

**Determination of Influences  
on Support Strength of  
Crushed Aggregate Base  
Course Due to Gradational,  
Regional and Source  
Variations**

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**WISCONSIN HIGHWAY RESEARCH PROGRAM # 0092-02-01**

**DETERMINATION OF INFLUENCES ON SUPPORT STRENGTH  
OF CRUSHED AGGREGATE BASE COURSE DUE TO  
GRADATIONAL, REGIONAL, AND SOURCE VARIATIONS**

**FINAL REPORT**

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## **DISCLAIMER**

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16. Abstract This research investigates the range of load-carrying capability, in terms of resilient modulus ( $M_R$ ), of crushed aggregate base course in Wisconsin and how variables, such as physical characteristics, material type, source lithology and regional factors influence $M_R$ . Testing was conducted on 37 aggregate sources and the results statistically analyzed to look for correlations between $M_R$ and these variables and to determine if they could be used to predict $M_R$ . Results showed that $M_R$ did not differ between and/gravel pit and quarry groups and that carbonate quarries generally gave significantly higher $M_R$ values than Precambrian, felsic-plutonic quarries. Changing gradation of base course from a given source affected $M_R$ test results, but not consistently or predictably. Certain physical parameters, were found that influence $M_R$ in some of the geologic subsets. However, none of the correlations were strong enough to predict $M_R$ with sufficient confidence. The test data will provide a base of information that will be useful when WisDOT adopts a mechanistic-empirical pavement design process.			
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## **EXECUTIVE SUMMARY**

### ***PROJECT SUMMARY***

This research investigates the range of load-carrying capability of crushed aggregate base course (CABC) sources in the state of Wisconsin and how variables, such as physical characteristics, material type, source lithology and regional factors influence the load-carrying capability. Load-carrying capability was determined by calculating the resilient modulus values of sample materials in the laboratory (SHRP P46). The work was accomplished by dividing the state into nine geologic units and sampling and testing thirty-seven samples located throughout the state. Test results were statistically analyzed to characterize CABC load-carrying capability throughout the state and to determine if physical or geologic properties or regional factors can be used to predict the resilient modulus of a CABC. The test data also provides a base of information that will be useful when the Wisconsin Department of Transportation (WDOT) adopts a mechanistic-empirical pavement design process.

### ***BACKGROUND***

The State of Wisconsin uses approximately 10,000,000 tons of crushed aggregate base course (CABC) annually, primarily as a base course layer in its highway improvement projects. Source lithology and depositional histories of crushed aggregate base course in Wisconsin vary greatly and contribute to variations in quality. The state's source of CABC comes from two distinct geologic sources: stone quarries, and sand and gravel pits.

Crushed stone is the most important source of CABC in the state. The majority of the crushed stone used as crushed aggregate base course is produced in the southern approximately two-thirds of the state from a series of Ordovician, Silurian, and Devonian-aged sedimentary rocks consisting primarily of dolostone and limestone.

Sand and gravel pits are the other source of CABC in Wisconsin. The pits are found in deposits that were formed in two distinct depositional environments: glacial and fluvial. The most abundant types of deposits were formed as a result of glacial processes. Glacial deposits consist of a heterogeneous mixture of sedimentary, igneous, and metamorphic rocks. As the ice front retreated back toward Canada many rivers and streams were formed over, under, and in front of the wasting glacier. These rivers and streams transported and subsequently reworked many of the glacial deposits.

Current flexible pavement design methodology used by the State of Wisconsin is based on the structural number (SN) concept adopted from the 1981 revision of the AASHTO Interim Guide. This concept is a relationship between the thickness of each component layer of the pavement structure and the type of material that comprises the layer. At the present time, the statewide base course layer strength coefficient is 0.14 for crushed stone and 0.10 for crushed gravel. These coefficients were established based on the assumption that crushed aggregate from stone quarries has higher load-carrying capability than material from sand and gravel pits. Current  $k$ -values for rigid pavement design are estimated based on correlation to laboratory soil strength tests or soil types.

In later editions of the AASHTO Guide, each layer's strength coefficient in flexible pavement design and  $k$ -value in rigid pavement design is based on the resilient modulus of the material in that layer. The resilient modulus is a measure of the elastic properties of a material and is determined by dynamically loading the test specimen in a triaxial chamber under a confining pressure to simulate loading under traffic. It was selected for use in pavement design because, among other reasons, it indicated a basic material property that can be used in multi-layered pavement design and is internationally recognized as a method for characterizing materials for use in pavement design. The CABC resilient modulus will be required information for the upcoming WDOT mechanistic-empirical pavement design process.

OMNNI Associates of Appleton, Wisconsin, through the Wisconsin Highway Research Program, conducted the project. The Research Team included Paul R. Eggen, P.G.

(Principal Investigator), and Donald J. Brittnacher, P.E., P.G. (Investigator). The Project Committee, was chaired by Mr. Daniel D. Reid (WisDOT Central Office), and included Mr. Robert P. Arndorfer (WisDOT Central Office), Mr. Bruce J. Phister (WisDOT Central Office), Mr. Thomas F. Brokaw (WisDOT Central Office), Mr. Joseph V. White (WisDOT Central Office), Mr. Steven W. Krebs (WisDOT Central Office), Mr. Charles W. Orville (WisDOT District #1), and Dr. Bruce A. Brown (Wisconsin Geologic and Natural History Survey).

### ***PROCESS***

To accomplish the research objectives, samples were selected from groupings based on the origin of the materials. To determine the groupings, the Wisconsin Department of Transportation database of approved aggregate sources was reviewed, to observe trends of strength and durability parameters among samples based on location of the aggregate resource.

The WDOT database includes Los Angeles rattler (L.A.R.) wear test results for the majority of the approved sites. L.A.R. wear values are largely influenced by the hardness of the material, and serve as a good indicator of source lithology and degree of alteration or weathering. Differences in L.A.R. test data between bedrock formations were evident when the data was plotted on a state bedrock map. L.A.R. wear test results for sand and gravel pits were often considerably lower in the north and northwestern portions of the state than in the eastern portion of the state.

Since the visual results of the L.A.R. data corresponded with the various major geological groupings in Wisconsin, the sampling protocol for the present study was designed to reflect those groupings. A sampling plan was developed, in which the state was divided into six bedrock geologic regions and three sand/gravel deposit regions. The bedrock geologic regions generally were divided by age and lithology while the sand/gravel deposit regions were generally associated with glacial lobes.

Because of its extensive use, Wisconsin DOT Gradation Number 2 material was sampled from thirty-seven sources. Five samples were obtained from sources in the Eastern Wisconsin pit region and four samples were obtained from sources in each of the other pit and quarry regions.

A number of laboratory tests, including the laboratory resilient modulus test, were performed on each of the samples to determine physical properties and load carrying capability. Resilient modulus testing was performed on samples that were remolded to 95% of the Standard Proctor density at optimum moisture content by Braun Inertec of Edina, MN. A lithologic characterization scheme was developed and the lithology of each sample was characterized.

To analyze the effect of gradational changes on the resilient modulus of the CABC, 11 of the 37 samples were separated on the 12.5 mm, 9.5 mm and 4.75 mm sieves and recombined to produce two additional gradations. These gradations were blended so that, along with the as-sampled gradation, they produced three gradations that were generally on the fine, middle and coarse side of the WisDOT gradation no. 2 specified grading band. The gradation in the middle of the band was usually blended so that it followed the maximum density line of the FHWA .45 power curve as closely as possible. Resilient modulus testing was performed on samples that were remolded to 95% of the Standard Proctor density at optimum moisture content.

Upon completion of the testing phase, the data was reviewed to determine whether resilient modulus values tend to vary with geology, and whether any physical parameters can be used to predict the resilient modulus. A number of statistical techniques were used to determine relationships among the data.

### ***FINDINGS AND CONCLUSIONS***

The findings of this research were:

- a) The resilient modulus did not differ between pit and quarry groups.

- b) Carbonate quarries, as a whole, have significant higher resilient modulus values than Precambrian, felsic-plutonic quarries.
- c) Varying gradation of CABC from a given source results in changes in resilient modulus, but these changes are not consistently large or predictable.

Degree of saturation, foliated metamorphic content in the coarse fraction, 3:1 elongated coarse particle content, coefficient of uniformity and Proctor optimum moisture content influence resilient modulus values in some or all of the geologic subsets. However, none of the correlations were strong enough to predict resilient modulus with sufficient confidence.

There does not appear to be a single physical property, or combination of properties, which can be determined by simple and inexpensive testing, that can adequately predict resilient modulus of CABC.

We recommend that more resilient modulus testing be performed on CABC sources to provide a broader base of information from which to determine the range and variability of resilient modulus values for the various geologic formations present in the state. We also recommend that an analysis of the range of resilient modulus values encountered in the state to determine their effect on CABC layer thickness when used in a mechanistic-empirical pavement design. If CABC thickness is significantly affected by this variability, a method for selecting a design resilient modulus will need to be developed that will be an accurate reflection of the available CABC in any given area.

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## **I. INTRODUCTION**

Crushed aggregate base course is an important part of the pavement section, providing stability and protection against the effects of frost for the surface layer. The amount of base course needed in any particular road-building application is a function of the load-carrying capability of the base course and the underlying subgrade soils as well as the thickness of the overlying pavement. It is intended not only as a pavement support layer, but also as a stable working platform during the construction of the surface layer. To cost-effectively design road-building projects, the engineer needs an understanding of the load-bearing capabilities of the various aggregates available to the project from local quarries and pits. The Wisconsin road improvement program would benefit from a simple and inexpensive method of accurately estimating the load-carrying capability of any particular base course source.

### ***PURPOSE***

The purpose of this research was to determine the variability of load-carrying capability of CABC throughout the state and how variables such as gradation, angularity, source lithology and material type influence the load-carrying capability of CABC. An effort was made to determine whether there are any general trends in load-carrying capability based on broad groupings, such as whether the aggregate comes from a bedrock quarry or a sand and gravel pit, what the age of the quarry stone is, or which glacial lobe the pit material came from. A similar type of broad generalization presently exists in the design manual, which assumes that crushed quarry stone base course has a higher load-carrying capability than pit run sand and gravel base course.

A second purpose of this research was to identify which physical properties of base course materials, if any, can be used to predict the load-carrying capability of the material. Properties such as gradation, angularity, and material type were evaluated to determine their influence on the load-carrying capability of the aggregate.

## ***BACKGROUND***

### *--Use of Crushed Aggregate Base Course in Highway Design*

The State of Wisconsin uses approximately 10,000,000 tons of crushed aggregate base course annually, primarily as a base course layer in highway improvement projects. CABC is intended not only as a pavement support layer, but also as a stable working platform during the construction of the surface layer. Aggregate is produced from both stone quarries and sand and gravel deposits, and is therefore derived from materials with significantly different diageneses.

### *--Geology of Wisconsin Aggregate Resources*

Source lithology and depositional histories of CABCs in Wisconsin vary greatly and contribute to variation in physical properties and overall quality. The state's source of base course comes from two distinct geologic sources: stone quarries and sand and gravel pits.

Base course aggregate in Wisconsin is obtained primarily from carbonate quarries, where the material was formed in sea environments. This aggregate comes from a number of lithologies separated by millions of years: Prairie du Chien, Sinipee Platteville, Sinipee Galena, and Silurian. Each age represents a different depositional environment, and materials formed in the various ages have subsequently undergone different loading stresses, as well as fracturing and weathering processes. It would be expected that some differences in physical parameters or strength would occur because of these differences.

The bedrock geology of the state of Wisconsin is quite complex. The southern approximately two-thirds of the state is comprised of a thick series of Precambrian, Cambrian, Ordovician, Silurian, and Devonian-aged sedimentary rocks, including dolomites, limestones, shales, and sandstones. The northern approximately one-third of the state consists of a complex series of faulted and folded Precambrian and Archean-

aged intrusive igneous, metavolcanic, and metasedimentary rocks. These rocks include granites, gneisses, rhyolites, quartzites, anorthosites, and gabbros. Bedrock in southwestern Wisconsin, which is unglaciated, has undergone a different set of stresses, such as hydrothermal alteration, than similar bedrock types from glaciated portions of Wisconsin. (See Bedrock Geology of Wisconsin, Appendix 1)

A small amount of aggregate is also quarried in Wisconsin in Precambrian igneous and metamorphic bedrock locations. It would be expected that aggregate of this type would behave differently than carbonate aggregate.

Base course aggregate is also obtained from sand and gravel pits, where the material has been transported from another location, either by glacial or fluvial processes. The majority of marketable aggregate from Wisconsin sand and gravel pits is glacially derived. The Wisconsin Glaciation, the last of the major glacial events, was channeled into three major lobes as it flowed into the state from Canada. As the ice advanced, it scoured large amounts of previously deposited glacial drift as well as produced new material. The glacial material was deposited as unstratified and stratified drift. Unstratified glacial deposits include drumlins and moraines. Stratified deposits include eskers, kames, and outwash deposits. (See Glacial Lobes During the Wisconsin Glaciation, Appendix 1)

As the ice front retreated back toward Canada, many rivers and streams were formed over, under, and in front of the wasting glacier. These rivers and streams transported and subsequently reworked many of the above glacial deposits.

Pits in eastern Wisconsin contain gravel transported largely from carbonate parent material, while pits in northwestern and north central Wisconsin contain material derived primarily from Precambrian parent material. The transportation process causes rounding and sorting of material. It would be expected that some differences in physical parameters or strength would occur based on depositional history.

*--DOT/AASHTO Specifications and Design Requirements*

The current specification for crushed aggregate base course contains material requirements for soundness, wear, plastic limit and plastic index of fines (finer than 425  $\mu\text{m}$ ), crush count of the fraction retained on the 4.75 mm sieve, and gradation. During the time that base course sampling and testing was being performed for this study and up until November 2003, gradation requirements for crushed gravel and crushed stone were specified separately as gradation numbers 1, 2 and 3. Gradation number 2 (19.0 mm nominal maximum particle size) was typically required as crushed aggregate base course under the older editions of the Wisconsin DOT (WisDOT) Standard Specifications (1).

Since November of 2003, the WisDOT base course gradation specifications have been revised to 3-inch, 1 $\frac{1}{4}$ -inch and  $\frac{3}{4}$ -inch gradations (2). The 1 $\frac{1}{4}$ -inch gradation is typically required for the crushed aggregate base course layer. Soundness, wear, and plasticity tests are performed on each source at least every five years, while gradation and gravel crush count are performed during production and placement as a method of field control. Because of the relatively large range of gradation allowed within the specification, significant differences in particle size and grading can occur within each gradation designation.

Current flexible pavement design methodology used by the State of Wisconsin is based on the structural number (SN) concept adopted from the 1981 revision of the AASHTO Interim Guide (3). This concept is a relationship between the thickness of each component layer of the pavement structure and the type of material that comprises the layer. At the present time, the statewide base course layer strength coefficient is 0.14 for crushed stone and 0.10 for crushed gravel. An assumption has been made that material from quarries behaves the same, and material from sand and gravel pits behaves the same. The current method also assumes that material from a crushed stone quarry is stronger, requiring less thickness in the base course layer, than material obtained from a

sand and gravel pit. Current  $k$ -values for rigid pavement design are estimated based on correlation to laboratory soil strength tests or soil types.

In later editions of the AASHTO Guide, each layer's strength coefficient in flexible pavement design and  $k$ -value in rigid pavement design is based on the resilient modulus ( $M_R$ ) of the material in that layer (4). The resilient modulus is a measure of the elastic properties of a material and is determined by dynamically loading the test specimen in a triaxial chamber under a confining pressure to simulate loading under traffic. It is the ratio of the applied stress to the recoverable strain.

The Wisconsin Department of Transportation currently plans to adopt a mechanistic-empirical approach to pavement design when the upcoming AASHTO 2002 Pavement Design Guide becomes available. This method will also use the resilient modulus value for each layer in the pavement section to determine the thickness of each individual layer in the section.

This present study is intended to provide a baseline of information that can be used in the development of mechanistic-empirical pavement design in Wisconsin.

#### *--Measurement of Pavement Support*

For the purpose of measuring in the laboratory the ability of each crushed aggregate base course material to provide pavement support and load distribution, the resilient modulus test of unbound materials (SHRP Protocol P46) was used for this study. Several reasons for choosing this test exist. First, the test uses a repeated dynamic loading under stress, which more closely simulates traffic loads than other laboratory tests. In addition, it is currently used in the 1993 AASHTO pavement design guide for calculating layer coefficients and  $k$ -values, as well as in mechanistic-empirical pavement design, and is widely used both nationally and internationally. This allows us to benefit from other research that has been conducted on the relationship between CABC properties and its ability to provide pavement support.

Also, the resilient modulus test is performed on laboratory compacted samples, which can be prepared to produce test samples of known gradation, lithology and angularity. Finally, the test can be performed at a predetermined moisture content and unit weight to better approximate the expected service conditions and reduce the variations in test results that would be introduced by varying levels of compaction and moisture contents.

#### *--Recent Research*

Because AASHTO has based layer coefficient and  $k$ -value on the resilient moduli of the component layers in the pavement structure since the 1985 edition of its design guide, most of the recent research available on crushed aggregate base course strength has focused on the effect that various factors have on  $M_R$ . Research work done in Oklahoma has explored the relationships between aggregate moisture, gradation and compaction method and the resilient modulus of six different commonly used aggregates (5). Statistical correlations have been made between resilient modulus and the California bearing ratio (CBR) value, as well as cohesion and friction angles. In general, the research indicates that the resilient modulus is affected by stress state, material type, gradation, angularity, particle shape, moisture content, and degree of compaction (5,6,7,8).

#### ***OBJECTIVES***

This study of base course aggregates in Wisconsin has three objectives. The first objective is to determine if the resilient modulus is influenced by the crushed aggregate base course material type, source area and/or geology. Secondly, based on the results of sampling and testing, efforts were made to determine if the resilient modulus is influenced by commonly measured physical properties such as gradation, angularity or hardness. Finally, if strong enough correlations existed, a method would be devised to

predict the resilient modulus of a base course aggregate, at an acceptable level of confidence, based on correlations to source area, geology and/or physical properties.

## **II. METHODS USED IN THIS STUDY**

### ***SELECTION OF SOURCES AND SAMPLING***

To accomplish the objectives of this study, a sampling protocol was designed to select base course materials representative of the various aggregate sources in Wisconsin.

#### *--Review of Aggregate Resources*

The design called for the selection of samples from groupings based on the origin of the materials. To determine the groupings, the Wisconsin Department of Transportation database of approved aggregate sources was reviewed, to observe trends of strength and durability parameters based on location of the aggregate resource.

The database contains test results for the Los Angeles rattler test and the sodium sulfate soundness test for the majority of aggregate sources approved for use on D.O.T. projects. It also includes freeze/thaw test data and chert content information for a number of the carbonate bedrock quarry sources. Because test results were available for all aggregate sources qualified by the Wisconsin Department of Transportation, the L.A.R. test and the sodium sulfate soundness test results were the two tests of base course strength and durability that were used to help determine these groupings.

The L.A.R. data from quarry sources was plotted on a state bedrock map, and the L.A.R. data from sand and gravel pits was plotted on a state glacial geology map. Data for each group was divided into three relatively equal-sized groups, i.e., the lowest L.A.R. values were coded in one color, the intermediate L.A.R. values in another, and the highest L.A.R. values in a third color. The correlation between L.A.R. value and geology was

quite apparent from the mapping of both quarry and pit data. (See Quarry L.A.R. Results, and Pit L.A.R. Results, Appendix 1)

Because the L.A.R. wear test results are largely influenced by the hardness of the material, the test data serves as a good indicator of source lithology and degree of alteration or weathering. Differences in L.A.R. test data between bedrock formations were evident when the data was plotted on a state bedrock map. Test data from the Precambrian plutonic igneous bedrock sources located in the central portion of the state were noticeably lower than data from the carbonate bedrock sources. Also, L.A.R. values of carbonate sources from the Ordovician-aged Sinnipee group and Silurian-aged Niagara formation in the eastern portion of the state were noticeably lower than the Sinnipee group and Prairie du Chien formation in the western and southern portions of the state.

L.A.R. values for sand and gravel pits located in stratified and unstratified glacial drift were considerably lower in the north and northwestern portions of the state than in the eastern portion of the state. This difference is a reflection of the difference in lithology between the predominantly igneous/metamorphic lithology of the aggregates deposited by the Wisconsin Valley, Langlade, Superior and Chippewa Lobes of the Wisconsin glaciation in the north and northwestern portions of the state, and the predominantly carbonate lithology of the aggregates deposited by the Green Bay and Lake Michigan Lobes in the eastern portion of the state.

The sodium sulfate soundness data were similarly plotted and reviewed. Unlike the L.A.R. data, no visual trends based on geology were apparent from the plots of S.D.S. values.

#### *--Formation of Geologic Units*

Since the visual results of the L.A.R. data corresponded with the various major geological groupings in Wisconsin, the sampling protocol for the present study was designed to

reflect those groupings. A sampling plan was developed, in which the state was divided into the following groupings.

The quarries were divided into the following six sampling regions:

1. Eastern Wisconsin; Niagaran bedrock
2. Eastern Wisconsin; Sinnipee bedrock
3. Southwestern Wisconsin; unglaciated Sinnipee bedrock
4. Southwestern Wisconsin; unglaciated Prairie du Chien bedrock
5. Western Wisconsin; Prairie du Chien bedrock
6. Central Wisconsin; Precambrian bedrock

The pits were divided into the following three sampling regions:

1. Eastern Wisconsin; Green Bay/Lake Michigan Lobes
2. North central Wisconsin; Wisconsin Valley/Langlade Lobes
3. Northwestern Wisconsin; Superior/Chippewa Lobes

The sampling protocol was limited by budget to no more than 40 test locations. The plan called for taking four samples from each of the above nine groups for extensive testing.

#### *--Selection of Sources*

Because of its extensive use at the time of sampling, the gradation number 2 crushed aggregate base course from the 1996 edition of the WisDOT Standard Specifications for Highway and Structure Construction was used for this research. The actual sample locations were determined from a second list of aggregate sources supplied by the Department of Transportation. This list consisted of active sources that were thought to have stockpiles of gradation #2 crushed aggregate base course available for sampling. Because many of the WisDOT qualified pits and quarries did not produce crushed aggregate base course or had none available at the time, the list was quite small. While the mapping often contained 50 or more aggregate sources within sampling units, the list of available sources usually contained less than eight. Selection of sample locations,

therefore, consisted of going down the list, calling operators, and setting up sampling events based at four locations available within a given unit. In each geologic unit, an effort was made to spread the sampling out geographically and also across the range of L.A.R. wear test values.

The final set of sampling locations included 24 quarries and 13 sand and gravel pits. (See Quarry Site Locations, and Pit Site Locations, Appendix 1)

#### *--Field Sampling Protocol*

Crushed aggregate base course was sampled from a total of 37 sources. Aggregate samples were primarily obtained from the working face of existing stockpiles located at the aggregate source quarry or pit, and were sampled in general accordance with Section 13.4.4 of the Wisconsin Department of Transportation's Construction and Materials Manual. Approximately 400 pounds of sample was obtained from each source. When available, an end loader was used to cut into the working face of the stockpile at the quarter points of the pile working face. When no end loader was available, the sample was obtained by hand at the 1/3 and 2/3 level at the quarter points of the pile working face.

OMNNI received assistance in obtaining samples from a few locations. The Kraemer Company provided samples from the Myklbust pit, and the Clockmaker, Householder, Marsalek, Wetzel quarries. The sample from the Moser quarry was obtained from the end of the conveyor belt during aggregate production.

### ***LABORATORY TESTING AND GEOLOGIC EVALUATION***

#### *--Laboratory Testing*

Data from laboratory testing was obtained for each source from the Wisconsin Department of Transportation database of approved aggregate sources and from testing

performed on the obtained samples. To obtain as much basic information on the physical properties of the CABC samples, many of the tests normally performed by most private and WisDOT laboratories were performed. These tests included gradation, crush count, flat and elongated particles, specific gravity and absorption, fine aggregate angularity, sand equivalency and Standard Proctor. The reasons for performing these tests were twofold. First, they are relatively easy and inexpensive to perform and provided data on the physical characteristics of the CABC. Secondly, the test data may provide information that would correlate to the resilient modulus result, thereby providing an inexpensive means to estimate resilient modulus values for any given CABC source. (See Source information and Test Data Table, Appendix 3)

Field samples were reduced to testing size in accordance with AASHTO T248. Representative portions of the samples were sent to the WisDOT Central Laboratory in Madison, WI for Micro-Deval testing and to Braun Inertec in Edina, MN for resilient modulus testing. L.A.R. wear and sodium sulfate soundness tests were not performed on the obtained samples because this information was available from WisDOT for all sources from source qualification testing. The following laboratory tests were performed:

*WisDOT Central Laboratory – Source Qualification Testing*

AASHTO T96	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
AASHTO T104	Soundness of Aggregate by Use of Sodium Sulfate of Magnesium Sulfate

*OMNNI Associates – Obtained Samples*

AASHTO T11	Materials Finer than the #200 Sieve
AASHTO T27	Sieve Analysis of Aggregates
AASHTO T99	The Moisture-Density Relations of Soils Using a (2.5 kg) 5.5 lb. Rammer and a (305 mm) 12 in. Drop
ASTM C128	Specific Gravity and Absorption of Fine Aggregates
ASTM C127	Specific Gravity and Absorption of Coarse Aggregates

AASHTO T304	Uncompacted Voids Content of Fine Aggregates (FAA)
ASTM D4791	Flat and Elongated Particles in Coarse Aggregate
WisDOT C&M Manual	Fractured Particles

*WisDOT Central Laboratory – Obtained Samples*

AASHTO TP58-02	Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
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*Braun Inertec, Edina, MN – Obtained Samples*

SHRP P46	Resilient Modulus Test
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Resilient modulus tests were performed on all samples obtained at the gradation at which they were sampled. The laboratory resilient modulus test involves applying an axial stress to a sample, which is also undergoing confining pressure. The test is run under 15 predetermined combinations of axial stress and confining pressure conditions. Resilient modulus test samples were remolded to a 6-inch diameter and a height of approximately 12 inches and tested on a MTS 858 Table Top Load frame using a load cell with a 5,500-pound capacity. At the end of the resilient modulus test sequence, a triaxial shear test was performed on each sample. Tests were performed at optimum moisture and approximately 95% of the maximum Standard Proctor density.

It was necessary to maintain the same level of compaction and relative moisture content between sources to determine the effect of lithology, gradation, angularity and particle shape on the resilient modulus. Optimum moisture was selected for the resilient modulus test because it is likely to be on the upper end of the typical in-place CABC moisture content range. A test density of 95% of the Standard Proctor density was chosen because it is the lowest level of compaction at which a CABC should be placed, thereby producing a conservative resilient modulus result for each material at the optimum moisture content.

In some of the tests performed, there was a loss of moisture during the resilient modulus testing because of water draining from the sample. In these cases, Braun Intertec determined the moisture content both before and after testing and included both values on the test report. In these cases, the moisture content values shown is an average of the two moisture contents. (See Source information and Test Data Table, Appendix 3)

The resilient modulus test provides test results for each of the 15 predetermined combinations of axial stress and confining pressure conditions. To represent the material response to each of these stress conditions, the 15 resilient modulus test results for each sample was plotted against the corresponding bulk stress ( $\theta$ ). Because the constitutive model that will be used for mechanistic-empirical pavement design by the Wisconsin DOT has not yet been determined, the existing constitutive model for coarse-grained material found in the 1993 AASHTO Design Guide was used to determine the resilient modulus at any given stress state. This model uses the equation:

$$M_R = K_1 (\theta)^{K_2}$$

(See As-received Grading FHWA.45 Power Curves and Resilient Modulus vs. Bulk Stress Curves – All Sources, Appendix 4)

To analyze the effect of gradational changes on the resilient modulus test result, 11 of the 37 samples were separated on the 12.5 mm, 9.5 mm and 4.75 mm sieves and recombined to produce two additional gradations. These gradations were blended so that, along with the as-sampled gradation, they produced three gradations that were generally on the fine, middle and coarse side of the WisDOT gradation no. 2 specified grading band. The gradation in the middle of the band was usually blended so that it followed the maximum density line of the FHWA 0.45 power curve as closely as possible. Both maximum particle size and the coarseness of the gradation were limited by the requirements of the Proctor test. The test is limited to material with a 19 mm maximum particle size and the gradation cannot be so coarse that it no longer produces a well-defined moisture-density curve. (See Re-blend Test Data Table, Appendix 3)

Two of the four samples blended from pits had gradations that were finer than the specification limits and did not have enough coarse aggregate material in the sample to produce a blend that was on the coarse side of the gradation band. For these two samples, one additional gradation was blended to closely follow the maximum density line of the FHWA 0.45 power curve, and another was blended to be on the fine side of the specification band. Standard Proctor tests were performed on all of the blends, and resilient modulus testing was performed at 95% of the Proctor maximum dry density at optimum moisture content. (See Re-blend Test Data Table, Appendix 3 and Re-blend FHWA.45 Power Curves and Resilient Modulus vs. Bulk Stress Curves, Appendix 4)

To quantify the overall deviation of each grading curve from the maximum density line when plotted on the FHWA 0.45 power curve, the density deviator index (DDI) was devised. This index is an accumulation of the distance from the maximum density line at each sieve size used to develop the gradation curve. The coefficient of uniformity, coefficient of curvature, as-tested void ratio, and as-tested degree of saturation were also determined from the test data. Because grain size distribution was determined through the 0.075 mm (#200) sieve, the coefficient of uniformity and coefficient of curvature values for eleven of the thirty-seven samples, for which the amount passing the 0.075 mm was over 10%, were calculated using estimated  $D_{10}$  values that were extrapolated from the grain size distribution curves. (See Source information and Test Data Table, Appendix 3)

#### *--Geologic Evaluation*

To geologically evaluate each source sampled, a lithologic characterization scheme was devised for fine and coarse aggregates. The purpose of the scheme was to provide a broad characterization of the lithology of the CABG samples that would not require extensive study or testing. The fine and coarse fractions were characterized separately because, in sand and gravel pits, the lithology of the two fractions can be very different.

In addition, characterizing fine aggregates based on the scheme devised for the coarse aggregates would be very difficult to impossible.

#### Characterization of Lithology of Coarse Fraction (Retained on #4 sieve)

The percentage by weight of the following components was determined:

1. *Felsic Plutonic*: granite, syenite, quartz monzonite, monzonite, granodiorite, syenodiorite and tonalite
2. *Mafic Plutonic*: diorite, gabbro and ultramafics
3. *Felsic Volcanic*: felsite and felsic tuff (ryolite, dacite)
4. *Mafic Volcanic*: basalt, andesite
5. *Siliclastics*: arenites, wackes, mudstones and iron formations
6. *Carbonates*: dolostone and limestone
7. *Non-foliated Metamorphic*: gneiss, quartzite
8. *Foliated (micaceous) Metamorphic*: pyllite, slate, schist

#### Characterization of Lithology of Fine Fraction (Passing the #4 sieve)

The percentage of each of the following components was estimated using a comparison chart for visual percentage estimation.

1. *Quartz*
2. *Carbonates*
3. *Feldspars*
4. *Other lithics*

All lithological characterizations were conducted visually, with the exception of the percentage of carbonates in the fine fraction. This was determined by dissolving the carbonate material from a small portion of the fine aggregate sample (approximately 20g) with hydrochloric acid. The carbonate percentage was determined by expressing the weight lost after the acid treatment as a percentage of the total sample weight prior to the acid treatment. (See Source information and Test Data Table, Appendix 3)

## *DATA REVIEW TECHNIQUES*

Upon completion of the testing phase, the data was reviewed to determine whether resilient modulus values vary with geology, and whether any physical parameters can be used to predict resilient modulus values. A number of statistical techniques were used to determine relationships among the data. As with all statistical techniques, the strength of any conclusions made based on the analyses is directly related to the sample size.

Because of the limited number of samples in this study, any discussion of trends must be entered into with a degree of caution. Within this study, observations made on larger subsets of data should enjoy more stature than those made on smaller data sets.

Initial review of data involved simple plots, which were useful in showing general relationships among sampling data. Viewing two-dimensional plots of large data sets will often provide an indication of what the overlying population encompassing the sample data might look like.

The analysis of variance (ANOVA) test was used to determine the likelihood that two or more groups of sample data belong to the same population, and therefore have similar properties. ANOVA testing was used to determine the likelihood that crushed aggregate from various parts of the state would behave similarly under load-bearing conditions. Samples were grouped based on geological source, and ANOVA testing was performed on the resilient modulus values of the various groups to detect any differences in strength based on geology.

Boxplots were used to provide a simple visual picture of how the data in sample sets were grouped. Typically, the boxplot includes a box around the interquartile range of a data set, with the box bottom at the 25<sup>th</sup> percentile and the box top at the 75<sup>th</sup> percentile. A line is placed within the box at the data set's median value. When boxplots for various data sets are plotted alongside each other on the same scale, the likelihood that the data sets belong to the same population can be estimated. As with ANOVA testing, the size of

the sample set dictates the confidence one has in making estimates from comparing boxplots.

Correlation coefficient analyses were performed on all the test results to measure the strength and direction of the linear relationship between pairs of tests. The values of the correlation coefficient can range from -1 to +1. If there is no linear relationship between two variables, the value of the coefficient is 0. If there is a perfect positive relationship, the value is +1, while a value of -1 indicates a perfect negative relationship. A value above 0.7 means high positive correlation, and a value below -0.7 means high negative correlation.

Regression analysis was used to determine whether certain physical parameters of crushed aggregate appear to produce stronger load-bearing properties. In simple linear regression, a scatter plot of all the pairs of data – physical parameters and resilient modulus values – is plotted, and the best fitting straight line is drawn. The closer the line fits all the data points, the stronger the relationship between the physical parameter and its resultant resilient modulus value.

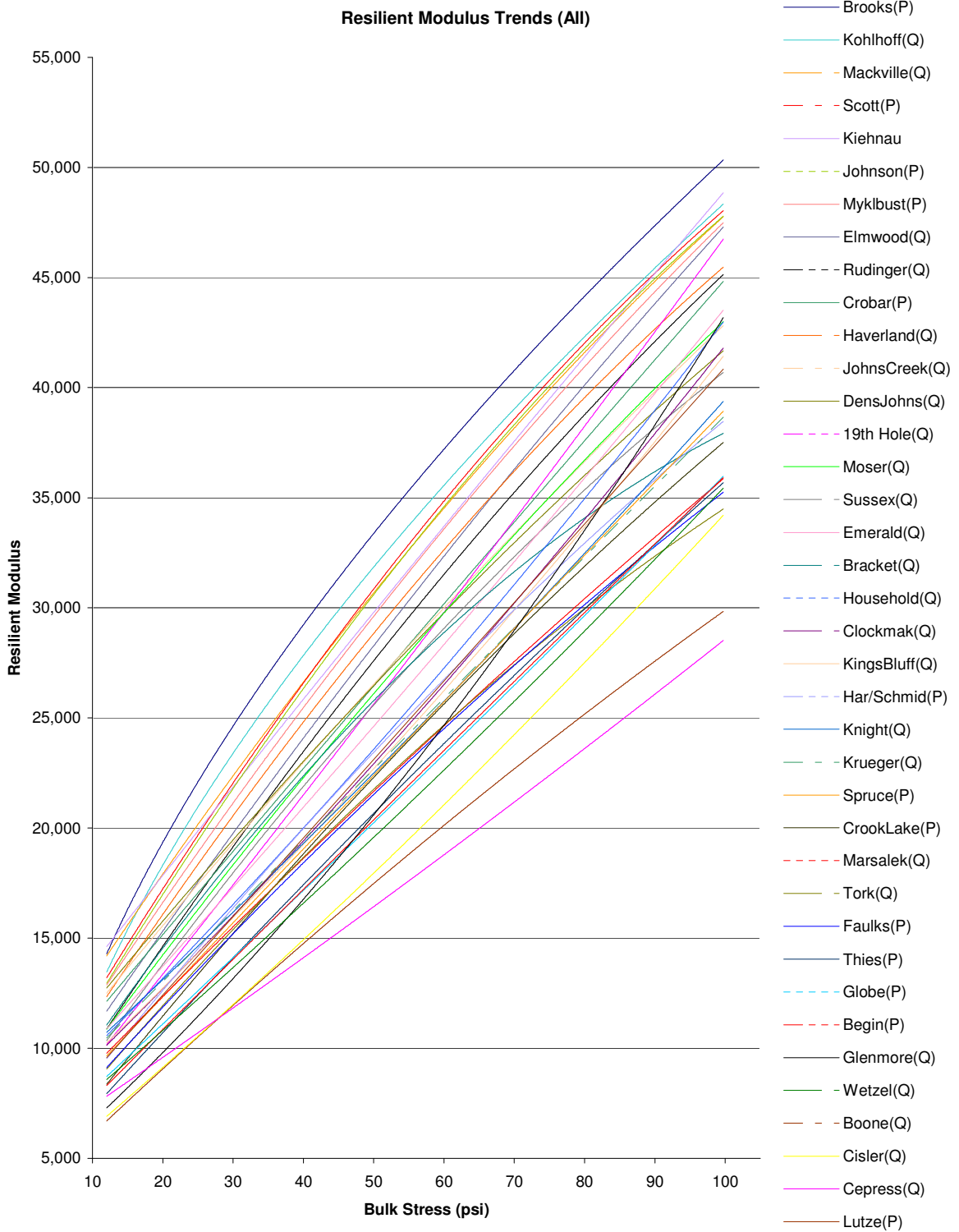
Multiple regression analysis was also performed, to determine how well combinations of physical parameters could be used to predict resilient modulus values.

### **III. DISCUSSION**

#### ***GENERAL TRENDS IN RESILIENT MODULUS VALUES***

##### *--General trends in resilient modulus values based on geology*

The complete set of laboratory test results for the 37 samples was plotted. In viewing the plot, the quarry and pit data appear intermingled. (See Figure 1 – Resilient Modulus Values for All Samples.) The plot indicates that quarry stone as a group is as likely as pit material to exhibit high, intermediate, or low load-bearing strength.



**Figure 1 – Resilient Modulus Values for All Samples**

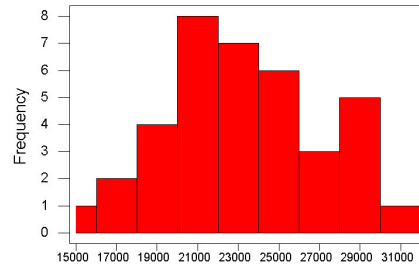
The order in which the various samples appear on the plot remains relatively consistent as increased stresses are placed on the samples. Samples with relatively low resilient modulus values under lower stress conditions have relatively low resilient modulus values under higher stress conditions, in comparison to the other samples. Therefore, during further trend analysis of the data, the average resilient modulus value produced by the laboratory testing was used.

The quarry data was compared with the pit data. Histograms and boxplots were drawn of average resilient modulus values. (See Histograms 1 – 3, and Boxplots 1 – 3.)

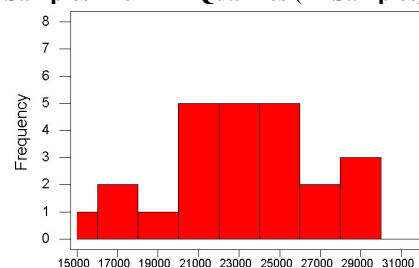
No significant differences were apparent. These results were confirmed, using ANOVA statistical tests.

The quarry data was further broken down into carbonate quarry and non-carbonate quarry fractions. Histograms and boxplots were drawn of the resilient modulus values for the two groups. (See Histograms 4 – 5, and Boxplots 4 – 5.) The three lowest resilient modulus values belonged to samples taken from non-carbonate quarries. The mean resilient modulus value for the non-carbonate quarries is significantly lower than the mean values for the other groups. These results were confirmed, using ANOVA statistical tests.

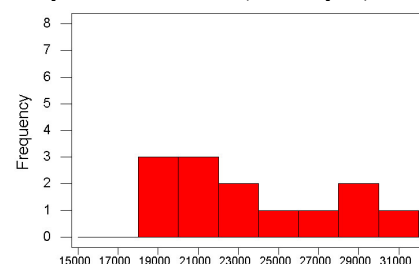
**Histogram 1 – Resilient Modulus Values (psi) of Samples From All Quarries and Pits (37 Samples)**



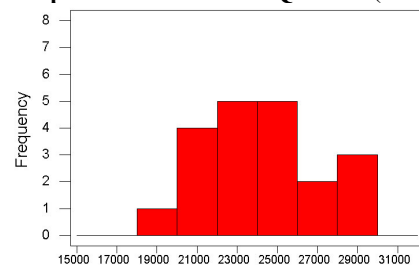
**Histogram 2 – Resilient Modulus Values (psi) of Samples From All Quarries (24 Samples)**



**Histogram 3 – Resilient Modulus Values (psi) of Samples From All Pits (13 Samples)**

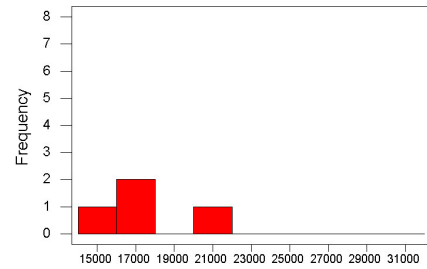


**Histogram 4 – Resilient Modulus Values (psi) of Samples From Carbonate Quarries (20 Samples)**



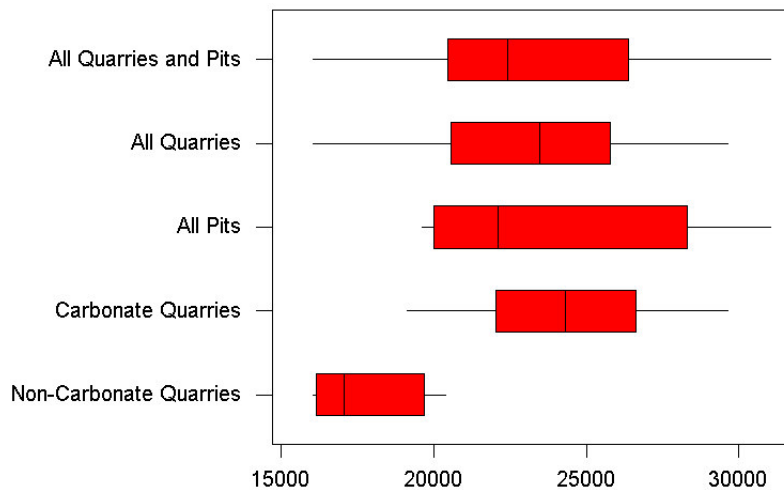
The data was further broken down into the six bedrock types and three geological lobes within the study. Boxplots were drawn of the resilient modulus values for the nine groups. (See Boxplots 6 – 14.) ANOVA testing was carried out to compare the mean resilient modulus values for the bedrock types and geological lobes.

**Histogram 5 - Resilient Modulus Values (psi) of Samples From Non-Carbonate Quarries (4 Samples)**

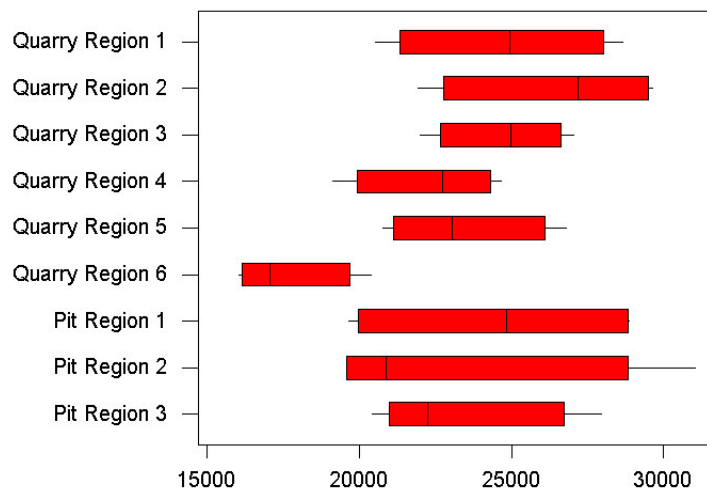


Due to the low number of data points within each group, care must be taken in evaluating the ANOVA results. The results identified that the non-carbonate resilient modulus data is significantly lower than the values from any other group.

**Boxplots 1 - 5 – Resilient Modulus Values (psi) of Samples**



**Boxplots 6 - 14 – Resilient Modulus Values (psi) of Samples**



The resilient modulus values from the 37 sample locations were sorted and divided into quartiles. Sample locations with values within the lowest and highest quartiles were plotted on State of Wisconsin bedrock and glacial maps. Again, the pattern of low resilient modulus values at the non-carbonate quarries was apparent.

The assumption that resilient modulus values of quarry material are generally higher than those of pit material is not substantiated by this data. Quarry stone, as a whole, does not appear to bear loads significantly better than pit gravel, as a whole, as measured by the resilient modulus test. Rather, with the exception of aggregate from non-carbonate quarries, it appears that materials from base course sources in Wisconsin exhibit a range of load-carrying capabilities, and, based upon the limited sampling performed in this study, this range is not influenced significantly by the geological source of the material.

*--General trends in the physical properties based on geology*

The analysis of variance test was used to detect differences in aggregate quality between quarries and pits, among the various lithologies in bedrock quarries, and among the different gravel pit locations, based on the glacial lobes transporting the material to them.

In comparing the quarry data with the pit data, variations between aggregate base course physical properties were observed. The following physical parameters varied significantly between the two groups:

- Gravel pit material contained higher concentrations of mafic-plutonic, felsic-volcanic, mafic-volcanic, siliclastic, foliated metamorphic, and non-foliated metamorphic material in the coarse fraction, and higher concentrations of quartz and lithics in the fine fraction. Quarry material contained higher carbonate concentrations in both fractions. This reflects the fact that most of the quarries in Wisconsin are located in sedimentary carbonate formations, while gravel pits often contain significant amounts of glacial drift that was derived from igneous and metamorphic parent rock.

- Variations occurred in grain-size analysis. Pit material passed higher fractions of 1/2-inch, 3/8-inch, #4, and #10, while quarry material passed a higher #100 fraction. The coefficient of uniformity of quarry material was significantly higher than that of pit material.
- Quarry samples showed higher triaxial shear strength and L.A.R. wear values.
- Quarry material showed higher values for uncompacted void content (method A), optimum moisture content during proctor testing, average % moisture during resilient modulus testing, and void ratio during resilient modulus testing. This is likely a result of the higher angularity of the crushed stone base course produced from the quarries. In crushed count determinations, quarry material showed higher one-faced particles and lower rounded particles.
- Pit material showed higher values for sand equivalence, bulk specific gravity of the coarse fraction, maximum dry density during proctor testing, and dry density during resilient modulus testing.

Resilient modulus values did not vary significantly between quarry and pit samples.

In reviewing the quarry data alone, regional patterns in the physical parameters of the aggregate samples were observed. Much of the variation in physical parameters found in reviewing the test results is a result of including the Precambrian quarry aggregate with the later carbonate stone:

- Precambrian quarry samples showed higher felsic plutonic, mafic plutonic, siliclastic, and non-foliated metamorphic concentrations in the coarse fraction, and higher quartz, feldspar, and lithic contents in the fine fraction. Carbonate locations showed higher carbonate concentrations in both the coarse and fine fractions.

- Resilient modulus, Micro-Deval, and L.A.R. wear values were lower for Precambrian quarries than for carbonate locations.
- Crush counts showed higher concentrations of rounded material in region 4, the unglaciated Prairie du Chien, and lower concentrations of one-faced and two-faced material in the samples tested from that region.
- There were regional differences for uncompacted void content (methods A and C), bulk specific gravity in both the coarse and fine fractions, absorption in the coarse fraction, and average % moisture during resilient modulus testing.

If the Precambrian quarry data is removed from the quarry data set, and the carbonate quarries (which include the bulk of aggregate resources in Wisconsin) are viewed alone, the physical parameters showed much more consistency among the quarries, regardless of the age of the stone in the quarry. If only carbonate quarries are viewed, the following physical parameters varied significantly, based on the age of the dolostone:

- Crush counts showed higher concentrations of rounded material in region 4, the unglaciated Prairie du Chien, and lower concentrations of one-faced and two-faced material in the samples tested from that region.
- There were regional differences for uncompacted void content (methods A and C), average % moisture during resilient modulus testing, and bulk specific gravity and absorption in the coarse fraction.
- There were also regional differences in Micro-Deval test results.

Resilient modulus values did not vary significantly based on the region of the bedrock quarry.

In reviewing the gravel pit data alone, regional patterns in the physical parameters of the aggregate samples were observed, based on depositional processes and parent material. The following physical parameters varied, based on the location of the pit:

- The gravel pits in eastern Wisconsin, located in the Green Bay and Lake Michigan lobes, contained higher carbonate concentrations in the coarse and fine fractions. The eastern pits also contained lower mafic volcanic and siliclastic content in the coarse fraction, and lower lithic content in the fine fraction.
- L.A.R. wear values were higher for the eastern pits.
- There were also significant regional differences for felsic volcanic and non-foliated metamorphic content in the coarse fraction, grain-size (passing the  $\frac{3}{4}$ -inch sieve) and elongation (3:1, face).

Resilient modulus values did not vary significantly based on the region of the sand and gravel pit.

*--Physical properties of base course materials which influence resilient modulus values*  
Correlation coefficient analyses were performed on all test results, to determine whether any physical parameters would be useful in predicting the resilient modulus value of a base course sample. (See Correlations Among Physical Test Results for All Pits and Quarries, Appendix 2)

Four different data sets were viewed: all the data from all quarries and pits, only the data from the quarries, only the data from the carbonate quarries, and only the data from the pits. The data provides a wealth of information regarding correlations among aggregate physical parameters. (See Correlations Among Physical Tests From Pit, Quarry and Carbonate Quarry Samples, Appendix 2)

Based on the limited number of samples in the study, there were only two physical parameters identified that were highly correlated with the resilient modulus value. In the data set including all quarries (including both carbonate and non-carbonate quarries), the resilient modulus values were highly correlated with quartz and carbonate concentrations in the fine fraction. Resilient modulus values of quarry samples tend to increase with carbonate concentrations and decrease with quartz concentrations.

With the above exception, no other individual parameters were found which were highly correlated with the resilient modulus value. Individual physical parameters do not seem to be good predictors of resilient modulus values.

The correlation coefficient analyses also provided valuable information concerning the direction of correlation between parameters. Although in many instances the strength of the relationship between parameters in data sets was insufficient to support a finding of correlation, nevertheless the sign of the correlation coefficient provided information regarding whether the parameters tended to behave in a direct or inverse fashion. The correlation tables provided a broad picture of the crushed aggregate base course resource in Wisconsin.

To gain a better understanding of whether multiple physical parameters interacting together might be useful in predicting the resilient modulus value of a sample, a “multiple regression analysis” was performed. The “stepwise regression” procedure was used, which allows one to determine the predictive ability of multiple sets of parameters.

The following data sets were reviewed: all quarries and pits combined, quarries alone, carbonate quarries alone, and pits alone.

The multiple regression analyses identified subsets of parameters with predictive value. Of particular interest were subsets capable of explaining at least half of the variability of the resilient modulus values obtained. These parameter groupings influence the resilient modulus values to an extent, although there still remains significant variability in the resilient modulus values, which cannot be explained or predicted by the parameter subsets.

The stepwise regression procedure identified that, for the data set involving all quarries and pits, the sample’s degree of saturation and its foliated metamorphic content in the coarse fraction are useful in predicting resilient modulus behavior. The resilient modulus values of the samples in the data set of all quarries and pits tend to go up as the degree of saturation goes down and the foliated metamorphic content in the coarse fraction goes up.

For the data set including only the quarries, the stepwise regression analysis identified that the quartz content in the sample's fine fraction influences its resilient modulus. This confirms trends identified earlier during correlation analyses of pairs of parameters, and reflects the lower resilient modulus results obtained from the Precambrian bedrock sources, which have a higher quartz content in the fine fraction. The resilient modulus values of samples in this data subset tend to go up as the quartz content in the fine fraction goes down.

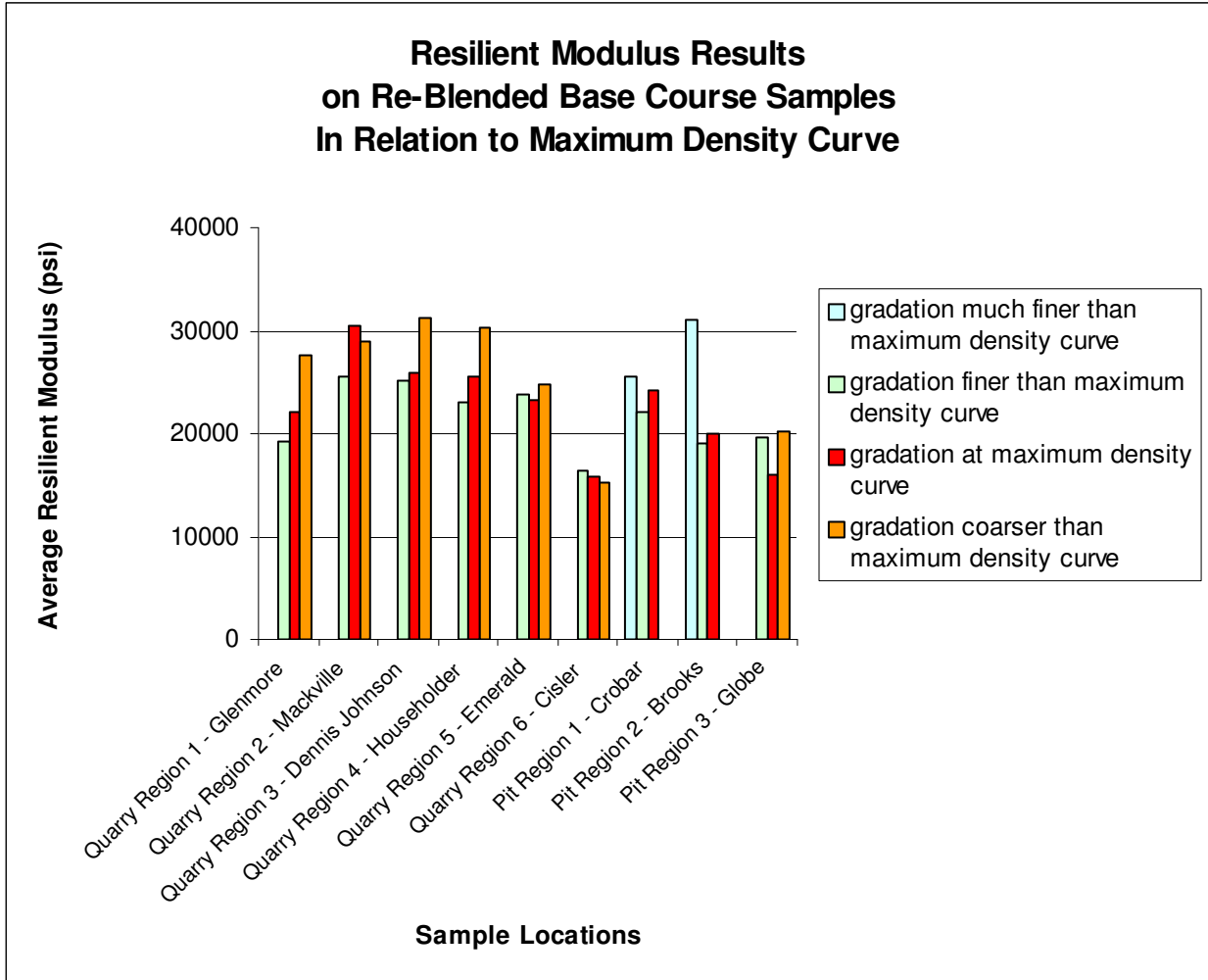
For the data set including only the carbonate quarries, the stepwise regression analysis identified that the resilient modulus values tend to go up as the degree of saturation goes down and the elongation (3:1, elong.) goes up.

For the data set including only the pits, the best subset of physical parameters for predicting the resilient modulus values within the pit samples includes the coefficient of uniformity and Proctor optimum moisture content. The resilient modulus values tend to go up as the coefficient of uniformity and optimum percent moisture during the proctor go down.

*--Effect of Gradational Changes*

Test results from the eleven samples, from which additional resilient modulus testing was performed on samples from each source, which had been blended with varied gradations, indicate that, for any given source, changes in material grading will affect the average resilient modulus. (See Resilient Modulus Result on Re-blended Base Course Samples in Relation to Maximum Density Curve, Figure 2 below and Re-blended Sample Test Data, Appendix 3)

Figure 2



However, this limited amount of data also indicates that the change in resilient modulus within a source, due to gradational changes, varies between sources and that the direction of change is not predictable. Six of the sources had highest resilient modulus test result from the gradation that was blended to be on the coarse side of the gradation specification band. Four of the sources had the highest resilient modulus test result from the gradation that was blended to be on the fine side of the gradation specification band and one of the sources had the highest resilient modulus test result from the gradation that was blended to be in the middle of the specified gradation band, closely follow the FHWA .45 power curve maximum density line.

The range in the resilient moduli for each source, as expressed by the lowest average resilient modulus as a percentage of the highest average resilient modulus was, on average, lower for pits than it was for quarries. On average, the lowest value was 74% of the highest value for pits and 84% for quarries, indicating a greater range of resilient moduli between the tests performed for each pit source. This may be an indication that CABC produced from sand/gravel pits are affected by gradational changes more than materials produced from quarry sources. In addition, the highest average resilient modulus for three out of the four pit sources tested were obtained from gradations that were near or above the gradation specification upper limit. However, because only a small number of samples were tested and two of the pit sources were not tested with gradations on the coarse side of the specification range, it is difficult to accurately assess the affect that gradational changes has on the resilient modulus of CABC produced from sand/gravel pits.

In addition to having a lower range of average resilient modulus test values between the tests performed for source, five out or seven quarry sources obtained the highest average resilient modulus from gradations that were blended on the coarse side of the specification band.

A number of physical properties were determined for each gradation blend under the conditions at which the resilient modulus test was performed. These physical properties include coefficient of uniformity, coefficient of curvature, density deviator index, degree of saturation, and void ratio. Table 1, below, shows the number of sources in which the highest resilient modulus was obtained at the lowest, middle or highest value for each of the physical properties shown.

Table 1

<b>NUMBER OF SOURCES WITH THE HIGHEST RESILIENT MODULUS</b>			
	<i>TEST VALUE RATING</i>		
<b>Test</b>	<b>Low</b>	<b>Middle</b>	<b>High</b>
Coefficient of Uniformity	8	2	1
Coefficient of Curvature	6	2	3
Density Deviator Index	1	4	6
Degree of Saturation	3	7	1
Void Ratio	5	2	4

Although the limited amount of data makes the identification of trends uncertain, the inverse correlation between degree of saturation and resilient modulus observed when all pit and quarry data were analyzed was not apparent in the re-blended sample data. Only three out of eleven sources had the highest resilient modulus result from the gradation that resulted in the lowest degree of saturation. It should be noted that the variations in degree of saturation observed were a result of changes in gradation and optimum moisture content. Changes in degree of saturation in material from a given source with similar gradation and density, but varied moisture content may yield different results.

The inverse correlation between coefficient of uniformity and resilient modulus that was observed when all pit data and carbonate quarry data was analyzed is evident in the re-blended sample data. Eight out of eleven sources had the highest resilient modulus result from the gradation with the lowest coefficient of curvature.

No evidence of correlation between resilient modulus and coefficient of curvature, density deviator index and void ratio was observed from the limited amount of data obtained from varying the gradation of samples from eleven sources.

## IV. CONCLUSIONS AND RECOMMENDATIONS

### *RESILIENT MODULUS TEST DATA ANALYSIS*

The resilient modulus test results did not differ significantly between the quarry and pit groups. Quarry stone, as a whole, does not appear to vary significantly from pit gravel, as a whole, as measured by the resilient modulus test.

The resilient modulus test results differed significantly among the quarry groups. Carbonate quarries, as a whole, have significantly higher resilient modulus values than Precambrian quarries.

The resilient modulus test results did not differ significantly among the carbonate quarry groups or the sand and gravel pits. The age of carbonate stone does not appear to influence its resilient modulus value, and does not seem to be a useful indicator. Among the gravel pits, the parent material does not appear to influence the aggregate's resilient modulus value.

The only regional or depositional indicator of an aggregate's resilient modulus value is that Precambrian quarry stone, as a whole, has a lower resilient modulus value than the rest of the sampled locations. Greater hardness and cleavage planes in the feldspars that dominate the mineralogy of the Precambrian plutonic rocks in the central portion of the state may be the cause of their lower resilient modulus values. The combination of harder rock particles with smooth surfaces may result in lower friction between particles and greater permanent strain when placed under a repeated load.

Varying gradation within a source did affect the resilient modulus of the CABC from a given aggregate source. However, it was determined that varying the gradation of a limited number of selected samples, generally within the WisDOT CABC gradation no. 2 specification band, did not result in consistently large or predictable differences in resilient modulus test results in a given source. Marginally higher resilient modulus test results obtained from varied gradations from within the majority of quarry sources were

observed when the gradation was near the coarse side of the specification range. In addition, only one of the eleven sources, in which gradation was varied, had the highest resilient modulus value result from the gradation that was blended to be in the middle of the specified gradation range, closely follow the FHWA .45 power curve maximum density line. As the gradation for each source was altered, an inverse correlation between coefficient of uniformity and resilient modulus was observed in the majority of the samples.

In attempting to isolate a set of physical parameters useful in predicting resilient modulus results, none of significance were found. The resilient modulus values of quarry data highly correlated with carbonate and quartz concentrations in the quartz fraction, but this was a reflection of the significantly lower resilient modulus test results from the Precambrian predominantly felsic-plutonic quarries, when compared to resilient modulus test results from the carbonate quarries. Multiple regression analysis identified physical properties, such as degree of saturation and foliated metamorphic content in the coarse fraction for all sources, degree of saturation and 3:1 elongated coarse particles for quarry sources, and coefficient of uniformity and Proctor optimum moisture content for pit sources, influence resilient modulus. However, none of the correlations were strong enough to predict resilient modulus with a sufficient confidence. Based on the limited number of sample locations in this study, there does not appear to be a single test or combination of inexpensive physical testing that can replace the more expensive resilient modulus test and provide similar information. Our test data indicates that strong correlation to physical properties did not exist when many sources located over a wide geographical area with significant geologic diversity are considered.

We recommend that more resilient modulus test data be obtained from other sources to obtain a broader base of information from which to determine the range and variability of results throughout the various geologic formations present in Wisconsin. Stronger conclusions regarding the effect of regional and geologic factors, as well as physical properties, may be made if more data is available to analyze. Also, other less prominent geologic formations, such as the Baraboo quartzite and trap rock quarried in the

northwest corner of the state, were not addressed in this research. In our opinion, a database including approximately two hundred samples, involving replications at some of the sources, would be desired to produce enough data to provide a higher level of statistical reliability.

### ***PAVEMENT DESIGN CONSIDERATIONS***

Because the highest average resilient modulus value for the samples obtained for this study was approximately two times higher than the lowest value, we recommend that an analysis be performed to determine the effect of the expected variation of resilient modulus values, in any given area, on base course layer thickness in a typical mechanistic-empirical pavement design. This analysis will provide information necessary to determine the degree of confidence required when selecting a base course resilient modulus value for a pavement design at any given location in the state. This analysis could also determine what effect the amount of variation observed between resilient modulus values by varying gradation within the same aggregate source will have on the base course layer thickness in a typical mechanistic-empirical pavement design.

If, based on the results of this analysis, base course thickness is significantly affected by the expected variation of resilient modulus results in any given area, a method for selecting a design resilient modulus will need to be developed that will provide a value, at the expected stress state, that will be an accurate reflection of the available base course sources in that area. Because resilient modulus results appear to vary significantly from source to source, and a pavement designer doesn't know which source will be used when designing a pavement, a method should be used that would account for the variation in resilient modulus values within the area around the project site that the crushed aggregate base course source used for the project could reasonably lie within.

One proposed method to accomplish this would be to obtain resilient modulus results for every source supplying crushed aggregate base course on WisDOT projects by requiring the test to be conducted as part of the source qualification testing. All approved sources

would be located on a geographic information system (GIS)-based map that is linked to a database, which contains source location and test information. A designer could access the database to obtain source information and resilient modulus test data for all crushed aggregate base course sources located within a given area around the design project. After determining the bulk stress condition that would likely exist in the base course layer for the project, the designer would determine the resilient modulus value for each of these sources and perform an analysis of the data to obtain a resilient modulus test value that would provide an acceptable level of confidence.

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