Development of the Pressure Method for Determining Maximum Theoretical Specific Gravity of Bituminous Paving Mixtures

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The viability of using an air meter (Type B) for determining the maximum theoretical specific gravity (MTSG) of asphalt mixtures was evaluated. The air meter normally has been used for determining the percentage of air in fresh portland cement concrete. A series of experiments were performed using this new method (herein called the "pressure method") and the current standard (Rice) method. The primary experiment involved determining MTSG by two methods on 10 asphalt mixtures with varying asphalt contents. There was good correlation and no significant difference in the performance or precision between the two methods. There was little difference in obtaining the optimum asphalt content by the two methods. The results of the additional experiments with aggregates from three different sources indicated no difference in precision between methods or operators. Suggestions were made for modifying and improving the air meter for pressure method testing, to add versatility in the options for determining the MTSG of asphalt mixtures (and other materials of a porous or water-absorbent nature).

The maximum theoretical specific gravity (MTSG) of asphalt concrete (AC) is the specific gravity at which zero air voids are present in the mixture (*1,2*). MTSG is one of the most important properties of an asphalt mixture; not only does it provide an upper limit for the possible compaction in the field, but its determination is also critical in later computing the voids in the compacted asphalt pavement (*3,4*). MTSG is also used in the computation of voids filled with asphalt (VFA), which is a measure of asphalt cement coating on the mineral aggregate. These two parameters play important roles in determining engineering properties of asphalt mixtures and in evaluating potential for pavement distress modes such as raveling, shoving, rutting, flushing, and cracking.

In addition, the Marshall method of asphalt mix design requires that the optimum asphalt content (OAC) be found using the voids criteria, among others, which require the determination of the MTSG.

Proper and precise determination of the MTSG is important in the asphalt mix design procedure and in evaluating performance of asphalt pavements, which make up approximately 70 percent of the nation's highway system.

The current experimental method is the Rice method (AASHTO T-209 and ASTM D2041–78), which uses a volumetric flask, vacuum apparatus, and water (see Figure 1). The Rice method is primarily a displacement method in which a known mass of prepared asphalt mixture is introduced into an empty flask of known volume, which is then filled with water. Air entrapped within the asphalt and water mixture in the flask is expelled by a vacuum. The MTSG is then calculated by computing the displaced volume of water. All of the air is not expelled during the application of the vacuum, possibly because of the affinity of air for the asphaltic compounds in the mixture. The new method does not have this problem, because the entrapped air is accounted for in the computation.

The new method, herein called the "pressure method," makes use of the Type B air meter (AASHTO T-152-82 and ASTM C231-80), which works on the principle of Boyle's law, i.e., the operational principle of this meter consists of equalizing a known volume of air at a known pressure in a sealed air chamber with an unknown volume of air in the sample of asphalt mixture and water. The dial on the pressure gauge is calibrated in terms of percent of air for the observed pressure at which equalization takes place (see Figure 2).

In the pressure method, a weighed sample of prepared asphalt mixture is introduced into the bowl of the air meter, and the meter is filled to capacity with water. No attempt is made to remove any entrapped air. The filled air meter is weighed, and the weight of water obtained. The air content of the meter is then determined in accordance with the method in AASHTO T-152. Back calculations are performed and the volume of the sample of asphalt mixture is found. The MTSG is then the weight in grams of the sample divided by its volume in cubic centimeters.

The objectives of this study were

1. Evaluation of the viability of the pressure method to determine MTSG (Experiment 1),
2. Confirmation of the viability of the method using various types of aggregates from three different sources (Experiment 2), and
3. Verification of the precision and repeatability of the pressure method (Experiments 3A and 3B).

EXPERIMENTAL PROGRAMS

Experimental programs included the sampling and processing of the aggregates (both coarse and fine), producing the asphalt

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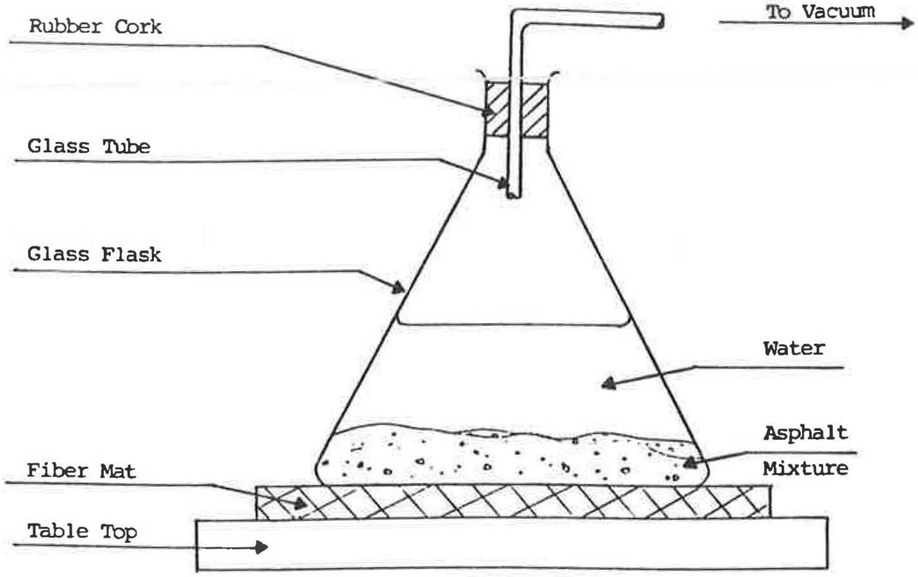

FIGURE 1 Schematic diagram of the experimental setup for the Rice method.

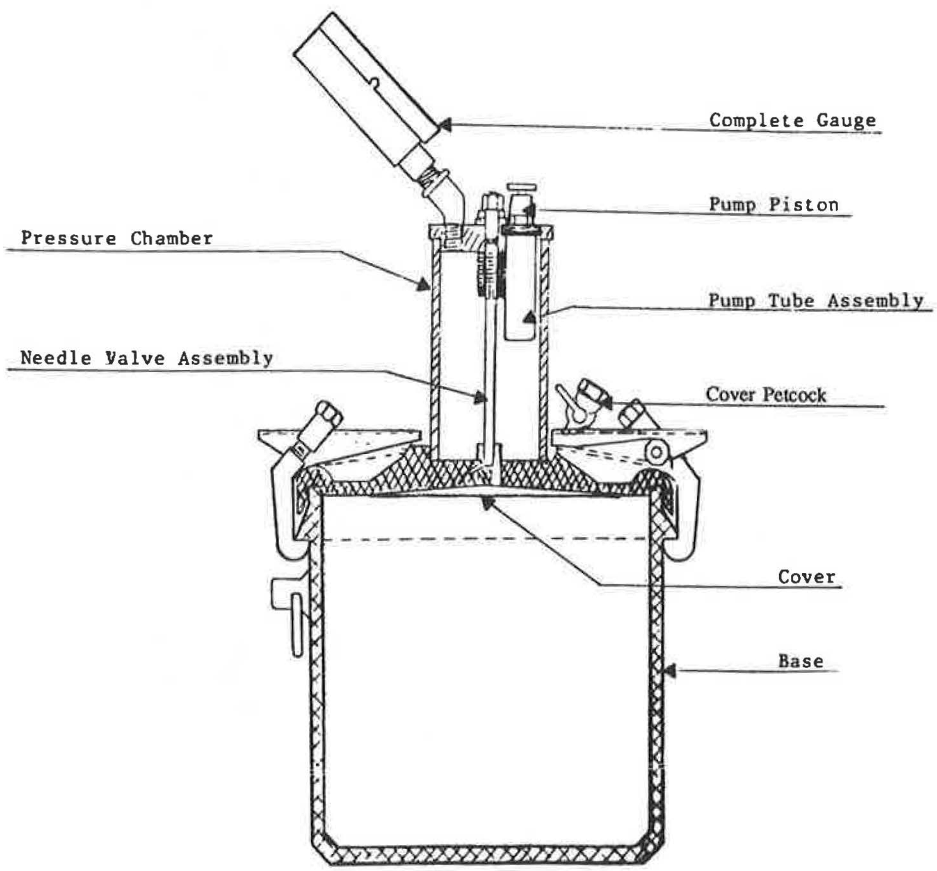

FIGURE 2 A cross section of an air meter indicating main components.

mixtures, fabrication of Marshall core specimens when required, testing of specimens, comparative analysis of the methods used, and drawing conclusions.

Materials

Mineral Aggregates

Coarse aggregates from three local suppliers were used. Two of the aggregate sources were of fine-grained, trap rock with low absorption characteristics. The other source was a crushed gravel, which also had low absorption characteristics (see Table 1). The aggregates were sieved into their individual sizes. The fine aggregates consisted of crushed-stone and natural sand; their characteristics are presented in Table 2. The aggregates were sieved into individual-sized fractions as presented in Column C of Table 3. Both crushed and fine aggregates were blended to have the gradation of Rhode Island Class I–1 standard-surface course mix with a maximum size of ¾ in.

For Experiment 1, aggregates were obtained from one supplier and sieved into individual sizes in sufficient quantity to produce enough material for 10 sets of cores. For Experiment 2, aggregates were obtained from three different suppliers and sieved into individual sizes in sufficient quantity to produce enough material for 4 sets of cores.

Asphalt Cement

AC–20 from a single source was used; it was obtained in a number of quart-sized containers.

Plant Asphalt Hot-Mix

In conducting Experiment 3, a production mix from one of the three suppliers, consisting of the same class of asphalt mixture, i.e., Class I–1 surface course, was used.

TABLE 1 PHYSICAL PROPERTIES OF COARSE AGGREGATE

Aggregate Supplier	Apparent Specific Gravity	Absorption (percent)	Unit weight (lbs./ cu. ft.)	Bulk Specific Gravity
Gammino Inc.	2.757	1.10	102.90	2.674
Forte Bros.	2.789	0.97	100.73	2.715
Cardi Corp.	2.668	1.16	94.80	2.588

TABLE 2 PHYSICAL PROPERTIES OF FINE AGGREGATE

Aggregate Supplier	Apparent Specific Gravity	Absorption (percent)	Unit Wt. (lbs./ cu. ft.)	Bulk Specific
Gammino Inc.	2.738	1.10	117.14	2.659
Forte Bros.	2.777	0.45	119.10	2.750
Cardi Corp.	2.668	0.71	121.9	2.618

TABLE 3 GRADATION OF RHODE ISLAND CLASS I-1 MIX FOR SURFACE COURSE

(A) Sieve Opening	(B) Percent Passing	(C) Aggregate Size	(D) Percent of Individual Size
3/4"	100.0	3/4" - 1/2"	10.0
1/2"	90.0	1/2" - 3/8"	10.0
3/8"	80.0	3/8" - #4	20.0
#4	60.0	#4 - #8	17.5
#8	42.5	#8 - #30	19.0
#30	23.5	#30 - #50	5.5
#50	18.0	#50 - #100	6.0
#100	12.0	#100 - #200	6.5
#200	5.5	passing #200	5.5

Testing Programs

Experiment 1

Asphalt cores were made by combining the coarse and fine aggregate together with the AC. In 10 different sets of four cores each, the asphalt content values were, 4.0, 4.3, 4.6, 4.9, 5.2, 5.5, 5.8, 6.1, 6.4, and 6.7 percent. The bulk specific gravity was determined for each set of cores according to Method B of AASHTO T-166. The cores were then tested for stability and flow according to Sections 4 and 5 of AASHTO T-245.

Preparation of Samples. The four cores of the set were heated in an oven at 105°C to remove traces of moisture and to separate the particles of the sample as described in the Rice method procedures. The separated sample was then split into two portions, with the portion for the Rice method weighing approximately 1,500 to 1,600 g.

Rice Method. The MTSG was determined according to the Rice method procedure (AASHTO T-209, Section 6.7, Flask Determination). This sample portion was then retained, air-dried, and rerun to obtain a second result. The average of two results was taken for analysis and comparison.

Pressure Method. The MTSG was determined for the second portion of samples according to the following procedures:

1. The air meter to be used was cleaned, calibrated, and weighed. The initial air line was determined before commencement of the experiment.
2. The volume of the air meter was ascertained by filling the bowl with distilled water and introducing additional water into the petcocks until overflow occurred. The temperature of the water was noted, as well as the weight of the air meter filled with water. From the differences in weight, the amount of water required to fill the meter was determined. Then, using the temperature correction factor for the water, the volume of the air meter was calculated to the nearest 0.1 mL. The water was then discarded, and the meter was dried completely.
3. The sample was weighed accurately in the dry bowl of the meter to the nearest 0.1 g.
4. Distilled water was introduced to the bowl with the sample, and the bowl was agitated by tapping on the sides to expel large air bubbles.
5. The top of the meter was then placed securely to the bowl, and additional water was inserted through the petcocks until overflow occurred.
6. The pump was primed until the needle rested on the initial pressure line.
7. The petcocks were closed, and the meter was wiped dry so as not to leave any overflow water on the outside.
8. The air meter, water, and sample were then weighed to the nearest 0.1 g.
9. The air valve was opened to equalize the pressure between the chambers, and the percentage of air was read on the dial (AASHTO T-152, Section 7.3).
10. This procedure was repeated twice to obtain two more air percentage readings.
11. The pressure was then released, and the temperature of the water in the meter was recorded.
12. The sample was saved, air-dried, and retained to obtain the second set of air percentage readings.
13. The MTSG was calculated with temperature correction. The reported MTSG was then the average of the three results. A form for determination of specific gravity by the pressure method is shown in Figure 3.

Air Meter #:______________ Date:__________

Balance #: ______________ Name of Tester:________

Sample # & I.D.:__________ Sampled By:___________

<u>Test Procedure</u>

1) Wt. of Air Meter (dry) ________ gms.

2) Wt. of Air Meter & Asphalt Sample ________ gms.

2b) (zero or tare the balance)

	Run 1	Run 2	Run 3	
2c) (fill meter with water)				
3) Wt. of Water in Meter				gm
4) Temp. of Water				°C
4b) (correction factor F)				
5) Air Reading (percent)				

6) Wt. of Air Meter & Water (full) ________ gms.

<u>Calculations</u>

	Run 1	Run 2	Run 3	
7) Vol. of Air Meter [(6)-(1)]/(4b)				ml
8) Vol. of Water in Air Meter (3)/(4b)				ml
9) Vol. of Air (5)X(7)/100%				ml
10) Wt. of Asphalt Mix (2)-(1)				gm
11) Vol. of Asphalt (7)-(8)-(9)				ml
12) Specific Gravity [(10)/(11)]/(4b)				

Maximum Specific Gravity of Mix (Avg. of Runs) = ______

FIGURE 3 A form for the determination of specific gravity by the pressure method.

Experiment 2

Aggregate materials from three different suppliers were obtained and processed. Asphalt mix designs for the standard RI Class I–1 mix were made for each of the materials, using the Marshall method. Four sets of four cores were made for each mix design at asphalt contents of 5.0, 5.5, 6.0, and 6.5 percent. The average bulk specific gravity for each set was determined. The cores were then tested (AASHTO T-245) and each set of cores was dried and prepared (AASHTO T-209). The tests were performed by both the Rice and pressure methods and repeated after the samples were thoroughly air-dried.

The mix design results were plotted for each of the three different mixes, and a voids analysis was carried out using the MTSG obtained by the Rice and pressure methods. Comparative analysis of results determined the following:

- Confirmation of viability of the pressure method and results obtained in Experiment 1, and
- Any significant impact on the mix design (i.e., whether the OAC values were more or less the same).

Experiment 3

Experiment 3A. A standard RI Class I–1 production mix sample was obtained weighing approximately 100 kg and prepared as previously (*1*). This production sample was then subdivided into 17 lots using a sample splitter. Each lot was further divided to provide two test samples, of approximately 1,500 to 1,600 g for the Rice method and of approximately 3,400 to 3,500 g for the pressure method.

The samples for this series of 17 dual tests were run only once with the following stipulations:

- The tests were run on two different sets of apparatuses for both methods,
- Two operators were interchanged midway during the test programs, and

- The two methods were run simultaneously on the same day and within 1 hr of each other.

Experiment 3B. Two out of 17 subsamples were tested repeatedly (eight times) following the same test procedures as described previously, except that the operators were not interchanged; each test method had a unique operator.

RESULTS

Experiment 1

The results of Experiment 1 are presented in Table 4, and further analysis was carried out, as follows:

- Statistical Comparison. A statistical comparison of the results obtained by the two methods indicated that there was no significant difference in performance between the Rice and pressure methods. Figure 4 shows a comparison of MTSG results from these methods.
- Precision. The analysis did not detect a difference in precision between the two methods.
- Sensitivity. The Rice method was more sensitive to the change in asphalt content because as the asphalt content increased, the MTSG of the mix decreased at a relatively uniform rate. For the pressure method, the MTSG did not always decrease at a uniform rate with increase of asphalt content (see Figure 5).
- Marshall Mix Design. The difference in the OAC values determined by the air voids obtained by the Rice and pressure methods was about 0.1 percent.

Experiment 2

Table 5 presents three suppliers of aggregates, asphalt content of each of the mixes, calculated MTSG, two Rice method results, two pressure method results, and the average of results. Further analysis was performed as follows:

- Average Values. The average values of the MTSG obtained by the Rice and pressure methods were within 0.08 percent of each other. The calculated average value for the MTSG was 0.8 percent lower than for the other methods. Table 6 presents the voids analysis for the mix design by calculation, Rice, and pressure methods.
- Standard Deviations. The standard deviation for the calculated MTSG was lower than that for the Rice and pressure methods. The standard deviations for the Rice and pressure methods were of the same magnitude.
- Performance. No difference in performance was detected from individual Rice method runs, individual pressure method runs, or runs between two methods (see Table 7).
- Correlation. There was good correlation between the three methods (see Table 7).
- Mix Design. Figure 6 shows a typical Marshall properties plot for one of the three different mixes used to determine OAC values. The OAC value determined by the three methods did not vary by more than 0.1 percent.

Experiment 3A

Tables 8 and 9 present the subsamples, operators, apparatus, and MTSG obtained by the Rice and pressure methods,

TABLE 4 MTSG OF BITUMINOUS MATERIALS—RESULTS OF RICE AND PRESSURE METHODS FOR EXPERIMENT 1

a) Results of Rice Method

Day	AC (%)	Rice Method Run1	Run2	Avg.	d_{1-2}
1	4.0	2.553	2.552	2.553	0.001
2	4.3	2.574	2.570	2.572	0.004
3	4.6	2.561	2.559	2.560	0.002
4	4.9	2.545	2.542	2.544	0.003
5	5.2	2.542	2.539	2.541	0.003
6	5.5	2.521	2.522	2.522	-0.001
7	5.8	2.519	2.519	2.519	0.000
8	6.1	2.504	2.505	2.505	-0.001
9	6.4	2.494	2.495	2.495	-0.001
10	6.7	2.493	2.491	2.492	0.002

Note: d_{1-2} = Result of Run 1 - Result of Run 2

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TABLE 4 (*continued*)

b) Results of the Pressure Method

Day	AC (%)	Pressure Method			
		Run1	Run2	Avg.	d_{1-2}
1	4.0	2.565	2.563	2.564	0.002
2	4.3	2.566	2.567	2.567	-0.001
3	4.6	2.549	2.548	2.549	0.001
4	4.9	2.555	2.552	2.554	0.003
5	5.2	2.525	2.524	2.525	0.001
6	5.5	2.520	2.530	2.525	-0.010
7	5.8	2.528	2.528	2.528	0.000
8	6.1	2.517	2.510	2.514	0.007
9	6.4	2.502	2.503	2.503	-0.001
10	6.7	2.494	2.493	2.494	0.001

Note: d_{1-2} = Result of Run 1 - Result of Run 2

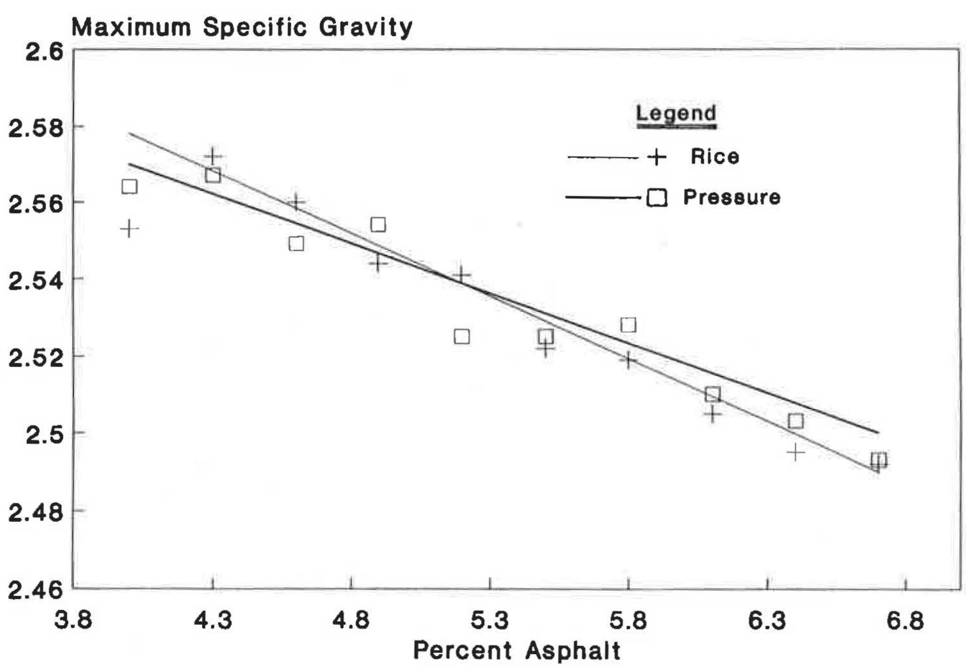

FIGURE 4 Maximum specific gravity versus asphalt content for Experiment 1.

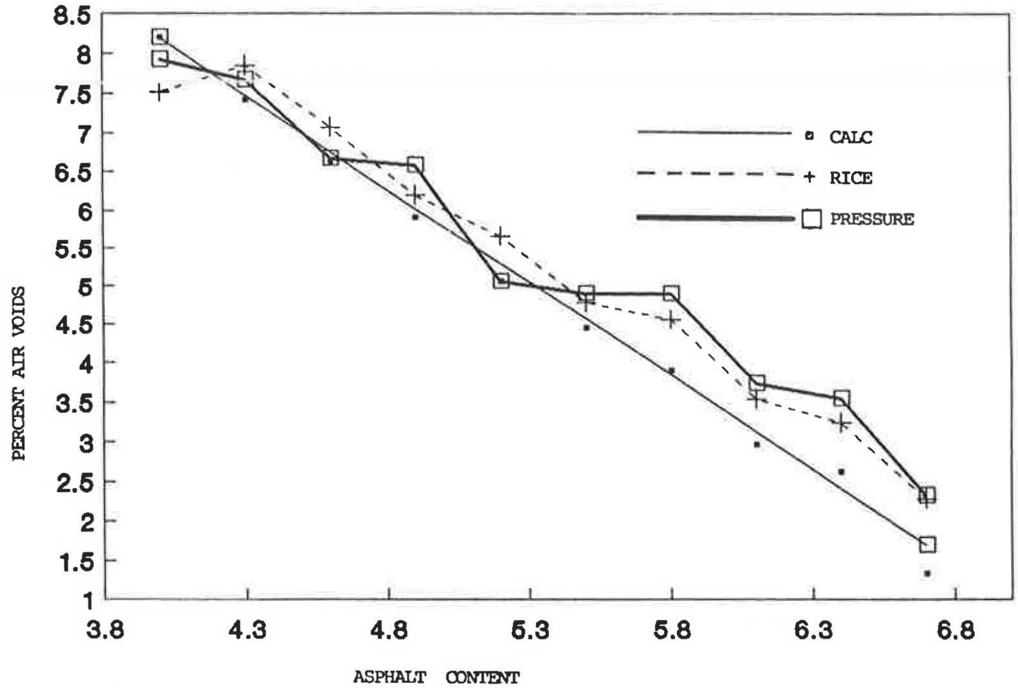

FIGURE 5 Total air voids versus asphalt content using the three different methods for Experiment 1.

TABLE 5 TESTING RESULTS OF RICE AND PRESSURE METHODS FOR EXPERIMENT 2

a) Results of Rice Method

Supplier	AC (%)	Calc.	Rice			
			FL	R1	R2	Avg. R
Cardi	5.0	2.470	II	2.445	2.439	2.442
	5.5	2.452	I	2.450	2.434	2.442
	6.0	2.434	II	2.421	2.421	2.421
	6.5	2.417	I	2.419	2.419	2.419
Forte	5.0	2.567	II	2.572	2.562	2.567
	5.5	2.547	I	2.547	2.542	2.545
	6.0	2.527	II	2.525	2.551	2.538
	6.5	2.508	I	2.527	2.531	2.529
Gammino	5.0	2.532	II	2.591	2.592	2.592
	5.5	2.513	I	2.583	2.575	2.579
	6.0	2.494	II	2.562	2.570	2.566
	6.5	2.475	I	2.553	2.544	2.549
n		12		12	12	12
$\bar{x}$		2.495		2.516	2.515	2.516
s		0.0462		0.0645	0.0662	0.0651

Notes: FL = Flask number. R1 = Results of Run 1.
R2 = Results of Run 2.

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TABLE 5 (*continued*)

b) Results of Pressure Method

Supplier	AC (%)	Calc.	Pressure			
			FL	P1	P2	Avg. P
Cardi	5.0	2.470	II	2.452	2.452	2.460
	5.5	2.452	I	2.441	2.421	2.431
	6.0	2.434	II	2.423	2.409	2.416
	6.5	2.417	I	2.415	2.404	2.410
Forte	5.0	2.567	II	2.578	2.566	2.572
	5.5	2.547	I	2.591	2.569	2.580
	6.0	2.527	II	2.544	2.522	2.533
	6.5	2.508	I	2.528	2.511	2.520
Gammino	5.0	2.532	II	2.525	2.601	2.563
	5.5	2.513	I	2.576	2.570	2.573
	6.0	2.494	II	2.603	2.548	2.576
	6.5	2.475	I	2.536	2.530	2.533
n		12		12	12	12
$\bar{x}$		2.495		2.518	2.510	2.514
s		0.0462		0.0678	0.0686	0.0664

Notes: FL = Flask number. P1 = Results of Run 1.
P2 = Results of Run 2.

TABLE 6 MIX DESIGN VOIDS ANALYSIS FOR EXPERIMENT 2

Spec. Set No.*	Asphalt Content (%)	Bulk S.G.	Theoretical Spec. Gravity		
			Calc. Method	Rice Method	Pressure Method
A1	5.0	2.371	2.471	2.442	2.460
A2	5.5	2.382	2.453	2.442	2.431
A3	6.0	2.382	2.436	2.421	2.417
A4	6.5	2.382	2.418	2.419	2.410
B1	5.0	2.483	2.570	2.567	2.572
B2	5.5	2.476	2.550	2.545	2.572
B3	6.0	2.486	2.531	2.538	2.533
B4	6.5	2.487	2.511	2.529	2.520
C1	5.0	2.460	2.534	2.592	2.563
C2	5.5	2.486	2.515	2.579	2.573
C3	6.0	2.493	2.496	2.566	2.576
C4	6.5	2.500	2.472	2.549	2.533

Spec. Set No.*	Asphalt Content (%)	Bulk S. G.	Total Voids in Mix		
			Calc. Method	Rice Method	Pressure Method
A1	5.0	2.371	4.05	2.91	3.62
A2	5.5	2.382	2.89	2.46	2.02
A3	6.0	2.382	2.22	1.61	1.45
A4	6.5	2.382	1.49	1.53	1.16
B1	5.0	2.483	3.38	3.27	3.46
B2	5.5	2.476	2.90	2.71	4.03
B3	6.0	2.486	1.78	2.05	1.86
B4	6.5	2.487	0.96	1.67	1.31
C1	5.0	2.460	2.92	5.09	4.02
C2	5.5	2.486	1.15	3.61	3.38
C3	6.0	2.493	0.12	2.84	3.22
C4	6.5	2.500	-0.93	1.92	1.30

* A - Cardi, B - Forte, C - Gammino

Note: Cardi, Forte, and Tilcon Gammino were the three aggregate suppliers used in this study.

TABLE 7 COMPUTATIONS FOR PERFORMANCE ANALYSIS FOR EXPERIMENT 2

Supplier	AC	R1-R2	P1-P2	R-P	R-C	P-C
Cardi	5.0	0.0060	-0.0150	-0.0175	-0.0280	-0.0105
	5.5	0.0160	0.0200	0.0110	-0.0100	-0.0210
	6.0	0.0000	0.0140	0.0050	-0.0130	-0.0180
	6.5	0.0000	0.0110	0.0095	0.0020	-0.0075
Forte	5.0	0.0100	0.0120	-0.0050	0.0000	0.0050
	5.5	0.0050	0.0220	-0.0355	-0.0025	0.0330
	6.0	-0.0260	0.0220	0.0050	0.0110	0.0060
	6.5	-0.0040	0.0170	0.0095	0.0210	0.0115
Gammino	5.0	-0.0010	-0.0760	-0.0285	0.0595	0.0310
	5.5	0.0080	0.0060	0.0060	0.0660	0.0600
	6.0	-0.0080	0.0550	-0.0095	0.0720	0.0815
	6.5	0.0090	0.0060	0.0155	0.0735	0.0580
n		12	12	12	12	12
$\bar{x}_d$		0.0013	0.0078	0.0019	0.0210	0.0191
s_d		0.0109	0.0309	0.0167	0.0367	0.0336
u		0.0069	0.0196	0.0106	0.0233	0.0213
Difference in Performance		No	No	No	No	No

Note: R indicates results of Rice Method
P indicates results of Pressure Method
C indicates results of Calculation Method

If $|\bar{x}_d|<u$, a difference in performance is not indicated.

respectively. The statistical analysis of the results is presented in Tables 10 and 11.

- Average Value. The difference in the average MTSG values between the two methods was 0.14 percent.
- Standard Deviation. The standard deviation of the MTSG for the pressure method was greater than that for the Rice method.
- Performance. No significant difference in performance between the two methods (see Table 10) was discernable.
- Precision. The analysis detected a difference in precision between the two methods. Though the Rice method was more precise, the difference was not significant (see Table 11).

Experiment 3B

Tables 12 and 13 present results of the single-operator precision study for better methods. Further analysis was carried out as follows:

- Average Values. The differences in average MTSG values for samples 2R and 13R were 0.21 and 0.25 percent, respectively.
- Standard Deviation. The standard deviation for the pressure method was greater than for the Rice method.
- Precision. The statistical analysis did not detect any difference in the precision between the two methods or between the four sets of tests, i.e., 2R, 13R, 2A, and 13A (see Table 14 and the Appendix).

DISCUSSION OF RESULTS

Comparison for the Time and Performance

The Rice method is simple, but needs a laboratory setup primarily because of the necessity of a vacuum. Relatively easy to perform, the Rice method requires a moderate amount of technique to obtain good consistency. It has a 15-min actual run time for the expulsion of air from the flask and requires an additional 5 to 10 min to prepare the weighing of the sample and water in the flask. Should the method need to be repeated, 20 to 25 min would be added. Generally, one run of the test after sample preparation takes between 25 and 30 min.

The pressure method requires the use of a calibrated air meter and balance accurate to 0.1 g. This method does not require a laboratory setup and could be easily used in the field, making it a versatile method for computing the MTSG of an asphalt mix. It is relatively easy to perform and does not require much skill, except that care should be taken to ensure that the weights and temperatures are recorded accurately.

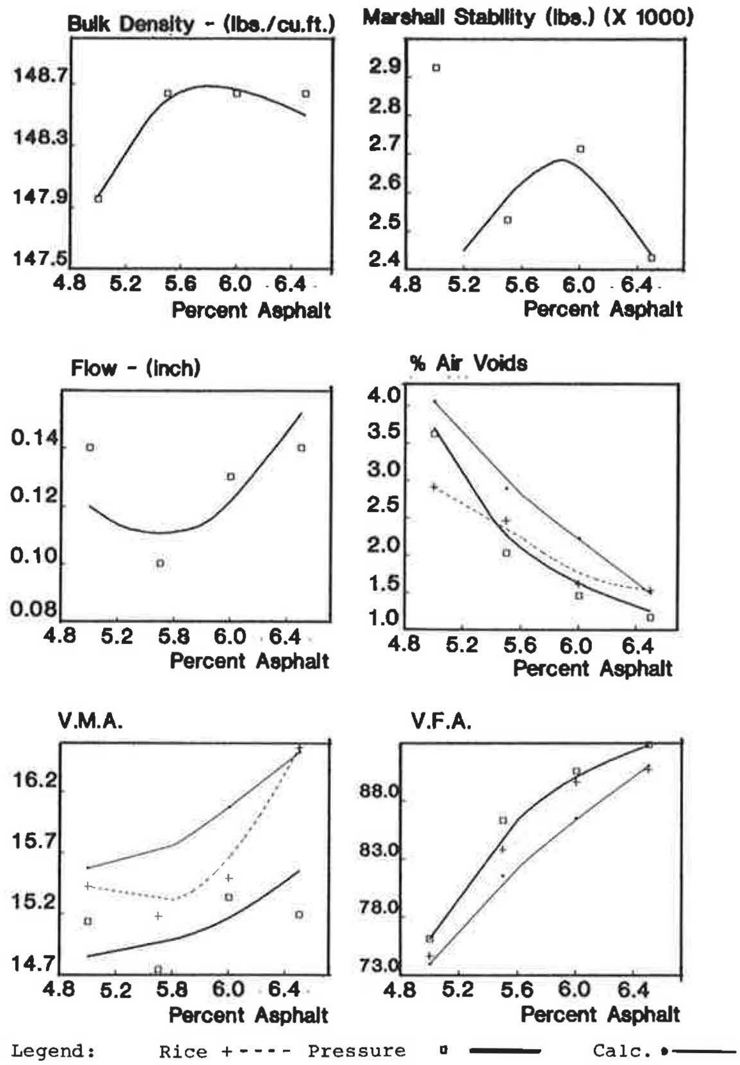

FIGURE 6 A typical Marshall mix design plot for the Cardi mix for Experiment 2.

TABLE 8 OVERALL PRECISION ANALYSIS FOR THE RICE METHOD FOR EXPERIMENT 3A

Sample	Operator	Date	Flask	Specific Gravity
1	1	10-31-88	II	2.492
2		10-31-88	I	2.481
3		10-31-88	II	2.485
4		10-31-88	I	2.493
5		11-01-88	II	2.506
6		11-01-88	I	2.482
7		11-01-88	II	2.472
8		11-02-88	I	2.492
9		11-04-88	II	2.488
10		11-04-88	I	2.496
11	2	11-07-88	II	2.482
12		11-07-88	I	2.479
13		11-09-88	I	2.389*
14		11-09-88	II	2.499
15		11-09-88	I	2.489
16		11-10-88	II	2.491
17		11-10-88	I	2.505

Note: Samples with 6% asphalt content from Forte (supplier) were divided into 17 subsamples.

Note: Sample No. 13 is an outlier. Therefore sample No. 13 was not included in computation.

TABLE 9 OVERALL PRECISION ANALYSIS FOR THE PRESSURE METHOD FOR EXPERIMENT 3A

Sample	Operator	Date	Meter	Readings 1	2	3	Average
1	2	10-31-88	F947	2.491	2.486	2.486	2.488
2		10-31-88	F947	2.449	2.446	2.450	2.448
3		10-31-88	F947	2.476	2.475	2.477	2.476
4		11-01-88	F947	2.493	2.492	2.485	2.490
5		11-01-88	F947	2.509	2.481	2.508	2.499
6		11-01-88	F947	2.484	2.482	2.486	2.484
7		11-02-88	F947	2.481	2.478	2.475	2.478
8		11-02-88	F947	2.462	2.464	2.463	2.463
9		11-04-88	D676	2.487	2.489	2.488	2.488
10	1	11-04-88	D676	2.520	2.504	2.505	2.510
11		11-09-88	D676	2.490	2.486	2.485	2.487
12		11-09-88	D676	2.510	2.500	2.511	2.507
13		11-09-88	D676	2.494	2.488	2.487	2.490*
14		11-10-88	D676	2.504	2.505	2.502	2.504
15		11-10-88	D676	2.481	2.476	2.480	2.479
16		11-10-88	D676	2.487	2.483	2.483	2.484
17		11-14-88	D676	2.491	2.488	2.488	2.489

Notes: Samples were 6 percent asphalt content from Forte supplies and were divided into 17 subsamples.
Sample No. 13 is an outlier. Therefore sample No. 13 was not included in computation.

TABLE 10 COMPUTATIONS FOR PERFORMANCE ANALYSIS FOR EXPERIMENT 3A

Sample	Rice	Pressure	$x_d = x_A - x_R$
1	2.492	2.488	-0.004
2	2.481	2.448	-0.033
3	2.485	2.476	-0.009
4	2.493	2.490	-0.003
5	2.506	2.499	-0.007
6	2.482	2.484	0.002
7	2.472	2.478	0.006
8	2.492	2.463	-0.029
9	2.488	2.488	0.000
10	2.496	2.510	0.014
11	2.482	2.487	0.005
12	2.479	2.507	0.028
13	2.389*	2.490*	
14	2.499	2.504	0.005
15	2.489	2.479	-0.010
16	2.491	2.484	-0.007
17	2.505	2.489	-0.016
n	16	16	16
$\bar{x}$	2.490	2.486	-0.003625
s	0.00930	0.0158	0.01494
u			0.007959

$|x_d| < u$. Therefore, the pressure method does not differ from the Rice Method in performance.

Note 1: Forte sample with 6% binder was divided into 17 subsamples.

Note 2: Sample no. 13 is an outlier. Therefore, sample no. 13 was not included in computation.

The size and weight of the air meter with sample plus water (approximately 17 to 18 kg) could be a problem to an operator of slight build. The actual run time is approximately 5 to 7 min, including securing the top of the meter to the bowl, filling up the petcock with water, wiping the meter dry, pumping up the chamber and setting the needle to the initial pressure line, taking a reading, weighing the meter with the sample and water, and noting the temperature of the water. The repeated runs take approximately 4 to 5 min each, and the whole experiment can be accomplished in 15 to 20 min. Although this method is faster, it also reduces the potential for procedural error, because no agitation of the meter is required. (With the Rice method, the flask has to be agitated for 2 min every 15 ± 2 min).

The air meter should be accurately calibrated before beginning the experiment; otherwise, the results will be erroneous. For this project, the calibration was performed before the start of each series of experiments. The pressure method apparatus also is capable of rough handling because there are no delicate components. Hence, it is suitable for field use.

TABLE 11 STATISTICAL ANALYSIS RESULTS FOR OVERALL PRECISION FOR EXPERIMENT 3A

	Rice	Pressure
$\bar{x}$	2.490	2.486
s	0.00930	0.0158
s^2	8.64EE-5	2.49EE-4

F-Test for comparison of variances, $\alpha = 0.05$

$$F = \frac{s_P^2}{s_R^2} = \frac{2.49EE\text{-}4}{8.64EE\text{-}5} = 2.884$$

$F_{\alpha/2,15,15} = 2.86$

$F > F_{0.025,15,15}$. Therefore, the F-Test has detected a difference in precision. Pressure Method is less precise than the Rice Method.

Interpretation of Results

- Performance. The average values of the MTSG obtained by the two methods were in close agreement, inferring that implementation of the pressure method would be a viable alternative. Confirmed by the statistical analysis, there is no significant difference in performance between the two methods.
- Precision. The results and analysis also show that there was no significant difference in precision between the Rice method and the pressure method.
- Sensitivity. Experiment 1 indicated that the Rice method was more sensitive to change in asphalt content than the pressure method; the Rice method results were also more consistent than those of the pressure method.

TABLE 12 SINGLE OPERATOR PRECISION ANALYSIS FOR THE RICE METHOD FOR EXPERIMENT 3B

Operator	Sample	Date	Flask	Specific Gravity	
2	2R	11-10-88	I	2.483	$\bar{x}$ = 2.480
	2R	11-15-88	I	2.483	s = 0.00542
	2R	11-15-88	I	2.486	s^2 = 2.93EE-5
	2R	11-16-88	I	2.484	
	2R	11-17-88	II	2.477	
	2R	11-17-88	II	2.476	
	2R	11-18-88	II	2.471	
	13R	11-09-88	I	2.389*	Omitting the outlier value 2.389:
	13R	11-10-88	II	2.496	$\bar{x}$ = 2.501
	13R	11-15-88	II	2.494	s = 0.00505
	13R	11-15-88	II	2.498	s^2 = 2.55EE-5
	13R	11-16-88	I	2.508	
	13R	11-17-88	IV	2.505	Including the Value 2.389:
	13R	11-18-88	IV	2.502	$\bar{x}$ = 2.487
	13R	11-18-88	IV	2.503	s = 0.0398
					s^2 = 0.00159

Note: Forte samples 2R and 13R are from a larger sample of RI Class I-1 mixture with 6% binder content.

TABLE 13 SINGLE OPERATOR PRECISION ANALYSIS FOR THE PRESSURE METHOD FOR EXPERIMENT 3B

Oper-ator	Sam-ple	Date	Meter	Reading 1	Reading 2	Reading 3	Average Reading
1	2A	11-14-88	D676	2.478	2.477	2.475	2.477
	2A	11-17-88	F947	2.468	2.471	2.469	2.469
	2A	11-18-88	F947	2.485	2.480	2.488	2.484
	2A	11-21-88	F947	2.477	2.476	2.478	2.477
	2A	11-22-88	F947	2.488	2.486	2.484	2.486
	2A	11-22-88	F947	2.469	2.470	2.463	2.467
	2	11-23-88	f947	2.462	2.462	2.464	2.463
	13A	11-09-88	D676	2.494	2.488	2.487	2.490
	13A	11-17-88	F947	2.506	2.504	2.500	2.503
	13A	11-18-88	F947	2.493	2.492	2.491	2.492
	13A	11-21-88	F947	2.510	2.508	2.506	2.508
	13A	11-21-88	F947	2.494	2.498	2.493	2.495
	13A	11-22-88	F947	2.473	2.482	2.480	2.478
	13A	11-23-88	F947	2.496	2.497	2.494	2.496

Note: Forte sample 2R, 13R are from a larger sample of RI Class I-1 mixture with 6% binder content.

Note:

Sample	x	s	s^2
2A	2.475	0.00864	7.56ee-5
13A	2.495	0.00962	9.26ee-5
2A + 13A	2.485	0.136	1.84ee-4

TABLE 14 ANALYSIS FOR SINGLE OPERATOR PRECISION FOR EXPERIMENT 3B

Rice Method					
Operator	Sample	Repeat Runs	$\bar{x}$	s^2	#
1	2R	7	2.480	2.93EE-5	1
Flasks:	13R	7	2.501	2.55EE-5	2
I,II,IV	2R+13R	14	2.490	1.42EE-4	3

Pressure Method					
Operator	Sample	Repeat Runs	$\bar{x}$	s^2	#
2	2A	7	2.4751	7.56EE-5	4
Meters:	13A	7	2.4951	9.26EE-5	5
D676,F947	2A+13A	14	2.4851	1.84EE-4	6

Suggested Improvements for the Apparatus of the Pressure Method

Some improvements for the apparatus of the pressure method are as follows:

1. The air meter is a cumbersome piece of equipment weighing approximately 8.3 kg empty and approximately 17.5 kg filled. Reducing its size and weight would allow smaller samples to be taken and decrease the physical strain on the operator, making the testing effort much easier.

2. The air meter dial has a logarithmic scale running from 0 to 100 percent. In this experiment, the air percentage readings were in the range of 0 to 2 percent. It would be an improvement if the range of the air meter could be reduced to 0 to 5 percent, and spread out over the present scale. The intermediate graduations could also be given to the nearest 0.01 percent, which would increase the accuracy of the reading. Interpolation was used to determine the air percentage to the nearest 0.01 percent. This process is difficult because it is more natural to interpolate arithmetically than logarithmically.

3. The pressure-sensing mechanism consists of a curved, hollow tube connected to the air chamber at the open end, which deflects under change of pressure in the chamber. At the closed end, a ratchet system is connected to the spring dial, which then reads the air percentage in the chamber on a logarithmic scale. In order to obtain more consistent and precise readings, mechanical improvements to this system should be further investigated.

CONCLUSIONS AND RECOMMENDATIONS

The pressure method is a viable tool for the determination of the MTSG of asphalt mixture. With the current apparatus, the pressure method would be appropriate for use in the Marshall mix design procedures, acceptance testing, and as a rapid test method in the field. For research and where sophisticated evaluation of the MTSG of an asphalt mixture is desired, the Rice method could be used concurrently. The pressure method could also be used to determine the MTSG of materials that have an affinity for air when immersed in water, or have a porous structure from which all the free air would have to be expelled to determine the specific gravity, e.g., aggregates, porous concrete products, and bottom ash. This topic could undergo future research.

Efforts should also be made to improve the consistency and sensitivity of the air meter to attain greater precision in results. These efforts, which would require some research into mechanical aspects of the air meter, would be challenging for the mechanically inclined. In any case, the scope of the project will be broadened by soliciting other laboratories in the area to run MTSG tests by the pressure method so that interlaboratory results can be obtained and analyzed. The final goal is to have the pressure method accepted as an alternative to the Rice method for determining MTSG of asphalt mixtures.

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APPENDIX—THE *F*-TEST

To test the significance of variance differences; i.e., to test the null hypothesis $S_A^2 = S_B^2$:

$$F = S_A^2/S_B^2 \qquad \text{(A-1)}$$

where

S_A^2 = the larger variance estimate, $n - 1$ degrees of freedom,
S_B^2 = the smaller variance estimate, $n - 1$ degrees of freedom, and
α = 0.05, 95 percent confidence level.

$$S_1^2, S_2^2\text{: } F = \frac{2.93\text{EE} - 5}{2.55\text{EE} - 5} = 1.151 < F_{0.025,6,6} = 5.82 \qquad \text{(A-2)}$$

Therefore, no difference in precision.

$$S_5^2, S_4^2\text{: } F = \frac{9.26\text{EE} - 5}{7.56\text{EE} - 5} = 1.226 < F_{0.025,6,6} = 5.82 \qquad \text{(A-3)}$$

Therefore, no difference in precision.

$$S_4^2, S_1^2\text{: } F = \frac{7.56\text{EE} - 5}{2.93\text{EE} - 5} = 2.576 < F_{0.025,6,6} = 5.82 \qquad \text{(A-4)}$$

Therefore, no difference in precision.

$$S_5^2, S_2^2\text{: } F = \frac{9.26\text{EE} - 5}{2.55\text{EE} - 5} = 3.635 < F_{0.025,6,6} = 5.82 \qquad \text{(A-5)}$$

Therefore, no difference in precision.

$$S_6^2, S_3^2\text{: } F = \frac{1.84\text{EE} - 5}{1.42\text{EE} - 5} = 1.292 < F_{0.025,13,13} = 3.12 \qquad \text{(A-6)}$$

Therefore, no difference in precision.

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