EFFECTS OF SUPERPAVE RESTRICTED ZONE ON PERMANENT DEFORMATION

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16. Abstract

The Superpave system adopted the voids in mineral aggregate (VMA) criteria developed by McLeod using the 75-blow Marshall compactor for conventional dense-graded hot mix asphalt (HMA) mixtures. This VMA criteria is a function of only the nominal size of aggregate regardless of shape, texture, or gradation. The Superpave volumetric mixture design process contains a required minimum value for fine aggregate angularity (FAA) as a function of traffic level and position of the layer within the pavement structure. This parameter is reported as the percentage of uncompacted air voids, with larger values generally indicating increased aggregate angularity and, thus, higher VMA and better resistance to permanent deformation.

The purpose of this study was to evaluate the effects of FAA and gradation on the resulting VMA of certain HMA mixtures. The effect of FAA was evaluated using mixtures containing coarse limestone combined with six different fine aggregates. Mixtures with three gradations which pass through, above, and below the restricted zone; three different mineral filler contents; and four different values of FAA were analyzed to evaluate the effects of these parameters on VMA of Superpave mixtures.

Based on analyses of these tests, mixtures containing fine granite or limestone showed less permanent deformation than mixtures containing fine river gravel or natural rounded sand. FAA values and permanent deformation did not correlate well. Gradations that pass through the restricted zone did not significantly affect mixture VMA. Mineral filler contents and FAA value did affect mixture VMA significantly. Higher FAA values yielded higher VMA.

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EFFECTS OF AGGREGATE GRADATION AND ANGULARITY ON VMA AND RUTTING RESISTANCE

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CHAPTER I

INTRODUCTION

GENERAL

About 85 percent of hot mix asphalt (HMA) by volume and 95 percent of HMA by weight consists of mineral aggregate. The Strategic Highway Research Program (SHRP) research effort concentrated on properties and testing of asphalt binders in the development of the Superpave binder specification and mixture design methodology (*1*). As a result, data to assess the effects of aggregate gradation, type, and angularity on pavement performance for Superpave mixtures are relatively scarce.

The concept of adequate voids in the mineral aggregate (VMA) is fundamental in the design of dense-graded HMA mixtures and is considered in Superpave criteria for mixture design. It is often difficult to achieve the minimum VMA requirements in Superpave mixtures due to an increased compaction effort required by the Superpave gyratory compactor (SGC), coarser aggregate gradations than formerly incorporated in conventional mixtures, and relatively high asphalt contents (*2*).

A controversial component of the Superpave volumetric mixture design process is the aggregate gradation restricted zone. The restricted zone was adopted primarily to reduce premature rutting, defined as permanent deformation of the pavement surface that develops in the wheel paths under channelized traffic (*3*). It has been shown that the densest packing of aggregate particles is approximated by a straight line from the origin to the maximum aggregate size on the 0.45 power gradation chart. Gradations close to this line typically produce mixtures with low VMA and thus inadequate space for the asphalt cement. The restricted zone lies along this straight line and is designed to avoid the use of these gradations with low VMA (*4*).

The Superpave volumetric mix design process also contains a required minimum value for fine aggregate angularity (FAA) as a function of traffic level and position of the layer within the pavement structure. This parameter is reported as the percentage of uncompacted air voids, with larger values generally indicating increased aggregate angularity and, thus, better resistance to permanent deformation.

The Superpave criteria aims to reduce the occurrence of HMA pavement rutting. To address the concerns raised about mixture volumetrics and evaluate the Superpave aggregate criteria, a limited study was performed to determine the effects of aggregate properties on VMA and the effects of FAA on mixture resistance to rutting.

STATEMENT OF THE PROBLEM

VMA is considered an important parameter in HMA mixture design. It is believed that minimum VMA requirements are necessary to ensure that sufficient space is available for the quantity of asphalt necessary to produce a mixture that will perform well and include space for asphalt expansion at elevated temperatures (*2*). VMA requirements in the Superpave system were adopted from those developed by McLeod (*7*) using the 75-blow Marshall compactor for conventional dense-graded HMA mixtures. This VMA requirement is a function of only the nominal maximum size of the aggregate regardless of shape, texture, or gradation of the aggregate. One of the key elements ensuring the success of the Superpave design process is production of an aggregate gradation significantly coarser than those used in conventional dense-graded mixtures (*3*). There is, therefore, concern that VMA requirements for these coarser gradations with correspondingly lower specific surface areas may be excessive.

Excessive VMA can be detrimental to performance, producing a mixture that requires excessive asphalt and, thus, may exhibit stability problems and be uneconomical to produce. "Tender mixes" may also be promoted by excessive VMA, and the mat may resist compaction in the normal manner because it is slow in developing sufficient stability to withstand the weight of compaction equipment. Allowing lower VMA values in mixtures may decrease tenderness problems sometimes experienced with Superpave mixtures. In fact, many experts advise against using HMA mixtures having VMA values that exceed the minimum specified value by more than 2 percent. Some advise, for heavy-duty pavements, not to exceed the minimum specified value by more than 1 percent (*5*).

The restricted zone is a new aggregate requirement developed during SHRP and incorporated in the Superpave volumetric mixture design process. This zone is an area lying along the maximum density line extending from the 0.30-mm (No. 50) sieve to the 2.36-mm

(No. 8) or 4.75-mm (No. 4) sieve depending on the nominal maximum size, through which it is undesirable for a mixture gradation to pass (*3*). The purposes of the restricted zone are to limit the inclusion of large amounts of rounded gravel or local sands that cause "humps" in the gradation curve in the 0.6-mm range and to discourage gradations that fall on the maximum density line and thus have inadequate VMA (*6*). McLeod (*7*) suggested adequate VMA will allow enough asphalt cement for adequate durability. Based on test results for mixtures with three different aggregates in another ICAR study, it was concluded that the use of gradations that pass through the restricted zone does not significantly impact rutting performance and that adequate VMA is not guaranteed by avoiding the use of these gradations (*8, 9*).

The FAA requirements in Superpave specifications are intended to control angularity of the fine portion of the aggregate blend to ensure that fine aggregates have adequate internal friction that contributes to HMA rutting resistance (*3*). These requirements depend on the traffic level and the proximity of the layer to the pavement surface and are based on the assumption that more fractured faces will result in higher void contents in a loosely compacted sample. Researchers, however, have discovered that cubical-shaped particles, even with 100 percent fractured faces, may not meet the FAA requirement for high-volume traffic (*1, 10*).

Several research projects have shown that the Superpave restricted zone [Purdue (*11*), NCAT (*12*), and WesTrack (*13*)] and FAA [University of Florida (*14*)] requirements do not significantly affect mixture rutting resistance (*8, 9, 10*). An expanded study is necessary to examine the effect of these properties on rutting resistance and VMA of mixtures.

OBJECTIVES OF STUDY

The objective of this study was to evaluate VMA data collected during a recent International Center for Aggregate Research (ICAR) sponsored project that examined the effects of the restricted zone on permanent deformation. The ultimate goals of this research were to determine the aggregate properties that affect VMA and establish relationships between FAA and mixture rutting resistance.

ORGANIZATION OF STUDY

This report is divided into five chapters. Chapter I serves as an introduction stating the nature of the problem to be addressed and objectives of the research.

Chapter II summarizes the factors that affect VMA and permanent deformation in the scope of this study. It addresses permanent deformation; gradations, including the restricted zone and mineral filler; FAA; and VMA and provides a brief description of the Asphalt Pavement Analyzer (APA) used in the FAA experiments.

Chapter III describes the FAA study. It addresses materials selection, the FAA test, mix design process, volumetric properties, the APA test method, and analysis of test data.

Chapter IV briefly describes the asphalt binder and aggregates selected for the study, the Superpave volumetric mixture design process, and analysis of volumetric parameters for four different aggregates with three different gradations. This chapter covers the effect of aggregate gradation on VMA for four different materials with three different gradations, the effect of mineral filler content on VMA for granite with a gradation through the restricted zone, and the effect of FAA on VMA for the FAA study described in Chapter III.

Chapter V presents conclusions and recommendations based on findings from the study.

CHAPTER II

LITERATURE REVIEW

GENERAL

The factors that affect VMA of compacted HMA are diverse and difficult to define, but asphalt researchers know that aggregate gradation and FAA play a significant role in terms of VMA and its relation to mixture rutting resistance. Permanent deformation resistance is primarily provided by the aggregate structure. The aggregate in a HMA mixture is expected to provide a strong stone skeleton to resist deformation during application of heavy and/or repeated loads.

Aggregate properties such as gradation, mineral filler content, and FAA are also known to influence HMA mixture resistance to rutting through their contribution to formation of the aggregate structure during compaction. These properties are briefly described in this section. The Asphalt Pavement Analyzer, a laboratory device for measuring relative rutting resistance, is also discussed.

PERMANENT DEFORMATION

Permanent deformation is a primary form of HMA pavement distress characterized by a surface cross section that is no longer in its original position. It is called permanent deformation because it represents an accumulation of small amounts of unrecoverable deformation that occur each time a load is applied (*15*). The most significant form of permanent deformation in HMA highway pavements is rutting.

The type of rutting of most concern to asphalt mix designers is deformation in the asphalt layer. Wheelpath rutting, the most common form of permanent deformation, can be defined as a depression that occurs in the asphalt pavement's wheel path as a result of traffic loads. It typically occurs in the top 7.5 to 10 mm of an asphalt pavement (*16*).

Most asphalt pavement rutting occurs during the summer, when higher pavement temperatures are prevalent, the viscosity of the asphalt binder is low, and the traffic load is primarily carried by the mineral aggregate structure (*16*). While this might suggest that rutting is solely an asphalt cement problem, it is more correct to address resistance to rutting by considering the combined resistance (shear strength) of the mineral aggregate and asphalt cement (*15*).

Rutting is normally a significant safety problem in rainy weather when water begins to pond in the wheel path. A rutted pavement poses a hazard because of hydroplaning or ice formation in cold weather (*3*). The cross slope of the pavement section is the controlling factor in determining when a specified rut depth is acceptable or not. At speeds of 90 km/hr (56 mph) or more for pavements with crown slopes of the order of 2 percent and rut depths of about 12.5 mm, ponding is sufficient to cause vehicles to hydroplane *(17)*.

For normal cross slope values, a rut depth of 12.5 mm is normally accepted by most state highway agencies as the maximum allowable rut depth (*16, 17*).

AGGREGATE GRADATION

Aggregate gradation analysis and the combining of aggregates to obtain the proper mixture properties for adequate pavement performance are important steps in the HMA design process (*18*). The aggregate gradation must meet the gradation of the project specifications and yield a mixture design that meets the criteria of the design method. The gradation should incorporate the most economical aggregates available that are of suitable quality.

Superpave Gradation Requirements

To provide a better means of relating actual aggregate gradation to maximum density gradation, Superpave uses the 0.45 power chart, a unique graphing technique, to define a permissible gradation.

A maximum density gradation is defined as a straight line plotted from the lower left corner of the chart, zero percent passing a theoretical sieve size of zero, upward and toward the right to any specific maximum sieve size. The maximum density gradation represents a gradation in which the aggregate particles fit together in their densest possible arrangement. VMA can typically be achieved by adjusting the gradation curve plots further away from the maximum density line (*18*). Superpave uses a standard set of ASTM sieves and the following definitions with respect to aggregate size (*3*):

- maximum (sieve) size: This is one sieve size larger than the nominal maximum size.
- nominal maximum (sieve) size: This is one sieve size larger than the first sieve to retain more than 10 percent.

To specify aggregate gradation, control points and a restricted zone are added to the 0.45 power chart. Control points function as master ranges through which gradation must pass. For a 19-mm nominal maximum size gradation, they are placed on the nominal maximum size, an intermediate size (2.36 mm), and dust size (75 μm). Superpave gradation limits for 19-mm nominal maximum aggregate size are shown in Figure 1 (*3*).

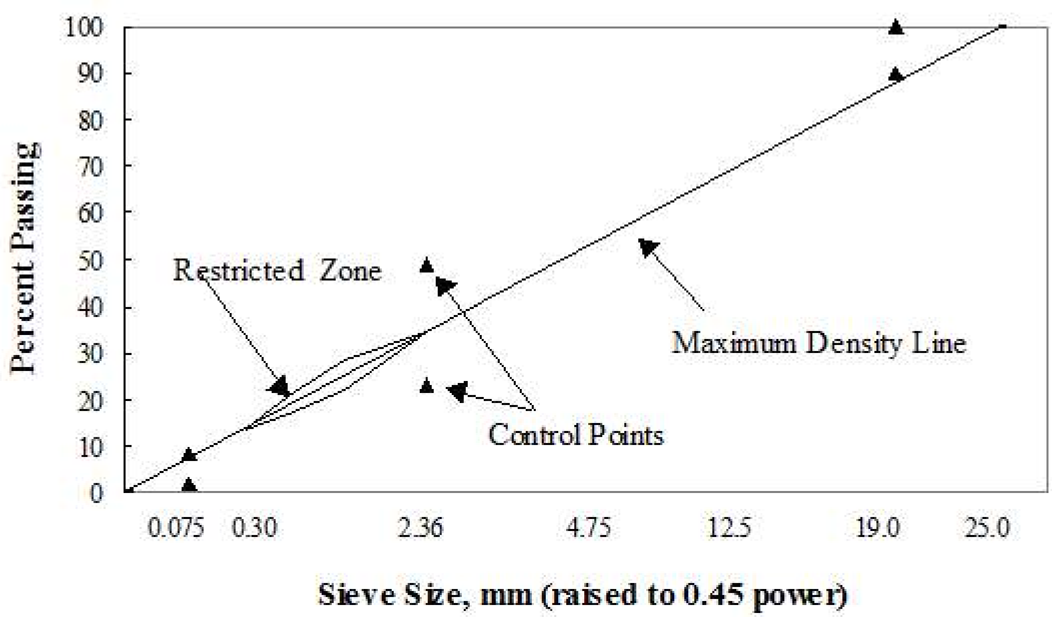

FIGURE 1 Superpave Gradation Limits, 19-mm Nominal Maximum Size

Mineral Filler

As the aggregate passing the 75-µm sieve (filler) increases, the VMA normally decreases because the mineral filler fills the void spaces between the coarse and fine aggregate particles. If there is more than enough filler to fill voids between the coarse and fine particles, however, the excess filler begins to push the coarse and fine aggregate particles apart, and thus, VMA will increase (*19*).

Aschenbrener et al. (*20*) showed that the quantity of minus 75-µm sieve size material affects the VMA. Lower quantities of minus 75-µm material produced higher VMA values. The VMA values of gradations on the fine side of the maximum density line were affected more by the quantity of minus 75-µm than were the VMA values of gradations on the coarse side of the maximum density line (*20*).

FINE AGGREGATE ANGULARITY

The FAA test recommended by Superpave was originally developed by the National Aggregate Association and was later adopted by the American Society for Testing & Materials (ASTM) as method C 1252 and by American Association of State Highway and Transportation Officials (AASHTO) as method T 304 (*3*). Method A of this procedure was selected for use in Superpave mixture design. The test procedure is described in ASTM standard test manual (*21*).

Effect of FAA on VMA

It is commonly accepted that increased aggregate angularity contributes to higher VMA and better resistance to permanent deformation. Normally, angular-shaped and rough-textured sand size aggregates are more desirable than rounded particles. Therefore, changing the source of an aggregate can have a significant influence on VMA of a HMA mixture.

Field (*22*) demonstrated that replacing rounded aggregates with angular aggregates increased the stability, void content, and VMA of HMA for a given compaction level. The higher VMA values allow additional asphalt in the mixture, and therefore, the durability of the HMA is normally improved. Kennedy et al. stated that aggregates with rough surface texture provide higher VMA than smooth-textured aggregates in a compacted mass because they tend to form stronger mechanical bonds (*16*). Aschenbrener and MacKean (*20*) demonstrated that higher quantities of angular aggregates and more angular aggregates will produce higher VMA in HMA. Conversely, higher quantities of rounded sands and more rounded particles will result in lower VMA.

Effect of FAA on Rutting Resistance

The aggregate structure of a HMA mixture provides the primary resistance to permanent deformation. A strong stone skeleton can be obtained from aggregate to resist repeated load applications. Shape and surface texture of aggregates are important factors that affect the development of this skeleton. Mixtures with more angular, rough-textured aggregates have demonstrated more rut resistance than mixtures with rounded, smooth-textured aggregates (*3*).

The role of fine aggregate in rut resistant mixtures has been investigated by several researchers. Button et al. (*23*) showed that an excessive amount of rounded sand contributed to a loss of rut resistance in asphalt pavements. Total deformation and rate of deformation increased as the percentage of rounded sand was increased. Shape and texture of the fine aggregate were major factors affecting plastic deformation in HMA (*23*). Yeggoni et al. (*24*) demonstrated that HMA pavements containing gravel and natural rounded sands did not perform as well as pavements containing crushed coarse aggregates and manufactured sands. Crawford (*25*) concluded that rounded, uncrushed aggregates were more likely to contribute to tender mixtures and, therefore, be more susceptible to rutting, especially as the amount of uncrushed material passing the 4.75-mm sieve increases. Kallas et el. (*26*) stated that an increase in angularity of fines increased the Marshall and Hveem stability values at the optimum asphalt content. He also showed that an increase in angularity in the fine aggregate also increased the VMA, void content, and the optimum asphalt content at a given compactive effort. In contrast with the above, a study of relationships between fine aggregate angularity and rut resistance of paving mixtures demonstrated that rut depths measured using the APA did not correlate with angularity of the fine aggregate (*27*). In that study (*27*), researchers tested asphalt mixtures with fine aggregates of four different FAA values.

VOIDS IN THE MINERAL AGGREGATE (VMA)

VMA is defined as the volume of inter-granular void space between the aggregate particles of a compacted asphalt paving mixture that includes the air voids and the effective asphalt content. VMA is calculated on the basis of the bulk specific gravity of the aggregate and is expressed as a percentage of the bulk volume of the compacted paving mixture (*28*).

Minimum requirements in Superpave specifications (based on 4 percent air voids) are a function of nominal maximum aggregate size (*3*). Table 1 shows Superpave VMA requirements.

TABLE 1 Superpave VMA Requirements

Nominal Maximum Size (mm)	Minimum VMA (%)
9.5	15.0
12.5	14.0
19.0	13.0
25.0	12.0
37.5	11.0

In current Superpave HMA mixture specifications, VMA requirements for compacted mixtures depend only upon the nominal maximum size of the aggregate in the mixture. As expected, VMA requirements decrease as maximum aggregate size increases, but void structure in HMA is dependent upon aggregate gradation as well as nominal maximum aggregate size. Coarser graded HMA mixtures, such as Superpave mixtures, possess a greater volume concentration of aggregate and lower specific surface area than typical pre-Superpave dense-graded mixtures and, thus, may have a lower capacity for VMA.

McLeod (*19*, 29) presented several papers on VMA in mixture design. In 1956, his explanation for the VMA requirements was that it provided a minimum volume of void space in the mineral aggregate of compacted HMA to provide room for the air voids specified and for the volume of bituminous binder needed to provide a durable pavement (*19*). In 1957, Lefebvre (*30*) reported difficulty in obtaining paving mixtures with more than 15 percent VMA when compacted using a Marshall hammer at an asphalt content that produced 3-5 percent air voids. The data showed that VMA could be increased by using more fine aggregate, more fine sand in the fine aggregate, and less mineral filler, but no performance relationships with actual pavements were given. However, it is the authors' opinion that using these methods in some mixtures to increase the VMA could significantly decrease resistance to rutting. In 1959, McLeod (*29*) presented a paper that was concerned primarily with the use of bulk specific gravity for computing both air voids and VMA with allowance for absorbed asphalt cement. The minimum VMA limits for durable pavement were recommended, but no correlations were given between VMA and pavement performance.

In contrast with McLeod's research, several papers that show no correlation between VMA and pavement performance are presented. Metcalf (*31*) stated that VMA did not correlate with performance in his tests, as no minimum VMA could separate pavements that performed satisfactorily from those that were brittle or plastic. Huber et el. (*32*) found that a clear division between acceptable and unacceptable performance was not apparent from the plot of VMA versus rutting performance. Foster (*33*) stated that a minimum VMA requirement in mixture design does not necessarily guarantee good performance in an asphalt pavement. In conclusion, a number of factors, including VMA, play important roles in developing a mixture that contains enough asphalt cement to be durable and yet perform in a satisfactory manner.

The current Superpave VMA requirements may be appropriate; however, there are enough questions about these requirements to warrant further research. It currently appears that coarser Superpave mixtures permit lower values of VMA than conventional finer mixtures.

If VMA requirements for Superpave mixture design are excessive, this may:

- cause difficulty in obtaining a mixture design that meets the specification,
- invite the introduction of excessive sand-size particles or the production of gap-graded mixtures,

- disallow sufficient filler (minus No. 200 material) to provide the desired mixture stiffness,
- needlessly increase the asphalt binder content and thus cost of the mixture,
- produce mixtures with thick asphalt films that exhibit tenderness during construction,
- produce more rut-susceptible mixtures (just the opposite of the purpose of VMA requirements), and/or
- potentially yield more permeable pavements.

All of these problems have been associated, on occasion, with Superpave mixtures.

CHAPTER III

FINE AGGREGATE ANGULARITY EXPERIMENT

This research focused on examining the effects of fine aggregate angularity on voids in the mineral aggregate and permanent deformation in Superpave HMA mixtures. The role of FAA was evaluated by substituting various fine aggregates into a Superpave mixture design and measuring the effect using laboratory test devices. The coarse aggregate retained on the 4.75-mm sieve remained unchanged, while the fine aggregate passing the 4.75-mm sieve was varied. A coarse gradation was chosen to represent Superpave gradation. Laboratory testing in the APA was used to predict pavement rutting.

The work plan was divided into the following five steps:

- Materials Selection. This phase included identification and collection of six fine aggregate types, a coarse aggregate, and a binder to prepare the HMA blends for further material characterization.
- Measurement of FAA. Six different fine aggregates were tested to determine FAA values and compare with Superpave minimum requirements.
- Superpave Volumetric Mix Design. Several trial blends were prepared to obtain the design asphalt content for six different fine aggregates combined with limestone coarse aggregate at a given gradation. In this phase, the relationship between FAA and VMA was analyzed.
- Experimental Design. This phase described the specimens that were used in the mixture evaluation test.
- Asphalt Concrete Mixture Evaluation. APA tests to evaluate rutting resistance of the HMA mixtures were performed.

MATERIALS SELECTION

Four fine aggregates selected in this task are a partially crushed river gravel supplied by Fordyce, McAllen, Texas; a crushed granite supplied by Martin Marietta, Forsyth Quarry, Georgia; a crushed limestone supplied by Vulcan Materials, Brownwood, Texas; and rounded natural sand obtained from the Brazos River, Texas. Two more fine aggregates were prepared by blending two of those four aggregates. The three crushed aggregates have shown good performance in the field for many years, and one rounded natural sand was obtained to compare with the crushed aggregates. Blend 1 was composed of 85 percent crushed granite and 15 percent natural rounded sand. Blend 2 was composed of 70 percent limestone and 30 percent natural rounded sand. Blended fine aggregates were used in order to achieve certain FAA values. The FAA values reported for these two blends were calculated (weighted average of FAA of the constituting fines). Six HMA mixtures with the same gradation composed of limestone coarse aggregate supplied by Vulcan Materials, Brownwood, Texas, with four different fine aggregates were designed according to the Superpave volumetric mix design as subsequently described.

The performance grade (PG) binder that corresponded to a selected geographic location (Lubbock, Texas) and specified traffic level (3 to 10-million equivalent single axle load [ESALs]) was obtained from the Long-Term Pavement Performance Binder selection (LTPP BIND) program (*34*). PG 64-22 was selected for these conditions using a 98 percent reliability level .

MEASUREMENTS OF FINE AGGREGATE ANGULARITY

Fine aggregate angularity tests (ASTM C-1252, Method A) were conducted on crushed granite, crushed limestone, crushed river gravel, and uncrushed natural rounded sand. Duplicate FAA values and bulk specific gravities were determined. For bulk specific gravity determinations, the aggregate samples were finer than the 4.75-mm sieve. The average from two replicate tests was used in the calculation of uncompacted air voids. If the difference between two results of bulk specific gravity was 0.032 or greater, both results were discarded and the duplicate tests were repeated. It is noteworthy that a change in bulk specific gravity of

0.05 will change the calculated uncompacted air voids by approximately one percent. Table 2 shows bulk specific gravities and FAA of the six selected fine aggregates.

TABLE 2 Bulk Specific Gravity and FAA Values of Fine Aggregates

Fine Aggregate Type	Bulk Specific Gravity	FAA Value
Partially Crushed River Gravel	2.578	44.3
Crushed Granite	2.672	48.0
Crushed Limestone	2.633	43.5
Rounded Natural Sand	2.572	39.0
Blend 1 (85% Gr + 15% NS)	2.657	46.0
Blend 2 (70% LS + 30% NS)	2.615	42.0

Although the three crushed aggregates have shown good performance in the field for many years, only the granite met the FAA Superpave criteria. Limestone and crushed river gravel did not meet the Superpave FAA criteria. As expected, natural rounded sand showed the lowest FAA value and did not meet the FAA criteria.

SUPERPAVE VOLUMETRIC MIXTURE DESIGN

The gradation selected for this portion of the study was below the restricted zone and used coarse limestone aggregate with the six different fine aggregates. The original Superpave guidelines recommended gradations passing below the restricted zone.

To develop the two aggregate blends, the aggregates were sieved, separated into bins, and then recombined. The different fine aggregates (Table 2) were separately combined with a limestone coarse aggregate (19-mm nominal maximum size) to obtain six different aggregate blends. The coarse aggregate properties, including the gradation, were essentially the same for each blend. The specific gradation used is shown in Appendix A, Table A1 and Figure A1.

Mixing

Once the aggregate blends were selected and the initial trial asphalt binder content was calculated using the assumptions in the Superpave volumetric mixture design process, the HMA mixtures were prepared (*3*). Mixing and compaction temperature of the apshalt was determined using the procedure recommended by Superpave. Mixing procedures consisted of the following main steps:

- heat the aggregates and asphalt binder to the mixing temperature (159 ± 3 ˚C),
- mix asphalt binder and aggregates at the mixing temperature (159 ± 3 ˚C) and age the mixture for four hours at 135 ˚C.
- place the mixture in an oven at the compaction temperature (145 ± 3 ˚C) until it reaches the desired compaction temperature.

Compaction

All specimens were compacted using the Superpave gyratory compactor. In the Superpave volumetric mixture design process, asphalt mixtures are designed at a specific compaction effort. For the Superpave volumetric mixture design procedure, this is a function of the design number of gyrations, N_{des}. N_{des} is used to vary the compaction effort of the mixture as a function of climate and traffic level. Two other gyration levels are also of interest, the initial number of gyrations (N_{ini}) and the maximum number of gyrations (N_{max}). These gyration levels are related to N_{des} as follows:

$$\text{Log } N_{ini} = 0.45 \text{ Log } N_{des}$$

$$\text{Log } N_{max} = 1.10 \text{ Log } N_{des}$$

Climate is represented by the average design high air temperature. For Lubbock, Texas, this temperature is approximately 39 ˚C. The selected traffic level was 3-10 million ESALs, for design purposes. For the selected traffic level and representative climate site, $N_{ini,}$ N_{des}, and

N_{max} are 8, 96, and 152, respectively. Specimens for the volumetric analysis were compacted to 152 gyration numbers (N_{max}).

The Superpave volumetric mixture design process is well documented in the literature (*3, 15*). In Table 3, design asphalt content and VMA values are summarized for the six mixtures at 4 percent air voids. Detailed design information from the six mixture designs are presented in Appendix A.

TABLE 3 Design Asphalt Content and VMA Value

Fine Aggregate	Design Asphalt Content (%)	VMA (%)
Partially Crushed River Gravel	5.6	14.7
Crushed Granite	5.2	14.8
Crushed Limestone	4.8	13.8
Rounded Natural Sand	3.8	11.4*
Blend 1	5.6	14.8
Blend 2	4.2	11.9*

* Did not meet the Superpave specification

EXPERIMENTAL DESIGN

Each fine aggregate was combined with coarse limestone aggregate then mixed with the optimum percentage of asphalt cement given in Table 3. All uncompacted mixtures were subjected to four hours of short-term aging at 135 ˚C, then the mixtures were compacted to 4 ± 1 percent air voids using the SGC.

To calculate air void content for each sample, bulk specific gravity of the test specimens and maximum specific gravity of the test mixtures were determined in accordance with AASHTO T 166 and AASHTO T 209, respectively. Air void contents of all samples were determined in accordance with AASHTO T 269. Bulk specific gravity and air voids of all specimens are presented in Appendix A.

Each HMA specimen was tested using the APA to determine its relative resistance to rutting. The APA is a multi-functional loaded wheel tester (LWT) used primarily for evaluating mixture permanent deformation. The APA is a modified version of the Georgia load wheel tester developed by Geogia Department of Transportation (*35*). The load is applied by an oscillating wheel on top of a pressurized pneumatic hose that rests on top of the test specimen. Eight thousand cycles are typically used for a complete permanent deformation evaluation. Permanent deformation susceptibility of mixtures is assessed by placing a HMA beam or two cylindrical specimens under repetitive wheel loads and measuring the amount of permanent deformation in the wheel path (*35*). Cylindrical HMA specimens were compacted at 150 mm ± 0.5 mm in diameter and 75 mm ± 0.5 mm in height were fabricated. A Superpave gyratory compactor was used to compact the specimens. Uncut specimens were used in all APA testing. The APA accommodates six cylindrical specimens or three beam specimens for simultaneous testing.

ASPHALT MIXTURE EVALUATION

After room temperature preconditioning (approximately at 25 ˚C for 24 hours), the specimens were placed in the testing chamber of the APA for a minimum of five hours at 64 ˚C. The testing temperature of 64 ˚C was selected on the basis of the PG grade of the asphalt used in the mixture design. The test specimens were placed in the APA and secured on the specimen tray with restraining brackets.

After seating the specimens in the APA with 50 cycles of the test wheel, the automated test mode was used to perform 8000 cycles, as recommended by Pavement Technology Inc. *(35)*. A pressure of 700 kPa was used in the rubber hose, and a wheel load of 445 N was used to conduct all APA tests. The test temperature was 64 ±1 ˚C based on the expected high pavement temperature at a 20-mm depth in Lubbock, Texas. An APA test of 8000 cycles usually required about 2.5 to 3 hours to complete.

TEST RESULTS AND ANALYSIS

Data from testing with the APA were obtained and analyzed as discussed in the following subsections. Detailed test results for individual specimens are given in Appendix A.

Measured Rut Depths in the APA

Individual results from triplicate tests to 8000 cycles and their averages are shown in Table 4 and Figure 2 for each fine aggregate type.

Mixtures containing natural rounded sand with a FAA of 39 had the highest rut depth (9.2 mm). Mixtures containing river gravel with a FAA of 44.3 had a statistically equivalent rut depth (9.1 mm). Mixtures containing granite with the highest FAA of 48 showed the lowest rut depth (4.0 mm). Mixtures containing limestone with a FAA of 43.5 showed the second lowest rut depth, statistically equivalent to the measured rut depth of the granite mixtures.

Although river gravel exhibited a higher FAA value than limestone, the fractured face of river gravel has a smoother texture than granite and limestone. Uncrushed rounded natural sand had a smoother texture than any of the crushed aggregates. Mixtures containing granite and limestone had the lowest rut depth compared to mixtures containing river gravel and rounded natural sand. This suggests that aggregate texture plays an important role in mixture rutting resistance. This is in agreement with Fernandes et al. (*14*). Blend 1 and Blend 2 exhibited similar rut depths (5.3 mm and 2.2 mm), even though their FAA values varied by four percentage points.

Detailed rut depth data for the six different mixtures and plots of rut depth versus number of APA cycles are presented in Appendix A.

TABLE 4 Asphalt Pavement Analyzer Test Results

Fine Aggregate	FAA	Rut Depth after 8000 Cycles in the APA (mm)			
		Tray 1	Tray 2	Tray 3	Average
Partially Crushed River Gravel	44.3	9.8	9.1	8.4	9.1
Crushed Granite	48.0	4.1	3.6	4.2	4.0
Crushed Limestone	43.5	4.7	4.1	4.3	4.4
Rounded Natural Sand	39.0	9.5	9.4	8.8	9.2
Blend 1	46.0	5.6	5.2	5.1	5.3
Blend 2	42.0	4.8	5.2	5.7	5.2

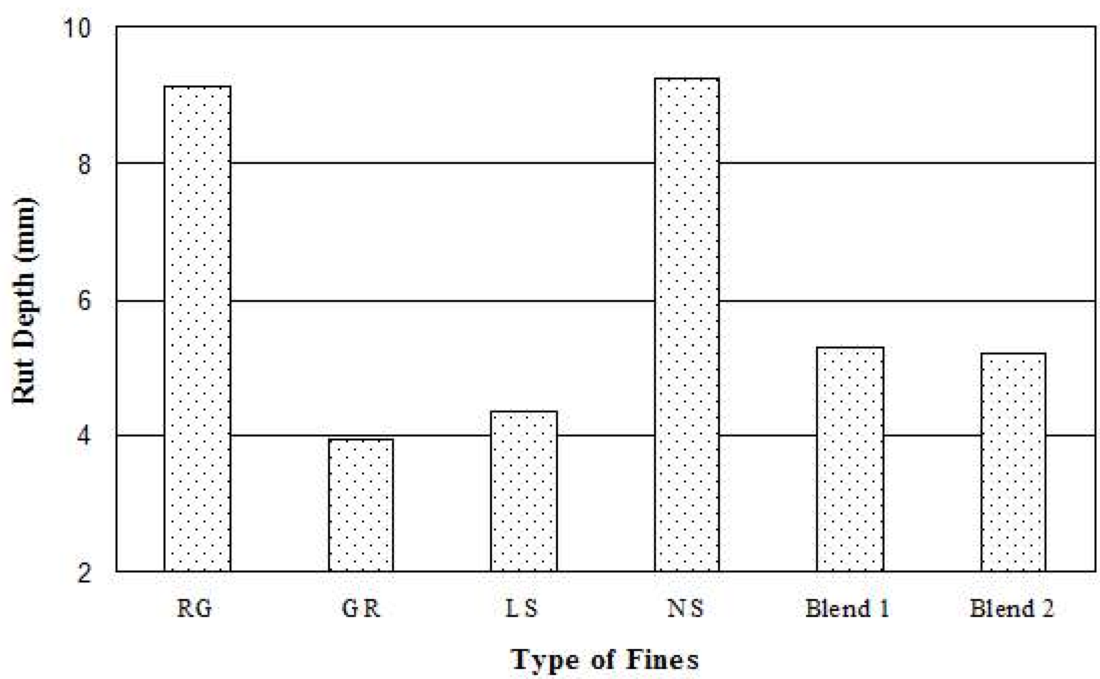

FIGURE 2 APA Rut Depth of Different Mixtures

Statistical Analysis

ANOVA at a 5 percent significance level ($\alpha = 0.05$) was conducted to examine the rut depth data from the APA for the six mixtures. Results are shown in Table 5.

The null hypothesis (H_0) is that the average rut depth of all six mixtures is the same. The alternate hypothesis (H_1) is that at least one of the average rut depth values differs from the rest.

TABLE 5 ANOVA (α = 0.05) for Average Rut Depth

Source	DF	Mean Square	F-Value	p-Value
Between Samples	5	16.678	90.923	4.1 E-09
Within Samples	12	0.183		
Total	17			

At a 5 percent significance level, H_0 can be rejected when the p-value (4.1 E-09) is smaller than the significance level (α = 0.05). The conclusion is that the average rut depths of all six mixtures are not the same at this significance level. Therefore, there is a significant effect of aggregate type on rut depth at a 5 percent significance level.

Based on ANOVA of their average values, mixtures containing fine granite and limestone exhibited the same rut depth statistically . On the same basis, mixtures containing fine river gravel and natural rounded sand showed the same rut depth. Average rut depths for mixtures containing fine granite and limestone were, however, significantly lower than those for mixtures containing fine river gravel and natural rounded sand at a 5 percent significance level. Average rut depths of Blend 1 and Blend 2 are statistically the same.

A linear correlation between FAA and average rut depth at 8000 cycles for each mixture produced a low regression coefficient (R^2 = 0.42), as shown Figure 3. Based on all of the statistical results for the mixtures investigated, FAA did not correlate well with average rut depth, as determined by the APA.

CHAPTER IV

EFFECTS OF AGGREGATE PROPERTIES ON VMA

The restricted zone study of the ICAR project was focused on examining the effect of aggregate gradation (through, above, and below the restricted zone) on rutting resistance in Superpave HMA mixtures (*8, 9*). From that part of the study, volumetric properties and mix design parameters were obtained for further analysis herein in terms of aggregate gradations and VMA. To study the effect of FAA on VMA, the FAA values, mix design parameters, and VMA values from Chapter III were used.

This research aimed to evaluate the effect of aggregate gradations, mineral filler content, and FAA on VMA using data collected from a previous restricted zone study and the FAA study (*8*) conducted as part of this project. The experiment was divided into the following steps:

- Materials Selection. This phase included selection of aggregates and one binder.
- Superpave Volumetric Mix Design. This step utilized the Superpave volumetric mix design process to establish design asphalt binder contents.
- Analysis of the Effect of Aggregate Gradation on VMA. The effects of gradations (through, above, and below the restricted zone) on VMA were investigated using statistical analyses.
- Analysis of the Effect of Mineral Filler Content on VMA. The effect of mineral filler content on VMA was evaluated.
- Analysis of the Effect of FAA on VMA. The effect of FAA on VMA was evaluated.

MATERIALS SELECTION

This study focused on mixtures containing crushed river gravel because these mixtures were assumed to be most sensitive to permanent deformation since they contained relatively rounded particles with smooth surface textures. Although the river gravel material had been crushed, it retained some rounded faces and smooth surface textures, and some of the smaller particles remained uncrushed. Granite and limestone were selected because they possess widely different characteristics and are commonly used in asphalt pavements. Fine natural sand and crushed river gravel were selected to represent lower quality materials for HMA.

Four different aggregates including partially crushed river gravel, crushed granite, crushed limestone, and uncrushed rounded natural sand were used. Origins of these materials are provided in Chapter III.

Binder selection was completed according to the Superpave binder specification (AASHTO MP1). In this specification, binders are selected on the basis of the climate and traffic conditions under which they are intended to serve. The geographic location selected for this study was Lubbock, Texas, and the selected traffic level was between 3 and 10 million ESALs for limestone and river gravel aggregates and between 1 and 3 million ESALs for granite. The traffic level for granite was different because its gradation curve passing through the restricted zone is a gradation curve commonly used in Georgia (provided by the Georgia DOT), and researchers could not achieve a Superpave volumetric mix design with a suitable VMA for 3 to10 million ESALs for this gradation. These traffic levels were selected because they correspond to an intermediate level of analysis in Superpave, and this is anticipated to be the predominant Superpave analysis used in typical highway applications (*3*). The PG grade that corresponded to this geographic location and the specified traffic levels (obtained from the LTPP BIND program using a 98 percent reliability level) was PG 64-22 (*34*). It was assumed that the projected pavements will be subjected to fast-moving loads, so no adjustment for the binder grade was required.

SUPERPAVE VOLUMETRIC MIXTURE DESIGN

The Superpave volumetric mixture design process used in this study is well documented in the literature (*3, 15*).

For the selected traffic levels, N_{ini}, N_{des}, and N_{max} are indicated in Table 6. Superpave volumetric criteria for the material used is shown in Table 7. The design asphalt binder content was established at 4.0 percent air voids, and the other mixture properties were checked (Table 8). A summary of the mix design data is presented in Appendix B.

TABLE 6 Superpave Gyratory Compaction Effort

Materials	N_{ini}	N_{des}	N_{max}
Partially River Gravel	8	96	152
Crushed Granite	7	86	134
Crushed Limestone	8	96	152
Rounded Natural Sand	8	96	152

TABLE 7 Superpave Volumetric Criteria for the Materials Used

Mix Property	River Gravel, Limestone, Rounded Natural Sand	Granite
% Air Voids at N_{design}	4.0	4.0
% VMA at N_{design}	13.0 min.	13.0 min.
% VFA at N_{design}	65 - 75	65-78
Dust Proportion	0.6 - 1.2	0.6 - 1.2
% G_{mm} at $N_{initial}$	≥ 89	≥ 89
% G_{mm} at $N_{maximum}$	≥ 98	≥ 98

ANALYSIS OF THE EFFECT OF AGGREGATE GRADATION ON VMA

To investigate the effect of aggregate gradation, particularly the restricted zone, on VMA, 12 mixtures (four aggregate types and three gradations above the restricted zone [ARZ], through the restricted zone [TRZ], and below the restricted zone [BRZ]) were used. Table 8 shows optimum asphalt content, voids of mineral aggregate, and voids filled with asphalt (VFA) based on 4 percent air voids for each aggregate type and each gradation combination.

For river gravel, limestone, and rounded natural sand, HMA mixtures with the gradation passing above the restricted zone required the lowest asphalt content, and mixtures with the gradation passing below the restricted zone had the highest optimum asphalt content. For granite, mixtures with all three gradations required almost the same asphalt content. As expected, natural rounded sand with coarse crushed river gravel yielded the lowest optimum asphalt content.

TABLE 8 Superpave Mixture Design Properties

Aggregate Type	Gradation	Optimum Asphalt Content (%)	VMA (%)	VFA (%)
Partially Crushed River Gravel	TRZ	5.3	14.7	73.0
	ARZ	5.0	14.0	69.3
	BRZ	5.6	15.1	74.2
Crushed Granite	TRZ	4.3	13.0	69.4
	ARZ	4.3	13.2	70.2
	BRZ	4.3	13.0	69.8
Crushed Limestone	TRZ	4.5	13.1	69.1
	ARZ	4.0	13.0	66.9
	BRZ	4.8	13.8	71.0
Rounded Natural Sand	TRZ	3.8	9.9	59.6
	ARZ	3.5	9.6	58.3
	BRZ	4.3	10.7	62.6

The limestone mixtures with gradations passing through the restricted zone and above the restricted zone and all granite mixtures barely met the minimum Superpave VMA requirements. The rounded natural sand mixtures with all three gradations did not meet the minimum requirements. Mixtures with all three gradations of river gravel, granite, and limestone met the Superpave VFA requirements. Only the mixtures containing rounded natural sand did not meet these requirements.

Statistical Analysis

Analysis of variance (ANOVA) was used to evaluate the effect of aggregate gradation on VMA. Table 9 shows the mean and standard deviation of VMA values for mixtures containing the four aggregates with different gradations passing TRZ, ARZ, and BRZ. ANOVA results at a 5 percent significance level is shown in Table 10.

TABLE 9 VMA Value for Mixtures with Different Gradations

Gradation	Mean VMA Value (%)	Standard Deviation (%)
TRZ	12.65	2.031
ARZ	12.23	1.895
BRZ	13.20	1.846

The null hypothesis (H_0) is that the average VMA value of all three mixtures with different gradations is equivalent. The alternate hypothesis (H_1) is that at least one of the average VMA values differs from the rest.

H_0 cannot be rejected when the p-value is greater than the significance level ($\alpha = 0.05$). The average VMA values of all three mixtures with different gradations is the same. Therefore, there is no significant effect of aggregate gradation at a 5 percent significance level.

TABLE 10 ANOVA ($\alpha = 0.05$) for VMA of Mixtures with Different Gradations

Source	DF	Mean Square	F-Value	p-Value
Between Samples	2	0.956	0.258	0.778
Within Samples	9	3.706		
Total	11			

The effect of aggregate type was also investigated using ANOVA. Table 11 shows the mean and standard deviation of VMA values from different aggregate types.

TABLE 11 VMA of Mixtures with Different Aggregate Types

Aggregate	Mean VMA Value (%)	Standard Deviation (%)
River gravel	14.57	0.681
Granite	13.20	0.200
Limestone	12.93	0.850
Natural rounded sand	10.07	0.569

The mixtures containing river gravel generally showed the highest VMA values when compared to mixtures with crushed granite or limestone. As expected, mixtures containing uncrushed rounded natural sand exhibited the lowest VMA. ANOVA results at a 5 percent significance level are shown in Table 12.

TABLE 12 ANOVA ($\alpha = 0.05$) for VMA of Aggregate Types

Source	DF	Mean Square	F-Value	p-Value
Between Samples	3	10.723	27.672	0.0001
Within Sample	8	0.387		
Total	11			

The null hypothesis (H_0) is that the average VMA value of all mixtures with the four aggregates is the same. The alternate hypothesis (H_1) is that at least one of the average VMA values differs from the rest.

H_0 can be rejected when the p-value is smaller than the significance level ($\alpha = 0.05$). The conclusion is that the average VMA value of all mixtures is not the same. Therefore, there is a significant effect of aggregate type at 5 percent significance level.

ANOVA was also used to examine the effect of crushed aggregate (river gravel, granite, and limestone) on VMA values. For this ANOVA, the p-value (0.042) was smaller than the significance level ($\alpha = 0.05$). Therefore, there is a significant effect of crushed aggregate type on VMA.

ANALYSIS OF THE EFFECT OF MINERAL FILLER ON VMA

To investigate the effects of mineral filler content on VMA, a mixture of granite with a gradation passing through the restricted zone was changed only in the percent passing the 75-µm sieve.

In the Superpave specification for a 19-mm nominal maximum aggregate gradation, control points are placed on the nominal maximum sieve, an intermediate sieve (2.36-mm), and the smallest sieve (75-µm). Superpave specifies that the gradation must be 2 percent to 8 percent passing the 75-µm sieve. A summary of the design data for the mixtures is shown in Table 13, and the gradations used in this study are presented in Tables B5 through B16 in Appendix B.

In the Superpave volumetric mixture design process using granite aggregate, mineral filler contents of 2, 5, and 7 percent were used. Asphalt content (4.1 percent) was unchanged, and the gradation was through the restricted zone. For the compaction effort, N_{ini}, N_{des}, and N_{max} were 8, 96, and 152, respectively. The volumetric analysis was conducted on specimens compacted using 152 gyrations (N_{max}).

Figure 4 shows that, at constant binder content, as the filler content increases, the VMA of the mixture decreases. The mineral filler is increasing the bulk viscosity of the mastic. Only the mixture with 2 percent mineral filler content meets the Superpave VMA criteria for a 19-mm nominal maximum size mixture. Superpave recommends a filler to asphalt ratio of 0.6 to 1.2. Although mixtures with 2 percent filler meet the Superpave gradation requirements, those containing aggregate with low angularity and/or smooth surface textures may exhibit low shear strength and thus be subject to permanent deformation. In addition, achieving a filler content as low as 2 percent is difficult for some aggregate sources, and washing of aggregate fines to

TABLE 13 Properties of Mixtures with Different Mineral Filler Contents

Mixture Property	Mineral Filler Content (%)			Criteria
	2	5	7	
% Air Voids at N_{design}	4.5	4.7	3.7	4
% VMA at N_{design}	13.1	12.9	12.4	13.0 min.
% VFA at N_{design}	65.3	63.9	69.8	65-78
Dust Proportion	0.5	1.2	1.7	0.6 - 1.2
% G_{mm} at $N_{initial}$	88.1	87.4	87.7	less than 89
% G_{mm} at $N_{maximum}$	96.5	96.3	97.3	less than 98

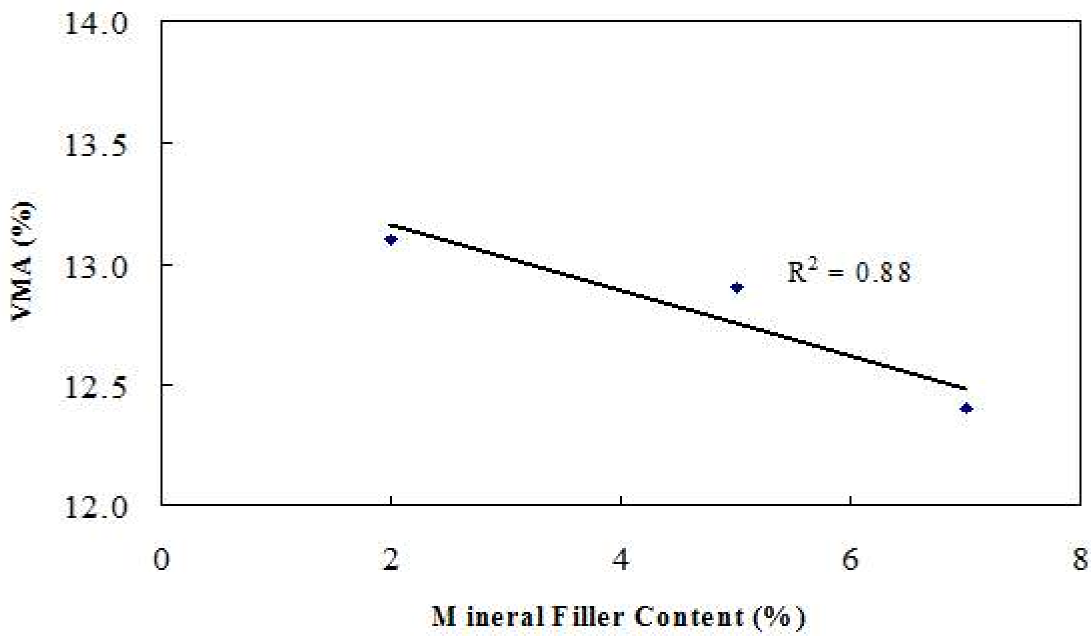

FIGURE 4 VMA versus Mineral Filler Content

remove filler is expensive and has negative impacts on the environment. The mixture with 7 percent filler exceeds the Superpave filler to asphalt ratio criteria.

ANALYSIS OF THE EFFECT OF FAA ON VMA

Details of the Superpave volumetric mixture design process, including measurement of FAA, was presented in Chapter III. Table 14 shows FAA values and Superpave mixture design properties of optimum asphalt content, VMA, and VFA based on 4 percent air voids.

TABLE 14 Properties of Mixtures with Different Fine Aggregates

Materials		FAA Value	Design A/C (%)	VMA (%)	VFA (%)	Criteria
Coarse	Fine					
Lime-stone	River Gravel	44.3	5.6	14.7	79.1	FAA: 45.0 (min) VMA:13.0 (min) VFA: 65-75
	Granite	48.0	5.2	14.8	74.8	
	Limestone	43.5	4.8	13.8	71.0	
	Natural Rounded Sand	39.0	3.8	11.4	61.7	
	Blend 1	46.0	5.6	14.8	74.3	
	Blend 2	42.0	4.2	11.9	66.4	

The Superpave specification gives 45 percent as the required minimum value for FAA at a traffic level of 3 million to 10 million ESALS. Only mixtures containing granite met the minimum requirement with an FAA value of 48 percent. FAA values of mixtures containing river gravel and limestone were slightly below the minimum requirement. As expected, mixtures with natural rounded sand yielded a FAA value lower than the required minimum. Figure 5 shows how VMA values varied with asphalt content during the Superpave volumetric mixture design process. For mixtures containing river gravel, granite, and limestone, the VMA values indicated that, regardless of the range of asphalt content, no difficulty was encountered in meeting the minimum Superpave VMA requirements. For natural rounded sand, the VMA value at any of the asphalt contents did not meet the requirement. At 4 percent air voids, mixtures containing river gravel required the highest asphalt content, and the mixture containing natural rounded sand required the lowest asphalt content.

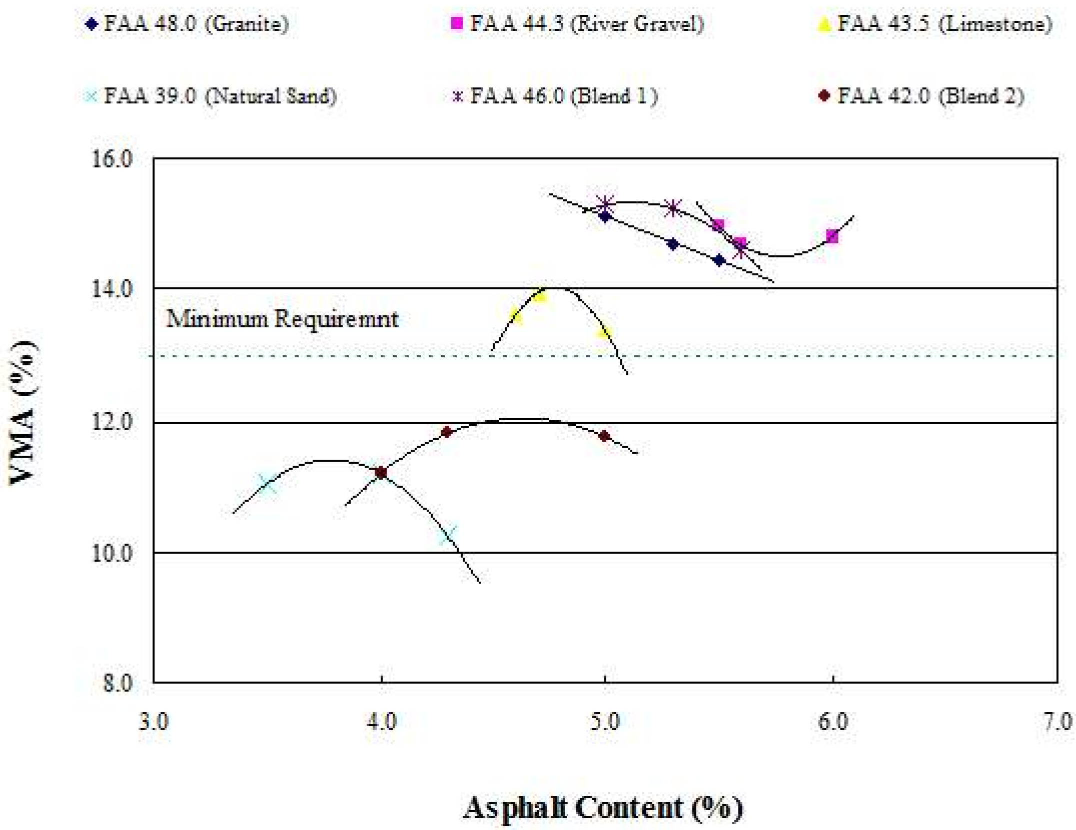

FIGURE 5 VMA during Superpave Volumetric Mixture Design

Figure 6 shows the relationship between FAA and VMA based on 4 percent air voids. The correlation between FAA and VMA statistically appeared fairly good ($R^2 = 0.70$). The granite mixture with a FAA of 48.0 percent yielded the highest VMA values, but, compared to mixtures containing river gravel (FAA = 44.3), limestone (FAA = 43.5), and Blend 1 (FAA = 46.0), VMA values were not significantly different based on ANOVA at a 5 percent significance level. HMA mixtures containing fines composed of 100 percent rounded natural sand and Blend 2 composed of 30 percent rounded natural sand both yielded very low VMA.

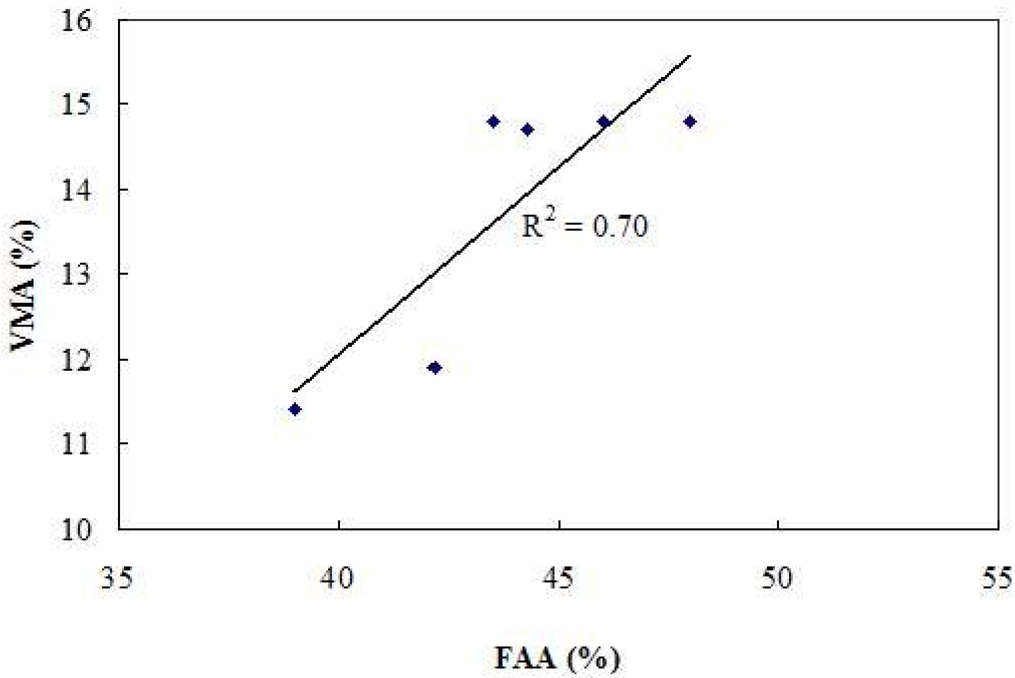

FIGURE 6 VMA versus FAA at 4 Percent Air Void

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This study examined the effects of fine aggregate angularity on permanent deformation and the effects of aggregate properties on voids in the mineral aggregate of HMA mixtures.

Laboratory tests using the Asphalt Pavement Analyzer were conducted to measure the permanent deformation of HMA mixtures composed of coarse limestone plus one of six different fine aggregates, which have widely differing FAA values. The fine aggregates selected for this study were crushed river gravel, crushed granite, crushed limestone, natural rounded sand, Blend 1, and Blend 2 with FAA values of 44.3, 48.0, 43.5, 39.0, 46.0, and 42.0, respectively.

To determine the influence of the factors that affect VMA, HMA mixtures with different gradations, mineral filler contents, and FAA values were examined. HMA mixtures containing crushed river gravel, crushed granite, crushed limestone, and natural rounded sand with three different gradations that pass through, above, and below the restricted zone were evaluated. Based on the findings, the following conclusions and recommendations are rendered.

Effects of FAA on Permanent Deformation

- Aggregate type plays an important role in permanent deformation. Mixtures containing granite fines with a FAA of 48.0 exhibited the lowest rut depth. Mixtures containing limestone fines with a FAA of 43.5 value had the second lowest rut depth. Rut depths of mixtures containing granite and limestone fines were not significantly different. Mixtures prepared using crushed river gravel fines with a FAA value of 44.3 and uncrushed natural rounded sand with a FAA of 39.0 showed more susceptibility to permanent deformation than those prepared with quarried granite or limestone fines. Blend 1 and Blend 2 yielded similar rut depths, even though their FAA values were significantly different.

- Although the trend was in the anticipated direction, rut depths measured using the APA did not correlate well with the FAA of the fine aggregates ($R^2 = 0.42$).

Effects of Aggregate Properties on VMA

- Mixtures containing crushed aggregates showed much higher VMA than mixtures containing uncrushed rounded natural sand.
- Mixtures containing river gravel, limestone, and rounded natural sand fines that pass below the restricted zone showed VMA values numerically higher than those passing above or through the restricted zone. However, for the four types of aggregate with gradations passing through, above, and below the restricted zone, HMA mixtures showed no significant differences in VMA based on a statistical analysis (ANOVA).
- Although some mixtures barely met the VMA specification or some barely failed the specification, their rutting performance was acceptable.
- Adding 30 percent (percentage of fine part) rounded natural sand reduced the VMA drastically.
- As mineral filler contents increase within the range required by Superpave, VMA decreases markedly.
- Higher FAA values typically yield higher VMA values in HMA.
- Correlations between FAA and VMA for the mixtures tested were good ($R^2 = 0.70$).

RECOMMENDATIONS

- Develop and conduct a laboratory program to evaluate the effects of VMA on performance of HMA, particularly with regard to permanent deformation, tenderness, permeability, and economy.

- The findings of the experimental work showed that higher FAA values did not necessarily improve rutting resistance as measured by one type of laboratory scale accelerated testing device (APA). Future research should focus on other accelerated tests to evaluate rutting resistance of mixtures with different fine aggregates and other measures of aggregate angularity.
- In the FAA study, only six HMA mixtures containing six different fine aggregates were used to examine permanent deformation. HMA mixtures composed of other fine aggregates with different angularity need to be tested to expand this study and further evaluate the effects of FAA on rutting resistance.
- More gradations and materials should be tested to investigate the effects of aggregate gradation on VMA.
- Research should be performed with the goal of developing an improved specification for VMA of HMA paving mixtures on the basis of current laboratory and field findings.

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APPENDIX A

MIXTURE PROPERTIES AND TEST RESULTS OF FAA STUDY

TABLE A1 Gradation of FAA Study (For All Six Mixtures)

Sieve Size (mm)	Total Percent Passing
25	100
19	96
12.5	86
9.5	77
4.75	55
2.36	32
1.18	20
0.6	14
0.3	9
0.15	5
0.075	3

TABLE A2 Properties of Mixture Containing River Gravel Fines

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=96)}$	4.0	4
% VMA at $N_{design\ (=96)}$	14.7	13.0 min.
% VFA at $N_{design\ (=96)}$	72.6	65-75
Dust Proportion	0.6	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	87.2	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	97.2	less than 98
Optimum Asphalt Content	5.6	N/A

TABLE A3 Properties of Mixture Containing Granite Fines

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=\ 96)}$	4.0	4
% VMA at $N_{design\ (=\ 96)}$	14.8	13.0 min.
% VFA at $N_{design\ (=96)}$	74.8	65-75
Dust Proportion	0.6	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	87.7	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	95.6	less than 98
Optimum Asphalt Content	5.2	N/A

TABLE A4 Properties of Mixture Containing Limestone Fines

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=\ 96)}$	4.0	4
% VMA at $N_{design\ (=\ 96)}$	14.8	13.0 min.
% VFA at $N_{design\ (=96)}$	74.8	65-75
Dust Proportion	0.8	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	85.4	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	97.4	less than 98
Optimum Asphalt Content	4.8	N/A

TABLE A5 Properties of Mixture Containing Rounded Natural Sand Fines

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=96)}$	4.0	4
% VMA at $N_{design\ (=96)}$	11.4	13.0 min.
% VFA at $N_{design\ (=96)}$	61.7	65-75
Dust Proportion	0.8	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	89.0	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	96.3	less than 98
Optimum Asphalt Content	3.8	N/A

TABLE A6 Air Voids of Specimens Containing River Gravel Fines (Maximum Density: 2.457 gm/cc)

Tray No.	Sample No.	Bulk Sp. Gravity	% Air Voids
1	1	2.358	4.0
	2	2.349	4.4
	Average		**4.2**
2	1	2.336	4.9
	2	2.357	4.1
	Average		**4.5**
3	1	2.337	4.9
	2	2.352	4.3
	Average		**4.6**

TABLE A7 Air Voids of Specimens Containing Granite Fines (Maximum Density: 2.500 gm/cc)

Tray No.	Sample No.	Bulk Sp. Gravity	% Air Voids
1	1	2.381	4.8
	2	2.395	4.2
	Average		**4.5**
2	1	2.394	4.2
	2	2.396	4.2
	Average		**4.2**
3	1	2.392	4.3
	2	2.397	4.1
	Average		**4.2**

TABLE A8 Air Voids of Specimens Containing Limestone Fines (Maximum Density: 2.457 gm/cc)

Tray No.	Sample No.	Bulk Sp. Gravity	% Air Voids
1	1	2.431	4.6
	2	2.436	4.4
	Average		**4.5**
2	1	2.436	4.4
	2	2.431	4.6
	Average		**4.5**
3	1	2.429	4.6
	2	2.434	4.4
	Average		**4.5**

TABLE A9 Air Voids of Specimens Containing Rounded Natural Sand Fines (Maximum Density : 2.519 gm/cc)

Tray No.	Sample No.	Bulk Sp. Gravity	% Air Voids
1	1	2.398	4.8
	2	2.406	4.5
	Average		**4.7**
2	1	2.407	4.4
	2	2.402	4.6
	Average		**4.5**
3	1	2.408	4.4
	2	2.406	4.5
	Average		**4.5**

TABLE A10 Rut Depths of Mixture Containing River Gravel Fines

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
0	0	0	0	0
200	1.4226	2.0065	2.2444	1.8912
400	2.2863	3.1004	3.3487	2.9118
600	3.1002	3.6503	3.8530	3.5345
800	3.7481	4.0693	4.2485	4.0220
1000	4.1321	4.4346	4.5535	4.3734
1200	4.5215	4.6771	4.8399	4.6795
1400	4.9130	5.0313	5.0941	5.0128
1600	5.1429	5.2087	5.3246	5.2254
1800	5.4059	5.5103	5.5263	5.4808
2000	5.7235	5.6870	5.7223	5.7109
2200	5.9319	5.9482	5.9006	5.9269
2400	5.9799	6.0606	6.0466	6.0290
2600	6.2355	6.3111	6.1680	6.2382
2800	6.4178	6.4148	6.2781	6.3716
3000	6.5688	6.6619	6.3770	6.5359
3200	6.7921	6.7428	6.4935	6.6761
3400	6.9503	6.9877	6.5964	6.8448
3600	7.1631	7.0608	6.7117	6.9785
3800	7.3119	7.2794	6.8097	7.1337
4000	7.4629	7.3322	6.9106	7.2352
4200	7.5891	7.4828	7.0003	7.3574
4400	7.7090	7.5726	7.0894	7.4570
4600	7.8270	7.6431	7.1847	7.5516
4800	7.9337	7.7855	7.2590	7.6594
5000	8.0456	7.8456	7.3346	7.7419
5200	8.1189	7.9119	7.4265	7.8191
5400	8.2509	8.0439	7.5165	7.9371
5600	8.4441	8.1546	7.6245	8.0744
5800	8.5491	8.1942	7.7069	8.1501
6000	8.6111	8.2779	7.7751	8.2214

TABLE A10 Rut Depths of Mixture Containing River Gravel Fines (continued).

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
6200	8.7267	8.4066	7.8579	8.3304
6400	8.8664	8.4595	7.9433	8.4231
6600	9.0194	8.5174	8.0156	8.5175
6800	9.1401	8.5986	8.0844	8.6077
7000	9.2269	8.6837	8.1432	8.6846
7200	9.3057	8.7630	8.1980	8.7556
7400	9.4580	8.8213	8.2754	8.8516
7600	9.5636	8.8651	8.3222	8.9170
7800	9.7450	8.9812	8.3830	9.0364
8000	9.8350	9.0699	8.4286	9.1112

TABLE A11 Rut Depths of Mixture Containing Granite Fines

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
0	0	0	0	0
200	0.5531	0.5684	0.6047	0.5754
400	0.7969	0.7916	0.7903	0.7929
600	1.0598	1.0455	0.9362	1.0138
800	1.3062	1.2356	1.0446	1.1955
1000	1.4810	1.3999	1.1459	1.3423
1200	1.6785	1.5840	1.2447	1.5024
1400	1.9343	1.7097	1.3824	1.6755
1600	2.1375	1.8590	1.4913	1.8293
1800	2.3029	1.9859	1.5527	1.9472
2000	2.4023	2.0612	1.6560	2.0398
2200	2.5617	2.2302	1.7912	2.1944
2400	2.6872	2.3016	1.9075	2.2988
2600	2.7952	2.4100	2.0127	2.4060
2800	2.9132	2.5290	2.1550	2.5324
3000	3.0274	2.5543	2.3010	2.6276
3200	3.1323	2.7249	2.3975	2.7516
3400	3.1954	2.7110	2.4858	2.7974
3600	3.2734	2.8290	2.6368	2.9131
3800	3.3630	2.8134	2.7584	2.9783
4000	3.3777	2.9283	2.8171	3.0410
4200	3.4582	2.9324	2.9510	3.1139
4400	3.4849	3.0637	3.0820	3.2102
4600	3.5581	3.0753	3.1413	3.2582
4800	3.6413	3.1609	3.1779	3.3267
5000	3.7101	3.132	3.2949	3.3790
5200	3.7800	3.2343	3.3821	3.4655
5400	3.8162	3.2036	3.4095	3.4764
5600	3.7794	3.2811	3.5022	3.5209
5800	3.7435	3.2076	3.6320	3.5277
6000	3.7303	3.3300	3.6777	3.5793

TABLE A11 Rut Depths of Mixture Containing Granite Fines (continued).

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
6200	3.8499	3.2734	3.7000	3.6078
6400	3.9442	3.3223	3.7999	3.6888
6600	3.9705	3.3616	3.8587	3.7303
6800	3.9357	3.3514	3.8743	3.7205
7000	3.9695	3.4871	3.9431	3.7999
7200	4.0520	3.4270	4.0388	3.8393
7400	4.1603	3.5257	4.0496	3.9119
7600	4.0968	3.5291	4.0856	3.9038
7800	4.0491	3.5158	4.1807	3.9152
8000	4.0885	3.5787	4.197	3.9547

TABLE A12 Rut Depths of Mixture Containing Limestone Fines

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
0	0	0	0	0
200	0.5830	0.6043	0.7306	0.6393
400	0.8148	0.7652	0.8712	0.8171
600	1.0080	0.8960	0.9470	0.9503
800	1.1740	0.9837	1.0413	1.0663
1000	1.3205	1.0696	1.1450	1.1784
1200	1.4343	1.1628	1.2416	1.2796
1400	1.6208	1.2378	1.3375	1.3987
1600	1.7796	1.3367	1.3731	1.4965
1800	2.1079	1.4047	1.4481	1.6536
2000	2.3286	1.5032	1.5063	1.7794
2200	2.5387	1.6227	1.6125	1.9246
2400	2.6949	1.6910	1.7174	2.0344
2600	2.8118	1.8621	1.8116	2.1618
2800	2.9029	1.9708	1.8972	2.2570
3000	3.0265	2.1492	2.0292	2.4016
3200	3.0706	2.2038	2.2053	2.4932
3400	3.1700	2.3357	2.4094	2.6384
3600	3.2491	2.4303	2.5866	2.7553
3800	3.2819	2.4812	2.7900	2.8510
4000	3.3168	2.5901	2.9802	2.9624
4200	3.4345	2.6764	3.1434	3.0848
4400	3.5120	2.7538	3.2947	3.1868
4600	3.5673	2.8788	3.4346	3.2936
4800	3.5889	2.9451	3.5366	3.3569
5000	3.6675	3.0893	3.6290	3.4619
5200	3.7984	3.1768	3.7100	3.5617
5400	3.8806	3.3095	3.7709	3.6537
5600	4.0196	3.3808	3.8234	3.7413
5800	4.1668	3.5219	3.8669	3.8519
6000	4.3017	3.4775	3.8973	3.8922

TABLE A12 Rut Depths of Mixture Containing Limestone Fines (continued).

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
6200	4.3781	3.5281	3.9418	3.9493
6400	4.4405	3.6540	3.9964	4.0303
6600	4.4579	3.7095	4.0548	4.0741
6800	4.4813	3.7432	4.1124	4.1123
7000	4.5055	3.7958	4.1598	4.1537
7200	4.5204	3.8627	4.2032	4.1954
7400	4.5623	3.9499	4.2454	4.2525
7600	4.6162	4.0301	4.2778	4.3080
7800	4.6485	4.0547	4.3076	4.3369
8000	4.6766	4.0876	4.3279	4.3640

TABLE A13 Rut Depths of Mixture Containing Rounded Natural Sand Fines

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
0	0	0	0	0
200	1.4171	1.6894	1.5184	1.1563
400	2.6526	2.6905	2.7962	2.7131
600	3.6877	3.2930	3.7184	3.5664
800	4.3922	3.7588	4.4103	4.1871
1000	5.1395	4.1686	4.8093	4.7058
1200	5.5855	4.4740	5.0940	5.0512
1400	5.7621	4.7835	5.3362	5.2939
1600	5.9323	5.0871	5.5297	5.5164
1800	6.1778	5.3103	5.6942	5.7274
2000	6.2698	5.5005	5.8284	5.8662
2200	6.2841	5.6664	5.9385	5.9630
2400	6.4455	5.8511	6.0357	6.1108
2600	6.5825	6.0820	6.1175	6.2607
2800	6.6833	6.2583	6.1846	6.3754
3000	6.7928	6.4204	6.2841	6.4991
3200	6.9383	6.5554	6.4100	6.6346
3400	7.0734	6.6982	6.5245	6.7654
3600	7.1336	6.8687	6.6233	6.8752
3800	7.2429	7.0177	6.7775	7.0127
4000	7.3974	7.1927	6.8909	7.1603
4200	7.5672	7.3554	6.9825	7.3017
4400	7.6416	7.4963	7.0791	7.4057
4600	7.7241	7.6010	7.2031	7.5094
4800	7.8796	7.6989	7.3529	7.6438
5000	8.0042	7.8276	7.4861	7.7666
5200	8.0754	7.9044	7.5539	7.8446
5400	8.2176	8.0310	7.6622	7.9703
5600	8.3287	8.1632	7.7939	8.0953
5800	8.4359	8.3018	7.8836	8.2071
6000	8.4862	8.3966	7.9376	8.2735

TABLE A13 Rut Depths of Mixture Containing Rounded Natural Sand Fines (continued).

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
6200	8.6228	8.5165	8.0191	8.3861
6400	8.7272	8.6484	8.1312	8.5023
6600	8.8069	8.7687	8.2049	8.5935
6800	8.9263	8.8728	8.2667	8.6886
7000	9.0481	8.9739	8.3676	8.7965
7200	9.1012	9.0616	8.4546	8.8725
7400	9.1998	9.1448	8.5188	8.9545
7600	9.3020	9.2643	8.5770	9.0478
7800	9.3841	9.3391	8.6801	9.1344
8000	9.4761	9.4201	8.7675	9.2212

TABLE A14 Rut Depths of Mixture Containing Blend 1 Fines (85% GR + 15% NS)

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
0	0	0	0	0
200	0.7845	0.8855	1.1095	0.9265
400	1.2027	1.2980	1.6555	1.3854
600	1.6191	1.7091	2.1258	1.8180
800	2.0907	2.1425	2.5412	2.2581
1000	2.5826	2.5212	2.8588	2.6542
1200	3.2035	2.8667	3.0891	3.0531
1400	3.6926	3.1326	3.2677	3.3643
1600	3.8724	3.3211	3.3820	3.5252
1800	3.9762	3.4698	3.5051	3.6504
2000	3.9995	3.6044	3.6217	3.7419
2200	4.1015	3.7303	3.7178	3.8499
2400	4.2557	3.8404	3.8062	3.9674
2600	4.3173	3.9463	3.8806	4.0481
2800	4.3309	4.0238	3.9534	4.1027
3000	4.3440	4.0885	4.0047	4.1457
3200	4.4418	4.1622	4.0731	4.2257
3400	4.5543	4.2186	4.1408	4.3046
3600	4.6215	4.2854	4.2102	4.3724
3800	4.6840	4.3509	4.2554	4.4301
4000	4.6995	4.4108	4.2946	4.4683
4200	4.7332	4.4513	4.3479	4.5108
4400	4.8307	4.5040	4.4185	4.5844
4600	4.9008	4.5684	4.4791	4.6494
4800	4.9083	4.6154	4.5247	4.6828
5000	4.9296	4.6718	4.5805	4.7273
5200	5.0378	4.7274	4.6226	4.7959
5400	5.0617	4.7494	4.6522	4.8211
5600	5.0638	4.7859	4.6950	4.8482
5800	5.1194	4.8351	4.7385	4.8976
6000	5.2139	4.8797	4.7786	4.9574

TABLE A14 Rut Depths of Mixture Containing Blend 1 Fines (85% GR + 15% NS) (continued)

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
6200	5.2226	4.9171	4.8091	4.9832
6400	5.2251	4.9523	4.8279	5.0018
6600	5.3110	4.9818	4.8574	5.0501
6800	5.3681	5.0115	4.9071	5.0956
7000	5.3854	5.0459	4.9551	5.1288
7200	5.3979	5.0826	4.9906	5.1570
7400	5.5267	5.1248	5.0182	5.2232
7600	5.5338	5.1399	5.0414	5.2384
7800	5.331	5.1581	5.0736	5.2549
8000	5.5951	5.1937	5.1030	5.2973

TABLE A15 Rut Depths of Mixture Containing Blend 2 Fines (70% LS + 30% NS)

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
0	0	0	0	0
200	1.0299	0.9526	1.1100	1.0308
400	1.4101	1.3093	1.4651	1.3948
600	1.6068	1.4975	1.7670	1.6238
800	1.7546	1.7101	2.0670	1.8439
1000	1.9066	1.9747	2.3639	2.0817
1200	1.9817	2.1905	2.6251	2.2658
1400	2.0790	2.4062	2.9076	2.4643
1600	2.2504	2.6913	3.1944	2.7120
1800	2.3688	2.8719	3.4829	2.9079
2000	2.4528	3.1879	3.7316	3.1241
2200	2.5362	3.3631	3.9009	3.2667
2400	2.7386	3.6307	4.0352	3.4682
2600	2.9129	3.7258	4.1518	3.5968
2800	2.9999	3.8364	4.2518	3.6960
3000	3.0407	3.9850	4.3611	3.7956
3200	3.1373	4.0034	4.4638	3.8682
3400	3.2653	4.1816	4.5393	3.9954
3600	3.4213	4.1853	4.5817	4.0628
3800	3.5199	4.3048	4.6402	4.1550
4000	3.5813	4.3165	4.7154	4.2044
4200	3.6770	4.3896	4.7828	4.2831
4400	3.7849	4.4385	4.8479	4.3571
4600	3.8827	4.4692	4.9006	4.4175
4800	3.9664	4.5840	4.9404	4.4969
5000	4.0410	4.5734	4.9892	4.5345
5200	4.1025	4.6897	5.0453	4.6125
5400	4.1628	4.6541	5.1191	4.6453
5600	4.2420	4.7820	5.1835	4.7358
5800	4.3164	4.7435	5.2281	4.7627
6000	4.3739	4.9089	5.2587	4.8472

TABLE A15 Rut Depths of Mixture Containing Blend 2 Fines (70% LS + 30% NS) (continued)

Cycle No.	Tray 1 (mm)	Tray 2 (mm)	Tray 3 (mm)	Average (mm)
6200	4.4178	4.8609	5.2898	4.8562
6400	4.4566	4.9763	5.3242	4.9190
6600	4.4872	4.9639	5.3754	4.9422
6800	4.5353	5.0226	5.4334	4.9971
7000	4.5934	5.0849	5.4874	5.0552
7200	4.6567	5.0828	5.5191	5.0862
7400	4.6958	5.1996	5.5381	5.1445
7600	4.7261	5.1434	5.5516	5.1404
7800	4.7534	5.2194	5.5873	5.1867
8000	4.7879	5.2078	5.6461	5.2139

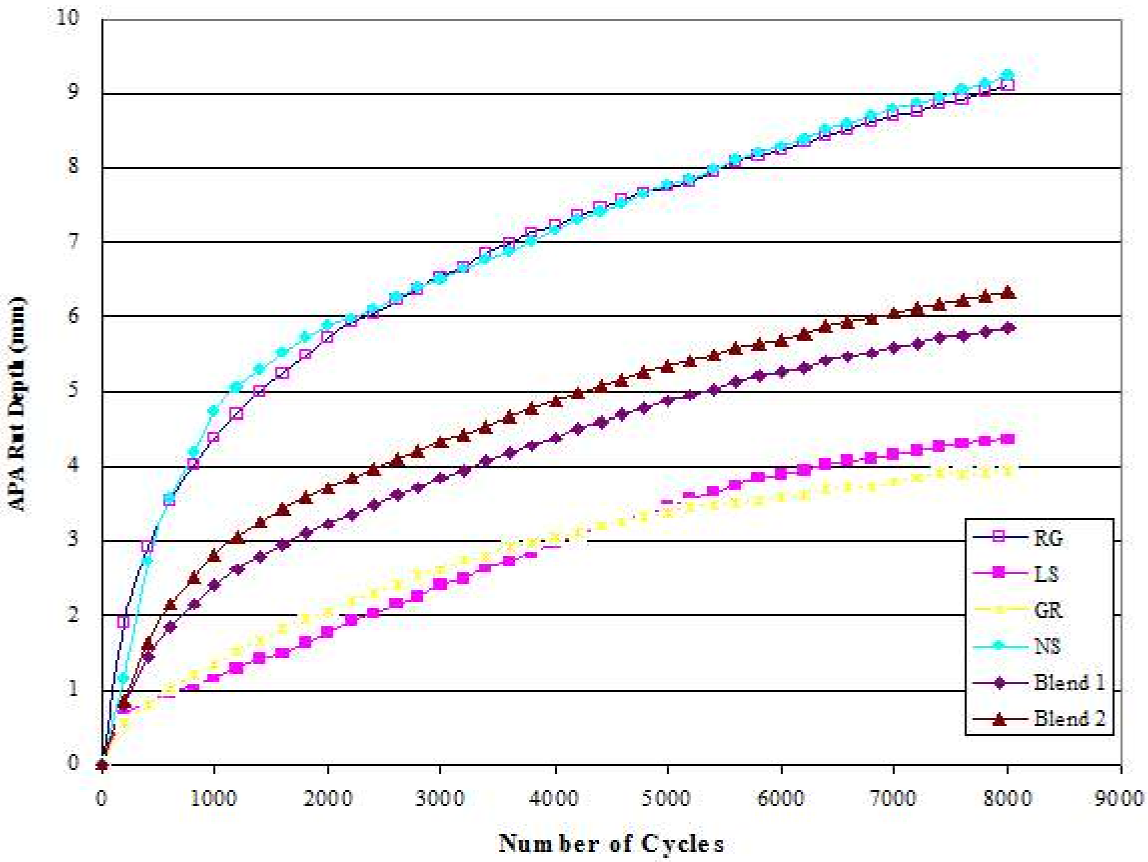

FIGURE A1 APA Rut Depth of Different Mixtures

APPENDIX B

PROPERTIES OF MIXTURES USED IN RESTRICTED ZONE AND VMA STUDIES

TABLE B1 River Gravel Gradations

Sieve Size (mm)	Control Points		Restricted Zone		TRZ	ARZ	BRZ
	Upper	Lower	Upper	Lower	% Total Passing	% Total Passing	% Total Passing
25					100	100	100
19	100	90			96	96	96
12.5		90			86	86	86
9.5					77	77	77
4.75					55	55	55
2.36	49	23	34.6	34.6	38	38	32
1.18			28.3	22.3	25	30	20
0.6			20.7	16.7	16	22	14
0.3			13.7	13.7	10	14	9
0.15					5	6	5.5
0.075	8	2			3	3	3.5

TABLE B2 Granite Gradations

Sieve Size (mm)	Control Points		Restricted Zone		TRZ	ARZ	BRZ
	Upper	Lower	Upper	Lower	% Total Passing	% Total Passing	% Total Passing
25					100	100	100
19	100	90			98	98	98
12.5		90			84	84	84
9.5					67	67	67
4.75					44	44	44
2.36	49	23	34.6	34.6	33	34.6	33
1.18			28.3	22.3	25	30	21
0.6			20.7	16.7	20	23	15.7
0.3			13.7	13.7	15	15	12.7
0.15					9	9	8
0.075	8	2			2	2	2

TABLE B3 Limestone Gradations

Sieve Size (mm)	Control Points		Restricted Zone		TRZ	ARZ	BRZ
	Upper	Lower	Upper	Lower	% Total Passing	% Total Passing	% Total Passing
25					100	100	100
19	100	90			96	96	96
12.5		90			86	86	86
9.5					77	77	77
4.75					55	55	55
2.36	49	23	34.6	34.6	38	36	32
1.18			28.3	22.3	25	30	20
0.6			20.7	16.7	16	22	14
0.3			13.7	13.7	10	14	9
0.15					5	4.5	5
0.075	8	2			3	3	3

TABLE B4 Rounded Natural Sand Gradations

Sieve Size (mm)	Control Points		Restricted Zone		TRZ	ARZ	BRZ
	Upper	Lower	Upper	Lower	% Total Passing	% Total Passing	% Total Passing
25					100	100	100
19	100	90			96	96	96
12.5		90			86	86	86
9.5					77	77	77
4.75					55	55	55
2.36	49	23	34.6	34.6	38	38	32
1.18			28.3	22.3	25	30	20
0.6			20.7	16.7	16	22	14
0.3			13.7	13.7	10	14	9
0.15					4	5	4
0.075	8	2			2	2	2

TABLE B5 Design Properties of HMA Mixtures Containing River Gravel with TRZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=96)}$	4.0	4
% VMA at $N_{design\ (=96)}$	14.8	13.0 min.
% VFA at $N_{design\ (=96)}$	73.0	65-75
Dust Proportion	0.69	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	88.3	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	97.2	less than 98
Optimum Asphalt Content	5.3	N/A

TABLE B6 Design Properties of HMA Mixtures Containing River Gravel with ARZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=96)}$	4.0	4
% VMA at $N_{design\ (=96)}$	13.8	13.0 min.
% VFA at $N_{design\ (=96)}$	69.3	65-75
Dust Proportion	0.73	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	89.0	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	97.0	less than 98
Optimum Asphalt Content	5.0	N/A

TABLE B7 Design Properties of HMA Mixtures Containing River Gravel with BRZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=\ 96)}$	4.0	4
% VMA at $N_{design\ (=\ 96)}$	15.1	13.0 min.
% VFA at $N_{design\ (=96)}$	74.2	65-75
Dust Proportion	0.76	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	87.6	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	97.2	less than 98
Optimum Asphalt Content	5.6	N/A

TABLE B8 Design Properties of HMA Mixtures Containing Granite with TRZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=86)}$	4.0	4
% VMA at $N_{design\ (=\ 86)}$	13.0	13.0 min.
% VFA at $N_{design\ (=86)}$	69.4	65-78
Dust Proportion	0.63	0.6 - 1.2
% G_{mm} at $N_{initial\ (=7)}$	88.4	less than 89
% G_{mm} at $N_{maximum\ (=134)}$	97.1	less than 98
Optimum Asphalt Content	4.3	N/A

TABLE B9 Design Properties of HMA Mixtures Containing Granite with ARZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=86)}$	4.0	4
% VMA at $N_{design\ (= 86)}$	13.4	13.0 min.
% VFA at $N_{design\ (=86)}$	70.2	65-78
Dust Proportion	0.63	0.6 - 1.2
% G_{mm} at $N_{initial\ (=7)}$	88.9	less than 89
% G_{mm} at $N_{maximum\ (=134)}$	96.8	less than 98
Optimum Asphalt Content	4.3	N/A

TABLE B10 Design Properties of HMA Mixtures Containing Granite with BRZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=86)}$	4.0	4
% VMA at $N_{design\ (= 86)}$	13.2	13.0 min.
% VFA at $N_{design\ (=86)}$	69.8	65-78
Dust Proportion	0.63	0.6 - 1.2
% G_{mm} at $N_{initial\ (=7)}$	87.2	less than 89
% G_{mm} at $N_{maximum\ (=134)}$	97.0	less than 98
Optimum Asphalt Content	4.3	N/A

TABLE B11 Design Properties of HMA Mixtures Containing Limestone with TRZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=\ 96)}$	4.0	4
% VMA at $N_{design\ (=\ 96)}$	12.9	13.0 min.
% VFA at $N_{design\ (=96)}$	69.1	65-75
Dust Proportion	0.82	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	86.4	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	97.4	less than 98
Optimum Asphalt Content	4.5	N/A

TABLE B12 Design Properties of HMA Mixtures Containing Limestone with ARZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=\ 96)}$	4.0	4
% VMA at $N_{design\ (=\ 96)}$	12.1	13.0 min.
% VFA at $N_{design\ (=96)}$	66.9	65-75
Dust Proportion	0.91	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	87.6	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	97.2	less than 98
Optimum Asphalt Content	4.0	N/A

TABLE B13 Design Properties of HMA Mixtures Containing Limestone with BRZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=\ 96)}$	4.0	4
% VMA at $N_{design\ (=\ 96)}$	13.8	13.0 min.
% VFA at $N_{design\ (=96)}$	71.0	65-75
Dust Proportion	0.77	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	85.4	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	97.4	less than 98
Optimum Asphalt Content	4.8	N/A

TABLE B14 Design Properties of HMA Mixtures Containing Rounded Natural Sand with TRZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (=\ 96)}$	4.0	4
% VMA at $N_{design\ (=\ 96)}$	9.9	13.0 min.
% VFA at $N_{design\ (=96)}$	59.6	65-75
Dust Proportion	0.52	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	90.7	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	96.8	less than 98
Optimum Asphalt Content	3.8	N/A

TABLE B15 Design Properties of HMA Mixtures Containing Rounded Natural Sand with ARZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (= 96)}$	4.0	4
% VMA at $N_{design\ (= 96)}$	9.6	13.0 min.
% VFA at $N_{design\ (=96)}$	58.3	65-75
Dust Proportion	0.57	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	90.8	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	96.6	less than 98
Optimum Asphalt Content	3.5	N/A

TABLE B16 Design Properties of HMA Mixtures Containing Rounded Natural Sand with BRZ

Mix Property	Results	Criteria
% Air Voids at $N_{design\ (= 96)}$	4.0	4
% VMA at $N_{design\ (= 96)}$	10.7	13.0 min.
% VFA at $N_{design\ (=96)}$	62.6	65-75
Dust Proportion	0.47	0.6 - 1.2
% G_{mm} at $N_{initial\ (=8)}$	88.7	less than 89
% G_{mm} at $N_{maximum\ (=152)}$	96.8	less than 98
Optimum Asphalt Content	4.3	N/A

TABLE B17 Gradations of HMA Mixtures Containing Different Amounts of Mineral Filler

Sieve Size (mm)	Control Points		Restricted Zone		Mineral Filler Content		
					2%	5%	7%
	Upper	Lower	Upper	Lower	% Total Passing	% Total Passing	% Total Passing
25					100	100	100
19	100	90			98	98	98
12.5		90			84	84	84
9.5					67	67	67
4.75					44	44	44
2.36	49	23	34.6	34.6	33	33	33
1.18			28.3	22.3	25	25	25
0.6			20.7	16.7	20	20	20
0.3			13.7	13.7	15	15	15
0.15					9	9	9
0.075	8	2			2	5	7