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# Influence of aggregate type and gradation on critical voids in the mineral aggregate in asphalt paving mixtures

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# Influence of aggregate type and gradation on critical voids in the mineral aggregate in asphalt paving mixtures

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# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

## ABSTRACT

The implementation of Superpave has led to concerns with volumetric mix design, in particular, the minimum voids in the mineral aggregate (VMA) requirements which are based exclusively on nominal maximum aggregate size (NMAS). Achieving the minimum VMA requirement is one of the most difficult tasks in Superpave volumetric mix design. Under current specifications, many otherwise sound mixtures are subject to rejection solely on the basis of failing to meet the VMA requirement.

The goal of this research was to validate the existing VMA criterion and to see if including additional aggregate factors would improve it. The work was accomplished in three phases: a literature review; extensive laboratory testing; and statistical analysis of test results.

The available literature on the development of the minimum VMA criterion is sketchy; the relationship was originally presented without supporting research or data and the suggestion that it would be modified with experience and test data. The literature review also suggested that the triaxial test was the preferred laboratory test for identifying when a mixture transitions from sound to unsound behavior, i.e., becomes plastic.

The laboratory testing involved triaxial testing with the Nottingham Asphalt Tester of 36 mixes with different aggregate properties. ANOVA and linear regression was used to examine the effects of identified aggregate factors on critical state transitions in asphalt paving mixtures and to develop predictive equations.

The results clearly demonstrate that the volumetric conditions of an asphalt mixture at the stable/unstable threshold are influenced by a composite measure of the maximum aggregate size and gradation and by aggregate shape and texture. The currently defined VMA criterion, while significant, is seen to be insufficient, *by itself*, to correctly differentiate sound from unsound mixtures. Based on the laboratory data and statistical analysis, a new paradigm to volumetric mix design is proposed that explicitly accounts for several aggregate factors (gradation, shape, and texture) in predicting the critical VMA of an asphalt paving mixture.

# CHAPTER 1. INTRODUCTION

In the analysis and design of asphalt mixtures, the volumetric proportions of the asphalt binder, aggregates, and air voids play an important role. In the simplest approach, a compacted asphalt mixture could be resolved into the individual volumes of the mineral aggregate, the asphalt binder, and air voids as shown in Figure 1. However, as shown in the figure, some of the asphalt binder is inevitably absorbed into the aggregate, and the sum of the individual component volumes exceeds the total volume of a compacted asphalt mixture. As a result, two secondary volumetric parameters are conventionally used:

1. Voids in the mineral aggregate (VMA), which is the combined volume of air voids and effective (non-absorbed) asphalt binder, and
2. Voids filled with asphalt (VFA), which is the ratio of the volume of effective binder to the VMA.

The three volumetric parameters of air voids, VMA, and VFA have been identified as significant indicators of mix performance. Excessive air voids, VFA, and inadequate VMA suggest potential durability problems. Insufficient air voids or excessive VFA indicate potential rutting problems. In Superpave, these volumetric properties are considered so important that a volumetric mix design protocol was established with limits on all three parameters.

The implementation of Superpave has led to concerns with volumetric mix design, in particular, the minimum VMA requirements which are based exclusively on nominal maximum aggregate size (NMAS). This research seeks to examine the premise that VMA is indeed a valid critical parameter, and that the sole aggregate factor affecting the magnitude of critical VMA is the NMAS.

## Rationale

In 1959, Dr. Norman W. McLeod first proposed the relationship between minimum VMA and NMAS for dense graded mixtures shown in Figure 2 (*1*). McLeod believed that mixes plotting in the gray area would be deficient in asphalt binder or air voids, and should not be expected to perform well. He felt that mixes plotting above the gray area would perform satisfactorily. McLeod suggested the relationship

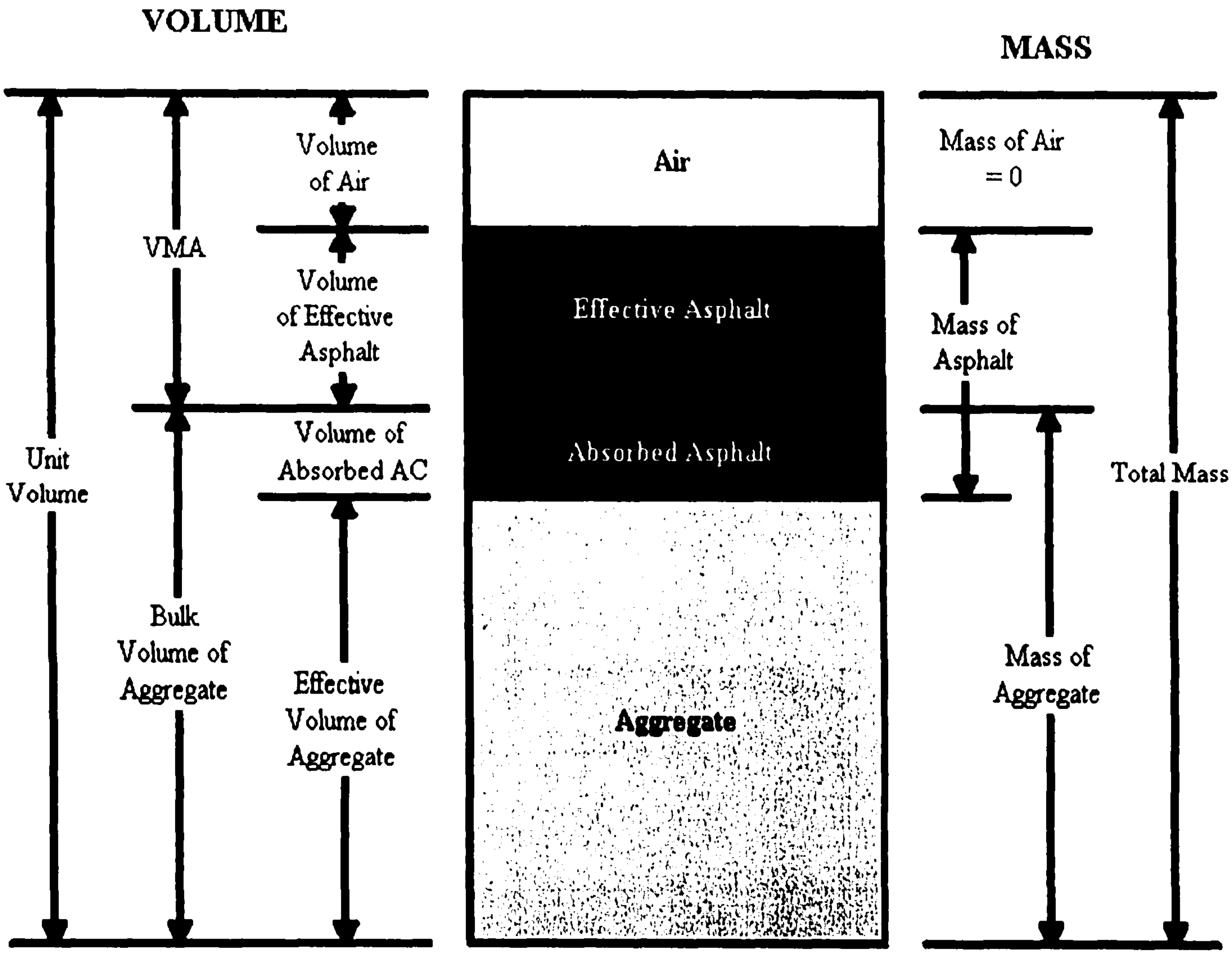


**Figure 1 Component Diagram of Compacted Hot-Mix Asphalt Sample**

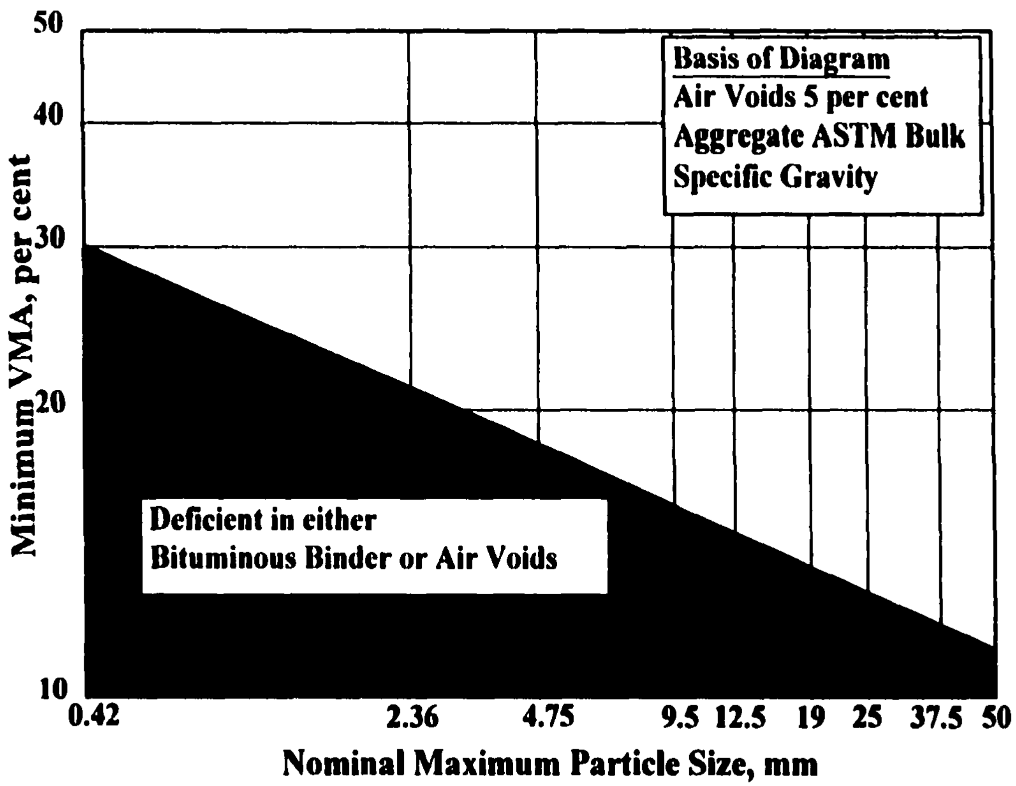


**Figure 2 Minimum VMA vs. Nominal Maximum Aggregate Size Relationship (*1*)**

without presenting the research or data from which it was derived and stated it was "... subject to modification as further experience and additional test data are accumulated" (pg. 103).

Dr. McLeod's VMA – NMAS relationship was adopted by The Asphalt Institute in 1962 (*2*) as a standard requirement of Marshall mix design. Over the 30 years prior to the implementation of Superpave, this VMA mix criterion was gradually adopted by several state highway agencies. However, as late as 1985, only 16 of 38 states using the Marshall method specified a minimum VMA (*3*). McLeod's home province in Canada, Ontario, made significant changes to reflect the effects of aggregate gradation in 1978 (*4*). In spite of this, the Strategic Highway Research Program (SHRP) researchers adopted McLeod's suggested relationship for inclusion in Superpave where it has become the primary control of aggregate gradation (*5*). The Superpave VMA requirements are listed in Table 1. The implementation of Superpave has brought significant awareness of, and renewed focus on, how this minimum VMA requirement impacts mix design.

**Table 1 Superpave VMA Criteria**

| NMAS | Specified (minimum) VMA (%) |
|---|---|
| 9.5 mm | 15.0 |
| 12.5 mm | 14.0 |
| 19.0 mm | 13.0 |
| 25.0 mm | 12.0 |
| 37.5 mm | 11.0 |

In Superpave, meeting McLeod's minimum VMA requirement is a deciding factor in whether or not an aggregate blend can be used. In recent years, some researchers have presented concerns that these minimum VMA requirements are too restrictive and may rule out economical mixes with acceptable performance properties (*6*). Others point out that evaluating and selecting the aggregate gradation to achieve VMA is the most difficult and time-consuming step in the Superpave mix design process (*7*). Some favor replacing or augmenting it with an asphalt film thickness specification (*6, 8-9*). Others suggest it is not applicable to all asphalt mixtures and propose refinements to it (*10*).

The definition of minimum (or critical) VMA adopted by Superpave is dependent only upon McLeod's suggested relationship to NMAS without regard to other significant aggregate-related properties. In practice, mix designers target the required minimum VMA, even for mixtures that might not be considered dense-graded. It appears reasonable to examine the effects of aggregate-related factors on critical VMA and to seek to expand and refine the McLeod/Superpave relationship.

Two essential steps must be completed prior to any investigation into aggregate-related factors of critical VMA. First, a practical and credible means must be found to identify a state of critical VMA in a laboratory mixture, or to identify the volumetric parameters of a mixture as it transitions from sound to unsound behavior. Second, the aggregate characteristics most likely to influence the critical VMA threshold must be identified.

**Objectives**

The research documented in this dissertation examines the McLeod/Superpave minimum VMA requirement based on NMAS that differentiates sound and unsound mixes. The primary objectives of this research are:

1. To review the published literature for laboratory methods of identifying critical transitions in asphalt paving mixtures.
2. To review the history and development of the McLeod/Superpave VMA vs. NMAS relationship.
3. To find published research results that address the effects of other aggregate-related factors on critical state transitions in asphalt paving mixtures.
4. To establish a laboratory method by which the transition of an asphalt paving mixture from sound to unsound behavior may be credibly identified and measured.
5. To use that method to examine and validate the McLeod/Superpave VMA vs. NMAS relationship.
6. To use that method to identify and to evaluate statistically the effects of several aggregate-related factors on the critical VMA of such mixtures.

7. To derive a predictive relationship relating critical state (e.g., critical VMA) to aggregate-related properties such as NMAS, gradation, shape, and texture.

## Scope

A total of 36 aggregate blends were used for this research. These blends included 3 NMAS (19 mm, 12.5 mm, and 9.5 mm); 3 gradations for each NMAS (fine, dense, and coarse), and four aggregate blends:

1. **Manufactured** - Each gradation is 100 percent crushed material.
2. **Natural** - Each gradation is 100 percent natural (uncrushed) material.
3. **50-50 Blend** - Each gradation is 50 percent manufactured - 50 percent natural on each sieve size.
4. **NCMF (Natural Coarse-Manufactured Fine)** - The material passing the 4.75 mm sieve was 100 percent manufactured and the material retained 100 percent natural. The coarse (natural) aggregate was washed to ensure that the p0.075 mm material was obtained entirely from the manufactured aggregates.

Replicate specimens at 5 asphalt contents (4,5,6,7 and 8%) were fabricated and tested in the Nottingham Asphalt Tester (NAT) for each of the 36 blends. From the NAT results and the volumetric properties, the critical VMA for each mix was determined. These values were then analyzed using ANOVA and linear regression to examine the effects of the aggregate-related factors on critical VMA.

## Definition of Terms

The following terms and abbreviations are used in this report:

1. Air voids: the percent by volume of compacted aggregate asphalt mix of air between coated aggregate particles.
2. Voids in the mineral aggregate (VMA): The percent by volume of effective asphalt binder plus air voids in a compacted aggregate asphalt mix.
3. Voids filled with asphalt (VFA): The percentage of VMA filled with asphalt.
4. Nominal maximum aggregate size (NMAS): One sieve size larger than the first sieve to retain more than 10 percent of the aggregate by weight.

5. Fineness modulus (FM): The sum of the percentages retained in a sieve analysis divided by 100, using standard sieves (0.150 mm, 0.300 mm, 0.600 mm, 1.18 mm, 2.36 mm, 4.75 mm, 9.5 mm, 19 mm, and 37.5 mm)
6. Coarse aggregate percent crushed (CAPC): The percentage of material retained on the 4.75 mm sieve by weight with two or more crushed faces.
7. Fine aggregate percent crushed (FAPC): The percentage of material passing the 4.75 mm sieve by weight with two or more crushed faces.

**Organization of this Study**

Chapter 2 provides a summary of the literature search and review on the effects of aggregate-related factors of critical VMA in asphalt paving mixtures. The third chapter briefly summarizes the materials used in the study; asphalt, fine and coarse aggregates. Chapter 4 presents the methodology used in laboratory testing, describing step-by-step the testing protocol used and any deviations from convention. Chapter 5 presents and discusses the results obtained from the testing program and statistical analysis. The significant factors are identified and predictive equations are developed and evaluated. Chapter 6 presents the conclusions of this research and recommendations for its application and further development.

# CHAPTER 2. LITERATURE REVIEW

The first three objectives of this study were:

1. To review the published literature for laboratory methods of identifying critical transitions in asphalt paving mixtures,
2. To review the history and development of the McLeod/Superpave VMA vs. NMAS relationship, and
3. To find published research results that address the effects of other aggregate-related factors on critical state transitions in asphalt paving mixtures.

## Laboratory Methods of Distinguishing Critical State Transitions in Asphalt Paving Mixtures

The critical VMA of an asphalt paving mixture is not commonly determined in mix design. Hence no mention of a test protocol or equipment for measuring it could be found in the literature. The focus shifted toward finding equipment capable of indicating when an asphalt mixture transitioned from sound to unsound, i.e., became plastic. This is essentially the same function performed by rutting or permanent deformation test equipment.

During the SHRP, permanent deformation was the focus of the SHRP A-003A project and SHRP report A-415 (*11*). The SHRP researchers examined a wide variety of test methods to find the best performance test for measuring permanent deformation response. While distinguishing the critical state transition was not one of their goals, their review and discussion of candidate test methods is useful in identifying equipment to determine the critical transition of a mixture.

The SHRP researchers examined and discussed four types of laboratory tests used to characterize the permanent deformation response of pavement materials:

1. Uniaxial stress tests: unconfined cylindrical specimens in creep, repeated, or dynamic loading.
2. Triaxial stress tests: confined cylindrical specimens in creep, repeated or dynamic loading.
3. Diametral tests: cylindrical specimens in creep or repeated loading.

4. Potential (new) tests: e.g., simple shear and hollow cylinder tests.

Of these, based on field simulation and simplicity, they ranked the simple shear test (SST) first, the triaxial tests second, and the creep tests third. They believed that the shear properties were the most important in rutting and that the SST provided the best means for directly measuring the effects of a specific stress state and the dilation characteristics of a mix. For distinguishing the critical state transition of a compacted hot-mix asphalt (HMA) specimen, the advantages of the SST are not worth the increased cost over the triaxial stress test apparatus.

The goal was to examine the existing and available literature to learn more about the triaxial test, test parameters, and the feasibility of using this equipment to distinguish the critical state transition.

*Triaxial Testing*

The triaxial test has been used by asphalt technologists since the early 1940s for characterizing asphalt mixtures. Most of this research was of an exploratory nature due to the cost and complexity of the test equipment. However, several influential researchers have used the test in a variety of ways.

Nijboer was one of the first to use the triaxial test for asphalt mixtures. He rejected existing test methods as inadequate for measuring plastic properties of asphalt mixtures (*12*). He recommended against using the Hveem stabilometer since it is a "closed-system" meaning the material cannot flow laterally. He recommended using an "open-system" triaxial shear test allowing lateral flow. Nijboer developed the triaxial test for bituminous mixtures and used it to study the influence of systematic changes in asphalt content, filler, and ratio of coarse to fine aggregate on resistance to plastic deformation.

Monismith and Vallerga examined the relationship between density and stability using an open-system triaxial test (*13*). They used one type of asphalt (3-8% by weight of aggregate), one type of aggregate and gradation, and a test temperature of 60 °C. They molded specimens using several different compaction schemes (pressure and tamping). Then they ran triaxial compression tests, using a lateral pressure of 1-2 bar and applying the vertical load at a constant rate of strain of 0.5 in./min.

Their test results suggested that during compaction, HMA behaves analogously to a cohesive soil in Proctor testing. Figure 3 shows the relationship between bulk specific gravity and stress for mixtures with binder contents between 3-7% at 2% strain. The figure shows that for binder contents above 5%, there is a maximum density beyond which the specimen begins to lose strength. Thus, 5% is the critical asphalt content at which the mix transitions from sound to unsound performance. The dashed line is the Hveem design binder content (5.6% by weight of aggregate) with compaction achieved by construction and one year of traffic. As shown in the figure, one can see that after this time, the mix would have a significant loss of stability.

Pell and Brown stressed the importance of reproducing in situ test conditions in laboratory tests and critically reviewed existing test methods (*14*). They suggested that the repeated load triaxial test will overestimate the permanent deformation characteristics of a mix relative to in situ conditions. They emphasized the need for direct shear testing to supplement repeated load triaxial testing for pavement design.

Francken used a repeated load triaxial apparatus to determine a phenomenological deformation law that could then be used in structural design to limit rutting (*15*). Examining five different mixes, he found that a threshold condition (dependent on stress and temperature) existed that clearly delineated whether or not plastic failure was imminent.

Brown and Cooper examined a variety of mixes for bases and base courses using several tests including Marshall stability, uniaxial and triaxial creep, and the repeated load triaxial test (*16*). They concluded that Marshall stability test could not be used to distinguish the relative deformation resistances of these mixes and stated (pg. 424) that "if a confined test is to be used, it is necessary to apply some form of repeated load".

The SHRP researchers (*11*) pointed out that previous research had suggested that the repeated load test was more sensitive to mix variables than the creep test. They found that the repeated load triaxial test provided a better measure of rutting characteristics than the creep test.

Nunn et al., using the NAT compared the repeated load axial test (both confined and unconfined) against wheel-tracking tests of the same materials and found that the repeated load test ranked the materials in a similar fashion to the wheel-tracking test (*17*).

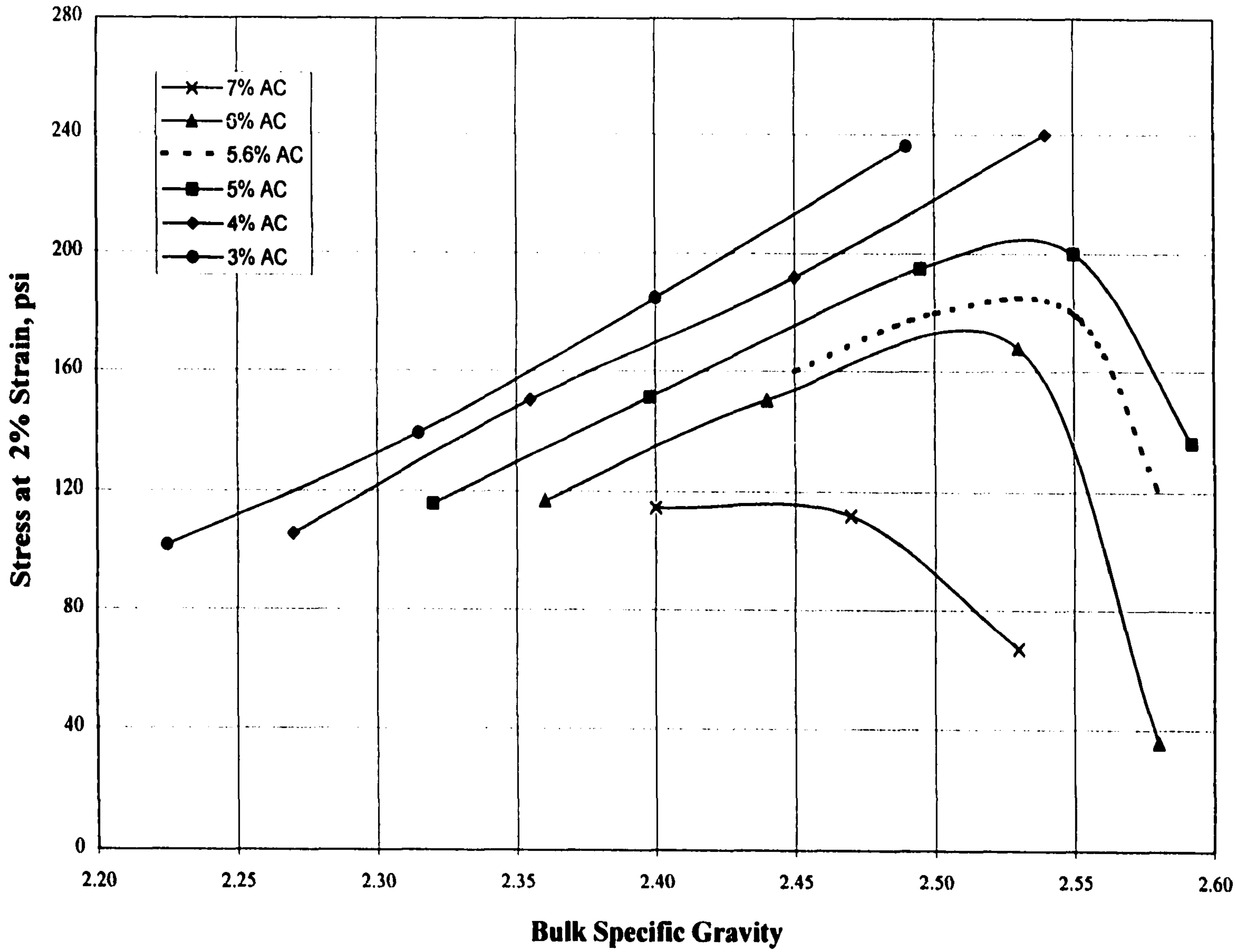


**Figure 3 Stress at 2% Strain vs. Bulk Specific Gravity (*13*)**

They found the unconfined test inadequate for evaluating resistance to permanent deformation. They recommended that the repeated load test be further evaluated to develop standard testing conditions and a precision statement.

Brown and Scholz also modified the NAT to convert the repeated load axial test into a repeated load triaxial test, using a vacuum to apply the confining stress (*18*). This approach limited the confining stress to 1 atmosphere (roughly 100 kPa) but made the test viable as a routine test. They then used the apparatus to examine two porous mixtures with the same gradation but different binders at different temperatures and confining stresses. They found that confining the specimen emphasized the role of aggregates in resisting permanent deformation.

**The History and Development of the Current VMA vs. NMAS Relationship**

In the early 1900s, the most widely used approaches to asphalt mix design focused on achieving maximum density or using aggregate surface area and asphalt film thickness to determine the optimum asphalt content (*19*). Mix designers using the first approach combined VMA, air voids, and experience to determine the best asphalt content. Those using the second approach combined air voids, the product of surface area and optimum film thickness, and experience to determine the best asphalt content. The Hubbard-Field design method is an example of the first approach and the Hveem design method an example of the second. Because experience was usually the critical factor, regardless of approach, they usually resulted in similar mix designs. Usually, the aggregate gradation was determined by specification, by locally available materials, or by theoretically "idealized" gradations.

The 'early' Marshall mix design approach did not have a VMA requirement (*20*). Marshall himself believed "no limits can be established for VMA, for universal application, because of the versatile application of bituminous materials to many types and gradations of aggregate(pg. 9)". McFadden and Ricketts presented the Corps of Engineers (COE) version of the Marshall method for design and field control of paving which used the five parameters shown in Table 2 to determine the design asphalt content (*21*). The peak values of all parameters except flow were averaged to determine the design asphalt content.

**Table 2 COE Marshall Mix Design Criteria (*21*)**

| Test Property | Requirement |
|---|---|
| Stability | 500 lbs. (Minimum) |
| Flow | 20 (Maximum) |
| Air Voids, Total Mix | 3-5 percent |
| VFA | 75-85 percent |
| Unit weight | ----- |

The shift towards a minimum VMA requirement began in the mid-1950s. McLeod, in 1955, presented his initial analysis on the voids properties of compacted paving mixtures, in which he laid out the basic principles of a minimum VMA requirement (*22*). His argument did not explicitly mention durability; he was concerned that specifications with requirements on both air voids and VFA were too restrictive at higher asphalt contents. He showed, for absorptive aggregates, that computed VMA and VFA would be wrong unless the bulk specific gravity of the aggregates was used in the calculations.

In 1956, McLeod presented a modified Marshall mix design methodology, which listed a minimum VMA requirement of 15 percent (*23*). He showed graphically (See Figure 4) that a VFA range of 65-80 percent was unachievable for mixes with asphalt contents above 10.5 percent by weight (approximately 20 percent by volume). He provided similar design charts that covered the range of aggregate specific gravities from 2.00 up to 3.00 and asphalt specific gravities from 0.95 up to 1.11. In all cases, the minimum asphalt content required would be at least 4 percent by aggregate weight, plus any absorbed asphalt. At a typical aggregate specific gravity of 2.65 and asphalt specific gravity of 1.01, McLeod's design charts specify a minimum asphalt content of 4.5 percent. McLeod believed that the physical test limits would broaden the range of acceptable aggregates, lower the cost of bituminous paving mixtures and provide satisfactory paving mixtures with respect to stability, voids, durability, etc.

The following year, McLeod again stated his case for using the bulk specific gravity and effective asphalt content for volumetric analysis of the mixture (*24*). He concluded that if the compacted paving mixture was restricted to 3-5 percent air voids, requiring a minimum VMA (15 percent) was less restrictive than requiring a VFA range of 75-85 percent. More importantly, he suggested that the VFA requirement would allow a pavement to be

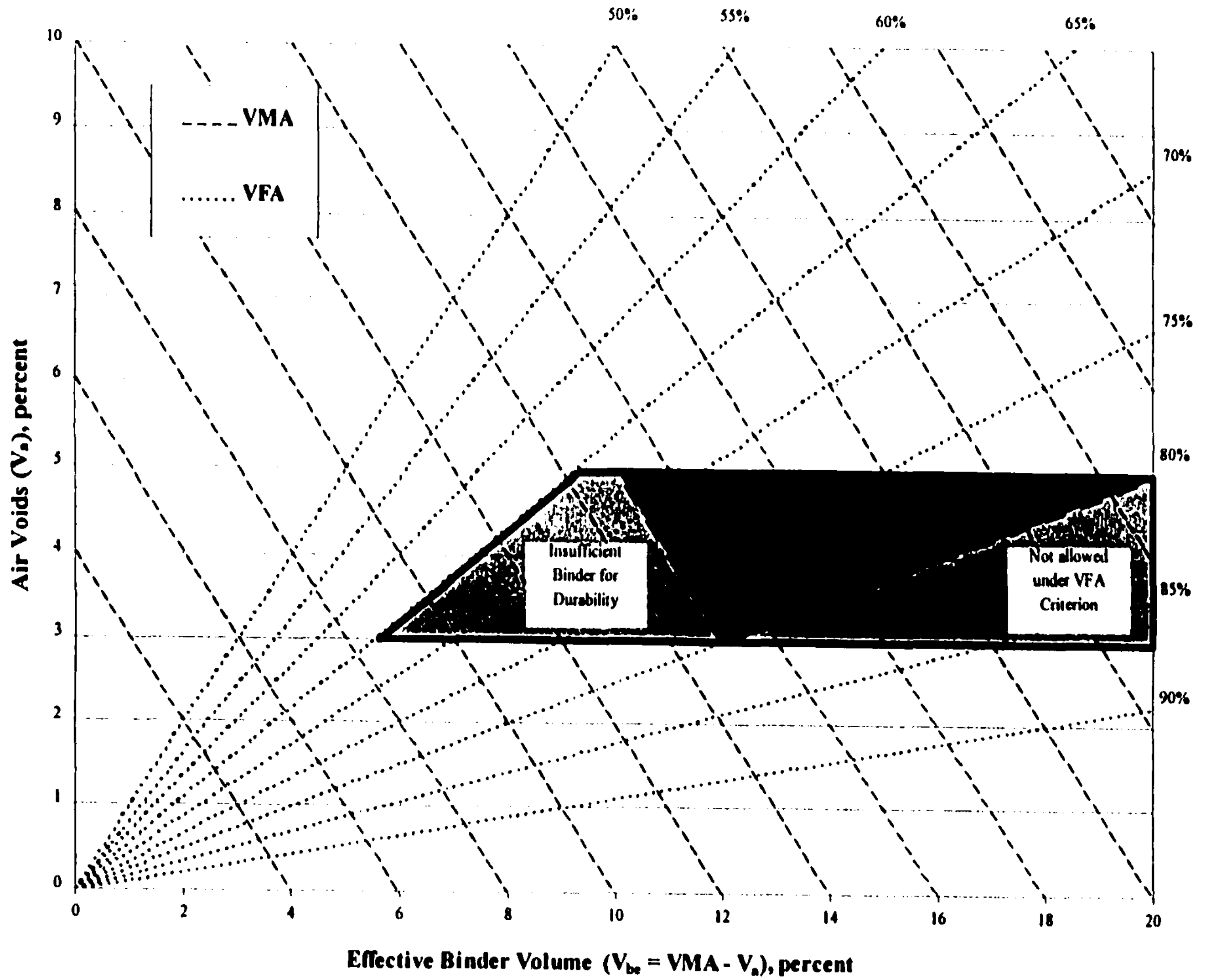


**Figure 4 McLeod's Concerns with VMA Criterion**

constructed with 3.76 percent asphalt, which he felt was too low for durability. The minimum VMA requirement would ensure at least 4.5 percent asphalt and provide adequate durability. McLeod observed that Canadian aggregates typically were too densely graded to provide the required VMA.

Also in 1957, Lefebvre re-emphasized the importance of minimum VMA (*25*). Aware of the difficulty of achieving 15 percent VMA and 3-5 percent air voids, he investigated the influence of the principal fractions of the mineral aggregate; coarse aggregate, fine aggregate, fine sand, and mineral filler on the performance of the paving mixture. He found that the fine aggregates were the most critical component, controlling the VMA and contributing to stability.

In 1959, McLeod suggested the currently used method of using VMA and air voids requirements in designing pavement mixtures (*1*). In place of his previously held requirements of 15 percent minimum VMA, he related minimum VMA to NMAS. Figure 1 shows McLeod's suggested relationship. He warned that the minimum VMA requirements were subject to modification as further experience and additional test data were accumulated.

Campen, et al. (1959) emphasized that asphalt film thickness, not VMA was essential to mixture durability (*26*). VMA is independent of the surface area of the aggregate. They presented data showing that two aggregate blends could have identical VMA and yet one could have twice the surface area or film thickness as the other. At the same time, they found that the surface area did not indicate the asphalt content required for minimum VMA. Increased surface area requires more asphalt, but there is no direct proportional relationship. They prescribed film thicknesses in the range of 6-8 microns as producing the most desirable paving mixtures.

The Asphalt Institute incorporated a new density-voids analysis, which accounted for asphalt absorption, into the Marshall mix design method in its 1962 MS-2 (*2*). VFA, previously a Marshall method design parameter in earlier editions, is not mentioned. No rationale for dropping VFA is presented. McLeod wrote an appendix in MS-2 presenting the inclusion of a minimum VMA requirement into the mix design process.

Hudson and Davis described an arithmetical method for computing VMA from the aggregate gradation, using factors for the ratio of percent passing one sieve divided by the percent passing the next smaller sieve (*19*). Their procedure differentiated between rounded and angular aggregate. They believed that their arithmetic method of computing VMA would allow the mix designer to estimate design asphalt content, if McLeod's chart (Figure 2) was used.

McLeod discussed the trend of modifying paving mixtures with rubber or asbestos to increase durability (*27*). As an alternative, to improve durability, he proposed using a conventional (unmodified) asphalt binder but requiring 2-3 percent more VMA than the values shown in Figure 2. He demonstrated that the VMA value of a dense graded paving mixture essentially controls the quantity of asphalt that can be incorporated into the mixture. Also, he argued that VMA should be determined through measurements of compacted mixtures; it cannot be determined from aggregate test properties alone. He offered several methods to increase VMA; most importantly using crushed angular aggregates.

Field presented the results of a study investigating the minimum VMA criterion, the accuracy of the test, and examining alternative approaches (*4*). He pointed out that the Ontario Ministry of Transportation and Communications (MTC) had supplied acceptable mixes that did not meet the required minimum VMA. The MTC was changing its requirements to those shown in Table 3, where it must be noted that the maximum size is the same as the Superpave NMAS.

Field also discussed four alternative approaches to using minimum VMA in getting mix durability:

1. A VFA requirement,
2. The surface area method,
3. The centrifuge kerosene equivalent (CKE) test, and
4. Visual observation of coatability.

A VFA requirement of 75-85 percent was ruled out because it would allow mixes with very low VMA and very low asphalt contents to be used. The surface area method provided mixes with average design asphalt contents 1.2 percent lower than those obtained using the VMA criterion. So, despite good laboratory test properties (except low VMA!) and

**Table 3 Ontario Ministry of Transportation and Communications Modification to VMA Requirements (4)**

| Mix Type | Percent Pass 4.75 mm * (By Mass) | NMAS (mm) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 2.36 | 4.75 | 9.5 | 13.2 | 16.0 | 19.0 | 26.5 |
| HL-2 | | 21 | 18.0 | 16 | | | | |
| HL-1 | 40 | | | | 13.5 | 13.0 | 12.5 | 11.5 |
| HL-3 | 45 | | | | 14.0 | 13.5 | 13.0 | 12.0 |
| HL-4 | 50 | | | | 14.5 | 14.0 | 13.5 | 12.5 |
| HL-5 | 55 | | | | 15.0 | 14.5 | 14.0 | 13.0 |
| HL-6 | 60 | | | | 15.5 | 15.0 | 14.5 | 13.5 |
| HL-8 | 65 | | | | 16.0 | 15.5 | 15.0 | 14.0 |

Additional notes:

1. The VMA shown above is for 3½ % voids

   Reduce the VMA shown above by amount of voids set less than 3½ %

   Increase the VMA shown above by amount of voids set more than 3½ %

2. A design mix must have at least a moderate to moderately rich asphalt coating appearance on aggregate particles before compaction.

* 3. When the difference between the bulk relative density of the retained 4.75 mm material and the bulk specific gravity of the pass 4.75 mm material is greater than 0.3, then the percent pass 4.75 mm must be on a volume basis.

no construction or performance problems, because of conceptual problems, the method was deemed unacceptable. The CKE approach was found unsatisfactory because it is "lengthy, tedious, subject to many errors, and not realistic." Using visual observation for coatability was deemed acceptable based on past projects where it had been used. The criteria involved making sure (1) the loose mix was moderately rich with respect to asphalt, (2) the compacted test specimen was moderately rich to rich in appearance, and (3) the aggregate particles were well coated with asphalt. He concluded that the minimum VMA requirement based on bulk specific gravity was the best method of establishing proper asphalt content for durability. Field also recommended follow up performance studies be conducted on pavements with VMA and void contents below the design criteria to provide the necessary experience and confidence.

Kandhal and Koehler reported there were still problems with the VMA criterion in 1985 (*3*):

> "The VMA is considered to be the most important mix design parameter which affects the durability of the asphaltic concrete mix. High VMA values allow enough asphalt to be incorporated into the mix to obtain maximum durability without the mix flushing. Additionally, such mixes have the following advantages compared to low VMA mixes:
>
> 1. Lower stiffness modulus at low temperatures. This is helpful in minimizing the severity of thermal and reflection cracking.
> 2. Lower susceptibility to variations in asphalt and fines content during production. Such variations can cause the mix to be too brittle or too rich.
>
> Unfortunately, only 16 of 38 states using the Marshall method specify a minimum VMA. Of these 16 states, only seven use the effective asphalt content (total asphalt minus the asphalt absorbed by the aggregate) to calculate the realistic VMA value, as recommended by the Asphalt Institute. If the effective asphalt content is not used, the calculated VMA values are not reliable especially when the mix contains an absorptive aggregate" (pg. 297).

Foster reviewed the use of voids in mix design and specifications (*28*). While acknowledging McLeod's explanation of VMA as providing "the desirable conditions for a good asphalt pavement" he questioned the minimum requirement of 15 percent VMA. He reviewed McLeod's 1956, 1957, and 1959 papers and Lefebvre's 1957 paper and pointed out that none report actual pavement VMA or performance data in support of the recommended criteria. Foster reported that, as of 1985, seventeen states were using VMA in their mix designs. He compared pavement performance data from several projects and his data is presented graphically in Figures 5 and 6.

Figure 5 presents, graphically, the volumetric mix data from traffic tests that the COE used to develop their Marshall design criteria. The data clearly shows that 3-5 percent air voids and that a VFA in the range of 68-77 percent will result in satisfactory pavements. The VMA criterion shows that a minimum of 14 percent is necessary to distinguish the 'almost plastic' pavements, but does not break out the 'almost brittle' pavements.

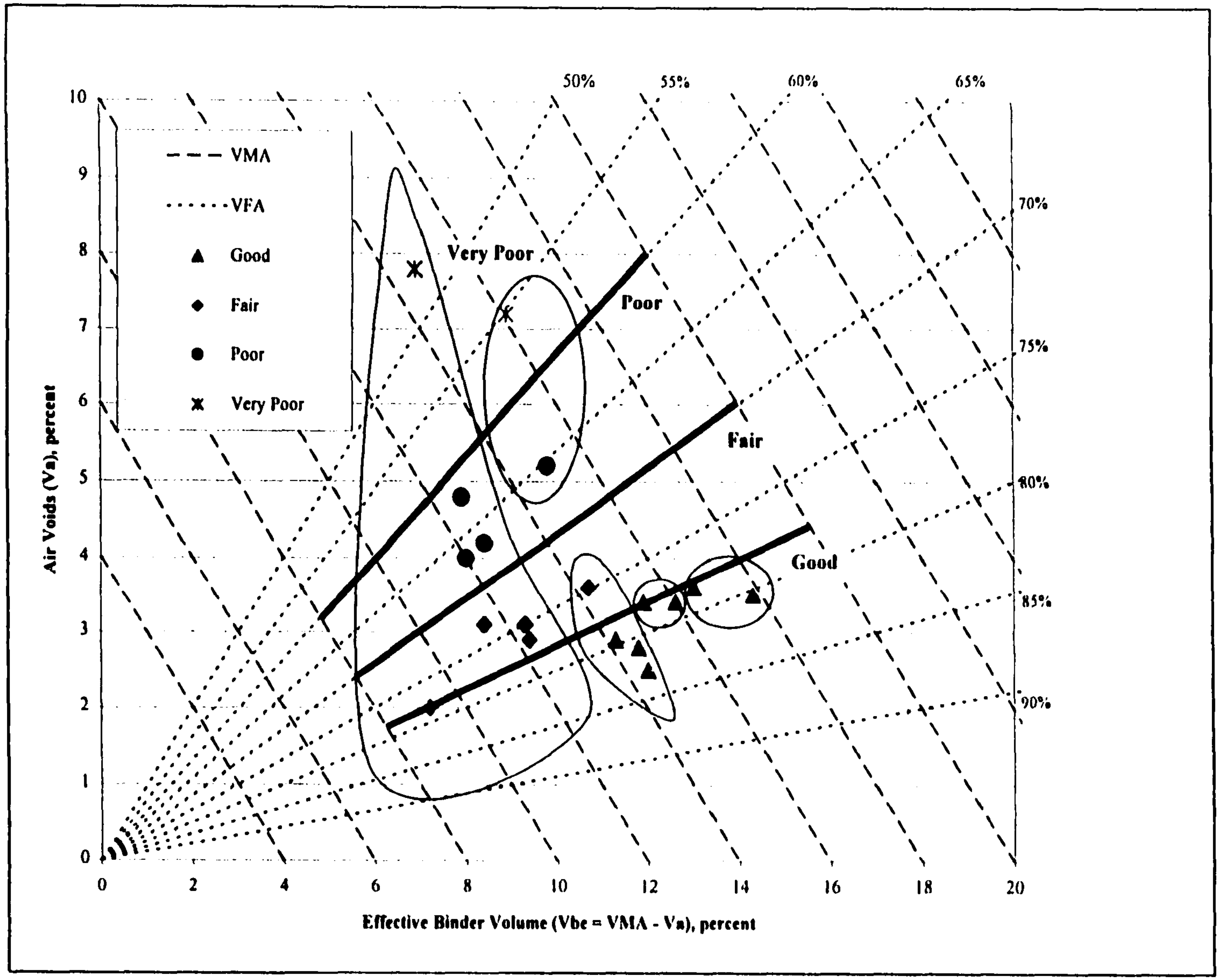


**Figure 6 Effectiveness of VFA for Predicting Pavement Performance (*28*)**

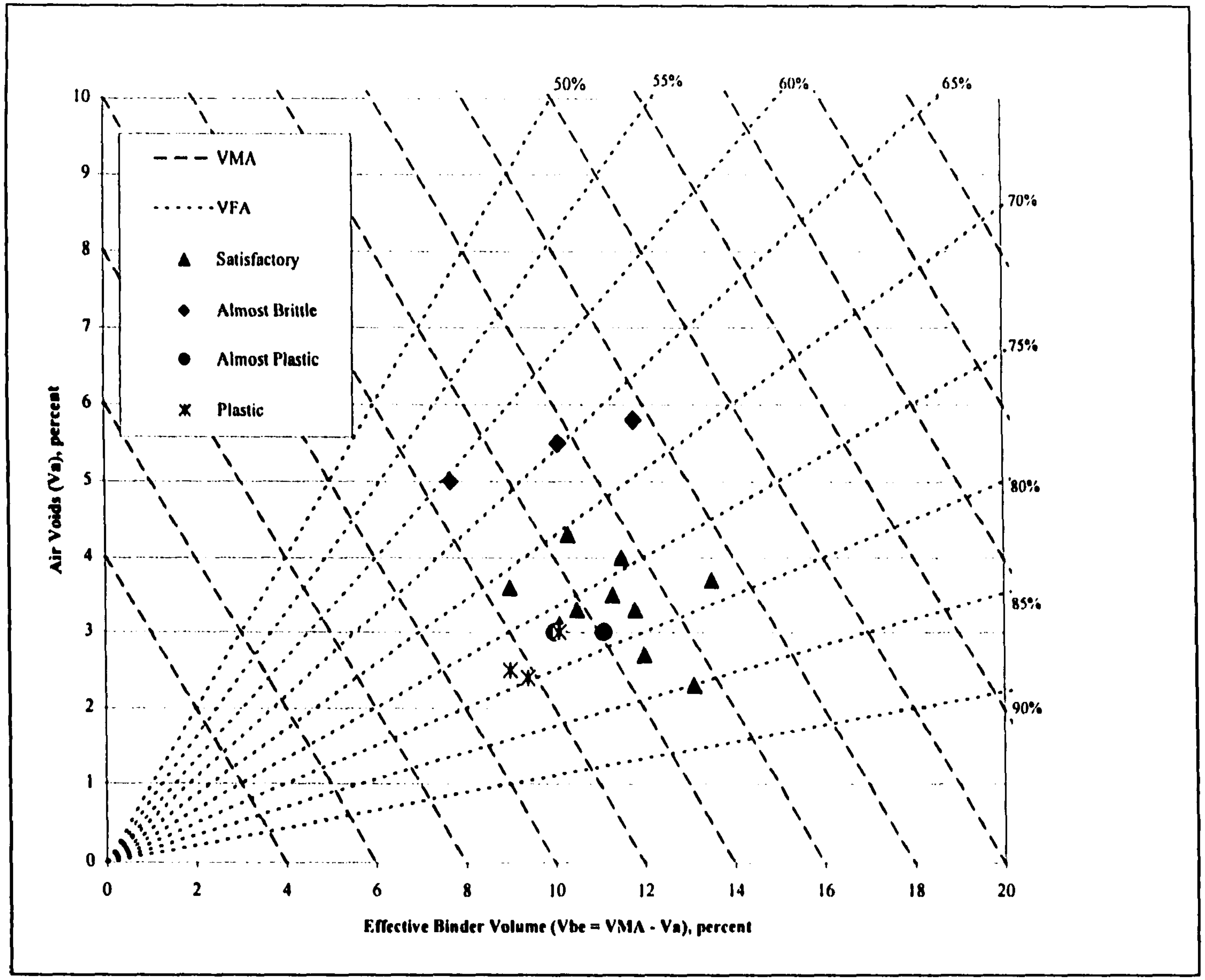


**Figure 5 Ineffectiveness of VMA to Distinguish Pavement Performance (*28*)**

Figure 6, shows graphically, the volumetric mix data from 18 experimental overlays on Nebraska highways from 1961-1972. The rings differentiate the different mix types; nominal maximum size was (primarily) 19.0 mm (¾ in.). The data clearly show that a VFA criterion of 68-83 percent (approximately) will result in fair or good pavements. The VMA criterion is ineffective at distinguishing pavement performance in this data.

Huber and Heiman examined 9 test sites in Saskatchewan to see if mix design characteristics differentiated pavements that performed well from those that rutted badly (*29*). For the mix characteristics examined, they found the threshold values listed in Table 4. If 4 percent air voids are taken as a design target, then their VMA and VFA criteria limit possible designs to a single point (Air Voids = 4%, VMA =13.5%, and VFA =70%). They concluded that asphalt content and VFA were the most basic parameters that effect rutting, with VFA including the effects of both air voids and VMA.

**Table 4 Observed Threshold Values for Mix Design Characteristics (*29*)**

| Parameter | Threshold Value |
|---|---|
| Air Voids | 4% minimum |
| Voids in the Mineral Aggregate | 13.5% minimum |
| Asphalt Content | 5.1% maximum |
| Voids Filled with Asphalt | 70% maximum |
| Fractured Faces | 60 % minimum |
| Marshall Stability | ----- |
| Hveem Stability | 37% minimum |

McLeod re-emphasized his earlier arguments for using VMA in mix design (*30*). Aware of Huber and Heiman's findings, he acknowledged that there was apparent justification for using air voids and VFA as design criteria. However, he felt using a percent air voids and VFA criteria of 75-85 percent would not be a practical specification for production. He further argued against placing requirements on all three volumetric parameters, air voids, VMA, and VFA, showing that they overlap. As a practical matter, he suggested that the only reasonable criterion is to use the minimum VMA based on NMAS and air voids requirement. He mentions that in Ontario during the OPEC oil crisis of 1973, the VMA requirements were significantly reduced as a cost saving measure, but quickly halted due to an epidemic of poor pavements and raveling problems.

Huber and Shuler focused on the relationship between VMA and the maximum density line (MDL) *(31)*. They concluded that the MDL needed to run from the origin to the 100 percent passing maximum sieve size. They tried to relate distance from the MDL to VMA but could find no general rule to ensure minimum VMA, because of the influence of aggregate angularity and surface texture on VMA. They also recommended against comparing gradations with large differences in material passing the 0.075 mm sieve.

Cominsky, Leahy, and Harrigan present and discuss the Superpave Level 1 mix design that was developed during the SHRP Program *(5)*. Based on the recommendations of a panel of experts using the Delphi method, the VMA requirements were absorbed into Superpave. The panel's final rating of the various aggregate and asphalt-aggregate mixture characteristics for inclusion into the specification is shown in Table 5. As can be seen, the panel strongly recommended air voids and VMA but was essentially neutral on VFA, dust/asphalt ratio, and film thickness.

In 1994, the Asphalt Institute re-introduced a VFA criterion into Marshall mix design, changed the design air voids to 4 percent, and added a table of VMA requirements depending on air voids and NMAS *(32)*. The stated purpose of the VFA criterion was to limit the maximum values of VMA and asphalt content.

Aschenbrenner and MacKean examined 101 mix designs to determine which MDL worked best for predicting VMA, achieving the best correlation with the Superpave definition *(33)*. They report that in 1993, the first year the Colorado Department of Transportation specified a minimum VMA, the average mix design asphalt content increased by 0.46 percent.

Kandhal and Chakraborty set out to reexamine the rationale behind the minimum VMA requirements currently being used and to establish an optimum film thickness for mix durability *(8)*. Like Foster, they could not find any significant rational data correlating pavement performance with the currently specified minimum VMA values for HMA mix design. They tested mixtures with six effective asphalt film thicknesses, aged both short and long term, and they tested specimens for resilient modulus and tensile strength. They also tested the recovered binder for penetration, viscosity, complex modulus, and phase angle. In their studies, they found that asphalt film thickness correlated well with resilient modulus,

**Table 5 Average Ratings of Asphalt-aggregate Mix Characteristics by SHRP Expert Task Group (*5*)**

| Characteristic | Rating* | Standard Deviation | "Best" Measurement |
|---|---|---|---|
| Air Voids | 6.77 | 0.44 | Rice specific gravity |
| VMA | 6.15 | 0.90 | Bulk specific gravity of aggregate ($G_{sb}$) |
| VFA | 4.00 | 1.68 | None identified |
| Dust/Asphalt Ratio | 4.46 | 1.85 | None identified |
| Film Thickness | 3.31 | 1.89 | MS-2 Procedure |

*Scaled ratings:

1 – very strongly disagree
2 – strongly disagree
3 – disagree
4 – Neutral
5 – agree
6 – strongly agree
7 – very strongly agree

and they recommended an average film thickness of 9-10 microns for specimens compacted at 8 percent air voids. Interestingly enough, a 9 micron film thickness at 4 percent air voids would require a minimum VMA of 15.6 percent, 1.6 percent higher than the Superpave specification.

Hinrichsen and Heggen also proposed using average film thickness in mix design *(6)*. They provided equations, which used the aggregate gradation and volumetric properties to determine the proper VMA for each mix design uniquely. To do this, they took the standard film thickness equation, assumed a standard film thickness, and back-calculated the amount of asphalt required providing this film thickness. Using volumetric relations, they computed the minimum VMA allowable with this asphalt content and a target air voids. They provided information that showed that mixes based on minimum VMA were not always the best in terms of performance and economics. They questioned the use of "rigid" minimum VMA specifications, showing that there is considerable variability in the tests performed to determine VMA, resulting in a standard deviation of 1.3 percent for VMA.

Anderson and Bahia found achieving VMA was the most difficult and time consuming step in Superpave volumetric mix design *(7)*. They analyzed 128 trial gradations from 32 mix designs performed by The Asphalt Institute from 1992-96 to determine if they could make any recommendations towards selecting an aggregate gradation. Their analysis agreed with prior researchers that VMA is dependent on more than just aggregate gradation. They found that current methods for increasing VMA were not absolutely effective. Their best recommendation to meet VMA requirements was to develop an S-shaped gradation curve ($r^2 = 0.58$) or to use the sum of the distances from the MDL ($r^2 < 0.20$) to meet the VMA requirements.

Kandhal, Foo, and Mallick assumed asphalt mix durability was dependent on film thickness *(9)*. Based on average film thickness, they found the current minimum VMA requirements inadequate for ensuring mix durability. They concluded that it penalized coarse graded mixes with low VMA but adequate film thickness. They recommended dropping the minimum VMA requirement in place of a minimum average film thickness of 8 microns. While they could not find the background research data on which The Asphalt Institute surface area factors are based, they felt they should still be used.

Mallick, et al., point out that McLeod used relatively fine-graded mixtures to develop his relationship *(10)*. Examining 9.5 mm, 12.5 mm, 19.0 mm, 25.0 mm, and 37.5 mm NMAS mixes, they found on average that a 5 percent increase in percent passing the 2.36 mm sieve would increase the VMA by 0.4 percent. They suggest that a more rational way of specifying VMA would be to specify VMA by the percent passing the 2.36 mm sieve. Their recommended design VMA requirements for dense-graded mixes are presented in Table 6.

**Effects of Other Aggregate-related Factors on Critical State Transitions**

In 1957, McLeod summarized the principal factors influencing VMA as follows *(24)*:

1. For any given particle size, the Fuller or Weymouth curve should produce maximum density.
2. Moving off the maximum density curve (To either side!) should provide less density and more VMA.

**Table 6 Proposed Minimum VMA based on NMAS and Percent Passing 2.36 mm (*10*)**

| 9.5 mm | | 12.5 mm | | 19 mm | | 25 mm | | 37.5 mm | |
|---|---|---|---|---|---|---|---|---|---|
| P2.36* | VMA | P2.36 | VMA | P2.36 | VMA | P2.36 | VMA | P2.36 | VMA |
| 67-62 | 16.6 | 58-53 | 15.8 | 49-44 | 14.0 | 45-40 | 13.8 | 41-36 | 13.6 |
| 62-57 | 16.2 | 53-48 | 15.5 | 44-39 | 13.7 | 40-35 | 13.4 | 36-31 | 13.2 |
| 57-52 | 15.7 | 48-43 | 15.2 | 39-34 | 13.4 | 35-30 | 13.1 | 31-26 | 12.8 |
| 52-47 | 15.4 | 43-38 | 14.9 | 34-29 | 13.1 | 30-25 | 12.7 | 26-21 | 12.2 |
| 47-42 | 15.0 | 38-33 | 14.5 | 29-23 | 12.7 | 25-19 | 12.3 | 21-15 | 11.7 |
| 42-37 | 14.6 | 33-28 | 14.1 | | | | | | |
| 37-32 | 14.2 | | | | | | | | |

* P2.36 is the percent by weight of aggregate finer than 2.36 mm

3. Using slightly more (or less) fine aggregate than that of the maximum density curve should open space between the coarser particles resulting in higher VMA.
4. Using appreciably less fine aggregate will result in an "open graded" mixture with relatively high VMA.
5. If the quantity of fine material ranges from slightly less to appreciably more than the Fuller curve, the VMA in the resulting dense graded mixture will increase steadily (slowly) but so will the required asphalt content such that the air voids will still be in the range of 3-5 percent.
6. Choosing to add or reduce fine aggregate depends on (1) required pavement surface texture, (2) whether or not the resulting pavement would be durable enough for local climate and traffic conditions, and (3) relative cost of coarse and fine aggregates.
7. Mineral filler can rapidly increase VMA.

Lefebvre investigated the influence of the principal fractions of the mineral aggregate; coarse aggregate, fine aggregate, fine sand, and mineral filler on the performance of the paving mixture (*25*). He found that the fine aggregates were the most critical component, controlling the VMA and contributing to stability. His recommendations included using a moderately high percentage of fine aggregate containing a small percentage of fine sand. The fine aggregate should be angular, with rough surface texture, and suitably graded. The coarse aggregates, while good for stability, are bad for VMA particularly if mineral filler is present. Mineral filler was not recommended, because it fills voids and takes the place of bitumen, and may be detrimental to durability.

Vallerga examined how aggregate characteristics of size, shape, and surface roughness effect the stability of asphalt paving mixtures (*34*). Based on triaxial testing, he concluded that the most important aggregate characteristic was surface roughness, and believed that size and shape were less important than generally believed.

Campen, et al., stressed that a satisfactory mixture is one where the aggregate contains enough voids to permit the addition of sufficient asphalt to provide comparatively thick films without filling all the voids in the aggregate (*26*). They showed data suggesting that engineers typically use a high coarse aggregate content to control the voids.

Hudson and Davis felt VMA depended on the following conditions (*19*):

1. Particle arrangement or degree of compaction,
2. Relationship between sizes of aggregate particles, in particular the ratio between percents passing adjacent sieves,
3. The range of size between fine and coarse materials, and
4. Aggregate shape.

Field discussed how the MTC adjusted The Asphalt Institute's standard VMA requirement (*4*):

1. For aggregates near the borderline acceptable VMA, if the percent passing 4.75 mm sieve was increased by 5 percent, the required VMA increased by 0.5 percent.
2. For aggregates of good VMA with desirable mix characteristics – cohesion, stability, and coatability, if the passing 4.75 mm sieve was increased by 5 percent, the required VMA increased by 0.8 percent.
3. The minimum VMA should correspond to a minimum air voids content, e.g., if VMA of 15 percent is required for air voids of 5 percent, then if design air voids are decreased, the minimum VMA should decrease correspondingly.

Aschenbrenner and MacKean examined 24 laboratory mixes to study the effects of four variables on VMA (*33*):

1. Gradation,
2. Percent passing 75 μm sieve (filler),
3. Size distribution passing 75 μm sieve, and
4. The fine aggregate angularity.

They found that gradation played a role in influencing VMA, but got such poor correlation that VMA could not effectively be predicted from gradation. The percent filler significantly effects VMA, in particular for gradations on the fine side of the MDL. Lower percent passing 75 μm sieve increased VMA, higher reduced VMA. They recommended that the fine aggregate be kept well off the MDL. Their results examining size distribution passing the 75 μm sieve were inconclusive. They found aggregate angularity to substantially affect the VMA, with crushed aggregates providing more VMA and rounded aggregates less. The fine aggregate angularity was more influential for coarse mixes or mixes following the MDL than for mixes on the fine side of the MDL.

Epps and Hand examined Superpave mixes for mixture sensitivity to asphalt content and percent passing 75 μm sieve, and found the coarse mixtures to be extremely sensitive to small changes in both. They list the following aggregate-related factors as contributing to mixture sensitivity (*35*):

1. Rounded or sub-rounded aggregates;
2. Aggregates with smooth surface texture;
3. An aggregate blend with a high fine aggregate fraction;
4. An aggregate blend with a high natural sand content; and
5. Aggregate blends with a high to intermediate sand content.

**Summary of Literature Review**

The purpose of the literature review was threefold: (1) to examine available laboratory tests for determining the critical transition from sound to unsound mixture, (2) to review how the minimum VMA criterion currently specified in Superpave developed (and any proposed refinements), and (3) locate any information on other aggregate-related factors, e.g., gradation, particle shape, or texture.

Only one paper, by Monismith and Vallerga (*13*), presented an approach that clearly defined the critical asphalt content at which a mix would transition from a sound to unsound condition. They used the triaxial test to evaluate mixture performance. The SHRP permanent deformation research suggests that a variety of laboratory tests, in addition to the triaxial test, could be used for determining the critical state transition. Considerable research has been performed using the triaxial test, however, as indicated by the literature reviewed, the test procedures and conditions have not been standardized.

The available literature on the development of the minimum VMA criterion is sketchy; McLeod presented his relationship without the research or data from which it was derived. He anticipated that it would be modified with experience and test data; the implementation of Superpave has renewed focus on how the minimum VMA requirements impact mix design.

Several authors have pointed out and discussed problems with the VMA criterion in Superpave volumetric mix design and a few have proposed changes. These changes have centered on modifying the minimum VMA criterion to differentiate coarse and fine gradations. A few have argued for replacing the minimum VMA vs. NMAS criterion with a minimum asphalt film thickness specification.

Several authors have pointed out aggregate factors other than NMAS that effect VMA. These include percent filler, shape, surface texture, percent crushed aggregate, fine aggregate angularity, and coarseness of the gradation. Of particular note was the extreme sensitivity of VMA to percent filler; one study recommended against comparing gradations unless the percent filler was held constant.

# CHAPTER 3. MATERIALS

## Asphalt Binder

The asphalt selected for this study was a Superpave performance grade (PG) 58-28 binder supplied by Jebro, Inc., of Sioux City, Iowa. This binder grade is commonly used in Iowa for highway projects. The Superpave binder test results for this binder and the AASHTO MP1 specification requirements are listed in Table 7.

**Table 7 Superpave Test Properties of Asphalt Binder used in Laboratory Testing.**

| | Test Results | Specification Requirements |
|---|---|---|
| Original Properties | | |
| Flash Point Temperature, °C | 230 °C | |
| Rotational Viscosity, 135 °C | 0.247 | 3.0 maximum |
| Dynamic Shear, @ 10 rad/s kPa | 1.024 @ 58 °C | 1.0 minimum |
| Rolling Thin Film Oven (RTFO) Residue | | |
| Mass Loss, % | 0.248 | 1.0 maximum |
| Dynamic Shear, @ 10 rad/s kPa | 2.515 @ 58°C | 2.2 minimum |
| Pressure Aging Vessel (PAV) Residue | | |
| Dynamic Shear, @ 10 rad/s kPa | 4253 @ 19°C | 5000 maximum |
| Creep Stiffness @ 60 s, MPa | 239 @ -18 °C | 300 maximum |
| m-value | 0.303 @ -18 °C | 0.300 minimum |

## Aggregates

Two local sources of aggregates used to construct hot-mix asphalt pavements were used in the study. The manufactured aggregates (both coarse and fine) were 100 percent crushed limestone from Ames, IA was supplied by Martin-Marietta Aggregates. Automated Sand and Gravel, of Fort Dodge, IA provided both the coarse and fine natural aggregates used in this study.

**Aggregate Blends**

The two sources of aggregates were sieved and recombined into the four aggregate blends shown in Table 8. Formally defined, the four blends are:

1. **Manufactured** - Each gradation is 100 percent crushed material (coarse and fine).
2. **Natural** - Each gradation is 100 percent natural material (coarse and fine).
3. **50-50 Blend** - Each gradation is a blend of 50 percent manufactured, 50 percent natural on each sieve size.
4. **NCMF (Natural Coarse-Manufactured Fine)** - The material passing the 4.75 mm sieve was 100 percent manufactured and the material retained 100 percent natural. The coarse (natural) aggregate was washed to ensure that the p0.075 mm material was obtained entirely from the manufactured aggregates.

It was believed that these four blends would provide enough information to evaluate the effects of gradation and shape for both the fine and coarse aggregates.

**Table 8 Aggregate Blends used in Laboratory Testing**

| | Coarse Fraction (% retained on 4.75 mm sieve) | | Fine Fraction (% passing 4.75 mm sieve) | |
|---|---|---|---|---|
| Blend | Manufactured | Natural | Manufactured | Natural |
| 1. Manufactured | 100 | --- | 100 | --- |
| 2. Natural | --- | 100 | --- | 100 |
| 3. 50-50 | 50 | 50 | 50 | 50 |
| 4. NCMF | --- | 100 | 100 | --- |

**Aggregate Gradations**

Three NMAS, 19 mm, 12.5 mm, and 9.5 mm, were selected to represent the asphalt mixes commonly used in Iowa. For each NMAS, a fine, dense, and coarse aggregate gradation was developed as listed in Table 9 and shown in Figures 7-9. Because the literature review suggested against comparing gradations with different percent filler, the filler was held constant for all gradations.

**Table 9 Aggregate Gradations used in the Study**

| Sieve Size (mm) | Percent Passing | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 9.5 mm NMAS | | | 12.5 mm NMAS | | | 19.0 mm NMAS | | |
| | Fine | Dense | Coarse | Fine | Dense | Coarse | Fine | Dense | Coarse |
| 19.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 12.5 | 100 | 100 | 100 | 95 | 95 | 95 | 87 | 74 | 65 |
| 9.5 | 95 | 95 | 95 | 86 | 73 | 65 | 78 | 65 | 55 |
| 4.75 | 80 | 65 | 55 | 65 | 54 | 45 | 59 | 47 | 40 |
| 2.36 | 60 | 47 | 36 | 50 | 39 | 32 | 45 | 34 | 28 |
| 1.18 | 45 | 34 | 25 | 37 | 29 | 22 | 33 | 25 | 20 |
| 0.600 | 32 | 26 | 17 | 27 | 21 | 15 | 25 | 18 | 14 |
| 0.300 | 22 | 19 | 12 | 18 | 15 | 10 | 18 | 13 | 10 |
| 0.150 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| 0.075 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |

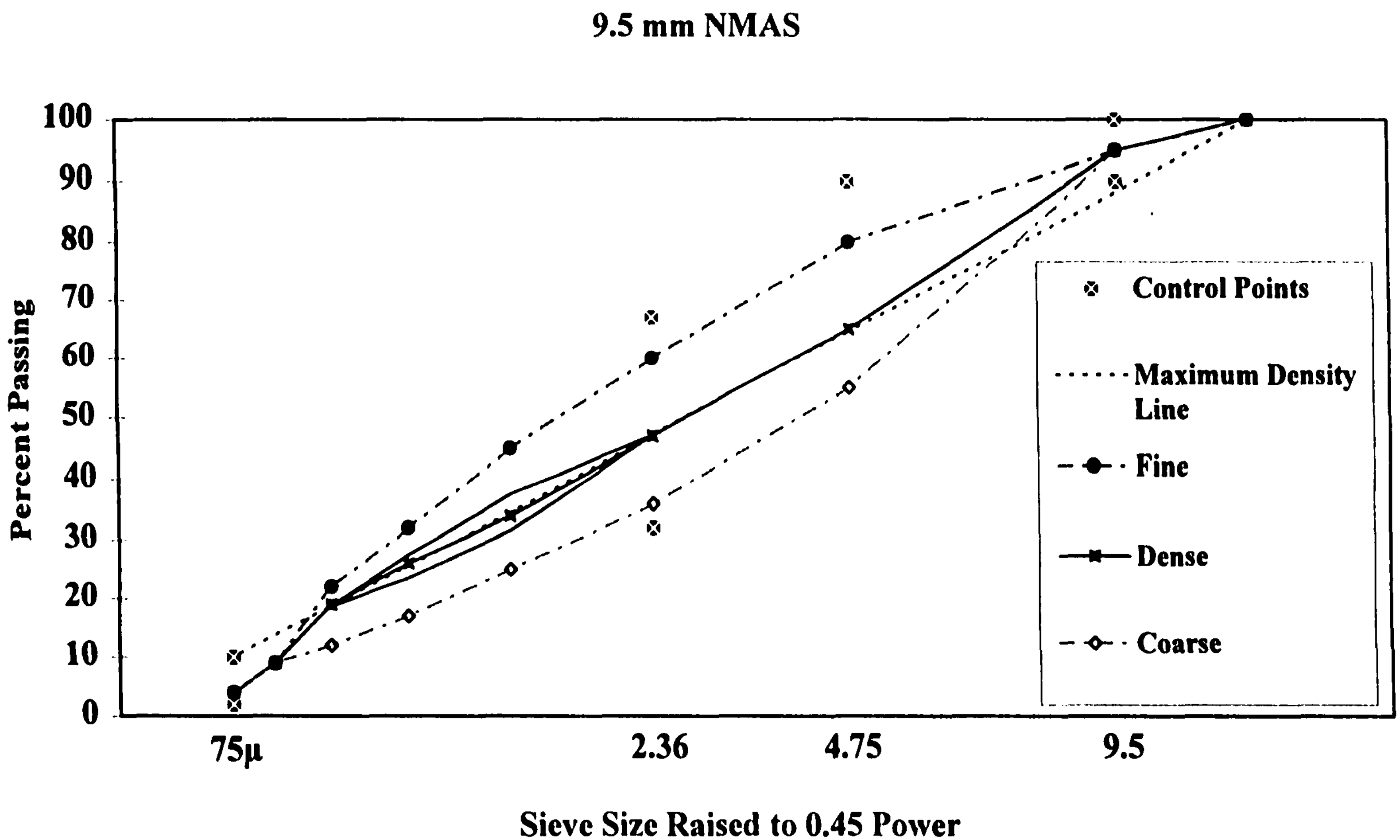


**Figure 7 9.5 mm NMAS Gradations used in Study**

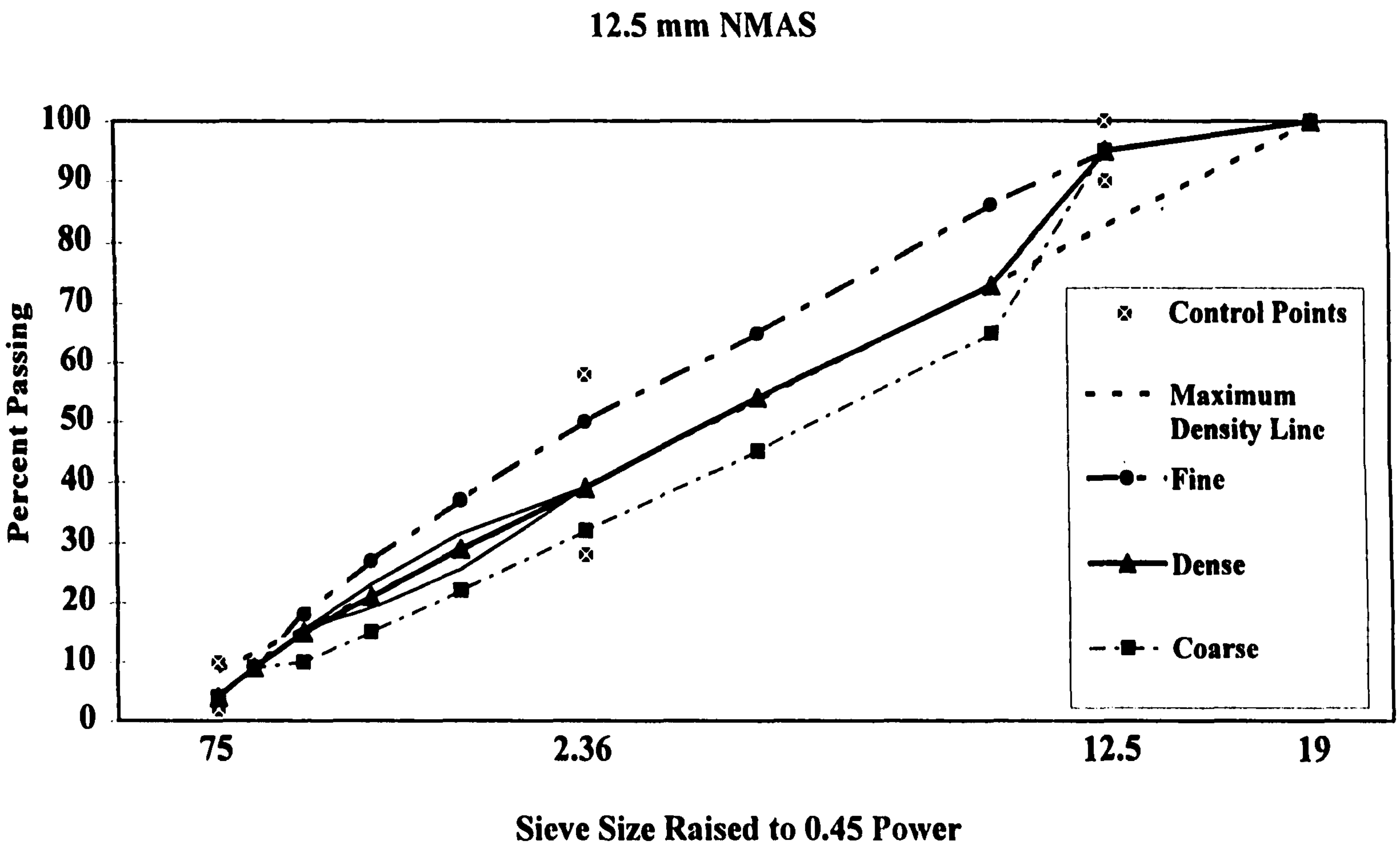


Figure 8 12.5 mm NMAS Gradations used in Study

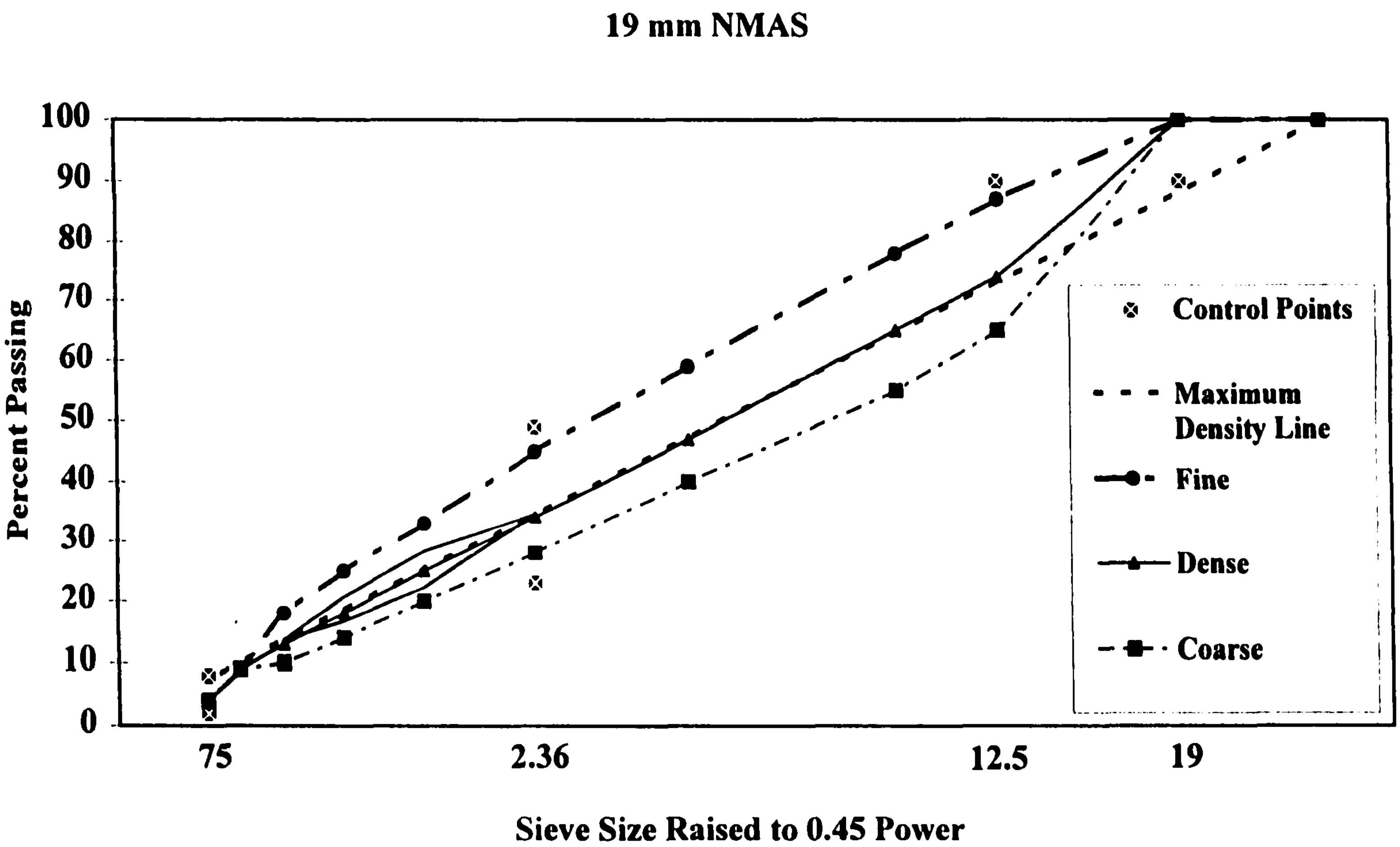


Figure 9 19 mm NMAS Gradations used in Study

**Aggregate Properties**

In Superpave, two categories of aggregate properties are required: consensus properties and source properties. The consensus properties, which measure critical aggregate characteristics necessary to achieve good performance, require the following tests:

1. Coarse aggregate angularity,
2. Fine aggregate angularity,
3. Flat, elongated particles, and
4. Clay content.

The source properties, which are also important to mixture performance but source specific and related to the inherent quality of the parent material, require the following tests:

1. Toughness,
2. Soundness, and
3. Deleterious materials.

The consensus tests were performed on both types of aggregates. Since both sources of aggregates are used in hot-mix asphalt production, the source tests were not performed.

**Superpave Consensus Properties**

*Coarse Aggregate Angularity*

The test specified in Superpave for determining the percentage of fractured particles in the coarse aggregate is ASTM D5821. The test is performed on aggregates retained on the 4.75 mm sieve. A fractured particle is defined as a particle with one or more crushed faces, with ASTM specifying a crushed section as having a minimum crushed area of 25% of the maximum cross sectional area of the particle. The results for both types of aggregates are shown in Table 10.

**Table 10 Percentage of Fractured Particles in the Coarse Aggregates used in Study**

| Aggregate | Fractured Faces (% mass) | | | |
|---|---|---|---|---|
| | Fractured Faces | 12.5 mm | 9.5 mm | 4.75 mm |
| Natural | 1 or more | 0 | 0 | 0 |
| | 2 or more | 0 | 0 | 0 |
| Manufactured | 1 or more | 100 | 100 | 100 |
| | 2 or more | 100 | 100 | 100 |

For the natural aggregates, most of the material had obviously been fractured at one time but had been subsequently worn smooth. There were no freshly fractured faces. All of the manufactured aggregate had two or more fractured faces.

*Flat or Elongated Particles in Coarse Aggregate*

The test specified in Superpave for determining the percentage of fractured particles in the coarse aggregate is ASTM D4791. Flat and elongated particles impede compaction and consequently affect strength. This test uses a proportional caliper device to determine whether each particle exceeds a specified ratio of maximum to minimum dimension ratio. The results for both types of aggregates are shown in Table 11.

**Table 11 Percentage of Flat and Elongated Particles in the Coarse Aggregates used in Study**

| Aggregate | | Flat and elongated particles (% mass) | | |
|---|---|---|---|---|
| | | 12.5 mm | 9.5 mm | 4.75 mm |
| Natural | 3:1 | 0.5 | 0.5 | 2.3 |
| | 5:1 | 0 | 0 | 0 |
| Manufactured | 3:1 | 1.5 | 1.2 | 1.3 |
| | 5:1 | 0 | 0 | 0 |

Both the natural and manufactured aggregates had a few flat particles but none that were elongated.

*Fine Aggregate Angularity*

Superpave uses the uncompacted void content of fine aggregate test (ASTM C1252), method A, to measure fine aggregate angularity. In this test, fine aggregate, of a specified gradation, is funneled into a cylinder. The amount that is retained in the cylinder is weighed and the voids are computed using the bulk specific gravity of the fine aggregate. This test was performed on both types of aggregates and the results obtained are shown in Table 12. The results indicate that the manufactured and natural aggregates were significantly different in uncompacted void content.

**Table 12 Fine Aggregate Angularity of Aggregates used in Study**

| Aggregate Type | Uncompacted Voids |
|---|---|
| Manufactured | 46.7 |
| Natural | 40.7 |

*Clay Content*

Superpave uses the Plastic Fines in Graded Aggregates and Soils by Use of Sand Equivalent Test (ASTM D2419) test to measure the percentage of clay in the aggregate fraction that is finer than the 4.75 mm sieve. For both aggregate sources, the gradation with the highest content of material passing the 4.75 mm sieve was used. The results of these tests are shown in Table 13 and suggest that both types of aggregates were very clean. Since all gradations were combined from the same materials, the other gradations were not tested.

**Table 13 Clay Content Results**

| Aggregate | Blend | Sand Equivalent |
|---|---|---|
| Manufactured | 9.5 Fine | 95 |
| Natural | 9.5 Fine | 91 |

*Aggregate Specific Gravity*

The aggregate bulk specific gravity is extremely important in volumetric mix designs, where it is used to calculate VMA, as shown in the equation below.

$$VMA = 100 - \frac{Gmb * Ps}{Gsb}$$

where Gmb = Bulk specific gravity of the compacted mixture,

Ps = Aggregate content, percent by total mass of mixture, and

Gsb = Bulk specific gravity of total aggregate.

In the study, it was deemed more efficient to measure specific gravity on each sieve size separately and then compute the specific gravity for each gradation. Three test methods were used to determine aggregate specific gravity:

1. Specific Gravity and Absorption of Fine Aggregate (ASTM C128)
2. Specific Gravity and Absorption of Coarse Aggregate (ASTM C127)

3. Density of Hydraulic Cement (ASTM C188-89)

The first two methods are commonly used for aggregates, but the difficulties inherent in getting the relatively single-sized sieved material finer than 1.18 mm to an identifiable saturated-surface dry condition are considerable. For this reason, ASTM C188-89, which uses a Le Chatelier's flask was used on the 0.60 mm sieve and finer sized aggregates. It must be noted that in this test, the aggregates are not given time to absorb water, hence, the results are more an apparent specific gravity than a bulk specific gravity. The absorption for the natural aggregate averaged 2.7% and the manufactured aggregates averaged 2.4% (both had standard deviations of 0.4 %). The single size sieve results for specific gravity are listed in Appendix A. The aggregate bulk specific gravities were computed two ways:

1. Assuming no absorption for the material tested using Le Chatelier's flask, and
2. Adjusting the apparent specific gravity obtained in Le Chatelier's flask by the average absorption of the coarse material to get a bulk specific gravity.

The computed bulk specific gravities of all 36 blends using both methods is presented in Table 14. Close scrutiny of Table 14 shows that assuming no absorption raises the bulk specific gravity for all aggregate blends by 0.018 on average, effecting the finer gradations more, and the coarse less. The ASTM precision statement on test method C-128 gives an acceptable range of 0.032 between two tests, suggesting that either method could be used. However, it seems more reasonable to assume that the absorption for the aggregates finer than 1.18 mm would be close to that obtained for the coarse material than to assume no absorption.

**Table 14 Calculated Specific Gravity for each Aggregate Blend**

| Mix | | Manufactured | | Natural | | NCMF | | 50-50 | |
|---|---|---|---|---|---|---|---|---|---|
| NMAS | Gradation | $G_{sa}$* | $G_{sb}$** | $G_{sa}$ | $G_{sb}$ | $G_{sa}$ | $G_{sb}$ | $G_{sa}$ | $G_{sb}$ |
| 9.5 mm | Fine | 2.647 | 2.620 | 2.580 | 2.549 | 2.632 | 2.605 | 2.613 | 2.584 |
| | Dense | 2.628 | 2.608 | 2.559 | 2.536 | 2.601 | 2.581 | 2.593 | 2.572 |
| | Coarse | 2.612 | 2.597 | 2.542 | 2.525 | 2.577 | 2.563 | 2.577 | 2.561 |
| 12.5 mm | Fine | 2.631 | 2.609 | 2.565 | 2.540 | 2.607 | 2.586 | 2.597 | 2.574 |
| | Dense | 2.616 | 2.599 | 2.554 | 2.534 | 2.590 | 2.573 | 2.585 | 2.567 |
| | Coarse | 2.604 | 2.591 | 2.544 | 2.529 | 2.573 | 2.560 | 2.573 | 2.560 |
| 19 mm | Fine | 2.624 | 2.604 | 2.560 | 2.538 | 2.599 | 2.580 | 2.592 | 2.571 |
| | Dense | 2.608 | 2.593 | 2.549 | 2.532 | 2.580 | 2.566 | 2.578 | 2.563 |
| | Coarse | 2.599 | 2.587 | 2.543 | 2.530 | 2.570 | 2.559 | 2.571 | 2.558 |

* $G_{sa}$ - Apparent specific gravity obtained in Le Chatelier's flask used for aggregates finer than 1.18 mm sieve without considering absorption

** $G_{sb}$ - Apparent specific gravity obtained in Le Chatelier's flask used for aggregates finer than 1.18 mm sieve modified to account for absorption.

# CHAPTER 4. METHODOLOGY

The fourth objective of this dissertation was to establish a laboratory method by which the transition of an asphalt paving mixture from sound to unsound behavior may be credibly identified and measured. The test equipment selected for identifying the critical state transition was the Nottingham Asphalt Tester (NAT) manufactured by Cooper Research Technology Limited of Derbyshire, U.K. This equipment, shown in Figure 10, is extremely versatile and has come close to being the standard testing device throughout Europe under the developing European Standards (EN). The NAT repeated load triaxial (RLT) test is a promising new configuration for assessing deformation resistance.

The laboratory testing consisted of two studies, a pilot study and the main study. The pilot study was conducted to gain familiarity with the NAT and to determine the test conditions (temperature, stress regime, duration) that would be used in the main study.

## Pilot Study

The pilot study was undertaken to ascertain the capabilities and limitations of the NAT. Since the RLT apparatus is still a prototype test, standard test specifications are still under development. Temperatures of 40, 45, and 50°C, (104, 113, and 122 °F) were used in conjunction with confining pressures of 35, 70, and 100 kPa. Initially, a deviator stress of 250 kPa was used; this was raised to 300 kPa, the limit of the equipment, when a new source of air pressure was installed. Of critical importance was determining the number of cycles to be used in each test. The load frequency is fixed at 2 Hz, hence there would be 1800 load applications in one hour. Due to the number of specimens to be tested, it was deemed imperative that the test be no longer than one hour. It was also necessary to determine the conditioning time for a specimen to get to test temperature. The following information was learned from the pilot study:

1. Test conditions of 45 °C (113°F), 17 kPa confining stress, 300 kPa deviator stress, and a test duration of 1800 cycles (one hour) would be used. It takes approximately 125 minutes for the specimens to get to test temperature; therefore 130 minutes was used as the conditioning time for the study.

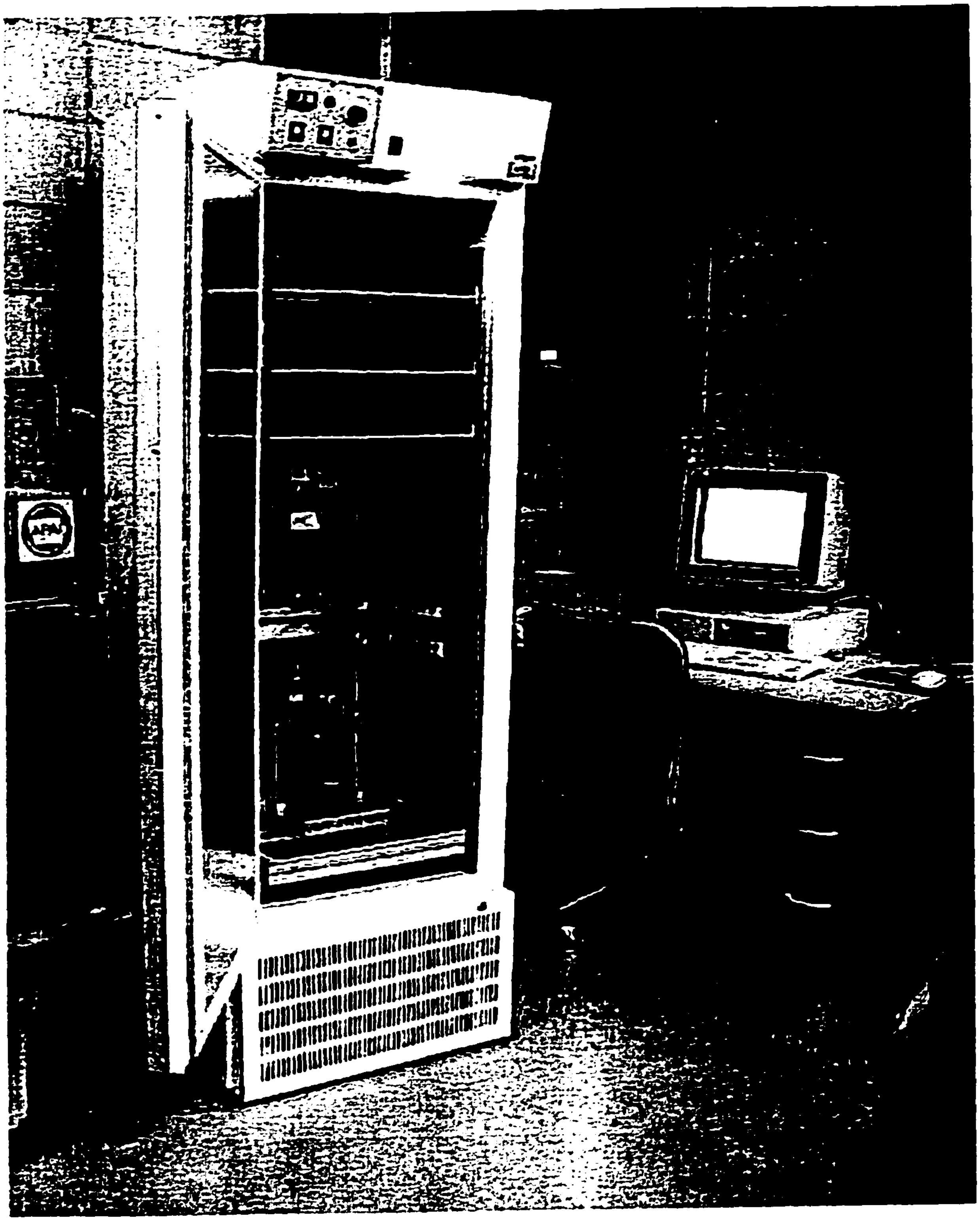

**Figure 10 The Nottingham Asphalt Tester**

2. The RLT measures vertical strain and computes stiffness. There is no measure of volumetric strain.
3. The RLT is compatible with specimens compacted in the Superpave Gyratory Compactor (SGC). However, specimens of normal height (115 mm) are the upper limit of the equipment as configured and awkward to test. This limits the maximum practical height to diameter ratio to about 0.75, which is below the conventionally accepted minimum ratio of 1-1 for triaxial testing of asphalt mixtures.
4. The specimens would not be sawn and polished; however they would be lubricated with silicon grease prior to testing as recommended. Figure 11 shows the differences between sawn and unsawn specimen.
5. Based on the conditioning time of 130 minutes and assuming an average time of 10 minutes to remove and replace test specimens, 5 to 6 specimens could be tested in a typical day.

The conditions used for testing are summarized in Table 15.

**Table 15 Test Conditions used in the Study**

| Test Property | Test Conditions |
|---|---|
| Temperature, | 45°C |
| Deviator stress, | 300 kPa |
| Confining stress, | 17 kPa |
| Number of repetitions | 1800 cycles (1 hour) |
| Specimen Ends | Unsawn, Lubricated |
| Preconditioning | 2 hours at test temperature |

The awkwardness of testing 115 mm, 4700 g specimens made it desirable to use a different size of specimen. Previous research indicated that the density of the SGC compacted HMA would not be significantly affected if the specimen height was decreased to 75 mm, 3375 g (*37*). To verify this, and examine the effects of this change on NAT testing, specimens fabricated from two different mixes were tested using the conditions specified in Table 15. Figure 12 shows the size difference between the 4700 and 3375 gram specimens. The results are shown in Table 16.

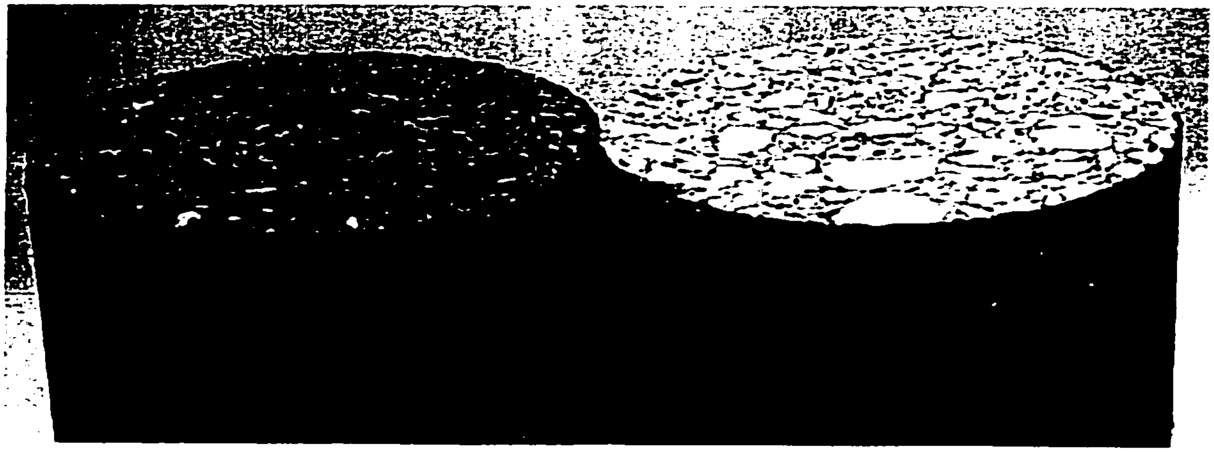

**Figure 11 Unsawn and Sawn Ends of Compacted Specimens**

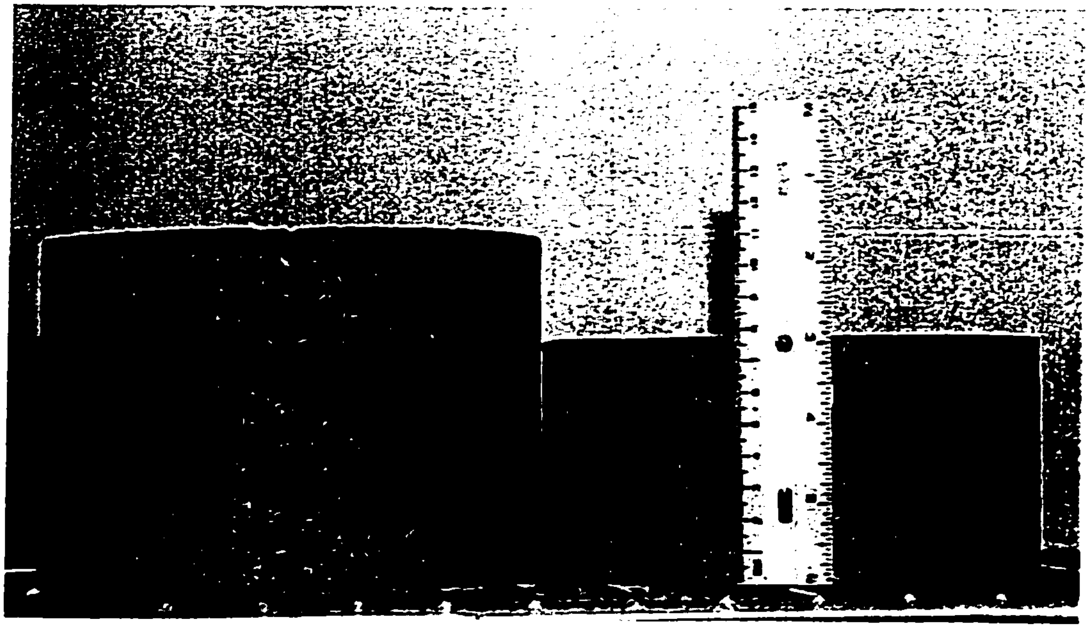

**Figure 12 Comparison of 4700 g Conventional Superpave Specimen and Smaller 3375 g Specimen used in Study**

**Table 16 Effects of Different Specimen Heights**

| Specimen ID | Height (mm) | Bulk Specific Gravity of Mix | Air Voids (%) | NAT µ-strain |
|---|---|---|---|---|
| A1 | 80.2 | 2.4158 | 3.9 | 9895 |
| A2 | 112.2 | 2.4175 | 3.9 | 10444 |
| S1 | 79.8 | 2.4669 | 2.9 | 7205 |
| S2 | 110.2 | 2.4682 | 2.8 | 8072 |
| Average Change %) | 28% | 0.06% | | 8% |

The data in Table 16 supports the claim that the volumetric properties are not effected by the reduction in size. For the NAT results, the size reduction reduced accumulated micro-strain by 8% on average. This implies that small changes in specimen height should not effect the determination of the critical transition.

## Main Study

*Laboratory Testing Protocol*

The protocol used for laboratory testing followed AASHTO standards wherever possible. However, because there were some deviations from convention, for discussion purposes, the laboratory work is broken down into distinct steps:

1. Batching,
2. Mixing, Aging, and Compaction,
3. Pre-NAT Bulk Specific Gravity,
4. NAT Testing,
5. Post-NAT Bulk Specific Gravity, and
6. Theoretical Maximum Specific Gravity.

The laboratory process is shown graphically in the flowchart shown in Figure 13.

*Batching*

Prior to testing, the aggregates had been dried, sieved, and stored in 20 gallon containers. Once a gradation blend was selected, the first step was to determine the quantity of filler (material passing the 75 µm sieve) contained in that blend. To do this, a washed

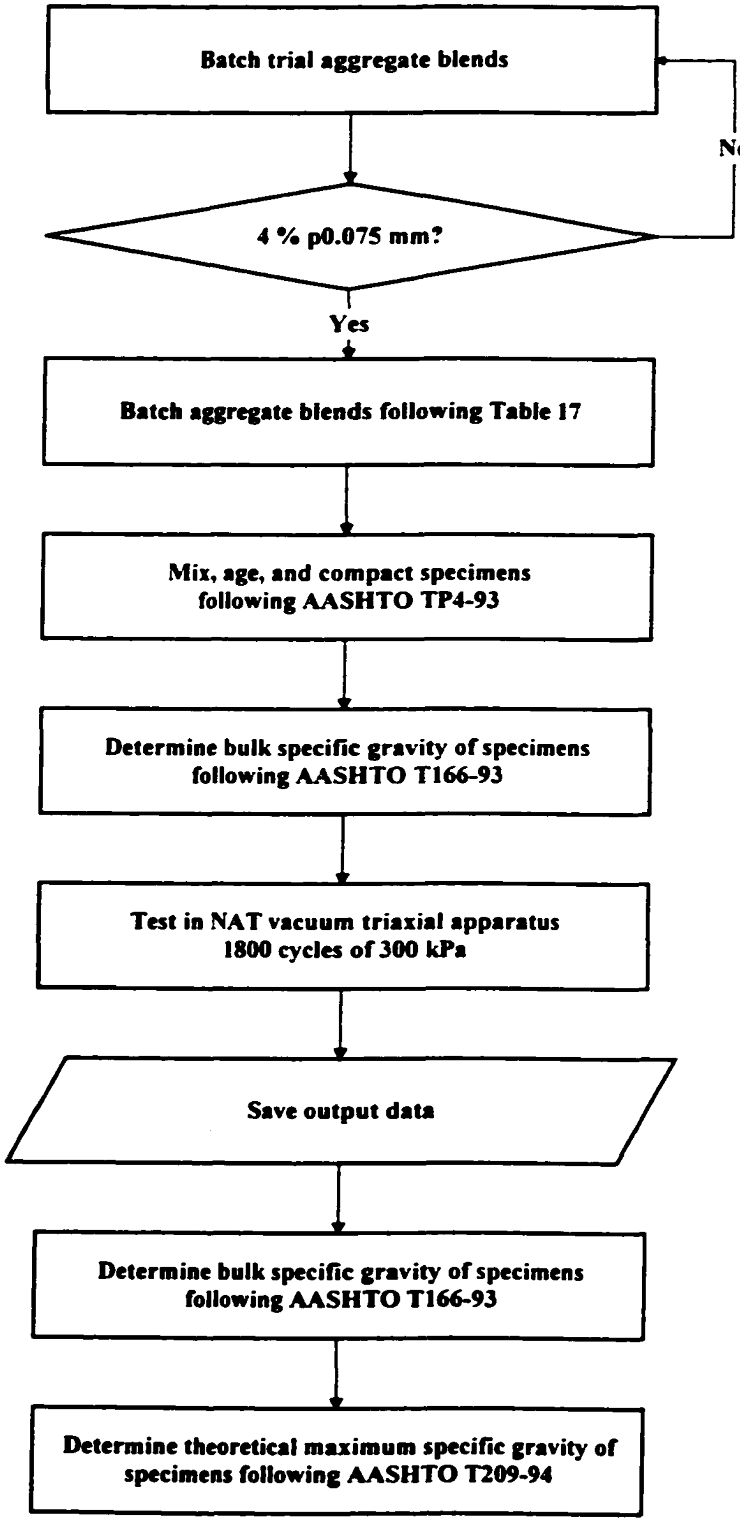


**Figure 13 Flow Chart of Laboratory Testing**

sieve analysis was performed following AASHTO T11-91, on two 1000 g samples. The test results were averaged and if the difference in p0.075 mm material was more than 0.5 percent, a third test was performed.

Once the percent of filler was determined, aggregate for ten specimens (two at each asphalt content) were blended as shown in Table 17. The blended aggregates were heated in an oven overnight to approximately 160 °C. The asphalt was heated at 147 °C until sufficiently fluid for mixing.

**Table 17 Batch Aggregate Weights used in Laboratory Testing**

| Asphalt Content (%) | Wt. of Blended Aggregate (g) |
|---|---|
| 4 | 3240.0 |
| 5 | 3206.3 |
| 6 | 3172.5 |
| 7 | 3138.8 |
| 8 | 3105.0 |

**Mixing, Aging, and Compaction**

Mixing, aging, and compaction were performed in accordance with AASHTO TP4-93 (*38*). The viscosity of the binder targeted a mixing temperature of 147 °C and compaction temperature of 135 °C. The aggregates were placed into a heated mixing bowl and dry mixed by hand. The asphalt was added then the asphalt-aggregate mixture was mixed mechanically for 30-45 seconds (until a uniform coating was observed). The mix was then transferred to a pan and aged for two hours in an oven at 135°C. After an hour the mix was stirred to ensure uniform heating and aging.

The specimens were compacted to 109 gyrations in the SGC then allowed to cool overnight. Some of the "rich" mixes required using two sets of papers in the mold to prevent the compacted specimen from sticking to the ram. Once cooled, the bulk specific gravity of the compacted specimens was obtained following AASHTO T166-93. The specimens were then "air-dried" back to within 1g of their original weight. Volumetric data for all specimens tested is tabulated in Appendix B.

**NAT Testing**

Prior to testing, the specimens were conditioned in the NAT for 130 minutes to ensure that they were equilibrated at the test temperature of 45 °C. The NAT requires specimen heights to the nearest millimeter, the SGC provides height data to a tenth of a millimeter. After checking several specimens with a micrometer, it was decided to use the SGC height data and round to the nearest millimeter.

Once the specimens were at test temperature, the platens of the apparatus were coated with a thick layer of silicon-teflon grease. The specimen was placed on the bottom platen, the rubber membrane slid over the specimen, and secured with an O-ring. The top platen was set in place and secured with an O-ring. Then, the jacketed specimen was placed in the temperature chamber, and the vacuum hose connected. The vacuum of 17 kPa would draw the membrane tight, any wrinkles were smoothed out, and then the apparatus would be centered in the load frame, the crosshead adjusted to the correct height, and the linear variable displacement transducers (LVDTs) centered for testing. With practice, the procedure can be done very quickly, only taking a few minutes. There is a 2-minute period of load pre-conditioning prior to the test beginning. After this, the specimen receives 1800 applications of a 300 kPa load and the accumulated axial strain is measured.

Once the test is complete, the specimen is carefully removed and allowed to cool to room temperature, the platens and membrane are cleaned and wiped dry, and the next test is started. NAT data for all specimens tested is in Appendix C.

**Post-NAT Testing**

After cooling, the bulk specific gravities of the specimens were again measured in accordance with AASHTO T166-93. There usually was not a significant difference between the pre-NAT and post-NAT bulk specific gravity. The specimens were then placed in a pan and heated for approximately two hours at 135 °C to soften and break apart prior to determining their theoretical maximum specific gravity following AASHTO T209-94.

**Summary**

Developing a consistent, rigorous, and most importantly, usable test protocol was a fundamental task in the study. It was important to follow existing specifications wherever possible, yet at the same time, perform the testing on schedule.

AASHTO specifications were followed with one notable exception in that the mass of the SGC specimens was 3375 g, instead of 4500-4700 g. This was necessary since the NAT is intended for specimens between 40 and 100 mm thick. The compacted specimens ranged in height from 75 to 87 mm. The preliminary study into the effects of specimen height indicated that this would have only a slight impact on the NAT results and would not affect the determination of the critical change of state where the mix becomes unsound.

The applicable British Standards calling for specimen ends to be sawn and polished was not followed as it would have been time consuming and created difficulties with determining the theoretical maximum specific gravity of the test specimen. The specimen ends were lubricated as required in the British Standards.

# CHAPTER 5. RESULTS AND DISCUSSION

## Determination of the Critical State

Once the laboratory testing was complete, the test data was analyzed to determine the critical volumetric properties for each of the 36 aggregate blends. The first step of the analysis was to determine the critical transition asphalt content of the compacted HMA mixture based on a visual analysis of the NAT results. To show how this was done, the test results for two of the 100 percent manufactured 9.5 mm NMAS mixes are shown in Figure 14. In this figure, each point is the average of two specimens. The accumulated microstrain of the Dense mix (MM9.5D) seems to increase slowly with increasing asphalt content until about 6.9 percent asphalt content where the axial strain begins to increase dramatically. Thus, 6.9 percent asphalt is the critical asphalt content for this mix where it transitions from sound to unsound behavior. Thirty-one of the thirty-six mixes showed this transition clearly. The other five mixes were similar to the fine mix (MM9.5F) and did not have a clear peak and were not further analyzed.

In performing the visual analysis, it was observed that the critical transition was usually close to the peak "dry density" (Gmd) or maximum aggregate concentration of the asphalt mix. Figure 15 shows how axial microstrain compared with dry density for two of the 100% natural 9.5 NMAS mixes. When the visually observed critical asphalt contents were regressed against the measured peak dry density of the mixes tested, the two methods agreed remarkably well with an adjusted $R^2 = 0.883$. Thus, the peak dry density of the compacted mix provides a rational method of identifying the critical change of state threshold in asphalt mixtures.

For each of the thirty-one mixes that became plastic (i.e., unsound), Table 18 lists the critical asphalt contents obtained using visual analysis (eye) and Gmd, and the critical air voids ($V_a$), VMA, VFA, and asphalt film thickness (FT), that were calculated using the critical asphalt content ($pb_{crit}$) obtained with Gmd. The five mixes that did not show a critical value are shaded and marked N/A.

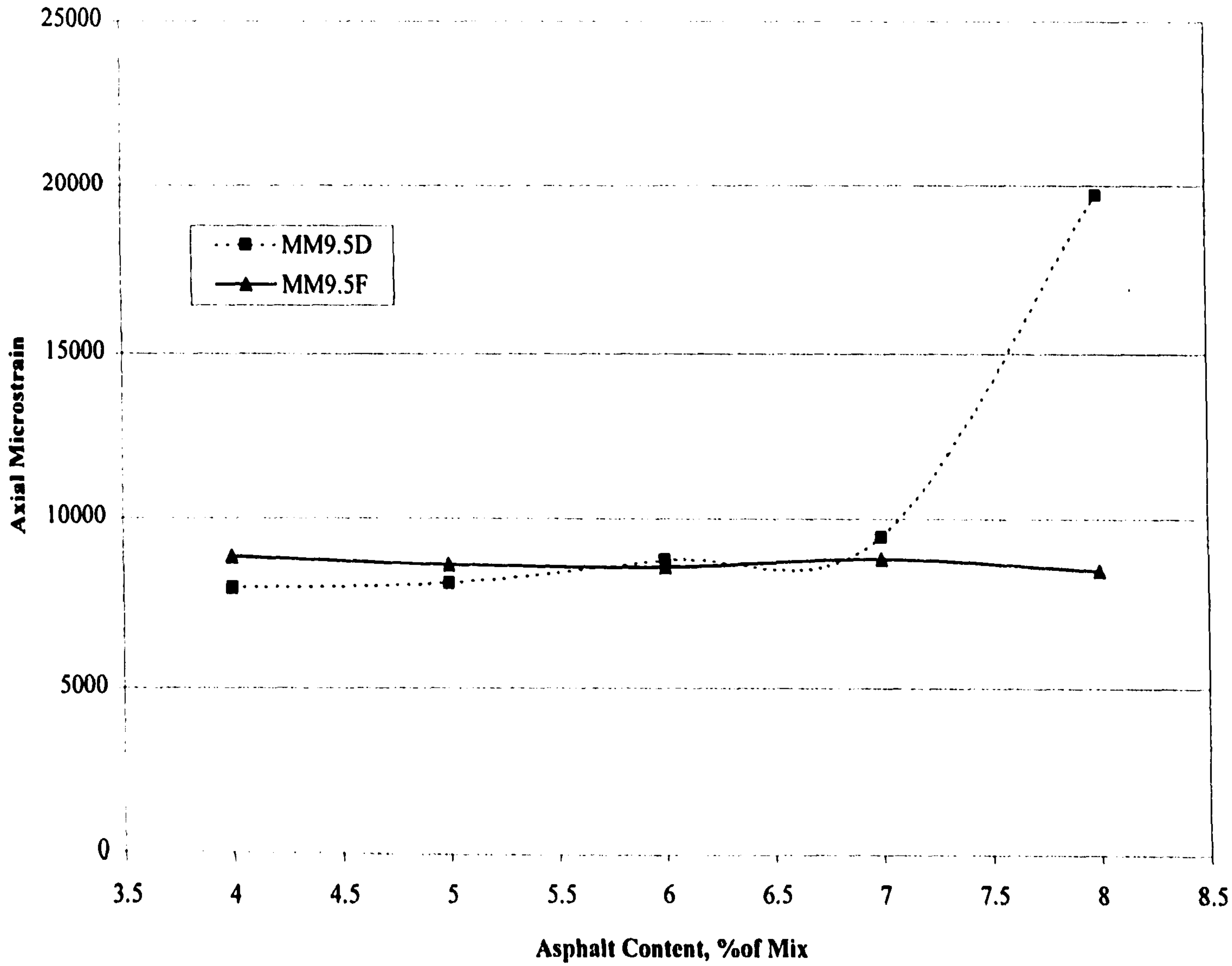


**Figure 14 Typical NAT Results used for Determining Critical Transition Asphalt Content**

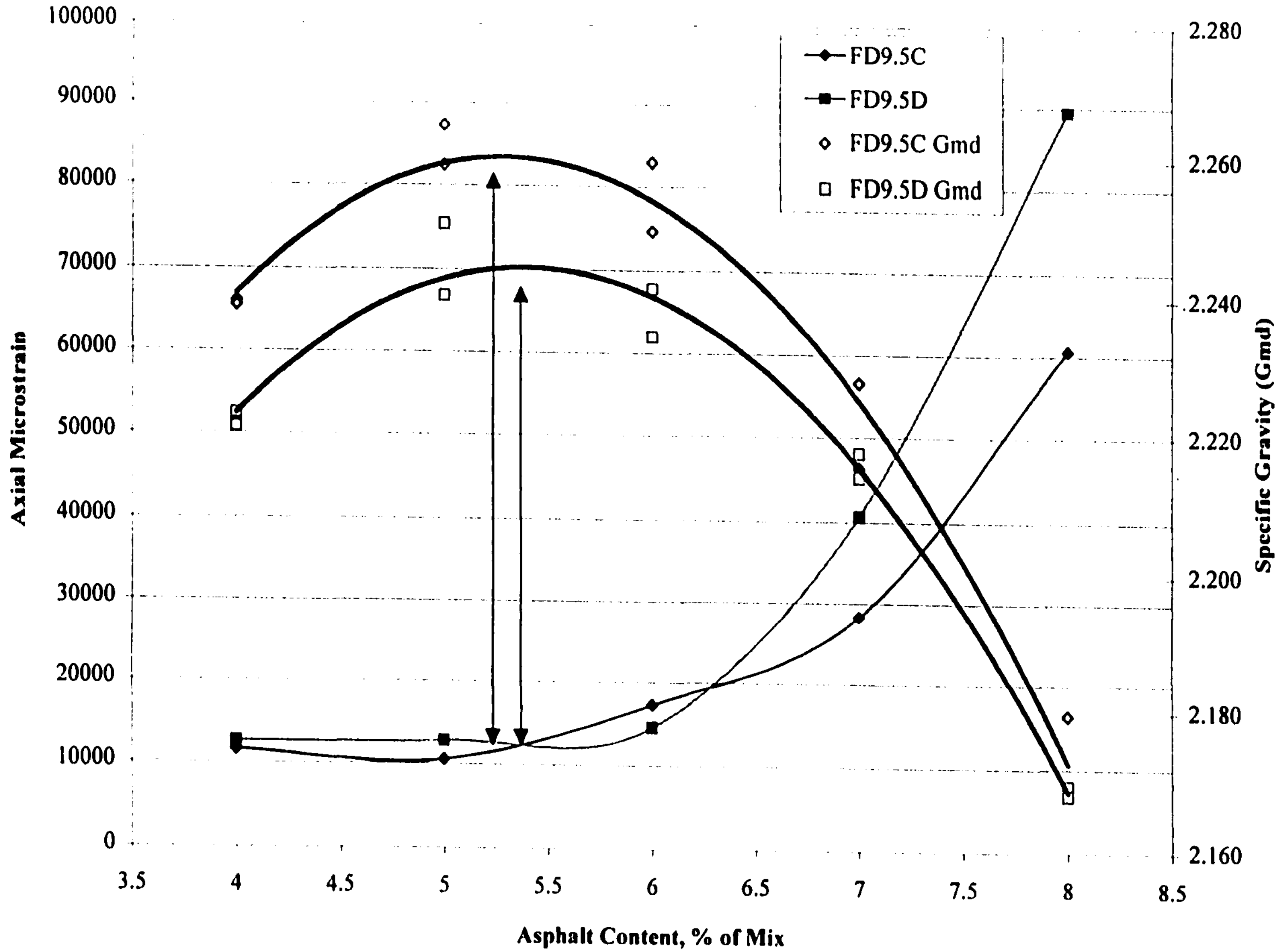


**Figure 15 Comparison of Critical Asphalt Transition using NAT Results and Peak Dry Density**

**Table 18 Volumetric Parameters at the Critical Transition**

| NMS | Gradation | C/F | $Pb_{Crit}$ (eye) | $Pb_{Crit}$ (Gmd) | Va | VMA | VFA | FT |
|---|---|---|---|---|---|---|---|---|
| 9.5 | Coarse | M/M | 6.9 | 6.2 | 2.8 | 13.3 | 79.2 | 8.8 |
| | | 50-50 | 7.1 | 6.2 | 2.8 | 13.2 | 76.9 | 8.6 |
| | | MFNC | 7.0 | 6.3 | 3.5 | 13.2 | 73.5 | 8.0 |
| | | N/N | 6.1 | 5.3 | 2.4 | 10.8 | 77.4 | 7.1 |
| | Dense | M/M | 6.9 | 7.1 | 1.1 | 14.0 | 91.9 | 9.0 |
| | | 50-50 | 7.0 | 6.4 | 3.1 | 13.8 | 77.3 | 7.6 |
| | | MFNC | 6.9 | 7.2 | 1.2 | 14.0 | 91.4 | 8.9 |
| | | N/N | 6.0 | 5.4 | 2.9 | 11.8 | 75.1 | 6.3 |
| | Fine | M/M | N/A | | | N/A | | |
| | | 50-50 | N/A | | | N/A | | |
| | | MFNC | N/A | | | N/A | | |
| | | N/N | N/A | 5.1 | 5.6 | 13.5 | 58.4 | 5.0 |
| 12.5 | Coarse | M/M | 6.5 | 6 | 1.6 | 11.6 | 86.4 | 8.9 |
| | | 50-50 | 6.3 | 5.4 | 3.0 | 11.1 | 73.4 | 7.3 |
| | | MFNC | 6.0 | 5.6 | 2.5 | 10.9 | 77.5 | 7.4 |
| | | N/N | 6.1 | 5.5 | 2.7 | 11.7 | 77.2 | 8.3 |
| | Dense | M/M | 6.4 | 6 | 3.2 | 13.1 | 75.3 | 7.7 |
| | | 50-50 | 6.2 | 5.6 | 1.8 | 11.1 | 84.1 | 7.2 |
| | | MFNC | 6.3 | 5.8 | 2.2 | 11.6 | 79.5 | 7.2 |
| | | N/N | 5.5 | 5 | 2.1 | 9.9 | 78.9 | 6.1 |
| | Fine | M/M | N/A | | | N/A | | |
| | | 50-50 | 6.7 | 5.9 | 3.4 | 13.5 | 74.7 | 7.2 |
| | | MFNC | N/A | | | N/A | | |
| | | N/N | 6 | 5.3 | 3.2 | 12.0 | 73.7 | 6.3 |
| 19 | Coarse | M/M | 6.0 | 5.4 | 3.0 | 11.5 | 73.4 | 7.6 |
| | | 50-50 | 5.8 | 4.8 | 2.9 | 9.5 | 69.1 | 6.0 |
| | | MFNC | 5.9 | 5.1 | 2.3 | 9.2 | 75.4 | 6.2 |
| | | N/N | 5.5 | 4.8 | 2.4 | 8.4 | 71.7 | 5.3 |
| | Dense | M/M | 6.3 | 5.7 | 2.2 | 11.6 | 81.2 | 7.6 |
| | | 50-50 | 5.3 | 4.4 | 4.8 | 10.6 | 54.3 | 4.7 |
| | | MFNC | 6.3 | 5.3 | 3.1 | 10.7 | 71.2 | 6.2 |
| | | N/N | 5.2 | 4.5 | 3.2 | 8.7 | 63.5 | 4.5 |
| | Fine | M/M | 6.9 | 6.4 | 3.4 | 14.4 | 76.2 | 8.0 |
| | | 50-50 | 5.7 | 5.1 | 2.2 | 10.2 | 78.4 | 5.8 |
| | | MFNC | 6.7 | 6.0 | 2.9 | 12.5 | 77.0 | 6.9 |
| | | N/N | 5.9 | 5.1 | 2.8 | 10.2 | 72.8 | 5.3 |

In looking at the data presented in Table 18, the critical VMA values identified are defined at the measured air content where the mixture became unsound, whereas McLeod specified VMA at 5 percent air voids, and Superpave at 4 percent air voids. At the critical threshold VMA, the mixes tested averaged 2.6% air voids and ranged from 1.1% to 5.6%.

**Validation of the McLeod/Superpave Critical VMA Requirement**

The fifth objective of this study was to examine and validate the McLeod/Superpave VMA vs. NMAS relationship, to see whether the specified VMA values given in Table 1 adequately discriminate between sound and unsound mixtures.

Using regression analysis, the critical VMA values in Table 18 were regressed against log (NMAS), yielding Equation 1 and the results shown in Table 19:

$$VMA_{crit} = 20.531 - 7.821\log_{10}(NMAS) \qquad \textbf{(1)}$$

with an adjusted $r^2 = 0.340$ and a standard error of the estimate (s.e.e.) = 1.342. This indicates that the observed relationship between measured critical VMA and NMAS alone is tenuous at best ($r^2 = 0.34$). Comparing the predicted results using equation (1) against the specified values in Table 1, the results in Table 20 are obtained.

**Table 19 Regression Results of McLeod VMA vs. NMAS Relationship**

| Model | Sum of Squares | Degrees of Freedom | Mean Square | F |
|---|---|---|---|---|
| Regression | 29.663 | 1 | 29.663 | 16.476 |
| Residual | 52.211 | 29 | 1.800 | |
| Total | 81.875 | 30 | | |

**Table 20 Comparison of Predicted and McLeod/Superpave Critical VMA**

| NMAS | Critical VMA | |
|---|---|---|
| | Specified (Table 1) | Predicted (Equation 1) |
| 9.5 mm | 15.0 | 12.9 |
| 12.5 mm | 14.0 | 12.0 |
| 19.0 mm | 13.0 | 10.5 |

Figure 16 shows the relationship between the specified and critical VMA identified in this project. At first glance, the McLeod/Superpave minimum VMA criteria appears effective, as it fails for only 1 out of 31 results, where the observed critical VMA exceeded the specified values. However, close examination reveals two problems:

1. One mixture, A in Figure 16, compacted to the design level of compaction, exhibits a VMA of 14.4%. This exceeds the specified minimum value of 13% for a 19 mm gradation. All other factors aside, this would be deemed to be an acceptable mixture. *However, it should be realized that if this mixture were to be "overcompacted" to 14% or 13.5% VMA, it would* ***still*** *be deemed acceptable even though it has here been identified to be unstable at any magnitude of VMA less than 14.4%.*
2. A different mixture, B in Figure 16, compacted to the design degree of compaction, exhibits a VMA of 10%. This does not meet the specified minimum VMA requirements and would be rejected as unacceptable. *However, this mixture would, in fact, exhibit stable behavior.*

While it may appear to work well, it seems clear that the McLeod/Superpave design criterion is **not** a robust predictor of the threshold between sound and unsound mix performance.

**Significant Aggregate-related Factors**

The sixth objective of this dissertation is to identify and to evaluate statistically the effects of several aggregate-related factors on the critical state of asphalt mixtures. The current criteria for critical VMA (Table 1) are based solely on NMAS. As discussed in the literature review, percent filler, shape, surface texture, percent crushed aggregate, fine aggregate angularity (FAA), and coarseness of the gradation influence the VMA of a compacted mix. As previously noted, percent filler was held constant for all mixes, and consequently not a variable in the study.

Examining the aggregate factors listed above, it becomes clear that for the aggregate types, gradations, and blends used in the study, some are not significant and others need to be refined, as shown in Table 21.

**Table 21 Identified Aggregate Factors, Associated Superpave Test/Property, and Variables used in Study**

| Aggregate-related Factor | Superpave Test/Property | Variables in Study |
|---|---|---|
| Shape & Surface Texture | Flat or Elongated Particles<br>Coarse Aggregate Angularity<br>Fine Aggregate Angularity | Manufactured vs. Natural |
| Percent Crushed Aggregate | Flat or Elongated Particles<br>Coarse Aggregate Angularity<br>Fine Aggregate Angularity | Coarse Aggregate Percent Crushed<br>Fine Aggregate Percent Crushed |
| Fine Aggregate Angularity | Fine Aggregate Angularity | Not Used |
| Gradation | Gradation | Fineness Modulus<br>Fine, Dense, Coarse |
| NMAS | NMAS | NMAS<br>Fineness Modulus |

Shape and surface texture are not directly measured by the Superpave tests, but are indicated well by the aggregate type, manufactured or natural. Percent crushed aggregate has been split into two variables, percent coarse and percent fine aggregate crushed. The fine aggregate angularity was not used because using Method A, as specified by Superpave, would not differentiate NMAS or gradation. Information on gradation was indicated by fineness modulus and type: fine, dense, and coarse. The fineness modulus, not usually used for asphalt mixes, was considered as a possible refinement of NMAS.

An additional factor to be considered is aggregate surface area. In Iowa, the DOT has for many years relied on the use of film thickness to limit binder content. While film thickness is primarily a function of the binder content, it is also a function of the surface area of the aggregate blend. Surface area is not a measured quantity, but is computed based on surface area coefficients for each size fraction of the aggregate. Consequently, surface area (as defined) is a possible factor in the determination of a critical VMA.

Looking at Figure 16, there appears to be a trend in that the 100% natural material has the lowest critical VMA, the 50-50 and NCMF blends are intermediate, and the 100% manufactured material has the highest critical VMA.

This leads to the hypothesis that the critical VMA in a mixture is a function of several aggregate properties, or:

$$VMA_{crit} = f(NMAS, CAPC, FAPC, FM, SA) + \varepsilon \qquad \textbf{(2)}$$

where:

NMAS = Nominal Maximum Aggregate Size (mm)
CAPC = Coarse Aggregate Percent Crushed
FAPC = Fine Aggregate Percent Crushed
FM = Fineness Modulus (ASTM C 33)
SA = Surface Area (Asphalt Institute, MS-2)

An ANOVA analysis of the data in Table 18 was performed to identify the significance and quality of the influence of these factors on the critical VMA identified in each mixture tested. As shown in Table 22, the results indicated that only three of the factors (FM, CAPC, and FAPC) and two interactions (FM x CAPC and FM x FAPC) were significant at the 5% level.

**Table 22 ANOVA Results for VMA versus NMAS, CAPC, FAPC, FM, and SA**

| Source | Sum of Squares | Degrees of Freedom | Mean Square |
|---|---|---|---|
| Corrected Model | 81.875 | 30 | 2.729 |
| Intercept | 4223.423 | 1 | 4223.423 |
| Coarse | 12.088 | 2 | 6.044 |
| Fine | 3.774 | 1 | 3.774 |
| FM | 54.077 | 8 | 6.760 |
| Coarse * FM | 9.777 | 13 | .752 |
| Fine * FM | 2.159 | 6 | .360 |

NMAS and SA were identified as being of no statistical significance when fineness modulus was include in the analysis. This is not unexpected since fineness modulus is related to both NMAS and surface area.

The statistically significant aggregate factors were found to be fineness modulus (FM), coarse aggregate percent crushed (CAPC), and fine aggregate percent crushed (FAPC) and two interactions (FM x CAPC and FM x FAPC). As the contribution of the two interactions to the variance was small, they were dropped from the analysis. This reduced the regression to the observed critical VMA vs. FM, CAPC, and FAPC.

This regression analysis yields Equation 3 and the results shown in Table 23:

$$VMA_{crit} = 23.58 - 3.34\ FM + 0.0129\ CAPC + 0.0155\ FAPC \qquad \textbf{(3)}$$

As shown in Table 23, the adjusted $r^2$ is 0.73 and the standard error of the estimate is 0.86. Comparing this to the McLeod/Superpave regression (Equation 1),

$$VMA_{crit} = 20.531 - 7.821\log_{10}(NMAS)$$

which had an adjusted $r^2 = 0.34$ and a standard error of estimate of 0.1.34, it is clear that adding the aggregate factors significantly improves the accuracy. The $r^2$ is more than doubled and the standard error of estimate is almost halved. The results can be further improved if two mixes (the 100% Natural 12.5mm NMAS Coarse and the 50-50 19 mm NMAS Fine) are thrown out, resulting in the regression equation

$$VMA_{crit} = 23.58 - 3.34\ FM + 0.0129\ CAPC + 0.0155\ FAPC \qquad \textbf{(4)}$$

with adjusted $r^2 = 0.897$ and standard error of the estimate = 0.542, as shown in Table 24.

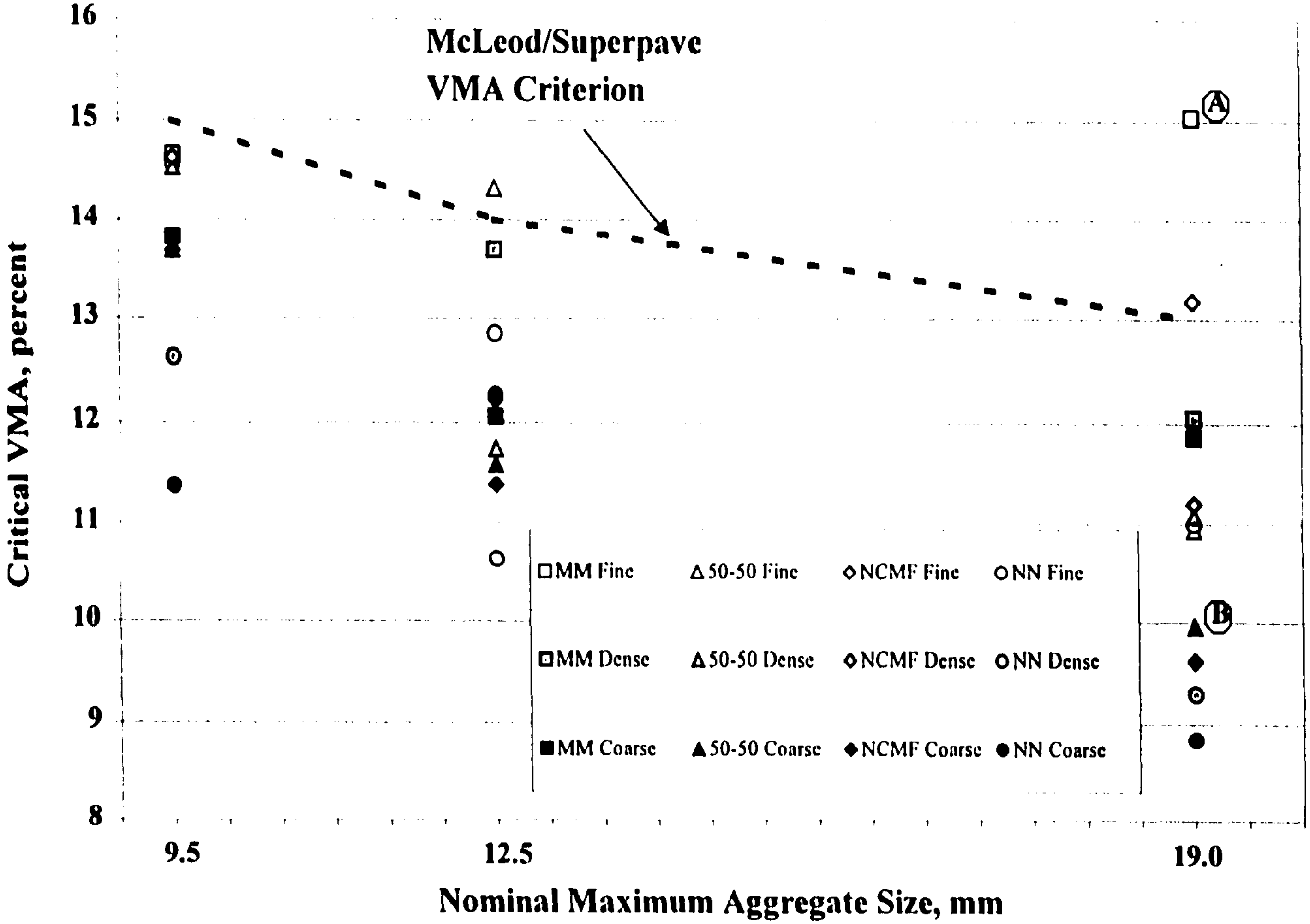


**Figure 16 Observed Critical VMA for All Mixtures**

**Table 24 Regression Results for $VMA_{crit} = f(FM, CAPC, FAPC)$**

SUMMARY OUTPUT

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.870 |
| R Square | 0.756 |
| Adjusted R Square | 0.729 |
| Standard Error | 0.8599 |
| Observations | 31 |

ANOVA

| | *Df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 61.912 | 3 | 20.637 | 27.912 | .000 |
| Residual | 19.963 | 27 | .739 | | |
| Total | 81.875 | 30 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* |
|---|---|---|---|---|---|---|
| Intercept | 23.578 | 1.647 | 14.320 | .000 | 20.200 | 26.957 |
| FM | 1.524E-02 | .004 | 3.593 | .001 | .007 | .024 |
| CAPC | 1.006E-02 | .004 | 2.301 | .029 | .001 | .019 |
| FAPC | -2.865 | .363 | -7.901 | .000 | -3.608 | -2.121 |

The meaning and limitations of these predictive equations must be understood. They predict the magnitude of the critical VMA for the mixtures tested and compacted at 109 gyrations of the SGC. They provide a means by which the *critical* VMA of an asphalt mixture may be estimated based on aggregate factors, which is a refinement of the McLeod/Superpave VMA requirement. As Figure 16 shows, there is a very good fit between predicted and observed critical VMA for the data set studied. However, the relationship needs to be validated with field and laboratory data prior to being used as design criteria.

Again, it must be noted that the air void content is not constant. However, it should be recalled that the specified values are specifically set to allow for an air void content of 4%. The measured values obtained by testing do not contain 4% air voids (Table 18), averaging 2.6%. This suggests that the volume of effective binder is a significant variable and may be a better predictor of mix performance. Two alternative parameters, VFA and asphalt film thickness, are functions of the volume of effective binder and hence may be more effective than VMA at indicating mix performance.

**Table 25 "Improved"Regression Results for $VMA_{crit} = f(FM, CAPC, FAPC)$**

SUMMARY OUTPUT

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.953 |
| R Square | 0.908 |
| Adjusted R Square | 0.897 |
| Standard Error | 0.5422 |
| Observations | 29 |

ANOVA

| | *Df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 72.356 | 3 | 24.119 | 82.036 | .000 |
| Residual | 7.350 | 25 | .294 | | |
| Total | 79.706 | 28 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* |
|---|---|---|---|---|---|---|
| Intercept | 25.098 | 1.064 | 23.584 | .000 | 22.907 | 27.290 |
| FM | 1.788E-02 | .003 | 6.478 | .000 | .012 | .024 |
| CAPC | 1.180E-02 | .003 | 4.255 | .000 | .006 | .018 |
| FAPC | -3.247 | .237 | -13.726 | .000 | -3.734 | -2.760 |

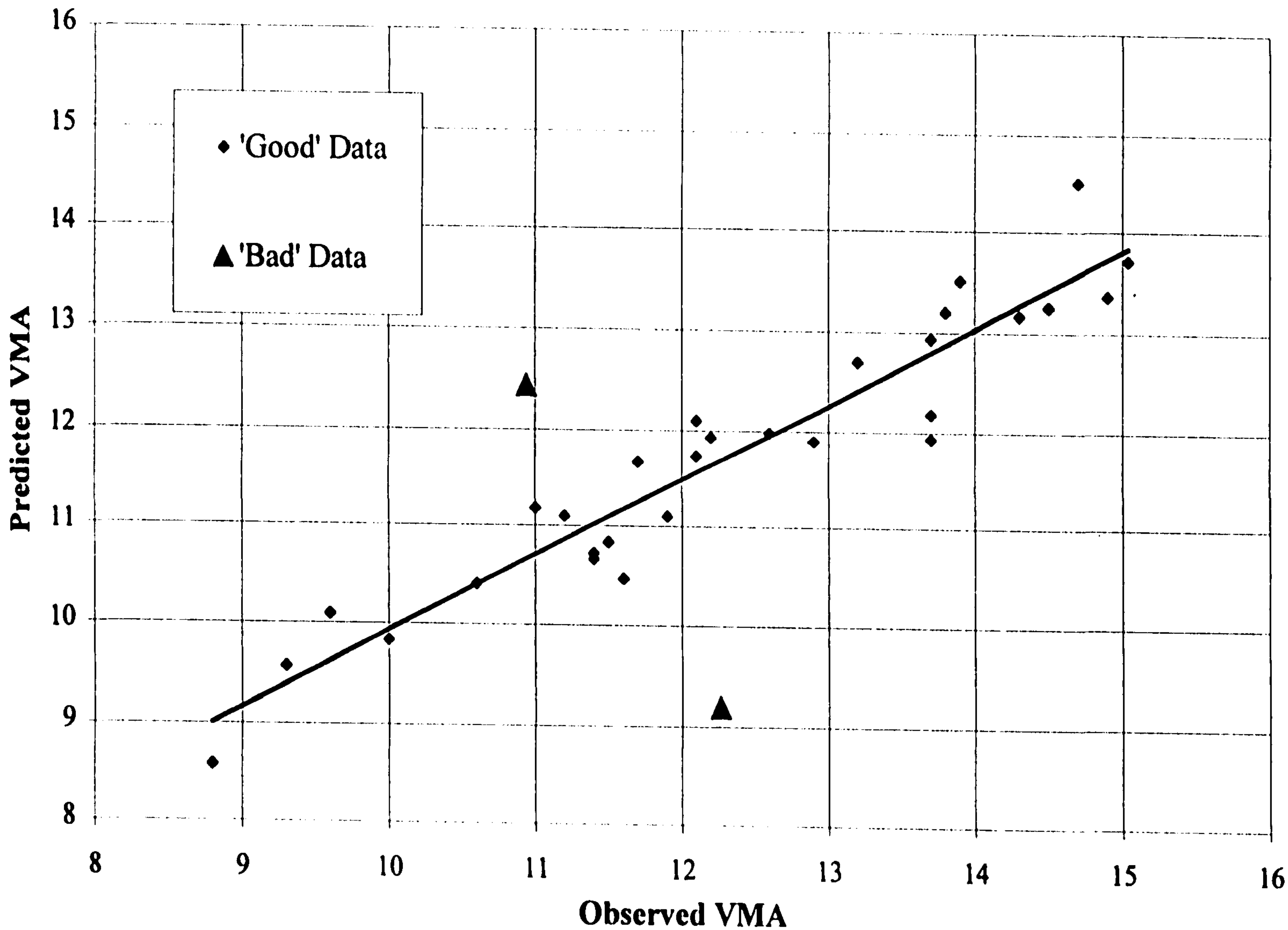


**Figure 17 Comparison of Predicted versus Observed Critical VMA**

# CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Mix designers target mixture parameters close to the specifications as a matter of economy. As shown in the literature review, achieving the required VMA is often the most difficult step in the mix design process. It appears prudent to expand and refine the McLeod/Superpave relationship to include the effects of aggregate-related factors such as gradation, percent crushed coarse aggregate, and percent crushed fine aggregate. The goals of this project were to examine whether or not this was feasible; and if so, to provide a rational method for adjusting the current minimum VMA vs. NMAS relationship. It must be emphasized that the conclusions are based upon carefully controlled laboratory testing of a limited number of specimens, at one level of compaction, and have not been verified in the field.

Based on the literature search, laboratory testing, and analysis of test data, the following conclusions are made:

## Conclusions

### *Literature Review*

1. The definition of minimum (or critical) VMA adopted by Superpave is dependent only upon NMAS without regard to other significant aggregate-related properties (*5*).
2. The minimum VMA criterion adopted by the SHRP Expert Task Group for Superpave was essentially that proposed by Norman McLeod in 1959 (*1*).
3. The available literature on the development of the minimum VMA criterion is sketchy; McLeod presented his relationship without the research or data from which it was derived and suggested that it would be modified with experience and test data (*1*).
4. The implementation of Superpave has brought significant awareness of and renewed focus on how difficult and problematic meeting the minimum VMA criterion can be for mix designers (6-*7*).
5. Prior to SHRP, there was some awareness of difficulties in meeting minimum VMA. Some researchers attempted to develop rational methods of increasing VMA based on gradation and others modified the criterion to account for gradation. (*19,4*).
6. There is considerable interest in using asphalt film thickness either to supplement or to replace the minimum VMA criteria (*6 8-9*).

7. The laboratory tests that seem best suited for determining the critical state transition of asphalt paving mixtures are the permanent deformation tests. Reviewing the literature, there is not a consensus as to which laboratory test would best distinguish the critical state of VMA. Based on cost, availability, ease of use, and the SHRP findings (*11*), the repeated load triaxial test apparatus appears to be the preferred method.
8. Several researchers have pointed out aggregate factors other than NMAS that effect VMA. These include percent filler, shape, surface texture, percent crushed aggregate, fine aggregate angularity, and coarseness of the gradation.

*Analysis of Test Data*

1. As shown in Figure 15, the specified VMA values provided by Superpave (Table 1) do not appear to be adequate for identifying mixture performance; only 1 out of 31 results was correctly identified; a success rate of about 3%.
2. ANOVA analysis of the test data identified three factors, fineness modulus (FM), coarse aggregate percent crushed (CAPC), fine aggregate percent crushed (FAPC), and two interactions (FM x CAPC and FM x FAPC) as significant.
3. ANOVA analysis identified the nominal maximum aggregate size (NMAS) and surface area (SA) of the gradation as being of no statistical significance when the fineness modulus was included in the analysis.
4. Linear regression analysis showed the current VMA specification (VMA vs. log (NMAS)) had an adjusted $r^2$ value of 0.34.
5. Linear regression analysis of VMA versus FM, CAPC and FAPC had an adjusted $r^2$ value of 0.90.

Thus from the literature review, testing, and statistical analysis performed on this project, it appears that the current minimum VMA requirements specified in Superpave mix design protocol are overly restrictive and unnecessary, ruling out candidate aggregate gradations that could perform adequately.

**Recommendations**

The literature review, testing, and statistical analysis performed on this project have suggested the following recommendations:

1. The predictive relationship for critical VMA obtained in this study needs to be compared with field data and verified or adjusted as necessary.
2. If a minimum VMA is to be specified, it should include fineness modulus, coarse aggregate percent crushed, and fine aggregate percent crushed, and their interactions.
3. The volume of effective binder, which is strongly related to VFA and asphalt film thickness, may be a more significant measure of mix performance than commonly believed.

# APPENDIX A. AGGREGATE SPECIFIC GRAVITY RESULTS

**Table A-1 Specific Gravity Results for Individual Sieve Sizes**

| Sieve Size | Specific Gravity | |
|---|---|---|
| | Manufactured | Natural |
| 12.5 mm* | 2.558 | 2.481 |
| 9.5 mm* | 2.556 | 2.515 |
| 4.75 mm* | 2.553 | 2.519 |
| 2.36 mm* | 2.591 | 2.543 |
| 1.18 mm* | 2.593 | 2.546 |
| 0.60 mm** | 2.712 | 2.648 |
| 0.30 mm** | 2.706 | 2.638 |
| 0.15 mm** | 2.741 | 2.664 |
| 0.075 mm** | 2.777 | 2.673 |
| P0.075 mm** | 2.817 | 2.640 |

* Bulk specific gravity

** Apparent specific gravity

# APPENDIX B. VOLUMETRIC DATA RESULTS

| | |
|---|---|
| $G_{sb}$ = | Bulk Specific Gravity of the Aggregate |
| SA = | Surface Area |
| $G_{se}$ = | Effective Specific Gravity of the Aggregate |
| Abs. (%) = | Percent Asphalt Absorption |
| Gmb = | Bulk Specific Gravity of the Compacted HMA Specimen |
| Gmm = | Theoretical Maximum Specific Gravity of the HMA |
| Air Voids = | Percent Air Voids in the Compacted HMA Specimen |
| VMA = | Voids in the Mineral Aggregate |
| VFA = | Voids Filled with Asphalt |
| Dust/Pbe Ratio | Ratio of %P0.075 mm Material to Effective Asphalt Content |
| K = | Richness Modulus |
| Film Thickness | Average Asphalt Film Thickness (microns) |

**Table B-1 Summary of Volumetric Results for 100% Crushed Specimens**

| Property | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| $G_{sb}$ | 2.620 | 2.608 | 2.597 | 2.609 | 2.599 | 2.591 | 2.604 | 2.593 | 2.587 |
| SA | 6.65 | 5.95 | 4.98 | 5.99 | 5.37 | 4.68 | 5.80 | 5.02 | 4.56 |
| $G_{se}$ | 2.736 | 2.727 | 2.724 | 2.728 | 2.727 | 2.718 | 2.727 | 2.722 | 2.721 |
| Abs. (%) | 1.66 | 1.69 | 1.83 | 1.72 | 1.85 | 1.84 | 1.79 | 1.86 | 1.94 |

| Gmb | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.213 | 2.292 | 2.310 | 2.275 | 2.325 | 2.353 | 2.307 | 2.358 | 2.362 |
| 4 | 2.199 | 2.291 | 2.304 | 2.285 | 2.336 | 2.352 | 2.301 | 2.352 | 2.390 |
| 5 | 2.236 | 2.319 | 2.363 | 2.318 | 2.367 | 2.390 | 2.350 | 2.402 | 2.415 |
| 5 | 2.220 | 2.347 | 2.341 | 2.305 | 2.369 | 2.396 | 2.345 | 2.397 | 2.402 |
| 6 | 2.256 | 2.350 | 2.381 | 2.337 | 2.400 | 2.438 | 2.360 | 2.446 | 2.438 |
| 6 | 2.282 | 2.355 | 2.412 | 2.331 | 2.405 | 2.435 | 2.359 | 2.447 | 2.442 |
| 7 | 2.289 | 2.414 | 2.413 | 2.376 | 2.435 | 2.429 | 2.411 | 2.432 | 2.433 |
| 7 | 2.308 | 2.410 | 2.413 | 2.396 | 2.433 | 2.425 | 2.417 | 2.432 | 2.431 |
| 8 | 2.351 | 2.403 | 2.408 | 2.400 | 2.409 | 2.406 | 2.406 | 2.409 | 2.403 |
| 8 | 2.336 | 2.403 | 2.405 | 2.400 | 2.405 | 2.404 | 2.406 | 2.400 | 2.409 |

| Gmm | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.564 | 2.557 | 2.553 | 2.556 | 2.559 | 2.551 | 2.558 | 2.552 | 2.553 |
| 4 | 2.564 | 2.557 | 2.553 | 2.556 | 2.559 | 2.551 | 2.558 | 2.552 | 2.553 |
| 5 | 2.525 | 2.518 | 2.514 | 2.516 | 2.521 | 2.512 | 2.518 | 2.513 | 2.513 |
| 5 | 2.525 | 2.518 | 2.514 | 2.516 | 2.521 | 2.512 | 2.518 | 2.513 | 2.513 |
| 6 | 2.486 | 2.480 | 2.476 | 2.477 | 2.483 | 2.475 | 2.480 | 2.475 | 2.475 |
| 6 | 2.486 | 2.480 | 2.476 | 2.477 | 2.483 | 2.475 | 2.480 | 2.475 | 2.475 |
| 7 | 2.449 | 2.443 | 2.439 | 2.440 | 2.446 | 2.439 | 2.444 | 2.438 | 2.438 |
| 7 | 2.449 | 2.443 | 2.439 | 2.440 | 2.446 | 2.439 | 2.444 | 2.438 | 2.438 |
| 8 | 2.413 | 2.407 | 2.403 | 2.404 | 2.411 | 2.404 | 2.408 | 2.402 | 2.403 |
| 8 | 2.413 | 2.407 | 2.403 | 2.404 | 2.411 | 2.404 | 2.408 | 2.402 | 2.403 |

| Air Voids | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 13.7% | 10.4% | 9.5% | 11.0% | 10.4% | 7.8% | 9.9% | 8.2% | 7.5% |
| 4 | 14.3% | 10.4% | 9.8% | 10.6% | 10.5% | 7.8% | 10.1% | 8.4% | 6.4% |
| 5 | 11.4% | 7.9% | 6.0% | 7.9% | 8.0% | 4.9% | 6.7% | 5.2% | 3.9% |
| 5 | 12.1% | 6.8% | 6.9% | 8.4% | 6.9% | 4.6% | 6.9% | 5.4% | 4.4% |
| 6 | 9.2% | 5.3% | 3.8% | 5.6% | 5.4% | 1.5% | 4.9% | 2.1% | 1.5% |
| 6 | 8.2% | 5.1% | 2.6% | 5.9% | 5.2% | 1.6% | 4.9% | 2.0% | 1.3% |
| 7 | 6.5% | 1.2% | 1.0% | 2.6% | 1.3% | 0.4% | 1.3% | 1.3% | 0.2% |
| 7 | 5.8% | 1.4% | 1.1% | 1.8% | 1.5% | 0.6% | 1.1% | 1.3% | 0.3% |
| 8 | 2.5% | 0.2% | -0.2% | 0.2% | 0.3% | -0.1% | 0.1% | 0.9% | 0.0% |
| 8 | 3.2% | 0.2% | -0.1% | 0.1% | 0.3% | 0.0% | 0.1% | 1.3% | -0.2% |

**Table B-1 (Cont'd)**

| VMA | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 18.9% | 16.3% | 14.6% | 16.3% | 14.1% | 12.8% | 15.0% | 12.7% | 12.3% |
| 4 | 19.4% | 16.3% | 14.8% | 15.9% | 13.7% | 12.9% | 15.2% | 12.9% | 11.3% |
| 5 | 18.9% | 16.2% | 13.6% | 15.6% | 13.5% | 12.4% | 14.3% | 12.0% | 11.3% |
| 5 | 19.5% | 15.1% | 14.4% | 16.0% | 13.4% | 12.1% | 14.5% | 12.2% | 11.8% |
| 6 | 19.0% | 15.9% | 13.8% | 15.8% | 13.2% | 11.6% | 14.8% | 11.3% | 11.4% |
| 6 | 18.1% | 15.8% | 12.7% | 16.0% | 13.0% | 11.7% | 14.8% | 11.3% | 11.3% |
| 7 | 18.7% | 14.6% | 13.6% | 15.3% | 12.9% | 12.8% | 13.9% | 12.8% | 12.5% |
| 7 | 18.1% | 14.7% | 13.6% | 14.6% | 12.9% | 13.0% | 13.7% | 12.8% | 12.6% |
| 8 | 17.4% | 15.9% | 14.7% | 15.4% | 14.7% | 14.6% | 15.0% | 14.5% | 14.5% |
| 8 | 18.0% | 15.9% | 14.8% | 15.3% | 14.9% | 14.6% | 15.0% | 14.9% | 14.3% |

| VFA | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 27.5% | 33.8% | 34.9% | 32.5% | 35.2% | 39.5% | 34.3% | 40.1% | 39.9% |
| 4 | 26.6% | 33.7% | 34.2% | 33.4% | 36.5% | 39.3% | 33.8% | 39.4% | 44.0% |
| 5 | 39.5% | 49.2% | 55.7% | 49.5% | 54.9% | 60.7% | 53.1% | 63.3% | 65.8% |
| 5 | 38.0% | 53.3% | 52.1% | 47.8% | 55.1% | 61.8% | 52.2% | 62.2% | 62.6% |
| 6 | 51.4% | 65.7% | 72.4% | 64.2% | 74.8% | 86.9% | 67.2% | 89.7% | 87.1% |
| 6 | 54.6% | 66.6% | 79.6% | 63.1% | 75.8% | 86.0% | 67.0% | 90.1% | 88.3% |
| 7 | 65.1% | 91.5% | 92.3% | 82.9% | 96.5% | 97.0% | 90.5% | 98.2% | 98.4% |
| 7 | 68.1% | 90.4% | 92.2% | 87.5% | 95.9% | 95.6% | 92.0% | 98.0% | 97.7% |
| 8 | 85.4% | 98.7% | 101.5% | 98.9% | 99.6% | 100.6% | 99.5% | 102.0% | 100.2% |
| 8 | 82.3% | 98.9% | 100.5% | 99.0% | 98.3% | 100.1% | 99.6% | 99.5% | 101.8% |

| Dust/Pbe Ratio | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 1.7 | 1.7 | 1.8 | 1.7 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 |
| 4 | 1.7 | 1.7 | 1.8 | 1.7 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 |
| 5 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.3 |
| 5 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.3 |
| 6 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 |
| 6 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 |
| 7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 |
| 7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 |
| 8 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| 8 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |

| K | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.56 | 2.52 | 2.47 | 2.51 | 2.47 | 2.42 | 2.50 | 2.44 | 2.40 |
| 5 | 3.23 | 3.18 | 3.12 | 3.17 | 3.12 | 3.05 | 3.15 | 3.08 | 3.03 |
| 6 | 3.92 | 3.86 | 3.78 | 3.84 | 3.78 | 3.70 | 3.82 | 3.74 | 3.68 |
| 7 | 4.62 | 4.55 | 4.46 | 4.53 | 4.46 | 4.37 | 4.51 | 4.41 | 4.34 |
| 8 | 5.33 | 5.26 | 5.15 | 5.24 | 5.15 | 5.05 | 5.21 | 5.09 | 5.01 |

**Table B-1 (Cont'd)**

| Film Thickness | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | [redacted] | D | [redacted] | F | [redacted] | C | [redacted] | D | [redacted] |
| 4 | [redacted] | 3.9 | [redacted] | 3.8 | [redacted] | 4.6 | [redacted] | 4.3 | [redacted] |
| 5 | [redacted] | 5.6 | [redacted] | 5.5 | [redacted] | 6.8 | [redacted] | 6.2 | [redacted] |
| 6 | [redacted] | 7.2 | [redacted] | 7.2 | [redacted] | 8.9 | [redacted] | 8.2 | [redacted] |
| 7 | [redacted] | 8.9 | [redacted] | 8.8 | [redacted] | 11.0 | [redacted] | 10.2 | [redacted] |
| 8 | [redacted] | 10.6 | [redacted] | 10.5 | [redacted] | 13.2 | [redacted] | 12.2 | [redacted] |

**Table B-2 Volumetric Results for 50% Crushed/ 50% Natural Specimens**

| Property | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| $G_{sb}$ | 2.613 | 2.593 | 2.577 | 2.597 | 2.585 | 2.573 | 2.592 | 2.578 | 2.571 |
| SA | 6.65 | 5.95 | 4.98 | 5.99 | 5.37 | 4.68 | 5.80 | 5.02 | 4.56 |
| $G_{se}$ | 2.696 | 0.000 | 2.691 | 37.318 | 37.257 | 37.116 | 37.189 | 37.032 | 37.065 |
| Abs. (%) | 1.21 | 1.30 | 1.69 | 1.21 | 1.46 | 1.78 | 1.43 | 1.79 | 1.88 |

| Gmb | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.215 | 2.273 | 2.295 | 2.294 | 2.340 | 2.351 | 2.386 | 2.389 | 2.427 |
| 4 | 2.198 | 2.272 | 2.279 | 2.312 | 2.346 | 2.360 | 2.393 | 2.399 | 2.390 |
| 5 | 2.245 | 2.309 | 2.316 | 2.346 | 2.392 | 2.386 | 2.422 | 2.408 | 2.448 |
| 5 | 2.224 | 2.323 | 2.321 | 2.329 | 2.395 | 2.396 | 2.440 | 2.399 | 2.426 |
| 6 | 2.277 | 2.369 | 2.365 | 2.356 | 2.427 | 2.425 | 2.436 | 2.423 | 2.449 |
| 6 | 2.284 | 2.343 | 2.362 | 2.380 | 2.437 | 2.427 | 2.444 | 2.435 | 2.439 |
| 7 | 2.305 | 2.388 | 2.402 | 2.394 | 2.418 | 2.415 | 2.424 | 2.411 | 2.395 |
| 7 | 2.314 | 2.381 | 2.402 | 2.385 | 2.412 | 2.409 | 2.421 | 2.385 | 2.416 |
| 8 | 2.347 | 2.374 | 2.380 | 2.380 | 2.380 | 2.381 | 2.398 | | |
| 8 | 2.346 | 2.381 | 2.378 | 2.382 | 2.376 | 2.384 | 2.390 | 2.376 | 2.357 |

| Gmm | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.529 | 2.528 | 2.527 | 2.519 | 2.517 | 2.531 | 2.528 | 2.535 | 2.535 |
| 4 | 2.529 | 2.528 | 2.527 | 2.519 | 2.517 | 2.531 | 2.528 | 2.535 | 2.535 |
| 5 | 2.491 | 2.493 | 2.489 | 2.481 | 2.478 | 2.493 | 2.491 | 2.497 | 2.497 |
| 5 | 2.491 | 2.493 | 2.489 | 2.481 | 2.478 | 2.493 | 2.491 | 2.497 | 2.497 |
| 6 | 2.453 | 2.458 | 2.453 | 2.445 | 2.441 | 2.456 | 2.455 | 2.459 | 2.461 |
| 6 | 2.453 | 2.458 | 2.453 | 2.445 | 2.441 | 2.456 | 2.455 | 2.459 | 2.461 |
| 7 | 2.417 | 2.424 | 2.417 | 2.410 | 2.405 | 2.421 | 2.419 | 2.423 | 2.425 |
| 7 | 2.417 | 2.424 | 2.417 | 2.410 | 2.405 | 2.421 | 2.419 | 2.423 | 2.425 |
| 8 | 2.382 | 2.392 | 2.382 | 2.376 | 2.369 | 2.386 | 2.385 | | |
| 8 | 2.382 | 2.392 | 2.382 | 2.376 | 2.369 | 2.386 | 2.385 | 2.388 | 2.391 |

| Air Voids | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 12.4% | 10.1% | 9.2% | 8.9% | 7.0% | 7.1% | 5.6% | 5.7% | 4.3% |
| 4 | 13.1% | 10.1% | 9.8% | 8.2% | 6.8% | 6.8% | 5.3% | 5.3% | 5.7% |
| 5 | 9.9% | 7.3% | 7.0% | 5.5% | 3.5% | 4.3% | 2.8% | 3.5% | 2.0% |
| 5 | 10.7% | 6.8% | 6.8% | 6.1% | 3.4% | 3.9% | 2.0% | 3.9% | 2.9% |
| 6 | 7.2% | 3.6% | 3.6% | 3.6% | 0.6% | 1.3% | 0.7% | 1.5% | 0.5% |
| 6 | 6.9% | 4.7% | 3.7% | 2.7% | 0.1% | 1.2% | 0.4% | 1.0% | 0.9% |
| 7 | 4.6% | 1.5% | 0.6% | 0.7% | -0.5% | 0.2% | -0.2% | 0.5% | 1.2% |
| 7 | 4.3% | 1.8% | 0.6% | 1.1% | -0.3% | 0.5% | -0.1% | 1.6% | 0.4% |
| 8 | 1.4% | 0.8% | 0.1% | -0.2% | -0.5% | 0.2% | -0.5% | | |
| 8 | 1.5% | 0.5% | 0.2% | -0.3% | -0.3% | 0.1% | -0.2% | 0.5% | 1.4% |

**Table B-2 (Cont'd)**

| VMA | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 18.6% | 15.8% | 14.5% | 15.2% | 13.1% | 12.3% | 11.6% | 11.0% | 9.4% |
| 4 | 19.2% | 15.9% | 15.1% | 14.6% | 12.9% | 12.0% | 11.4% | 10.7% | 10.8% |
| 5 | 18.4% | 15.4% | 14.6% | 14.2% | 12.1% | 11.9% | 11.2% | 11.3% | 9.5% |
| 5 | 19.1% | 14.9% | 14.4% | 14.8% | 12.0% | 11.5% | 10.5% | 11.6% | 10.3% |
| 6 | 18.1% | 14.1% | 13.7% | 14.7% | 11.7% | 11.4% | 11.6% | 11.7% | 10.5% |
| 6 | 17.8% | 15.0% | 13.8% | 13.9% | 11.4% | 11.3% | 11.4% | 11.2% | 10.8% |
| 7 | 18.0% | 14.4% | 13.3% | 14.3% | 13.0% | 12.7% | 13.0% | 13.0% | 13.3% |
| 7 | 17.7% | 14.6% | 13.3% | 14.6% | 13.2% | 12.9% | 13.1% | 14.0% | 12.6% |
| 8 | 17.4% | 15.8% | 15.0% | 15.7% | 15.3% | 14.9% | 14.9% | | |
| 8 | 17.4% | 15.5% | 15.1% | 15.6% | 15.4% | 14.8% | 15.2% | 15.2% | 15.7% |

| VFA | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 33.3% | 36.3% | 36.6% | 41.3% | 46.4% | 42.2% | 51.7% | 48.0% | 54.4% |
| 4 | 32.0% | 36.2% | 34.9% | 43.5% | 47.2% | 43.5% | 52.9% | 49.9% | 46.7% |
| 5 | 46.4% | 52.2% | 52.3% | 61.6% | 71.1% | 63.9% | 75.4% | 68.5% | 79.2% |
| 5 | 44.1% | 54.3% | 53.1% | 58.6% | 71.9% | 66.4% | 80.9% | 66.3% | 72.3% |
| 6 | 60.3% | 74.4% | 74.0% | 75.3% | 95.2% | 88.9% | 93.6% | 87.3% | 95.4% |
| 6 | 61.4% | 69.0% | 73.2% | 80.7% | 98.7% | 89.6% | 96.1% | 91.3% | 92.0% |
| 7 | 74.2% | 89.5% | 95.3% | 95.4% | 104.2% | 98.1% | 101.4% | 96.1% | 90.7% |
| 7 | 75.8% | 87.7% | 95.3% | 92.8% | 102.4% | 96.4% | 100.6% | 88.6% | 97.0% |
| 8 | 91.7% | 95.2% | 99.4% | 101.0% | 103.0% | 98.7% | 103.5% | | |
| 8 | 91.4% | 97.1% | 98.8% | 101.7% | 101.8% | 99.3% | 101.3% | 96.6% | 90.9% |

| Dust/Pbe Ratio | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 1.41 | 1.47 | 1.71 | 1.40 | 1.56 | 1.78 | 1.52 | 1.75 | 1.82 |
| 4 | 1.41 | 1.47 | 1.71 | 1.40 | 1.56 | 1.78 | 1.52 | 1.75 | 1.82 |
| 5 | 1.04 | 1.08 | 1.20 | 1.04 | 1.12 | 1.23 | 1.10 | 1.21 | 1.24 |
| 5 | 1.04 | 1.08 | 1.20 | 1.04 | 1.12 | 1.23 | 1.10 | 1.21 | 1.24 |
| 6 | 0.82 | 0.85 | 0.92 | 0.82 | 0.88 | 0.94 | 0.86 | 0.93 | 0.94 |
| 6 | 0.82 | 0.85 | 0.92 | 0.82 | 0.88 | 0.94 | 0.86 | 0.93 | 0.94 |
| 7 | 0.68 | 0.70 | 0.75 | 0.68 | 0.72 | 0.76 | 0.71 | 0.75 | 0.76 |
| 7 | 0.68 | 0.70 | 0.75 | 0.68 | 0.72 | 0.76 | 0.71 | 0.75 | 0.76 |
| 8 | 0.58 | 0.60 | 0.63 | 0.58 | 0.61 | 0.64 | 0.60 | 0.63 | 0.64 |
| 8 | 0.58 | 0.60 | 0.63 | 0.58 | 0.61 | 0.64 | 0.60 | 0.63 | 0.64 |

**Table B-2 (Cont'd)**

| K | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.55 | 2.51 | 2.45 | 2.50 | 2.45 | 2.40 | 2.48 | 2.43 | 2.39 |
| 5 | 3.22 | 3.17 | 3.09 | 3.16 | 3.10 | 3.03 | 3.14 | 3.06 | 3.02 |
| 6 | 3.91 | 3.84 | 3.75 | 3.83 | 3.76 | 3.68 | 3.81 | 3.72 | 3.66 |
| 7 | 4.61 | 4.53 | 4.42 | 4.51 | 4.43 | 4.34 | 4.49 | 4.38 | 4.31 |
| 8 | 5.32 | 5.23 | 5.11 | 5.22 | 5.12 | 5.01 | 5.18 | 5.06 | 4.98 |

| Film Thickness | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 4.2 | 4.5 | 4.6 | 4.7 | 4.7 | 4.7 | 4.4 | 4.4 | 4.7 |
| 5 | 5.7 | 6.2 | 6.6 | 6.3 | 6.6 | 6.9 | 6.4 | 6.4 | 6.8 |
| 6 | 7.2 | 7.9 | 8.7 | 8.0 | 8.5 | 9.0 | 8.4 | 8.4 | 9.0 |
| 7 | 8.7 | 9.6 | 10.7 | 9.7 | 10.3 | 11.1 | 10.4 | 10.4 | 11.2 |
| 8 | 10.2 | 11.3 | 12.7 | 11.3 | 12.2 | 13.3 | 11.3 | 12.4 | 13.4 |

**Table B-3 Volumetric Results for Manufactured Fine-Natural Coarse Specimens**

| Property | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| $G_{sb}$ | 2.584 | 2.572 | 2.561 | 2.574 | 2.567 | 2.560 | 2.571 | 2.563 | 2.558 |
| SA | 6.65 | 5.95 | 4.98 | 5.99 | 5.37 | 4.68 | 6.80 | 5.02 | 4.56 |
| $G_{se}$ | 2.696 | 2.699 | 2.691 | 2.680 | 2.684 | 2.694 | 2.689 | 2.700 | 2.698 |
| Abs. (%) | 1.64 | 1.88 | 1.93 | 1.58 | 1.74 | 1.99 | 1.74 | 2.03 | 2.07 |

| Gmb | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.215 | 2.273 | 2.295 | 2.294 | 2.340 | 2.351 | 2.386 | 2.389 | 2.427 |
| 4 | 2.198 | 2.272 | 2.279 | 2.312 | 2.346 | 2.360 | 2.393 | 2.399 | 2.390 |
| 5 | 2.245 | 2.309 | 2.316 | 2.346 | 2.392 | 2.386 | 2.422 | 2.408 | 2.448 |
| 5 | 2.224 | 2.323 | 2.321 | 2.329 | 2.395 | 2.396 | 2.440 | 2.399 | 2.426 |
| 6 | 2.277 | 2.369 | 2.365 | 2.356 | 2.427 | 2.425 | 2.436 | 2.423 | 2.449 |
| 6 | 2.284 | 2.343 | 2.362 | 2.380 | 2.437 | 2.427 | 2.444 | 2.435 | 2.439 |
| 7 | 2.305 | 2.388 | 2.402 | 2.394 | 2.418 | 2.415 | 2.424 | 2.411 | 2.395 |
| 7 | 2.314 | 2.381 | 2.402 | 2.385 | 2.412 | 2.409 | 2.421 | 2.385 | 2.416 |
| 8 | 2.347 | 2.374 | 2.380 | 2.380 | 2.380 | 2.381 | 2.398 | | |
| 8 | 2.346 | 2.381 | 2.378 | 2.382 | 2.376 | 2.384 | 2.390 | 2.376 | 2.357 |

| Gmm | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.529 | 2.528 | 2.527 | 2.519 | 2.517 | 2.531 | 2.528 | 2.535 | 2.535 |
| 4 | 2.529 | 2.528 | 2.527 | 2.519 | 2.517 | 2.531 | 2.528 | 2.535 | 2.535 |
| 5 | 2.491 | 2.493 | 2.489 | 2.481 | 2.478 | 2.493 | 2.491 | 2.497 | 2.497 |
| 5 | 2.491 | 2.493 | 2.489 | 2.481 | 2.478 | 2.493 | 2.491 | 2.497 | 2.497 |
| 6 | 2.453 | 2.458 | 2.453 | 2.445 | 2.441 | 2.456 | 2.455 | 2.459 | 2.461 |
| 6 | 2.453 | 2.458 | 2.453 | 2.445 | 2.441 | 2.456 | 2.455 | 2.459 | 2.461 |
| 7 | 2.417 | 2.424 | 2.417 | 2.410 | 2.405 | 2.421 | 2.419 | 2.423 | 2.425 |
| 7 | 2.417 | 2.424 | 2.417 | 2.410 | 2.405 | 2.421 | 2.419 | 2.423 | 2.425 |
| 8 | 2.382 | 2.392 | 2.382 | 2.376 | 2.369 | 2.386 | 2.385 | | |
| 8 | 2.382 | 2.392 | 2.382 | 2.376 | 2.369 | 2.386 | 2.385 | 2.388 | 2.391 |

| Air Voids | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 12.4% | 10.1% | 9.2% | 8.9% | 7.0% | 7.1% | 5.6% | 5.7% | 4.3% |
| 4 | 13.1% | 10.1% | 9.8% | 8.2% | 6.8% | 6.8% | 5.3% | 5.3% | 5.7% |
| 5 | 9.9% | 7.3% | 7.0% | 5.5% | 3.5% | 4.3% | 2.8% | 3.5% | 2.0% |
| 5 | 10.7% | 6.8% | 6.8% | 6.1% | 3.4% | 3.9% | 2.0% | 3.9% | 2.9% |
| 6 | 7.2% | 3.6% | 3.6% | 3.6% | 0.6% | 1.3% | 0.7% | 1.5% | 0.5% |
| 6 | 6.9% | 4.7% | 3.7% | 2.7% | 0.1% | 1.2% | 0.4% | 1.0% | 0.9% |
| 7 | 4.6% | 1.5% | 0.6% | 0.7% | -0.5% | 0.2% | -0.2% | 0.5% | 1.2% |
| 7 | 4.3% | 1.8% | 0.6% | 1.1% | -0.3% | 0.5% | -0.1% | 1.6% | 0.4% |
| 8 | 1.4% | 0.8% | 0.1% | -0.2% | -0.5% | 0.2% | -0.5% | | |
| 8 | 1.5% | 0.5% | 0.2% | -0.3% | -0.3% | 0.1% | -0.2% | 0.5% | 1.4% |

**Table B-3 (Cont'd)**

| VMA | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 18.6% | 15.8% | 14.5% | 15.2% | 13.1% | 12.3% | 11.6% | 11.0% | 9.4% |
| 4 | 19.2% | 15.9% | 15.1% | 14.6% | 12.9% | 12.0% | 11.4% | 10.7% | 10.8% |
| 5 | 18.4% | 15.4% | 14.6% | 14.2% | 12.1% | 11.9% | 11.2% | 11.3% | 9.5% |
| 5 | 19.1% | 14.9% | 14.4% | 14.8% | 12.0% | 11.5% | 10.5% | 11.6% | 10.3% |
| 6 | 18.1% | 14.1% | 13.7% | 14.7% | 11.7% | 11.4% | 11.6% | 11.7% | 10.5% |
| 6 | 17.8% | 15.0% | 13.8% | 13.9% | 11.4% | 11.3% | 11.4% | 11.2% | 10.8% |
| 7 | 18.0% | 14.4% | 13.3% | 14.3% | 13.0% | 12.7% | 13.0% | 13.0% | 13.3% |
| 7 | 17.7% | 14.6% | 13.3% | 14.6% | 13.2% | 12.9% | 13.1% | 14.0% | 12.6% |
| 8 | 17.4% | 15.8% | 15.0% | 15.7% | 15.3% | 14.9% | 14.9% | | |
| 8 | 17.4% | 15.5% | 15.1% | 15.6% | 15.4% | 14.8% | 15.2% | 15.2% | 15.7% |

| VFA | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 33.3% | 36.3% | 36.6% | 41.3% | 46.4% | 42.2% | 51.7% | 48.0% | 54.4% |
| 4 | 32.0% | 36.2% | 34.9% | 43.5% | 47.2% | 43.5% | 52.9% | 49.9% | 46.7% |
| 5 | 46.4% | 52.2% | 52.3% | 61.6% | 71.1% | 63.9% | 75.4% | 68.5% | 79.2% |
| 5 | 44.1% | 54.3% | 53.1% | 58.6% | 71.9% | 66.4% | 80.9% | 66.3% | 72.3% |
| 6 | 60.3% | 74.4% | 74.0% | 75.3% | 95.2% | 88.9% | 93.6% | 87.3% | 95.4% |
| 6 | 61.4% | 69.0% | 73.2% | 80.7% | 98.7% | 89.6% | 96.1% | 91.3% | 92.0% |
| 7 | 74.2% | 89.5% | 95.3% | 95.4% | 104.2% | 98.1% | 101.4% | 96.1% | 90.7% |
| 7 | 75.8% | 87.7% | 95.3% | 92.8% | 102.4% | 96.4% | 100.6% | 88.6% | 97.0% |
| 8 | 91.7% | 95.2% | 99.4% | 101.0% | 103.0% | 98.7% | 103.5% | | |
| 8 | 91.4% | 97.1% | 98.8% | 101.7% | 101.8% | 99.3% | 101.3% | 96.6% | 90.9% |

| Dust/Pbe Ratio | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 1.41 | 1.47 | 1.71 | 1.40 | 1.56 | 1.78 | 1.52 | 1.75 | 1.82 |
| 4 | 1.41 | 1.47 | 1.71 | 1.40 | 1.56 | 1.78 | 1.52 | 1.75 | 1.82 |
| 5 | 1.04 | 1.08 | 1.20 | 1.04 | 1.12 | 1.23 | 1.10 | 1.21 | 1.24 |
| 5 | 1.04 | 1.08 | 1.20 | 1.04 | 1.12 | 1.23 | 1.10 | 1.21 | 1.24 |
| 6 | 0.82 | 0.85 | 0.92 | 0.82 | 0.88 | 0.94 | 0.86 | 0.93 | 0.94 |
| 6 | 0.82 | 0.85 | 0.92 | 0.82 | 0.88 | 0.94 | 0.86 | 0.93 | 0.94 |
| 7 | 0.68 | 0.70 | 0.75 | 0.68 | 0.72 | 0.76 | 0.71 | 0.75 | 0.76 |
| 7 | 0.68 | 0.70 | 0.75 | 0.68 | 0.72 | 0.76 | 0.71 | 0.75 | 0.76 |
| 8 | 0.58 | 0.60 | 0.63 | 0.58 | 0.61 | 0.64 | 0.60 | 0.63 | 0.64 |
| 8 | 0.58 | 0.60 | 0.63 | 0.58 | 0.61 | 0.64 | 0.60 | 0.63 | 0.64 |

**Table B-3 (Cont'd)**

| K | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.55 | 2.51 | 2.45 | 2.50 | 2.45 | 2.40 | 2.48 | 2.43 | 2.39 |
| 5 | 3.22 | 3.17 | 3.09 | 3.16 | 3.10 | 3.03 | 3.14 | 3.06 | 3.02 |
| 6 | 3.91 | 3.84 | 3.75 | 3.83 | 3.76 | 3.68 | 3.81 | 3.72 | 3.66 |
| 7 | 4.61 | 4.53 | 4.42 | 4.51 | 4.43 | 4.34 | 4.49 | 4.38 | 4.31 |
| 8 | 5.32 | 5.23 | 5.11 | 5.22 | 5.12 | 5.01 | 5.18 | 5.06 | 4.98 |

| Film Thickness | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 4.2 | 4.5 | 4.6 | 4.7 | 4.7 | 4.7 | 4.4 | 4.4 | 4.7 |
| 5 | 5.7 | 6.2 | 6.6 | 6.3 | 6.6 | 6.9 | 6.4 | 6.4 | 6.8 |
| 6 | 7.2 | 7.9 | 8.7 | 8.0 | 8.5 | 9.0 | 8.4 | 8.4 | 9.0 |
| 7 | 8.7 | 9.6 | 10.7 | 9.7 | 10.3 | 11.1 | 10.4 | 10.4 | 11.2 |
| 8 | 10.2 | 11.3 | 12.7 | 11.3 | 12.2 | 13.3 | 11.3 | 12.4 | 13.4 |

**Table B-4 Volumetric Results for 100% Natural Specimens**

| Property | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| $G_{sb}$ | 2.549 | 2.536 | 2.525 | 2.540 | 2.534 | 2.529 | 2.538 | 2.532 | 2.530 |
| SA | 6.65 | 5.95 | 4.98 | 5.99 | 5.37 | 4.68 | 5.80 | 5.02 | 4.56 |
| $G_{se}$ | 2.667 | 2.643 | 2.642 | 2.641 | 2.648 | 2.635 | 2.672 | 2.680 | 2.687 |
| Abs (%) | 1.78 | 1.64 | 1.79 | 1.55 | 1.73 | 1.63 | 2.03 | 2.22 | 2.37 |

| Gmb | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.286 | 2.312 | 2.329 | 2.328 | 2.360 | 2.315 | 2.365 | 2.403 | 2.404 |
| 4 | 2.274 | 2.310 | 2.328 | 2.316 | 2.349 | 2.307 | 2.360 | 2.406 | 2.410 |
| 5 | 2.307 | 2.352 | 2.378 | 2.355 | 2.414 | 2.333 | 2.394 | 2.436 | 2.442 |
| 5 | 2.336 | 2.363 | 2.372 | 2.348 | 2.391 | 2.349 | 2.407 | 2.439 | 2.442 |
| 6 | 2.319 | 2.368 | 2.385 | 2.385 | 2.405 | 2.384 | 2.408 | 2.440 | 2.437 |
| 6 | 2.350 | 2.376 | 2.395 | 2.377 | 2.401 | 2.379 | 2.414 | 2.438 | 2.437 |
| 7 | 2.331 | 2.373 | 2.371 | 2.376 | 2.389 | 2.364 | 2.404 | 2.398 | 2.406 |
| 7 | 2.336 | 2.369 | 2.384 | 2.368 | 2.377 | 2.380 | 2.396 | 2.394 | 2.399 |
| 8 | 2.336 | 2.343 | 2.343 | 2.347 | 2.345 | 2.336 | 2.364 | 2.365 | |
| | 2.337 | 2.342 | 2.354 | 2.353 | 2.348 | 2.325 | 2.368 | 2.374 | |

| Gmm | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.503 | 2.486 | 2.486 | 2.484 | 2.491 | 2.480 | 2.511 | 2.519 | 2.524 |
| 4 | 2.503 | 2.486 | 2.486 | 2.484 | 2.491 | 2.480 | 2.511 | 2.519 | 2.524 |
| 5 | 2.465 | 2.449 | 2.449 | 2.448 | 2.454 | 2.444 | 2.474 | 2.482 | 2.487 |
| 5 | 2.465 | 2.449 | 2.449 | 2.448 | 2.454 | 2.444 | 2.474 | 2.482 | 2.487 |
| 6 | 2.428 | 2.414 | 2.414 | 2.413 | 2.419 | 2.409 | 2.437 | 2.446 | 2.450 |
| 6 | 2.428 | 2.414 | 2.414 | 2.413 | 2.419 | 2.409 | 2.437 | 2.446 | 2.450 |
| 7 | 2.392 | 2.380 | 2.380 | 2.378 | 2.384 | 2.375 | 2.402 | 2.411 | 2.414 |
| 7 | 2.392 | 2.380 | 2.380 | 2.378 | 2.384 | 2.375 | 2.402 | 2.411 | 2.414 |
| 8 | 2.358 | 2.346 | 2.347 | 2.345 | 2.351 | 2.342 | 2.368 | 2.376 | |
| 8 | 2.358 | 2.346 | 2.347 | 2.345 | 2.351 | 2.342 | 2.368 | 2.376 | |

**Table B-4 (Cont'd)**

| Air Voids | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 9.0% | 7.0% | 6.3% | 6.3% | 5.3% | 6.7% | 5.8% | 4.6% | 4.8% |
| 4 | 9.5% | 7.1% | 6.3% | 6.8% | 5.7% | 7.0% | 6.0% | 4.5% | 4.5% |
| 5 | 7.3% | 4.0% | 2.9% | 3.8% | 1.6% | 4.5% | 3.2% | 1.9% | 1.8% |
| 5 | 6.7% | 3.5% | 3.1% | 4.1% | 2.6% | 3.9% | 2.7% | 1.7% | 1.8% |
| 6 | 4.2% | 1.9% | 1.2% | 1.2% | 0.6% | 1.0% | 1.2% | 0.2% | 0.5% |
| 6 | 4.9% | 1.6% | 0.8% | 1.5% | 0.7% | 1.2% | 0.9% | 0.3% | 0.5% |
| 7 | 3.0% | 0.3% | 0.4% | 0.1% | 0.2% | 0.5% | 0.1% | 0.5% | 0.3% |
| 7 | 2.8% | 0.4% | 0.2% | 0.4% | 0.3% | -0.2% | 0.3% | 0.7% | 0.7% |
| 8 | 1.3% | 0.1% | 0.2% | -0.1% | 0.2% | 0.2% | 0.2% | 0.5% | |
| 8 | 1.3% | 0.2% | 0.3% | -0.3% | 0.1% | 0.7% | 0.0% | 0.1% | |

| VMA | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 13.9% | 12.5% | 11.5% | 12.0% | 10.6% | 12.1% | 10.5% | 8.9% | 8.8% |
| 4 | 14.4% | 12.5% | 11.5% | 12.5% | 11.0% | 12.4% | 10.7% | 8.8% | 8.5% |
| 5 | 14.0% | 11.9% | 10.5% | 11.9% | 9.5% | 12.3% | 10.4% | 8.6% | 8.3% |
| 5 | 12.9% | 11.5% | 10.8% | 12.2% | 10.4% | 11.7% | 9.9% | 8.5% | 8.3% |
| 6 | 14.5% | 12.2% | 11.2% | 11.7% | 10.8% | 11.4% | 10.8% | 9.4% | 9.5% |
| 6 | 13.3% | 11.9% | 10.9% | 12.0% | 10.9% | 11.5% | 10.6% | 9.5% | 9.5% |
| 7 | 14.9% | 13.0% | 12.7% | 13.0% | 12.3% | 13.1% | 11.9% | 11.9% | 11.5% |
| 7 | 14.8% | 13.1% | 12.2% | 13.3% | 12.8% | 12.5% | 12.2% | 12.1% | 11.8% |
| 8 | 15.7% | 15.0% | 14.6% | 15.0% | 14.9% | 15.0% | 14.3% | 14.1% | |
| 8 | 15.6% | 15.0% | 14.2% | 14.8% | 14.8% | 15.4% | 14.2% | 13.7% | |

| VFA | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 37.7% | 43.8% | 45.0% | 47.5% | 50.5% | 45.1% | 44.9% | 48.3% | 45.7% |
| 4 | 36.2% | 43.5% | 44.9% | 45.5% | 48.3% | 43.8% | 44.0% | 49.0% | 47.0% |
| 5 | 54.3% | 66.5% | 72.3% | 68.1% | 82.9% | 63.3% | 68.9% | 78.5% | 78.3% |
| 5 | 59.5% | 69.2% | 70.6% | 66.5% | 75.3% | 67.0% | 72.8% | 79.9% | 78.5% |
| 6 | 69.0% | 84.5% | 89.1% | 90.2% | 94.5% | 90.9% | 88.8% | 97.5% | 94.3% |
| 6 | 75.9% | 86.7% | 92.7% | 87.7% | 93.3% | 89.3% | 91.1% | 96.7% | 94.3% |
| 7 | 82.9% | 97.8% | 96.9% | 99.3% | 101.5% | 96.4% | 100.7% | 95.8% | 97.0% |
| 7 | 84.1% | 96.6% | 101.4% | 96.7% | 97.7% | 101.8% | 97.9% | 94.2% | 94.4% |
| 8 | 94.2% | 99.1% | 98.9% | 100.6% | 98.4% | 98.4% | 98.8% | 96.7% | |
| 8 | 94.4% | 98.7% | 102.2% | 102.3% | 99.2% | 95.2% | 99.9% | 99.3% | |

**Table B-4 (Cont'd)**

| Dust/Pbe Ratio | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 1.8 | 1.7 | 1.8 | 1.6 | 1.7 | 1.6 | 1.9 | 2.1 | 2.3 |
| 4 | 1.8 | 1.7 | 1.8 | 1.6 | 1.7 | 1.6 | 1.9 | 2.1 | 2.3 |
| 5 | 1.2 | 1.2 | 1.2 | 1.1 | 1.2 | 1.2 | 1.3 | 1.4 | 1.5 |
| 5 | 1.2 | 1.2 | 1.2 | 1.1 | 1.2 | 1.2 | 1.3 | 1.4 | 1.5 |
| 6 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 | 1.1 |
| 6 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 | 1.1 |
| 7 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 |
| 7 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 |
| 8 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | [illegible] |
| 8 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | [illegible] |

| K | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 2.49 | 2.45 | 2.40 | 2.44 | 2.41 | 2.36 | 2.43 | 2.38 | 2.35 |
| 5 | 3.14 | 3.10 | 3.03 | 3.09 | 3.04 | 2.98 | 3.07 | 3.01 | 2.97 |
| 6 | 3.81 | 3.76 | 3.67 | 3.74 | 3.69 | 3.61 | 3.73 | 3.65 | 3.60 |
| 7 | 4.49 | 4.43 | 4.33 | 4.41 | 4.35 | 4.26 | 4.39 | 4.30 | 4.24 |
| 8 | 5.19 | 5.12 | 5.01 | 5.10 | 5.02 | 4.92 | 5.08 | 4.97 | 4.90 |

| Film Thickness | 9.5 | | | 12.5 | | | 19 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | D | C | F | D | C | F | D | C |
| 4 | 3.3 | 4.0 | 4.7 | 4.1 | 4.2 | 5.1 | 3.4 | 3.5 | 3.6 |
| 5 | 4.8 | 5.6 | 6.4 | 5.8 | 6.1 | 7.2 | 5.1 | 5.5 | 5.8 |
| 6 | 6.3 | 7.3 | 8.5 | 7.4 | 8.0 | 9.3 | 6.8 | 7.5 | 8.0 |
| 7 | 7.8 | 9.0 | 10.5 | 9.1 | 9.8 | 11.5 | 8.6 | 9.5 | 10.1 |
| 8 | 9.3 | 10.7 | 12.5 | 10.8 | 11.7 | 13.6 | 10.3 | 11.5 | [illegible] |

# APPENDIX C. NOTTINGHAM ASPHALT TESTER (NAT) RESULTS

**Table C-1 Accumulated Axial Microstrain at 1800 Cycles for 100% Crushed Specimens**

| Asphalt Content (%) | Specimen ID | 9.5C | 12.5C | 19C | 9.5D | 12.5D | 19D | 9.5F | 12.5F | 19F |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 9462 | 9645 | 9645 | 7729 | 8545 | 8510 | 8101 | 8690 | 7331 |
| 4 | 2 | 9974 | 8617 | 9494 | 8234 | 8516 | 8267 | 9640 | 8152 | 8669 |
| 5 | 1 | 9822 | 9254 | 9758 | 8049 | 9508 | 10408 | 7606 | 8358 | 7475 |
| 5 | 2 | 9228 | 9468 | 9264 | 8207 | 8988 | 8069 | 9696 | 8057 | 8128 |
| 6 | 1 | 9130 | 9546 | 10347 | 8819 | 8352 | 9876 | 8257 | 8165 | 8158 |
| 6 | 2 | 8984 | 9532 | 11315 | 8748 | 8004 | 10696 | 8916 | 8719 | 8492 |
| 7 | 1 | 11920 | 16206 | 14205 | 9552 | 14669 | 17169 | 8193 | 8282 | 8974 |
| 7 | 2 | 9250 | 14845 | 12979 | 9392 | 12520 | 18699 | 9450 | 6296 | 9456 |
| 8 | 1 | 21091 | 27823 | 29365 | 18880 | 24661 | 30125 | 8692 | 21515 | 23615 |
| 8 | 2 | 28868 | 33258 | 27849 | 20559 | 21188 | 34319 | 8297 | 17029 | 20653 |

**Table C-2 Stiffness (kPa) at 1800 Cycles for 100% Crushed Specimens**

| Asphalt Content (%) | Specimen ID | 9.5C | 12.5C | 19C | 9.5D | 12.5D | 19D | 9.5F | 12.5F | 19F |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 416474 | 451482 | 451340 | 406157 | 430875 | 462183 | 347307 | 407752 | 431472 |
| 4 | 2 | 422562 | 463575 | 451482 | 386504 | 415363 | 418794 | 334382 | 400414 | 411522 |
| 5 | 1 | 404934 | 460068 | 426515 | 400278 | 423545 | 437259 | 365337 | 399758 | 426515 |
| 5 | 2 | 403323 | 443302 | 442657 | 426515 | 416582 | 445032 | 340021 | 396157 | 414312 |
| 6 | 1 | 379882 | 436631 | 457146 | 402788 | 405394 | 447297 | 363169 | 401194 | 392394 |
| 6 | 2 | 385124 | 430219 | 432123 | 388881 | 404847 | 401892 | 360558 | 399088 | 395455 |
| 7 | 1 | 384993 | 379507 | 420343 | 371790 | 401472 | 396454 | 336041 | 380731 | 380858 |
| 7 | 2 | 391926 | 398611 | 391161 | 375554 | 389600 | 355558 | 336785 | 421432 | 388844 |
| 8 | 1 | 333357 | 332237 | 357025 | 340629 | 355315 | 354466 | 379657 | 331866 | 318677 |
| 8 | 2 | 307768 | 319363 | 339072 | 360934 | 352780 | 334485 | 342461 | 353621 | 329653 |

Table C-3 Accumulated Axial Microstrain at 1800 Cycles for 50% Crushed/50% Natural Specimens

| Asphalt Content (%) | Specimen ID | 9.5C | 12.5C | 19C | 9.5D | 12.5D | 19D | 9.5F | 12.5F | 19F |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 10992 | 9597 | 11081 | 11380 | 8570 | 9404 | 12467 | 10343 | 9089 |
| 4 | 2 | | 10865 | 10400 | 9168 | 8781 | 8938 | 11446 | 9819 | 8320 |
| 5 | 1 | 12523 | 12621 | 9524 | 10241 | 10419 | 10168 | 11080 | 10964 | 9755 |
| 5 | 2 | 11846 | 11765 | 10093 | 8991 | 9235 | 9570 | 10599 | 11581 | 9508 |
| 6 | 1 | 12059 | 10406 | 17080 | 10793 | 10347 | 15402 | 11925 | 11238 | 15625 |
| 6 | 2 | 12443 | 10016 | 17907 | 11021 | 13950 | 20918 | 11267 | 10799 | 15415 |
| 7 | 1 | 11088 | 22742 | 37021 | 10680 | 31132 | 48486 | 12176 | 12526 | 37860 |
| 7 | 2 | 11932 | 24185 | 42603 | 9876 | 26056 | 37240 | 10529 | 15897 | 39707 |
| 8 | 1 | 29083 | 49430 | | 28016 | 61633 | | 13934 | 34376 | 62955 |
| 8 | 2 | 29179 | 48128 | | 26620 | 59107 | 70514 | 13940 | 36540 | 72204 |

Table C-4 Stiffness (kPa) at 1800 Cycles for 50% Crushed/50% Natural Specimens

| Asphalt Content (%) | Specimen ID | 9.5C | 12.5C | 19C | 9.5D | 12.5D | 19D | 9.5F | 12.5F | 19F |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 388216 | 354624 | 386411 | 349868 | 398876 | 418380 | 352809 | 374877 | 405941 |
| 4 | 2 | | 374014 | 406015 | 354591 | 390869 | 404302 | 338577 | 362134 | 412633 |
| 5 | 1 | 363417 | 351161 | 381981 | 334944 | 365511 | 383481 | 323646 | 344790 | 377947 |
| 5 | 2 | 335309 | 350521 | 380988 | 355443 | 365072 | 368528 | 339323 | 335309 | 374175 |
| 6 | 1 | 313511 | 345495 | 369912 | 330469 | 358041 | 335971 | 345752 | 329021 | 342666 |
| 6 | 2 | 322145 | 348370 | 348939 | 315462 | 345681 | 318580 | 291142 | 333774 | 344277 |
| 7 | 1 | 316974 | 306785 | 293081 | 314955 | 288934 | 286673 | 288485 | 306496 | 279561 |
| 7 | 2 | 325316 | 294156 | 280845 | 312263 | 290079 | 268051 | 298558 | 276761 | 270776 |
| 8 | 1 | 261861 | 256207 | | 260710 | 239651 | | 291568 | 259570 | 254449 |
| 8 | 2 | 260710 | 258664 | | 256429 | 249108 | 255986 | 285006 | 252931 | 255986 |

**Table C-5 Accumulated Axial Microstrain at 1800 Cycles for Manufactured Fine-Natural Coarse Specimens**

| Asphalt Content (%) | Specimen ID | 9.5C | 12.5C | 19C | 9.5D | 12.5D | 19D | 9.5F | 12.5F | 19F |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 10992 | 14524 | 14811 | 9743 | 11038 | 13235 | 7943 | 10736 | 10411 |
| 4 | 2 | | 19698 | 12385 | 10127 | 11019 | 13669 | 8179 | 10473 | 10171 |
| 5 | 1 | 12523 | 12675 | 19088 | 11731 | 11149 | 11847 | 8603 | 12901 | 11241 |
| 5 | 2 | 11846 | 12025 | 14177 | 8906 | 11532 | | 8338 | 12513 | 11036 |
| 6 | 1 | 12059 | 12032 | 15024 | 9098 | 10358 | 11988 | 8837 | 11367 | 11422 |
| 6 | 2 | 12443 | 11291 | 16792 | 9062 | 9719 | 12137 | 8707 | 11137 | 12515 |
| 7 | 1 | 11088 | 18469 | 33259 | 10618 | 24262 | 26485 | 9097 | 12201 | 17099 |
| 7 | 2 | 11932 | 20216 | 31923 | 10224 | 24004 | 28121 | 9818 | 11012 | 14190 |
| 8 | 1 | 29083 | 43253 | | 22862 | 41988 | 52038 | 9527 | 21456 | 30816 |
| 8 | 2 | 29179 | 40346 | | 24057 | 42817 | 48077 | 9987 | 15296 | 34341 |

**Table C-6 Stiffness (kPa) at 1800 Cycles for Manufactured Fine-Natural Coarse Specimens**

| Asphalt Content (%) | Specimen ID | 9.5C | 12.5C | 19C | 9.5D | 12.5D | 19D | 9.5F | 12.5F | 19F |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 388216 | 377686 | 412626 | 361395 | 382853 | 389379 | 358100 | 370424 | 414285 |
| 4 | 2 | | 349788 | 413200 | 376690 | 398723 | 418878 | 375609 | 385368 | 397692 |
| 5 | 1 | 363417 | 362798 | 354466 | 371302 | 380731 | 375966 | 367831 | 371302 | 362894 |
| 5 | 2 | 335309 | 363676 | 372256 | 372634 | 381214 | | 359033 | 374426 | 387395 |
| 6 | 1 | 313511 | 373192 | 383984 | 382522 | 388335 | 377065 | 360976 | 357093 | 402562 |
| 6 | 2 | 322145 | 368099 | 380493 | 368166 | 370860 | 341468 | 356841 | 351386 | 372256 |
| 7 | 1 | 316974 | 337145 | 317183 | 371790 | 326621 | 345088 | 352190 | 345681 | 356423 |
| 7 | 2 | 325316 | 323734 | 315711 | 349868 | 335601 | 341468 | 344311 | 350113 | 354697 |
| 8 | 1 | 261861 | 285827 | | 301819 | 298179 | 294042 | 337145 | 311320 | 315626 |
| 8 | 2 | 260710 | 291156 | | 308087 | 285003 | 297283 | 332355 | 323542 | 308408 |

Table C-7 Accumulated Axial Microstrain at 1800 Cycles for 100% Natural Specimens

| Asphalt Content (%) | Specimen ID | 9.5C | 12.5C | 19C | 9.5D | 12.5D | 19D | 9.5F | 12.5F | 19F |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 10758 | 14403 | 15315 | 12607 | 9863 | 12183 | 14351 | 11907 | 14218 |
| 4 | 2 | 12396 | 12273 | 16147 | 12489 | 9582 | 9667 | 15480 | 15004 | 17262 |
| 5 | 1 | 10891 | 12107 | 11832 | 12321 | 12191 | 13035 | 14677 | 13738 | 13489 |
| 5 | 2 | 10101 | 12526 | 13073 | 13174 | 12194 | 11623 | 19689 | 11222 | 14664 |
| 6 | 1 | 18232 | 11021 | 21302 | 12779 | 17131 | 21202 | 19519 | 15176 | 18905 |
| 6 | 2 | 16199 | 11583 | 23555 | 14461 | 25865 | 26812 | 19767 | 14962 | 15966 |
| 7 | 1 | 27495 | 27204 | 44417 | 44819 | 55150 | 73594 | 21338 | 43538 | 57230 |
| 7 | 2 | 29094 | 25779 | 38136 | 36508 | 61953 | 79839 | 19788 | 57563 | 50712 |
| 8 | 1 | 56096 | 43946 | | 90560 | | | 46030 | 76767 | |
| 8 | 2 | 65151 | 59604 | | 88263 | | | 42281 | 84825 | |

Table C-8 Stiffness (kPa) at 1800 Cycles for 100% Natural Specimens

| Asphalt Content (%) | Specimen ID | 9.5C | 12.5C | 19C | 9.5D | 12.5D | 19D | 9.5F | 12.5F | 19F |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 331339 | 350419 | 345967 | 313456 | 362894 | 339460 | 306315 | 353611 | 327944 |
| 4 | 2 | 345858 | 319707 | 361054 | 316031 | 344790 | 365891 | 291961 | 321981 | 310946 |
| 5 | 1 | 310327 | 297692 | 332931 | 324899 | 330388 | 323190 | 346907 | 320448 | 343787 |
| 5 | 2 | 323172 | 297405 | 337534 | 343703 | 325457 | 345088 | 256940 | 317769 | 327470 |
| 6 | 1 | 264900 | 309687 | 306756 | 331495 | 306813 | 300697 | 248452 | 291442 | 282291 |
| 6 | 2 | 273445 | 286912 | 275234 | 290519 | 280423 | 287546 | 262864 | 297717 | 295342 |
| 7 | 1 | 267019 | 248691 | 251269 | 238979 | 232146 | 209970 | 244851 | 237656 | 237350 |
| 7 | 2 | 239742 | 256969 | 274069 | 235790 | 225790 | 224594 | 261483 | 200532 | 245197 |
| 8 | 1 | 213258 | 223343 | | 194690 | | | 209583 | 213108 | |
| 8 | 2 | 194316 | 210068 | | 222625 | | | 224101 | 199070 | |

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