ASPHALT: Mixture Design Method To Minimize Rutting

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A major type of asphaltic concrete pavement failure is rutting, which is manifested at the surface. Rutting may originate in any of the pavement layers; rutting that originates in the upper asphaltic concrete layers of surface or binder course is discussed. Recently researchers have recommended the computer program ASPHALT for estimating a design asphalt content for paving mixtures. Its basis is described and its use illustrated. The results of a comparison of laboratory designs for asphalt content with field performance related to rutting are described.

The objectives of the computer program ASPHALT are to estimate the design of asphalt content for paving mixtures to minimize the possibility of a rutting failure (by flow) and to have sufficient asphalt for good durability (1). Basically, rutting is minimized with a low asphalt content and durability is enhanced with a high asphalt content. The paving mixture is envisioned as having been on the roadway under traffic for about 5 years so that its physical characteristics have become stabilized. The age of the mixture is important to the concepts of the program. The experience of the author has indicated that by the age of about 5 years the asphalt layer must have (a) more than 2 percent air voids to not show bleeding or rutting and (b) a so-called asphalt film thickness ranging from 6 to 12 μm to show good resistance to cracking and stripping. The failures mentioned are those that would have originated in the asphaltic course. Rutting that originates by shear failure of a soil course is not a part of the asphaltic concrete mixture design.

The ruts that are of concern are grooves essentially parallel to lane lines and on the wheelpaths. The depths are measured from crest to valley, and the critical depth is considered to be ⅜ in. This value was selected because a rut of this depth filled with water would be conducive to hydroplaning of a vehicle. Grooves of less than ⅜ in. may result in compression of the mixture after it has been constructed. For example, a 3-in. layer placed with an air void content to 8 percent would have a groove of ⅛ in. after traffic reduced the air void content to 4 percent; this would not be a rut as defined.

The quantity of asphalt to satisfy stability and durability needs is a direct function of the voids in the mineral aggregate (VMA). It is also known that the VMA is a function of aggregate gradation; consequently, there must be a criterion for VMA that is based on aggregate particle size. The following sections will give more details of the process involved.

PROPERTIES OF AGGREGATES AND ASPHALT

Gradation of the aggregate blend must be expressed for a particular nesting inclusive of sizes 1 ½, ¾, ⅜ in. and Nos. 4, 8, 16, 30, 50, 100, and 200 as a percentage passing on a volume basis. Of course, if the blend is of particles all having the same specific gravity, the gradation may be expressed on a weight basis. The aggregate must have a water absorption value of less than 2.5 percent. The asphalt absorption value can be estimated: an average value is 0.6 to 0.7 percent by weight of aggregate. For the calculation of asphalt content the effective specific gravity of the aggregate is used as well as that for the asphalt (± 1.020).

The criterion on VMA was set with reference to the nominal maximum particle size. The maximum particle size corresponds to the sieve opening on which 10 percent of the aggregate would be retained. The target or minimum VMAs for the design are as follows: maximum particle size, 1, ¾, ½, and ⅜ in.; and minimum VMA, 13, 14, 15, and 16 percent.

The listed VMAs are those of the aggregate about 5 years after construction and not of the laboratory compacted mixture.

The VMA of an aggregate blend is calculated with the use of factors described by Hudson and Davis (2). It is assumed that the shape and surface texture characteristics of the aggregate blend meet normal requirements or that the surface texture index (3) is greater than 1.5

The asphalt film thickness is obtained by using the surface area of the aggregate blend calculated with the California surface area factors (4, p. 36).

EXAMPLES OF DESIGN PROCEDURE

The following gradations and assumed aggregate characteristics (Table 1) will be used to illustrate the use of criteria and ASPHALT to obtain an estimate of a design asphalt content. Table 2 is a copy of the program's output.

The 1-in. gradation from Table 3 of ASTM D3515-796 has been chosen to illustrate the process for analyzing data from ASPHALT. As indicated in the footnote of the table, specific gravity values and asphalt absorption have been assumed. If one chooses the midpoint values of the gradation band set by the specification, the minimum VMA (after 5 years of traffic) would be 13.4 percent; however, ASPHALT yielded a VMA value of 12.4 percent. Consequently, the gradation should be opened and one would not proceed with testing of asphaltic

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TABLE 1 Aggregate Characteristics and Results of Program ASPHALT

	AGGREGATE				
	Total Percent Passing				
Sieve Size	Specs*	Mid Point	(FMDC)	Upper Limit	Within Limits
1½	100	100		100	100
1	90-100		(100)		
0.75		81	(87)	92	90
0.50	56-80				
0.375		59	(61)	74	70
#4	29-59	44	(43)	59	52
#8	19-45	32	(31)	45	30
#16		24	(22)	35	18
#30		16	(15)	25	12
#50	5-17	11	(11)	17	7
#100		6	(8)	11	5
#200	1-7	4	(5.5)	7	3
VMA, % min.	13.4			14.2	14.0

	ASPHALT**					
VMA, %	12.4		13.1		14.3	
A.V. %	A.C. %	F.T., μ	A.C. %	F.T., μ.	A.C. %	F.T., μ
2	4.4	8.5	4.7	5.9	5.2	13.3
3	3.9	7.6	4.3	5.3	4.8	12.1
4	3.5	6.6	3.9	4.7	4.4	10.9
5					4.0	9.6
6					3.6	8.4

* ASTM D3515 Table 3
** For the program it was assumed that the effective specific gravity of the aggregate was 2.650, the asphalt specific gravity was 1.020, and asphalt absorption was 0.7 percent.

mixtures. However, if one must use the gradation established, the asphalt content recommended for initial testing would be a low value of 3.9 percent.

Examining the upper limit of the gradation band shows that the gradation has been opened but that the VMA value of 13.1 percent is still below the required minimum of 14.2 percent. In addition, the film thickness at a minimum value of air voids is 5.9 μm, which is also below the required minimum of 6.0. This gradation would be rejected completely.

The within gradation yields acceptable values for the criteria of ASPHALT. The selected design asphalt content would be 4.8 percent. Film thickness of 12.1 μm could possibly yield a low Hveem stability value.

Table 1 illustrates the danger of establishing a gradation down the middle of many specification bands because doing so leads to a maximum density gradation that corresponds to a low value of VMA.

The criteria selected for the program are representative of what would be expected in the roadway after it has become stabilized by the action of traffic. For laboratory compacted specimens, design values for VMA and air voids should be extrapolated backwards and with reference to the compaction effort given. Using 75 B/F Marshall compaction would require ranges of values for the following:

● Air voids, 4 to 6 percent; and
● VMA: ½-in. aggregate, 16 to 17 percent minimum; ¾-in. aggregate, 15 to 16 percent minimum.

DESIGNS AND ANALYSES WITH ASPHALT

The concepts of ASPHALT for mixture design have been used since the early 1970s. However, verification on a national basis was not attempted until 1985. The following sections show comparisons of design asphalt contents, determined by laboratory strength testing, with those calculated with ASPHALT, which does not require testing. Also presented

TABLE 2 Computer Output for Midpoint Gradation

Sieve Size	Percent Passing (P)	R	Voidage Reduction Factor (F)	Aggregate Voidage %	Surface Area Factor	Surface Area (Sq. ft./lb)
200.000	4.0	.00	.000	32.00	160.	6.40
100.000	6.0	1.50	.897	28.71	60.	3.60
50.000	11.0	1.83	.944	27.11	30.	3.30
30.000	16.0	1.45	.893	24.21	14.	2.24
16.000	24.0	1.50	.897	21.72	8.	1.92
8.000	32.0	1.33	.892	19.37	4.	1.28
4.000	44.0	1.38	.891	17.26	2.	.88
.375	59.0	1.34	.891	15.38	0.	2.00
.750	81.0	1.37	.891	13.70	0.	.00
1.500	100.0	1.23	.902	12.37	0.	.00

TOTAL SURFACE AREA = 21.62

Air Voids, Percent	Asphalt Content, Percent	Film Thickness, Microns
2.00	4.36	8.53
3.00	3.95	7.56
4.00	3.55	6.59
5.00	3.13	5.62
6.00	2.72	4.64

Effective Specific Gravity	= 2.650
Asphalt Specific Gravity	= 1.020
Asphalt Absorption Value	= .700

are several analyses of pavement surface performance with the results of the program.

Mixture Designs

The first check of the program's output with national mixture designs was made in 1986. A questionaire to state departments of transportation resulted in information on mixture design data that could be incorporated into the ASPHALT program. Figure 1 shows a comparison between design asphalt content established with laboratory procedures and asphalt content determined with the criteria of the program (*1*). As shown, comparisons were made with high and low calculated asphalt contents because consideration was given to calculated values of VMA, air voids, and asphalt film thickness.

At the request of FHWA's western region office, determinations were made for the asphalt contents of two mixtures for comparison with those obtained by laboratory testing (J. Massucco, personal communication). The first was a 1½-in. mixture because the testing for strength was performed on the portion passing the 1-in. sieve. The design asphalt content was set by testing at 4.7 percent (4.9 oil ratio), and the calculated value was 4.2 percent for a terminal air void content of 3.0 percent.

The second was identified as a ¾-in. mixture that had a design asphalt content of 5.0 percent (5.3 oil ratio). The ASPHALT program yielded an asphalt content of 4.9 percent at 3.0 percent air void and film thickness of 10.1 μm.

More recently, *NCHRP Report 338* (*5*) presented a graph showing a comparison between the asphalt contents calculated with ASPHALT and those selected by the Marshall (50/B/F) and Hveem design procedures. The graph is shown in this paper as Figure 2. Figure 3, from the same source, shows the effects of gradation on asphalt content for the combinations of the available aggregates. The inset shows that at 5 percent air voids, the asphalt content remained relatively constant but the asphalt film thickness increased from 8 to 10.6 μm.

In Figure 2, an alignment of points along the line of equality is noted for Hveem specimens at 5 percent air voids and for Marshall specimens at 3 percent air voids. As mentioned, the Marshall specimens were compacted with 50 B/F.

In 1989 Bedenkop (personal communication) requested a review of the job mix formula (JMF) for a pavement system in Phoenix. The JMF data and results obtained from the program are shown in Table 3.

The results obtained with the ASPHALT program indicate that the JMF gradation without tolerances is tight because its terminal VMA is less than the criterion value. The selected asphalt content for design at 3.0 percent air voids is shown
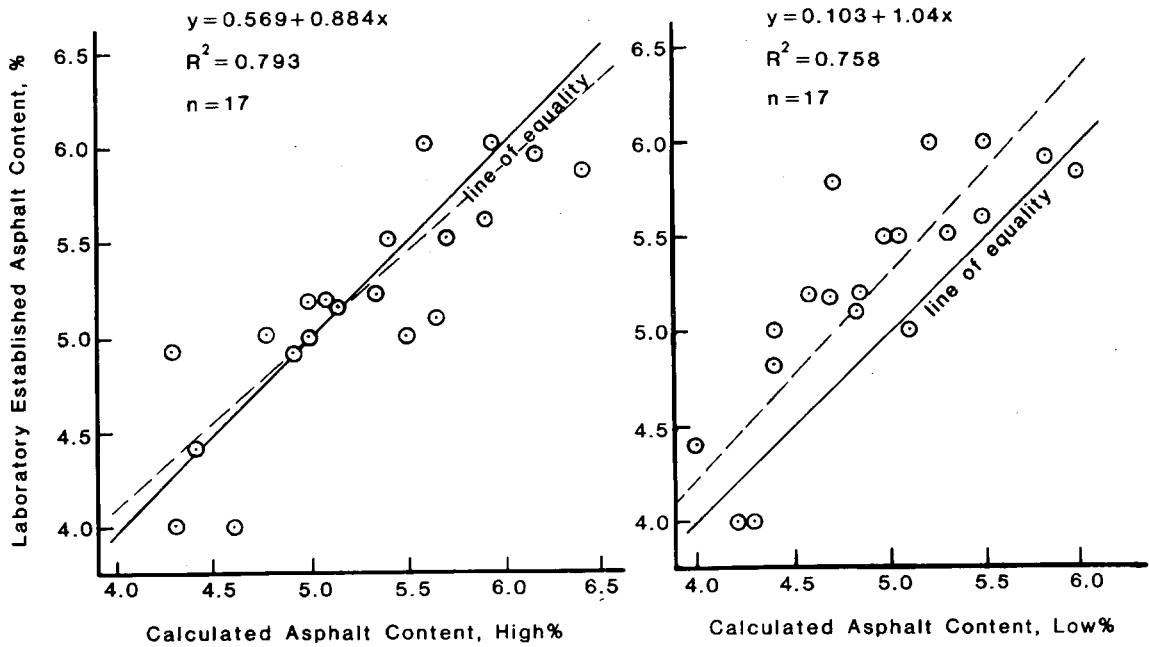
FIGURE 1 Comparisons of laboratory-established asphalt content with calculated values for various highway department mixtures (1).

to be 4.3 and 5.0 percent for the base and surface, respectively. These values correspond to those for the JMF.

Mixture Analyses

ASPHALT has been used in analyzing the performance of many pavements that have failed or given good performance at the time in question.

Huber and Heiman (6) presented data to show effects of mixture properties on rutting performance. Field data obtained from cores were used in ASPHALT to relate calculated values of asphalt content to asphalt content of cores from sections showing rutting performance and rut depths. Table 4 presents the comparisons in the order of descending values of rut depths. As indicated, acceptable rutting has been as-
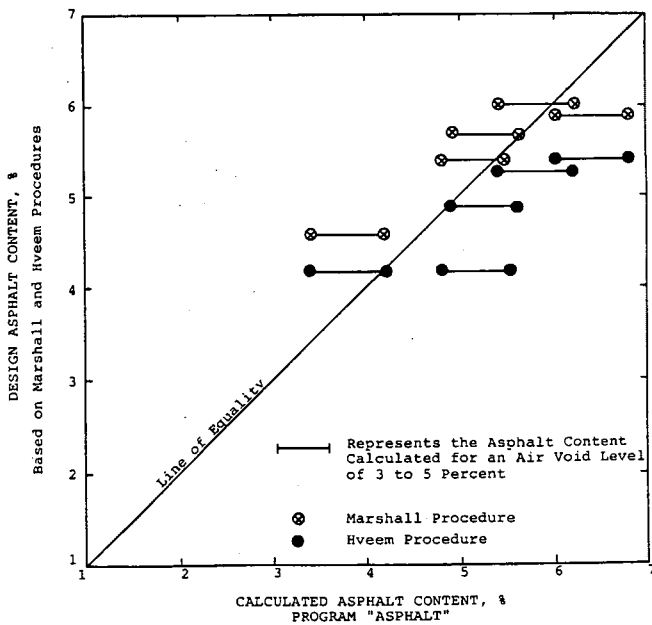

FIGURE 2 Comparisons of asphalt contents determined by Marshall and Hveem procedures with calculated values by ASPHALT (5).
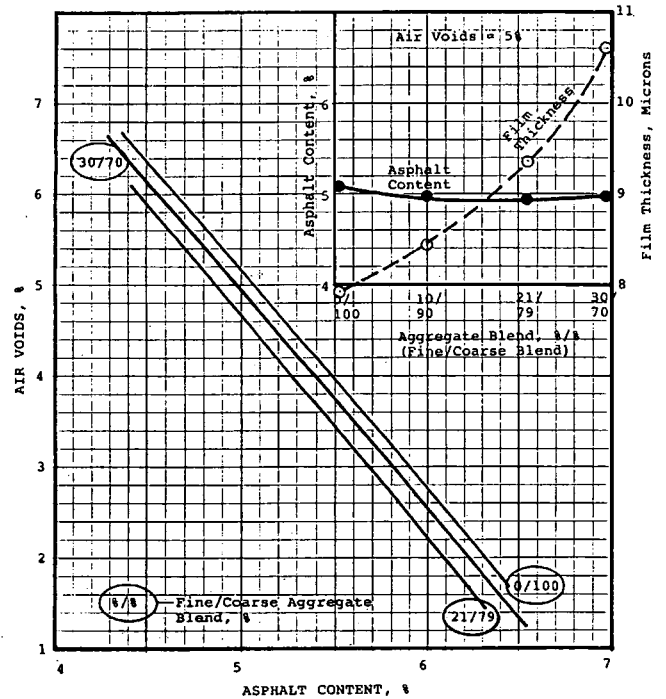

FIGURE 3 Asphalt content–Air void relationships calculated with ASPHALT for Colorado mixtures (5).

TABLE 3 JMF and ASPHALT Mixture Design Data

Sieve	1½"	1"	¾	⅜	#4	#8	#30	#200	A.C., %
				Gradation and Asphalt Content for JMF					
Base	100	93±7	88	58	43	35±5	20	5±2	4.3±0.4
Surface		100	97±7	78	58	45±5	25	5±2	5.1±0.4

ASPHALT

	Base		Surface	
Criterion VMA, % min.	13.8		15.0	
Terminal VMA, %	13.1		14.4	
Air Void, %	2.0	3.0	2.0	3.0
Asphalt Content, %	4.8	4.3	5.4	5.0
Film Thickness, μ	7.9	7.1	7.8	7.1

signed for depths of less than 10 mm (⅜ in.). The critical and computed asphalt content at 2 percent air voids is generally less than the cores' asphalt content for air voids of less than 2 percent, and those sections were evaluated as having poor rutting performance. The cores having air voids of greater than 2 percent generally were in sections having fair or good performance and whose asphalt contents generally were close to the values obtained with the program. Variations between prediction and performance will occur because the reliability of the core data is representative of the sections' properties.

In 1987 Massucco (personal communication) requested analyses of core data from two pavement surfaces that had shown poor performance very soon after construction. The information given and ASPHALT results are shown in Tables 5 and 6.

An examination of the data shown in Table 5 indicates that the gradation for the mixture was too tight because the ter-

minal VMAs were much less than the criterion minimum value of 15.0 percent. Also, the actual asphalt contents, ranging from 5.4 to 5.7 percent, were greater than the calculated and critical values ranging from 4.9 to 5.3 percent for calculated air void contents of 2.0 percent.

As for Project A, the gradation for Project B was too tight. Table 6 shows that the asphalt contents were about 0.5 percent higher than would be recommended (for 3.0 percent air content), and the film thicknesses were very low to give good durability.

Another pavement analysis is related to a paper given by Al-Dhalaan et al. at the 1990 meeting of the Association of Asphalt Paving Technologists (AAPT) (2). A discussion of that paper appears in the AAPT's *Journal* journal and is presented here.

The AAPT paper gave mixture characteristics for pavements that had rutted or were showing good performance.

TABLE 4 Characteristics of Theoretical and Core Properties of Saskatchewan Pavement (6)

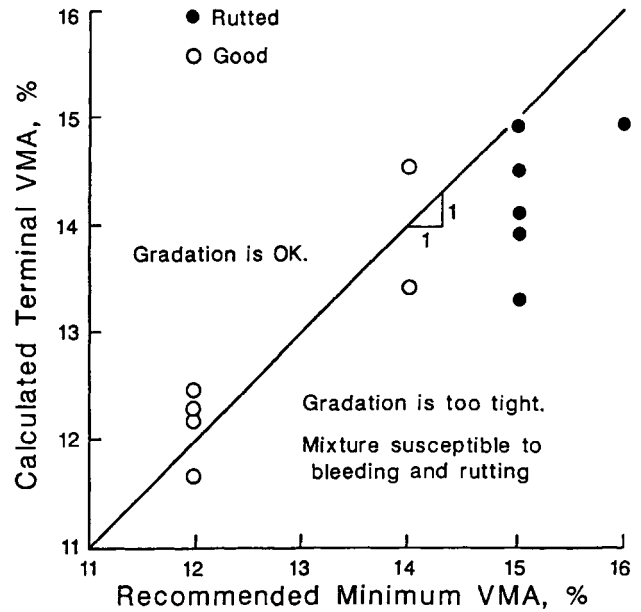| Rut Depth mm	Site No.	Optimum Asp. Cont. %	At 2% Air Void Asp. Cont %	Asp. Cont. %	Air Void %	Rutting Peform.
		Theoretical Values		Core		
15.0	1	4.5	4.9	5.2	0.5	Poor
15.0	7	4.5	4.9	5.9	0.9	Poor
12.0	8	4.9	5.3	5.8	1.3	Fair
11.5	9	4.5	4.9	5.4	3.7	Good
10.0*	3	4.9	5.3	6.3	1.4	Poor
6.5	2	4.6	5.0	4.8	3.1	Fair
6.0	4	4.7	5.1	6.0	1.8	Poor
4.5	5	4.8	5.2	5.0	3.3	Fair
4.0	11	4.3	4.7	5.9	2.0	Good
3.0	10	4.7	5.1	5.4	1.4	Good
2.0	6	4.1	4.9	5.3	8.0	Good

* A limiting rut depth of 9.5 mm (⅜ in.) to minimize hydroplaning.

TABLE 5 Core and ASPHALT Data for Project A

Cores:

	A-1		A-2		A-3	
Average Asphalt Content, %	5.4		5.7		5.4	
Average Air Voids, %	4.7		2.3		3.4	
Comment on Field Performance -	Severe rutting and flushing as soon as ambient temperature was up.					

ASPHALT:

Criterion VMA, % min.	15.0		15.0		15.0	
Terminal VMA, %	13.5		14.3		13.6	
Air Void, %	2.0	3.0	2.0	3.0	2.0	3.0
Asphalt Content, %	4.9	4.5	5.3	4.9	5.0	4.6
Film Thickness, μ	5.4	4.9	5.9	5.3	5.1	4.6

FIGURE 4 Relationship between minimum and terminal VMAs on rutting susceptibility (7).

Analyses of the mixtures were made from the information given in the early preprint. The upper portion of Figure 4 shows the conditions of the various pavements and also the VMAs of criterion and calculated terminal ones. The plot of the minimum VMA compared with that of terminal VMA shows that all the rutted pavements were predicted by the program. Of the good pavements two were predicted to be rutted; that is, the program was in error. However, at the time of the meeting Al-Dhalaan stated that the one good Ring Road surface had become "shiny"; that is, it was bleeding.

The final pavement analyses presented are concerned with the study of rutting reported by Cross and Brown (8). The study involved 42 sites, with two to three layers examined. The data used for ASPHALT were from layer materials defined by quality control–quality analysis from which gradation and aggregate effective specific gravity could be obtained. The sections and layers used for analysis are shown in Table 7. The table has measurements reported by the National Center for Asphalt Technology (NCAT) and results obtained with

ASPHALT. The following listings summarize the comparison for pavement performance.

Rutted Sections (> 0.375 in.)		Good Sections (< 0.375 in.)	
NCAT	*ASPHALT*	*NCAT*	*ASPHALT*
6	Y	3	Y
12	Y	7	Y
13	Y	15	No
16	Y	18	No
17	Y	20	No
21	No	28	Y
23	Y		
29	No		
32	Y		
33	Y		
34	Y		
35	Y		

TABLE 6 Core and ASPHALT Data for Project B

CORES:

	B-2		B-8	
Average Asphalt Content, %	4.7		4.9	
Average Air Voids, %	7.4		9.9	
Comment on Field Performance-	Severe raveling. Entire surface raveled down to CTB in one month (cold weather paving).			

ASPHALT:

Criterion VMA, % min.	15.0		15.0	
Terminal VMA, %	12.7		13.0	
Air Void, %	2.0	3.0	2.0	3.0
Asphalt Content, %	4.6	4.2	4.8	4.3
Film Thickness, %	6.0	5.4	5.4	4.8

TABLE 7 ASPHALT Analyses for NCAT Rut Study

NCAT				Program ASPHALT						
Site & Layer	Rut In.	ESAL 10⁶	A.C. %	Criterion VMA, % min.	Grad. VMA, %	@ 2% Air Void A.C., %	@ 2% Air Void F.T. μ	@ Layer A.C. A.V. %	Prob. Rut Y or N	Comment
Rut Depths Greater Than 0.375 Inch										
6-1	0.575	4.1	5.2	16.0	15.4	5.7	7.0	3.1	No	
2			5.3	15.5	14.4	5.2	8.1	2.0	Yes	
12-1	1.450	0.4	6.4	16.5	15.9	6.1	8.7	1.0	Yes	
2			4.7	13.5	12.5	4.3	8.3	1.0	Yes	
13-1	1.656	2.9	6.3	16.5	15.7	5.8	10.3	1.0	Yes	
2			4.3	13.5	12.3	4.2	7.6	1.5	Yes	
16-1	0.547	0.9	7.4	15.0	15.4	5.7	9.8	1.0	Yes	
2			4.9	14.5	14.1	5.1	11.2	2.5	No	
17-1	0.463	1.7	6.7	15.5	14.1	5.2	10.9	1.0	Yes	
2			4.2	14.5	14.6	5.4	15.0	5.0	No	Excessive high F.T.
21-1	1.370	0.5	6.5	15.5	17.8	6.7	14.3	2.5	No	Excessive high F.T.
2			5.6	14.5	16.8	6.3	14.8	4.0	No	Excessive high F.T.
3			5.0	13.7	14.7	5.4	17.9	3.0	No	Excessive high F.T.
23-1	0.586	3.3	5.1	15.0	13.6	4.8	5.7	1.0	Yes	Low F.T.
2			5.1	15.0	13.6	5.0	6.1	2.0	Yes	Low F.T.
29-1	0.513	1.4	5.0	16.0	14.4	5.3	7.2	4.0	No	Grad. too tight
2			5.0	16.0	14.4	5.3	7.2	4.0	No	Grad. too tight
3			4.4	15.0	14.1	5.2	7.0	5.0	No	Grad. too tight
32-1	0.980	1.5	5.5	15.0	15.2	5.5	7.8	2.0	Yes	
2			5.5	15.0	15.2	5.6	8.1	2.2	Yes	
3			5.5	15.0	15.2	5.6	8.1	2.2	Yes	
33-1	0.700	1.1	-	-	-	-	-	-	-	
2			-	-	-	-	-	-	-	
3			5.5	15.0	15.2	5.6	8.1	2.2	Yes	
34-1	0.980	1.2	-	-	-	-	-	-	-	
2			5.4	14.6	14.3	5.1	6.8	1.5	Yes	
3			-	-	-	-	-	-	-	
35-1	0.633	1.0	-	-	-	-	-	-	-	
2			-	-	-	-	-	-	-	
.3			5.4	14.6	14.3	5.2	6.9	1.5	Yes	
Rut Depths Less Than 0.375 Inch										
3-1	0.375	3.1	-	-	-	-	-	-		
2			5.3 (Lab)	16.0	19.4	7.7	12.0	-	No	
7-1	0.344	1.7	5.2	16.0	17.1	6.5	8.0	5.2	No	
2				16.0	15.6	5.8	7.4	4.8	No	
15-1	0.094	0.9	7.8	16.0	14.6	5.2	8.7	0	Yes	Low ESAL
2			4.9	14.5	13.5	4.8	9.7	1.8	Yes	Low ESAL
18-1	0.200	1.5	-	-	-	-	-	-	-	
2			6.1	15.0	13.3	4.7	6.3	0	Yes	
20-1	0.317	0.3	-	-	-	-	-	-	-	
2			5.8	15.0	13.4	4.8	6.6	0	Yes	Low ESAL
3			5.7	15.5	13.3	4.8	6.7	0	Yes	Low ESAL
28-1	0.300	0.7	5.7	16.0	15.4	5.8	7.6	2.2	No	
2			4.5	15.5	14.2	5.4	6.9	4.0	No	

The program did not indicate that rutting would have been a problem for Sections 21 and 29, of the 12 sections with ruts greater than 0.375 in. However, the high film thickness for the layers of Section 21 would indicate low shear strength for the mixtures. The text of the report also mentioned that "permanent deformation of the gravel base course had occurred."

Comparison of performance of the sections with depressions of less than 0.375 in. was not as good as that for the rutted sections. In addition, predicted poor performance of Layer 15-1 was based on the asphalt content of 7.8 percent, which yielded an air void content of 0. It is possible that the 7.8 value is in error because it is higher than any of those for the rutted sections. In defense of the program, it is noted that the rut depth for Section 20 was near the value of 0.375 in. and that traffic had a low ESAL of 0.3×10^6—all indicating the eventual rutting of the pavement.

The good pavement sections 3 and 7 had asphalt layers with aggregate gradations classified as ⅜ in., showing that good resistance to rutting can be obtained with small stone mixtures.

CONCLUDING REMARKS

The design concepts and criteria in this paper are for mixtures that have stabilized after about 5 years of traffic, and in which rutting of the top asphaltic courses is minimized.

This paper has given the background of the computer program ASPHALT and presented examples of its use for mixture design and analyses of mixture performance in pavements. The results obtained from the verification of the program are considered satisfactory.

REFERENCES

1. Jimenez, R. A., and D. A. DaDeppo. Asphaltic Concrete Mix Design Evaluation. Report FHWA/AZ-86-189. Arizona Department of Transportation, 1986.
2. Hudson, S. B., and R. L. Davis. Relationship of Aggregate Voidage to Gradation, *Proc., Association of Asphalt Paving Technologists*, Vol 34, 1965, pp. 574–593.
3. Jimenez, R. A. Flow Rate as an Index of Shape-Texture of Sands. In *Transportation Research Record 1259*, TRB, National Research Council, Washington, D.C., 1990, pp. 120–132.
4. *Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types, Manual Series No. 2*. The Asphalt Institute, 1984.
5. Von Quintos, H. L., J. A. Scherocman, C. S. Hughes, and T. W. Kennedy. *NCHRP Report 338: Asphalt-Aggregate Mixture Analysis System*. TRB National Research Council, Washington, D.C., 1991.
6. Huber, G. A., and G. H. Heiman. Effect of Asphalt Concrete Pavements on Rutting Performance: A Field Investigation. *Proc., Association of Asphalt Paving Technologists*, Vol. 56, 1987, pp. 33–55.
7. Al-Dhalaan, M. A., S. S. Khan, T. A. Farouki, and T. A. Farwana. A Comprehensive Approach to the Rutting Problem in the Kingdom of Saudi Arabia. *Journal of the Association of Asphalt Paving Technologists*, Vol. 59, 1990, pp. 560–589.
8. Cross, S. A., and E. R. Brown. *A National Study of Rutting in Hot Mix Asphalt (HMA) Pavements*. Draft report for the National Center for Asphalt Technology. Auburn University, Auburn, Ala., Dec. 1991.