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6. Abstract

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Research Project 3-9-88-1158
Impact of Aggregate Gradation and Type on Asphalt Mixture Characteristics

conducted for

Texas State Department of Highways
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by the

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PREFACE

This is the first and final report for Research Study 3-9-88-1158, "Impact of Aggregate Gradation and Type on Asphaltic Mixture Characteristics." The report contains: a literature search relative to Hot Mix Asphalt Concrete (HMAC) characteristics, especially VMA; an investigation of the current production of HMAC in Texas with respect to voids in the mineral aggregate (VMA); the results of laboratory investigations to determine the effects of aggregate gradation and type on HMAC properties; and an investigation of the economic consequences of including VMA in specifications for HMAC.

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November 1990

ABSTRACT

This report addresses the impact of aggregate gradation and type on Hot Mix Asphaltic Concrete (HMAC) characteristics. Several different, but related, topics are covered, and results from several experiments are presented. An overview of HMAC is presented, covering factors affecting mixture characteristics and performance, in addition to a review of the literature relating to aggregate gradation and type. The results of a study of construction data from the Texas State Department of Highways and Public Transportation (SDHPT) are presented.

Two laboratory studies were conducted relating to asphalt content, aggregate gradation, and aggregate type. The summarized results and interpretations of these results are included. The economic impact of specifications changes currently proposed by the SDHPT to improve HMAC quality is addressed. Finally, conclusions and recommendations are drawn based on all preceding material.

Key Words: Hot Mix Asphaltic Concrete (HMAC), asphaltic content, aggregate gradation, aggregate type, economic impact

SUMMARY

This report addresses the impact of aggregate gradation and type on Hot Mix Asphaltic Concrete (HMAC) characteristics. Topics covered are summarized as follows:

(1) An overview of HMAC, covering factors affecting mixture characteristics and performance, and a review of the literature relating to aggregate gradation and type.
(2) A study of construction data from the Texas State Department of Highways and Public Transportation (SDHPT).
(3) Two laboratory studies relating to asphalt content, aggregate gradation, and aggregate type.
(4) Economic impact of specification changes currently proposed by the Texas SDHPT.
(5) Conclusions and recommendations drawn from previous sections.

IMPLEMENTATION STATEMENT

This report provides information about factors affecting HMAC characteristics, especially VMA. The report explores the current production of HMAC in Texas and experiments related to factors affecting VMA. The likely economic impact of VMA specifications on HMAC prices in Texas is also explored.

The information from this report can be used to evaluate the VMA of mixtures in Texas for comparison purposes. The report contains a list of progressive measures to be taken for mixtures with insufficient VMA which are likely to produce VMA changes. The economic evaluation may be used to estimate the effects of VMA specifications for HMAC on the production price of HMAC and possible implications for future funding and supply.

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CHAPTER 1. INTRODUCTION

In September 1987, the Texas State Department of Highways and Public Transportation (SDHPT) contracted with The University of Texas at Austin Center for Transportation Research, under Research Study 3-9-88-1158, to investigate aggregate gradations and types used by the Department for hot mix asphaltic concrete (HMAC). The SDHPT was preparing to update the *Standard Specifications for Construction of Highways, Streets and Bridges* and was particularly interested in knowing the effect of including "Voids in the Mineral Aggregate" (VMA) requirements in specifications for hot mix asphaltic concrete.

To address the concerns and interests of the SDHPT, the formulated objectives of this study were as follows: to review HMAC characteristics, especially VMA, in the literature; to investigate the current production of HMAC in Texas with respect to VMA and to develop correlations between VMA and HMAC parameters; to conduct laboratory investigations to determine the effects of aggregate gradation and type on HMAC properties; and to investigate the economic consequences of including VMA in specifications for HMAC.

This is the first and final report for Research Study 3-9-88-1158, "Impact of Aggregate Gradation and Type on Asphaltic Mixture Characteristics." The scope of this study and report is as shown below:

(1) Background—literature review,
(2) Evaluation of current gradations used in Texas;
(3) Laboratory evaluation of variation in mix properties with asphalt content and aggregate gradation;
(4) Laboratory evaluation of aggregate substitution on VMA;
(5) Economic impact of specification changes; and
(6) Conclusions/recommendations.

"Background—Literature Review" involves a review of the literature pertaining to aggregate gradation and type and their effects on mixture properties as well as a review of the requirements of selected other states which address aggregate gradation.

During the 1987 construction season, the SDHPT collected construction data for 92 hot mix asphaltic concrete (HMAC) mixtures. The Center for Transportation Research, in Research Study 3-9-88-1197, organized these data into a database and performed some preliminary analysis to describe the current production of hot mix asphaltic concrete. "Evaluation of Current Gradations Used in Texas" describes an analysis of this construction database as it relates to the focus of this project.

Initially, this project was also to address long-term pavement performance of projects contained in the Research Study 3-9-88-1197 database, but the SDHPT has decided to conduct their own analysis of the long-term pavement performance for construction projects included in this database. Specially trained department personnel and equipment will be used uniformly across the state, and the information from Research Study 3-9-88-1197 will be used for long-term pavement performance studies and pavement management. Therefore, Research Study 3-9-88-1158 will not address the long-term pavement performance aspects of aggregate gradation and type on HMAC.

"Laboratory Evaluation of Variation in Mix Properties with Asphalt Content and Aggregate Gradation" details the analysis of mixture properties of two HMAC designs, each design obtained from a different SDHPT district, and each with variations in aggregate gradation and asphalt content.

"Laboratory Evaluation of Aggregate Substitution on VMA" consists of a laboratory evaluation of one mixture design with substitution of one of the component aggregates with one of two others, to evaluate changes in design parameters.

"Economic Impact of Specification Changes" is a discussion of the economic impact of changes to specifications currently being proposed by the Texas SDHPT.

"Conclusions/Recommendations" is a summary of the significant results obtained from the project phases and any recommendations made based on these results.

CHAPTER 2. BACKGROUND—LITERATURE REVIEW

The literature review is divided into three areas relative to the objectives of this study. Information basic to understanding HMAC is initially addressed. Next, research pertaining to aggregate gradation and type, with special emphasis on VMA and maximum density grading curves, is investigated. Finally, the requirements of various state highway departments, with respect to mixture design procedures and VMA, are summarized.

HOT MIX ASPHALT CONCRETE—COMPONENTS, PERFORMANCE, AND ECONOMICS

HMAC consists of a combination of aggregate, asphalt cement, and air voids. The production of HMAC involves blending different types and sizes of aggregate, heating, and coating with asphalt cement. This material is then transported to the road site, placed on the roadway in a uniform thickness, and compacted to form part of the road structure. Manipulation of the three components of HMAC can result in wide variations in the stability and durability of the mixture. Also, variations in mixture properties can occur with variations in compaction. The three components of HMAC and compaction are interrelated, and manipulating one component to change the stability of a mixture may have detrimental effects on durability and vice versa.

A good road will support the loads placed on it, last a long time, and be economical. Hot Mix Asphalt Concrete (HMAC) is one of the most widely-used road building materials in the world, and, if designed correctly, will demonstrate the characteristics desired in a road. Correctly designing an HMAC is not an easy task since the mixture characteristics needed for load support and long-term durability are often at odds with each other. The material must be designed to arrive at a compromise which will best fulfill these needs.

The road characteristic of "supporting the loads placed on it" is a broad requirement which encompasses resistance to failure due to both permanent deformation and load stress (tensile, compressive, and shear). This is essentially the same characteristic that Jimenez and Dadeppo[11] describe as stability, which will be used to describe this characteristic.

The road characteristic meaning "last a long time" is another broad requirement which will be described by "durability." Durability encompasses fatigue resistance (repeated load) and resistance to environmental effects such as temperature, moisture, oxidation, and time (examples: thermal cracking and stripping).

ASPHALT

Asphalt is the binder which holds an HMAC together. For good HMAC durability, one needs to use as much asphalt cement in the mixture as possible. This gives greater resistance to asphalt aging (oxidation) and water damage. Also, there is evidence in the literature[11,7,5] to indicate that increased asphalt content results in greater fatigue life. Too much asphalt, however, can result in bleeding or flushing of the pavement surface (asphalt migrates to the surface, resulting in reduced surface friction), as well as in an unstable pavement which is unable to carry loads without permanent deformation. Too little asphalt results in an HMAC prone to asphalt oxidation and subsequent mix embrittlement, less resistance to moisture damage, and a decreased fatigue life. Insufficient asphalt can also initially produce a mix which is unable to withstand the load stresses placed on it. Therefore, either too little or too much asphalt can result in decreased pavement life. The optimum amount of asphalt for a given hot mix must be determined by balancing the beneficial and detrimental effects of asphalt content on a mixture. Most mixture designs use the philosophy, "Use as much asphalt as possible without detrimental loss of stability."[11]

AIR VOIDS

Air voids are a critical part of a mixture and provide insurance against bleeding or flushing of the pavement surface (asphalt migrates to the surface, resulting in reduced surface friction), as well as against an unstable pavement which is unable to carry loads without permanent deformation. High air void contents decrease durability by aiding asphalt oxidation. High air voids can also enable further compaction in service by traffic and result in permanent deformation. Low air void contents may allow bleeding or flushing and instability to take place. Most design procedures take into account the detrimental effects of extremes in air void content by placing upper and lower limits on air voids. The Marshall mix design method calls for air voids in the range of 3 to 5 percent. The SDHPT Hveem design criteria call for 3 or 4 percent air voids, depending on how the percentage of air voids is calculated.[16] These limits were set to balance the detrimental and beneficial effects of air void content for the majority of mixtures and were derived from experience over time.

AGGREGATE

Aggregate forms the skeleton or the supporting structure of an HMAC and, as such, is responsible for the majority of the load-bearing capacity of the mixture. Most HMAC is composed of a continuously-graded aggregate blended from several different sizes and types of aggregate. Aggregate can be of different geologic origin, can result from different methods of production, and can represent specific sizes of the production. As such, virtually all mixes are different with respect to aggregate gradation and type.

Aggregate characteristics which may differ include: size distribution, shape, surface texture, surface area, asphalt absorption, and chemical/mineralogic composition. When combining three or more separate aggregates, all of which may have different characteristics, one can see how complicated the study of mixture aggregate gradation can become.

Aggregate can affect the mixture properties in many ways. Particle shape and surface texture of the aggregate play a large part in how closely the aggregates may be compacted. Evidence suggests that rounded particles result in a "more compactable" mix.[5] Rough surface texture results in less compactability, and the associated higher surface areas require more asphalt for the same film thickness.[6] Certain aggregates are also more prone to moisture damage than others. There are many other aggregate-induced effects, such as mixture tenderness, but the exact causes are hard to quantify because of the complexities of aggregates.

COMPACTION

Compaction is external to the material itself, but plays just as an important a role in HMAC mixture performance as do the ingredients. Most mix design procedures utilize some form of standard compaction technique which insures that the designed mixture has the capability of being compacted to the range desired (not too much and not too little). The performance of the final product is a function of the degree of compaction attained on the roadway. Assuming the mixture ingredients are capable of performing satisfactorily, the degree of compaction can result either in a stable and durable roadway component or in premature failure. Adequate compaction will result in proper utilization of the asphalt as a binder in the mixture, an air void content low enough to preclude early asphalt oxidation and exclude moisture from the mix, and aggregates consolidated enough to provide the stability necessary to resist further consolidation under normal traffic conditions. Inadequate compaction may result in a mix which will be prone to asphalt oxidation, moisture damage, and lower fatigue life, one which will exhibit instability due to consolidation under traffic and, ultimately, early failure.

HMAC PERFORMANCE

As can be seen from the foregoing paragraphs, mixture performance is influenced by many variables which are interrelated. Asphalt, air voids, aggregate, and compaction work in combination to produce a material which will perform satisfactorily as a roadway component. Changing any of the components in the mixture, or their relative proportions, may result in substantial changes in the properties of that mixture due to other interrelated variables. As an example, increasing the asphalt content of a given mixture may result in lower-than-expected air voids because of more asphalt in the mixture and increased compactability of the aggregate from lubrication effects of the asphalt. This could result in a more durable pavement (less prone to asphalt oxidation and moisture damage, with a higher resistance to fatigue cracking due to repeated loading), but could also result in instability of the mixture (prone to permanent deformation due to plastic flow). The actual effects depend on how sensitive the mixture is to changes in asphalt content from the design or baseline condition.

ECONOMICS

The last characteristic desired in a roadway is that it be economical. The goal of any mixture design procedure is to produce a mixture that satisfies durability and stability requirements and also is economical. Mixture design procedures do this by allowing the use of local (low transportation costs) aggregates as long as they produce mixtures meeting the design criteria which are, at least in theory, devised to provide stability and durability.

RESEARCH PERTAINING TO AGGREGATE GRADATION AND TYPE

Aggregates, their gradation, and their type have been studied for many years. The studies have been based on trends in the industry, experience with mixes placed on the roadway, and laboratory experiments. The results have developed many interesting concepts, but most conclusions have been made in generic terms. Two concepts which have received the most attention are Voids in the Mineral Aggregate (VMA) and Maximum Density Grading Curves.

VMA

Voids in the mineral aggregate (VMA) is a measure of the amount of void space available between the aggregates of a compacted HMAC. This void space consists of the space available for asphalt, which gives durability and cohesiveness to the mixture, and air voids—insurance against asphalt migration and subsequent instability of the pavement. The VMA is a function of aggregate characteristics, asphalt characteristics, the proportions of asphalt and aggregate in the mixture, and compaction.

As such, VMA must be determined based on actual compacted specimens of the materials and proportions of interest. If one uses a standard compaction technique, VMA may be studied without compaction as a variable. Because VMA is indicative of the amount of space available for asphalt and air within a given mixture, it is included in HMAC specifications by many highway agencies.

The Asphalt Institute, in its publication "Mix Design Methods for Asphaltic Concrete and Other Hot Mix Types,"[1] recommends minimum VMAs for HMAC based on the nominal maximum particle size of the aggregate in Marshall mix design. The larger the nominal maximum particle size, the lower the minimum VMA required. This recommendation is based on work by Mcleod,[18] which was published in ASTM Special Technical Publication No. 252 in 1959.

VMA CALCULATIONS

VMA currently is determined by the formula:

$$VMA = 100 - \frac{G_a * \%Agg}{G_{Agg}}$$

where

G_a = actual specific gravity of compacted mixture,

$\%Agg$ = percentage of aggregate in the mixture by weight (100—%Asphalt), and

G_{Agg} = bulk specific gravity of aggregates, or

G_{Agg} = effective specific gravity of aggregates.

There has been some question concerning which G_{Agg} should be used in the equation. The controversy revolves around whether pores in the aggregate, which can absorb asphalt, should be included as part of the VMA. The asphalt absorbed into these pores is effectively lost in terms of asphalt available for use as a binder in the mixture. Many researchers[1,2,6] use the bulk specific gravity of the aggregate in the above VMA definition, which excludes aggregate pore volume as part of VMA. They view VMA as the space available in a compacted mixture for asphalt, which functions as a binder, and air. Other researchers prefer to use the effective specific gravity of the aggregate in the above VMA definition instead of the bulk specific gravity of the aggregate.[11,19] This includes the aggregate pore volume which absorbs asphalt as part of the VMA. Some researchers view VMA as the space available for air and asphalt, whether or not the asphalt functions as a binder. For aggregates which do not absorb asphalt, the two VMA calculations will yield identical results, but as asphalt absorption increases, using the effective specific gravity of the aggregate will yield higher VMA calculations.

Using the bulk specific gravity of the aggregate produces VMA values representing the space available for asphalt and air in the mixture after all asphalt absorption has been satisfied. If absorptive aggregates are used, there may seem to be a discrepancy between the amount of asphalt used and the amount of available room for asphalt (VMA—Air Voids). The volume of asphalt used could be more than the room available for asphalt as determined by VMA. The discrepancy is not real, since in using the bulk specific gravity of the aggregate for VMA calculation, the volume of asphalt absorbed is not included.

For this study, the bulk specific gravity of the aggregate will be used for all VMA calculations.

ALTERNATE VMA DETERMINATIONS

There have been several procedures developed for determining the VMA directly from the aggregate and not calculating the VMA from an actual compacted specimen of the HMAC. Procedures include generic voidage reduction factors and actual particle packing techniques.

VOIDAGE REDUCTION FACTORS

Hudson and Davis,[12] in a paper presented to AAPT in 1965, developed a method of determining the VMA of a mixture based on the aggregate gradation. This approach uses particle packing and void-filling principles in which small-size particles, with inherent voids in their packed volumes, fill void spaces in larger-size packed particles; this blend fills voids in still-larger-size packed particles. There is an optimum percentage of each size component to product minimum voids in the entire blend resulting in minimum VMA. Adding more or less than the optimum percentage of each component will cause the blend to exhibit more than the minimum VMA.

Hudson and Davis used the ratio of cumulative percent passing successive sieve sizes and derived voidage reduction factors to ultimately calculate the Aggregate Voidage of the mixture. Voidage reduction factors were derived for certain generic aggregate types, and their use depends on the use of specific sieve sizes to describe the aggregate gradation. Comparisons of calculated Aggregate Voidage with VMA determined in Bureau of Public Roads data showed reasonable correlation (range of differences between calculated and BPR VMA values were -1.2 to +0.7).

This method is reasonable; however, the Voidage Reduction Factors for the various aggregate types are too generic to result in more accurate results. There are too many aggregate types and resulting shapes and surface textures for generic factors to apply accurately.

Jimenez and Dadeppo,[11] in a 1986 report for the Arizona Department of Transportation, developed a mixture design procedure based in part on the concepts developed by Hudson and Davis. In this mix design process, aggregate gradation is used to calculate VMA using Voidage Reduction Factors, and aggregate surface area is determined using Surface Area Factors. The optimum mixture proportions are selected based on the VMA of the aggregate (the VMA is the ultimate VMA of the mixture and not that currently used in specifications) and asphalt content required to give adequate film thickness.

Jimenez and Dadeppo report good correlation of optimum asphalt determinations for mixtures from several highway departments from around the country (R^2=0.79), but lower correlation for mixtures from the Arizona Department of Transportation (R^2=0.18). This may be due to the generic Voidage Reduction Factors and Surface Area Factors being more applicable to the nation as a whole (wide variety of aggregates) and less applicable to Arizona aggregates.

PARTICLE PACKING USING ACTUAL AGGREGATE

Sharma and Rao,[10] in a 1984 paper submitted to the Indian Roads Congress, describe a method of determination of aggregate voids in multi-component aggregate blends using particle packing and void characteristics. The process involves determining the minimum percent voids in a two-component blend of the two largest aggregate sizes and then treating this optimized blend as one component and finding the optimum blend with the next smallest component. The process proceeds until all sizes are represented in the final blend. This final blend would represent the minimum VMA for those aggregates. The process can be adjusted to calculate the VMA of any aggregate blend in the same manner.

The procedure utilizes the oven dry bulk specific gravity (BSG_{od}) of the aggregate blend in question and its Dry Rodded Unit Weight (DRUW) to calculate the percent voids.

This procedure is similar to the one used in the concrete industry to achieve near-minimum aggregate voids for a "filter block effect" in the design of portland cement concrete to be placed by pumping. A "filter block effect" results when the aggregate has so few voids that as a concrete pump moves the fluid portion of the mixture (water), the solid portion (aggregate and cement particles) must be carried along with it.

A problem in using this procedure for HMAC design is that individual aggregates, which in themselves represent a range of sizes, may produce inaccurate Dry Rodded Unit Weights owing to segregation. To address this problem, blends of consecutive aggregate sizes would have to be made to form "new" aggregates, limiting segregation effects in the DRUW determination. This would greatly complicate the process of voids determination for an HMAC aggregate blend.

Another problem is that this procedure does not take into account the lubricating effect asphalt has on VMA, since this procedure tests only the dry aggregates. Griffith and Kallas[5] reported data obtained from two aggregate blends tested similarly in 1957 and found the procedure not to be a reliable method of determining aggregate voids in bituminous mixtures. This may be due to segregation, asphalt lubrication, or procedural differences.

This procedure does address some aspects which have been downplayed by the Void Reduction Factor methods, namely aggregate shape and surface texture. Since the actual aggregate is used, the actual shape and surface texture characteristics and their impact on the aggregate voids is taken into account. To achieve a specified void content, the process would involve trial and error.

MAXIMUM-DENSITY GRADING CURVES

Maximum-Density Grading Curves are methods to graphically depict the maximum-density capability of selected aggregate sizes. Actual aggregate gradations may be compared with the maximum-density curve to see where deviations from the maximum-density line occur. HMAC aggregate gradations with certain types of deviations from the maximum-density line have been found to exhibit specific problems, most notably mixture tenderness. It is suggested that adjusting the actual gradation in relation to the maximum-density line may solve some HMAC problems. Other observations regarding deviations from the maximum-density line are said to give more room in the mixture for asphalt (VMA) and hence increase HMAC durability.

Maximum-density grading curves take into account only the standard sieve sizes normally used in HMAC specifications. As such, maximum-density curves do not take aggregate shape or surface texture into account.

DEVELOPMENT OF THE 0.45 POWER CHART

In 1962, Goode and Lufsey,[13] of the Bureau of Public Roads, proposed the use of a new chart to display aggregate gradation and maximum density. The new chart would replace the traditional maximum-density chart, which expressed the percentage passing (arithmetic scale) versus the sieve size (logarithmic scale). According to Goode and Lufsey, the traditional "logarithmic gradation chart" yielded a maximum-density line as a "deeply sagging curve, the shape of which is hard to define."

The new Goode and Lufsey chart was based on the development of an equation to describe the maximum density of an aggregate gradation. The equation was:

$$P = 100 * \left(\frac{S}{M}\right)^{0.45}$$

where

M = maximum size of aggregate in microns,
S = size of opening for a particular sieve, and
P = percent passing the particular sieve.

If the percent passing a particular sieve size is plotted arithmetically, versus the sieve size raised to the 0.45 power, the resulting maximum-gradation curve is a line extending from 0 (zero) percent passing the 0 (zero) sieve size through the actual percent retained on the nominal maximum sieve size (nominal maximum sieve size is the largest standard sieve size which actually retains any particles) and continuing to intersect the 100 percent passing line. The sieve size indicated at the 100 percent passing point is termed the effective maximum aggregate size for the mixture. The effective maximum aggregate size may not be one of the standard sieve sizes.

Goode and Lufsey used this new chart in the study of "tender" mixtures, defined as mixtures which conform to specifications, but which can not be compacted in the normal manner because they are slow in developing sufficient stability to withstand the weight of rolling equipment. They observed that many "tender" mixes displayed a "hump" or positive deviation from the maximum-density line at or near the No. 30 sieve. They concluded that this "hump," produced by an excess of fine sand, resulted in lower compacted densities and decreased stability due to separation of coarse aggregate and less coarse aggregate interlock. With further lab work, they found that a hump at the No. 30 sieve size (with other things being equal) resulted in increased VMA and lower Marshall Stability. They concluded that the hump "may be a contributing factor toward the unsatisfactory behavior of mixtures" and is, therefore, undesirable.

In 1989, Kandhal[20] reported that designers at highway agencies were using three variations of the "maximum density line." One of the lines used is defined as Goode and Lufsey proposed in 1962. The other two lines represent variations or alternate interpretations of the line. They all begin at 0 (zero) percent passing the 0 (zero) sieve size, but differ in the location of the end-point for the maximum sieve size. This indicates that some disagreement or confusion exists regarding the definition and use of maximum-density lines.

ALTERNATE MAXIMUM-DENSITY LINE

In 1987, D.E. Edge[14] of the Asphalt Institute noted that the 0.45 power maximum-density chart (now known as the FHWA 0.45 Power Chart) indicates that more material passing the No. 200 sieve should be used than most highway agencies choose to use. He thought another maximum-density line based on the 0.45 Power Chart might be more appropriate. His idea was a "maximum-density line" formed by "a straight line drawn between the desired percent passing the No. 200 sieve and the desired percent passing the nominal maximum sieve size." He even went further to say that a "straight line drawn between any two sieve sizes describes a maximum-density grading between those two sizes."

This idea could be extended to say that any specific aggregate gradation has a maximum-density line formed by drawing a line from the actual percent passing the No. 200 sieve to the actual percent retained on the nominal maximum sieve size. In this manner, each gradation has its own maximum-density curve.

VMA AND MAXIMUM-DENSITY LINES

In theory, any aggregate gradation that falls on the "maximum-density line" results in the maximum aggregate density possible for the aggregate sizes represented. Maximum aggregate density also means minimum VMA. Consequently, any deviation from the maximum-density line implies that the VMA of the mixture is more than the minimum. Many researchers have studied VMA and deviations from the maximum-density line and made general statements regarding how various aggregate sizes affect VMA and how deviations from the maximum-density line affect the VMA. A list of some of these observations and conclusions follows.

FROM THE ASPHALT INSTITUTE[1]

Gradings that closely approach the maximum density line must be adjusted away from it within acceptable limits to increase the VMA.

As a general approach to obtaining higher VMA the aggregate grading should be adjusted by adding more coarse or fine aggregate.

FROM FIELD[2]

For aggregates of borderline minimum VMA, the VMA increases by 0.5% for every 5% increase in pass 4.75mm (No. 4) sieve material.

For aggregates of good VMA, the VMA increases by 0.8% for every 5% increase in pass 4.75mm (No. 4) sieve material.

An increase of 1% pass 75 mm (No. 200) sieve lowers the voids and VMA by 0.8%.

Angular coarse aggregate particles will provide for higher VMA than rounded particles.

FROM ASPHALT—THE MAGAZINE OF THE ASPHALT INSTITUTE[3]

An increase in the volume concentration of stone in a mix corresponds to a decrease in VMA.

FROM GRIFFITH AND KALLAS[4]

Increased angularity and roughness of surface texture of fine aggregate produced increased minimum percent aggregate voids in asphaltic concrete mixes compacted by the methods specified for the Marshall and Hveem methods.

FROM GRIFFITH AND KALLAS[5]

For a given aggregate, gradation, and compaction method, void values normally decrease with increasing asphalt contents to a minimum value and then increase as the increased amount of asphalt prevents aggregate particles from achieving their most intimate contact. This occurs even though air voids still exist in the mix.

The separation of aggregate particles by increased amounts of asphalt, after minimum void values have been reached, affects the strength characteristics of a mix by decreasing its ability to withstand shearing stresses.

Stability tests such as the Marshall and Hveem generally indicate stability decreases for asphalt contents greater than that necessary for producing minimum aggregate voids in a mix.

Selection of an optimum asphalt content for a given mix, using the criteria of the Marshall and Hveem methods of mix design, normally results in an asphalt content near, or slightly less than, the amount required to produce minimum aggregate voids. Therefore, the optimum asphalt content appears to be closely related to the voids in the mineral aggregate. Furthermore, the asphalt content is almost directly proportional to the amount of aggregate voids for mineral aggregates having low asphalt absorption.

The uncrushed gravel mix specimens, as a group, indicated lower aggregate voids than the crushed rock mixes through the gradations investigated.

Coarse aggregate particle shape, whether the aggregates are crushed or uncrushed , has considerable influence on aggregate voids, particularly when the coarse fractions are greater than 50%.

Aggregate voids in compacted asphalt paving mixes vary in a logical and orderly fashion. Actual values, however, are primarily dependent upon type and gradation of the aggregate, asphalt content and method of compaction.

FROM MCLEOD[6]

Increasing the percent of fine aggregate in dense graded bituminous concrete, the percent of voids in the mineral aggregate can be substantially increased.

When a range of air voids and a minimum percent age of VMA are specified this automatically establishes a minimum bitumen content by weight for the paving mixture.

FROM ACOTT[8]

The state of Illinois achieved significant improvements in HMAC properties by increasing the VMA. The VMA increase was accomplished by moving the gradation away from the maximum density line. This involved substituting a coarse crushed sand for a fine natural sand.

FROM EDGE[14]

The 0.45 curve will probably not have a sufficient VMA to allow an adequate coating of the aggregate and still have 3 to 5% air voids in the design mix.

To increase the VMA, a continuous grading curve either above or below the 0.45 curve may be incorporated.

A gradation below the 0.45 curve will be a harsher graded mix, and subject to segregation.

A gradation above the 0.45 curve will increase the VMA but usually not as dramatic as going below the 0.45 line.

The ratio of the material passing the No. 30 sieve but retained on the No. 200 to the material passing the No. 8 sieve but retained on the No. 200 sieve can define the departure from the 0.45 curve in the fine aggregate fraction. (This signals a hump possibly indicative of tender mix problems.)

FROM THE ASPHALT INSTITUTE ES-3[15]

A poor aggregate gradation often is a leading contributor to tender (slow-setting), or unstable mixes. Tender mixes are frequently typified by an excess of the middle-size sand fraction in the material passing the 4.75mm (No. 4) sieve. A hump in the grading curve caused by the excess sand could appear on nearly any sieve below the 4.75mm (No. 4) and above the 150mm (No. 100). If there is a deviation exceeding 3 percent upward from a straight line drawn from the origin of an 0.45-power grading chart to the point at which the gradation line crosses the 4.75mm (No. 4) sieve line, tenderness difficulties might be anticipated. This condition is most critical when occurring near the 600mm (No. 30) sieve. This deviation in the grading curve is nearly always accompanied by a relatively low amount of material passing the 75mm (No. 200) sieve in tender mixes.

Many of the observations and conclusions are based on the results of work with specific aggregate gradations, are generic in nature, and do have exceptions. Some of the exceptions are no doubt due to the maximum density line concept being unable to take particle shape and texture into account.

STATE REQUIREMENTS

State highway departments use different design methods and have different VMA requirements. This section summarizes the current practices of the states.

DESIGN METHODS

A paper presented to AAPT in 1985 by Kandhal and Koehler[17] summarizes the current practices of state highway departments with regard to mixture design procedures with special emphasis on Marshall design criteria. Thirty-eight states use the Marshall mix design procedures, ten use the Hveem method, one uses gradation specifications only, and Texas uses the "Texas Method."

VMA

Kandhal and Koehler found that of the 38 states using the Marshall design method, only 16 had requirements for VMA. Of the 16 states with VMA requirements, only 7 calculated the VMA in the manner recommended by the Asphalt Institute which takes into account the effective asphalt content. Table 2.1 shows state VMA requirements obtained from the survey by Kandhal and Koehler, supplemented by the newest known developments (39 states now use the Marshall design method).

Kandhal and Koehler reported that the Pennsylvania DOT's experience with VMA for their most commonly used surface course (3/8-in. nominal maximum size) show many mixtures would fail to meet the Asphalt Institute guidelines of 16 percent VMA. The Pennsylvania DOT recommends 16 percent VMA but will accept a mix if 90 percent of the project VMA determinations exceed 15 percent.

The suggestion is that for local conditions using local aggregates, the Asphalt Institute recommendations may be difficult to achieve, and it may be necessary for some agencies to lower the requirements in order to get economical mixtures.

Oklahoma, which uses Hveem Mix design and is similar to Texas in the specimen compaction technique (gyratory), has VMA requirements. The VMA guidelines are the same as those proposed by the Asphalt Institute (example: VMA=16 for 3/8-in. nominal maximum size), even though they were developed for use with Marshall mixture design. Oklahoma found that to meet the VMA requirements more manufactured sands had to be used than natural, more rounded sands.

SUMMARY

This chapter discussed the interrelationships that exist between the components of HMAC and how they can affect the function and life of the pavement. VMA, maximum-density grading curves, and the connection between them both were explored. Finally, the practices of the various state highway departments with respect to mixture design procedures and VMA requirements were summarized.

The result of the literature investigation has shown that, while there is basic agreement on many causes of pavement distress and failure, there is a great deal of disagreement on VMA and maximum density grading curves. Much work is yet to be done with bituminous mixtures.

TABLE 2.1. VMA REQUIREMENTS FOR COMMONLY USED SURFACE MIXTURES FOR STATES USING MARSHALL MIXTURE DESIGN

State	Nominal Maximum Aggregate Size (in.)	VMA (min)	VMA (max)
Arizona	1/2	15.5	18.5
Arkansas	1/2	14	
Delaware	3/8	16	
Florida	3/8	15	
Illinois	1/2	15	
Indiana	1/2	15	
Iowa	1/2	15	
Maryland	3/8	16	
Michigan	1/2	15.5	
New Jersey	3/4 – 1/2	14 – 16	
New Mexico	1/2 – 3/8	14	20
North Dakota	3/4		18
Ohio	3/8	16	
Pennsylvania	3/8	15	
Vermont	1/2	15	
Virginia	1/2	14.8	20
W.Virginia	3/8	16	
Wisconsin	1/2	15	
Wyoming	3/4 – 1/2	13	17

CHAPTER 3. EVALUATION OF CURRENT GRADATIONS USED IN TEXAS

During the 1987 construction season, construction data were obtained for 92 hot mix asphaltic concrete (HMAC) mixtures from 18 districts and were organized into a database by the Center for Transportation Research in its Research Study 3-9-88-1197. The database represents a unique opportunity to study in detail construction data from a large number of projects and to develop a snapshot of current production of HMAC in the state of Texas. This chapter focuses on the construction data in this database and on an analysis of certain aspects which are relevant to this project and of interest to the SDHPT.

The 1197 database contains information provided by the district responsible for the execution of each project. All of the information requested for each project was not always available; therefore, the database does not include all information of interest for all projects.

Much of the current interest of the SDHPT is in projects for which the HMAC design information is present. It is also desirable to compare design information with as-built information. Therefore, the analysis of the database information will be conducted in four sections. The first section will analyze projects from the database for which reliable HMAC design information was obtained. The second, involving as-built information, will analyze a subset of those first-section projects with sufficient as-built information available. The third section will compare the design information with as-built information for projects for which both are available. The last section will summarize significant findings of the previous sections.

Because of an insufficient number of projects using mix types other than Types C and D, and because Types C and D represent the vast majority of surface mixes used, analyses will cover only these two mixture types.

PROJECTS WITH DESIGN INFORMATION

HMAC design information was obtained for 8 Type C mixtures and 24 Type D mixtures. The analysis performed for these projects involves the following:

1. plots of gradations as compared with two different 0.45 power maximum-density lines;
2. summary of several methods used to describe deviation of a gradation from a maximum-density line and other parameters;
3. analysis of possible trends between gradation deviations from maximum-density lines and other mixture parameters versus design VMA; and
4. analysis of aggregate type versus design VMA.

Tables A.1 and A.2 in Appendix A show design information, maximum-density line deviations, and other descriptive parameters which were either calculated or obtained from the Project 1197 database for Type C and Type D mixtures, respectively. Table D.1 in Appendix D shows aggregate type information obtained from the Project 1197 database for these projects. The information in these tables forms the basis for the analysis of the mixture designs.

GRADATION PLOTS

As stated in Chapter 2, there are several "maximum-density" lines in use to describe the maximum-density capability in a given mixture. This paper will investigate two maximum-density lines—the Goode and Lufsey proposed line, and a line developed as an extension of the concepts proposed by Edge. Both lines are based on the use of the 0.45 power chart in which the percent passing a particular sieve size is plotted arithmetically versus the sieve size raised to the 0.45 power. The difference between the two maximum-density lines lies in the definition of the points describing the line. The Goode and Lufsey points are at 0 (zero) percent passing the 0 (zero) sieve size and the actual percent retained on the nominal maximum sieve size. The Edge concept maximum-density line definition points are the actual percent passing the No. 200 sieve and the actual percent retained on the nominal maximum sieve size. Thus, the two definitions result in two different maximum-density lines, the difference being the lower point describing the line. For this paper, the Goode and Lufsey line will be referred to as the "old" maximum-density line, and the Edge concept line will be referred to as the "modified" maximum-density line.

The 0.45 power charts for the design gradations of the 32 mixtures are plotted in Appendix B. These charts show the design gradation and both "old" and "modified" maximum-density lines. A gradation plotting below a given maximum-density line indicates the mixture is coarser than a "maximum-density" gradation. A gradation plotting above a given maximum-density line indicates the mixture is finer than a "maximum-density" gradation. A gradation crossing a maximum-density line is more difficult to quantify. It could be coarser in one area and finer in another.

For Type C mixtures in Figs B.1 to B.8, most gradations cross the "old" line, but are finer than the "modified" line. For Type D mixtures in Figs B.9 to B.32, many gradations cross the "modified" line, but are coarser than the "old" line. Most of the Type D mixtures that cross the "old" maximum-density line would be classified by the Asphalt Institute as having a "hump" in the gradation curve around the #40 sieve. According to their criteria, these mixtures could suffer from tenderness problems.

DEVIATION AND OTHER PARAMETER DEFINITIONS

In addition to gradation information for all mixture designs, Tables A.1 and A.2 in Appendix A show other mixture parameters and several measures of deviation from both maximum-density lines. Below is a description of each parameter.

VMA

VMA was calculated from mixture-design information obtained from a manual search of hard-copy files used to assemble the Project 1197 database. The actual design information needed to calculate VMA, though not required by the database, was subsequently withdrawn by many of the districts from the project information they submitted. VMA was the one piece of information critical to this study; consequently, any project for which VMA could not be calculated was not used in any analysis.

ASPHALT CONTENT

Design asphalt content was found either by a manual search of records or in the Project 1197 database. It is important to note that this is *design* asphalt content and may not be that which is actually used in the field. The design asphalt content provides a starting point for field operations and may be adjusted in the field.

PVF

Percent of Voids Filled with asphalt (PVF) was calculated by knowing the VMA and the design air void criterion used to select the asphalt content. This criterion is either 4 percent air voids if Rice specific gravity is used for the maximum specific gravity, or 3 percent air voids if a calculated theoretical specific gravity based on component specific gravities is used. For this data, 3 percent was used by the districts for all projects, even though in some cases Rice gravities were used. PVF was calculated as follows:

$$\text{PVF} = \frac{(\text{VMA - Air Void Design Criteria}) * 100}{\text{VMA}}$$

where all terms are as previously defined.

DEVIATIONS FROM "OLD" AND "NEW" MAXIMUM-DENSITY LINES

Several attempts were made to quantify deviations from the maximum-density lines. Four different measures were developed, and each was applied to both the "old" and "modified" maximum-density lines. The first three were based on comparing the percent passing the standard sieve sizes, while the fourth used an area technique.

The first deviation measure was a sum of the differences in percent passing, between the maximum-density line and the actual gradation, for all standard sieves. Appendix A shows these as OLDL SUM(LINE-ACT) and MODL SUM(LINE-ACT). In this measure, positive deviations and negative deviations from the maximum-density line will cancel out; therefore, a small value may indicate either a small deviation from the maximum-density line or larger deviations on both sides of the line. Figure 3.1 shows an example of complications which can develop when using this deviation measure. The two displayed gradations, along with the "old" maximum-density line, result in the same value for OLDL SUM(LINE-ACT). The same can also be said of the "modified" line.

The second deviation measure was a sum of the absolute values of differences in percent passing, between the maximum-density line and the actual gradation, for all standard sieves. Appendix A shows these as OLDL SUM(ABS(LINE-ACT)) and MODL SUM(ABS(LINE-ACT)). In this measure, small values indicate small deviations from the line, but one cannot tell the difference between a gradation that crosses the line and one that is entirely on one side of the line. Figure 3.2 shows the "old" maximum-density line and two gradations which both result in OLDL SUM(ABS(LINE-ACT)) = 31.

The third deviation measure was a sum of the squares of the differences in percent passing, between the maximum-density line and the actual gradation, for all standard sieves. Appendix A shows these as OLDL SUM((LINE-ACT)^2) and MODL SUM((LINE-ACT)^2). This measure is similar to the absolute value of the differences, except that larger deviations contribute

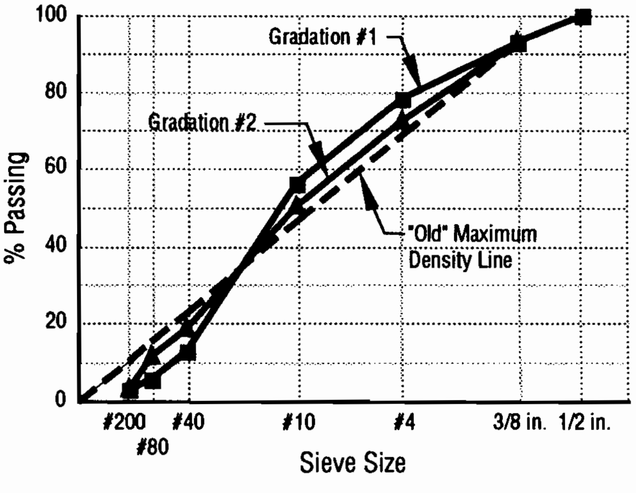

Fig 3.1. Gradations with equal sums of deviations.

more to the value than small deviations (small values mean small deviations from the line). It has the same problems; namely, one cannot tell the difference between a gradation that crosses the line and one that is entirely on one side of the line. Figure 3.2 shows the "old" maximum-density line and two gradations which both result in OLDL SUM((LINE-ACT)^2) = 193.

The last deviation measure developed was based on the area between the maximum-density lines and the actual gradation. Appendix A shows these as AREA(OLD-ACT) and AREA(MOD-ACT). A Microsoft EXCEL spreadsheet was developed which graphically integrated the area between the curves. When the actual gradation was entered, both "old" and "modified" maximum-density lines were calculated, integration between the actual gradation curve and each maximum-density line was performed for successive sieve sizes, and the total areas were summed. This process results in a deviation measure which more accurately determines the difference between a maximum-density line and the actual gradation. Figure 3.3 shows the "old" maximum-density line for two gradations which result in virtually the same area between the actual gradation and the maximum-density line. The examples given in figures for the other three deviation measures do not result in equal areas between actual gradations and maximum-density lines. Thus, the area measure more adequately represents the true deviation from the maximum-density line.

FINENESS MODULUS

The Fineness Modulus is defined as the summation of the cumulative percent retained on all standard sieves from #4 to #200, all divided by 100. The Fineness Modulus of the actual gradation was subtracted from the Fineness Modulus of the "old" or "modified" maximum-density line to arrive at another parameter for comparing gradations. This parameter resulted in a value which indicated whether the actual gradation was, overall, coarser or finer than the maximum-density line for that gradation. These values are listed in Appendix A as FM(OLD L)-FM(DESIGN) and FM(MOD L)-FM(DESIGN). This method has some of the same pitfalls as the sums of differences, absolute values of differences, and squares of differences in that since deviations can cancel out, gradations with large differences can have the same value.

SAND RATIO

A final parameter studied was the sand ratio, defined as the ratio of fine sand (-#40 to +#200) to total sand (-#10 to +#200). It is thought that this ratio can be related to VMA development.

TRENDS

Figures C.1 to C.43 in Appendix C present graphs developed to show relationships between various gradation measures and VMA. These graphs depict combined data (combined types C and D) and data for individual mixture types (C and D).

ASPHALT CONTENT

Figures C.1 to C.3 show design VMA versus design asphalt content. A correlation exists (R^2 = 0.49, 0.59, and 0.43) between the design asphalt content and VMA. Furthermore, for those mixtures where asphalt absorption data could be found (very few had this information), mixtures with the most deviation from the correlation line had higher asphalt absorption. These high absorption mixtures adversely affect the overall correlation. Excluding high-absorption mixes would most likely result in a much better correlation and supports the statement by Griffith and Kallas that "asphalt content is almost directly proportional to the amount of aggregate voids for mineral aggregates having low asphalt absorption."

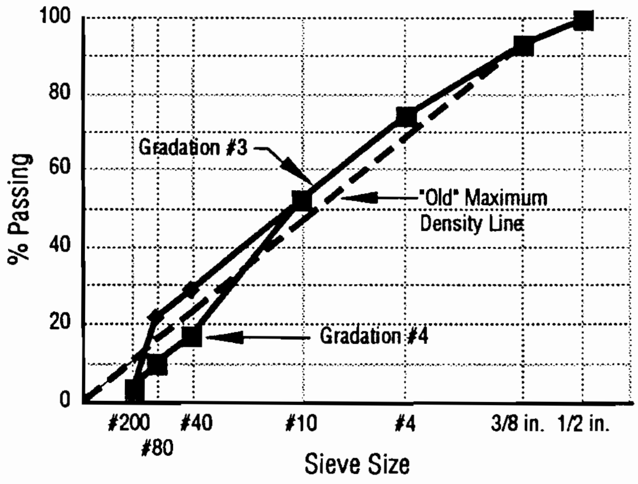

Fig 3.2. Gradations with equal sum ABS (Dev) & Sum (Dev)^2.

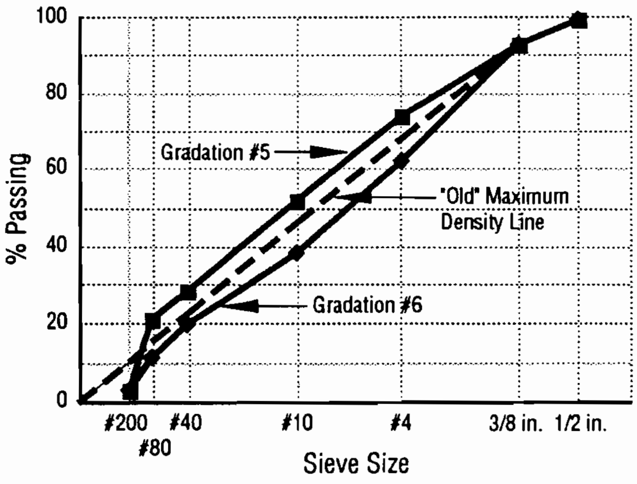

Fig 3.3. Gradations of equal area (actual gradation and maximum density).

PVF

Figures C.4 to C.6 show the relationship of Design VMA and PVF. Correlations for Type C, Type D, and Types C and D combined are very good (R^2=1.000). The reason for this is the method of calculation and the design air void criteria. Since PVF is that percentage of the VMA taken up by asphalt, it can be calculated by subtracting the air void content from the VMA, multiplying by 100, and dividing by the VMA. The Hveem design procedure specifies that the optimum asphalt content is that asphalt content resulting in 3 percent air voids (4 percent if designing by Rice specific gravity) and acceptable Hveem Stability. The use of this criteria results in a very narrow range of PVF for design. Figure 3.4 below shows a PVF histogram and some descriptive statistics for the 32 total designs available.

OLD MAXIMUM-DENSITY LINE SUM(LINE-ACT)
OLD MAXIMUM-DENSITY LINE SUM(ABS(LINE-ACT))
OLD MAXIMUM-DENSITY LINE SUM((LINE-ACT)^2)

VMA versus Old Maximum Density Line Sum(Line-Act), Sum(ABS(Line-Act)), and Sum((Line-Act)^2) for Type C&D mixtures, Type C mixtures, and Type D mixtures are shown in Figs C.7 to C.15. There is no reason to expect that one type of mixture should have a correlation and another should not, except for lack of sufficient data (especially Type C). Generally, no useful correlations are seen in these plots. Most plots resemble "shotgun" patterns. Type C mixtures have more similar gradations as seen in 0.45 power chart plots, than the Type D mixtures. This, as well as the smaller number of data points, may be the reason some correlations (albeit poor) are obtained.

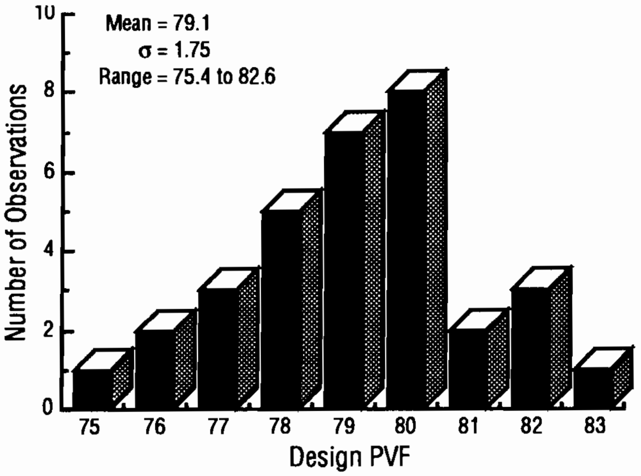

Fig 3.4. Histogram of design PVF.

AREA BETWEEN OLD MAXIMUM-DENSITY LINE AND ACTUAL GRADATION

Figures C.16 to C.18 display VMA versus Area Between Old Maximum-Density Line and Actual Gradation. Better correlations are seen, but, again, a "shotgun" pattern best describes the results. Type C mixtures show a higher correlation (R^2=0.567), but the small number of data points and several points off the correlation line render this measure questionable as a predictor of VMA.

MODIFIED MAXIMUM-DENSITY LINE SUM(LINE-ACT)
MODIFIED MAXIMUM-DENSITY LINE SUM(ABS(LINE-ACT))
MODIFIED MAXIMUM-DENSITY LINE SUM((LINE-ACT)^2)

VMA versus Modified Maximum-Density Line Sum(Line-Act), Sum(ABS(Line-Act)), and Sum((Line-Act)^2) for Type C and D mixtures, Type C mixtures, and Type D mixtures are shown in Figs C.19 to C.27. Again, there is no reason to expect that one type of mixture should have a correlation and another should not, except for lack of sufficient data (especially Type C). Generally, no useful correlations are seen in these plots; however, slight improvements are seen over the same measures using the "old" maximum-density line. Most plots still resemble "shotgun" patterns.

AREA BETWEEN MODIFIED MAXIMUM-DENSITY LINE AND ACTUAL GRADATION

Plots of VMA versus Area Between Modified Maximum-Density Line and Actual Gradation are found in Figs C.28 to C.30. No useful trends are developed. Any correlations are essentially the same or only slightly improved over the same measure using the "old" maximum-density line.

FM(OLD MAXIMUM-DENSITY LINE) – FM(DESIGN)

FM(MODIFIED MAXIMUM-DENSITY LINE) – FM(DESIGN)

VMA versus Fineness Modulus of the "Old" and "Modified" Maximum-Density Lines are shown in Figs C.31 to C.36. No useful correlations are obtained using these measures. The similarity of the Type C designs accounts for the increased correlation factors seen with these mixtures. The correlations disappear when all mixtures are plotted. The basic "shotgun" pattern is evident once more.

SAND RATIO

VMA versus Sand Ratio, seen in Figs C.37 to C.39, fails to discriminate between high and low VMA mixtures. This measure might be useful for research on "tender" mixtures, which is beyond the scope of this project.

MATERIAL PASSING #200 SIEVE OR DUST

Figures C.40 to C.43 show VMA versus material passing the #200 sieve. In using the Voidage Reduction Concept, one would expect VMA to be highly dependent on the amount of material passing the #200 sieve. When one looks at both Types C and D mixtures combined, this is not evident. Type C mixtures alone do show some evidence of this dependency. When one data point is eliminated from the data set, one sees a very good correlation between the amount of materials passing the #200 sieve and VMA (R^2=0.831).

MULTIPLE REGRESSION

Multiple regression was performed for the parameters discussed above to investigate whether combinations of measures could predict VMA for Types C and D mixtures. It was thought that any correlations should be applicable to all mixes; therefore, individual mixture types were not investigated in this manner. These multiple regression analyses were unsuccessful in improving VMA prediction. Combinations of measures usually made correlations worse, instead of better, and the statistical significance of the combinations was low. This indicates that for this data and the parameters used, combinations were no better than individual parameters as a means of predicting VMA.

AGGREGATE TYPE

The Project 1197 database contains basic information on aggregate type for 8 of the 8 Type C, and for 22 of the 24 Type D, mixtures. This information may be found in Appendix D. Sufficient information was deemed available to conduct a analysis of variance (ANOVA) of aggregate type on VMA. The projects were divided into two groups based on aggregate type. One group consisted of mixtures containing gravel (rounded particles) as a component of the mixture. The other group consisted of mixtures containing aggregates other than gravel (crushed particles such as limestone and sandstone). The classification was based solely on the type of coarse aggregate, intermediate aggregate, and aggregate screenings present in the mixture. Field sand was not used as a basis for classification since only limited data were available. Analysis of variance (ANOVA) was performed separately for Types C and D mixtures yielding the ANOVA analysis shown in the next column.

The ANOVA analysis gives low values of the F statistic which translates into high p-values. These p-values (numbers between 0 and 1) indicate the probability that VMA was not effected by aggregate type. For these data, the probability of no effect of aggregate type on VMA is 0.63 (63 percent) for Type C mixtures and 0.758 (75.8 percent) for Type D mixtures. These data therefore show no statistically significant difference in VMA based on aggregate type.

Type C ANOVA of Aggregate Type on VMA

Source	df	SS	MS	F	p
Aggregate Type (Gravel = 1, Other = 0)	1	0.234	0.234	0.26	0.63
Error	6	5.455	0.909		
Total	7	5.689			

Type D ANOVA of Aggregate Type on VMA

Source	df	SS	MS	F	p
Aggregate Type (Gravel = 1, Other = 0)	1	0.2	0.2	0.1	0.758
Error	20	40.54	2.03		
Total	21	40.73			

In the past, researchers have reported that rounded aggregates tend to produce lower VMA's. This is not evident from Project 1197 data. The lower VMA's could be caused by the various aggregate types present, differences in shape and texture of aggregates, the small amount of data available, incomplete database information, incorrect aggregate type information present in the database, or effects from the field sand which were not included in analysis.

AS-BUILT INFORMATION (PROJECTS WITH SUFFICIENT DESIGN AND AS-BUILT DATA)

Of the 8 Type C and 24 Type D mixtures for which adequate design information was obtained, 2 Type C and 11 Type D mixtures also had sufficient as-built data for analysis. The analysis for these projects involves the following:

(1) plots of gradations as compared to two different 0.45 power maximum-density lines; and
(2) analysis of possible trends between gradation deviations from maximum-density lines and other mixture parameters versus design VMA.

Tables E.1 and E.2 in Appendix E show as-built information, maximum-density line deviations, and other descriptive parameters either calculated or obtained from the Project 1197 database for Type C and Type D mixtures respectively. The parameters investigated are the same as those investigated for the design information with the exception of Fineness Modulus measures. Fineness Modulus was not deemed appropriate for the as-built data because the aggregate gradations represent averages over the course of the project. The information in Appendix E forms the basis of the following interpretation of gradation charts and trends.

GRADATION PLOTS

The 0.45 power charts for the design gradations of the 13 mixtures are plotted in Appendix F. These charts show the design gradation and both "old" and "modified" maximum-density lines.

Most 0.45 power plots show the same general shape for as-built as they did for design gradations. Some variability in the gradation plots is expected because the values represent project averages which incorporate the normal variability of the HMAC plant.

If design proportions of aggregates are adhered to in the field, one would expect the as-built gradations to exhibit some aggregate degradation in the mix plant, resulting in somewhat finer mixes' being placed than being designed. On comparing the design and the as-built 0.45 power plots, many mixes do exhibit this degradation (coarse particles become smaller particles). There are some mixes which do not show this phenomenon, and for these mixtures it is believed that an effort was made to compensate for expected degradation or to adjust for this as the project progressed.

The Type D as-built gradations are quite complex, with the gradation line crossing the "old," "modified," or both maximum-density lines.

TRENDS

Figures G.1 to G.12 in Appendix G are graphs depicting relationships between various gradation measures and VMA for the as-built projects. Only Type D mixtures were used to investigate trends for as-built mixtures since only two Type C mixtures were available. It is important to understand that the field VMA represents HMAC which was plant-mixed but laboratory-compacted. Thus this field VMA does not represent the VMA actually on the road. The specimens were compacted under controlled laboratory temperature and compaction conditions.

The design procedure results in a mixture which forms the starting point for field mixture production. In many cases the asphalt content and gradation are modified in the field to reflect plant conditions, mixture characteristics, and field experience. Because the design proportions are changed many times, one would expect any trends seen in the design mixtures to be less apparent in the as-built mixtures. The projects investigated in this report confirmed this expectation.

ASPHALT CONTENT

Figure G.1 shows field VMA versus as-built asphalt content. The reasonable correlation seen in design for Type D mixtures, R^2=0.47, is reduced to R^2=0.215 for field mixtures.

PVF

Figure G.2 shows the relationship of field VMA and field PVF for Type D mixtures. The PVF was obtained from the Project 1197 database and was determined in the same manner as design, except that the actual air void content for the molded specimens was used. Differences in asphalt content, gradation, and possibly other parameters such as moisture content, resulted in different air void contents than the 3 percent (4 percent for Rice Gravity) specified in the design procedure. The correlation between VMA and PVF is, consequently, lower.

OLD MAXIMUM-DENSITY LINE SUM(LINE-ACT)

OLD MAXIMUM-DENSITY LINE SUM(ABS(LINE-ACT))

OLD MAXIMUM-DENSITY LINE SUM((LINE-ACT)^2)

AREA BETWEEN OLD MAXIMUM-DENSITY LINE AND ACTUAL GRADATION

MODIFIED MAXIMUM-DENSITY LINE SUM(LINE-ACT)

MODIFIED MAXIMUM-DENSITY LINE SUM(ABS(LINE-ACT))

MODIFIED MAXIMUM-DENSITY LINE SUM(ABS(LINE-ACT)^2)

AREA BETWEEN MODIFIED MAXIMUM-DENSITY LINE AND ACTUAL GRADATION

SAND RATIO

MATERIAL PASSING #200 SIEVE OR DUST

Figures G.3 to G.12 show field VMA versus deviations from the "old" and "modified" maximum-density lines, sand ratio, and material passing the #200 sieve. No discernible pattern or correlation is obtained from any of these parameters.

COMPARISON OF DESIGN TO AS-BUILT

For the 13 projects (2 Type C and 11 Type D) for which both design and as-built data were available, the design and field VMA's were compared. Figure 3.5 shows a plot of design VMA and field VMA for each project. In all but one case, the design VMA is higher than the field VMA. Figure 3.6 shows a histogram and descriptive statistics for the difference between the design and field VMA's from each project. The histogram looks reasonably normally distributed and shows a mean difference between design and field VMA's of 1.54. The histogram offers more evidence that design VMA's are higher than field VMA's.

A statistical analysis was performed using the T-test to determine whether the mean difference of 1.54 was statistically significant. The T-test for m=1.54, s=0.88, and n=13 (df=12) yields a t-value of 6.29. Where m is the sample mean, s is the sample standard deviation, and n is number of observations in the sample. This high t-value indicates there is less than a 1-in-10,000 chance that this difference in VMA's is strictly coincidence. One concludes that field VMA's as a whole are less than design VMA's.

SUMMARY OF SIGNIFICANT FINDINGS

Some comments which can be made as a result of the studies conducted in this chapter are given below.

(1) The use of 0.45 power plots can be useful in describing an aggregate gradation and any "maximum-density" lines used. The power plots can be used to visually compare areas or the distance between the "maximum-density" line for several mixtures or several gradations resulting from various combinations of the same aggregates.

(2) Several measures of gradation deviation from any chosen maximum-density line may be developed. One must realize the shortcomings of deviation parameters used. The area between a maximum-density line and the actual gradation is the better of the developed parameters.

(3) VMA versus Design Asphalt Content is reasonably correlated and if asphalt absorption is taken into account, the correlation would likely be better. This observation is consistent with engineering literature which indicates that VMA is proportional to asphalt content for non-absorptive aggregates.

(4) In the design process, the use of Hveem design criteria yields a narrow range of PVF.

(5) Taken as a whole, the 32 studied mixture designs failed to yield useful correlations relating design VMA to any of the developed deviation parameters or other factors such as fineness modulus, sand ratio, or percent passing the #200 sieve.

(6) The analysis of variance of aggregate type (obtained from the Project 1197 database) on design VMA showed no statistically significant difference between aggregate type and design VMA for the mixtures investigated. This lack of difference could be caused by the various aggregate types present, differences in shape and texture of aggregates, the small amount of data available, incomplete database information, incorrect aggregate type information present in the database, or effects from the field sand which were not included in analysis.

(7) Asphalt content adjustments, and minor aggregate differences, which can occur in the field, affect the field VMA and PVF. These changes contribute to poor correlation of field VMA with field asphalt content and field PVF.

(8) Field data studied yielded no useful correlations relating field VMA to any of the developed deviation parameters or other factors such as fineness modulus, sand ratio, or percent passing the #200 sieve.

(9) Field VMA's are significantly lower than design VMA's.

Some useful information was obtained from studying the 1197 database. Information concerning VMA, design asphalt content, and design PVF is significant and relevant. Other analyses proved fruitless. Looking for correlations among VMA and other parameters for all designs together is an oversimplification of how aggregate and asphalt affect VMA. There are many factors which cannot be measured in such simple terms. For design mixtures, these include particle shape and particle texture. For field mixtures, one may add more, such as moisture content and aggregate degradation in the mixing process. Each mixture has characteristics unique to that asphalt-aggregate combination, and each mixture generally cannot be compared to other mixtures in terms of VMA.

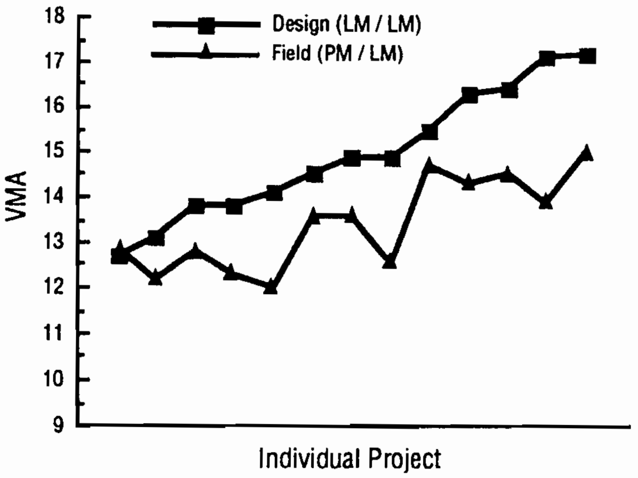

Fig 3.5. VMA—design and field.

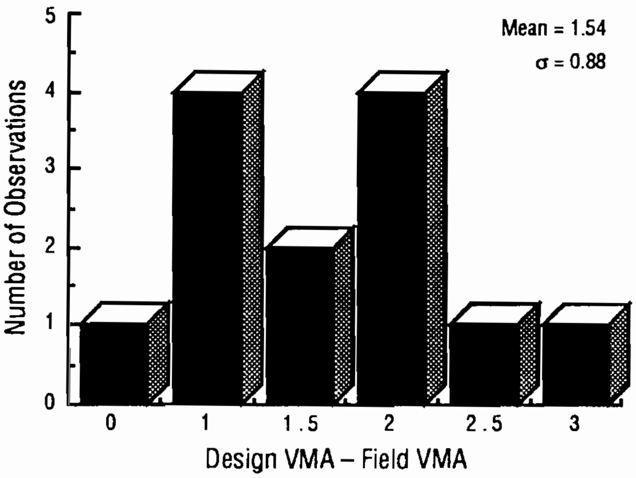

Fig 3.6. Design-field VMA histogram.

CHAPTER 4. LABORATORY EVALUATION OF VARIATION IN MIX PROPERTIES WITH ASPHALT CONTENT AND AGGREGATE GRADATION

A laboratory evaluation of variation in mix properties with asphalt content and aggregate gradation was performed using one HMAC design from each of two State Department of Highways and Public Transportation (SDHPT) districts. The districts selected were District 6, Odessa, and District 14, Austin. For each design, aggregates, asphalt, and design parameters were obtained. The laboratory work for each district mixture consisted of a set of factorial experiments of aggregate gradation and asphalt content on a number of mixture properties. The properties chosen for investigation were VMA, air voids, indirect tensile strength and secant modulus at failure, Marshall stability and flow, and Hveem stability.

The optimum mixture proportions, as reported by the district (mix design), were used as the base point, and changes were made to investigate effects on the above mixture properties. The District 6 investigation used three levels of asphalt content and two levels of aggregate gradation. The District 14 investigation used three levels of asphalt content and three levels of aggregate gradation. Asphalt levels were chosen as mixture design optimum, optimum plus 1 percent asphalt, and optimum minus 1 percent asphalt. The District 6 aggregate gradation levels were the design gradation and a "coarser" gradation obtained by adding more coarse aggregate at the expense of the fine aggregate (screenings). The District 14 aggregate gradation levels were the design gradation, a "coarser" gradation (as coarse as the current specification will allow with the aggregates), and a "finer" gradation (as fine as the current specification will allow with the aggregates). The terms "coarser" and "finer" are qualitative terms used to describe the gradation change with respect to the design gradation. Information for all aggregate gradation levels appears in Appendix H.

Twelve compacted specimens of laboratory-mixed HMAC were fabricated for each asphalt level at each gradation for each of the two district evaluations. Since measuring air voids and VMA is non-destructive, a measurement for each specimen was taken, and the set of twelve was then broken down into four groups of three specimens for the remaining four tests.

Statistical analysis (analysis of variance) of the data from the experiments was performed using MINITAB statistical software on The University of Texas' Instructional VAX computer. Using the analysis of variance, F-tests were performed to determine if changes in asphalt content and/or aggregate gradation resulted in statistically significant differences in the mixture properties. Where significant differences were indicated owing to a factor used at three levels, a multiple-comparison test was used to indicate which levels of the factor produced significantly different results. The data from factorial experimentation and the associated statistical analysis appear in Appendix I.

DISCUSSION OF FACTORIAL EXPERIMENTS

Tables 4.1 and 4.2 below are statistical summaries of the two sets of factorial experiments based on the analyses of variance in Appendix I.

The set of experiments shows that one may alter some mixture properties by changing asphalt content and/or aggregate gradation. Many of the changes seen are expected events, such as increased asphalt content resulting

TABLE 4.1. DISTRICT 6 STATISTICAL ANALYSIS SUMMARY

Property	Factor Affecting Mixture Property	
	Asphalt Content	Aggregate Gradation
VMA	X	
Air Voids	X	X
Resilient Modulus		
Marshall Stability	X	
Marshall Flow	X	X
Indirect Tensile Strength	X	X
Secant Modulus @ Failure	X	X
Hveem Stability	X	X

TABLE 4.2. DISTRICT 14 STATISTICAL ANALYSIS SUMMARY

Property	Factor Affecting Mixture Property	
	Asphalt Content	Aggregate Gradation
VMA	X	X
Air Voids	X	X
Resilient Modulus		X
Marshall Stability		X
Marshall Flow	X	X
Indirect Tensile Strength	X	X
Secant Modulus @ Failure	*	*
Hveem Stability	X	X

* ANOVA indicated significant interaction between factors, invalidating the use of F-tests for the main effects.

in decreased air voids. Indeed, some of these phenomena form the basis of the Hveem and Marshall mixture design procedures.

It is not the intention of this project to indicate that increases or decreases in specific properties are beneficial or detrimental to a paving mixture, even though some properties may be indicative of pavement life or performance. No conclusions will be drawn regarding the property values exhibited by any of the experimental mixtures.

A study of the results of the factorial experiments requires the consideration of two questions. First, does the nature of the variables (asphalt content and aggregate gradation) have an impact on the outcome of the analysis of variance, and, second, do the levels used in the factorial represent possible field use of the materials?

EFFECT OF VARIABLES

The nature of the variables may have an impact on the differences seen in an ANOVA.

Asphalt content is a quantitative variable; that is, a number can be used to describe the asphalt content level and discrete levels can be chosen with a measurable difference between levels. The difference in asphalt content which results in a significant change in measured properties can be "quantified." This type of variable easily lends itself to interpretation in an analysis of variance.

Alternately, aggregate gradation is a qualitative variable and as such there is no way to specify, in "measurable" terms, the difference which exists between two gradations. Gradation or particle size distribution, as used to describe the aggregate in an HMAC, consists of percentages passing and/or retained on a number of different standard sieve sizes. If two aggregates have different percentages passing certain sieve sizes, one can say they are different, but not *how* different. Even two aggregates with the same percentages passing the standard sieve sizes will probably not have the same particle size distribution between any two standard sieves. Statistically significant differences in HMAC properties owing to aggregate gradation are a function of how much the gradation is changed. As a result, qualitative variables such as aggregate gradation are not as easily interpreted in an analysis of variance.

FIELD LEVEL POSSIBILITIES

A factorial experiment, as conducted for this project, does not represent changes which would be considered for use in the field. While aggregate gradation and asphalt content are not tied together in the factorial experiment, they are linked in the design procedure which determines the "optimum" asphalt content for a specific aggregate gradation. As an example, the SDHPT Hveem design procedure specifies "optimum" asphalt content as the point at which a gyratory compacted specimen exhibits 3 percent air voids (or 4 percent depending on the method of determination of the maximum theoretical specific gravity) and adequate Hveem stability. Consequently, changing the aggregate gradation will most likely result in a change in optimum asphalt content. With this in mind, some of the factorial data were reviewed so that the optimum asphalt content for each gradation and the VMA at the optimum asphalt content could be predicted.

OPTIMUM ASPHALT AND VMA DETERMINATIONS AND COMPARISONS

The optimum asphalt content, corresponding VMA's, and the 95 percent confidence interval (CI) for each were predicted for all gradations used in the factorial experiments. "Optimum" predictions were made using MINITAB regression analysis of the experimental data and the Texas SDHPT Hveem design criteria (4 percent air voids based on Rice specific gravity). The results are presented in Table 4.3 below.

The "optimum" predictions and the 95 percent confidence intervals were both obtained when the appropriate regression analysis and prediction instructions were given to MINITAB. The 95 percent confidence interval is the range in which one is 95 percent sure the actual population average lies. This means there is less than a 1-in-20 chance that the actual optimum value lies outside this range. If the 95 percent CI's for two predictions overlap, then there is insufficient evidence to indicate that a statistically significant difference exists between the two predicted property values at the 95 percent confidence level.

For the above data, the District 6 gradations show overlapping 95 percent CI's for both optimum asphalt content and VMA. The difference between the two gradations was not large enough to produce statistically significant differences in optimum asphalt content or VMA. The difference in the predicted values could be due to random error.

The District 14 data do not show overlapping 95 percent CI's for either asphalt content or VMA for any of the

TABLE 4.3. OPTIMUM ASPHALT CONTENTS, VMA'S, AND 95 PERCENT CI'S

Factorial Gradations	Optimum Asphalt	Asphalt 95% CI	VMA @ Opt AC	VMA 95% CI
District 6				
Design Gradation	5.38	5.30 – 5.46	12.90	12.78 – 13.02
Coarse Gradation	5.26	5.20 – 5.32	12.82	12.73 – 12.92
District 14				
Design Gradation	4.76	4.73 – 4.79	14.71	14.62 – 14.81
Gradation #2	5.11	5.08 – 5.14	15.68	15.58 – 15.78
Gradation #3	3.96	3.89 – 4.03	13.19	13.07 – 13.31

three gradations. The three gradations were sufficiently different to produce statistically different asphalt contents and VMA's.

VMA AND GRADATION DEVIATION PARAMETERS

In Chapter 3, mixtures from across Texas had many uncontrolled variables which resulted in no one developed parameter correlating well with VMA. The mixtures and subsequent specimens used for factorial analyses were made in a manner which controlled many of these variables. For each district factorial set, the same aggregates were used, and all laboratory-controllable conditions were identical. If comparisons are made for each District's mixtures at "optimum" asphalt content, the main uncontrolled variable is aggregate gradation. Since the same aggregates were used, merely in different proportions, one could rationalize that differences in particle shape, surface texture, and surface area between the different gradations were minimized. Therefore, one (or some) of the deviation parameters may now be indicative of changes in VMA.

Appendix J shows each gradation used for each district factorial on a 0.45 power chart. These gradation charts show visually the differences in the gradations used. Both "old" and "modified" maximum-density lines, optimum asphalt content, and corresponding VMA are shown on each chart. Appendix H contains the deviation parameters calculated for each gradation. The Appendix H gradation deviation parameters have the same definitions as are used in Chapter 3. Table 4.4, in the next column, shows a summary of the "optimum" VMA and the deviation parameters for each gradation, taken from the previous section and from Appendix H.

Chapter 3 discussed the various problems with individual deviation parameters and proposed that the area between a maximum-density curve and the actual gradation is the parameter most representative of the deviation of the actual gradation from the maximum-density line. Therefore, this parameter will be studied for the factorial gradations.

The District 6 data showed that as the gradation changed from the design to the coarse gradation, the area parameter (indeed, all deviation parameters calculated) increased, for both "old" and "modified" maximum-density lines. The VMA decreased from the design to the coarse gradation. The previous section showed that this difference in VMA was not statistically significant. No useful information or correlation can be developed from these data.

The District 14 data showed statistically significant differences in VMA. The VMA increased from Gradation #3, to the Design Gradation, to Gradation #2. The values of area between the "old" maximum-density line and actual gradation do not track the development of VMA. However, as the area between the "modified" maximum-density line and the actual gradation increases, so does VMA.

TABLE 4.4. VMA AND DEVIATION PARAMETERS

Parameter	VMA	Max Den Old	Max Den Mod
D-6 Design Gradation	12.9		
SUM(L - A)		35.5	10.0
SUM(ABS(L - A))		35.5	17.3
SUM(L - A)^2		290.96	99.79
Area MAX & ACT		3.721	2.089
D-6 Coarse Gradation	12.82		
SUM(L - A)		55.1	26.2
SUM(ABS(L - A))		55.1	27.7
SUM(L - A)^2		703.83	324.69
Area MAX & ACT		6.284	4.047
D-14 Design Gradation	14.7		
SUM(L - A)		10.7	-13.7
SUM(ABS(L - A))		16.6	15.2
SUM(L - A)^2		97.15	81.99
Area MAX & ACT		0.7125	1.8813
D-14 Gradation #2	15.68		
SUM(L - A)		-0.5	-24.8
SUM(ABS(L - A))		26.7	25.3
SUM(L - A)^2		149.45	219.74
Area MAX & ACT		2.189	3.432
D-14 Gradation #3	13.19		
SUM(L - A)		28.5	5.2
SUM(ABS(L - A))		28.5	10.7
SUM(L - A)^2		183.47	32.62
Area MAX & ACT		2.615	1.048

SUMMARY OF SIGNIFICANT FINDINGS

Some comments which can be made as a result of the studies conducted in this chapter are listed below.

(1) Differences in Hot Mix Asphaltic Concrete material properties can be achieved through changing asphalt content and/or aggregate gradation.

(2) Aggregate gradation is a qualitative variable, and, because it is, differences in properties resulting from gradation changes are a function of how much change is made in the gradation. There are no current measures of gradation change.

(3) Comparisons of laboratory mixtures are more realistic if they are compared at optimum asphalt content, use the same aggregates (with only the proportions varying), and use uniform laboratory conditions and procedures.

(4) Gradations used for the District 6 factorial experiments failed to show any statistically

significant differences in optimum asphalt content and corresponding VMA. They also failed to show any relationship between VMA and gradation deviation parameters. One reason no relationships were developed may be the statistical insignificance of optimum asphalt content and VMA differences between the two gradations used.

(5) Gradations used for the District 14 factorial experiments showed statistically significant differences in optimum asphalt content and corresponding VMA. They also showed a relationship between VMA and the area between the "modified" maximum-density line and the gradation (increased area corresponded to increased VMA).

The literature[1,2,8,14] indicates that for mixtures with insufficient VMA, moving the gradation "away" from the maximum-density line should yield higher VMA values. The maximum-density line which is discussed in the literature is what this study describes as the "old" maximum-density line. The experimental data do not indicate that a deviation from this "old" line results in an increase in VMA. The data suggest that the "modified" maximum-density line may be the more appropriate maximum-density line to use for gradation adjustment to change the VMA.

More work with many different mixtures is needed to verify this observation. However, currently, if a mixture was deficient in VMA, the first step in rectifying the problem might be to adjust the aggregate gradation away from the "modified" maximum-density line and see if the VMA was increased.

CHAPTER 5. LABORATORY EVALUATION OF AGGREGATE SUBSTITUTION ON VMA

A laboratory evaluation of VMA variation with aggregate type was conducted to examine the possible effects of aggregate mineralogy. The investigation involved using a baseline HMAC design and substituting, individually, one of two alternate aggregates to determine if changes in VMA were produced.

EXPERIMENT DESCRIPTION

One HMAC design, including all materials and proportions, from Texas SDHPT District 9 (Waco), was obtained for use as the baseline design. Four aggregate fractions were used in this design—a coarse limestone, an intermediate limestone, a fine limestone (screenings), and a local field sand. All of the limestone was crushed and all originated from the same pit. This limestone was recognized as being relatively soft and relatively high in asphalt absorption.

Two alternate crushed fine aggregates (screenings) were chosen for substitution into the baseline design. Each alternate screenings was substituted for the original to determine if VMA differences were produced. One fine aggregate (screenings), recognized as a hard limestone with little asphalt absorption, was obtained from a source in the area of Chico, Texas. The other fine aggregate (screenings), a rhyolite recognized as having high asphalt absorption, was obtained from the Odessa, Texas, area.

All of the screenings used, arranged from softest to hardest, were design limestone, Chico limestone, and Odessa rhyolite. The goal of the experiment was to emphasize the differences in aggregates as opposed to gradation. As such, differences in asphalt absorption may have played a part in determining optimum asphalt content, but differences in VMA at optimum asphalt content were assumed to be a function of the aggregate mineralogy. Aggregate mineralogy would include such factors as hardness, surface texture, and particle shape as well as chemical composition. Although intuitively included in aggregate mineralogy, chemical composition should play a minimal role in determining the physical characteristic of VMA.

To enable aggregate mineralogy to be the main uncontrolled variable (when aggregate substitutions were made), the gradation had to be held as constant as possible. To accomplish this, the design screenings were wet-sieved to wash off all minus #200 sieve material clinging to larger sizes which resulted in the true gradation contribution from the screenings. Both the hard limestone and rhyolite screenings for substitution were also wet-sieved and the components subsequently dried to provide clean, separated materials for substitution. Substitution was made according to the wet-sieve analysis of the design limestone screenings. Substituted total mixture gradations as close to the design gradation as possible were attained using the standard sieve sizes for mixture design and 0.45 power charts.

Aggregate gradation information for each mixture is presented in Tables K.1 to K.3. These tables also include the gradation deviation information. Since aggregate substitution resulted in identical gradations for the standard sieves, the deviation parameters for all three mixtures are the same. The 0.45 power chart for the mixtures is shown in Fig K.1. Only one chart is necessary since all three mixtures have the same gradation within the limits of the standard sieve sizes.

All three aggregate mixtures were evaluated for air voids, VMA, and Hveem stability with the design asphalt at the reported "optimum" asphalt content (5.8 percent), "optimum" plus 1 percent, and "optimum" minus 1 percent. The results of this experiment are shown in Table K.4. The mixture using the hard limestone screenings substitution was evaluated only at the reported "optimum" asphalt content and at "optimum" minus 1 percent.

STATISTICAL ANALYSIS OF OPTIMUM ASPHALT CONTENT AND VMA

Data in Table K.4 provide a basis for reevaluating the original "optimum" asphalt content and determining a new "optimum" asphalt content for the substituted mixtures (based on the SDHPT Hveem design criteria of 4 percent air voids using Rice specific gravity and adequate Hveem stability) and the corresponding VMA. Regression analysis using MINITAB statistical software predicted these values. Table 5.1 gives the optimum asphalt contents of each mixture, the corresponding VMA's, and the 95 percent confidence interval for both values. All "optimum" mixtures proved to have adequate Hveem stability.

A study of this table shows the asphalt contents are slightly different, but the 95 percent confidence intervals all overlap each other. This indicates that there is no statistically significant difference between the optimum asphalt contents of all three mixtures. Making the aggregate substitutions did not significantly change the asphalt demand. The aggregate with the recognized high asphalt absorption did have the highest calculated optimum asphalt, which may explain the wider range for the 95 percent confidence interval (it is more sensitive to changes in asphalt content than the others).

The VMA's of the optimum mixtures differed more from each other than did the asphalt contents. None of the 95 percent confidence intervals for VMA overlap,

TABLE 5.1. OPTIMUM ASPHALT CONTENTS, VMA'S, AND 95 PERCENT CI'S

Aggregate Gradations	Optimum Asphalt	Asphalt 95% CI	VMA @ Opt AC	VMA 95% CI
District 9 Design	5.16	5.12 – 5.19	14.11	14.00 – 14.22
Design w/Hard LS	5.22	5.18 – 5.25	14.51	14.42 – 14.61
Design w/Rhyolite	5.24	5.02 – 5.47	14.81	14.71 – 14.91

indicating that aggregate substitution resulted in statistically different VMA's.

EXPERIMENTAL INTERPRETATION

In this experiment, substitution of aggregate screenings of different mineralogy did not produce statistically significant differences in optimum asphalt content, but did produce statistically significant differences in VMA.

It is interesting to note that as the hardness of the screenings progressed from soft to hard, the VMA at optimum asphalt content increased. One possible explanation for this phenomenon is that softer materials may degrade more during mixing and compaction. During this degradation the sharper edges associated with crushed materials may be broken off softer aggregate particles, resulting in more rounded aggregates which could be compacted more easily and produce a lower VMA. The information from Chapter 3 which showed a decrease in VMA from design to production mixtures may also be a manifestation of this phenomenon.

VMA AND DEVIATION PARAMETERS

The aggregate substitutions were devised to result in the same gradation when using standard sieves. This produced one 0.45 power chart to represent all three mixtures. Consequently, the calculated deviation parameters were the same for all three mixtures. Since the VMA's were different but had the same deviation parameters, one must conclude that VMA is dependent on more than just gradation alone. It would be erroneous to compare the deviation parameters of mixtures of different aggregate types and then make conclusions across the board regarding the differences in deviation parameter values needed to effect a specific change in VMA.

Data in this chapter reinforce the Chapter 3 conclusion that across-the-board comparisons of mixtures containing different aggregates and different gradations do not result in any correlations between VMA and gradation deviation parameters. Only by controlling the many factors affecting VMA can valid comparisons be made.

SIGNIFICANCE OF AGGREGATE BULK SPECIFIC GRAVITY

The aggregate substitution gradation tables (Tables K.1 to K.3) show that the only difference among the three aggregate mixtures was the difference in the bulk specific gravity of the screenings, which in turn affected the overall mixture bulk specific gravity. Consequently, VMA calculations are highly dependent on the aggregate bulk specific gravity used. Chapter 2 discussed the problem of whether aggregate pores which absorb asphalt should be included in VMA (which aggregate specific gravity to use), but did not address the importance of accuracy in choosing specific gravity.

Field[2] showed that errors in the bulk specific gravity can produce significant differences in calculated VMA. In particular, he concluded that the specific-gravity determination of the fine-aggregate portion (i.e., aggregate screenings) was the most prone to error. This is true because a judgment must be made as to when the aggregate is saturated-surface dry.

For the aggregate substitution experiment, the aggregates were changed, which changed not only the aggregate bulk specific gravities but also the mineralogy of the screenings. VMA calculations respond only to the parameters used in their calculation—namely, the specific gravity of compacted specimens, the percent of aggregate in the mixture, and the bulk specific gravity of the aggregate. The factors influenced by mineralogy—compactability, absorption, etc.—are reflected in the actual specific gravity of compacted specimens. The percentage of aggregate is known (especially in laboratory specimens). The aggregate bulk specific gravity is the weak link in the VMA calculation.

If specifications for VMA are used for HMAC and a specific mixture fails to achieve the minimum specification requirements, the first priority should be to determine if the VMA problem is real or possibly brought on by the use of inaccurate aggregate bulk specific gravities. In reality, aggregates may change slightly in specific gravity over the course of a job (particularly large jobs). Errors in procedure or calculation may also result in inaccurate specific gravities' being used initially. Only after ensuring that the problem is real should other, more drastic measures be taken.

SUMMARY OF SIGNIFICANT FINDINGS

Some comments which can be made as a result of the study conducted in this chapter are:

(1) VMA is affected by so many variables that to investigate one variable involves controlling all others as much as possible to be able to isolate that one variable's effects.

(2) This project segment attempted to control the aggregate gradation to investigate the effect of aggregate mineralogy on VMA. This was done by manufacturing "new" aggregates for substitution into a chosen design which conformed to the same gradation within the limits of current practice. This type of aggregate substitution could not be realistically done in the field. Field substitution would involve replacement of one aggregate fraction for another (e.g., Screenings #2 replacing Screenings #1) which would not have the same gradation and would result in a change in the total gradation of the mixture.

(3) The aggregate substitution in this experiment did not result in statistically different "optimum" asphalt contents, but *did* result in statistically significant differences in VMA.

(4) The VMA's in the experimental mixtures increased as harder fine aggregate (screenings) replaced softer fine aggregate (screenings). This may be due to the breakdown of the softer particles during mixing and compaction, resulting in more compactable aggregates.

(5) Since the same 0.45 power chart could be used for all three mixtures, each had the same values for calculated gradation deviation parameters. This would mean that there are not absolute limits on any of the deviation parameters investigated, a principle which could apply to all mixtures across the board. If any deviation parameter can be used to indicate VMA development, the values would be mixture-specific.

(6) Accurate bulk specific gravities are critical to accurate VMA calculations. Mixtures with "failing" VMA's should be checked for accurate bulk specific gravity determinations (i.e., the problem is real) before more drastic measures are taken to achieve the specification requirements.

CHAPTER 6. ECONOMIC IMPACT OF SPECIFICATION CHANGES

The Texas State Department of Highways and Public Transportation is currently in the process of revising specifications for their publication *Standard Specifications for Construction of Highways, Streets and Bridges.* Specifications for hot mix asphaltic concrete are included in this revision. The proposed specifications for HMAC incorporate several significant changes which are designed to improve the quality of HMAC in Texas. The changes, while designed to improve quality, may impact the cost of hot mix in the state. The proposed changes and their probable effect on HMAC cost will be covered in this chapter.

PROPOSED SPECIFICATION CHANGES

There are three major changes proposed for HMAC specifications. These changes include: (1) narrowing the specification master gradation limits for mixture types; (2) limiting the use of field sand or other uncrushed fine aggregate to a maximum of 15 percent; and (3) requiring a minimum percent VMA for each mixture type.

MASTER GRADATION LIMITS

The master gradation limits for all mixture types will be narrowed. The narrower limits will provide a smaller window to which design gradations must conform. Because of this improvement, gradations will be "well graded," and consequently the chance of having gap-graded mixtures should be lessened. The new gradation limits will also reduce the possibility and/or severity of a hump in the gradation (0.45 power chart) around the #40 sieve, which has been linked to tender mixture problems. Figure 6.1 shows an example of the master gradation limit changes proposed for Type D mixtures. Tolerances will still apply to production mixtures; a "design" gradation may be near or at the master gradation limits and production mixtures may fall outside those limits to the extent the tolerances allow.

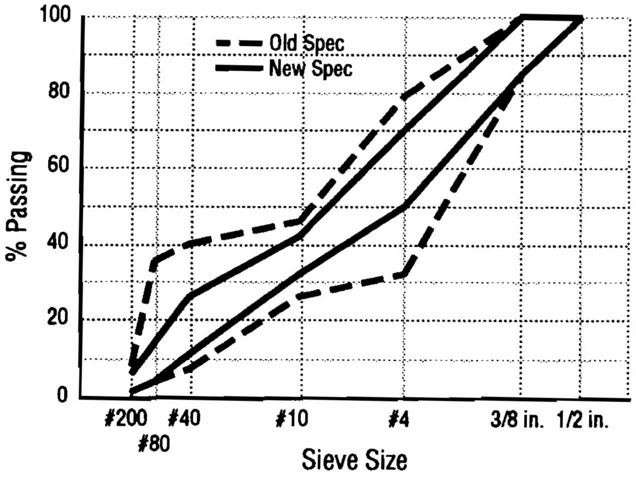

Fig 6.1. Type D master gradation limits.

UNCRUSHED FINE AGGREGATE LIMIT

A maximum of 15 percent field sand or other uncrushed fine aggregate is included in the proposed specification for all mixtures.

Field sand or uncrushed fine aggregate is usually reported in the literature as contributing to lower VMA's. The mechanism may act as a lubricant (e.g., ball bearings), increasing the compactability and thereby making it harder to obtain VMA in a mixture. Because of the sieve sizes inherent in these materials, they contribute to forming the "hump" in the gradation curve associated with tender mixtures. They also contribute to increased surface area, resulting in thinner asphalt films for the same asphalt content.

In their effect on mixtures, the specification changes limiting uncrushed aggregate and narrowing master gradation limits will work together. Narrowing of the master gradation limits will probably automatically limit the amount of uncrushed fine aggregate (field sand) which can be used in a mixture. Likewise, limiting the amount of uncrushed fine aggregate (field sand) will bring mixture gradation closer to the proposed master gradation limits.

MINIMUM PERCENT VMA

Requirements for minimum percent VMA in HMAC design are included in the proposed specifications. The inclusion of VMA in the specification will replace the asphalt content range requirements in the current specification.

The Texas design procedure (Hveem) requires that an optimum mixture contain a fixed air void content. Utilizing an asphalt content range in a specification may result in the use of less asphalt than is necessary to provide adequate film thicknesses. This may lead to lower fatigue resistance, more rapid asphalt aging, and subsequent decrease in the life of the pavement.

VMA (as calculated by the SDHPT) is a measure of the volume available in a compacted mixture for air and effective asphalt (asphalt used as binder). VMA minus the air void content results in the volume of effective asphalt. Minimum limits on VMA effectively provide minimum limits on asphalt content. As VMA goes up, so does the minimum asphalt requirement.

As the nominal aggregate size of a mixture decreases, the surface area increases, requiring more asphalt to maintain the same asphalt film thicknesses. Thus, a VMA requirement which increases as nominal maximum aggregate size decreases, provides a sliding scale for minimum asphalt content by volume and thereby controls minimum asphalt film thicknesses. Accordingly, the proposed VMA requirements do increase with decreasing nominal maximum aggregate size.

Specific VMA requirements were set up in the same manner as the Asphalt Institute limits, while also recognizing that the Texas gyratory compaction technique is likely to result in slightly denser compacted specimens than the Marshall hammer. The proposed minimum limits are set at 1 to 2 VMA percentage points lower than Asphalt Institute recommendations to account for these differences. The actual limits are shown in Table 6.1. The limits are specified only to the nearest whole number, resulting in rounding to the nearest whole number for design requirements. As an example, a Type D mixture exhibiting a 13.5 percent VMA would be rounded up to 14 for specification purposes and would, therefore, be acceptable. A Type D mixture exhibiting 13.4 percent VMA would be rounded to 13 and would fail to meet the specification requirements.

TABLE 6.1. PROPOSED VMA SPECIFICATION REQUIREMENTS

Mixture Type	A	B	C	D	F
Nominal Maximum Aggregate Size (in.)	1-1/2	1	7/8	1/2	3/8
VMA (%)	11	12	13	14	15

The impact of VMA requirements on HMAC operations across the state may be substantial. For the 24 Type D designs investigated in this project, 5 would fail to meet the VMA specification criteria. Since the VMA requirement currently applies to the design phase only, these 5 failing mixtures would have required redesign, possibly changing the individual aggregate percentages or calling for substitution of other aggregates which would enable the mixtures to satisfy the VMA requirement. Currently no information exists about the performance of these 5 mixtures as compared to those with adequate VMA.

ECONOMIC IMPACT OF SPECIFICATION CHANGES

Implementation of the proposed specification changes could result in increased costs for HMAC. Although the exact economic implications are impossible to estimate, one can assume that some HMAC designs will not incur any additional costs, while other mixtures will require changes at considerable expense to comply with the specifications. The types of changes that will enable specific mixtures to meet the proposed specifications may best be shown in several examples.

Four Type D mixtures from various locations in Texas were chosen from the HMAC projects used in this investigation. Each was analyzed for compliance with the proposed specification. Table 6.2 shows the proposed specification limits and the data from each project used for analysis. For mixtures where specification non-compliance has been determined, the values are outlined in double lines. Each mixture will be discussed individually as to possible actions necessary to bring the mixture into compliance with the proposed specification.

D21HUS83

This mixture shows non-compliance in several areas. It does not comply with any of the three major proposed changes to the current specification (gradation master limits, field sand or uncrushed fine aggregate limit, and VMA).

The gradation falls outside the specification on only one sieve, and this size is one for which field sand is the usual contributor. Thus, if the field sand was reduced to the 15 percent limit, the gradation would probably be within the proposed limits. There may be a question about whether the concrete sand used in this design could be classified as uncrushed fine aggregate. If so, this would require that this material be replaced by a crushed aggregate. The economic impact of adjusting the field sand fraction should be minimal.

The VMA minimum represents a significant problem for this mixture. Adjusting the aggregate gradation away from the modified maximum-density line may result in some increase in VMA and should be tried first. The mixture uses all natural materials (not crushed), which in the literature has been shown to result in low VMA's. This mixture is from the Pharr District, located in the Rio Grande Valley, where natural, uncrushed river aggregates are used extensively. In order to achieve adequate VMA, it may be necessary to use crushed aggregates in the mixture. If aggregate substitution is needed to achieve VMA, a substantial economic impact may be realized, particularly if aggregates must be hauled in from other areas of the state for this purpose. Increased aggregate and transportation costs would increase the production cost of the HMAC, resulting in higher bid prices from the contractor.

This particular mix may be one which could suffer from lower pavement life because of the low asphalt content used. Increased VMA will require the use of more asphalt. Since asphalt is the highest cost ingredient in HMAC, this increase in asphalt demand may prove to be the change which most affects the HMAC price.

D12MIH45

This mixture does not comply with any of the three major proposed changes to the current specification

TABLE 6.2. MIXTURE SPECIFICATION ANALYSIS DATA

% Pass	Proposed Specification	D21HUS83	D12MIH45	D3WUS82	D10ANU28
1/2 in.	100	100.0	100.0	100.0	100.0
3/8 in.	'85-100	91.0	92.7	99.1	95.0
#4	'50-70	61.5	56.3	61.0	60.5
#10	'32-42	40.6	40.0	40.5	35.5
#40	'11-26	26.9	29.0	30.0	24.3
#80	'4-14	11.5	11.5	17.1	13.2
#200	'1-6	2.8	5.0	2.5	3.0
Aggr (%)		Coarse Gr	D Polish	Limestone	Sandstone
		40%	30%	33%	62%
		IM Gr	D Limestone	IM Sand stone	
		18%	30%	32%	
	Uncrushed Fine	Conc. Sand	LS Scrn.	LS Scrn.	SS Scrn.
	Aggregate	22%	20%	15%	38%
	(Field Sand)	Field Sand	Field Sand	Field Sand	
	15% Max	20%	20%	20%	
VMA	14 Min	12.2	12.7	17.1	15.5
AC (%)		4.0	5.9	6.0	5.4

(gradation master limits, field sand or uncrushed fine aggregate limit, and VMA).

The gradation falls outside the specification limits on one sieve. This size is one for which field sand is usually a major contributor. Thus, if the field sand was reduced to the 15 percent limit, the gradation would probably be within the proposed limits. This particular mixture is from the Houston District, which has to import most aggregates other than field sand from sources outside the district. Reducing the field sand would require an increase in other more costly imported aggregates, but the actual economic impact would probably be small since it would require only an incremental increase in the amount of aggregate already imported.

This mixture does not comply with the minimum VMA. A decrease in the field sand may result in improved VMA but will probably not solve the problem alone, since the VMA is significantly lower than the proposed specification minimum. Initially, one may try to adjust the gradation away from the modified maximum-density line. This, along with decreased field sand, may help the VMA problem. If these actions—which cause minimal economic impact—fail to increase the VMA to compliance, aggregate replacement is the next step. All aggregates except the field sand are already crushed, so substitution with a different or harder crushed aggregate may help. Since the Houston District imports a majority of the coarse aggregates it uses, at relatively high cost, the economic impact of changing aggregates will be lessened because the transportations costs (representing the largest part of the aggregate cost) will not change drastically.

Increased VMA will result in greater asphalt demand and increased cost for asphalt.

D3WUS82

This mixture shows non-compliance in two areas. It does not comply either with the gradation master limits or with the field sand limit. It *does* meet the requirements for VMA.

The gradation deviations are in the size ranges mostly affected by the field sand. If the field sand in this mixture is reduced to 15 percent, with adjustments to one or more of the other aggregates, both gradation and field sand would meet the specifications while probably not adversely affecting the VMA. The economic impact should be minimal, since only minor changes in aggregate percentages are all that is needed. Asphalt costs would probably not change significantly for this mixture since VMA need not be increased. This design shows that even mixtures which would meet the VMA requirements may need adjustments to comply with all specifications.

D10ANU28

This mixture already complies with all proposed specification requirements. It meets the master gradation limits, is composed of 100 percent crushed aggregates, and has sufficient VMA. No additional cost would be incurred for this mixture.

ECONOMIC IMPACT SUMMARY

Any change in mix design which results in the use of more expensive aggregates to achieve sufficient VMA or more crushed aggregates at the expense of field sand will result in an increase in cost. The impact of this cost may be minimal or may be significant, depending on the difference in aggregate and transportation costs between original and alternate aggregates. Transportation costs will be the largest part of any HMAC cost increase owing to adjustments in the aggregates used.

Any change in mix design which results in the use of more asphalt will result in an increase in cost. Increasing VMA requires increasing the asphalt content. Since asphalt is the single most costly ingredient in HMAC, costs would increase accordingly. Absorption of asphalt also plays a part in the amount of asphalt actually used. The use of highly absorptive aggregates will increase asphalt demand. Absorbed asphalt is lost for use as binder. The use of less absorptive aggregates in place of more absorptive ones may be a strategy for contractors to lower the asphalt demand of a mixture while still providing adequate asphalt films on the aggregate. A combination of factors makes determining actual effects on asphalt costs for a specific mixture difficult to determine.

With respect to Texas as a whole, some general comments may be made which will affect the statewide average price which the SDHPT pays for HMAC. More asphalt will be used than is used currently, resulting in increased statewide cost. Also, more crushed aggregates will be used, resulting in increased aggregate transportation costs. There may also be additional demand for harder and less absorptive aggregates, resulting in a shift to different aggregate suppliers. Some aggregates may no longer be economical, or they may be impossible to use and may alter the supply-and-demand situation. The likely result is increased aggregate costs.

CHAPTER 7. CONCLUSIONS/RECOMMENDATIONS

The focus of this study was aggregate gradation, aggregate type, and their effects on mixture characteristics, in particular VMA. As stated in Chapter 1, the objectives of the study were to: conduct a literature search relative to HMAC characteristics, especially VMA; investigate the current production of HMAC in Texas with respect to VMA, and develop correlations between VMA and HMAC parameters; conduct laboratory investigations to determine the effects of aggregate gradation and type on HMAC properties; and investigate the economic consequences of including VMA in specifications for HMAC. The literature search proved that there is much work to be done in order to fully understand HMAC. The work done to address the other objectives yielded the following conclusions and recommendations.

CONCLUSIONS FROM STUDYING THE PROJECT 1197 DATABASE

(1) A calculation (integration) of the area between a gradation and a corresponding maximum-density line on a 0.45 power plot describes the amount of deviation between the two better than any other deviation parameter used in this study.

(2) When studying design mixtures as a whole, VMA and design asphalt content are reasonably correlated, and if asphalt absorption were taken into account, the correlation would be better. This agrees with the literature, that is, design asphalt content and VMA were found to be proportional for non-absorptive aggregates.

(3) Hveem design criteria yields a narrow range of Percent of Voids Filled with asphalt (PVF). This occurs in part because the optimum asphalt content is specified at a particular air void content.

(4) Factors affecting VMA are complex. Trying to establish correlations between VMA and mix design properties for the entire population of mix designs is an oversimplification of how aggregate and asphalt affect VMA. There are many factors affecting VMA which can not be described in such simple terms. Individual mixtures exhibit characteristics unique to that asphalt-aggregate combination, and they generally cannot be compared to other mixtures in terms of VMA.

(5) Correlations between VMA and asphalt content or PVF are significantly reduced in field mixtures since variations in asphalt content and aggregate adjustments are made in the field.

(6) Field VMA's (plant-mixed, lab-molded) are significantly lower than the corresponding design VMA's.

CONCLUSIONS FROM LABORATORY FACTORIAL EXPERIMENTATION

(1) Differences in Hot Mix Asphaltic Concrete material properties can be achieved through changing asphalt content and/or aggregate gradation. This was expected and is documented in the literature.

(2) Aggregate gradation is a qualitative variable which makes analyzing differences in properties difficult because of gradation changes.

(3) To compare mixtures, as many variables as possible must be controlled. Comparisons are more realistic if mixes use the same aggregates (just vary the proportions), have uniform laboratory conditions, and are compared at "optimum" asphalt content.

(4) The gradation differences used in the District 6 evaluation were not sufficient to produce statistically significant differences in VMA. No relationship was developed between VMA and gradation deviation parameters.

(5) The gradation differences used in the District 14 evaluation were significant enough to produce statistically significant differences in VMA. Also, as the area between the actual gradation and the "modified" maximum-density line increased, the VMA increased.

(6) The "modified" maximum-density line, as defined in this report, may be more appropriate for gradation adjustment to enhance VMA than the line developed by Goode and Lufsey.

CONCLUSIONS FROM EVALUATION OF AGGREGATE SUBSTITUTION

(1) In the experiment conducted, aggregate substitution did not result in statistically different "optimum" asphalt contents, but did result in statistically significant differences in VMA.

(2) VMA's increased as harder fine aggregate (screenings) replaced softer fine aggregate (screenings). A rational explanation for this may be that the breakdown of softer aggregate particles during mixing and compaction results in more compactible aggregates and lower VMA's.

(3) Any correlations which might exist between VMA and aggregate deviation parameters (area between gradation and "modified" maximum-density line) are mixture-specific. No specific parameter differences will result in specific VMA changes.

(4) Accurate bulk specific gravities are critical to accurate VMA calculations.

CONCLUSIONS FROM ECONOMIC EVALUATION

(1) Any mix design change which results in the use of more expensive aggregates to achieve VMA or to replace field sand will result in increased cost to the contractor and subsequently to the SDHPT.

(2) Increasing VMA requires the use of more asphalt. Increasing asphalt content results in increased cost of the mixture.

(3) Implementation of the specification changes proposed by the SDHPT will likely result in a statewide average increase in HMAC costs. This is due to the probability that more asphalt will be used statewide and more crushed aggregates will be used to replace less expensive local aggregates.

(4) Some realignment of aggregate suppliers is likely because of changing demands for aggregate usage. This too may result in increased HMAC prices.

RECOMMENDATIONS

(1) It is believed that the area between the "modified" maximum-density line and the actual gradation may be a useful tool by which to adjust gradations on a mixture-specific basis to increase VMA. The experimental data assembled in this project indicate this, but more work should be done using many more mixtures to verify this phenomenon.

(2) Since the bulk specific gravity significantly influences the calculation of VMA, steps should be taken to insure the accuracy of bulk specific gravity determinations. This may be done through a statewide monitoring program.

(3) If a specific mixture has insufficient VMA, the following procedure is recommended, first to verify that a problem exists and then to make changes to increase the VMA:

  (a) Check the accuracy of the bulk specific gravities involved in the VMA calculations.

  (b) If it is determined that a VMA problem truly exists, adjust the aggregate gradation away from the "modified" maximum-density line. This may increase VMA. Several different adjustments may be needed to ascertain the effect on VMA.

  (c) If gradation adjustment fails to increase the VMA sufficiently, aggregate substitution may be used. More crushed materials, harder materials, or mineralogically different materials may be used.

  (d) If taken to extremes, aggregate substitution may result in a total redesign of the mixture.

This procedure progresses from the least costly to the most costly measures and is a trial-and-error process which terminates when the desired VMA is attained.

(4) The specification changes proposed by the SDHPT seem sound, and, while likely to result in higher statewide costs, should result in more durable pavements. You get what you pay for.

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APPENDIX A. MIXTURE DESIGNS—DESIGN DATA AND DEVIATION DATA

TABLE A.1. TYPE C MIXTURES

Sieves (%P)	C1LMSH19-D	C5LUUS84-D	C14BUS28-D
7/8	100.0	100.0	100.0
5/8	99.8	98.5	98.9
3/8	83.1	74.1	76.1
4	60.3	51.6	59.7
10	41.7	36.3	38.4
40	25.7	20.8	26.6
80	14.0	10.1	12.9
200	6.2	3.3	3.7

Sieves (%P)	Old Max Den	Old Max Den	Old Max Den
7/8			
5/8	99.8	98.5	98.9
3/8	79.3	78.3	78.6
4	58.0	57.2	57.5
10	39.3	38.8	38.9
40	19.4	19.2	19.3
80	13.2	13.0	13.1
200	8.9	8.8	8.8
0	0.0	0.0	0.0

Sieves (%P)	Mod Max Den	Mod Max Den	Mod Max Den
7/8			
5/8	99.8	98.5	98.9
3/8	78.7	77.0	77.4
4	56.7	54.7	55.1
10	37.5	35.1	35.5
40	17.1	14.4	14.8
80	10.7	7.8	8.2
200	6.2	3.3	3.7
VMA Design	14.9	14	14.1
PVF	79.87	78.57	78.72
Asphalt Content	5.5	4.8	4.9
Old L Sum(Line-Act)	-12.9	19.1	-1.2
Old L Sum(ABS(Line-Act))	18.3	22.3	17.9
Old L Sum((Line-Act)^2)	72.58	96.47	91.37
Area (Old-Act)	2.118	2.189	1.381
Mod L Sum(Line-Act)	-24.1	-3.8	-22.6
Mod L Sum (ABS(Line-Act))	24.1	15.9	25.3
Mod L Sum((Line-Act)^2)	135.48	66.40	193.30
Area (Mod-Act)	3.037	1.835	2.693
FM (Old L)-FM (Design)	0.09	-0.15	0.04
FM (Mod L)-FM (Design)	0.20	0.07	0.24
Sand Ratio	0.549	0.530	0.660

TABLE A.1. TYPE C MIXTURES (CONTINUED)

Sieves (%P)	C16JUS28A-D	C16JUS28B-D	C18DIH63-D
7/8	100.0	100.0	100.0
5/8	99.2	99.6	100.0
3/8	80.6	80.5	75.3
4	57.5	58.0	53.5
10	39.9	40.5	36.3
40	23.7	23.8	22.8
80	14.9	11.6	5.8
200	4.2	2.3	1.2

Sieves (%P)	Old Max Den	Old Max Den	Old Max Den
7/8			
5/8	99.2	99.6	
3/8	78.8	79.1	75.3
4	57.6	57.9	55.1
10	39.0	39.2	37.3
40	19.3	19.4	18.5
80	13.1	13.2	12.6
200	8.8	8.9	8.4
0	0.0	0.0	0

Sieves (%P)	Mod Max Den	Mod Max Den	Mod Max Den
7/8			
5/8	99.2	99.6	
3/8	77.8	77.7	75.3
4	55.5	54.8	52.9
10	36.0	34.8	33.2
40	15.2	13.6	12.3
80	8.7	6.9	5.8
200	4.2	2.3	1.2
VMA Design	13.7	13.7	13.2
PVF	78.10	78.10	77.27
Asphalt Content	4.8	4.8	5.3
Old L Sum(Line-Act)	-4.0	1.0	12.2
Old L Sum(ABS(Line-Act))	13.5	15.3	20.9
Old L Sum((Line-Act)^2)	47.61	68.61	120.30
Area (Old-Act)	0.990	1.042	1.019
Mod L Sum(Line-Act)	-23.4	-26.5	-14.3
Mod L Sum (ABS(Line-Act))	23.4	26.5	14.3
Mod L Sum((Line-Act)^2)	137.41	176.14	120.26
Area (Mod-Act)	2.578	3.158	1.702
FM (Old L)-FM (Design)	0.02	-0.02	-0.12
FM (Mod L)-FM (Design)	0.21	0.24	0.14
Sand Ratio	0.546	0.563	0.615

TABLE A.1. TYPE C MIXTURES (CONTINUED)

Sieves (%P)	C19MUS59-D	C19PUS59-D
7/8	100.0	100.0
5/8	97.7	98.0
3/8	74.1	78.3
4	56.6	54.8
10	42.1	38.6
40	27.1	26.6
80	14.3	18.2
200	1.9	3.4
Sieves (%P)	**Old Max Den**	**Old Max Den**
7/8		
5/8	97.7	98.0
3/8	77.6	77.9
4	56.8	56.9
10	38.5	38.6
40	19.0	19.1
80	12.9	13.0
200	8.7	8.7
0	0.0	0.0
Sieves (%P)	**Mod Max Den**	**Mod Max Den**
7/8		
5/8	97.7	98.0
3/8	76.1	76.7
4	53.6	54.5
10	33.9	35.0
40	13.0	14.4
80	6.5	7.9
200	1.9	3.4
VMA Design	16.1	14
PVF	81.37	78.57
Asphalt Content	5.9	4.8
Old L Sum(Line-Act)	-2.6	-5.7
Old L Sum(ABS(Line-Act))	23.6	20.6
Old L Sum((Line-Act)^2)	138.99	116.72
Area (Old-Act)	2.160	1.375
Mod L Sum(Line-Act)	-31.1	-28.0
Mod L Sum (ABS(Line-Act))	35.1	28.0
Mod L Sum((Line-Act)^2)	339.32	270.83
Area (Mod-Act)	3.715	2.618
FM (Old L)-FM (Design)	0.06	0.05
FM (Mod L)-FM (Design)	0.33	0.26
Sand Ratio	0.627	0.659

TABLE A.2. TYPE D MIXTURES

Sieves (%P)	D1FNUS82-D	D1HUSH50-D	D1LMUS82-D
1/2	100	100	100
3/8	93.6	96.3	93.9
4	54	62.4	58.2
10	41	39.2	40.3
40	29.4	26.5	28
80	15.5	17.1	13.2
200	4.5	5.8	2
Sieves (%P)	**Old Max Den**	**Old Max Den**	**Old Max Den**
1/2			
3/8	93.6	96.3	93.9
4	68.4	70.4	68.7
10	46.4	47.7	46.5
40	23.0	23.6	23.0
80	15.6	16.1	15.7
200	10.5	10.8	10.5
0	0	0	0
Sieves (%P)	**Mod Max Den**	**Mod Max Den**	**Mod Max Den**
1/2			
3/8	93.6	96.3	93.9
4	66.6	68.9	66.1
10	43.0	44.9	41.7
40	17.9	19.4	15.8
80	10.0	11.4	7.6
200	4.5	5.8	2.0
VMA Design	16.3	14.5	16.4
PVF	81.60	79.31	81.71
Asphalt Content	5.8	5.2	5.8
Old L Sum(Line-Act)	19.5	17.6	22.7
Old L Sum(ABS(Line-Act))	32.3	25.4	32.6
Old L Sum((Line-Act)^2)	314.70	170.80	251.42
Area (Old-Act)	3.492	2.685	2.916
Mod L Sum(Line-Act)	-2.5	-0.7	-8.5
Mod L Sum (ABS(Line-Act))	31.6	25.0	27.0
Mod L Sum((Line-Act)^2)	326.90	158.04	244.12
Area (Mod-Act)	3.537	2.427	2.823
FM (Old L)-FM (Design)	-0.19	-0.18	-0.23
FM (Mod L)-FM (Design)	0.02	0.01	0.09
Sand Ratio	0.682	0.620	0.679

TABLE A.2. TYPE D MIXTURES (CONTINUED)

Sieves (%P)	D3WUS82-D	D4CUS60-D	D5GAFM65-D
1/2	100	100	100
3/8	99.1	92.7	95.7
4	61	63.8	63.6
10	40.5	40.6	34.5
40	30	19.3	20.2
80	17.1	10.4	8.9
200	2.5	4.5	3.3

Sieves (%P)	Old Max Den	Old Max Den	Old Max Den
1/2			
3/8	99.1	92.7	95.7
4	72.5	67.8	70.0
10	49.1	45.9	47.4
40	24.3	22.7	23.5
80	16.5	15.5	16.0
200	11.1	10.4	10.7
0	0	0	0

Sieves (%P)	Mod Max Den	Mod Max Den	Mod Max Den
1/2			
3/8	99.1	92.7	95.7
4	69.9	66.0	67.7
10	44.2	42.6	43.2
40	17.0	17.7	17.1
80	8.4	9.9	9.0
200	2.5	4.5	3.3
VMA Design	17.1	14.3	13.9
PVF	82.46	79.02	78.42
Asphalt Content	6	4.8	4.8

Old L Sum(Line-Act)	22.4	23.7	37.0
Old L Sum(ABS(Line-Act))	34.9	23.7	37.0
Old L Sum((Line-Act)^2)	311.99	116.16	322.72
Area (Old-Act)	3.409	2.159	3.828
Mod L Sum(Line-Act)	-9.1	2.1	9.8
Mod L Sum (ABS(Line-Act))	34.2	6.2	15.9
Mod L Sum((Line-Act)^2)	336.51	11.39	101.58
Area (Mod-Act)	3.296	0.708	1.981
FM (Old L)-FM (Design)	-0.22	-0.24	-0.37
FM (Mod L)-FM (Design)	0.09	-0.02	-0.10
Sand Ratio	0.724	0.410	0.542

TABLE A.2. TYPE D MIXTURES (CONTINUED)

Sieves (%P)	D5LUUS84-D	D5GAUS84-D	D10ANU28-D
1/2	100	100	100
3/8	97.3	97.2	95.0
4	63.7	63.3	60.5
10	38.3	38.4	35.5
40	21.7	19.6	24.3
80	12.4	8.5	13.2
200	4.1	1.7	3.0
Sieves (%P)	**Old Max Den**	**Old Max Den**	**Old Max Den**
1/2			
3/8	97.3	97.2	95.0
4	71.1	71.1	69.5
10	48.2	48.1	47.1
40	23.9	23.8	23.3
80	16.2	16.2	15.8
200	10.9	10.9	10.7
0	0	0	0
Sieves (%P)	**Mod Max Den**	**Mod Max Den**	**Mod Max Den**
1/2			
3/8	97.3	97.2	95.0
4	69.1	68.3	67.2
10	44.3	42.9	42.7
40	18.1	16.0	16.8
80	9.8	7.6	8.6
200	4.1	1.7	3.0
VMA Design	14.4	17.2	15.5
PVF	79.17	82.56	80.65
Asphalt Content	4.9	6.3	5.4
Old L Sum(Line-Act)	30.1	38.7	29.9
Old L Sum(ABS(Line-Act))	30.1	38.7	31.9
Old L Sum((Line-Act)^2)	218.93	317.25	281.96
Area (Old-Act)	3.265	3.722	3.436
Mod L Sum(Line-Act)	5.2	5.0	1.7
Mod L Sum (ABS(Line-Act))	17.6	14.0	26.0
Mod L Sum((Line-Act)^2)	84.99	58.93	174.38
Area (Mod-Act)	1.943	1.609	2.609
FM (Old L)-FM (Design)	-0.30	-0.39	-0.30
FM (Mod L)-FM (Design)	-0.05	-0.05	-0.02
Sand Ratio	0.515	0.488	0.656

TABLE A.2. TYPE D MIXTURES (CONTINUED)

Sieves (%P)	D12GFM17-D	D12MFM13-D	D12MIH45-D
1/2	100	100	100
3/8	87	94.1	92.7
4	49.9	64.5	56.3
10	34.5	40.8	40
40	23.7	27.3	29
80	6.2	10.8	11.5
200	3	5.3	5

Sieves (%P)	Old Max Den	Old Max Den	Old Max Den
1/2			
3/8	87.0	94.1	92.7
4	63.6	68.8	67.8
10	43.1	46.6	45.9
40	21.3	23.1	22.7
80	14.5	15.7	15.5
200	9.8	10.6	10.4
0	0	0	0

Sieves (%P)	Mod Max Den	Mod Max Den	Mod Max Den
1/2			
3/8	87.0	94.1	92.7
4	61.6	67.2	66.1
10	39.3	43.6	42.8
40	15.6	18.6	18.1
80	8.2	10.8	10.4
200	3.0	5.3	5.0
VMA Design	14.9	13.1	12.7
PVF	79.87	77.10	76.38
Asphalt Content	5.3	5.5	5.9
Old L Sum(Line-Act)	35.0	16.0	20.5
Old L Sum(ABS(Line-Act))	39.7	24.5	33.0
Old L Sum((Line-Act)^2)	382.02	121.58	250.79
Area (Old-Act)	3.899	1.844	3.101
Mod L Sum(Line-Act)	10.3	-3.2	0.7
Mod L Sum (ABS(Line-Act))	26.5	14.3	24.7
Mod L Sum((Line-Act)^2)	228.28	90.84	224.10
Area (Mod-Act)	3.103	1.455	2.874
FM (Old L)-FM (Design)	-0.35	-0.16	-0.20
FM (Mod L)-FM (Design)	-0.10	0.03	-0.01
Sand Ratio	0.657	0.620	0.686

TABLE A.2. TYPE D MIXTURES (CONTINUED)

Sieves (%P)	D16NSH44-D	D16RUS77-D	D16RUS77B-D
1/2	100	100.0	100.0
3/8	89.8	91.3	90.6
4	57.6	55.3	53.2
10	40.5	34.4	38.8
40	18	19.3	26.6
80	5	10.9	20.8
200	1.4	2.8	5.3

Sieves (%P)	Old Max Den	Old Max Den	Old Max Den
1/2			
3/8	89.8	91.3	90.6
4	65.7	66.8	66.2
10	44.5	45.2	44.9
40	22.0	22.4	22.2
80	15.0	15.2	15.1
200	10.1	10.2	10.2
0	0	0	0

Sieves (%P)	Mod Max Den	Mod Max Den	Mod Max Den
1/2			
3/8	89.8	91.3	90.6
4	63.0	64.5	64.8
10	39.6	41.0	42.1
40	14.6	16.1	18.1
80	6.8	8.2	10.5
200	1.4	2.8	5.3
VMA Design	15.3	14.8	14.8
PVF	80.39	79.73	79.73
Asphalt Content	5.1	5.3	5.3
Old L Sum(Line-Act)	34.7	37.1	13.9
Old L Sum(ABS(Line-Act))	34.7	37.1	34.1
Old L Sum((Line-Act)^2)	271.53	331.87	282.30
Area (Old-Act)	2.933	4.192	3.356
Mod L Sum(Line-Act)	3.0	9.9	-3.9
Mod L Sum (ABS(Line-Act))	11.6	21.7	33.7
Mod L Sum((Line-Act)^2)	45.01	145.71	322.58
Area (Mod-Act)	1.277	2.629	3.350
FM (Old L)-FM (Design)	-0.35	-0.37	-0.14
FM (Mod L)-FM (Design)	-0.03	-0.10	0.04
Sand Ratio	0.425	0.522	0.636

TABLE A.2. TYPE D MIXTURES (CONTINUED)

Sieves (%P)	D17BSH21-D	D17BSH36-D	D19CUS59-D
1/2	100.0	100.0	100.0
3/8	95.0	95.0	99.3
4	65.0	65.0	64.7
10	40.0	40.0	41.5
40	27.0	27.0	22.5
80	16.0	16.0	7.2
200	5.0	5.0	2.5
Sieves (%P)	**Old Max Den**	**Old Max Den**	**Old Max Den**
1/2			
3/8	95.0	95.0	99.3
4	69.5	69.5	72.6
10	47.1	47.1	49.2
40	23.3	23.3	24.4
80	15.8	15.8	16.6
200	10.7	10.7	11.1
0	0	0	0
Sieves (%P)	**Mod Max Den**	**Mod Max Den**	**Mod Max Den**
1/2			
3/8	95.0	95.0	99.3
4	67.7	67.7	70.0
10	43.8	43.8	44.3
40	18.5	18.5	17.0
80	10.5	10.5	8.5
200	5.0	5.0	2.5
VMA Design	14.8	13	13.8
PVF	79.73	76.92	78.26
Asphalt Content	4.8	4.4	5.3
Old L Sum(Line-Act)	13.3	13.3	35.4
Old L Sum(ABS(Line-Act))	21.0	21.0	35.4
Old L Sum((Line-Act)^2)	115.37	115.37	287.04
Area (Old-Act)	1.924	1.924	3.231
Mod L Sum(Line-Act)	-7.4	-7.4	3.8
Mod L Sum (ABS(Line-Act))	20.6	20.6	14.8
Mod L Sum((Line-Act)^2)	124.63	124.63	67.40
Area (Mod-Act)	1.754	1.754	1.576
FM (Old L)-FM (Design)	-0.13	-0.13	-0.35
FM (Mod L)-FM (Design)	0.07	0.07	-0.04
Sand Ratio	0.629	0.629	0.513

TABLE A.2. TYPE D MIXTURES (CONTINUED)

Sieves (%P)	D21CFM14-D	D21HUS83-D	D21SFM75-D
1/2	100.0	100.0	100.0
3/8	96.2	91.0	88.3
4	63.4	61.5	55.8
10	40.4	40.6	38.3
40	26.0	26.9	27.9
80	10.6	11.5	7.7
200	1.8	2.8	0.6
Sieves (%P)	**Old Max Den**	**Old Max Den**	**Old Max Den**
1/2			
3/8	96.2	91.0	88.3
4	70.3	66.5	64.5
10	47.6	45.1	43.7
40	23.6	22.3	21.6
80	16.0	15.2	14.7
200	10.8	10.2	9.9
0	0	0	0
Sieves (%P)	**Mod Max Den**	**Mod Max Den**	**Mod Max Den**
1/2			
3/8	96.2	91.0	88.3
4	67.6	64.3	61.7
10	42.5	40.9	38.4
40	15.9	16.0	13.7
80	7.6	8.2	6.0
200	1.8	2.8	0.6
VMA Design	14.8	12.2	14.8
PVF	79.73	75.41	79.73
Asphalt Content	5.2	4	5.2
Old L Sum(Line-Act)	26.2	16.0	24.3
Old L Sum(ABS(Line-Act))	31.0	25.1	36.8
Old L Sum((Line-Act)^2)	216.84	133.80	281.71
Area (Old-Act)	2.525	1.816	2.763
Mod L Sum(Line-Act)	-6.7	-11.0	-9.7
Mod L Sum (ABS(Line-Act))	19.4	17.2	22.0
Mod L Sum((Line-Act)^2)	132.36	135.70	238.27
Area (Mod-Act)	1.924	1.736	2.535
FM (Old L)-FM (Design)	-0.26	-0.16	-0.24
FM (Mod L)-FM (Design)	0.07	0.11	0.10
Sand Ratio	0.627	0.636	0.724

TABLE A.2. TYPE D MIXTURES (CONTINUED)

Sieves (%P)	D23BFM45-D	D23LU190-D	D24CUS62-D
1/2	100.0	100.0	100.0
3/8	94.5	92.8	95.1
4	57.5	61.5	63.5
10	35.9	34.2	39.3
40	21.1	23.6	20.1
80	5.9	9.9	11.6
200	2.9	2.4	3.3

Sieves (%P)	Old Max Den	Old Max Den	Old Max Den
1/2			
3/8	94.5	92.8	95.1
4	69.1	67.9	69.5
10	46.8	46.0	47.1
40	23.2	22.8	23.3
80	15.8	15.5	15.9
200	10.6	10.4	10.7
0	0	0	0

Sieves (%P)	Mod Max Den	Mod Max Den	Mod Max Den
1/2			
3/8	94.5	92.8	95.1
4	66.8	65.4	67.3
10	42.4	41.4	42.9
40	16.6	15.9	17.1
80	8.5	8.0	8.9
200	2.9	2.4	3.3
VMA Design	12.6	13.8	14.4
PVF	76.19	78.26	79.17
Asphalt Content	4	5.5	4.9
Old L Sum(Line-Act)	42.1	30.9	28.7
Old L Sum(ABS(Line-Act))	42.1	32.5	28.7
Old L Sum((Line-Act)^2)	414.06	274.61	180.01
Area (Old-Act)	4.362	3.171	2.850
Mod L Sum(Line-Act)	14.0	1.5	1.7
Mod L Sum (ABS(Line-Act))	22.9	20.7	13.1
Mod L Sum((Line-Act)^2)	155.39	129.76	43.86
Area (Mod-Act)	2.598	2.058	1.350
FM (Old L)-FM (Design)	-0.42	-0.31	-0.29
FM (Mod L)-FM (Design)	-0.14	-0.02	-0.02
Sand Ratio	0.552	0.667	0.467

APPENDIX B. 0.45 POWER GRADATION CHARTS FOR DESIGN MIXTURES

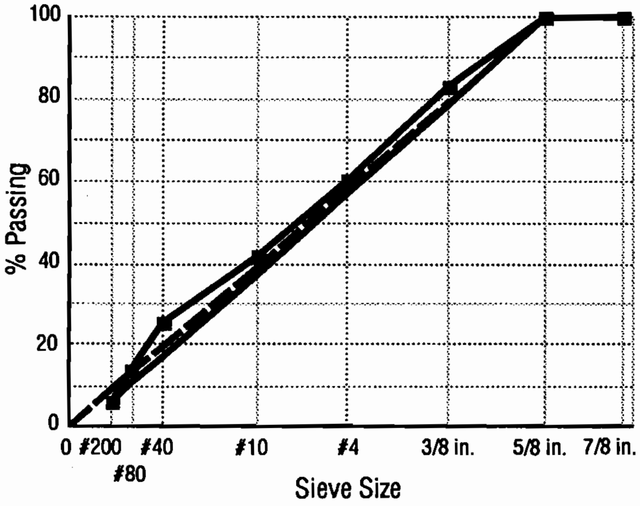

Fig B.1. C1LMSH19-D.

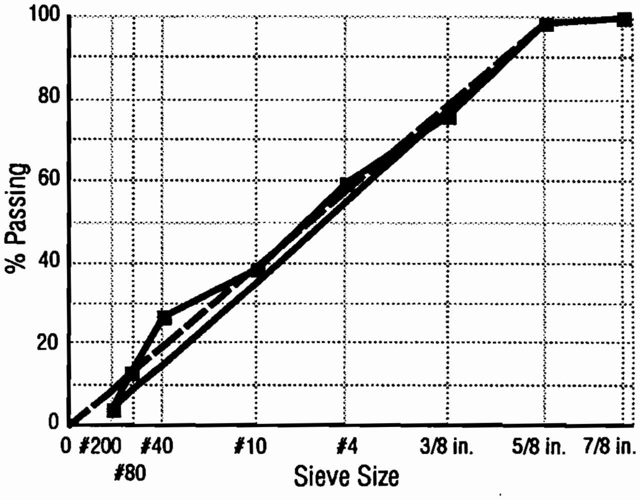

Fig B.3. C14BUS28-D.

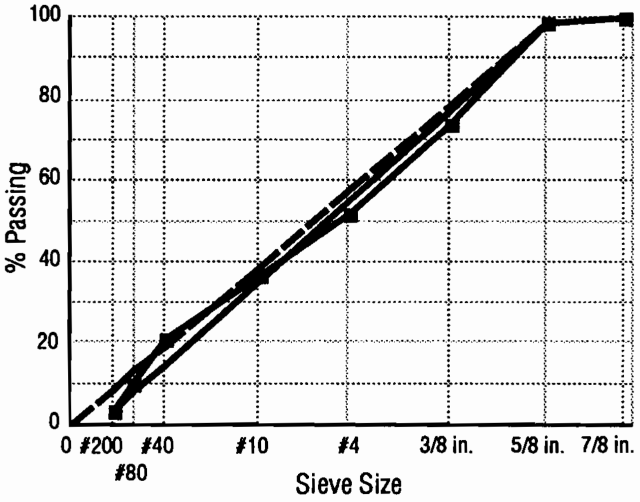

Fig B.2. C5LUUS84-D.

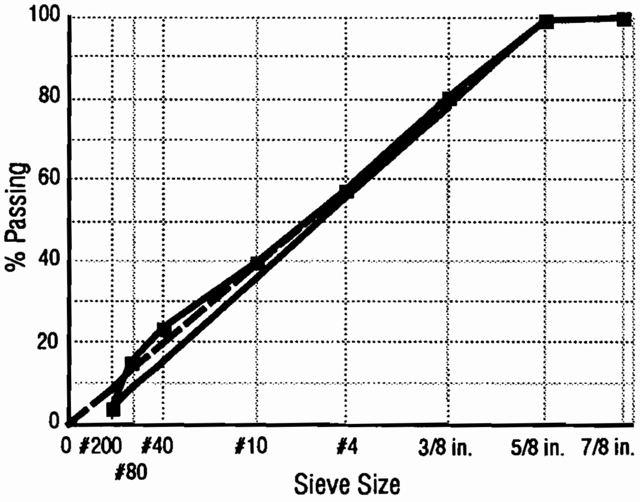

Fig B.4. C16JUS28A-D.

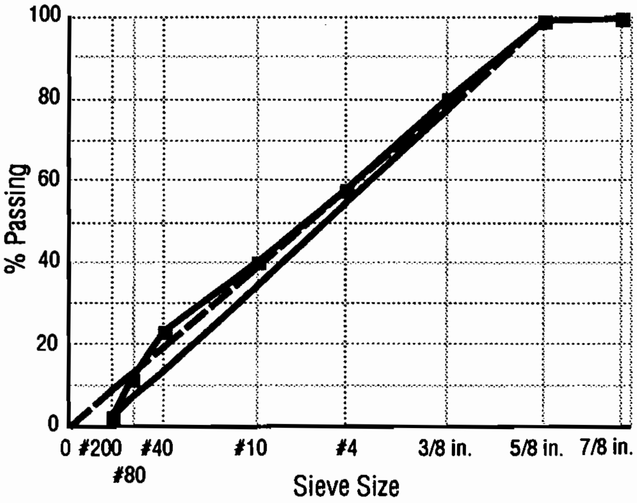

Fig B.5. C16JUS28B-D.

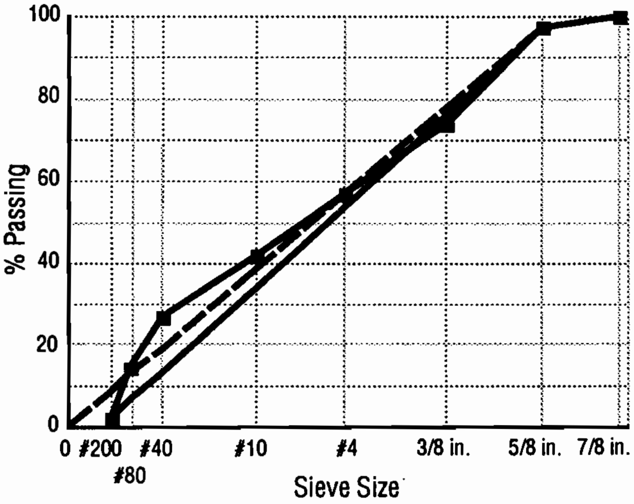

Fig B.7. C19MUS59-D.

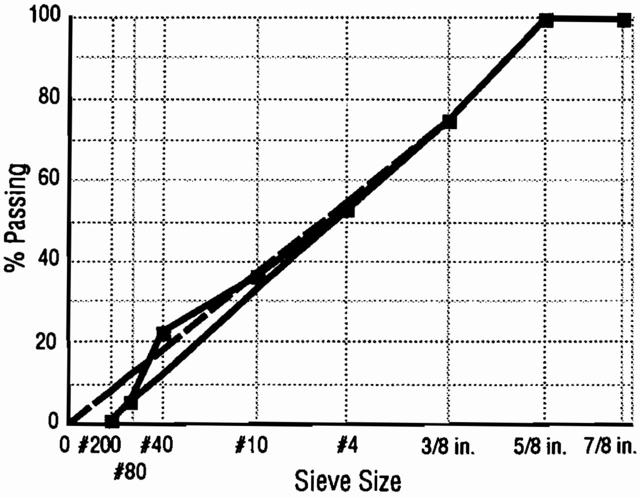

Fig B.6. C18DIH63-D.

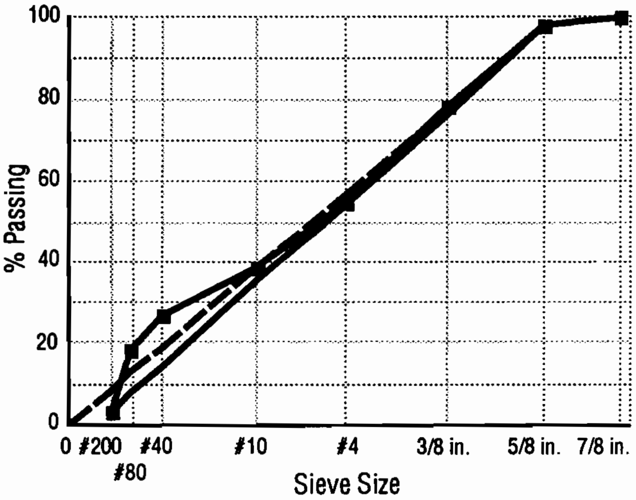

Fig B.8. C19PUS59-D.

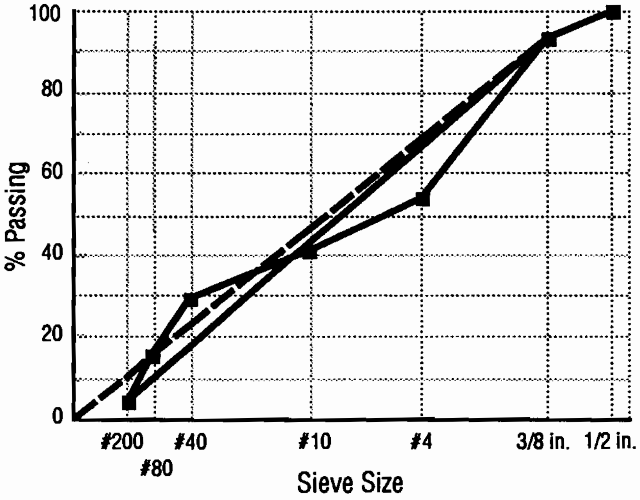

Fig B.9. D1FNUS82-D.

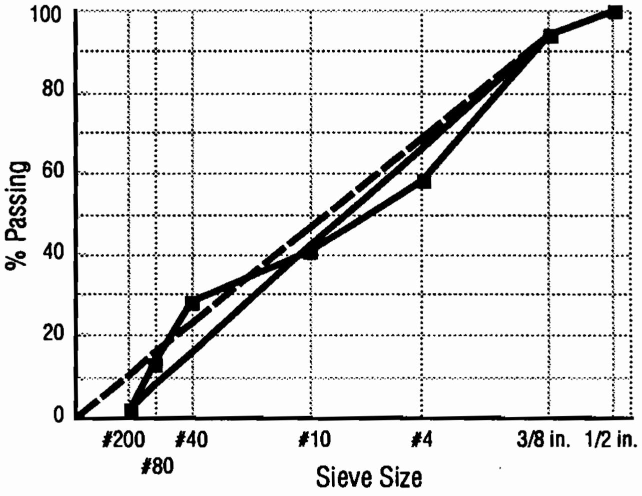

Fig B.11. D1LMUS82-D.

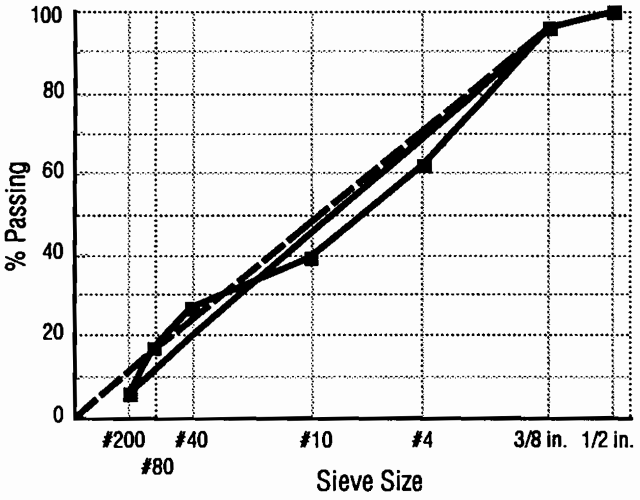

Fig B.10. D1HUSH50-D.

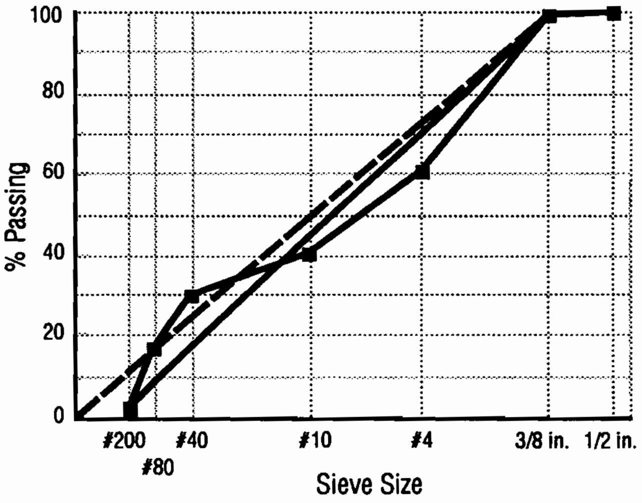

Fig B.12. D3WUS82-D.

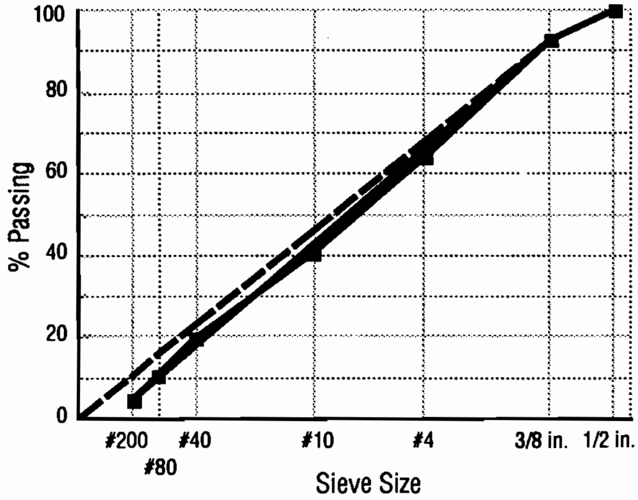

Fig B.13. D4CUS60-D.

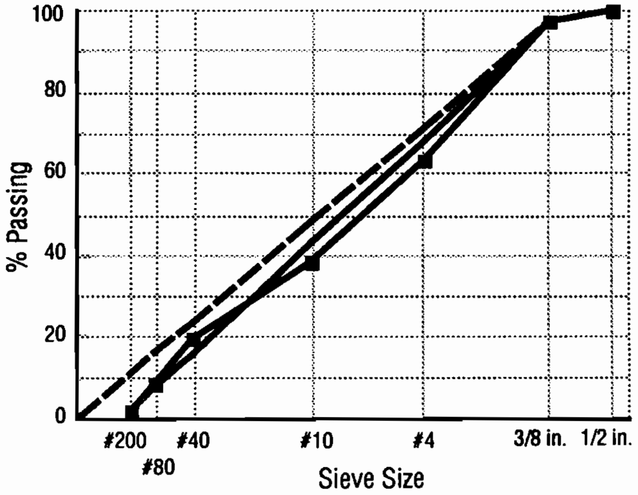

Fig B.15. D5GAUS84-D.

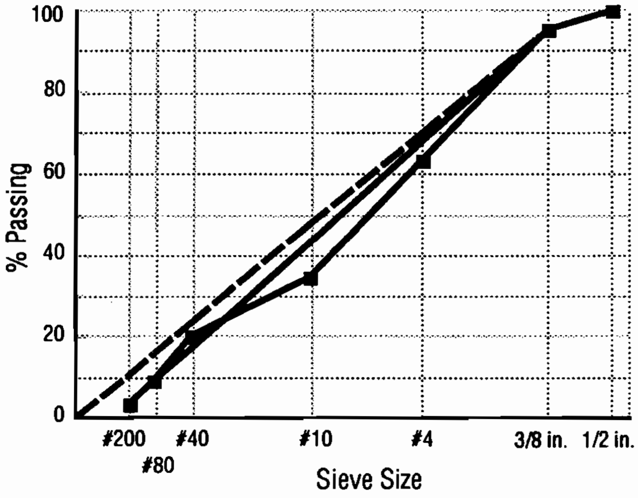

Fig B.14. D5GAFM65-D.

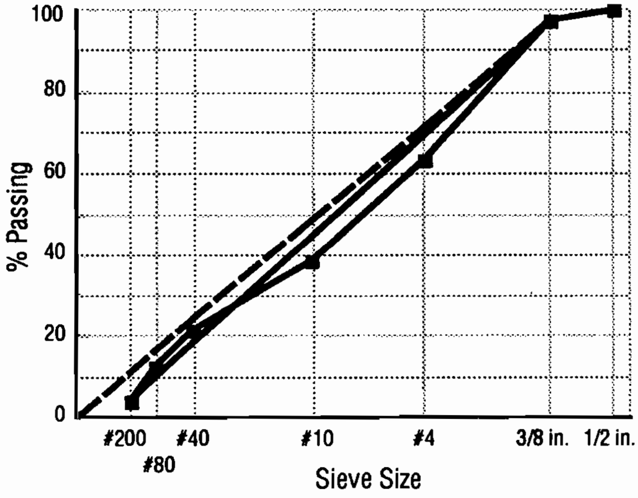

Fig B.16. D5LUUS84-D.

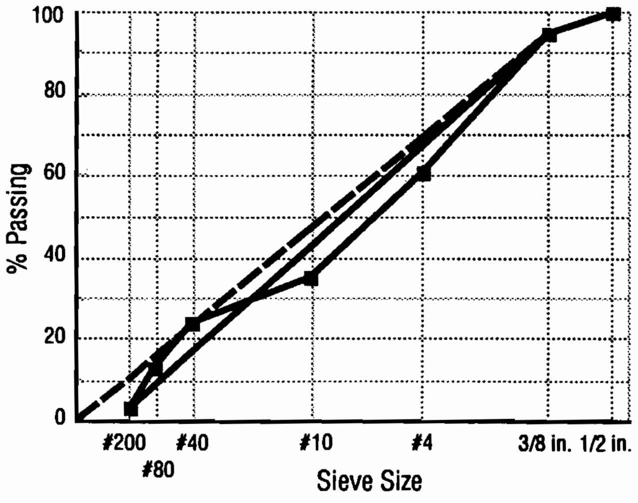

Fig B.17. D10ANU28-D.

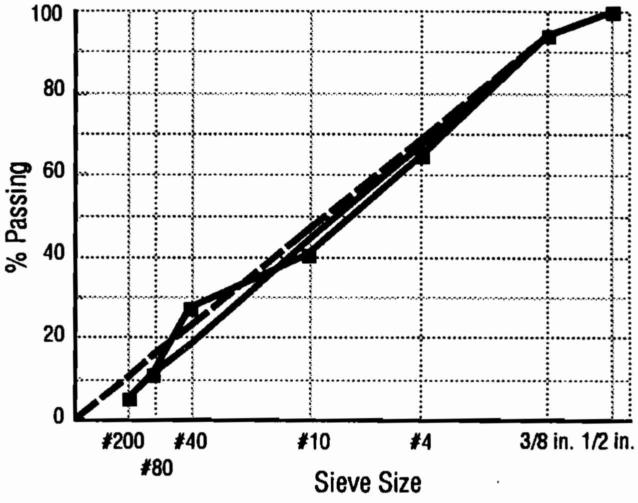

Fig B.19. D12MFM13-D.

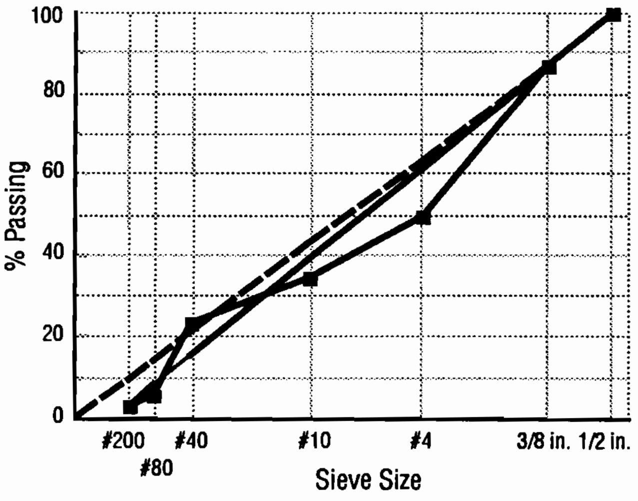

Fig B.18. D12GFM17-D.

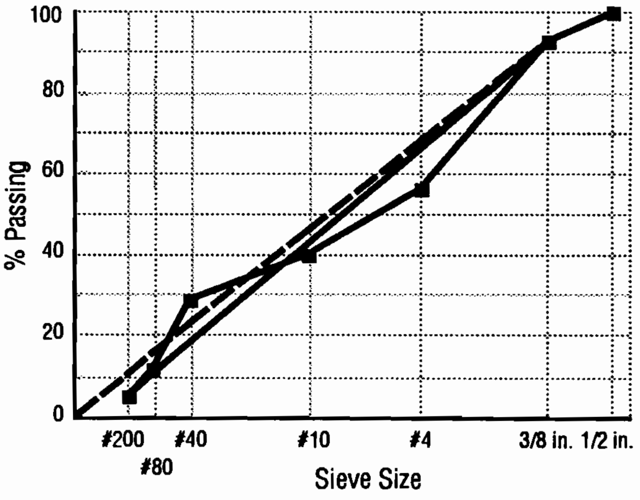

Fig B.20. D12MIH45-D.

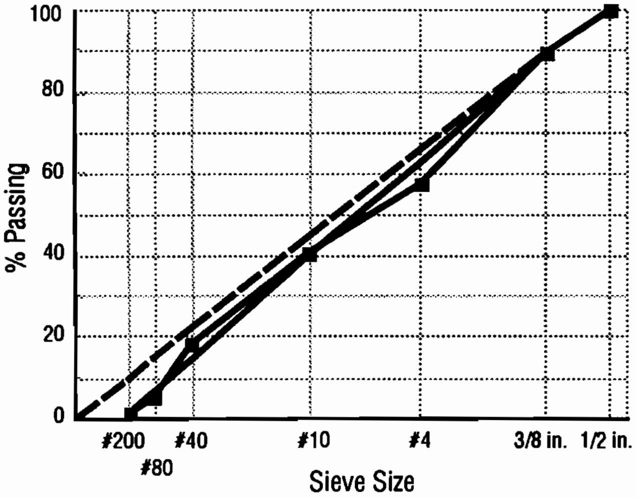

Fig B.21. D16NSH44-D.

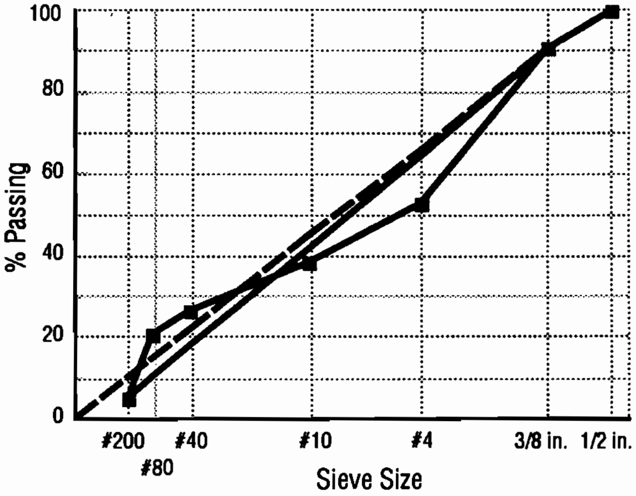

Fig B.23. D16RUS77B-D.

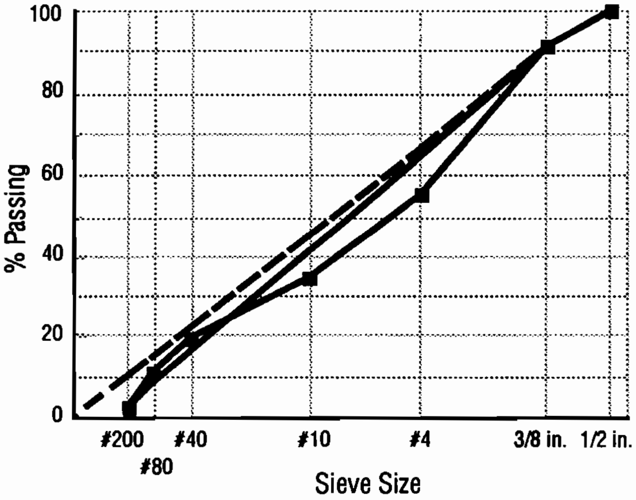

Fig B.22. D16RUS77-D.

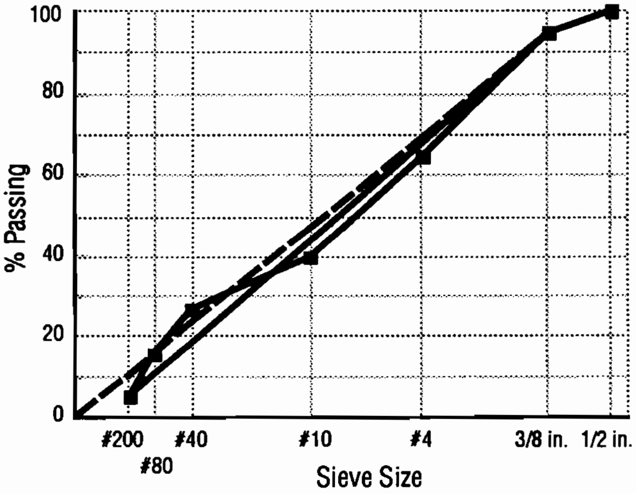

Fig B.24. D17BSH21-D.

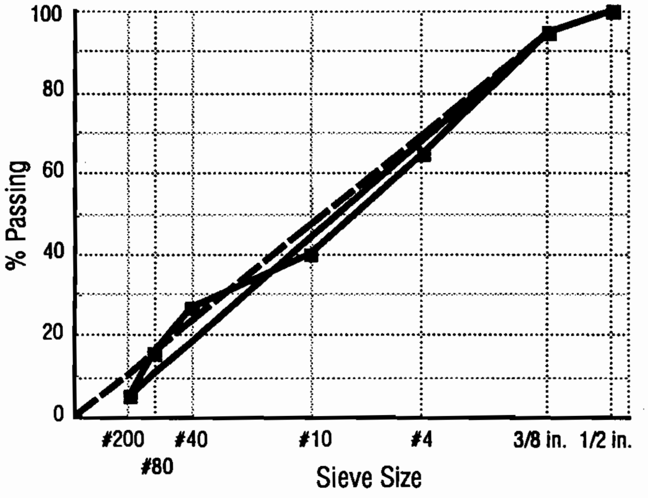

Fig B.25. D17BSH36-D.

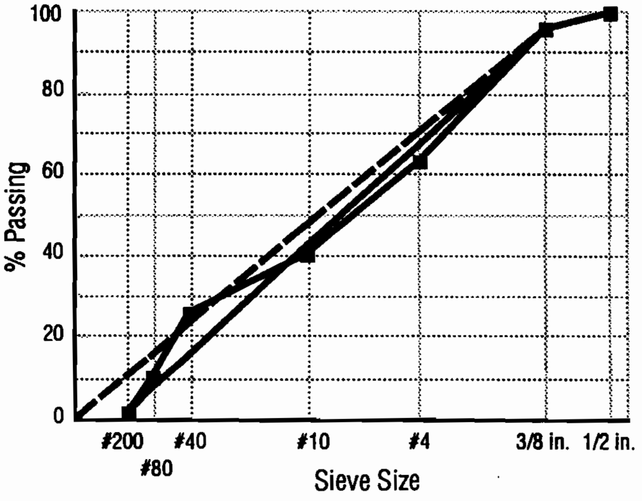

Fig B.27. D21CFM14-D.

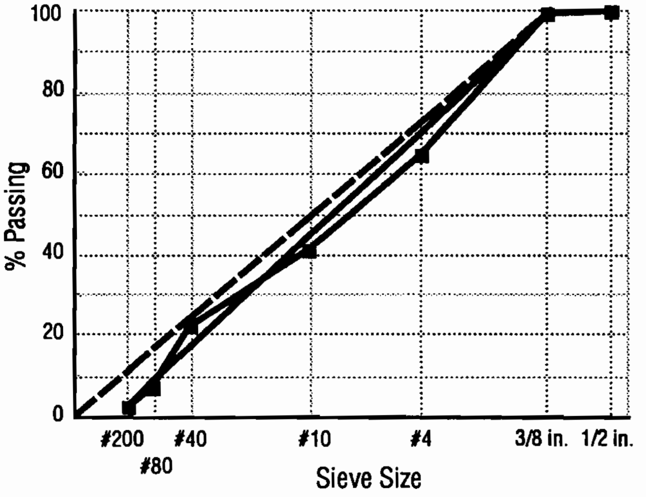

Fig B.26. D19CUS59-D.

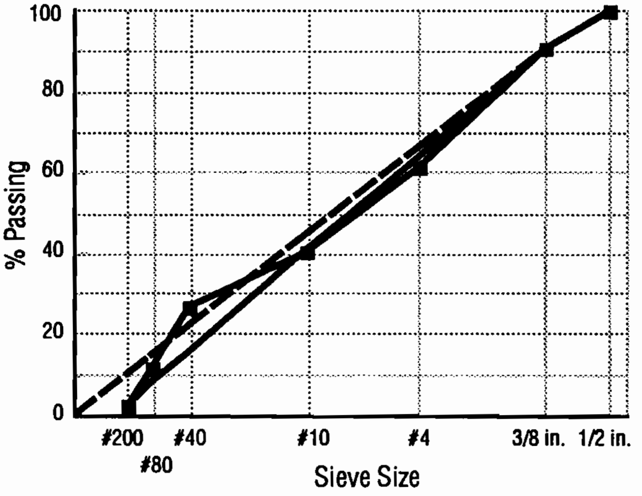

Fig B.28. D21HUS83-D.

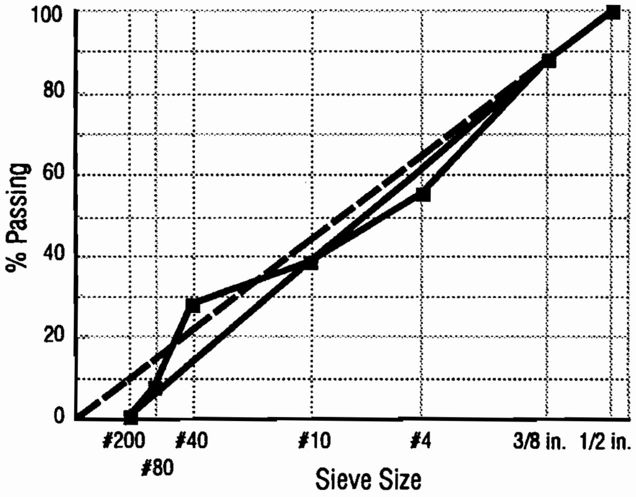

Fig B.29. D21SFM75-D.

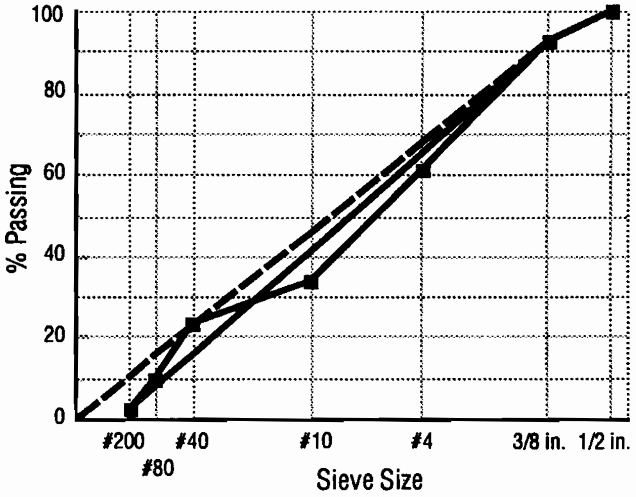

Fig B.31. D23LU190-D.

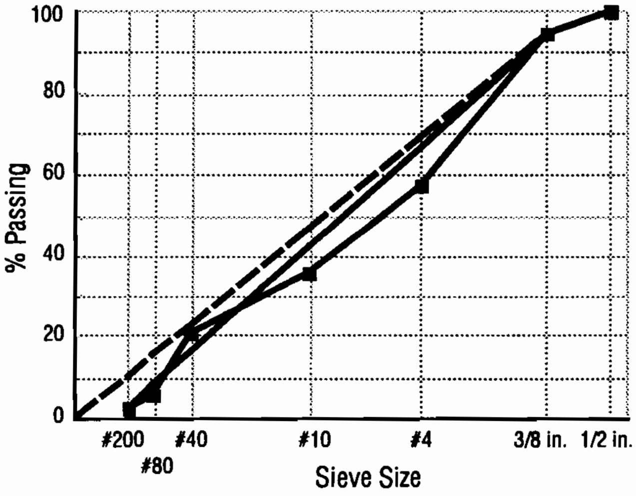

Fig B.30. D23BFM45-D.

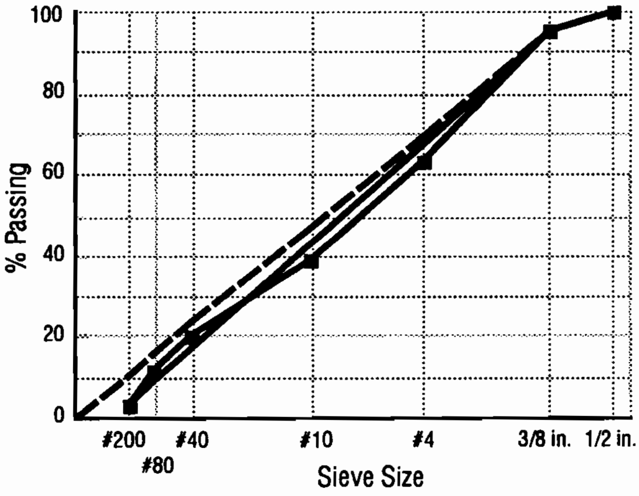

Fig B.32. D24CUS62-D.

APPENDIX C. DESIGN TRENDS

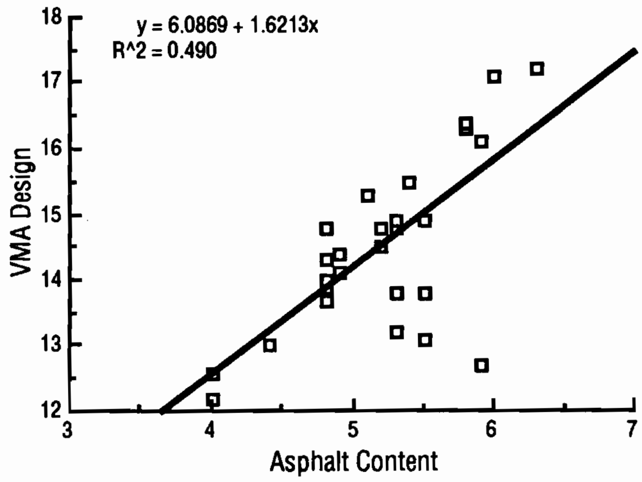

Fig C.1. VMA versus C & D asphalt content.

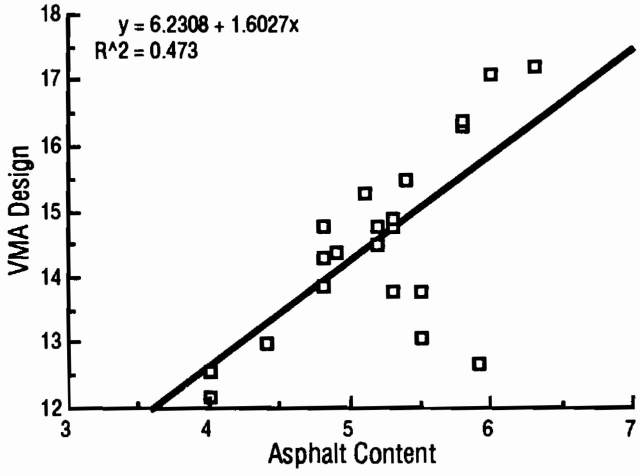

Fig C.3. VMA versus D asphalt content.

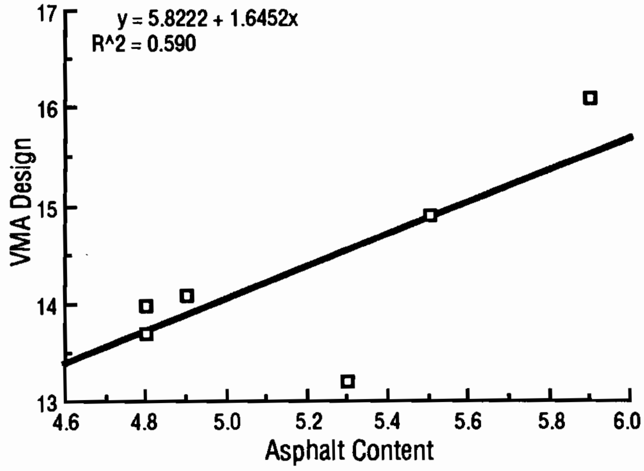

Fig C.2. VMA versus C asphalt content.

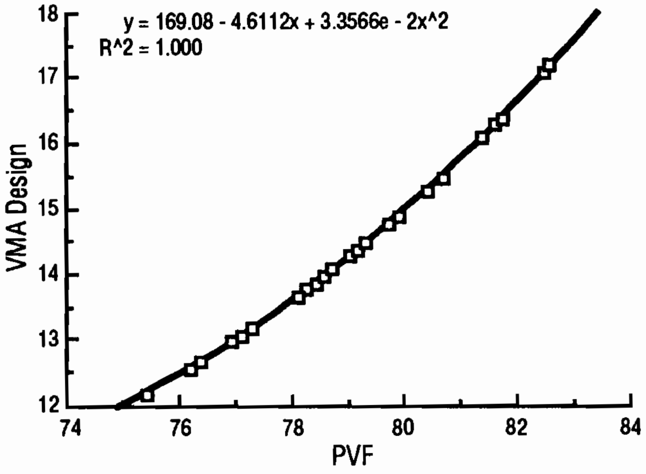

Fig C.4. VMA versus C & D PVF.

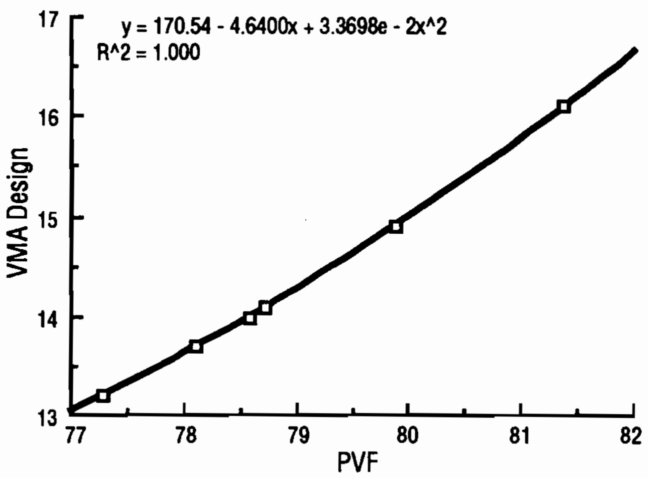

Fig C.5. VMA versus C PVF.

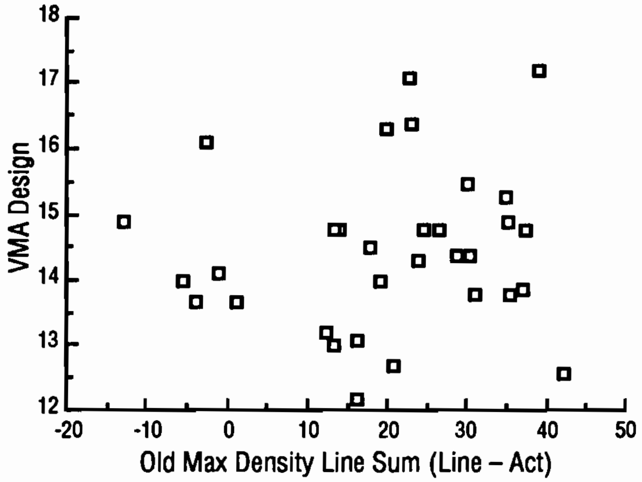

Fig C.7. C & D OLDSUM(L-A).

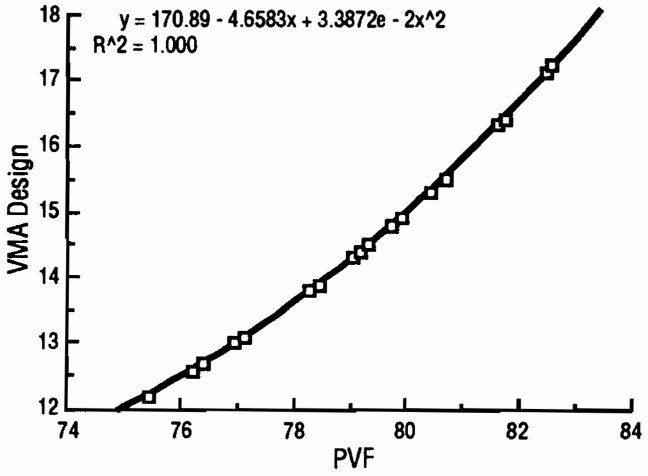

Fig C.6. VMA versus D PVF.

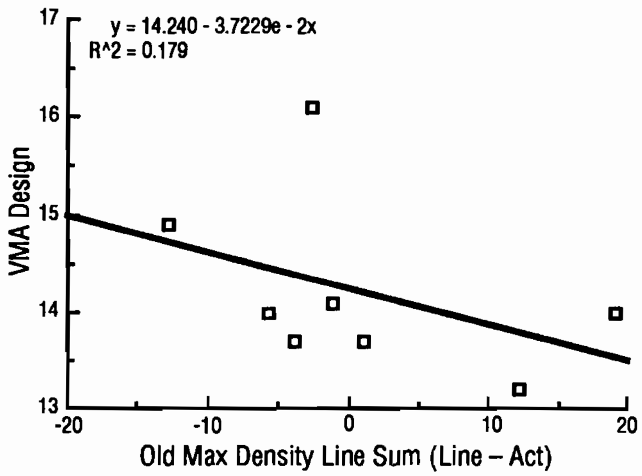

Fig C.8. VMA versus C OLDSUM(L-A).

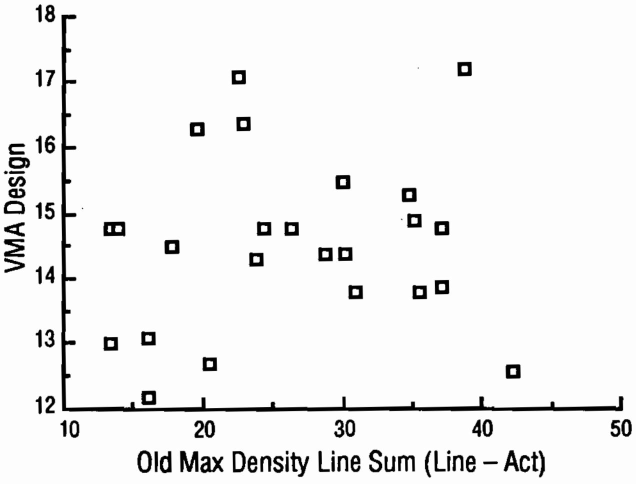

Fig C.9. VMA versus D OLDSUM(L-A).

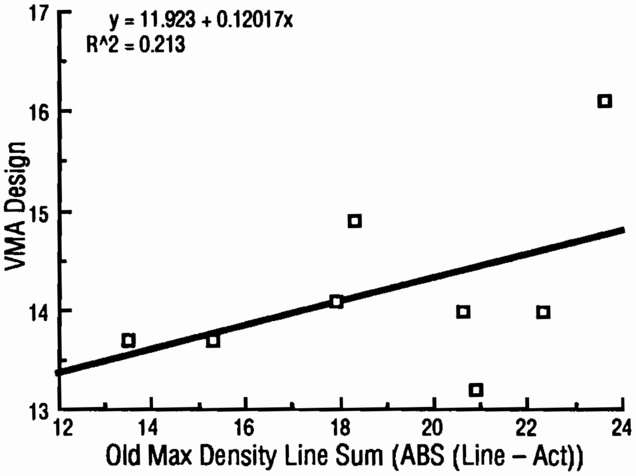

Fig C.11. VMA versus C OLDSUMABS(L-A).

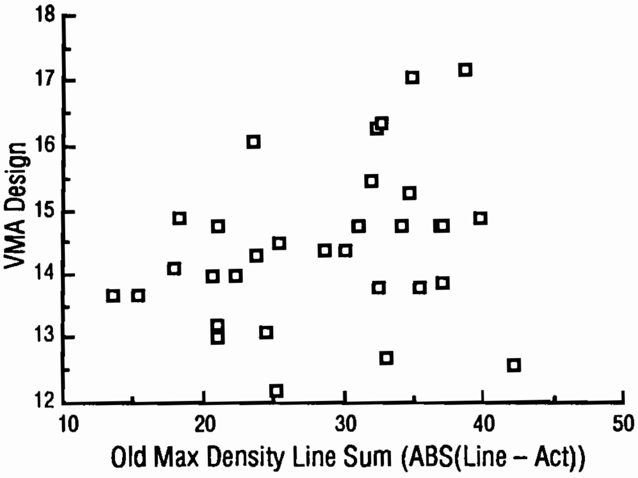

Fig C.10. VMA versus C&D OLDSUMABS(L-A).

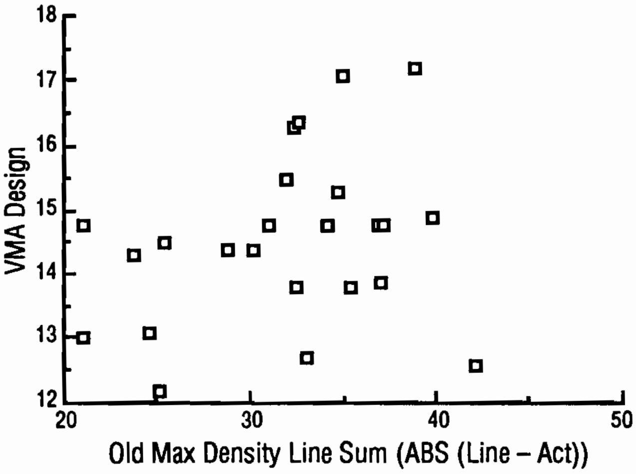

Fig C.12. VMA versus D OLDSUMABS(L-A).

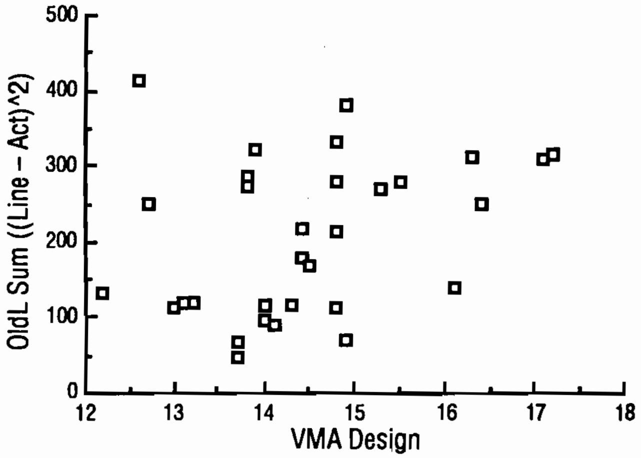

Fig C.13. VMA versus C&D OLDSUM(L-A)^2.

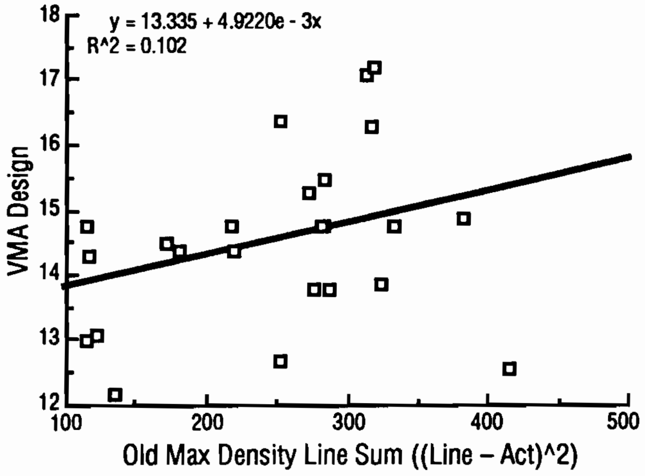

Fig C.15. VMA versus D OLDSUM(L-A)^2.

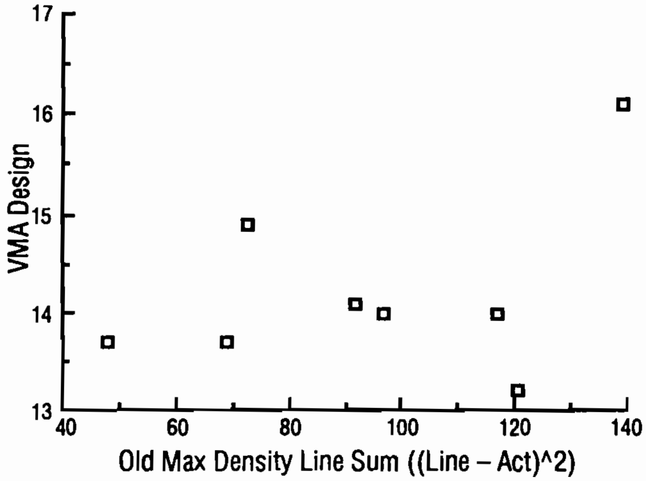

Fig C.14. VMA versus C OLDSUM(L-A)^2.

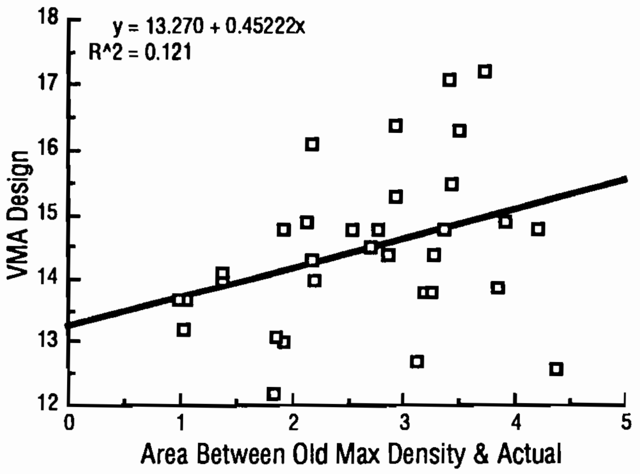

Fig C.16. VMA versus C&D AREA(OLD-ACT).

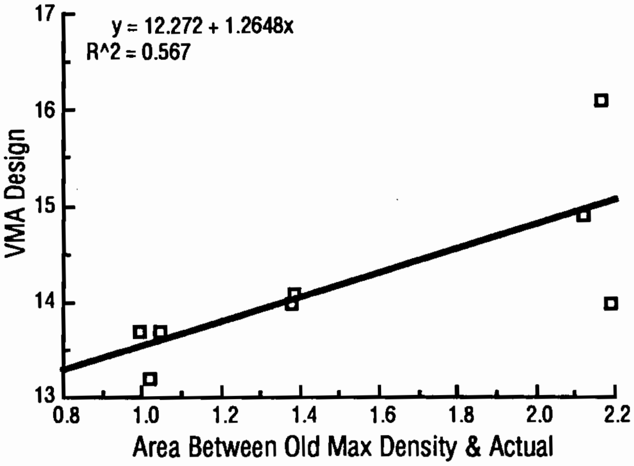

Fig C.17. VMA versus C AREA(OLD-ACT).

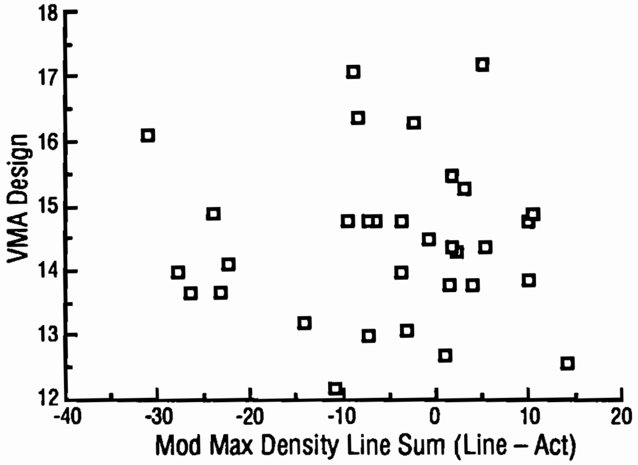

Fig C.19. C&D MODSUM(L-A).

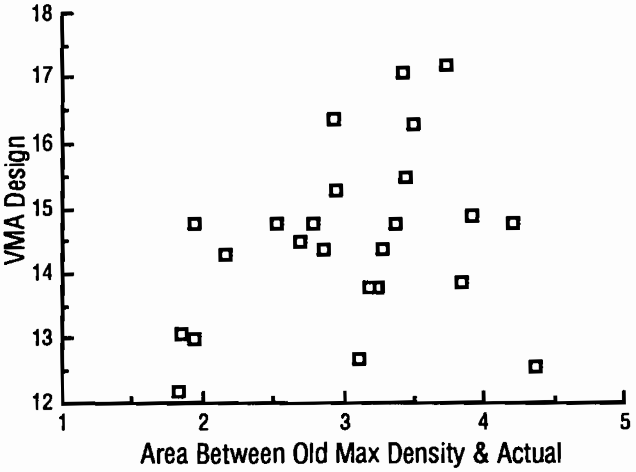

Fig C.18. VMA versus D AREA(OLD-ACT).

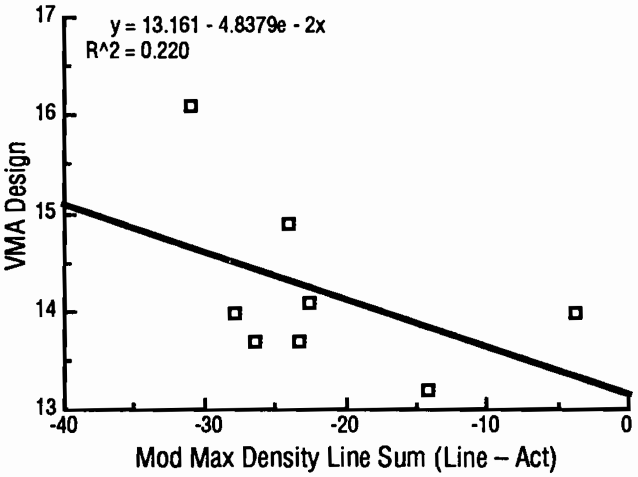

Fig C.20. VMA versus C MODSUM(L-A).

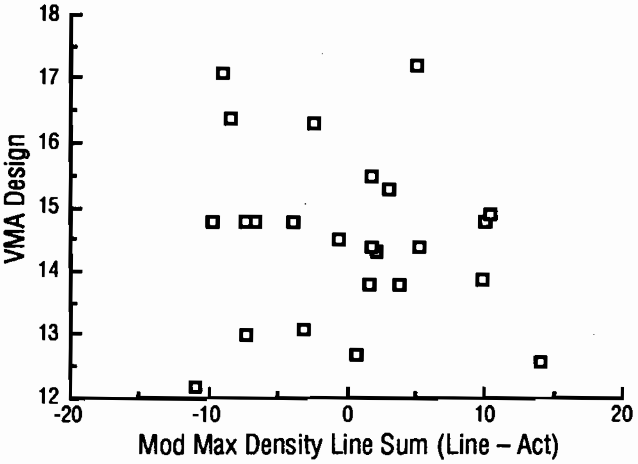

Fig C.21. VMA versus D MODSUM(L-A).

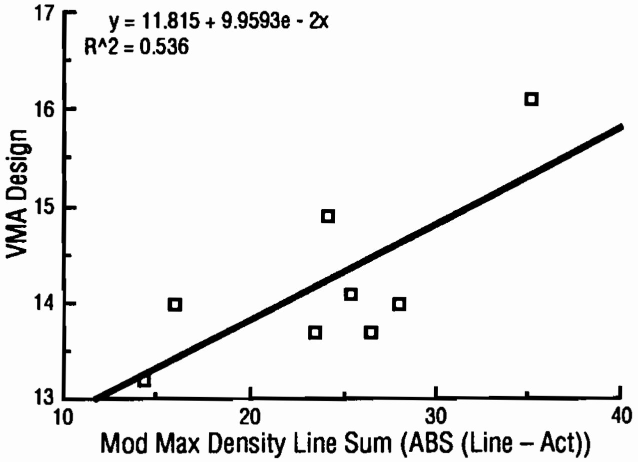

Fig C.23. VMA versus C MODSUMABS(L-A).

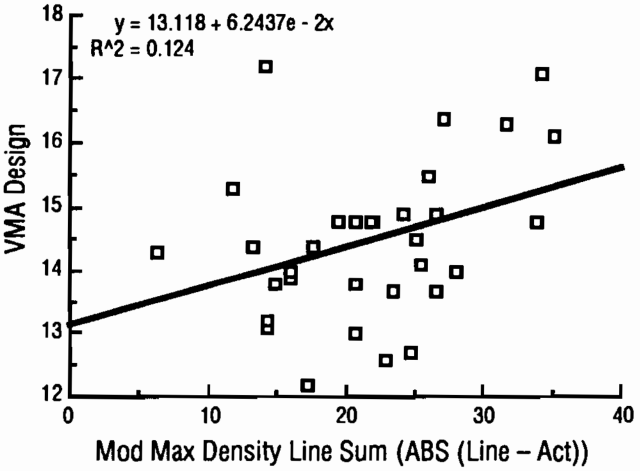

Fig C.22. VMA versus C&D MODSUMABS(L-A).

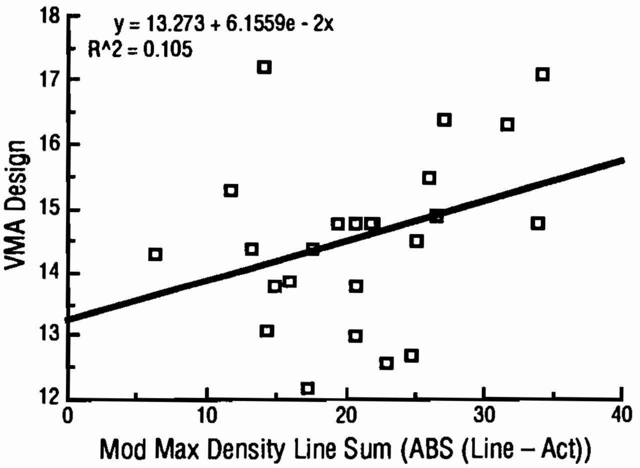

Fig C.24. VMA versus D MODSUMABS(L-A).

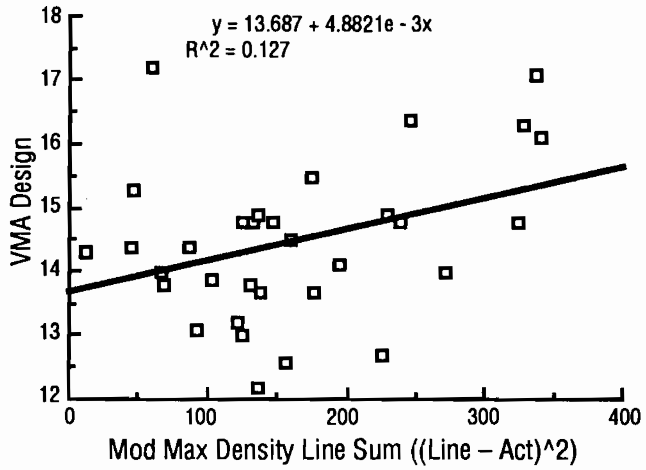

Fig C.25. VMA versus C&D MODSUM(L-A)^2.

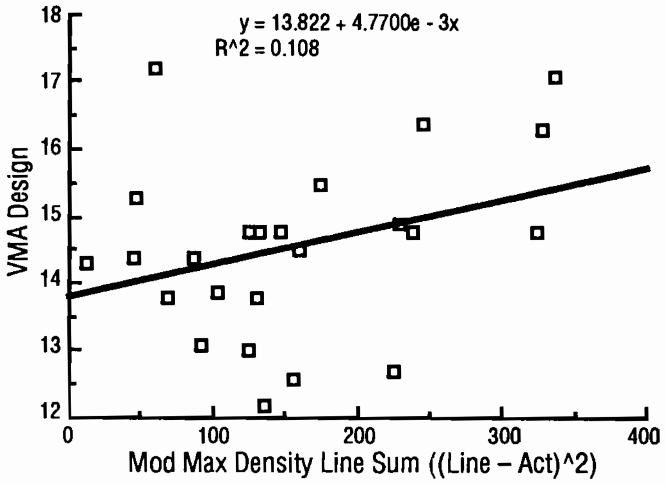

Fig C.27. VMA versus D MODSUM(L-A)^2.

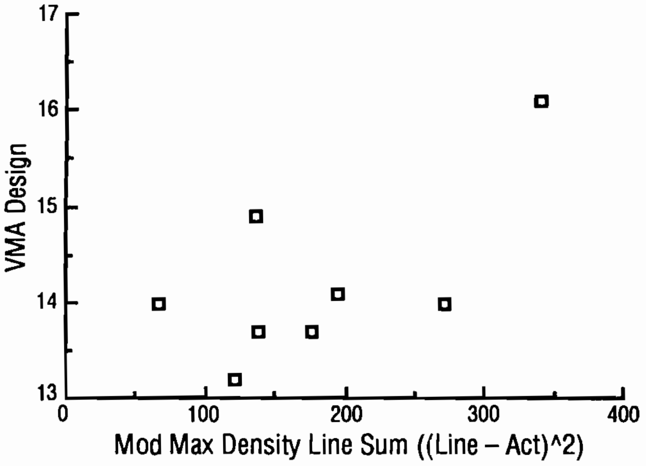

Fig C.26. VMA versus C MODSUM(L-A)^2.

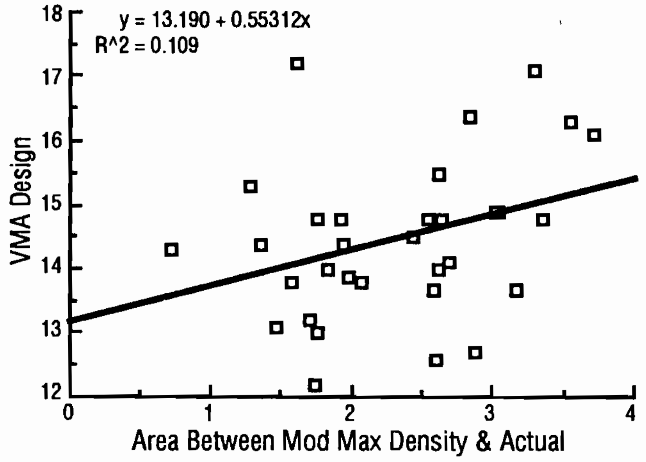

Fig C.28. VMA versus C&D AREA(MOD-ACT).

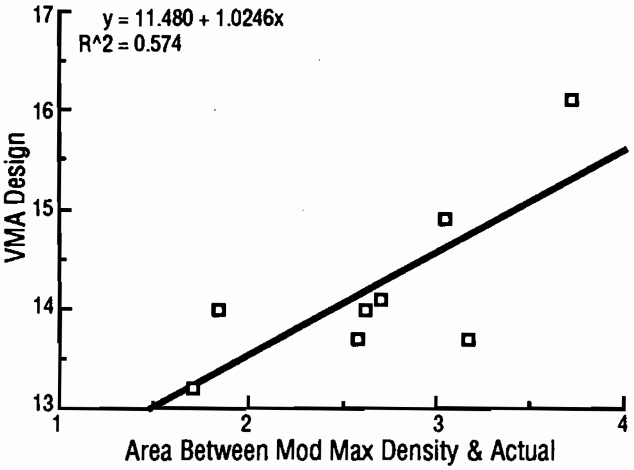

Fig C.29. VMA versus C AREA(MOD-ACT).

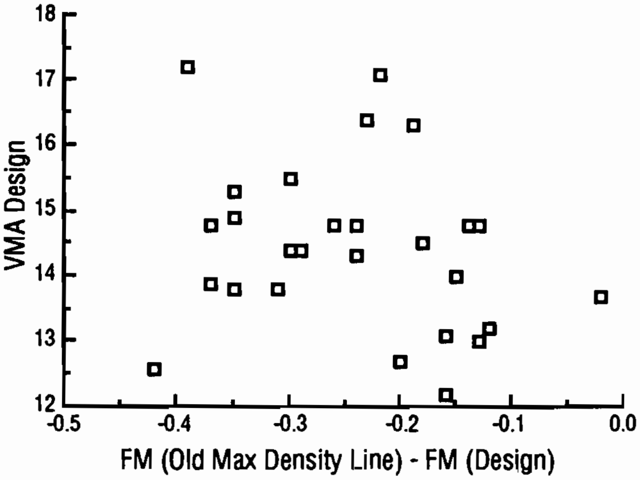

Fig C.31. VMA versus C&D FM(OLD-ACT).

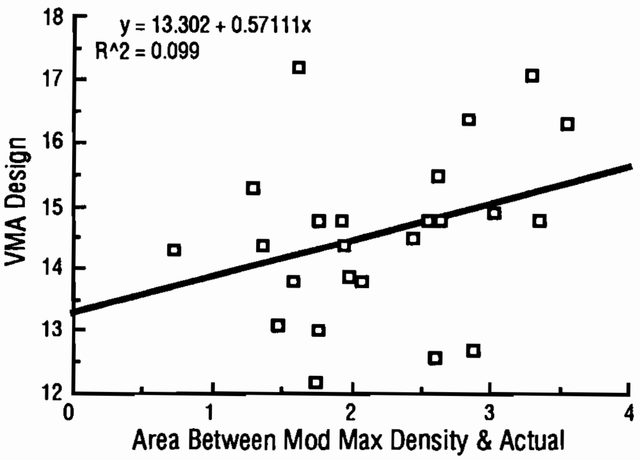

Fig C.30. VMA versus D AREA(MOD-ACT).

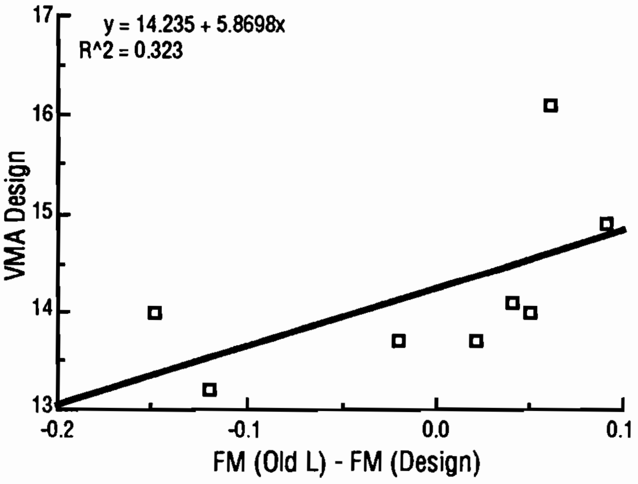

Fig C.32. VMA versus C FM(OLD-ACT).

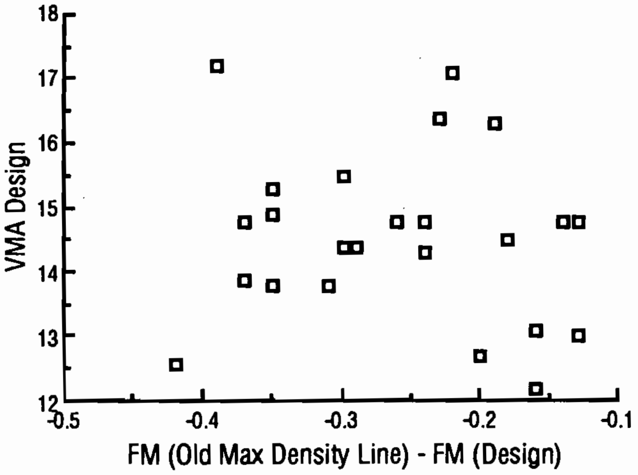

Fig C.33. VMA versus D FM(OLD-ACT).

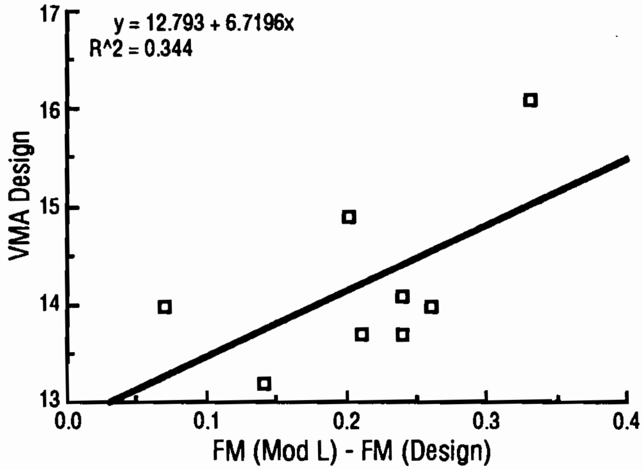

Fig C.35. VMA versus C FM(MOD-ACT).

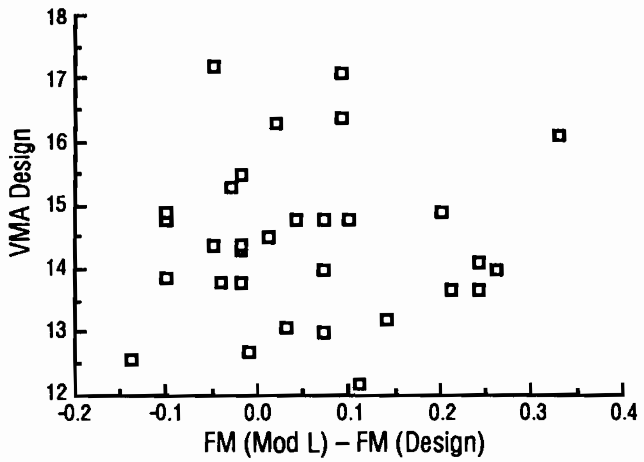

Fig C.34. VMA versus C&D FM(MOD-ACT).

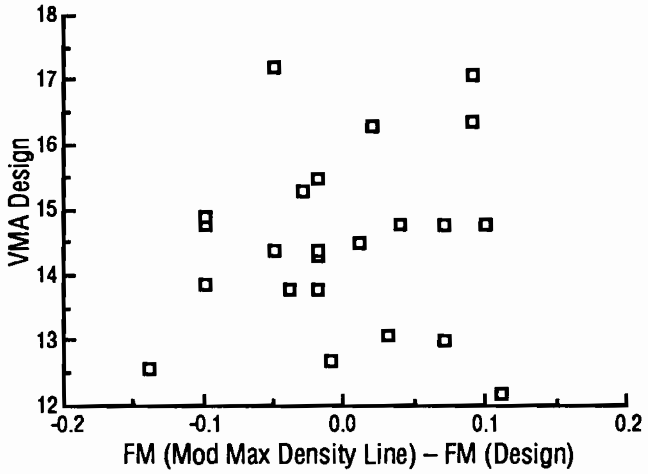

Fig C.36. VMA versus D FM(MOD-ACT).

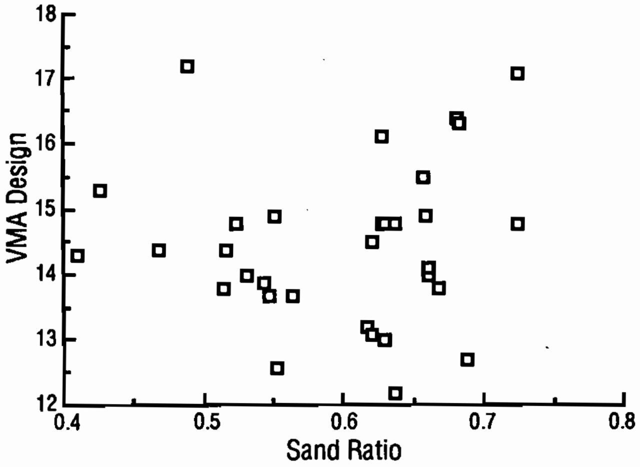

Fig C.37. VMA versus C&D SAND RATIO.

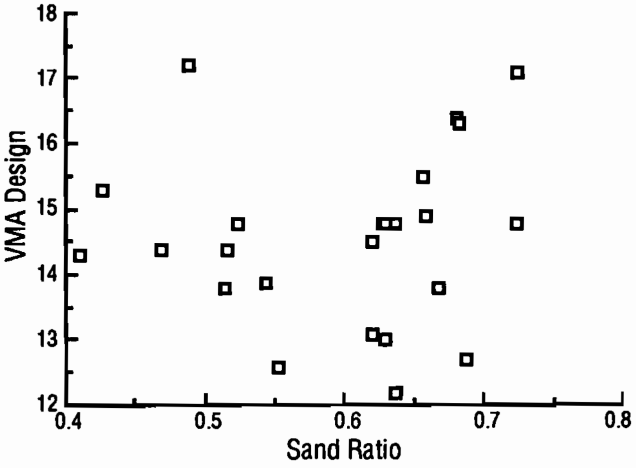

Fig C.39. VMÅ versus D SAND RATIO.

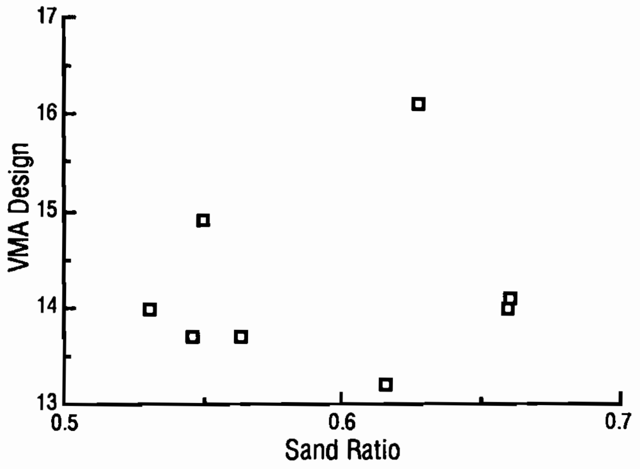

Fig C.38. VMÅ versus C SAND RATIO.

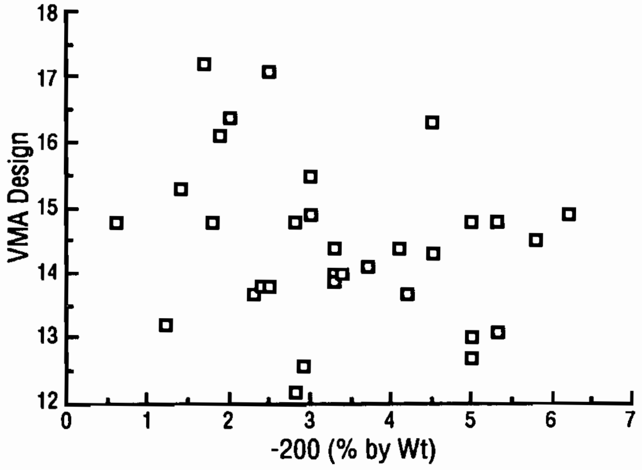

Fig C.40. VMA versus C&D-#200.

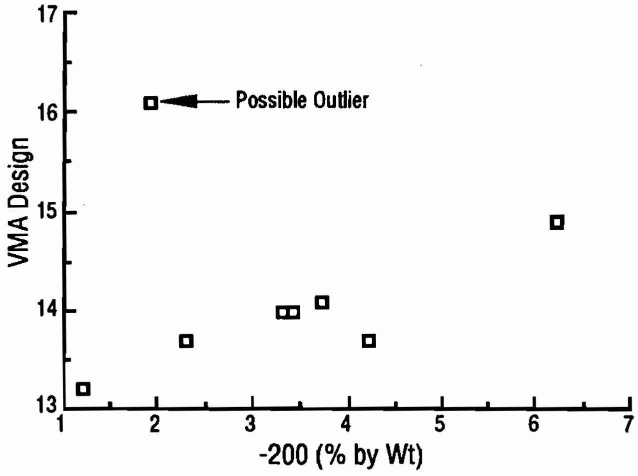

Fig C.41. VMA versus C-#200.

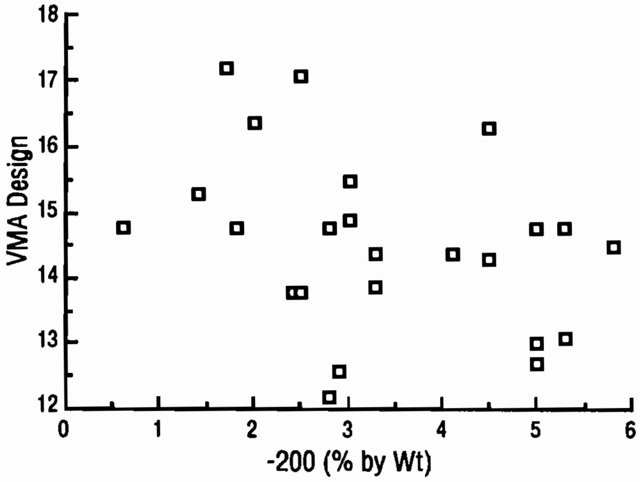

Fig C.43. VMA versus D-#200.

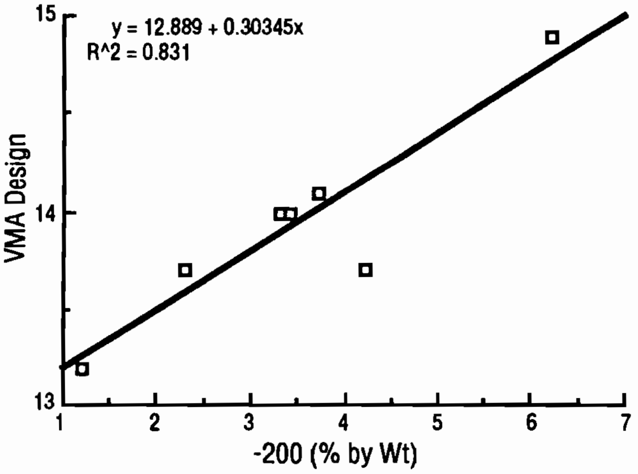

Fig C.42. VMA versus C-#200(-OUTLIER).

APPENDIX D. DESIGN MIXTURES—VMA AND AGGREGATE TYPE

TABLE D.1. DESIGN MIXTURES—VMA AND AGGREGATE TYPE

		Aggregate Type			
Project	VMA	Coarse	Intermed	Screenings	Field Sand
C1LMSH19	14.9	Sandstone	Sandstone	Sandstone	River Sand
C5LUUS84	14.0	Caliche		Limestone	Sil Sand
C14BUS28	14.1	Sandstone		Limestone	Silica
C16JUS28A	13.7	Limestone	Limestone	Limestone	
C16JUS28B	13.7	Limestone	Limestone	Limestone	
C18DIH63	13.2	Limestone	Pea Gravel		
C19MUS59	16.1	Sil Gravel	Sil Gravel	Sil Gravel	
C19PUS59	14.0	Sil Gravel	Sil Gravel	Sil Gravel	
D1FNUS82	16.3	Sandstone		Sandstone	
D1HUSH50	14.5	Sandstone		Sandstone	
D1LMUS82	16.4	Sandstone		Sandstone	
D3WUS82	17.1	Limestone	Sandstone	Limestone	
D4CUS60	14.3	Limestone		Limestone	
D5GAFM65	13.9	Limestone		Limestone	Sil Sand
D5LUUS84	14.4	Caliche		Limestone	Sil Sand
D5GAUS84	17.2	Caliche		Caliche	
D10ANU28	15.5	Sandstone		Sandstone	
D12GFM17	14.9	Limestone		Limestone	
D12MFM13	13.1	Sandstone	Limestone	Limestone	
D12MIH45	12.7	Limestone	Limestone	Limestone	
D16NSH44	15.3	Sandstone	Cr Gravel	Dol Gravel	
D16RUS77	14.8	Cr Gravel	Cr Gravel		
D16RUS77B	14.8	Cr Gravel	Cr Gravel		
D17BSH21	14.8	Limestone		Limestone	
D17BSH36	13.0	Limestone		Limestone	
D19CUS59	13.8	Sandstone	Sandstone	Sandstone	
D21CFM14	14.8				
D21HUS83	12.2	Gravel	Gravel	Conc Sand	
D21SFM75	14.8	Gravel	Gravel	Conc Sand	
D23BFM45	12.6	Limestone			
D23LU190	13.8	Limestone	Limestone	Limestone	Sil Sand
D24CUS62	14.4				

APPENDIX E. FIELD MIXTURES—FIELD DATA AND DEVIATION DATA

TABLE E.1. TYPE C MIXTURES

Sieves (% P)	C1LMSH19-E	C14BUS28-E
7/8	100.0	100.0
5/8	100.0	99.8
3/8	83.8	77.6
4	59.6	59.3
10	41.3	38.1
40	23.9	25.4
80	13.1	12.7
200	4.6	4.5
Sieves (% P)	**Old Max Den**	**Old Max Den**
7/8		
5/8		99.8
3/8	83.8	79.3
4	61.3	58.0
10	41.5	39.3
40	20.6	19.4
80	14.0	13.2
200	9.4	8.9
0	0	0
Sieves (% P)	**Mod Max Den**	**Mod Max Den**
7/8		
5/8		99.8
3/8	83.8	78.3
4	59.8	56.0
10	38.8	36.4
40	16.4	15.6
80	9.4	9.1
200	4.6	4.5
VMA	13.6	12
PVF	82.9	79.8
Asphalt Content	5.3	4.6
Old L Sum (Line-Act)	4.2	0.6
Old L Sum (ABS(Line - Act))	10.9	15.0
Old L Sum ((Line - Act)^2)	38.29	60.28
Area (Old - Act)	0.716	1.003
Mod L Sum (Line - Act)	-13.5	-17.6
Mod L Sum (ABS(Line - Act))	14.0	19.1
Mod L Sum ((Line - Act)^2)	76.14	122.59
Area (Mod - Act)	1.355	2.005
Sand Ratio (Fine/Total)	0.526	0.621

TABLE E.2. TYPE D MIXTURES

Sieves (%P)	D1FNUS82-E	D1HUSH50-E	D1LMUS82-E
1/2	100.0	100.0	100.0
3/8	95.1	95.2	94.7
4	57.6	56.1	57.1
10	40.1	37.0	36.4
40	27.9	25.8	24.7
80	14.5	17.6	12.4
200	5.5	6.2	1.6

Sieves (%P)	Old Max Den	Old Max Den	Old Max Den
1/2			
3/8	95.1	95.2	94.7
4	69.5	69.6	69.2
10	47.1	47.1	46.9
40	23.3	23.3	23.2
80	15.8	15.9	15.8
200	10.7	10.7	10.6
0	0	0	0

Sieves (%P)	Mod Max Den	Mod Max Den	Mod Max Den
1/2			
3/8	95.1	95.2	94.7
4	68.0	68.2	66.5
10	44.2	44.6	41.8
40	19.0	19.5	15.6
80	11.1	11.6	7.4
200	5.5	6.2	1.6
VMA Plant Mix-Lab Mold	14.3	13.6	14.5
PVF	85.9	83.6	80.8
Asphalt Content	5.5	5.3	5.6
Old L Sum (Line-Act)	20.7	24.1	33.5
Old L Sum (ABS(Line-Act))	30.0	32.4	36.5
Old L Sum ((Line-Act)^2)	240.81	315.95	351.49
Area (Old-Act)	3.166	3.837	3.807
Mod L Sum (Line-Act)	2.0	7.6	0.7
Mod L Sum (ABS(Line-Act))	26.9	32.0	28.9
Mod L Sum ((Line-Act)^2)	217.29	280.65	225.24
Area (Mod-Act)	2.970	3.523	2.997
Sand Ratio	0.648	0.637	0.663

TABLE E.2. TYPE D MIXTURES

Sieves (%P)	D3WUS82-E	D5GAUS84-E	D10ANU28-E
1/2	100.0	100.0	100.0
3/8	98.8	98.4	94.8
4	61.7	64.7	58.5
10	41.6	39.2	35.9
40	29.4	21.9	26.2
80	15.3	11.8	14.4
200	4.1	3.7	4.3

Sieves (%P)	Old Max Den	Old Max Den	Old Max Den
1/2			
3/8	98.8	98.4	94.8
4	72.3	72.0	69.3
10	48.9	48.7	47.0
40	24.2	24.1	23.3
80	16.5	16.4	15.8
200	11.1	11.0	10.6
0	0	0	0

Sieves (%P)	Mod Max Den	Mod Max Den	Mod Max Den
1/2			
3/8	98.8	98.4	94.8
4	70.1	69.7	67.4
10	45.0	44.6	43.3
40	18.3	17.9	17.8
80	9.9	9.6	9.8
200	4.1	3.7	4.3
VMA Plant Mix-Lab Mold	13.9	15	14.7
PVF	74.6	77.4	85.7
Asphalt Content	4.9	5.2	5.4
Old L Sum (Line-Act)	20.9	30.9	26.7
Old L Sum (ABS(Line-Act))	31.1	30.9	32.6
Old L Sum ((Line-Act)^2)	241.10	222.94	291.39
Area (Old-Act)	3.035	3.228	3.549
Mod L Sum (Line-Act)	-4.7	4.2	3.4
Mod L Sum (ABS(Line-Act))	28.2	16.7	29.3
Mod L Sum ((Line-Act)^2)	233.96	75.53	226.18
Area (Mod-Act)	2.875	1.810	3.054
Sand Ratio	0.673	0.512	0.695

TABLE E.2. TYPE D MIXTURES

Sieves (%P)	D12GFM17-E	D12MFM13-E	D12MIH45-E
1/2	100.0	100.0	100.0
3/8	93.2	96.2	94.0
4	55.7	63.8	54.9
10	36.4	41.2	40.1
40	25.3	29.7	27.9
80	9.9	13.4	9.5
200	4.3	6.7	3.6
Sieves (%P)	**Old Max Den**	**Old Max Den**	**Old Max Den**
1/2			
3/8	93.2	96.2	94.0
4	68.2	70.3	68.8
10	46.2	47.7	46.6
40	22.9	23.6	23.1
80	15.5	16.0	15.7
200	10.5	10.8	10.5
0	0	0	0
Sieves (%P)	**Mod Max Den**	**Mod Max Den**	**Mod Max Den**
1/2			
3/8	93.2	96.2	94.0
4	66.3	69.1	66.7
10	42.7	45.3	42.7
40	17.6	20.1	17.2
80	9.8	12.2	9.2
200	4.3	6.7	3.6
VMA Plant Mix-Lab Mold	12.5	12.2	12.9
PVF	79.3	74.5	63
Asphalt Content	4.9	5.3	5.2
Old L Sum (Line-Act)	31.5	13.7	28.6
Old L Sum (ABS(Line-Act))	36.4	25.9	38.2
Old L Sum ((Line-Act)^2)	324.92	145.95	343.00
Area (Old-Act)	3.748	2.306	3.576
Mod L Sum (Line-Act)	9.0	-1.3	3.4
Mod L Sum (ABS(Line-Act))	24.7	20.2	25.4
Mod L Sum ((Line-Act)^2)	209.71	138.80	259.31
Area (Mod-Act)	2.951	2.109	3.122
Sand Ratio	0.654	0.666	0.665

TABLE E.2. TYPE D MIXTURES

Sieves (%P)	D19CUS59-E	D23LU190-E
1/2	100.0	100.0
3/8	96.4	94.3
4	62.8	60.9
10	41.6	34.1
40	22.2	24.9
80	8.8	16.9
200	3.6	4.6
Sieves (%P)	**OLD MAX DEN**	**OLD MAX DEN**
1/2		
3/8	96.4	94.3
4	70.5	68.9
10	47.7	46.7
40	23.6	23.1
80	16.1	15.7
200	10.8	10.6
0	0	0
Sieves (%P)	**MOD MAX DEN**	**MOD MAX DEN**
1/2		
3/8	96.4	94.3
4	68.3	67.1
10	43.6	43.3
40	17.5	18.0
80	9.3	10.1
200	3.6	4.6
VMA Plant Mix-Lab Mold	12.8	12.3
PVF	75.2	78.5
Asphalt Content	4.7	5.2
Old L Sum (Line-Act)	29.8	23.7
Old L Sum (ABS(Line-Act))	29.8	29.6
Old L Sum ((Line-Act)^2)	203.80	264.22
Area (Old-Act)	2.805	3.330
Mod L Sum (Line-Act)	3.4	1.8
Mod L Sum (ABS(Line-Act))	12.7	29.1
Mod L Sum ((Line-Act)^2)	56.64	216.81
Area (Mod-Act)	1.479	2.829
Sand Ratio	0.488	0.690

APPENDIX F. 0.45 POWER GRADATION CHARTS FOR FIELD MIXTURES

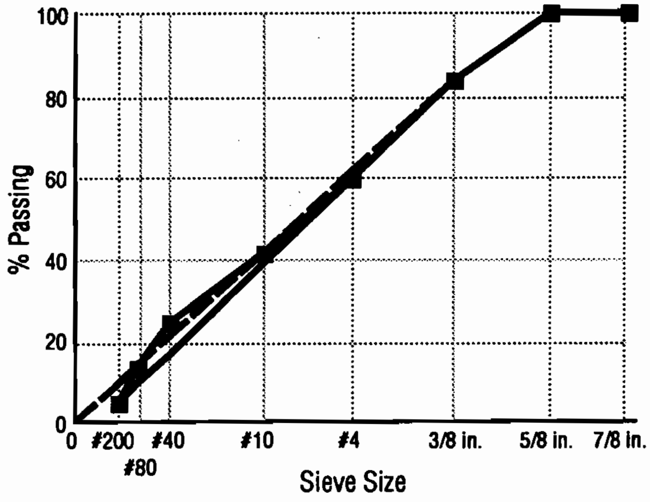

Fig F.1. CILMSH19-E.

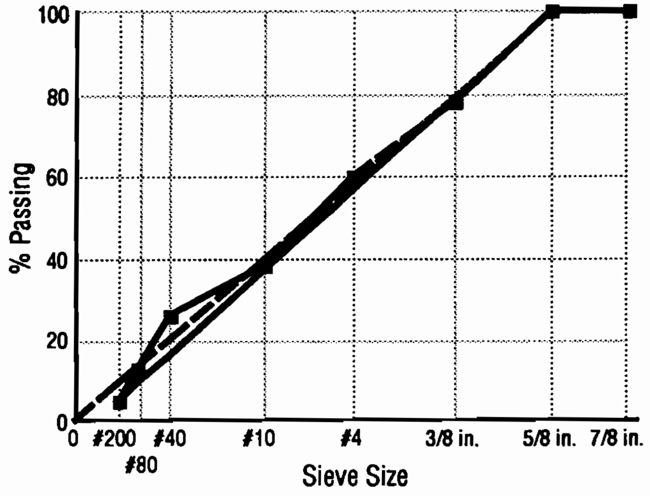

Fig F.2. C14BUS28-E.

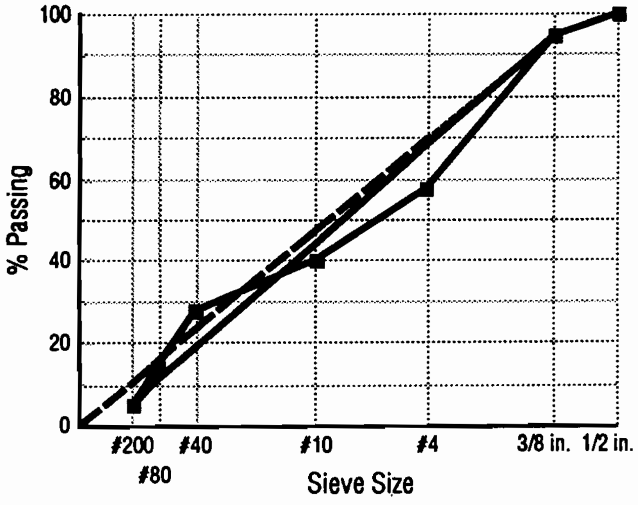

Fig F.3. D1FNUS82-E.

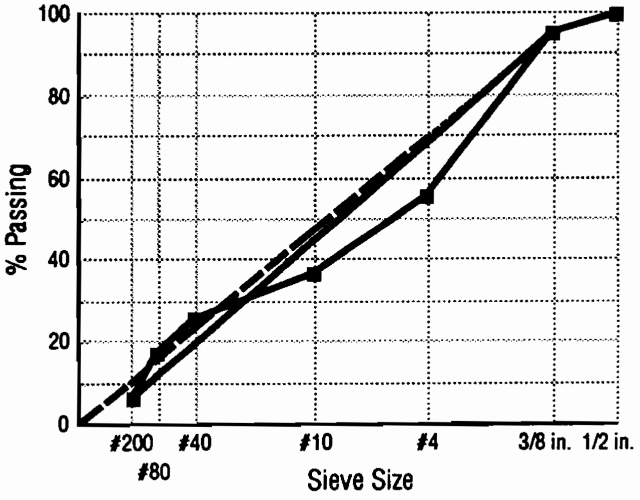

Fig F.4. D1HUSH50-E.

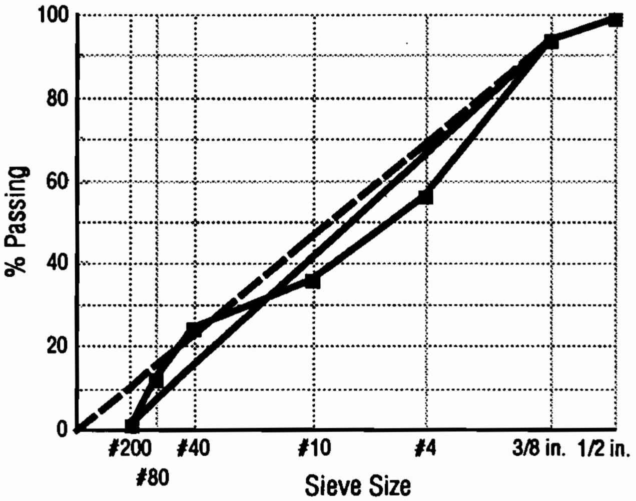

Fig F.5. D1LMUS82-E.

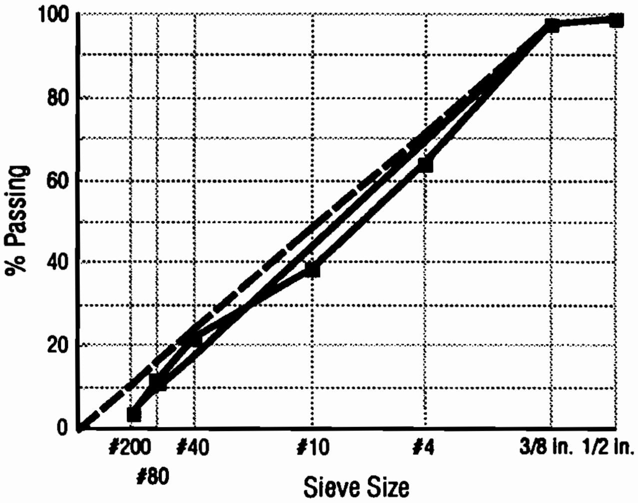

Fig F.7. D5GAUS84-E.

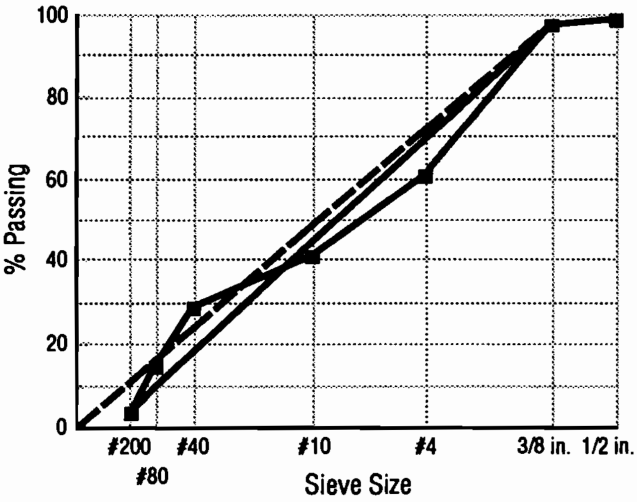

Fig F.6. D3WUS82-E.

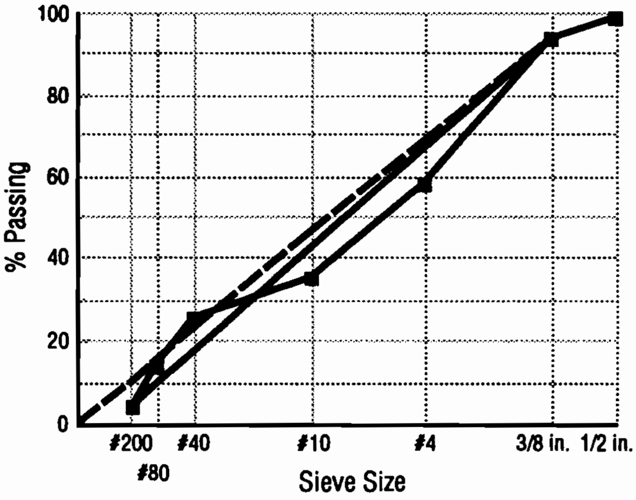

Fig F.8. D10ANU28-E.

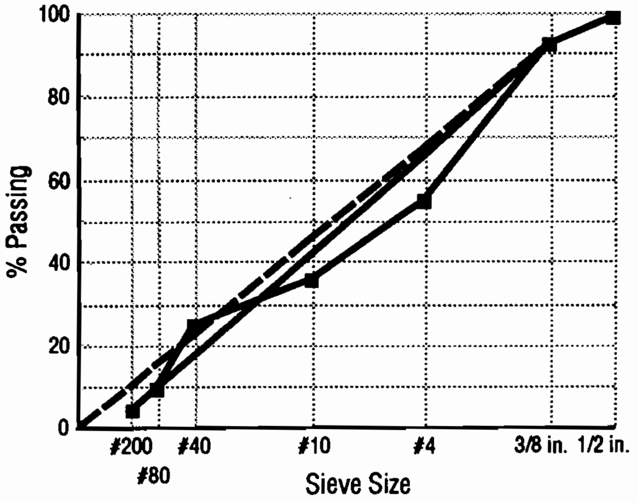

Fig F.9. D12GFM17-E.

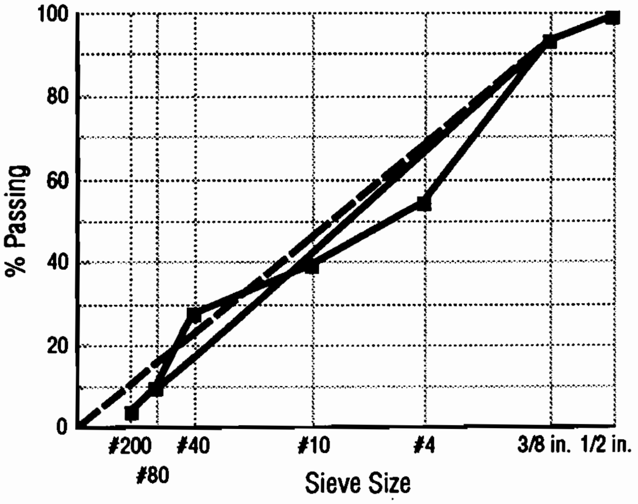

Fig F.11. D12MIH45-E.

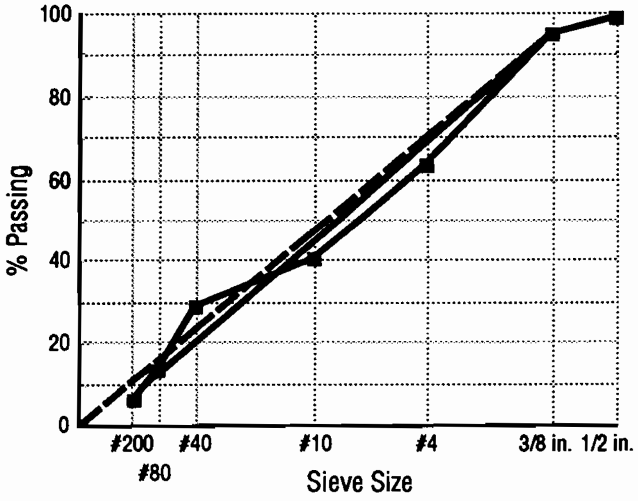

Fig F.10. D12MFM13-E.

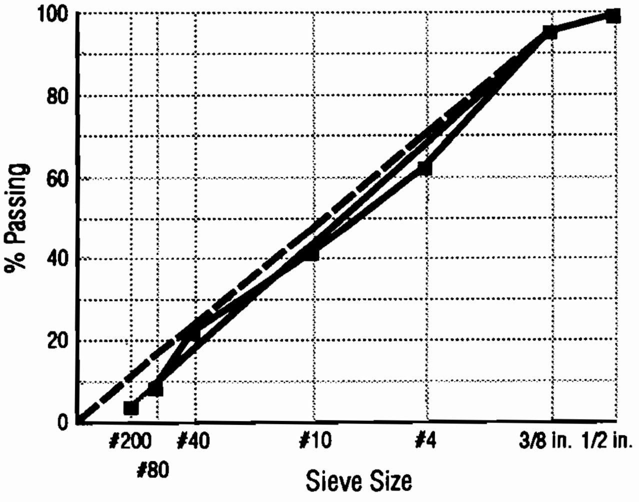

Fig F.12. D19CUS59-E.

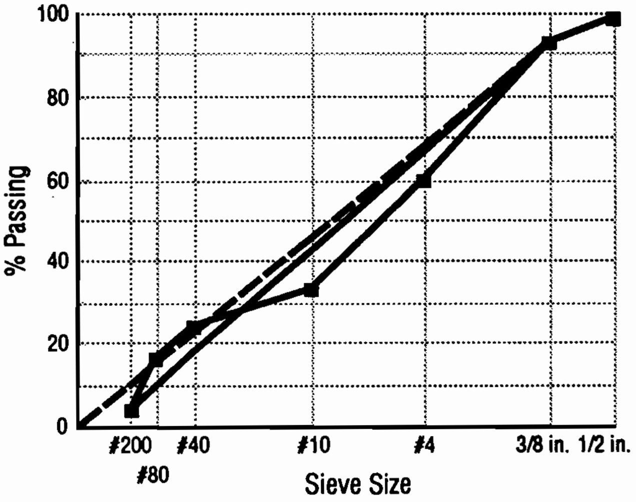

Fig F.13. D23LU190-E.

APPENDIX G. FIELD TRENDS

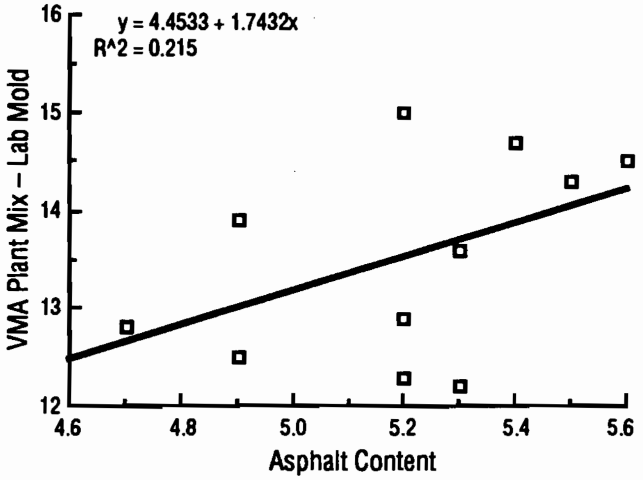

Fig G.1. VMA vs D asphalt content.

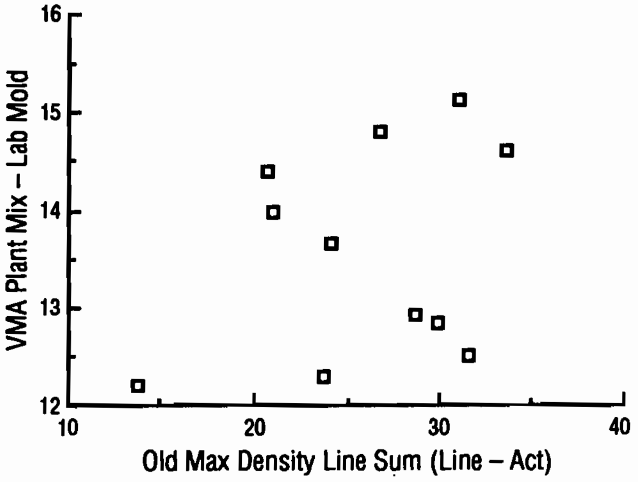

Fig G.3. VMA vs D OLDSUM(L – A).

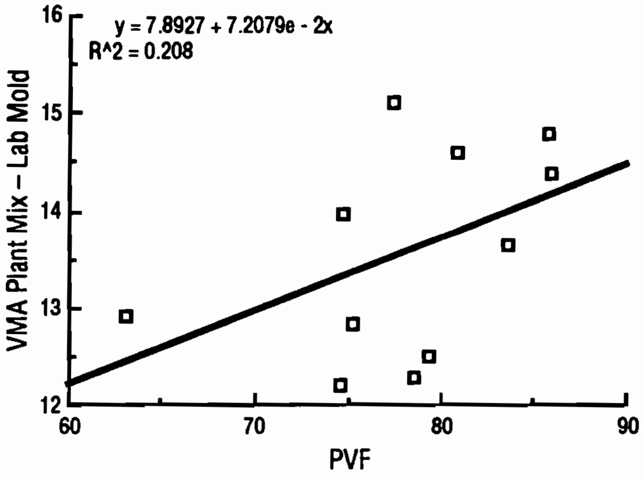

Fig G.2. VMA vs D PVF.

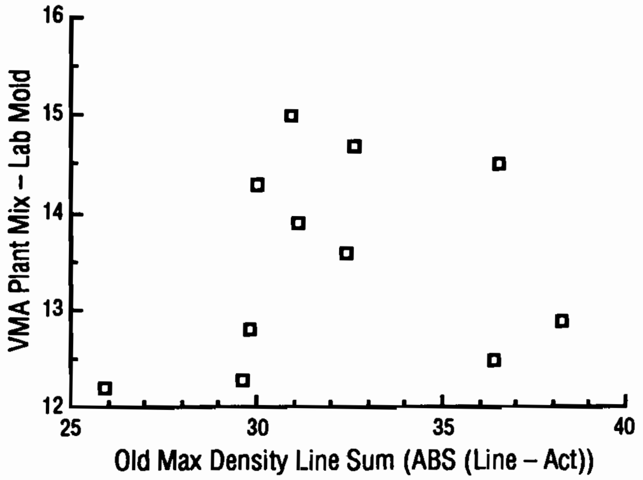

Fig G.4. VMA vs D OLDSUMABS(L – A).

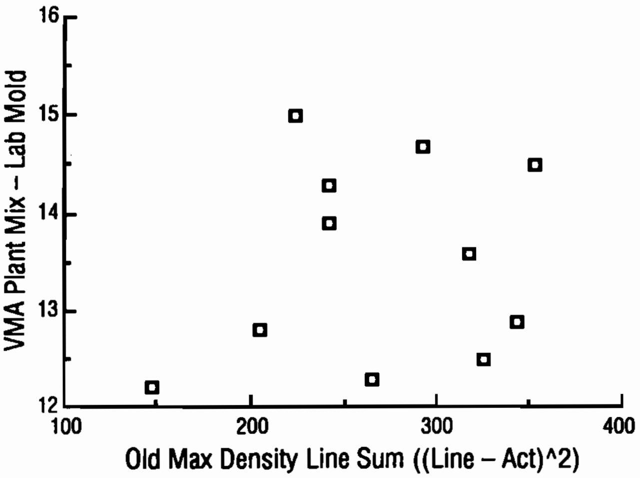

Fig G.5. VMA vs D OLDSUM(L – A)^2.

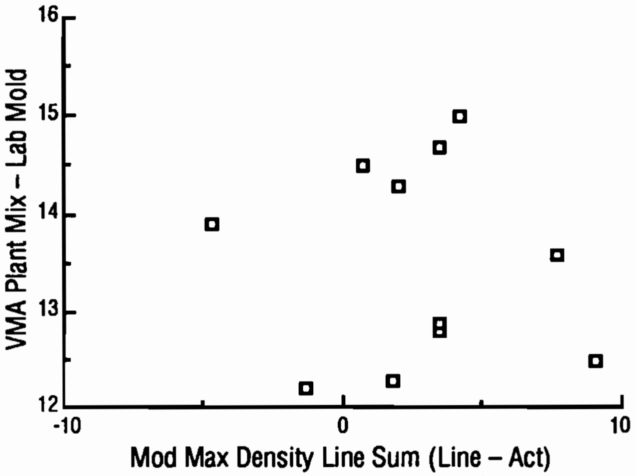

Fig G.7. VMA vs D MOD SUM(L – A).

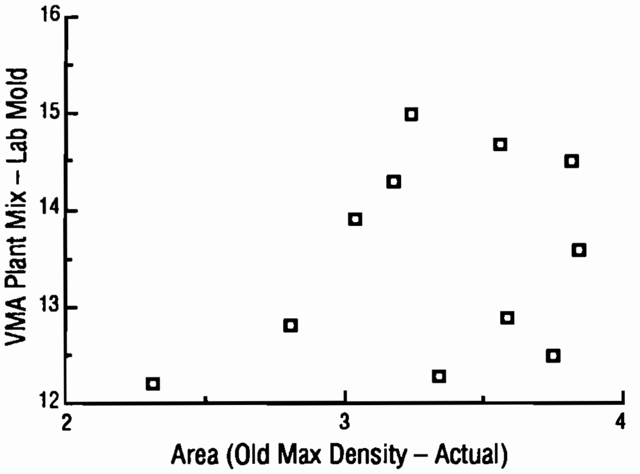

Fig G.6. VMA vs D AREA(OLD – ACT).

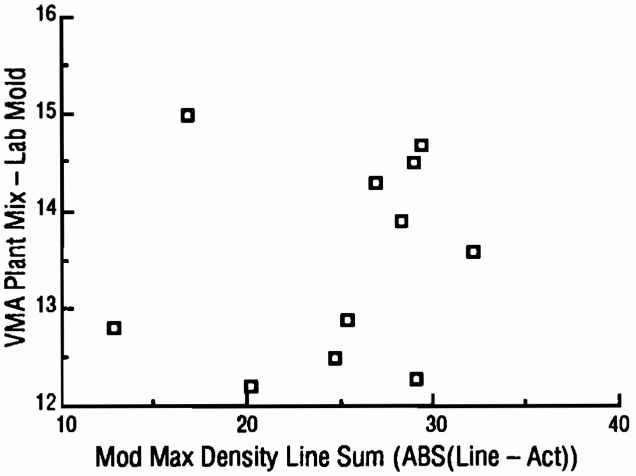

Fig G.8. VMA vs D MODSUMABS(L – A).

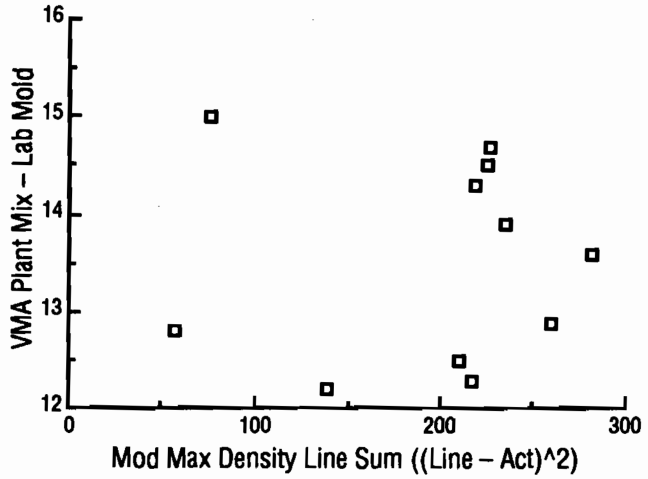

Fig G.9. VMA vs D MODSUM(L – A)^2.

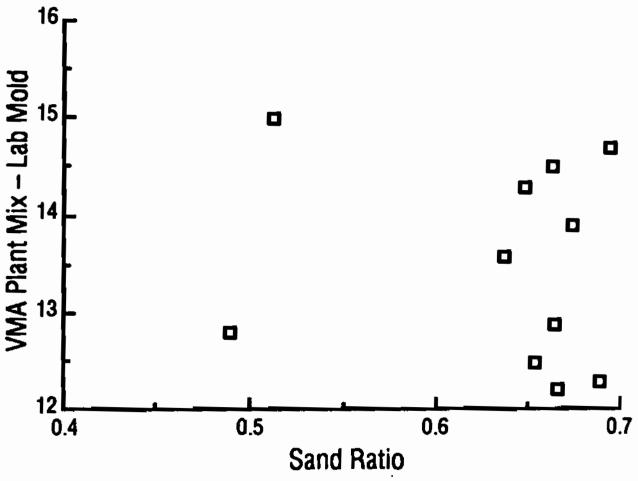

Fig G.11. VMA vs D SAND RATIO.

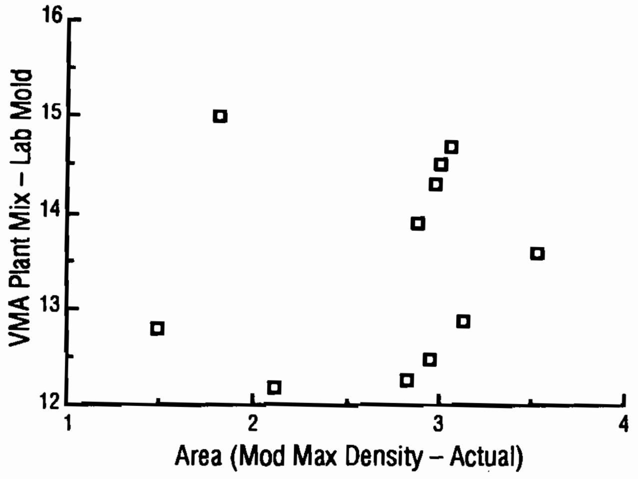

Fig G.10. VMA vs D AREA (MOD – ACT).

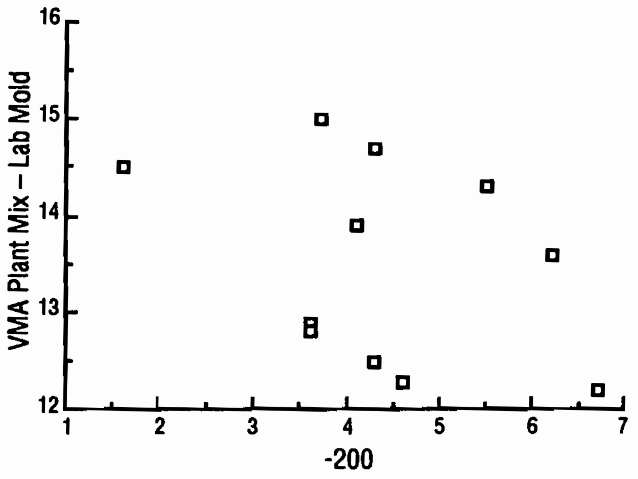

Fig G.12. VMA vs D -#200.

APPENDIX H. AGGREGATE GRADATION INFORMATION FOR FACTORIAL EXPERIMENTS

TABLE H.1. DISTRICT 6 DESIGN GRADATION INFORMATION

Gradation Data Design Grad.

Sieve	Coarse Rhyolite (%)	Scrns Fine (%)	Sand (%)	Comb Grad (%)
	56	37	7	100
+1/2	0.0	0.0	0.0	0.0
- 1/2 + 3/8	5.9	0.0	0.4	3.3
- 3/8 + #4	60.8	0.6	1.8	34.4
- #4 + #10	29.2	23.7	0.6	25.2
- #10 + #40	3.6	36.6	1.5	15.7
- #40 + #80	0.3	18.6	77.0	12.4
- #80 + #200	0.1	10.4	17.6	5.1
- #200	0.1	10.1	1.1	3.9
Total	100.0	100.0	100.0	100.0

Bulk Spgr Calc

+ #10	2.440	2.207	
- #10 + #80	2.389	2.389	
- #80		2.775	
Combined Ind	2.437	2.409	2.663
Combined Bulk Spgr =	2.441		

Max Den Calc's

Sieves	Sieves	Sieve ^0.45	Max Den Old	Max Den Mod	Dsgn Grad % Pass
7/8	0.875	0.9417			
5/8	0.625	0.8094			
1/2	0.5	0.7320			100.0
3/8	0.375	0.6432	96.7	96.7	96.7
#4	0.187	0.4702	70.7	68.6	62.3
#10	0.0787	0.3186	47.9	43.9	37.1
#40	0.0165	0.1577	23.7	17.8	21.4
#80	0.007	0.1072	16.1	9.6	9.0
#200	0.0029	0.0721	10.8	3.9	3.9
	0	0	0		

Deviation Calc

Sum (L-A)	35.5	10.0
Sum (ABS(L-A))	35.5	17.3
Sum ((L-A)^2)	290.96	99.79
Area Max & Act	3.721	2.089

TABLE H.2. DISTRICT 6 COARSE GRADATION INFORMATION

Gradation Data Coarse Grad.

Sieve	Coarse Rhyolite (%)	Scrns Fine (%)	Sand (%)	Comb Grad (%)
	66	27	7	100
+1/2	0.0	0.0	0.0	0.0
- 1/2 + 3/8	5.9	0.0	0.4	3.9
- 3/8 + #4	60.8	0.6	1.8	40.4
- #4 + #10	29.2	23.7	0.6	25.7
- #10 + #40	3.6	36.6	1.5	12.4
- #40 + #80	0.3	18.6	77.0	10.6
- #80 + #200	0.1	10.4	17.6	4.1
- #200	0.1	10.1	1.1	2.9
Total	100.0	100.0	100.0	100.0

Bulk Spgr Calc

+ #10	2.440	2.207	
- #10 + #80	2.389	2.389	
- #80		2.775	
Combined Ind	2.437	2.409	2.663
Combined Bulk Spgr =	2.444		

Max Den Calc's

Sieves	Sieves	Sieve ^0.45	Max Den Old	Max Den Mod	Dsgn Grad % Pass
7/8	0.875	0.9417			
5/8	0.625	0.8094			
1/2	0.5	0.7320			100.0
3/8	0.375	0.6432	96.1	96.1	96.1
#4	0.187	0.4702	70.2	67.9	55.7
#10	0.0787	0.3186	47.6	43.1	29.9
#40	0.0165	0.1577	23.6	16.8	17.6
#80	0.007	0.1072	16.0	8.6	7.0
#200	0.0029	0.0721	10.8	2.9	2.9
	0	0	0		

Deviation Calc

Sum (L-A)	55.1	26.2
Sum (ABS(L-A))	55.1	27.7
Sum ((L-A)^2)	703.83	324.69
Area Max & Act	6.284	4.047

TABLE H.3. DISTRICT 14 DESIGN GRADATION INFORMATION

Gradation Data Design Grad.

Sieve	Type "C" Coarse Weir (%)	Type "D" Coarse Weir (%)	Type "F" Im Weir (%)	Scrns Fine Weir (%)	Sand Berdoll Fine (%)	Comb Grad (%)
	22	23	17	20	18	100
+ 7/8	0.0	0.0	0.0	0.0	0.0	0.0
+ 5/8	0.0	0.0	0.0	0.0	0.0	0.0
-5/8 + 3/8	89.4	17.7	0.0	0.0	0.0	23.7
- 3/8 + #4	9.4	71.4	8.6	0.0	0.0	20.0
- #4 + #10	0.2	8.8	79.2	11.4	0.7	17.9
- #10 + #40	0.2	1.1	9.4	49.8	33.4	17.9
- #40 + #80	0.2	0.3	1.0	24.1	53.8	14.8
- #80 + #200	0.4	0.3	0.8	9.8	8.7	3.8
- #200	0.2	0.4	1.0	4.9	3.4	1.9
Total	100.0	100.0	100.0	100.0	100.0	100.0

Bulk Spgr Calc

+ #10	2.497	2.547	2.551	2.457	
- #10 + #80			2.550	2.65	2.62
- #80				2.783	2.741
Combined Ind	2.497	2.547	2.551	2.645	2.634
Combined Bulk Spgr =		2.571			

Max Den Calc's

Sieves	Sieves	Sieve ^0.45	Max Den Old	Max Den Mod	Dsgn Grad % Pass
7/8	0.875	0.9417			100.0
5/8	0.625	0.8094			100.0
1/2	0.5	0.7320			
3/8	0.375	0.6432	76.3	76.3	76.3
#4	0.187	0.4702	55.8	53.7	56.3
#10	0.0787	0.3186	37.8	34.0	38.4
#40	0.0165	0.1577	18.7	13.0	20.5
#80	0.007	0.1072	12.7	6.5	5.7
#200	0.0029	0.0721	8.6	1.9	1.9
	0	0	0		

Deviation Calc

Sum (L-A)	10.7	-13.7
Sum (ABS(L-A))	16.6	15.2
Sum ((L-A)^2)	97.15	81.99
Area Max & Act	0.7125	1.8813

TABLE H.4. DISTRICT 14 GRADATION NO. 2 INFORMATION

Gradation Data Gradation #2

Sieve	Type "C" Coarse Weir (%)	Type "D" Coarse Weir (%)	Type "F" Im Weir (%)	Scrns Fine Weir (%)	Sand Berdoll Fine (%)	Comb Grad (%)
	20	20	15	25	20	100
+ 7/8	0.0	0.0	0.0	0.0	0.0	0.0
+ 5/8	0.0	0.0	0.0	0.0	0.0	0.0
-5/8 + 3/8	89.4	17.7	0.0	0.0	0.0	21.4
- 3/8 + #4	9.4	71.4	8.6	0.0	0.0	17.5
- #4 + #10	0.2	8.8	79.2	11.4	0.7	16.7
- #10 + #40	0.2	1.1	9.4	49.8	33.4	20.8
- #40 + #80	0.2	0.3	1.0	24.1	53.8	17.0
- #80 + #200	0.4	0.3	0.8	9.8	8.7	4.5
- #200	0.2	0.4	1.0	4.9	3.4	2.2
Total	100.0	100.0	100.0	100.0	100.0	100.0

Bulk Spgr Calc

+ #10	2.497	2.547	2.551	2.457	
- #10 + #80			2.550	2.65	2.62
- #80				2.783	2.741
Combined Ind	2.497	2.547	2.551	2.645	2.634
Combined Bulk Spgr =		2.578			

Max Den Calc's

Sieves	Sieves	Sieve ^0.45	Max Den Old	Max Den Mod	Dsgn Grad % Pass
7/8	0.875	0.9417			100.0
5/8	0.625	0.8094			100.0
1/2	0.5	0.7320			
3/8	0.375	0.6432	78.6	78.6	78.6
#4	0.187	0.4702	57.5	55.4	61.1
#10	0.0787	0.3186	38.9	35.1	44.5
#40	0.0165	0.1577	19.3	13.6	23.7
#80	0.007	0.1072	13.1	6.9	6.6
#200	0.0029	0.0721	8.8	2.2	2.2
	0	0	0		

Deviation Calc

Sum (L-A)	-0.5	-24.8
Sum (ABS(L-A))	26.7	25.3
Sum ((L-A)^2)	149.45	219.74
Area Max & Act	2.189	3.432

TABLE H.5. DISTRICT 14 GRADATION NO. 3 INFORMATION

Gradation Data Gradation #3

Sieve	Type "C" Coarse Weir (%)	Type "D" Coarse Weir (%)	Type "F" Im Weir (%)	Scrns Fine Weir (%)	Sand Berdoll Fine (%)	Comb Grad (%)
	30	25	21	10	14	100
+ 7/8	0.0	0.0	0.0	0.0	0.0	0.0
+ 5/8	0.0	0.0	0.0	0.0	0.0	0.0
-5/8 + 3/8	89.4	17.7	0.0	0.0	0.0	31.2
- 3/8 + #4	9.4	71.4	8.6	0.0	0.0	22.5
- #4 + #10	0.2	8.8	79.2	11.4	0.7	20.1
- #10 + #40	0.2	1.1	9.4	49.8	33.4	12.0
- #40 + #80	0.2	0.3	1.0	24.1	53.8	10.3
- #80 + #200	0.4	0.3	0.8	9.8	8.7	2.6
- #200	0.2	0.4	1.0	4.9	3.4	1.3
Total	100.0	100.0	100.0	100.0	100.0	100.0

Bulk Spgr Calc

+ #10	2.497	2.547	2.551	2.457	
- #10 + #80			2.550	2.65	2.62
- #80				2.783	2.741
Combined Ind	2.497	2.547	2.551	2.645	2.634
Combined Bulk Spgr =		2.554			

Max Den Calc's

Sieves	Sieves	Sieve ^0.45	Max Den Old	Max Den Mod	Dsgn Grad % Pass
7/8	0.875	0.9417			100.0
5/8	0.625	0.8094			100.0
1/2	0.5	0.7320			
3/8	0.375	0.6432	68.8	68.8	68.8
#4	0.187	0.4702	50.3	48.3	46.3
#10	0.0787	0.3186	34.1	30.4	26.1
#40	0.0165	0.1577	16.9	11.4	14.2
#80	0.007	0.1072	11.5	5.5	3.9
#200	0.0029	0.0721	7.7	1.3	1.3
	0	0	0		

Deviation Calc

Sum (L-A)	28.5	5.2
Sum (ABS(L-A))	28.5	10.7
Sum ((L-A)^2)	183.47	32.62
Area Max & Act	2.615	1.048

APPENDIX I. STATISTICAL ANALYSIS OF LABORATORY FACTORIAL EXPERIMENTS OF ASPHALT CONTENT AND AGGREGATE GRADATION ON SELECTED MIXTURE PROPERTIES

STATISTICAL ANALYSES OF FACTORIAL EXPERIMENTS

Data and corresponding statistical analyses from each of the factorial experiments from both District mixture designs are presented. All statistical tests are done at the 95% confidence level (a=0.05).

For all properties investigated, analysis of variance (F-tests) are presented where appropriate. The analysis of variance (ANOVA) is a statistical procedure used to indicate whether differences in a property due to changes in one or more factors are really different or could be attributed to random variation. If the analysis of variance indicates significant differences exist due to a factor for which three levels were used, a multiple comparisons procedure is used to indicate which levels differ significantly.

VMA is of special interest to the Highway Department and the testing program resulted in more data for VMA, therefore descriptive statistics for each level of both factors are presented.

PROCEDURES USED FOR THE STATISTICAL TESTS

ANALYSIS OF VARIANCE F-TESTS

The procedure for conducting F-tests to determine significance calls first for examining the interaction of asphalt content and aggregate gradation. If the interaction is not significant or is significant but orderly, F-tests for the main effects of asphalt content and aggregate gradation will be meaningful and may proceed. If the interaction is significant and not orderly, the usefulness of the F-test for the main effects is in doubt.

The tests in these analyses require comparison to tabulated F values. The F values depend on the number of degrees of freedom associated with the effect investigated andm for the error associated with the analysis. The F values needed for the following analyses are:

$F^*(2,66) = 3.14$, $F^*(1,66) = 3.99$, $F^*(2,12) = 3.89$, $F^*(1,12) = 4.75$, $F^*(2,99) = 3.09$, $F^*(4,99) = 2.46$, $F^*(2,18) = 3.55$, and $F^*(4,18) = 2.93$,

where "*" means the value was obtained from a statistical table.

MULTIPLE COMPARISONS

If the ANOVA analysis (F-test) indicates significant differences in a property exist due to a factor for which only two levels were used, one can say which level resulted in higher or lower values. If the ANOVA analysis (F-test) indicates significant differences in a property exist due to a factor for which three levels were used, it only means that at least one level resulted in statistically significant differences, but not which one or ones are different. One must use a multiple comparisons procedure to determine this. For this data the use of the Fisher's Least Significant Difference Test with unpooled error and interaction (enough degrees of freedom are present in the denominator) is appropriate. It is quick and less complicated than others, but as the number of comparisons increases the effective confidence level is lower. With only three levels, the compromise is not much.

DISTRICT 6 ANALYSIS

VOIDS IN THE MINERAL AGGREGATE

In viewing the data, one can make the following comments:

1. Increasing asphalt content seems to results in increased VMA.
2. Differences due to aggregate gradation are difficult to discern.

TABLE I.1. DATA FOR THE 3X2 FACTORIAL EXPERIMENT OF VMA

Asphalt Content (%)	Design Gradation		Coarse Gradation	
5.2	12.9	13.0	12.8	12.8
	12.7	12.9	12.4	12.8
	13.1	12.8	13.0	13.2
	12.5	12.9	12.7	12.8
	13.1	13.1	12.7	13.1
	12.9	12.9	12.6	12.9
6.2	13.1	12.8	12.8	12.9
	12.9	13.1	13.2	13.2
	13.3	13.4	13.2	13.1
	13.5	13.6	13.4	12.9
	12.4	13.1	13.1	13.2
	12.6	13.5	13.3	13.2
7.2	14.0	13.8	13.7	13.9
	13.6	13.8	13.7	13.7
	13.8	13.6	13.8	14.1
	13.7	14.1	13.7	13.9
	13.7	14.1	13.8	13.6
	13.9	13.8	13.7	13.8

DESCRIPTIVE STATISTICS

The following descriptive statistics were obtained from MINITAB. References are such that 5.2, 6.2, and 7.2 refer to asphalt content and DG and CG refer to Design Gradation and Coarse Gradation respectively.

	N	Mean	Median	STDEV	Semean	Min	Max
5.2-DG	12	12.90	12.9	0.176	0.051	12.5	13.1
6.2-DG	12	13.11	13.1	0.378	0.109	12.4	13.6
7.2-DG	12	13.83	13.8	0.171	0.049	13.6	14.1
5.2-CG	12	12.82	12.8	0.217	0.063	12.4	13.2
6.2-CG	12	13.13	13.2	0.176	0.051	12.8	13.4
7.2-CG	12	13.78	13.75	0.134	0.039	13.6	14.1

The descriptive statistics intuitively indicate differences in VMA with asphalt content, but probably not with gradation.

ANALYSIS OF VARIANCE

The ANOVA table from the two way analysis of variance follows:

Source	df	SS	MS	F
Asphalt Content	2	11.4719	5.7360	115.18
Aggr Gradation	1	0.0235	0.0235	0.47
Interaction	2	0.0303	0.0151	0.30
Error	66	3.2875	0.0498	
Total	71	14.8132		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(2,66) = 3.14 > F = 0.30$, insufficient evidence exists to indicate an interaction between Asphalt Content and Gradation.

b) Next, test for no difference between asphalt contents. Since $F^*(2,66) = 3.14 < F = 115.18$, one concludes that there are significant differences in VMA due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(1,66) = 3.99 > F = 0.47$, insufficient evidence exists to indicate differences in VMA due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT – VMA)

$LSD = t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=66) = 1.998$

$s^2 = 0.0498$ (from ANOVA)
$n = 24$

$LSD = 0.1287$

using both DG & CG shows:

Asphalt Content	*Average VMA*
5.2	12.86
6.2	13.12
7.2	13.79

Differences in VMA:

$5.2\ \&\ 6.2 = 0.26 > LSD$ $5.2\% < 6.2\%$
$6.2\ \&\ 7.2 = 0.67 > LSD$ $6.2\% < 7.2\%$
$5.2\ \&\ 7.2 = 0.93 > LSD$ $5.2\% < 7.2\%$

This comparison procedure indicates the asphalt contents all produce VMA's significantly different from each other.

AIR VOIDS

TABLE I.2. DATA FOR THE 3X2 FACTORIAL EXPERIMENT OF AIR VOIDS

Asphalt Content (%)	Design Gradation		Coarse Gradation	
5.2	4.3	4.4	4.0	4.0
	4.0	4.3	3.6	4.1
	4.4	4.1	4.2	4.5
	3.9	4.3	4.0	4.0
	4.5	4.5	4.0	4.4
	4.3	4.3	3.8	4.2
6.2	2.6	2.2	2.1	2.2
	2.3	2.5	2.5	2.5
	2.8	2.8	2.5	2.4
	2.9	3.0	2.7	2.2
	1.7	2.6	2.4	2.5
	2.0	2.9	2.6	2.6
7.2	1.2	0.9	0.7	1.0
	0.7	1.0	0.7	0.8
	1.0	0.7	0.9	1.2
	0.8	1.3	0.7	1.0
	0.9	1.3	0.9	0.6
	1.1	1.0	0.7	0.9

ANALYSIS OF VARIANCE

The ANOVA table from the two way analysis of variance follows:

Source	df	SS	MS	F
Asphalt Content	2	127.141	63.571	1054.24
Aggr Gradation	1	0.405	0.405	6.716
Interaction	2	0.041	0.020	0.32
Error	66	3.976	0.060	
Total	71	131.564		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since

$F^*(2,66) = 3.14 > F = 0.32$, insufficient evidence exists to indicate an interaction between Asphalt Content and Gradation.

b) Next, test for no difference between asphalt contents. Since $F^*(2,66) = 3.14 < F = 1054.24$, one concludes that there are significant differences in Air Voids due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(1,66) = 3.99 < F = 6.716$, one concludes that there are significant differences in Air Voids due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT - AIR VOIDS)

$LSD = t^*_{\alpha/2} \sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=66) = 1.998$

$s^2 = 0.0603$ (from ANOVA)
$n = 24$

$LSD = 0.1416$

using both DG & CG shows:

Asphalt Content	*Average Air Voids*
5.2	4.17
6.2	2.48
7.2	0.917

Differences in VMA:

5.2 & 6.2 = 1.69 > LSD	5.2% > 6.2%
6.2 & 7.2 = 1.56 > LSD	6.2% > 7.2%
5.2 & 7.2 = 3.25 > LSD	5.2% > 7.2%

This comparison procedure indicates the asphalt contents all produce Air Voids significantly different from each other.

RESILIENT MODULUS

TABLE I.3. DATA FOR THE 3X2 FACTORIAL EXPERIMENT OF RESILIENT MODULUS (PSI)

Asphalt Content (%)	Design Gradation	Coarse Gradation
5.2	258,034	463,194
	384,615	816,661
	759,199	443,611
6.2	499,643	784,564
	314,749	366,727
	831,510	534,930
7.2	454,939	462,023
	396,181	551,368
	286,083	432,687

In viewing the data one can see no general trends for this asphalt-aggregate combination.

ANALYSIS OF VARIANCE

The ANOVA table from the two way analysis of variance follows:

Source	df	SS	MS	F
Asphalt Content	2	4.985E + 10	2.493E + 10	0.634
Aggr Gradation	1	2.50E + 10	2.50E + 10	0.635
Interaction	2	8.412E + 9	4.206E + 9	0.107
Error	12	4.719E + 11	3.932E + 10	
Total	17	5.551E + 11		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(2,12) = 3.89 > F = 0.107$, insufficient evidence exists to indicate an interaction between Asphalt Content and Gradation.

b) Next, test for no difference between asphalt contents. Since $F^*(2,12) = 3.89 > F = 0.634$, one concludes that there are not significant differences in Resilient Modulus due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(1,12) = 4.75 > F = 0.635$, one concludes that there are not significant differences in Resilient Modulus due to aggregate gradation.

MARSHALL STABILITY AND FLOW

TABLE I.4. DATA FOR THE 3X2 FACTORIAL EXPERIMENT OF MARSHALL STABILITY AND FLOW

Asphalt Content (%)	Design Gradation Marshall Stab (%)	Design Gradation Marshall Flow	Coarse Gradation Marshall Stab (%)	Coarse Gradation Marshall Flow
5.2	3,135	19	3,108	12
	3,086	20	2,812	10
	2,928	18	2,974	10
6.2	2,594	17	2,719	12
	2,657	18	2,412	10
	2,530	20	2,631	11
7.2	2,341	20	2,282	12
	2,160	20	2,166	13
	2,501	21	2,289	12

In viewing the data, the general trends for this asphalt-aggregate combination seem to be:

1) Increasing asphalt content results in decreased Stability. Flow changes due to asphalt content are difficult to determine.
2) The "coarser" aggregate gradation results in decreased Flow. Stability changes due to aggregate changes are difficult to determine.

ANALYSIS OF VARIANCE FOR MARSHALL STABILITY

The ANOVA table from the two way analysis of variance for Marshall Stability follows:

Source	df	SS	MS	F
Asphalt Content	2	1.557E + 6	7.786E + 5	48.37
Aggr Gradation	1	16,140	16,140	1.003
Interaction	2	6,462	3,231	0.201
Error	12	193,151	16,096	
Total	17	1.773E + 6		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(2,12) = 3.89 > F = 0.201$, insufficient evidence exists to indicate an interaction between Asphalt Content and Gradation.

b) Next, test for no difference between asphalt contents. Since $F^*(2,12) = 3.89 < F = 48.37$, one concludes that there are significant differences in Marshall Stability due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(1,12) = 4.75 > F = 1.003$, one concludes that there are not significant differences in Marshall Stability due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT – MARSHALL STABILITY)

$LSD = t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=12) = 2.179$

$s^2 = 16{,}096$ (from ANOVA)
$n = 6$

LSD = 159.6

using both DG & CG shows:

Asphalt Content	*Average Marshall Stability*
5.2	3,007
6.2	2,590
7.2	2,290

Differences in Stability:

5.2 & 6.2 = 417 > LSD	5.2% > 6.2%
6.2 & 7.2 = 300 > LSD	6.2% > 7.2%
5.2 & 7.2 = 717 > LSD	5.2% > 7.2%

This comparison procedure indicates the asphalt contents all produce Marshall Stability's significantly different from each other. For this data, increasing asphalt content decreases the Marshall Stability.

ANALYSIS OF VARIANCE FOR MARSHALL FLOW

The ANOVA table from the two-way analysis of variance for Marshall Flow follows:

Source	df	SS	MS	F
Asphalt Content	2	10.11	5.06	4.77
Aggr Gradation	1	280.06	280.06	264.21
Interaction	2	0.78	0.39	0.368
Error	12	12.67	1.06	
Total	17	303.61		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(2,12) = 3.89 > F = 0.368$, insufficient evidence exists to indicate an interaction between Asphalt Content and Gradation.

b) Next, test for no difference between asphalt contents. Since $F^*(2,12) = 3.89 < F = 4.77$, one concludes that there are significant differences in Marshall Flow due to asphalt content at the 95% confidence level. At the 97.5% confidence level $F^*(2,12)=5.10$. At this level one would say that differences in Marshall Flow due to asphalt content are not statistically significant.

c) Finally, test for no difference between aggregate gradations. Since $F^*(1,12) = 4.75 > F = 264.21$, one concludes that there are significant differences in Marshall Flow due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT – MARSHALL FLOW)

$LSD = t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=12) = 2.179$

$s^2 = 1.06$ (from ANOVA)
$n = 6$

LSD = 1.29

using both DG & CG shows:

Asphalt Content	*Average Marshall Flow*
5.2	14.83
6.2	14.67
7.2	16.33

Differences in Flow:

5.2 & 6.2 = 0.16 < LSD	
6.2 & 7.2 = 1.66 > LSD	6.2% > 7.2%
5.2 & 7.2 = 1.50 > LSD	5.2% > 7.2%

This comparison procedure indicates the asphalt contents of 5.2% and 6.2% produce Marshall Flow values significantly different from 7.2%, but the 5.2% and 6.2% do not differ significantly from each other.

TABLE I.5. DATA FOR THE 3X2 FACTORIAL EXPERIMENT OF INDIRECT TENSILE STRENGTH AND SECANT MODULUS AT FAILURE

Asphalt Content (%)	Design Gradation		Coarse Gradation	
	Str (psi)	Secant Mod (psi @ fail)	Str (psi)	Secant Mod (psi @ fail)
5.2	153	14,709	122	39,010
	166	14,504	128	40,963
	153	13,401	125	36,951
6.2	188	13,881	129	27,666
	154	9,870	131	31,441
	168	11,555	129	33,157
7.2	127	5,299	108	20,723
	152	7,308	112	18,650
	152	7,325	114	19,919

INDIRECT TENSILE STRENGTH AND SECANT MODULUS AT FAILURE

In viewing the data one can see the general trends for this asphalt-aggregate combination are:

1) Increasing asphalt content results in a peak in ITS at 6.2%, and decreased Secant Modulus.
2) The "coarser" aggregate gradation results in decreased ITS and increased Secant Modulus.

Source	df	SS	MS	F
Asphalt Content	2	1,521.3	760.7	7.92
Aggr Gradation	1	5,512.5	5,512.5	57.36
Interaction	2	64.0	32.0	0.333
Error	12	1,152.7	96.1	
Total	17	8,250.5		

ANALYSIS OF VARIANCE FOR INDIRECT TENSILE STRENGTH

The ANOVA table from the two way analysis of variance for Indirect Tensile Strength follows:

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(2,12) = 3.89 > F = 0.333$, insufficient evidence exists to indicate an interaction between Asphalt Content and Gradation.

b) Next, test for no difference between asphalt contents. Since $F^*(2,12) = 3.89 < F = 7.92$, one concludes that there are significant differences in Indirect Tensile Strength due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(1,12) = 4.75 > F = 57.36$, one concludes that there are significant differences in Indirect Tensile Strength due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT - ITS)

$LSD = t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=12) = 2.179$

$s^2 = 96.1$ (from ANOVA)
$n = 6$

LSD = 12.3

using both DG & CG shows:

Asphalt Content	*Average ITS*
5.2	141.2
6.2	149.8
7.2	127.5

Differences in ITS:
5.2 & 6.2 = 8.6 < LSD
6.2 & 7.2 = 22.3 > LSD   6.2% > 7.2%
5.2 & 7.2 = 13.5 > LSD   5.2% > 7.2%

This comparison procedure indicates the asphalt contents of 5.2% and 6.2% produce Indirect Tensile Strengths significantly different from 7.2%, but the 5.2% and 6.2% do not differ significantly from each other.

ANALYSIS OF VARIANCE FOR SECANT MODULUS AT FAILURE

The ANOVA table from the two way analysis of variance for Secant Modulus at Failure follows:

Source	df	SS	MS	F
Asphalt Content	2	5.449E + 8	2.725E + 8	86.42
Aggr Gradation	1	1.617E + 9	1.617E + 9	512.8
Interaction	2	1.017E + 8	5.089E + 7	16.1
Error	12	3.783E + 7	3.153E + 6	
Total	17	2.302E + 9		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(2,12) = 3.89 < F = 16.1$, evidence exists to indicate an interaction between Asphalt Content and Gradation. Figure I.1 indicates an orderly interaction between asphalt content and gradation, therefore F-test for the main effects are still meaningful.

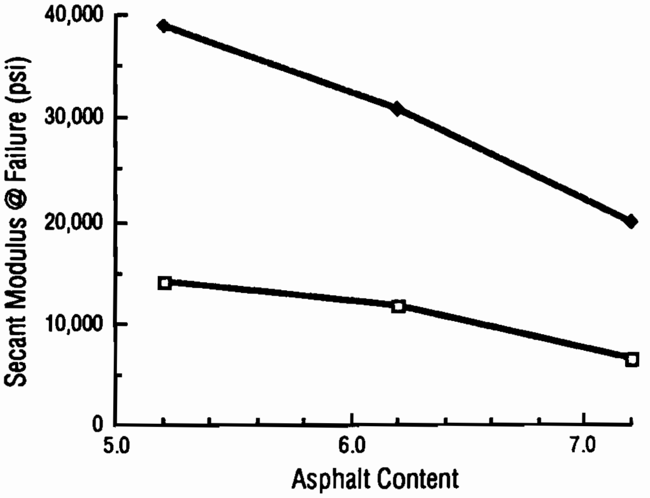

Fig I.1. D-6 secant modulus interaction.

b) Next, test for no difference between asphalt contents. Since $F^*(2,12) = 3.89 < F = 86.42$, one concludes that there are significant differences in Secant Modulus at Failure due to asphalt content at the 95% confidence level.

c) Finally, test for no difference between aggregate gradations. Since $F^*(1,12) = 4.75 > F = 512.8$, one concludes that there are significant differences in Secant Modulus at Failure due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT - SECANT MODULUS)

$LSD = t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=12) = 2.179$

$s^2 =$ 3.153E+6 (from ANOVA)
$n = 6$

LSD = 2234

using both DG & CG shows:

Asphalt Content	*Average Secant Modulus*
5.2	26,590
6.2	21,262
7.2	13,204

Differences in Modulus:
5.2 & 6.2 = 5,328 > LSD 5.2% > 6.2%
6.2 & 7.2 = 8,058 > LSD 6.2% > 7.2%
5.2 & 7.2 = 13,386 > LSD5.2% > 7.2%

This comparison procedure indicates the asphalt contents all produce Secant Moduli at Failure significantly different from each other. For this data, increasing asphalt content decreases the Secant Moduli at Failure.

HVEEM STABILITY

TABLE I.6. DATA FOR THE 3X2 FACTORIAL EXPERIMENT OF HVEEM STABILITY

Asphalt Content (%)	Design Gradation Hveem Stab (%)	Coarse Gradation Hveem Stab (%)
5.2	45	41
	40	39
	45	42
6.2	36	35
	36	34
	37	36
7.2	35	25
	34	24
	35	25

In viewing the data one can see the general trends for this asphalt-aggregate combination are:

1) Increasing asphalt content results in decreased Hveem Stability.
2) The "coarser" aggregate gradation results in decreased Hveem Stability.

ANALYSIS OF VARIANCE FOR HVEEM STBILITY

The ANOVA table from the two way analysis of variance for Hveem Stability follows:

Source	df	SS	MS	F
Asphalt Content	2	456.4	228.2	108.15
Aggr Gradation	1	98.0	98.0	46.44
Interaction	2	65.3	32.7	15.49
Error	12	25.3	2.11	
Total	17	645.1		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(2,12) = 3.89 < F = 15.49$, evidence exists to indicate an interaction between Asphalt Content and Gradation. Figure I.2 indicates a quasi-orderly interaction between asphalt content and gradation (even though the lines are not parallel, increased asphalt decreases Hveem Stability and the lines do not intersect), therefore it is assumed that F-test for the main effects are still meaningful.

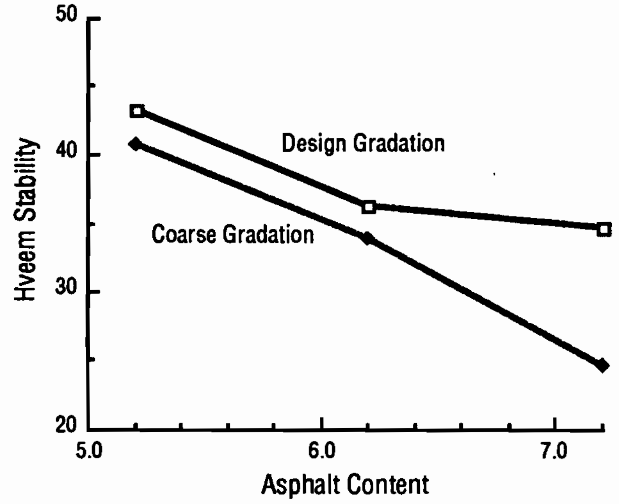

Fig I.2. D-6 Hveem interaction.

b) Next, test for no difference between asphalt contents. Since $F^*(2,12) = 3.89 < F = 108.15$, one concludes that there are significant differences in Hveem Stability due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(1,12) = 4.75 < F = 46.44$, one concludes that there are significant differences in Hveem Stability due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT - HVEEM STABILITY)

$LSD = t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=12) = 2.179$

$s^2 =$ 2.11 (from ANOVA)
$n = 6$

LSD = 1.83

using both DG & CG shows:

Asphalt Content	*Average Hveem Stability*
5.2	42.0
6.2	35.7
7.2	29.7

Differences in Stability:

5.2 & 6.2 = 6.3 > LSD	5.2% > 6.2%
6.2 & 7.2 = 6.0 > LSD	6.2% > 7.2%
5.2 & 7.2 = 12.3 > LSD	5.2% > 7.2%

This comparison procedure indicates the asphalt contents all produce Hveem Stabilities significantly different from each other. For these data, increasing asphalt content decreases the Hveem Stability.

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TABLE I.7. DATA FOR THE 3X3 FACTORIAL EXPERIMENT OF VMA

Asphalt Content (%)	Design Gradation VMA		Gradation #2 VMA		Gradation #3 VMA	
4.1	15.6	14.7	15.8	16.0	13.2	13.4
	15.6	15.1	15.7	15.9	13.4	13.2
	15.0	15.3	16.1	15.7	13.6	13.3
	15.4	15.1	16.1	15.7	13.1	13.2
	15.3	15.2	16.1	15.8	12.9	13.0
	15.1	15.1	15.7	16.1	13.0	13.1
5.1	14.9	14.4	15.7	15.9	13.6	13.5
	14.5	14.7	15.6	15.7	13.7	13.4
	14.4	14.7	15.5	15.6	13.5	13.7
	14.7	14.8	15.5	16.0	13.4	13.5
	14.6	14.7	15.5	15.8	13.7	13.8
	14.7	14.6	15.7	15.7	13.4	13.5
6.1	15.2	15.1	15.4	15.5	14.4	14.5
	15.0	15.2	15.8	15.7	14.3	14.6
	15.2	15.2	15.8	16.0	14.4	14.3
	15.2	15.2	15.6	15.6	14.5	14.6
	15.0	15.0	15.8	15.6	14.2	14.6
	15.1	15.2	15.8	15.9	14.4	14.4

In viewing the data, one can see that Gradation #2 seems to exhibit the highest VMA, followed by the Design Gradation and Gradation #3.

DESCRIPTIVE STATISTICS

The following descriptive statistics were obtained from MINITAB. References are such that 4.1, 5.1, and 6.1 refer to asphalt content while DG, G2, and G3 refer to Design Gradation, Gradation #2, and Gradation #3, respectively (see chart, right):

	N	Mean	Median	STDEV	Semean	Min	Max
4.1-DG	12	15.21	15.15	0.254	0.073	14.7	15.6
5.1-DG	12	14.64	14.7	0.151	0.043	14.4	14.9
6.1-DG	12	15.13	15.2	0.089	0.026	15.0	15.2
4.1-G2	12	15.89	15.85	0.178	0.051	15.7	16.1
5.1-G2	12	15.68	15.7	0.159	0.046	15.5	16.0
6.1-G2	12	15.71	15.75	0.173	0.050	15.4	16.0
4.1-G3	12	13.20	13.2	0.200	0.058	12.9	13.6
5.2-G3	12	13.56	13.5	0.138	0.040	13.4	13.8
6.1-G3	12	14.43	14.4	0.130	0.038	14.2	14.6

The descriptive statistics intuitively indicate differences in VMA with asphalt content and gradation.

ANALYSIS OF VARIANCE

The ANOVA table from the two way analysis of variance follows:

Source	df	SS	MS	F
Asphalt Content	2	4.0813	2.0406	71.35
Aggr Gradation	2	75.7002	37.8501	1323.43
Interaction	4	8.1637	2.0409	71.36
Error	99	2.8358	0.0286	
Total	104	90.7810		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since F*(4,99) = 2.46 < F = 71.36, evidence exists to indicate an interaction between Asphalt Content and Gradation. Figure I.3 indicates interaction exists, but it is relatively orderly. Therefore, it will be assumed that F-tests for the main effects are still meaningful.

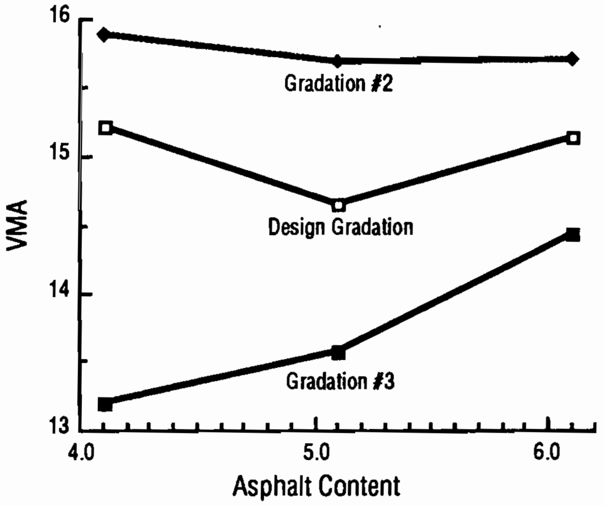

Fig I.3. D-14 VMA interaction.

b) Next, test for no difference between asphalt contents. Since F*(2,99) = 3.09 < F = 71.35, one concludes that there are significant differences in VMA due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(2,99) = 3.09 << F = 1323.43$, one concludes that there are significant differences in VMA due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT—VMA)

$LSD = t^*\sqrt{_{\alpha/2}\, 2s^2/n}$ with $t^*(\alpha/2=0.025, df=99) = 1.987$

$s^2 = 0.0286$ (from ANOVA)
$n = 36$

$LSD = 0.079$

using DG, G2 & G3 shows:

Asphalt Content	*Average VMA*
4.1	14.76
5.1	14.62
6.1	15.09

Differences in VMA:

4.1 & 5.1 = 0.14 > LSD	4.1% > 5.1%
5.1 & 6.1 = 0.47 > LSD	5.1% < 6.1%
4.1 & 6.1 = 0.33 > LSD	4.1% < 6.1%

This comparison procedure indicates the asphalt contents all produce VMA's significantly different from each other.

MULTIPLE COMPARISONS PROCEDURE (GRADATION – VMA)

$LSD = t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=99) = 1.987$

$s^2 = 0.0286$ (from ANOVA)
$n = 36$

$LSD = 0.079$

using all asphalt contents shows:

Gradation	*Average VMA*
DG	14.99
G2	15.76
G3	13.73

Differences in VMA:

DG & G2 = 0.77 > LSD	DG < G2
G2 & G3 = 2.03 > LSD	G2 < G3
DG & G3 = 1.26 > LSD	DG < G3

This comparison procedure indicates the gradations all produce VMA's significantly different from each other.

AIR VOIDS

TABLE I.8. DATA FOR THE 3X3 FACTORIAL EXPERIMENT OF AIR VOIDS

Asphalt Content (%)	Design Gradation Air Voids		Gradation #2 Air Voids		Gradation #3 Air Voids	
4.1	6.2	5.2	6.3	6.5	3.7	4.0
	6.1	5.5	6.2	6.4	4.0	3.7
	5.5	5.8	6.6	6.1	4.2	3.9
	5.9	5.6	6.7	6.2	3.7	3.8
	5.8	5.7	6.7	6.2	3.5	3.6
	5.6	5.6	6.1	6.6	3.6	3.6
5.1	3.4	2.8	3.9	4.2	2.4	2.3
	3.0	3.2	3.8	3.9	2.5	2.2
	2.8	3.2	3.7	3.8	2.2	2.5
	3.1	3.3	3.7	4.3	2.1	2.3
	3.1	3.2	3.7	4.0	2.5	2.6
	3.2	3.1	3.9	3.9	2.2	2.2
6.1	0.6	0.5	1.5	1.6	0.9	1.0
	0.4	0.6	1.9	1.8	0.8	1.2
	0.6	0.7	1.9	2.1	0.9	0.8
	0.6	0.7	1.6	1.6	1.0	1.1
	0.5	0.4	1.9	1.7	0.7	1.2
	0.5	0.6	1.9	2.0	0.9	0.9

In viewing the data there seem to be differences in air voids due to asphalt content and aggregate gradation.

ANALYSIS OF VARIANCE

The ANOVA table from the two-way analysis of variance follows:

Source	df	SS	MS	F
Asphalt Content	2	315.9874	157.9937	4,224.43
Aggr Gradation	2	50.4235	25.2118	674.11
Interaction	4	17.8220	4.4555	119.13
Error	99	3.7000	0.0374	
Total	107	387.9330		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(4,99) = 2.46 < F = 119.13$, evidence exists to indicate an interaction between Asphalt Content and Gradation. Figure I.4 indicates interaction exists and is not totally orderly. Therefore, F-Tests for the main effects are questionable. Since the data is essentially linear, the F-tests will be performed.

b) Next, test for no difference between asphalt contents. Since $F^*(2,99) << F = 4424.43$, one concludes that there are significant differences in VMA due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(2,99) = 3.09 << F = 674.11$, one concludes that there are significant differences in VMA due to aggregate gradation.

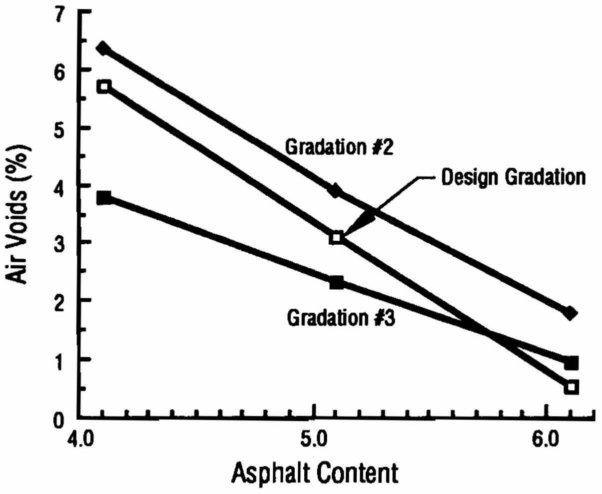

Fig I.4. D-14 air voids interaction.

MULTIPLE COMPARISONS PROCEDURE (APHALT CONTENT - AIR VOIDS)

LSD = $t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=99) = 1.987$

$s^2 = 0.0374$ (from ANOVA)
n = 36

LSD = 0.091

using DG, G2 & G3 shows:

Asphalt Content	*Average Air Voids*
4.1	5.29
5.1	3.12
6.1	1.10

Differences in Air Voids:

4.1 & 5.1 = 2.17 > LSD	4.1% > 5.1%
5.1 & 6.1 = 2.02 > LSD	5.1% > 6.1%
4.1 & 6.1 = 4.19 > LSD	4.1% > 6.1%

This comparison procedure indicates the asphalt contents all produce Air Voids significantly different from each other.

MULTIPLE COMPARISONS PROCEDURE (GRADATION - AIR VOIDS)

LSD = $t^*_{\alpha/2}\sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=99) = 1.987$

$s^2 = 0.0374$ (from ANOVA)
n = 36

LSD = 0.091

using all asphalt contents shows:

Gradation	*Average Air Voids*
DG	3.13
G2	4.02
G3	2.35

Differences in Air Voids:

DG & G2 = 0.89 > LSD	DG < G2
G2 & G3 = 1.67 > LSD	G2 > G3
DG & G3 = 0.78 > LSD	DG > G3

This comparison procedure indicates the gradations all produce Air Voids significantly different from each other.

RESILIENT MODULUS

TABLE I.9. DATA FOR THE 3X3 FACTORIAL EXPERIMENT OF RESILIENT MODULUS (PSI)

Asphalt Content (%)	Design Gradation Resilient Mod (psi)	Gradation #2 Resilient Mod (psi)	Gradation #3 Resilient Mod (psi)
4.1	476,117	1,022,677	1,321,321
	525,469	1,739,851	2,518,390
	759,033	668,125	982,835
5.1	883,128	1,796,210	901,011
	678,571	3,239,964	1,248,267
	834,168	1,238,671	2,168,133
6.1	756,456	1,735,617	649,415
	574,362	1,115,669	898,360
	355,041	2,081,016	589,401

On observation, there appears to be differences in Resilient Modulus produced by some asphalt contents and some gradation.

ANALYSIS OF VARIANCE

The ANOVA table from the two way analysis of variance follows:

Source	df	SS	MS	F
Asphalt Content	2	1.050E12	5.249E11	1.69
Aggr Gradation	2	4.377E12	2.189E12	7.07
Interaction	4	1.759E12	4.397E11	1.42
Error	18	5.570E12	3.095E11	
Total	26	1.276E13		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(4,18) = 2.93 > F = 1.42$, insufficient evidence exists to indicate an interaction between Asphalt Content and Gradation.

b) Next, test for no difference between asphalt contents. Since $F^*(2,18) = 3.55 > F = 1.69$, one concludes that there are not significant differences in Resilient Modulus due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since F*(2,18) = 3.55 < F = 7.07, one concludes that there are significant differences in Resilient Modulus due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (GRADATION-RESILIENT MODULUS)

LSD = $t^*_{\alpha/2} \sqrt{2s^2/n}$ with $t^*(\alpha/2{=}0.025, df{=}18) = 2.101$

$s^2 = 3.095E11$ (from ANOVA)
$n = 9$

LSD = 5.5099E5

using all asphalt contents shows:

Gradation	*Average Resilient Modulus*
DG	6.4915E5
G2	1.6264E6
G3	1.2530E6

Differences in Resilient Modulus:

DG & G2 = 9.7725E5 > LSD DG < G2
G2 & G3 = 3.7340E5 < LSD
DG & G3 = 6.0385E5 > LSD DG < G3

This comparison procedure indicates the Design Gradation is significantly different from Gradations 2 & 3, but Gradations 2 & 3 are not significantly different from each other.

MARSHALL STABILITY AND FLOW

TABLE I.10. DATA FOR THE 3X3 FACTORIAL EXPERIMENT OF MARSHALL STABILITY FLOW

Asphalt Content (%)	Design Gradation		Gradation #2		Gradation #3	
	Marshall		Marshall		Marshall	
	Stab (%)	Flow	Stab (%)	Flow	Stab (%)	Flow
4.1	2,730	13	2,006.55	13	2,145	15
	2,613	16	2,058	14	2,145	15
	2,613	14	1,874	14	2,145	15
5.1	2,730	14	2,132	15	1,833	18
	2,613	14	2,058	14	2,207	21
	2,808	16	2,145	13	2,730	20
6.1	2,262	15	2,184	14	2,106	22
	2,418	16	2,262	13	2,106	18
	2,441	16	2,058	14	2,106	23

On examination, there appear to be differences in Marshall Stability and Flow for some asphalt contents and some gradations.

ANALYSIS OF VARIANCE FOR MARSHALL STABILITY

The ANOVA table from the two way analysis of variance follows:

Source	df	SS	MS	F
Asphalt Content	2	101,156	50,578	1.83
Aggr Gradation	2	1,262,391	631,195	22.86
Interaction	4	191,174	47,793	1.73
Error	18	497,011	27,612	
Total	26	2,051,731		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since F*(4,18) = 2.93 > F = 1.73, insufficient evidence exists to indicate an interaction between Asphalt Content and Gradation.

b) Next, test for no difference between asphalt contents. Since F*(2,18) = 3.55 > F = 1.83, one concludes that there are not significant differences in Marshall Stability due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since F*(2,18) = 3.55 < F = 22.86, one concludes that there are significant differences in Marshall Stability due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (GRADATION – MARSHALL STABILITY)

$LSD = t^*_{\alpha/2} \sqrt{2s^2/n}$ with
$t^*(\alpha/2=0.025, df=18) = 2.101$

$s^2 = 27612$ (from ANOVA)
$n = 9$

$LSD = 165$

using all asphalt contents shows:

Gradation	*Average Marshall Stability*
DG	2,581
G2	2,087
G3	2,169

Differences in Marshall Stability:

DG & G2 = 494 > LSD   DG < G2
G2 & G3 = 82 < LSD
DG & G3 = 412 > LSD   DG < G3

This comparison procedure indicates the Design Gradation is significantly different from Gradations 2 & 3, but Gradations 2 & 3 are not significantly different from each other.

ANALYSIS OF VARIANCE FOR MARSHALL FLOW

The ANOVA table from the two way analysis of variance follows:

Source	df	SS	MS	F
Asphalt Content	2	28.74	14.37	8.60
Aggr Gradation	2	112.52	56.26	33.69
Interaction	4	33.93	8.48	5.08
Error	18	30.00	1.67	
Total	26	205.19		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(2,18) = 2.93 < F = 5.08$, evidence exists to indicate an interaction between Asphalt Content and Gradation. Figure I.5 indicates a quasi- orderly interaction between asphalt content and gradation in that the lines for each gradation do not cross one another. It will be assumed that F-test for the main effects are still meaningful.

b) Next, test for no difference between asphalt contents. Since $F^*(2,18) = 3.55 > F = 8.60$, one concludes that there are significant differences in Marshall Flow due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(2,18) = 3.55 < F = 33.69$, one concludes that there are significant differences in Marshall Flow due to aggregate gradation.

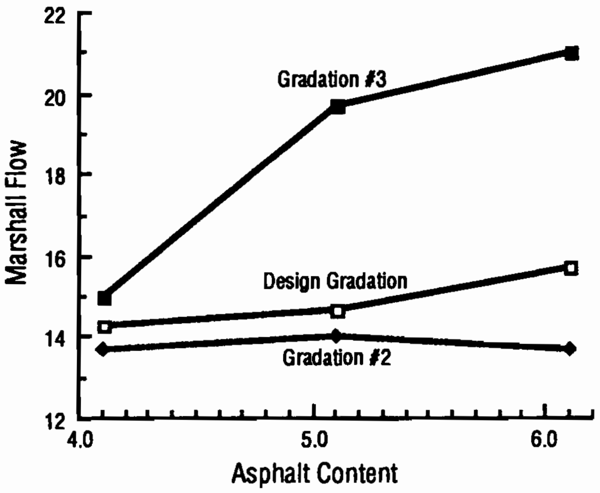

Fig I.5. D-14 Marshall flow interaction.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT—MARSHALL FLOW)

$LSD = t^*_{\alpha/2} \sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=18) = 2.101$

$s^2 = 1.67$ (from ANOVA)
$n = 9$

$LSD = 1.28$

using DG, G2 & G3 shows:

Asphalt Content	*Average Marshall Flow*
4.1	14.33
5.1	16.13
6.1	16.80

Differences in Marshall Stability:

4.1 & 5.1 = 1.80 > LSD   4.1 < 5.1
5.1 & 6.1 = 0.67 < LSD
4.1 & 6.1 = 2.47 > LSD   4.1 < 6.1

This comparison procedure indicates the 4.1% is significantly different from 5.1% & 6.1%, but 5.1% & 6.1% are not significantly different from each other.

MULTIPLE COMPARISONS PROCEDURE (GRADATION – MARSHALL FLOW)

$LSD = t^*_{\alpha/2} \sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=18) = 2.101$

$s^2 = 1.67$ (from ANOVA)
$n = 9$

$LSD = 1.28$

using all asphalt contents shows:

Gradation	*Average Marshall Flow*
DG	14.90
G2	13.80
G3	18.57

Differences in Marshall Stability:

DG & G2 = 1.10 < LSD
G2 & G3 = 4.77 > LSD   G2 < G3
DG & G3 = 3.67 > LSD   DG < G3

This comparison procedure indicates Gradation 3 is significantly different from the Design Gradation and Gradation 2, but the Design Gradation and Gradation 2 are not significantly different from each other.

INDIRECT TENSILE STRENGTH AND SECANT MODULUS AT FAILURE

TABLE I.11. DATA FOR THE 3X3 FACTORIAL EXPERIMENT OF INDIRECT TENSILE STRENGTH AND SECANT MODULUS @ FAILURE

Asphalt Content (%)	Design Gradation		Gradation #2		Gradation #2	
	Str (psi)	Secant Mod, (psi @ fail)	Str (psi)	Secant Mod (psi @ fail)	Str (psi)	Secant Mod (psi @ fail)
4.1	116	31,946	128	35,264	108	32,065
	110	32,520	134	34,463	109	32,210
	117	32,212	136	33,714	117	28,975
5.1	132	36,391	146	32,966	119	28,578
	129	33,116	140	29,117	102	23,076
	131	33,598	138	34,301	116	24,711
6.1	122	24,128	140	28,383	101	20,496
	121	24,433	139	28,987	108	21,826
	120	27,221	138	29,476	103	21,482

On examination of the data, it appears that 5.1% asphalt results in a peak in ITS, but the trends are less defined for Secant Modulus.

ANALYSIS OF VARIANCE FOR INDIRECT TENSILE STRENGTH

The ANOVA table from the two way analysis of variance for Indirect Tensile Strength follows:

Source	df	SS	MS	F
Asphalt Content	2	373.9	186.9	9.73
Aggr Gradation	2	3653.4	1826.7	95.14
Interaction	4	275.7	68.9	3.59
Error	18	346.0	19.2	
Total	26	4649.0		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since F*(4,18) = 2.93 < F = 3.59, evidence exists to indicate some interaction between Asphalt Content and Gradation. Figure I.6 indicates an orderly interaction between asphalt content and gradation, therefore, F-test for the main effects are still meaningful.

b) Next, test for no difference between asphalt contents. Since F*(2,18) = 3.55 > F = 9.73, one concludes that there are significant differences in ITS due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since F*(2,18) = 3.55 < F = 95.14, one concludes that there are significant differences in ITS due to aggregate gradation.

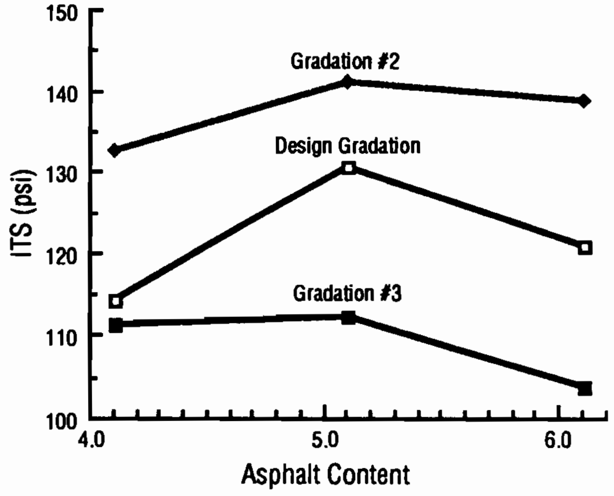

Fig I.6. D-14 ITS interaction.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT—ITS)

$\text{LSD} = t^*_{\alpha/2}\, R(2s^2/n)$ with $t^*(\alpha/2=0.025, df=18) = 2.101$

$s^2 = 19.2$ (from ANOVA)
$n = 9$

LSD = 4.3

using DG, G2 & G3 shows:

Asphalt Content	Avg ITS
4.1	119.4
5.1	128.1
6.1	121.3

Differences in ITS:

4.1 & 5.1 = 8.7 > LSD   4.1 < 5.1
5.1 & 6.1 = 6.8 > LSD   5.1 > 6.1
4.1 & 6.1 = 1.9 < LSD

This comparison procedure indicates the 5.1% is significantly different from 4.1% & 6.1%, but 4.1% & 6.1% are not significantly different from each other.

MULTIPLE COMPARISONS PROCEDURE (GRADATION - ITS)

$\text{LSD} = t^*_{\alpha/2}\, \sqrt{2s^2/n}$ with $t^*(\alpha/2=0.025, df=18) = 2.101$

$s^2 = 19.2$ (from ANOVA)
$n = 9$

LSD = 4.3

using all asphalt contents shows:

Gradation	*Average ITS*
DG	122.0
G2	137.7
G3	109.2

Differences in ITS:

DG & G2 = 15.7 > LSD   DG < G2
G2 & G3 = 28.5 > LSD   G2 > G3
DG & G3 = 12.8 > LSD   DG > G3

This comparison procedure indicates all gradations produce ITS's significantly different from each other.

ANALYSIS OF VARIANCE FOR SECANT MODULUS AT FAILURE

The ANOVA table from the two way analysis of variance for Secant Modulus at Failure follows:

Sources	df	SS	MS	F
Asphalt Content	2	2.6777E8	1.3388E8	46.24
Aggr Gradation	2	1.7539E8	8.7692E7	30.28
Interaction	4	6.0073E7	1.5018E7	5.18
Error	18	5.2118E7	2.8954E6	
Total	26	5.5535E		

The first test of significance is for interaction between Asphalt Content and Gradation. Since F*(4,18) = 2.93 < F = 5.18, evidence exists to indicate interaction between Asphalt Content and Gradation. Figure I.7 does not indicate an orderly interaction between asphalt content and gradation, therefore, F-test for the main effects are not meaningful. The analysis of variance is not useful for this data.

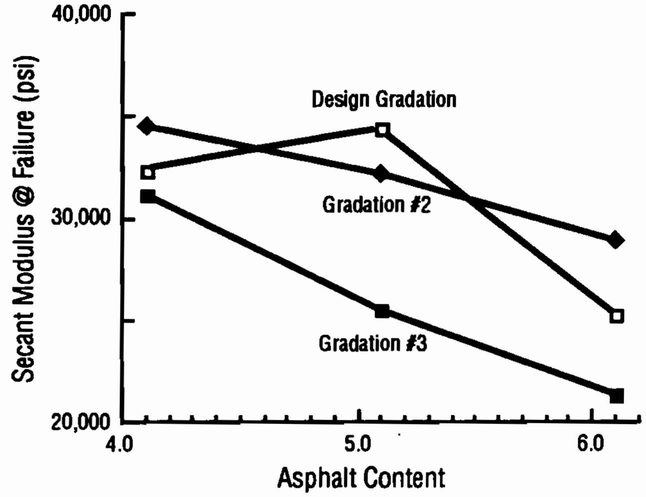

Fig 1.7. D-14 Secant modulus interaction.

HVEEM STABILITY

TABLE I.12. DATA FOR THE 3X3 FACTORIAL EXPERIMENT OF HVEEM STABILITY

Asphalt Content (%)	Design Gradation Hveem Stab (%)	Gradation #2 Hveem Stab (%)	Gradation #3 Hveem Stab (%)
4.1	56	55	52
	57	55	52
	58	56	52
5.1	54	51	45
	55	53	46
	51	53	45
6.1	50	47	40
	50	47	38
	47	50	38

On examination of the data, it appears that gradation #3 produces lower Hveem Stabilities than the other two gradations. The differences between the other two gradations are less apparent. Increasing asphalt content seems to result in decreased Hveem Stability.

ANALYSIS OF VARIANCE FOR HVEEM STABILITY

The ANOVA table from the two way analysis of variance for Hveem Stability follows:

Source	df	SS	MS	F
Asphalt Content	2	411.56	205.78	126.25
Aggr Gradation	2	314.89	157.44	96.58
Interaction	4	32.89	8.22	5.04
Error	18	29.33	1.63	
Total	26	788.67		

a) The first test of significance is for interaction between Asphalt Content and Gradation. Since $F^*(4,18) = 2.93 < F = 3.59$, evidence exists to indicate some interaction between Asphalt Content and Gradation. Figure I.8 indicates an orderly interaction between asphalt content and gradation, therefore, F-test for the main effects are still meaningful.

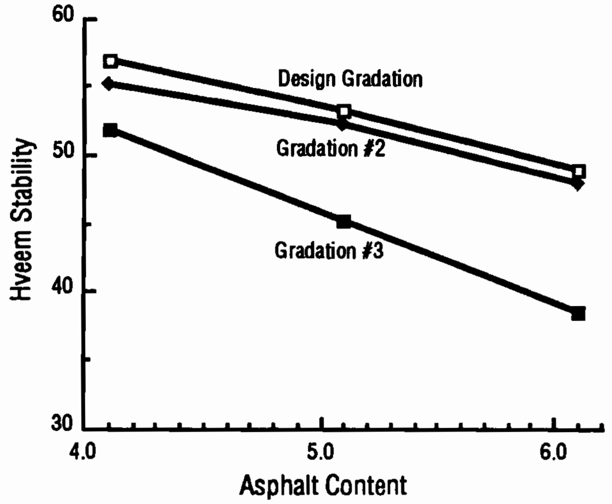

Fig I.8. D-14 Hveem interaction.

b) Next, test for no difference between asphalt contents. Since $F^*(2,18) = 3.55 > F = 126.25$, one concludes that there are significant differences in Hveem Stability due to asphalt content.

c) Finally, test for no difference between aggregate gradations. Since $F^*(2,18) = 3.55 < F = 96.58$, one concludes that there are significant differences in Hveem Stability due to aggregate gradation.

MULTIPLE COMPARISONS PROCEDURE (ASPHALT CONTENT – HVEEM STABILITY)

$LSD = t^*_{\alpha/2} \sqrt{2s^2/n}$ with $t^*(\alpha/2{=}0.025, df{=}18) = 2.101$

$s^2 = 1.63$ (from ANOVA)
$n = 9$

$LSD = 1.3$

using DG, G2 & G3 shows:

Asphalt Content	*Average Hveem Stability*
4.1	54.8
5.1	50.3
6.1	45.2

Differences in Hveem Stability:
4.1 & 5.1 = 4.5 > LSD   4.1 > 5.1
5.1 & 6.1 = 5.1 > LSD   5.1 > 6.1
4.1 & 6.1 = 9.6 < LSD   4.1 > 6.1

This comparison procedure indicates all asphalt contents produce Hveem Stabilities significantly different from each other. Increasing asphalt content results in decreased Hveem Stability.

MULTIPLE COMPARISONS PROCEDURE (GRADATION – HVEEM STABILITY)

$LSD = t^*_{\alpha/2} \sqrt{2s^2/n}$ with $t^*(\alpha/2{=}0.025, df{=}18) = 2.101$

$s^2 = 1.63$ (from ANOVA)
$n = 9$

$LSD = 1.3$

using all asphalt scontents shows:

Gradation	*Average Hveem Stability*
DG	53.1
G2	51.9
G3	45.3

Differences in Hveem Stability:
DG & G2 = 1.2 < LSD
G2 & G3 = 6.6 > LSD   G2 > G3
DG & G3 = 7.8 > LSD   DG > G3

This comparison procedure indicates Gradation 3 is significantly different from the Design Gradation and Gradation 2, but that the Design Gradation and Gradation 2 are not significantly different from each other.

APPENDIX J. 0.45 POWER CHARTS WITH OPTIMUM ASPHALT CONTENTS AND VMA'S FOR FACTORIAL EXPERIMENT MIXTURES

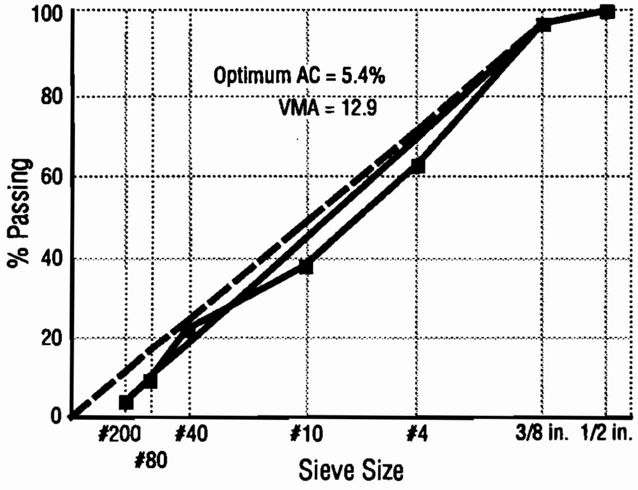

Fig J.1. District 6—Design gradation.

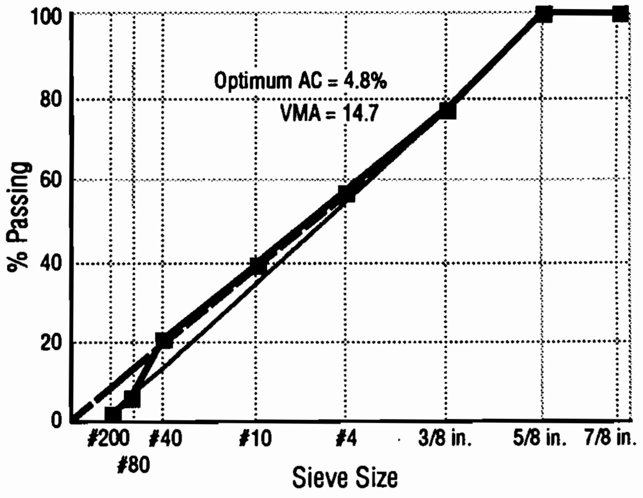

Fig J.3. District 14—Design gradation.

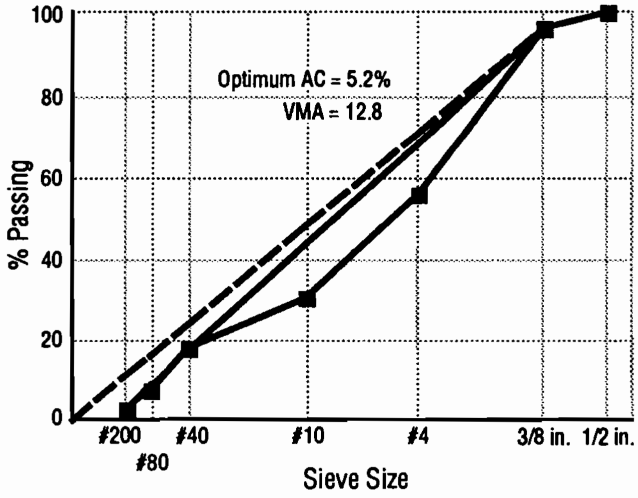

Fig J.2. District 6—Coarse gradation.

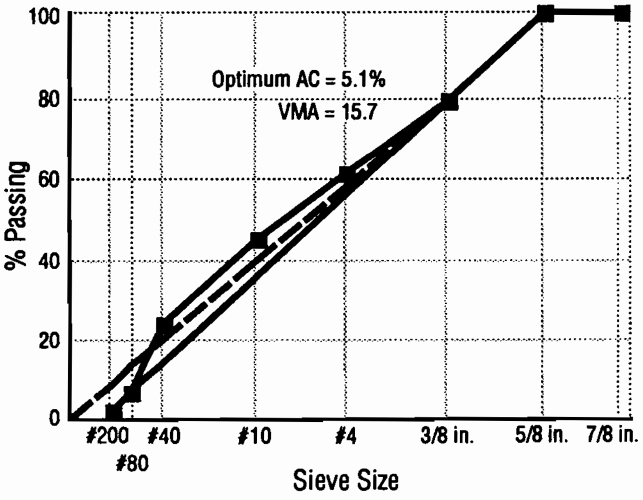

Fig J.4. District 14—Gradation No. 2.

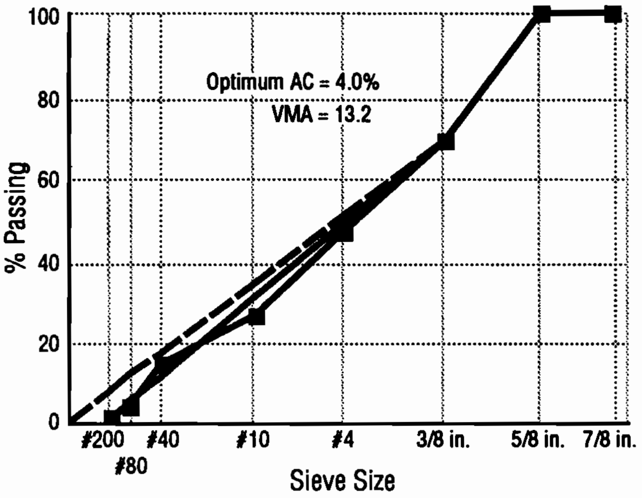

Fig J.5. District 14—Gradation No. 3.

APPENDIX K. AGGREGATE SUBSTITUTION DATA

TABLE K.1. GRADATION DATA—DISTRICT 9

Gradation Data District 9

Sieve	Type "D" Coarse Tehuacana	Type "F" IM Tehuacana	Scrns Soft LS Tehuacana	Field Sand Fine	Comb Grad
	48%	12%	30%	10%	100%
+1/2	0.0	0.0	0.0	0.0	0.0
- 1/2 + 3/8	10.3	0.0	0.0	0.0	4.9
- 3/8 + #4	63.8	26.6	0.0	0.0	33.8
- #4 + #10	21.7	65.6	14.1	0.0	22.5
- #10 + #40	1.8	4.6	55.5	0.0	18.1
- #40 + #80	0.4	0.5	15.1	28.1	7.6
- #80 + #200	1.0	1.5	13.1	60.3	10.6
- #200	1.0	1.2	2.2	11.6	2.4
Total	100.0	100.0	100.0	100.0	100.0

Bulk Spgr Calc

Combined Ind	2.486	2.685	2.542	2.680
Combined Bulk Spgr =		2.544		

Max Den Calc's

Sieves	Sieves	Sieve ^0.45	Max Den Old	Max Den Mod	Grad % Pass
7/8	0.875	0.9417			
5/8	0.625	0.8094			
1/2	0.5	0.7320			100.0
3/8	0.375	0.6432	95.1	95.1	95.1
#4	0.187	0.4702	69.5	67.0	61.2
#10	0.0787	0.3186	47.1	42.4	38.7
#40	0.0165	0.1577	23.3	16.3	20.7
#80	0.007	0.1072	15.8	8.1	13.1
#200	0.0029	0.0721	10.7	2.4	2.4
	0	0	0		

Deviation Calc

Sum (L-A)	30.3	0.2
Sum (ABS(L-A))	30.3	18.7
Sum ((L-A)^2)	220.43	89.99
Area Max & Act	3.191	1.860

TABLE K.2. GRADATION DATA—HARD LIMESTONE

Gradation Data District 9 w/Hard LS

Sieve	Type "D" Coarse Tehuacana	Type "F" IM Tehuacana	Scrns Soft LS Tehuacana	Field Sand Fine	Comb Grad
	48%	12%	30%	10%	100%
+1/2	0.0	0.0	0.0	0.0	0.0
- 1/2 + 3/8	10.3	0.0	0.0	0.0	4.9
- 3/8 + #4	63.8	26.6	0.0	0.0	33.8
- #4 + #10	21.7	65.6	14.1	0.0	22.5
- #10 + #40	1.8	4.6	55.5	0.0	18.1
- #40 + #80	0.4	0.5	15.1	28.1	7.6
- #80 + #200	1.0	1.5	13.1	60.3	10.6
- #200	1.0	1.2	2.2	11.6	2.4
Total	100.0	100.0	100.0	100.0	100.0

Bulk Spgr Calc

Combined Ind	2.486	2.685	2.681	2.680	
Combined Bulk Spgr =		2.584			

Max Den Calc's

Sieves	Sieves	Sieve ^0.45	Max Den Old	Max Den Mod	Grad % Pass
7/8	0.875	0.9417			
5/8	0.625	0.8094			
1/2	0.5	0.7320			100.0
3/8	0.375	0.6432	95.1	95.1	95.1
#4	0.187	0.4702	69.5	67.0	61.2
#10	0.0787	0.3186	47.1	42.4	38.7
#40	0.0165	0.1577	23.3	16.3	20.7
#80	0.007	0.1072	15.8	8.1	13.1
#200	0.0029	0.0721	10.7	2.4	2.4
	0	0	0		

Deviation Calc

Sum (L-A)	30.3	0.2
Sum (ABS(L-A))	30.3	18.7
Sum ((L-A)^2)	220.43	89.99
Area Max & Act	3.191	1.860

TABLE K.3. GRADATION DATA—RHYOLITE SCREENINGS SUBSTITUTION

Gradation Data District 9 with Rhyolite

Sieve	Type "D" Coarse Tehuacana	Type "F" IM Tehuacana	Scrns Soft LS Tehuacana	Field Sand Fine	Comb Grad
	48%	12%	30%	10%	100%
+1/2	0.0	0.0	0.0	0.0	0.0
- 1/2 + 3/8	10.3	0.0	0.0	0.0	4.9
- 3/8 + #4	63.8	26.6	0.0	0.0	33.8
- #4 + #10	21.7	65.6	14.1	0.0	22.5
- #10 + #40	1.8	4.6	55.5	0.0	18.1
- #40 + #80	0.4	0.5	15.1	28.1	7.6
- #80 + #200	1.0	1.5	13.1	60.3	10.6
- #200	1.0	1.2	2.2	11.6	2.4
Total	100.0	100.0	100.0	100.0	100.0

Bulk Spgr Calc

Combined Ind	2.486	2.685	2.566	2.680
Combined Bulk Spgr =		2.551		

Max Den Calc's

Sieves	Sieves	Sieve ^0.45	Max Den Old	Max Den Mod	Grad % Pass
7/8	0.875	0.9417			
5/8	0.625	0.8094			
1/2	0.5	0.7320			100.0
3/8	0.375	0.6432	95.1	95.1	95.1
#4	0.187	0.4702	69.5	67.0	61.2
#10	0.0787	0.3186	47.1	42.4	38.7
#40	0.0165	0.1577	23.3	16.3	20.7
#80	0.007	0.1072	15.8	8.1	13.1
#200	0.0029	0.0721	10.7	2.4	2.4
	0	0	0		

Deviation Calc

Sum (L-A)	30.3	0.2
Sum (ABS(L-A))	30.3	18.7
Sum ((L-A)^2)	220.43	89.99
Area Max & Act	3.191	1.860

TABLE K.4. AGGREGATE SUBSTITUTION PROPERTIES

Dist 9 Design				Dist 9 w/ Rhyolite Screenings			
Asphalt Content	Air Voids	VMA	Hveem Stab	Asphalt Content	Air Voids	VMA	Hveem Stab
4.8	4.8	14.2	46	4.8	4.5	14.7	48
	4.6	14.0	46		4.4	14.7	48
	4.8	14.2	45		4.5	14.8	48
5.8	2.7	14.2	46	5.8	3.4	14.8	47
	2.6	14.1	47		3.5	14.9	46
	2.7	14.2	47		3.5	14.9	47
6.8	0.6	14.3	25	6.8	1.0	15.4	17
	0.5	14.2	28		0.9	15.3	20
	0.6	14.3	28		0.8	15.3	20

Dist 9 w/ Hard LS Screenings			
Asphalt Content	Air Voids	VMA	Hveem Stab
4.8	5.1	14.7	50
	5.0	14.6	48
	5.1	14.7	51
5.8	2.6	14.4	45
	2.4	14.2	45
	2.5	14.3	45

Fig K.1. Gradation—Aggregate substitution.