Final Report 930-464

# AN EVALUATION OF ALABAMA AGGREGATE PROPERTIES FOR ASPHALT MIXTURES

*Prepared by*

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NOVEMBER 2004

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*Sponsored by*

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# ABSTRACT

## AN EVALUATION OF ALABAMA AGGREGATE PROPERTIES FOR ASPHALT MIXTURES

Aggregates are the major constituents of asphalt pavement. Appropriate aggregate properties are crucial to the construction of strong and durable asphalt pavement. Five Alabama aggregates with varying values of the properties specified by Alabama Department of Transportation for three types of asphalt mixture designs- Superpave, Marshall and Stone Matrix Asphalt- were selected. Mix designs for these three types of asphalt mixtures were done with the five aggregates. The mixtures were tested for rutting susceptibility and stripping propensity with the Asphalt Pavement Analyzer (APA) and Tensile Strength Ratio (TSR) tests, respectively. Attempts were made to correlate aggregate properties with mixture test results.

It was found that aggregates with close to 100 % percent crushed particles are needed for mixtures to perform adequately in the APA test. Weighted uncompacted voids of the aggregates showed promise in differentiating mixture rutting susceptibility. TSR was positively correlated only to the conditioned tensile strength of the mixtures.

# CHAPTER 1. INTRODUCTION

## 1.1 Background

The design of asphalt concrete has recently experienced many advances. Large volumes of heavy trucks with high tire pressure began to cause premature rutting, stripping and other failure mechanisms in dense graded asphalt concrete designed with the Marshall and Hveem methods. There has been intensive research into the causes of those premature failures. As a result, a new mix design system for dense graded mix (Superpave), and a new mix type , Stone Matrix Asphalt (SMA) have been developed which promise to deliver more durable and rut resistant flexible pavement.

Taking advantage of recent research, Alabama Department of Transportation (ALDOT) revised specifications for Marshall designed mixes and introduced specifications for Superpave and SMA mixes. A portion of the changes dealt with specifications for aggregate. Aggregate typically makes up 93-96% of a mix by weight or 80-88% by volume. The role played by aggregate in sustaining traffic loading without permanent deformation, and in withstanding the degradation effect of environmental factors has been increasingly realized through recent studies. New specifications place higher requirements on those aggregate properties, such as percentage of particles with fractured faces, percentage of flat or elongated particles, Los Angeles abrasion loss, uncompacted voids of fine aggregate, sand equivalent, etc., which are deemed to be closely linked to long term pavement performance.

Alabama has extensive aggregate resources with widely varying properties. To fully utilize these aggregate resources to provide a first class highway system several questions need answers. Should specified aggregate properties for Marshall, Superpave and SMA mixes be the same or different? Are the specifications able to insure the aggregates for the best performing pavement ? Are some of the properties somehow related ? Are other tests (than those specified) better correlated to pavement performance? And, what are the fundamental aggregate parameters affecting asphalt mix performance ? These are some of the questions this study will try to answer.

## 1.2 Objective

The objectives of the study are to determine if ALDOT's specification for aggregates in Section 424 Superpave , Section 423 Stone Matrix Asphalt (SMA), Section 429 Improved Bituminous Concrete (Marshall) produce mixes with adequate rutting and stripping resistance; to assess the efficacy of other aggregate properties in predicting pavement performance; to probe the relationship ( if any) between different aggregate properties, mix design parameters and mix performance test values, in order to fine tune the specifications so that the aggregate sources in Alabama can be used more efficiently; and to determine if aggregate specifications should be the same or different for the several mix types.

## 1.3 Scope

The research involved the following tasks:

1) study and comparison of aggregate specifications for the several type of mixes mentioned above;
2) selection of aggregate sources;
3) aggregate characterization with an array of tests, either included in the specification or candidates for inclusion;
4) mix design: 12.5 mm maximum size and 25 mm maximum size mixes were designed according to the specification of each of the three mix types- Superpave, Marshall, SMA- with each of the selected aggregates;
5) mix performance test: each mix was evaluated for rutting potential and stripping susceptibility using APA and TSR tests, respectively.

# CHAPTER 2. TEST PLAN AND PROCEDURES

## 2.1 Specifications for Section 424 Superpave Bituminous Concrete , Section 429 Improved Bituminous Concrete( Marshall), AND Section 423 Stone Matrix Asphalt Mixes

Table 2.0 lists the main features of the aggregate and volumetric specifications for Marshall, Superpave and SMA mixes. As defined herein, coarse and fine aggregate are portions that are respectively, retained on and pass through the 4.75 mm sieve. Some of the criteria depend on design traffic range and the position of the mix in the pavement structure. The higher the traffic level and the closer to the pavement surface, the more stringent the criteria. The mixes for this study were designed as surface or binder courses for traffic range D (3 million to 10 million ESALs). The gradations were on the coarse side of limits.

The number of specified items and criteria for Superpave and Marshall mixes are similar. The only difference is in the specification of flat and/or elongated particles.

The aggregate criteria for SMA are more stringent than for Superpave and Marshall mixes. Crushed stone aggregates are required with stricter flat and elongated, sand equivalent and fine aggregate uncompacted voids requirement. SMA gradation and VMA requirements are different and minimum asphalt contents are specified for SMA mixes.

More aggregate tests than are listed in Table2.0 were included in the study. These were uncompacted voids of coarse aggregate, Micro Deval Abrasion and Methylene Blue, to see how well they related to mix performance.

Table 2.0 Summary of ALDOT Bituminous Concrete Specifications

| Specification | | Section 424 | Section 429 | Section 423 |
|---|---|---|---|---|
| Coarse Aggregate Properties | Flat and/or Elongated Particles | 5:1 ratio, less than 10%, F&E by count | 3:1 ratio, less than 20% and 5:1 ratio, less than 10% F or E by mass | 3:1 ratio, less than 20%, and 5:1 ratio, less than 5% F& E by count |
| | Fractured Face Count | No requirement to 100 % two or more (depending on traffic range and postion in the pavement structure) | No requirement to 100% two or more (depending on traffic range and postion in the pavement structure) | 100% crushed stone |
| | Soundness by Sodium Sulfate | less than 10% | less than 10% | less than 10% |
| | L.A. Abrasion | less than 48% | less than 48% | less than 48% |
| | Note | | | coarse aggregate shall be 100% crushed |
| Fine Aggregate Properties | Fine Aggregate Angularity (uncompacted voids) | No requirement to mininum 45% (depending on traffic range and position in the pavement structure) | No requirement to mininum 45% (depending on traffic range) | mininum 45% |
| | Sand Equivalent | mininum 40 to 45% (depending on traffic range) | mininum 40 to 45% (depending on traffic range) | minimum 50% |
| | Note | | | fine aggregate shall be 100% crushed |
| Mix Properties | Gradation | Superperpave control limits and restricted zone | Superperpave control limits and restricted zone | SMA control limits |
| | Binder Content | | | minimum 5.9% for 12.5 mm mix, minimum 5.3% for 37.5 mm mix |
| | Air Voids | 4% | 4% | 4% |
| | VMA | minimum 12 to 16% depending on maximum aggregate size and gradation | minimum 12 to 16% depending on maximum aggregate size and gradation | minimum 17% |

## 2.2 Aggregate Selection

Five aggregates were used in the study for their contrasting properties and diverse origins. These were: a pair of crushed limestones, an uncrushed gravel , a natural sand and a crushed gravel (source for crushing same as uncrushed gravel).

## 2.3 Aggregate Characterization

After aggregates were sampled , they were dried and separated into individual fractions. Figures 2.3.1 to 2.3.3 show some of the size fractions of different aggregates. The following tests were performed on these individual fractions or blends produced with individual fractions:

a) for coarse aggregate:

1) Specific Gravity and Absorption (AASHTO T 85)

2) Percentage of Flat and Elongated Particles(3:1 and 5:1, by weight and by count, ASTM D4791),

3) Percentage of Particles with Fractured Faces ( with more than one face and with more than two faces, by weight and by count, ASTM D5821),

4) Los Angeles Abrasion Loss( AASHTO T96),

5) Micro Deval Abrasion,

6) Soundness by Use of Magnesium Sulfate( AASHTO T104),

7) Uncompacted Voids of Coarse Aggregate

b) for fine aggregate:

1) Specific Gravity and Absorption (AASHTO T84)

2) Sand Equivalent ( AASHTO T176),

3) Fine Aggregate Uncompacted Void Content (ASTM C1252)

4) Methylene Blue Value of Minus 200 Sieve Fraction,

All tests were done in triplicate- three samples were used in each test.

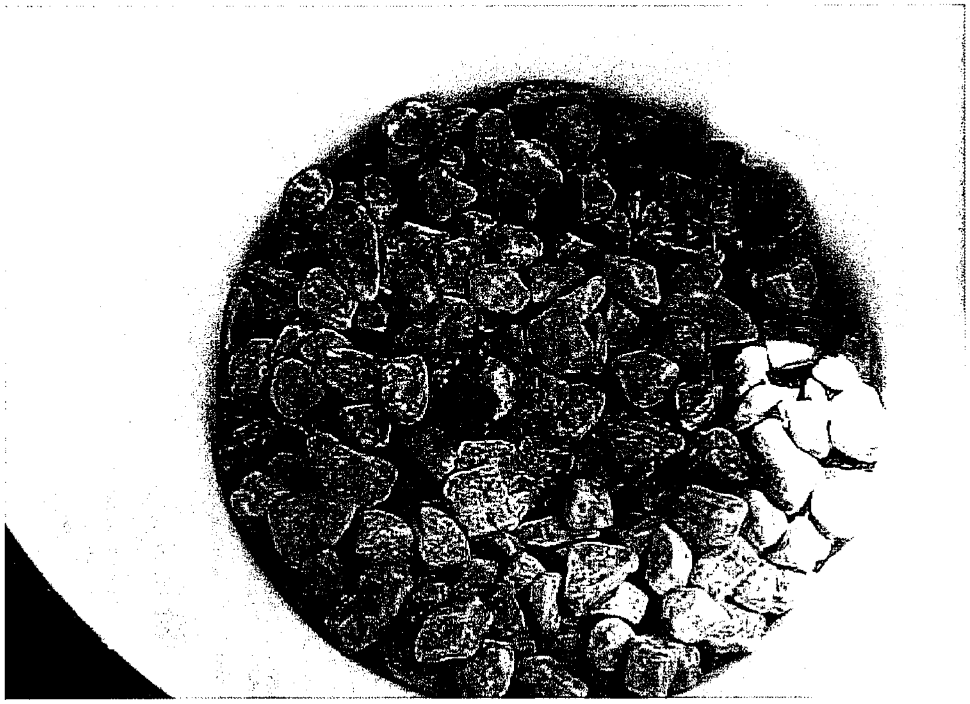


Figure 2.3.1 Limestone #1 (3/4")

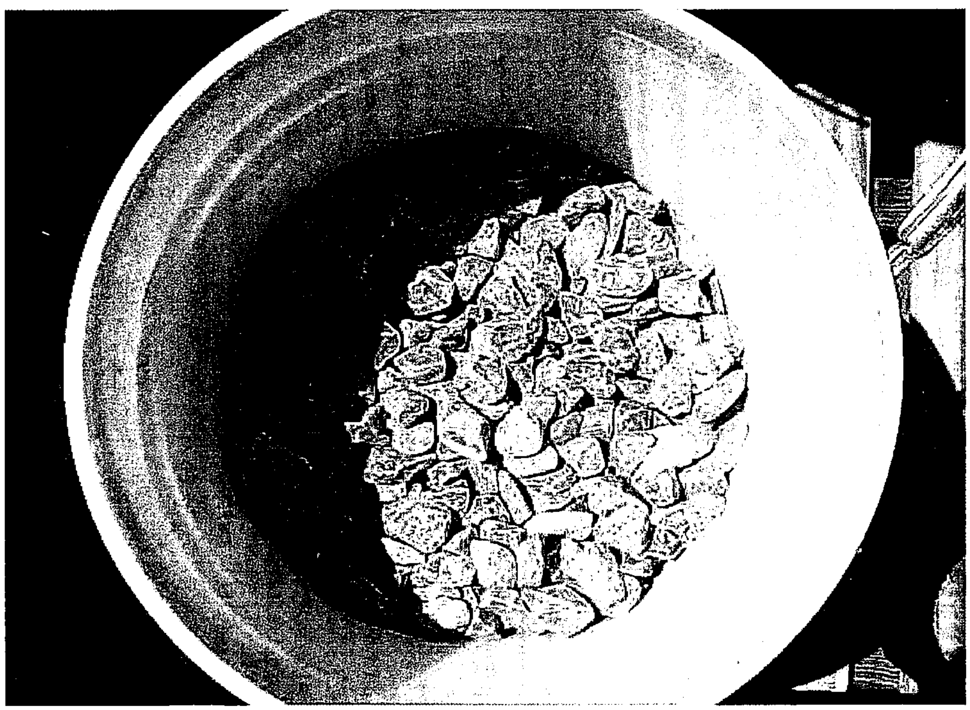


Figure 2.3.2 Limestone #2 (3/4")

Figure 2.3.3 Uncrushed Gravel (No.4)

## 2.4 Mix Design

### 2.4.1 Aggregate Blend, Mix Series

Aggregate blends for the two limestones and the crushed gravel were composed entirely of the aggregate from each source. The uncrushed gravel was combined with the natural sand to produce an acceptable aggregate blend. The natural sand made up size fractions from minus 200 up to No.16, and the natural gravel made up the coarse fractions from No.8 to maximum size.

Complete mix designs of Superpave, Marshall and SMA mixes, which included three gradations trial, were done with limestone designated as (CrLs#1). The gradation selected from these three gradations (with minor modification) was used for all other aggregate sources or combinations thereof, variously designated as CrLs#2 (the other crushed limestone), GNS( combination of uncrushed gravel and natural sand), and CG( crushed gravel). Thus, the effects of gradation were eliminated when results from mixes with different aggregate blends were compared.

The gradations for the three types of mixes-each with two different maximum aggregate sizes, 25 mm and 12.5 mm -are shown in Figures 2.4.1.1 to 2.4.1.4. Gradation limits and the selected gradations were the same for Superpave and Marshall mixes with the same maximum aggregate sizes. Altogether 21 designs were completed.

The asphalt used for Superpave and Marshall mixes was PG 64-22. During mix design, Superpave mixes were aged in oven at 300 F for two hours before compaction. The Marshall mixes were aged for 45 minutes at 300°F before compaction. The asphalt used for SMA mixes was PG 76-22. SMA were compacted at temperature 320° F, cellulose fiber at 0.35 percent of the mix weight was used in the SMA mixes

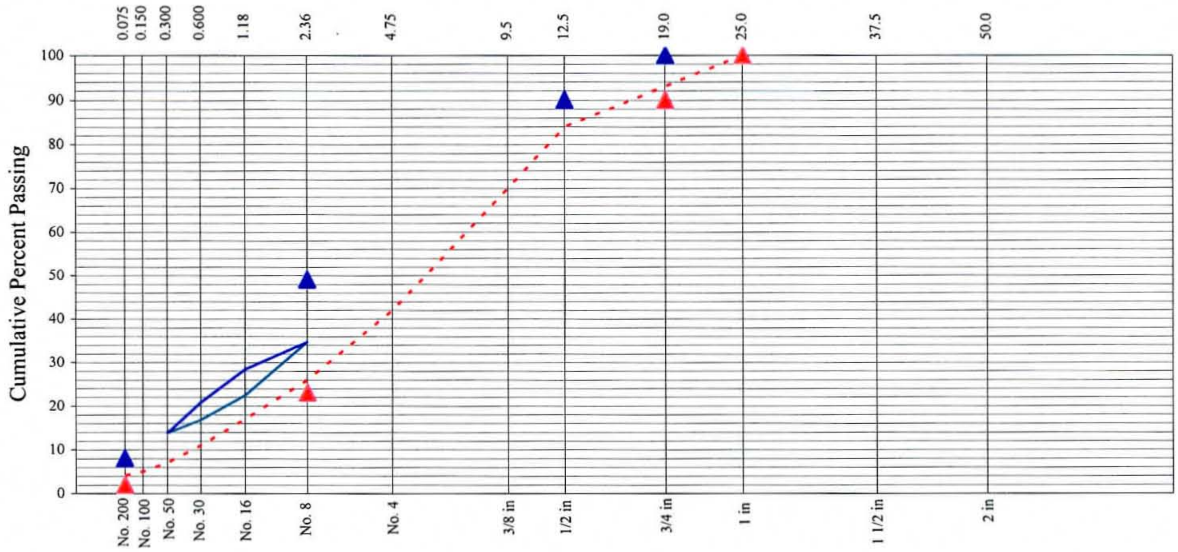



**Fig 2.4.1.1 Gradation For Superpave & Marshall Mix, 25 mm Maximum Aggregate Size**

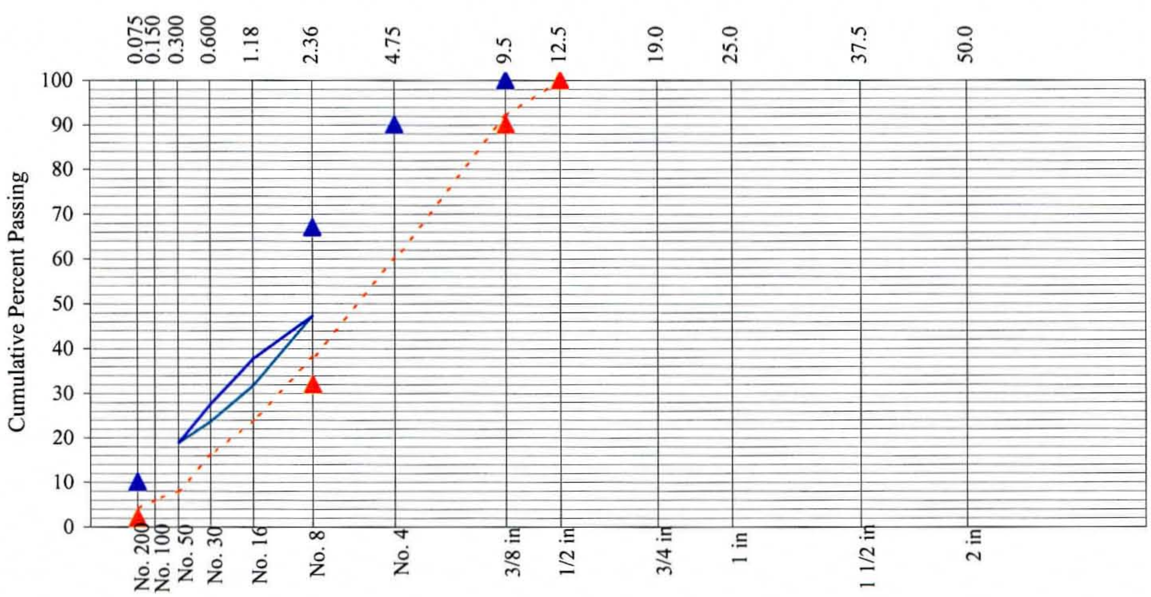



**Fig 2.4.1.2 Gradation For Superpave & Marshall Mixes, 12.5 mm Maximum Aggregate Size**

Note: ▲ is the specification upper gradation limit▲ is the lower limit. The enclosed area between No.50 and No.8 sieves is the restricted zone.

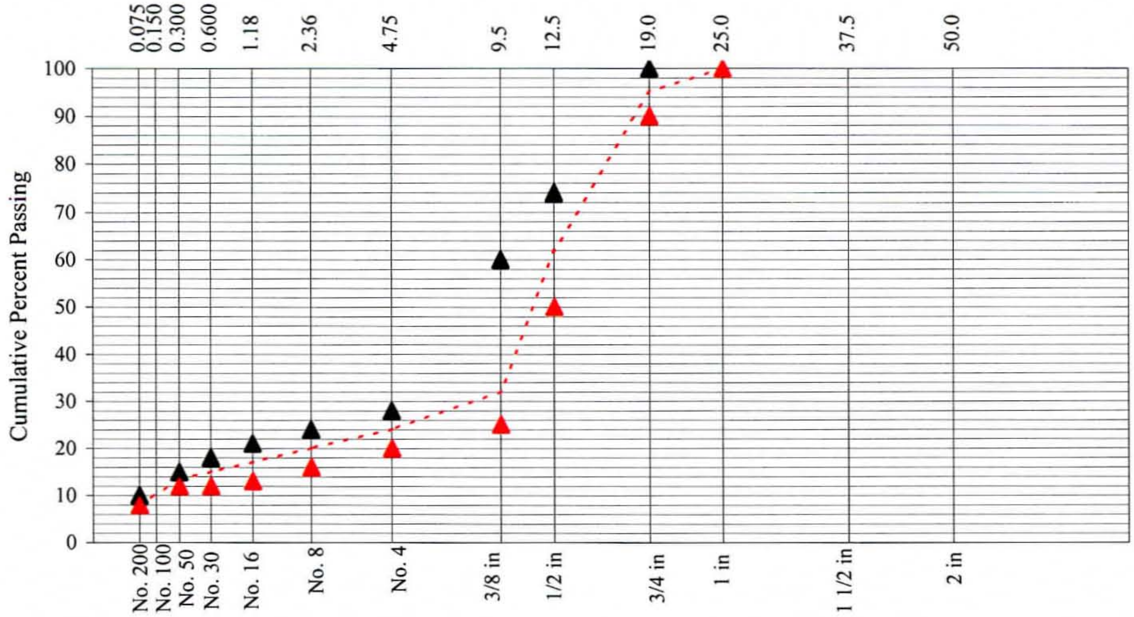



**Fig 2.1.4.3 Gradation For SMA mixes,**

**25 mm Maximum Aggregate Size**

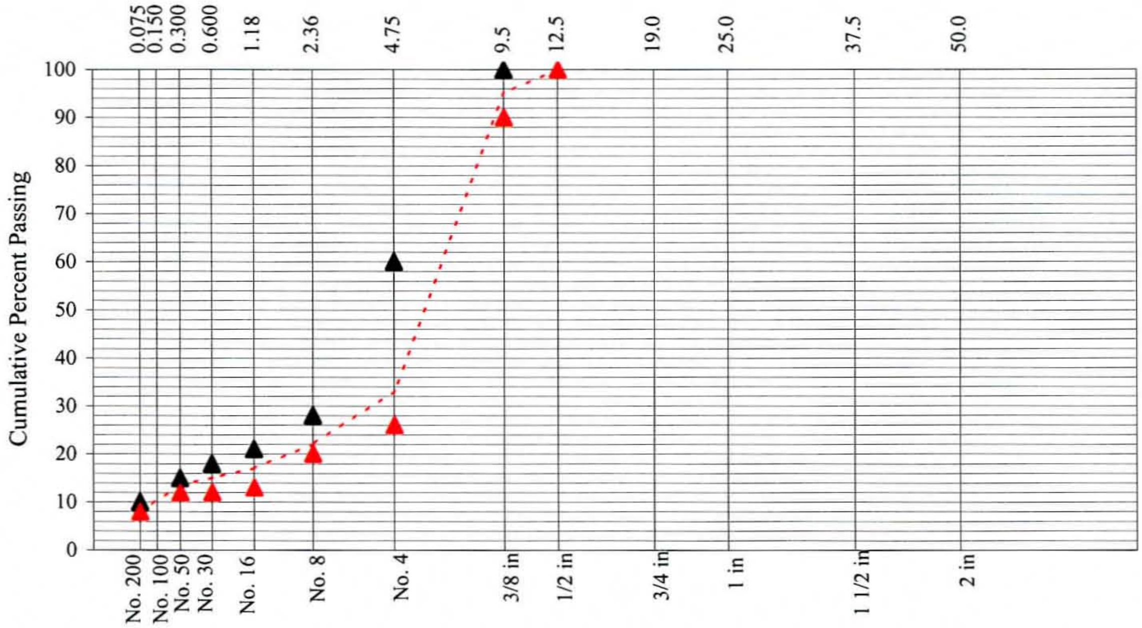



**Fig 2.4.1.4 Gradation For SMA Mixes,**

**12.5 mm Maximum Aggregate Size**

### 2.4.2 Design Category and Method

Compaction levels for mix designs were selected to provide consistency between mix types within the framework of ALDOT specifications. Superpave mixes were compacted with $N_{design}$ =100 gyrations of the Superpave gyratory compactor(SGC). Marshall mixes were compacted with 75 blows, each side, from the mechanical Marshall hammer. SMA mixes were compacted with 50 blows, each side, from the Marshall hammer. One hundred gyrations are specified to design Superpave mixes for upper binder and surface layers for applied ESALs ranging from $3x10^6$ to $3x10^7$. Seventy five blows are specified to design Marshall mixes for applied ESALs greater than $3x10^6$. Fifty blows are specified to design all SMA mixes

All the three types of mixes were designed for void content of 4 %. In addition, the gradation selected were such that minimum VMA requirement of 13% to 15 % (13% for 25 mm maximum aggregate size, 15% for 12.5 mm maximum aggregate size) for Superpave and Marshall mixes, 17% for SMA mixes were met as much as possible. For SMA mixes, the dry rodded value of voids between coarse aggregates ($VCA_{drc}$) were to be greater than that ($VCA_{mix}$) calculated from the gradation and mix volumetrics data.

## 2.5 Mix Performance Test

Upon completion of mix designs, mixes with selected asphalt contents were prepared and rutting tests with the Asphalt Pavement Analyzer(APA) and TSR stripping tests were performed.

### 2.5.1 APA Rut Test

#### 2.5.1.1 Procedures for Making APA Specimens

##### 2.5.1.1.1 Superpave Specimens

APA testing requires six 150 mm diameter, 75 mm thick specimens. Superpave mix is designed with 150 mm diameter, 115 mm thick specimens. APA specimens of Superpave were made by compacting the same size batches at design gyrations to produce 150 mm diameter, 115 mm thick specimens at around 4 % air voids. After bulk gravities were measured and air voids determined, specimens with air voids 0.5 % greater or less than 4% thrown out. Acceptable specimens were sawed to thickness of 75 mm.

##### 2.5.1.1.2 Marshall and SMA Specimens

The Marshall hammer was used to compact specimens 100 mm in diameter, 63.5 mm in height for the design of Marshall and SMA mixes. However, the SGC was used to compact 150 mm diameter samples for the APA test. A trial and error process was used to select gyrations to make specimens with target 4% voids. The SGC was used to compact specimens at trial numbers of gyrations spaced at 10 apart. A relationship between number of gyrations and voids was established and the gyration level which gave 4% air voids selected. After this step the specimen preparation process was the same as for Superpave mixes.

### 2.5.1.2 Testing Parameters

#### 2.5.1.2.1 Loading Conditions

The APA machine subjects pairs of cylindrical specimens (slab samples can also be used) to loaded steel wheels tracking a pressurized rubber hoses placed on top of the specimens. Specimens are enclosed on their sides by plastic moulds, the sawed side facing bottom. The testing is done inside a heated testing chamber with temperature control (see Figure 2.5.1.2.1).

The load on the wheels was set at 120 lbs and the pressure in the hoses was set at 120 psi. The testing temperature in the chamber was set at the high temperature of the PG graded asphalt used, i.e. 147 °F for Marshall and Superpave samples and 169 °F for SMA samples. Samples were preheated to test temperatures in an oven for 16 hours before start of testing.

#### 2.5.1.2.2 Rut Depth Measurement

Rut depths of specimens were manually measured after 8000 cycles of loading, using a template set on the mould and a digital micrometer. The template is a piece of metal about the length of the rectangular mould. Along the center line of the template, there are four evenly spaced ( two for each specimen) slots at right angle to the centerline where the pressurized hose loads the specimens (see Figure 2.5.1.2.2).

The rut depth was determined from the difference between the readings taken before the test and after 8000 cycles of loading. The before test reading was taken on the center line of the specimen – in the middle of each of the slot. The after test reading was taken at the point of deepest rut, which was not always on the centerline( the initial position). Reported the rut depths are the average from six specimens.

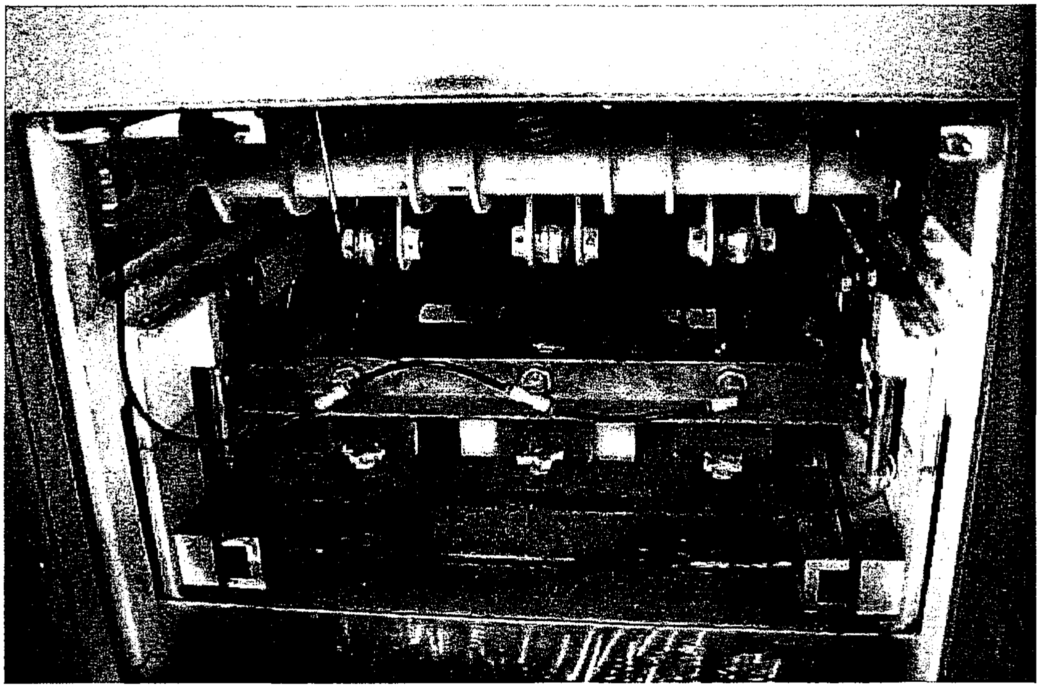


Figure 2.5.1.2.1 APA testing Chamber

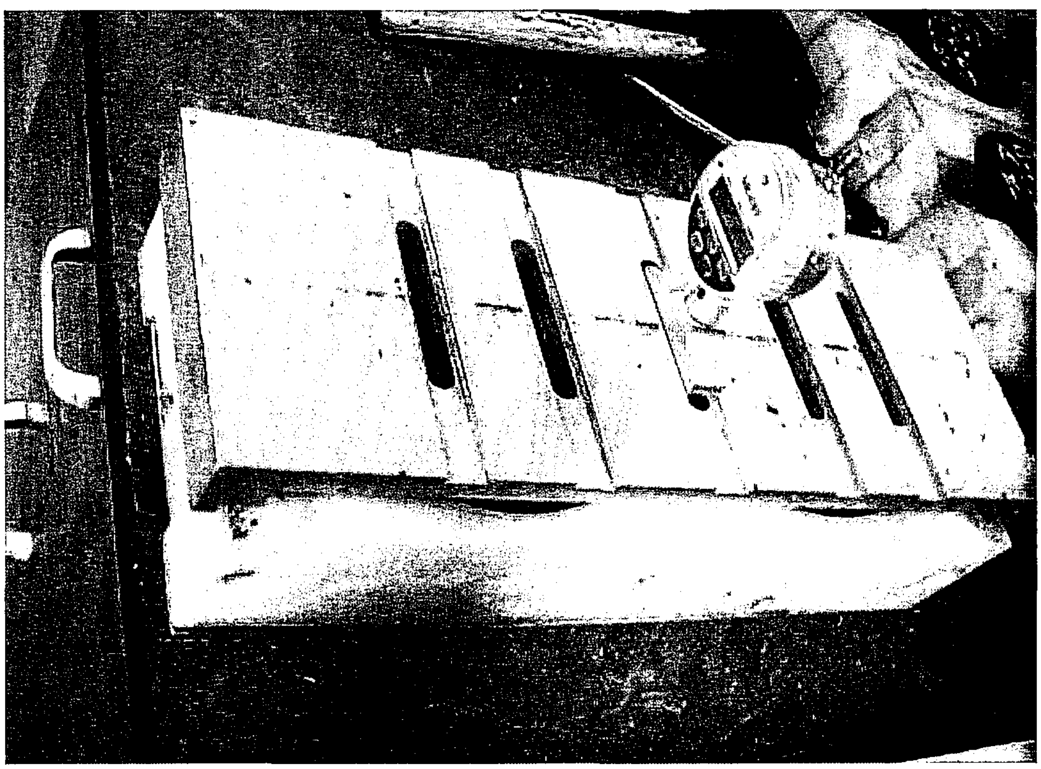


Figure 2.5.1.2.2 Rut Measurement

### 2.5.2 TSR test

#### 2.5.2.1 Procedures for Making the TSR Specimens

##### 2.5.2.1.1 Superpave Specimens

The TSR test requires specimens at 7$\pm$1 % air voids to simulate density of newly constructed pavement. Superpave mixes are designed with specimens that are 150 mm in diameter and 115 mm in height. In the trial and error process to compact the specimen to 7 % air voids, the SGC was set to compact specimens to a predetermined height of 100 mm (the specified dimension by ALDOT for TSR specimens of maximum aggregate size of 25 mm). A number of specimens with amounts of mix materials varying by about 50 grams around the calculated amount (based on the maximum specific gravity of the mix-Gmm) to give 7% air voids were compacted. The amount of materials that gave 7 % void at the preset height of 100 mm was then established with this trial and error process.

##### 2.5.2.1.2 Marshall and SMA Specimens

The TSR tests for Marshall and SMA mixes use 100 mm diameter, 63 mm high samples. It was more difficult to compact the specimens to the 7 % air voids with the right height since two variable needed to be manipulated – the amount of mix materials in each specimen and the number of blows of compaction- to satisfy the double criteria of height and air voids. The amount of mix primarily determined the height (even when air voids were 2-3 % amiss). The number of blows determined the air voids. Therefore, the trial and error process was broken up into two steps. In the first step, the amount of material to produce a compacted specimen 63 mm thick with approximately 7% voids was determined. With the amount of mix materials set, the number of blows was adjusted to give 7 % air voids.

### 2.5.2.2 Conditioning and Testing Procedures

The Alabama DOT 's test procedure BMTP (Bureau of Materials and Tests Procedures) 361 was followed for specimen conditioning and testing. Six specimens were divided into two groups of three each, on the basis of equal average air voids for each group. The specimens in the conditioned group were vacuum saturated to 55-80% and then conditioned for 24 hours at 60 °C in a water bath. After removal from the 60°C water bath, the conditioned group specimens and the unconditioned group specimens were submerged in a 25°C water bath for an hour before being split diametrically at a loading rate of 5cm /minute.

# CHAPTER 3. TEST RESULTS AND ANALYSIS

## 3.0 Aggregate Processing

Aggregate samples were collected from quarries or pits, oven dried, broken into standard size fractions, and put into separate individually labeled drums or buckets for storage. Aggregate properties tests were performed on samples prepared by combining portions of standard size fractions to produce desired test gradation.

## 3.1 Coarse Aggregate Test

### 3.1.1 Specific Gravity and Absorption, AASHTO T85

The specific gravity and absorption samples were taken from the stockpiles of each particular source that consisted mainly of coarse aggregates. The minus No.4 size fractions of the samples were sieved out.

**Table. 3.1.1 Summary of Specific Gravity and Absorption of Coarse Aggregate**

| | CrLs #2 | | | | Uncrushed Gravel | | | | Crushed Gravel | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Samples | 1 | 2 | 3 | avg. | 1 | 2 | 3 | avg. | 1 | 2 | 3 | avg. | 1 | 2 | 3 | avg. |
| Apparent Specific Gravity | 2.790 | 2.782 | 2.785 | 2.786 | 2.721 | 2.721 | 2.722 | 2.721 | 2.654 | 2.641 | 2.648 | 2.648 | 2.648 | 2.649 | 2.648 | 2.648 |
| Bulk Specific Gravity | 2.709 | 2.715 | 2.716 | 2.713 | 2.671 | 2.670 | 2.674 | 2.672 | 2.617 | 2.607 | 2.613 | 2.612 | 2.600 | 2.589 | 2.592 | 2.594 |
| Bulk SSD Specific Gravity | 2.738 | 2.739 | 2.741 | 2.739 | 2.689 | 2.689 | 2.691 | 2.690 | 2.631 | 2.620 | 2.626 | 2.626 | 2.618 | 2.611 | 2.614 | 2.614 |
| Water Absorption(%) | 1.1 | 0.9 | 0.9 | 1.0 | 0.7 | 0.7 | 0.7 | 0.7 | 0.5 | 0.5 | 0.5 | 0.5 | 0.7 | 0.9 | 0.8 | 0.8 |

## 3.1.2 Percentage of Fractured Particles , ASTM D5821

The specification for the test has two ways of calculating the percentages of particles with fracture faces: by weight or by count. The results in Table 3.1.2 indicate the values from the two methods are rather close, no more than 3 % apart, and percentages by weight are consistently lower than by count.

The two crushed limestones have 100 % percent crushed particles with two or more fractured faces. The crushed gravel only has size fractions up to 9.5 mm.

Comparing fractured face counts for the uncrushed and crushed gravel indicates crushing greatly increases the percentage of particles with crushed faces. If the crushed face count is a major factor in the stripping or rutting performance, mixes made with uncrushed and crushed gravels should be able to show contrast accordingly.

**Table 3.1.2. Percentage of Particles with Fractured Faces**

| Aggregate Souce | Sieve Size | | Percentage of Fractured Particles | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | one or more fractured faces | | | | | | two or more fractured faces | | | | | |
| | | | 1 | 2 | 3 | avg. | STD | C.V. | 1 | 2 | 3 | avg. | STD | C.V. |
| uncrushed gravel | 4.75 mm | by count | 27% | 25% | 34% | 29% | 4% | 12% | 6% | 5% | 15% | 9% | 4% | 49% |
| | | by weight | 26% | 21% | 30% | 26% | 3% | 12% | 5% | 5% | 13% | 8% | 4% | 46% |
| | 9.5 mm | by count | 24% | 21% | 19% | 21% | 2% | 8% | 9% | 4% | 6% | 6% | 2% | 28% |
| | | by weight | 22% | 20% | 18% | 20% | 1% | 7% | 6% | 3% | 5% | 5% | 1% | 24% |
| | 12.5 mm | by count | 29% | 17% | 21% | 22% | 4% | 20% | 4% | 5% | 8% | 6% | 2% | 27% |
| | | by weight | 29% | 12% | 19% | 20% | 6% | 30% | 5% | 3% | 6% | 5% | 1% | 24% |
| | 19.5 mm | by count | 17% | 9% | 14% | 13% | 3% | 22% | 3% | 1% | 4% | 3% | 1% | 42% |
| | | by weight | 16% | 9% | 13% | 13% | 2% | 19% | 3% | 1% | 3% | 2% | 1% | 38% |
| crushed gravel | 4.75 mm | by count | 99% | 98% | 98% | 98% | 0% | 0% | 94% | 93% | 94% | 94% | 0% | 0% |
| | | by weight | 100% | 95% | 97% | 97% | 2% | 2% | 93% | 90% | 89% | 91% | 2% | 2% |
| | 9.5 mm | by count | 96% | 98% | 99% | 98% | 1% | 1% | 83% | 87% | 88% | 86% | 2% | 2% |
| | | by weight | 95% | 97% | 99% | 97% | 1% | 1% | 82% | 86% | 86% | 85% | 2% | 2% |

### 3.1.3 Percentage of Flat and Elongated Particles, ASTM D4791

In ASTM test method D4791, particles are classified as flat and/or elongated by means of a caliper with openings formed by a lever pivoted on a base plate and two steel posts positioned on a line with the pivot and at set distances about the length of the lever. At the longer end of the lever, the gap between the lever and the steel post measures the maximum dimension of the particle. At the shorter end of the lever is the minimum dimension below which the aggregate is termed flat or elongated. The lengths of the lever's arms determine the ratios of the opening dimensions (2:1, 3:1, 5:1) and, thus, the severity of the indicated particle's flatness and elongatedness.

This is a simple test, but is time consuming and tedious to perform. For this project, all coarse aggregate fractions 9.5 mm and larger were tested for flat and elongated ratios of 3:1 and 5:1. Smaller size particles were harder to test, and the results were likely less accurate. The crushed gravel didn't have larger than 9.5 mm fractions, so only one fraction was tested. The results are shown in Table 3.1.3

As with the fractured face count test, this test has by weight or by count options for calculating the percentage of flat and elongated particles. Here again the values by either methods do not differ by more than 6% ( normally only by 2 –3 %), with by weight percentage consistently lower. The percentages with 5:1 ratio are generally low, mostly below 10%. The percentages with 3:1 ratio show much bigger ranges of values. Based on the 3:1 ratio, the crushed gravel has the least amount of flat and elongated particles, the uncrushed gravel the second lowest, limestone #1 the second highest and limestone #2 the highest.

**Table 3.1.3. Summary of Percentage of Flat and Elongated Particles**

| Aggregate Source | Sieve Size | | Percentage of Flat and Elongated of Particles | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Ratio Used: 5:1 | | | | | | Ratio Used: 3:1 | | | | | |
| | | | 1 | 2 | 3 | avg. | STD | C.V. | 1 | 2 | 3 | avg. | STD | C.V. |
| crushed limestone #1 | 9.5mm | by count | 10% | 15% | 10% | 12% | 2% | 19% | 33% | 33% | 37% | 34% | 2% | 5% |
| | | by weight | 8% | 11% | 9% | 9% | 1% | 12% | 32% | 30% | 34% | 32% | 1% | 4% |
| | 12.5mm | by count | 6% | 3% | 5% | 5% | 1% | 24% | 26% | 17% | 16% | 20% | 4% | 21% |
| | | by weight | 5% | 2% | 3% | 3% | 1% | 33% | 21% | 12% | 11% | 15% | 4% | 29% |
| | 19.5mm | by count | 0% | 0% | 1% | 0% | 0% | --- | 3% | 4% | 4% | 4% | 0% | 12% |
| | | by weight | 0% | 0% | 0% | 0% | 0% | --- | 3% | 3% | 4% | 3% | 0% | 13% |
| crushed limestone #2 | 9.5mm | by count | 17% | 17% | 18% | 17% | 0% | 3% | 61% | 45% | 54% | 53% | 6% | 10% |
| | | by weight | 12% | 13% | 12% | 12% | 0% | 4% | 61% | 40% | 52% | 51% | 7% | 14% |
| | 12.5mm | by count | 8% | 8% | 4% | 7% | 2% | 27% | 28% | 25% | 25% | 26% | 1% | 5% |
| | | by weight | 5% | 5% | 3% | 4% | 1% | 21% | 21% | 19% | 20% | 20% | 1% | 3% |
| | 19.5 | by count | 3% | 2% | 0% | 2% | 1% | 67% | 14% | 15% | 15% | 15% | 0% | 3% |
| | | by weight | 2% | 1% | 0% | 1% | 1% | 67% | 12% | 16% | 13% | 14% | 2% | 11% |
| uncrushed gravel | 9.5mm | by count | 1% | 1% | 5% | 2% | 2% | 76% | 25% | 21% | 26% | 24% | 2% | 8% |
| | | by weight | 1% | 0% | 3% | 1% | 1% | 83% | 20% | 23% | 26% | 23% | 2% | 9% |
| | 12.5mm | by count | 1% | 2% | 0% | 1% | 1% | 67% | 14% | 17% | 13% | 15% | 2% | 11% |
| | | by weight | 1% | 1% | 0% | 1% | 0% | 67% | 12% | 14% | 11% | 12% | 1% | 9% |
| | 19.5mm | by count | 1% | 0% | 1% | 1% | 0% | 67% | 9% | 4% | 9% | 7% | 2% | 30% |
| | | by weight | 1% | 0% | 1% | 1% | 0% | 67% | 8% | 3% | 8% | 6% | 2% | 35% |
| crushed gravel | 9.5mm | by count | 1% | 0% | 0% | 0% | 0% | 133% | 3% | 0% | 2% | 2% | 1% | 67% |
| | | by weight | 0% | 0% | 0% | 0% | 0% | --- | 2% | 0% | 2% | 1% | 1% | 67% |

Note: The sign --- signifies instances when coefficient of variation can't be calculated because of a mean value of zero.

## 3.1.4 Toughness and Abrasion Resistance Tests

In the Los Angeles Abrasion test, ASTM C131, and the Micro Deval test, Ontario (Canada) Standard Test Method LS-619, aggregate samples of specified gradings are put through a degradation process. In L.A. abrasion, 5000 grams of aggregates are tumbled and impacted with a specific number and weight (varying according to aggregate sample gradation) of 46.8 mm diameter steel balls in a revolving steel drum. In the Micro Deval test, 1500 grams of aggregates are soaked in water for no less than one hour, placed in a jar mill with 2.0 liters of water and an abrasive charge of 5000 grams of 9.5 mm diameter steel balls and rotated for 2 hours at 100 rpm. The L.A. abrasion test has a long established record of use for distinguishing rock toughness and abrasion resistance quality since it came into being in the city of its namesake many decades ago. The only drawback for the L.A. abrasion test is that it is a dry test. Aggregates are abraided in a dry condition. However some aggregates may soften when in prolonged contact with water, which is often the situation for aggregates in pavement. Hence, the Micro Deval Test, in which the aggregate sample is submerged in water for conditioning before and during the testing, offers an alternative.

In the study, standard gradation B of ASTM C131 was used in the L.A. Abrasion test, and standard gradation 7.2 of Ontario (Canada) Standard Test Method LS-619 was used in the Micro Deval test. The gradations were chosen for their compatibility with the 25 mm maximum size gradation.

Comparisons of the test results (shown in Tables 3.1.4.1 and 3.1.4.2 ) for L.A. Abrasion and Micro Deval Abrasion tests indicate, the Micro Deval abrasion loss is generally smaller than L.A. abrasion loss for a given aggregate. What is interesting is that gravels have significantly higher L.A. abrasion losses than limestones but significantly lower Micro Deval losses. The reason could be that limestones aggregates (composed mainly of calcium carbonate) are more elastic than gravel (composed mainly of quartz), are able to absorb impact loading in the L.A. degradation process. While the harder and more brittle gravel fare much better when subjected to grinding with much smaller steel balls in the wet Micro Deval process.

Also for limestones of similar L.A. Abrasion values, the Micro Deval test indicates a difference. For the gravels, because of the same mineralogical composition, it is not surprising to find the Micro Deval values for the two are close. The uncrushed gravel unexpectedly has substantially higher LA abrasion loss. It appears that crushed faces and changes in dimension ratios and other changes caused by crushing improved the toughness of the gravel.

**Table 3.1.4.1 Summary of LA Abrasion Results**

| Aggregate Source | sample 1 | sample 2 | sample 3 | average | STD | C.V. |
|---|---|---|---|---|---|---|
| Crushed Limestone #1 | 23% | 25% | 25% | 24% | 1.2% | 4.8% |
| Crushed Limestone #2 | 24% | 24% | 24% | 24% | 0.0% | 0.0% |
| Uncrushed Gravel | 47% | 48% | 47% | 47% | 0.6% | 1.3% |
| Crushed Gravel | 37% | 38% | 37% | 37% | 0.5% | 1.2% |

**Table 3.1.4.2 Summary of Micro Deval Test**

| Aggregate Source | sample 1 | sample 2 | sample 3 | average | STD | C.V. |
|---|---|---|---|---|---|---|
| Crushed Limestone #1 | 24.2% | 24.2% | 22.5% | 24.0% | 1.0% | 4.1% |
| Crushed Limestone #2 | 15.4% | 15.1% | 14.6% | 15.0% | 0.4% | 2.7% |
| Uncrushed Gravel | 5.2% | 5.0% | 5.7% | 5.3% | 0.4% | 6.8% |
| Crushed Gravel | 5.8% | 6.4% | 6.2% | 6.1% | 0.3% | 5.0% |

## 3.1.5 Uncompacted Void Content of Coarse Aggregate, AASHTO TP56

The uncompacted void content test for coarse aggregate uses the same methodology for determining the void content between aggregate as AASHTO T304, fine aggregate angularity (FAA) test. The apparatus used for coarse aggregate is a scaled up version of that used in FAA test. In this test, 5000 grams of coarse aggregates of a specific gradation were poured into a funnel (flap doors closing off the bottom of the funnel at the beginning of the test) with a calibrated cylindrical measure centered under it. Then the latch holding the flap door is pulled out, the flaps swing open, and the aggregates are allowed to flow freely into the measure. After the funnel empties, the excess aggregate above the top of the full cylindrical measure is struck off until aggregates are level with the cylindrical top rim. The uncompacted void is the difference between the volume of the cylindrical measure and absolute volume of the coarse aggregate collected in the measure caculated from the weight and specific gravity of the coarse aggregate.

In this study uncompacted void test for coarse aggregate were run on two standard gradations; a 19 mm gradation compatible with the gradation of the 25 mm maximum size mixes, and a 12.5mm gradation compatible with gradation of the 12.5 mm maximum aggregate size mixes. The crushed gravel did not have large particles for the 19 mm standard gradation.

As can been seen from table 3.1.5.1 and 3.1.5.2, the gradation of the samples causes a difference of about 2% in the values obtained for the same aggregate. The change in the maximum size of the gradation on the trend of the uncompacted void content for crushed limestone #1 and uncrushed gravel contradicted previous experience of similar work done at Auburn and the consensus expectation, which suggests that smaller size gradations samples ought to have larger uncompacted voids. The explanation could be the combination of effects of the variations in sampling both in the testing of specific gravity test and in this particular test. The samples used for the two tests are of different gradations

What is reassuringly unequivocal is that crushing increases the uncompacted void content of gravel, by about 2% in this study, just as expected.

**Table. 3.1.5.1 Summary of Uncompacted Void Content of Coarse Aggregate (19 mm Standard Gradation)**

| Aggregate Source | sample 1 | sample 2 | sample 3 | average | STD | C.V. |
|---|---|---|---|---|---|---|
| Crushed Limestone #1 | 46.6% | 46.7% | 47.0% | 46.8% | 0.2% | 0.0 |
| Crushed Limestone #2 | 48.4% | 48.0% | 47.9% | 48.1% | 0.3% | 0.0 |
| Uncrushed Gravel | 42.3% | 43.9% | 43.9% | 43.4% | 0.9% | 0.0 |

**Table. 3.1.5.2 Summary of Uncompacted Void Content of Coarse Aggregate (12.5 mm Standard gradation)**

| Aggregate Source | sample 1 | sample 2 | sample 3 | average | STD | C.V. |
|---|---|---|---|---|---|---|
| Crushed Limestone #1 | 45.4% | 45.9% | 46.4% | 45.9% | 0.5% | 0.0 |
| Crushed Limestone #2 | 50.1% | 50.3% | 50.0% | 50.1% | 0.2% | 0.0 |
| Uncrushed Gravel | 41.4% | 41.0% | 40.5% | 41.0% | 0.5% | 0.0 |
| Crushed Gravel | 43.5% | 43.0% | 43.8% | 43.4% | 0.4% | 0.0 |

### 3.1.6 Soundness of Aggregate by Use of Magnesium Sulfate, AASHTO T104

The test uses the expansion of magnesium sulfate crystals precipitates in the surface voids of aggregates to simulate the forces of disintegration caused by water freezing and thawing in the cracks of aggregate. In the study, the standard sample gradation used (the combination of 330 grams of 9.5 mm fraction and 670 grams of 12.5 mm fraction) was that for 19.0 mm to 9.5 mm size particles. Because crushed gravel didn't have large sizes, it was not included in the test. The value of magnesium soundness of the crushed gravel was assumed to be comparable to that for the uncrushed gravel in the data analysis later. The results are shown below.

**Table 3.1.6 Summary of Soundness by Use of Magnesium Sulfate**

| Aggregate Source | sample 1 | sample 2 | sample 3 | average | STD | C.V. |
|---|---|---|---|---|---|---|
| Crushed Limestone #1 | 19.3% | 18.3% | 24.7% | 20.8% | 3.4% | 0.2 |
| Crushed Limestone #2 | 1.4% | 1.7% | 3.4% | 2.2% | 1.1% | 0.5 |
| Uncrushed Gravel | 0.0% | 0.0% | 0.1% | 0.0% | 0.1% | 1.7 |

The three aggregates showed a range of values, with the uncrushed gravel showing no loss, limestone #2 a small loss, and limestone #1 a substantial loss

## 3.2 Fine Aggregate Tests

### 3.2.1 Specific Gravity and Absorption , AASTHTO T84

The plus No. 4 size fractions were removed from the screenings of crushed limestone and crushed gravel. Results from these resulting materials and the natural sand are shown below.

**Table. 3.2.1 Summary of Specific Gravity And Absorption Of Fine Aggregate**

| | CrLs #1 | | | | CrLs #2 | | | | Natural Sand | | | | Crushed Gravel | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | avg. | 1 | 2 | 3 | avg. | 1 | 2 | 3 | avg. | 1 | 2 | 3 | avg. |
| Apparent Specific Gravity | 2.775 | 2.752 | 2.765 | 2.764 | 2.734 | 2.720 | 2.721 | 2.725 | 2.652 | 2.651 | 2.650 | 2.651 | 2.661 | 2.653 | 2.655 | 2.656 |
| Bulk Specific Gravity | 2.566 | 2.561 | 2.565 | 2.564 | 2.650 | 2.656 | 2.682 | 2.663 | 2.438 | 2.439 | 2.449 | 2.442 | 2.628 | 2.626 | 2.624 | 2.626 |
| Bulk SSD Specific Gravity | 2.641 | 2.630 | 2.637 | 2.636 | 2.681 | 2.679 | 2.696 | 2.685 | 2.519 | 2.519 | 2.525 | 2.521 | 2.640 | 2.636 | 2.636 | 2.637 |
| Water Absorption(%) | 2.9 | 2.7 | 2.8 | 2.8 | 1.2 | 0.9 | 0.5 | 0.9 | 3.3 | 3.3 | 3.1 | 3.2 | 0.5 | 0.4 | 0.4 | 0.4 |

### 3.2.2 Uncompacterd Void Content of Fine Aggregate, AASHTO T304

The uncompacted void content was included in the Superpave design system for the fine aggregate portions of the blends to insure particles were sufficiently angular to prevent problems like tender mixes and rutting. It was suspected that natural sand played a major role in the problems because it was believed that natural sand would have lower uncompacted voids than manufactured (or crushed) sand.

Method A- standard graded samples made up of 44 grams of No. 16 fraction, 57 grams of No.30 fraction, 72 grams of No.50 fraction and 17 grams of No. 100 fraction were tested. The results in Table 3.2.2 show the FAA values for the four fine aggregate differ by a maximum of only 2.2%. The natural sand, the LS#2 and the crushed gravel have exactly the same value of 46.5%. This suggests the uncompacted voids test does not distinguish types of fine aggregates very well and that the opinion regarding the test and natural sand may not be valid. All four are above the generally accepted minimum requirement of 45%.

**Table 3.2.2. Summary of Fine aggregate Angularity Test**

| Aggregate Source | sample 1 | sample 2 | sample 3 | average | STD | C.V. |
|---|---|---|---|---|---|---|
| Crushed Limestone #1 | 49.0% | 48.9% | 48.3% | 48.7% | 0.4% | 0.0 |
| Crushed Limestone #2 | 46.6% | 46.4% | 46.5% | 46.5% | 0.1% | 0.0 |
| Natural Sand | 46.5% | 46.6% | 46.5% | 46.5% | 0.1% | 0.0 |
| Crushed Gravel | 46.2% | 46.8% | 46.6% | 46.5% | 0.3% | 0.0 |

### 3.2.3 Sand Equivalent Test, AASHTO T176 and Methylene Blue Test, AASHTO TP57

The sand equivalent test measures the amount of silt and clay size particles in a fine aggregate. The methylene blue test measures the size, shape and activity of the particles in the minus No. 200 fraction. Results are presented in Tables 3.2.3.1 and 3.2.3.2.

**Table: 3.2.3.1 Summary of Sand Equivalent Test**

| Aggregate Source | sample 1 | sample 2 | sample 3 | average | STD | C.V. |
|---|---|---|---|---|---|---|
| Crushed Limestone #1 | 27 | 27 | 25 | 27 | 1.2 | 0.0 |
| Crushed Limestone #2 | 66 | 68 | 68 | 68 | 1.2 | 0.0 |
| Natural Sand | 34 | 30 | 32 | 32 | 2.0 | 0.1 |
| Crushed Gravel | 92 | 93 | 83 | 90 | 5.5 | 0.1 |

**Table 3.2.3.2 Summary of Methylene Blue Value Test**

| Aggregate Source | sample 1 | sample 2 | sample 3 | average | STD | C.V. |
|---|---|---|---|---|---|---|
| Crushed Limestone #1 | 12.0 | 11.5 | 12.0 | 11.8 | 0.3 | 0.0 |
| Crushed Limestone #2 | 6.0 | 6.0 | 6.0 | 6.0 | 0.0 | 0.0 |
| Natural Sand | 11.5 | 10.5 | 10.0 | 10.7 | 0.8 | 0.1 |
| Crushed Gravel | 2.8 | 2.8 | 2.5 | 2.7 | 0.2 | 0.1 |

Considering that clay and silt size particles pass the No.200 sieve, these two values may be related. For the four fine aggregates, the SE and MBV are strongly correlated as can be seen in Figure 3.2.3.1 This data fits well with data from earlier research (see reference No.2). All of the data are compiled in Table 3.2.3.3 and plotted in Figure 3.2.3.2. The linear trend between MBV and SE is strengthened by the addition of data from the new aggregates, as shown by an increase of $R^2$ from 0.55 of previous data to the present 0.58 (see reference No.2).

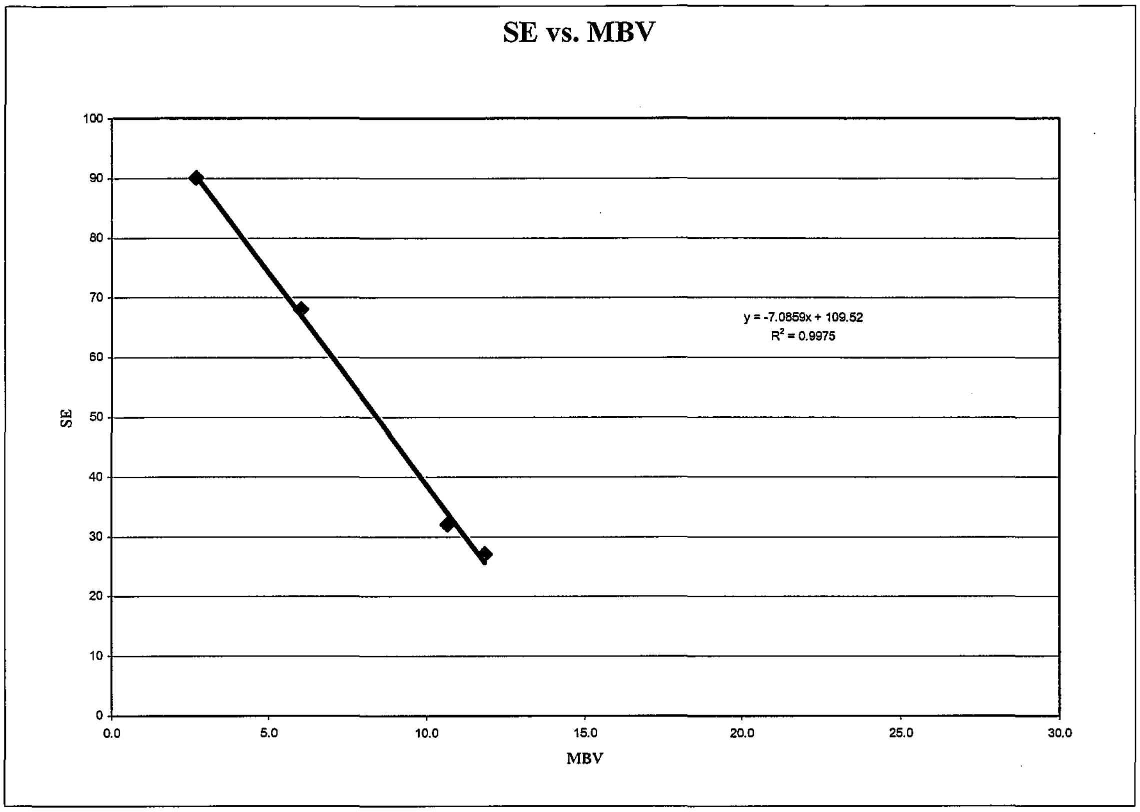



**Fig.3.2.3.1 Comparison of SE and MBV**

## 3.3 Mix Design

All together, 21 mixes were designed for 4% air voids. The gradations for Superpave and Marshall mixes were the same for given maximum aggregate size. Superpave mixes of both 25 mm and 12.5 mm mixes were designed with Superpave gyratory compactor with 100 design gyrations. Marshall mixes of both maximum aggregate sizes were designed with 75 blows of the Marshall hammer. Stone Matrix Asphalt mixes of both maximum aggregate sizes were designed with 50 blows of the Marshall Hammer. Optimum asphalt content and resulting VMA of the mixes are shown in Table 3.3

**Table 3.2.3.3 Table of SE & MBV Data (with data from previous studies)**

| Project | Aggregate Type | Source | SE | MB |
|---|---|---|---|---|
| Fine Aggregate Study, 1997 | Washed Natura Sands | WS3 | 83 | 5.0 |
| | | WS5 | 76 | 6.0 |
| | | | | |
| | Pit Run Natural Sands | PRS1 | 95 | 2.0 |
| | | PRS2 | 42 | 7.3 |
| | | PRS3 | 38 | 16.9 |
| | | PRS4 | 55 | 7.0 |
| | | PRS5 | 82 | 4.7 |
| | | PRS6 | 89 | 1.1 |
| | | PRS7 | 84 | 11.0 |
| | | PRS8 | 36 | 13.9 |
| | | PRS9 | 37 | 11.6 |
| | | PRS10 | 17 | 11.7 |
| | | PRS11 | 27 | 18.4 |
| | | | | |
| | Crushed Gravels | CG1(3/8") | 92 | 3.0 |
| | | CG2(3/4") | 60 | 2.0 |
| | | CG3(1/2") | 85 | 2.0 |
| | | CG4(3/8") | 88 | 3.0 |
| | | | | |
| | Crushed Stones | CS1(LS) | 64 | 3.0 |
| | | CS2(LS) | 72 | 1.9 |
| | | CS3(LS) | 67 | 4.4 |
| | | CS4(LS) | 65 | 1.3 |
| | | CS5(D) | 82 | 1.1 |
| | | CS6(D) | 40 | 7.9 |
| | | CS7(LS) | 64 | 3.4 |
| | | CS8(LS) | 66 | 1.7 |
| | | CS9(LS) | 87 | 1.7 |
| | | CS10(D) | 73 | 4.5 |
| | | CS11(D) | 96 | 0.5 |
| | | CS12(SS) | 40 | 6.4 |
| | | CS13(GR) | 60 | 2.9 |
| | | CS14(BFS) | 87 | 0.9 |
| | | CS15(GR) | 65 | 0.8 |
| | | | | |
| Present Study | | Limestone #1 | 27 | 11.8 |
| | | Limestone #2 | 68 | 6.0 |
| | | Natural Sand | 32 | 10.7 |
| | | Crushed Gravel | 90 | 2.7 |

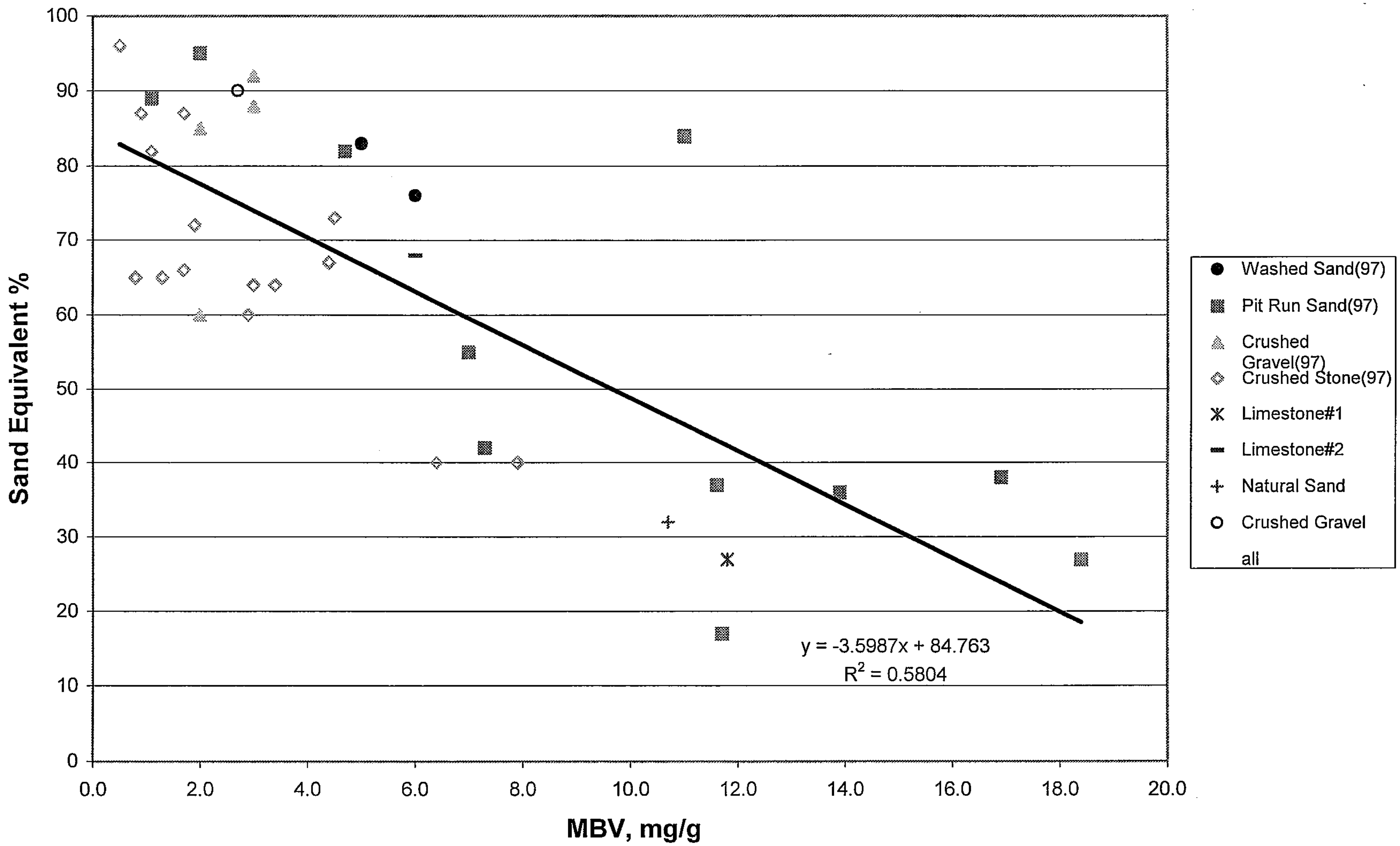



**Fig. 3.2.3.2 MBV vs.SE (compilation data from all projects)**

## Table. 3.3 Summary Of Mix Design

| Mix | Optimum A.C.(@4% air voids,%) | VMA(%) |
|---|---|---|
| CrLs#2_Superpave_25mm | 5.6 | 15.5 |
| CrLs#2_Marshall_25 mm | 6.4 | 16.3 |
| CrLs#2_SMA_25 mm | 5.5 | 15.8 |
| | | |
| CrLs#2_Superpave_12.5mm | 6.3 | 16.8 |
| CrLs#2_Marshall_12.5 mm | 6.3 | 16.9 |
| CrLs#2_SMA_12.5 mm | 6.5 | 17.3 |
| | | |
| CrLs#1_Superpave_25mm | 6.0 | 14.4 |
| CrLs#1_Marshall_25 mm | 6.2 | 14.3 |
| CrLs#1_SMA_25 mm | 5.1 | 14.6 |
| | | |
| CrLs#1_Superpave_12.5mm | 6.0 | 14.4 |
| CrLs#1_Marshall_12.5 mm | 6.2 | 14.7 |
| CrLs#1_SMA_12.5 mm | 5.7 | 15.7 |
| | | |
| GNS_Superpave_25mm | 4.8 | 11.0 |
| GNS_Marshall_25 mm | 5.5 | 13.2 |
| GNS_SMA_25 mm | 7.2 | 17.3 |
| | | |
| GNS_Superpave_12.5mm | 5.7 | 13.0 |
| GNS_Marshall_12.5 mm | 6.5 | 14.9 |
| GNS_SMA_12.5 mm | 8.5 | 20.2 |
| | | |
| CG_Superpave_12.5mm | 5.8 | 15.8 |
| CG_Marshall_12.5 mm | 6.6 | 17.5 |
| CG_SMA_12.5 mm | 7.0 | 18.6 |

### 3.3.1 Asphalt Content of Mixes

As shown in Figure 3.3.1, the uncrushed gravel GNS_SMA mixes seem to have abnormally high asphalt content, especially the 12.5 mm maximum aggregate size. This is contrary to conventional wisdom which says rounded natural sand and natural gravel improve the packing of aggregates, hence requiring less A.C. to achieve 4% air void.

There are several factors which need to be considered in relation to asphalt content. Compaction energy, nature of P200 material and its interaction with asphalt, particle size, particle shape, angularity and surface texture.

Studies (see Reference No.5) have shown that 100 gyrations by SCG impart more compaction energy to specimen than 75 standard Marshall blows. This is borne out by the optimum asphalt contents of different aggregate mixes in this study. Generally, the Marshall mixes have higher asphalt content than Superpave mixes with the same aggregate . The 50 blow Marshall used in compacting SMA samples involves considerably less compaction energy than 75 blow Marshall, but it needs to be remembered that aggregates and asphalt are different for the two mix types when making comparisons.

The mineralogical nature of the natural sand may have also been a factor in the high asphalt content for the GNS_SMA mixes. The clay minerals may have stiffened the asphalt ( as evidenced by relatively high tensile strength of 12.5 maximum aggregate size GNS_SMA mixes, refer to Figure 3.4.2.1), thus making the mix more difficult to compact. The need for more asphalt in GNS_SMA mixes was likely accentuated by the higher P200 content of SMA mixes. SMA mixes had 8% P200 while Marshal and Superpave had only 4%.

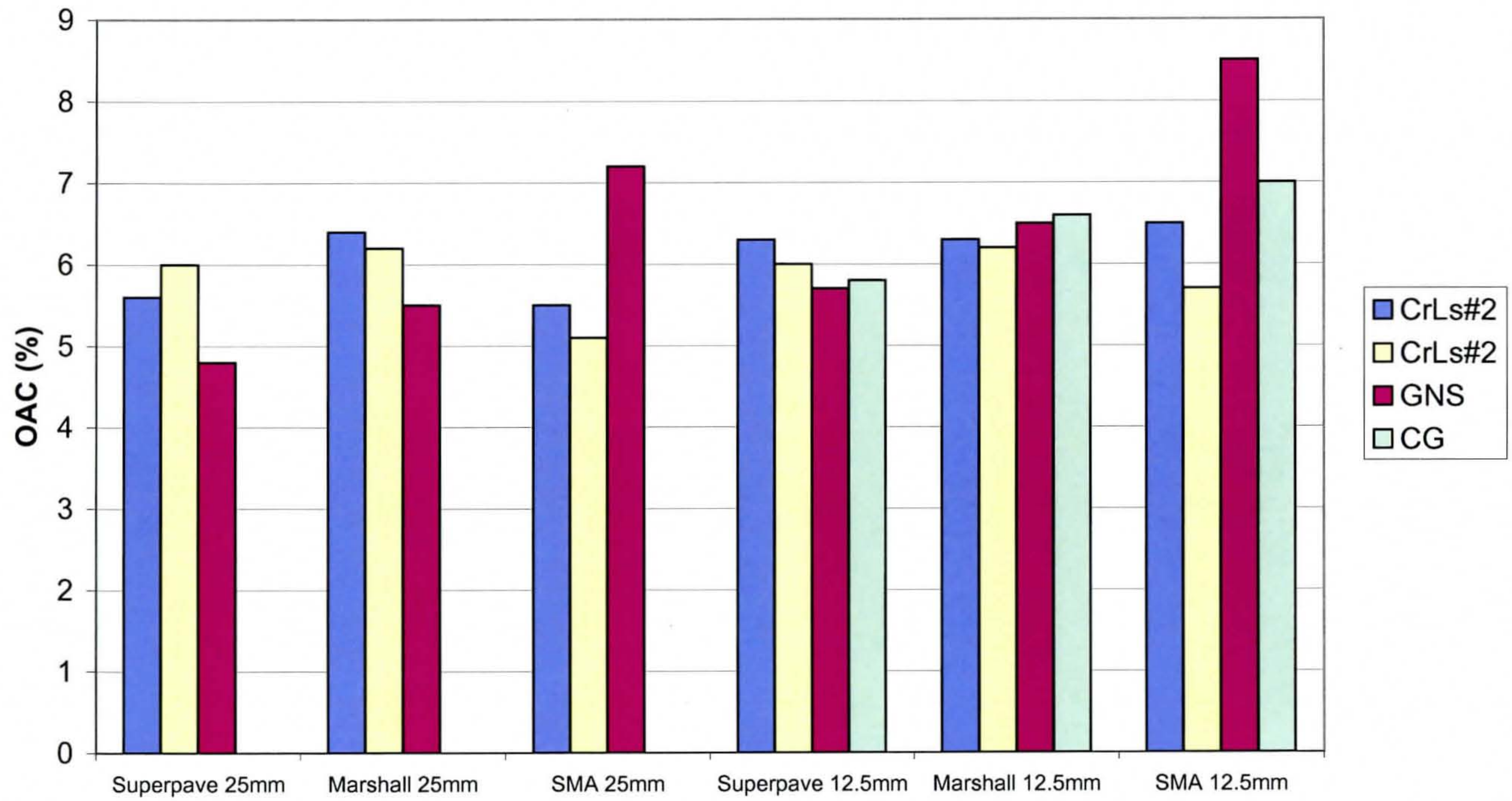



**Fig. 3.3.1 The Optimum Asphalt Content(@4% voids) Of All Mixes**

On the other hand, the mineralogically inert limestones and crushed gravel fines likely fulfilled the conventional expectation for filler, without significantly stiffening the asphalt.

## 3.4 Mixture Performance Test

Two mixture performance tests were carried out on all mixes. Tensile strength ratio (TSR) is commonly used to evaluate a mixture's susceptibility to stripping, while rut depths from the APA give a measure of mixture rutting potential. The results from the two tests are summarized in Table 3.4

### 3.4.1 TSR and Tensile Strength of Gravel Mixes

The TSR values (see Figure 3.4.1) range from lows in the 60%-70% to a high of just over 110%. Three of the 12.5 mm aggregate size gravel mixes exhibit abnormally large TSR values, GNS_Superpave_12.5 mm, CG_Marshall_12.5mm and CG_SMA_12.5mm. This is somewhat surprising. In the above three cases, the unconditioned strength are also 10% to 20% lower than other mixes in the three 12.5 mm groups, see Figure 3.4.2.1.

While TSR is large for the GNS Superpave 12.5 mm mix, CG Marshall and SMA 12.5 mm maximum aggregate mixes have large TSRs. The TSR value for the GNS mixes goes down in the order of Superpave, Marshall and SMA, while the reverse is true for CG mixes. The asphalt contents (see Figure 3.3.1) go up from Superpave to Marshall to SMA mixes for both aggregates of 12.5 maximum aggregate size series. This seems to suggest the effect of increased asphalt on the stripping resistance for uncrushed gravel and crushed gravel mixes are entirely different depending on the nature of fine aggregate. The expected result is that TSR should increase as asphalt content increases, which is consistent with the CG mixes.

## Table 3.4 Summary Of Mix Performance Test Results

| Mix | conditioned strength(MPa) | unconditioned strengthth(MPa) | TSR | APA rut depth after 8000 cycles (mm) |
|---|---|---|---|---|
| CrLs#2_Superpave_25mm | 0.699 | 0.756 | 92.50% | 5.05 |
| CrLs#2_Marshall_25 mm | 0.674 | 0.743 | 90.70% | 6.41 |
| CrLs#2_SMA_25 mm | 0.664 | 0.859 | 77.30% | 4.74 |
| | | | | |
| CrLs#2_Superpave_12.5mm | 0.740 | 0.897 | 82.50% | 6.60 |
| CrLs#2_Marshall_12.5 mm | 0.748 | 0.929 | 80.50% | 7.91 |
| CrLs#2_SMA_12.5 mm | 0.783 | 1.062 | 73.70% | 3.19 |
| | | | | |
| CrLs#1_Superpave_25mm | 0.426 | 0.625 | 68.20% | 5.22 |
| CrLs#1_Marshall_25 mm | 0.656 | 0.799 | 82.10% | 6.03 |
| CrLs#1_SMA_25 mm | 0.572 | 0.645 | 88.70% | 5.66 |
| | | | | |
| CrLs#1_Superpave_12.5mm | 0.578 | 0.800 | 72.30% | 5.88 |
| CrLs#1_Marshall_12.5 mm | 0.731 | 0.887 | 82.40% | 6.61 |
| CrLs#1_SMA_12.5 mm | 0.751 | 1.006 | 74.70% | 5.81 |
| | | | | |
| GNS_Superpave_25mm | 0.758 | 0.916 | 82.80% | 21.18 |
| GNS_Marshall_25 mm | 0.711 | 0.875 | 81.30% | 23.91 |
| GNS_SMA_25 mm | 0.529 | 0.815 | 64.90% | 22.29 |
| | | | | |
| GNS_Superpave_12.5mm | 0.745 | 0.713 | 104.50% | 23.68 |
| GNS_Marshall_12.5 mm | 0.740 | 0.917 | 80.70% | 27.28 |
| GNS_SMA_12.5 mm | 0.949 | 1.211 | 78.40% | 24.85 |
| | | | | |
| CG_Superpave_12.5mm | 0.687 | 0.902 | 76.20% | 14.58 |
| CG_Marshall_12.5 mm | 0.853 | 0.805 | 106.00% | 21.42 |
| CG_SMA_12.5 mm | 1.056 | 0.939 | 112.50% | 16.83 |

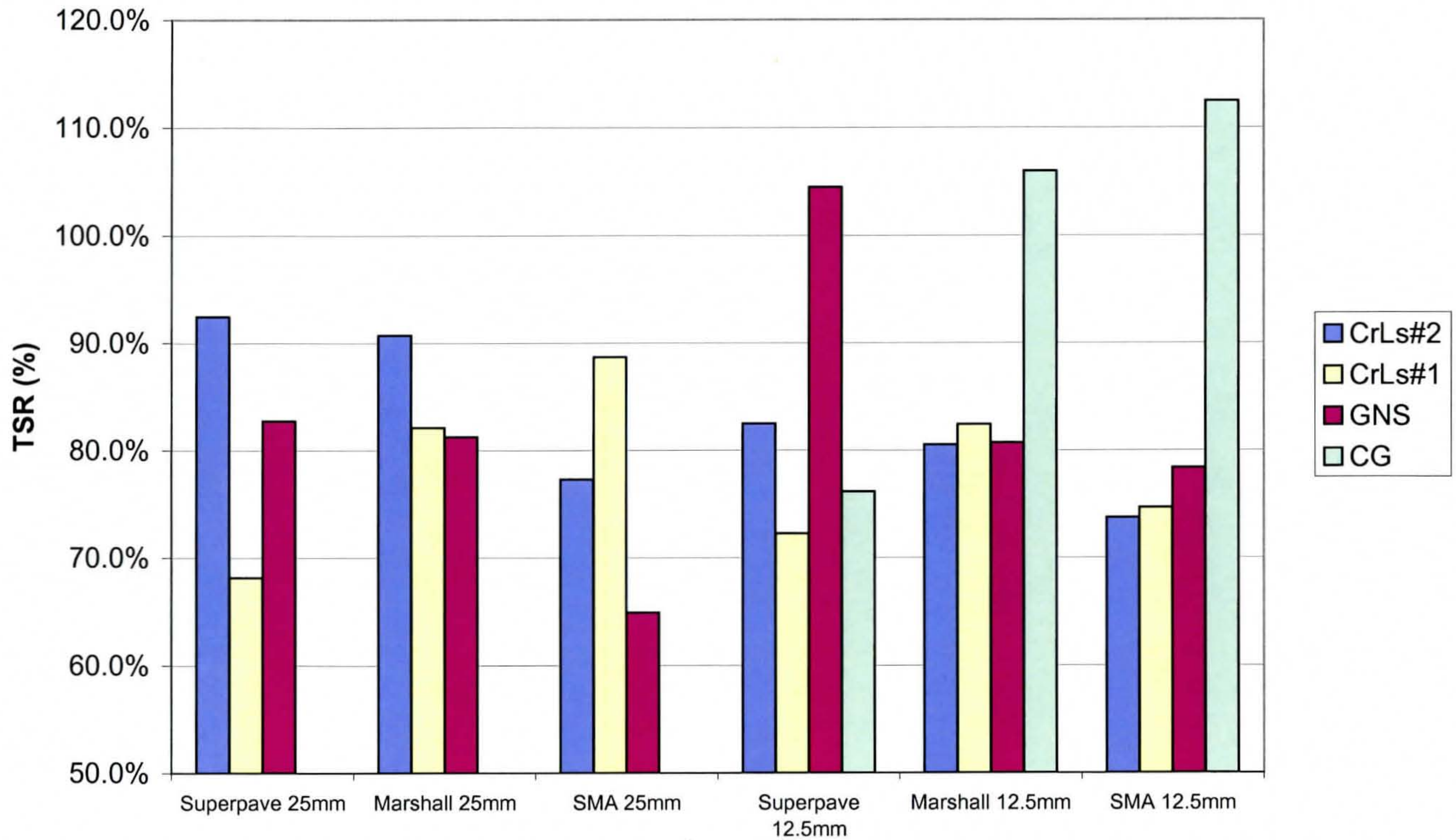



**Fig. 3.4.1 TSR of All Mixes**

In some ways, tensile strength of specimen can be seen as an indicator of the bond between asphalt and aggregate. For both 25 mm and 12.5mm maximum aggregate size gravel mixes, the asphalt content (refer to Figure 3.3.1) goes up from Superpave to Marshall and then to SMA. While for the 25 mm maximum size, the tensile strength (refer to Figure 3.4.2.1) of GNS gradually goes down, and its TSR does the same; but for the 12.5 mm maximum aggregate size, the tensile strength goes sharply up and still TSR drops down. This demonstrates the effect of gradation or maximum aggregate size of the mix has on tensile strength.

It can be seen from the results that for mixes with natural sand making up the fines in the aggregate blend, as is the case with GNS mixes, increased asphalt content will increase strength for the finer mixes, but also make the mixes (both fine and coarse) more susceptible to stripping. This is in contrast with CG mixes whose tensile strength and stripping resistance both go up with asphalt content.

For CG mixes, asphalt content also goes up in the order of Superpave, Marshall, then SMA, this didn't bring about much variations in tensile strength, but TSR increased dramatically from Superpave to Marshall and SMA. Crushed fines improve the stripping resistance at higher asphalt content.

### 3.4.2 TSR and Tensile Strength of Crushed Limestone Mixes

On average, CrLs #2 has higher tensile strength than CrLs #1 (refer to Figures 3.4.2.1 and 3.4.2.2). This difference in strength may be explained by the fact that CrLs #2 had cleaner fines. A washed screenings was used for CrLs#2 , but an unwashed screening was used for CrLs #1. This increased the possibility that CrLs #1 fines contained undesirable constituents( claylike minerals). The tensile strength of 25 mm maximum aggregate mixes are generally lower than that of 12.5 mm maximum aggregate size mixes, while the TSRs of 25 mm mixes are greater than those of 12.5 mm mixes.

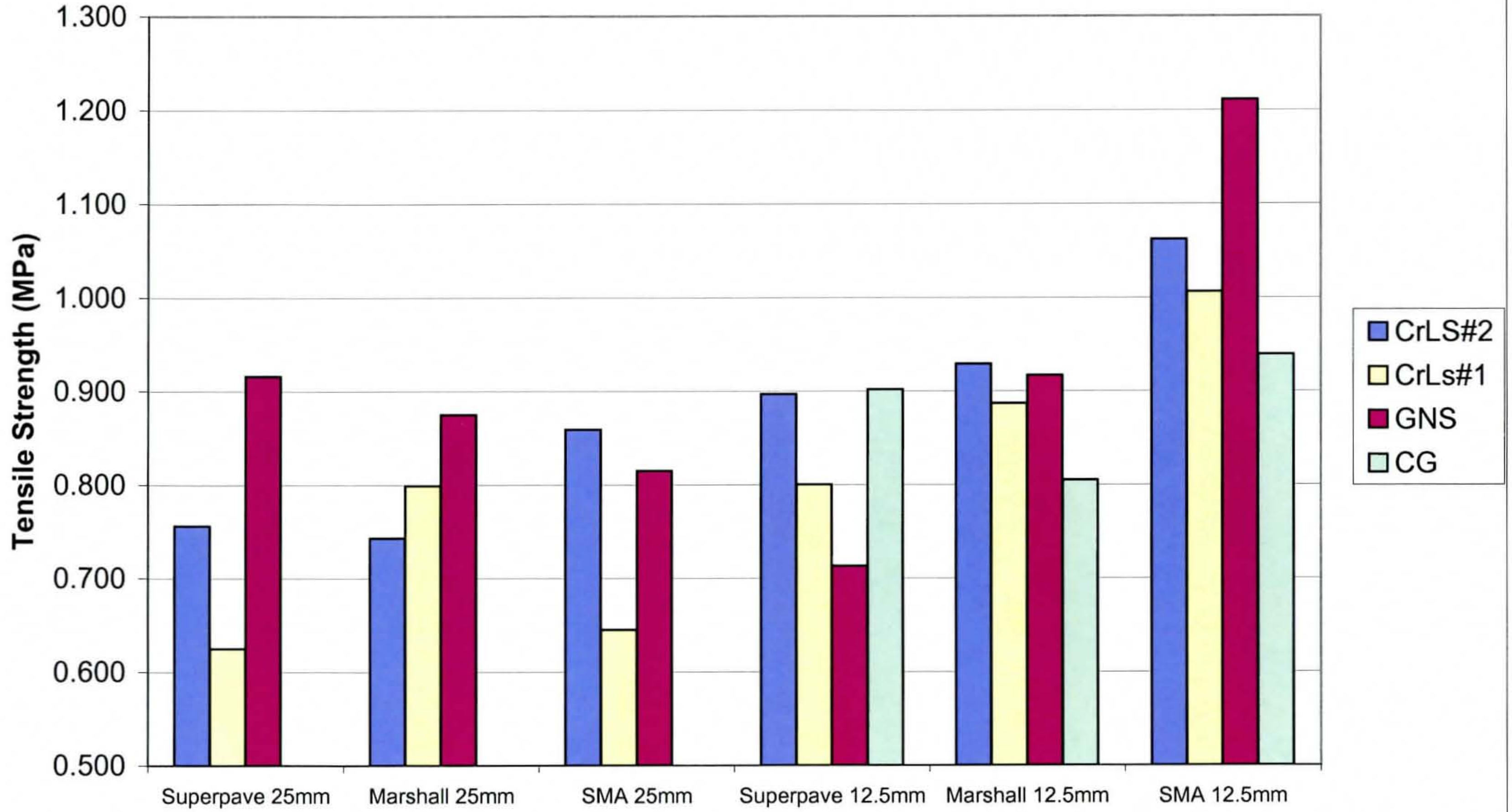



**Fig. 3.4.2.1 Tensile Strength of All Mixes (unconditioned specimens)**

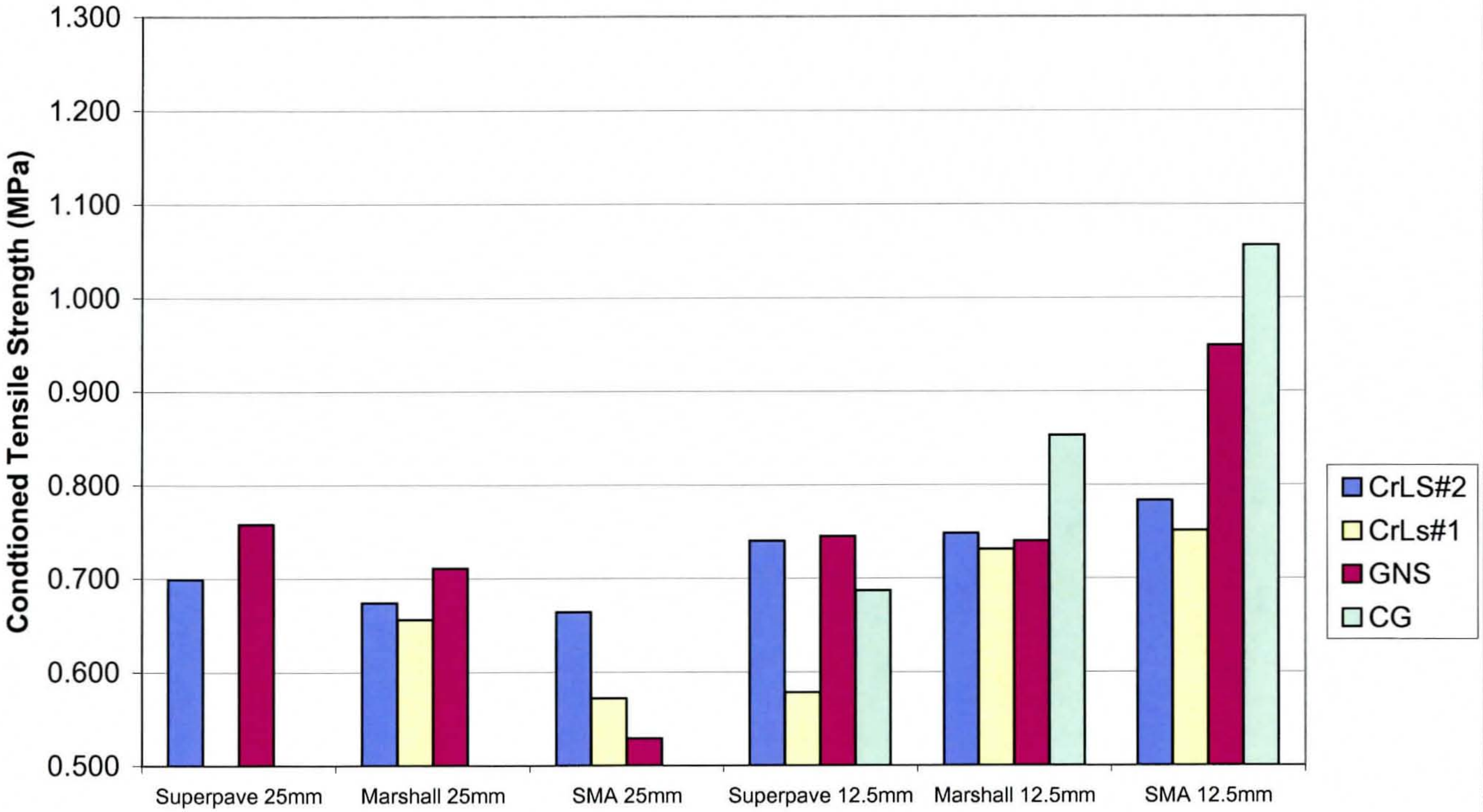



**Fig. 3.4.2.2 Tensile Strength of All Mixes (conditioned specimens)**

### 3.4.3 APA Rut Depth

APA rut depths for all mixes are shown as a bar chart in Figure 3.4.3. The most obvious feature about of the bar chart is the high rut depths of GNS mixes. The second highest rut depths are for the CG mixes. Mixes of the two limestone have the lowest rut depths.

For each aggregate of the same maximum size, the Marshall mix has the highest rut depths, Superpave and SMA have comparable rut depths. This can be explained by the higher asphalt content of Marshall in relation to Superpave mixes(see Figure 3.3.1). However the differences in rutting for Marshall and Superpave of the two crushed limestone sources do not appear appreciably different.

## 3.5 Relationships Between Aggregate Properties and Mix Performance Tests

### 3.5.1 MBV vs. Mix Performance Test Results

MBV is an index of the quality of the P200 materials, which may have a large impact on asphalt and aggregates bonding.

In the analysis, the MBV value for each aggregate source is weighted by the percentage of minus 200 materials in a mix. Superpave and Marshall mixes have 4 percent P200 and are given a weighting factor of 1. SMA mixes have 8 percent P200 and are given a weighting factor of 2 (refer to Table 3.5.1). Weighted MBV and TSR from Table 3.5.1 are plotted in Figure 3.5.1.1. There is a weak general trend of decreasing TSR with increased weighted MBV. This is the expected trend but the large scatter is indicative of numerous other factors that influence TSR.

Weighted MBV is not correlated to rut depth (see figure 3.5.1.2).

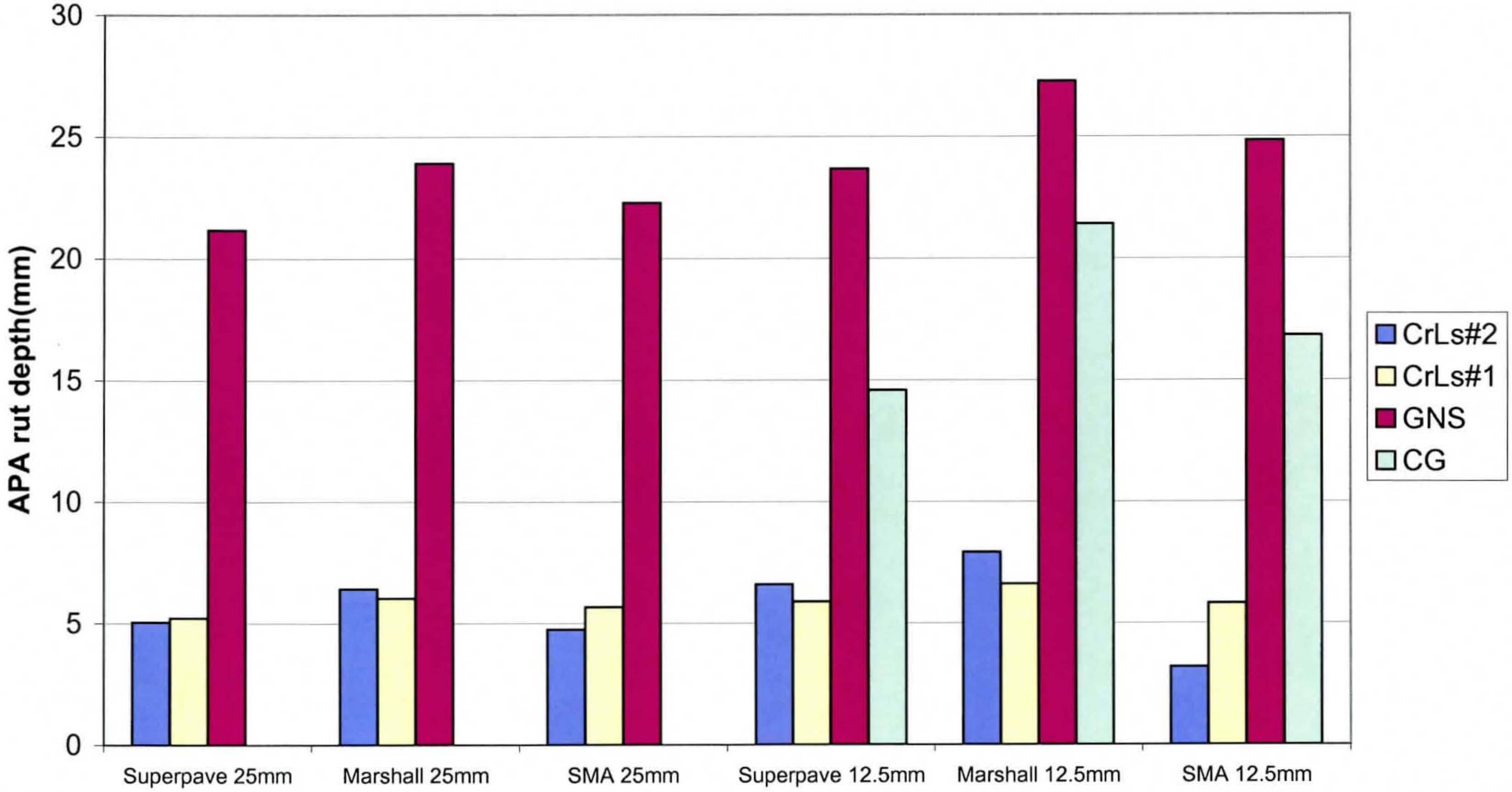



**Fig. 3.4.3 The APA Rut Depth (after 8000 cycles) Of All Mixes**

# Table 3.5.1 Table of Weighted MBV

| Mix | P200 percentage | MBV of P200 material | Weight | Weighted MBV |
|---|---|---|---|---|
| CrLs#2_Superpave_25mm | 4 | 6 | 1 | 6 |
| CrLs#2_Marshall_25mm | 4 | 6 | 1 | 6 |
| CrLs#2_SMA_25mm | 8 | 6 | 2 | 12 |
| | | | | |
| CrLs#2_Superpave_12.5mm | 4 | 6 | 1 | 6 |
| CrLs#2_Marshall_12.5mm | 4 | 6 | 1 | 6 |
| CrLs#2_SMA_12.5mm | 8 | 6 | 2 | 12 |
| | | | | |
| CrLs#1_Superpave_25mm | 4 | 11.8 | 1 | 11.8 |
| CrLs#1_Marshall_25mm | 4 | 11.8 | 1 | 11.8 |
| CrLs#1_SMA_25mm | 8 | 11.8 | 2 | 23.6 |
| | | | | |
| CrLs#1_Superpave_12.5mm | 4 | 11.8 | 1 | 11.8 |
| CrLs#1_Marshall_12.5mm | 4 | 11.8 | 1 | 11.8 |
| CrLs#1_SMA_12.5mm | 8 | 11.8 | 2 | 23.6 |
| | | | | |
| GNS_Superpave_25mm | 4 | 10.7 | 1 | 10.7 |
| GNS_Marshall_25mm | 4 | 10.7 | 1 | 10.7 |
| GNS_SMA_25mm | 8 | 10.7 | 2 | 21.4 |
| | | | | |
| GNS_Superpave_12.5mm | 4 | 10.7 | 1 | 10.7 |
| GNS_Marshall_12.5mm | 4 | 10.7 | 1 | 10.7 |
| GNS_SMA_12.5mm | 8 | 10.7 | 2 | 21.4 |
| | | | | |
| CG_Superpave_12.5mm | 4 | 2.7 | 1 | 2.7 |
| CG_Marshall_12.5mm | 4 | 2.7 | 1 | 2.7 |
| CG_SMA_12.5mm | 8 | 2.7 | 2 | 5.4 |

Note. Superpave and Marshall have the same gradation,

For 12.5 mm maximum size mix, the coarse aggregate fractions start from No.2( 2.36 mm) up,
MBV is weighted by P200 percentage, with 4 % given weight of 1, 8 % given weight of 2.

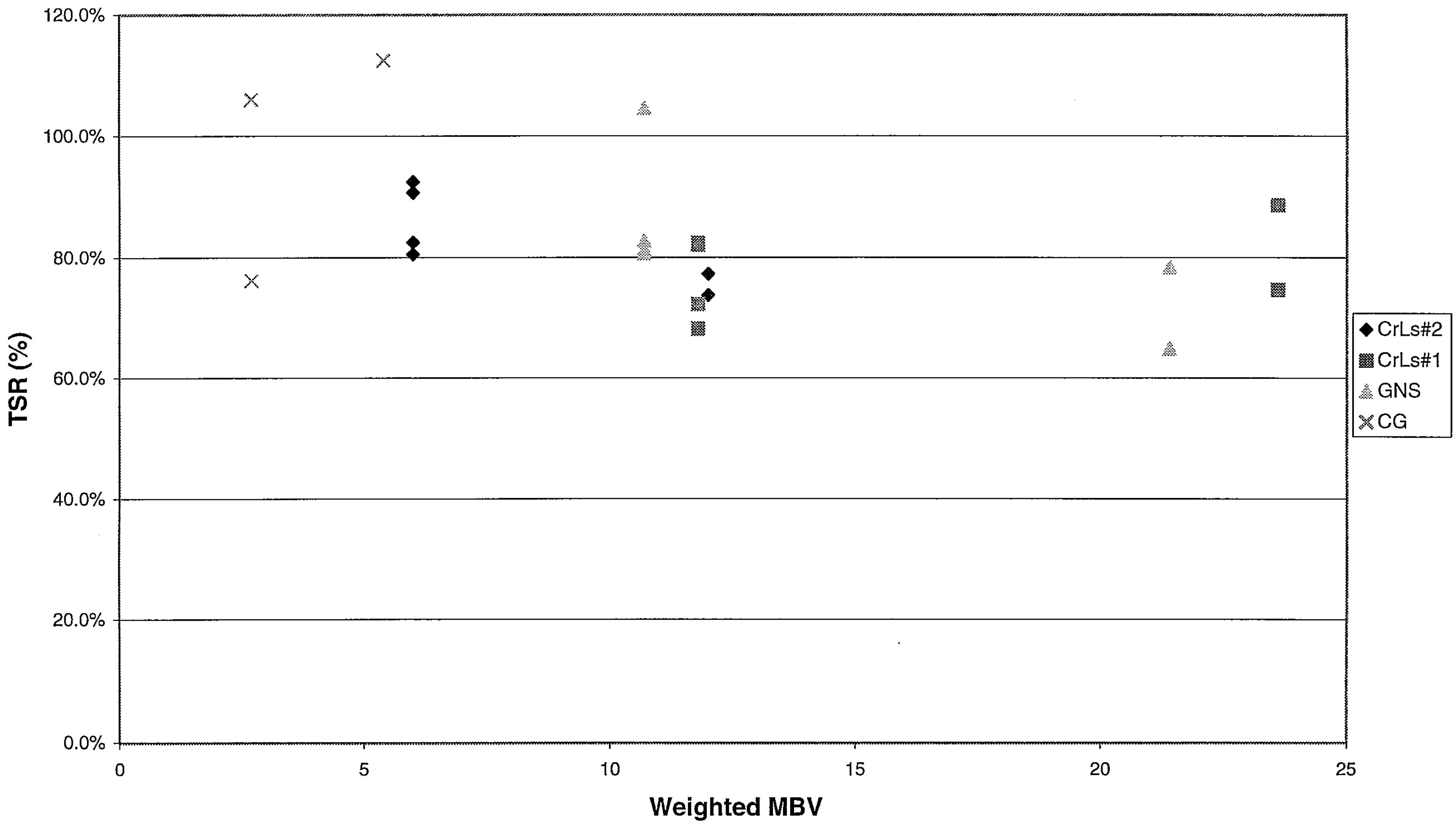



**Fig. 3.5.1.1 MBV vs. TSR of All Mixes By Aggregate Source**

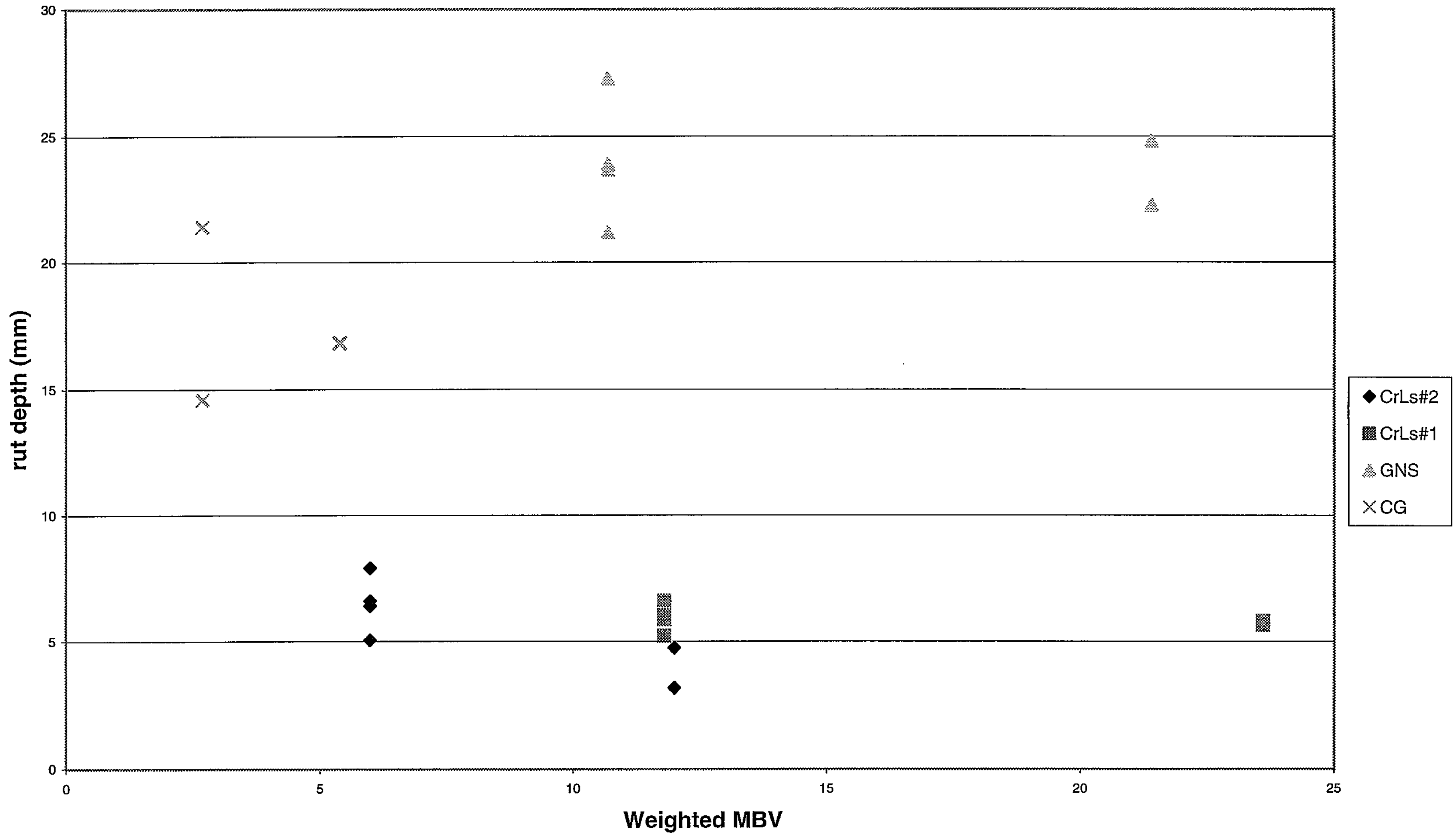



**Fig. 3.5.1.2 MBV vs. Rut Depth of All Mixes By Aggregate Source**

### 3.5.2 Film Thickness vs. Mix Performance Test Results

When aggregates are mixed with asphalt, aggregate particles are coated with a film of asphalt which binds the aggregate together. It is this asphalt film on the aggregate surface which enables the mix to withstand tensile stress induced by external load. Generally thicker asphalt film provide the mix with better protection against stripping and the harmful effects of oxidation. So, the thickness of the asphalt film is often used as a parameter to determine the adequacy of the mix design.

A value called average film thickness is calculated from gradation, with surface factors, asphalt content and asphalt specific gravities (refer to Table 3.5.2, for method of calculation refer to "Hot Mix Materials, Mixture Design and Construction" listed in the reference). However from plots of TSR vs film thickness shown in Figure 3.5.2.1 and 3.5.2.2 , there is no evidence of any correlation.

There may be some positive correlation between film thickness and rut depth. With Superpave and Marshall mixes, the rut depth rises with increasing thickness of the film for gravel and natural sand blend (see Figure 3.5.2.3). There were only two mixes with crushed gravel which is insufficient to speculate about trends and there seems to be no correlation for crushed limestones. The trend for SMA mixes, across all the aggregates (see Figure 3.5.2.4), has a relatively strong coefficient of determination.

### 3.5.3 Combined Effect of MBV and Film thickness vs. TSR

Even though film thickness didn't seem directly related to TSR, the average thickness should be a major factor in the resistance of HMA against stripping. Higher film thickness ought to contribute to higher retained strenghth. MBV has been shown related to TSR. Higher MBV, indicating poor quality of fines, may result in a lowering of the

# Table 3.5.2 Calculation of Film Thickness of the Mixes

| Mix | bulk specific gravity of the mix | bulk specific gravity of the aggregate | effective specific gravity of the aggregate | absorbed asphalt by weight | Optimum A.C.(@4% air voids,%) | effective asphalt volume in a cubic decimeter of specimen | Surface Area ($m^2/kg$) | Film Thickness (Microns) |
|---|---|---|---|---|---|---|---|---|
| CrLs#2_Superpave_25mm | 2.314 | 2.668 | 2.728 | 0.8% | 5.6 | 108.0 | 3.741 | 13.2 |
| CrLs#2_Marshall_25 mm | 2.325 | 2.668 | 2.735 | 0.9% | 6.4 | 124.8 | 3.741 | 15.3 |
| CrLs#2_SMA_25 mm | 2.311 | 2.670 | 2.698 | 0.4% | 5.5 | 114.9 | 6.166 | 8.5 |
| CrLs#2_Superpave_12.5mm | 2.287 | 2.667 | 2.716 | 0.7% | 6.3 | 125.7 | 4.355 | 13.5 |
| CrLs#2_Marshall_12.5 mm | 2.283 | 2.667 | 2.708 | 0.6% | 6.3 | 127.8 | 4.355 | 13.7 |
| CrLs#2_SMA_12.5 mm | 2.286 | 2.670 | 2.727 | 0.8% | 6.5 | 127.6 | 6.219 | 9.6 |
| CrLs#1_Superpave_25mm | 2.337 | 2.654 | 2.775 | 1.7% | 6.0 | 100.3 | 3.741 | 12.2 |
| CrLs#1_Marshall_25 mm | 2.36 | 2.654 | 2.785 | 1.8% | 6.2 | 103.1 | 3.741 | 12.5 |
| CrLs#1_SMA_25 mm | 2.35 | 2.679 | 2.715 | 0.5% | 5.1 | 105.3 | 6.166 | 7.7 |
| CrLs#1_Superpave_12.5mm | 2.329 | 2.636 | 2.764 | 1.8% | 6.0 | 97.5 | 4.355 | 10.2 |
| CrLs#1_Marshall_12.5 mm | 2.329 | 2.636 | 2.761 | 1.8% | 6.2 | 102.9 | 4.355 | 10.8 |
| CrLs#1_SMA_ 12.5 mm | 2.313 | 2.679 | 2.731 | 0.7% | 5.7 | 112.5 | 6.219 | 8.3 |
| GNS_Superpave_ 25mm | 2.31 | 2.538 | 2.666 | 1.9% | 4.8 | 66.3 | 3.741 | 8.1 |
| GNS_Marshall_25 mm | 2.271 | 2.538 | 2.666 | 1.9% | 5.5 | 80.9 | 3.741 | 10.1 |
| GNS_SMA_25 mm | 2.214 | 2.573 | 2.663 | 1.4% | 7.2 | 127.8 | 6.166 | 10.1 |
| GNS_Superpave_ 12.5mm | 2.281 | 2.545 | 2.664 | 1.8% | 5.7 | 88.7 | 4.355 | 9.5 |
| GNS_Marshall_ 12.5 mm | 2.247 | 2.545 | 2.664 | 1.8% | 6.5 | 105.2 | 4.355 | 11.5 |
| GNS_SMA_12.5 mm | 2.161 | 2.573 | 2.651 | 1.2% | 8.5 | 155.8 | 6.219 | 12.7 |
| CG_Superpave_ 12.5mm | 2.266 | 2.604 | 2.650 | 0.7% | 5.8 | 113.6 | 4.355 | 12.2 |
| CG_Marshall_12.5 mm | 2.229 | 2.604 | 2.646 | 0.6% | 6.6 | 130.4 | 4.355 | 14.4 |
| CG_SMA_ 12.5 mm | 2.209 | 2.597 | 2.624 | 0.4% | 7.0 | 142.0 | 6.219 | 11.1 |

Note. 1. The specific gravity of the PG 64-22 is 1.028, that of the PG 76-22 is 1.03

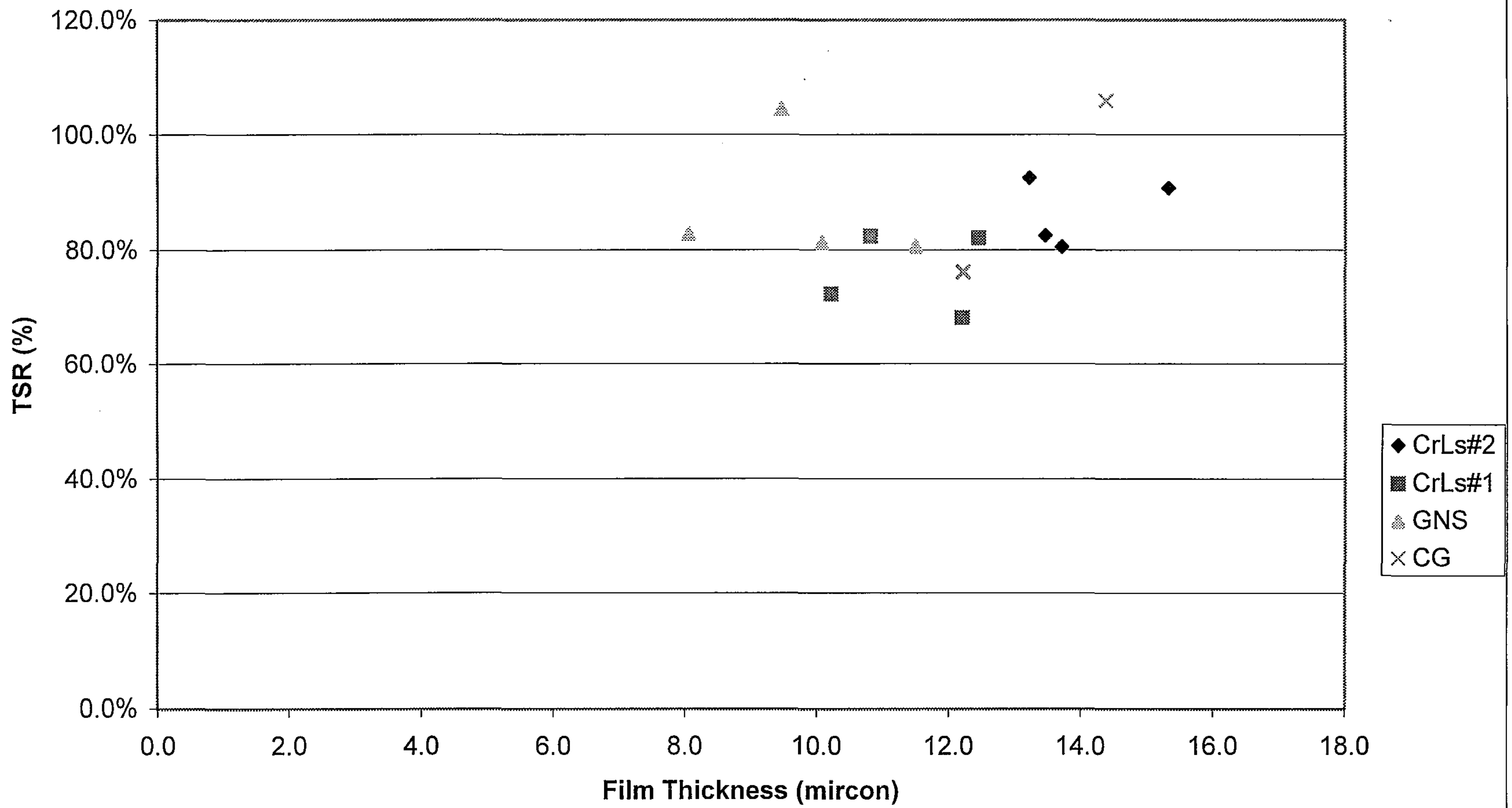



**Fig. 3.5.2.1 Film Thickness Vs. TSR (Superpve & Marshall mixes) by Aggregate Source**

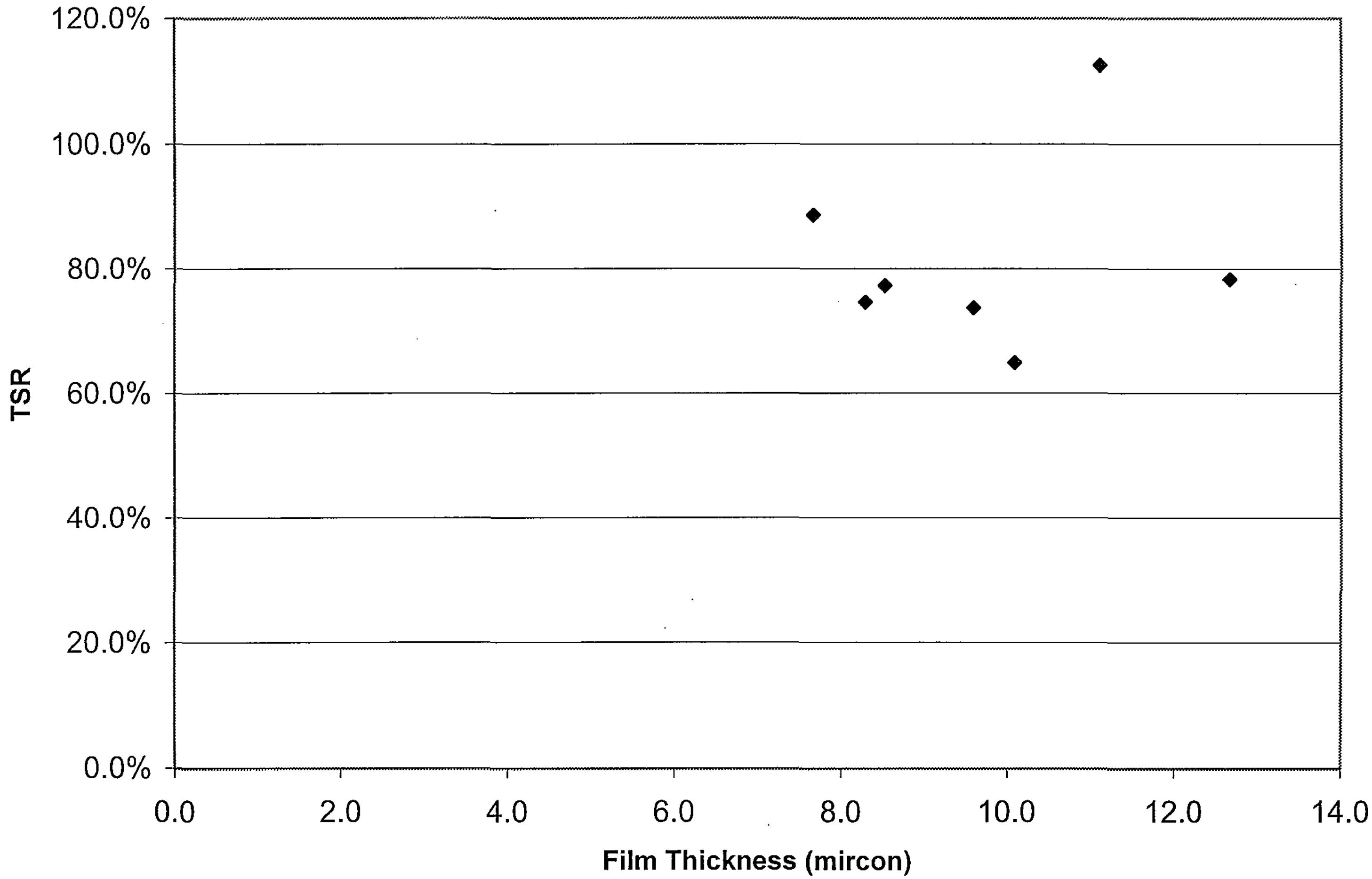



**Fig. 3.5.2.2 Film Thickness Vs. TSR( SMA mixes)**

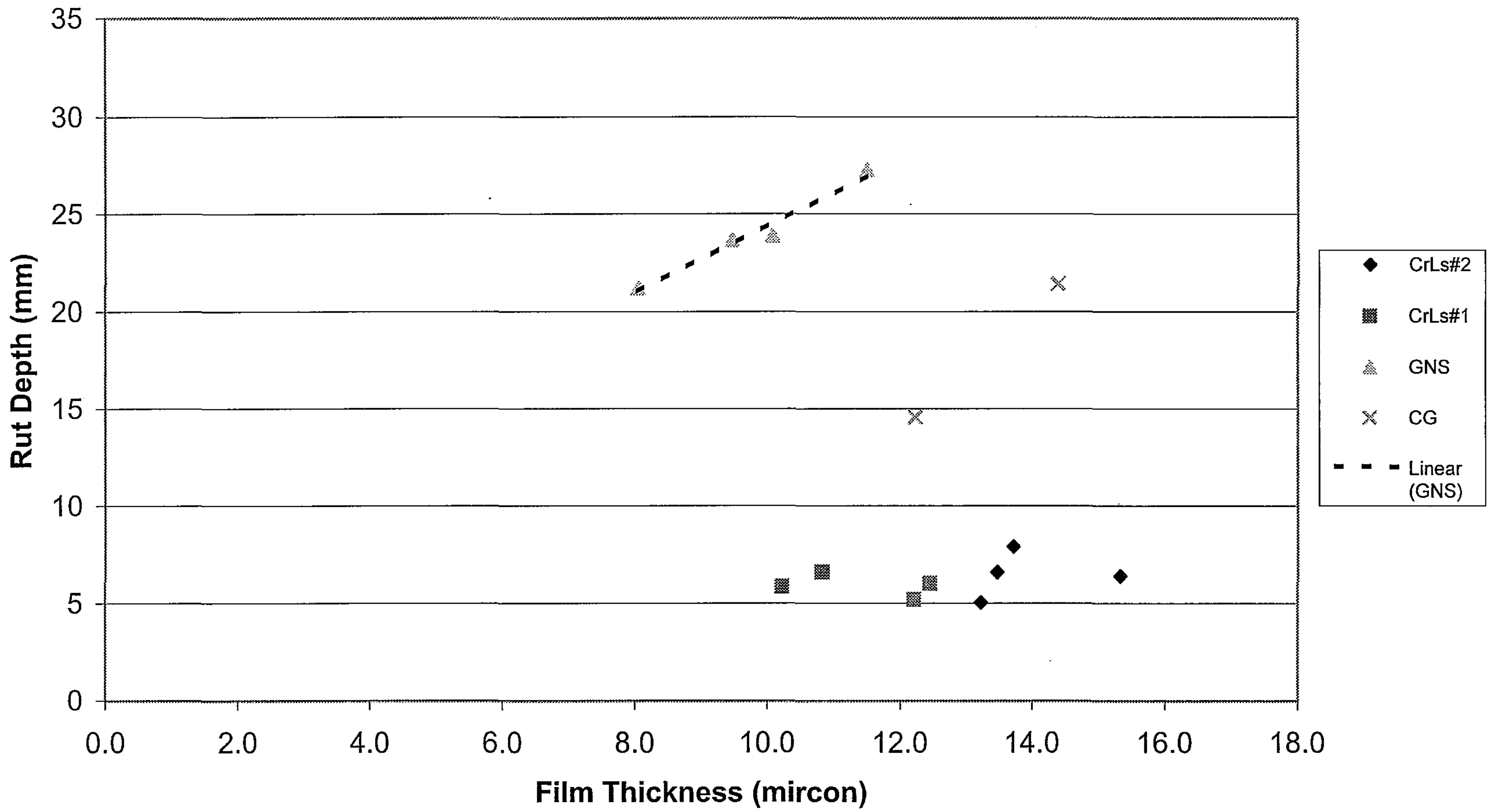



**Fig. 3.5.2.3 Film Thickness Vs. Rut (Superpve & Marshall mixes) by Aggregate Source**

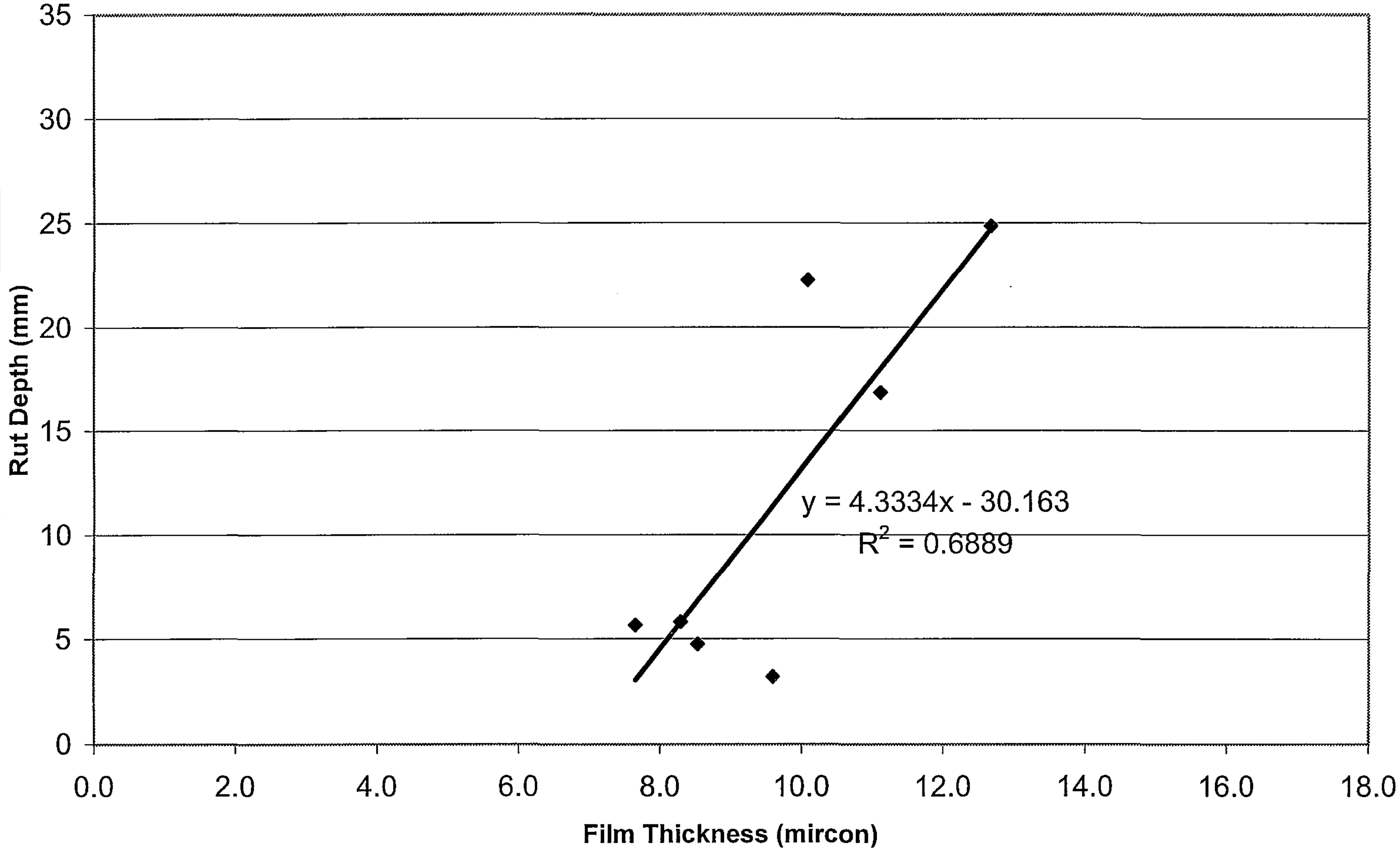



**Fig. 3.5.2.4 Film Thickness Vs. Rut Depth ( SMA mixes)**

resistance to stripping. Weighted MBV value and ten times film thickness in terms of microns for the mixes are about the same degree of magnitude. When weighted MBV divided by ten times the film thickness is plotted against TSR, there appears to be some correlation(see Figure 3.5.3). There appears to be a decrease in TSR as the ratio increases.

### 3.5.4 Percentage of Flat and Elongated Particles vs. Mix performance Test Results

Aggregate shape affects the way particles pack when compacted, hence the volumetrics of a mix, which are a major requirement of current specification, are also affected. It is hard to directly gauge the shape of fine aggregate, and as a result, only the shape of the coarse aggregate is controlled by specification.

More equidimensionals particle are preferred because these particles are better able to effect strong face to face contact and withstand the external load without breaking up. Flat and elongated particles tend to break and change the gradation which compromises mix volumetrics , and possibly jeopardizes mix performance. Today's specifications use the percentage of flat and elongated particles as a measure to control the shape of coarse aggregate particles.

In order to arrive at a value which describes the shape of all of coarse size fractions in the mixes, the percentage of flat and elongated particles of No. 4 size fractions were approximated by linear extrapolation (see Table 3.5.4.1). These values and measured values for larger size fractions were used to compute the weighted percentage of flat and elongated particles of the coarse aggregates for the mixes(see Table.3.5.4.2)

Figures 3.5.4.1 and 3.5.4.2 indicate no relationship between the percentage of flat or elongated particles and mix susceptibility to rutting. For the gravel mixes, there is some indication that rut depth may increase with increasing percentage of flat and elongated

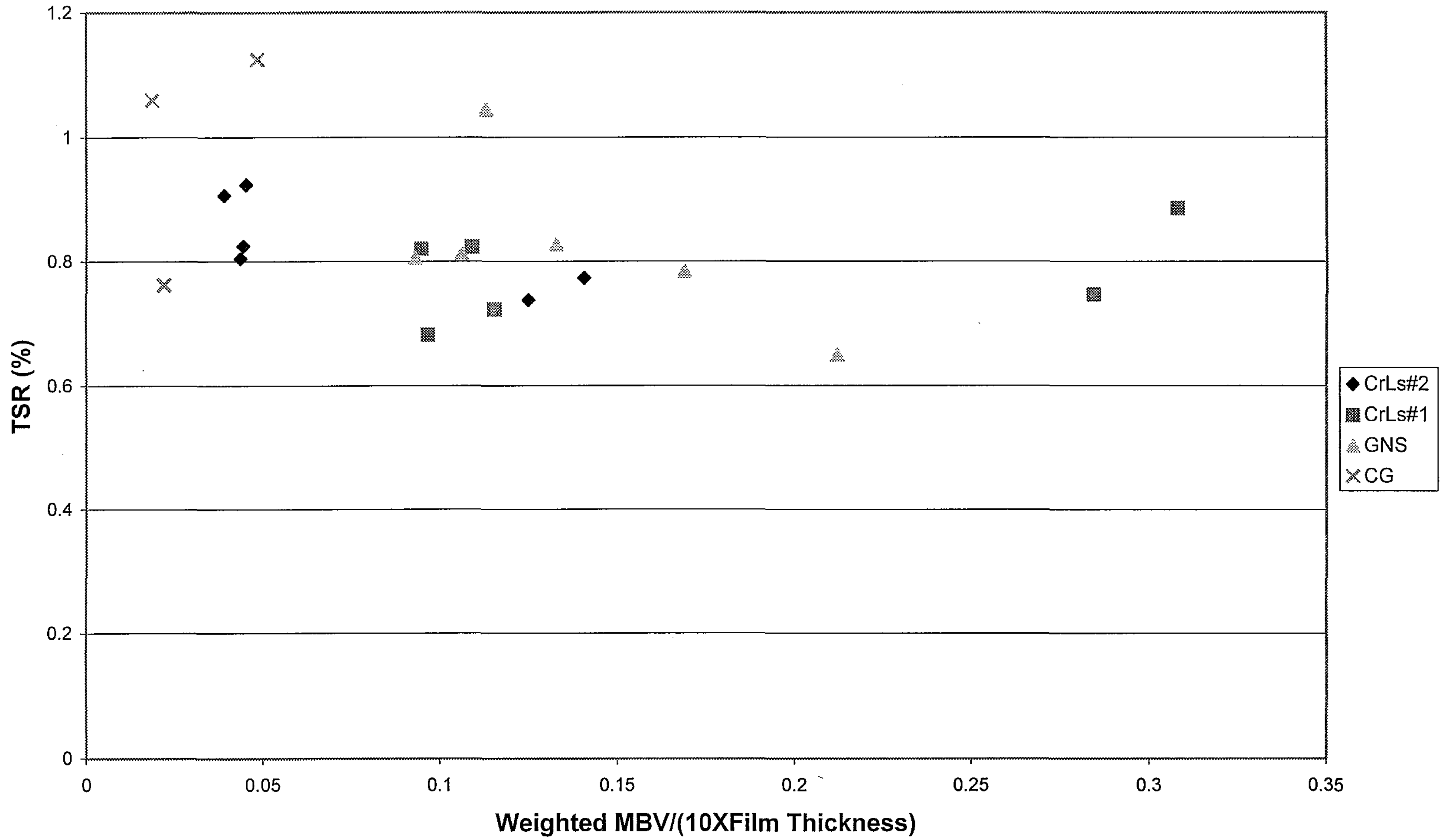
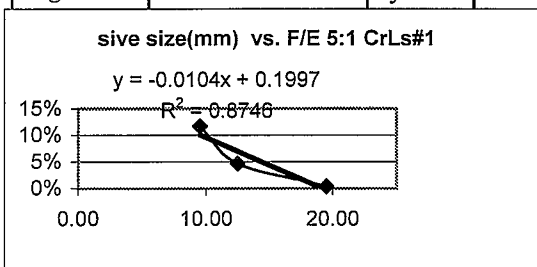
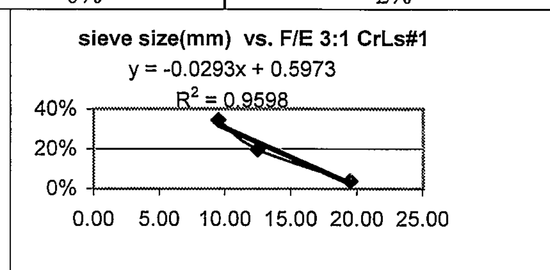


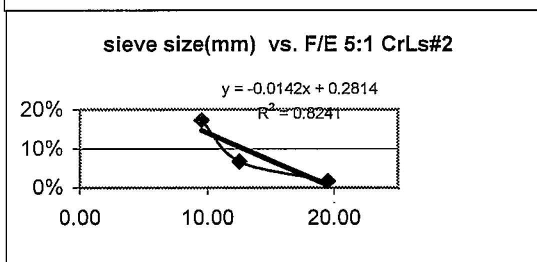

**Fig. 3.5.3 Weighted MBV/(10X Film Thickness) vs. TSR of all mixes by aggregate source**

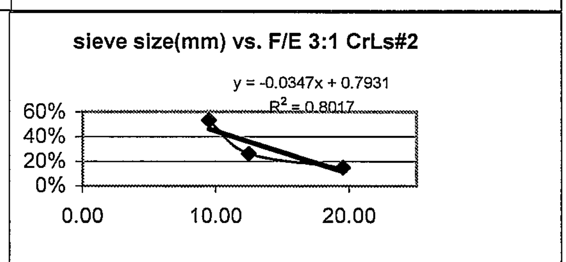
Table 3.5.4.1 Percentages of F&E Particles of Coarse Aggregates ( by linear extrapolation)

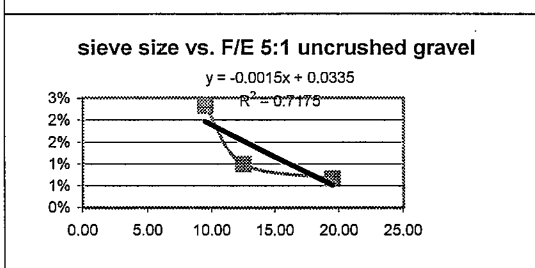
| Aggregate Souce | Sieve Size (mm) | | 5:1 ratio | 3:1 ratio |
|---|---|---|---|---|
| crushed limestone #1 | 4.75 | by extr. | 15% | 46% |
| | 9.50 | by count | 12% | 34% |
| | 12.50 | by count | 5% | 20% |
| | 19.50 | by count | 0% | 4% |
| crushed limestone #2 | 4.75 | by extr. | 21% | 63% |
| | 9.50 | by count | 17% | 53% |
| | 12.50 | by count | 7% | 26% |
| | 19.50 | by count | 2% | 15% |
| uncrushed gravel | 4.75 | by extr. | 3% | 29% |
| | 9.50 | by count | 2% | 24% |
| | 12.50 | by count | 1% | 15% |
| | 19.50 | by count | 1% | 7% |
| crushed gravel | 4.75 | by count | 1% | 5% |
| | 9.50 | by count | 0% | 2% |

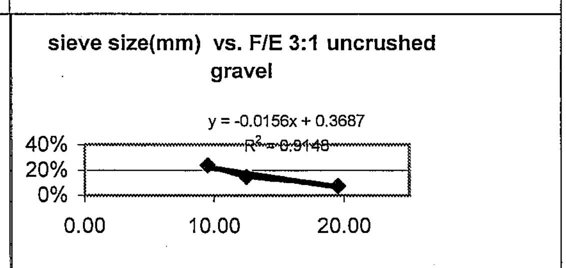


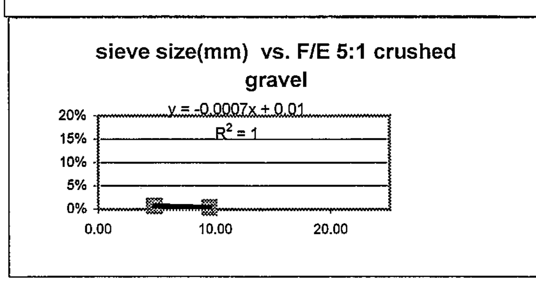



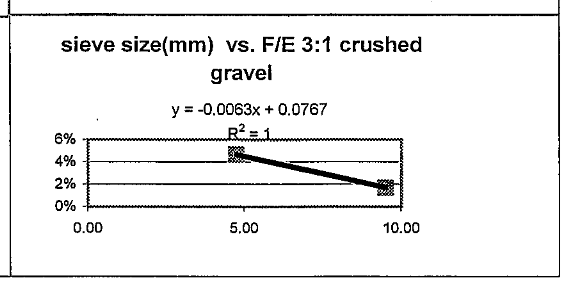




Note: The x axis is the sieve size in mm.
The y axis the percentage of flat or enlongated particles.

Table 3.5.4.2 Weighted Percentages of F&E Particles of Coarse Aggregates of Mixes

| Aggregate Souce | Sieve Size | 5:1 ratio | 3:1 ratio | Superpave, Marshall 12.5mm | | | Superpave,Marshall 25mm | | | SMA 12.5mm | | | SMA 25mm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | weights | 5:1 | 3:1 | weights | 5:1 | 3:1 | weights | 5:1 | 3:1 | weights | 5:1 | 3:1 |
| crushed limestone #1 | 4.75mm | 15% | 46% | 0.8 | 12% | 37% | 0.48 | 7% | 22% | 0.93 | 14% | 43% | 0.11 | 2% | 5% |
| | 9.5mm | 12% | 34% | 0.2 | 2% | 7% | 0.24 | 3% | 8% | 0.07 | 1% | 2% | 0.39 | 5% | 13% |
| | 12.5mm | 5% | 20% | | | | 0.16 | 1% | 3% | | | | 0.43 | 2% | 8% |
| | 19.5mm | 0% | 4% | | | | 0.12 | 0% | 0% | | | | 0.07 | 0% | 0% |
| | | Weighted F/E | | | 14% | 44% | | 11% | 34% | | 15% | 45% | | 8% | 27% |
| crushed limestone #2 | 4.75mm | 21% | 63% | 0.8 | 17% | 50% | 0.48 | 10% | 30% | 0.93 | 20% | 58% | 0.11 | 2% | 7% |
| | 9.5mm | 17% | 53% | 0.2 | 3% | 11% | 0.24 | 4% | 13% | 0.07 | 1% | 4% | 0.39 | 7% | 21% |
| | 12.5mm | 7% | 26% | | | | 0.16 | 1% | 4% | | | | 0.43 | 3% | 11% |
| | 19.5mm | 2% | 15% | | | | 0.12 | 0% | 2% | | | | 0.07 | 0% | 1% |
| | | Weighted F/E | | | 21% | 61% | | 16% | 49% | | 21% | 62% | | 12% | 40% |
| uncrushed gravel | 4.75mm | 3% | 29% | 0.8 | 2% | 24% | 0.48 | 1% | 14% | 0.93 | 2% | 27% | 0.11 | 0% | 3% |
| | 9.5mm | 2% | 24% | 0.2 | 0% | 5% | 0.24 | 1% | 6% | 0.07 | 0% | 2% | 0.39 | 1% | 9% |
| | 12.5mm | 1% | 15% | | | | 0.16 | 0% | 2% | | | | 0.43 | 0% | 6% |
| | 19.5mm | 1% | 7% | | | | 0.12 | 0% | 1% | | | | 0.07 | 0% | 1% |
| | | Weighted F/E | | | 3% | 28% | | 2% | 23% | | 3% | 29% | | 2% | 19% |
| crushed gravel | 4.75mm | 1% | 5% | 0.8 | 1% | 4% | | | | 0.93 | 1% | 4% | | | |
| | 9.5mm | 0% | 2% | 0.2 | 0% | 0% | | | | 0.07 | 0% | 0% | | | |
| | | Weighted F/E | | | 1% | 4% | | | | | 1% | 4% | | | |

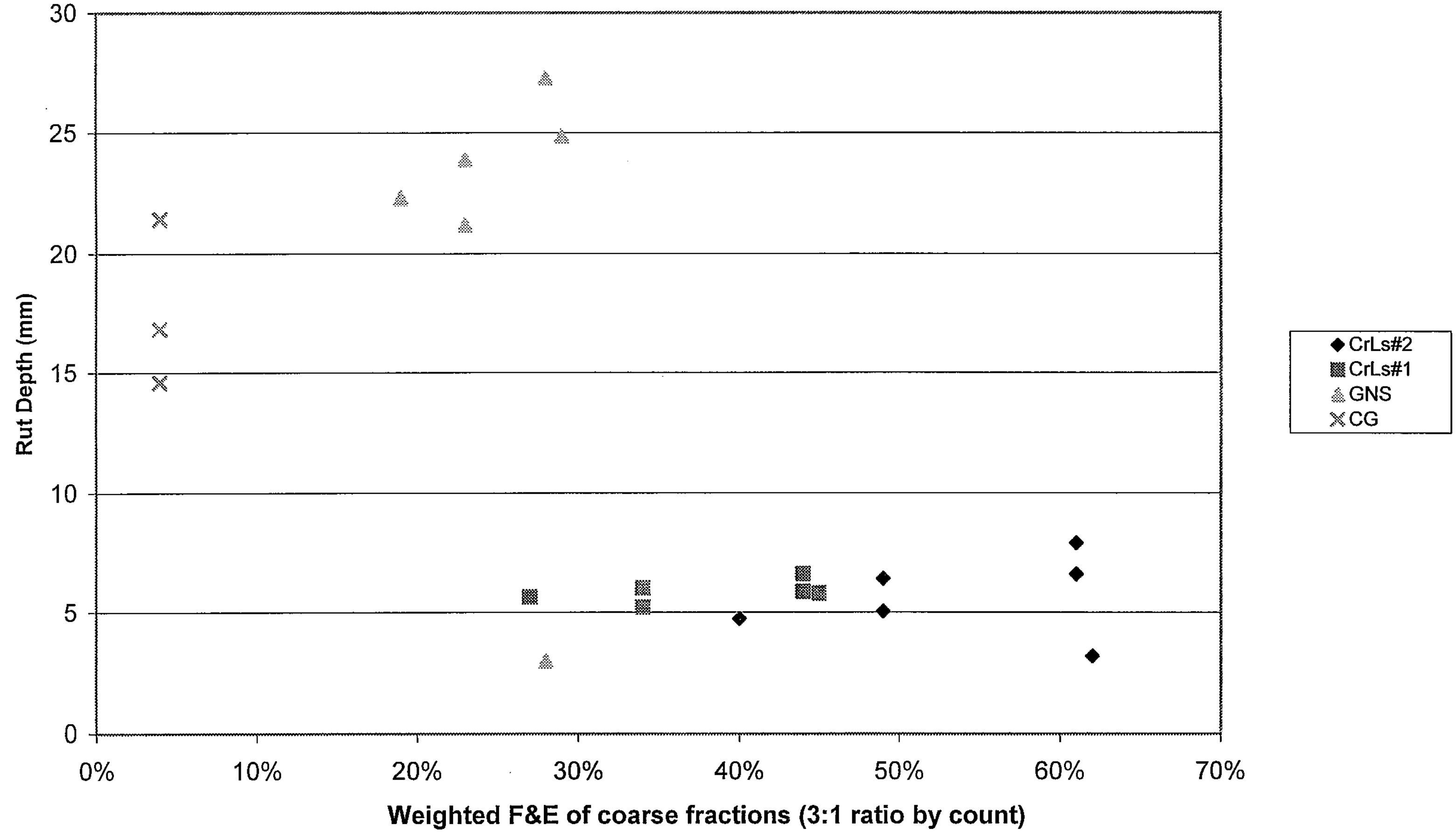



**Fig.3.5.4.1 Weighted F&E(3:1 by count ) vs. Rut Depth**

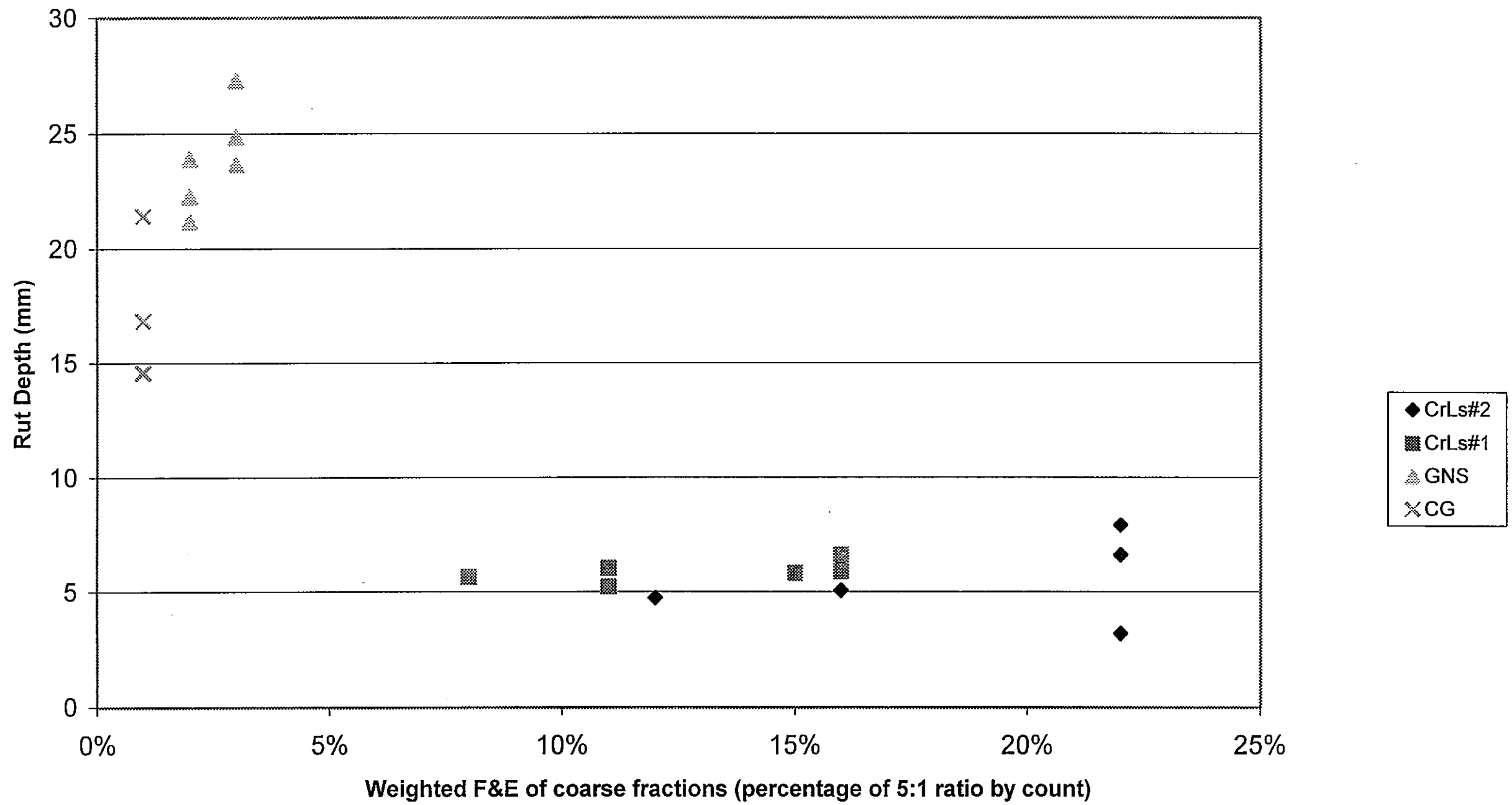



**Fig.3.5.4.2 Weighted F&E (5:1) vs. Rut Depth by aggregat source type of all mixes**

particles, but for the two limestone mixes, flat and elongated particles have no influence on rutting susceptibility.

### 3.5.5 Fractured Face Count vs. Mix Performance Test Results

The surface texture and angularity of the aggregate plays a important role in how well the asphalt is able to bond with aggregate. Rounded gravel has smooth surfaces which may not bond well and is therefore less able to resist the tendency to displace through the actions of external loads than crushed angular gravel with fractured surfaces which have much rougher texture that facilitates strong bonds and mechanical interlocking. Fractured face count is an index of the angularity and surface texture of aggregates.

Fractured face count tests measure the percentages of particles with fractured faces.
The two crushed limestone mixes have 100 % of particles with one and two or more fractured faces. GSN and CG mixes present interesting contrast between uncrushed gravel and crushed gravel.

For the two gravel mix series, the percentages of coarse aggregate particles with fractured faces (one or more and two or more) were determined. A weighted average for the coarse aggregate fractions is calculated according to the gradation (refer to Table 3.5.5.1). Weighted percentage of particles with fractured faces is plotted vs. TSR in Figure 3.5.5.1. There is no relationship apparent.

Plots of weighted percentage of particles with fractured faces vs. rut depths in Figure 3.5.5.2 and Figure 3.5.5.3 indicate a dramatic difference between the gravel and crushed limestone mixes. The crushed gravel mixes rutted somewhat less than the natural gravel mixes, but rut depths for crushed limestone mixes with 100 % crushed faces were much smaller. Tests on mixes with aggregates having intermediate crushed face counts are needed to better define the relationships. Possible shapes are sketched in Figures 3.5.5.2 and 3.5.5.3

Table 3.5.5.1 Weighted Average of Percentages of Particles With Fractured Faces

| Aggregate Souce | Sieve Size | | Percentage of one face | Percentage of two faces | Superpave, Marshall12.5mm | | | Superpave, Marshall12.5mm | | | SMA 12.5mm | | | SMA 25mm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | average | average | weights | one | two | weights | one | two | weights | one | two | weights | one | two |
| uncrushed Shorter gravel | 4.75mm | by count | 29% | 9% | 0.8 | 23% | 7% | 0.48 | 14% | 4% | 0.93 | 27% | 8% | 0.11 | 3% | 1% |
| | 9.5mm | by count | 21% | 6% | 0.2 | 4% | 1% | 0.24 | 5% | 2% | 0.07 | 1% | 0% | 0.39 | 8% | 2% |
| | 12.5mm | by count | 22% | 6% | | | | 0.16 | 4% | 1% | | | | 0.43 | 10% | 2% |
| | 19.5mm | by count | 13% | 3% | | | | 0.12 | 2% | 0% | | | | 0.07 | 1% | 0% |
| | | | Weighted Average | | | 27% | 8% | | 24% | 7% | | 28% | 9% | | 22% | 6% |
| crushed shorter | 4.75mm | by count | 98% | 94% | 0.8 | 79% | 75% | | | | 0.93 | 91% | 87% | | | |
| | 9.5mm | by count | 98% | 86% | 0.2 | 20% | 17% | | | | 0.07 | 7% | 6% | | | |
| | | | Weighted Average | | | 98% | 92% | | | | | 98% | 93% | | | |

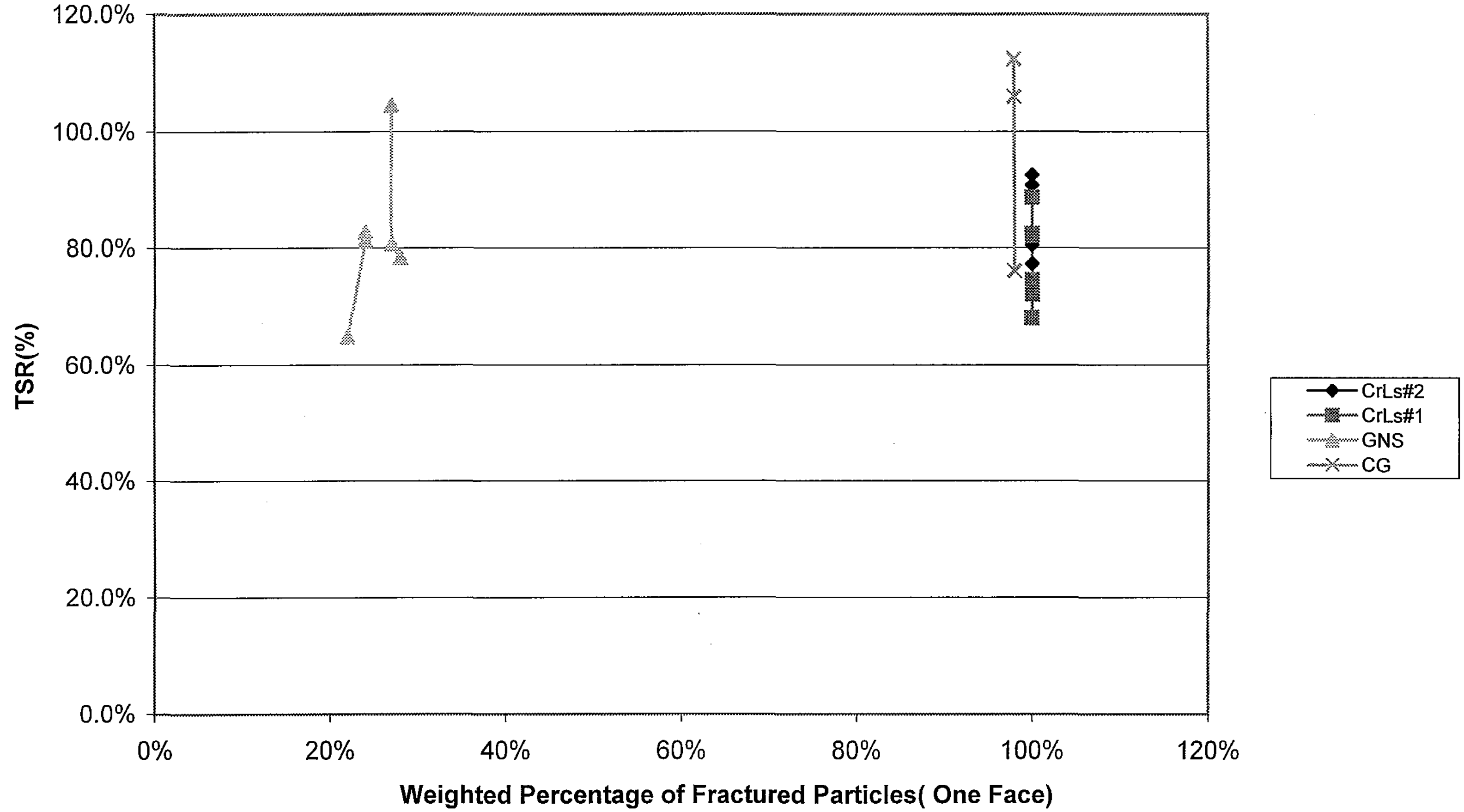



**Fig. 3.5.5.1 Weighted Percentage of Particles with Fractured Faces (one face) vs. TSR**

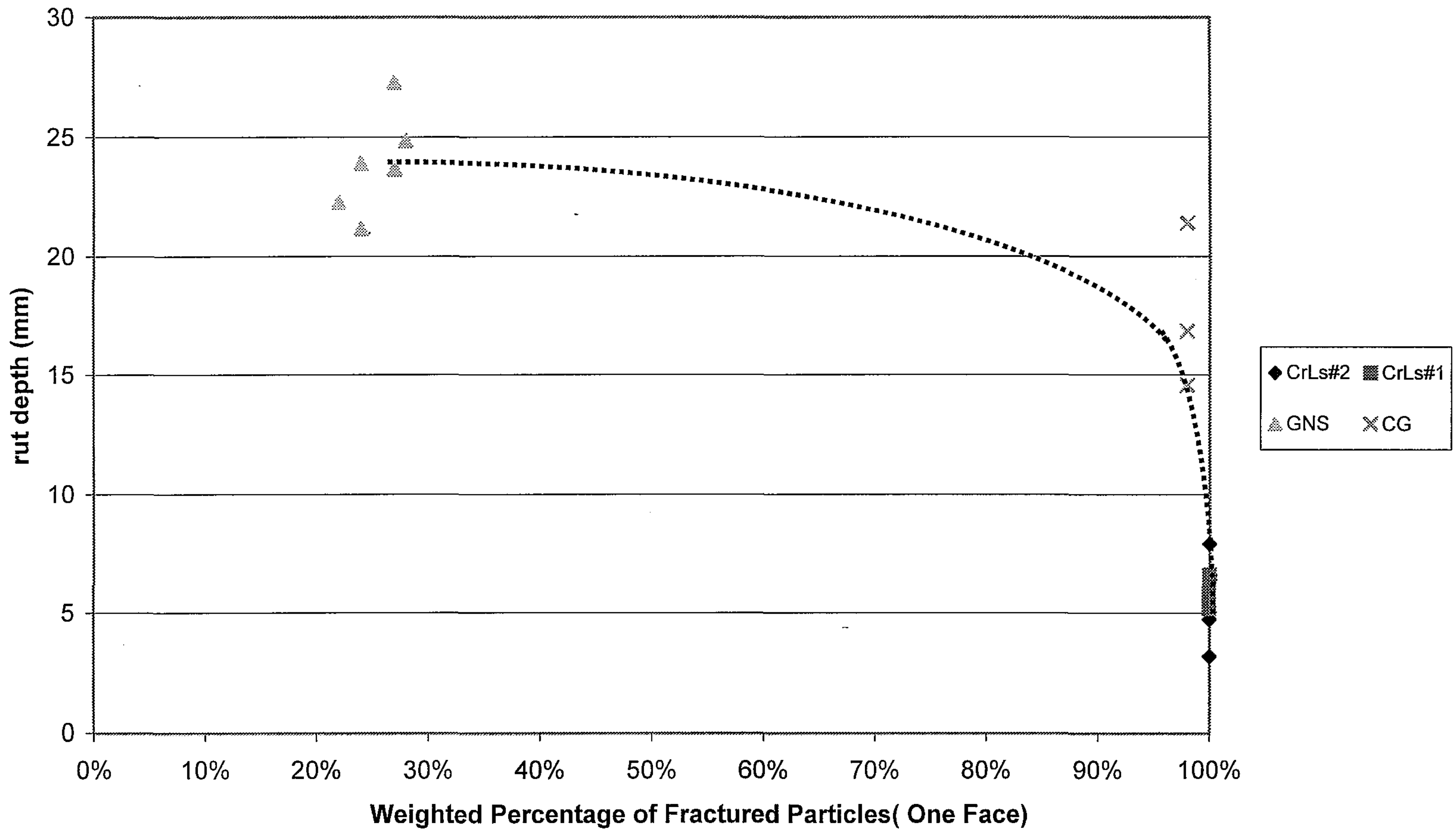



**Figure 3.5.5.2 Weighted Percentage of Particles with Fractured Faces (one face) vs. Rutting**

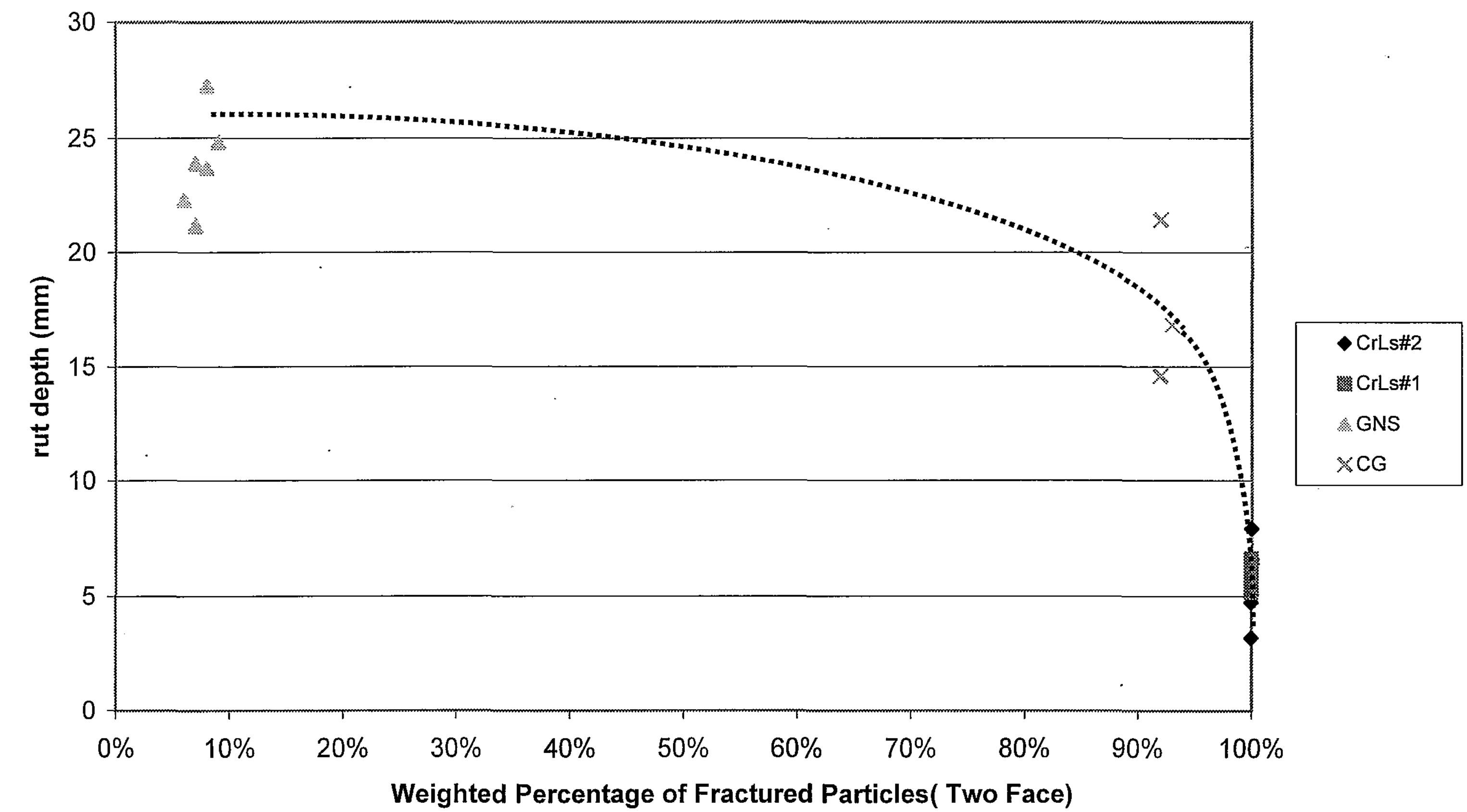



**Fig. 3.5.5.3 Weighted Percentage of Particles with Fractured Faces(two face) vs. Rut Depth**

The APA is being adopted by some state DOTs to evaluate mix rutting susceptibility. Table 3.5.5.2 summarizes specifications for three states.

**Table 3.5.5.2 DOT APA Rut Depth Requirements**

| State | Traffic Level | Test Parameters | APA requirement |
|---|---|---|---|
| Georgia | up to 2,000 ADT | 64 °C, 100 lb, 100 psi, 8,000 cycles | maximum 7mm |
| | 2,000-25,000 ADT | | maximum 6mm |
| | >25,000 ADT | | maximum 5mm |
| Arkansas | | 64 °C, 100 lb, 100 psi,, 8,000 cycles | maximum 3-8 mm depending on design gyration |
| Virginia | <3 million ESL | 49 °C , 120 lb, 120 psi, 8,000 cycles | maximum 7mm |
| | 3 to 10 million ESALs | | maximum 5mm |
| | > 10 million ESALs | | maximum 3.5mm |

Allowing for variations in test parameters such as temperature, load and pressure, APA rut depth requirements of 8 mm or less may require 100 % crushed aggregates.

## 3.5.6 Uncompacted Voids vs. Mix Performance Test Results

Uncompacted voids reflect the combined effect of aggregate angularity, surface texture and shape. For this project, the uncompacted voids of coarse aggregate and uncompacted voids of fine aggregate were determined using samples with standard gradations. A weighted uncompacted voids of the entire blend was calculated from the uncompacted voids of the coarse and fine fractions. (see Table 3.5.6).

The weighted uncompacted voids are plotted vs. APA rut depth in Figure 3.5.6.1. There is clear indicated trend of decreasing rut depth with increasing weighted uncompacted voids. The relationship in Figure 3.5.6.1 indicates a combined aggregate uncompacted voids of about 47% will be necessary to insure an APA rut depth of about 8 mm or less

**Table 3.5.6** **Table of Uncompacted Voids**

| Mix | coarse aggregate portion | uncompacted voids of coarse aggregate | fine aggregate portion | uncompacted voids of fine aggregate | weighted uncompacted voids |
|---|---|---|---|---|---|
| CrLs#2_Superpave_25mm | 0.58 | 48.1% | 0.42 | 46.5% | 47.4% |
| CrLs#2_Marshall_25 mm | 0.58 | 48.1% | 0.42 | 46.5% | 47.4% |
| CrLs#2_SMA_25 mm | 0.76 | 48.1% | 0.24 | 46.5% | 47.7% |
| | | | | | |
| CrLs#2_Superpave_12.5mm | 0.62 | 50.1% | 0.38 | 46.5% | 48.7% |
| CrLs#2_Marshall_12.5 mm | 0.62 | 50.1% | 0.38 | 46.5% | 48.7% |
| CrLs#2_SMA_12.5 mm | 0.78 | 50.1% | 0.22 | 46.5% | 49.3% |
| | | | | | |
| CrLs#1_Superpave_25mm | 0.58 | 46.8% | 0.42 | 48.7% | 47.6% |
| CrLs#1_Marshall_25 mm | 0.58 | 46.8% | 0.42 | 48.7% | 47.6% |
| CrLs#1_SMA_25 mm | 0.76 | 46.8% | 0.24 | 48.7% | 47.3% |
| | | | | | |
| CrLs#1_Superpave_12.5mm | 0.62 | 45.9% | 0.38 | 48.7% | 47.0% |
| CrLs#1_Marshall_12.5 mm | 0.62 | 45.9% | 0.38 | 48.7% | 47.0% |
| CrLs#1_SMA_12.5 mm | 0.78 | 45.9% | 0.22 | 48.7% | 46.5% |
| | | | | | |
| GNS_Superpave_25mm | 0.58 | 43.4% | 0.42 | 46.5% | 44.7% |
| GNS_Marshall_25 mm | 0.58 | 43.4% | 0.42 | 46.5% | 44.7% |
| GNS_SMA_25 mm | 0.76 | 43.4% | 0.24 | 46.5% | 44.1% |
| | | | | | |
| GNS_Superpave_12.5mm | 0.62 | 41.0% | 0.38 | 46.5% | 43.1% |
| GNS_Marshall_12.5 mm | 0.62 | 41.0% | 0.38 | 46.5% | 43.1% |
| GNS_SMA_12.5 mm | 0.78 | 41.0% | 0.22 | 46.5% | 42.2% |
| | | | | | |
| CG_Superpave_12.5mm | 0.62 | 43.4% | 0.38 | 46.5% | 44.6% |
| CG_Marshall_12.5 mm | 0.62 | 43.4% | 0.38 | 46.5% | 44.6% |
| CG_SMA_12.5 mm | 0.78 | 43.4% | 0.22 | 46.5% | 44.1% |

Note. Superave and Marshall have the same gradation

For 12.5 mm maximum size mix, the coarse aggregate fractions start from No.2( 2.36 mm) up

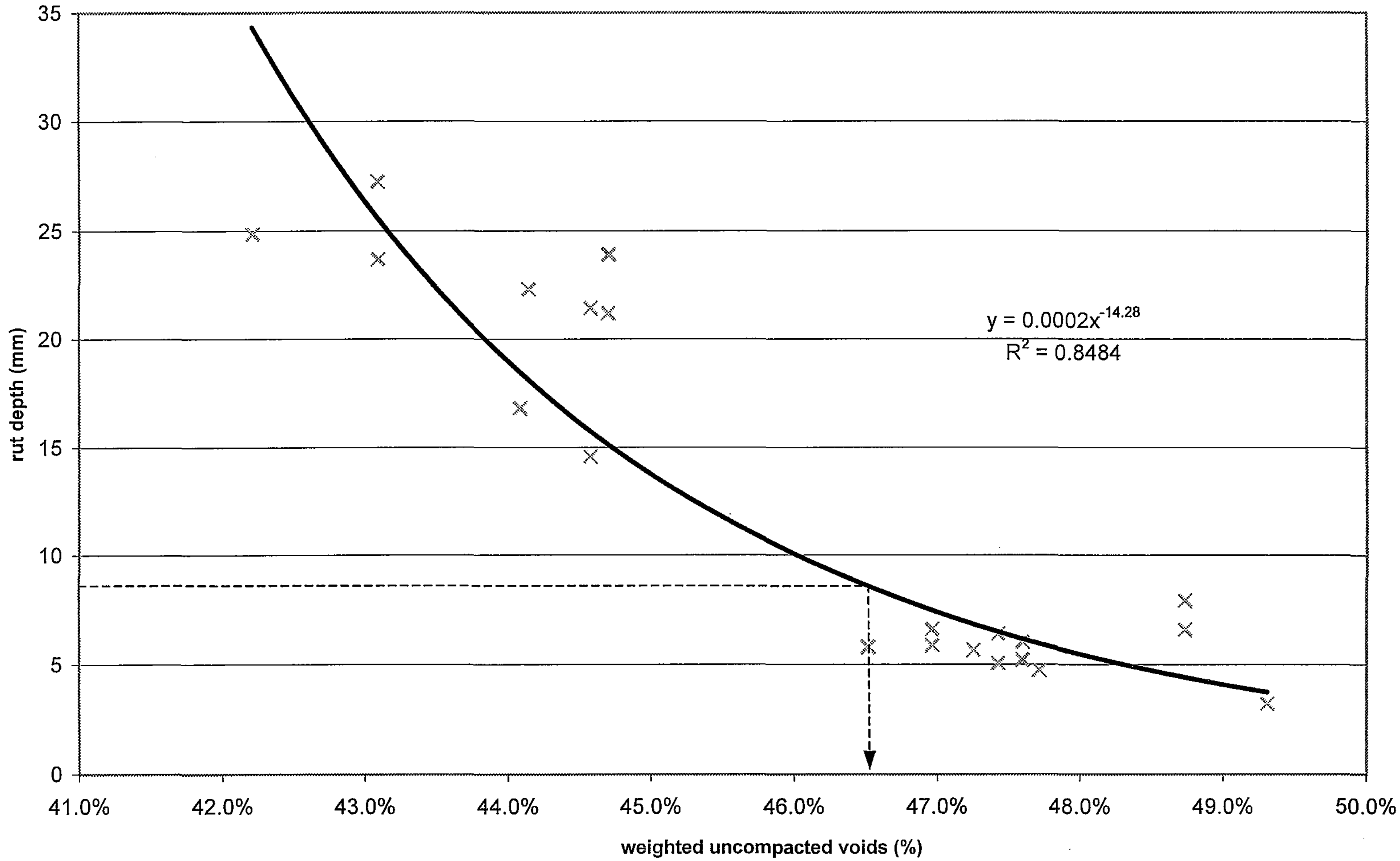



**Fig. 3.5.6.1 Weighted Uncompacted Voids of The Mix vs. Rut Depth**

There was no apparent relationship between weighted uncompacted voids and TSR.

## 3.6 Relationship Between Mix Volumetrics and Mix Design and Mix Performance Test Results

### 3.6.1 VMA Vs. A.C.

VMA is the volume of the effective asphalt plus air voids expressed as a percentage of total volume. Asphalt content is the amount, mass or weight, of asphalt expressed as a percentage of total mix mass or weight to achieve 4% air voids. For certain compaction conditions, i.e. , 50 or 75 blow Marshall or 100 gyrations Superpave, these two values are clearly related and from Figure 3.6.1 it can be seen that there is as expected strong linear relationship between the two.

### 3.6.2 VMA vs. Mix Performance Test Results

VMA is a major mix volumetric parameter currently specified. Much of the mix design work involve finding the right aggregate blend to achieve adequate VMA in the aggregate mix.

From the VMA vs. rut depth plot in Figure 3.6.2 for Superpave and Marshall mixes, it can be seen that, for a given aggregate, the rut depth may increase linearly with increasing VMA. There is no neat relationship between VMA and rut depth across different aggregates and inclusion of SMA mixes detracts from trends shown in Figure 3.6.2. for given aggregate sources.

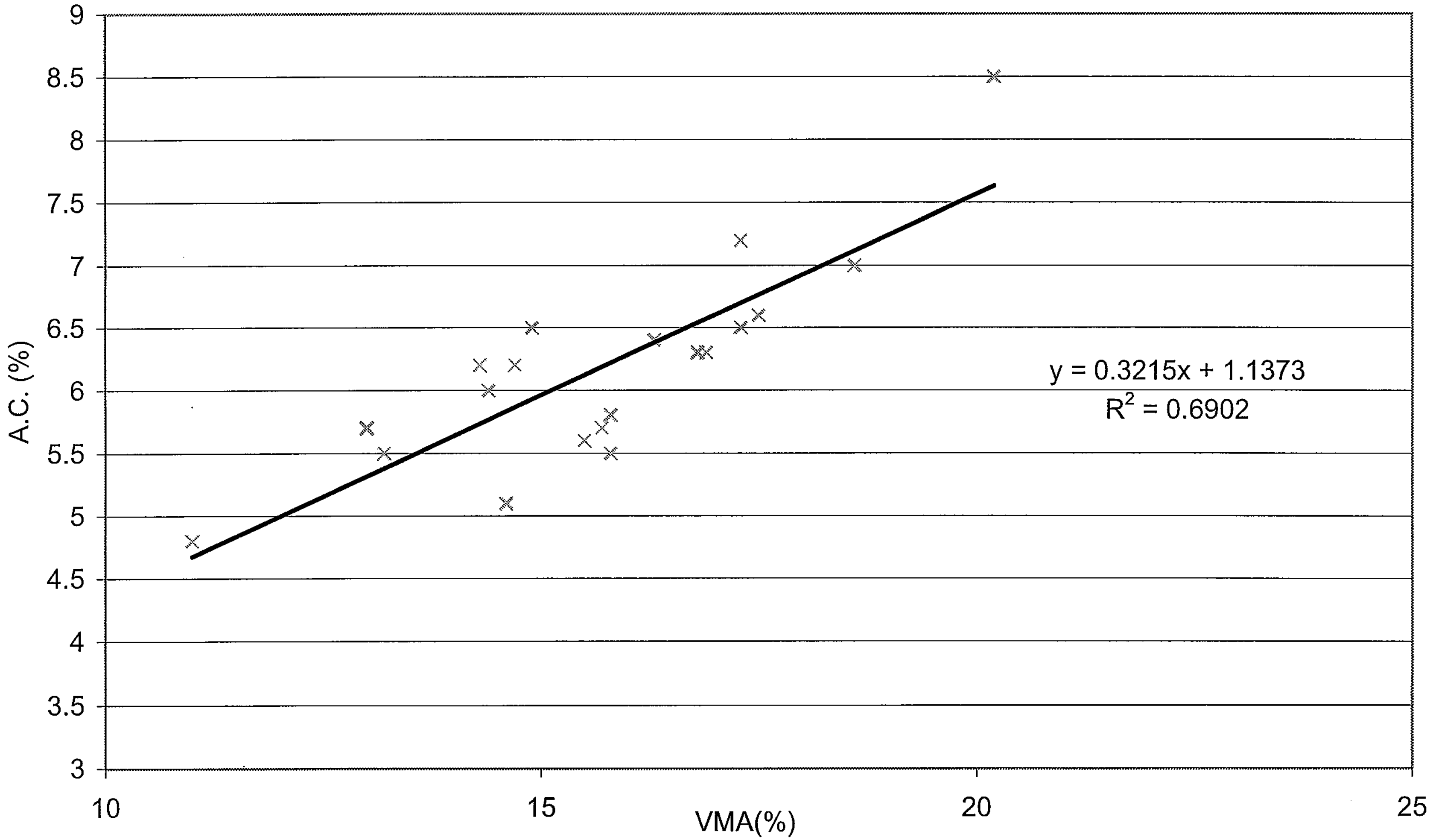



**Fig. 3.6.1 VMA vs. A.C (All Aggregate Sources)**

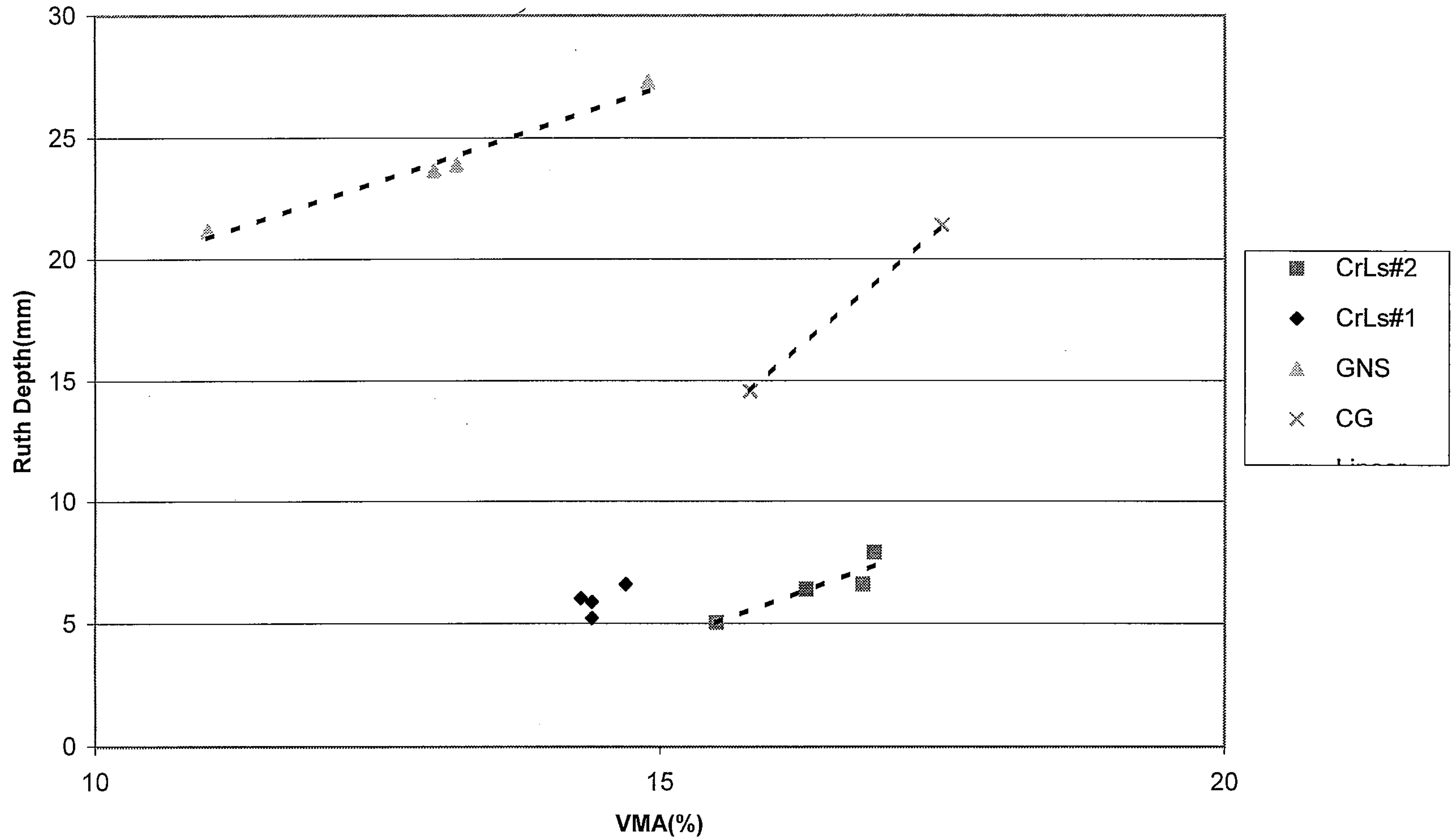



**Fig. 3.6.2 VMA vs. Rut Depth (Superave and Marshall Mixes)**

### 3.6.3 TSR vs Conditoned Strength

In this study, the TSR test was used as a major investigative tool in assessing mix stripping susceptibility. Even though the test has been widely used, there has always been reservations about the use of only TSR because it may mask some poor mixes which have low tensile strengths, conditioned and unconditioned, but high TSR. To investigate the relationship between TSR and tensile strength, TSR research data from two earlier projects: Study of Stripping Potential of Asphalt Concrete Mixtures (ALDOT Project Number ST 2019-6, 1999), Evaluation of Crushed Gravel Quality For Asphalt Concrete( ALDOT Project Number 930-323, 1993) were combined with data from this project and compiled in Table 3.6.3 .

Data from Table 3.6.3 are plotted in Figure 3.6.3 and a linear relationship was found with a fairly strong positive correlation between TSR and conditioned tensile strength ($R^2$ =0.53). The linear regression equation at TSR of 80% gives a conditioned strength of 0.75 MPa (110psi). In addition a TSR of 80% will insure, with 95% confidence, that the conditioned strength will be greater than 0.5 MPa (70psi).

### 3.7.3 Table of TSR Data (with data from previous studies)

| Project | Mix | conditioned strength MPa | unconditioned strengthth MPa | TSR |
|---|---|---|---|---|
| Present Project | CrLs#2_Superpave_25mm | 0.699 | 0.756 | 92.5% |
| | CrLs#2_Marshall_25 mm | 0.674 | 0.743 | 90.7% |
| | CrLs#2_SMA_25 mm | 0.664 | 0.859 | 77.3% |
| | | | | |
| | CrLs#2_Superpave_12.5mm | 0.740 | 0.897 | 82.5% |
| | CrLs#2_Marshall_12.5 mm | 0.748 | 0.929 | 80.5% |
| | CrLs#2_SMA_12.5 mm | 0.783 | 1.062 | 73.7% |
| | | | | |
| | CrLs#1_Superpave_25mm | 0.426 | 0.625 | 68.2% |
| | CrLs#1_Marshall_25 mm | 0.656 | 0.799 | 82.1% |
| | CrLs#1_SMA_25 mm | 0.572 | 0.645 | 88.7% |
| | | | | |
| | CrLs#1_Superpave_12.5mm | 0.578 | 0.800 | 72.3% |
| | CrLs#1_Marshall_12.5 mm | 0.731 | 0.887 | 82.4% |
| | CrLs#1_SMA_12.5 mm | 0.751 | 1.006 | 74.7% |
| | | | | |
| | GNS_Superpave_25mm | 0.758 | 0.916 | 82.8% |
| | GNS_Marshall_25 mm | 0.711 | 0.875 | 81.3% |
| | GNS_SMA_25 mm | 0.529 | 0.815 | 64.9% |
| | | | | |
| | GNS_Superpave_12.5mm | 0.745 | 0.713 | 104.5% |
| | GNS_Marshall_12.5 mm | 0.740 | 0.917 | 80.7% |
| | GNS_SMA_12.5 mm | 0.949 | 1.211 | 78.4% |
| | | | | |
| | CG_Superpave_12.5mm | 0.687 | 0.902 | 76.2% |
| | CG_Marshall_12.5 mm | 0.853 | 0.805 | 106.0% |
| | CG_SMA_12.5 mm | 1.056 | 0.939 | 112.5% |
| | | | | |
| Project 930-323 | Chert1 and Limestone C | 0.782 | 1.167 | 67.0% |
| | Chert1 and Limestone E | 0.752 | 1.106 | 68.0% |
| | Chert2 and Limestone C | 0.949 | 1.157 | 82.0% |
| | Chert2 and Limestone E | 1.015 | 1.025 | 99.0% |
| | Chert3 and Limestone C | 0.898 | 1.020 | 88.0% |
| | Chert3 and Limestone E | 0.908 | 1.135 | 80.0% |
| | Quartz and Limestone C | 0.96 | 1.116 | 86.0% |
| | Quartz and Limestone E | 1.063 | 1.168 | 91.0% |
| | | | | |
| Project ST 2019-6 | A-Lab | 0.236 | 0.754 | 31.3% |
| | F-Lab | 0.61 | 0.868 | 70.3% |
| | G-Lab | 0.536 | 0.945 | 56.7% |
| | H-Lab | 0.302 | 0.536 | 56.3% |
| | I-Lab | 0.894 | 1.419 | 63.0% |
| | | | | |
| | A Base/Binder Hla | 0.917 | 1.239 | 74.0% |
| | A Base/Binder BAb | 0.924 | 1.185 | 78.0% |
| | A Base/Binder KBb | 0.945 | 1.125 | 84.0% |
| | A Base/Binder KBc | 1.069 | 1.188 | 90.0% |
| | | | | |
| | B Base/Binder HLa | 0.993 | 0.955 | 104.0% |
| | B Base/Binder BAb | 0.965 | 0.726 | 133.0% |
| | B Base/Binder KBb | 1.014 | 0.948 | 107.0% |

### 3.7.3 Table of TSR Data (with data from previous studies)

| Project | Mix | conditioned strength MPa | unconditioned strengthth MPa | TSR |
|---|---|---|---|---|
| | B Base/Binder KBc | 1.103 | 0.855 | 129.0% |
| | | | | |
| Gravel Evaluation Project, 1999 | Chert1 and Limestone C Lime | 0.981 | 1.274 | 77.0% |
| | Chert1 and Limestone E Lime | 1.015 | 1.223 | 83.0% |
| | Chert2 and Limestone C Lime | 1.054 | 1.109 | 95.0% |
| | Chert2 and Limestone E Lime | 0.947 | 1.214 | 78.0% |
| | Chert3 and Limestone C Lime | 1.08 | 1.286 | 84.0% |
| | Chert3 and Limestone E Lime | 0.818 | 1.023 | 80.0% |
| | Quartz and Limestone C Lime | 1.155 | 1.167 | 99.0% |
| | Quartz and Limestone E Lime | 1.261 | 1.249 | 101.0% |
| | | | | |
| | Chert1 and Limestone C AS1 | 1.097 | 1.192 | 92.0% |
| | Chert1 and Limestone E AS1 | 1.028 | 1.105 | 93.0% |
| | Chert2 and Limestone C AS1 | 0.986 | 1.060 | 93.0% |
| | Chert2 and Limestone E AS1 | 1.137 | 1.148 | 99.0% |
| | Chert3 and Limestone C AS1 | 0.941 | 1.001 | 94.0% |
| | Chert3 and Limestone E AS1 | 1.163 | 1.011 | 115.0% |
| | Quartz and Limestone C AS1 | 1.065 | 1.034 | 103.0% |
| | Quartz and Limestone E AS1 | 1.208 | 1.098 | 110.0% |
| | | | | |
| | Chert1 and Limestone C AS2 | 1.208 | 1.285 | 94.0% |
| | Chert1 and Limestone E AS2 | 1.198 | 1.198 | 100.0% |
| | Chert2 and Limestone C AS2 | 1.036 | 0.959 | 108.0% |
| | Chert2 and Limestone E AS2 | 1.178 | 1.190 | 99.0% |
| | Chert3 and Limestone C AS2 | 0.974 | 0.974 | 100.0% |
| | Chert3 and Limestone E AS2 | 1.191 | 1.113 | 107.0% |
| | Quartz and Limestone C AS2 | 1.064 | 1.097 | 97.0% |
| | Quartz and Limestone E AS2 | 1.381 | 1.244 | 111.0% |

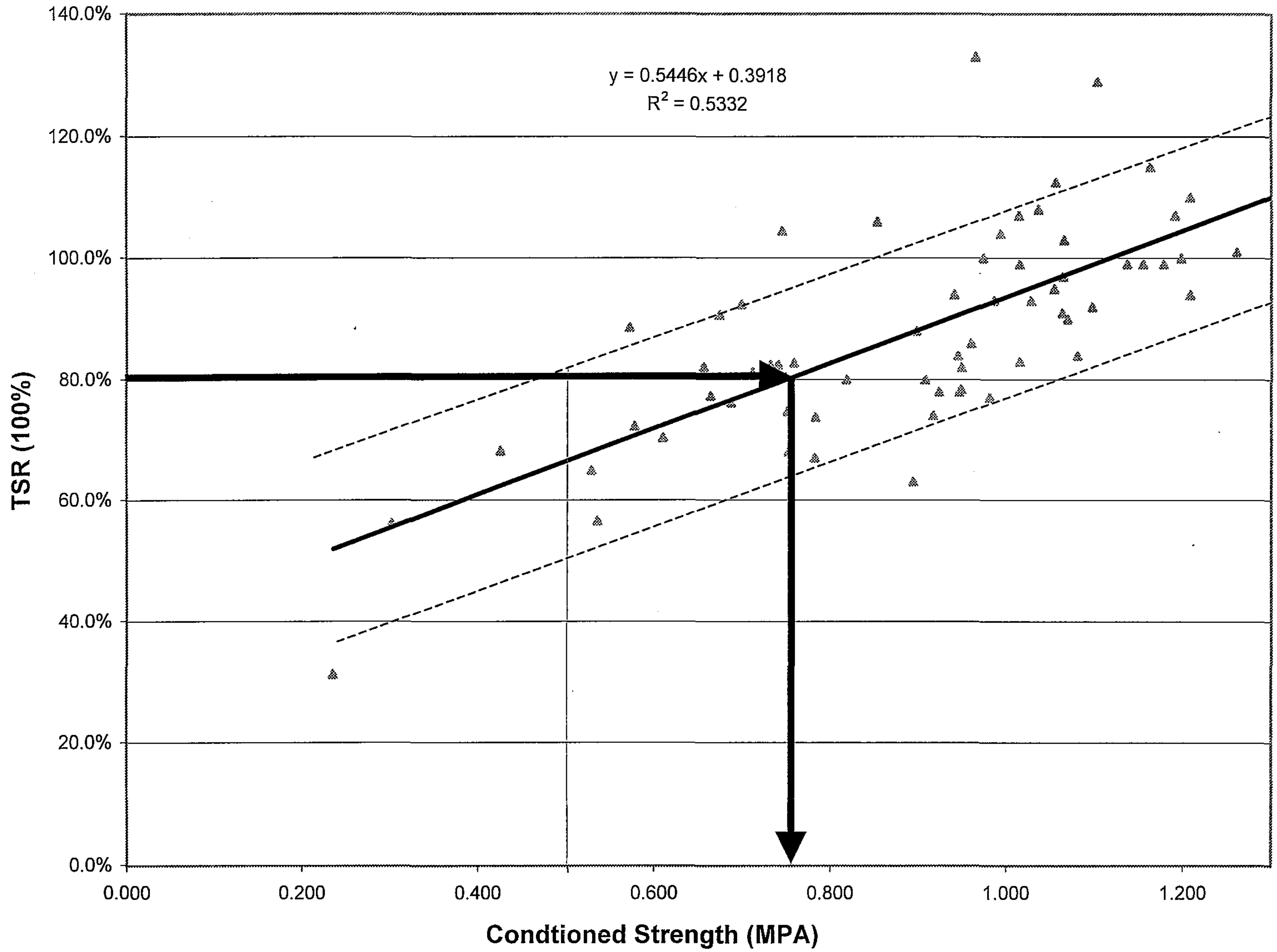



**Fig. 3.6.3 Conditioned Strength vs. TSR**

# CHAPTER 4. CONCLUSIONS

In this study, different types of asphalt mixtures were designed with aggregates having varying values of those properties thought to be linked to mixture performance. The mixtures were evaluated for stripping potential and rutting susceptibility. The tests were carried out, as much as possible, in strict observance of test procedures under highly controlled lab conditions. The following conclusions are drawn:

1. Of the several aggregate properties investigated TSR was correlated to only weighted MBV.
2. TSR was positively correlated to conditioned tensile strength. By setting an appropriate TSR requirement, minimum conditioned tensile strength can ensured, and vice versa. However, the asphalt cement grade is critical for mixture tensile strength. PG76-22, PG64-22 and AC20 were used in mixes analyzed. More testing with other grades of asphalt are needed to establish more general numerical requirements.
3. Mixes with 100 % crushed aggregates perform far better than mixes with uncrushed, or partially crushed aggregates in rutting test. The threshold in terms of percentage of fractured particles for dramatically improving rutting performance appears to be greater than 90%.
4. The value which reflects the combined effect of shape angularity and surface texture of the aggregate blend, the weighted uncompacted void (calculated from the uncompacted void of fine and coarse aggregates, weighted by the percentage of each) appears to be a good indicator of APA rutting performance. There is a narrow range of weighted uncompacted voids, from 45-47%, which separates rutting resistant mixes from the rutting susceptible mixes.

5. Uncompacted voids of only the fine aggregate portion of an aggregated blend will be a poor indicator of mix rutting susceptibility. A weighted uncompacted void value for the entire blend will be a more rational indicator.
6. MBV and sand equivalent values for fine aggregate are fairly strongly correlated.

# REFERENCES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