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ASPHALT CONCRETE MIX DESIGN

Prepared by:
R.A. Jiminez
D.A. Dadeppo
Arizona Transportation & Traffic Institute
College of Engineering
The University of Arizona
Tucson, Arizona 85721

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16. Abstract

This report is concerned with a review of asphaltic concrete as designed by the Arizona Department of Transportation and its relationship to pavement performance. The examination consisted of analyses of the Hveem and Marshall mixture design, calculations to determine the magnitude and location of maximum tensile and shear stresses within the surface course of various pavement systems, the sampling of pavements considered to be of "good", "cracked", and "rutted" conditions, and comparing results obtained from a new mixture design procedure with values of air voids, voids in the mineral aggregate, and asphalt content obtained from measurements made on cores taken from pavements that had been in service. Additionally, details of the method of tests used in the design of paving mixtures were examined. The results of the study showed there was a relationship between pavement condition and the values of both air voids and voids in the mineral aggregate. The final density of pavement cores were higher than the density obtained in design using either Hveem or 75-blow Marshall compaction. Recommendations include the study of laboratory compaction procedures to duplicate pavement density and to consider using the Hveem stabilometer followed by the Marshall test on the same specimen to obtain measures of resistance to rutting and cracking, respectively; additionally, the Marshall stability would be used for field control of the paving mixture.

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We sincerely value the importance given by ADOT and FHWA to the sponsorship of this investigation. We believe that the evaluation for and design of asphaltic paving mixtures are still necessary and need to be reviewed periodically.

METRIC CONVERSION FACTORS

1 in.	=	0.0254 m
1 psi	=	689.4 Pa
1 poise	=	0.1 Pa-s
1 pcf	=	16.03 kg/m_3
1 lbf	=	4.44 N
°F	=	32 + 1.8°C

ASPHALTIC CONCRETE MIX DESIGN EVALUATION

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ASPHALT CONCRETE MIX DESIGN EVALUATION

SYNOPSIS

This report is concerned with a review of asphaltic concrete as designed by the Arizona Department of Transportation and its relationship to pavement performance. The examination consisted of analyses of the Hveem and Marshall mixture design, calculations to determine the magnitude and location of maximum tensile and shear stresses within the surface course of various pavement systems, the sampling of pavements considered to be of "good," "cracked," and "rutted" conditions, and comparing results obtained from a new mixture design procedure with values of air voids, voids in the mineral aggregate, and asphalt content obtained from measurements made on cores taken from pavements that had been in service. Additionally, details of the method of tests used in the design of paving mixtures were examined. The results of the study showed there was a relationship between pavement conditions and the values of both air voids and voids in the mineral aggregate. The final density of pavement cores were higher than the density obtained in design using either Hveem or 75-blow Marshall compaction. Recommendations include the study of laboratory compaction procedures to duplicate pavement density and to consider using the Hveem stabilometer followed by the Marshall test on the same specimen to obtain measures of resistances to rutting and cracking, respectively; additionally, the Marshall stability would be used for field control of the paving mixture.

INTRODUCTION

Background

During 1981 the Highway Operations Research Advisory Committee for the Arizona Department of Transportation developed a questionnaire on research needs. The questionnaire consisted of fourteen (14) topics and was sent to ADOT's district engineers for responses on the need and priority of each item. The replies to the request indicated an immediate need and high priority for a study and evaluation of asphaltic concrete mixture design procedures available and as practiced by the State. The consensus in selecting the evaluation of asphaltic concrete mixture design may have come from the differences in both the design procedure used and the design values obtained between the central and district laboratories for the same paving job. At an ADOT seminar a concern over asphalt properties and pavement performance elicited the following statements from C. B. Potts, District Engineer (1):

1. "Now in my opinion, we have probably always had some unstable mixes, but we were saved by asphalts that hardened. The asphalt people assure us that the new, or present-day, asphalts are softer and will have a longer life. We can tell right now that they are alive by the way they bleed..."

2. "There is one thought that I sincerely hope you will carry away from this meeting -- 'IT IS POSSIBLE FOR A PAVEMENT TO BLEED AND STILL HAVE INSUFFICIENT ASPHALT IN IT'."

Those statements made by Potts in 1967, apparently still had an effect on those responding to the 1981 questionnaire in their thinking that the asphaltic concrete design procedure used then still needed better interpretation or modifications.

Asphaltic Concrete

Asphaltic concrete for highway pavements has been used in this country since before the turn of the century (2) and in Arizona since around the 1920s (3). The requirements and the evaluation of those paving mixtures have changed since those early times; however, their function of serving traffic with a smooth and safe road surface remains the same today.

The following paragraphs present thoughts on the requirements of asphaltic concrete for pavement surfaces. The concepts are not original with the writers nor can any one person claim to be the first proponent of the basic design philosophy or principle. Fred N. Finn (4) has listed seven mixture properties that are required of asphaltic concrete in order to obtain a good paving mixture. These are:

1. Stability
2. Durability
3. Flexibility
4. Fatigue Resistance
5. Skid Resistance
6. Permeability
7. Fracture (Tensile) Strength

With some hesitation and with concern of oversimplification, we suggest that the required properties for good asphaltic concrete can be reduced to three broad characteristics of (a) stability, (b) durability, and (c) fatigue resistance. The contribution of each of these three characteristics to a good paving mixture will be associated with general mixture specifications and related to in-service performance of modern pavements.

Stability.

Many engineers have defined stability as "resistance to deformation" with an implied emphasis towards resistance to flow or rutting in an asphaltic or soil layer. It is noted that no special unit is given to stability. For our purpose and specifically for asphaltic concrete, we want to broaden that definition by including resistance to tensile, compressive, and shear stresses that cause failure in a pavement surface. With this addition we satisfy the need for fracture strength and account for resistance to flow or rutting with a shear strength consideration.

The stability of asphaltic paving mixtures has been evaluated by different procedures, some of them attempted to subject a specimen to loading conditions simulating those in a pavement while others were quite arbitrary with the loading set-up without regards to field conditions. Our observations of structural failures of asphaltic concrete indicate that the distresses were caused principally by tensile stresses (for cracking), shear stresses (for deformation), and compressive stresses may cause a change (by compaction) in the asphaltic concrete that will eventually result in a shear failure. It would then appear that a mixture design procedure should include stability tests to evaluate the shear strength and also tensile strength in order to account for its resistance to failure by rutting (flow) and cracking, respectively. At this time it is not our intention to discuss in detail the principles of present-day procedures used for mixture design, but we do want to give examples for showing the strength characteristics evaluated by the Hveem method and also the Marshall method; both of those procedures have been used by the Arizona Department of Transportation.

Hveem Method. The Hveem stability is expressed as a number which may vary from 0 to 100 and which is obtained from a closed-cell triaxial test. Many asphalt paving technologists accept this stability value as a measure of the angle of internal friction (ϕ) in the Coloumb shear strength equation. In fact, Hveem stated (5), "It was soon evident that the stabilometer principle (which was later designated in certain quarters as a triaxial shear or compression test) primarily measures interparticle friction which is the principal variable that contributes to 'stability'."

As one would now expect, stabilometer values did not show significant differences due to asphalt viscosity during the early development of the design procedure. In order to explain the differences which existed in performance between pavements using cutbacks and asphaltic cements, the cohesiometer test was developed (6). The cohesiometer value is considered to be a measure of tensile strength of a paving mixture and an implication of its name is that it represents the parameter C in the Coloumb shear strength equation. In Reference 6, the authors Stanton and

Hveem stated, "The fact that the mixtures of very low tensile strength can and do remain smooth under traffic and also that mixtures of quite high tensile strength have been known to become waved and rutted, is proof that high tensile strength is not essential for resistance to the distorting effect of vehicles."

One's response to the above statement can be that rutting or distortion is caused principally by shear stresses and thus tensile strength is of secondary importance for resistance to this type of distress or failure.

Analysis of the Hveem mixture design procedure and computed stresses in flexible pavements show the following:

1. The Hveem mixture design procedure requires that specimens be formed using a Triaxial Institute type kneading compactor.
2. The procedure called for testing for both stability and cohesiometer values in order to obtain separate measures of ϕ and C in Coloumb's shear strength equation of $S_s = C + \sigma_n \tan \phi$.
3. The more important strength parameter for thin (less than ± 2 inches) asphaltic surfacings is C (tensile strength) in the Coloumb equation; therefore, stability value or ϕ can be low. For thicker surfacings the magnitude of stability (i.e., frictional strength) is more important than tensile strength.

It is noted that requirements of a minimum Hveem stability of 35 has been specified from before 1955 (7) to the present (8).

Marshall Method. The Marshall method of mixture design is one of the most popular procedures used in this country. The general acceptance of this procedure appears to be based on the simplicity of the test and its good portability for field control of paving mixtures. The Marshall apparatus was patented by Bruce G. Marshall of Jackson, Mississippi (9); however, the present design procedures and specifications include major concepts developed by the U. S. Corps of Engineers. An extensive description of the development and verification of the mixture design procedure are given in the Highway Research Board publication of a symposium devoted for that purpose (10).

A review of the literature indicates that the Marshall stability value is a measure of tensile strength. V. R. Smith (11) wrote in a discussion to Reference 10 that the Marshall value was affected primarily "by the tensile strength or cohesion properties of a mixture." Others such as Benson (12) found a linear relationship between the Marshall stability and the cohesiometer value; the same type of linearity was found by Darter et al. (13) in comparing Marshall stability with indirect tensile strength. It would seem to be apparent that the Marshall test does give a measure of tensile strength and that the method's success in preventing shear deformation (rutting) failures comes from the control of aggregate texture and gradation, asphalt content, and compaction.

It is of interest to note the evolvement of minimum Marshall stability requirements through the years. C. R. Foster in Reference 10 concluded in 1949 that a Marshall stability of 500 pounds was satisfactory for carrying airfield single wheel loads of up to 37,000 pounds. Those specimens were compacted with 15 blows of a 10-pound weight falling 18 inches plus a leveling load of 5,000 pounds on a 4-inch diameter sample. Presently (1986), The Asphalt Institute (8) recommends a minimum Marshall stability of 1,500 pounds for specimens compacted with 150 blows and ADOT requires a minimum stability of 2,000 pounds (14).

The above paragraphs have been concerned principally with the measurement of stability -- resistance to deformation -- since it is not the intent at this time to discuss factors that affect the value of stability. A point we wish to make in that the method(s) of testing for stability should give a measure of those strengths required to prevent specific types of failures; that is, a tensile-type test should be used to assess the resistance to cracking and a shear-type test should be used in consideration of flow or rutting failures.

Durability.

Durability has been defined as the resistance to the effects of weather and its combination with other forces. A desirable mixture is one that maintains the good or desirable properties of the component parts and their combinations and is affected principally by the ability of the asphalt to remain bonded to the aggregate and to the amount of asphalt in the mixture. Durability is enhanced with high asphalt content; however, resistance to flow or deformation is impaired with high asphalt content. As a consequence, the amount of asphalt to be used in a paving mixture must be in a balance to optimize durability but yet maintain adequate stability. The account for the durability needed for a paving mixture will establish or control the permeability property required by Finn (4).

Fatigue Resistance.

In 1955, Hveem evaluated pavement cracking with regards to fatigue failures (15) and showed that asphaltic concrete behaved in a manner similar to metals by cracking from many repetitions of a stress which was much below its tensile strength. Several asphalt paving technologists have worked on the flexural fatigue property of asphaltic concrete. Jimenez (16) was the first to show that the optimum asphalt content for resistance to flexural fatigue was at a higher value than for Hveem stability. At the present there are no standard specifications nor tests related to fatigue properties to be used in the design of asphaltic concrete; however, the optimum asphalt content is approached by the axiom which states, "Use as much asphalt as possible without detrimental losses of stability." In using a high-asphalt content with consideration of stability, durability and fatigue, the design will approach the optimum condition for producing a flexible mixture; that is, one that will conform to slow and differential settlement of a subsoil layer and as recommended by Finn (4).

Elements Affecting Mixture Properties

There are many factors that affect the design properties of asphaltic concrete. However, we believe these can be covered under three general areas of aggregates, asphalt, and compaction. The contributions of these three principal items will be discussed briefly in the following sections.

Aggregates.

The mineral aggregates on an asphaltic concrete constitute about 95 percent of the mixture on a weight basis and about 85 percent on a volume basis. The type or characteristics of the aggregates contribute greatly to the following factors:

(a) Stability - by the gradation, particle surface texture and particle shape,

(b) Durability - by the gradation, cleanliness, and chemical composition,

(c) Fatigue Resistance - by gradation, particle surface texture, and particle shape.

Asphalts.

As indicated above, the asphalt makes up about five percent by weight of a paving mixture; however, its contribution to the total serviceability of a mixture is extremely high and important. The asphalt is the binder that holds the mixture together and affects the following design requirements:

(a) Stability - by its viscosity and its lubricating action during the compaction process.

(b) Durability - by its resistance to aging, its adhesiveness, its cohesiveness, and its viscosity-temperature susceptibility.

(c) Fatigue Resistance - by its viscosity, resistance to aging, and its adhesiveness.

Compaction.

Compaction as an element affecting the serviceability of a paving mixture is as -- or more -- important than the two components listed above. Compaction affects mixture requirements of

(a) Stability - by the degree that density affects ϕ , the angle of internal friction and also tensile strength.

(b) Durability - by the control of air void content to minimize the intrusion of air and water into the mixture.

(c) Fatigue Resistance - by increasing tensile strength and reducing areas of stress concentration through control of air void content.

Program of Study

Prior to 1981, the central laboratory of ADOT used the Hveem stabilometer for the design of asphaltic concrete mixtures; however, some of the district laboratories were using the Marshall method for verifying and changing the job-mix-formula (JMF) of the paving material (17, 18). As shown above, mixture design procedures were developed many years ago and seemingly for different parts of the country. Many changes in traffic and materials have taken place since the 1960s and 1970s and these have resulted in variations in design and performance of asphaltic concrete. As a consequence, the request for proposals (RFP) for this project stated that "an evaluation of the present design procedures is needed to ascertain their efficiency" in the Arizona regime.

The work to be done included a literature survey, discussions with ADOT and other agencies involved in the design of asphaltic concrete and the testing of pavement samples that have shown good and poor performance. Analyses of the above were made for the search of common and consistent aspects of mixture design for the promotion of good pavement performance. Specific efforts were made in the following:

1. Calculate maximum tensile and shearing stresses for various pavement systems. These values would be indicative of the requirements for preventing or minimizing distress by cracking or rutting,
2. To search for combinations of aggregate, asphalt, and compaction that enhance a mixtures' resistance to those failures,
3. To determine means for optimizing those combinations in the laboratory design procedures, and
4. To determine procedures for the best implementation of the laboratory design for field control.

It must be realized that comments to or references will be made to conditions or to performance that have occurred in the past and are no longer applicable to present circumstances of mixture design and pavement performance.

STRESS ANALYSIS OF PAVEMENT SURFACES

In the structural design of any system, the maximum and critical stresses must be considered with reference to their location and magnitude. Knowing these parameters helps to establish the dimensions and physical properties of the materials used in the structure.

Stresses in the surface courses (asphaltic concrete) of pavements were analyzed using Burmister's (19) equations and with the aid of a computer program developed by Warren and Dieckmann (20) of the Chevron Research Company. The input-output statements and related FORMAT statements originally written for the IBM 7090 Computer were modified to permit use of the program on a VAX II Computer. The theoretical analysis of Burmister (19) and, therefore, the program, is based on the assumptions that:

1. Each layer in the pavement is essentially a uniform semi-infinite slab made of an isotropic material that obeys Hooke's Law. All but the lowest layer (subgrade) are of finite thickness. The lowest layer is assumed to be infinitely thick.
2. Complete bonding exists between the layers at their interfaces; i.e., slip and/or separation along an interface is not permitted.
3. The wheel load is applied to the top surface layer as a uniform pressure over a circular area. The pressure is equal to the tire inflation pressure and the radius of the area is chosen so that the resultant pressure force is equal to the wheel load.

Because of axial symmetry, the nonzero stresses on a typical element of material in cylindrical coordinates are the vertical stress, σ_Z , the tangential stress, σ_T , the radial stress σ_R , and the shear stress, τ , shown in Figure 1a. It is noted that along the Z-axis, by virtue of the axial symmetry, $\tau = 0$ and $\sigma_R = \sigma_T$. Output from the program consists of the stresses identified in Figure 1a at designated points defined by coordinates R and Z. The program has no provisions for the printing of principal stresses or maximum shear stress at a point. Consequently, semi-manual processing of the output data, using a programmable hand calculator, was used to obtain maximum stresses.

The parameters that define the layered pavement system considered in the numerical studies are identified in Figure 1b. Table 1 contains a listing of the variations of the parameters employed.

The selections of values for modulus of elasticity of the various layers and magnitudes of the single-wheel load were founded on studies reported by Jimenez (21) for research performed for ADOT. The choices for the inflation pressures considered were based on the Jimenez report (22) for the 105-pound-per-square-inch value and on the possibility that tire inflation pressures may increase up to 150 pounds per square inch.

Tensile Stresses

Without exception, in the numerous (but not exhaustive) computations that were carried out, it was found that the maximum tensile stress in the upper layer occurred at the bottom of that layer at R = 0 (i.e., on the Z-axis). This stress is identified in Figure 1b as σ_T . The

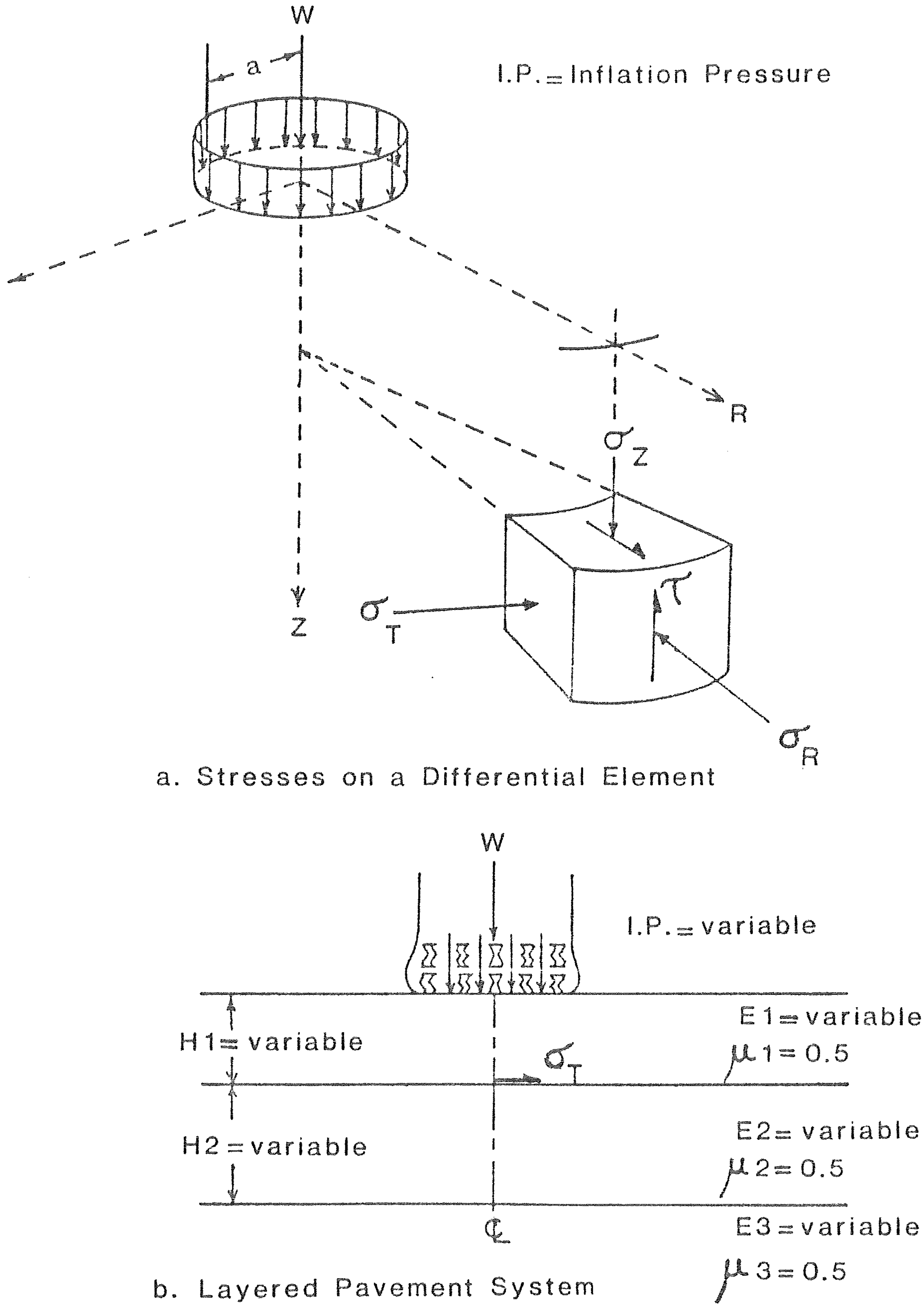

Figure 1. Sketches of Elemental Stresses and Layered Pavement System

Table 1. Listing of Variables for Tensile Stresses Shown in Table A 1 and Shear Stresses in Table A 2.

Tensile Stresses

W, lb	4,000	6,000		
I.P., psi	105	130	150	
H 1, in.	3	6	9	
H 2, in.	3	6	9	
E 1, ksi	100	200		
E 2, ksi	20	30	40	
E 3, ksi	3	6	9	12

Shear Stresses

W, lb	4,000		
I.P., psi	150		
H 1, in.	3	6	9
H 2, in.	3	6	9
E 1, ksi	200	400	
E 2, ksi	20	40	
E 3, ksi	6	9	

maximum tensile stresses for the 1,296 pavement systems are listed in Table A1 of Appendix A.

Figure 2 is a typical plot showing the effects of pavement parameters on the maximum tensile stress. Examination of the data presented in that figure and in Table 2 indicate that for those pavement conditions, the following items affect tensile stress as indicated:

1. An increase of H1 by a factor of 2.0 (3 to 6 in.) decreased the tensile stress by factors of 1.3 to 2.1 (120 to 250 psi).
2. An increase in the inflation pressure by a factor of 1.43 (105 to 150 psi) increased the tensile stress by factors of 1.1 to 1.3.
3. An increase of E2 by a factor of 2.0 decreased the tensile stress by factors of 1.3 to 1.8.
4. An increase of the wheel load, W , by a factor of 1.5 (4,000 to 6,000 lb) increased the tensile stress by factors of 1.1 to 1.3 (170 to 200 psi).

From the above, it seems that the way(s) to reduce tensile stresses most effectively on the surface course would be to increase its thickness or to reduce the absolute difference in the values of modulus of elasticity, E , between the surface and base courses. The increase in stress due to an increase of inflation pressure appears to be highest when the reduction in stress due to an increase in E2 is also greatest, thus resulting in a compensating effect.

Shear Stresses

It was not expedient to process manually the data from a sufficient number of layered pavement systems to draw any hard, general conclusions

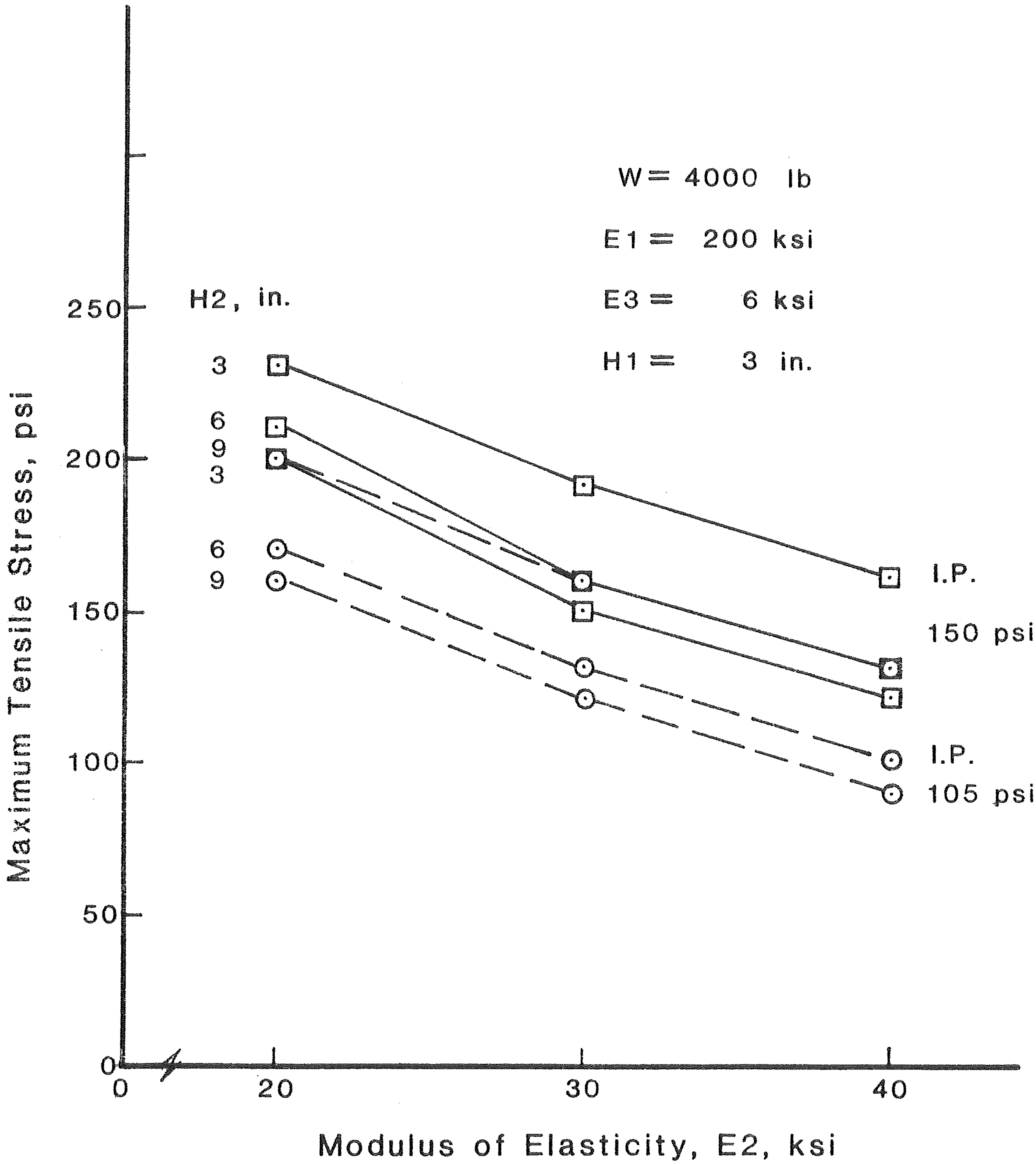

Figure 2. Effects of E2 with Inflation Pressure and Base Thickness on Maximum Tensile Stress for Pavement Systems

Table 2. Selected Values of Tensile Stresses to Show Influence of Various Pavement Properties.

E 1 = 200 ksi E 3 = 6 ksi H 2 = 6 in.

W, lb	I.P., psi	H 1, in.	E 2, ksi: 20	30	40
4,000	105	3	170	130	100
		6	80	70	60
	150	3	210	160	130
		6	90	80	70
6,000	105	3	200	150	110
		6	110	90	80
	150	3	250	190	150
		6	120	100	90

in regard to maximum shear stress. The data contained in Table A2 of Appendix A was generated to illustrate, at least in part, the situation with regard to maximum shear stress in the surface course. The entries in Table A2 are the extreme shear stresses at selected points (on a rectangular R,Z grid). With regard to that table, it should be noted that for the 150 psi inflation pressure, the radius of the loaded circular area is R_a = 2.91 inches. Therefore, points at radial distance R = 3.0 inches lie just outside of the area over which the pressure acts. Large stress gradients are expected near $R = R_a$; as a consequence, the entries for R = 3 inches may not be representative of the level of stress in the neighborhood of R = 3 inches.

Parts 1 and 2 of Table A2 for the 3- and 6-inch surface layers and for all three thicknesses of the base course indicate that the extreme shear stress occurs at the bottom of the surface course at R = 0, on the axis of symmetry. For the 9-inch surface layer in Parts 2, 3, 4 and 5 of that table, in all cases, the extreme shear stress occurs at Z = 3 inches and R = 1 inch and the next smaller shear stress occurs at Z = 3 inches and R = 0 (i.e., on the axis of symmetry). The above statements are represented, perhaps in a clearer fashion, in Table 3 and Figures 3 and 4.

From Table A2 it can be seen that for the conditions chosen, the extreme shear stress calculated was as large as 135 psi. Also, it is noted as shown in Figure 4 that when the extreme shear stress is located at Z = 3 inches and R = 1 inch, the shear value is equal to approximately 0.27 I.P. Also from Table 3 it is seen that the influence of the surface

Table 3. Radial Location and Magnitude of Extreme Shear Stress in psi for Pavement Systems Where

W = 4,000 lb, I.P. = 150 psi

E 1, ksi		200		200	200	400
E 2, ksi		20		20	40	40
E 3, ksi		6		9	9	9
H 1, in.	3	6	9	9	9	9
H 2, in.						
			Radial Distance = 0 in.			
3	135.3	55.1				
6	124.6	51.8				
9	120.5	50.0				
			Radial Distance = 1 in.			
3	131.8	54.2	40.4	41.1	41.3	40.1
6	120.9	50.8	40.7	41.2	42.0	40.6
9	116.7	48.7	40.9	41.4	41.1	40.4

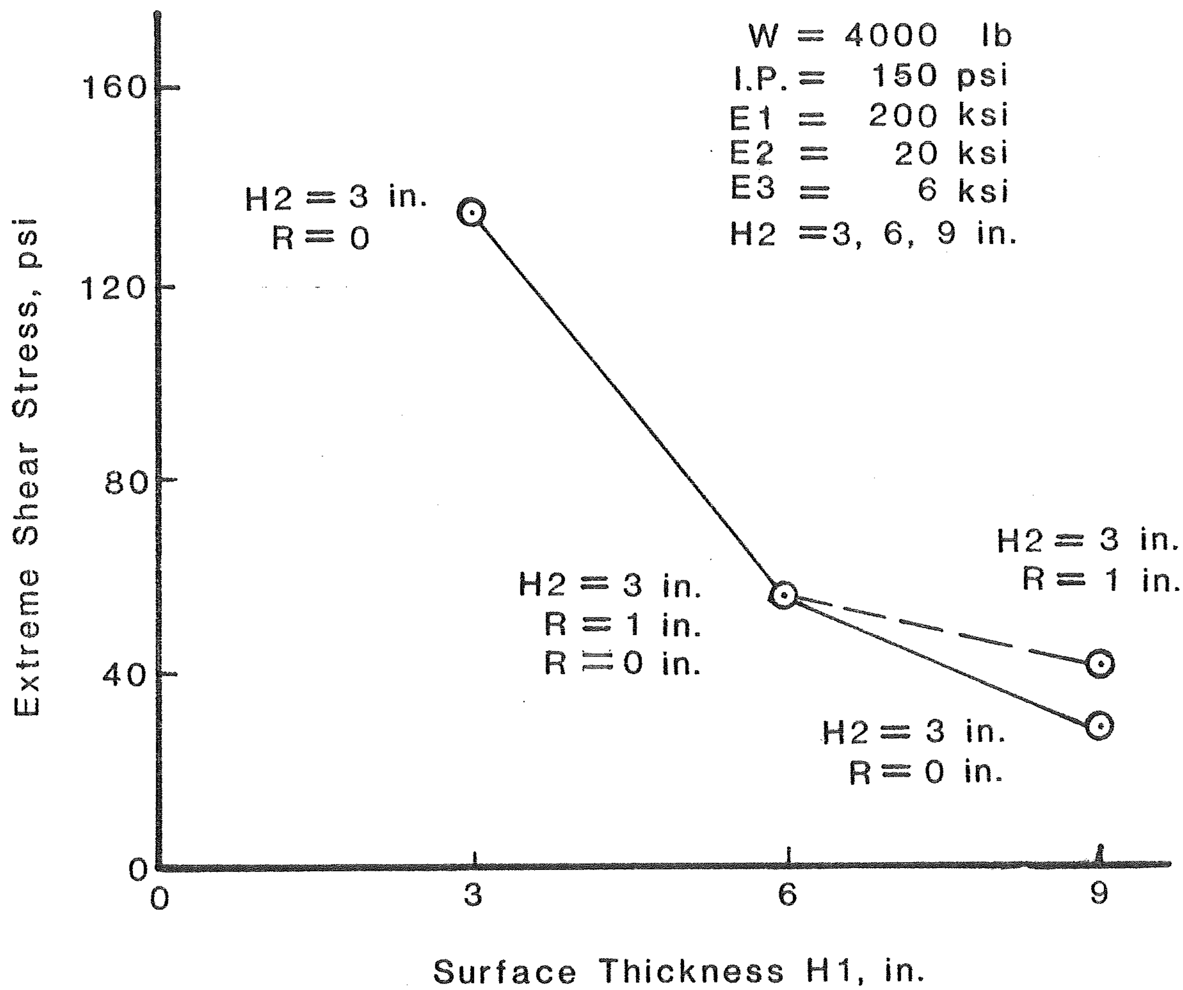

Figure 3. Relationship Between H1 and Extreme Shear Stress for Pavement Systems.

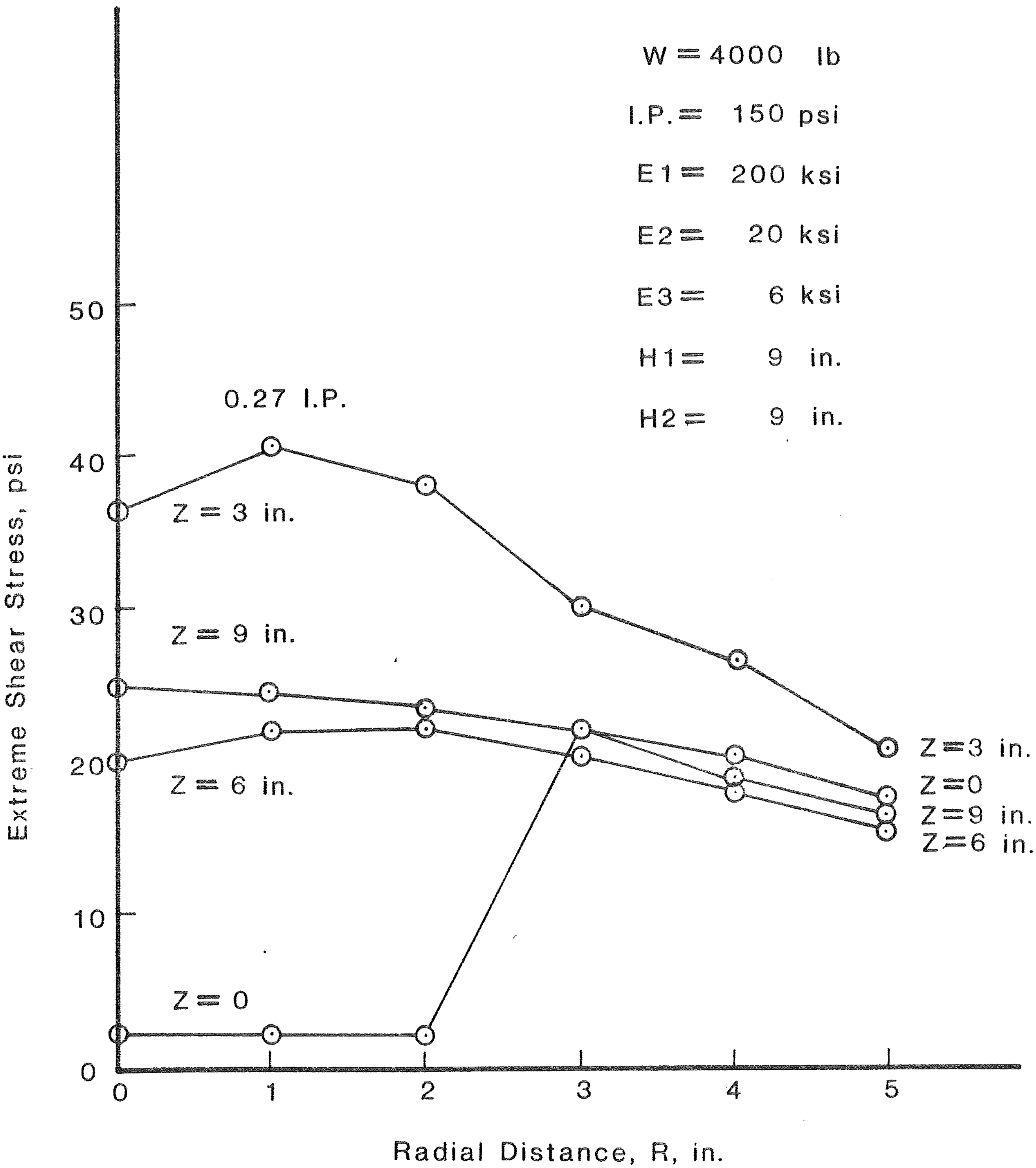

Figure 4. Relationship Between Radial Distance R with Depth Z and Extreme Shear Stress for a Pavement System

course thickness H1 on the value of shear stress is greater than differences in either modulus of subgrade, E3, or base thickness, H2.

Analyses of systems with a surface course thickness of 7 and 8 inches yielded results similar to those found for H1 = 9 inches; namely, that the point of maximum shear stress had shifted from the bottom of the slab on the axis of symmetry to a point within the upper third of the surface course. For the 7- and 8-inch surface layers, the maximum shear stress occurred just inside the boundary of the surface pressure area at R = 2.8 inches (R_a = 2.91 inches), the second highest shear occured at Z = 1, and the next highest at Z = 0.

If the maximum shear stress in a thick surface course occurs in the upper third of the course (as the results generated in this study indicate) the analysis of these stresses may be further complicated because, as pointed out by Warren and Dieckmann (20), the computations in the Chevron Program are more subject to error at points near the surface (i.e., in the upper one-third of the surface course).

It appears that the only feasible approach to the analysis of maximum shear stress is to supplement the Chevron Program with a data-processing program that will calculate and automatically print out maximum shear stress at each sample point in the surface course. The organization of data in the VAX II output files indicates that it would not be too difficult or time consuming to write a data-processing program to accomplish this shear stress analysis. A systematic study of surface layers of increasing thickness using a relatively fine grid of sample points could very well resolve questions concerning the influence of possible computational errors on the location and magnitude of maximum shear stress.

A NEW MIXTURE DESIGN PROCEDURE

Basis for a Calculated Asphalt Content

The quality of the aggregate and asphalt in a paving mixture are certainly important factors in the service performance of the asphaltic concrete. The contributions of the individual components will not be discussed here; however, we will present a method for establishing a starting or optimum asphalt-content for the laboratory testing of mixtures to determine the design amount of asphalt. The design asphalt content to be used in construction will be established through laboratory tests for stability and durability. A basic throught in this new approach is that the laboratory compacted specimen will be viewed with the potential of having certain properties approaching those of the pavement surface after it has been in service for a period of time (4-5 years) so that the rate of change in properties is not as great as immediately after construction. The procedure is based on controlling the voids in the mineral aggregate (VMA), the amount of air voids (AV) in a compacted mixture, and having an adequate asphalt film thickness on the aggregate. The values of VMA and AV are those that are thought to be necessary for stable paving mixtures that have been in service long enough to have reached a constant amount.

Initial Material Testing

Estimates for the optimum asphalt content would be obtained without physical testing of compacted mixtures. A limited amount of testing for information on material properties will be performed to obtain the following component characteristics:

1. Aggregate - gradation, effective specific gravity, and water absorption must be less than 2.5 percent,
2. Asphalt - specific gravity.

If desired, an estimate (since no direct measurements is available) of the absorption of asphalt by the aggregate can be used in the procedure as will be shown later.

Target Values for Estimating the Asphalt Content

The new approach for calculating the optimum asphalt content has certain criteria or target values that have been selected for controlling (a) the mixture's resistance to rutting and (b) durability. The target values are to provide a balance among VMA, AV, and asphalt film thickness after four to five years of service. These values are as listed in the following:

1. A minimum AV of 2 percent calculated with the effective specific gravity (ESG) of the aggregate. This amount is to preclude bleeding and rutting originating within the asphaltic course.
2. A minimum VMA calculated with the ESG of the aggregate blend. The minimum value of VMA is to provide space in the compacted aggregate to accommodate the 2 percent AV and sufficient asphalt for durability considerations. The suggested VMAs for various maximum aggregate size of a blend are:
    * 15 percent for a 1/2-inch mixture,
    * 14 percent for a 3/4-inch mixture, and
    * 13 percent for a 1-inch mixture.

The maximum aggregate size is established on the basis that approximately 10 percent is retained on the "maximum size" sieve and 100 percent passes the next larger sieve for a standard nesting. The standard nesting is shown on the example discussed later.

3. Asphalt film thickness may range from 8 to 14 microns (μ) if total asphalt content is used in the calculation and from 6 to 12 microns if asphalt absorption is considered. Those apshalt film thicknesses have been found in pavement surfaces that have shown good performance.

We reiterate that the target VMA and AV values are end points in the pavement and not for specimens compacted in the laboratory with present-day standard procedures.

The VMA of an aggregate blend is calculated from its gradation using the procedure described by Hudson and Davis (23). We are limiting the procedure to those aggregate blends that have a combined water absorption of less than 2.5 percent and to those that do not have highly textured surfaces such as certain manufactured aggregates and cinders. (Special mixture design criteria are used for these aggregates.) Also, for the present, we have accepted all -#200 sieve-size particles to have a VMA value of 32 percent. We assume this value to be a compromise between the VMA values for one-sized spheres ranging from the loosest (VMA = 47 percent) to the densest (VMA = 26 percent) conditions. The VMA of an aggregate blend is reduced from the 32 percent on the basis of ratios of percentages passing successive sieves from a specific nesting which includes the #200, #100, #50, #30, #16, #8, #4, 3/8", 3/4", and 1-1/2".

The surface area of the aggregate is required for the calculation of asphalt film thickness. The California surface area factors listed by The Asphalt Institute in Reference 8 are applied to amounts passing each of the same sieves listed above for the determination of VMA.

Sample Calculations for Optimum Asphalt Content

As mentioned earlier, no testing of the paving mixture is done. The aggregate and asphalt in the examples are described as follows and listed in Table 4. Also, the asphalt has a specific gravity of 1.020 and the aggregate blend has a "maximum" particle size of 3/4-inch.

A computer program has been developed for the calculations of VMA, SA, and also the total asphalt content by weight of mixture, as well as the asphalt film thicknesses that correspond to variable amounts of air voids. The film thickness is calculated using the effective asphalt content.

Input into the program are as follows:

1. Percentages passing the corresponding sieves,
2. Effective specific gravity of the aggregate blend,
3. Specific gravity of the asphalt, and
4. An assumed value for asphalt absorption of the aggregate.

Copies of computer printouts for the three trials listed are shown in Tables 5, 6, and 7 on the following pages.

Table 4 - Aggregate Characteristics

Gradation

Sieve Size	Total Percent Passing Trial 1	Trial 2	Trial 3
1.5"	100	100	100
0.75"	93	86	90
0.375"	77	66	70
#4	65	52	55
#8	49	37	41
#16	35	24	26
#30	24	12	16
#50	25	5	9
#100	9	2	5
#200	5	1	2

	Trial 1	Trial 2	Trial 3
Effective Specific Gravity	2.680	2.680	2.680
Asphalt Absorption (Assumed), %	0.6	0.6	0.6

Examination of Table 5 for Trial 1 shows the calculated final value of VMA to be 14.5 percent, which meets the criterion calling for a minimum value of 14.0 percent. If we believe that 14.5 VMA is too close to the minimum recommended, but acceptable, we can compensate by selecting an asphalt content corresponding to an air void value of 3 percent. That asphalt content would be 4.9 percent and the effective film thickness would be 7.4 microns.

If we were uncomfortable with the VMA value of 14.5 percent, then we would have opened the gradations perhaps to that shown as in Trial 2. Table 6 shows that the VMA was 18.1 percent and the SA was 12.4 square feet per pound. An upper limit for VMA has not been recommended; however, as can be shown, the asphalt film thickness for up to 6 percent

Table 5 - Computer Output for Trial No. 1

Sieve Size	Percent Passing (P)	R	Voidage Reduction Factor (F)	Aggregate Voidage	Surface Area Factor	Surface Area (Sq Ft/Lb)
200.000	5.0	0.00	0.000	32.00	160.	8.00
100.000	9.0	1.80	0.940	30.08	60.	5.40
50.000	15.0	1.67	0.922	27.72	30.	4.50
30.000	24.0	1.60	0.911	25.24	14.	3.36
16.000	35.0	1.46	0.893	22.55	8.	2.80
8.000	49.0	1.40	0.891	20.09	4.	1.96
4.000	65.0	1.33	0.893	17.93	2.	1.30
0.375	77.0	1.18	0.917	16.44	0.	2.00
0.750	93.0	1.21	0.909	14.93	0.	0.00
1.500	100.0	1.08	0.969	14.48	0.	0.00

TOTAL SURFACE AREA = 29.32

Air Voids (Percent)	Apshalt Content (Percent)	Film Thickness (Microns)
2.00	5.26	8.09
3.00	4.86	7.36
4.00	4.45	6.63
5.00	4.05	5.91
6.00	3.63	5.18

EFFECTIVE SPECIFIC GRAVITY = 2.680
ASPHALT SPECIFIC GRAVITY = 1.020
ASPHALT ABSORPTION VALUE = 0.600

Table 6 - Computer Output for Trial No. 2

Sieve Size	Percent Passing (P)	R	Voidage Reduction Factor (F)	Aggregate Voidage	Surface Area Factor	Surface Area (Sq Ft/Lb)
200.000	1.0	0.00	0.000	32.00	160.	1.60
100.000	2.0	2.00	0.965	30.87	60.	1.20
50.000	5.0	2.50	0.013	31.28	30.	1.50
30.000	12.0	2.40	0.005	31.42	14.	1.68
16.000	24.0	2.00	0.965	30.31	8.	1.92
8.000	37.0	1.54	0.902	27.35	4.	1.48
4.000	52.0	1.41	0.891	24.37	2.	1.04
0.375	66.0	1.27	0.899	21.90	0.	2.00
0.750	86.0	1.30	0.894	19.59	0.	0.00
1.500	100.0	1.16	0.927	18.15	0.	0.00

TOTAL SURFACE AREA = 12.42

Air Voids (Percent)	Apshalt Content (Percent)	Film Thickness (Microns)
2.00	6.98	26.63
3.00	6.58	24.84
4.00	6.17	23.05
5.00	5.76	21.25
6.00	5.35	19.46

EFFECTIVE SPECIFIC GRAVITY = 2.680
ASPHALT SPECIFIC GRAVITY = 1.020
ASPHALT ABSORPTION VALUE = 0.600

air voids is excessive at 19.5 microns and thus would be considered inadequate since the air-void values would be too high at lowered asphalt content and film thickness.

Trial 3 is suggested as a compromise in between the other two gradations. Table 7 shows a VMA of 16.2 percent for this aggregate blend. In reference to the criterion for film thickness, the data indicate an asphalt content of either 4.9 or 5.3 percent which correspond to final air-void values of 5.0 and 4.0 percent, respectively.

Table 8 - Summary Data from New Design Method.

Gradation	VMA, %	Void, %	Content, BTW, %	Film Thickness
Trial 1	14.5	3.0	4.9	7.4
		4.0	4.5	6.6
Trial 2	18.1	6.0	5.3	19.5
Trial 3	16.2	4.0	5.3	13.2
		5.0	4.9	12.0

Table 8 shows a summary listing of the salient values of the calculations discussed above.

Now, one must select a specific value of asphalt content for initiating laboratory stability testing, which usually includes a minimum number of mixtures at plus-and-minus 0.5 percent asphalt from the calculated optimum amount. For the gradations shown, we would recommend as follows:

a. Trial 1 - 4.9 percent

b. Trial 2 - Not acceptable

c. Trial 3 - 5.3 percent

Table 7 - Computer Output for Trial No. 3

Sieve Size	Percent Passing (P)	R	Voidage Reduction Factor (F)	Aggregate Voidage	Surface Area Factor	Surface Area (Sq Ft/Lb)
200.000	2.0	0.00	0.000	32.00	160.	3.20
100.000	5.0	2.50	0.013	32.43	60.	3.00
50.000	9.0	1.80	0.940	30.48	30.	2.70
30.000	16.0	1.78	0.937	28.56	14.	2.24
16.000	26.0	1.63	0.915	26.13	8.	2.08
8.000	41.0	1.58	0.907	23.71	4.	1.64
4.000	55.0	1.34	0.891	21.13	2.	1.10
0.375	70.0	1.27	0.898	18.98	0.	2.00
0.750	90.0	1.29	0.896	17.02	0.	0.00
1.500	100.0	1.11	0.953	16.21	0.	0.00

TOTAL SURFACE AREA = 17.96

Air Voids (Percent)	Apshalt Content (Percent)	Film Thickness (Microns)
2.00	6.06	15.61
3.00	5.66	14.40
4.00	5.26	13.19
5.00	4.85	11.98
6.00	4.43	10.77

EFFECTIVE SPECIFIC GRAVITY = 2.680
ASPHALT SPECIFIC GRAVITY = 1.020
ASPHALT ABSORPTION VALUE = 0.600

It is apparent that due to acceptable ranges of VMA, AV and film thickness and their interrelation, a certain amount of experience in mixture design is required to select the calculated optimum amount of asphalt for the paving mixture. Since the recommended minimum and maximum values for the design parameters are for a potential end point condition in a road, one must accept that values for VMA and AV for laboratory design must be different to allow for traffic compaction of the mixture.

Basis for Selection Design Asphalt Content

Data resulting from measurements of cores taken from existing pavements have indicated certain relationships between performance and values of VMA and AV. Additionally, it has been found that core densities were higher than the corresponding laboratory compacted values. The recommendations made for selecting a design asphalt content are based in consideration of laboratory duplication of pavement densities. However, at the present, this duplication is not possible, yet we must now make specific recommendations for laboratory mixture design criteria.

The mixture design criteria are based on the following assumptions:

1. Mixing temperature of 275-285°F followed with loose curing of mixture for 15 hours at 140°F.

2. Compaction temperature of 250°F with 75 B/F of the Marshall mechanized device.

3. The aggregate blend will have a water absorption value of less than 2.5 percent.

4. The effective specific gravity of the aggregate will be used and determined with the cured mixture.

The requirements of the compacted mixture for selecting the design asphalt content are as listed below and are for aggregate blends of 3/4- and 1/2-inch "maximum" particle size:

1. Hveem Stability, 140°F, dry, min 40
2. Marshall Stability, 140°F wet, lb. min 1500
3. Marshall Flow, 140°F wet, 0.01 in. 8-16
4. Air Voids, % 4-6
5. VMA, %, min

    (1/2-inch aggregate) 17

    (3/4-inch aggregate) 16

The Hveem stability (a measure of frictional strength) is to be performed before the Marshall test (a measure of tensile strength). Its minimum value of 40 is set temporarily until sufficient data are obtained for determining effects of Marshall compaction.

If laboratory specimens do not meet design criteria or if there is a change in gradation, then the mixture should be re-examined with the calculations of the theoretical procedure. It is anticipated that a new design procedure will need adjustments as information is obtained for its verification in estimating the design asphalt content.

Construction Control of Paving Mixtures

The present ADOT procedures for the construction control of paving mixtures are considered appropriate. However, since some additions have been proposed for the laboratory design practice, these have to be reconciled in the control measurements. The present controls and additions are as follows:

1. Aggregate gradation.
2. Asphalt content.
3. Compaction of mixture on the roadway must be such that air void content value is a maximum of nine percent based on the effective specific gravity of the aggregate; i.e., the "Rice" specific gravity of the mixture.
4. Stability control of the paving mixture to be based on a 1,500-pound Marshall.

CALCULATED DESIGN ASPHALT CONTENTS COMPARED TO LABORATORY ESTABLISHED ONES

In order to aid in the verification of the new design for asphalt content procedure, it was deemed necessary to compare calculated values with those established through laboratory testing. A questionnaire was developed and sent to all State Highway Departments and some Canadian provinces. The questionnaire, contained in Appendix B, requested information on job-mix-formulas obtained from laboratory testing in addition to specific gravity and water absorption values.

The gradations and values or estimates for effective specific gravity and asphalt absorption were used to calculate service end point amounts of VMA, and the corresponding values of asphalt content for various and selected amounts of air voids.

Table B-1 in Appendix B has the data obtained from the various responding highway departments for comparing asphalt content. It will be noted that in most cases the calculated asphalt content was selected on the basis of air voids having values of two or three percent. The exceptions to selecting AVs of two or three percent were due to the values of VMA or asphalt film thickness being below those considered desirable. Also shown in the table are values of AV and film thickness for asphalt content from the agencies which varied greatly from those calculated with the new method.

In Figure 5 are two plots for a visual comparison between calculated and laboratory-established asphalt content. The statistical data shown on the plots indicate a surprisingly high value for coefficient of

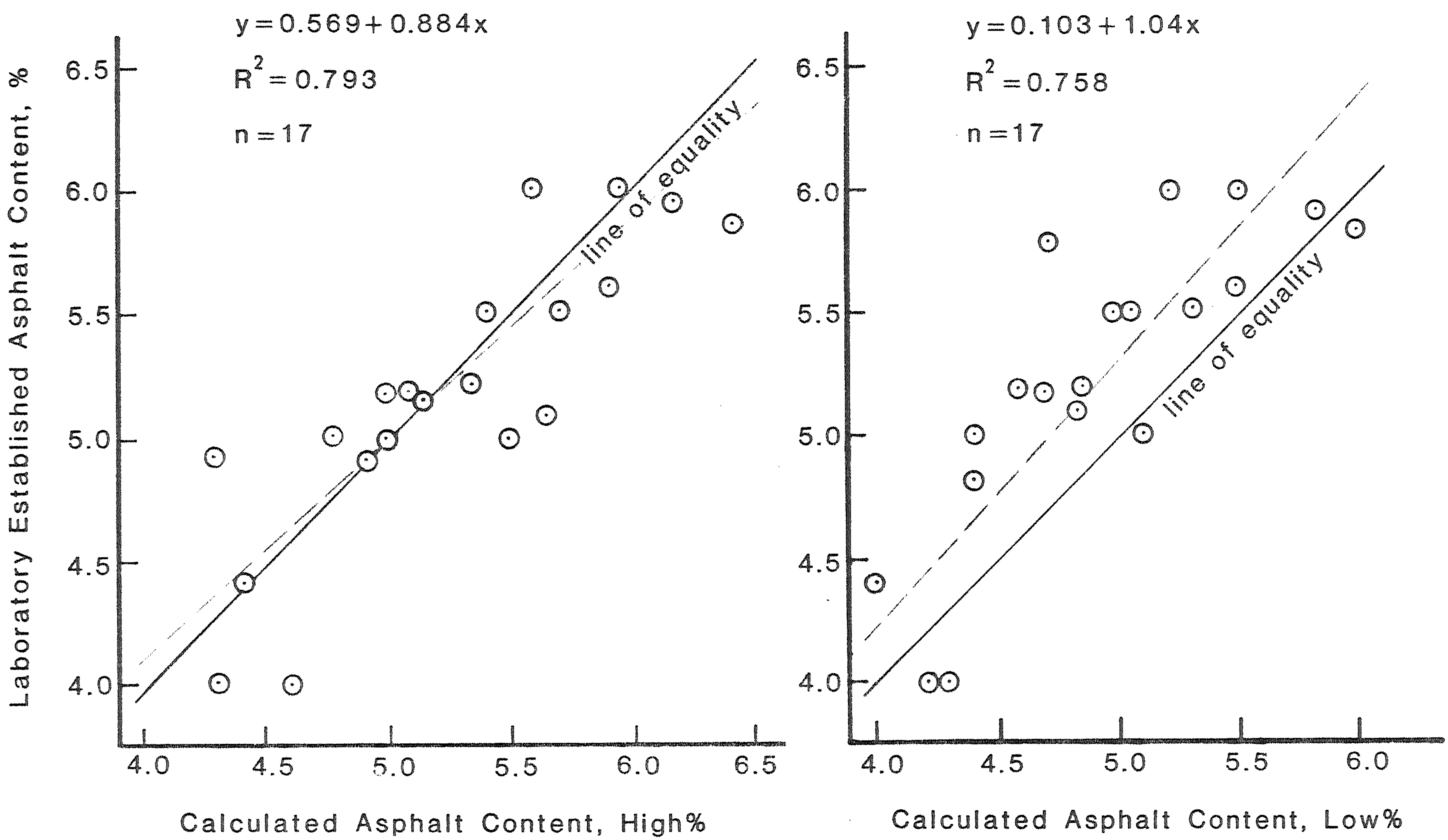

Figure 5. Comparisons of Laboratory Established Asphalt Content with Calculated Values for Various Highway Department Mixtures

correlation, R_2 , of 0.76 and 0.79, and also that the slope for the equation has a value near unity.

The Materials Division of ADOT responded to the questionnaire with JMF for several 1/2-inch and 3/4-inch mixtures that had been designed with the Marshall method using 75-blow compaction. A listing of asphalt contents obtained by calculation and laboratory testing appears as Table B-2 in Appendix B. As indicated before, the calculated asphalt content was generally selected for a corresponding AV of either two or three percent. Figure 6 presents plots comparable to those of Figure 5, except that the "measured" as opposed to "calculated" values of design asphalt content are from ADOT testing. For this comparison, the statistical analysis does not show a good correlation between the two values. The sample number n of 22 indicates that both 1/2-inch and 3/4-inch mixtures were included in the analysis. A study of 1/2-inch mixtures alone as well as the 3/4-inch mixtures alone did not show much difference in the R_2 and slope values as for the combined analysis. It is noted that the laboratory value for asphalt content determined by ADOT had a small range of basically 4.5 to 5.5 percent, while the range for the other highway departments was from 4.0 to 6.0 percent.

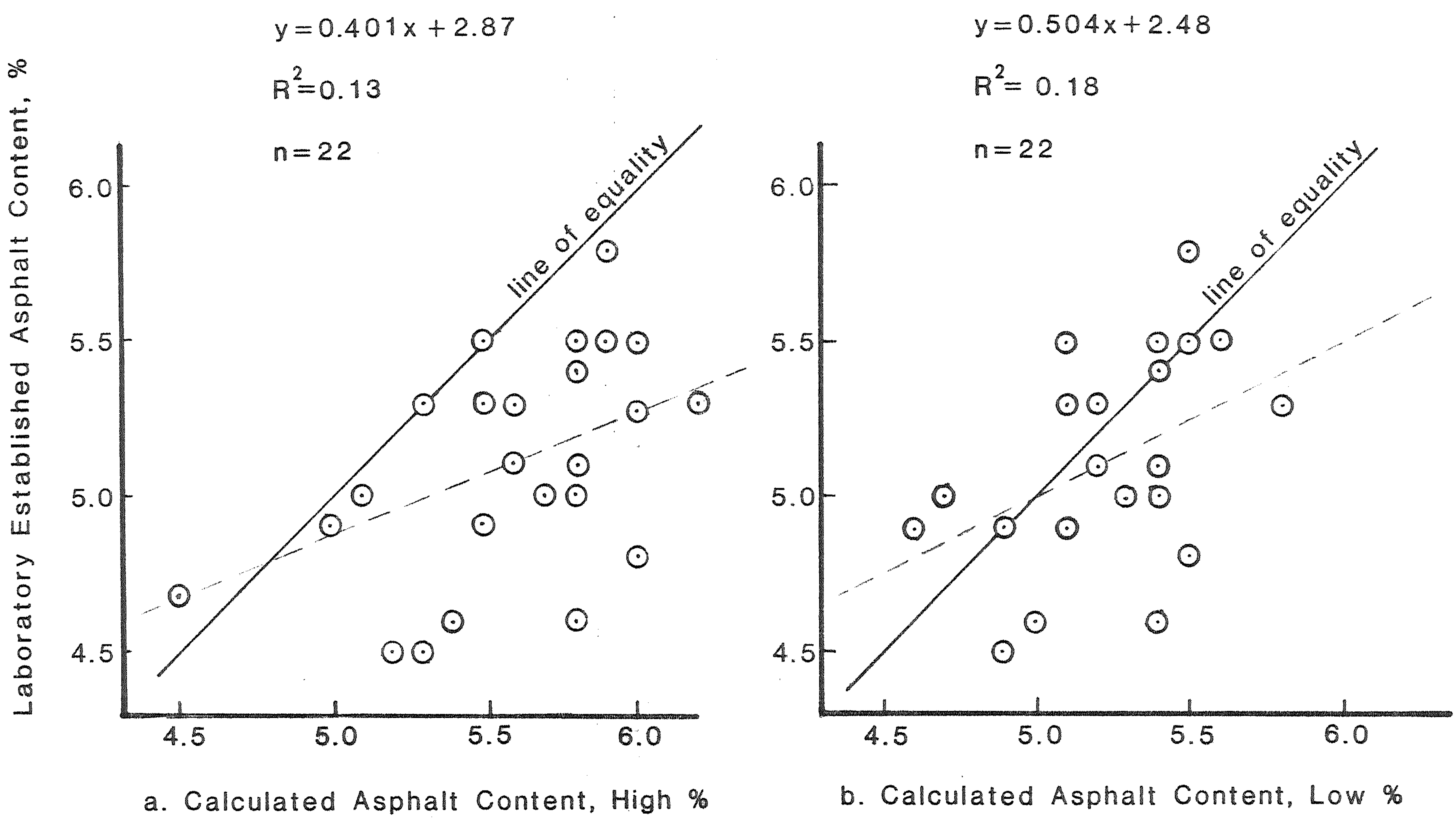

Figure 6. Comparisons of Laboratory Established Asphalt Content with Calculated Values for ADOT Mixtures

MEASUREMENTS ON PAVEMENT CORES

An important portion of the work program was to take samples of pavement surfaces whose conditions were characterized by "good", "cracked", or "rutted". Various measurements of the cores were taken for comparing with the condition of the pavement and with comparable values obtained with the new design procedure.

The pavements classified as "good" were selected (as approved by ADOT) and sampled by the personnel from the University of Arizona's Asphalt Laboratory. The pavements representing "cracked" and "rutted" ones were sampled by ADOT and the cores were sent to the University of Arizona Asphalt Laboratory. All cores were of 4-inch diameter and of the full depth of the pavement surface.

A minimum of two cores were taken from the outer-, in-between-, and inner-wheel paths (O.W.P., B.W.P., and I.W.P.) at each site. However, as noted, in some instances only one core as received in the laboratory was suitable for isolating the surface course for measurements.

Upon receiving the cores, they were separated and identified as to condition, roadway location, location within lane, and thickness of surface. The surface course was trimmed from the core with a diamond-tipped masonry saw. The sawing was done at ambient temperature; however, the cores representing the rutted sections had been cooled to 0°F prior to cutting.

The trimmed cores were measured for density and Marshall stability and then followed with extraction of the aggregate for gradation and effective specific gravity determinations. The measured data of the cores were compared with ADOT's laboratory design values.

The calculated values for VMA, AV, and asphalt content shown in Table C of the Appendix were calculated with the following conditions:

1. The effective specific gravity of the aggregate were "measured" using a mixture with five percent asphalt having a specific gravity of 1.018.
2. The VMA of the -#200 sieve material was 32 percent.
3. The asphalt absorption of the aggregate was 0.60 percent.
4. The asphalt film thickness was based on the effective asphalt content and so the limits were changed from six to twelve microns for the selection of asphalt content.

The results of the measurements and calculations of the cores are listed in Appendix C; Table C-1 for the "good" pavements, Table C-2 for the "cracked" ones, and Table C-3 for the "rutted" ones. A summary of those results is shown listed in Table 9. It is to be noted that average age for the pavements of different condition varied a great deal; e.g., the "good" ones had an average age of one year, the "rutted" ones of about 6.5 years and the "cracked" ones were about 14 years old.

The following figures will be used to show comparisons of density, AV, VMA, and gradation between values obtained for the field cores and those obtained in the laboratory design or based on theory.

Figure 7 presents a plot of specimen densities for comparing those obtained in the laboratory design process with those obtained after construction and traffic compaction. It can be seen that the laboratory

Table 9. Summary of Core and ADOT Design Data.

Project Condition		Core: Age, Yr.	Core: VMA, %	Core: Air Voids, %	Core: Density, pcf	ADOT Design: VMA, %	ADOT Design: Air Voids, %	ADOT Design: Density,[a/] pcf
I-8-1(80)	Meas.	1.5	16.7	4.1	143.4	16.9	5.8	M 141.5
Good	Calc.		13.6	0.5				
I-8-2(80)	Meas.	1.5	17.4	5.2	144.1	17.0	5.8	M 142.0
Good	Calc.		14.1	1.5				
I-10-3(148)	Meas.	0.5	18.5	6.3	139.7	16.3	5.5	M 140.9
Good	Calc.		16.7	4.7				
I-IR-10-4(66)	Meas.	5.0	13.8	1.5	147.7	15.5	4.6	H 142.3
Rutted	Calc.		14.4	2.2				
I-17-2(48)	Meas.	10.5	14.0	0.7	156.1	15.5	5.3	H 148.0
Rutted	Calc.		13.3	0.5				
I-40-4(70)	Meas.	5.5	13.9	0.3	166.2	15.9	4.2	H 166.0
Rutted	Calc.		15.2	0.8				
I-10-1(46)	Meas.	15.0	18.3	5.8	143.5	15.6	4.7	H 144.0
Cracked	Calc.		13.8	0.8				
I-40-4(42/87)	Meas.	16.0	21.5	7.6	135.7	15.2	5.1	H 147.0
Cracked	Calc.		16.2	1.3				
I-10-6(67)	Meas.	10.0	19.1	7.5	141.0	17.0	7.2	H 144.0
Cracked	Calc.		15.1	2.9				

a/ M = 75-blow Marshall
H = Hveem

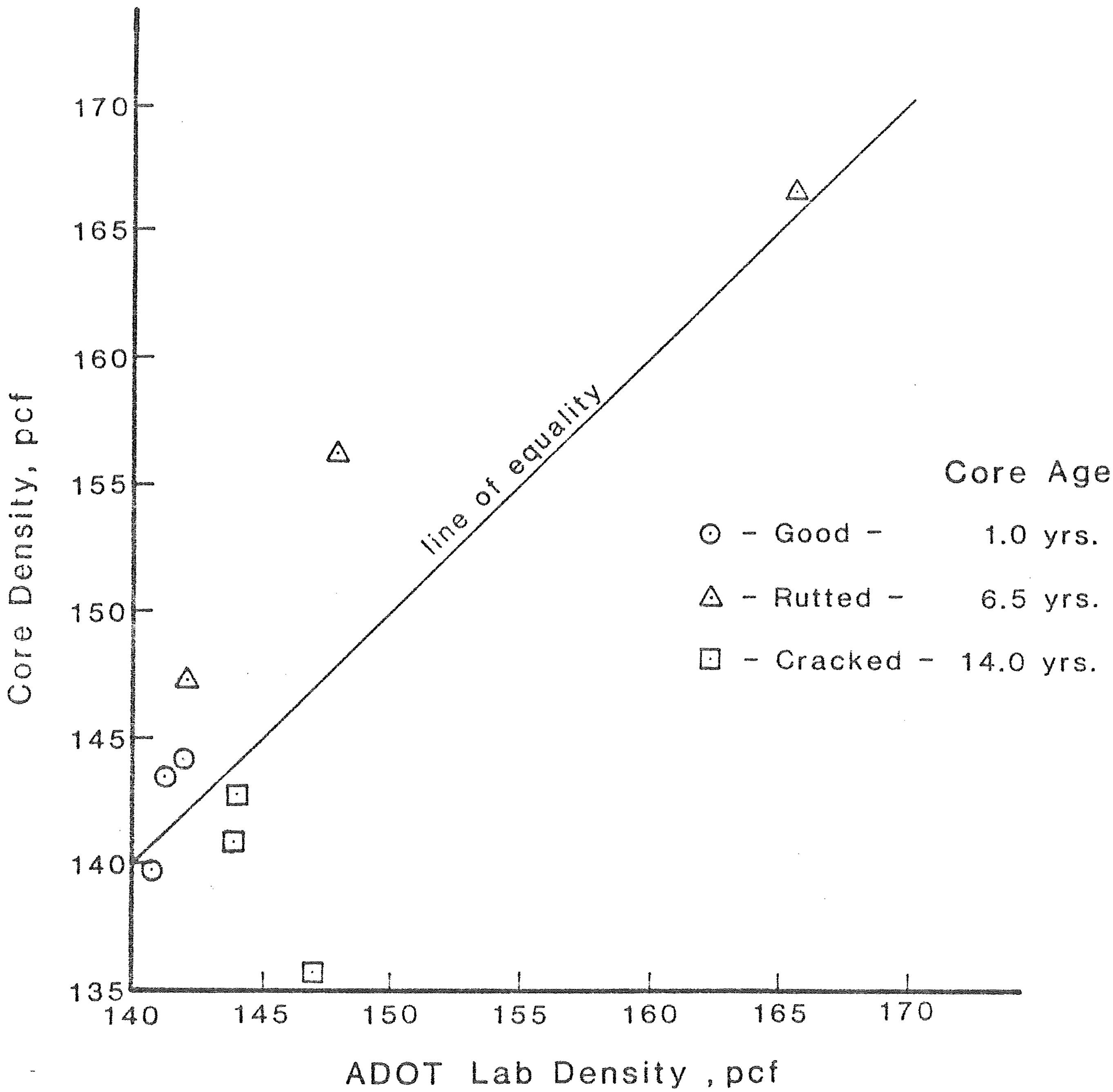

Figure 7. Comparison of Mixture Laboratory Density and Pavement Core Density

compaction results in less density than will be achieved in the roadway. The cores showing less density than that achieved by laboratory compactions are either not very old (0.5 year) or were cracked. The stresses causing the cracked condition would also cause a reduction of density from some higher value. This relationship should be considered in setting limits for both AV and VMA on design values for present laboratory compaction procedures.

Figures 8a and 8b show data for comparing values of AV and VMA of cores with the condition of the pavements from which they were taken. As might have been anticipated, the high values for both AV and VMA were for the "cracked" pavments and the low values were for the "rutted" ones. The position of the pavement is not related to time in the figure nor do we know when the "rutted" pavements became so. One may speculate because of the young ages of the "good" cores and the low values of both AV and VMA for 3/4-inch gradations that these pavements will be susceptible to "rutting" under compaction by future traffic.

In Figures 9, 10 and 11 we have plotted the averaged aggregate gradations for each sampling of the pavement of the three conditons of "good", "cracked", and "rutted". Also shown as a broken line is a maximum density gradation expressed by Fuller's maximum density (FMD) equation of

$$p = \sqrt{d/D} \times 100$$

where p is the perecent passing the sieve of size d and

D is the largest particle size of the aggregate blend.

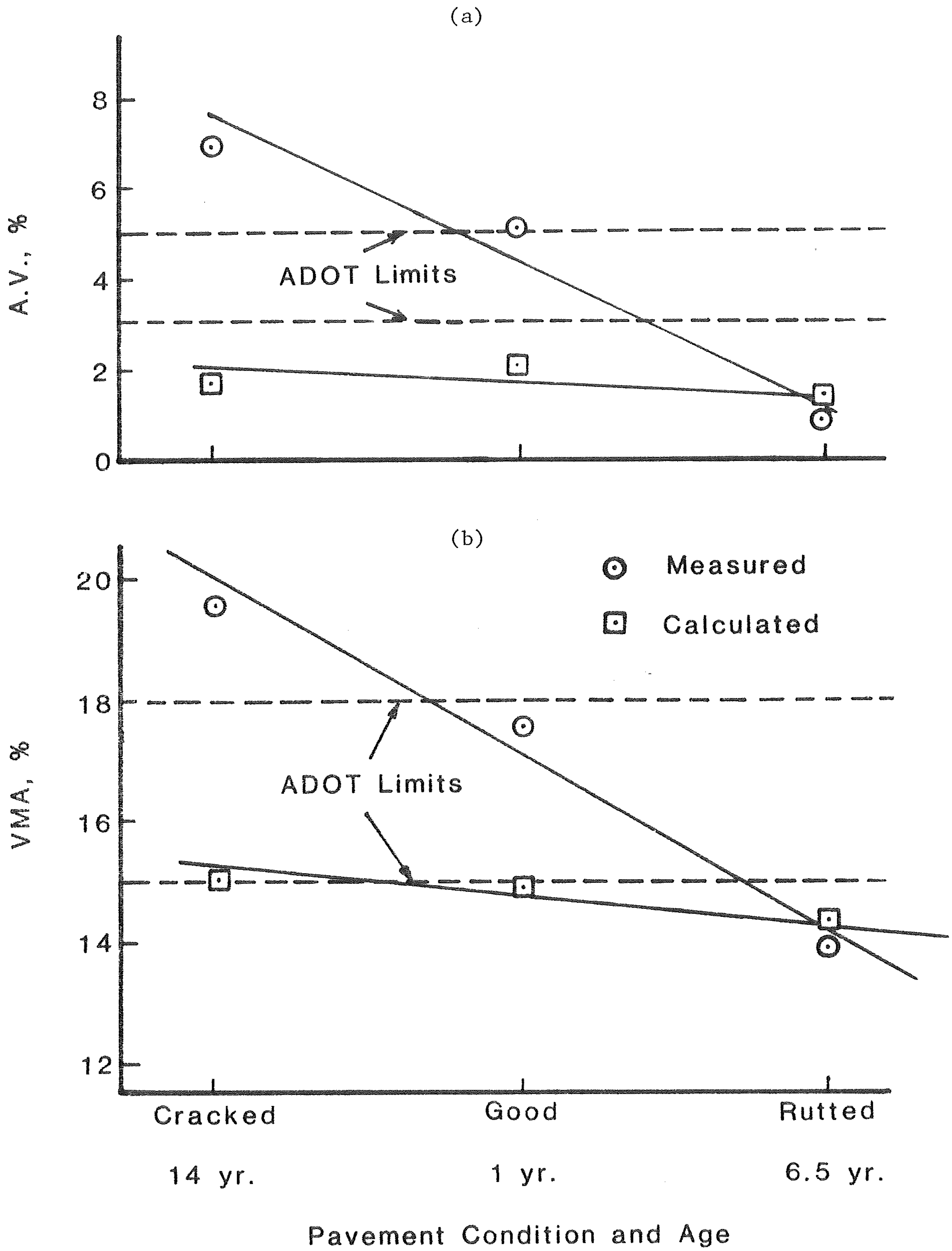

Figure 8. Comparison of Pavement Condition with VMA and A.V. of Cores

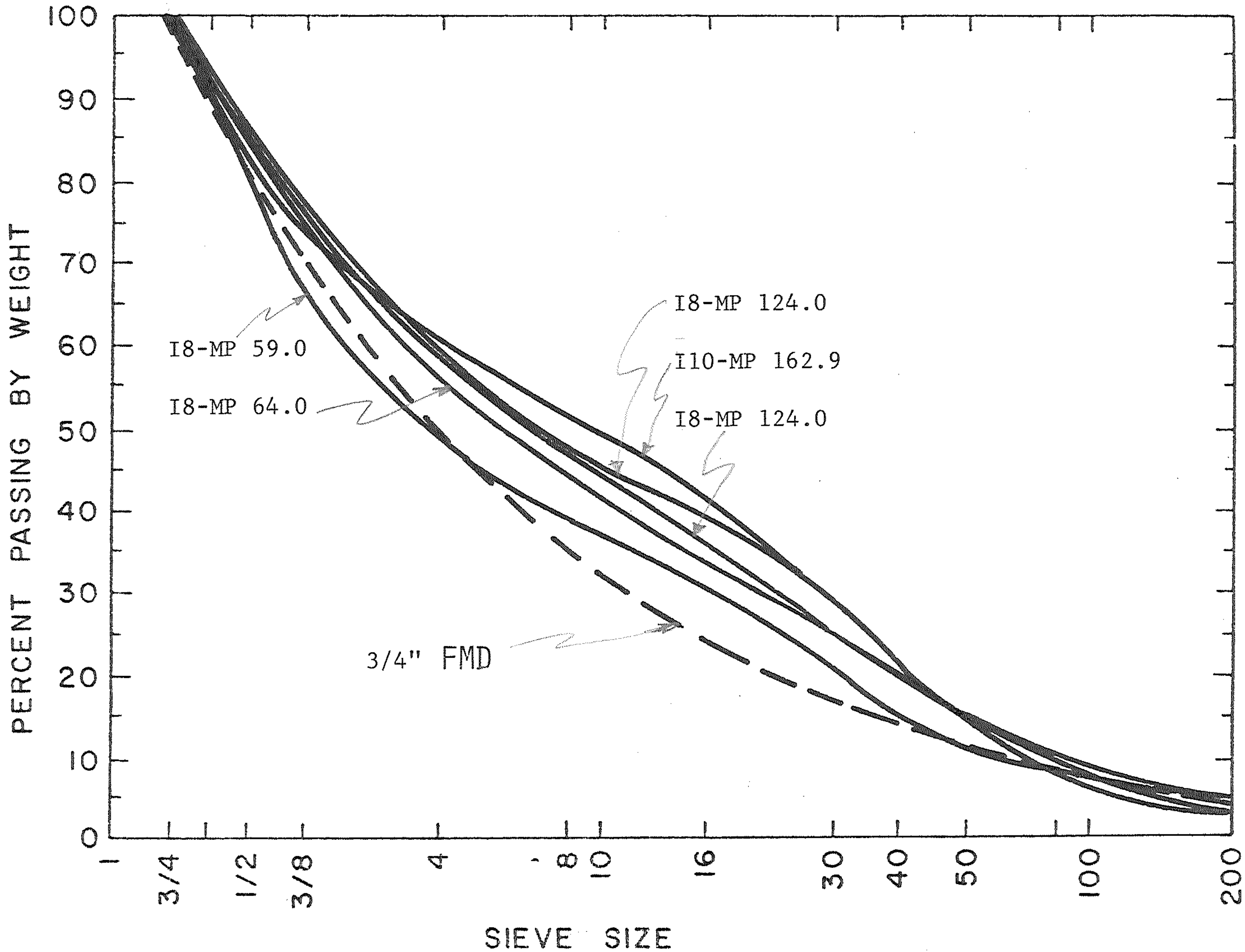

Figure 9. U of A Core Gradations from Good Surface Pavements

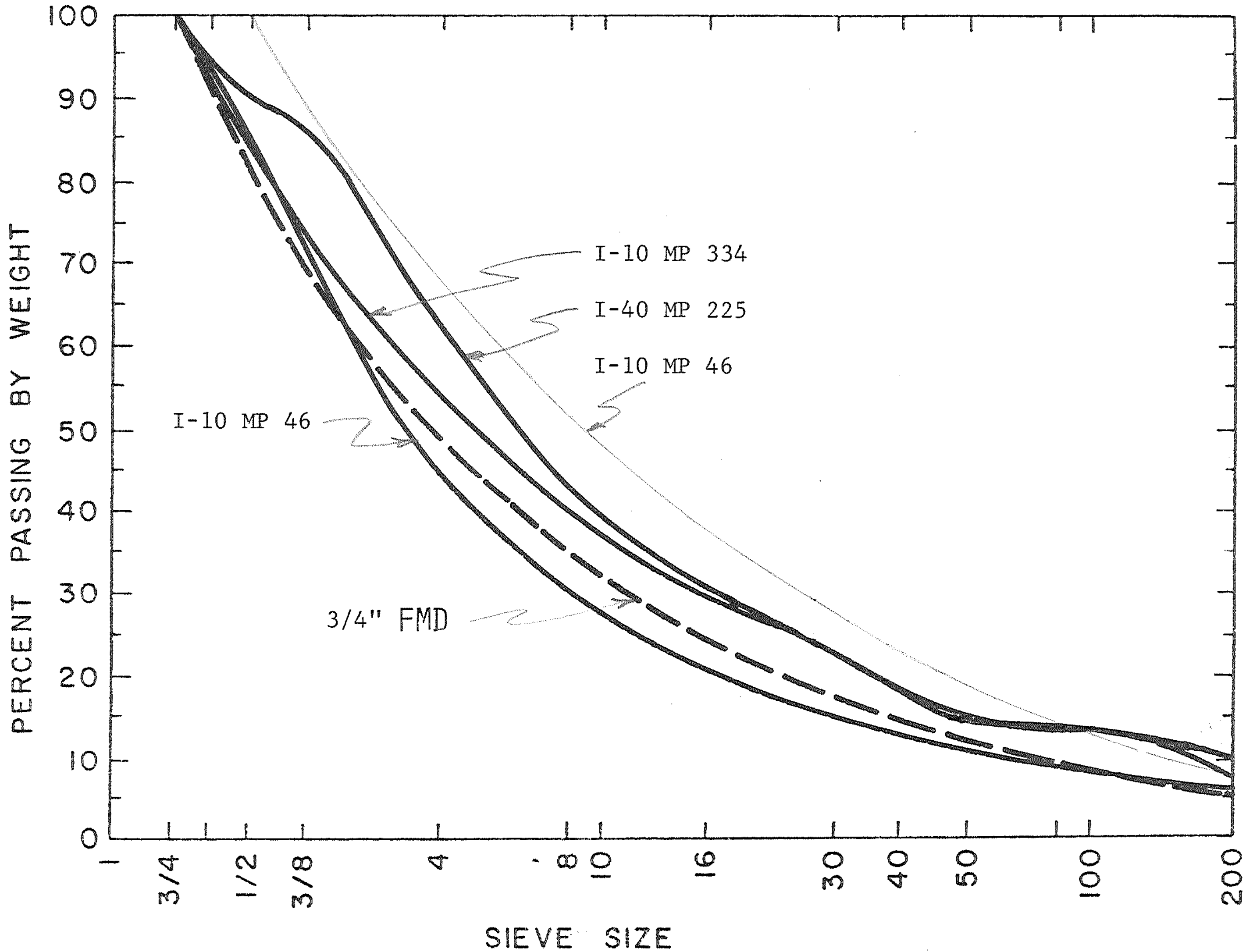

Figure 10. Core Gradations from Cracked Surface Pavements

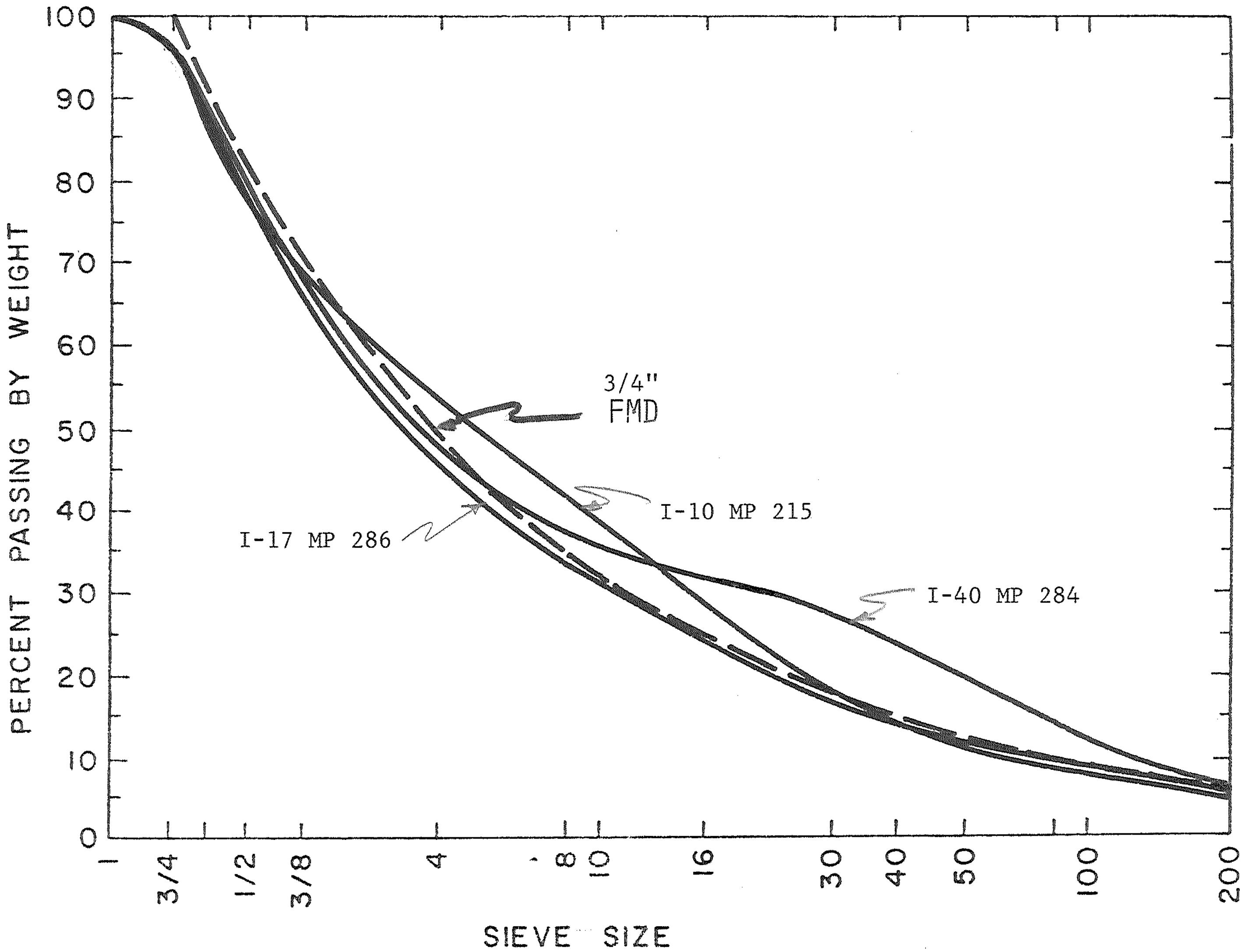

Figure 11. Core Gradations from Rutted Surface Pavements

The indication of a maximum density gradation is that it will result in a minimum value of VMA. It is to be noted that gradation of the aggregates for the "rutted" pavements (Figure 11) are grouped the closest to the FMD curve. This observation backs up the statement of Potts (1) quoted earlier and recommendations made by Jimenez in his report to ADOT in 1981 (18).

REVIEW OF LABORATORY PROCEDURES AND CALCULATIONS

The Materials Section of ADOT abandoned the Hveem (California) procedure for asphaltic concrete in the Fall of 1981 and instituted the Marshall method. As mentioned in References 17 and 18, prior to that change the Central Laboratory was using the Hveem procedure but the District Laboratories were verifying and modifying the mixture design on the basis of the Marshall method. In reviewing the present use of the Marshall method for mixture design, we found that, in general, the various tests and controlling specifications are in conformance with those used by 76 percent of State highway agencies (24) that utilize that method.

Beginning the Spring of 1984, the Technical Subcommittee of the Governor's Asphaltic Concrete Specification Committee has been reviewing and suggesting modifications to test procedures and specifications for the design of these paving mixtures. The Subcommittee members are representatives of ADOT, the Associated General Contractors (AGC), a consulting engineer, and a civil engineering professor from The University of Arizona. Through the efforts of the Subcommittee, many changes have been made to improve test procedures and acceptance of specifications by the contractors.

Jimenez, one of the authors of this report and also the Chairman of the ADOT-AGC Subcommittee, is in general agreement with ADOT's present Marshall mix design method for Asphaltic Concrete (ARIZ 815c, April 1985). However, exception is taken to the bases for calculating

"Percent Voids in Mineral Aggregate" and "Effective Air Voids." The expression for these values as given by ARIZ 815c, April 1985 are as follows:

a. % Voids in Mineral Aggregate (VMA)

$$VMA = (100) - \left[\begin{array}{c} \text{Volume of} \\ \text{Aggregate } (V_{ag}) \end{array} \right] - \left[\begin{array}{c} \text{Volume of Mineral} \\ \text{Admixture } (V_{mx}) \end{array} \right]$$

where the volume of aggregate is obtained using its bulk oven dry specific gravity and the volume of mineral admixture is calculated using its specific gravity.

b. Effective Air Voids (EAV)

$$EAV = 1 - \left[\frac{\begin{array}{c} \text{Average Measured Bulk Specific} \\ \text{Gravity of Specimens } (G_{mb}) \end{array}}{\begin{array}{c} \text{Maximum Specific Gravity of} \\ \text{Bituminous Mixture } (G_{mm}) \end{array}} \right] 100$$

Our objection to these expressions is that in one case (a) the specific gravity of the aggregate is obtained in consideration of water absorption and in the second case (b) it is in consideration of absorption of asphalt. This means that the volume of aggregate is being calculated with two different specific gravities. In the past, it has been recommended (18) that the effective or virtual specific gravity be used for the computation of both voids in the mineral aggregate and effective air voids.

SUMMARY AND CONCLUSIONS

General

The evaluation of ADOT's asphaltic concrete design procedure included the development and analysis of the Hveem and Marshall design procedures, the calculation of stresses in various three-layered asphaltic concrete pavement systems, and characteristics of paving mixtures from pavements showing "good", "cracked", and "rutted" conditions. Over 1,200 calculations were performed to delineate the location and maximum tensile and shear stresses. At least two cores were taken from the outer-, in-between-, and inner-wheel paths from three different pavements representing conditions of "good", "cracked", and "rutted".

The core samples were evaluated for density, Marshall stability, air void content, VMA, asphalt content, and gradation. Those measured values for the core were compared to corresponding values established in the initial laboratory design and also with values obtained from a new design method based only on computations for estimating an optimum asphalt content.

Conclusions

The study was of limited coverage and extended time. However, the findings are considered to be significant enough to warrant the following conclusions as applied to the study.

1. Both of the Hveem and Marshall methods of mixture design are empirical in nature; especially since neither yield results in common engineering units. However, the Hveem is considered to be more realistic since it accounts for measures of both frictional and cohesive resistance to deformation of a paving mixture. Additionally, the specifications for minimum stability has not changed since its beginning. The Marshall strength criterion has increased from 500 to 2,000 pounds since its development by the U. S. Corps of Engineers.

2. The Marshall stability is generally considered to be primarily a measure of cohesive or tensile strength, and as a consequence, it does not reflect a measure of resistance to rutting which is caused by shearing stresses.

3. The most efficient way to reduce tensile stresses in the asphaltic concrete surface was to increase its thickness; this is immediately apparent since the section modulus is a function of thickness squared. However, the next most efficient way was to reduce the difference in modulus between the surface and the base layer; that is, to reduce the E1/E2 ratio. The magnitude of tensile stresses in a typical pavement section could be over 200 psi.

4. As was the case for tensile stress, the most effective way to reduce shear stresses was to increase the thickness of the surface course. The maximum value of shear occurred generally at the bottom of the thinner surface layers and at the upper part of

the 9-inch surface course. The maximum shear stress found in the study was on the order of 130 psi.

5. The new mixture design procedure for estimating an optimum asphalt content for dense-graded paving mixtures had good correlation (R_2 = 0.79) when compared with JMF of several highway departments; however, it had a low R_2 value of 0.18 when compared with ADOT mixtures.

6. The highway cores had densities that were higher than those established in the laboratory for the mixture design.

7. Values of both air void content and VMA for the cores had a definite relation to condition of the pavement. The "cracked" pavements had high values and the "rutted" ones had low values. For example, the high values were approximately 20 and 7 percent and the low values were approximately 14 and 1 percent for VMA and air void, respectively.

8. ADOT uses different values of specific gravity of the aggregate for calculating VMA and air void content.

9. ADOT's method for the Marshall procedure of asphaltic mixture design was in general conformance to procedures and specifications used by other states.

10. ADOT is making an exemplary effort in updating design procedures and specifications for asphaltic concrete.

RECOMMENDATIONS

In recommending changes for improving mixture design procedures, one must avoid pie-in-the-sky approaches. The suggestions to be made for improving asphaltic concrete mixture design are considered to be practical for implementation in the design laboratory and in the field control of such mixtures.

1. Continue the field sampling of pavements in order to determine equilibrium or stabilized values of air void and VMA.
2. Evaluate new laboratory compaction methods; e.g., Texas gyrotory or University of Arizona vibratory, to obtain specimen density equal to that obtained after construction and ultimate traffic compaction.
3. Presently, most laboratory designs for asphaltic concrete produce a compacted specimen that will have a higher density compared to that of the mixture immediately after construction. It is suggested that this practice be continued until one of the suggested procedures be implemented and checked. It is recommended that a laboratory procedure attempt to produce specimens having characteristics comparable to those the pavement will have sometime (4-5 years) in the future past construction. As a consequence, higher mixing and/or compaction temperatures will be needed and also higher compactive efforts that will not degrade the aggregate.

4. Consider using the Hveem stability and Marshall stability on the same specimen to obtain obtain measures of frictional resistance (Hveem) and cohesive resistance (Marshall). The resistance to rutting would be determined with the Hveem procedure and the resistance to cracking with the Marshall. A separate and limited study by this laboratory indicated that the same Marshall stability was obtained for specimens that had or had not been first tested in the Hveem stabilometer. The Hveem and Marshall stability would both have minimum values specified for design. The field control could include the Marshall stability.

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APPENDIX A
LIST OF TABLES

Table A 1. Maximum Tensile Stress, psi, on Surface Course for System Shown, Part 1.

E 1 = 100 ksi   E 2 = 20 ksi

H 1 = 3 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	130	120	110	100
	105	6	100	100	100	100
		9	90	90	90	90
		3	150	130	130	120
4,000	130	6	120	110	110	110
		9	110	110	110	110
		3	160	150	140	130
	150	6	130	130	120	120
		9	120	120	120	120
		3	160	140	120	110
	105	6	110	110	110	100
		9	100	100	110	100
		3	180	160	140	140
6,000	130	6	130	130	130	120
		9	120	120	120	120
		3	200	170	160	150
	150	6	140	140	140	140
		9	140	140	140	140

Table A1. Part 2.

E 1 = 100 ksi   E 2 = 30 ksi

H 1 = 3 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	100	90	80	70
	105	6	70	60	60	60
		9	60	60	60	60
		3	110	100	90	90
4,000	130	6	80	80	80	70
		9	70	70	70	70
		3	120	110	100	90
	150	6	90	90	80	80
		9	80	80	80	80
		3	110	100	90	80
	105	6	70	70	70	70
		9	60	60	60	60
		3	130	110	100	100
6,000	130	6	80	80	80	80
		9	70	70	80	80
		3	140	120	110	110
	150	6	90	90	90	90
		9	80	90	90	90

Table A1. Part 3.

E1 = 100 ksi　　　　E2 = 40 ksi

H1 = 3 in.

W lb	I.P. psi	H2 in.	E3, ksi 3	6	9	12
		3	70	60	60	50
	105	6	40	40	40	40
		9	40	40	40	40
		3	80	70	70	60
4,000	130	6	50	50	50	50
		9	50	50	50	50
		3	90	80	70	70
	150	6	60	60	60	60
		9	50	50	50	50
		3	80	70	60	60
	105	6	40	40	40	40
		9	30	30	40	40
		3	90	80	70	70
6,000	130	6	50	50	50	50
		9	40	50	50	50
		3	100	90	80	80
	150	6	60	60	60	60
		9	50	50	60	60

Table A1. Part 4.

E1 = 100 Ksi   E2 = 20 ksi

H1 = 6 in.

W lb	I.P. psi	H2 in.	E3, ksi 3	6	9	12
		3	70	60	60	60
	105	6	60	60	50	50
		9	50	50	50	50
		3	80	70	60	60
4,000	130	6	60	60	60	60
		9	60	60	50	50
		3	80	70	70	60
	150	6	70	60	60	60
		9	60	60	60	60
		3	100	90	80	70
	105	6	80	70	70	70
		9	70	70	70	70
		3	110	90	80	80
6,000	130	6	90	80	80	70
		9	80	70	70	70
		3	110	100	90	80
	150	6	90	80	80	80
		9	80	80	80	70

Table A 1. Part 5.

E 1 = 100 ksi   E 2 = 30 ksi

H 1 = 6 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	60	50	50	50
	105	6	40	40	40	40
		9	40	40	40	40
		3	60	50	50	50
4,000	130	6	50	40	40	40
		9	40	40	40	40
		3	60	60	50	50
	150	6	50	50	40	50
		9	40	40	40	40
		3	80	70	60	60
	105	6	60	50	50	50
		9	50	50	50	50
		3	90	70	70	60
6,000	130	6	60	60	60	50
		9	50	50	50	50
		3	90	80	70	70
	150	6	70	60	60	60
		9	60	60	50	50

Table A1. Part 6.

E 1 = 100 ksi   E 2 = 40 ksi

H 1 = 6 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	50	40	40	40
	105	6	30	30	30	30
		9	30	30	30	30
		3	50	50	40	40
4,000	130	6	40	30	30	30
		9	30	30	30	30
		3	50	50	40	40
	150	6	40	30	30	30
		9	30	30	30	30
		3	70	60	50	50
	105	6	40	40	40	40
		9	40	30	30	30
		3	70	60	60	50
6,000	130	6	50	40	40	40
		9	40	40	40	40
		3	70	60	60	50
	150	6	50	50	50	40
		9	40	40	40	40

Table A1. Part 7.

E1 = 100 ksi E2 = 20 ksi

H1 = 9 in.

W lb	I.P. psi	H2 in.	E3, ksi 3	6	9	12
		3	40	40	30	30
	105	6	30	30	30	30
		9	30	30	30	30
		3	40	40	30	30
4,000	130	6	30	30	30	30
		9	30	30	30	30
		3	40	40	30	30
	150	6	40	30	30	30
		9	30	30	30	30
		3	60	50	50	40
	105	6	50	40	40	40
		9	40	40	40	40
		3	60	50	50	40
6,000	130	6	50	50	40	40
		9	50	40	40	40
		3	60	50	50	50
	150	6	50	50	50	40
		9	50	40	40	40

Table A1. Part 8.

E1 = 100 ksi E2 = 30 ksi

H1 = 9 in.

W lb	I.P. psi	H2 in.	E3, ksi 3	6	9	12
		3	30	30	30	30
	105	6	30	30	20	20
		9	20	20	20	20
		3	40	30	30	30
4,000	130	6	30	30	20	20
		9	20	20	20	20
		3	40	30	30	30
	150	6	30	30	20	20
		9	20	20	20	20
		3	50	40	40	40
	105	6	40	30	30	30
		9	30	30	30	30
		3	50	50	40	40
6,000	130	6	40	40	30	30
		9	30	30	30	30
		3	50	50	40	40
	150	6	40	40	30	30
		9	30	30	30	30

Table A1. Part 9.

E1 = 100 ksi E2 = 40 ksi

H1 = 9 in.

W lb	I.P. psi	H2 in.	E3, ksi 3	6	9	12
		3	30	30	20	20
	105	6	20	20	20	20
		9	20	20	20	20
		3	30	30	20	20
4,000	130	6	20	20	20	20
		9	20	20	20	20
		3	30	30	20	20
	150	6	20	20	20	20
		9	20	20	20	20
		3	40	40	30	30
	105	6	30	30	30	30
		9	30	20	20	20
		3	40	40	30	30
6,000	130	6	30	30	30	30
		9	30	30	20	20
		3	50	40	40	30
	150	6	30	30	30	30
		9	30	30	30	20

Table A1. Part 10.

E1 = 200 ksi E2 = 20 ksi

H1 = 3 in.

W lb	I.P. psi	H2 in.	E3, ksi 3	6	9	12
		3	230	200	180	170
	105	6	180	170	170	160
		9	170	160	160	160
		3	250	220	210	190
4,000	130	6	200	190	190	180
		9	190	180	180	180
		3	260	230	220	210
	150	6	220	210	200	200
		9	200	200	200	190
		3	280	240	220	200
	105	6	220	200	190	190
		9	190	190	180	180
		3	310	270	250	230
6,000	130	6	240	230	220	220
		9	220	220	210	210
		3	330	290	270	250
	150	6	270	250	240	240
		9	240	240	230	230

Table A 1. Part 11.

E 1 = 200 ksi E 2 = 30 ksi

H 1 = 3 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	180	160	150	140
	105	6	140	130	130	130
		9	120	120	120	120
		3	200	180	170	160
4,000	130	6	150	150	150	140
		9	140	140	140	140
		3	210	190	180	170
	150	6	170	160	160	160
		9	150	150	150	150
		3	220	190	180	170
	105	6	260	150	150	140
		9	140	150	130	130
		3	250	220	200	190
6,000	130	6	180	170	170	170
		9	160	160	160	160
		3	270	240	220	210
	150	6	200	190	190	180
		9	180	180	180	170

Table A 1. Part 12.

E 1 = 200 ksi   E 2 = 40 ksi

H 1 = 3 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	150	130	130	120
	105	6	110	100	100	100
		9	90	90	90	90
		3	170	150	140	130
4,000	130	6	120	120	120	120
		9	110	110	110	110
		3	180	160	150	150
	150	6	130	130	130	130
		9	120	120	120	120
		3	180	160	150	140
	105	6	120	110	110	110
		9	100	100	100	100
		3	210	180	170	160
6,000	130	6	140	130	130	130
		9	120	120	120	120
		3	220	200	180	170
	150	6	150	150	150	160
		9	140	140	140	140

Table A1. Part 13.

E1 = 200 ksi   E2 = 20 ksi

H1 = 6 in.

W lb	I.P. psi	H2 in.	E3, ksi 3	 6	 9	 12
		3	100	90	90	80
	105	6	90	80	80	80
		9	80	80	80	80
		3	110	100	90	90
4,000	130	6	90	90	80	80
		9	90	80	80	80
		3	110	100	90	90
	150	6	100	90	90	80
		9	90	90	80	80
		3	140	130	110	110
	105	6	120	110	110	100
		9	110	110	100	100
		3	150	130	120	110
6,000	130	6	130	120	110	110
		9	120	110	110	110
		3	150	140	130	120
	150	6	130	120	120	110
		9	120	120	110	110

Table A1. Part 14.

E 1 = 200 ksi E 2 = 30 ksi

H 1 = 6 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	90	80	80	70
	105	6	70	70	70	70
		9	70	70	60	60
		3	100	90	80	80
4,000	130	6	80	70	70	70
		9	70	70	70	70
		3	100	90	80	80
	150	6	80	80	70	70
		9	70	70	70	70
		3	130	110	100	90
	105	6	100	90	90	90
		9	90	90	80	80
		3	130	120	110	100
6,000	130	6	110	100	100	90
		9	100	90	90	90
		3	140	120	110	110
	150	6	110	100	100	100
		9	100	100	90	90

Table A1. Part 15.

E 1 = 200 ksi　　　　E 2 = 40 ksi

H 1 = 6 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	80	70	70	60
	105	6	60	60	60	60
		9	60	50	50	50
		3	90	80	70	70
4,000	130	6	70	60	60	60
		9	60	60	60	60
		3	90	80	70	70
	150	6	70	70	60	60
		9	60	60	60	60
		3	110	100	90	90
	105	6	90	80	80	70
		9	70	70	70	70
		3	120	110	100	90
6,000	130	6	90	90	80	80
		9	80	80	70	70
		3	120	110	100	100
	150	6	90	90	90	80
		9	80	80	80	80

Table A 1. Part 16.

E 1 = 200 ksi   E 2 = 20 ksi

H 1 = 9 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	50	50	50	40
	105	6	50	50	40	40
		9	50	40	40	40
		3	50	50	50	40
4,000	130	6	50	50	40	40
		9	50	40	40	40
		3	60	50	50	40
	150	6	50	50	40	40
		9	50	40	40	40
		3	80	70	60	60
	105	6	70	60	60	60
		9	60	60	60	60
		3	80	70	70	60
6,000	130	6	70	70	60	60
		9	70	60	60	60
		3	80	70	70	60
	150	6	70	70	60	60
		9	70	60	60	60

Table A 1. Part 17.

E 1 = 200 ksi   E 2 = 30 ksi

H 1 = 9 in.

W lb	I.P. psi	H 2 in.	E 3, ksi 3	6	9	12
		3	50	40	40	40
	105	6	40	40	40	40
		9	40	40	30	30
		3	50	50	40	40
4,000	130	6	40	40	40	40
		9	40	40	40	30
		3	50	50	40	40
	150	6	40	40	40	40
		9	40	40	40	40
		3	70	60	60	60
	105	6	60	60	50	50
		9	50	50	50	50
		3	70	70	60	60
6,000	130	6	60	60	50	50
		9	60	50	50	50
		3	70	70	60	60
	150	6	60	60	60	50
		9	60	50	50	50

Table A1. Part 18.

E1 = 200 ksi E2 = 40 ksi

H1 = 9 in.

W lb	I.P. psi	H2 in.	E3, ksi 3	6	9	12
		3	50	40	40	40
	105	6	40	30	30	30
		9	30	30	30	30
		3	50	40	40	40
4,000	130	6	40	30	30	30
		9	30	30	30	30
		3	50	40	40	40
	150	6	40	40	30	30
		9	30	30	30	30
		3	70	60	50	50
	105	6	50	50	50	40
		9	50	40	40	40
		3	70	60	60	50
6,000	130	6	50	50	50	50
		9	50	50	40	40
		3	70	60	60	50
	150	6	60	50	50	50
		9	50	50	40	40

Table A 2. Extreme Shear Stress, psi, at Selected Points in a Surface Course for System Shown, Part 1.

W = 4,000 lb. E 1 = 200 ksi

I.P. = 150 psi E 2 = 20 ksi

Ra = 2.91 in. E 3 = 6 ksi

H 1 = 3 in.

H 2 in.	Z in.	Radial Distance, in. 0	1	2	3
3	0	91.0	88.0	79.1	89.1
	1	1.6	22.9	51.2	72.3
	2	61.2	72.8	76.4	63.5
	3	135.3	131.8	116.5	93.0
6	0	78.6	75.4	67.1	78.1
	1	5.9	21.4	48.4	69.7
	2	58.4	69.3	72.4	60.6
	3	124.6	120.9	105.7	82.6
9	0	71.9	68.8	60.6	72.0
	1	8.8	21.7	47.7	68.8
	2	57.8	68.6	71.4	59.4
	3	120.5	116.7	101.5	78.6

Table A 2. Part 2.

W = 4,000 lb. E 1 = 200 ksi

I.P. = 150 psi E 2 = 20 ksi

Ra = 2.91 in. E 3 = 6 ksi

H 1 = 6 in.

H 2 in.	Z in.	Radial Distance, in. 0	1	2	3
	0	23.0	22.3	21.2	44.5
	2	34.6	41.8	42.4	44.3
3	4	35.1	40.0	39.8	35.6
	6	55.1	54.2	50.5	46.8
	0	19.7	19.2	17.3	38.9
	2	35.6	42.7	43.2	43.5
6	4	34.2	38.9	38.7	33.8
	6	51.8	50.8	47.1	41.2
	0	17.6	17.1	15.9	35.9
	2	36.3	43.3	43.8	43.2
9	4	33.8	38.5	38.1	33.2
	6	50.0	48.7	44.8	39.4

Table A 2. Part 3.

W = 4,000 lb. E 1 = 200 ksi

I.P. = 150 psi E 2 = 20 ksi

Ra = 2.91 in. E 3 = 6 ksi

H 1 = 9 in.

H 2 in.	Z in.	Radial Distance, in. 0	1	2	3
3	0	4.5	4.3	3.8	26.0
	3	36.1	40.4	37.8	30.6
	6	20.5	22.8	23.0	21.4
	9	27.4	27.2	25.8	24.2
6	0	3.4	3.1	2.7	22.2
	3	36.4	40.7	38.0	30.4
	6	20.2	22.5	22.6	20.9
	9	26.1	25.7	24.5	22.9
9	0	2.6	2.5	2.1	22.2
	3	36.6	40.9	38.2	30.3
	6	20.1	22.3	22.4	20.7
	9	25.4	25.0	23.9	22.2

Table A 2. Part 4.

W = 4,000 lb. E 1 = 200 ksi

I.P. = 150 psi E 2 = 20 ksi

Ra = 2.91 in. E 3 = 9 ksi

H 1 = 9 in.

H 2 in.	Z in.	Radial Distance, in. 0	1	2	3
3	0	2.9	2.7	2.3	22.2
	3	36.7	41.1	38.4	30.5
	6	20.3	22.6	22.7	21.1
	9	26.2	25.8	24.7	23.0
6	0	2.1	1.9	1.6	22.2
	3	36.9	41.2	38.5	30.3
	6	20.1	22.4	22.5	20.8
	9	25.3	24.9	23.8	22.1
9	0	1.6	1.4	1.1	23.2
	3	37.0	41.4	38.6	30.2
	6	20.0	22.2	22.3	20.6
	9	24.9	24.4	23.3	

Table A 2. Part 5.

W = 4,000 lb. | E 1 = 200 ksi

I.P. = 150 psi | E 2 = 40 ksi

Ra = 2.91 in. | E 3 = 9 ksi

H 1 = 9 in.

H 2 in.	Z in.	Radial Distance, In. 0	1	2	3
3	0	1.5	1.3	1.0	22.2
	3	37.0	41.3	38.5	30.1
	6	19.9	22.1	22.1	20.4
	9	23.0	22.6	21.6	20.2
6	0	1.1	1.3	1.6	22.1
	3	37.8	42.0	39.1	29.6
	6	19.5	21.5	21.5	19.6
	9	20.6	20.2	19.2	17.7
9	0	0.1	0.3	0.7	21.7
	3	37.5	41.1	38.9	29.8
	6	19.6	21.7	21.7	19.8
	9	21.3	20.9	19.9	18.4

Table A 2. Part 6.

W = 4,000 lb.
I.P. = 150 psi
Ra = 2.91 in.

E 1 = 400 ksi
E 2 = 40 ksi
E 3 = 9 ksi

H 1 = 9 in.

H 2 in.	Z in.	Radial Distance, in. 0	1	2	3
3	0	5.6	5.3	4.9	27.1
	3	35.6	40.1	37.4	30.7
	6	20.7	23.1	23.2	21.6
	9	28.3	27.9	26.8	25.1
6	0	3.4	3.3	2.9	25.0
	3	36.2	40.6	38.0	30.3
	6	20.1	22.4	22.5	20.7
	9	25.9	25.5	24.3	22.6
9	0	4.3	4.1	3.7	25.9
	3	36.0	40.4	37.7	30.5
	6	20.3	22.6	22.7	21.0
	9	26.7	26.3	25.2	23.5

APPENDIX B

QUESTIONNAIRE

Questionnaire - Typical Information Used for the Design of Asphalt Paving Mixtures

LIST OF TABLES

QUESTIONNAIRE

- Typical Information Used for the Design of Asphalt Paving Mixtures

PLEASE RETURN BY: 1/5/84
Date

TO: Prof. R. A. Jimenez
Civil Engineering Department
University of Arizona
Tucson, ARIZONA 85721

IDENTIFICATION:
Agency AHD
Prepared By F. Strickland
Title C.E. IV
Date 12-21-83 Phone 261-2589

IF YOU DESIRE THAT YOUR REPLIES TO THIS QUESTIONNAIRE BE HELD IN CONFIDENCE, PLEASE CHECK HERE: ☐

1. What asphaltic concrete mixture design method is used (i.e., Marshall, Hveem, other)? Marshall

2. Values for typical designed laboratory mixtures:

		AGGREGATE GRADATION TYPE				
		1"-Dense	3/4"-Dense	1/2"-Dense	1/2"-Gapped	3/8"-Dense
TOTAL PERCENT PASSING	1"	100				
	3/4"	90	100			
	1/2"	74	100(-)	100		
	3/8"	62	88	94		100
	#4	48	69	75		70
	#8	40	54	63		60
	#16					
	#30					
	#50	11	13	17		23
	#100	6	8	6		7
	#200	3	4	2		3
AGGREGATE SPECIFIC GRAVITY	Bulk	2.514	2.573	2.574		2.479
	Apparent	2.640	2.653	2.623		2.663
	Effective	2.611	2.614	2.606		2.519
Absorbed Water, %		DO NOT DETERMINE				
Sand Equivalent		NA	NA	NA		NA
ASPHALT CONTENT, %	B.T.W.	4.44	5.84	6.10		6.54
	B.A.W.	4.65	6.20	5.75		7.00
Asphalt S.G.		1.039	1.037	1.038		1.040
Rice S.G.		2.447	2.401	2.398		2.305

Table B1. Comparisons of Calculated Values for Theoretically Stable Surfaces with Design Asphalt Content Reported by Highway Departments.

State Job Mix Formula			U. of A.'s Suggested Asphalt Content and Corresponding Properties			
Name & Method	Mixture Type	Asphalt Content BTW, %	Asphalt Content BTW, %	Air Voids, %	Film Thickness, μ	VMA, %
Alabama	3/4" Dense	5.8	6.4	2	10.8	16.4
(M-75)			6.0	3	10.0	
	1" Dense	4.4	4.4	5	9.0	14.9
			4.0	6	8.0	
Arkansas	1/2" Dense	5.1	5.2	2	6.4	14.1[a]
(M-75)			4.8	3	5.8[a]	
	3/4" Dense	4.0	4.3	2	6.0	12.2[a]
California	3/4" CSE	4.9	4.3	3	7.7	13.0[a]
(H)			3.9[a]	4	6.8	
	1" Dense	4.8	4.8	2	9.5	13.3
			4.4	3	8.5	
Colorado	1/2" Dense	5.8	5.1	2	5.7[a]	14.2
(H)			4.7	3	5.2[a]	
	3/4" Dense	5.5	4.7	2	6.2	13.3[a]
Delaware	1/2" Dense	5.2	5.2	2	8.3	15.0
(M-75)			4.8	3	7.5	
	1" Dense	4.0	4.6	2	8.5	13.4
			4.2	3	7.6	
District of Columbia	ACSC "C"	5.6	5.9	2	9.1	16.7
(M-50)			5.5	3	8.4	
	ACSC "C"	5.9	6.2	2	10.1	16.6
			5.8	3	9.4	
Hawaii	1" Dense	4.9	6.5 (4.9)	2 (6.0)	9.7 (7.0)	17.8
(H)			6.1	3	9.0	
Illinois	3/4" Dense	4.5	5.7 (4.5)	2 (5.0)	9.9 (7.5)	15.9
(M-75)			5.3	3	9.1	
Iowa	3/4" Dense	5.5	5.4	2	9.1	14.6
(M-75)			5.0	3	8.3	
Kansas	3/8" Dense	5.5	5.5	2	6.7	15.0[a]
(M-75)			5.1	3	6.2	
Minnesota	3/4" Dense	6.0	5.6	2	7.2	15.2
(M-75)			5.2	3	6.6	

[a] Considered to be extremely low.

Table B1. Continued.

State Job Mix Formula			U. of A.'s Suggested Asphalt Content and Corresponding Properties			
Name & Method	Mixture Type	Asphalt Content BTW, %	Asphalt Content BTW, %	Air Voids, %	Film Thickness, μ	VMA, %
Montana (M-75)	3/4" Dense	5.7	4.7 4.3	2 3	6.4 5.8[a]	13.2[a]
Nebraska (Mod. M)	3/4" Dense	5.0	4.8 4.4	2 3	6.0 5.4[a]	13.6
New Hampshire (M-75)	1/2" Dense	6.0	5.9 5.5	2 3	10.8 9.9	16.1
New Mexico (M-75)	3/4" Dense	5.2	5.1 4.7	2 3	7.1 6.5	14.2
North Dakota (M-75)	3/4" Dense	7.0	5.9 5.5 (7.0)	2 3 (<2)	6.4 5.9[a]	16.0
Oklahoma (Mod. H)	1/2" Dense	5.0	5.5 5.1	2 3	7.0 6.4	14.9
Oregon (H)	3/4" Dense	6.0	4.7 4.3 (6.0)	2 3 (<2)	8.5 7.7	13.3[a]
Pennsylvania (M-75)	1/2" Dense	6.7	6.9 6.5	2 3	11.4 10.6	17.5
Texas (Mod. H)	3/4" Dense	5.3	6.3 5.9 (5.3)	2 3 (4.5)	10.6 9.7 (8.6)	16.3
Washington (H)	3/4" Dense	6.0	4.8 4.4 (6.0)	2 3 (<2)	7.3 6.6	13.7
West Virginia (M-75 or H)	3/4" Dense	5.2	4.8 4.4	2 3	7.3 6.6	13.7
Alberta (M-75)	1/2" Dense	5.5	5.7 5.3	2 3	7.5 6.9	15.2
Saskatchewan (M-75)	3/4" Dense	5.2	5.0 4.6	2 3	7.5 6.8	13.9

[a] Considered to be extremely low.

Table B 2. Comparison of Calculated Values for Theoretically Stable Surfaces with ADOT's Design Asphalt Contents.

ADOT's			U. of A.'s Calculated Values			
Mixture No.		Asphalt Content BTW, %	Asphalt Content BTW, %	Air Voids, %	Film Thickness, μ	VMA, %
1/2"	#2	5.5	5.8	2	9.8	15.2
			5.4	3	8.9	
	#3	5.5	5.5	2	9.6	14.7
			5.1	3	8.8	
	#4	5.0	5.7	2	9.4	15.4
			5.3	3	8.6	
	#5	4.9	5.5	2	9.0	14.6
			5.1	3	8.2	
	#6	5.1	5.6	2	10.3	14.8
			5.2	3	9.4	
1/2"	#7	4.8	6.0	2	10.5	15.7
			5.5	3	9.6	
	#8	5.1	5.8	2	10.7	15.6
			5.4	3	9.8	
	#9	5.0	5.1	2	7.8	14.1
			4.7	3	7.0	
	#10	4.6	5.4	2	8.8	14.6
			5.0	3	8.0	
	#11	5.5	6.0	2	12.6	16.0
			5.6	3	11.6	
1/2"	#12	5.4	5.8	2	10.9	15.5
			5.4	3	10.0	
3/4"	#2	5.5	5.9	2	12.3	15.5
			5.5	3	11.3	
	#3	5.8	5.9	2	11.1	15.7
			5.5	3	10.2	
	#4	5.0	5.7	2	9.9	15.3
			5.3	3	9.0	
	#5	5.3	5.5	2	9.1	14.7
			5.1	3	8.3	
	#6	5.3	5.6	2	10.3	14.8
			5.2	3	9.4	
3/4"	#7	4.6	5.8	2	9.8	15.4
			5.4	3	9.0	
	#8	5.3	5.2	4	12.4	16.7
			5.1	5	11.3	

Table B2. Continued.

ADOT's		U. of A.'s Calculated Values			
Mixture No.	Asphalt Content BTW, %	Asphalt Content BTW, %	Air Voids, %	Film Thickness, μ	VMA, %
3/4" #9	4.9	5.0	2	8.7	13.8
		4.6	3	7.9	
#10	4.5	5.3	2	8.1	14.5
		4.9	3	7.4	
#11	5.0	5.8	2	11.9	15.4
		5.4	3	10.9	
3/4" #12	5.3	6.2	2	12.4	16.5
		5.8	3	11.5	
1" #2	5.4	4.9	2	12.0	13.6
		4.5	3	11.0	

APPENDIX C

LIST OF TABLES

Table C 1a. Data for Cores from Asphaltic Concrete Pavement.[a/]

Project No. I-8-1(80) Mile Posts 59.0 & 64.0 Lane WB Travel

Construction Date Summer 1982 Surface Thickness MP 59.0 - 1.25"
MP 64.0 - 1.50"

Sample Date Winter 1984 Surface Condition Good

	Sieve No.	Mile Post 59.0 WB OWP	BWP	IWP	Mile Post 64.0 WB OWP	BWP	IWP	ADOT's Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	100	100	100	100	100
	3/4"	98	100	100	99	99	98	99
	1/2"	73	84	82	85	88	87	82
	3/8"	59	70	69	73	76	74	73
	#4	43	51	53	55	59	56	58
	#8	35	41	43	42	47	43	45
	#16	28	32	34	33	36	33	33
	#30	21	24	25	25	29	26	26
	#50	11	13	14	15	16	15	13
	#100	7	8	8	9	10	9	6
	#200	4.4	4.6	5.1	5.3	6.2	5.3	5.3
Marshall Stability, wet, lb		5,405	4,725	5,915	4,570	4,265	4,825	2,200
Flow, .01 in.		9	11	9	11	10	10	12
Density, pcf		144.7	141.0	144.0	143.3	140.5	142.8	141.5
Eff., S.G.[b/]		2.600	2.600	2.600	2.596	2.596	2.596	--
VMA, %	Meas.	15.6	18.1	16.3	16.4	18.4	16.7	--
	Calc.	13.2	13.8	13.7	13.8	14.3	14.1	16.9
Air Voids, %	Meas.	3.4	5.4	3.5	4.1	5.3	4.4	--
	Calc.	0.5	0.5	0.4	1.2	0.6	1.4	5.8
Binder Content, % BTW	Meas.	5.4	5.7	5.7	5.4	5.9	5.5	--
	Calc.[c/]	4.0-4.4	4.3-4.7	4.2-4.6	6.3-7.1	4.9-5.3	4.8-5.2	5.2

[a/] Average of at least two 4"D cores.

[b/] From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

[c/] Range based on VMA and film thickness.

Table C1b. Data for Cores from Asphaltic Concrete Pavement.[a/]

Project No. I-8-2(80) Mile Post 124.0 Lane EB & WB Travel

Construction Date Summer 1982 Surface Thickness 1.5"

Sample Date Winter 1984 Surface Condition Good

	Sieve No.	Mile Post 124.0 EB OWP	BWP	IWP	Mile Post 124.0 WB OWP	BWP	IWP	ADOT's Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	100	100	100	100	100
	3/4"	100	100	100	99	100	99	99
	1/2"	86	81	93	86	85	84	85
	3/8"	79	73	83	72	75	77	75
	#4	63	56	63	54	60	62	60
	#8	49	44	50	44	47	50	47
	#16	37	34	38	36	39	42	39
	#30	27	25	28	27	29	31	23
	#50	16	15	18	15	15	16	15
	#100	10	10	11	8	8	9	9
	#200	5.8	5.6	6.5	3.6	3.8	3.7	5.1
Marshall Stability, wet, lb		4,260	3,895	4,000	2,420	2,985	2,625	1,860
Flow, .01 in.		11	10	11	8	9	9	12
Density, pcf		144.8	141.7	145.7	145.4	142.6	144.0	142.0
Eff., S.G.[b/]		2.648	2.648	2.648	2.632	2.632	2.632	--
VMA, %	Meas.	17.0	18.5	16.6	16.6	18.5	17.9	--
	Calc.	14.4	13.7	14.3	15.7	16.0	16.9	17.0
Air Voids, %	Meas.	4.1	7.6	4.1	3.5	4.8	3.4	--
	Calc.	1.0	2.1	1.3	2.5	1.9	2.4	5.8
Binder Content, % BTW	Meas.	5.7	4.9	5.5	5.7	6.1	6.3	--
	Calc.[c/]	4.3-4.7	4.4-4.8	4.4-4.8	5.5-5.9	5.7-6.1	6.1-6.5	5.4

[a/] Average of at least two 4"D cores.

[b/] From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

[c/] Range based on VMA and film thickness.

Table C 1c. Data for Cores from Asphaltic Concrete Pavement.[a/]

Project No. I-10-3(148) Mile Post 162.9 Lane WB Travel & Passing

Construction Date Summer 1983 Surface Thickness 2.0"

Sample Date Winter 1983 Surface Condition Good

	Sieve No.	Mile Post 162.9 Travel OWP	Mile Post 162.9 Travel BWP	Mile Post 162.9 Travel IWP	Mile Post 162.9 Passing OWP	Mile Post 162.9 Passing BWP	Mile Post 162.9 Passing IWP	ADOT's Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	100		100		100
	3/4"	98	95	97		99		94
	1/2"	86	81	87		83		79
	3/8"	76	73	80		74		71
	#4	62	59	64		59		56
	#8	52	50	54		50		47
	#16	42	40	43		40		37
	#30	29	28	30		29		24
	#50	16	15	16		15		12
	#100	8	7	8		7		5
	#200	4.4	3.6	3.6		3.6		2.6
Marshall Stability, wet, lb		1,515	1,085	1,130		1,320		2,626
Flow, .01 in.		11	13	13		9		9
Density, pcf		139.9	139.8	139.5		140.7		140.9
Eff., S.G.[b/]		2.594	2.594	2.594		2.609		--
VMA, %	Meas.	18.5	18.3	18.7		18.5		--
	Calc.	16.2	16.2	17.6		16.5		16.3
Air Voids, %	Meas.	6.2	6.4	6.2		7.2		--
	Calc.	4.8	4.3	5.0		4.0		5.5
Binder Content, % BTW	Meas.	5.6	5.5	5.7		5.5		--
	Calc.[c/]	5.5-6.3	5.7-6.5	5.9-6.8		5.7-6.5		5.3

[a/] Average of at least two 4"D cores.

[b/] From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

[c/] Range based on VMA and film thickness.

Table C 2a. Data for Cores from Asphaltic Concrete Pavement.[a/]

Project No. I-10-1(46)   Mile Post 45.6-58.4   Lane EB Travel

Construction Date Spring 1969   Surface Thickness 2.2"

Sample Date Summer 1984   Surface Condition Cracked

	Sieve No.	Mile Post 45.6-58.4 OWP[b/]	BWP[b/]	IWP	Mile Post ____ OWP	BWP	IWP	ADOT's Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	100				100
	3/4"	100	99	100				98
	1/2"	100	85	89				88
	3/8"	89	69	77				76
	#4	69	43	47				55
	#8	53	30	32				43
	#16	38	22	22				31
	#30	28	16	16				20
	#50	18	12	12				18
	#100	13	11	10				8
	#200	8.6	7.7	6.9				4.0
Marshall Stability, wet, lb		3,470	7,010	3,750				Hveem 47
Flow, .01 in.		14.0	19.0	20.0				--
Density, pcf		139.6	144.0	147.5				144.0
Eff., S.G.[c/]		2.662	2.662	2.662				--
VMA, %	Meas.	20.5	18.1	16.2				--
	Calc.	13.9	14.0	13.5				15.6
Air Voids, %	Meas.	8.6	5.6	3.2				--
	Calc.	1.1	1.0	0.4				4.7
Binder Content, % BTW	Meas.	5.4	5.5	5.6				--
	Calc.[d/]	4.2-4.6	4.3-4.7	4.1-4.5				4.9

[a/] Average of at least two 4"D cores.

[b/] Values of one core only.

[c/] From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

[d/] Range based on VMA and film thickness.

Table C 2b. Data for Cores from Asphaltic Concrete Pavement.[a/]

Project No. I-10-6(67) Mile Post 334.0-338.0 Lane EB

Construction Date Spring 1974 Surface Thickness 2.33"

Sample Date Summer 1984 Surface Condition Cracked

	Sieve No.	Mile Post 334.0-338.0 OWP	BWP	IWP	Mile Post OWP	BWP	IWP	ADOT's Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	100				100
	3/4"	100	98	100				98
	1/2"	86	86	88				82
	3/8"	74	75	78				73
	#4	52	54	55				46
	#8	40	41	42				33
	#16	30	31	32				24
	#30	23	24	24				17
	#50	16	17	17				12
	#100	15	16	15				9
	#200	7.2	7.7	7.6				7
Marshall Stability, wet, lb		2,030	1,260	1,720				--
Flow, .01 in.		14.0	14.0	20.0				--
Density, pcf		141.5	141.3	140.6				144.0
Eff., S.G.[b/]		2.650	2.650	2.650				--
VMA, %	Meas.	18.9	19.1	19.4				--
	Calc.	15.3	15.3	14.7				17.0
Air Voids, %	Meas.	7.4	7.4	7.6				--
	Calc.	3.2	3.2	2.4				7.2
Binder Content, % BTW	Meas.	5.2	5.2	5.3				--
	Calc.[c/]	5.3-5.7	5.3-5.7	5.0-5.4				4.8

[a/] Average of at least two 4"D cores.

[b/] From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

[c/] Range based on VMA and film thickness.

Table C 2c. Data for Cores from Asphaltic Concrete Pavement.[a/]

Project No. I-40-4(42/87) Mile Post 225.0-228.0 Lane WB Travel

Construction Date Fall 1968 Surface Thickness 2"

Sample Date Summer 1984 Surface Condition Cracked

	Sieve No.	Mile Post 225.0-228.0 OWP	BWP	IWP	Mile Post OWP	BWP	IWP	ADOT's Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	100				100
	3/4"	100	100	100				100
	1/2"	95	96	97				98
	3/8"	86	86	90				79
	#4	61	62	66				50
	#8	41	43	46				34
	#16	28	30	32				24
	#30	22	24	26				16
	#50	18	20	21				11
	#100	18	19	20				8
	#200	9.5	10.6	10.8				6.0
Marshall Stability, wet, lb		2,590	2,430	1,980				Hveem 40
Flow, .01 in.		18.0	18.0	23.0				--
Density, pcf		135.1	137.7	134.4				147.0
Eff., S.G.[b/]		2.587	2.587	2.587				--
VMA, %	Meas.	21.8	20.2	22.4				--
	Calc.	16.4	15.9	16.4				15.2
Air Voids, %	Meas.	7.9	6.7	8.1				--
	Calc.	1.6	1.2	1.0				5.1
Binder Content, % BTW	Meas.	6.5	6.4	6.8				--
	Calc.[c/]	5.9-6.4	6.1	6.4				5.25

a/ Average of at least two 4"D cores.

b/ From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

c/ Range based on VMA and film thickness.

Table C 3a. Data for Cores from Asphaltic Concrete Pavement.[a/]

Project No. I-IR-10-4(66) Mile Post 215.0-220.0 Lane WB Travel

Construction Date Fall 1976 Surface Thickness 2.0"

Sample Date Summer 1984 Surface Condition Rutted

	Sieve No.	Mile Post 215.0-220.0 OWP	BWP	IWP	Mile Post OWP	BWP	IWP	ADOT's Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	--				100
	3/4"	97	96	100				90
	1/2"	76	76	79				70
	3/8"	66	68	72				63
	#4	51	54	55				48
	#8	40	44	42				41
	#16	28	30	28				33
	#30	18	19	18				23
	#50	10	10	11				12
	#100	8	8	8				6
	#200	4.6	4.6	4.6				4
Marshall Stability wet, lb		2,420	1,960	2,710				Hveem 43
Flow, .01 in.		8	7	10				--
Density, pcf		148.1	146.0	148.9				142.3
Eff., S.G.[b/]		2.602	2.602	2.602				--
VMA, %	Meas.	13.4	15.1	13.0				--
	Calc.	14.5	14.9	13.9				15.5
Air Voids, %	Meas.	1.6	2.2	0.8				--
	Calc.	2.7	2.0	1.8				4.6
Binder Content, % BTW	Meas.	5.1	5.6	5.2				--
	Calc.[c/]	5.0-5.4	5.1-5.6	4.3-4.7				4.9

[a/] Average of at least two 4"D cores.

[b/] From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

[c/] Range based on VMA and film thickness.

Table C 3b. Data for Cores from Asphaltic Concrete Pavement.[a]

Project No. I-17-2(48) Mile Post 286.0-291.4 Lane NB Travel

Construction Date Spring 1974 Surface Thickness 2.25"

Smaple Date Summer 1984 Surface Condition Rutted

	Sieve No.	Mile Post 286.0-291.4 OWP	BWP	IWP	Mile Post OWP	BWP	IWP	Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	100				100
	3/4"	96	96	96				97
	1/2"	79	77	80				78
	3/8"	68	64	68				63
	#4	46	45	46				45
	#8	34	33	34				34
	#16	24	24	24				24
	#30	17	18	18				19
	#50	12	12	12				7
	#100	10	10	10				5
	#200	6.0	6.3	5.8				4.0
Marshall Stability wet, lb		2,480	2,320	2,120				Hveem 45
Flow, .01 in.		20	14	12				--
Density, pcf		156.3	155.0	157.0				148.0
Eff., S.G.[b]		2.750	2.750	2.750				--
VMA, %	Meas.	13.9	14.6	13.5				--
	Calc.	13.3	13.2	13.5				15.5
Air Voids, %	Meas.	0.6	1.6	0.0				--
	Calc.	0.2	0.4	0.8				5.3
Binder Content, % BTW	Meas.	5.3	5.2	5.2				--
	Calc.[c]	3.8-4.2	3.8-4.2	3.9-4.3				4.8

[a] Average of at least two 4"D cores.

[b] From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

[c] Range based on VMA and film thickness.

Table C 3c. Data for Cores from Asphaltic Concrete Pavement.[a/]

Project No. I-40-4(70) Mile Post 283.0-290.0 Lane EB Travel

Construction Date Summer 1978 Surface Thickness 2.5"

Sample Date Summer 1984 Surface Condition Rutted

	Sieve No.	Mile Post 283.0-290.0 OWP[b/]	BWP	IWP	Mile Post ____ OWP	BWP	IWP	ADOT's Design
GRADATION, TOTAL PERCENT PASSING	1"	100	100	100				100
	3/4"	100	96	98				92
	1/2"	87	78	75				72
	3/8"	77	68	64				62
	#4	55	48	45				45
	#8	44	39	35				36
	#16	36	32	30				29
	#30	31	28	26				23
	#50	21	19	18				12
	#100	12	14	12				5
	#200	6.8	6.6	5.9				3.0
Marshall Stability, wet, lb		--	1,010	1,560				Hveem 47
Flow, .01 in.		--	12	18				--
Density, pcf		--	165.5	166.8				166.0
Eff., S.G.[c/]		2.922	2.922	2.922				--
VMA, %	Meas.	--	14.3	13.4				--
	Calc.	15.1	15.0	15.3				15.9
Air Voids, %	Meas.	--	0.3	0.2				--
	Calc.	0.0	0.0	1.6				4.2
Binder Content, % BTW	Meas.	6.1	5.7	5.3				--
	Calc.[d/]	4.7-5.1	4.7-5.1	4.8-5.2				4.5

[a/] Average of at least two 4"D cores.

[b/] Values of one core only.

[c/] From mixture with 5% asphalt having specific gravity of 1.018 gm/cc.

[d/] Range based on VMA and film thickness.

APPENDIX D

ASPHALT PROGRAM

Program ASPHALT has been developed as an aid for asphaltic concrete mixture design. The design is based partially on the control of voids in the mineral aggregate (VMA) and on the "film thickness" of the asphaltic cement covering the aggregate.

ASPHALT Program Execution

The program is currently stored in two forms. A binary (compiled) version of the program is stored on disk on the cyber (BN 3850461J) as permanent file ASPHALT. The FORTRAN source code of the program is stored as file ASPHAL on the DEC - 10 (PPN 4271, 57254).

To execute the program on the Cyber, the job control statements and the data set should first be created as a file on the DEC - 10. This file is then sent to the Cyber to execute the program. The job control statements and the data set sould take the following form.

```
JIMENEZ, BN3856041J
PW= password
ATTACH, X, ASPHALT, ID= JIMENEZ.
X.
^Z (This is a control Z -- it separates the control
    cards from the data set).
Data set (see format for Data)
```

Once the control statement and data set file has been successfully prepared this file is sent from the DEC - 10 to the Cyber using the statement.

```
TOCDC Filename
```

Where Filename is the name given to the file containing the control statements and data set.

Input Parameter Descriptions

AAV: Asphalt Absorption Value in percent (e.g. 1.2%)

ASG: Asphalt specific gravity (e.g. 1.016)

AV(1): Aggregate voidage value for the smallest sieve used (e.g. for #200 sieve AV(1) = 32.00).

ESG: Effective specific gravity (e.g. 2.685).

N: Number of sieves used. Maximum value is 10.

NAME: Run identification label. Maximum of 60 characters.

PP(I): Percent passing each sieve. N values required. Input in order of smallest sieve size to largest sieze used.

S(I): Sieve sizes used (e.g., 200., 100., 50., etc.) Input from smallest size to largest size. For sieve sizes greater than 4. (e.g. 3/8 or 3/4) the size is entered in decimal form (e.g. .375 or .75). N values required.

SAF(I): Surface area factor corresponding to each sieve size. Entered in order corresponding to order of sieve sizes. For sieve size greater than 4 SAF(I) = 0. N values required.

Input Parameter List

Variable Name	No. of Values	Format	No. of Cards
NAME	1	6A10	1
N	1	I2	1
S(I)	N	F10.3	N/8
AV(1)	1	F10.3	1
SAF(I)	N	F10.3	N/8
PP(I)	N	F10.3	N/8
ESG, ASG, AAV	1 each	3F10.3	1

Parameters Set Within the Program Structure

FR(31)	Voidage Reduction Factors for rounded aggregate (see Table 1).
RR(31):	Ratio of percent passing one sieve to the percent passing the next smaller sieve associated with the values of FR(31) (see Table 1). Minimum value 1.00, Maximum value 2.50.
UV:	The Total Unit Volume is set at 1.000
AIRV:	Air Voids percent is initialized at 2.0

The values of these parameters can only be changed by changing the source code of the program.

Table I. Voidage-Reduction Factors

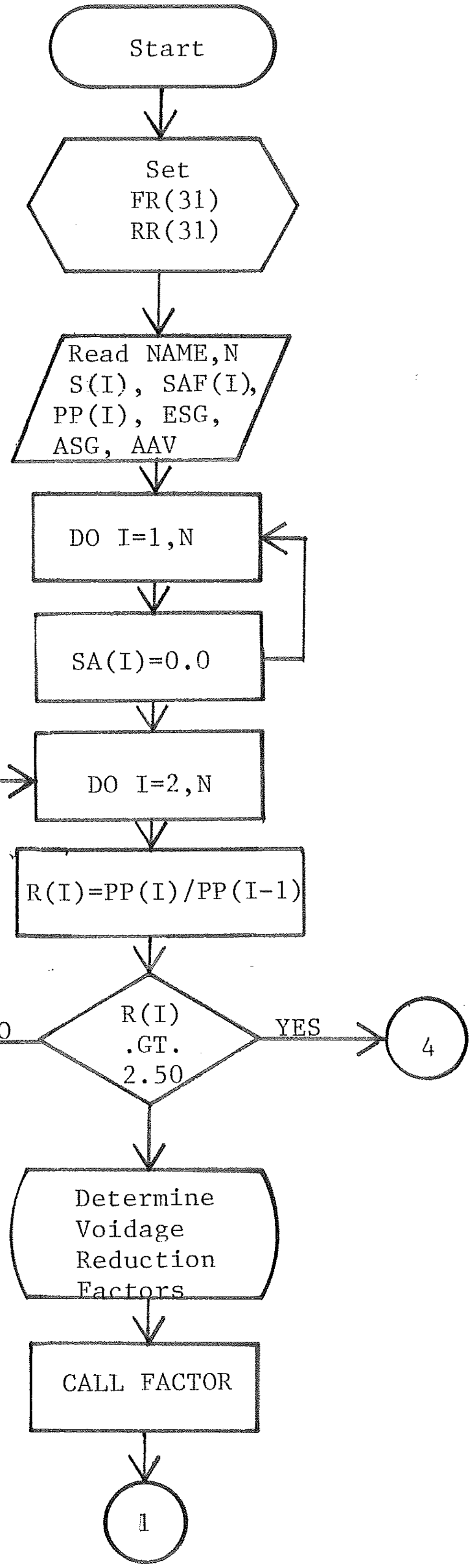
R	F_r	F_a
1.00	1.0000	1.000
1.05	.9805	.985
1.10	.9583	.970
1.15	.9325	.951
1.20	.9098	.935
1.25	.9015	.924
1.30	.8945	.920
1.35	.8908	.919
1.40	.8908	.919
1.45	.8926	.920
1.50	.8971	.921
1.55	.9032	.924
1.60	.9107	.926
1.65	.9193	.931
1.70	.9260	.938
1.75	.9332	.947
1.80	.9400	.955
1.85	.9465	.963
1.90	.9528	.970
1.95	.9589	.978
2.00	.9647	.985
2.05	.9703	.993
2.10	.9757	1.000
2.15	.9805	
2.20	.9856	
2.25	.9905	
2.30	.9953	
2.35	1.0000	
2.40	1.0045	
2.45	1.0090	
2.50	1.0133	

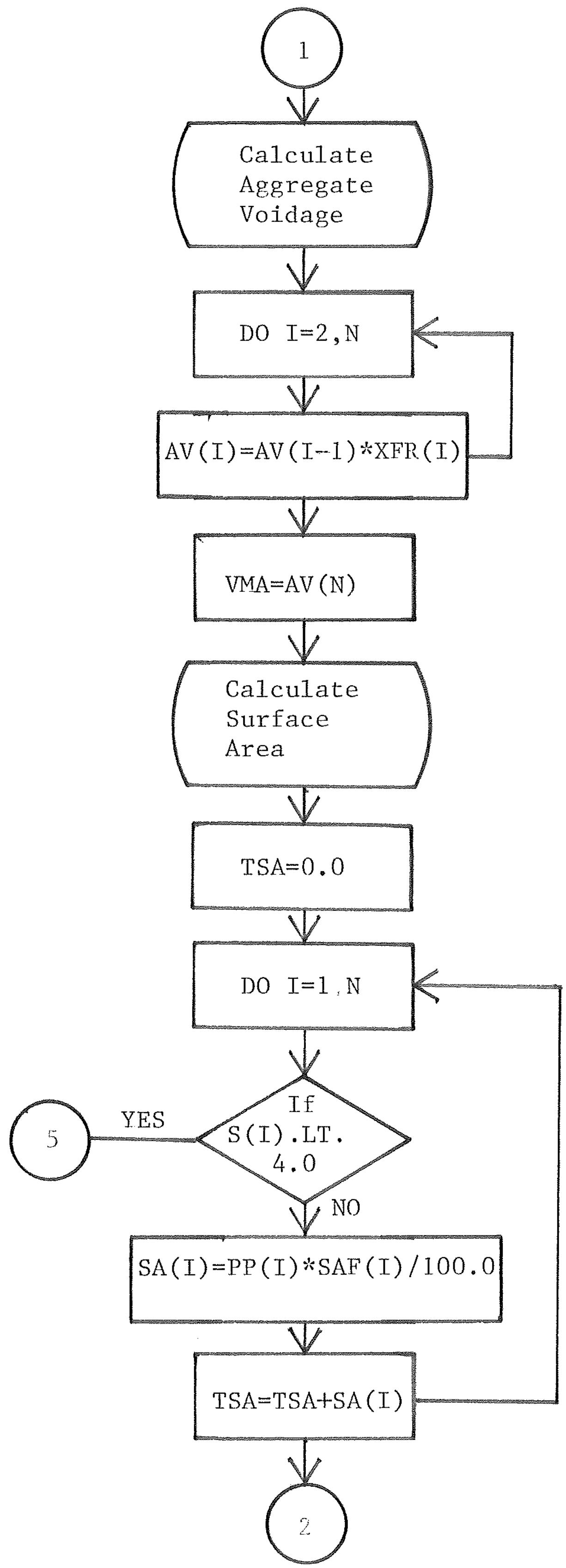
R = The ratio obtained by dividing the per cent passing one sieve by the per cent passing the next smaller sieve in the specified sieve series.

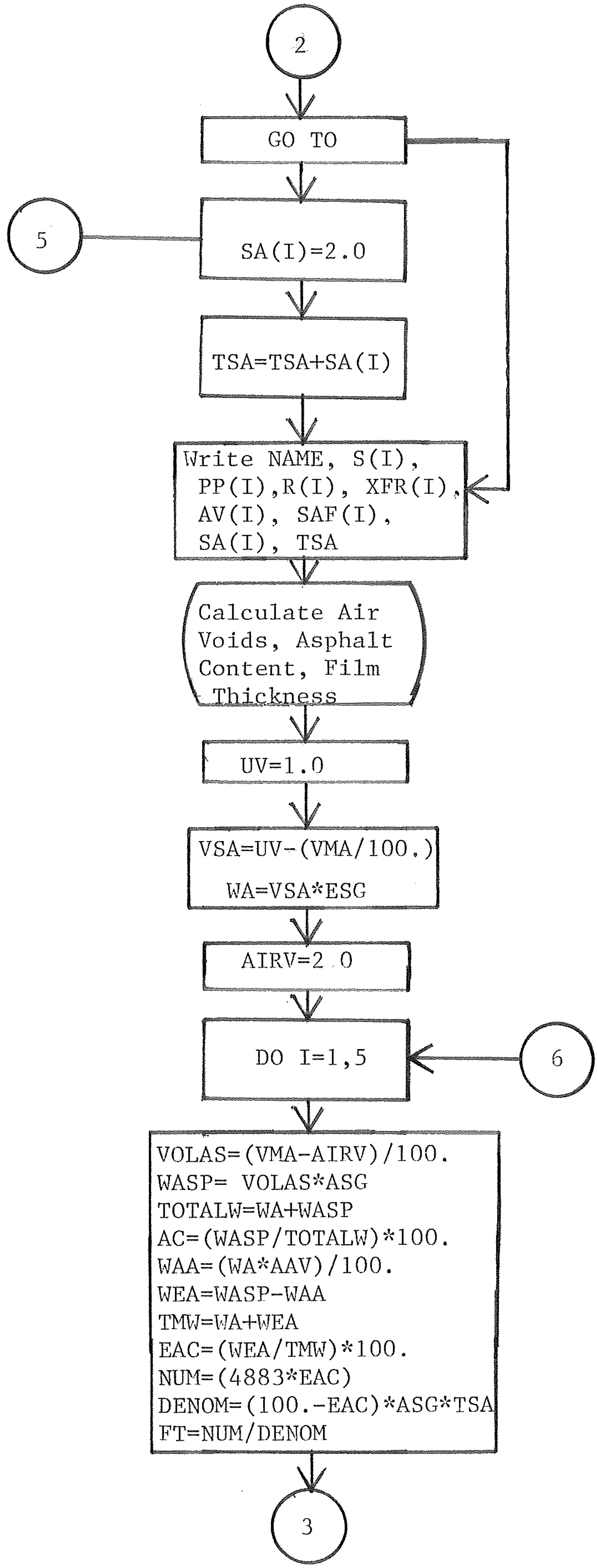
F_r = Factors for rounded aggregate, such as natural sand or gravel or cubical crushed stone.

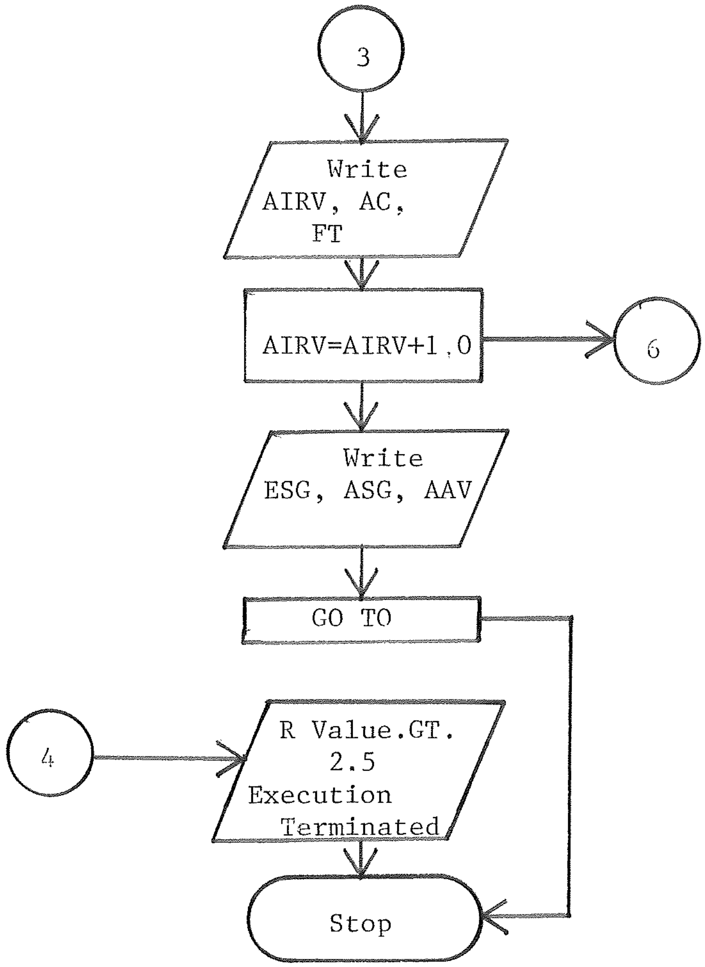
F_a = Approximate factors for angular aggregate, such as manufactured sand, screenings, or elongated or slabby crushed stone.

Program ASPHALT




1
Calculate Aggregate Voidage
DO I=2,N
AV(I)=AV(I-1)*XFR(I)
VMA=AV(N)
Calculate Surface Area
TSA=0.0
DO I=1,N
If S(I).LT. 4.0
YES
5
NO
SA(I)=PP(I)*SAF(I)/100.0
TSA=TSA+SA(I)
2

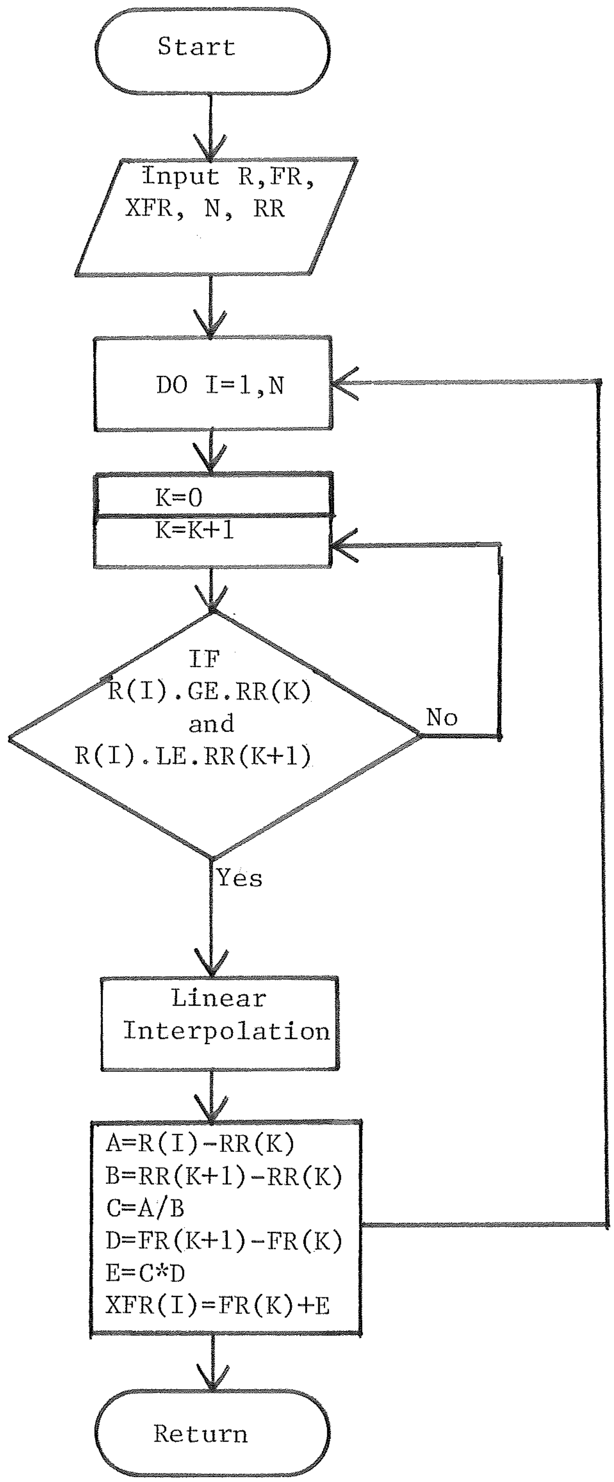

2
GO TO
5
SA(I)=2.0
TSA=TSA+SA(I)
Write NAME, S(I), PP(I),R(I), XFR(I), AV(I), SAF(I), SA(I), TSA
Calculate Air Voids, Asphalt Content, Film Thickness
UV=1.0
VSA=UV-(VMA/100.)
WA=VSA*ESG
AIRV=2.0
DO I=1,5
6
VOLAS=(VMA-AIRV)/100.
WASP= VOLAS*ASG
TOTALW=WA+WASP
AC=(WASP/TOTALW)*100.
WAA=(WA*AAV)/100.
WEA=WASP-WAA
TMW=WA+WEA
EAC=(WEA/TMW)*100.
NUM=(4883*EAC)
DENOM=(100.-EAC)*ASG*TSA
FT=NUM/DENOM
3


3
Write
AIRV, AC,
FT
AIRV=AIRV+1.0
6
Write
ESG, ASG, AAV
GO TO
4
R Value.GT.
2.5
Execution
Terminated
Stop

Subroutine FACTOR

This subroutine determines the value of the voidage reduction factor, XFR(I), associated with each value of R(I). Using the table of values for RR(I) and FR(I), the subroutine compares R(I) to RR(I) and selects the appropriate value for XFR(I) from the FR(I) table. When R(I) is between RR(I) and RR(I+1) linear interpolation is used to calculate the value of XFR(I).

Subroutine FACTOR



Sample Output

TEST DATA

SIEVE SIZE	PERCENT PASSING (P)	R	VOIDAGE REDUCTION FACTOR (F)	AGGREATE VOIDAGE	SURFACE AREA FACTOR	SURFACE AREA (SQFT/LB)
200.000	5.5	.00	.000	32.00	160.	8.80
100.000	7.0	1.27	.898	28.75	60.	4.20
50.000	11.0	1.57	.906	26.06	30.	3.30
30.000	19.0	1.73	.930	24.23	14.	2.66
16.000	31.0	1.63	.916	22.20	8.	2.48
8.000	45.0	1.45	.893	19.82	4.	1.80
4.000	58.0	1.29	.896	17.76	2.	1.16
.375	73.0	1.26	.900	15.99	0.	2.00
.750	100.0	1.37	.891	14.24	0.	.00

TOTAL SURFACE AREA= 26.40

AIR VOIDS PERCENT	ASPHALT CONTENT PERCENT	FILM THICKNESS MICRONS
2.00	5.22	7.87
3.00	4.81	7.05
4.00	4.40	6.23
5.00	3.99	5.41
6.00	3.57	4.58

EFFECTIVE SPECIFIC GRAVITY= 2.622
ASPHALT SPECIFIC GRAVITY = 1.011
ASPHALT ABSORPTION VALUE = 1.200

Program ASPHALT Source Code

```
      PROGRAM ASPHALT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION S(10),PP(10),R(10),AV(10),SAF(10),SA(10),FR(31),XFR(10),
     1RR(31),NAME(6)
      DATA FR/1.0000,0.9805,0.9583,0.9325,0.9098,0.9015,0.8945,0.8908,
     10.8908,0.8926,0.8971,0.9032,0.9107,0.9193,0.9260,0.9332,0.9400,
     20.9465,0.9528,0.9589,0.9647,0.9703,0.9757,0.9805,0.9856,0.9905,
     30.9953,1.0000,1.0045,1.0090,1.0133/
      DATA RR/1.00,1.05,1.10,1.15,1.20,1.25,1.30,1.35,1.40,1.45,1.50,
     11.55,1.60,1.65,1.70,1.75,1.80,1.85,1.90,1.95,2.00,2.05,2.10,2.15,
     22.20,2.25,2.30,2.35,2.40,2.45,2.50/
C     READ INPUT DATA
      READ(5,5) NAME
      READ(5,1) N
    1 FORMAT(I2)
      READ(5,2) (S(I),I=1,N)
    2 FORMAT(10F10.3)
      READ(5,3) AV(1)
    3 FORMAT(F10.3)
      READ(5,2) (SAF(I),I=1,N)
      READ(5,2) (PP(I),I=1,N)
      READ(5,4) ESG,ASG,AAV
    4 FORMAT(3F10.3)
    5 FORMAT(6A10)
      DO 50 I=1,N
50    SA(I)=0.0
C     CALCULATE R VALUES
      DO 100 I=2,N
      R(I)=PP(I)/PP(I-1)
      IF(R(I).GT.2.50) GO TO 500
100   CONTINUE
C     DETERMIN VOIDAGE REDUCTION FACTORS
      CALL FACTOR(R,FR,XFR,N,RR)
C     CALCULATE AGGREGATE VOIDAGE
      DO 200 I=2,N
      AV(I)=AV(I-1)*XFR(I)
200   CONTINUE
C     SET VALUE FOR VOIDS IN MINERAL AGGREGATE
      VMA=AV(N)
C     CALCULATE SURFACE AREA
      TSA=0.0
      DO 300,I=1,N
      IF(S(I).LT.4.0) GO TO 400
      SA(I)=PP(I)*SAF(I)/100.0
      TSA=TSA+SA(I)
300   CONTINUE
      GO TO 440
400   SA(I)=2.0
      TSA=TSA+SA(I)
440   WRITE(6,450) NAME
450   FORMAT('-',6A10)
C     PRINT SIEVE SIZE, PERCENT PASSING, R VALUE, XFR VALUE,
C     AGGREGATE VOIDS,SURFACE AREA FACTOR AND SURFACE AREA
      WRITE(6,600)
600   FORMAT('-',10X,'SIEVE',5X,'PERCENT',11X,'VOIDAGE',21X,'SURFACE',
     15X,'SURFACE')
```

```
      WRITE(6,700)
700   FORMAT(' ',10X,'SIZE',6X,'PASSING',5X,'R',5X,'REDUCTION',5X,'AGGREG
     1ATE',6X,'AREA',8X,'AREA')
      WRITE(6,800)
800   FORMAT(' ',22X,'(P)',13X,'FACTOR (F)',4X,'VOIDAGE',7X,'FACTOR',
     15X,'(SQFT/LB)')
      WRITE(6,900)
900   FORMAT(' ',10X,'-------------------------------------------------
     1---------------------------')
      DO 1000, I=1,N
      WRITE(6,1100) S(I),PP(I),R(I),XFR(I),AV(I),SAF(I),SA(I)
1100  FORMAT(' ',9X,F7.3,5X,F5.1,5X,F4.2,5X,F5.3,9X,F5.2,8X,F4.0,
     13X,F5.2)
1000  CONTINUE
      WRITE(6,950) TSA
950   FORMAT(' ', 59X,'TOTAL SURFACE AREA=',1X,F5.2)
C     CALCULATE AIR VOIDS, ASPHALT CONTENT, AND FILM THICKNESS
C     SET TOTAL UNIT VOLUME
      UV=1.0
      VSA=UV-(VMA/100.)
      WA=VSA*ESG
C     SET AIR VOIDS PERCENT
      AIRV=2.0
      WRITE(6,1200)
1200  FORMAT('-',20X,'AIR',10X,'ASPHALT',7X,'FILM')
      WRITE(6,1300)
1300  FORMAT(' ',20X,'VOIDS',6X,'CONTENT',7X,'THICKNESS')
      WRITE(6,1400)
1400  FORMAT(' ',20X,'PERCENT',6X,'PERCENT',7X,'MICRONS')
      WRITE(6,1500)
1500  FORMAT(' ',20X,'------------------------------------')
C     I EQUALS THE AIR VOID INDEX
      DO 1600 I=1,5
      VOLAS=(VMA-AIRV)/100.
      WASP=VOLAS*ASG
      TOTALW=WA+WASP
      AC=(WASP/TOTALW)*100.
      WAA=(WA*AAV)/100.
      WEA=WASP-WAA
      TMW=WA+WEA
      EAC=(WEA/TMW)*100
      NUM=(4883*EAC)
      DENOM=(100.-EAC)*ASG*TSA
      FT=NUM/DENOM
      WRITE(6,1700) AIRV,AC,FT
1700  FORMAT(' ',20X,F6.2,8X,F6.2,8X,F6.2)
      AIRV=AIRV+1.0
1600  CONTINUE
      WRITE(6,1750) ESG
      WRITE(6,1751) ASG
      WRITE(6,1752) AAV
1750  FORMAT('-',1X,'EFFECTIVE SPECIFIC GRAVITY=',1X,F5.3)
1751  FORMAT(' ',1X,'ASPHALT SPECIFIC GRAVITY  =',1X,F5.3)
1752  FORMAT(' ',1X,'ASPHALT ABSORPTION VALUE  =',1X,F5.3)
      GO TO 1800
500   WRITE(6,1900)
1900  FORMAT(' ',20X,'R VALUE GT 2.50 EXECUTION TERMINATED')

1800  STOP
      END
```

```
      SUBROUTINE FACTOR(R,FR,XFR,N,RR)
      DIMENSION R(10),FR(31),XFR(10),RR(31)
      DO 100 I=2,N
      K=0
2     K=K+1
      IF((R(I).GE.RR(K)).AND.(R(I).LE.RR(K+1))) GO TO 1
      GO TO 2
C     LINEAR INTERPOLATION
1     A=R(I)-RR(K)
      B=RR(K+1)-RR(K)
      C=A/B
      D=FR(K+1)-FR(K)
      E=C*D
      XFR(I)=FR(K)+E
100   CONTINUE
      RETURN
      END
```