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Evaluation of the Supplemental Procedure of the Maximum Specific Gravity Test for Bituminous Paving Mixtures

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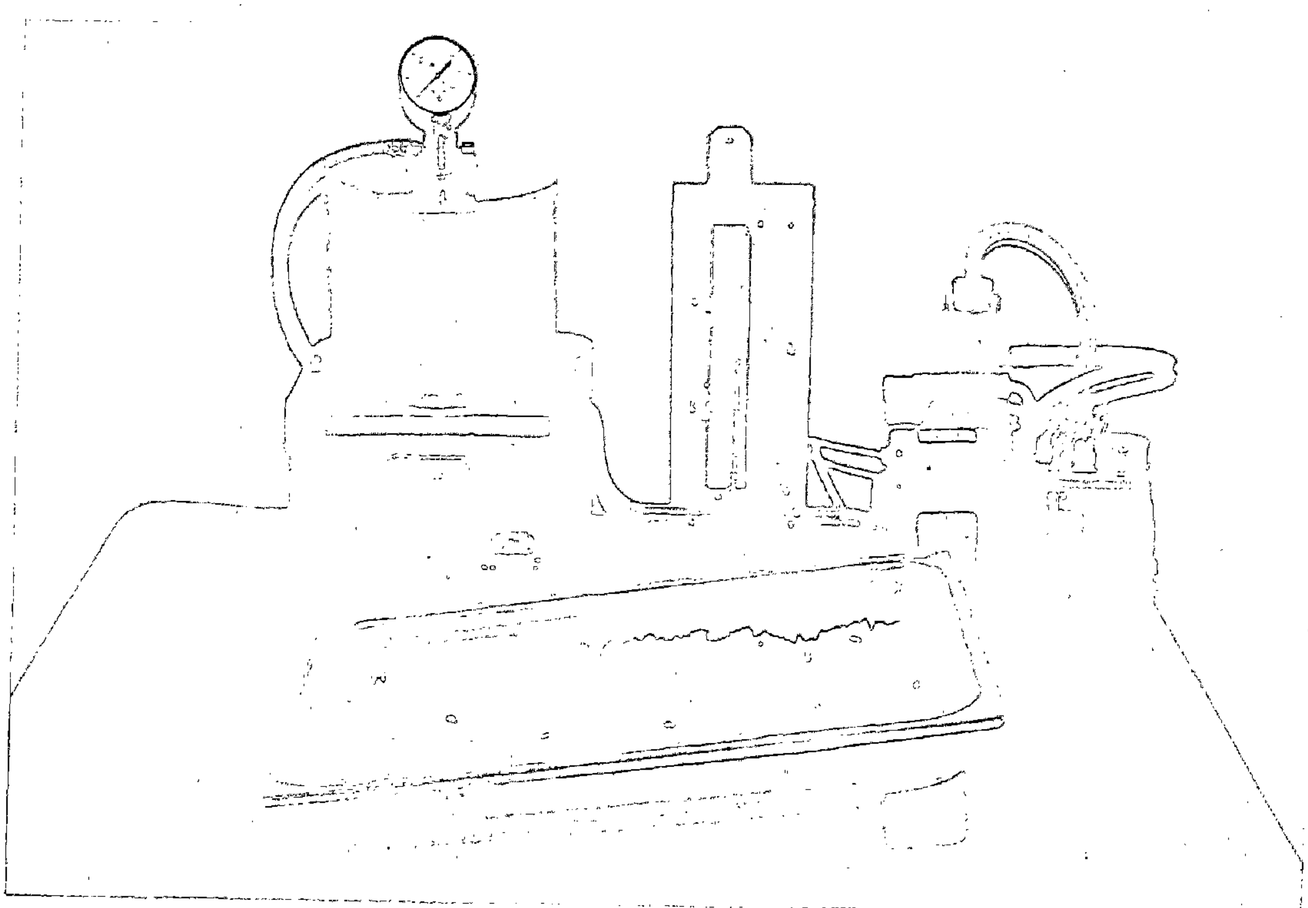

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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McLean, Virginia 22101-2296

FOREWORD

This report presents the findings of a staff research study to determine the effects of performing the supplemental procedure of AASHTO T 209 (or ASTM D 2041), entitled "Maximum Specific Gravity of Bituminous Paving Mixtures," on the percent air voids, effective aggregate specific gravity, and the maximum specific gravity of a bituminous paving mixture. The supplemental procedure provides a correction factor when testing mixtures containing absorptive aggregates which are not completely coated. This report will be of interest to individuals concerned with the mixture design and quality control testing of bituminous paving mixtures.

Sufficient copies of this report are being distributed to provide one copy to each FHWA regional office and division office and each State highway agency. Direct distribution is being made to the division offices. Additional copies for the public are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Thomas J. Pasko, Jr.
Director, Office of Engineering
and Highway Operations
Research and Development

NOTICE

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15. Supplementary Notes
This study was performed in the FHWA Bituminous Mixtures Laboratory located at the Turner-Fairbank Highway Research Center, McLean, VA. This laboratory is part of the Pavements Division, HNR-20.

16. Abstract
The objective of this study was to investigate the effects of performing the supplemental procedure of AASHTO T 209 (or ASTM D 2041) on the percent air voids, the effective aggregate specific gravity, and the maximum specific gravity of a bituminous paving mixture, using both thoroughly coated aggregates and partially coated aggregates. The supplemental procedure should correct the test data for water absorbed into the aggregate during the test. Although the supplemental procedure can be used when designing mixtures, it is most often used for determining the maximum specific gravities of moisture damaged pavement samples, or cores or specimens where sawing has exposed a significant amount of aggregate. The majority of aggregates used in this study had water absorptions below 2.5 percent and thus were not highly absorptive.

It is recommended that the supplemental procedure not be performed on laboratory mixtures or pavement cores having aggregates with water absorptions below 2.5 percent. When testing any mixture prepared in the laboratory during the mixture design process, the procedure for determining the maximum specific gravity should only be performed on well coated mixtures so that the supplemental procedure does not have to be used. For highly absorptive aggregates, it is recommended that the test only be performed at high binder contents which provide thick coatings. Only binder contents close to or slightly above the optimal binder content should be used. The maximum specific gravities for the lower binder contents can be calculated using the effective specific gravity of the aggregate. For laboratory mixtures containing highly absorptive aggregates, the supplemental procedure may indicate whether the coating is sufficient.

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Maximum specific gravity, Rice gravity, Effective specific gravity, Air voids, Asphalt mixtures, Asphalt mixture design, Asphalt absorption, AASHTO T 209, ASTM D 2041, Stripping	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

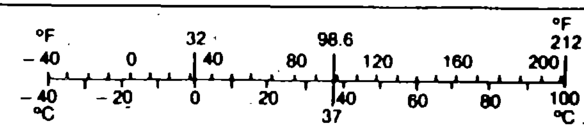
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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1. INTRODUCTION

When designing a bituminous mixture for highway pavements, the level of air voids in the compacted mixture is one of the most important factors controlling the amount of binder that will be used and the performance of the mixture. The maximum and bulk specific gravities of the mixture are used to calculate the level of air voids. The specific gravity of a material is the ratio of its mass per volume to the mass of an equal volume of water. Tests are performed at 77 °F (25 °C). Methods for measuring the maximum specific gravity (specific gravity of the uncompacted voidless mixture) are given in American Association of State Highway and Transportation Officials (AASHTO) T 209 (or American Society for Testing and Materials (ASTM) D 2041), while methods for measuring the bulk specific gravity (specific gravity of the mixture compacted to some air void level) are given in AASHTO T 166 (or ASTM D 2726).[1,2] AASHTO T 209 and ASTM D 2041 are also referred to as the Rice method. The percent air voids are calculated using AASHTO T 269 (or ASTM D 3203), which uses the following equation:

$$\text{Air Voids, \%} = 100(1-(\text{Bulk Specific Gravity}/\text{Maximum Specific Gravity})) \qquad (1)$$

To determine the maximum specific gravity of a mixture, the mass of the loose sample in air and the mass in water are needed. To determine the mass in water, the sample is first submerged in water and subjected to a partial vacuum to removed entrapped air. The mass of the sample in water is then determined and the maximum specific gravity is calculated by:

$$\text{Maximum specific gravity} = A/(A-C) \qquad (2)$$

A = mass of dry sample in air, g.
C = mass of sample in water, g.
A-C = mass of the volume of water displaced by the sample, g.

This equation is for the bowl method of determining the maximum gravity. Other equations, as given in AASHTO T 209 (or ASTM D 2041), apply if a flask or pycnometer is used. Conglomerations of the fine aggregate portion of the mixture must be separated to less than 1/4 in (6.4 mm) before the mixture is tested to facilitate the removal of air by the vacuum procedure.

The vacuum procedure may cause water to enter the aggregates if they are not thoroughly sealed. Because of this, the maximum gravity test contains a supplemental procedure to be performed on mixtures containing porous aggregates which are not completely coated. It is used to correct the volume of the sample for water which has entered the aggregate during the test by determining the saturated surface-dry mass of the sample. After determining the mass in air and the mass in water, the sample is dried by intermittently stirring it before an electric fan. The sample is weighed at 15-minute intervals until its loss in mass is less than 0.5 g for the interval (ASTM uses a loss in mass of less than 0.05 percent based on the mass of the sample). The supplemental procedure often requires 2 hours to complete, and is sometimes referred to as the dryback procedure. When the supplemental procedure is used, equation 2 becomes:

$$\text{Maximum specific gravity} = A/(B-C) \tag{3}$$

A = mass of dry sample in air, g.
B = mass of saturated surface-dry sample, g.
C = mass of sample in water, g.
B-C = mass of the volume of water displaced by the sample, g.

If the volume of the mixture is not corrected for the water absorbed by the aggregate; the percent air voids, the effective specific gravity of the aggregate, and the maximum specific gravity of the mixture will be high and incorrect. When designing a mixture, an erroneously high air void level will lead to extra binder being placed in the mixture and thus, possibly, rutting. Although the supplemental procedure can be used when designing mixtures, it is most often used for determining the maximum specific gravities of moisture damaged pavement samples, or cores or specimens where sawing has exposed a significant amount of aggregate.

The effective specific gravity of the aggregate, which is used to calculate the amount of binder absorbed by the aggregate in a mixture, is also obtained through the test method for maximum specific gravity. The effective specific gravity of the aggregate is the ratio of its mass per volume to that of water, where the volume of the aggregate includes the total volume of void space in the aggregate minus the void space filled with binder. An erroneously high effective specific gravity will indicate more binder is being absorbed than actually is being absorbed. Also, if the maximum specific gravity test is performed at only one binder content when designing a mixture, the effective aggregate gravity is one parameter used to calculate the maximum specific gravities for the other binder contents. Thus all maximum specific gravities used in a design could be in error.

2. OBJECTIVE

The objective of this study was to investigate the effects of performing the supplemental procedure on the percent air voids, the effective specific gravity of the aggregate, and the maximum specific gravity of a mixture, using both thoroughly coated aggregates and partially coated aggregates.

3. SCOPE

This study consisted of evaluating test results obtained under various staff studies over the past 9 years in the Federal Highway Administration's (FHWA's) Bituminous Mixtures Laboratory, located in McLean, VA. The test data are the original data from these studies for pavement cores and mixtures designed in the laboratory using the Marshall method. Additionally, new data were obtained by testing four moisture susceptible mixtures. These mixtures were prepared in the laboratory and partially stripped of binder to expose a high amount of aggregate surface.

The supplemental dryback procedure was performed on each mixture. The percent air voids, the effective specific gravity of the aggregate, and the maximum specific gravity of the mixture, with and without including the effects of the supplemental procedure, were calculated. All tests were performed in duplicate and the data averaged. The bowl method of determining the maximum specific gravity was used in every case.

4. TEST RESULTS - LABORATORY COMPACTED SPECIMENS

The data with and without the supplemental procedure for the samples prepared in the laboratory are given in table 1. Also included are the bulk

Table 1. Evaluation of AASHTO T 209 supplemental procedure using specimens compacted in the laboratory.

Mixture Description	Property	Without Procedure	With Procedure
1. Nebraska	Maximum S.G. of Mixture	2.491	2.487
	Effective S.G. of Aggregate	2.596	2.592
1980 staff study on	Air Voids, percent	3.3	3.2
Sulphlex - lab design	Aggr. Abs., percent = 0.44		
	Bulk S.G. of Mixture = 2.408		
	Binder, percent = 6.2 (Design = 5.4)		
2. Florida	Maximum S.G. of Mixture	2.446	2.363
	Effective S.G. of Aggregate	2.575	2.476
1980 staff study on	Air Voids, percent	8.4	5.2
Sulphlex - lab design	Aggr. Abs., percent = 3.68		
	Bulk S.G. of Mixture = 2.240		
	Binder, percent = 7.8 (Design = 8.0)		
3. Michigan	Maximum S.G. of Mixture	2.523	2.517
	Effective S.G. of Aggregate	2.661	2.654
1980 staff study on	Air Voids, percent	1.9	1.5
Sulphlex - lab design	Aggr. Abs., percent = 2.17		
	Bulk S.G. of Mixture = 2.477		
	Binder, percent = 7.5 (Design = Unknown)		
4. Texas	Maximum S.G. of Mixture	2.464	2.463
	Effective S.G. of Aggregate	2.600	2.598
1980 staff study on	Air Voids, percent	4.3	4.2
Sulphlex - lab design	Aggr. Abs., percent = 1.90		
	Bulk S.G. of Mixture = 2.359		
	Binder, percent = 8.0 (Design = 8.7)		
5. Stafford, AZ	Maximum S.G. of Mixture	2.430	2.394
	Effective S.G. of Aggregate	2.588	2.542
1980 staff study on	Air Voids, percent	4.7	3.2
Sulphlex - lab design	Aggr. Abs., percent = 2.48		
	Bulk S.G. of Mixture = 2.317		
	Binder, percent = 9.5		
6. Minot, ND	Maximum S.G. of Mixture	2.502	2.483
	Effective S.G. of Aggregate	2.692	2.667
1980 staff study on	Air Voids, percent	3.4	2.7
Sulphlex - lab design	Aggr. Abs., percent = 2.43		
	Bulk S.G. of Mixture = 2.416		
	Binder, percent = 10.1 (Design = 8.5)		
7. Grayson, GA	Maximum S.G. of Mixture	2.420	2.403
	Effective S.G. of Aggregate	2.630	2.607
1985 staff study on	Air Voids, percent	4.0	3.3
moisture damage tests	Aggr. Abs., percent = 0.31		
	Bulk S.G. of Mixture = 2.323		
	Binder, percent = 5.6 (Design = 5.65)		

Note: The percent binder is by weight of the mixture.

Table 1. Evaluation of AASHTO T 209 supplemental procedure using specimens compacted in the laboratory (continued).

Mixture Description	Property	Without Procedure	With Procedure
8. Kennesaw, GA	Maximum S.G. of Mixture	2.500	2.492
	Effective S.G. of Aggregate	2.777	2.766
1985 staff study on	Air Voids, percent	3.7	3.4
moisture damage tests	Aggr. Abs., percent = 0.40		
	Bulk S.G. of Mixture = 2.407		
	Binder, percent = 6.6 (Design = 6.4)		
9. Norcross, GA	Maximum S.G. of Mixture	2.487	2.461
	Effective S.G. of Aggregate	2.726	2.692
1985 staff study on	Air Voids, percent	4.0	3.0
moisture damage tests	Aggr. Abs., percent = 0.39		
	Bulk S.G. of Mixture = 2.387		
	Binder, percent = 5.9		
10. Rome, GA	Maximum S.G. of Mixture	2.458	2.455
	Effective S.G. of Aggregate	2.689	2.685
1985 staff study on	Air Voids, percent	4.0	3.9
moisture damage tests	Aggr. Abs., percent = 1.28		
	Bulk S.G. of Mixture = 2.359		
	Binder, percent = 5.9 (Design = 6.25)		
11. Staker, UT	Maximum S.G. of Mixture	2.667	2.661
	Effective S.G. of Aggregate	2.841	2.834
1985 staff study on	Air Voids, percent	4.0	3.8
moisture damage tests	Aggr. Abs., percent = 1.03		
	Bulk S.G. of Mixture = 2.560		
	Binder, percent = 3.8		
12. Hattiesburg, MS	Maximum S.G. of Mixture	2.410	2.390
	Effective S.G. of Aggregate	2.560	2.547
1985 staff study on	Air Voids, percent	4.0	3.6
moisture damage tests	Aggr. Abs., percent = 1.83		
	Bulk S.G. of Mixture = 2.304		
	Binder, percent = 4.5		
13. Julian, MD	Maximum S.G. of Mixture	2.449	2.441
	Effective S.G. of Aggregate	2.673	2.662
1985 staff study on	Air Voids, percent	4.0	3.7
moisture damage tests	Aggr. Abs., percent = 0.38		
	Bulk S.G. of Mixture = 2.351		
	Binder, percent = 5.7		
14. Genstar, MD	Maximum S.G. of Mixture	2.528	2.490
	Effective S.G. of Aggregate	2.773	2.724
1985 staff study on	Air Voids, percent	4.0	2.5
moisture damage tests	Aggr. Abs., percent = 0.42		
	Bulk S.G. of Mixture = 2.427		
	Binder, percent = 5.7		

Table 1. Evaluation of AASHTO T 209 supplemental procedure using specimens compacted in the laboratory (continued).

Mixture Description	Property	Without Procedure	With Procedure
15. Chantilly, VA	Maximum S.G. of Mixture	2.655	2.632
	Effective S.G. of Aggregate	2.922	2.893
Local aggregate used in misc. staff studies[1]	Air Voids, percent	8.5	7.8
	Aggr. Abs., percent = 0.80		
	Bulk S.G. of Mixture = 2.428		
	Binder, percent = 5.5		
16. AMRL #3	Maximum S.G. of Mixture	2.421	2.415
	Effective S.G. of Aggregate	2.612	2.605
AMRL aggregates[2] (AASHTO)	Air Voids, percent	5.5	5.3
	Aggr. Abs., percent = 1.61		
	Bulk S.G. of Mixture = 2.288		
	Binder, percent = 5.2		
17. ALF Surface Mixture	Maximum S.G. of Mixture	2.609	2.607
	Effective S.G. of Aggregate	2.871	2.869
1985 aggregate used in the FHWA ALF pavement[3]	Air Voids, percent	2.0	1.9
	Aggr. Abs., percent = 1.52		
	Bulk S.G. of Mixture = 2.557		
	Binder, percent = 5.6		
18. ALF Binder Mixture	Maximum S.G. of Mixture	2.652	2.644
	Effective S.G. of Aggregate	2.869	2.859
1985 aggregate used in the FHWA ALF pavement	Air Voids, percent	2.7	2.4
	Aggr. Abs., percent = 1.61		
	Bulk S.G. of Mixture = 2.580		
	Binder, percent = 4.5		
19. Coke Breeze Mixture	Maximum S.G. of Mixture	1.810	1.791
	Effective S.G. of Aggregate	2.107	2.077
1986 staff study on asphalt-coke breeze mixtures	Air Voids, percent	4.7	3.7
	Aggr. Abs., percent = unknown		
	Bulk S.G. of Mixture = 1.725		
	Binder, percent = 15.75		
20. Riverton, VA	Maximum S.G. of Mixture	2.496	2.475
	Effective S.G. of Aggregate	2.726	2.699
1986 study on elongated aggregate	Air Voids, percent	2.7	1.9
	Aggr. Abs., percent = 1.02		
	Bulk S.G. of Mixture = 2.428		
	Binder, percent = 5.5		

[1]The air void levels are high for the Chantilly, VA mixture. In the studies where this mixture was used, the compaction effort was only 15 Marshall blows.
[2]AASHTO Materials Reference Laboratory.
[3]Accelerated Loading Facility.

Note: Some of these mixtures contained Sulphlex binder, which is flexible binder made from sulfur with rheological properties similar to asphalt binders. Technically, mixtures made from it are not bituminous paving mixtures.

specific gravities of the compacted mixtures, the percent water absorptions of the aggregates if known, and the percent binder by the weight of mixture.

Water absorptions were known for 19 out of the 20 aggregates and averaged 1.35 percent. Only one of these 19 mixtures (mixture 2) had an absorption above 2.5 percent, which was considered the cutoff between low and high absorption in this study. The coke breeze mixture (mixture 19) contained a highly absorptive coke breeze aggregate. Its water absorption could not be measured as water quickly drains from coke breeze. It is also doubtful whether a percent water absorption for this aggregate would have the same meaning as for aggregates normally used in pavements.

Each mixture in table 1 is generally the optimal mixture determined through the Marshall design method. If the data are not for the optimal mixture, then both the binder content used in the maximum specific gravity test and the optimal or design binder content are included. Because the aggregates were visually thoroughly coated, it was hypothesized that the data (percent air voids, effective specific gravity of the aggregate, and the maximum specific gravity of the mixture) with and without the supplemental procedure would be virtually equal. Also, most of the aggregates had water absorptions below 2.5 percent. These are typical levels for aggregates which are not highly absorptive.

Student's paired *t*-test at a 95 percent confidence level was used to statistically analyze the differences between the data with and without the supplemental procedure. The paired *t*-test determines whether or not two data sets are significantly different when the data are paired or related.[3]

a. Air Void Levels

As shown by the statistical results in table 2, the average air void level was lower when the supplemental procedure was used. The average difference was 0.7 percent air voids. By examining table 1, the range in this difference for all mixtures was found to be from 0.1 to 3.2 percent.

The differences in air voids for the mixtures were regressed against the percent water absorptions for the aggregates, as increased water absorption

Table 2. Results of the paired *t*-tests on air voids, effective specific gravity, and maximum specific gravity for the specimens compacted in the laboratory.

	Average Percent Difference in Air Voids	*t*-test Result
Air Voids with supplemental procedure versus without supplemental procedure	-0.7	With < Without

	Average Difference in the Various Aggregate Gravities	*t*-test Result
Effective specific gravity with supplemental procedure versus without supplemental procedure	-0.022	With < Without
With the supplemental procedure		
Effective versus Bulk Dry	0.027	Effective > Bulk Dry
Effective versus Bulk SSD	-0.002	Effective = Bulk SSD
Effective versus Apparent	-0.053	Effective < Apparent
Without the supplemental procedure		
Effective versus Bulk Dry	0.050	Effective > Bulk Dry
Effective versus Bulk SSD	0.020	Effective > Bulk SSD
Effective versus Apparent	-0.031	Effective < Apparent

	Average Difference in Maximum Gravities	*t*-test Result
Maximum specific gravity with supplemental procedure versus without supplemental procedure	-0.017	With < Without
With the supplemental procedure		
Measured versus estimated using Bulk Dry	0.023	Measured > Estimated
Measured versus estimated using Bulk SSD	-0.001	Measured = Estimated
Measured versus estimated using Apparent	-0.042	Measured < Estimated
Without the supplemental procedure		
Measured versus estimated using Bulk Dry	0.040	Measured > Estimated
Measured versus estimated using Bulk SSD	0.016	Measured > Estimated
Measured versus estimated using Apparent	-0.025	Measured < Estimated

might increase the difference between the air voids. However, the coefficient of determination, or r^2, obtained through a linear regression, was only 0.24. Therefore, there was no correlation. The data is shown in figure 1.

b. Effective Specific Gravity of the Aggregate

The maximum specific gravity of a mixture and the effective specific gravity of the aggregate are related as follows:

$$G_{mix} = \frac{100}{\dfrac{P_{agg}}{G_{agg}} + \dfrac{P_b}{G_b}} \tag{4}$$

G_{mix} = Maximum specific gravity of the mixture.
P_{agg} = Percentage of aggregate by total weight of mixture = $(100 - P_b)$.
P_b = Percentage of binder by total weight of mixture.
G_{agg} = Effective specific gravity of the aggregate.
G_b = Specific gravity of the binder.

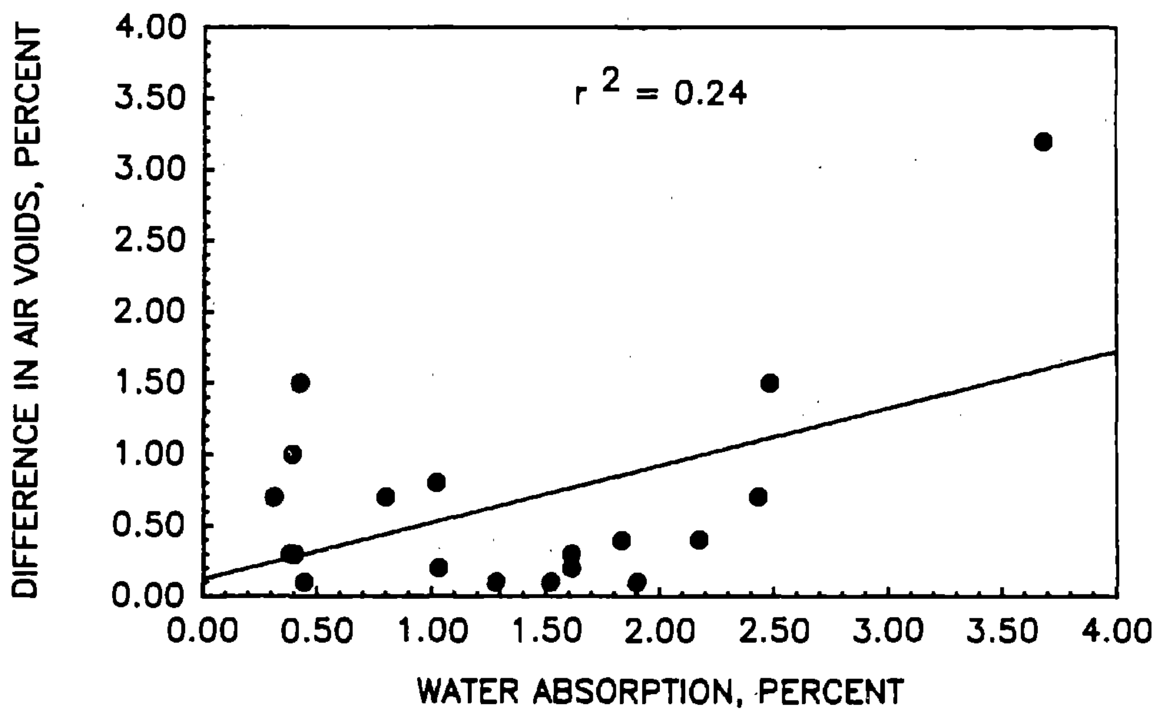

Figure 1. Percent difference in air voids versus percent water absorption for the mixtures prepared in the laboratory.

By measuring the maximum specific gravity and by knowing P_b and G_b, the effective specific gravity of the aggregate can be calculated by rearranging and using equation 4. Table 3 shows the effective specific gravities of the aggregates calculated using this equation, and the bulk dry specific gravities, bulk saturated surface-dry (SSD) specific gravities, apparent specific gravities, and water absorptions of the aggregates obtained through AASHTO test methods T 84 and T 85 (or ASTM C 127 and C 128).[1,2] Some of the mixtures given in table 1 are not included in this table because all of the necessary data were not available.

The effective specific gravity must be between the bulk dry and the apparent specific gravities. The volume of aggregate used for calculating its bulk dry specific gravity includes the total volume of void space in the aggregate (water impermeable and permeable), while the volume used for calculating its apparent specific gravity only includes the volume of water impermeable void space. As stated previously, the volume of aggregate used for calculating its effective specific gravity includes the total volume of void space minus the void space filled with binder.

As shown by the statistical results in table 2, the average effective specific gravity was lower when the supplemental procedure was used. The effective specific gravities were generally close to the bulk SSD specific gravities of the aggregate with the supplemental procedure. However, a review of the data in table 3 shows that for mixtures 7, 8, 9, 13, and 14, the effective specific gravities are lower than the bulk dry specific gravities, which cannot be correct. Without the supplemental procedure, table 2 shows that the effective specific gravities were generally between the bulk SSD and apparent specific gravities and no discrepancies were found by reviewing table 3.

The data in table 3 indicates that the supplemental procedure, or the methods for determining the specific gravities of the aggregate, or both, are flawed. It could be argued that most of the errors are within the precisions of the test methods. However, by examining the samples of mixture after each supplemental procedure was completed, it was observed that the samples contained small amounts of water in the air void spaces of the conglomerations even though the particles of the fine aggregate portions were broken down to

Table 3. Specific gravities of the aggregates used in the specimens compacted in the laboratory.

Mixture Description	Effective S.G. of aggregate		Specific Gravities and Absorption of Aggregates			
	with[1]	without[2]	Bulk Dry	Bulk SSD	Apparent	Abs, %
5. Stafford, AZ	2.542	2.588	2.482	2.542	2.645	2.48
6. Minot, ND	2.667	2.692	2.584	2.647	2.757	2.43
7. Grayson, GA	2.607	2.630	2.615	2.623	2.637	0.31
8. Kennesaw, GA	2.766	2.777	2.771	2.782	2.802	0.40
9. Norcross, GA	2.692	2.726	2.706	2.717	2.735	0.39
10. Rome, GA	2.685	2.689	2.620	2.653	2.711	1.28
11. Staker, UT	2.834	2.841	2.775	2.804	2.857	1.03
12. Hattiesburg, MS	2.547	2.560	2.511	2.557	2.632	1.83
13. Julian, MD	2.662	2.673	2.667	2.677	2.694	0.38
14. Genstar, MD	2.724	2.773	2.762	2.773	2.794	0.42
15. Chantilly, VA	2.893	2.922	2.877	2.903	2.952	0.87
18. ALF Binder Mix, VA	2.859	2.869	2.781	2.824	2.906	1.61
20. Riverton, VA	2.699	2.726	2.669	2.697	2.744	1.02
Average	2.706	2.728	2.679	2.708	2.759	1.11

[1]With the supplemental procedure.

[2]Without the supplemental procedure.

less than 1/4 in (6.4 mm) and most were less than 1/8 in (3.2 mm). Some of these air void spaces were only the size of pin holes. Thus, at least some of the errors were due to the supplemental procedure. Also, it is hypothesized that the amount of water which can be dried out of these small air void spaces may depend on the relative atmospheric humidity, which is not controlled while performing the test.

c. Maximum Specific Gravity of the Mixture

Table 4 shows the maximum specific gravities of the mixtures with and without the supplemental procedure, which were given previously in table 1. As shown by the statistical results in table 2, the average measured maximum specific gravity was lower when the supplemental procedure was used. This, in effect, duplicates the analyses previously performed on the air voids.

d. Estimates for the Maximum Specific Gravity

Maximum specific gravities estimated from the aggregate and binder properties are given in table 4. The bulk dry, bulk SSD, and apparent specific gravities of the aggregate, shown in table 3, were each substituted for the effective specific gravity of the aggregate (G_{agg}) in equation 4. The percentage of binder by total weight of mixture (P_b) and the specific gravities of the binders (G_b) are also given in table 4.

Table 2 shows that the measured maximum specific gravities were generally close to the values estimated from the bulk SSD specific gravities with the supplemental procedure. Without the supplemental procedure, the measured maximum specific gravities were between the estimates using the bulk SSD and apparent specific gravities. Because the best overall estimate for the maximum specific gravity would be based on the bulk SSD specific gravity of the aggregate, this aggregate gravity can be used to estimate the amount of material needed to fabricate a Marshall or Hveem specimen. A method is given in appendix A.

Table 5 shows the average percent errors in air voids obtained when the aggregate specific gravities are used to estimate the maximum specific gravities of the mixtures. The data for all mixtures is given in table 6. The

Table 4. Maximum specific gravities of the mixtures compacted in the laboratory.

Mixture Description	Measured Maximum S.G. of mixture with[1]	without[2]	Estimated Maximum S.G. of mixture based on Bulk Dry	Bulk SSD	Apparent	Binder % (P_b)	S.G. (G_b)
5. Stafford, AZ	2.394	2.430	2.345	2.394	2.476	9.5	1.538
6. Minot, ND	2.483	2.502	2.418	2.467	2.553	10.1	1.538
7. Grayson, GA	2.403	2.420	2.409	2.415	2.426	5.6	1.036
8. Kennesaw, GA	2.492	2.500	2.495	2.503	2.519	6.6	1.036
9. Norcross, GA	2.461	2.487	2.471	2.480	2.494	5.9	1.036
10. Rome, GA	2.455	2.458	2.403	2.429	2.475	5.9	1.036
11. Staker, UT	2.661	2.667	2.611	2.635	2.680	3.8	1.044
12. Hattiesburg, MS	2.390	2.401	2.359	2.398	2.461	4.5	1.034
13. Julian, MD	2.441	2.449	2.444	2.452	2.465	5.7	1.025
14. Genstar, MD	2.490	2.528	2.519	2.528	2.544	5.7	1.026
15. Chantilly, VA	2.632	2.655	2.619	2.640	2.678	5.5	1.032
18. ALF Binder Mix, VA	2.644	2.652	2.582	2.617	2.684	4.5	1.026
20. Riverton, VA	2.475	2.496	2.451	2.473	2.510	5.5	1.019
Average	2.494	2.511	2.471	2.495	2.536		

[1]With the supplemental procedure. [2]Without the supplemental procedure.

Table 5. Average errors in air voids if estimated using aggregate gravities.

	Average Error in Air Voids	*t*-test Result
With the supplemental procedure		
Measured versus estimated using Bulk Dry	0.9	Measured > Estimated
Measured versus estimated using Bulk SSD	0.0	Measured = Estimated
Measured versus estimated using Apparent	-1.6	Measured < Estimated
Without the supplemental procedure		
Measured versus estimated using Bulk Dry	1.6	Measured > Estimated
Measured versus estimated using Bulk SSD	0.6	Measured > Estimated
Measured versus estimated using Apparent	-0.9	Measured < Estimated

Table 6. Percent difference in air voids between those measured using the maximum specific gravity test method and those estimated from the specific gravities of the aggregates.

Mixture Description	Estimated maximum S.G. using the bulk dry S.G. compared to the measured		Estimated maximum S.G. using the bulk SSD S.G. compared to the measured		Estimated maximum S.G. using the apparent S.G. compared to the measured	
	with[1]	without[2]	with	without	with	without
5. Stafford, AZ	2.0	3.5	0.0	1.5	-3.2	-1.7
6. Minot, ND	2.6	3.3	0.6	1.3	-2.7	-2.0
7. Grayson, GA	-0.3	0.4	-0.5	0.2	-0.9	-0.2
8. Kennesaw, GA	-0.1	0.2	-0.4	-0.1	-1.0	-0.7
9. Norcross, GA	-0.4	0.6	-0.7	0.3	-1.3	-0.3
10. Rome, GA	2.1	2.2	1.0	1.1	-0.8	-0.7
11. Staker, UT	1.9	2.1	1.0	1.2	-0.7	-0.5
12. Hattiesburg, MS	1.3	1.7	-0.3	0.1	-2.8	-2.4
13. Julian, MD	-0.1	0.2	-0.4	-0.1	-0.9	-0.6
14. Genstar, MD	-1.1	0.4	-1.5	0.0	-2.1	-0.6
15. Chantilly, VA	0.5	1.2	-0.2	0.5	-1.5	-0.8
18. ALF Binder Mix, VA	2.3	2.6	1.0	1.3	-1.5	-1.2
20. Riverton, VA	1.0	1.8	0.1	0.9	-1.4	-0.6
Average	0.9	1.6	0.0	0.6	-1.6	-0.9

[1]With the supplemental procedure.

[2]Without the supplemental procedure.

Note: A positive value indicates the measured is greater than the estimated value.

best estimate for the maximum specific gravity of a mixture would be based on the bulk SSD specific gravity, although using this estimate could produce an error in air voids up to approximately 1.5 percent with or without the supplemental procedure. This is a significant error and thus the maximum specific gravity should be measured using AASHTO T 209 or ASTM D 2041. The *t*-test results in table 5 should and do match the results in table 2 for maximum specific gravity.

Basing the maximum specific gravity on the apparent specific gravity of the aggregate, which is sometimes practiced because this specific gravity is easy to measure, can produce errors in air voids over 2.0 percent. The measured air voids were always less than the estimated air voids. When designing a mixture, the use of the estimated value would lead to more than the optimal amount of binder being placed in a mixture. Basing the maximum specific gravity on the bulk dry specific gravity of the aggregate can produce errors in air voids over 3.0 percent. In this case the measured air voids were generally greater than the estimated air voids. When designing a mixture, the use of this estimated value would generally lead to less than the optimal amount of binder being placed in a mixture.

e. Water Absorption Versus Binder Absorption

Correlations between the percent water absorptions, shown in table 1, and the percent binder absorptions for both the data with and without the supplemental procedure were performed as additional analyses. The percent binder absorption by weight of the aggregate is calculated using[4]:

$$\text{Binder Absorption, percent by agg wt} = 100(G_b)\,\frac{(G_{effective} - G_{bulk\ dry})}{(G_{effective})(G_{bulk\ dry})} \tag{5}$$

$G_{effective}$ = Effective specific gravity of the aggregate.
$G_{bulk\ dry}$ = Bulk dry specific gravity of the aggregate.
G_b = Specific gravity of the binder.

The data is shown in table 7 and in figures 2 and 3. The coefficients of determination, or r^2, were 0.86 with the supplemental procedure and 0.89 without the supplemental procedure, thus showing a good correlation of

Table 7. Percent binder absorption by weight of the aggregate.

Mixture Description	Percent binder absorption by weight of the aggregate	
	with[1]	without[2]
5. Stafford, AZ	1.46	2.54
6. Minot, ND	1.85	2.39
7. Grayson, GA	-0.12	0.23
8. Kennesaw, GA	-0.07	0.08
9. Norcross, GA	-0.20	0.28
10. Rome, GA	0.96	1.01
11. Staker, UT	0.78	0.87
12. Hattiesburg, MS	0.58	0.79
13. Julian, MD	-0.07	0.09
14. Genstar, MD	-0.52	0.15
15. Chantilly, VA	0.20	0.55
18. ALF Binder Mix, VA	1.01	1.13
20. Riverton, VA	0.42	0.80
Average	0.48	0.84

[1]With the supplemental procedure.

[2]Without the supplemental procedure.

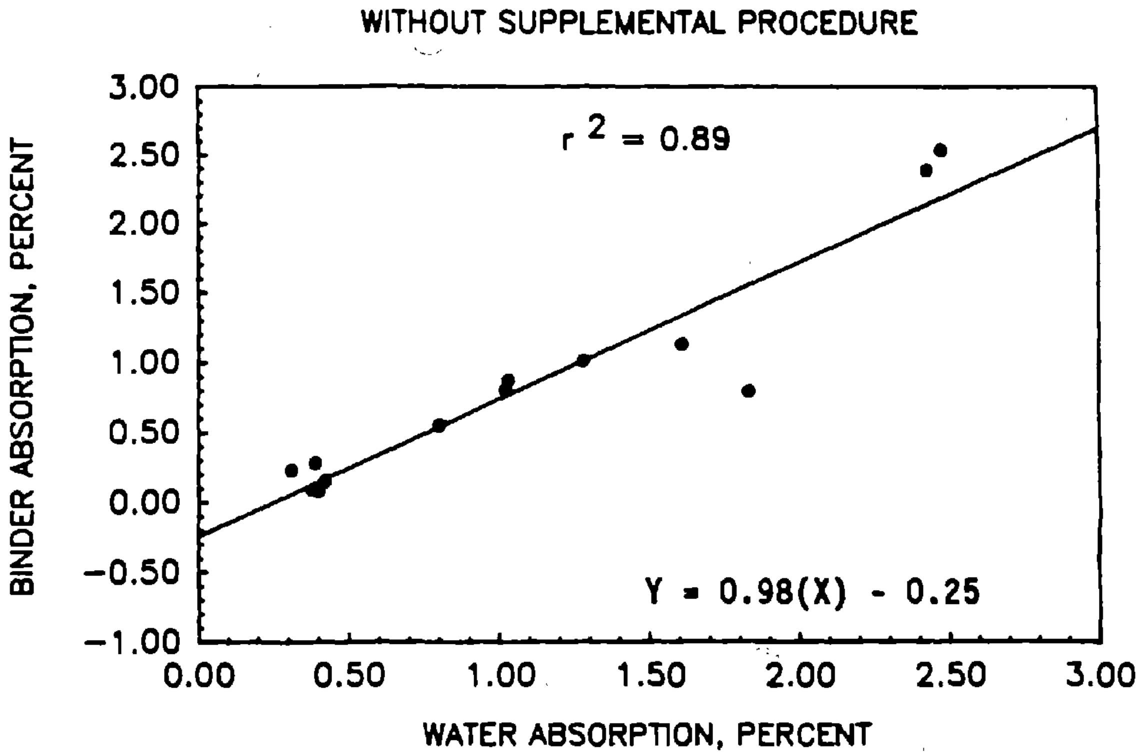

Figure 2. Percent binder absorption versus percent water absorption without the supplemental procedure.

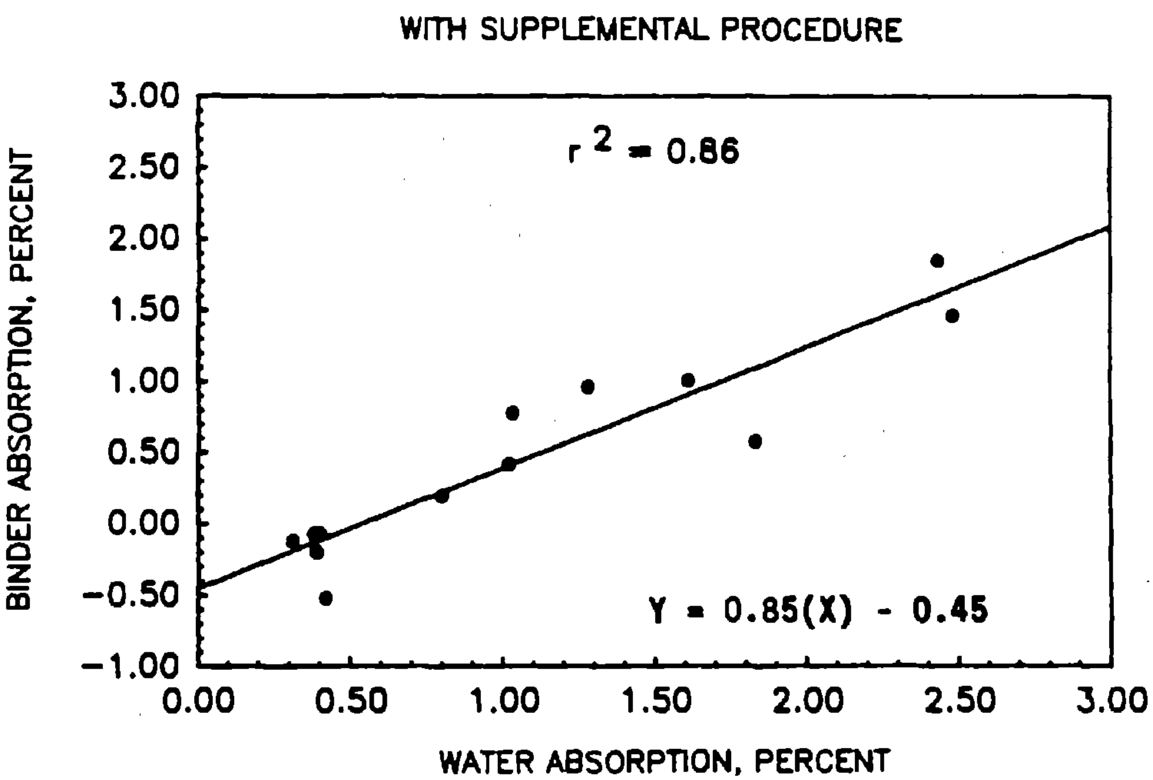

Figure 3. Percent binder absorption versus percent water absorption with the supplemental procedure.

increasing binder absorption with increasing water absorption as expected. The amount of absorbed binder was lower using the supplemental procedure as expected.

One slight discrepancy was noted for the data without the supplemental procedure. The percent binder absorption (2.54 percent) for mixture 5 is slightly greater than the percent water absorption (2.48 percent). However, this difference is insignificant, and thus the absorptions can be considered equal. Using the supplemental procedure, mixtures 7, 8, 9, 13, and 14 provided negative binder absorptions. Most of these were very slight but the data and the intercepts in figures 2 and 3 tend to indicate that either the supplemental procedure or the methods for determining the specific gravities and absorption of aggregate, or both, are flawed. This analysis in effect duplicates the previous analyses on the effective specific gravities of the aggregates.

5. TEST RESULTS - PAVEMENT CORES

Pavement cores were obtained from various State highway agencies as part of a study on evaluating the performance of sulfur extended asphalt (SEA) pavements. Cores from both asphalt control and SEA pavement sections were obtained. The results of the maximum specific gravity tests performed on the asphalt control cores were used in this evaluation of the supplemental procedure, plus one additional set of cores taken from the Accelerated Loading Facility (ALF) pavement in McLean, VA. The ALF pavement was 6 months old when cored, while the ages of the cores obtained from the State highway agencies ranged from 3 to 8 years. The cores were heated to constant weight at 230 °F (110 °C) and the mixtures separated until the fine aggregate portions were less than 1/4 in (6.4 mm), as required by the supplemental test procedure. Within the cores, all of the aggregates were visually thoroughly coated, although the coatings were thin in some cases.

All cores were 4 in (10.16 cm) in diameter. While coring operations produce uncoated aggregate surfaces, the percentage of exposed surface is low compared to the percentage of coated surface. However, the supplemental procedure may still be needed. Estimates for the percentages of exposed aggregate were not recorded.

The laboratory specimens previously evaluated and the pavement cores were not the same mixtures. Thus the experimental design of this study is less than optimal. However, it was assumed that both sets of data were representative of the population of mixtures.

The data with and without the supplemental procedure for these cores are given in table 8. Also included are the bulk specific gravities of the cores, the percent water absorptions of the aggregates if known, and the percent binder by weight of the mixture.

Only the water absorptions for aggregates from projects 2, 9, 10, and 20 could be obtained from project records. The water absorptions for the other aggregates were estimated by performing the tests on extracted aggregates. Because all of the absorbed binder might not be removed during the extraction, and the specific gravity and absorption tests can be difficult to perform on extracted aggregates due to residual oily coatings, these absorptions should only be considered estimates. Extractions were performed using the centrifuge method of AASHTO T 164 (or ASTM D 2172). The aggregates were washed thoroughly using a trichloroethylene/ethyl alcohol (90/10) solvent blend. The use of ethyl alcohol increases the efficiency of the extraction process. The water absorptions averaged 1.61, compared to 1.35 percent for the aggregates used in the mixtures prepared in the laboratory (see table 1), and only two aggregates had absorptions above the 2.5 percent cutoff level for high and low absorption. Comparisons between the various specific gravities of the aggregates, as in table 3, and between measured and estimated maximum specific gravities, as in table 4, were not included in this part of the study. The bulk dry, bulk saturated surface-dry (SSD), and apparent specific gravities of the aggregates could only be considered estimates.

As shown by the statistical results in table 9, the average air void level, average effective specific gravity of the aggregate, and the average maximum specific gravity of the mixture were lower when the supplemental procedure was used. These differences are less than those shown in table 2 for the mixtures prepared in the laboratory. The average difference in air voids for the pavement cores was 0.4 percent, compared to 0.7 percent for the laboratory mixtures. By examining table 8, the range in this difference was

Table 8. Evaluation of AASHTO T 209 supplemental procedure using pavement core specimens.

Core Description	Property	Without Procedure	With Procedure
1. Anaheim, CA (Lincoln Avenue) AR-4000 with 20 percent sulfur, Surface	Maximum S.G. of Mixture	2.394	2.387
	Effective S.G. of Aggregate	2.590	2.582
	Air Voids, percent	8.9	8.7
	Aggr. Abs., percent = 2.23		
	Bulk S.G. of Core = 2.181		
	Binder, percent = 6.4		
2. Barstow/Baker, CA (I-15) AR-2000, Surface	Maximum S.G. of Mixture	2.410	2.407
	Effective S.G. of Aggregate	2.604	2.600
	Air Voids, percent	6.7	6.6
	Aggr. Abs., percent = 0.80		
	Bulk S.G. of Core = 2.248		
	Binder, percent = 5.3		
3. Barstow/Baker, CA (I-15) AR-4000, Surface	Maximum S.G. of Mixture	2.413	2.408
	Effective S.G. of Aggregate	2.609	2.603
	Air Voids, percent	7.7	7.6
	Aggr. Abs., percent = 0.80		
	Bulk S.G. of Core = 2.226		
	Binder, percent = 5.4		
4. Greenwood, DE (Route 13) AC-20, Surface	Maximum S.G. of Mixture	2.535	2.534
	Effective S.G. of Aggregate	2.750	2.749
	Air Voids, percent	5.3	5.3
	Aggr. Abs., percent = 0.59		
	Bulk S.G. of Core = 2.401		
	Binder, percent = 5.2		
5. Bainbridge Bypass, GA (U.S. 84) AC-20, Surface	Maximum S.G. of Mixture	2.411	2.407
	Effective S.G. of Aggregate	2.664	2.659
	Air Voids, percent	1.5	1.3
	Aggr. Abs., percent = 0.61		
	Bulk S.G. of Core = 2.375		
	Binder, percent = 6.9		
6. Elk City, ID (State Route 14) AR-4000, Surface	Maximum S.G. of Mixture	2.512	2.507
	Effective S.G. of Aggregate	2.759	2.753
	Air Voids, percent	5.0	4.8
	Aggr. Abs., percent = 0.66		
	Bulk S.G. of Core = 2.386		
	Binder, percent = 6.0		
7. Johnson Co, KS (151st Street) AC-20, Base	Maximum S.G. of Mixture	2.506	2.491
	Effective S.G. of Aggregate	2.665	2.648
	Air Voids, percent	10.5	9.9
	Aggr. Abs., percent = 2.32		
	Bulk S.G. of Core = 2.242		
	Binder, percent = 4.6		

Note: The percent binder is by weight of the mixture.

Table 8. Evaluation of AASHTO T 209 supplemental procedure using pavement core specimens (continued).

Core Description	Property	Without Procedure	With Procedure
8. LA 22, LA AC-30, Surface	Maximum S.G. of Mixture	2.391	2.380
	Effective S.G. of Aggregate	2.569	2.556
	Air Voids, percent	2.8	2.3
	Aggr. Abs., percent = 1.59		
	Bulk S.G. of Core = 2.325		
	Binder, percent = 5.1		
9. Benton ME (I-95) AC-10, Surface	Maximum S.G. of Mixture	2.467	2.460
	Effective S.G. of Aggregate	2.707	2.698
	Air Voids, percent	1.4	1.1
	Aggr. Abs., percent = 1.06		
	Bulk S.G. of Core = 2.433		
	Binder, percent = 5.9		
10. Crystal, ME (U.S. 2) AC-10, Surface	Maximum S.G. of Mixture	2.472	2.463
	Effective S.G. of Aggregate	2.691	2.679
	Air Voids, percent	2.4	2.0
	Aggr. Abs., percent = 2.18		
	Bulk S.G. of Core = 2.441		
	Binder, percent = 5.6		
11. Rochester, MN TH-63 AC 200-300, Surface	Maximum S.G. of Mixture	2.446	2.432
	Effective S.G. of Aggregate	2.665	2.646
	Air Voids, percent	3.0	2.4
	Aggr. Abs., percent = 1.33		
	Bulk S.G. of Core = 2.373		
	Binder, percent = 5.7		
12. Neshoba Co, MS (Route 15) AC-20, Surface	Maximum S.G. of Mixture	2.409	2.398
	Effective S.G. of Aggregate	2.600	2.587
	Air Voids, percent	6.8	6.4
	Aggr. Abs., percent = 1.79		
	Bulk S.G. of Core = 2.244		
	Binder, percent = 5.5		
13. Neshoba, MS (Route 15) AC-40, Base	Maximum S.G. of Mixture	2.437	2.411
	Effective S.G. of Aggregate	2.592	2.561
	Air Voids, percent	10.9	9.9
	Aggr. Abs., percent = 2.58		
	Bulk S.G. of Core = 2.171		
	Binder, percent = 4.7		
14. NW of Minot, ND (U.S. 2) AC 120-150, Surface	Maximum S.G. of Mixture	2.449	2.424
	Effective S.G. of Aggregate	2.718	2.685
	Air Voids, percent	3.1	2.1
	Aggr. Abs., percent = 3.21		
	Bulk S.G. of Core = 2.373		
	Binder, percent = 6.8		

Table 8. Evaluation of AASHTO T 209 supplemental procedure using pavement core specimens (continued).

Core Description	Property	Without Procedure	With Procedure
15. Carlsbad, NM	Maximum S.G. of Mixture	2.598	2.590
(U.S. 62/180)	Effective S.G. of Aggregate	2.778	2.768
AC-10, Surface	Air Voids, percent	7.5	7.2
	Aggr. Abs., percent = 2.11		
	Bulk S.G. of Core = 2.404		
	Binder, percent = 4.2		
16. College Station, TX	Maximum S.G. of Mixture	2.432	2.425
(MH 153)	Effective S.G. of Aggregate	2.628	2.619
AC-20, Base	Air Voids, percent	2.7	2.4
	Aggr. Abs., percent = 1.03		
	Bulk S.G. of Core = 2.367		
	Binder, percent = 5.4		
17. Pecos, TX	Maximum S.G. of Mixture	2.432	2.408
(I-10)	Effective S.G. of Aggregate	2.591	2.556
AC-20, Binder	Air Voids, percent	8.0	6.8
	Aggr. Abs., percent = 2.12		
	Bulk S.G. of Core = 2.244		
	Binder, percent = 4.3		
18. Nocogdoches, TX	Maximum S.G. of Mixture	2.305	2.298
(Loop 495)	Effective S.G. of Aggregate	2.610	2.601
AC-20, Surface	Air Voids, percent	12.5	12.3
	Aggr. Abs., percent = 1.49		
	Bulk S.G. of Core = 2.016		
	Binder, percent = 8.8		
19. Wittenberg, WI	Maximum S.G. of Mixture	2.431	2.418
(State Highway 29)	Effective S.G. of Aggregate	2.701	2.684
AC 120-150, Surface	Air Voids, percent	2.5	2.0
	Aggr. Abs., percent = 2.13		
	Bulk S.G. of Core = 2.370		
	Binder, percent = 6.9		
20. ALF Binder Core, VA	Maximum S.G. of Mixture	2.631	2.621
	Effective S.G. of Aggregate	2.865	2.855
1985 aggregate used in	Air Voids, percent	3.5	3.1
the FHWA ALF pavement	Aggr. Abs., percent = 1.61		
Lane 2, site 3, Binder	Bulk S.G. of Core = 2.539		
	Binder, percent = 5.0		

Table 9. Results of the paired *t*-tests on air voids, effective specific gravity, and maximum specific gravity for the pavement core specimens.

	Average Percent Difference in Air Voids	*t*-test Result
Air Voids with supplemental procedure versus without supplemental procedure	-0.4	With < Without

	Average Difference in the Various Aggregate Gravities	*t*-test Result
Effective specific gravity with supplemental procedure versus without supplemental procedure	-0.013	With < Without

	Average Difference in Maximum Gravities	*t*-test Result
Maximum specific gravity with supplemental procedure versus without supplemental procedure	-0.011	With < Without

found to be from 0.0 to 1.2 percent, compared to 0.1 to 3.2 percent for the laboratory mixtures.

As with the mixtures prepared in the laboratory, the differences in air voids were regressed against the percent water absorptions for the aggregates. The coefficient of determination, or r^2, obtained through linear regression was 0.53. Although this is a low r^2, it indicates there is a trend of an increasing difference in air voids with increasing water absorption. The data are shown in figure 4.

The supplemental procedure does not appear to be valid for mixtures having low aggregate water absorptions as evaluated in this study. By examining the core samples after performing the procedure, very little water could be seen in the air void spaces of the samples. It appears that while the cores are more difficult to physically separate to the 1/4 in (6.4 mm) requirement, they can be separated more efficiently than newly prepared laboratory mixtures because they are less sticky, or the air void system is different. However, water may still be trapped in air void spaces. The amount of this water and the amount absorbed into the aggregate cannot be separately measured.

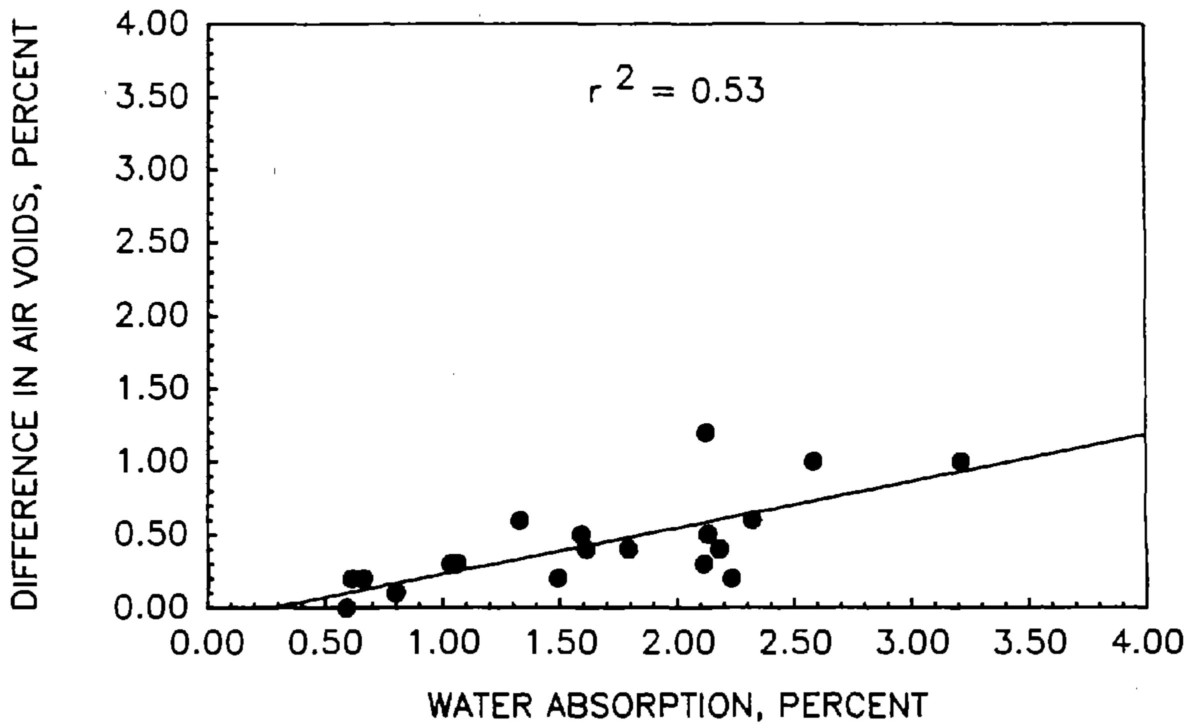

Figure 4. Percent difference in air voids versus percent water absorption for the pavement core specimens.

An additional argument against the use of the supplemental procedure is that exposed aggregate surfaces are dried too long during the procedure to be considered at a saturated surface-dry condition. The supplemental procedure generally requires 1-1/2 to 2 hours to complete, and sometimes up to 3 hours. Drying coarse aggregates using AASHTO T 85 (or ASTM C 127) to get a saturated surface-dry condition generally requires less than 10 minutes.

6. TEST RESULTS - SAMPLES PARTIALLY STRIPPED OF BINDER

Because the pavement cores had low percentages of exposed aggregate surfaces compared to the amount of coated surfaces, four mixtures were prepared in the laboratory to evaluate the effects of the supplemental procedure on mixtures having higher amounts of exposed aggregate surfaces. Mixtures 8, 12, 15 and 16 given in table 1 were prepared in duplicate and the aggregates partially stripped of binder using a static immersion moisture conditioning procedure. The temperature of the water bath was slightly less than 212 °F (100 °C), the immersion time was a minimum of 3 days, and the mixtures were abraded with brushes to remove loose films. No part of a mixture was lost or removed from its container during this process. After the mixtures were conditioned and abraded, they were vacuum desiccated in air at less than 30 mm of Hg to constant weight. This was performed to remove any water which may have entered the aggregate pores during the conditioning process. The maximum specific gravity test with and without the supplemental procedure was performed before and after the samples were conditioned and abraded. A percent visual stripping for each mixture was also estimated. All four mixtures are susceptible to stripping in pavements when no antistripping additives are used.

The data with and without the supplemental procedure before moisture conditioning are given in table 10. The maximum specific gravities of the mixtures and the effective specific gravities of the aggregates are close to those for the original mixtures given in table 1, except for the maximum specific gravity of the North Dakota mixture. A different binder was used in this mixture because the original binder was not available. Although these mixtures were not compacted and the binder of the North Dakota mixture was changed, the bulk specific gravities given in table 1 were used to calculate percent air void levels so that the effect of the supplemental procedure on

Table 10. Results of the tests performed on the additional samples before being subjected to moisture conditioning and abrasion.

	Mixture # 8 North Dakota		Mixture # 12 Rome, Georgia		Mixture # 15 Hattiesburg, Mississippi		Mixture # 16 Julian, Maryland	
Aggregate Water Absorption, Percent	2.43		1.28		1.83		0.38	
	with[1]	without[2]	with	without	with	without	with	without
Maximum S.G. of Mixture	2.447	2.465	2.452	2.459	2.415	2.424	2.461	2.462
Effective S.G. of Aggregate	2.684	2.707	2.698	2.707	2.577	2.588	2.688	2.690
Air Voids, Percent	1.3	2.0	3.8	4.1	4.6	5.0	4.5	4.5

[1]With the supplemental procedure.

[2]Without the supplemental procedure.

air void levels could be estimated. The effects of the procedure on the data were the same as those previously found. The supplemental procedure generally produced lower data.

The data after conditioning are given in table 11 along with the estimates for the percent visual stripping. The maximum specific gravities of the mixtures, effective specific gravities of the aggregates, and the percent air voids all increased. Reasons for these increases were not apparent. It can be speculated that the increases are at least partially due to increased binder absorption resulting from the use of the hot soaking process of the moisture conditioning procedure. However, increases were even found for the Hattiesburg, Mississippi mixture which had 65 percent visual stripping. It had been assumed that all moisture absorbed during the conditioning and abrasion processes had been removed by the vacuum desiccation process.

The data with and without the supplemental procedure in table 11 are very close except for the Hattiesburg, Mississippi mixture which was 65 percent visually stripped. Whether the data with the procedure represent a saturated surface-dry condition is still questionable even for this mixture. Each supplemental procedure still took 1-1/2 to 2 hours to perform. The data with and without the supplemental procedure after conditioning for each of the other three mixtures were closer to each other than before conditioning. Again, it can be speculated that like the pavement cores, the mixtures could be separated more efficiently after conditioning because they were less sticky.

The mixtures were then dried to constant weight at 230 °F (110 °C). Each mixture lost some weight based on the original dry weight of the mixture before testing. Apparently, all of the water was not removed by the vacuum desiccation process. However, the amounts were so small (several grams) that they should have little effect on the data in table 11. A slight decrease in the percent visual stripping due to the heating process was noted for the Rome, Georgia mixture, as the percent visual stripping dropped from 10 to 5 percent.

The mixtures were dried to duplicate how cores would be handled in the laboratory. Cores have to be heated in the laboratory in order to break them

Table 11. Results of the tests performed on the additional samples after being subjected to moisture conditioning and abrasion.

	Mixture # 8 North Dakota		Mixture # 12 Rome, Georgia		Mixture # 15 Hattiesburg, Mississippi		Mixture # 16 Julian, Maryland	
Aggregate Water Absorption; Percent	2.43		1.28		1.83		0.38	
Visual Stripping, Percent	20		10		65		17	
	with[1]	without[2]	with	without	with	without	with	without
Maximum S.G. of Mixture	2.469	2.472	2.466	2.467	2.425	2.448	2.468	2.466
Effective S.G. of Aggregate	2.717	2.723	2.716	2.718	2.589	2.616	2.698	2.695
Air Voids, Percent	2.1	2.3	4.3	4.4	5.0	5.9	4.7	4.7

[1]With the supplemental procedure.

[2]Without the supplemental procedure.

apart for testing. The maximum gravity test was repeated and the data with and without the supplemental procedure are given in table 12. The results are similar to those in table 11. By comparing tables 10 and 12, it was concluded that the supplemental procedure was of little to no benefit.

Unexpectedly, the variation in the replicate data for the stripped samples was low. The greatest difference between any two replicate maximum specific gravities was 0.009. The supplemental procedure was used in this case. This difference is less than the acceptable difference of 0.018 given in the test method.[1,2] It is also below the acceptable difference of 0.011 when the supplemental procedure is not used. All replicate data for all tests performed in this study were within AASHTO and ASTM acceptable differences.

Out of the 44 mixtures and cores tested throughout this study, only the aggregate from Florida (mixture 2 in table 1), which had a water absorption of 3.68 percent, provided data which would indicate that the supplemental procedure should be used. It is speculated that this aggregate was not thoroughly coated. Although the binder content used when determining the maximum specific gravity was close to the optimal binder content, the air void level of the compacted mixture was high.

7. SUMMARY

The maximum and bulk specific gravities of a bituminous paving mixture are used to calculate its air void level. To determine the maximum specific gravity of a mixture, the mass of the loose mixture in air and the mass in water are needed. To determine the mass in water, the sample is first submerged in water and subjected to a partial vacuum to removed entrapped air. This vacuum procedure may cause water to enter the pores of the aggregates if they are not thoroughly sealed. Because of this, the standardized test method in AASHTO T 209 (or ASTM D 2041) for maximum specific gravity contains a supplemental procedure to be performed on mixtures containing porous aggregates which are not completely coated with binder.[1,2] The supplemental procedure should correct the data for water absorbed into the aggregate during the test. Although the supplemental procedure can be used when designing mixtures, it is most often used for determining the maximum specific gravities of moisture damaged pavement samples, or cores or specimens where sawing has

Table 12. Results of the tests performed on the additional samples after being subjected to moisture conditioning and abrasion and then dried in an oven at 230 °F (110 °C).

	Mixture # 8 North Dakota		Mixture # 12 Rome, Georgia		Mixture # 15 Hattiesburg, Mississippi		Mixture # 16 Julian, Maryland	
Aggregate Water Absorption, Percent	2.43		1.28		1.83		0.38	
Visual Stripping, Percent	20		5		65		17	
	with[1]	without[2]	with	without	with	without	with	without
Maximum S.G. of Mixture	2.465	2.480	2.459	2.462	2.420	2.440	2.458	2.462
Effective S.G. of Aggregate	2.707	2.727	2.707	2.710	2.583	2.606	2.685	2.690
Air Voids, Percent	2.0	2.6	4.1	4.2	4.8	5.6	4.4	4.5

[1]With the supplemental procedure.

[2]Without the supplemental procedure.

exposed a significant amount of aggregate. The supplemental procedure often requires 2 hours to complete and is sometimes referred to as the dryback procedure.

The objective of this study was to investigate the effects of performing the supplemental procedure on the percent air voids, the effective specific gravity of the aggregate, and the maximum specific gravity of a bituminous paving mixture, using both thoroughly coated aggregates and partially coated aggregates. The effective specific gravity of the aggregate is used to calculate the amount of binder absorbed by the aggregate in a mixture. Also, if the maximum specific gravity test is performed at only one binder content when designing a mixture, the effective aggregate gravity is one parameter used to calculate the maximum specific gravities for the other binder contents.

This study consisted of evaluating test results obtained under various staff studies over the past 9 years in the Federal Highway Administration's (FHWA's) Bituminous Mixtures Laboratory, located in McLean, VA. The test data are the original data from these studies for pavement cores and mixtures designed in the laboratory using the Marshall method. Additionally, new data were obtained by testing four moisture susceptible mixtures. These mixtures were prepared in the laboratory and partially stripped of binder to expose a high amount of aggregate surface. The majority of aggregates used in this study had water absorptions below 2.5 percent and thus were not highly absorptive.

8. CONCLUSIONS

- For all mixtures (laboratory mixtures and pavement cores) the use of the supplemental procedure in the maximum specific gravity test (AASHTO T 209 or ASTM D 2041) produced a lower average (1) percent air void level, (2) effective specific gravity of the aggregates, (3) maximum specific gravity, and (4) amount of binder absorption.

- The data indicated that the supplemental procedure or the methods for determining the specific gravities and absorption of the aggregate, or both, are flawed. Five out of 18 mixtures where the properties of the aggregates were known had effective specific gravities lower than the bulk dry specific gravities and negative binder absorptions. It could be argued that most of the errors were within the precisions of the test methods. However, it was observed that the samples of mixture contained small amounts of water in the air void spaces of the mixture conglomerations after the supplemental procedure was completed. This causes an error.

- The differences between the air void levels for all mixtures (laboratory mixtures and pavement cores) with and without the supplemental procedure did not correlate to the percent water absorptions of the aggregates. The hypothesis that increased water absorption might increase the difference in air void level was not found to be true, although there was a general trend of an increasing difference in air voids with increasing water absorption for the pavement cores. The differences between the air void levels were calculated by subtracting the air void levels using the procedure from those without using the procedure.

- The effect of the supplemental procedure on the test results (percent air void level, effective specific gravity of the aggregate, and maximum specific gravity) was slightly greater for the mixtures prepared in the laboratory compared to the pavement cores. It was hypothesized that the opposite should occur as cores contain uncoated aggregate particles. However, the difference was not statistically significant.

- The supplemental procedure was of no benefit for most mixtures, even those partially stripped of binder. Out of 44 mixtures tested in this study, only one aggregate which had a water absorption of 3.68 percent provided data which would indicate that the supplemental procedure should be used.

- Exposed aggregate surfaces are dried too long during the supplemental procedure for them to be considered at a saturated surface-dry condition. It appears that the supplemental procedure will not properly correct the data when a correction for absorbed water is needed.

- The maximum specific gravity of a mixture should be measured using AASHTO T 209 or ASTM D 2041. Estimating the maximum specific gravity from the specific gravities of the aggregates can result in significant errors in the maximum specific gravity, or maximum density, and air void levels. (Also, according to AASHTO and ASTM methods, the test method for maximum specific gravity is a more precise method compared to those for the specific gravities of the aggregates.)[1,2]

- As expected, there was a trend of increasing binder absorption with increasing aggregate water absorption.

- The bulk saturated surface-dry specific gravity of the aggregate can be used to estimate the quantity of aggregate needed for a Marshall or Hveem specimen. A procedure is given in appendix A.

9. RECOMMENDATIONS

- It is recommended that the supplemental procedure not be performed on laboratory mixtures or pavement cores having aggregates with water absorptions below 2.5 percent.

- It is recommended that when testing any mixture prepared in the laboratory during the mixture design process, that the procedure for determining the maximum specific gravity only be performed on well coated mixtures so that the supplemental procedure does not have to be used. For highly absorptive aggregates, it is recommended that the test only be performed at binder contents which provide thick coatings. Thin coatings, which may appear to be visually complete, should even be avoided. Only binder contents close to or slightly above the optimal binder content should be used. The maximum specific gravities for the lower binder contents can be calculated using the effective specific gravity of the aggregate. One caution is that excessively high binder contents can make the mixture difficult to handle and thus should also be avoided.

- When testing mixtures prepared in the laboratory during the mixture design process that contain aggregates with water absorptions above 2.5 percent and low binder contents, use of the supplemental procedure in some cases may show when the binder coating is very poor. It is speculated that the one aggregate used in this study where the supplemental procedure had a significant effect on the data was not thoroughly coated.

- For pavement cores which have absorptions above 2.5 percent, no recommendations can be given based on this study. Additional research is needed for high levels of absorption. At some absorption level, use of the supplemental procedure should provide a better estimate of the maximum specific gravity even though the procedure is imperfect.

- A new procedure would be beneficial, even for pavement cores having aggregates with water absorptions below 2.5 percent. This study indicated that the supplemental procedure was not useful below this level. Still, corrections for absorbed water may have been needed for some of the mixtures. Whether corrections were needed is unknown.

- It is speculated that the amount of water which can be dried out of the small air void spaces of the mixture during the supplemental procedure may depend on the relative atmospheric humidity, which is not controlled while performing the test. If the supplemental procedure is to be used, the effects of humidity should be evaluated.

APPENDIX A: METHOD FOR ESTIMATING THE AMOUNT OF MATERIAL NEEDED FOR PREPARING TEST SPECIMENS

The bulk SSD specific gravity of the aggregate can be used to estimate the amount of material needed to obtain the required heights of specimens by the following procedure.

(1) Estimate the maximum specific gravity of the mixture (G_{mix}):

$$G_{mix} = \frac{100}{\dfrac{P_{agg}}{G_{agg}} + \dfrac{P_b}{G_b}} \qquad \text{(A1)}$$

G_{mix} = Estimated maximum specific gravity of the mixture.
P_{agg} = Estimated percentage of aggregate by total weight of mixture = $(100-P_b)$. (Average = 94.5 percent)
P_b = Estimated percentage of binder by total weight of mixture. (Average = 5.5 percent)
G_{agg} = Bulk SSD specific gravity of the combined aggregate.
G_b = Specific gravity of the binder.

(2) Estimate the bulk specific gravity of the mixture (BSG_{mix}):

$$BSG_{mix} = ((100 - \text{Percent Air Voids})/100)G_{mix} \qquad \text{(A2)}$$

For a average design air void level of 4 percent:

$$BSG_{mix} = (0.96)(G_{mix}) \qquad \text{(A2)}$$

(3) Estimate the weight (g) of the mixture per specimen (Wt_{mix}):

$$Wt_{mix} = (\text{Volume of Specimen, cm}^3)(BSG_{mix}) \qquad \text{(A3)}$$

For a 10.16-cm (4-in) diameter by 6.35-cm (2.5-in) thickness (Marshall or Hveem):

$$Wt_{mix} = (514.8\ \text{cm}^3)(BSG_{mix}) \qquad \text{(A3)}$$

(4) Estimate the weight of aggregate (g) per specimen (Wt_{agg}):

$$Wt_{agg} = Wt_{mix} - (Wt_{mix})(P_b\ /100) \qquad \text{(A4)}$$

(5) The weight of binder (g) for each binder content can then be calculated (Wt_b):

$$Wt_b = \frac{(Wt_{agg})(P_b)}{(100 - P_b)} \qquad \text{(A5)}$$

where P_b is now each percent binder content to be used in the design.

For most mixtures, the specimens will be within the 2.5 in (63.5 mm) +/- 0.05 in (1.27 mm) height requirement in AASHTO T 245 or ASTM 1559 for Marshall-sized specimens. Hveem specimens have a larger tolerance of +/- 0.1 in (+/- 3 mm).

It should be noted that this procedure gives a rough estimate for the maximum gravity of a mixture. Errors in the air void levels if any of the aggregate gravities are used to calculate the maximum specific gravities can be high as shown in tables 5 and 6.

Volumes that can be used in equation A3 are:

Marshall or Hveem (4 in x 2.5 in)	=	514.8 cm^3
Immersion-Compression (4 in x 4 in)	=	823.7 cm^3
Dynamic Modulus (4 in x 8 in)	=	1647.4 cm^3
Beam (3.25 in x 3.5 in x 15 in)	=	2796.0 cm^3

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