4.54	2.36	2.18	1.08
28	41.76	24.97	16.79	1.150	2.653	26.490	27.46	2.50	6.25	6.00	0.70	5.30	0.13
29	42.26	27.40	14.86	2.065	2.642	25.935	15.43	9.05	81.90	6.38	0.30	6.08	0.05
30	45.30	25.39	19.91	2.330	2.621	23.030	19.47	10.00	100.00	6.17	1.80	4.37	0.41
31	43.68	25.39	18.29	0.780	2.698	32.240	7.46	4.40	19.36	5.14	0.86	4.28	0.20
32	46.69	27.51	19.18	1.005	2.670	25.730	.	2.30	5.29	6.04	0.60	5.44	0.11
33	48.87	29.24	19.63	1.050	2.639	27.720	.	1.90	3.61	11.21	4.83	6.38	0.76
34	44.10	25.00	19.10	1.530	2.626	28.490	8.06	1.60	2.56	4.13	1.43	2.70	0.53
35	43.21	27.12	16.09	0.880	2.638	22.400	.	1.10	1.21	4.41	1.86	2.55	0.73
36	41.02	24.72	16.30	.	.	.	.	1.10	1.21	4.59	1.16	3.43	0.34
37	47.85	25.73	22.12	2.470	2.517	38.170	3.01	0.50	0.25	1.41	0.14	1.27	0.11
38	44.69	22.55	22.14	1.970	2.592	34.760	.	0.70	0.49	2.28	0.12	2.16	0.06
39	42.37	23.95	18.42	1.320	2.634	24.790	11.30	0.70	0.49	4.01	0.64	3.37	0.19
40	40.10	22.05	18.05	1.150	2.689	24.390	.	1.20	1.44	3.61	0.47	3.14	0.15
41	42.50	22.01	20.49	1.690	2.639	26.705	5.38	1.00	1.00	3.60	0.16	3.44	0.05

```
                              The SAS System
                                           13:15 Wednesday, June 21, 2000

                Stepwise Procedure for Dependent Variable PV

Step 1   Variable AB Entered       R-square = 0.44272690   C(p) = 22.86726163

                    DF       Sum of Squares     Mean Square          F   Prob>F

    Regression       1         170.02372250    170.02372250      27.01   0.0001
    Error           34         214.01375250      6.29452213
    Total           35         384.03747500

                 Parameter         Standard         Type II
    Variable      Estimate            Error  Sum of Squares          F   Prob>F

    INTERCEP   22.49064418       0.84983969   4408.51710725     700.37   0.0001
    AB          2.01758941       0.38820347    170.02372250      27.01   0.0001

Bounds on condition number:           1,           1
-----------------------------------------------------------------------------------------

Step 2   Variable TACID Entered    R-square = 0.58749755   C(p) = 10.61362418

                    DF       Sum of Squares     Mean Square          F   Prob>F

    Regression       2         225.62107410    112.81053705      23.50   0.0001
    Error           33         158.41640090      4.80049700
    Total           35         384.03747500

                 Parameter         Standard         Type II
    Variable      Estimate            Error  Sum of Squares          F   Prob>F

    INTERCEP   20.42283904       0.95916404   2176.36961585     453.36   0.0001
    AB          2.12667074       0.34052860    187.23176227      39.00   0.0001
    TACID       0.42415378       0.12463482     55.59735160      11.58   0.0018

Bounds on condition number:     1.008939,     4.035756
-----------------------------------------------------------------------------------------
```

```
Step 3   Variable MG Entered       R-square = 0.67498398   C(p) =  4.00000000

                 DF        Sum of Squares       Mean Square           F   Prob>F

    Regression    3          259.21914296       86.40638099       22.15   0.0001
    Error        32          124.81833204        3.90057288
    Total        35          384.03747500

                 Parameter        Standard           Type II
    Variable      Estimate           Error    Sum of Squares          F   Prob>F

    INTERCEP   19.46590784      0.92403421     1731.01816500     443.79   0.0001
    AB          1.72124710      0.33660619      101.99306429      26.15   0.0001
    MG          0.21049031      0.07171981       33.59806886       8.61   0.0061
    TACID       0.47863961      0.11387029       68.91675437      17.67   0.0002

Bounds on condition number:     1.246012,     10.48733
---------------------------------------------------------------------------------------

All variables left in the model are significant at the 0.1500 level.
No other variable met the 0.1500 significance level for entry into the model.


             Summary of Stepwise Procedure for Dependent Variable PV

          Variable          Number   Partial     Model
    Step  Entered Removed       In      R**2      R**2        C(p)           F   Prob>F

       1  AB                     1    0.4427    0.4427     22.8673     27.0114   0.0001
       2  TACID                  2    0.1448    0.5875     10.6136     11.5816   0.0018
       3  MG                     3    0.0875    0.6750      4.0000      8.6136   0.0061
```