Effect of Aggregate Gradation on Measured Asphalt Content

PRITHVI S. KANDHAL AND STEPHEN A. CROSS

It is necessary to closely control the asphalt content in hot-mix asphalt (HMA) mixes to obtain optimum serviceability and durability. However, coarser mixes (binder and base courses) made with larger maximum particle-sized aggregate tend to segregate. The resulting variation in the aggregate gradation of the sampled HMA mix can significantly affect the measured asphalt content. A study was done to evaluate the effect of aggregate gradation on the measured asphalt content. Actual mix composition (asphalt content and gradation) data from a major Interstate paving project were obtained and analyzed. A total of 547 binder course and 147 wearing course mix samples were obtained behind the paver and subjected to extraction analysis. A substantial amount of segregation was observed in the binder course mix, which provided the opportunity to correlate the aggregate gradation with the measured asphalt content. Some of the deviation in the measured asphalt content of the binder course mixes from the job mix formula (JMF) was determined to be the result of the change in gradation of the mix from JMF. The percentages of material passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves are correlated with measured asphalt contents. For segregated binder course mixes, equations were developed to adjust the measured asphalt content to account for the change in gradation from the JMF as measured on the 12.5-mm (½-in.) and either 4.75-mm (No. 4) or 2.36-mm (No. 8) sieves.

Asphalt content must be closely controlled in hot-mix asphalt (HMA) mixes to obtain optimum serviceability and durability. An HMA pavement can ravel or crack if it is deficient in asphalt content by as little as ½ percent, whereas ½ percent excessive asphalt content can cause flushing and rutting.

Quality control and quality assurance (QA) of HMA pavements generally require the measurement of asphalt content in HMA mixes during production using either a standard extraction test or a nuclear asphalt content gauge. However, the measured value can vary from test to test because of material, sampling, and testing variability. In recent years, the material variability has been reduced substantially by the use of automated HMA facilities. Testing proficiency can be improved through training. Obtaining a representative HMA sample for testing still remains a problem because of either segregation or ineffective sampling and splitting techniques. When coarser mixes (binder and base courses) made with larger maximum particle-sized aggregates are involved, the sampling variation can overshadow the material and testing variations. Coarse HMA mixes tend to segregate. The coarse aggregate fraction in the HMA mix holds less asphalt cement by weight compared with the fine aggregate fraction. Segregation causes the proportions of coarse and fine aggregate particles (therefore, the gradation) to vary in HMA samples and thus affect the measured asphalt contents. There is a need to evaluate the effect of aggregate gradation on measured asphalt content so that an adjusted asphalt content that is closer to the asphalt content actually incorporated in the HMA mix can be ascertained.

P. S. Kandhal, National Center for Asphalt Technology, 211 Ramsay Hall, Auburn University, Auburn, Ala. 36849-5354. S. A. Cross, Civil Engineering Department, University of Kansas, 2006 Learned Hall, Lawrence, Kans. 66045.

PROJECT DETAILS

The test data for this study were obtained from a major four-lane Interstate paving project in Pennsylvania. This rehabilitation project involved 50.8 mm (2 in.) of Pennsylvania ID-2 binder course (a dense-graded binder mix with a maximum aggregate size of 38.1 mm or 1½ in.) and 38.1 mm (1½ in.) of Pennsylvania ID-2 wearing course (a dense-graded wearing mix with a maximum aggregate size of 12.5 mm or ½ in.). The job mix formulas (JMFs) for the binder and wearing course mixtures are given in Tables 1 and 2, respectively.

Northbound (NB) and southbound (SB) lanes were paved with separate pavers. Because the mix acceptance or QA samples were obtained behind each paver separately, the test data have been reported and analyzed separately for NB and SB lanes. Pennsylvania Department of Transportation (PennDOT) has a statistically based end result specification for HMA pavements that requires obtaining loose mix samples behind the paver at random locations. The entire loose mix is scraped out of a well-defined area (usually 229 × 229 mm or 9 × 9 in.) at the selected random location to minimize segregation as a result of sampling operation. Five loose mix sublot samples are obtained for each lot consisting of about 500 Mg (550 tons). These samples are sent to PennDOT central laboratory for extraction to determine the mix composition. Roadway cores are also obtained after compaction and sent to the central laboratory for determination of the pavement density. Price adjustments for each lot are calculated by the central laboratory on the basis of three pay items: asphalt content, the percentage of material passing a 75-μm (No. 200) sieve, and the roadway density.

A total of 547 binder mix samples (271 in NB lanes and 276 in SB lanes) and 147 wearing mix samples (67 in NB lanes and 80 in SB lanes) were obained behind the paver and tested by the central laboratory.

A substantial amount of segregation was observed in the compacted binder course mix of this project apparently because of mix handling and placing operations. Obviously, the mix gradation of sublot samples obtained behind the paver varied considerably and affected the extracted asphalt con-

TABLE 1 Summary Statistics for Binder Mixes

Test Parameter	JMF	NB Lanes n=271 Mean	NB Lanes n=271 Std. Dev.	SB Lanes n=276 Mean	SB Lanes n=276 Std. Dev.	All n= 547 Mean	All n= 547 Std. Dev.
Asphalt Content (%)	4.8	4.70	0.429	4.66	0.416	4.68	0.422
Density (pcf)	N/A	153.6	1.69	153.5	1.96	153.6	1.83
1-1/2 Inch (%)	100	99.9	0.77	100.0	0.00	100.0	0.54
1 Inch (%)	92	92.2	6.74	91.9	5.16	92.0	5.99
1/2 Inch (%)	56	63.0	8.32	62.2	7.78	62.6	8.05
No. 4 (%)	39	40.4	5.19	42.7	5.81	41.5	5.63
No. 8 (%)	30	30.8	3.77	32.3	4.07	31.6	4.00
No. 16 (%)	19	22.1	2.70	22.2	2.81	22.2	2.75
No. 30 (%)	12	16.3	2.27	15.7	2.16	16.0	2.23
No. 50 (%)	8	11.2	1.67	10.5	1.69	10.8	1.71
No.100 (%)	6	7.59	0.984	7.42	1.094	7.51	1.044
No. 200 (%)	4.8	5.34	0.693	5.37	0.807	5.36	0.752

tent. Because a large number of binder mix samples were obtained at random locations behind the paver on this project and were analyzed for mix composition (asphalt content and gradation), a unique opportunity was available for evaluating the effect of aggregate gradation on the measured asphalt contents. Material production variability was considered to be minimal on this project because an automated HMA facility was used, and the mix samples obtained at the facility were reasonably uniform in composition. The testing variability is also considered to be minimal because all extraction testing was done in the PennDOT central laboratory by essentially the same testing crew. ASTM D2172 (Method D) was used for extracting the asphalt cement from HMA mix samples.

It is possible to conduct a similar study in a laboratory. A mix can be prepared with a known asphalt content, intentionally segregated, and then extracted. This would eliminate the inherent material variation. However, it is not possible to simulate the segregation that occurs in the field. Also, it is not practical to test a very large number of samples as was done in this study.

TEST RESULTS

Because of space restrictions it is not possible to include in this paper the mix composition test data for 547 binder mix samples and 147 wearing mix samples. However, Tables 1

TABLE 2 Summary Statistics for Wearing Mixes

Test Parameter	JMF	NB Lanes n=67 Mean	NB Lanes n=67 Std. Dev.	SB Lanes n=80 Mean	SB Lanes n=80 Std. Dev.	All n= 147 Mean	All n= 147 Std. Dev.
Asphalt Content (%)	6.6	6.37	0.270	6.45	0.342	6.41	0.313
Density (pcf)	N/A	143.6	2.38	142.5	2.70	143.0	2.61
1/2 Inch (%)	100	100.0	0.00	100.0	0.00	100.0	0.00
3/8 Inch (%)	96	96.6	1.43	96.8	1.48	96.7	1.46
No. 4 (%)	72	70.8	4.35	71.8	3.36	71.3	3.86
No. 8 (%)	48	49.4	3.82	49.8	2.35	49.6	3.10
No. 16 (%)	34	35.0	2.49	34.9	1.49	34.9	2.00
No. 30 (%)	24	25.7	1.88	25.5	1.17	25.6	1.53
No. 50 (%)	16	16.4	1.83	16.6	1.36	16.5	1.59
No.100 (%)	10	9.28	1.253	9.54	0.913	9.42	1.085
No. 200 (%)	4.5	5.54	0.779	5.57	0.654	5.56	0.711

and 2 give the summary statistics for binder mixes and wearing mixes, respectively. Figures 1 through 4 give the control charts of the test data for asphalt content, the percent passing the 12.5-mm (½-in.), 4.75-mm (No. 4), and 2.36-mm (No. 8) sieves for 271 binder mix samples obtained from the NB lanes of the paving project. The control charts of the test data from the SB lanes are similar to those from the NB lanes and, therefore, are not included.

ANALYSIS OF TEST RESULTS

The purpose of this study was to determine the effect of a change in gradation on the corresponding measured asphalt content. If a strong correlation exists between gradation and asphalt content, a part of the deviation from the JMF in the measured asphalt content could be explained by the measured deviation in gradation.

As mentioned earlier, the summary statistics of mean and standard deviation for the quality assurance data are shown in Table 1 for the binder mixes and Table 2 for the wearing mixes. For the binder mixes, the standard deviation is over 5 percent for percent passing the 25.4-mm (1-in.), 12.5-mm (½-in.), and 4.75-mm (No. 4) sieves, and 0.42 percent for asphalt content.

Table 2 shows lower standard deviations for the wearing mixes for most sieve sizes; none of the sieve sizes had a standard deviation over 3.9 percent. The standard deviation for asphalt content was 0.31 percent for the wearing mixes. However, a review of the control charts showed that the standard deviation for asphalt content might be artificially high because of an apparent change in the JMF asphalt content by the contractor that did not appear in the test records.

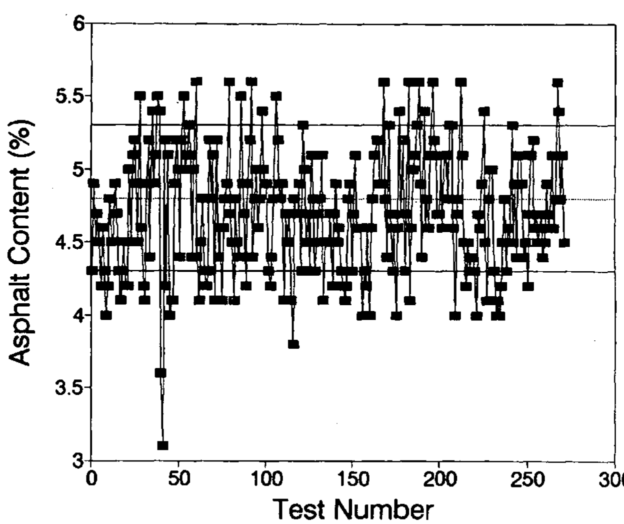

FIGURE 1 Control chart for asphalt content in binder mixes (NB lanes).

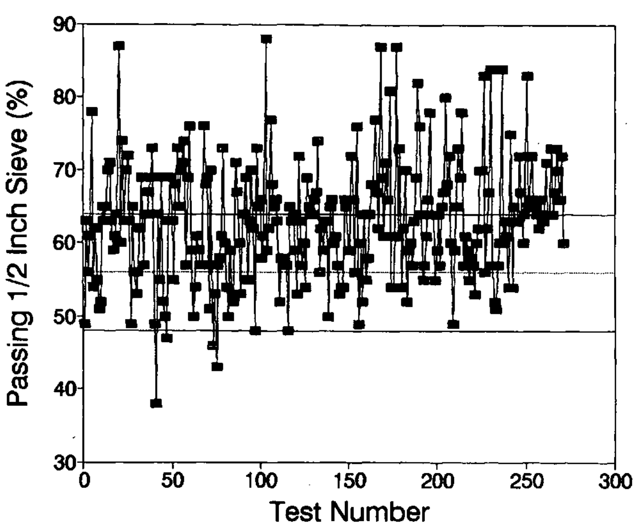

FIGURE 2 Control chart for passing ½-in. sieve in binder mixes (NB lanes).

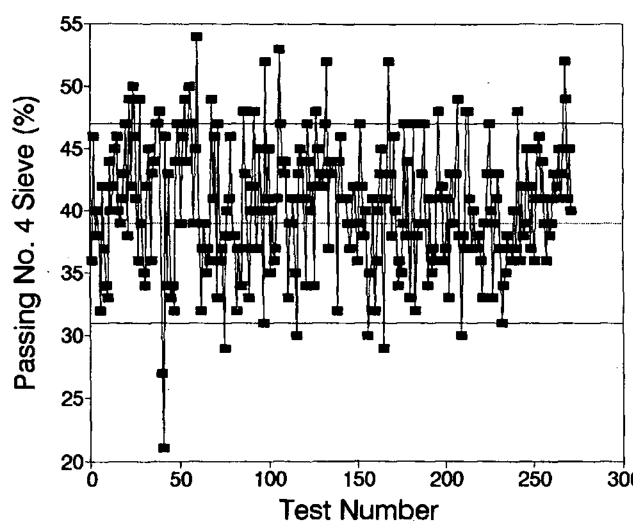

FIGURE 3 Control chart for passing No. 4 sieve in binder mixes (NB lanes).

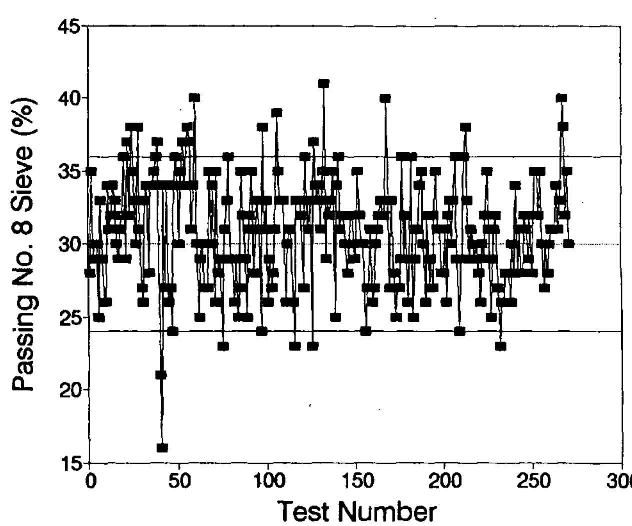

FIGURE 4 Control chart for passing No. 8 sieve in binder mixes (NB lanes).

Control charts of the test data for asphalt content and the percent passing the 12.5-mm (½-in.), 4.75-mm (No. 4), and 2.36-mm (No. 8) sieves for the binder mixes (NB lanes) are shown in Figures 1 through 4. The permissible tolerance limits for these four test parameters were ±0.5, ±8, ±8, and ±6 percent, respectively. Tables 3 and 4 show the frequency with which the above test parameters were within and outside the specification tolerance limits for the binder and wearing mixes, respectively. For the binder mix, asphalt content was outside the specification limits 23.4 percent of the time and the percent passing the 12.5-mm (½-in.), 4.75-mm (No. 4), and 2.36-mm (No. 8) sieves 28.9, 20.3, and 17.5 percent of the time, respectively. From the control charts and the data in Table 3, it is obvious that the binder mix sampled from the roadway was not uniform. Review of the test data and visual observations showed segregation of the mix to be a major problem on both the NB and SB lanes.

Table 4 shows the frequency with which the wearing mix test parameters of asphalt content and the percent passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves were within specification tolerance limits. The permissible tolerance limits for these three test parameters were ±0.4, ±8, and ±6 percent, respectively. Asphalt content was outside the specification limits 21.8 percent of the time, and the percent passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves 2.1 and 5.5 percent of the time, respectively. Review of the control charts and test data showed that the gradation of the mix was within project limits 95 percent of the time. Some of the scatter in asphalt content occurred when the contractor lowered the asphalt content on the NB lanes from 6.6 percent to approximately 6.2 percent after 35 tests. However, the available test data did not show a corresponding change in the JMF asphalt content. If the JMF had been changed to 6.2 percent, as the data indicate, and the applicable tolerance of 0.4 percent applied, the percent of the asphalt content tests within specification limits would have changed from 76.1 to 97.0 percent for the NB lanes and from 78.2 to 87.8 percent for all of the data.

Correlation analysis was performed to determine whether the mat density or the percentages passing various sieve sizes correlate with asphalt content. Table 5 shows the results of the correlation analysis for the binder mixes, by lane, and with all of the data. The results show that all of the parameters except unit weight (density of the core samples) and percent passing the 38.1-mm (1½-in.) sieve have a high probability of a true correlation ($\alpha = 0.0001$) with asphalt content. The best

TABLE 3 Frequency Distribution of Test Data for Binder Mixes

		NB Lanes	SB Lanes	All
Asphalt Content	In Spec.	74.2	79.0	76.6
	Out - Low	15.9	16.7	16.3
	Out - High	9.9	4.3	7.1
Percent Passing 1/2 Inch Sieve	In Spec.	67.5	74.6	71.1
	Out - Low	9.2	9.8	9.5
	Out - High	23.3	15.6	19.4
Percent Passing No. 4 Sieve	In Spec.	84.9	74.6	79.7
	Out - Low	1.5	1.5	1.5
	Out - High	13.6	23.9	18.8
Percent Passing No. 8 Sieve	In Spec.	87.8	77.2	82.5
	Out - Low	2.2	1.8	2.0
	Out - High	10.0	21.0	15.5

TABLE 4 Frequency Distribution of Test Data for Wearing Mixes

		NB Lanes	SB Lanes	All
Asphalt Content	In Spec.	76.1	80.0	78.2
	Out - Low	23.9	12.5	17.7
	Out - High	0.00	7.5	4.1
Percent Passing No. 4 Sieve	In Spec.	95.5	100.0	97.9
	Out - Low	3.0	0.0	1.4
	Out - High	1.5	0.0	0.7
Percent Passing No. 8 Sieve	In Spec.	89.5	98.8	94.5
	Out - Low	1.5	0.0	0.7
	Out - High	9.0	1.2	4.8

TABLE 5 Summary of Correlation Coefficients (*R*) with Asphalt Content for Binder Mixes

	NB Lanes		SB Lanes		All	
	n=271		n=276		n= 547	
Parameter	R	Alpha*	R	Alpha*	R	Alpha*
Density	0.121	0.0474	-0.033	0.589	0.040	0.3546
1 1/2 Inch	0.056	0.3577	N/A	N/A	N/A	N/A
1 Inch	0.413	0.0001	0.517	0.0001	0.455	0.0001
1/2 Inch	0.649	0.0001	0.790	0.0001	0.716	0.0001
No. 4	0.822	0.0001	0.842	0.0001	0.800	0.0001
No. 8	0.819	0.0001	0.825	0.0001	0.795	0.0001
No. 16	0.738	0.0001	0.682	0.0001	0.707	0.0001
No. 30	0.635	0.0001	0.556	0.0001	0.597	0.0001
No. 50	0.586	0.0001	0.457	0.0001	0.521	0.0001
No.100	0.640	0.0001	0.474	0.0001	0.554	0.0001
No. 200	0.611	0.0001	0.476	0.0001	0.535	0.0001

* 1-Alpha = Probability correlation coefficient (R) not equal to 0.

correlations with asphalt content for the binder mixes were with the percent passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves.

The results of the correlation analysis for the wearing mixes are shown in Table 6. The analysis shows the highest probability of a true correlation ($\alpha = 0.0001$) with asphalt content for the percent passing the 300-μm (No. 50), 150-μm (No. 100), and 75-μm (No. 200) sieves. However, the correlation coefficients (*R*) are not only too low to be useful, but they also indicate an unexpected trend—that is, the asphalt content decreases with an increase in the material passing these sieves.

To further investigate the relationship between asphalt content and gradation, regression analysis was performed. The purpose of this study is to determine whether asphalt content could be predicted from measured gradation; therefore, asphalt content was selected as the dependent variable and gradation as the independent variable. Table 7 is a summary of the best coefficients of determination (R^2) by lane and by mix type for the binder and wearing mixes.

The data in Table 7 indicate that no correlation exists between asphalt content and the percent passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves for the wearing mix. There is very little spread in the gradation data, and no segregation was observed in the field. Therefore, all the scatter appears to be caused by the normal variation in the material, sampling, and testing operations.

Figures 5 and 6 show the relationship between asphalt content and the percent passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves for the binder mix in both lanes, respectively. The results show that there is a relationship between change in gradation and measured asphalt content. The re-

TABLE 6 Summary of Correlation Coefficients (*R*) with Asphalt Content for Wearing Mixes

	NB Lanes		SB Lanes		ALL	
	n=67		n=80		n= 147	
Parameter	R	Alpha*	R	Alpha*	R	Alpha*
Density	-0.022	0.8577	-0.003	0.9807	-0.038	0.6489
1/2 Inch	N/A	N/A	N/A	N/A	N/A	N/A
3/8 Inch	0.443	0.0002	0.114	0.3135	0.247	0.0025
No. 4	-0.106	0.3942	0.073	0.5174	0.009	0.9144
No. 8	-0.165	0.1824	0.124	0.2716	-0.014	0.8653
No. 16	-0.113	0.3637	0.242	0.0307	0.050	0.5495
No. 30	-0.264	0.0308	0.078	0.4940	-0.101	0.2229
No. 50	-0.418	0.0004	-0.330	0.0028	-0.345	0.0001
No.100	-0.326	0.0071	-0.490	0.0001	-0.375	0.0001
No. 200	-0.257	0.0356	-0.522	0.0001	-0.391	0.0001

* 1 - alpha = Probability correlation coefficient (R) not equal to 0.

TABLE 7 Summary of Coefficients of Determination (R^2) with Asphalt Content for ID2 Mixes

	NB Lanes	SB Lanes	All
Number of Observations	n=271	n=276	n= 547
	R^2	R^2	R^2
Independent Variable	ID2 Binder Mixes		
1/2 Inch Sieve	0.422	0.625	0.515
No. 4 Sieve	0.676	0.708	0.640
No. 8 Sieve	0.671	0.680	0.632
1/2 Inch & No. 4 Sieves	0.686	0.722	0.669
1/2 Inch & No. 8 Sieves	0.685	0.729	0.676
	ID2 Wearing Mixes		
No. 4 Sieve	0.011	0.005	0.000
No. 8 Sieve	0.027	0.016	0.000

lationships show that as the mix becomes finer for the given sieve size, the asphalt content increases. The relationships have the following form:

$$AC = 2.186 + 0.060(P4) \qquad R^2 = 0.64 \tag{1}$$

$$AC = 2.025 + 0.084(P8) \qquad R^2 = 0.63 \tag{2}$$

where

AC = asphalt content,
$P4$ = percent passing the 4.75-mm (No. 4) sieve, and
$P8$ = percent passing the 2.36-mm (No. 8) sieve.

Equations 1 and 2 indicate that the measured asphalt contents of the binder course mix in this study increase by 0.06 and 0.08 percent (on the basis of slopes of the regression lines) with each 1 percent increase in the material passing 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves, respectively, from the JMF. Conversely, there will be a similar decrease in the measured asphalt contents if the sampled mix is coarser than the JMF. These so-called "correction factors" can be used to correct the measured asphalt content for each 1 percent deviation from the JMF. Some researchers (*1–3*) have developed the following "correction factors" for binder course mixes (maximum aggregate size greater than 25.4 mm or 1 in.) on the basis of the material passing the 2.36-mm (No. 8) sieve after analyzing limited field data.

Researcher	*Correction Factor (%)*
Customary in United Kingdom for rolled-asphalt mix before 1970 (*1*)	0.08
Goodsall and Mathews (*1*)	0.14
Warden (*2*)	0.16
Brown et al. (*3*)	0.10
Kandhal and Cross (this paper)	0.08

The "correction factor" is expected to be generally dependent on the fine aggregate gradation, the particle shape and surface texture of the aggregates, and the actual asphalt content of the binder course mix.

Further analysis was performed to determine whether a multivariable model would give a statistically stronger model.

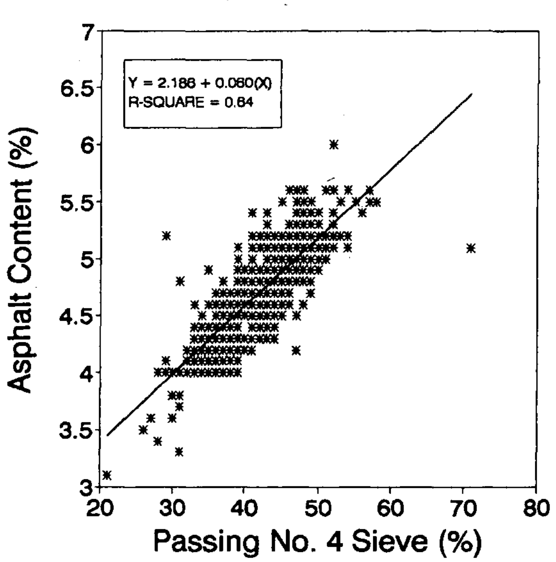

FIGURE 5 Percentage passing No. 4 sieve versus asphalt content (binder mixes from both lanes).

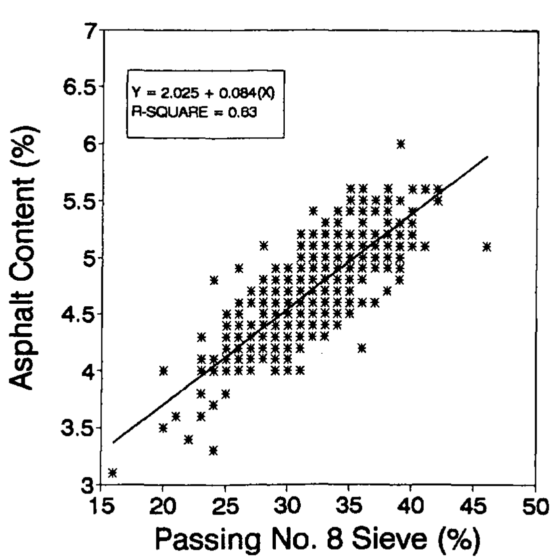

FIGURE 6 Percentage passing No. 8 sieve versus asphalt content (binder from both lanes).

The best multivariable model was found by including the 12.5-mm (½-in.) sieve with either the 4.75-mm (No. 4) or 2.36-mm (No. 8) sieve. The relationship between the asphalt content and the percent passing the 12.5-mm (½-in.) sieve is shown in Figure 7. The relationship has an R^2 of 0.52. By combining the 12.5-mm (½-in.) sieve with the 4.75-mm (No. 4) sieve the model has an R^2 of 0.67. The relationship has the following form:

$$AC = 1.947 + 0.014(P½) + 0.045(P4) \qquad R^2 = 0.67 \qquad (3)$$

where

AC = asphalt content,
$P½$ = percent passing 12.5-mm (½-in.) sieve, and
$P4$ = percent passing 4.75-mm (No. 4) sieve.

A slightly stronger model was found by using th 12.5-mm (½-in.) an 2.36-mm (No. 8) sieves. The relationship is shown in Figure 8 and has the following form:

$$AC = 1.757 + 0.016(P½) + 0.061(P8) \qquad R = 0.68 \qquad (4)$$

where

AC = asphalt content,
$P½$ = percent passing 12.5-mm (½-in.) sieve, and
$P8$ = percent passing 2.36-mm (No. 8) sieve.

The data shown in Figures 6 through 8 show that the measured asphalt content is affected by a change in gradation. A change in gradation will cause a corresponding change in the measured asphalt content. By using any of the four models, the measured asphalt content can be adjusted for the amount caused by the change in gradation. The adjusted asphalt content can then be checked against the tolerance limits for the JMF asphalt content to determine whether the variation in asphalt content is caused by the change in gradation or segregation or by a true change in the asphalt content.

To check the models developed, the measured asphalt contents were adjusted for the measured change in gradation using Equations 1, 2, and 4. The adjusted asphalt content (AAC) is determined by adding the difference between the measured asphalt content (MAC) and the predicted asphalt content (PAC) to the JMF. The AAC is then checked against the upper and lower tolerance limits of the JMF asphalt content.

$$AAC = JMFAC + (MAC - PAC) \qquad (5)$$

where

AAC = asphalt content adjusted for gradation,
JMFAC = job mix formula asphalt content,
MAC = measured asphalt content, and
PAC = predicted asphalt content from Equation 1, 2, 3, or 4.

Figure 9 shows the control charts for the asphalt content adjusted using Equation 5 for binder mix samples from NB lanes. Table 8 shows the frequency with which AAC, adjusted

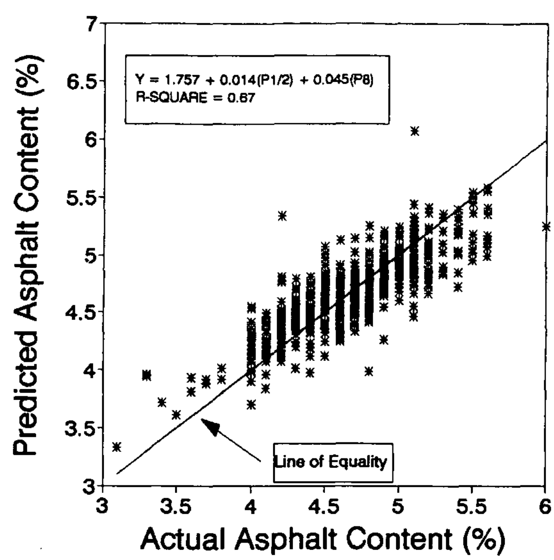

FIGURE 8 Actual versus predicted asphalt content (binder mixes from both lanes).

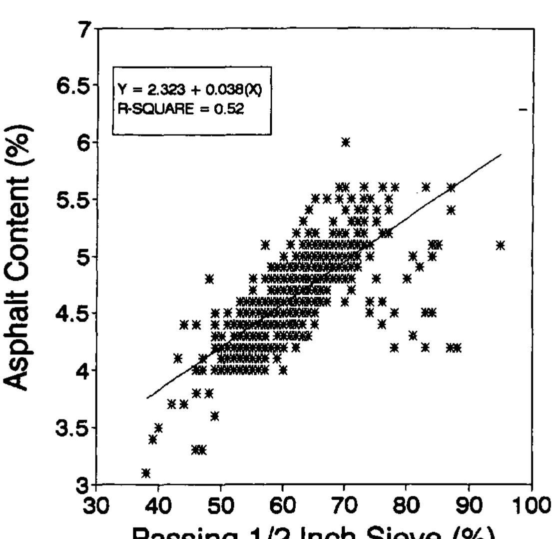

FIGURE 7 Percentage passing ½-in. sieve versus asphalt content (binder mixes from both lanes).

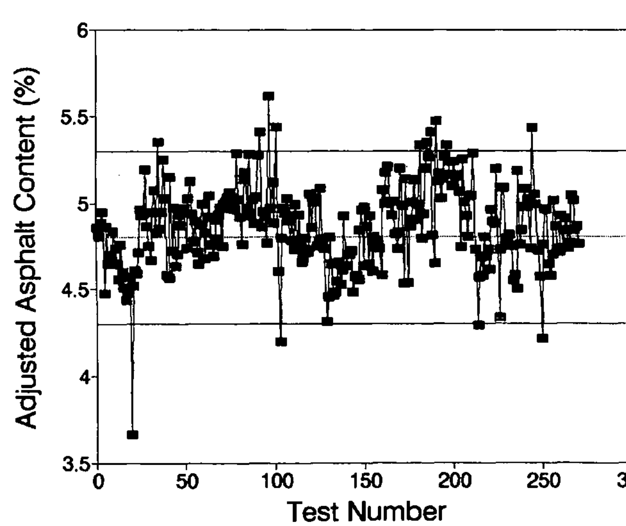

FIGURE 9 Control chart for asphalt content adjusted for ½-in. and No. 8 sieves (binder mixes from NB lanes).

TABLE 8 Frequency Distribution of Adjusted Asphalt Content for Binder Mixes

Asphalt Content		NB Lanes	SB Lanes	All
Adjusted on No. 4 Sieve (eq. 1)	In Spec.	93.7	96.7	95.2
	Out - Low	0.4	0.8	0.5
	Out - High	5.9	2.5	4.2
Adjusted on No. 8 Sieve (eq. 2)	In Spec.	94.1	96.0	95.1
	Out - Low	0.4	2.9	1.6
	Out - High	5.5	1.1	3.3
Adjusted on 1/2" & No. 8 Sieve (eq. 4)	In Spec.	94.8	96.4	95.6
	Out - Low	1.5	0.7	1.1
	Out - High	3.7	2.9	3.3

using Equations 1, 2, and 4, is within specification limits. The results show 95 percent of the AACs within specification limits regardless of the equations used. The AACs for the binder mix show a compliance percentage very similar to that obtained for the wearing mixes in which segregation was not a problem.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the data obtained in this study the following conclusions are warranted.

1. In segregated HMA pavements, some of the deviation in asphalt content from the JMF is controlled by the change in gradation of the mix from the JMF.
2. When segregated binder course mixes were sampled behind the paver, the percent passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves correlated with MAC.
3. For segregated binder course mixes, the asphalt content can be adjusted to account for the change in gradation from the JMF as measured on the 12.5-mm (½-in.) and either the 4.75-mm (No. 4) or 2.36-mm (No. 8) sieves, as shown in Equations 3 and 4. However, these equations are valid for the aggregates and the JMF used in this study. Care should be taken in applying these formulas to other mixes.
4. Because no significant segregation occurred during the laydown of the wearing course mix, gradation could not be related to the measured asphalt content.

REFERENCES

1. Goodsall, G. D., and D. H. Mathews. Sampling of Road Surfacing Materials. *Journal of Applied Chemistry*, Vol. 20, Dec. 1970.
2. Warden, W. B. Bitumen Extraction Testing. Presented at 6th World Meeting of the International Road Federation, Montreal, Quebec, Canada, Oct. 1970.
3. Brown, E. R., R. Collins, and J. R. Brownfield. Investigation of Segregation of Asphalt Mixtures in State of Georgia. In *Transportation Research Record 1217*, TRB, National Research Council, Washington, D.C., 1989.

The opinions, findings, and conclusions expressed here are those of the authors and not necessarily those of the National Center for Asphalt Technology or Auburn University or the University of Kansas.

Publication of this paper sponsored by Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures.