

COMPACTION OF HOT MIX ASPHALT CONCRETE

BY

F. N. Finn and J. A. Epps

RESEARCH REPORT 214-21

Engineering, Economy and Energy Considerations in Design,
Construction and Materials

2-9-74-214

Sponsored by

State Department of Highways
and Public Transportation

August 1980

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843



TABLE OF CONTENTS

	Page
SUMMARY	iii
INTRODUCTION	1
BASIC CONCEPTS	2
COMPACTION AND PAVEMENT PERFORMANCE	6
Mechanical Properties	7
Stability	7
Fatigue Properties	7
Tensile Strength	9
Durability	9
Permeability	11
FACTORS INFLUENCING COMPACTION	12
Aggregate Characteristics	13
Asphalt Properties	13
Asphalt Concrete Properties	16
Cessation Temperature	17
Compaction Equipment	18
Related Considerations	19
COMPACTION CONTROL	20
SPECIFICATIONS	22
CONCLUSIONS	24
RECOMMENDATIONS	25
REFERENCES	26
APPENDIX A	36

SUMMARY

The need for adequate compaction of asphalt concrete has been recognized since the very beginning of asphalt pavement construction. The first asphalt pavements in the United States were built around 1870 and the first successful tandem steam roller was built in 1875. Since 1875 engineers have learned a great deal about the need for and benefits of achieving high densities in the asphalt concrete surfacing of a flexible pavement.

This report is an attempt to briefly review the state of the art relative to compaction of asphalt concrete. The report is divided into five sections covering (1) basic concepts, (2) performance relationships, (3) factors influencing compaction, (4) compaction control, and (5) specifications.

The report summarizes why compaction is important and how adequate compaction can be achieved.

There are a large number of factors which can influence the compaction of asphalt concrete. The present state of the art is such that a great deal of dependence must be placed on field personnel if adequate compaction is to be achieved. It is necessary to be knowledgeable of the effects of materials, equipment and the environment. Also, field personnel must be aware of the consequences which may result if the mix design is changed in order to achieve the desired degree of compaction.

The report concludes that, "Good compaction is not likely to happen by accident nor by a total dependence on past experience.

What worked on the last project may or may not work on the next'. The knowledge and experience of field personnel is a crucial factor in developing the necessary compaction procedures for each project.



INTRODUCTION

It is generally conceded that the compaction of asphalt concrete is one of the most critical factors associated with the performance of flexible pavements. In 1972 the Chief Engineer of The Asphalt Institute made the following statement at the meeting of the Association of Asphalt Paving Technologists (1):

"The compaction and densification of asphalt mixtures are the most important construction operations with regard to the ultimate performance of the completed pavement, regardless of the thickness of the course being placed".

At the 1977 meeting of the Association of Asphalt Paving Technologists the Construction Engineer for the New Jersey Turnpike made the following statement (2):

"The single most important construction control that will provide for long term serviceability is compaction".

Mr. Charles Foster, in preparing a superintendents' manual on compaction starts off with the following comment (3):

"The primary reason for compacting asphalt pavements is to make them water tight and reasonably impermeable to air. An uncompacted, poorly compacted pavement would let water leak into the base or subgrade and would be permeable to air. The water would increase the moisture content of the subgrade, and the base, if it is an untreated base, causing a reduction in strength, resulting in pavement settlement and cracking".

These comments generally summarize the attitude of experienced engineers toward the subject of compaction of asphalt concrete.

The purpose of this report is to document the importance of compaction and to encourage engineers to take appropriate actions

to achieve adequate density during the placement of hot mix asphalt concrete.

The report has been divided into five parts as follows:

1. Basic concepts of compaction
2. Relationship of compaction to expected performance of HMAC
3. Factors influencing compaction of HMAC
4. Compaction control procedures
5. Compaction specifications

The information provided in this report represents a consensus of the many studies which have been conducted on the subject of asphalt concrete compaction and pavement performance. The references included herein will provide sources of information if the reader is interested in exploring the subject further.

BASIC CONCEPTS

The basic objective of compacting asphalt concrete is to obtain density in the mix sufficient to develop the necessary mechanical properties and provide a durable and impermeable surface for the maximum possible life cycle, compatible with the inherent properties of the asphalt and aggregate components.

In order to discuss the basic concepts associated with compaction it is necessary to understand the terms of reference to be used in this report. Most engineers are familiar with most of the terms; however, experience indicates there can be some confusion if specific definitions are not established.

Definitions and Discussion

Hot mix asphalt concrete is composed of asphalt, mineral aggregate and air. Compaction is the process by which the asphalt and aggregate are compressed into a reduced volume. For HMAC this process is achieved by rolling the upper surface of each layer of the asphalt concrete with various types of rollers during construction, or by pneumatic tired vehicles (traffic) after construction. It is highly desirable to achieve compaction during construction. If reliance is placed on traffic to obtain compaction, two objectionable outcomes could result: (1) compaction may not be achieved, and (2) rutting may occur. An analogy can be made to the forward pass in football; i.e. three outcomes can result from a forward pass and two are undesirable (incompletion and interception).

Density can be defined as the unit weight of the asphalt concrete achieved through the compaction process. Hence, the objective of compaction is to produce a dense mass with high unit weight. Again, the choice is between achieving a high density at the time of construction by means of construction equipment, or to allow traffic to develop the final density.

Studies by the New York DOT (4) indicate that the density of asphalt concrete does increase under traffic. However, it is also clear that it takes time to achieve a stable condition. Depending on the volume of traffic and initial density, it may require up to five years before the "ultimate field density, can be achieved, according to these studies. During this five year period some undersirable things can happen to the pavement.

Definitions and Discussion

Hot mix asphalt concrete is composed of asphalt, mineral aggregate and air. Compaction is the process by which the asphalt and aggregate are compressed into a reduced volume. For HMAC this process is achieved by rolling the upper surface of each layer of the asphalt concrete with various types of rollers during construction, or by pneumatic tired vehicles (traffic) after construction. It is highly desirable to achieve compaction during construction. If reliance is placed on traffic to obtain compaction, two objectionable outcomes could result: (1) compaction may not be achieved, and (2) rutting may occur. An analogy can be made to the forward pass in football; i.e. three outcomes can result from a forward pass and two are undesirable (incompletion and interception).

Density can be defined as the unit weight of the asphalt concrete achieved through the compaction process. Hence, the objective of compaction is to produce a dense mass with high unit weight. Again, the choice is between achieving a high density at the time of construction by means of construction equipment, or to allow traffic to develop the final density.

Studies by the New York DOT (4) indicate that the density of asphalt concrete does increase under traffic. However, it is also clear that it takes time to achieve a stable condition. Depending on the volume of traffic and initial density, it may require up to five years before the "ultimate field density, can be achieved, according to these studies. During this five year period some undersirable things can happen to the pavement.

The net conclusion is that density in HMAC should be achieved at the time of placement rather than rely on any improvements which may be achieved after construction.

Density is a "means to an end" and not the "end in itself". Actually, the critical consideration in the compaction of the HMAC is to achieve an acceptable volume of air voids in the mix. Since density is influenced by the specific gravity, or unit weight of the aggregate, it does not tell the whole story without further evaluation.

Air Voids in the HMAC are expressed as the relative volume of air contained in the compacted volume of mix. As will be shown, the volume of voids in the aggregate portion of the HMAC, called voids in the mineral aggregate (VMA), and the total volume of voids are the major characteristics which influence the performance of the HMAC. Density is simply a means for controlling the voids.

Figure 1 can be used to illustrate density and voids in the asphalt concrete. In this illustration the HMAC has been divided into separate weights and volumes for the three components; i.e. air, asphalt, and aggregate.

There are relatively simple procedures for measuring the density and analyzing voids in a compacted specimen of HMAC. An excellent description of such procedures is contained in The Asphalt Institute manual on mix design methods for asphalt concrete, Chapter V (5). Also, the appropriate methods for measuring specific gravity are contained in the Institute manual. It is extremely important to use the correct procedures in computing voids in the asphalt concrete. If care is not taken, erroneous results will be reported which have no meaning in terms

of prevailing criteria. Also, methods should be used which take into account asphalt, not water absorption in the mixture. The most convenient procedure for allowing for absorption is by use of ASTM test method D2041, "Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures". Again, these procedures are described in Reference (5) and must be followed very carefully if they are to have any comparative meaning to the present state-of-the-art.

For those interested in more details concerning specific gravity and how air voids and voids in mineral aggregate (VMA) are calculated, a more complete description of terms and procedures can be found in Appendix A.

The terms "relative density" and "relative compaction" are often used to mean the same thing. In either case the "relative" refers to the ratio of field density to either laboratory maximum density or to theoretical maximum density or density of the voidless mass.

Maximum laboratory density is based on the density obtained in the laboratory when a sample of HMAC is compacted under known and very specific conditions; i.e. temperature, amount and type of compactive effort. In the field it is important to remember that the maximum density will vary with the tolerable variations in the mix being produced. It is, therefore, important to recognize these variations when establishing a measure of the relative compaction. Later in this report recommendations for compaction control will be provided for future consideration.

Theoretical maximum density refers to the density (unit weight) of a voidless mass of asphalt and aggregate in the proportions being used by

the asphalt plant.

In general, most agencies prefer to evaluate relative density using maximum laboratory density as a reference. This is acceptable providing the maximum laboratory density is tied to some acceptable level of voids.

In summary, it is the consensus of engineers that compaction to achieve low air voids in asphalt concrete is important and that compaction should be accomplished in the construction phase.

In analyzing the amount of voids in a mix care must be taken to use the correct procedures for measuring specific gravity of the compacted mix and the individual components.

COMPACTION AND PAVEMENT PERFORMANCE

The Texas Transportation Institute and the State Department of Highways and Public Transportation (SDHPT) have conducted extensive studies pertinent to compaction of HMAC (6). In the following pages a very brief resume of reference (6) will be provided along with pertinent results of similar studies by other agencies. Detailed information can be found in the references cited.

It is pertinent to note that the studies reported in Reference (6) regarding traffic compaction in Texas are very similar to those reported by engineers involved in the New York DOT studies. Specifically, traffic will lower the void content of asphalt concrete but it may take over two years in some cases to reduce the voids to an acceptable level. This time delay is especially probable when voids obtained during construction are high.

As previously stated the objective of compaction or densification is to enhance the mechanical properties (stability, flexibility and tensile strength) and to provide a durable and impermeable material for use in construction of flexible type pavements.

Mechanical Properties

For purposes of this report, mechanical properties are defined as stability, fatigue properties and tensile strength.

Stability - Stability can be defined as the resistance to deformation of an asphalt concrete pavement when subjected to traffic loadings under a variety of environmental conditions. Extensive investigations have been reported in the literature on the stability of asphalt concrete mixes. The major conclusion from this research indicates that for a given mix, stability increases as density increases, or voids decrease. Figure 2 from Reference (6) indicates that Hveem stability of Texas asphalt concrete is reduced, on the average, by one point for each percent increase in air voids. For marginal mixes this can be important. It should also be noted that overcompaction, below three percent voids, can cause a reduction in stability as shown in Figure 3. In this case stability is reduced by five or more points for each percent decrease in air voids.

There are many factors which can affect the stability of HMAC; however, the preponderance of information indicates that for any given mix at a specified asphalt content, the stability will be increased as the voids are reduced toward three percent.

Fatigue Properties - Fatigue properties of asphalt concrete refer

to the cumulative effects of repeated bending. When the fatigue limit is reached the pavement will crack, resulting in the so-called "alligator cracking".

Fatigue properties have been studied extensively. The results of these studies demonstrate that fatigue properties are related to the total voids in the mix. Laboratory investigations indicate that the fatigue life of asphalt concrete could be reduced by 35 percent (or more) for each one percent increase in air voids (7).

Other investigators suggest that the effective thickness of the asphalt concrete layer would be affected by the void content (8, 9). The following tabulation illustrates the possible effect of increased voids on asphalt concrete thicknesses of 4 inches and 6 inches.

For example, assume a base coat of 7 percent air voids in the HMAC. In this case the effective thickness of a 4 inch or 6 inch layer of HMAC would not be reduced by the amount of air voids. If the air voids were increased to 8 percent the effective thickness of 4 inches of HMAC would be reduced to 3.5 inches and the 6 inch HMAC would be reduced to 5 inches. The tabulation shows the estimated effect of increasing air voids.

HMAC Air Voids percent	Effective Thickness of HMAC, inches	
7*	4*	6*
8	3.5	5
9	3.0	4.5
10	2.5	4.0
12	2.0	4.0

* Base case

Thus, fatigue properties and the life cycle of a pavement can be significantly influenced by voids in the total mix.

Investigators for the National Cooperative Research Program (10) recommend the following maximum air void requirements for construction of asphalt concrete:

<u>Asphalt Concrete Layer</u>	<u>Air Voids</u>	
	<u>Light Traffic</u>	<u>Moderate to Heavy Traffic</u>
Upper 1 ½ - 2 inches	8	7
Base (below 2 inches)	7	6

Foster (3) suggests 7 to 8 percent voids for dense graded asphalt concrete and 10 to 11 percent for sand mixes.

Tensile Strength - Tensile strength (cohesion) of HMAC combines with shear strength to resist plastic deformation within the mix. It is also an important property in minimizing the occurrence of low temperature cracking.

Figure 4 illustrates the effect of air voids on cohesiometer values for studies made in Texas (6).

Durability

The durability of asphaltic concrete has been defined as the long-term resistance to the effects of aging (11). Good durability can be described as the ability to provide long-term performance without premature cracking or raveling.

The durability of asphalt concrete is largely a matter of the durability of the asphalt cement. The measure of durability of asphalt is indicated by the rate at which the asphalt hardens; i.e. reduction in penetration or increase in viscosity with time.

Research has shown that for a given asphalt the rate at which an asphalt hardens is related to the total air voids in the asphalt concrete

and to the asphalt content (film thickness).

Figure 5 illustrates the effect of initial air voids on the rate of hardening of asphalt (12).

Conclusions from an extensive study of field aging of asphalt (13) included the following item:

"For approximately 12 year old 'surviving' pavements, weight percent of binder and volume percent of air voids appeared to be the principal mixture properties affecting the hardening of asphalt binders".

This study included some 56 field projects located in 19 states and the District of Columbia. One of the states in the study was Texas.

In order to have a mix which can accommodate an adequate amount of asphalt without approaching zero air voids, there must be sufficient volume in the compacted aggregate system; this requirement will be satisfied if there are adequate voids in the mineral aggregate (VMA).

Current criteria (5) suggest the following VMA requirements:

<u>Maximum Size of Aggregate, Inches</u>	<u>Void in the Mineral Aggregate Minimum Percent</u>
1 1/2	12
1	13
3/4	14
1/2	15
3/8	16

Adjustments in the amount of VMA are made by making adjustments within the aggregate gradation. Use of SDHPT standard specifications will usually produce adequate VMA but should be checked for each mix used.

The adverse effects associated with asphalt hardening are raveling and the development of a brittle mix. Studies indicate that when the penetration of the in-service asphalt approaches 30 or less, or the

viscosity at 140°F exceeds 35,000 poise, the pavement is highly susceptible to cracking.

In order to reduce the rate of asphalt hardening to a minimum, the voids should be reduced to approximately 2 percent (14). To avoid bleeding some compromise is necessary; hence, most mix design criteria are designed to limit the in-service voids to 3 to 5 percent. Procedures of the SDHPT call for 3 percent voids (15) as a mix design requirement.

In the section under fatigue properties it was recommended that compaction (density) requirements for construction should range from 6 to 8 percent. This may not be ideal but is considered acceptable, and overall, cost effective. Reduced voids requirements could be impractical in consideration of the ability to achieve such conditions and still satisfy all requirements of the mix. For example, it might be necessary to increase the asphalt content to produce a more compactible mix. The consequences of such a decision could be to produce an unstable mix and probably would result in excessive asphalt (bleeding) on the surface of the pavement.

Permeability

The permeability of a well-compacted asphalt concrete is approximately 1.0×10^{-9} feet per minute compared with 1.0×10^{-7} feet per minute for portland cement concrete (16). Thus, permeability will not be a problem for an uncracked section of asphalt concrete which has been well compacted. However, the permeability of a mix with poor compaction, less than 92 percent of laboratory maximum can be 600 percent greater than a well compacted mix; i.e., 97 percent or greater relative density. (17). Zube (17) concludes his studies of permeability with the

following statement:

"The results of field studies clearly indicate that pavements, even of the so-called dense-graded mixtures, have been constructed that are quite permeable to the entrance of surface water". . . "Field tests indicate that adequate compaction, together with some form of pneumatic rolling are very important factors in reducing pavement permeability".

FACTORS INFLUENCING COMPACTION

Compaction of asphalt concrete may appear to be a complicated process; however, boiled down to its essentials, compaction is simply the application of compactive effort to HMAC while it is susceptible to densification. There are of course, a number of factors which influence the ability to compact HMAC but none is as important as having the right roller on the mix at the right time.

A great deal of information has been reported in the technical literature concerning compaction of asphalt concrete. Also, the construction industry and equipment manufacturers provide useful information particularly with regard to field practice (3, 18).

The major considerations associated with the compaction process are the following:

1. Aggregate characteristics
2. Asphalt properties
3. Asphalt concrete properties
4. Cessation temperature
5. Equipment
6. Related factors
 - a. Joints
 - b. Subgrade support

In discussing the compaction process it will be appropriate to consider the procedure in stages as illustrated in Figure 6 (12).

Aggregate Characteristics

In terms of compaction the angularity and harshness of the aggregate gradation will influence the compactability of the mix. Also, the ratio of the filler (-200 material by volume) to asphalt (by volume) can influence the compactability of HMAC (6).

The optimum filler asphalt ratio reported by a California investigation (Santucci and Schmidt) was approximately 0.17. A dense graded mix with 6 percent asphalt and 3 percent filler would have an approximate filler asphalt ratio of 0.17. Thus, relatively low percentages of filler could enhance the compaction characteristics of a mix.

It is possible that for some mixes, made with an all crushed aggregate, it will be impossible to achieve the densities recommended in this report. While these types of mixes are extremely stable and not likely to exhibit plastic deformation, it is still important to achieve a high degree of density in order to minimize the hardening rate of the asphalt. In cases of this kind it may be advisable to consider substituting an uncrushed blend sand to improve the compactability of the mix, providing adequate stability can be achieved. Increasing the asphalt content is another alternative provided the voids (mix design) are maintained in the range of 3 to 5 percent.

Asphalt Properties

The viscosity of the asphalt at elevated temperatures will influence

the compactability of the HMAC

Figure 7 illustrates the effect of asphalt viscosity on density as a function of compaction temperature while using a constant compactive effort. In evaluating this information it should be remembered that a difference of 1 pcf in density could produce a 0.7 percent (approximate) change in air voids. Thus, a density difference between 148 pcf and 146 pcf could create an increase of 1.4 percent in voids. This increase in voids could reduce the fatigue life of a pavement by more than 35 percent (7).

From information contained in Reference 12 the following tabulation of temperature and viscosity values can be produced for the low and high viscosity asphalts referred to in Figure 7.

Viscosity, Poises	Temperature	
	Low Viscosity Asphalt	High Viscosity Asphalt
100	175	200
10	225	255
1	310	340

Thus, a difference in temperature of 25F to 30F would be required to develop comparable asphalt viscosity in the usual range of temperatures associated with compaction.

The general rule in selecting the best rolling temperature is to use the highest temperature possible. The highest temperature possible will be a function of the asphalt viscosity, mix stability, roller weights and types of rollers. The behavior of the HMAC under the roller is the best on-the-job indication of the highest temperature. If a large bulge develops ahead of the drum when a steel roller is used, or if the mat squeezes out from under the tires when a rubber tired roller is used, the mix is too hot. When the mat shoves excessively under the roller,

Lower densities (decompaction) will be obtained and roller cracks (checking) will develop.

Foster (3) indicates that the breakdown temperature for well graded mixes composed mostly of crushed aggregate could be 300°F; however, for most mixes the highest temperature will range from 260°F to 285°F depending on the viscosity of the asphalt and the stability of the mix. Cosby (19) indicates that mixes can be compacted at higher temperatures with vibratory compactors; up to 325°F without causing any longitudinal displacement. Field observations are necessary to confirm this suggestion.

While it is not possible to assign rolling temperatures solely on the basis of asphalt viscosity most studies indicate the viscosity should be in the vicinity of 150 poise or less based on the properties of the original asphalts (20). Additional comments will be made in the section on mix properties regarding rolling temperatures and asphalt viscosity.

Based on field measurements made on Texas projects (6) the asphalt viscosity associated with air voids less than 8 percent ranged from 17 poises at 225°F to 140 poises at 180°F. These temperatures tend to be somewhat lower than those reported by other investigators; however, the viscosity is in the vicinity of expected values. The viscosity of the asphalt for mixes with air voids in excess of 10 percent ranged from 50 poise at 185°F to 270 poise at 170°F. Clearly other factors are influencing the final results; however, the relationship of air voids and asphalt viscosity at breakdown temperatures is evident. For example, for the projects just referenced the average asphalt viscosity of breakdown temperature for low voids was 62 poise compared with 113 poise for high voids.

Most engineers believe that very little densification will occur when

mixes are rolled at temperatures less than 175°F. Unfortunately, in the matter of rolling temperature there always seems to be an unusual number of exceptions to the rule. On-the-job results will always be the final judge.

In summary, there is ample evidence from both laboratory and field studies to indicate that the rolling temperature for the breakdown roll is crucial in obtaining maximum density of asphalt concrete. Compaction characteristics of the HMAC should be studied carefully during the first few days of placement in order to establish rolling patterns and mix temperatures necessary to obtain the target density for the remaining construction.

Asphalt Concrete Properties

Obviously the properties of the asphalt concrete will be an important consideration for compaction.

Kari (21) discusses in detail some of the concerns associated with mix properties. A summary of his comments are provided as follows:

1. There appears to be an optimum mix stability which permits maximum compaction to occur under a given roller. A mix can be so stable that negligible shear and compaction will take place with a particular roller. The roller rides up on the stable surface and no increase in density or reduction in voids occurs.

2. The other extreme occurs when the mix has such a low stability that it cannot support the weight of the roller.

To describe these extremes, Kari refers to an "understressed" and "overstressed" mix. An overstressed mix may decrease in density with additional rolling.

3. For understressed mixes the highest possible temperature will be in the upper range of expected values approaching 300°F. For overstressed mixes the highest possible temperature will be in the lower range of expected values approaching 200°F.

Kari (21) also discusses "tender" mixes or mixture toughness and compaction. He reports that toughness was a function of density and asphalt viscosity. Mixes that densify properly become tough enough to resist surface scuffing and indentations.

Cessation Temperature

As previously discussed, compaction of asphalt concrete must be accomplished while the asphalt consistency is relatively low and the mix is at elevated temperatures. In order for the compaction process to be effective, the mix temperature should not drop below some minimum temperature referred to as the cessation temperature.

Extensive field studies have been reported regarding the relationship between cessation temperature and (1) mix temperature, (2) base temperature, and (3) time. The results of these studies have been summarized in Reference 22 by Smith and Epps prepared for the State Department of Highways and Public Transportation.

Table 1 summarizes recommendations by Foster (3) published by the National Asphalt Pavement Association. In preparing these recommendations it was assumed that the wind was blowing at 11 to 12 mph, the air temperature was 40°F with dense cloud cover. The intent was to set minimum laydown temperatures that would provide at least 15 minutes before the mat cooled to a cessation temperature of 175°F.

The actual time to a cessation temperature will depend on a number of factors; e.g. mix stability, asphalt viscosity, air temperature, type of compaction equipment, mix thickness, etc. The important point to remember is that there is a temperature at which the compaction process is virtually stopped and this temperature may occur within 4 to 15 minutes after laydown.

Again, actual on-the-job experience should be obtained to determine the time available for compaction. This can easily be accomplished by careful monitoring of temperature and density under field conditions.

Compaction Equipment

There is a considerable amount of disagreement among investigators as to the relative effectiveness of different compaction equipment. Steel wheel rollers and pneumatic tired rollers have been traditionally used. Vibratory compactors have recently provided a third choice. Each of the types comes in a variety of configurations and sizes (weights).

Reference (6) summarizes the many pros and cons of the various pieces of equipment available for compaction. The net conclusion from the reports on compaction indicates that good results can be obtained from each type of equipment if it is properly used and ballasted.

The important factors associated with equipment are:

- a. Unit pressure (contact pressure) or weight per lineal inch of width
- b. Speed
- c. Frequency and amplitude (vibratory compactors)
- d. Coverages or passes

A detailed description of each of the above items is beyond the scope of this report. For those interested in more details, information can be found in References (3, 6, 22, 23, 24, 25, 26, 27, 28, 29, and 30).

Probably the principal conclusion to be reached is to encourage field trials to find that combination of procedures which works best with available equipment in order to obtain an acceptable density. Some experimentation may be required before the right combination is found. In some cases different equipment may be required.

In general, with regard to equipment, the objective is to apply the heaviest load or level of energy possible at the highest temperature possible without overstressing the mix. If relatively light equipment is used, more coverages or passes will be required at the highest temperature possible.

Related Considerations

There are a number of additional considerations which need to be evaluated relative to compaction. A wide range of these are covered in Reference (6). Two will be discussed briefly herein; specifically, subgrade support and joints.

Subgrade Support - For purposes of this discussion subgrade support refers to the condition or bearing capacity of the materials upon which the HMAC is being placed.

Marker (31), Chief Engineer of the Asphalt Institute maintains that ". . .it is necessary for the rolling effort to be supported by a firm base". Most engineers agree with this statement; however, there are no criteria to apply. A visual evaluation based on experience is required. If the equipment is causing excessive deflection it may be necessary to use lighter loads at higher temperatures.

Construction Joints - If the longitudinal construction joints are not properly compacted, premature raveling and potholes can be expected in this area. It is one of the most common deficiencies associated with the placement of asphalt concrete.

Proper overlapping techniques are discussed in References (3) and (29). If at all possible, a construction procedure which provides a semi-hot joint should be agreed to with the contractor. A semi-hot joint is obtained by having the paver drop back to place the second lane before the material in the first lane drops below 140°F; this could be between 2 and 4 hours. A hot joint is best; i.e. paving in echelon. Such procedures are not always possible except on large projects.

It is likely that longitudinal construction joints may not be compacted to the same density as the rest of the lane, particularly if the joint is a cold joint. For this reason, on the surface layer the joint should never be located in the wheelpath area. The next least desirable location is in the center of a trafficked lane where oil drippings can accumulate.

Adequate density can be achieved in the longitudinal joint if good construction practices are followed; primarily, to be sure that an adequate amount of material is crowded into the joint and that the mix is properly compacted.

COMPACTION CONTROL

Procedures for the control or measurement of density are discussed in separate reports produced by the SDHPT and are only briefly discussed herein.

The basic objective of compaction control, as used for this report, is to aid in achieving the desired density and void content in the compacted HMAC.

There can be two different kinds of objectives; (1) to develop a compaction process which will maximize the density which can be obtained with the equipment and mix on the job, or (2) to develop a compaction process which achieves a specified density. In the latter case, it may be necessary to modify the mix or the equipment used in the initial trials.

The best way to develop an optimum compaction procedure for a specific mix and set of equipment is by the test strip or control strip technique.

Hughes (32) describes the test strip technique as follows:

"A 300 foot section of one lane roadway consisting of the material to be used throughout the project. The first control strip is on the first lift of bituminous plant mix. The control strip provides a realistic requirement because it is placed in the same environment and usually with the same equipment as the remainder of the roadway, and thus replaces the maximum theoretical or laboratory density as the standard reference".

"Since the density requirement to be specified for a considerable length of the project is established by the control strip, the importance of obtaining the maximum possible density cannot be overemphasized".

In this procedure a record of density versus compactive effort and temperature should be recorded and evaluated. It may be necessary to study several control strips before the most effective compaction process is developed.

In order to be efficient the control strip procedure requires a quick measurement of the effectiveness of the compaction process. It is

not necessary to measure density except for quality assurance. Nuclear testing equipment can be used to indicate when maximum density is achieved; it is not necessary to convert the nuclear count to density. Bulk specific gravity should be measured from cores for some assurance that acceptable voids are being achieved by the process.

The second procedure can operate with test strips, except that in this case the end result is to obtain a compaction process which will meet a density and void content requirement. In this procedure it may be necessary to change the mix, asphalt content or experiment with equipment in order to obtain the necessary in-place condition.

Implementation of field trials as part of the initial phase of construction should prove beneficial. The net effect will be to develop compaction procedures which will reliably produce an HMAC with good performance potential. Any change in the mix must be approved by laboratory evaluation to be sure that stability and voids criteria are met.

SPECIFICATIONS

Compaction specifications generally fall into two categories; (1) procedural and (2) end result.

Procedural specifications specify the minimum equipment and rolling procedures that must be used by the contractor in compacting the asphalt concrete. Most procedural specifications will also limit the atmospheric conditions under which the mix may be placed.

End result specifications establish minimum requirements for density based on relative laboratory or theoretical density. Most end result specifications do not specify the exact compaction procedure; however,

minimum equipment requirements are sometime stipulated.

The federal Aviation Administration (FAA) specifications (33) handle end result requirements in the following way:

"Rollers may be of the vibratory, steel wheel or pneumatic type" . . . "The number, type and weight of rollers shall be sufficient to compact the mixture to the required density without detrimentally affecting the compacted material", and

"Each lot of compacted pavement will be accepted with respect to density, when the average field density is equal to or greater than 98 percent of the average density of the laboratory-prepared specimen and when no individual determination deviates more than 1.8 percent from the average field density".

The specifications include some descriptive information regarding rolling procedure; e.g. " . . .rolling shall be initiated with the drive wheel toward the paving machine", as well as environmental constraints.

The Corps of Engineers, end-result specifications (34) stipulate the equipment requirements and a minimum density of 95 percent of laboratory compacted specimens of the same mixture. Mix temperature and rolling procedures similar to those of the FAA are also stipulated.

The Asphalt Institute (35) uses the following specification for density control:

"Each lot of the compacted base and surface will be accepted when the average of the five density determinations is equal to or greater than 97 percent, and when no individual determination is lower than 95 percent of the average density of six laboratory-prepared specimens".

Each of these end-result specifications is attempting to achieve an average void content of approximately 7 percent with not more than 2 percent of the area with voids in excess of 10 percent.

Current SDHPT Specifications (36) are basically of the procedural type; however, provision is made for end results if desired.

Section 340.4 specifies the minimum requirements for compaction equipment. Procedures are included in Section 340.6 (5). Compaction shall be "(a) as directed by the Engineer . . .", using procedures described in paragraph (b). Paragraph (c) provides for in-place density requirements as " . . .shown on the plans and determined by the test method specified on the plans".

CONCLUSIONS

Both laboratory and field studies document the crucial importance of achieving high densities in HMAC at the time of construction.

The compaction process is influenced by a number of considerations ranging from aggregate properties to atmospheric conditions. Studies have provided some general guidelines which are useful in achieving density and reducing air voids. However, the final results will depend on the attention provided during the initial stages of construction. Good compaction is not likely to happen by accident nor by total dependence on past experience. What worked on the last project may or may not work on the next.

Field engineers should be encouraged to establish effective compaction procedures, to document those procedures during construction, and to monitor the results.

RECOMMENDATIONS

Based on currently available information the following recommendations are proposed:

1. Construction specifications should include a density requirement similar to that recommended by The Asphalt Institute; specifically, the average density should be equal to or greater than 97 percent of the maximum laboratory density used for mixture design and no individual determination should be less than 95 percent of the laboratory value (35). Field test strips have proven to be useful in establishing roller patterns and mix temperatures that will produce acceptable density.
2. Hot mix asphalt concrete should be designed to meet the following VMA (voids in mineral aggregate) requirements (5):

<u>Maximum (nominal) Size of Aggregate, Inches</u>	<u>VMA (Minimum Value)</u>
1 ½	12
1	13
¾	14
½	15
¾	16

REFERENCES

1. Marker, V., "Construction Methods - Symposium on Thick Lift Construction", Proceedings, Association of Asphalt Paving Technologists, pp. 354-364, (1972).
2. Noel, R. Burce, "Compacting Heavy Duty Highway Pavements", Proceedings, Association of Asphalt Paving Technologists, (1977).
3. Foster, Charles R., "Superintendents' Manual on Compaction", National Asphalt Pavement Association, Training Aid Series 12.
4. Palmer, R. K. and J. J. Thomas, "Pavement Density - How it Changes", Proceedings, Association of Asphalt Paving Technologists, Vol. 37, pp. 542, (1968).
5. "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types", The Asphalt Institute, Manual Series No. 2, Fourth Edition, (1974).
6. Epps, J., B. M. Gallaway, W. J. Harper, W. W. Scott, Jr., and J. W. Seay, "Compaction of Asphalt Concrete Pavements", Texas Transportation Institute, Research Report 90-2F, (1969).
7. Epps, J. and C. L. Monismith, "Influence of Mixture Variables on Flexural Fatigue Properties of Asphalt Concrete", Proceedings, Association of Asphalt Paving Technologists, pp. 423, (1969).
8. Pell, P. S., Prepared discussion, Proceedings, Third International Conference on the Structural Design of Asphalt Pavements, Vol. 1, pp. 248-268, (1972).
9. "Interim Guide to Full-Depth Asphalt Paving Using Various Asphalt Mixes", The Asphalt Institute, Pacific Coast Division, PCD-1, (1976).
10. Finn, F. N., K. Nair and J. Hilliard, "Minimizing Premature Cracking in Asphaltic Concrete Pavement", NCHRP Report 195, (1978).
11. Finn, F. N., "Factors Involved in the Design of Asphaltic Pavements Surfaces", National Cooperative Highway Research Program, Report 39, (1967).
12. McLeod, N. W., "Influence of Viscosity of Asphalt-Cements on Compaction of Paving Mixtures in the Field", Highway Research Record 158, pp. 76, (1967).
13. Zenewitz, J. A. and J. Y. Welborn, "Predicting Asphalt Performance", Report No. FHWA-RD-76-133, (Nov. 1975).

14. Vallerga, B. A., R. White and F. Rostler, "Changes in the Fundamental Properties of Asphalt During Service in Pavements", Final Report, Materials Research and Development, (1970).
15. "Construction Bulletin, C-14", Texas Highway Department, Construction Division.
16. Ridgeway, H. H., "Infiltration of Water Through the Pavement Surface", Transportation Research Record No. 616, pp. 98-100, (1976).
17. Zube, E., "Compaction Studies of Asphalt Concrete Pavements as Related to the Water Permeability Test", Highway Research Bulletin 358, pp. 12,(1962).
18. "Construction Industry - Vibratory Roller Handbook", Construction Industry Manufacturers Association, (1978).
19. Cosbey, H., "Asphalt Compaction by Vibratory Roller", Proceedings, Association of Asphalt Paving Technologists, pp. 279, (1977).
20. LeClerc, R., "Washington Experience on Thick Lift Construction of Asphalt Concrete with Pneumatic Breakdown Compaction", Proceedings, Association of Asphalt Paving Technologists, pp. 325, (1967).
21. Kari, W. J., "Mix Properties as They Influence Compaction", Proceedings, Association of Asphalt Paving Technologists, (1967).
22. Smith, Roy A. and J. Epps, "Environmental Conditions for Placing Asphaltic Concrete Pavements", Research Report 214-11, (1975).
23. Schmidt, R. J., L. Santucci, and W. A. Garrison, "High Temperature Pneumatic Compaction", Highway Research Record 132, (1966).
24. Arena, P., S. C. Shah, V. Adams, "Compaction of Asphaltic Concrete Pavement with High Intensity Pneumatic Roller", Highway Research Record 178, (1967).
25. Serafin, P. J., and L. L. Kole, "Comparative Studies of Pneumatic Tire Rolling", Proceedings, Association of Asphalt Paving Technologists, pp. 418-456, (1962).
26. Cechetini, J., "Vibratory Compaction of Asphalt Concrete Pavements", Proceedings, Association of Asphalt Paving Technologists, pp. 384, (1974).
27. "Vibratory Compaction of Asphalt Pavements", Proceedings, Association of Asphalt Paving Technologists, pp. 260, (1977).

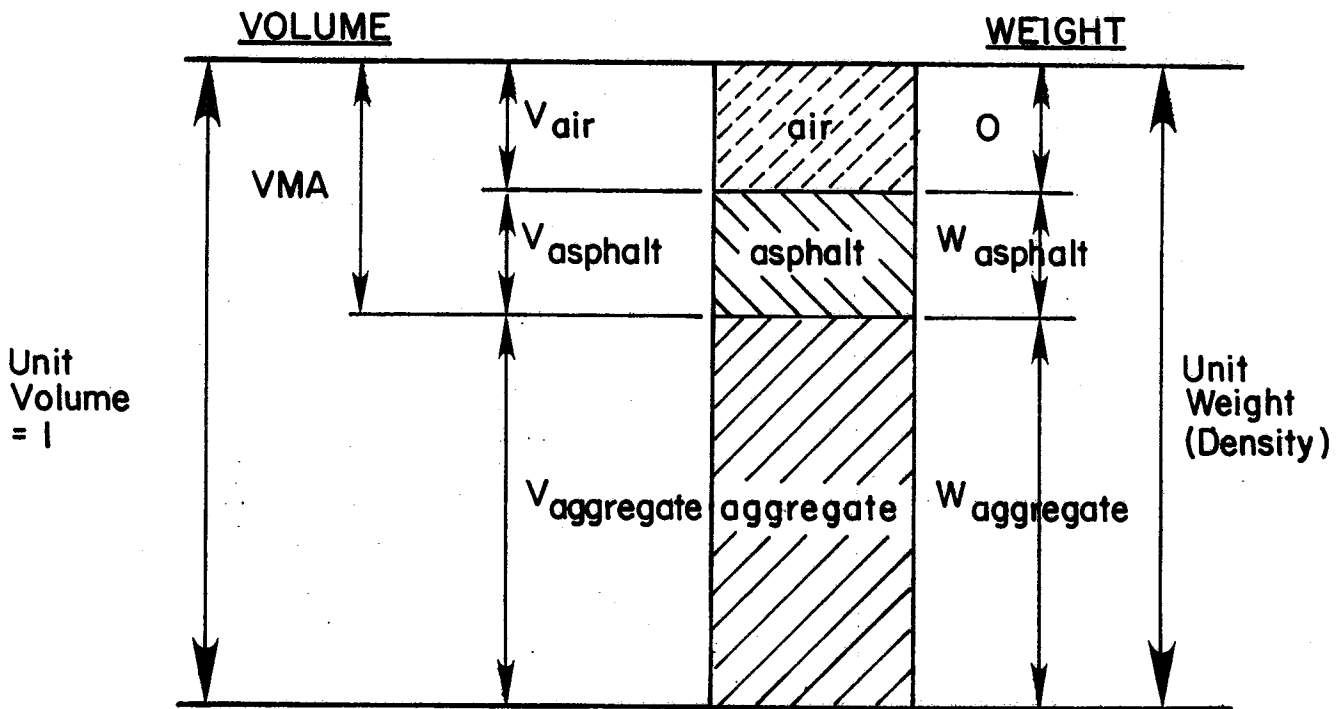
28. Foster, C. R., "Effect of New Equipment on Asphalt Pavement Construction - Compaction Equipment", Proceedings, Association of Asphalt Paving Technologists, pp. 656, (1970).
29. "Asphalt Paving Manual", The Asphalt Institute, Manual Series No. 8, Third Edition, (1978).
30. Kilpatrick, M. J. and R. G. McQuate, "Bituminous Pavement Construction", Federal Highway Administration (1967) reprinted by the National Asphalt Paving Association.
31. Marker, V., "Compaction of Asphalt Concrete", Proceedings, Association of Asphalt Paving Technologists, pp. 288, (1967).
32. Hughes, C. S., "Methods of Compaction Control", Proceedings, Association of Asphalt Paving Technologists, pp. 309, (1967).
33. Standards for Specifying Construction of Airports, "Bituminous Surface Course", FAA Advisory Circular AC No. 150/5370-10CH1, Item P401, (1977).
34. Guide Specification for Military Construction, "Bituminous Intermediate and Surface Courses for Roads, Streets and Open Storage Areas (Central-Plant Hot-Mix)", Corps of Engineers, CE-807.12, (1972).
35. "Model Construction Specifications for Asphalt Concrete and Other Plant-Mix Types", The Asphalt Institute Specification Series No. 1, (1975).
36. "Standard Specifications for Construction of Highways, Streets, and Bridges", Texas Highway Department, (1972).

Table 1. Cessation Requirements.

Base Temperature	Recommended Minimum Laydown Temperature, °F					
	1/2"	3/4"	1"	1-1/2"	2"	3" and Greater
20-32	-	-	-	-	-	285 ¹
+32-40	-	-	-	305	295	280
+40-50	-	-	310	300	285	275
+50-60	-	310	300	295	280	270
+60-70	310	300	290	285	275	265
+70-80	300	290	285	280	270	265
+80-90	290	280	275	270	265	260
+90	280	275	270	265	260	255
Rolling time, min.	4	6	8	12	15	15

¹Increase by 15° when placement is on base or subbase containing frozen moisture.

After Reference 3



$V_{\text{aggregate}}$ = Volume of aggregate

V_{asphalt} = Volume of asphalt

V_{air} = Total volume of air voids

$V_{\text{air}} + V_{\text{asphalt}}$ = Volume of voids in mineral aggregate (VMA)

W_{asphalt} = Weight of asphalt

$W_{\text{aggregate}}$ = Oven dry weight of aggregate

FIGURE 1 - Relative Composition of Compacted Hot Mix Asphalt Concrete

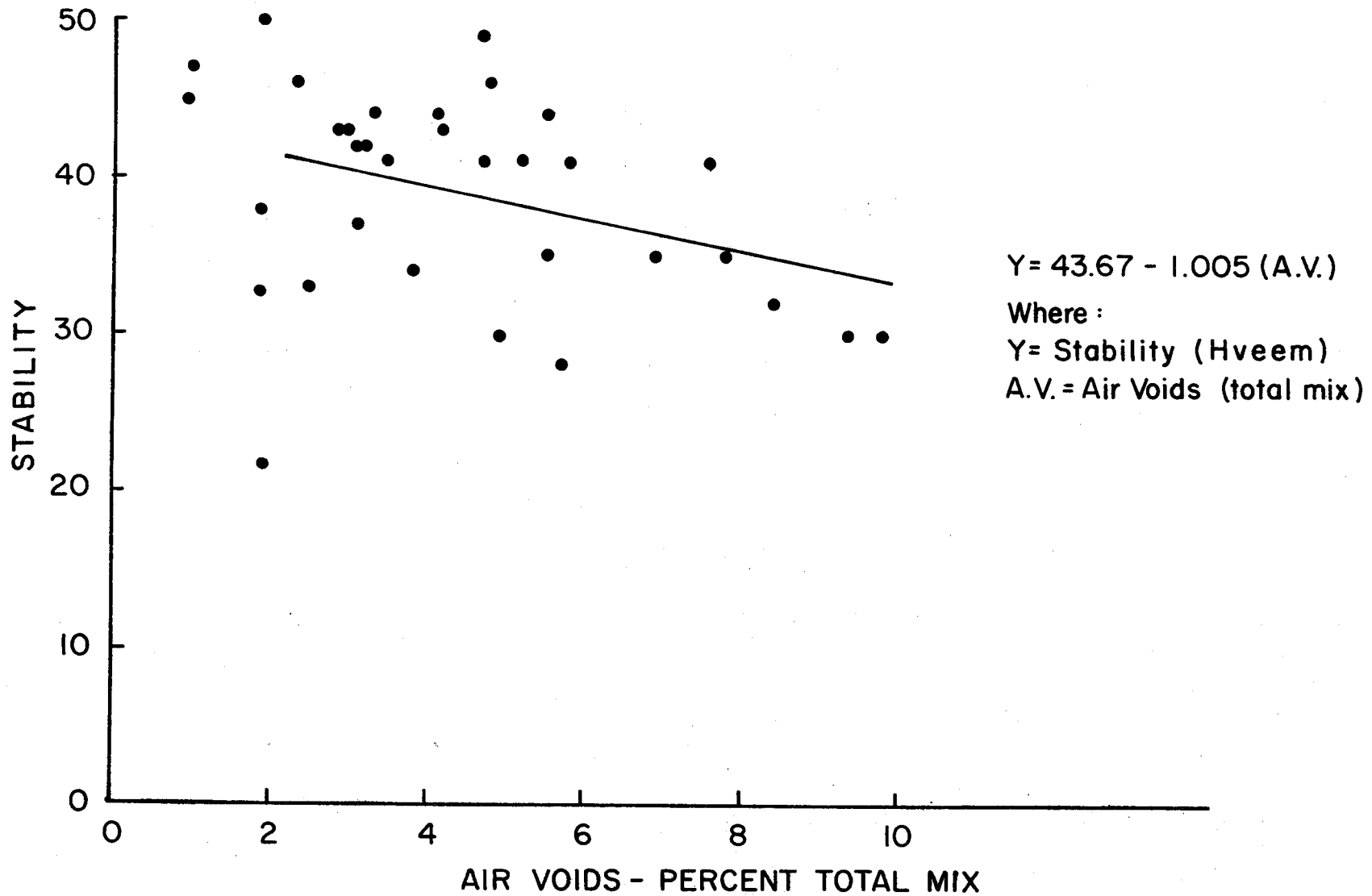


FIG. 2 - RELATIONSHIP BETWEEN STABILITY AND AIR VOIDS
(After reference 6, Table 8)

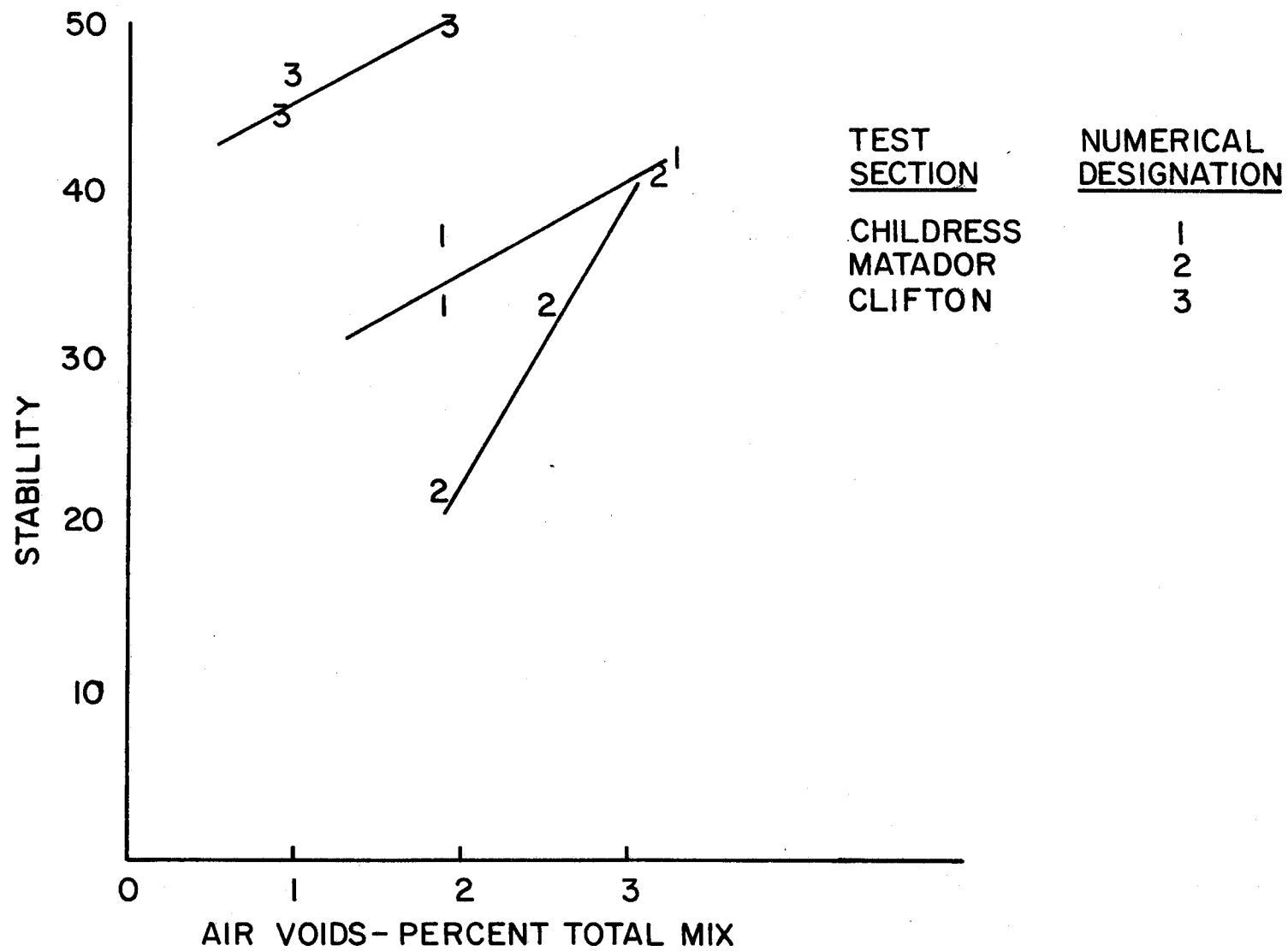


FIG 3 - RELATIONSHIP BETWEEN STABILITY AND AIR VOIDS
(After reference 6, Table 8)

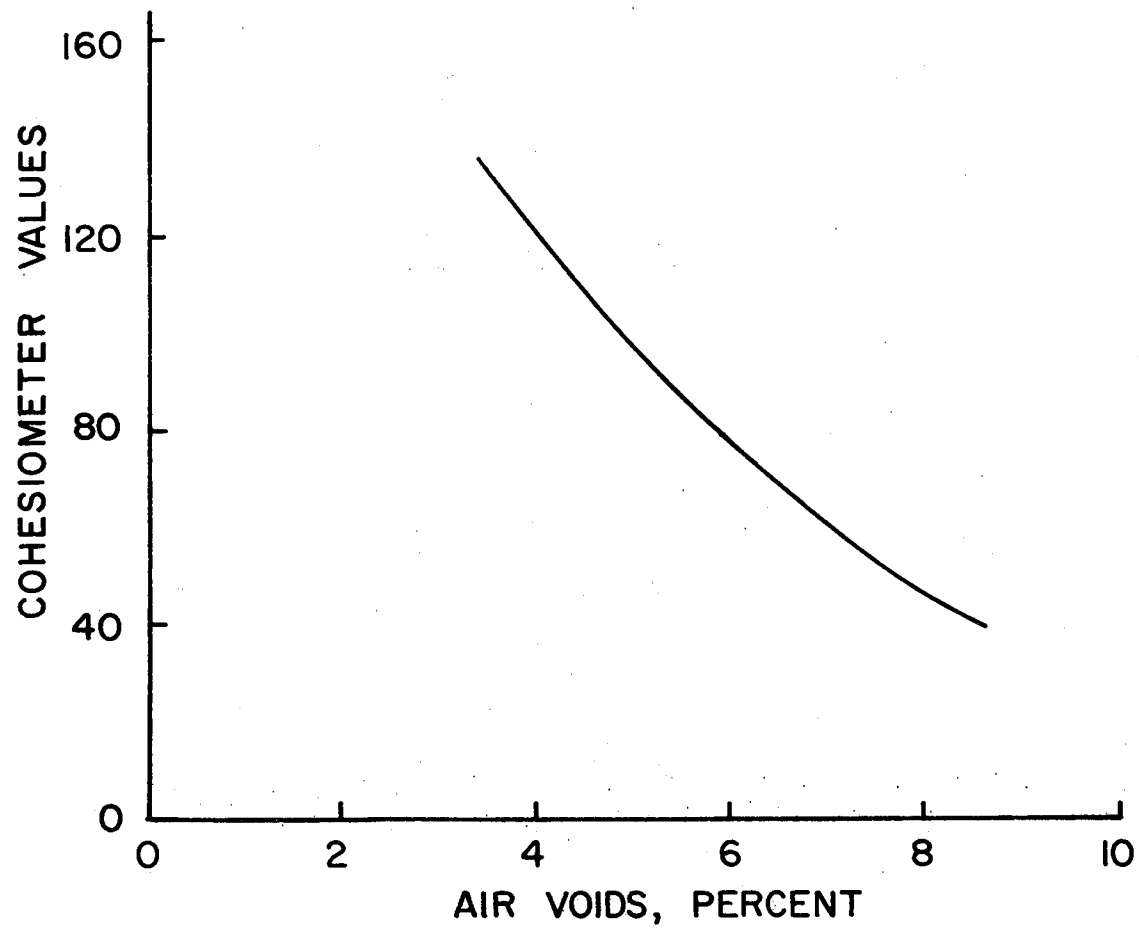


Fig. 4 - Relation between cohesimeter value and air void content
(After reference 6)

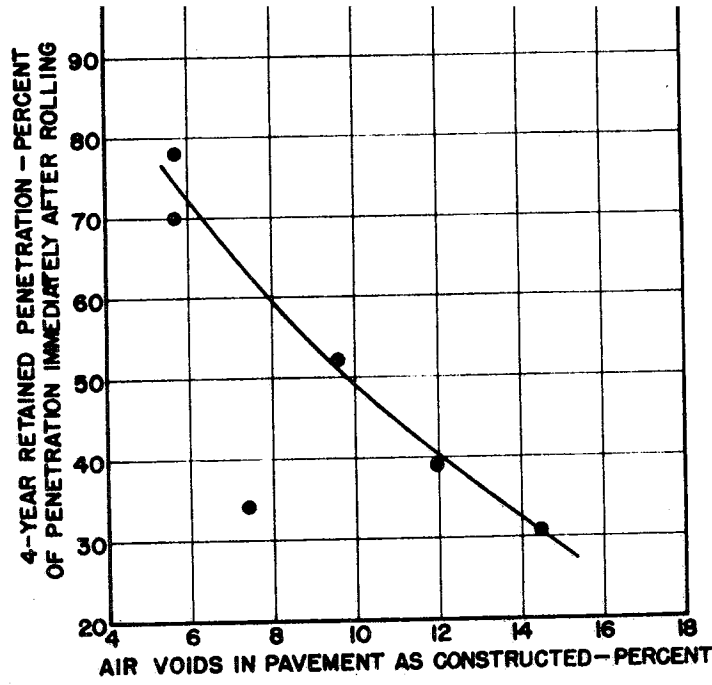


Fig. 5 - Effect of initial air voids in pavement on change in penetration of asphalt after four years of service.

(After reference 12)

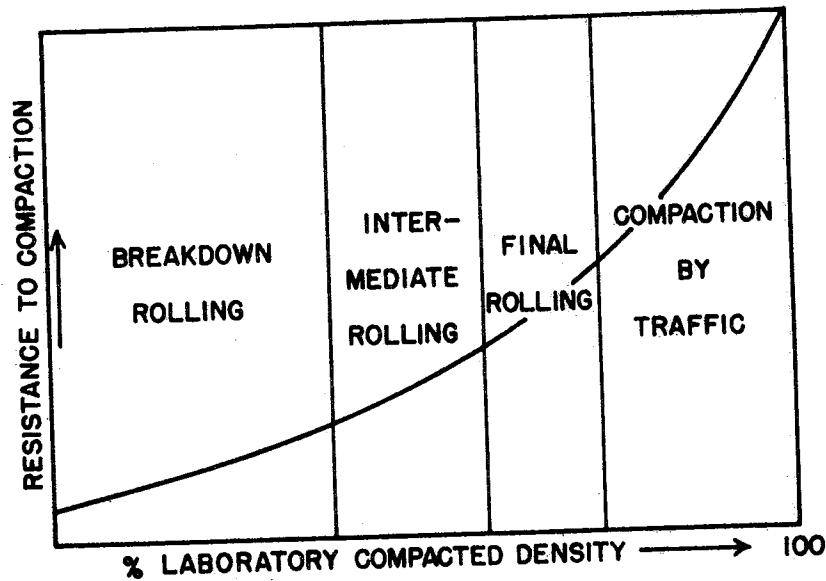


Fig. 6 - Division between the easier portion of pavement density to be achieved by rolling during construction, and the much more difficult portion of pavement density left for compaction by traffic.

(After reference 12)

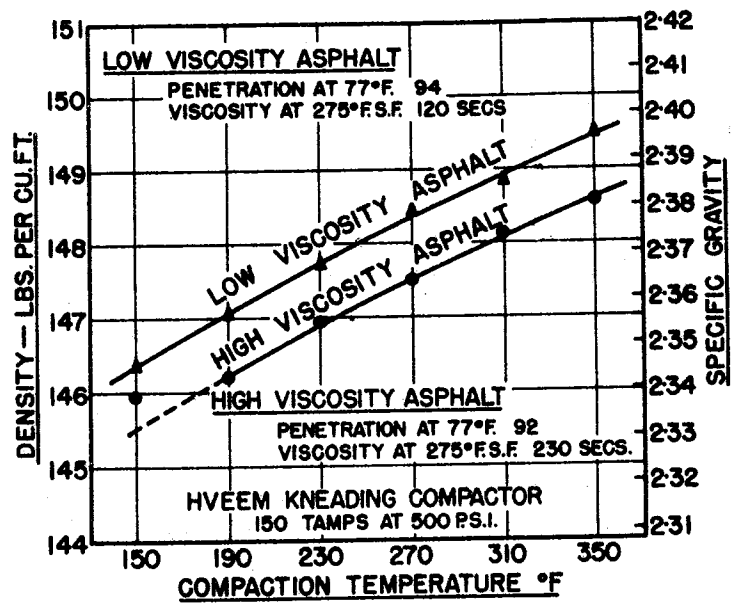


Fig. 7 - Influence of asphalt viscosity on ease of compaction of paving mixtures.

(After reference 12)



APPENDIX A

DEFINITIONS OF TERMS AND DESCRIPTION OF AGGREGATE AND MIXTURE
PROPERTIES USED IN VOIDS ANALYSIS OF COMPACTED ASPHALT CONCRETE



INTRODUCTION

A basic understanding of weight-volume relationships of compacted asphalt concrete mixtures is important from both a mixture design standpoint and from a field construction standpoint. The two most important parameters are volume of voids on air voids in the compacted asphalt concrete and volume of voids in the mineral aggregate (VMA). Figure 1 illustrates these volumes in a simplistic format. Unfortunately accurate calculation of these volumes is compounded by the partial absorption of asphalt cement into the aggregate. If asphalt cement is not absorbed into the aggregate, the calculations are relatively straightforward in that the bulk specific gravity of the aggregate can be used to calculate the volume of aggregate. If asphalt cement absorption is identical to water absorption as defined by ASTM C127 and C128, the calculations are relatively straightforward in that the apparent specific gravity of the aggregate can be used to calculate the volume of aggregate. Since almost all mixtures have partial asphalt absorption, the calculations are more cumbersome as explained below.

DEFINITIONS

A more complete understanding of weight-volume relationships must start with definitions. The definitions given below are consistent with those advanced by ASTM, AASHTO and The Asphalt Institute.

Voids in the Mineral Aggregate (VMA) - The volume of intergranular void space between the aggregate particles of a compacted paving mixture

that includes the air voids and volume of the asphalt not absorbed into the aggregate (see Figures 1 and A-1).

Air Voids - The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture (see Figures 1 and A-1).

In order to calculate either voids or VMA, it is necessary to have information concerning the bulk specific gravity of the compacted HMA (ASTM D1188 or D2726) and the appropriate specific gravity values of the individual components of the mixtures; i.e., asphalt (ASTM D70) and aggregate (ASTM C127 and C128).

In order to facilitate further explanations relative to voids, it will be useful to define the methods used for measuring specific gravity of the aggregates and their relevancy to voids considerations. Specific gravity is needed in voids calculations in order to convert from weight measurements to volume determinations. There are four generally accepted types of specific gravities for aggregate used in calculations associated with pavement materials.

1. Apparent specific gravity
2. Bulk specific gravity, dry
3. Bulk specific gravity, saturated surface dry (SSD) and
4. Effective specific gravity

Apparent specific gravity considers the volume as being the overall volume of the aggregate exclusive of the volume of pores or capillaries that become filled with water after a 24 hour soaking. Bulk specific gravity (Dry and SSD) considers the overall volume of the aggregate

particle, including the pores that become filled with water after a 24 hour soaking. The effective specific gravity considers the overall volume of the aggregate exclusive of the volume of pores that absorb asphalt.

Apparent Specific Gravity (ASTM C127 and C128) - The ratio of the oven dry weight in air of a unit volume of an impermeable material at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature (see Figure A-2).

Apparent specific gravity is normally only used for weight to volume calculations of the mineral filler, since bulk specific gravity values of this fraction are very difficult to obtain.

Bulk Specific Gravity, Dry (ASTM C127 and C128) - the ratio of the oven dry weight in air of a unit volume of a permeable material (including both permeable and impermeable voids normal for the material) at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature (see Figure A-3).

Bulk Specific Gravity, SSD (ASTM C127 and C128) - The ratio of the SSD weight in air of a unit volume of a permeable material (including both permeable and impermeable voids normal for the material) at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature (Figure A-4).

Effective Specific Gravity of an Aggregate - The ratio of the oven dry weight in air of a unit volume of a permeable material (excluding voids permeable to asphalt) at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature (see Figure A-5).

Bulk Specific Gravity, Compacted Asphalt Concrete (ASTM D1189 and D2726) - The ratio of the weight in air of a unit volume of a compacted specimen of asphalt concrete (not including permeable voids) at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature. The value is used to determine weight per unit volume of the compacted mixture.

Maximum Theoretical Specific Gravity of Bituminous Paving Mixtures (ASTM D2041) - The ratio of the weight in air of a unit volume of an uncompacted bituminous paving mixture at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature (see Figure A-3).

A review of the above specific gravity definitions indicates the following:

1. The difference between apparent and bulk specific gravity (dry) is the volume of the aggregate. The difference between these volumes is equal to the volume that the absorbed water occupies in the permeable voids (differences between SSD and oven dry weights of aggregate). Both specific gravities use the oven dry weight of the aggregate.

2. The difference between bulk (dry) and bulk (SSD) specific gravity is the weight of the aggregate as the volume of the aggregate is identical for both specific gravities. The differences in the weight is equal to the absorbed water in the permeable voids (difference between SSD and oven dry weights of aggregate).

3. The differences among apparent, bulk (dry) and effective specific gravity is the volume of the aggregate. All three specific gravities use oven dry weights of aggregate.

4. The difference between the compacted bulk specific gravity and maximum theoretical specific gravity is the volume as the weights are identical. The difference in the volumes is that associated with the volume of the air in the compacted mixture.

5. The measured values of the above specific gravities can be conveniently checked to a first approximation by realizing the following:

- a. The apparent specific gravity will always be larger than the effective specific gravity which will always be larger than the bulk (dry) specific gravity.
- b. The bulk (SSD) specific gravity will always be larger than the bulk (dry) specific gravity.
- c. The maximum theoretical specific gravity will always be larger than the compacted bulk specific gravity of the asphalt concrete mixture.
- d. The aggregate specific gravity [apparent, effective bulk (dry), bulk (SSD)] will always be larger than the maximum theoretical specific gravity of the asphalt concrete mixture.

CALCULATIONS

Calculations associated with weight-volume relationships for asphalt concrete mixtures can be found in considerable detail in Asphalt Institute publications (5). These calculations are summarized below. Figure A-7 should be used as a guide for definition of terms associated with these calculations.

Bulk Specific Gravity of Combined Aggregates - Most hot mixes contain several different aggregates (crushed limestone, lightweight, gravel, field sand, screenings, etc.) which are combined to meet the desired gradation. Usually these aggregates have different specific gravities and need to be combined for ease of calculation of mixtures weight-volume relationships. Equation 1 given below can be used to determine the average specific gravity of the combined aggregate.

$$G_{SB} = \frac{P_1 + P_2 + P_3 \dots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \frac{P_3}{G_3} + \frac{P_n}{G_n}} \quad (1)$$

where

G_{SB} = bulk (dry) specific gravity of the total aggregate

P_1, P_2, P_3, P_n = percentages by weight of aggregates 1, 2, 3 and n.

G_1, G_2, G_3, G_n = bulk (dry) specific gravities of aggregates 1, 2, 3, n.

The bulk specific gravity of mineral filler is difficult to determine accurately at the present time. However, apparent specific gravity of the filler can be used and the error is negligible.

Volume of Voids in Mineral Aggregate - As noted above the volume of voids in the mineral aggregate VMA is an important factor for mixture design and can be used for field quality control. Equation 2 given below can be used to determine VMA.

$$VMA = 100 - \frac{G_{MB} P_S}{G_{SB}} \quad (2)$$

where

VMA = voids in mineral aggregate (percent of bulk volume)

GSB = bulk specific gravity of aggregate

GMB = bulk specific gravity of compacted mixture (ASTM D1188
or D2726)

P_S = aggregate, percent by total weight of mixture

Air Voids in Compacted Mixture - The preferred method of determining the percent air voids in a compacted mixture of asphalt concrete is by use of ASTM D3203 which uses the following equation.

$$V_A = 100 \left(1 - \frac{G_{MB}}{G_{MM}} \right) \quad (3)$$

Which can be rearranged in a more convenient form to

$$V_A = 100 \left(\frac{G_{MM} - G_{MB}}{G_{MM}} \right) \quad (4)$$

Where

$$V_A = [1 - V_{\text{Aggregate}} + V_{\text{Asphalt}}] 100 \quad (5)$$

Figure 1 is sufficient to define the terms in the equation.

The problems with the use of the equation involve the volume of the absorbed asphalt in its aggregate. If apparent specific gravity is used to calculate the volume of the aggregate, it is assumed that asphalt is absorbed by all of the water-permeable pores or voids in the aggregate. If bulk specific gravity is used, it is assumed that the asphalt is not absorbed by the water permeable pores or voids. Except in rare cases, neither is true. Thus, a suitable alternative

has been developed which makes use of aggregate effective specific gravity as defined above. Equation 5 in an expanded form can be used for the calculation.

$$V_A = [1 - (V_{\text{Aggregate}} + V_{\text{Asphalt}} - V_{\text{Absorbed}})] \quad (6)$$

where

$$V_{\text{Aggregate}} = \frac{W_a}{G_{SB}} \quad (7)$$

$$V_{\text{Asphalt}} = \frac{W_B}{G_B} \quad (8)$$

$$V_{\text{Absorbed}} = \frac{W_{BA}}{G_B} \quad (9)$$

G_B = specific gravity of asphalt

W_A = weight of aggregate per unit volume of a compacted mixture (see Figure A-7).

W_{BA} = weight of absorbed asphalt per unit volume of compacted mixture (see Figure A-7)

$$W_{BA} = (P_{BA}) (W_A) \quad (10)$$

$$P_{BA} = 100 \left(\frac{G_{SE} - G_{SB}}{G_{SB} G_{SE}} \right) G_B \quad (11)$$

P_{BA} = absorbed asphalt, percent by weight of aggregate

G_{SE} = effective specific gravity of aggregate

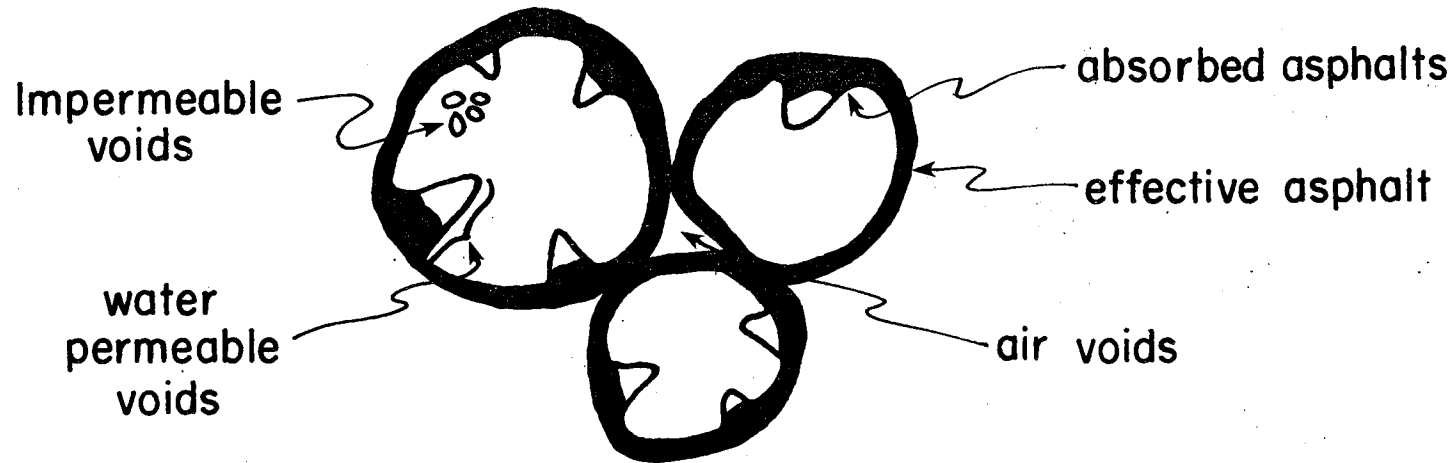
$$G_{SE} = \frac{P_{MM} - P_B}{\frac{P_{MM}}{G_{MM}} - \frac{P_B}{G_B}} \quad (12)$$

where

P_{MM} = 100 or total mixture, percent by that of weight of mixture

P_B = asphalt, percent by total weight of mixture

From a practical standpoint, air void contents can be calculated to sufficient accuracy by using bulk (dry) specific gravity provided water absorption is less than about 1 to 1.5 percent. However, the use of Equations 3 or 4 is recommended for both low and high water absorption mixtures.



voids in mineral aggregate = air voids plus volume of effective asphalt

EXAMPLE: ASSUME BULK SPECIFIC GRAVITY OF COMPACTED MIX = 2.250

VOLUME OF AIR VOIDS = 4%

ASPHALT CONTENT = 6.2%

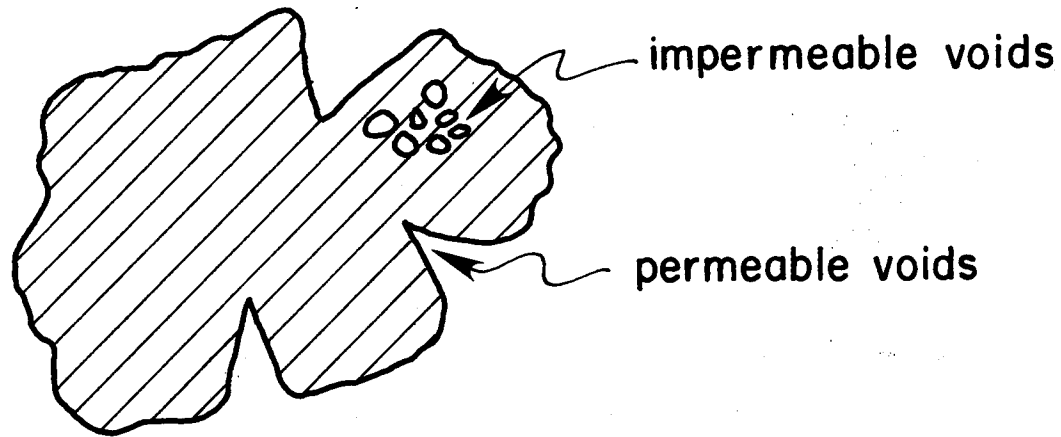
ABSORPTION = 2%

EFFECTIVE ASPHALT CONTENT = 4.2%

VOLUME OF EFFECTIVE ASPHALT CONTENT = $\frac{2.250 \times .042}{1.02} \times 100 = 9.3\%$

VOLUME OF VOIDS IN MINERAL AGGREGATE = 4% + 9.3% = 13.3%

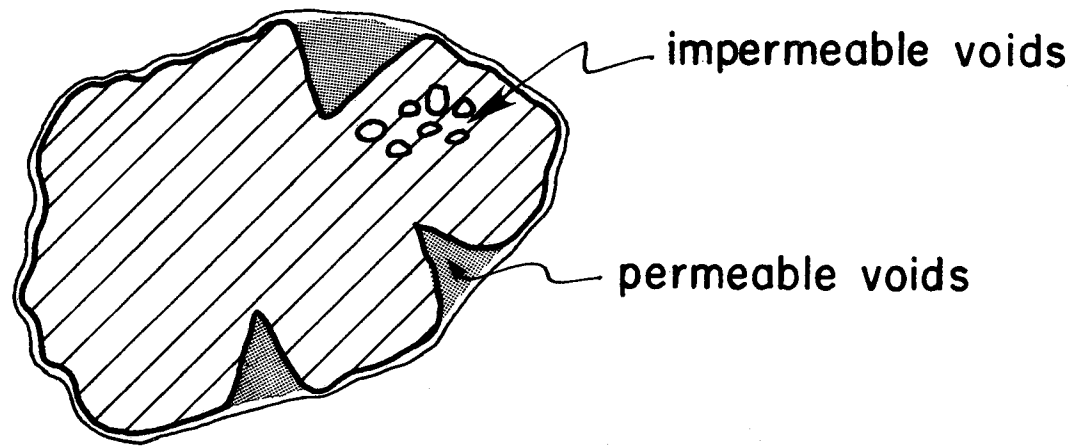
Figure A-1: Diagrammatic Representation of Air Void and Voids in Mineral (VMA).



$$\text{apparent specific gravity} = \frac{\text{weight of oven dry aggregate}}{\text{volume of aggregate plus volume of impermeable voids}}$$

VOLUME IS DETERMINED BY DISPLACEMENT IN WATER WITH OVEN DRY AGGREGATE OR USING A SATURATED SURFACE DRY AGGREGATE AND THEN SUBTRACTING THE VOLUME OF WATER EQUAL TO THE AGGREGATE WATER ABSORPTION

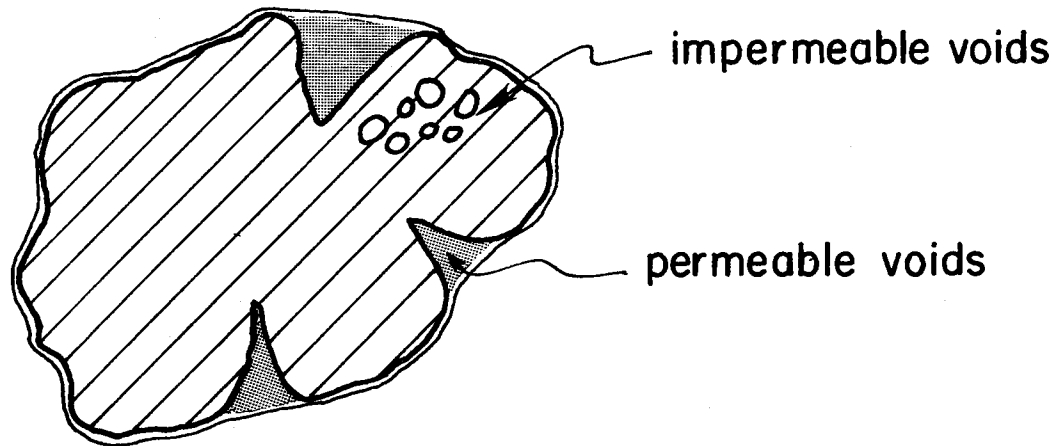
Figure A-2: Diagrammatic Representation of Apparent Specific Gravity.



$$\text{bulk (dry) specific gravity} = \frac{\text{weight of oven dry aggregate}}{\text{volume of aggregate plus volume of impermeable voids and permeable voids}}$$

VOLUME IS DETERMINED BY DISPLACEMENT IN WATER WITH SATURATED SURFACE DRY AGGREGATE

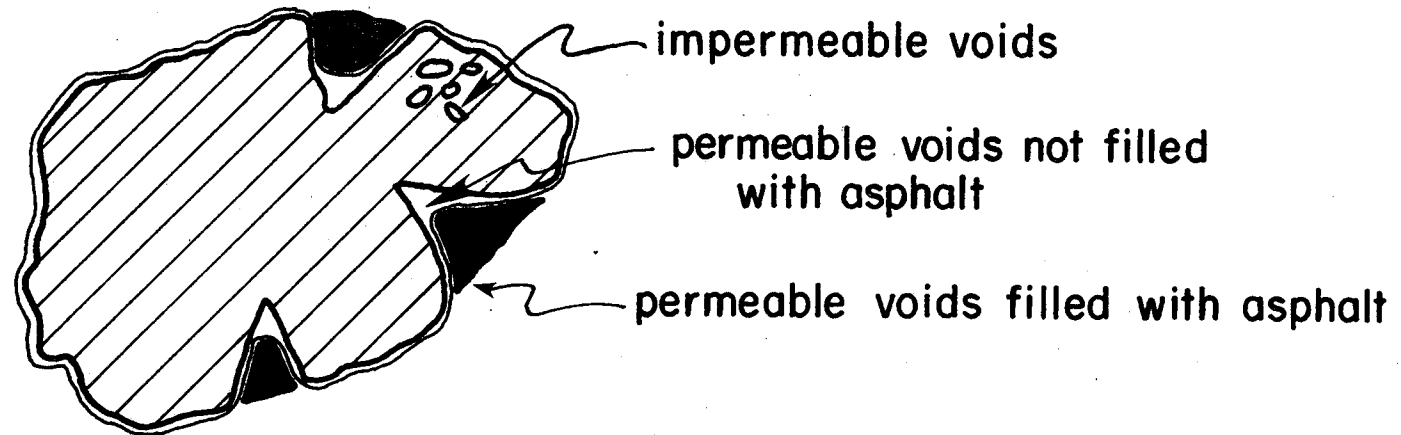
Figure A-3: Diagrammatic Representation of Bulk (dry) Specific Gravity.



$$\text{bulk(saturated surface dry) specific gravity} = \frac{\text{weight of oven dry aggregate plus weight of water in permeable voids}}{\text{volume of aggregate plus volume of impermeable voids and permeable voids}}$$

VOLUME IS DETERMINED BY DISPLACEMENT IN WATER WITH SATURATED SURFACE DRY AGGREGATE

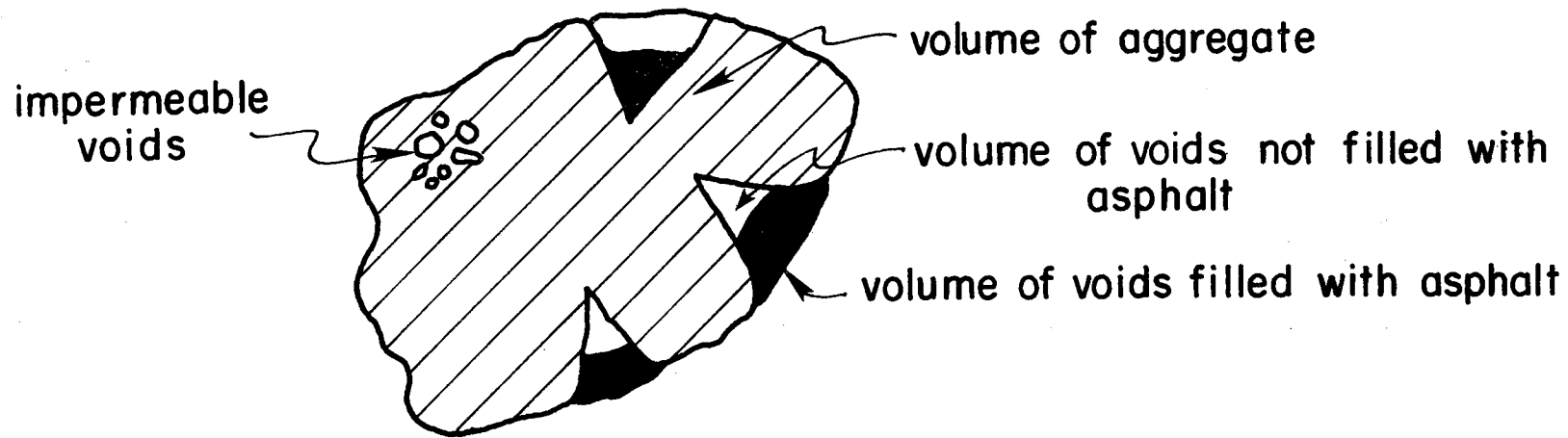
Figure A-4: Diagrammatic Representation of Bulk (SSD) Specific Gravity.



$$\text{effective specific gravity of aggregate} = \frac{\text{weight of oven dry aggregate}}{\text{volume of aggregate plus volume of impermeable voids plus volume of water permeable voids less volume of absorbed asphalt}}$$

EFFECTIVE SPECIFIC GRAVITY DETERMINED BY PROCEDURES OUTLINED IN ASTM D2041.
 BULK IMPREGNATED SPECIFIC GRAVITY OF CORPS OF ENGINEERS USUALLY INDICATES MORE ASPHALT ABSORPTION AND HIGHER EFFECTIVE SPECIFIC GRAVITY.
 EFFECTIVE SPECIFIC GRAVITY SHOULD FALL BETWEEN APPARENT AND BULK (DRY) SPECIFIC GRAVITY.

Figure A-5: Diagrammatic Representation of Effective Specific Gravity of Aggregate.



maximum theoretical specific gravity of mixture = $\frac{\text{weight of aggregate plus weight of asphalt}}{\text{volume of aggregate plus volume of impermeable voids plus volume of permeable voids not filled with asphalt plus total volume of asphalt}}$

$$GMM = \frac{P_{MM}}{\frac{P_S}{G_{SE}} + \frac{P_B}{G_B}}$$

P_{MM} = TOTAL WEIGHT OF MIX

P_S = WEIGHT OF AGGREGATE

P_B = WEIGHT OF ASPHALT

G_{SE} = EFFECTIVE SPECIFIC GRAVITY OF AGGREGATE COATED WITH ASPHALT

G_B = SPECIFIC GRAVITY OF ASPHALT

Figure A-6: Diagrammatic Representation of Maximum Theoretical Specific Gravity of Mixture.

