Selection of Maximum Theoretical Specific Gravity for Asphalt Mixture Design

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The volume of air has been cited in technical literature as one of the most important performance indicators of asphalt paving mixtures. Air-void content is not measured directly; instead it is calculated mathematically by comparing the bulk specific gravity of a mixture with the maximum theoretical specific gravity of the mixture at the same asphalt content. The test method developed by Rice (ASTM D-2041) is the most accepted means of determining maximum theoretical specific gravity. Nevertheless, agencies have used and continue to use other methods and calculations to determine this value. The purpose of this study was to compare mixture properties determined by the Rice method with those determined by the method established by the Texas State Department of Highways and Public Transportation (SDHPT). The SDHPT procedure is often referred to as the Martin method. Data from 42 mix designs were analyzed. The analysis determined that on average, use of the Rice method to determine maximum theoretical specific gravity resulted in asphalt content about 0.35 percent higher than did use of the Martin method. The difference in selected asphalt content derived from the two methods increased as aggregate absorption increased. The difference between the two methods proved insignificant for aggregate with low absorption capacities. The results revealed that the Martin method developed a reasonable approximation for maximum theoretical specific gravity during the mix-design phase.

Performance characteristics of asphalt mixtures have been related to various asphalt mixture properties (*1–4*). Some studies indicate that the most important performance predictor is the volume of air. The effect of air voids on the mixture properties is shown in a conceptual plot in Figure 1 (*4*). Such relationships substantiate most of the experience of asphalt technologists in the last 50 years and illustrate the importance of achieving an optimum level of air voids within the range of 3 to 8 percent. Apparently, determination of air-void content is an extremely important issue. Attention is most often focused on the air-void content of trial mixtures during the mix-design phase and during plant quality control. Air voids are considered again after field compaction and after a certain amount of traffic.

According to the Asphalt Institute mix design manual (*5*), air void content is calculated by

$$Pa = 100\,(Gmm - Gmb)/Gmm$$

where

Pa = air-void content (percent of total volume),
Gmm = maximum theoretical specific gravity of the mixture, and
Gmb = bulk specific gravity of the mixture.

In this formula, *Gmm* is intended to be measured experimentally by means of the Rice method (ASTM D-2041). Determination of *Gmm* and air-void content in this manner is the most accepted procedure. Nevertheless, there are numerous variations of determining *Gmm,* and each has unique implications, especially during the mix-design phase.

The Rice procedure and the procedure used by the Texas State Department of Highways and Public Transportation (SDHPT) and other agencies in Texas were used to examine the effect of *Gmm* on asphalt content and other mixture properties. As recently as 1988, more than 23 million tons of hot-mix asphalt were placed in Texas, ostensibly by the current SDHPT procedure (*6*).

BACKGROUND OF TEXAS PROCEDURE

The procedure currently used by agencies in Texas is a variation of the method developed in the 1950s by Rogers Martin, a former employee of SDHPT (*7*). The Martin procedure, applied during mix design, improves the determination of *Gmm* by molding specimens at higher-than-normal asphalt contents to simulate a mixture without voids. At the asphalt content at which the mixture is considered saturated (i.e., zero voids), the effective specific gravity of the combined aggregates in the molded specimen is determined by the following formula:

$$Gse = (100 - Pb)/[(100/Gmb) - (Pb/Gb)]$$

where

Gse = effective specific gravity of combined aggregates,
Pb = percent asphalt by weight of mix,
Gb = specific gravity of the asphalt binder, and
Gmb = bulk specific gravity of the mixture assumed to represent zero air voids.

After determination of *Gse* in this manner, *Gmm* is determined at other asphalt contents in the mix design by

$$Gmm = 100/[(Ps/Gse) + (Pb/Gb)]$$

where *Ps* is the percent aggregate by weight of mixture and *Gb* is the asphalt specific gravity.

With the exception of the saturation approach for determining *Gmm,* the density/voids analyses of trial mixtures of

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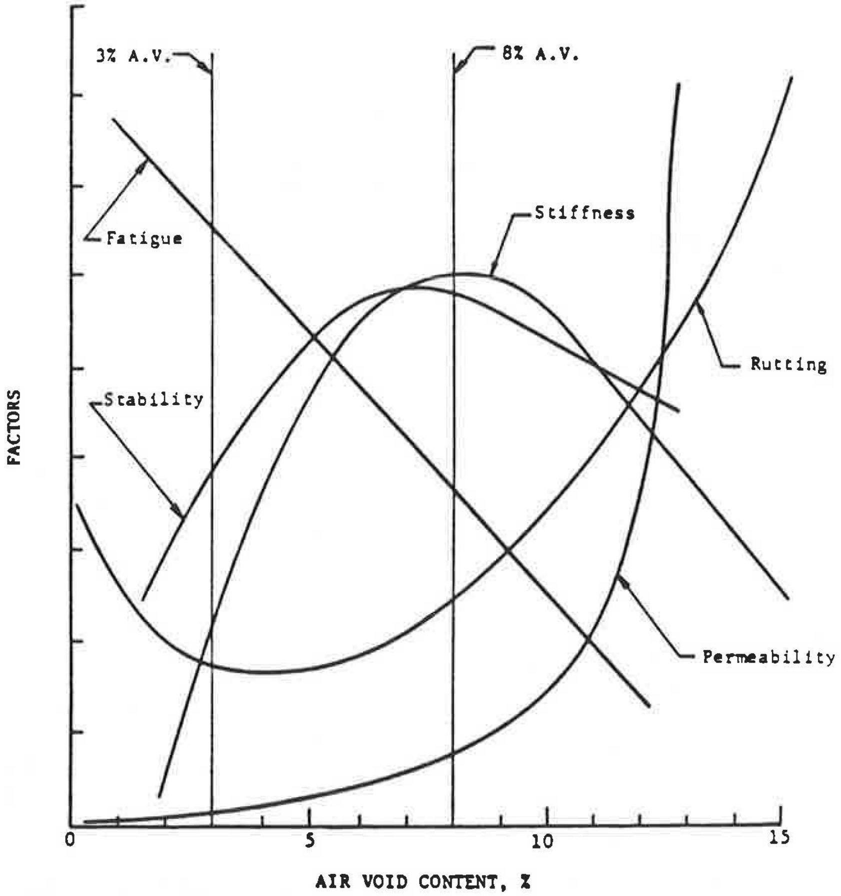

FIGURE 1 Relationships between mixture properties and air-void content (*4*).

the Martin procedure are exactly the same as those outlined in the Asphalt Institute design manual (*5*).

Although density/voids analyses do not take into account the method of compaction, it should be noted that the Texas SDHPT uses a gyratory shear compactor to mold mix-design specimens. The standardized process (*8–10*) requires all trial mix specimens to be compacted so that the specimens achieve a constant resisting pressure of 150 psi.

Another interesting aspect of the Martin approach is the manner by which it accounts for absorption of asphalt by aggregates. In order to best simulate project conditions, loose trial mix specimens are oven-cured to facilitate absorption. The standard Martin procedure specifies that loose samples be placed in an oven at 250°F for 2 hr.

During the early 1980s, Texas SDHPT personnel and various other asphalt technologists in Texas began experimental use of the Rice procedure (ASTM D-2041). Such use was initiated on the basis of in-place density specifications being promoted in Texas and elsewhere. In this application, *Gmm* determined by the Rice procedure was used as a reference to determine the air-void content of hot-mix asphalt after field compaction. Because of this practice, it seemed logical that the air-void content determined during mix design should use the same reference (*Gmm*) as determined by the Rice procedure. Because previous mix-design experience in Texas was within the framework of the Martin procedure to determine *Gmm*, three key questions needed to be answered:

1. How would the use of the Rice method affect density/voids analyses?
2. Would the use of the Rice method result in fundamental changes in asphalt content selection?
3. How does aggregate absorption capacity affect questions 1 and 2?

LABORATORY STUDY

In order to resolve these questions, asphalt contents selected from density/voids analyses were compared using the Rice and Martin methods. A typical design plot illustrating the approach is shown in Figure 2. The two air-void curves shown in Figure 2 were determined on the basis of *Gmm* determined from the Rice and Martin procedures.

A data base containing 42 mix designs was evaluated. The mixes were placed on a wide variety of facilities in southeast Texas ranging from low-volume city and county streets to interstate highways. They were all dense-graded surface courses with approximately 100 percent passing the 1/2-in. sieve.

Mix designs were performed for the various aggregate blends and types. The aggregate blends consisted of various combinations of sandstone or limestone, limestone screenings,

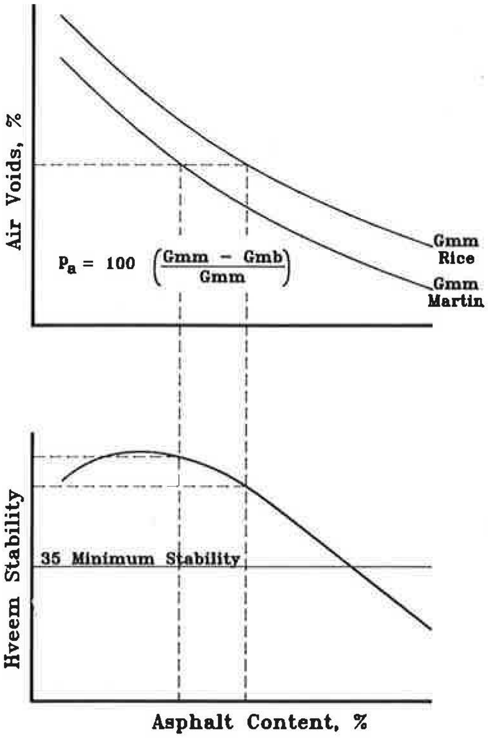

FIGURE 2 **Selection of optimum AC content.**

and siliceous sand. Normally, the inclusion of sandstone implied that the mixture was intended to be nonpolishing. Trial blends were computed using various percentages of the individual aggregates to satisfy agency gradation requirements. An example of these computations is presented in Table 1.

Aggregate gradations for the 42 designs were similar. The principal difference between the aggregates was their absorption properties. Therefore, mixtures were grouped into nine categories on the basis of their water and asphalt absorption capacity. Table 2 presents the mix groups and their coding. The mix code is designated by *Mwa*, where *w* refers to the water absorption level and *a* to the asphalt absorption level.

The Martin method was used with one exception. During preparation of trial mixtures, an additional sample was prepared at each asphalt content for determination of *Gmm* using the Rice method. The overall procedure is shown in Figure 3. The procedure was used to determine optimum binder content for the 42 mix designs. Optimum binder content was selected at the project-specified air-void content, normally 3 to 5 percent.

MIX DESIGN RESULTS

Effect of Absorption

Aggregates and their combinations used in this study exhibited a general relationship between water and asphalt ab-

TABLE 1 PROPERTIES OF AGGREGATE BLENDS AND JOB MIX FORMULA

Sieve Size	*Aggr. 1* % Ret.	*Aggr. 1* Sp. Gr.	*Aggr. 1* (%) Abs	*Aggr. 2* % Ret.	*Aggr. 2* Sp. Gr.	*Aggr. 2* (%) Abs	*Aggr. 3* % Ret.	*Aggr. 3* Sp. Gr.	*Aggr. 3* (%) Abs	*Aggr. 4* % Ret.	*Aggr. 4* Sp. Gr.	*Aggr. 4* (%) Abs	*Job Mix* Formula (% Ret.)	*SDHPT* Item 340 Type "D"
1 1/2 - 1"	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1 - 1/2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1/2 - 3/8	24.2	2.486	2.7	0.2	-	-	-	-	-	-	-	-	6.5	0 - 15
3/8 - No.4	59.8	2.452	3.3	52.3	2.590	1.3	0.6	-	-	0.3	-	-	35.6	21 - 53
No.4 - No.10	12.4	2.440	3.4	42.8	2.575	1.7	14.9	2.538	2.6	1.5	-	-	21.7	11 - 32
Total No.10	96.4	-	-	95.3	-	-	15.5	2.495*	3.5*	1.8	2.600*	0.9*	63.8	54 - 74
No.10 - 40	0.8	-	-	2.8	-	-	45.0	2.792**	-	20.4	2.789**	-	12.3	6 - 32
No.40 - 80	0.3	-	-	0.2	-	-	12.2	-	-	64.1	-	-	15.5	4 - 27
No.80 - 200	0.7	-	-	0.2	-	-	8.7	-	-	12.2	-	-	4.2	3 - 27
Pass No.200	1.8	-	-	1.5	-	-	18.6	-	-	1.5	-	-	4.2	1 - 8
TOTAL	100	-	-	100.0			100.0			100.0			100.0	

Notes :

Aggr.1 - Sandstone
Aggr.2 - Type D-F Limestone
Aggr.3 - Limestone Screening
Aggr.4 - Field Sand

Job Mix Formula:

27% Aggr.1
37% Aggr.2
15% Aggr.3
21% Aggr.4

TOTAL 100

* Results are for fractions passing #10 and retained on #80 sieve
** Results are for fractions passing #80 sieve

TABLE 2 DESIGNATION OF MIX GROUPS

Aggregate Asphalt Absorption Level (%)	*Aggregate Water Absorption Level (%)*		
	Low (l) < 2.0 %	Medium (m) 2.0 - 2.5 %	High (h) > 2.5 %
Low(l) < 1.0 %	Mll	Mml	Mhl
Medium (m) 1.0 - 1.5 %	Mlm	Mmm	Mhm
High (h) > 1.5 %	Mlh	Mmh	Mhh

sorption. A low level of water absorption tended to correlate with low asphalt absorption. Conversely, aggregates with high water absorption exhibited high asphalt absorption.

Analysis of absorption characteristics of all mixtures resulted in the distribution of mixes within various groups (Table 3). The frequency of occurrence of each group is shown in Figure 4.

This grouping indicates that mix group *Mmm* (medium water and medium asphalt absorption) was the most likely to occur. As expected, no mix fell within the group *Mhl*, and only one mix was found in each of the groups *Mlh* and *Mmh*.

During the early phases of this study, the effect of aggregate absorption on *Gmm* determined by the Rice procedure was observed to be an interesting phenomenon. In the Rice procedure (ASTM D-2041), there is no guidance on this effect. Because more than half of the aggregate showed medium-to-high asphalt absorption potential, it seemed reasonable that the *Gmm* measured by the Rice procedure might be affected. In this sense, the measured *Gmm* would vary for the same mixture depending on when the sample was tested and its cure time.

This hypothesis was tested for a mixture in the *Mmm* category. Figure 5 shows the result. Loose samples were mixed and placed in an oven according to the Martin procedure. Using the Rice procedure, *Gmm* was determined for the samples at 1, 2, 3, 4, and 5 hr. An additional sample was tested immediately after mixing and cooling. Use of *Gmm* within the range shown would result in as much as 2 percent difference in the calculated air-void content. Based on this experience, all loose mixes used to determine Rice's *Gmm* were oven-cured for 2 hr at 250°F.

Effect of Selected Specific Gravity

For each of the 42 mix designs, asphalt content was determined at 5 air-void contents (1–5 percent) according to Texas agency specifications. It should be noted that asphalt content is normally selected in the range of 3 to 5 percent air voids. In some cases, a value of asphalt content at 5 percent air voids was not available, so no comparison was made (i.e., no extrapolation was used).

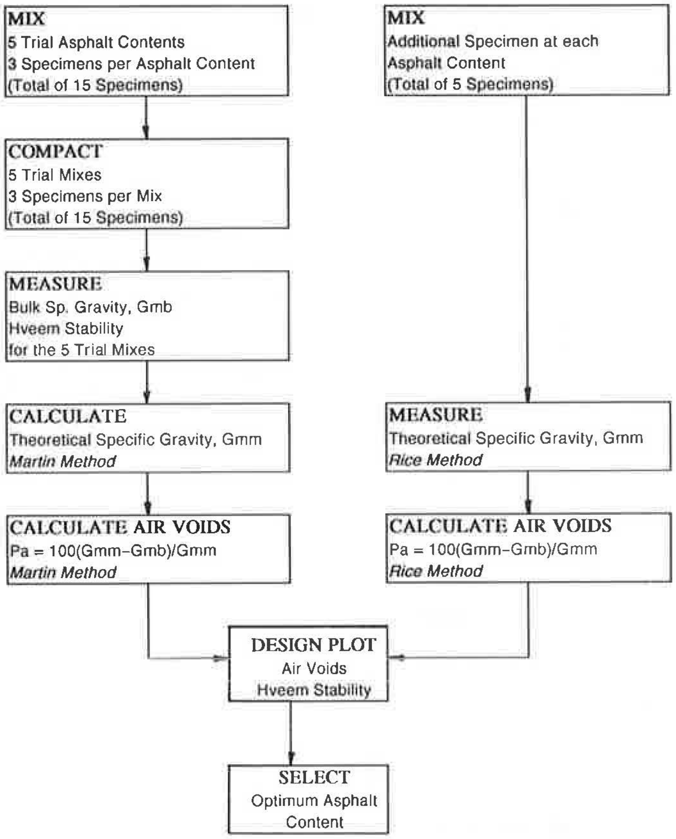

FIGURE 3 Texas method of mix design modified for Rice method.

TABLE 3 FREQUENCY OF OCCURRENCE OF MIX GROUPS

Aggregate Asphalt Absorption Level (%)	*Aggregate Water Absorption Level (%)*		
	Low (l) < 2.0 %	Medium (m) 2.0 - 2.5 %	High (h) > 2.5 %
Low(l) < 1.0 %	[Mll] N = 7 F = 16.7 %	[Mml] N = 6 F = 14.3 %	[Mhl] N = 0 F = 0.0 %
Medium (m) 1.0 - 1.5 %	[Mlm] N = 3 F = 7.1 %	[Mmm] N = 11 F = 26.2 %	[Mhm] N = 6 F = 14.3 %
High (h) > 1.5 %	[Mlh] N = 1 F = 2.35 %	[Mmh] N = 1 F = 2.35 %	[Mhh] N = 7 F = 16.7 %

Results for each cell in Table 2 were grouped to determine the average values of asphalt content at different air-void contents for all mixtures within the same group. The results for all groups are presented in Table 4 and shown in Figure 6. The average difference in asphalt content values between the two methods are shown in Figure 7.

DISCUSSION OF RESULTS

Use of the Rice *Gmm* resulted in higher asphalt contents than those selected from the Martin *Gmm*. When analyzed as a whole, all 42 mix designs at the 5 air-void contents showed that, on average, the Rice *Gmm* resulted in 0.35 percent more asphalt cement (Table 5).

The only exception to this trend was for groups *Mlh* and *Mmh*. Because these groups only consisted of two mixes, no definitive statements can be made regarding trends for those mixtures within the scope of this study.

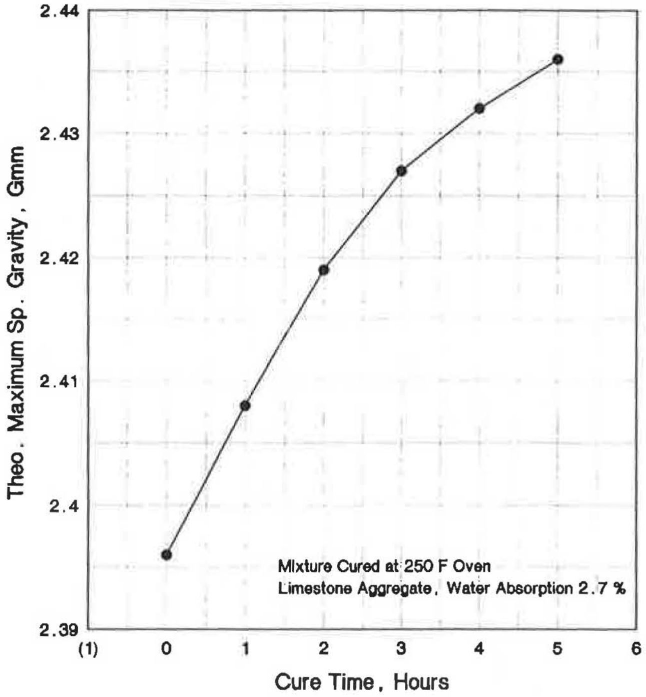

FIGURE 5 Influence of curing time on *Gmm* determination (Rice method).

The results in Figure 7 show that the differences between the Rice and Martin methods are relatively small. To determine the statistical significance of the difference between asphalt contents determined by the two methods, *t*-tests were conducted (*11*). The null hypothesis (H_o) was that there is no significant difference between asphalt content determined

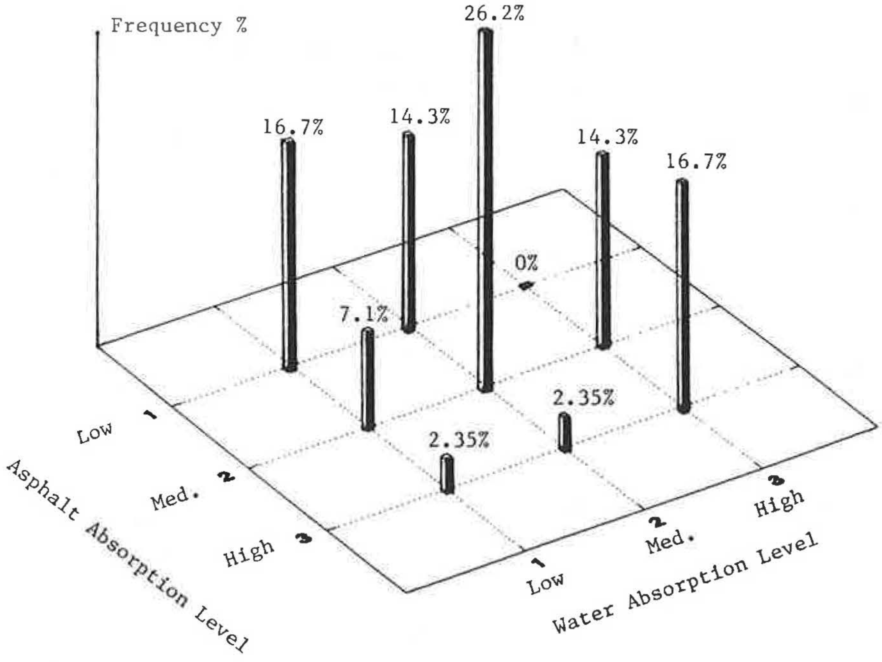

FIGURE 4 Frequency of occurrence of specific mix groups.

TABLE 4 SUMMARY OF AVERAGE ASPHALT CONTENT BASED ON DIFFERENT *Gmm*

Air Voids	AC% Based on: Bulk	Martin	Rice	Difference in AC% M-B	R-B	R-M	AC% Based on: Bulk	Martin	Rice	Difference in AC% M-B	R-B	R-M	AC% Based on: Bulk	Martin	Rice	Difference in AC% M-B	R-B	R-M
	Mll					(N = 7)	**Mml**					(N = 6)	**Mhl**					(N = 0)
1 %	5.46	5.94	6.60	0.49	1.14	0.66	5.82	6.25	6.88	0.43	1.07	0.63	NO MIXES ARE FOUND IN THIS GROUP					
2 %	5.11	5.50	5.91	0.39	0.80	0.41	5.45	5.80	6.12	0.35	0.67	0.32						
3 %	4.73	5.17	5.36	0.44	0.63	0.19	5.12	5.48	5.65	0.37	0.53	0.17						
4 %	4.53	4.77	4.90	0.24	0.37	0.13	4.75	5.00	5.27	0.25	0.52	0.27						
5 %	4.30	4.66	4.58	0.36	0.28	-0.08	4.70	4.73	4.95	0.03	0.25	0.22						
	Mlm					(N = 3)	**Mmm**					(N = 11)	**Mhm**					(N = 6)
1 %	5.47	6.33	7.07	0.87	1.60	0.73	5.05	6.11	6.68	1.06	1.64	0.57	5.50	6.82	7.24	1.32	1.74	0.42
2 %	5.17	5.97	6.33	0.80	1.17	0.37	4.74	5.65	5.92	0.91	1.18	0.27	5.13	6.23	7.04	1.10	1.91	0.81
3 %	4.87	5.53	5.77	0.67	0.90	0.23	4.52	5.17	5.41	0.65	0.89	0.24	4.80	5.75	6.47	0.95	1.67	0.72
4 %	4.90	5.23	5.20	0.33	0.30	-0.03	4.30	4.85	4.95	0.55	0.65	0.11	5.10	5.37	5.85	0.27	0.75	0.48
5 %	4.55	4.45	4.80	-0.10	0.25	0.35	4.17	4.47	4.63	0.31	0.46	0.15	4.80	4.98	5.42	0.18	0.62	0.43
	Mlh					(N = 1)	**Mmh**					(N = 1)	**Mhh**					(N = 7)
1 %	6.10	7.50	7.80	1.40	1.70	0.30	5.30	6.70	6.30	1.40	1.00	-0.40	5.30	7.16	7.44	1.86	2.14	0.29
2 %	5.90	6.90	7.40	1.00	1.50	0.50	5.00	6.00	5.80	1.00	0.80	-0.20	4.93	6.40	6.71	1.47	1.78	0.31
3 %	5.60	6.50	7.20	0.90	1.60	0.70	4.70	5.70	5.30	1.00	0.60	-0.40	4.58	5.97	6.31	1.39	1.73	0.34
4 %	5.10	6.10	5.90	1.00	0.80	-0.20	4.30	5.30	4.90	1.00	0.60	-0.40	4.20	5.51	5.86	1.31	1.66	0.34
5 %	4.80	5.80	5.50	1.00	0.70	-0.30		5.00	4.70			-0.30		5.16	5.37			0.21

NOTE: B= bulk, M= Martin, R= Rice.

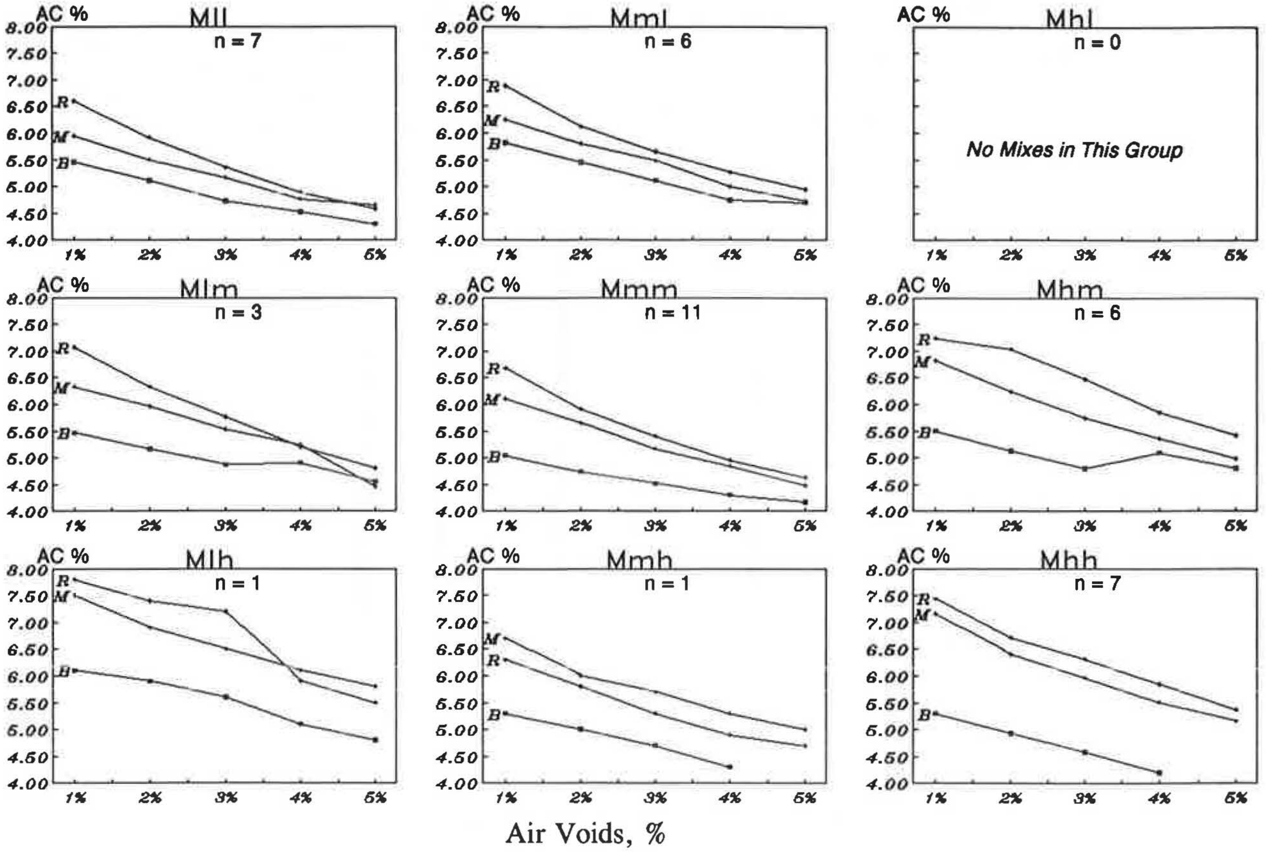

FIGURE 6 Average asphalt percent at different air voids for all mix groups (*B* = bulk, *M* = Martin, and *R* = Rice).

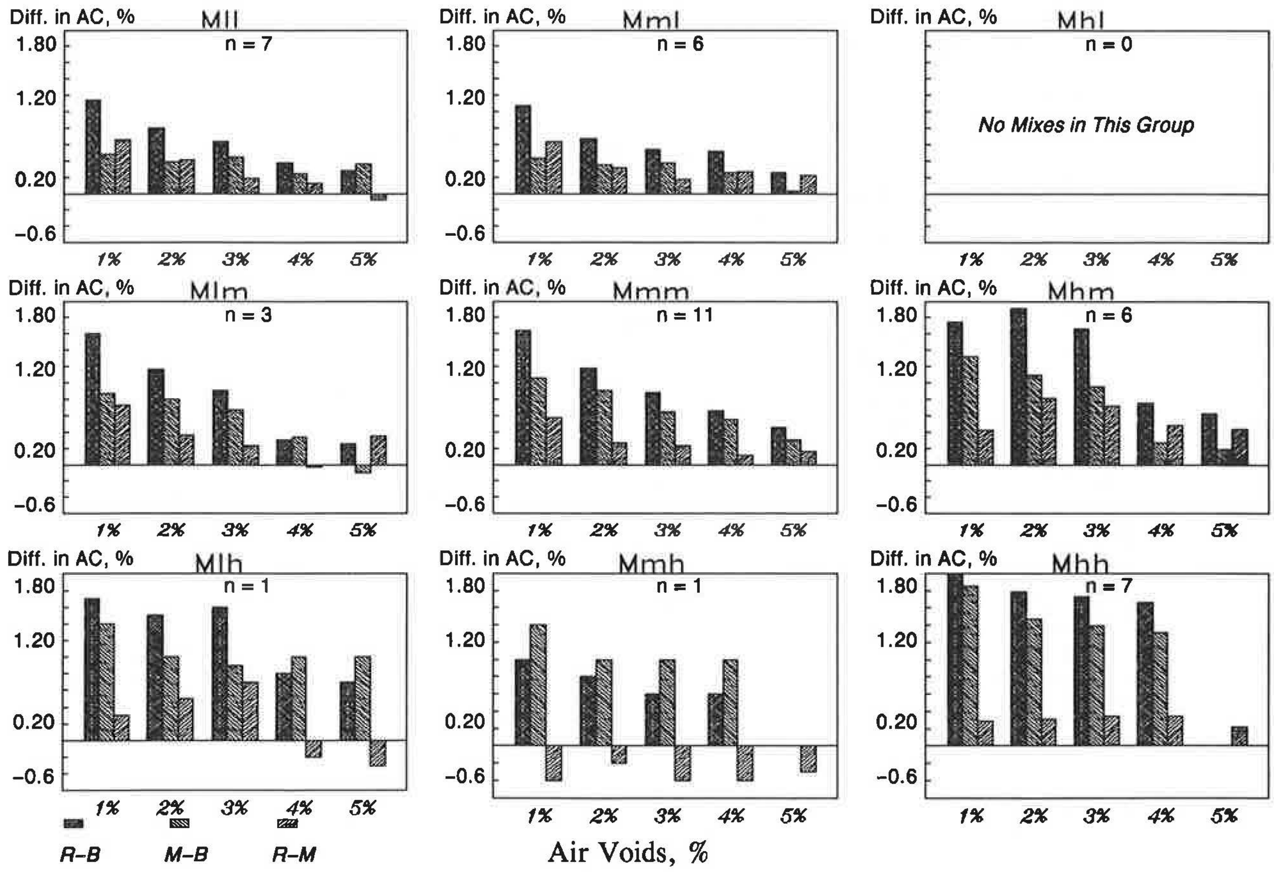

FIGURE 7 Comparison between AC percent determined for different *Gmm* methods (*B* = bulk, *M* = Martin, and *R* = Rice).

by either the Rice or Martin method. Results presented in Table 6 indicate the H_O cannot be rejected for all groups at a 1-percent significance level. Thus at a 1-percent significance level, both methods would be expected to yield a similar asphalt content at a designated level of air voids.

When significance levels were increased to 2 and 5 percent, chances for rejecting H_O became higher for mix groups with absorption characteristics. This indicates that whenever the asphalt absorption of aggregates is relatively high, results from the Rice and Martin methods tend to deviate significantly, whereas results tend to be closer for low-absorption mixtures.

No experimental work was performed to determine the fundamental reason for the observed differences. However, examination of technical literature (*10,12*) yielded a related

TABLE 5 OVERALL AVERAGE OF THE DIFFERENCE IN AC CONTENT

Parameter	Rice – Bulk	Martin – Bulk	Rice – Martin
N	167	174	201
Overall Average Diff. in AC %	1.204	0.874	0.354
Overall Std. Dev. Diff. in AC %	0.791	0.658	0.582

TABLE 6 STATISTICAL TEST ON THE SIGNIFICANCE OF THE DIFFERENCE IN AC CONTENT DETERMINED BY RICE AND MARTIN METHODS

Parameter for t-test	Designated Mix Group											
	[Mll]		n=7		[Mml]		n=6		[Mhl]		n=0	
Air Voids, %	4%		3%		4%		3%					
Difference in AC %	0.13		0.19		0.27		0.17					
t =	1.213		1.518		2.793		2.193					
t (cr) (1% S.L) =	4.032	A	3.707	A	4.032	A	4.032	A	No Mixes Available,			
t (cr) (2% S.L) =	3.365	A	3.143	A	3.365	A	3.365	A	t-test not applicable			
t (cr) (5% S.L) =	2.571	A	2.447	A	2.571	R	2.571	A				
	[Mlm]		n=3		[Mmm]		n=11		[Mhm]		n=6	
Air Voids, %	4%		3%		4%		3%		4%		3%	
Difference in AC %	-0.03		0.23		0.11		0.24		0.48		0.72	
t =	-0.184		0.819		2.794		2.277		2.185		2.090	
t (cr) (1% S.L) =	63.657	A	9.925	A	3.169	A	3.169	A	4.032	A	4.032	A
t (cr) (2% S.L) =	31.821	A	6.965	A	2.764	R	2.764	A	3.365	A	3.365	A
t (cr) (5% S.L) =	12.706	A	4.303	A	2.228	R	2.228	R	2.571	A	2.571	A
	[Mlh]		n=1		[Mmh]		n=1		[Mhh]		n=7	
Air Voids, %									4%		3%	
Difference in AC %									0.34		0.34	
t =									2.925		3.618	
t (cr) (1% S.L) =	Only ONE Mix,				Only ONE Mix,				3.707	A	3.707	A
t (cr) (2% S.L) =	t-test not applicable				t-test not applicable				3.143	A	3.143	R
t (cr) (5% S.L) =									2.447	R	2.447	R

Null Hypothesis (Ho) : There is no Difference Between AC% Determined by Either Rice Martin Method

Decision : Reject Ho if | t | > t (cr) A: Accept (Do not reject) R: Reject

comment. In the discussion following a 1957 paper (*13*), McLeod was asked to comment on the veracity of the Martin approach. He said:

> Experience tends to indicate that it would be very difficult, if not impossible, to expel all the air from some paving mixtures in spite of an appreciable excess of bitumen. If it is assumed that these mixtures contain no air, the values obtained for the effective specific gravity of the aggregate and for the bitumen absorbed by the aggregate will be in error by the amount of the entrapped air that actually remains in these compacted rich mixes.

McLeod's comment seems to offer the most plausible explanation for the observed differences: the volume of air that could not be displaced by increasing asphalt contents.

During placement of some of these mix designs, the impact of *Gmm* on quality control was accentuated. A serious failing of the Martin approach is that it only reflects mixture properties during the design phase. Properties of mixtures normally vary during construction. Use of this method will not account for normal fluctuation during production. Such variation in the specific gravity and absorption characteristics of aggregates will not be detected using an assumed *Gmm* from the mix design. The Rice method, performed on plant-produced materials, will detect this type of variation.

CONCLUSIONS

The Martin approach in determining *Gmm* is fundamentally sound. It rigorously addresses the issue of asphalt absorption during the mix-design phase. Because it only reflects mixture properties during the phase, however, the Martin method lacks applicability during plant quality control.

The Rice method resulted in about 0.35 percent more asphalt than did the Martin method. For mixtures with low absorption characteristics, the difference between the two methods was insignificant. The difference becomes more pronounced for mixtures with high absorption characteristics. The most likely cause of the difference is that it is impossible to saturate all air voids in a compacted specimen. The volume of air remaining in an assumed saturated sample will create an equal error in subsequent volumetric calculations.

The *Gmm* determined from the Rice method is dependent on time and absorption. Use of the oven-curing step inherent in the Martin approach was necessary to achieve accurate and precise values of *Gmm* from the Rice method.

The study revealed that caution should be exercised when mixes include absorptive aggregates. The aggregates should be permitted to absorb free asphalt before the test is conducted.

In 1989 and 1990, the Texas SDHPT began an extensive update of design procedures and specifications. During this process, it became apparent that use of the Rice method is desirable. SDHPT staff indicated that they believed the Rice method to be more precise as a mixture test. In addition, use of the Rice method to determine *Gmm* in the design phase was consistent with its use as a reference for in-place density control.

Many SDHPT districts and various cities and counties already have begun to use the Rice method. A phase-in period for all SDHPT districts will end in 1993. This will end formal use of the Martin method, which has been used by most agencies in Texas for more than 40 years.

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