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# Investigation of Coarse Aggregate Strength for Use in Stone Matrix Asphalt


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16. Abstract

Stone Matrix Asphalt is a gap-graded hot-mix asphalt mixture composed of a coarse aggregate skeleton and a binder-rich mortar. The mixture type was first introduced to the United States in 1991, with one of the first test sections placed on I-70 near Richmond, Indiana. To help control the selection of coarse aggregate, the Indiana Department of Transportation specified a maximum Los Angeles Abrasion loss value of 30 percent.

An investigation into the coarse aggregate specifications for use in Stone Matrix Asphalt was completed in this study. Emphasis was placed on evaluating various tests that may be useful is specifying coarse aggregates, and to develop a test or set of tests and specifications. Finally, the validity of the current 30 percent Los Angeles Abrasion loss value as requirement for coarse aggregate selection was determined.

A survey of state agencies revealed a large variation in the Los Angeles Abrasion values currently specified. Laboratory testing revealed that the Micro-Deval test is a good compliment to the Los Angeles Abrasion test. The Micro-Deval test presents an added benefit as it includes the presence of water. Of the four tests investigated, aggregate degradation during compaction was the most accurate method for predicting coarse aggregate performance of the four tests. A combination of the Los Angeles Abrasion, Micro-Deval, and aggregate degradation tests was even more accurate in predicting coarse aggregate performance.


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# *Investigation of Coarse Aggregate Strength for Use in Stone Matrix Asphalt*

## Introduction

Stone Matrix Asphalt (SMA) originated in Europe approximately 35 years ago, its original intent to provide pavements capable of resisting abrasion caused by studded tires. An added benefit of SMA was resistance to rutting. SMA is considered a premium paving material and expected to have a service life 20-30 percent longer than conventional dense-graded hot-mix asphalt. The longer service life is achieved by increased durability and resistance to permanent deformation. The latter is due to stone-on-stone contact of the coarse aggregates. The increased durability comes from the high binder content mortar used to cement the coarse aggregate together.

Due to early SMA successes, the Indiana Department of Transportation (INDOT) developed an SMA specification. Though the use of SMA in Indiana has increased, its widespread use is limited by the coarse aggregate requirements for the mixture. For use in SMA, the current INDOT specification requires that a coarse aggregate have a maximum Los Angeles Abrasion (LA Abrasion) value of 30 percent. Steel slag has primarily been used as the coarse aggregate in SMA in Indiana because of its durability. However, due its high density and limited availability, the material is costly to ship thus limiting its wider use.

The major objectives of this research study are to determine if the current maximum LA Abrasion loss value of 30 percent is a valid requirement for coarse aggregates used in SMA, evaluate various tests that might be useful in specifying coarse aggregate for SMA, and develop a test, or set of tests, and specifications that can be used to specify coarse aggregates for use in SMA.
To achieve the objectives, the first action was to conduct a state survey. The purpose of the survey was to reveal differences in testing methods and specifications. States typically using SMA were contacted. Upon completion of the state survey, a laboratory experiment was conducted that included a series of aggregate tests. In addition, a mixture design was completed for each of the aggregates used in the study. Specimens were then compacted in the Superpave Gyratory Compactor (SGC) and the aggregate degradation caused by the compactor observed. A total of six coarse aggregates were investigated: steel slag, three crushed gravels, and two dolomites.

## Findings

The results of the experiment indicate that for the well-crushed aggregates used in this project, the flat and elongated test appears to provide little useful information about a coarse aggregate’s ability to perform in SMA. However, the test should be retained in the specification to insure that coarse aggregates selected for use in SMA mixtures are properly crushed.

The current LA Abrasion value specified by INDOT for coarse aggregates in SMA mixtures is a maximum 30 percent loss. Testing appears to indicate that LA Abrasion value alone is not a sufficient indicator of acceptability of a coarse aggregate for SMA mixtures. Other coarse aggregate properties can also significantly affect SMA mixture performance. Additionally, as indicated in the state survey results, there have been successful SMA pavements that use coarse aggregates with LA Abrasion values well above 30 percent. The possibility of raising the INDOT LA Abrasion value of 30 percent maximum loss might be considered in the future. However, further evaluation of out of state aggregates needs to first be confirmed and validated with Indiana mixture procedures.

Two of the tests evaluated focused on degradation of coarse aggregate by abrasion: LA Abrasion and Micro-Deval. The main difference between these two tests is the presence of water in the Micro-Deval test. Many aggregates are more susceptible to degradation when wet than when dry. The presence of water suggests that the Micro-Deval test might be a suitable alternative for, or at the very least, a good complement to the LA Abrasion test for establishing acceptability of a coarse aggregate for use in a SMA pavements.

An observation of compaction degradation in the SGC provided a distinct separation between what appear to be acceptable and unacceptable coarse aggregates for use in SMA mixtures. When each of the tests was correlated with VMA to create a comparison between the test results and a successful SMA mixture design, the SGC compaction degradation correlated best with mixture VMA. If only one test were to be used in specifying coarse aggregates for use in SMA mixtures, the SGC compaction degradation may be a good option.

Data were also analyzed to determine if a combination of tests could provide a better criterion for selecting coarse aggregates. The results showed that a combination of the results from the LA Abrasion, Micro-Deval, and SGC degradation tests provided the best method to select suitable coarse aggregates for use in SMA mixtures.

## Implementation

Based on the research results, it is concluded that a draft Indiana Test Method (ITM) should be prepared to identify alternative aggregates for use in SMA mixtures. INDOT will identify potential SMA projects where the new ITM will be used to select the coarse aggregates. During design and construction of the SMA mixtures for these projects, the aggregates will be tested in the LA Abrasion, Micro-Deval, and SGC degradation tests. The results will be analyzed as a way to obtain feedback on the test methods recommended in the research.

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## LIST OF SYMBOLS

SMA – Stone Matrix Asphalt

HMA – Hot Mix Asphalt

INDOT – Indiana Department of Transportation

LA Abrasion – Los Angeles Abrasion

SGC – Superpave Gyratory Compactor

FHWA – Federal Highway Administration

AASHTO – American Association of State Highway and Transportation Officials

F&E – Flat and Elongated

VCA – Voids in the Coarse Aggregate

VMA – Voids in the Mineral Aggregate

VTM – Voids in the Total Mixture

# CHAPTER 1: INTRODUCTION

## 1.1. Background

Stone Matrix Asphalt (SMA) originated in Europe approximately 35 years ago. The original intent of SMA was to provide pavements capable of resisting abrasion caused by studded tires. An added benefit of SMA was resistance to rutting. SMA was introduced in the United States in 1991, one of the first projects being placed on I-70 near Richmond, Indiana (1). Today, Maryland and Georgia are among the leading users of SMA. Starting in 1992, both states were quick to place test sections on their state highways. In slightly more than ten years, Maryland has constructed more than 85 SMA projects, approximately 1,300 lane miles of paving (2).

SMA is considered a premium paving material and expected to have a service life 20-30 percent longer than conventional dense-graded hot-mix asphalt (HMA) (2). The longer service life is achieved by increased durability and increased resistance to permanent deformation. The increased resistance to permanent deformation is due to stone-on-stone contact of the coarse aggregates. The increased durability comes from the high binder content mortar used to cement the coarse aggregate together. The increase in performance provided by SMA carries a cost premium of 20-40 percent (2). The extra cost is endured during production. However, it is currently believed that SMA is worth the extra cost in appropriate applications, mainly on high traffic volume highways. This is based on European SMA performance and early experience in the United States. To properly assess the cost-to-benefit of SMA, it needs to be evaluated on a longer life-cycle cost than other HMA pavements (2).

Due to early SMA successes, the Indiana Department of Transportation (INDOT) developed an SMA specification. Though the use of SMA in Indiana has increased, its widespread use is limited by the coarse aggregate requirements for the mixture. For use in SMA, the current INDOT specification requires that a coarse aggregate have a maximum Los Angeles Abrasion (LA Abrasion) value of 30 percent. Steel slag has primarily been used as the coarse aggregate in SMA in Indiana because of its durability. However, due its high density and limited source areas in Indiana, the material is costly to ship thus limiting a wider use of SMA in Indiana.

## 1.2. Objectives

Given the current INDOT SMA specification, the major objectives of this research study are:

1. To determine if the current maximum LA Abrasion loss value of 30 percent is a valid requirement for coarse aggregates used in SMA;
2. Evaluate various tests that might be useful in specifying coarse aggregate for SMA; and
3. Develop a test or set of tests and specifications that can be used to specify coarse aggregates for use in SMA.

## 1.3. Scope

To achieve the objectives, the first action was to conduct a state survey. The purpose of the survey was to reveal differences in testing methods and specifications. States typically using SMA were contacted.

Upon completion of the state survey, a laboratory experiment was conducted. The testing included a series of aggregate tests. In addition, a mixture design was completed for each of the aggregates used in the study. Specimens were then compacted in the Superpave Gyratory Compactor (SGC) and the aggregate degradation caused by the compactor observed. A total of six coarse aggregates were investigated: steel slag, three crushed gravels, and two dolomites.

# CHAPTER 2: LITERATURE REVIEW

## 2.1. SMA Overview

HMA mixture performance can be altered by changing the aggregate gradation of the mixture. Figure 1 shows three common HMA mixture gradations. A dense-graded HMA mixture usually has an evenly distributed gradation, while a gap-graded mixture tends to have high quantities of aggregates retained on the 2.36-mm (No.8) sieve or higher and passing the 0.150-mm (No.100) sieve. A uniformly-graded mixture is composed of mainly one size of aggregate (3).

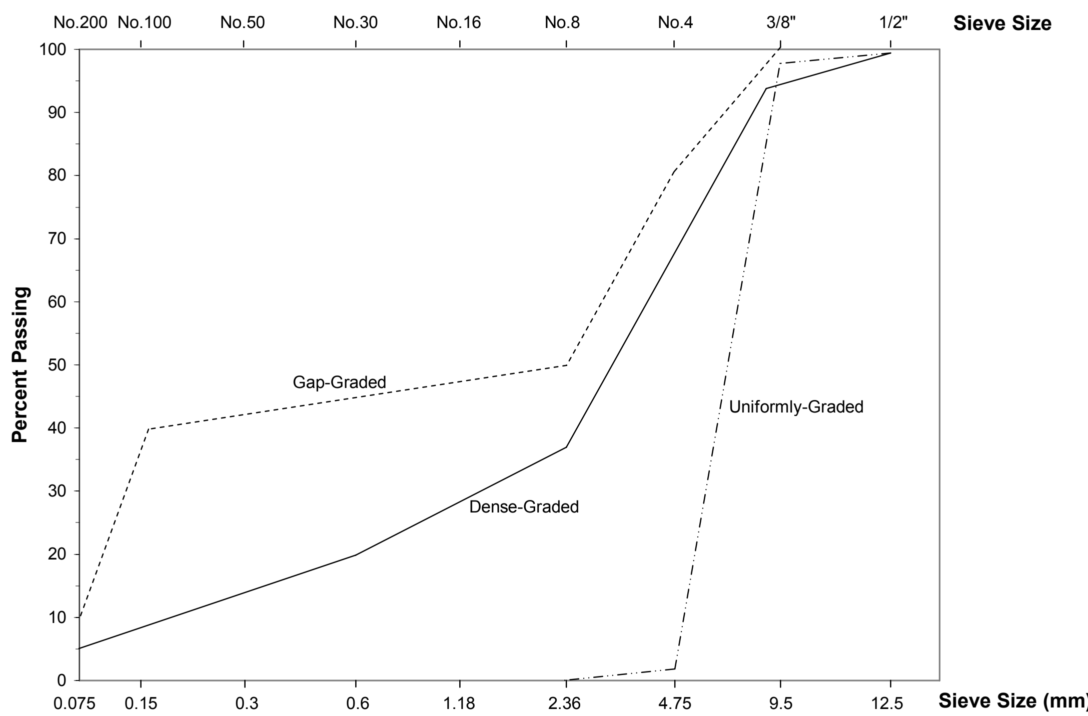


**Figure 1: Common HMA Mixture Aggregate Gradations (after (4))**

SMA is a gap-graded HMA mixture composed of a durable, coarse aggregate skeleton and a binder-rich mortar (4). The mortar consists of fine aggregate, mineral filler, asphalt binder, and a stabilizing additive. The strength of the mixture is achieved by the coarse aggregate stone-on-stone contact. Since the aggregate skeleton does not deform under loads as much as does asphalt binder, the stone-on-stone contact greatly reduces rutting (5). Rutting is caused by the progressive movement of materials under repeated loads in the asphalt pavement layer and/or in the underlying base (6). This can occur either through compaction or through plastic flow. Traffic loads after construction can result in additional compaction of the pavement. Plastic flow occurs laterally, typically caused by excessive asphalt binder (3). Figure 2 illustrates a case of rutting.

**Figure 2: Rutting Measurement (after (8))**

The majority of the voids between coarse aggregate particles in SMA are filled with the binder-rich mortar. As a result, slight variations in asphalt binder content can significantly alter SMA performance. This influence also exists in conventional HMA mixtures, but can be more prevalent in SMA. If the asphalt binder content becomes excessive, the desired stone-on-stone contact can be difficult to obtain. On the contrary, if the asphalt binder content is inadequate, air voids can increase beyond desirable levels. This may result in reduced durability from accelerated aging and moisture damage. An unwanted increase air voids can also result from an inadequate amount of fine aggregate and/or mineral filler.

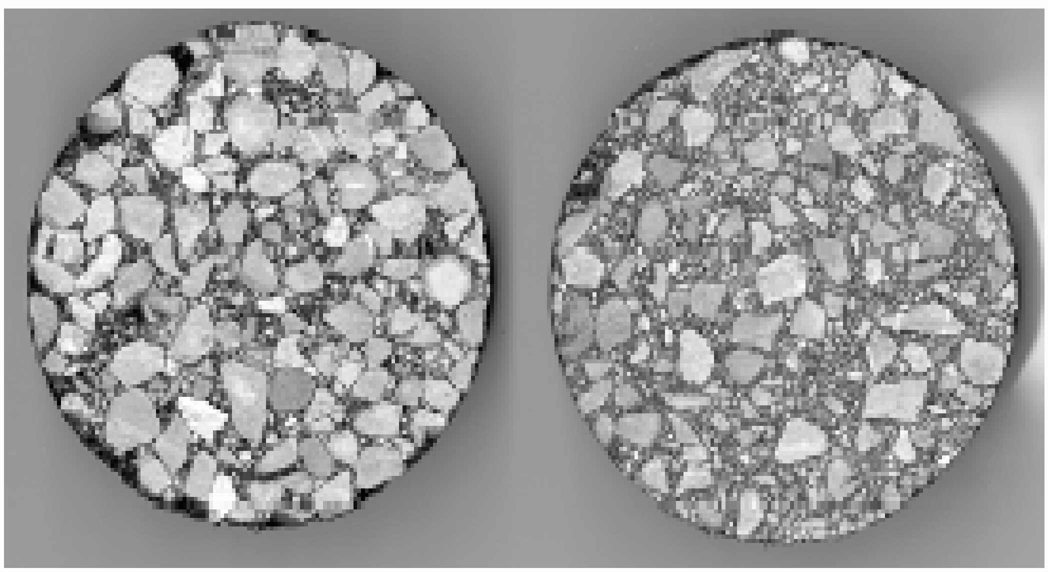

**Figure 3: Comparison of SMA (left) to HMA (right)**

Figure 3 illustrates the increase in coarse aggregate content for SMA compared to a dense-graded HMA by looking at the cross-section of 150-mm (6-in.) diameter specimens. HMA mixtures typically have 50 to 60 percent coarse aggregate compared to SMA which contains 75 to 85 percent coarse aggregate.

The increase in percent coarse aggregates puts an additional emphasis on selection of high quality coarse aggregates. The shape of the coarse aggregate must be angular with 100 percent crushed faces (7) and should be tough enough to resist abrasion under heavy traffic loads.

## 2.2. SMA History

SMA mixtures were originally developed in the 1970s by German contractors and were used throughout Europe and Scandinavia to provide resistance to abrasion caused by studded tires (2). When studded tires were banned, the use of SMA declined because of the higher construction and material costs compared to conventional, dense-graded HMA mixtures. During the 1980s, as tire pressures, wheel loads, and traffic volumes increased, problems with increased rutting caused a resurgence of SMA use in European countries.

SMA was introduced in the United States in 1991 and major SMA projects were constructed in Georgia, Indiana, Michigan, Missouri, and Wisconsin. From these projects some initial conclusions were established concerning SMA. The gradation of the mixture influences volumetric properties. This is more prevalent for SMA mixtures than dense-graded HMA. It was further found that changes in the percentages passing the 4.75-mm (No.4) and 2.36-mm (No.8) sieves had the greatest affect on voids. Lastly, it was determined that SMA mixtures compact quickly, so an excessive compactive effort would result in coarse aggregate degradation (8).

With passing time, more has been learned about SMA. In 1994, the Federal Highway Administration (FHWA) funded a study to evaluate performance of SMA pavements. A total of 140 SMA pavements were observed, paying special attention to mixture design, quality control, and performance. Some of the performance characteristics included, but were not limited to; rutting, fat spots, cracking, uniformity, and raveling (8).

From observation, the 1994 study concluded that minimal cracking occurred in the SMA pavements and the cracks that did occur were mainly reflective cracking on high-volume highways (8). An example of reflective cracking is seen in Figure 4. These cracks remained tight, showing no sign of raveling. Raveling is the progressive disintegration of the pavement from the surface downward as a result of the dislodgement of aggregate particles (6). Also, the SMA pavements displayed no significant thermal cracking. Thermal cracking are transverse cracks which generally run perpendicular to the roadway centerline. These cracks occur when the temperature at the surface of the pavement drops sufficiently to produce thermal shrinkage stresses that exceed the tensile strength of the pavement material (3).

**Figure 4: Reflective Cracking (after (8))**

On the majority of the study sections researchers used a straightedge to determine if rutting had occurred. Even though at the time of study the pavements were relatively young, they had been subjected to heavy traffic. In approximately 90 percent of the pavements there was less than 4 mm (0.16 in.) of rutting. Seventy percent of the pavements had less than 2 mm (0.08 in.) of rutting and 25 percent had no measurable rutting (8).

The FHWA funded study concluded that fat spots, Figure 5, are the most significant problem associated with SMA pavements. These spots can be caused by segregation, draindown, high asphalt binder content, or an improper type and/or amount of stabilizing additive (8). Segregation occurs when the SMA material being placed does not have a consistent gradation, usually the result of the coarse aggregate separating from the mortar (3). Draindown is the separation of binder from the uncompacted mixture during storage at elevated temperatures.

Draindown can occur during production, storage, transport, and placement of the mixture (9).

**Figure 5: Localized Fat Spot (after (8))**

2.3. Relevant Aggregate Properties

For SMA to be successful, choosing a durable aggregate is imperative. This parameter suggested the implementation of a specification requiring coarse aggregate to meet a maximum LA Abrasion loss value. The American Association of State Highway and Transportation Officials (AASHTO), and INDOT adopted this specification, establishing a maximum LA Abrasion loss value of 30 percent (10). The LA Abrasion loss value was a product of SMA experience in Europe and recommendations of a SMA Technical Working Group (11).

Despite the fact that AASHTO and INDOT have adopted the maximum LA Abrasion loss specification of 30 percent, little research has been done to demonstrate that such a low value is necessary. In fact, there is research evidence that suggests a different conclusion. As shown in Figure 6, Brown, et al. (11) reported that the amount of aggregate degradation during laboratory compaction in the SGC, as measured by the increase in the amount of aggregate passing the 4.75-mm (No.4) sieve, did not vary significantly for aggregates having LA Abrasion values between 28 and 46 percent. Although not shown, the same was true when identical mixtures were compacted by 50 blows of the flat-faced, static Marshall hammer. Note from Figure 6 that aggregates with LA Abrasion values of less than 25 percent did show less aggregate degradation during compaction in the SGC than the aggregates with LA Abrasion values above 25 percent. Brown, et al. concluded from their study that the data did not clearly recommend a maximum LA Abrasion loss specification of 30 percent. They suggested that perhaps the amount of aggregate breakdown occurring during production and placement of SMA should be quantified as a starting point for establishing coarse aggregate toughness criteria for SMA mixtures (11).

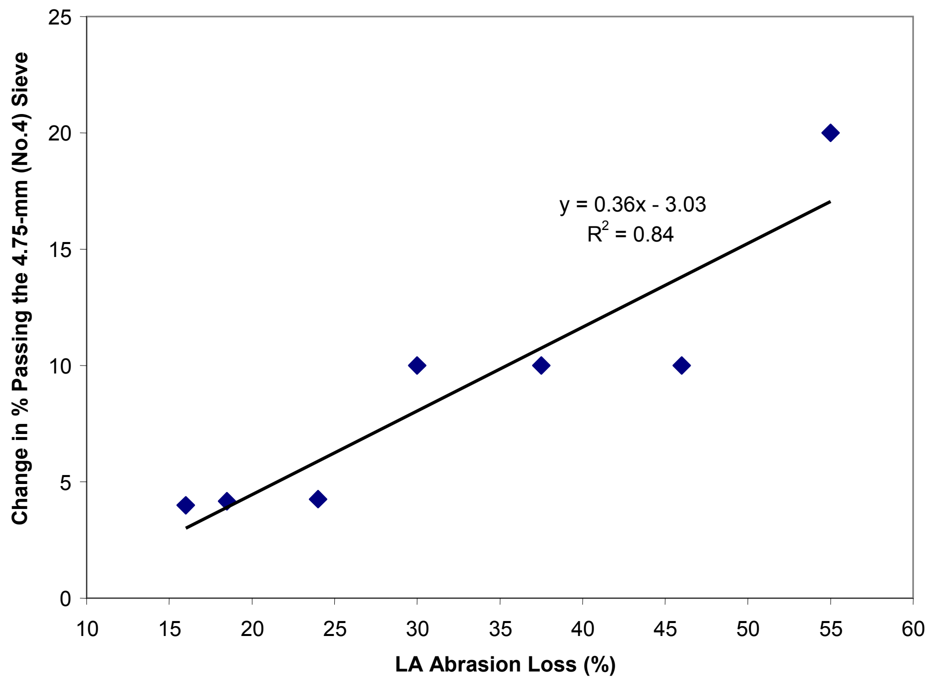


**Figure 6: Los Angeles Abrasion Loss during Compaction in the SGC (after (11))**

Work by Aho, et al. (12) did attempt to quantify coarse aggregate degradation in the field, although their work was performed using conventional HMA mixtures. The work resulted in several significant findings. First, their data indicated that a combination of LA Abrasion and Flat and Elongated (F&E) values were better indicators of aggregate toughness in the field, than was the LA Abrasion value alone. The F&E test investigates and classifies shape characteristics of aggregate particles. Higher LA Abrasion loss aggregates are more sensitive to F&E; aggregates with similar F&E values tend to degrade more as their LA Abrasion values increase. Additionally, the research indicated that if reasonable lift thicknesses are used in the field, aggregate degradation during laboratory compaction does not correlate well with degradation during construction. This is because the SGC tends to degrade the aggregates more than the construction process. Also it was reported that coarse aggregate degradation occurs in the construction process prior to arrival of the mixture to the paving machine; normal rolling does not cause further degradation.

The Micro-Deval test has been gaining popularity in Europe and Canada as an alternative to LA Abrasion. The test was developed in France and has been standardized by the European Union (13). It measures aggregate degradation when the material is tumbled in a rotating steel drum with water and steel balls and is believed to be a better indication of aggregate service when exposed to weather and moisture (13). This is particularly true in base courses and HMA applications where the actions of water and particle-to-particle interaction are important factors (13). The Micro-Deval test was first used in North America in Canada, where the Ontario Ministry of Transportation modified the test and used it to replace the LA Abrasion test for measuring the quality of coarse aggregates for use in transportation construction.

## 2.4. Gradation

As discussed, the aggregate gradation in an SMA mixture is one of the factors that can influence SMA pavement performance. For a given set of aggregates, the correct gradation is needed to obtain the desired stone-on-stone contact while maintaining void space for adequate amounts of mortar. In 1997, a study was conducted on ensuring stone-on-stone contact in SMA. Voids in the coarse aggregate (VCA) was found to best represent aggregate packing (14). VCA represents the volume of intergranular voids between the coarse aggregate particles and can be used to help identify the mortar requirements of mixture. It is determined by compacting dry coarse aggregate in a unit volume and then calculating the voids. The VCA of an SMA mixture can also be calculated once the mixture volumetrics are determined. As found in the study, the VCA of an SMA mixture should be less than or equal to the VCA of the coarse aggregate (14) to ensure stone-on-stone contact. The VCA in the mixture represents the air voids plus the volume of mortar.

Over the years, Robert Bailey developed a method to optimize the mixture design method. The Bailey Method focuses on the gradation selection in mixture designs. The defining aspect of the Bailey Method is the consideration of the packing characteristics of aggregates (15). The Bailey Method then applies the knowledge of how the aggregates would pack to provide an optimized gradation (15). The primary steps in the Bailey Method are combining aggregates by volume and analyzing the combined blend (15).

The Bailey Method uses two principles that are the basis of the relationship between aggregate gradation and mixture volumetrics: aggregate packing and definition of coarse and fine aggregate (15). Aggregate particles cannot be packed to fill all the voids in a given volume. The degree of packing depends on the type and amount of compactive effort (15). Other factors influencing packing are characteristics of the aggregates. The shape, surface texture, size distribution, and strength of the particles are considered in the

Bailey Method (15). In the Bailey Method, the definition of coarse and fine aggregates is more specific in order to determine packing and aggregate interlock provided by the combination of aggregates in various sized mixtures (15).

Coarse aggregate are large aggregate particles that when placed in a unit volume create voids. Fine aggregate are particles that can fill the voids created by the coarse aggregate in the mixture (15). All aggregate blends contain an amount and size of voids. The voids are a function of the packing characteristics. In combining the aggregates, the amount of and size of voids are created by the coarse aggregate, so the voids can be filled with the appropriate amount of fine aggregate (15).

The Bailey Method can be customized for different types of mixture designs. For the case of SMA, deriving resistance to permanent deformation from coarse aggregate is further enhanced (15). This gradation may not yield the final design, but it eliminates a majority of the trial and error procedure.

# CHAPTER 3: EXPERIMENTAL DESIGN

## 3.1. Overview

To achieve the project objectives, several tasks were completed including a survey of various state agencies. The materials required for the laboratory testing were identified and obtained from the producers. Four laboratory tests were conducted, including three aggregate tests and a mixture compaction test. Before completing the mixture compaction test, a mixture design for each coarse aggregate type was completed in accordance with INDOT specifications.

## 3.2. Survey

A survey of various states was conducted to evaluate current SMA practices in the United States. States agencies in near proximity to Indiana that use SMA were contacted along with the three largest SMA state agency users; Georgia, Maryland, and Virginia. Ultimately, a total of 20 states were contacted in addition to Indiana. These states were questioned about their respective SMA specifications and practices.

## 3.3. Laboratory Testing

Both aggregate and mixture testing were completed in the project. Four test methods were used, the first three having test methods defined by the American Society for Testing and Materials (ASTM):

- ASTM C131, "Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Abrasion Machine,"
- ASTM D6928, "Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus,"
- ASTM D4791, "Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate," and
- Compaction degradation.

The first three are common aggregate tests that measure properties believed to be associated with HMA mixture performance. The latter is a test whereby aggregate durability is measured by observing aggregate degradation after compacting HMA mixture samples in the SGC. The LA Abrasion and F&E tests were chosen for use in the project because it is thought that the two may work well in combination as shown by Aho, et al. (12). The Micro-Deval test has been shown to correlate well with the LA Abrasion test, but is thought to better differentiate between aggregates (16). Lastly, aggregate degradation in the SGC was used to allow for conclusions about aggregate toughness for use in SMA mixtures. INDOT field experience has shown that some dolomite aggregates degrade during compaction in the SGC, but not during field compaction by rollers.

The experimental matrix for the laboratory testing is shown in Table 1. In order to test the aggregates in the SGC compaction, a mixture design was completed for each combination of materials according to AASHTO MP8, “Standard Specification for Designing Stone Matrix Asphalt (SMA).” Specimens at the optimum binder content were then compacted in the SGC using 100 gyrations. When the specimens had cooled properly, the asphalt binder was extracted from them according to AASHTO T308 “Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method.” This method does not only apply to HMA, but is applicable to SMA as well. For each specimen, the gradation of the remaining aggregate was then determined according to AASHTO T11, “Materials Finer Than 75-μm (No.200) Sieve in Material Aggregates by Washing” and T27, “Sieve Analysis of Fine and Coarse Aggregates.”. The aggregate gradations of specimens compacted in the SGC were then compared to those of specimens that were mixed, but not compacted in order to compute the amount of aggregate degradation that occurred in the SGC compaction process.

**Table 1: Experimental Design**

| Aggregate Type | LA Abrasion | | Flat and Elongated | | Micro Deval | | Compaction Degradation | | |
|---|---|---|---|---|---|---|---|---|---|
| Steel Slag | X | X | X | X | X | X | X | X | X |
| Gravel A | X | X | X | X | X | X | X | X | X |
| Gravel B | X | X | X | X | X | X | X | X | X |
| Gravel C | X | X | X | X | X | X | X | X | X |
| Dolomite A | X | X | X | X | X | X | X | X | X |
| Dolomite B | X | X | X | X | X | X | X | X | X |

## 3.4. Materials

In order to select coarse aggregates for testing in the project, INDOT was consulted with the intention of identifying coarse aggregates currently in service in SMA projects. The coarse aggregates used in the project are identified in Table 2. Five of the six selected coarse aggregates are in use in SMA pavements in Indiana. This in effect results in SMA pavement sections that can be observed for long-term performance.

**Table 2: Identified Coarse Aggregates and Properties**

| Sieve Size | | Percent Passing | | | | | |
|---|---|---|---|---|---|---|---|
| (mm) | | Steel Slag | Gravel A | Gravel B | Gravel C | Dolomite A | Dolomite B |
| 12.5 | 1/2-in. | 100 | 100 | 100 | 100 | 100 | 100 |
| 9.5 | 3/8-in. | 85.2 | 81.2 | 83.1 | 81.8 | 69.7 | 63.6 |
| 4.75 | No.4 | 23.6 | 19.3 | 18.5 | 18.7 | 23.6 | 20.8 |
| 2.36 | No.8 | 2.7 | 2.6 | 3.7 | 1.5 | 2.7 | 1.4 |
| 1.18 | No.16 | --- | --- | --- | --- | --- | --- |
| 0.600 | No.30 | --- | --- | --- | --- | --- | --- |
| 0.300 | No.50 | --- | --- | --- | --- | --- | --- |
| 0.150 | No.100 | --- | --- | --- | --- | --- | --- |
| 0.075 | No.200 | 0.8 | 0.4 | 0.7 | 0.7 | 0.7 | 0.9 |
| Bulk Specific Gravity, $G_{sb}$ | | 3.610 | 2.691 | 2.653 | 2.735 | 2.721 | 2.462 |
| Apparent Specific Gravity, $G_{sa}$ | | 3.731 | 2.758 | 2.718 | 2.804 | 2.789 | 2.550 |

Steel slag was chosen because it is the best SMA coarse aggregate currently available in Indiana. Two dolomites were selected for use to determine if they would be durable enough for use in SMA. The use of dolomite aggregates in Indiana SMA mixtures has resulted in some concerns with degradation. Finally, crushed gravel was included as a viable option for SMA. Indiana gravels tend to be low abrasion loss materials.

Since SMA mixtures also contain fine aggregate, mineral filler, asphalt binder, and a stabilizing additive in addition to the coarse aggregates, these materials also had to be selected for the project. Each SMA mixture in the project used the same fine aggregate, mineral filler, and asphalt binder. This was done in order to accentuate the effect of the coarse aggregates. The selected asphalt binder is a modified PG76-22. The binder modification serves as the stabilizing additive. Table 3 shows the material properties of the fine aggregate and mineral filler. Bulk specific gravity is not measured for mineral filler. The apparent gravity is used as a reasonable estimate of the bulk specific gravity.

**Table 3: Fine Aggregate and Mineral Filler Properties**

| Sieve Size | | Percent Passing | |
|---|---|---|---|
| (mm) | | Sand | Mineral Filler |
| 12.5 | 1/2-in. | --- | --- |
| 9.5 | 3/8-in. | --- | --- |
| 4.75 | No.4 | 100 | --- |
| 2.36 | No.8 | 95.4 | --- |
| 1.18 | No.16 | 76.5 | 100 |
| 0.600 | No.30 | 49.2 | 99.9 |
| 0.300 | No.50 | 19.5 | 99.5 |
| 0.150 | No.100 | 6.8 | 93.5 |
| 0.075 | No.200 | 1.9 | 80.0 |
| | | | |
| Bulk Specific Gravity, $G_{sb}$ | | 2.628 | N/A[1] |
| Apparent Specific Gravity, $G_{sa}$ | | 2.699 | 2.800 |

[1] Not measured

3.5. Mixture Designs

Mixture designs were completed following INDOT's 2005 Standard Specifications. Within these standards, Section 410 refers to SMA. The gradation must meet the SMA Gradation Control Limits in section 410.05. The 9.5-mm ($^3/_8$-in.) limits were selected. In addition to the control limits, the Bailey Method was utilized to maximize efficiency in preparing a successful gradation. The gradations and control limits are shown in Figure 7.

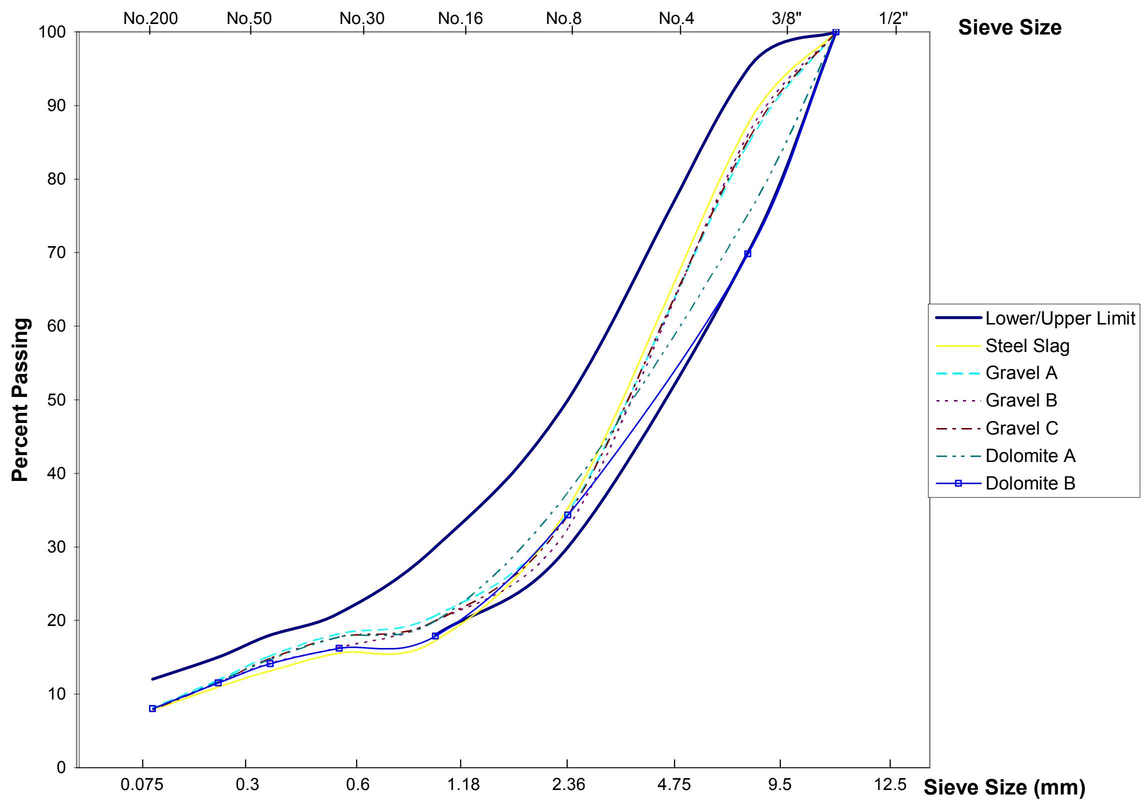


**Figure 7: Mixture Gradations**

After gradations were established, the aggregates were batched. First a sieve analysis was run on the coarse aggregate and sand to separate each into groups defined by sieve size. The coarse aggregate, sand, and mineral filler were batched according to the designed gradation. The total amount of aggregate used for the steel slag was 5200 g (11.46 lbs). The total amount of aggregate used was 4600 g (10.14 lbs) for all of the other coarse aggregate designs. The asphalt binder content of the mixture is based upon the combined bulk specific gravity of the aggregate. This value is correlated to a binder content from AASHTO MP8, Table 7. As the combined bulk specific gravity of the aggregate increases the asphalt binder content decreases.

With the aggregate batched and asphalt binder content selected, mixing was performed. This was conducted in accordance to AASHTO T312, “Standard Test Method for Preparation and Determination of the Relative Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyrator Compactor.” The care taken in preparing SMA and HMA does not vary. The aggregate, asphalt binder, mixing container, and mixing implements were heated until they reached a constant temperature of 165±5C (329±41F). The heated aggregate was placed in the mixing container and dry mixed. A crater is formed in the now blended, heated aggregate and the required mass of asphalt binder added. Mixing was then initiated and the aggregate and asphalt binder were mixed as quickly and thoroughly as possible.

SGC specimens were produced following AASHTO T312 standards. The mixture was aged for 2 hours, stirring after 1 hour. The compaction temperature of the mixture was 150±5C (302±41F) using 100 gyrations. To verify a valid mixture design, the volumetric properties were determined. These volumetric properties are voids in the mineral aggregate (VMA) and voids in the total mixture (VTM). VMA represents the volume of voids filled by the asphalt binder and air between coarse aggregate particles. VTM is the air voids in the specimen. These values are determined from four parameters. The combined bulk specific gravity of the aggregate and design asphalt binder content ($P_b$) are already known from earlier in the mixture design process. The other two parameters are obtained by completing the following tests: ASTM D2041, “Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving

Mixtures" and ASTM D2726, "Standard Test Method for Bulk Specific Gravity and Density on Non-Absorptive Compacted Bituminous Mixtures." In addition to these four parameters, the effective asphalt binder content ($P_{be}$), which is asphalt binder content not absorbed by the aggregate, was calculated as well. The VTM, or air voids, as specified by INDOT must be 4.0% at optimum asphalt binder content. The VMA is specified to be a minimum of 17.0 percent at the optimum asphalt binder content. These parameters and volumetric properties are summarized in Table 4.

**Table 4: Mixture Design Results**

| Coarse Aggregate | $G_{mb}$ | $G_{mm}$ | $G_{sb}$ | $P_b$ (%) | $P_{be}$ (%) | VMA (%) | VTM (%) |
|---|---|---|---|---|---|---|---|
| Steel Slag | 3.015 | 3.149 | 3.439 | 5.5 | 5.4 | 17.1 | 4.2 |
| Gravel A | 2.366 | 2.466 | 2.694 | 6.4 | 6.0 | 17.8 | 4.0 |
| Gravel B | 2.345 | 2.442 | 2.664 | 6.2 | 5.9 | 17.4 | 4.0 |
| Gravel C | 2.389 | 2.491 | 2.729 | 6.0 | 5.9 | 17.7 | 4.1 |
| Dolomite A | 2.445 | 2.543 | 2.719 | 6.1 | 5.8 | 15.6 | 3.9 |
| Dolomite B | 2.252 | 2.346 | 2.502 | 6.6 | 5.4 | 15.9 | 4.0 |

All the specifications were met with the exception of the VMA for the dolomite aggregates; both had values lower than the required 17 percent. However, this was expected due to the anticipated poor performance of dolomites during SGC compaction. The poor performance of the dolomites can be confirmed by evaluating the compaction degradation.

## CHAPTER 4: STATE SURVEY

The information requested from the states focused on testing and specifications for the selection of coarse aggregates for use in SMA mixtures. States contacted were selected based on a reputation for considerable use of SMA and/or geographic proximity to Indiana. A total of twenty states, excluding Indiana, were eventually surveyed. This was conducted via phone, email, and internet access. Complete response from eleven of the twenty states was achieved. These states are indicated in Appendix A1.

Of the eleven states that responded, all made use of the LA Abrasion value as the main criterion for selecting coarse aggregate for use in SMA. The range of maximum abrasion loss values was 30 to 55 percent and is illustrated in Figure 8. It was most common to see maximum loss values specified at 30 percent and between 40 and 50 percent. Of the states neighboring Indiana that have SMA specifications, Indiana has the lowest maximum LA Abrasion loss value, 30 percent. Ohio was the next lowest at 35 percent and Wisconsin was the highest at 45 percent. For Illinois, which uses some aggregate sources comparable to those found in Indiana, a maximum abrasion loss of 40 percent is specified. The average LA Abrasion loss value for all states that responded, including Indiana, was 38.7 percent.

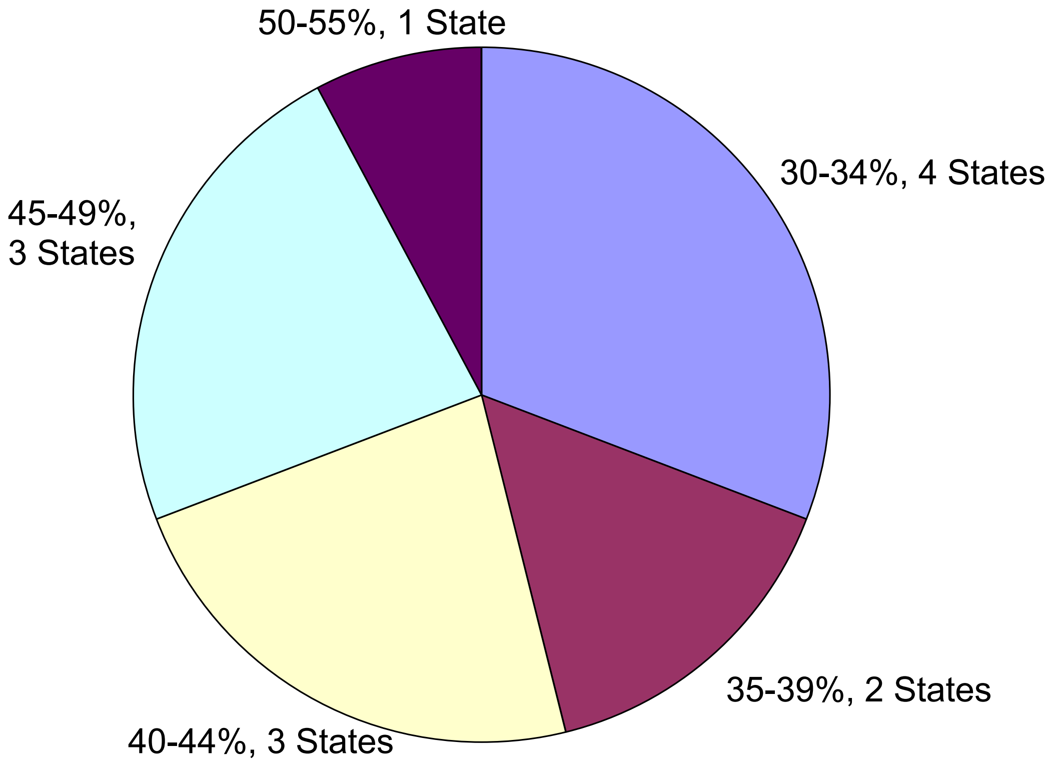


**Figure 8: Distribution of LA Abrasion Values Among Surveyed States**

The states specifying higher LA Abrasion values tend to have coarse aggregate with LA Abrasion values above the 30 percent loss value. Typically, these cases are found in southern states using granite. These SMA pavements perform just as well as pavements using lower LA Abrasion coarse aggregates. There were also some where high LA Abrasion value, crushed gravels were used. These had varying success.

In six cases, an F&E count was specified for 3-to-1 and 5-to-1 ratios with maximum percent by count of 20 percent and 5 percent respectively. In these surveyed states, the specification was for flat and elongated particles. Three states, however, did not provide specifications for the F&E test. It is believed with current crushing technology, this test has become somewhat unnecessary. The application of the Micro-Deval test was referenced only once, by the Texas DOT, as a supplemental resource for a design engineer for use in deciding between coarse aggregates. No standard values were specified for this test.

# CHAPTER 5: LABORATORY RESULTS AND ANALYSIS

## 5.1. Los Angeles Abrasion

### *5.1.1. Test Method*

The LA Abrasion test was conducted in accordance with ASTM C131. The scope of this test method covers a procedure for testing coarse aggregate sizes smaller than 37.5-mm (1½-in.) for resistance to degradation (17). The Los Angeles testing machine is shown in Figure 9 and consists of a steel drum that rotates at a rate of 30-33 revolutions per minute for a total of 500 revolutions (17). A specified number of steel spheres are placed inside the steel drum, in addition to the coarse aggregate sample. Within the steel drum is one steel flight, extending the full length of the drum, which picks the aggregate and steel spheres up on each rotation and drops them, thus aiding in the degradation process.

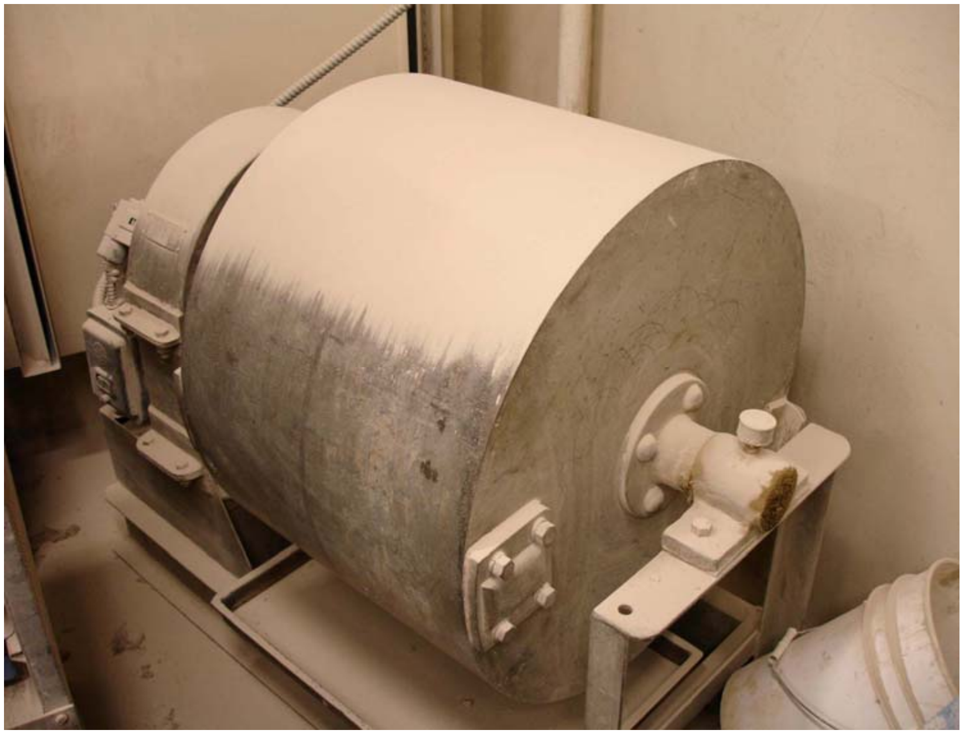

**Figure 9: Los Angeles Testing Machine**

The number of spheres is dictated by the grading selected. The steel spheres simulate a combined effect of abrasion, impact, and grinding that causes degradation. This test may simulate the type of wear experienced by coarse aggregates during SMA production.

**Table 5: Grading for Test Samples for use in the LA Abrasion Machine**

| Sieve Size (Square Opening) | | | | Mass of Indicated Sizes, g | | | |
|---|---|---|---|---|---|---|---|
| Passing | | Retained on | | Grading | | | |
| mm | | mm | | A | B | C | D |
| 37.5 | 1 1/2-in. | 25.0 | 1-in. | 1250±25 | --- | --- | --- |
| 25.0 | 1-in. | 19.0 | 3/4-in. | 1250±25 | --- | --- | --- |
| 19.0 | 3/4-in. | 12.5 | 1/2-in. | 1250±10 | 2500±10 | --- | --- |
| 12.5 | 1/2-in. | 9.5 | 3/8-in. | 1250±10 | 2500±10 | --- | --- |
| 9.5 | 3/8-in. | 6.3 | 1/4-in. | --- | --- | 2500±10 | --- |
| 6.3 | 1/4-in. | 4.75 | No.4 | --- | --- | 2500±10 | --- |
| 4.75 | No.4 | 2.36 | No.8 | --- | --- | --- | 5000±10 |
| Total | | | | 5000±10 | 5000±10 | 5000±10 | 5000±10 |

There are four grading options used in the LA Abrasion test as shown in Table 5. In Table 6 the number of steel spheres assigned to each grading is provided. Grading C was chosen for conducting this test due to the coarse aggregate size being used in the project.

**Table 6: Number of Steel Spheres for Selected Grading**

| Grading | Number of Spheres | Mass of Charge, g |
|---|---|---|
| A | 12 | 5000±25 |
| B | 11 | 4584±25 |
| C | 8 | 3330±20 |
| D | 6 | 2500±15 |

*5.1.2. Results*

Grading C requires 2500±10g (5.51±0.02lbs) retained on both the 6.3-mm ($^{1}/_{4}$-in.) and 4.75-mm (No.4) sieves, but all material passing the 9.5-mm ($^{3}/_{8}$-in.) sieve. For Grading C, eight steel spheres were used. Each aggregate was tested in duplicate. The results presented in Table 7 are the average values resulting from the LA Abrasion test. The complete results are shown in the appendix.

**Table 7: LA Abrasion Values**

| Aggregate | LA Abrasion Value (%loss) |
|---|---|
| Steel Slag | 15.7 |
| Gravel A | 18.9 |
| Gravel B | 20.3 |
| Gravel C | 19.3 |
| Dolomite A | 23.7 |
| Dolomite B | 30.7 |

Steel slag has the lowest loss at 15.7% while Dolomite B has the highest with 30.7 percent and is the only coarse aggregate in the project that does not meet the current INDOT SMA coarse aggregate specification of 30 percent loss, maximum. The three gravels and Dolomite A have comparable results.

## 5.2. Micro-Deval

### *5.2.1. Test Method*

The Micro-Deval test is used to determine aggregate abrasion loss in the presence of water. Unlike the LA Abrasion test, which is conducted using dry aggregate, the Micro-Deval test takes into consideration the influence of water on aggregate degradation.

Following the ASTM D6928 procedure, an aggregate sample of 1500±5g (3.31±0.01lbs) is soaked in 2.0±0.05L (67.6±2.0 fluid ounces) of tap water for a minimum of one hour (18). There are three possible gradations that can be used in the test method. The gradations correspond to a nominal maximum size of the coarse aggregate. The three nominal maximum sizes are 19.0-mm (3/4-in.), 12.5-mm (1/2-in.), and 9.5-mm (3/8-in.) or less. The gradation for each size is available in Table 8. The duration for testing is dependent upon the gradation used. Grading 8.2, 8.3, and 8.4 require a test time of 120±1, 105±1, and 95±1 minutes, respectively (18).

**Table 8: Test Sample Gradations**

| 19.0-mm | | | | |
|---|---|---|---|---|
| Passing | | Retained on | | Mass, g |
| mm | | mm | | |
| 19.0 | 3/4-in. | 16.0 | 5/8-in. | 375 g |
| 16.0 | 5/8-in. | 12.5 | 1/2-in. | 375 g |
| 12.5 | 1/2-in. | 9.5 | 3/8-in. | 750 g |
| 12.5-mm | | | | |
| Passing | | Retained on | | Mass, g |
| mm | | mm | | |
| 12.5 | 1/2-in. | 9.5 | 3/8-in. | 750 g |
| 9.5 | 3/8-in. | 6.3 | 1/4-in. | 375 g |
| 6.3 | 1/4-in. | 4.75 | No.4 | 375 g |
| 9.5-mm | | | | |
| Passing | | Retained on | | Mass, g |
| mm | | mm | | |
| 9.5 | 3/8-in. | 6.3 | 1/4-in. | 750 g |
| 6.3 | 1/4-in. | 4.75 | No.4 | 750 g |

The saturated aggregate and water were placed into the Micro-Deval abrasion container. Additionally, 5000±5g (11.02±0.01lbs) steel spheres were added and testing commenced. The Micro-Deval machine, seen in Figure 10, rotates the containers at a rate of 100±5 rpm (18).

**Figure 10: Micro-Deval Machine with and without Container**

Following completion of the test, the aggregate sample was sieved, and the saturated aggregate and steel spheres were poured over a 4.75-mm (No.4) sieve superimposed on a 1.18-mm (No.16) sieve. Using a magnet the steel spheres were separated from the saturated aggregate. Any material passing the 1.18-mm (No.16) sieve was discarded. The remaining aggregate was dried. The Micro-Deval abrasion loss value can be determined by comparing the initial and final dry aggregate masses. Values for this test typically do not exceed a loss value of 18 percent.

*5.2.2. Results*

For the Micro-Deval test, the maximum nominal size aggregate was 9.5-mm ($^3/_8$-in.). The corresponding grading was 750g (1.65lbs) of aggregate retained on both the 6.3-mm ($^1/_4$-in.) and 4.75-mm (No.4) sieves. The running time for the machine was 95±1 minutes.

**Table 9: Micro-Deval Values**

| Sample | Micro-Deval Value (%loss) |
|---|---|
| Steel Slag | 4.2 |
| Gravel A | 7.7 |
| Gravel B | 8.1 |
| Gravel C | 7.8 |
| Dolomite A | 8.9 |
| Dolomite B | 24.7 |

A summary of the Micro-Deval results are shown in Table 9. The complete results are shown in the appendix. The steel slag displayed the lowest loss value of 4.2 percent. Dolomite B had a loss value of 24.7%, which is significantly higher than any of the other aggregates as well as typical test results. The presence of water appears to influence the degradation of Dolomite B more than the other aggregates. The increase degradation in the presence of water can potentially be contributed to high clay content in Dolomite B.

## 5.3. Flat and Elongated

### *5.3.1. Test Method*

The F&E test was conducted on coarse aggregate samples to observe what amount of the material may be flat, elongated, or flat and elongated. The apparatus used in this test is a proportional caliper device that can be set to test for ratios of 2-to-1, 3-to-1, 4-to-1, or 5-to-1.

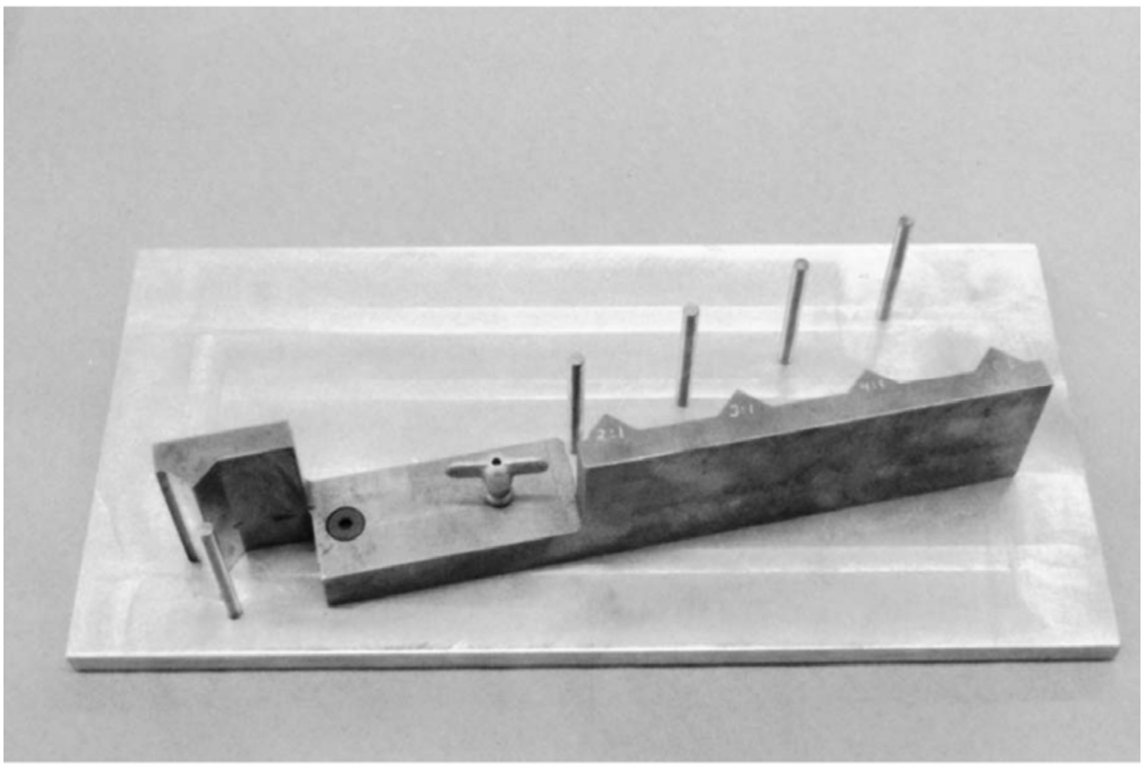

**Figure 11: Proportional Calibrator Device**

A flat particle is an aggregate particle having a ratio of width to thickness greater than a specified value. An elongated particle is an aggregate particle with a ratio of length to width greater than a specified value. Aggregate particles having a ratio of length to thickness greater than a specified value are considered flat and elongated. Testing for flatness or elongation is illustrated in Figure 12.

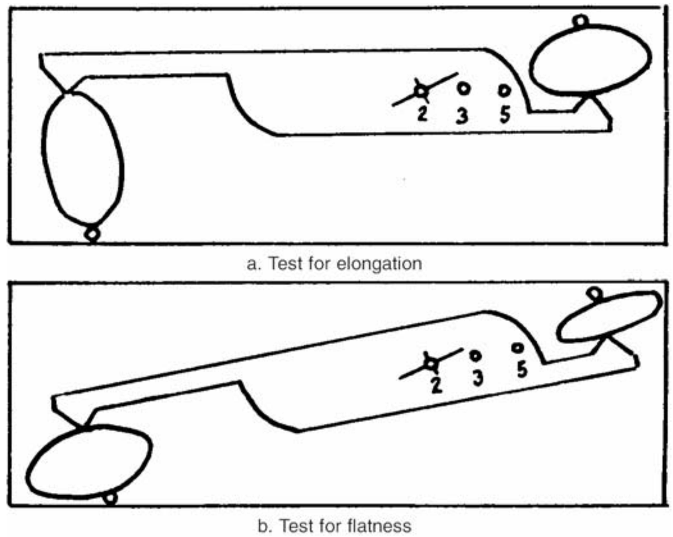


**Figure 12: F&E Test Execution**

These specific shape characteristics, as well as the test procedure, are defined in ASTM D4791. Characteristics of the aggregate's shape may be determined by mass or particle count. If determined by mass, the sample should be dried to a constant mass. Drying is not necessary, if determination is done by particle count.

### *5.3.2. Results*

In conducting the F&E test, percentages were based on a particle count. Material retained on the 4.75-mm (No.4) sieve was investigated. As required by INDOT, testing was completed for dimensional ratios of 3-to-1 and 5-to-1. The flat and elongated/flat or elongated results for each of the project's coarse aggregates are shown in Table 10.

**Table 10: Flat & Elongated Test Results**

*Flat or Elongated Particle Test*

| | 3:1 | | | 5:1 | | |
|---|---|---|---|---|---|---|
| Sample | Flat | Elongated | Neither | Flat | Elongated | Neither |
| Steel Slag | 0 | 0 | 100 | 0 | 0 | 100 |
| Gravel A | 0 | 0 | 100 | 0 | 0 | 100 |
| Gravel B | 0 | 0 | 100 | 0 | 0 | 100 |
| Gravel C | 0 | 0 | 100 | 0 | 0 | 100 |
| Dolomite A | 3 | 0 | 97 | 0 | 0 | 100 |
| Dolomite B | 5 | 0 | 95 | 0 | 0 | 100 |

*Flat and Elongated Particle Test*

| | 3:1 | | 5:1 | |
|---|---|---|---|---|
| Sample | Flat & Elongated | Neither | Flat & Elongated | Neither |
| Steel Slag | 0 | 100 | 0 | 100 |
| Gravel A | 0 | 100 | 0 | 100 |
| Gravel B | 0 | 100 | 0 | 100 |
| Gravel C | 0 | 100 | 0 | 100 |
| Dolomite A | 0 | 100 | 0 | 100 |
| Dolomite B | 0 | 100 | 0 | 100 |

INDOT specifies values for the F&E test by a percent by count for dimensional ratios of 3-to-1 and 5-to-1. The maximum percents by count are 20 percent for 3-to-1 and 5 percent for 5-to-1. The results of this test did not yield an aggregate that failed to pass INDOT specifications. Currently, the maximum limits for this test are typically not an issue for these coarse aggregates due to current crushing techniques.

## 5.4. Compaction Degradation

### *5.4.1. Test Method*

SGC specimens for the different coarse aggregates were produced to observe compaction degradation. The SGC and an SGC specimen are shown in Figure 13.


**Figure 13: Superpave Gyratory Compactor (SGC) and SGC Specimen**

To quantify the amount of degradation that occurs during compaction, the change in percent passing the 2.36-mm (No.8) sieve was calculated. To obtain this value, the binder was extracted from the SGC specimens using the ignition oven, shown in Figure 14. Use of the ignition oven followed standards outlined in AASHTO T308. The mass of specimens placed in the ignition oven is dependent upon the nominal maximum aggregate size. The nominal maximum aggregate size of the mixtures in this project was 9.5-mm ($^{3}/_{8}$-in.) resulting in a minimum

1500g (3.31lbs) specimen mass. The ignition oven temperature was set at 538C (1000F). Mixture samples that had never been compacted were also extracted in the ignition oven to determine a correction factor. The correction factor is the difference between the measured and design asphalt binder contents. The correction factor was used to minimize burning of the aggregates during extraction. If the correction factor exceeds 1.0 then correction factors are recalculated at a reduced ignition oven temperature, 482C (900F). Upon completion of extraction the remaining aggregate was washed, dried, and the gradation determined.


**Figure 14: Ignition Oven**

For comparison purpose, uncompacted specimens were extracted using solvents. This extraction technique follows Test Method A from AASHTO T164, “Standard Test Method for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA).” To extract the asphalt binder, methylene chloride was used. The solvent is added to the uncompacted specimen and stirred to extract the binder. The extraction solution is then filtered and the material passing the 0.075-mm (No.200) sieve is recovered with a high-speed centrifuge. This is repeated as necessary to fully extract the asphalt binder. A gradation is then run on the extracted aggregate. The fines collected in the high-speed centrifuge cup are added to the aggregate retained in the pan to complete the gradation.

After all the gradations for the uncompacted and SGC specimens are known, it is possible to evaluate compaction degradation that occurs on the 2.36-mm (No.8) sieve. To ensure that the results for the change in percent passing the 2.36-mm (No.8) sieve were caused only by compaction, the change in percent passing must be determined for the ignition oven using equation 1.

$$A = B - C \tag{1}$$

where,

A = change in percent passing the 2.38-mm (No.8) caused by the ignition oven;

B = percent passing the 2.38-mm (No.8) of uncompacted specimen using ignition oven; and

C = percent passing the 2.38-mm (No.8) of uncompacted specimen using solvent.

The change in percent passing from compaction was determined from the following equation:

$$D = E - F - A \tag{2}$$

where A is as before and,

D = change in percent passing the 2.38-mm (No.8) caused by the SGC;

E = percent passing the 2.38-mm (No.8) of SGC specimen after using ignition oven; and

F = percent passing the 2.38-mm (No.8) of mixture design.

These two calculations were repeated for all mixture designs to obtain the change in percent passing the 2.38-mm (No.8) caused by the SGC. Since, each SGC specimen was done in triplicate; the average value for each coarse aggregate was reported herein. The complete results are shown in the appendix.

*5.4.2. Results*

To quantify compaction degradation, the change in percent passing the 2.36-mm (No.8) sieve was calculated as shown in Table 11. Uncompacted and SGC specimens were first run through the ignition oven. The specimens were broken down and ran through the ignition oven in three trials. The average mass per test was 1600g (3.53lbs). The ignition oven temperature was set at 538C (1000F). Through previous trials it was determined that Gravel B and Dolomite A need to be run at a reduced ignition oven temperature, 482C (900F).

**Table 11: Change in Percent Passing on the 2.36-mm (No.8) Sieve**

| | Total Change in 2.36-mm Sieve | Change in 2.36-mm Sieve Due to Ignition Oven | Change in 2.36-mm Sieve Due to Compaction |
|---|---|---|---|
| Steel Slag | 1.1 | 0.9 | 0.2 |
| Gravel A | 4.1 | 2.8 | 1.3 |
| Gravel B | 3.1 | 1.0 | 2.1 |
| Gravel C | 5.0 | 3.2 | 1.8 |
| Dolomite A | 6.7 | 1.7 | 5.0 |
| Dolomite B | 8.4 | 1.0 | 7.4 |

The change in percent passing the 2.36-mm (No.8) sieve by compaction was negligible for the steel slag. The change for the dolomite B during compaction was the greatest at 7.4 percent. In the case of both dolomites the change in percent passing was great enough to affect the gradation of the mixture. This means during compaction the coarse aggregate experiences substantial degradation. This degradation increases the percent passing the 2.36-mm (No.8), increasing the amount of material that can fill the available voids space and decreases the voids sizes. These two changes are what prevent the VMA from reaching satisfactory values.

## 5.5. Discussion

Figure 15 shows the relationship between the LA Abrasion and Micro-Deval tests. From this linear relationship an LA Abrasion value can be directly correlated to a Micro-Deval value. Consequently, it would be expected that the Micro-Deval test would provide at the very least the same information about aggregate suitability as the LA Abrasion test. The expected advantage of using the Micro-Deval test is the presence of water during testing. The use of water in the Micro-Deval test has the potential to cause coarse aggregate degradation that would not necessarily occur under dry conditions. Since pavements are not subjected to completely dry conditions, the Micro-Deval test may better simulate in-service conditions. This influence of water is observed for Dolomite B. Its Micro-Deval loss value is higher than is expected.

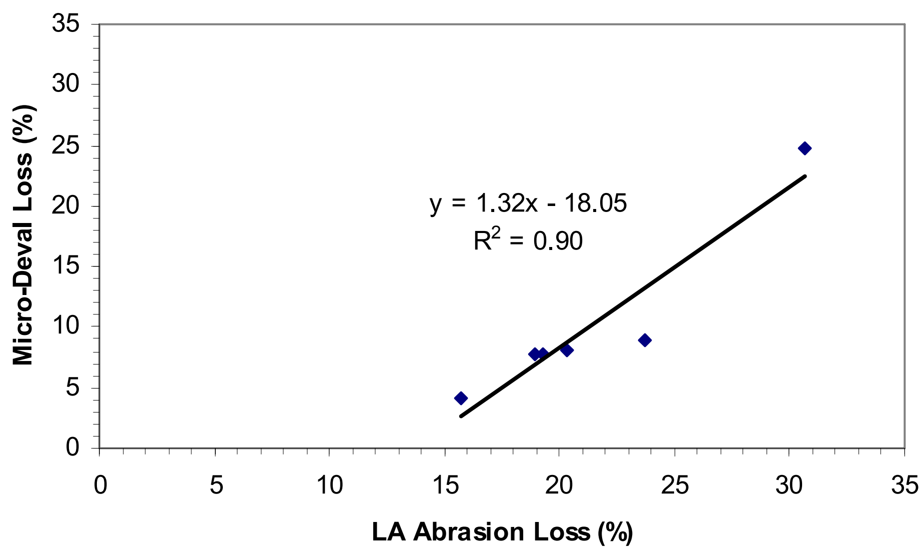


**Figure 15: LA Abrasion—Micro-Deval Relationship**

When comparing the LA Abrasion and Micro-Deval tests to the change in percent passing the 2.36-mm (No.8) sieve, similar trends occur. From Figure 16 it can be seen that the relationship between the changes in percent passing 2.36-mm (No.8) sieve and the LA Abrasion loss is better than that of the change in percent passing 2.36-mm (No.8) sieve and Micro-Deval loss.

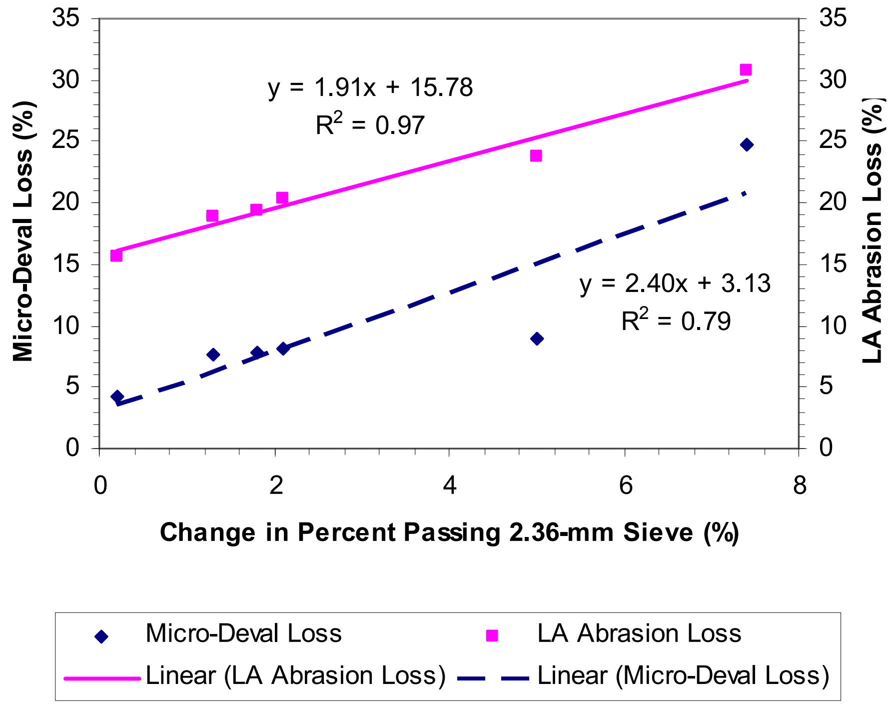


**Figure 16: Relationship of Change in Percent Passing 2.36-mm Sieve and Loss Values**

As discussed earlier, VMA is an important parameter for a successful SMA pavement and mixture design approval. In Figure 17, VMA is compared to the tests results. F&E was omitted since every result was zero and it therefore would have no relationship to VMA for these coarse aggregates. The best relationship to VMA is the change in the percent passing 2.36-mm (No.8) sieve. Excluding F&E, the Micro-Deval represented the poorest predictor of VMA.

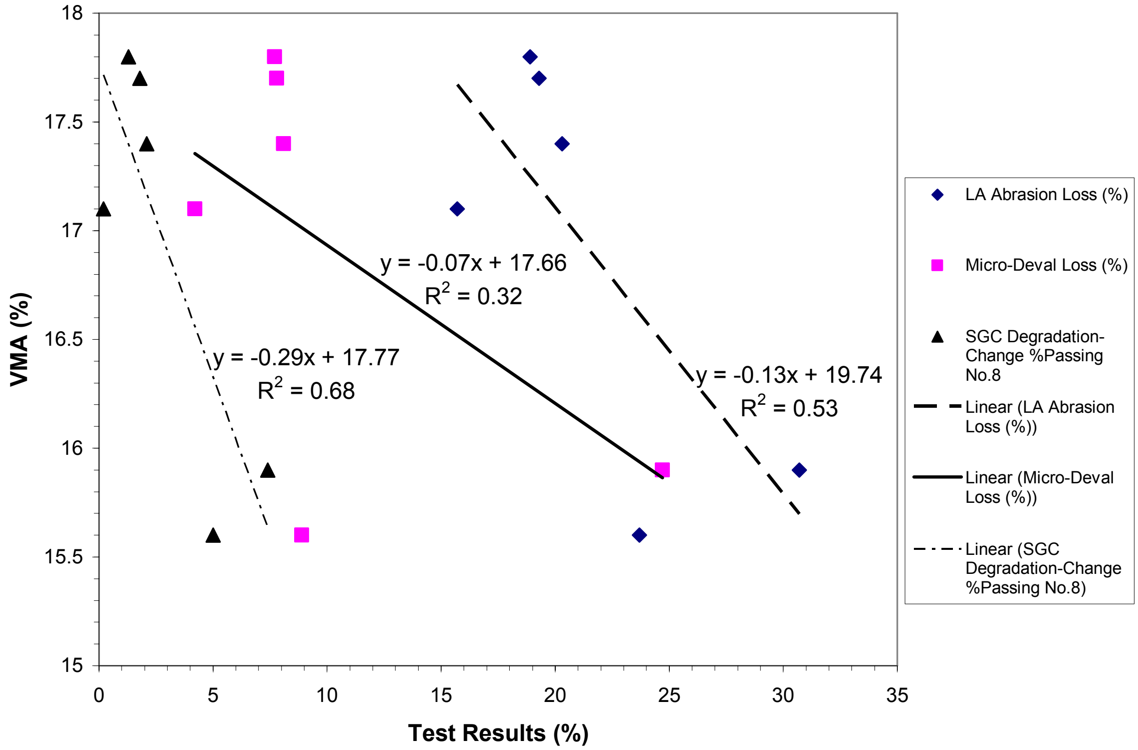


**Figure 17: Relationship of Aggregate Tests and VMA**

A regression analysis was completed to see if the results of the aggregate tests can be used to model (predict) the VMA. This analysis used independent variables LA Abrasion loss, Mirco-Deval loss, and the SGC degradation. Percent F&E was not used in the regression analysis; since all values were zero, it has no influence on VMA in this experiment. The response variable is VMA. The resulting regression model is represented by the equation:

$$VMA = 0.84LA - 0.10MD - 1.65DG + 4.85 \quad (3)$$

where,

LA = LA Abrasion loss;

MD = Micro-Deval loss; and

DG = SGC Degradation on the 2.36-mm (No. 8) Sieve.

Using this equation, VMA values for each of the experimental HMA mixtures were calculated and compared to the measured values. The results are shown graphically in Figure 18. As indicated in the figure, the three variables are able to explain 95 percent of the error.

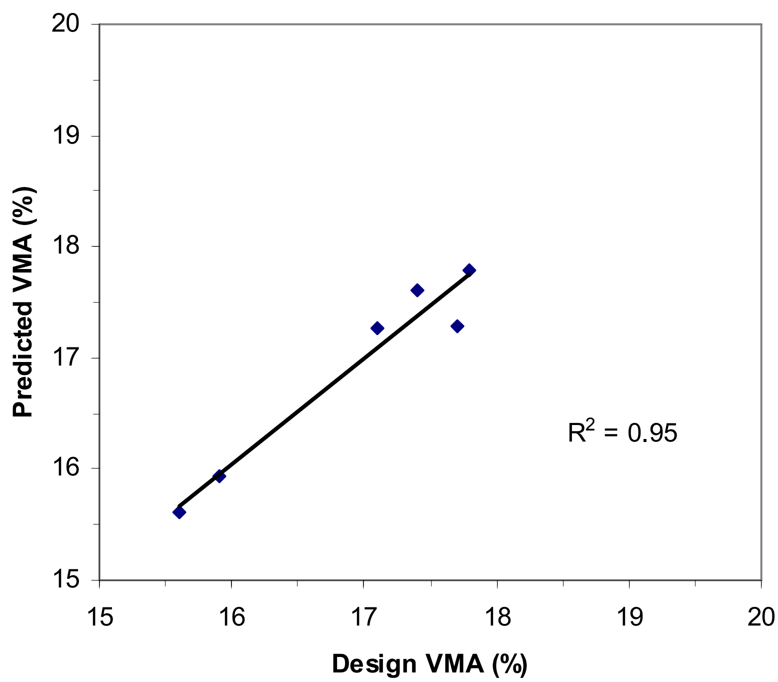


**Figure 18: Graphical Representation of Model**

In the normal ranges of LA Abrasion (15-40 percent) and Micro-Deval (4-18 percent) loss values, a 1 percent change in SGC degradation results in an approximately 1.5% change in the predicted VMA value. This 1.5% change remains roughly constant over an SGC degradation range of 1-6 percent. Over a

Micro-Deval loss range of 4-18 percent and SGC degradation range of 1-6 percent, a change in the LA Abrasion loss value of 2 percent results in a slightly less than 2 percent change in the VMA. This relationship remains consistent over a range an LA Abrasion loss values of 15-40 percent. A change in Micro-Deval loss shows the smallest effect on VMA. A 2 percent change in the Micro-Deval loss results in a consistent 0.2% change in VMA over a range of LA Abrasion from 15-40 percent and SGC degradation of 1-6 percent.

It should be remembered, that these levels of sensitivity and application of this relationship is strictly valid only when LA Abrasion and Micro-Deval losses, and SGC degradation amounts are within the ranges of those aggregates used for the experiment. Extrapolating beyond these ranges is not recommended.

## CHAPTER 6: SUMMARY AND CONCLUSIONS

Six coarse aggregates were selected for investigating coarse aggregate strength for use in SMA. Four of them appear to be acceptable for use in SMA. The steel slag, most commonly used in SMA, performed the best. The three crushed gravels all performed comparably and were close in performance to the steel slag. The two dolomites represent coarse aggregates that experience too much degradation during compaction for use in SMA. The two SMA mixtures containing dolomite coarse aggregates both failed to meet minimum VMA requirements.

In this project four tests were selected to evaluate the use of coarse aggregates in SMA. There were three aggregate tests: LA Abrasion, Micro-Deval, and F&E. The fourth test was a mixture test focusing on compaction degradation. Currently, INDOT uses the LA Abrasion value and F&E values to identify acceptable coarse aggregates for use in SMA mixtures. The results of the experiment indicate that for the well-crushed aggregates used in this project, the F&E test appears to provide little useful information about a coarse aggregate's ability to perform in SMA. However, the F&E test should be retained in the specification to insure that coarse aggregates selected for use in SMA mixtures are properly crushed.

The current LA Abrasion value specified by INDOT for coarse aggregates in SMA mixtures is a maximum 30 percent loss. Based on testing, this value does not appear to be correct. The LA Abrasion value alone is not a sufficient indicator of acceptability of a coarse aggregate for SMA mixtures. For example, Dolomite A is deemed an acceptable coarse aggregate for SMA (LA Abrasion=23.7%), but did not perform well in this study because it degraded too much during compaction. Additionally, as indicated in the state survey results, there have been successful SMA pavements that use coarse aggregates with LA Abrasion values well above 30 percent. This seems to indicate that coarse aggregate properties other than LA Abrasion loss can also significantly affect the performance of SMA mixtures.

Two of the tests evaluated focused on degradation of coarse aggregate by abrasion: LA Abrasion and Micro-Deval. The main difference between these two tests is the presence of water in the Micro-Deval test. Many aggregates are more susceptible to degradation when wet than when dry. This can be observed from Dolomite B. The LA Abrasion value was 30.7%, slightly above the specified maximum. The Micro-Deval test result of 24.7% for this aggregate is well above what might be considered an acceptable loss value for the test. The presence of water suggests that the Micro-Deval test might be a suitable alternative for, or at the very least, a good complement to the LA Abrasion test for establishing acceptability of a coarse aggregate for use in a SMA pavements.

An observation of compaction degradation in the SGC provided a distinct separation between what appear to be acceptable and unacceptable coarse aggregates for use in SMA mixtures. Coarse aggregates experiencing less than 3 percent compaction degradation in the SGC created successful mixture designs. When each of the tests was correlated with VMA to create a comparison between the test results and a successful SMA mixture design, the SGC compaction degradation correlated best with mixture VMA. If only one test were to be used in specifying coarse aggregates for use in SMA mixtures, the SGC compaction degradation appears to be the best option.

To further analyze data, a series of regression analyses was performed to determine if a combination of tests could provide a better criterion for selecting coarse aggregates. The results of the analyses showed that a combination of the results from the LA Abrasion, Micro-Deval, and SGC degradation tests provided the best method to select suitable coarse aggregates for use in SMA mixtures. The equation to predict VMA can potentially be used to denote an acceptable coarse aggregate for SMA based on a minimum predicted VMA value.

Finally, there was no work completed during this research to investigate the skid potential of the six aggregates tested. While the results of the testing indicate that four of the six aggregates have adequate strength for use in SMA mixtures, any one of them may be unsuitable from a skid property standpoint.

## CHAPTER 7: RECOMMENDATIONS AND IMPLEMENTATION

Considering the results of the study, the following are recommended:

1. The six coarse aggregates used in this study provide a limited amount of data. Additional coarse aggregates should be tested and the results added to the current data. Additional testing should include LA Abrasion, Micro-Deval, and SGC degradation testing as well SMA mixture design data. The results can be used to further refine the relationships established in this research;
2. The coarse aggregates in this study were chosen such that each is currently in use in an SMA pavement in the state of Indiana. These in-service pavements should be monitored for performance as a way to verify the relationships established in the research;
3. The current flat and elongated specification should be retained as it serves to insure that coarse aggregates are properly crushed;
4. The possibility of raising the maximum LA Abrasion loss for coarse aggregates to be used in SMA mixtures might be considered in the future. A review of the literature indicates that a few state departments of transportation with similar coarse aggregates do have higher numbers than Indiana. Further evaluation of these out of state

aggregates needs to be confirmed and validated with Indiana mixture procedures.

5. The Micro-Deval test should be considered for use in addition to the LA Abrasion test for specifying coarse aggregates for use in SMA mixtures;
6. The SGC degradation test should be considered for specification purposes when choosing coarse aggregates for SMA mixtures. It may be possible to use the test by itself, but as the research has shown, the maximum information is obtained by using this test in conjunction with the LA Abrasion and Micro-Deval tests;
7. The skid properties of coarse aggregates deemed acceptable for use in SMA mixtures should be investigated; and
8. Only one size of SMA mixture was investigated in this research. It is possible that as the NMAS changes the correct sieve for determining SGC degradation may also change. If larger or smaller SMA mixtures are used in the future, additional research should be completed for the applicable coarse aggregates.

Implementation of the research results should include the following:

1. A method for selecting alternative aggregates for use in SMA mixtures should be established. A draft ITM for this procedure should be prepared for use during the implementation phase of the research.
2. INDOT should identify candidate SMA projects where the new ITM can be applied. Samples should be taken from these projects and tested in

accordance with the ITM. The data should be reviewed on an annual basis to determine what, if any, refinements need to be made to the method. Five years is suggested for completion of the implementation.

## REFERENCES

1. Brown, E.R., Mallick, Rajib. “Experience with Stone Matrix Asphalt in the United States.” National Asphalt Pavement Association. NCAT Report No. 03-05, December 2003.

2. Kuennen, Tim. “Stone Matrix Asphalt is Catching On in the U.S.” Better Roads. September 2003.

3. Roberts, Freddy L., Prithvi S. Kandhal, E. R. Brown, Dah-Yinn Lee, and Thomas W. Kennedy. Hot Mix Asphalt Materials, Mixture Design and Construction. NAPA Education Foundation, Lanham, Maryland. 2nd Edition, 1996.

4. “Designing and Constructing SMA Mixtures – State of the Art Practice.” Quality Improvement Series 122, National Asphalt Pavement Association. January 1999.

5. Michael, L.M. “SMA in Maryland: Construction Performance of Stone Matrix Asphalt.” Maryland State Highway Administration, Office of Materials and Research. Western Regional Laboratory, Hancock, Maryland, 1996.

6. “Surface Distresses.” *WAPA Asphalt Pavement Guide.* <http://www.asphaltwa.com/wapa_web/modules/11_guidance/11_surface_distress.htm> November 11, 2005 2002

7. 2005 Standard Specifications. Indiana Department of Transportation.

8. Brown, E.R., Rajib B. Mallick, John E. Haddock, and John Bukowski. “Performance of Stone Matrix Asphalt (SMA) Mixtures in the United States.” *Journal of the Association of Asphalt Paving Technologists.* Vol. 66, 1997. pp 426-457.

9. “Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures.” ASTM D6390. Annual Book of ASTM Standards. Published April 2003.

10. Guidelines for Materials, Production, and Placement of Stone Matrix Asphalt (SMA). IS 118, National Asphalt Pavement Association, Lanham, MD, 1994.

11. Brown, E.R., John E. Haddock, Rajib B. Mallick, and Todd A. Lynn, “Development of a Mixture Design Procedure for Stone Matrix Asphalt (SMA).” *Journal of the Association of Asphalt Paving Technologists,* Vol. 66, 1997, pp. 1-30.

12. Aho, Brian D., William R. Vavrick, and Samuel H. Carpenter, “Effect of Flat and Elongated Coarse Aggregate on Field Compaction of Hot-Mix Asphalt.” *Transportation Research Record No. 1761*, Transportation Research Board, Washington, DC, 2001, pp.26-31.

13. Meininger, Richard. “Micro-Deval vs. L. A. Abrasion.” *Rock Products.* Apr 1, 2004

14. Brown, E.R. and John E. Haddock. "A Method to Ensure Stone-on-Stone Contact in Stone Matrix Asphalt Paving Mixtures." NCAT Report No. 97-2, January 1997.

15. Bailey, Roberts, Samuel H. Carpenter, William J. Pine, Gerald Huber, and William R. Vavrik. "Bailey Method for Gradation Selection in HMA Mixture Design." Transportation Research Board, Washington, DC. October 2002.

16. Rismantojo, Erza, Permanent Deformation and Moisture Susceptibility Related Aggregate Tests for use in Hot-Mix Asphalt Pavements. Ph.D. Dissertation, Purdue University, December 2002.

17. "Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Abrasion Machine." ASTM C131. Annual Book of ASTM Standards. Published April 2003.

18. "Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus." ASTM D6928. Annual Book of ASTM Standards. Published October 2003.

# APPENDIX

## A.1. Summary of State Survey

| | | | |
|---|---|---|---|
| State | Indiana | | |
| LA Abrasion | 30% loss maximum | | |
| Flat & Elongated | % by count 3:1 | 0 min | 20 max |
| | % by count 5:1 | 0 min | 5 max |

| | | | |
|---|---|---|---|
| State | Alabama | | |
| LA Abrasion | 48% loss maximum | | |
| | 55% loss maximum (for sandstone and blast furnace slag) | | |
| Flat & Elongated | % by count 3:1 | 0 min | 20 max |
| | % by count 5:1 | 0 min | 5 max |

| | | | |
|---|---|---|---|
| State | Maine | | |
| LA Abrasion | 30% loss maximum | | |
| Flat & Elongated | % by count 3:1 | 0 min | 20 max |
| | % by count 5:1 | 0 min | 5 max |

| | | | |
|---|---|---|---|
| State | Ohio | | |
| LA Abrasion | 35% loss maximum | | |
| Flat & Elongated | % by count 3:1 | 0 min | 20 max |
| | % by count 5:1 | 0 min | 5 max |

| | | | |
|---|---|---|---|
| State | South Carolina | | |
| LA Abrasion | 35% loss maximum | | |
| Flat & Elongated | % by count 3:1 | | |
| | % by count 5:1 | | |

| State | Maryland | | |
|---|---|---|---|
| LA Abrasion | 30% loss maximum | | |
| Flat & Elongated | % by count 3:1 | 0 min | 20 max |
| | % by count 5:1 | 0 min | 5 max |

| State | Georgia | | |
|---|---|---|---|
| LA Abrasion | 45% loss maximum | | |
| Flat & Elongated | % by count 3:1 | 0 min | 20 max |
| | % by count 5:1 | | |

| State | Texas | | |
|---|---|---|---|
| LA Abrasion | 30% loss maximum | | |
| Flat & Elongated | % by count 3:1 | | |
| | % by count 5:1 | 0 min | 10 max |

| State | Virginia | | |
|---|---|---|---|
| LA Abrasion | 40% loss maximum | | |
| Flat & Elongated | % by count 3:1 | 0 min | 20 max |
| | % by count 5:1 | 0 min | 5 max |

| State | Wisconsin | | |
|---|---|---|---|
| LA Abrasion | 45% loss maximum | | |
| Flat & Elongated | % by count 3:1 | | |
| | % by count 5:1 | | |

| State | Minnesota | | |
|---|---|---|---|
| LA Abrasion | 40% loss maximum | | |
| Flat & Elongated | % by count 3:1 | 0 min | 10 max |
| | % by count 5:1 | | |

| State | Illinois | | |
|---|---|---|---|
| LA Abrasion | 40% loss maximum | | |
| Flat & Elongated | % by count 3:1 | | |
| | % by count 5:1 | | |

# A.2. Micro-Deval Calculations

| Sample | Weight of Pan (g) | Weight of Aggregate (g) | Weight of Dried Aggregate + Pan (g) | Weight of Dried Aggregate (g) | Percent Loss |
|---|---|---|---|---|---|
| SS1 | 1274.3 | 1502.0 | 2714.8 | 1440.5 | 4.1% |
| SS2 | 1255.4 | 1499.9 | 2689.1 | 1433.7 | 4.4% |
| SS3 | 1260.6 | 1499.1 | 2697.7 | 1437.1 | 4.1% |
| Average | | | | | ***4.2%*** |
| GA1 | 1274.5 | 1497.4 | 2652.9 | 1378.4 | 7.9% |
| GA2 | 1275.8 | 1499.1 | 2664.8 | 1389.0 | 7.3% |
| GA3 | 1324.5 | 1497.8 | 2704.5 | 1380.0 | 7.9% |
| Average | | | | | ***7.7%*** |
| GB1 | 1274.5 | 1501.0 | 2652.9 | 1378.4 | 8.2% |
| GB2 | 1285.8 | 1502.2 | 2664.8 | 1379.0 | 8.2% |
| GB3 | 1324.5 | 1500.9 | 2704.5 | 1380.0 | 8.1% |
| Average | | | | | ***8.1%*** |
| GC1 | 1274.3 | 1495.3 | 2652.9 | 1378.6 | 7.8% |
| GC2 | 1275.8 | 1504.6 | 2664.8 | 1389.0 | 7.7% |
| GC3 | 1324.9 | 1499.9 | 2704.5 | 1379.6 | 8.0% |
| Average | | | | | ***7.8%*** |
| DA1 | 907.1 | 1501.4 | 2297.2 | 1390.1 | 7.4% |
| DA2 | 1275.3 | 1498.3 | 2693.5 | 1418.2 | 5.3% |
| DA3 | 1324.1 | 1500.5 | 2663.8 | 1339.7 | 10.7% |
| Average | | | | | ***7.8%*** |
| DB1 | 1269.3 | 1502.3 | 2400.7 | 1131.4 | 24.7% |
| DB2 | 1263.4 | 1501.6 | 2393.2 | 1129.8 | 24.8% |
| DB3 | 1272.2 | 1503.1 | 2406.4 | 1134.2 | 24.5% |
| Average | | | | | ***24.7%*** |

## A.3. Compaction Degradation Calculations

| | Total Loss=Average %Passing No.8 after Ignition Oven - Orginal Design | Ignition Loss=$Rice_{chemical}$-$Rice_{ignition}$ | Percent Loss Due to Compaction |
|---|---|---|---|
| SS | 1.1 | 0.9 | 0.2 |
| GA | 4.1 | 2.8 | 1.3 |
| GB | 3.1 | 1.0 | 2.1 |
| GC | 5.0 | 3.2 | 1.8 |
| DA | 6.7 | 1.7 | 5.0 |
| DB | 8.4 | 1.0 | 7.4 |

# A.4. Gradations (Percent Passing)

Steel Slag

| Sieve | Original Design | Rice (Chemical) | Rice (Ignition) | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|---|---|
| 3/8" | 87.5 | 88.2 | 89.2 | 88.6 | 88.3 | 89.2 |
| No.4 | 35.3 | 35.1 | 36.4 | 38.1 | 37.8 | 39.5 |
| No.8 | 17.3 | 16.3 | 17.2 | 18.4 | 18.3 | 18.6 |
| No.16 | 15.6 | 14.7 | 14.5 | 16.3 | 16.1 | 16.3 |
| No.30 | 13.2 | 12.6 | 12.3 | 13.9 | 13.7 | 13.9 |
| No.50 | 11.0 | 10.5 | 10.3 | 11.7 | 11.5 | 11.8 |
| No.100 | 9.4 | 9.2 | 8.8 | 10.1 | 10.0 | 10.1 |
| No.200 | 7.8 | 6.8 | 5.8 | 7.2 | 7.0 | 7.2 |
| Pan | 0.0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 |

Gravel A

| Sieve | Original Design | Rice (Chemical) | Rice (Ignition) | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|---|---|
| 3/8" | 84.8 | 86.3 | 86.3 | 86.4 | 86.4 | 86.6 |
| No.4 | 34.7 | 36.5 | 39.1 | 38.5 | 40.2 | 39.1 |
| No.8 | 20.7 | 21.7 | 24.5 | 24.7 | 24.7 | 24.8 |
| No.16 | 18.2 | 19.0 | 21.0 | 21.3 | 20.9 | 21.4 |
| No.30 | 15.2 | 15.9 | 17.2 | 17.6 | 16.7 | 17.5 |
| No.50 | 11.9 | 12.6 | 14.9 | 14.8 | 13.9 | 14.6 |
| No.100 | 10.0 | 10.6 | 13.5 | 13.1 | 12.2 | 13.0 |
| No.200 | 8.1 | 7.6 | 10.5 | 10.1 | 9.0 | 9.8 |
| Pan | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Gravel B

| Sieve | Original Design | Rice (Chemical) | Rice (Ignition) | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|---|---|
| 3/8" | 86.0 | 86.2 | 85.9 | 87.0 | 87.2 | 87.0 |
| No.4 | 32.6 | 31.6 | 32.4 | 35.9 | 36.6 | 35.8 |
| No.8 | 20.0 | 18.5 | 19.5 | 22.6 | 23.5 | 22.7 |
| No.16 | 16.4 | 15.3 | 16.4 | 18.6 | 19.4 | 18.9 |
| No.30 | 14.2 | 13.2 | 14.4 | 15.9 | 16.7 | 16.3 |
| No.50 | 11.6 | 10.9 | 12.1 | 13.2 | 14.1 | 13.8 |
| No.100 | 9.8 | 9.3 | 10.6 | 11.2 | 12.1 | 11.9 |
| No.200 | 8.0 | 7.0 | 7.8 | 8.1 | 9.0 | 8.6 |
| Pan | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Gravel C

| Sieve | Original Design | Rice (Chemical) | Rice (Ignition) | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|---|---|
| 3/8" | 85.3 | 86.8 | 86.6 | 88.3 | 87.5 | 88.6 |
| No.4 | 34.3 | 34.1 | 37.0 | 40.7 | 40.3 | 41.2 |
| No.8 | 20.0 | 20.2 | 23.4 | 24.5 | 25.3 | 24.9 |
| No.16 | 17.8 | 17.9 | 20.9 | 20.6 | 21.8 | 21.1 |
| No.30 | 14.8 | 14.9 | 17.6 | 16.3 | 17.8 | 16.6 |
| No.50 | 11.6 | 11.8 | 15.6 | 13.2 | 14.8 | 13.7 |
| No.100 | 9.7 | 9.9 | 14.3 | 11.2 | 12.9 | 11.6 |
| No.200 | 7.9 | 7.1 | 11.9 | 7.7 | 9.5 | 8.2 |
| Pan | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Dolomite A

| Sieve | Original Design | Rice (Chemical) | Rice (Ignition) | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|---|---|
| 3/8" | 75.2 | 79.1 | 76.1 | 79.1 | 79.8 | 78.7 |
| No.4 | 37.5 | 36.4 | 36.8 | 43.0 | 44.9 | 42.9 |
| No.8 | 20.0 | 19.5 | 21.2 | 25.3 | 27.8 | 25.5 |
| No.16 | 17.8 | 17.2 | 19.1 | 20.5 | 23.1 | 21.1 |
| No.30 | 14.7 | 14.4 | 16.5 | 16.5 | 19.3 | 17.3 |
| No.50 | 11.7 | 11.6 | 13.7 | 13.0 | 15.9 | 13.7 |
| No.100 | 9.9 | 9.8 | 12.0 | 10.7 | 13.6 | 11.5 |
| No.200 | 8.0 | 7.2 | 9.3 | 7.2 | 10.3 | 7.9 |
| Pan | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Dolomite B

| Sieve | Original Design | Rice (Chemical) | Rice (Ignition) | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|---|---|
| 3/8" | 69.8 | 70.2 | 68.8 | 74.5 | 75.2 | 74.7 |
| No.4 | 34.3 | 33.0 | 32.7 | 41.9 | 43.5 | 42.3 |
| No.8 | 17.9 | 17.7 | 18.7 | 25.2 | 27.3 | 25.2 |
| No.16 | 16.2 | 15.9 | 17.1 | 21.1 | 23.3 | 21.0 |
| No.30 | 14.1 | 13.9 | 15.1 | 18.1 | 20.4 | 18.1 |
| No.50 | 11.5 | 11.5 | 12.9 | 15.2 | 17.6 | 15.5 |
| No.100 | 9.8 | 9.6 | 11.2 | 13.4 | 15.8 | 13.7 |
| No.200 | 8.0 | 7.0 | 8.5 | 10.3 | 12.8 | 10.5 |
| Pan | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

## A.5. Bulk Specific Gravity

| | A | B | C | A/(B-C) |
|---|---|---|---|---|
| Sample | Mass of Dry Specimen in Air (g) | Mass of SSD Specimen in Air (g) | Mass of Specimen in Water (g) | $G_{mb}$ |
| SS1 | 5434.0 | 5449.8 | 3648.4 | 3.017 |
| SS2 | 5253.0 | 5267.7 | 3524.8 | 3.014 |
| Average | | | | ***3.015*** |
| GA1 | 4725.2 | 4746.8 | 2741.4 | 2.356 |
| GA2 | 4809.6 | 4822.1 | 2797.2 | 2.375 |
| Average | | | | ***2.366*** |
| GB1 | 4857.7 | 4867.6 | 2770.1 | 2.316 |
| GB2 | 4843.3 | 4850.6 | 2810.9 | 2.375 |
| Average | | | | ***2.345*** |
| GC1 | 4928.0 | 4940.2 | 2889.3 | 2.403 |
| GC2 | 4816.6 | 4832.3 | 2804.0 | 2.375 |
| Average | | | | ***2.389*** |
| DA1 | 4928.5 | 4934.5 | 2920.4 | 2.447 |
| DA2 | 4813.1 | 4820.8 | 2850.3 | 2.443 |
| Average | | | | ***2.445*** |
| DB1 | 4830.9 | 4849.3 | 2702.9 | 2.251 |
| DB2 | 4845.5 | 4859.4 | 2709.7 | 2.254 |
| Average | | | | ***2.252*** |

## A.6. Maximum Theoretical Specific Gravity

| | A | B | C | A/(A+B-C) |
|---|---|---|---|---|
| Sample | Mass of Dry Sample in Air (g) | Mass Bowl Under Water (g) | Mass of Bowl and Sample Under Water (g) | $G_{mm}$ |
| SS | 1562.0 | 1243.1 | 2309.0 | ***3.149*** |
| GA | 1642.3 | 1243.2 | 2219.4 | ***2.466*** |
| GB | 1559.9 | 1243.2 | 2164.3 | ***2.442*** |
| GC | 1565.4 | 1243.1 | 2180.2 | ***2.491*** |
| DA | 1538.7 | 1243.1 | 2176.8 | ***2.543*** |
| DB | 1577.8 | 1243.1 | 2148.3 | ***2.346*** |

# A.7. Corrected Relative Density

| | $h_8$ | $h_{100}$ | $(G_{mb}*h_m)/(G_{mm}*h_n)*100$ |
|---|---|---|---|
| Sample | Height of Specimen Recorded at Any Gyration (mm) | Height of Specimen Recorded at Final Gyration (mm) | $C_n$ |
| SS1 | 122.4 | 111.4 | 80.28 |
| SS2 | 123.5 | 112.4 | 81.98 |
| Average | | | ***81.13*** |
| GA1 | 134.8 | 119.5 | 84.23 |
| GA2 | 133.2 | 119.0 | 84.83 |
| Average | | | ***84.53*** |
| GB1 | 136.8 | 121.3 | 81.73 |
| GB2 | 137.3 | 121.8 | 81.70 |
| Average | | | ***81.71*** |
| GC1 | 134.3 | 118.6 | 85.68 |
| GC2 | 134.9 | 119.2 | 85.14 |
| Average | | | ***85.41*** |
| DA1 | 133.2 | 116.4 | 83.70 |
| DA2 | 130.7 | 114.5 | 83.59 |
| Average | | | ***83.65*** |
| DB1 | 146.2 | 125.2 | 81.22 |
| DB2 | 146.5 | 125.5 | 81.31 |
| Average | | | ***81.27*** |