# Development of an Analytical Model to Predict Volumetric Properties

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16. Abstract

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This report evaluated the ATSER method of estimating volumetric properties without preparing laboratory specimens. Existing methods of determining volumetric properties were evaluated. The study revealed that the Hudson and Davis method (Hudson and Davis, 1965) did not correlate well with actual mix designs. However, the Hensley method (Hensley, 1985) correlated well, although required final test data. The ATSER method utilized basic engineering properties to evaluate the proposed job mix formulas. The method proved to provide an excellent estimation of actual volumetric properties.

A new method of estimating volumetric properties was utilized in this study. The method is contained within a computer software program Asphalt - IT$^{TM}$. The user can enter preliminary laboratory test data and select a proposed job mix formula. The job mix formula's volumetric properties are estimated rapidly. Therefore, job mix formulas with a high potential for success can be verified in the laboratory. ATSER's method proved to be a valuable mix design "tool."

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# DEVELOPMENT OF AN ANALYTICAL MODEL TO PREDICT VOLUMETRIC MIX PROPERTIES

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# DEVELOPMENT OF AN ANALYTICAL MODEL TO PREDICT VOLUMETRIC MIX PROPERTIES

## 1.0 INTRODUCTION TO THE DESIGN OF HOT MIX ASPHALT CONCRETE (HMAC) MIXES

### 1.1 Background

Hot Mix Asphalt Concrete (HMAC) is a paving material that consists of mineral aggregate, asphalt cement, and air voids. The process of designing a HMAC is divided into three basic steps; the selection of an aggregate blend, the selection of a type of asphalt binder, and the determination of optimum values of volumetric properties.

Mineral aggregates are selected first. Mineral aggregates are any combination of sand, gravel, or crushed stone in their natural or processed state (Barksdale, 1993). Aggregates used in HMAC mixes are of two types: coarse and fine, and the distinction between these two types of aggregates is based on the Unified Soil Classification (Bowles, 1988).

Coarse aggregates are defined as any particles that are retained on a No. 4 sieve (4.75 mm. opening), usually river wash gravel or crushed stone. Fine aggregates, such as natural sands, can be defined as any material passing the No. 4 sieve but retained on the No. 200 sieve (75 μm opening).

The type of asphalt binder is then selected. Asphalt cement is a dark brown to black cementitious material that is refined from petroleum crude, a product formed over millions of years from the decay of organic sediments under varying conditions of temperature and pressure. It can either be naturally occurring, or can be refined from crude oil (Roberts et al., 1991).

Natural asphalt is formed over millions of years through a natural refining process. Previously formed petroleum crude, when forced to the surface by geological forces, accumulates in lakes of asphalt and hardens. Examples of these deposits are found in Trinidad Lake, in the island of Trinidad, and Bermunez Lake, in Venezuela.

Petroleum asphalts are colloidal dispersed hydrocarbons that are the by-product of the refining of crude petroleum. Since the discovery of refining in the early 1900, Petroleum Asphalts have been increasingly available to the paving industry, and today make up about 85 percent of the paving asphalt market (Asphalt Institute, 1994).

Asphalt is classified chemically as a hydrocarbon, since up to 95 percent of the composition of its molecules is made up of carbon and hydrogen atoms. The remaining five percent is made of two types of atoms, heteratoms and metals (Asphalt Institute, 1994).

Heteratoms are atoms such as nitrogen, oxygen and sulfur that often replace carbon atoms. The type and amount of these atoms that exist in an asphalt are function of both the source of the unrefined crude oil and its age. Heteratoms contribute too many of the unique chemical and physical properties of the asphalt.

The metal atoms that are also incorporated in the asphalt molecules are elements such as vanadium, nickel and iron. These atoms are present in far less quantities than the heteratoms, usually comprising up to one percent of the composition of the asphalt molecule. Since the type of these metal atoms varies from among different sources of crude oil, they provide a means of "fingerprinting" the asphalt.

For these reasons, asphalts from different sources and manufacturers have different properties, which makes the selection of binder a laborious process. In order to comply with the specifications issued by the regulatory agencies, designers perform different tests designed to determine the adequacy of a given binder. Discussing these tests is beyond the scope of the present document.

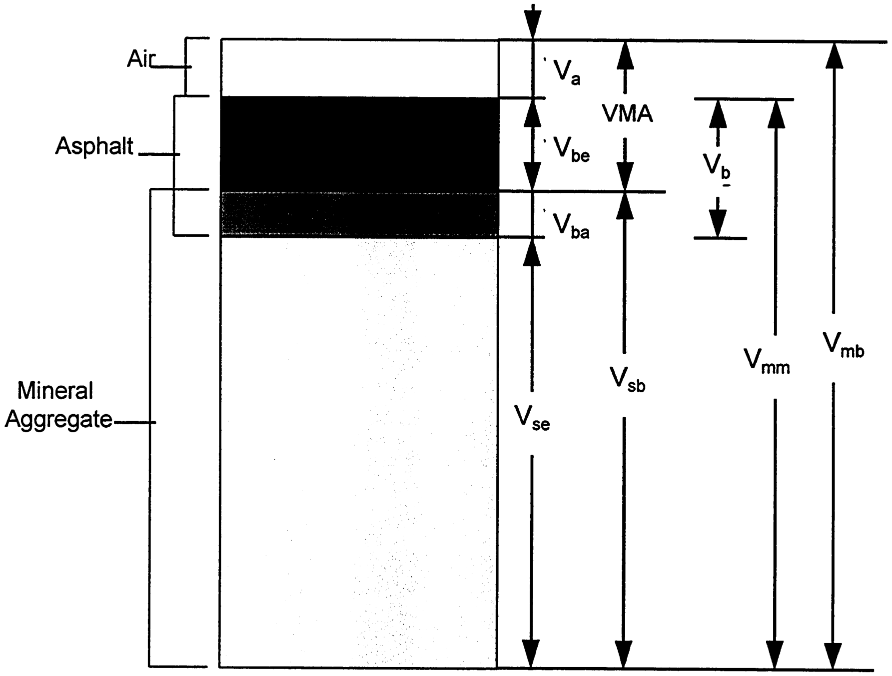
Efforts to facilitate the binder selection process have resulted in the Superpave™ binder selection procedure. Most regulatory agencies used the penetration, viscosity, or the Superpave™ binder grading system to specify acceptable materials. Local suppliers must then comply with said specifications to be considered.

The Superpave™ approach for designing paving mixtures is the central result of the Strategic Highway Research Program (SHRP). SHRP was a $150 million research program established by Congress in 1987 (Asphalt Institute, 1995a). A third of the funds initially allocated for Superpave™ were used for the development of the asphalt binder and mixture performance based specifications. The program was completed in 1993. The result of the SHRP research effort is the Superpave™ mix design method.

The third step in the process of designing an HMAC mix is to determine the volumetric properties of the HMAC mix. A given volume of an HMAC mix is made of three components, asphalt binder, aggregates, and air voids, and its volumetric properties are the set of relationships between the volumes, weights, physical and engineering properties of these components. There are three basic mix design methods that are used to determine these volumetric properties: the Marshall method, the Hveem method, or the Superpave™ method.

## 1.2 Volumetric Properties of HMAC Mixes

As outlined previously in Section 1.1, a Hot Mix Asphalt Concrete (HMAC) is a paving material that consists of mineral aggregate, asphalt cement, and air voids. The volumes considered in an evaluation of the volumetric properties of an HMAC mix are the volumes of voids filled with air and with asphalt, the volume of voids in mineral aggregates, as well as the volumes of binder, absorbed and effective. A schematic illustration of an HMAC mix showing its various components and defining the various volumes is shown in Figure 1.1.



$V_{ma}$ = Volume of voids in mineral aggregate
$V_{mb}$ = Bulk volume of compacted mix
$V_{mm}$ = Voidless volume of paving mix
$V_a$ = Volume of air voids
$V_b$ = Volume of asphalt
$V_{ba}$ = Volume of absorbed asphalt
$V_{be}$ = Volume of voids filled with asphalt
$V_{sb}$ = Bulk volume of mineral aggregate
$V_{se}$ = Effective volume of mineral aggregate

**Figure 1.1 Volumetric Properties of HMAC Mixes (After Asphalt Institute, 1984)**

Successful mix design methods results in a paving mixture that is stable and durable. Two important factors in the mix design process are economics and workability. The most economical aggregate available, that satisfies all property requirements, should be used.

Volumetric properties include air voids, $V_a$, the voids in the mineral aggregate, VMA, the voids filled with asphalt, VFA, and the effective asphalt content, $P_{be}$. In order to be able to determine these properties, one must first determine the bulk and effective specific gravity of the aggregates in the mix, $G_{sb}$ and $G_{se}$ (Asphalt Institute, 1993).

There are different methods that are used to determine these specific gravity values, the Marshall Method, Hveem Method, and the Superpave™ Method. While all these methods differ in the way they determine the specific gravity values, they are all based on the same basic volumetric relationships.

The bulk specific gravity of the aggregate in the mix, $G_{sb}$, is given by:

$$G_{sb} = \frac{\sum_i P_i}{\sum_i \frac{P_i}{G_{sb_i}}} \tag{1.1}$$

Where $G_{sbi}$ is the bulk specific gravity of the individual aggregate in the mix, and $P_i$ its proportion in the mix. One can calculate the bulk specific gravity of an oven dried aggregate, $G_{sb,Dry}$, or that of the saturated surface dry aggregate, $G_{sb,SSD}$.

The bulk specific gravity of a dry aggregate, $G_{sb,Dry}$, is defined as the ratio of the oven dried mass of a unit volume of aggregate, $W_d$ , to that of an equal volume of gas-free distilled water, both at a stated temperature. It is given by

$$G_{sb,Dry} = \frac{W_d}{W_{SSD} + W_{W+T} - W_{SSD+T}} \tag{1.2}$$

Where $W_{SSD}$ is the mass of the saturated sample, $W_{W+T}$ is the mass of a calibrated pycnometer filled with water, and $W_{SSD+T}$ the mass of the same pycnometer containing the saturated sample.

In order to determine the specific gravity of a saturated aggregate, the aggregate is placed in water for 24 hours. In order to achieve saturation for the bulk specific gravity of a saturated aggregate, $G_{sb,SSD}$, is then defined as the ratio of the mass of a unit volume of aggregate, $W_{SSD}$ , to that of an equal volume of gas-free distilled water, both at a stated temperature. It is given by

$$G_{sb,SSD} = \frac{W_{SSD}}{W_{SSD} + W_{W+T} - W_{SSD+T}} \tag{1.3}$$

The effective specific gravity of the aggregate, $G_{se}$, is determined as a function of the maximum specific gravity of the paving mixture, $G_{mm}$, which is determined using ASTM D 2041 (ASTM, 1995). The effective specific gravity of an aggregate is given by:

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \tag{1.4}$$

Where $P_b$ is the asphalt content, as a percentage of the weight of total mixture, at which the ASTM D 2041 test was performed (ASTM, 1995), and $G_b$ the specific gravity of the asphalt.

## 1.3 Determination of Reference Density

The United States currently has over ten methods to determine maximum theoretical specific gravity. The determination is critical to the actual voids in the total mixture, VTMs, of the paving mixture. Very small changes can result in large changes in the final VTM.

For design purposes, the maximum specific gravity of the mix, $G_{mm}$, should be determined for each different asphalt content, $P_b$. According to the Asphalt Institute, (1989) it is given by:

$$G_{mm} = \frac{100}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}} \qquad (1.5)$$

Where $P_s$ is the aggregate content, as a percentage of the total weight of the mix.

An important factor in determining the optimum asphalt content is to determine the asphalt absorption, $P_{ba}$. It is expressed as a percentage of the total weight of the aggregate rather than the total mix, and is given by:

$$P_{ba} = 100 \frac{G_{se} - G_{sb}}{G_{sb} G_{se}} G_b \qquad (1.6)$$

Where $G_{sb}$ is the bulk specific gravity of the aggregate in the mix, $G_{se}$ is the effective specific gravity of the aggregate, and $G_b$, the specific gravity of the asphalt.

The effective asphalt in a mix is then the asphalt that is not absorbed by the aggregate voids. The effective asphalt content, $P_{be}$, is given by:

$$P_{be} = P_b - P_s \frac{P_{ba}}{100} \qquad (1.7)$$

Where $P_{ba}$ is the asphalt absorption. $P_b$ and $P_s$ are respectively the asphalt content and the aggregate content, respectively, both expressed as a percentage of the total weight of the mix.

The voids in the mineral aggregate, VMA, is the volume of inter-granular void space between the aggregate particles of a compacted paving specimen that includes the air voids and the volume of the asphalt not absorbed into the aggregates. The %VMA is most often calculated on the basis of the bulk specific gravity of the aggregate, $G_{sb}$, and is expressed as percentage of the bulk volume of the compacted paving mixture. It can be calculated by subtracting the volume of the aggregate determined by the bulk specific gravity from the bulk volume of the compacted paving mixture. It can be determined either as a percentage of the weight of the total mixture, or as a percentage of the weight of the aggregate in the mix.

Figure 1.1 illustrates percent of voids in the mineral aggregate, %VMA, is defined as the sum of the percent by total volume of air voids, $V_a$, and the percent by total volume of the effective binder, $V_{be}$. The VMA is given by:

$$\mathrm{VMA} = V_a + V_{be} \tag{1.8}$$

The %VMA can also be expressed as (Asphalt Institute, 1989):

$$\%\mathrm{VMA} = 100 - \frac{G_{mb} \times P_s}{G_{sb}} \tag{1.9}$$

Where $P_s$ is the aggregate content, expressed as a percentage of the total weight of the mix, $G_{mb}$ the bulk specific gravity of the mix, and $G_{sb}$ the bulk specific gravity of the aggregate.

As a percentage of the aggregate in the mix, the %VMA, is given by:

$$\%\mathrm{VMA} = 100 \times \left[1 - \left(\frac{G_{mb}}{G_{sb}}\right) \times \left(\frac{100}{100 + P_b}\right)\right] \tag{1.10}$$

Where $P_b$ is the asphalt content, as a percentage of the weight of total mixture, at which the ASTM D 2041 (ASTM, 1995) test was performed, and $G_{sb}$ the bulk specific gravity of the aggregate.

Air voids in the compacted mixture, are defined as the spaces between the coated aggregate particles. The percent air voids in the total compacted paving mix, $V_a$, is expressed as a percentage of the total volume of the mix, and is given by:

$$\%V_a = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}} \tag{1.11}$$

HMA after laydown operations usually contains 15% to 20% by volume of the total mix of air voids (Asphalt Institute, 1989). In order to increase the strength of the mix, one has to increase the surface to surface contact of the aggregate particles; thereby, promoting inter-particle friction. This is achieved by compacting the mix to an air void content of less than 8% (Asphalt Institute, 1989), while the mix temperature is cooling from a placing temperature of 150°C (300°F) down to about 85°C (185°F). The proper air voids have been reported to enhance fatigue life, resistance to permanent deformation and low temperature cracking resistance (Roberts et. al., 1991). A key to pavement performance is achieving proper air void content.

A well compacted pavement improves resistance to rutting that is caused by subsequent traffic. In order to allow for thermal expansion without causing mix flushing or instability, it is important that the air voids not be less than 2% (Asphalt Institute, 1989). An over-consolidated mix, with a percentage by total volume of air voids less than 2%, has the disadvantage of being too rigid, and will therefore crack under repetitive loading.

Reduced air voids also have the advantage of minimizing the asphalt from the effects of aging, which can occur when the asphalt binder is exposed to air through the interconnected voids. An oxidized binder becomes brittle, which will decrease the elasticity of the mix and cause fatigue failure of the pavement shown by cracks developed under the effects of repetitive loading.

The percent voids filled with asphalt, %VFA, is defined as the percentage of the inter-granular void space between the aggregates in the mix that is filled with asphalt binder, and does not include the portion of asphalt that is absorbed by the aggregates. It is given by:

$$\%VFA = 100 \times \frac{\%VMA - \%V_a}{\%VMA} \tag{1.12}$$

## 2.0 PARAMETERS INFLUENCING VMA

The general consensus in the pavement literature is that the %VMA significantly affects the performance of a mixture (Roberts et al., 1991; Asphalt Institute, 1989), therefore, most regulatory agencies have set minimum requirements. There is, nevertheless, disagreement in the literature (Foster, 1986) as to the validity of minimum requirements on %VMA. Determination of VMA is an essential part of any mix design method including Marshall, Hveem, or Superpave™ methods. Therefore, it should be an essential part of any prediction of these mix design methods.

By definition, the percent voids in the mineral aggregates, %VMA, is the percent by total volume of the mix of the total volume of voids within the mass of the compacted aggregate. As shown in Equation 1.8, the volume of voids in the mineral aggregate is the sum of the air voids in the mixture and the volume of binder that is not absorbed by the mineral aggregates. These two parameters are in turn influenced by a number of factors, including aggregate gradation, the bulk specific gravity of the aggregate, the bulk specific gravity of the mix, actual asphalt content, aggregate shape, roughness and absorption capacity to cite a few.

The factors that are considered to affect the %VMA are therefore the air voids, aggregate gradation, the bulk specific gravity of the aggregate, the bulk specific gravity of the mix and the actual asphalt content and effective asphalt content.

### 2.1 Influence of Aggregate Gradation

Aggregate gradation is defined as the distribution of various particle size fractions of an aggregate blend (Barksdale, 1993). While gradation by volume is of most importance (Roberts et al. 1991), gradation by weight is standard practice. These two gradations are approximately the same provided the values of the specific gravity of the various aggregates being used are the same.

Aggregate mixes with larger sizes resist rutting better than mixes with smaller sizes (Barksdale, 1993). Large stone aggregate seems to improve aggregate to aggregate contact in the stone "skeleton" matrix.

A well graded aggregate blend is one that has a good representation of particle size fractions (Barksdale, 1993). In order to select a suitable aggregate gradation, the Talbot equation, an empirical gradation equation, can be used. This equation is the Fuller maximum density curve, (Fuller and Thompson, 1907). It relates the percent passing, P, of a sieve size, d, and the maximum aggregate size in the gradation, D, and uses an empirical gradation exponent, n. The equation is given by:

$$P = 100 \times \left(\frac{d}{D}\right)^n \qquad (2.1)$$

It has been established in the literature (Barksdale, 1993; Roberts et al. 1991; Fuller and Thompson, 1907) that there is a direct relationship between aggregate gradation and voids. This is therefore true of the relationship between aggregate gradation and VMA. The maximum density line plotted on the 0.45 chart provides a very good correlation with VMA (Aschenberg and MacKean, 1992).

## 2.2 Influence of Air Voids

Air voids are also referred to as voids in the total mix, VTM. As shown in Figure 1.1 and in Equation 1.8, the percent voids in the mineral aggregates, %VMA, is directly proportional to the percent air voids, $\%V_a$. This relationship is used by different methods of estimating VMA which is discussed in Section 6.

## 2.3 Influence of Gsb: Bulk Specific Gravity of the Aggregate in the Mix

As shown in Equation 1.9, the percent voids in the mineral aggregates, %VMA, is inversely proportional to $G_{sb}$, the bulk specific gravity of the aggregate.

The volume of asphalt binder absorbed by an aggregate is invariably less than that of the water absorbed primarily due to the asphalt viscosity. The effective specific gravity of an aggregate should therefore be less than its apparent specific gravity and more than its bulk specific gravity, so that:

$$G_{sb} < G_{se} < G_{sa} \qquad (2.2)$$

The apparent specific gravity of an aggregate is given by:

$$G_{sa} = \frac{\sum_i P_i}{\sum_i \frac{P_i}{G_{sa_i}}} \qquad (2.3)$$

Where $G_{sai}$ is the apparent specific gravity of the individual aggregate in the mix.

Since the bulk specific gravity is usually difficult to determine accurately one can substitute the apparent specific gravity for the bulk specific gravity in Equation 1.1 which results only in small errors (Asphalt Institute, 1989).

## 2.4 Influence of $G_{mb}$: Bulk Specific Gravity of the Compacted Mix

The bulk specific gravity of the mix, $G_{mb}$, is influenced by the degree of compaction of the mix. This is obvious in the case of both the Marshall and Superpave™ mix design procedures.

The value for the bulk specific gravity of the mix will vary depending on whether the number of blows the sample is subjected to during the compaction process is equal to 35, 50, or 75. The bulk specific gravity of the mix, $G_{mb}$, can be represented as a function of the unit weight of the bulk mix, $\gamma_{mb}$, and the unit weight of water, $\gamma_o$ (62.4 Lb/ft$^3$ or 9.81 KN/m$^3$). It is given by:

$$G_{mb} = \frac{\gamma_{mb}}{\gamma_o} \qquad (2.4)$$

In an initially loose mix, increasing compaction increases the unit weight of the mix, and thus its bulk specific gravity. The literature also shows evidence of increased densification of HMA mixes under increasing load cycles (Foster, 1982).

As shown in Equation 1.9, the percent voids in the mineral aggregates, %VMA, is dependent on $G_{mb}$, the bulk specific gravity of the mix. An increase in the degree of compaction, will generally cause a decrease in the value of the air voids, and therefore a corresponding decrease in the volume of voids in the mineral aggregates. This is not true in the case of an over-compacted mix (USACE, 1991), where an increase in compaction causes a decrease in density, and thus in the value of the bulk specific gravity of the mix.

## 2.5 Influence of Actual and Effective Asphalt Content

As shown in Equation 1.8, the percent voids in the mineral aggregates, %VMA is directly proportional to the effective volume of asphalt, $V_{be}$. Variations in the actual asphalt content affect the %VMA.

The actual asphalt content, $P_b$, is related to the effective asphalt content, $P_{be}$, the asphalt absorption, $P_{ba}$, and to the proportion of aggregate in the mix, $P_s$, by the following relationship:

$$P_{be} = \%AC - \frac{P_{ba} \times P_s}{100} \qquad (2.5)$$

The asphalt content therefore may only indirectly affect the VMA value. In some cases, increasing the asphalt content and keeping the aggregate proportion constant will increase the effective asphalt content. In other instances, an increase in the asphalt content and a change in the aggregate proportion may cancel each other out and not provide noticeable changes in the effective asphalt content.

The relationship between the actual asphalt content, $P_b$, and the %VMA is therefore not as clearly established as the relationship between the effective asphalt content, $V_{be}$, and %VMA.

## 3.0 VARIOUS METHODS OF REPRESENTING MAXIMUM DENSITY LINES

### 3.1 Definition

The 0.45 chart is based on the Fuller maximum density curve, shown previously in Equation 2.1. In the case of the 0.45 curve, the exponent, n, is set to 0.45, and the line thus plotted is considered to be the maximum density line (Roberts et al. 1991).

### 3.2 Methods of Representing Aggregate Gradation

The different methods to plot the 0.45 chart rely on different definitions of the maximum aggregate size in the gradation, D. There are six major methods listed in the literature (Aschenberg and MacKean, 1992). Table 3.1 lists these methods. The first five of these methods define the maximum density as the one plot from the origin to the points corresponding to 1) 100% passing and corresponding sieve size, 2) 100% passing and maximum sieve that retained aggregate, 3) actual % passing and maximum sieve that retained aggregate, 4) 100% passing and nominal maximum sieve size, 5) actual % passing and nominal maximum sieve size. The sixth density line is referred to as the Texas reference gradation line, and is drawn from the actual percent passing the largest sieve to retain any material to the actual percent passing the No. 200 sieve (75 µm opening).

**Table 3.1. Methods of Plotting the 0.45 Chart**

| METHOD |
|---|
| 100% Passing and Corresponding Sieve Size |
| 100% Passing and Maximum Sieve that Retained Aggregate |
| Actual % Passing and Maximum Sieve that Retained Aggregate |
| 100% Passing and Nominal Maximum Sieve Size |
| Actual % Passing and Nominal Maximum Sieve Size |
| Texas Reference Gradation Line |

The maximum density line is often used to adjust paving mixtures. For example, should a designer want to increase %VMA, they would simply select a job-mix formula that increased the distance from the maximum density line relative to their initial job-mix formula. The maximum density line is a relative "tool" to adjust paving mixtures volumetric properties.

## 4.0 STANDARD MIX DESIGN METHODS

### 4.1 Marshall Method

The Marshall Method of Mix Design is a HMA mix design method that is applicable to mixes containing aggregates whose maximum size are 1 inch. It was initially developed by Mr. Bruce Marshall, while serving as a Bituminous Engineer with the Mississippi State Highway Department (Asphalt Institute, 1989). The US Corps of Engineers later modified the procedure, which was then standardized and designated ASTM D 1559 (ASTM, 1995).

Once the aggregate blend has been selected and the specific gravity values of these aggregates determined, the engineer can begin the procedure. The Marshall mix design method is divided into four steps that are followed for each of the trial mixes (ASTM, 1995): the preparation of the test specimens for different levels of asphalt content (ASTM D 1559), the determination of the bulk specific gravity (ASTM D 1188), that of the values of the Marshall stability and the flow (ASTM D 1559), and the unit weight and void determination. Using the data for all these trial mixes, test property curves are then plotted for percent air voids, VMA, VFA, and unit weight of the mix (ASTM D 2726), stability, and flow, versus asphalt content.

Based on acceptability criteria, the asphalt content that satisfies the mix design parameters is selected from the test's properties charts. These acceptability criteria, or criteria for a satisfactory paving mix, are defined by specifications issued by the relevant regulatory agency.

The advantages of the Marshall method are the relative low cost of the procedure and the attention it places on density and void properties of asphalt mixes.

The method has two major disadvantages, however. First, the manner in which Marshall samples are prepared, using impact compaction, does not accurately replicate mixture densification as it occurs during actual field conditions. In addition, the Marshall stability value is not considered to properly reflect true pavement strength (Foster, 1982). Marshall stability is also not an adequate estimate of pavement shear strength (Asphalt Institute, 1989).

Because of these reasons, the Marshall method does not accurately estimate future pavement fatigue failure, or rutting, and thus is not an accurate predictor of performance under actual field conditions.

### 4.2 Hveem Method

The concepts of the Hveem method of mix design have been developed under the direction of Francis N. Hveem, during his tenure as a Materials Research Engineer with the California Department of Transportation (Asphalt Institute, 1989). The Hveem method of mix design is applicable to paving mixtures containing aggregates of a maximum size of 1 in. (25 mm). The method has been standardized and the test procedures are found in ASTM D 1560 and ASTM D 1561 (ASTM, 1995).

Initially, the appropriate aggregate blend must be selected and the specific gravity values of these aggregates determined. The Hveem mix design method is divided into four steps (ASTM, 1995) that are followed for each of the trial mixes: 1) the preparation of the test specimens for different percentages of asphalt content (ASTM D 4074), 2) determination of the molded specimens bulk specific gravity (ASTM D 1188 and 2726), 3) determination of Hveem stability (ASTM D 1559) for all molded specimens, and 4) the unit weight and void determination.

Using the data for all these trial mixes, test property curves are plotted for percent air voids, unit weight of the mix, and stability versus asphalt content. Based on these charts, the optimum asphalt content is selected as the highest percentage of asphalt that the mix will accommodate without reducing the stability below minimum values (Asphalt Institute, 1995b).

In addition, to the fact that the mixture resistance to swell is also often measured, the Hveem method has two advantages over the Marshall method. First, the densification of pavements in field conditions is better simulated by the kneading method of laboratory compaction. The Hveem stability is also considered to be a good estimate of shear strength, since it measures the ability of a test specimen to resist lateral displacement from application of a vertical load (Asphalt Institute, 1995a).

Aside from the fact that a Hveem mix design costs significantly more than a Marshall mix design, a major disadvantage of the Hveem method is that important mixture properties that are related to pavement durability are not routinely determined as part of the design procedure. In addition, it is believed (Asphalt Institute, 1995a), that the method of selecting asphalt content in the Hveem method is not objective enough and that it may result in mixes with critically low asphalt contents.

## 4.3 The Need for a Nationally Standardized Mix Design Method

Structural failures in flexible pavements that are directly related to mix design may result from surface fatigue, consolidation, or shear (Yoder and Witczak, 1975). Both the Marshall and Hveem mix design method provide satisfactory volumetric data to address consolidation problems, and the Hveem method provides satisfactory estimates of the shear strength of pavements. There is still, however, a need for a method that predicts performance as it relates to permanent deformation, low temperature cracking and fatigue failure in actual field conditions.

Various states and government agencies have attempted to develop methods that alleviate the shortcomings of the existing procedures (Collins, 1996). This resulted in a multitude of mix design procedures that vary among the many state and governmental regulatory agencies that are responsible for different portions of the national highways. This results not only in duplicated efforts and waste, but also in incompatible requirements, as well as limits the potential for economic comparisons of alternate materials.

The need for a new mix design method to be adopted at the national level is therefore essential, since it will not only provide a better performance prediction, but will also limit the flurry of method standards and regulations.

## 5.0 THE SUPERPAVE™ MIX DESIGN SYSTEM

In late 1987, the Strategic Highway Research Program (SHRP) targeted 50 million dollars to develop a performance base specification for HMA paving mixtures. As a direct result of this research, the Superior Performance Asphalt Pavement (i.e., Superpave™) system was developed. Superpave represents an improved system for specifying asphalt binders, mineral aggregates and developing asphalt mixture designs. The system also allows for predicting and analyzing paving mixture performance.

Figure 5.1 illustrates the Superpave™ mix design system. The Superpave™ mix design procedure is divided into three parts, binder selection, aggregate blend selection, and mix design procedure.

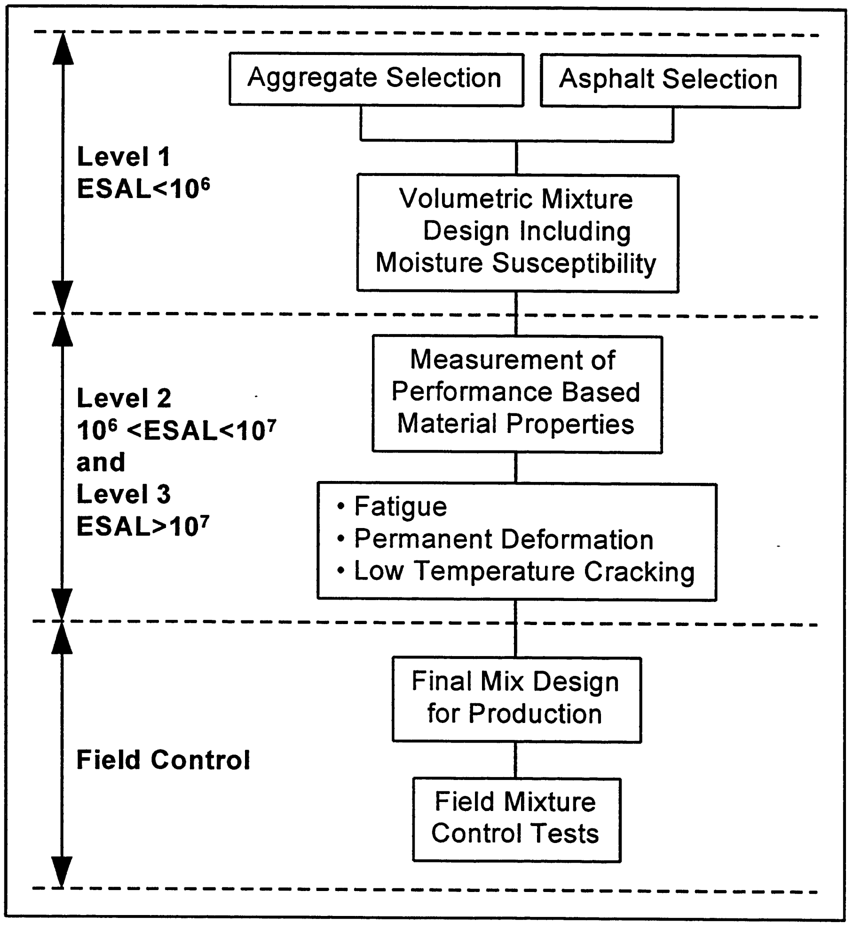


Figure 5.1 The Superpave™ Mix Design System.

Binder and aggregate selection is based on specific requirements issued by the Superpave™ system for asphalt binders and mineral aggregates. The binder tests for the most part are novel. Whereas the aggregate tests provide little advances to general practice.

The performance based tests and prediction models are important developments from the Superpave™ research program that address this problem (Asphalt Institute, 1995a). The models predict the performance life of an HMAC design based on Equivalent Single Axle Load (ESAL). Three mix design levels are defined, each are a function on the level of ESALs. Level 1, is for ESALs less than $10^6$, level 2 for ESALs between $10^6$ and $10^7$, and level 3 for ESALs higher than $10^7$.

The models developed in the SHRP research program have met some opposition as they began their implementation process. Significant evidence exists that the models, as delivered in the SHRP program require significant revisions prior to full implementation. Currently, the Superpave system makes use of the volumetric analysis system only. Future research could further refine these models and subsequently provide full implementation in the industry.

## 5.1 The Superpave™ Level 1 Mix Design Procedure

As outlined previously, the Superpave™ Level 1, volumetric mix design is used when the estimated ESALs are less than $10^6$. Once the binder has been selected, three different gradations are defined (a fine, an intermediate, and a coarse gradation).

The sample is then placed in the Superpave™ gyratory compactor and tested according to AASHTO TP 4 (AASHTO, 1995). Asphalt mixtures are designed at a specified level of compactive effort as a function of the design level of gyrations, $N_{des}$. Two other levels of gyration are also considered, the initial number of gyrations, $N_{ini}$, that is used to estimate the level of compactibility, and the maximum number of gyrations, $N_{max}$, at which the test specimen is compacted.

The effective specific gravity for each of the three blends, $G_{se}$, is determined as a function of the bulk specific gravity of the aggregate in the blend, $G_{sb}$, and of the apparent specific gravity of the mix, $G_{sa}$. It is given by:

$$G_{se} = G_{sb} + 0.8 \times (G_{sa} - G_{sb}) \qquad (5.1)$$

The percent volume of the asphalt binder, $V_{ba}$, is determined for a case when the sample has a 5% asphalt content by total weight of mix, a 95% aggregate percentage by total weight of mix, and a 4% air voids by total volume of mix. The percent volume of the asphalt binder is then given by:

$$V_{ba} = \frac{95 \times (100-4) \times \left(\frac{1}{G_{sb}} - \frac{1}{G_{se}}\right)}{\frac{5}{G_{ac}} + \frac{95}{G_{se}}} \tag{5.2}$$

Where $G_{ac}$ is the specific gravity of the asphalt. The effective volume of the binder, $V_{be}$, is then determined from the following empirical equation

$$V_{be} = 0.081 - 0.02931 \times \mathrm{Ln}|S_n| \tag{5.3}$$

Where $S_n$ is the largest sieve number in the gradation. An estimate of the percent by weight of binder, $P_{b,est}$, is determined as follows:

$$P_{b,est} = 100 \times \frac{G_{ac} \times (V_{be} + V_{ba})}{G_{ac} \times (V_{be} + V_{ba}) + W_s} \tag{5.4}$$

Where $W_s$, the weight of aggregates is estimated for a 95% aggregate percentage by total weight of mix, and a 4% air voids by total volume of mix. It is given by:

$$W_s = \frac{95 \times (1 - 0.04)}{\frac{5}{G_{ac}} + \frac{95}{G_{se}}} \tag{5.5}$$

The volume of the sample, $V_{est}$, is then estimated as a function of the diameter of the sample in the gyratory compactor, d, and the height of the sample in the mold during compaction, h. Assuming the sample to be smooth sided, the volume is given by:

$$V_{est} = \frac{\pi}{4} \times d^2 \times h \times 0.001 \tag{5.6}$$

Where h is a variable determined during the test. The estimated bulk specific gravity of the mix at any gyration level, $G_{mb,est}$, is then computed as:

$$G_{mb,est} = \frac{W}{V_{est} \times \gamma_o} \tag{5.7}$$

Where, W, is the weight of the sample in air. Since samples are not smooth sided, the volume would be over estimated, and the estimated bulk specific gravity of the mix under estimated. The specific gravity will then have to be corrected. After the compaction has been completed, the estimated bulk specific gravity ($G_{mb,est}$) of the mix at the maximum number of gyrations ($G_{mb,est}$@$N_{max}$), and the measured bulk specific gravity of the mix, ($G_{mb,measured}$), is then determined from test AASHTO 166 / ASTM D 2726 (Asphalt Institute, 1993). A correction factor, C, is then calculated as follows:

$$C = \frac{G_{mb,measured}}{G_{mb,est}@N_{max}} \tag{5.8}$$

The corrected bulk specific gravity of the mix at any other gyration level, $G_{mb,corr}$, is then computed as:

$$G_{mb,corr} = C \times G_{mb,est} \tag{5.9}$$

The air voids, $\%V_a$, are then determined as a function of the maximum theoretical specific gravity at $N_{des}$, $\%G_{mm}@N_{des}$:

$$\%V_a = 100 - \%G_{mm,corr}@N_{des} \tag{5.10}$$

The percent voids in the mineral aggregate, %VMA, is then determined as:

$$\%VMA_{initial} = 100 - \%G_{mm}@N_{des} \times G_{mm} \times \frac{P_s}{G_{sb}} \tag{5.11}$$

Where $G_{mm}$ is the maximum theoretical specific gravity of the mix, which is computed from Equation 1.5 or from test AASHTO T 209 / ASTM D 2041 (Asphalt Institute, 1993).

The estimated asphalt content at $N_{des}$ and 4 % air voids is then computed as:

$$P_{b,est} = P_{bi} - 0.4 \times (4 - V_a) \tag{5.12}$$

Where $P_{bi}$ is the initial (trial) asphalt content, and $V_a$ is the percent air voids at $N_{des}$ (trial). The estimated voids in the mineral aggregates, $VMA_{est}$, are then determined as:

$$\%VMA_{est} = \%VMA_{initial} + K \times (4 - V_a) \tag{5.13}$$

Where K is a constant equal to 1.0 if $V_a$ is less than or equal to 4%, and 2.0 if $V_a$ is more than 4%.

The estimated voids filled with aggregates, $VFA_{est}$, is then determined as:

$$\%VFA_{est} = 100 \times \frac{\%VMA_{est} - 4.0}{\%VMA_{est}} \tag{5.14}$$

The estimated percentages of the maximum theoretical specific gravity of the mix, $\%G_{mm}$, are determined at $N_{ini}$ and $N_{max}$ based on the trial $\%G_{mm}$ at $N_{ini}$ and $N_{max}$, and is given by:

$$\%G_{mm,est}@N_{ini} = \%G_{mm,trial}@N_{ini} - (4 - V_a) \tag{5.15}$$

$$\%G_{mm,est}@N_{max} = \%G_{mm,trial}@N_{max} - (4 - V_a) \qquad (5.16)$$

Superpave™ specifies limits of 89% on $\%G_{mm}@N_{ini}$, and 98% on $\%G_{mm}@N_{max}$.

The effective asphalt binder content, $P_{be}$, is then calculated as a percentage by total weight of mix as:

$$P_{be} = -P_s \times G_b \times \frac{G_{se} - G_{sb}}{G_{se} \times G_{sb}} + P_{b,est} \qquad (5.17)$$

Dust proportion, DP, is also a characteristic that is considered in Superpave™ designs. It is computed as a ratio of the percentage by total weight of mix of aggregates smaller than 75 µm (Passing the No. 200 sieve), $P_{75\mu m}$, and the effective asphalt content, $P_{be}$. The Superpave™ specification limits dust to effective asphalt ratio should range from 0.6 to 1.2.

A trial mix is considered acceptable if the values for the specified characteristics are within specifications. These characteristics are the percent air voids, $\%V_a$, percent voids in the mineral aggregates, %VMA, percent voids in the mineral aggregate that are filled with asphalt, %VFA, the dust proportion, DP, and percentages of the maximum theoretical specific gravity of the mix at $N_{ini}$ and $N_{max}$, $\%G_{mm}@N_{ini}$ and $\%G_{mm}@N_{max}$.

## 5.2 The Superpave™ Analysis and Performance Mix Design Procedures

Superpave™ analysis and performance (i.e., levels 2 and 3) mix designs are specified respectively for ESALs between $10^6$ and $10^7$, and for ESALs higher than $10^7$.

The requirements for level 2 are the same as those for level 1, with additional performance requirements that test for permanent deformation, fatigue cracking and low temperature cracking. The required tests are the simple shear strength test and frequency sweep test at constant sample height, indirect tensile strength test, indirect tensile creep compliance test, and binder creep stiffness and creep rate test.

The requirements for level 3 are the same as those for level 1, with additional enhanced performance requirements that investigate potential for permanent deformation, fatigue cracking and low temperature cracking. The required tests are uniaxial strain test, simple shear strength test and frequency sweep test at constant sample height, volumetric test, indirect tensile strength test, indirect tensile creep compliance and creep test, and binder creep stiffness and creep rate test. These tests are performed at different ranges of temperature.

At the time this report was written, these tests were not standardized, and further work was being undertaken to refine them.

# 6.0 KNOWN METHODS OF ESTIMATING VOIDS IN THE MINERAL AGGREGATE

Two methods to estimate aggregate voidage were found in the literature: a method by Hudson & Davis, and an empirical method by Hensley.

## 6.1 Hudson & Davis Method of Estimating VMA

This method (Hudson and Davis, 1965) estimates the voidage based solely on the aggregate gradation. The percent passing is determined for a given aggregate combination, and a ratio is computed. The percent passing considered is only for the following sieve sizes: #200, #100, #50, #30, #16, #8, #4, 3/8", 3/4", and 1½". Factors are then determined from tables. The void in the mineral aggregate is determined as the product of the voidage and that factor.

For each gradation i, a ratio, $R_i$, is determined as a function of the percent passing for that gradation, $P_i$, and the percent passing the next smaller sieve size in the specified gradation, $P_{i-1}$. The ratio is computed as follows:

$$R_i = \frac{P_i}{P_{i-1}} \qquad (6.1)$$

In their paper, Hudson and Davis suggest that the ratio be rounded to the nearest 0.05. Voidage reduction factors were determined based on the following equation:

$$F = \left(\frac{V_2}{V_1}\right)^{\frac{1}{n}} \qquad (6.2)$$

Where $V_2$ is the percent by volume of aggregate voids in the compacted mix, $V_1$ is the percent by volume of the voids, and n the number of size groups of aggregates in the total mix. Table 6.1 provides voidage reduction factors for round aggregates, $F_r$, and for angular aggregates, $F_a$, both as a function of ratio R.

**Table 6.1. Voidage-Reduction Factors**

| R | Fr | Fa |
|---|---|---|
| 1.00 | 1.000 | 1.000 |
| 1.11 | 0.9583 | 0.970 |
| 1.15 | 0.9325 | 0.951 |
| 1.20 | 0.9098 | 0.935 |
| 1.25 | 0.9015 | 0.924 |
| 1.30 | 0.8945 | 0.920 |
| 1.35 | 0.8908 | 0.919 |
| 1.40 | 0.8908 | 0.919 |
| 1.50 | 0.8971 | 0.921 |
| 1.55 | 0.9032 | 0.924 |
| 1.60 | 0.9107 | 0.926 |
| 1.70 | 0.9260 | 0.938 |
| 1.75 | 0.9332 | 0.947 |

| R | Fr | Fa |
|---|---|---|
| 1.80 | 0.9400 | 0.955 |
| 1.90 | 0.9528 | 0.970 |
| 1.95 | 0.9589 | 0.978 |
| 2.00 | 0.9647 | 0.985 |
| 2.05 | 0.9703 | 0.993 |
| 2.10 | 0.9757 | 1.000 |
| 2.15 | 0.9805 | |
| 2.20 | 0.9856 | |
| 2.30 | 0.9953 | |
| 2.35 | 1.0000 | |
| 2.40 | 1.0045 | |
| 2.50 | 1.0133 | |
| | | |

Based on these factors, a voidage value is then determined as a percentage by total volume of voids in the mineral aggregate, %VMA:

$$\%V_i = \sum_{i=2}^{n} V_{i-1} \times F_i \qquad (6.3)$$

Where $F_i$ is the voidage reduction factor determined for that aggregate gradation i, and $V_i$ is the voidage for that gradation. The initial voidage, $V_{1"}$, is assumed to be equal to 32% for commercial limestone fillers, and 38% for rock dust.

The percentage by total volume of voids in the mineral aggregate, %VMA, is then determined as the voidage value for the 3/4" sieve. The % VMA is given by:

$$\%VMA = V_{\frac{3}{4}"} \qquad (6.4)$$

An example of this method is shown in Table 6.2. This method results in a final VMA of 16.49%.

**Table 6.2. Example of Computation by the Hudson and Davis Method**

| Sieve | %Pass | $R_i$ | $R_i$ | $F_a$ | $V_i$ |
|---|---|---|---|---|---|
| # 200 | 5.0 | 1.39 | 1.40 | 0.919 | 29.41 |
| # 100 | 7.0 | 1.57 | 1.55 | 0.924 | 27.17 |
| # 50 | 10.9 | 1.46 | 1.45 | 0.920 | 25.00 |
| # 30 | 15.9 | 1.35 | 1.35 | 0.919 | 22.97 |
| # 16 | 21.5 | 1.47 | 1.50 | 0.921 | 21.16 |
| # 8 | 31.7 | 1.48 | 1.50 | 0.921 | 19.49 |
| # 4 | 46.9 | 1.56 | 1.50 | 0.921 | 17.95 |
| 3/8 " | 73.1 | 1.37 | 1.35 | 0.919 | 16.49 |
| 3/4 " | 100.0 | 1.00 | 1.00 | 1.000 | 16.49 |
| 1 1/2 " | 100.0 | | | | |
| Angular Aggregate Initial Voidage = 32.00 % | | | | | |
| **% VMA** = 16.49 % | | | | | |

## 6.2 Hensley Method of Estimating VMA

This method (Hensley, 1985) is an empirical method that uses regression analysis to predict the void in the mineral aggregate, VMA, as a function of the percent air voids, $V_a$, the percent by weight of asphalt, %AC, and the aggregate water absorption, $P_{abs}$. The empirical equation is as follows:

$$\%VMA = \%V_a + 1.69 + 2.02 \times \%AC - 0.35 \times P_{abs} \qquad (6.5)$$

In developing the method, the author relied on data from 39 test sites and over 200 mixes that performed well over time periods ranging from 6 months to 23 years (Hensley, 1985).

## 6.3 ATSER Method of Estimating VMA

ATSER has developed an estimate of the %VMA that does not require the determination of $G_{mb}$, the bulk specific gravity of the mix (ATSER, 1996). The estimated percentage of voids in the mineral aggregate in the total volume, $VMA_{est}$ in %, is defined by the following equation as (Asphalt Institute, 1995b):

$$VMA_{est} = V_a + V_{be} \tag{6.6}$$

Where $V_a$, in %, is the proportion by total volume of air contained in the total mix, and $V_{be}$, in %, is the proportion by total volume of the effective asphalt binder. The ATSER method calculates the value of $V_{be}$ by using the following equation:

$$V_{be} = F_n \times V_{bex} \tag{6.7}$$

Where $V_{bex}$ is the proportion by total volume of the effective binder for an aggregate blend of maximum density, and $F_n$ is a semi-empirical factor computed by Asphalt-It™, the HMAC mix design software developed by ATSER Systems.

## 6.4 Evaluation of the Three Methods of Predicting %VMA

Marshall mix designs were provided by the departments of transportation of Montana (MDT) and Georgia (GDOT). All three methods were used to compute the %VMA based on the submitted data. Table 6.3 and 6.4 present MDT and GDOT data, respectively. Figure 6.1 and 6.2 illustrate the variability of the methods.

**Table 6.3. Results of the Three Methods of Predicting %VMA (MDT Data)**

| **File** | Test01 | Test02 | Test03 | Test04 | Test05 | Test06 | Test07 | Test08 | Test09 | Test10 | Test11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Data | **15.0** | **16.93** | **16.31** | **16.03** | **16.48** | **14.93** | **16.2** | **15.97** | **16.50** | **14.20** | **13.85** |
| Hensley | 15.66 | 17.76 | 16.75 | 17.08 | 16.73 | 16.73 | 15.82 | 16.55 | 17.12 | 17.32 | 16.47 |
| ATSER | 14.50 | 14.67 | 14.58 | 14.45 | 14.63 | 14.63 | 14.66 | 14.77 | 14.73 | 14.64 | 14.64 |
| Hudson/Davis | 16.49 | 16.82 | 16.49 | 17.26 | 16.57 | 16.60 | 16.82 | 16.55 | 16.64 | 16.57 | 16.60 |
| **File** | Test12 | Test13 | Test15 | Test16 | Test17 | Test18 | Test19 | Test20 | Test21 | Test22 | Test24 |
| Actual Data | **15.18** | **14.86** | **15.99** | **15.67** | **16.86** | **16.71** | **15.31** | **15.59** | **16.67** | **16.46** | **15.7** |
| Hensley | 14.37 | 16.31 | 17.22 | 17.56 | 17.48 | 17.16 | 18.21 | 17.52 | 16.61 | 16.67 | 16.65 |
| ATSER | 14.71 | 14.66 | 14.24 | 14.69 | 14.67 | 14.75 | 14.75 | 14.64 | 14.58 | 14.63 | 14.73 |
| Hudson/Davis | 16.27 | 16.58 | 16.44 | 16.73 | 16.67 | 16.35 | 16.67 | 16.57 | 18.35 | 16.78 | 16.51 |
| **File** | Test25 | Test26 | Test27 | Test30 | Test31 | Test32 | Test33 | Test35 | Test36 | Test41 | Test42 |
| Actual Data | **16.13** | **15.43** | **15.75** | **15.30** | **14.12** | **15.51** | **14.34** | **17.86** | **15.52** | **15.71** | **14.25** |
| Hensley | 16.53 | 16.83 | 16.25 | 16.85 | 16.27 | 16.65 | 17.46 | 18.45 | 17.22 | 16.65 | 16.85 |
| ATSER | 14.71 | 14.73 | 14.66 | 14.63 | 14.62 | 14.58 | 14.43 | 14.69 | 14.13 | 14.59 | 14.71 |
| Hudson/Davis | 16.41 | 16.49 | 16.39 | 16.51 | 16.44 | 16.44 | 16.41 | 16.51 | 16.49 | 16.55 | 16.82 |
| **File** | Test46 | Test47 | Test48 | Test49 | | | | | | | |
| Actual Data | **14.86** | **15.53** | **15.76** | **16.36** | | | | | | | |
| Hensley | 16.73 | 17.82 | 18.27 | 16.47 | | | | | | | |
| ATSER | 14.75 | 14.78 | 14.76 | 14.70 | | | | | | | |
| Hudson/Davis | 16.60 | 16.65 | 16.67 | 16.42 | | | | | | | |

**Table 6.4. Results of the Three Methods of Predicting %VMA (GDOT Data)**

| **File** | GA01 | GA02 | GA03 | GA04 | GA05 | GA06 | GA07 | GA08 | GA09 | GA10 | GA11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Data | **14.74** | **16.88** | **16.96** | **16.17** | **16.91** | **14.51** | **13.79** | **14.22** | **16.40** | **14.42** | **14.39** |
| Hensley | 14.47 | 16.39 | 16.45 | 15.88 | 16.67 | 14.27 | 13.66 | 14.11 | 16.05 | 14.19 | 14.19 |
| ATSER | 15.36 | 16.31 | 16.30 | 16.36 | 16.32 | 14.48 | 14.47 | 14.14 | 16.00 | 15.37 | 15.01 |
| Hudson/Davis | 17.22 | 17.33 | 17.97 | 18.45 | 17.73 | 16.12 | 16.41 | 16.69 | 16.82 | 16.32 | 16.82 |
| **File** | GA12 | GA13 | GA14 | GA15 | GA16 | GA17 | GA18 | GA19 | GA20 | GA21 | GA22 |
| Actual Data | **15.15** | **14.47** | **15.56** | **15.25** | **16.75** | **16.17** | **15.30** | **14.84** | **14.30** | **15.23** | **16.86** |
| Hensley | 15.02 | 14.37 | 15.44 | 15.14 | 16.63 | 16.07 | 15.20 | 14.75 | 14.35 | 14.98 | 16.61 |
| ATSER | 14.50 | 14.20 | 15.36 | 15.06 | 16.32 | 16.02 | 14.57 | 14.27 | 14.42 | 14.12 | 16.35 |
| Hudson/Davis | 16.27 | 16.27 | 17.66 | 17.20 | 17.20 | 17.20 | 18.78 | 16.56 | 16.73 | 16.73 | 16.73 |
| **File** | GA23 | GA24 | GA25 | GA26 | | | | | | | |
| Actual Data | **16.08** | **15.85** | **16.55** | **16.30** | | | | | | | |
| Hensley | 15.84 | 15.64 | 16.39 | 16.17 | | | | | | | |
| ATSER | 15.36 | 16.05 | 16.37 | 16.07 | | | | | | | |
| Hudson/Davis | 17.60 | 18.35 | 17.64 | 17.64 | | | | | | | |

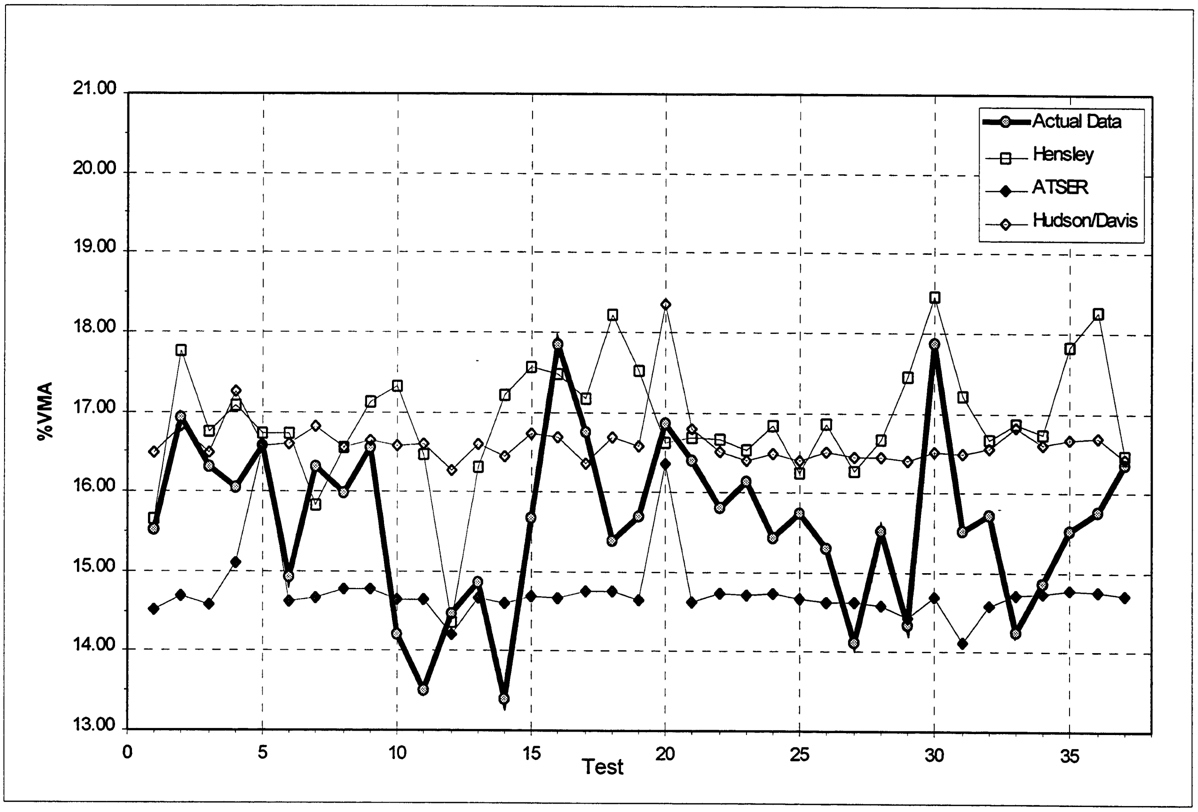


**Figure 6.1 Results of the Three Methods of Predicting %VMA (MDT Data)**

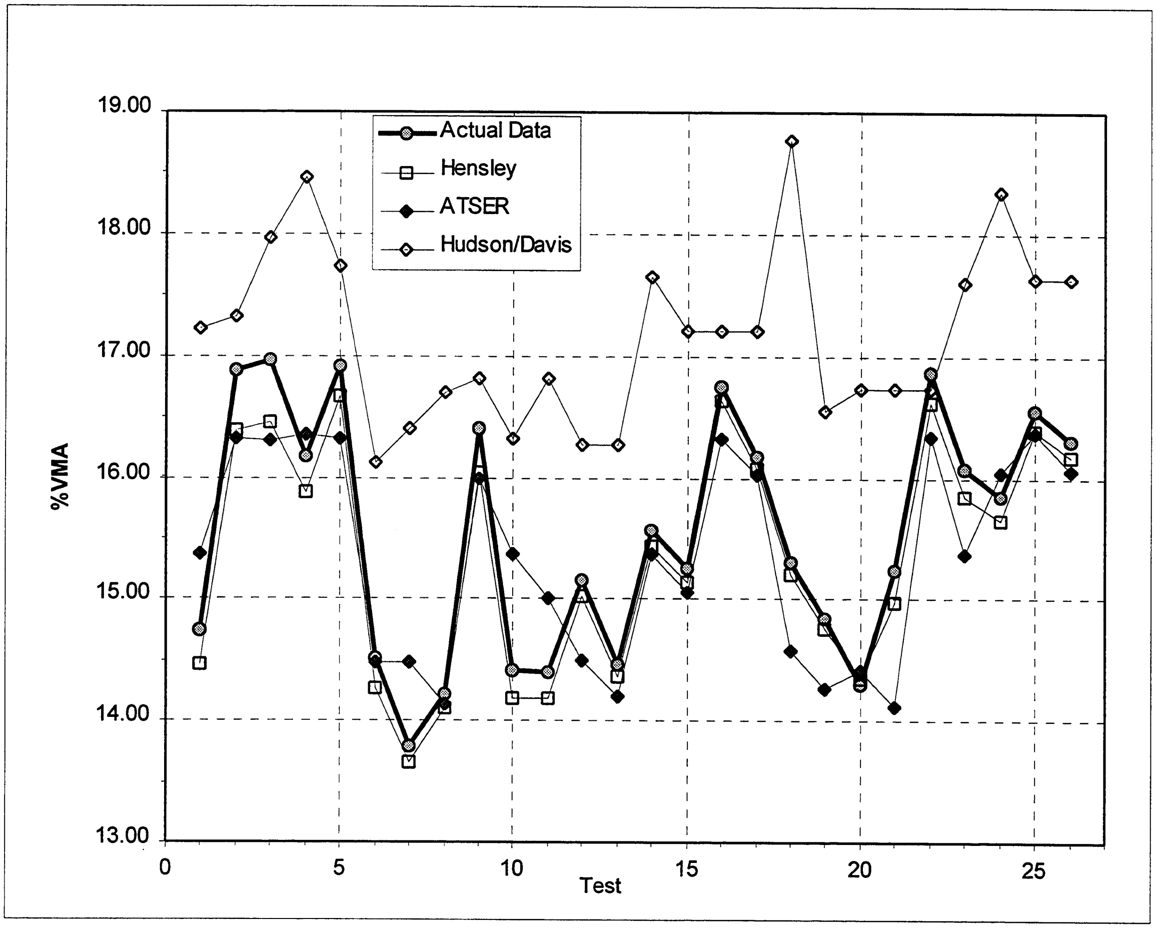


Figure 6.2 Results of the Three Methods of Predicting %VMA (GDOT Data)

The data revealed that ATSER's method indeed provided an efficient method for estimating VMA. Hensley method was also effective; however, it required final laboratory test data. Hudson and Davis was a poor method of estimating VMA based on this data.

ATSER's method only required the aggregate specific gravity and gradations. The JMF is selected by the user. The volumetric properties can be quickly evaluated using this method.

## 7.0 PROPOSED MARSHALL ESTIMATION MODEL

### 7.1 Description of the Model

Figure 7.1 illustrates the prediction method to estimate a Marshall mix design. The procedure to develop an estimate of a Marshall mix design is as follows:

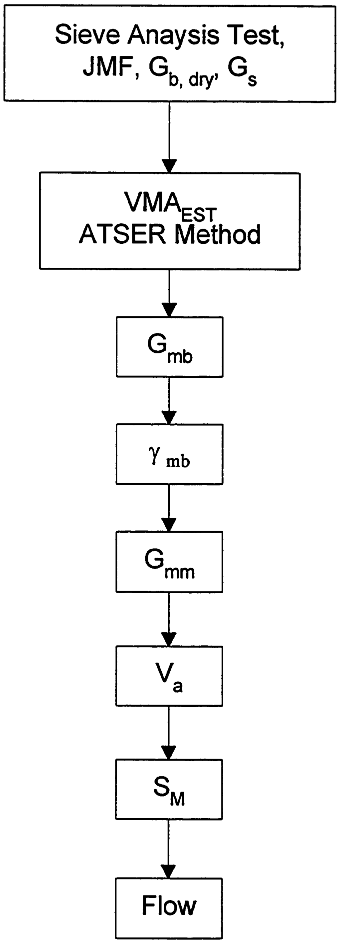


**Figure 7.1 The Proposed Marshall Estimation Procedure**

1. Conduct a sieve analysis to determine the gradation of the aggregates in the mix.

2. Estimate the percent void in the mineral aggregate, $\%VMA_{est}$, using Asphalt-It™.

3. Based on that corrected estimate of %VMA, the bulk specific gravity, $G_{mb}$, can then easily be determined for different values of asphalt content.

4. Determine the bulk unit weight, $\gamma_{mb}$ from the following equation:

$$\gamma_{mb} = G_{mb} \times \gamma_o \qquad (7.1)$$

5. Make a plot of unit weight versus asphalt content.

6. Determine the maximum theoretical specific gravity, $G_{mm}$, and plot it for different values of asphalt content. The maximum theoretical specific gravity is given by the following equation:

$$G_{mm} = \frac{100}{\frac{100 - \%AC}{G_{se}} + \frac{\%AC}{G_{ac}}} \qquad (7.2)$$

7. Determine the percentage by total volume of the mix of air voids, $V_a$, and plot it for different values of asphalt content. The air voids are computed as follows:

$$V_a = 100 \times \left(1 - \frac{G_{mb}}{G_{mm}}\right) \qquad (7.3)$$

8. Determine the Marshall stability, in lb., by using Asphalt-It™, and plot stability as a function of asphalt content.

9. Determine the flow by using Asphalt-It™, and plot it for different values of asphalt content.

## 7.2 Evaluation of the Model

The model was evaluated on two different sets of data that were obtained from the Montana (MDT) and Georgia Departments of Transportation (GDOT). The results of the comparisons for both data are summarized in Table 7.1.

**Table 7.1. Evaluation of the Model**

| | VMA | Gmb | AC | VFA | Stability | Flow |
|---|---|---|---|---|---|---|
| **Average Error (%)** | | | | | | |
| MDT | 7.32 | 1.31 | 5.21 | 2.64 | 54.35 | 25.08 |
| MDT (corr.) | 3.91 | N/A | N/A | 1.54 | N/A | N/A |
| GDOT | 2.90 | 0.32 | 4.09 | 1.05 | 23.37 | 26.14 |
| **Standard Deviation of the Error (%)** | | | | | | |
| MDT | 4.07 | 0.87 | 3.54 | 1.56 | 26.31 | 25.08 |
| MDT (corr.) | 3.10 | N/A | N/A | 1.34 | N/A | N/A |
| GDOT | 1.90 | 0.28 | 2.57 | 0.60 | 16.64 | 14.70 |
| **Coefficient of Variance of the Error (-)** | | | | | | |
| MDT | 0.56 | 0.67 | 0.68 | 0.59 | 0.48 | 0.69 |
| MDT (corr.) | 0.79 | N/A | N/A | 0.87 | N/A | N/A |
| GDOT | 0.66 | 0.87 | 0.63 | 0.56 | 0.71 | 0.56 |

The mixes from MDT incorporated aggregates with estimated gravities and different levels of water absorption. The results shown in the table are for GDOT and MDT. The MDT data is shown with and without correction for absorption. As shown for the MDT data, the absorption correction significantly improves the precision of the model, but still needs further testing. However, the existing model provided an excellent estimation "tool."

### 7.2.1 %VMA Estimation

Estimations for the %VMA were carried out on both MDT and GDOT data. The average error on the %VMA estimation on the data from MDT was 7.91%. A comparison between the model and actual data is shown in Figure 7.2 for the estimation of %VMA without absorption correction.

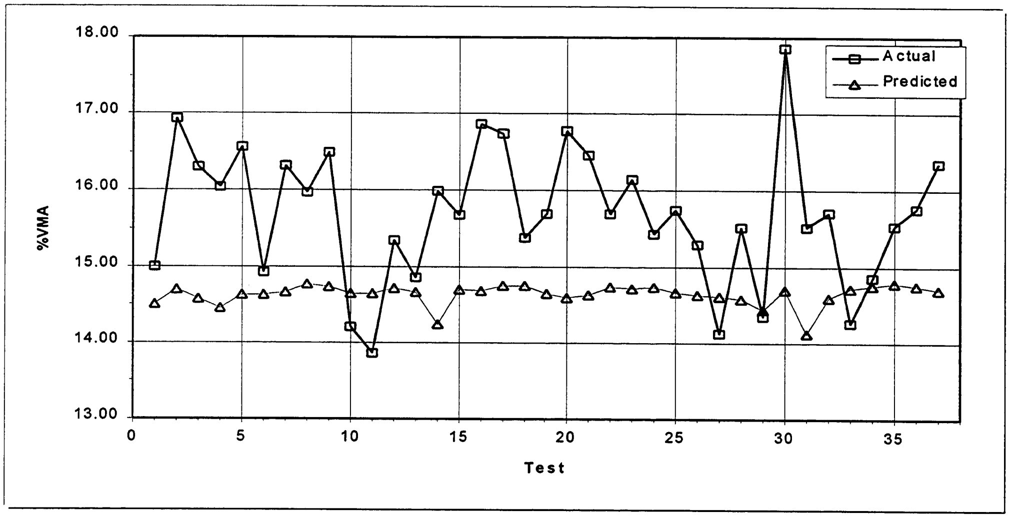


Figure 7.2 MDT Data: Estimation of the %VMA

When absorption was taken into account and incorporated into the model, the error on estimation of %VMA was reduced from 7.91% to 3.91%. A comparison between the model and actual data, in Figure 7.3, shows a significant improvement in the model. As seen in the figure, the corrected model fits the actual data very closely. The corrected model and the correction for absorption needs further evaluation.

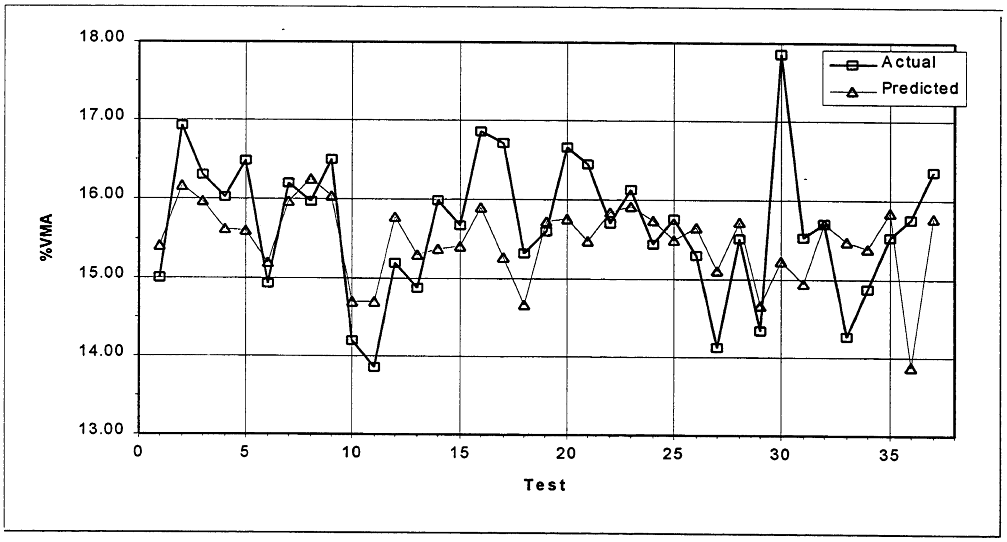


Figure 7.3 MDT Data: Corrected Estimation of the %VMA

The average error on the %VMA estimation on the data from GDOT was 2.90%. The comparison between the model and actual data is shown in Figure 7.4. The model fits the data very well.

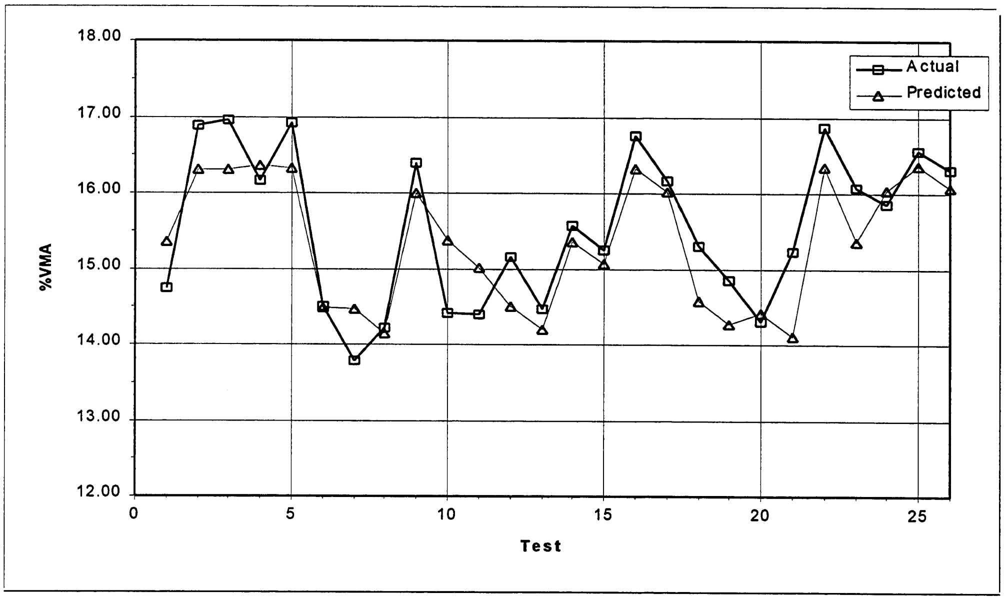


Figure 7.4 GDOT Data: Estimation of the %VMA

### 7.2.2 $G_{mb}$ Estimation

Estimations for the $G_{mb}$ were carried out on both MDT and GDOT data. The average error on the $G_{mb}$ estimation on the data from MDT was 1.31%. A comparison between the model and actual data is shown in Figure 7.5 for the estimation of $G_{mb}$ without absorption correction. While the model is shown to fit the data very closely, it is believed that correction for absorption will only improve the estimation.

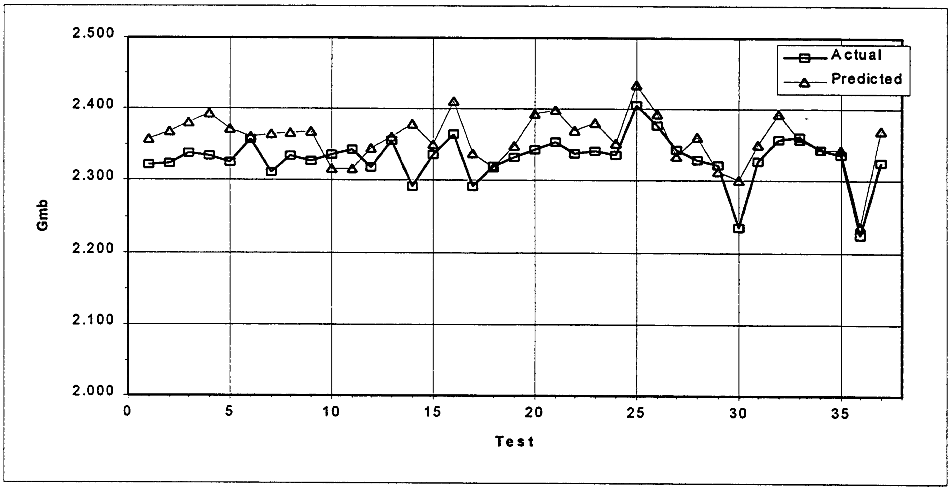


Figure 7.5 MDT Data: Estimation of $G_{mb}$

The average error on the $G_{mb}$ estimation on the data from GDOT was 0.32%. The comparison between the model and actual data is shown in Figure 7.6. The model fits the data very well.

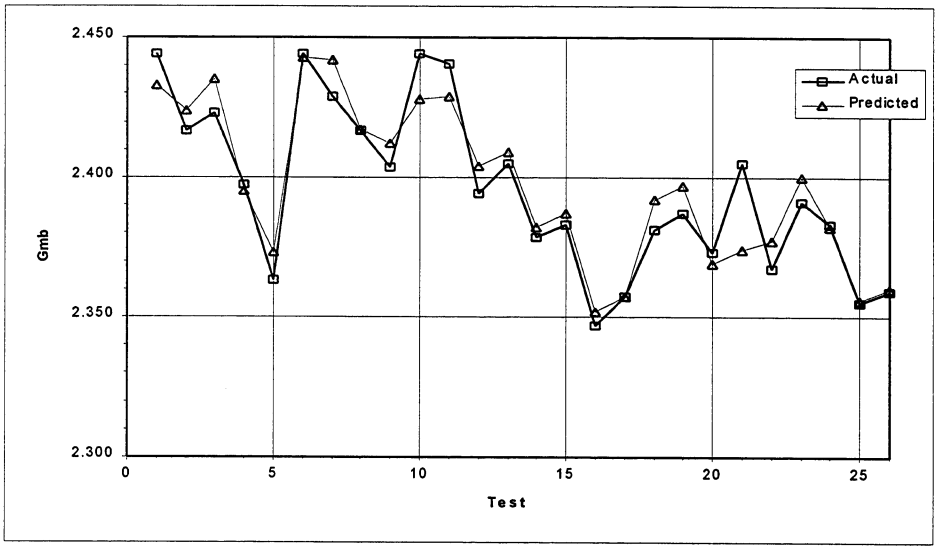


Figure 7.6 GDOT Data: Estimation of $G_{mb}$

### 7.2.3 %AC Estimation

Estimations for the %AC were carried out on both MDT and GDOT data. The average error on the %AC estimation on the data from MDT was 1.31%. A comparison between the model and actual data is shown in Figure 7.7 for the estimation of %AC without absorption correction. While the model is shown to fit the data very closely, it is believed that correction for absorption will only improve the estimation.

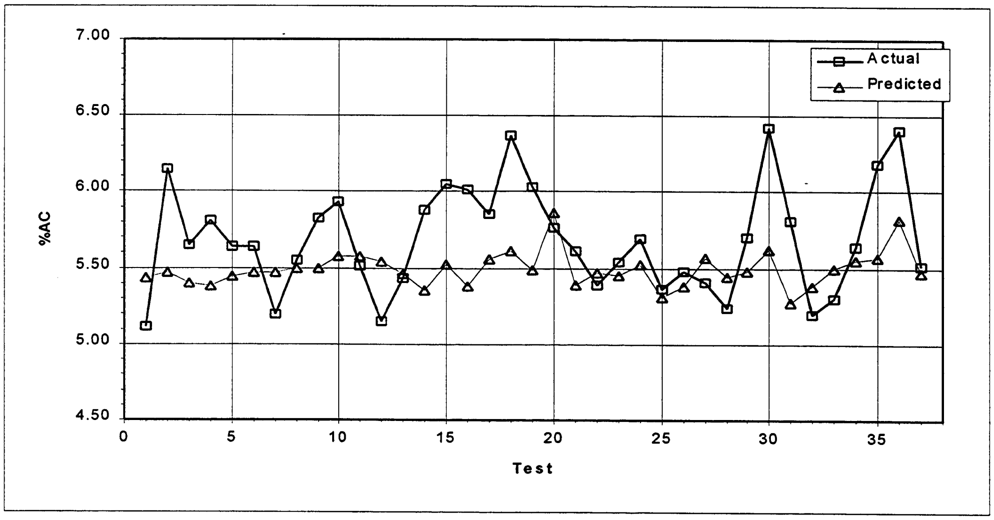


Figure 7.7 MDT Data: Estimation of the %AC

The average error on the %AC estimation on the data from GDOT was 0.32%. The comparison between the model and actual data is shown in Figure 7.8. The model fits the data very well.

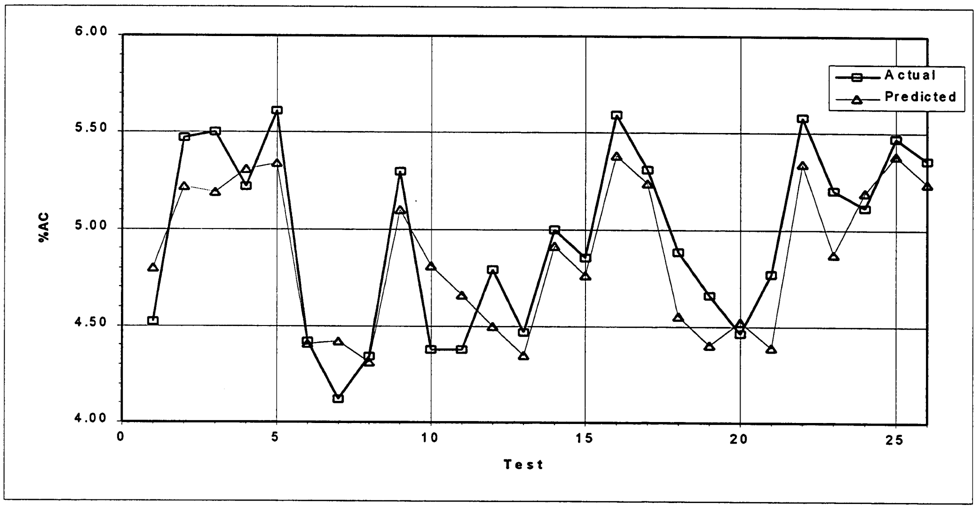


Figure 7.8 GDOT Data: Estimation of the %AC

### 7.2.4 %VFA Estimation

Estimations for the %VFA were carried out on both MDT and GDOT data. The average error on the %VFA estimation on the data from MDT was 2.64%. A comparison between the model and actual data is shown in Figure 7.9 for the estimation of %VFA without absorption correction.

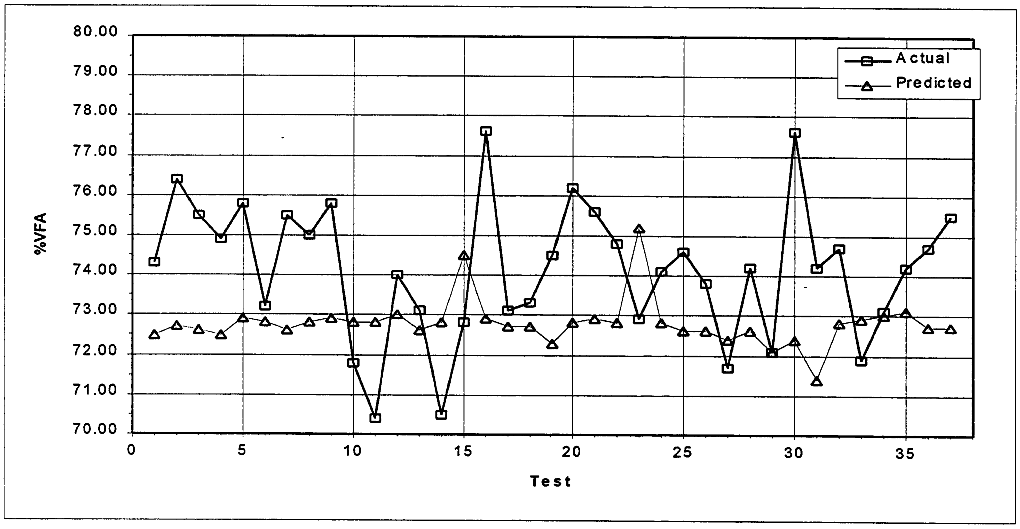


Figure 7.9 MDT Data: Estimation of the %VFA

When absorption was taken into account and incorporated into the model, the error on estimation of %VFA was reduced from 2.64% to 1.54%. In Figure 7.10, a comparison between the model and actual data shows this improvement. The new correction for absorption still needs further evaluation.

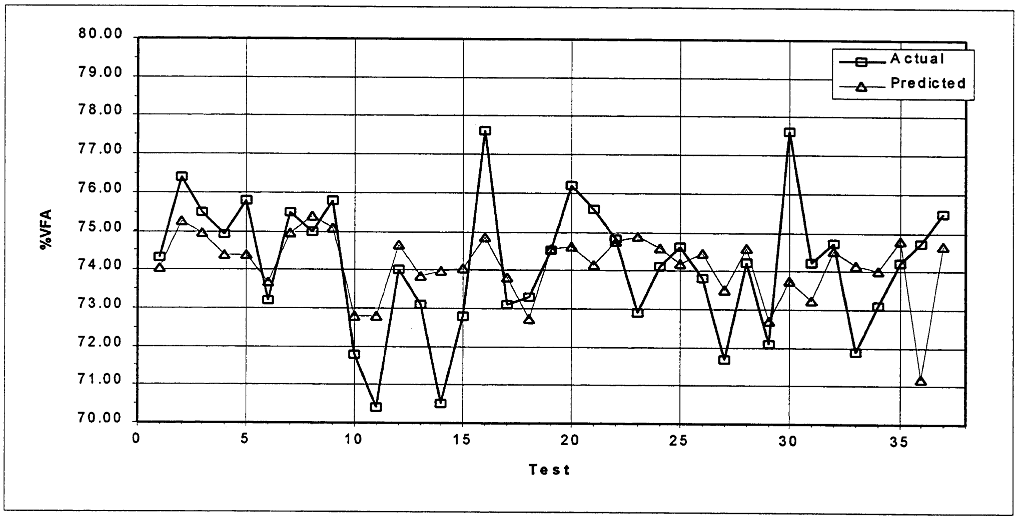


Figure 7.10 MDT Data: Corrected Estimation of the %VFA

The average error on the %VFA estimation on the data from GDOT was 1.05%. The comparison between the model and actual data is shown in Figure 7.11. The model fits the data very well.

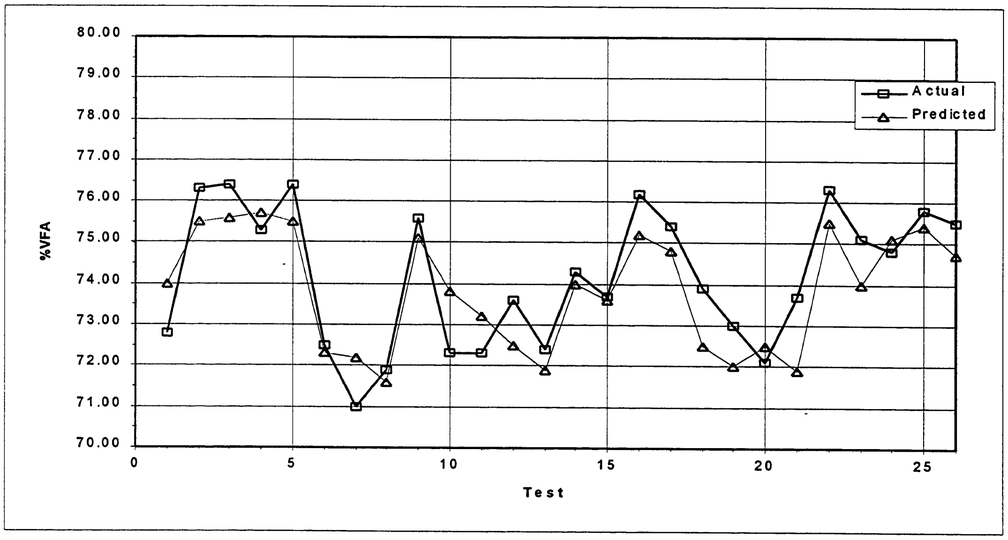


Figure 7.11 GDOT Data: Estimation of the %VFA

### 7.2.5 Estimation of Stability

Estimations for the stability were carried out on both MDT and GDOT data. The average error on the stability estimation on the data from MDT was 54.35%. A comparison between the model and actual data is shown in Figure 7.12 for the estimation of stability without absorption correction.

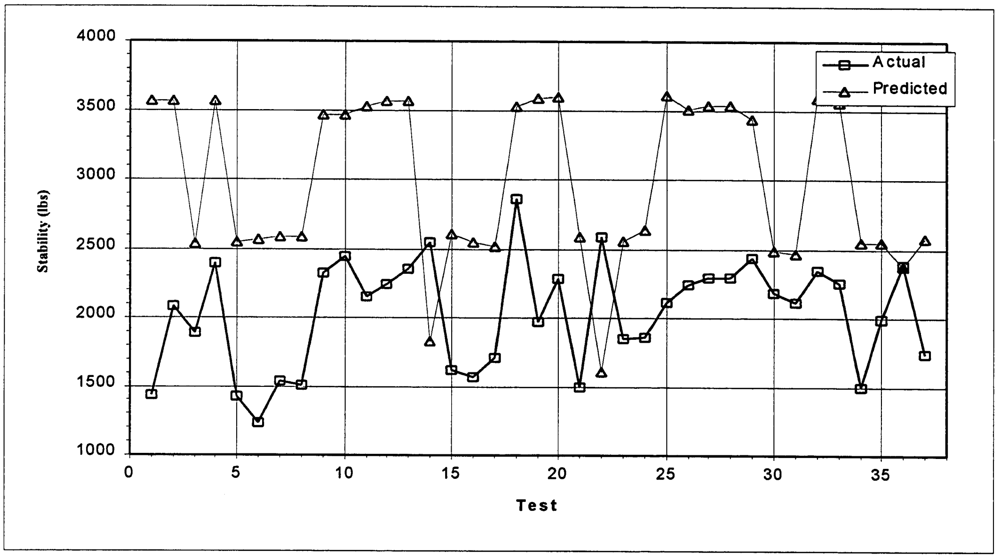


Figure 7.12 MDT Data: Estimation of Stability

The average error on the Marshall stability estimation on the data from GDOT was of 23.37%. The comparison between the model and actual data is shown in Figures 7.13. The model fits the data relatively well after applying the absorption correction.

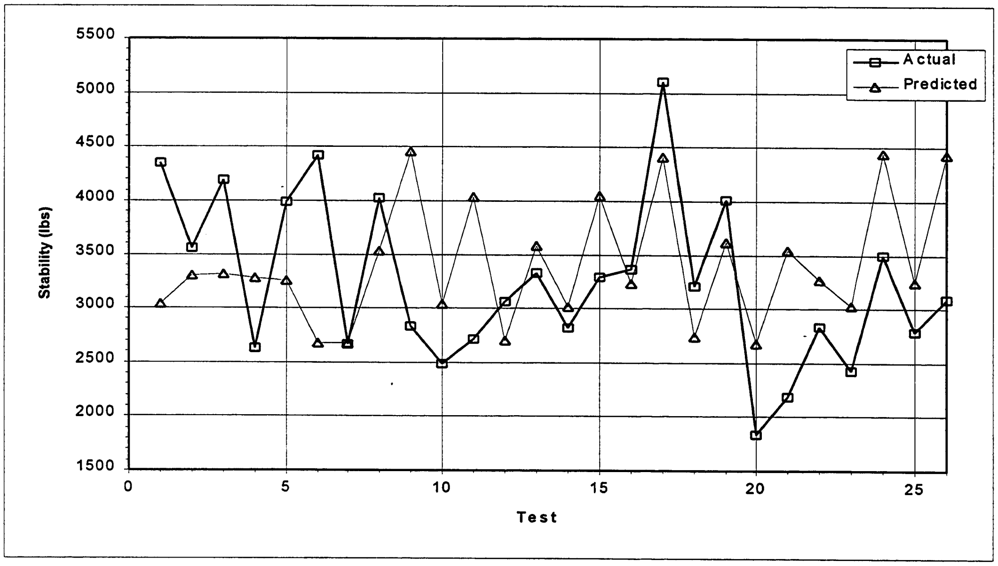


Figure 7.13 GDOT Data: Estimation of Stability

The Marshall stability test is essentially an unconfined compression test that cannot accurately represent actual field conditions (Road Research Laboratory, 1962). It is therefore not considered to properly reflect true pavement strength (Foster, 1982), and does not adequately reflect pavement properties such as shear strength (Asphalt Institute, 1989).

These reasons may explain the high average errors for the Marshall stability values. Since the parameter does not correlate well with mix parameters, it may not be accurately predicted by a model based on these parameters. It is therefore doubtful that any estimation model based on mix parameters would be able to accurately predict the Marshall stability value. Additionally, higher errors are expected since the repeatability of actual test methods approaches these values. Furthermore, because of the lack of correlation between Marshall stability and road performance, attempting to predict this value may not be worthwhile.

### 7.2.6 Estimation of Flow

Estimations for the Marshall flow were carried out on both MDT and GDOT data. The average error on the Marshall flow estimation on the data from MDT was 25.08%. A comparison between the model and actual data is shown in Figure 7.14 for the estimation of Marshall flow without absorption correction. While the model is shown to fit the data very closely, it is believed that correction for absorption will only improve the estimation.

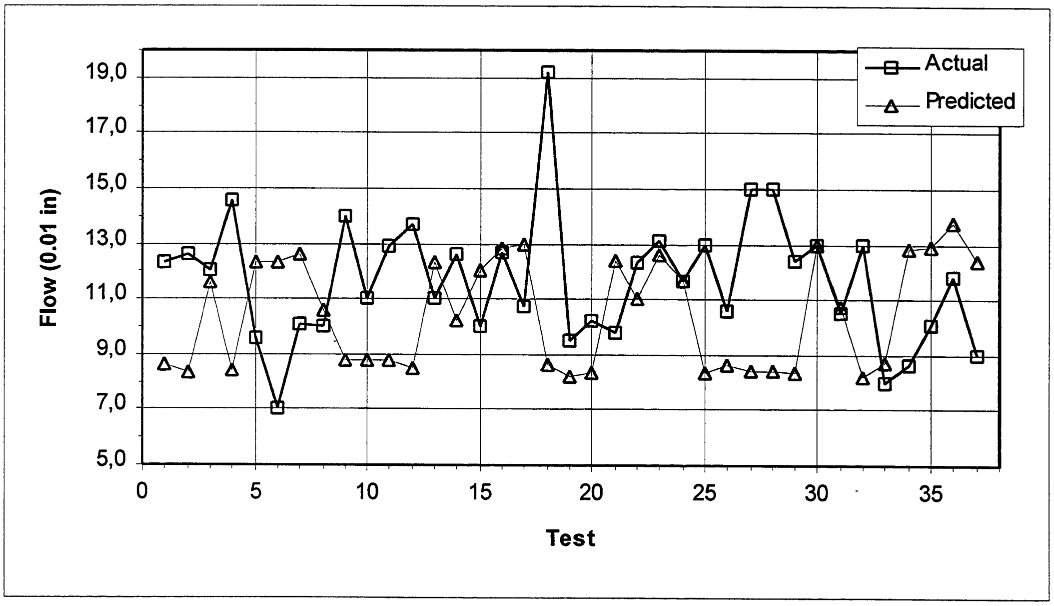


Figure 7.14 MDT Data: Estimation of Flow

The average error on the Marshall flow estimation on the data from GDOT was 26.14%. The comparison between the model and actual data is shown in Figure 7.15. The model fits the data very well except for flow and stability.

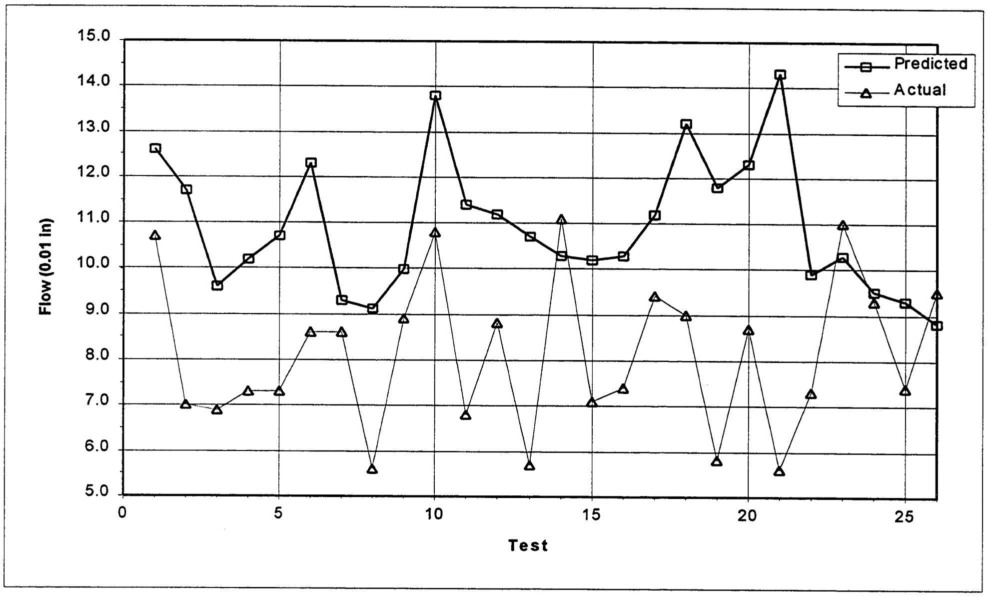


Figure 7.15 GDOT Data: Estimation of Flow

The data shows a large error in the estimation of the Marshall flow value in both sets of data. This, however, should not be a concern since it has long been established that the Marshall flow value is not representative of road performance (Road Research Laboratory, 1962) and does not correlate well with other mix parameters. As in the case of the Marshall stability value, any estimation model based on mix parameters may not be able to accurately predict the flow value. In addition, It may not be worthwhile to attempt to predict it because of the lack of correlation between Marshall flow and road performance.

# 8.0 PROPOSED SUPERPAVE™ ESTIMATION MODEL

## 8.1 Description of the Model

Figure 8.1 outlines the procedure to estimate a Superpave™ mix design. The various steps are as follows:

1. Conduct a sieve analysis to determine the gradation of the aggregates in the mix.

2. Estimate the percent void in the mineral aggregate, $\%VMA_{est}$, using Asphalt-It™.

3. $G_{se}$, is determined as a function of the bulk specific gravity of the aggregate in the blend, $G_{sb}$, and of the apparent specific gravity of the mix, $G_{sa}$. It is given by:

$$G_{se} = G_{sb} + 0.8 \times (G_{sa} - G_{sb}) \quad (8.1)$$

4. The percent volume of the asphalt binder, $V_{ba}$, is determined for a case when the sample has a 5% asphalt content by total weight of mix, a 95% aggregate percentage by total weight of mix, and a 4% air voids by total volume of mix. The percent volume of the asphalt binder can then be estimated by:

$$V_{ba} = \frac{95 \times (100-4) \times \left( \frac{1}{G_{sb}} - \frac{1}{G_{se}} \right)}{\frac{5}{G_{ac}} + \frac{95}{G_{se}}} \qquad (8.2)$$

5. An estimate of the asphalt content, $\%AC_{est}$ can then be determined as

$$\%AC_{est} = 100 \times \frac{G_{ac} \times (V_{be} + V_{ba})}{G_{ac} \times (V_{be} + V_{ba}) + W_s} \qquad (8.3)$$

Where $V_{be}$ is the effective volume of the binder, and $W_s$ is the weight of aggregates. $W_s$ is estimated for a 95% aggregate percentage by total weight of mix, and a 4% air voids by total volume of mix. It is given by:

$$W_s = \frac{95 \times (1-0.04)}{\frac{5}{G_{ac}} + \frac{95}{G_{se}}} \qquad (8.4)$$

6. Using Asphalt-It™, compute the estimated bulk specific gravity of the mix, $G_{mb,est}$.

7. Calculate C and $G_{mb,corr}$ using the following equations:

$$C = \frac{G_{mb,est} @ \%VMA_{est}}{G_{mb,est} @ Nmax} \qquad (8.5)$$

$$G_{mb,corr} = C \times G_{mb,est} \qquad (8.6)$$

8. Calculate $G_{mm,corr}$ as follows:

$$\%G_{mm,corr} = 100 \times \frac{G_{mb,corr}}{G_{mm}(Eq1.5)} \qquad (8.7)$$

9. Determine $V_a$ from the following equation:

$$Va = 100 - \%G_{mm,corr} @ N_{des} \qquad (8.8)$$

10. The %VMA can then be determined by the use of the following equation:

$$\%VMA = 100 - \%G_{mm}@Ndes \times G_{mm} \times \frac{100 - \%AC_{est}}{100 \times G_{b,dry}} \quad (8.9)$$

The designer should consider the estimations as analytical "tools" designed to facilitate and accelerate the design process. The designer should construct actual samples to support estimated values. Figure 8.1 illustrates the laboratory verification step.

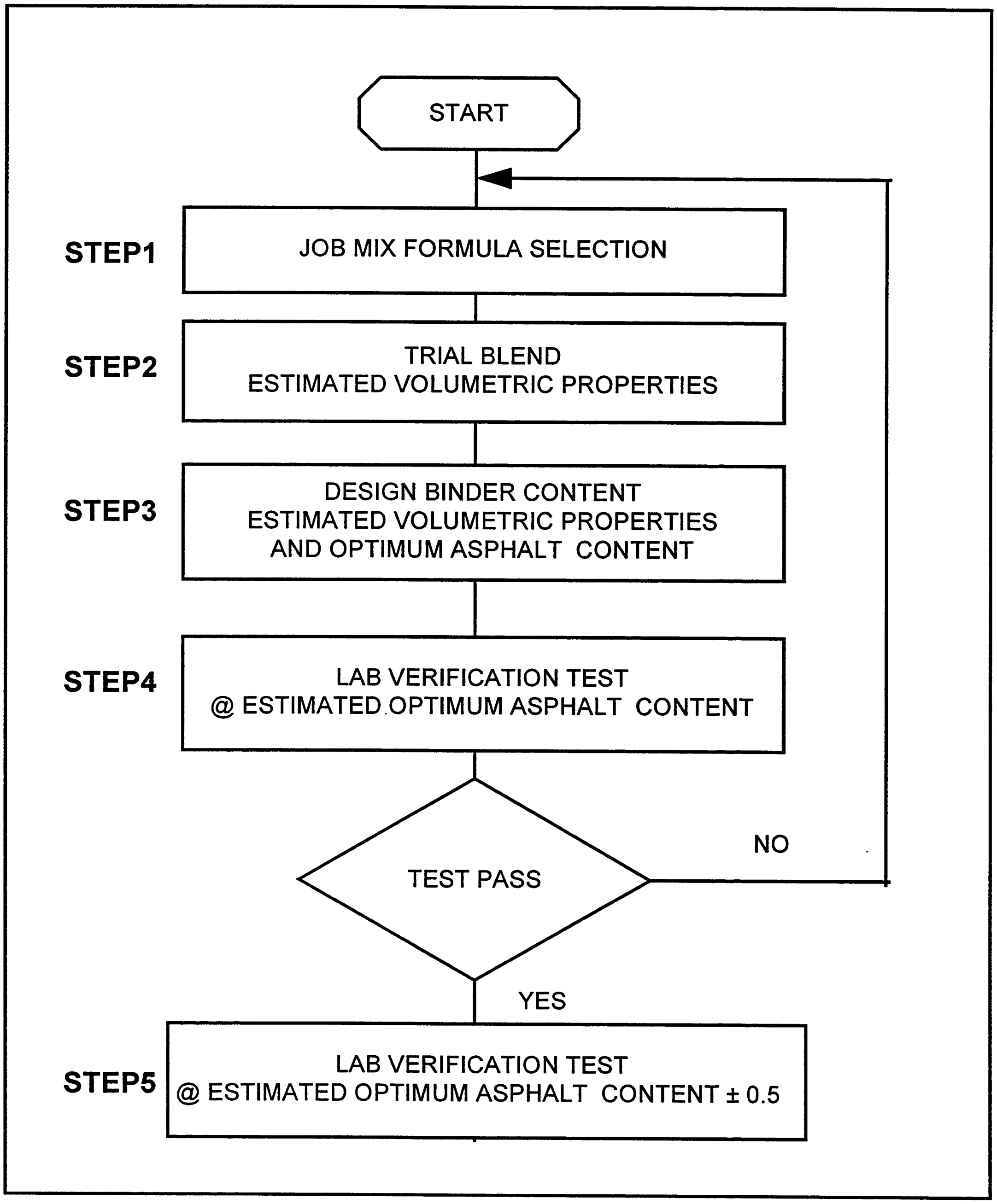


**Figure 8.1 ATSER Proposed Superpave™ Estimation Procedure**

## 8.2 Evaluation of the Model

Independent evaluations of 14 complete Superpave™ mix designs were found during the literature review process. Seven of these mix designs were from GDOT, and the remaining seven were obtained from Koch Materials. The ATSER estimation model for the Superpave™ mix design was evaluated by two independent reviewers from GDOT and Koch Materials. The results are summarized in Tables 8.1 and 8.2.

**Table 8.1. Results: Data from GDOT**

| | %VMA | | %VFA | | %AC | |
|---|---|---|---|---|---|---|
| | Predicted | Actual | Predicted | Actual | Predicted | Actual |
| 1 | 14.3 | 14.2 | 72.0 | 71.5 | 4.9 | 4.3 |
| 2 | 16.8 | 16.8 | 76.1 | 76.1 | 6.2 | 5.3 |
| 3 | 14.3 | 14.7 | 72.1 | 72.8 | 4.9 | 4.4 |
| 4 | 15.1 | 14.8 | 73.6 | 73.0 | 5.5 | 4.7 |
| 5 | 15.2 | 14.4 | 73.7 | 72.2 | 5.4 | 4.5 |
| 6 | 15.1 | 15.7 | 73.5 | 75.8 | 5.2 | 5.2 |
| 7 | 15.1 | 14.7 | 73.1 | 73.1 | 5.1 | 4.5 |

**Table 8.2. Results: Data from Koch**

| | %VMA | | %VFA | | %AC | |
|---|---|---|---|---|---|---|
| | Predicted | Actual | Predicted | Actual | Predicted | Actual |
| 1 | 16.8 | 16.3 | 76.2 | 75.0 | 6.6 | 6.0 |
| 2 | 16.6 | 16.3 | 75.9 | 75.4 | 5.9 | 6.2 |
| 3 | 16.7 | 16.0 | 76.0 | 75.0 | 5.9 | 6.4 |
| 4 | 13.3 | 12.9 | 70.0 | 69.0 | 5.2 | 5.6 |
| 5 | 13.0 | 12.8 | 68.8 | 67.0 | 4.4 | 4.2 |
| 6 | 14.2 | 14.9 | 71.8 | 73.2 | 5.1 | 5.2 |
| 7 | 14.4 | 14.5 | 72.2 | 72.0 | 5.1 | 4.7 |
| | Density | | %$G_{mm}$ @ $N_{max}$ | | %$G_{mm}$ @ $N_{ini}$ | |
| | Predicted | Actual | Predicted | Actual | Predicted | Actual |
| 1 | 2361 | 2530 | 98.7 | 97.0 | 83.6 | 86.0 |
| 2 | 2529 | 2529 | 98.4 | 97.4 | 84.4 | 85.3 |
| 3 | 2548 | 2548 | 97.3 | 98.7 | 83.9 | 85.5 |
| 4 | 2424 | 2415 | 98.1 | 97.5 | 86.2 | 84.5 |
| 5 | 2443 | 2440 | 97.5 | 97.0 | 88.2 | 85.5 |
| 6 | 2416 | 2416 | 97.8 | 97.3 | 87.1 | 86.4 |
| 7 | 2414 | 2404 | 97.8 | 97.4 | 87.0 | 85.4 |

**Table 8.3 Summary of Statistical Analysis**

**MDT**

| **MARSHALL** (Based on Gsb) | **VMA** | **Gmb** | **AC** | |
|---|---|---|---|---|
| Avg. (Error, %) | 7.32 | 1.31 | 5.21 | |
| Std Dev (Error, %) | 4.07 | 0.87 | 3.54 | |
| Coeff. of Variance (Error, %) | 0.56 | 0.67 | 0.68 | n=37 |

**MDT (Corrected for Absorption)**

| **MARSHALL** (Based on Gse) | **VMA** | **Gmb** | **AC** | |
|---|---|---|---|---|
| Avg. (Error, %) | 3.91 | - | - | |
| Std Dev (Error, %) | 3.10 | - | - | |
| Coeff. of Variance (Error, %) | 0.79 | - | - | n=37 |

**GDOT**

| **MARSHALL** (Based on Gse) | **VMA** | **Gmb** | **AC** | |
|---|---|---|---|---|
| Avg. (Error, %) | 2.90 | 0.32 | 4.09 | |
| Std Dev (Error, %) | 1.90 | 0.28 | 2.57 | |
| Coeff. of Variance (Error, %) | 0.66 | 0.87 | 0.63 | n=37 |

**GDOT**

| **SUPERPAVE™** (Based on Gse) | **VMA** | **$G_{mb}$** | **AC** | |
|---|---|---|---|---|
| Avg. (Error, %) | 2.51 | 1.12 | 13.24 | |
| Avg Dev (Error, %) | 1.37 | 0.82 | 4.32 | |
| Std Dev (Error, %) | 1.87 | 1.07 | 6.5 | n=7 |

**KOCH**

| **SUPERPAVE™** (Based on Gse) | **VMA** | **$G_{mb}$** | **AC** | **Density** | **%$G_{mm}$ @ $N_{max}$** | **%$G_{mm}$ @ $N_{ini}$** | |
|---|---|---|---|---|---|---|---|
| Avg. (Error, %) | 2.76 | 1.42 | 6.45 | 1.08 | 2.03 | 0.89 | |
| Avg Dev (Error, %) | 1.2 | 0.57 | 2.13 | 1.6 | 0.72 | 0.43 | |
| Std Dev (Error, %) | 1.48 | 0.79 | 2.61 | 2.47 | 1.01 | 0.52 | n=7 |

A statistical summary of the results is shown in Table 8.3. The data revealed VMA could be predicted within 0.2% without laboratory molding. The ATSER method improved the correlation between actual and estimate when corrected for absorption.

The % error between the actual and estimated values is highly dependent on aggregate gravities. As an example, a change in $G_{sb}$ of plus or minus 0.03 can result in changes in VMA of approximately one percent. Whereas, total voids in the mixture, VTM, is less sensitive to Gsb. A change in $G_{sb}$ of plus or minus 0.02 equates to approximately one percent change in VTM.

## 9.0 CONCLUSIONS

This research study focused on evaluating methods to estimate volumetric properties. The results revealed that the ATSER and Hensley methods provide the best estimations. However, the Hensley method requires the use of the final air voids and asphalt content. The ATSER method only requires preliminary aggregate specific gravities and sieve analysis data.

The Hudson and Davis method is sensitive only to gradation, and does not consider compaction, binder content, or asphalt absorption. As shown in Figure 6.2, for lots with similar gradations (Lots 20, 21, 22 and 15, 16, 17), the method predicts the same %VMA, regardless of asphalt content, degree of compaction, or asphalt absorption.

This study reviewed in excess of 80 mix designs. The mix design sources included Montana DOT, Georgia DOT, and Koch Materials. The results revealed that the ATSER method is an excellent "tool" for estimating volumetric properties of asphalt mixtures.

Based on professional experience, the authors grouped the data accordingly:

| % Error | Interpretation |
|---|---|
| Less than 4.0 | Excellent |
| Less than 7.0 | Very Good |
| Less than 10.0 | Good |
| Less than 13.0 | Satisfactory |
| Greater than 13.1 | Need Improvement |

GDOT and Koch results revealed the ATSER method of estimating volumetric properties is an excellent "tool." Whereas, MDT data revealed only good prediction capabilities due to the precision of the $G_{sb}$ data available. The study revealed many designers have very poor data concerning specific gravities.

GDOT and Koch Superpave mix designs were evaluated using the ATSER method. The results revealed the ATSER method provided an excellent prediction method. The analyses were also conducted by independent third parties.

Accuracy of the model is highly dependent on the quality of individual aggregate specific gravities. Proper fractionation and specific gravity information improves estimated results.

The ATSER method appears to provide tremendous value in preparing mix designs. With the aid of the estimations, the ATSER method would greatly reduce the time required for mix design. Actual time studies and time comparisons between different methods were beyond the scope of this study.

## 10.0 IMPLEMENTATION

This research facilitates the national implementation of Superpave™, a new design procedure. The SHRP program enacted by Congress in the mid 1980s was completed in the late 1993. A direct product of this research effort was the Superpave™ mix design procedure. The mix design procedure requires the designer to develop trial blends to identify a job mix formula aggregate structure that would provide satisfactory volumetric properties. Industry has expressed concerns for this new method of mix design, partly for the efforts necessary to identify the proper job mix formula. Experienced designers have reported that the procedure requires as many as 15 trials over a period of several weeks. Often the designer learns after this exhausted effort, that the job mix formula will not satisfy the criteria. The laboratory trial and error procedure begins again with a new job mix formula. Practitioners believe this approach is not practical and should be simplified.

ATSER has developed a rapid procedure for identifying a job mix formula that could satisfy required volumetric properties. By the use of this procedure the need to develop trial blends is reduced. The implementation of the Superpave™ has been facilitated by the use of this screening "tool."

This research should be used to facilitate implementation of the Superpave™ mix design method. The ATSER method of mix design permits an analytical evaluation of the proposed job mix formula blends. Potential blends should be evaluated analytically initially. Aggregate blends with a high potential for success can then be verified by actual laboratory specimens. The mix design time to identify suitable job mix formulas will be reduced.

## 11.0 RECOMMENDATIONS

Based on this research study the following recommendations are warranted:

1. A controlled laboratory experiment should be undertaken with 30 Superpave mix designs. The aggregate fractionation and their respective gravities should be closely controlled. A statistical analysis can then be conducted between the predicted mix design and the actual data. The study within this research utilized existing designs which provided limited specific gravity information.
2. Evaluate the influence of aggregate fractionation on the volumetric prediction. The comparison between predicted and actual results would reveal the sensitivity of aggregate combinations (JMF) to various methods of determining specific gravities.
3. The development of analysis and performance (Level 2 and 3) mix design procedures should be further investigated. Performance tests for fatigue, permanent deformation, and cracking should be included in a useful mix design system. Identifying aggregate combinations that satisfy volumetric properties is the first step in building successful pavements.
4. The volumetric design portion can be estimated. The use of moisture susceptibility and other performance tests could be included in the total mixture design analysis system.
5. MDT should investigate the development of a new specific gravity and sieve analysis test. For over 50 years the same "tools" have been utilized in the industry. An improved method for determining apparent specific gravities is needed. The development of these tests would improve the mix design procedure is needed.

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