Effect of Asphalt Mixture Characteristics and Design on Frictional Resistance of Bituminous Wearing Course Mixtures

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Investigations of 13 field test sections indicated that the key to preventing frictional resistance problems early in the life of dense-graded surface course mixtures is to maintain field air-void contents above 3.4 percent for 12.5-mm (½-in.) maximum aggregate size (ID-2) mixtures and 3.0 percent for 25.4-mm (1-in.) maximum aggregate size (ID-3) mixtures. Some existing mixture design and acceptance procedures, as well as existing field control and acceptance procedures, were determined to be primary contributors to the design and acceptance of mixtures which are likely to have low air-void contents and low frictional resistance. A procedure was developed and recommended to determine optimum asphalt content and to screen mixture designs that may be particularly sensitive to changes in asphalt content. A Texas gyratory compactor, modified to simulate the new Strategic Highway Research Program gyratory compactor, was found to do a better job than Marshall compaction of producing laboratory mixtures more representative of the field. However, additional studies are clearly needed to identify and validate the best laboratory compaction method. It was determined that one of the key factors in controlling frictional resistance problems is the control of air-void contents of laboratory-compacted plant-produced mixtures. More accurate determination of maximum specific gravities in the field would help in controlling air-void contents more accurately during construction.

Higher traffic levels, load magnitudes, and truck-tire pressures require higher quality asphalt mixtures that can maintain an adequate level of frictional resistance throughout the design life of the pavement. In recent years, Pennsylvania Department of Transportation (PennDOT) ID bituminous wearing courses have sometimes exhibited low wet weather frictional resistance early in their design lives, indicating that existing specifications, mixture designs, and/or construction procedures may be inadequate. However, before existing requirements and procedures could be improved, it was necessary to clearly identify the factors having the greatest influence on the frictional resistance characteristics of the ID bituminous surfaces. Much of the prior research in the area of frictional resistance has concentrated on long-term and seasonal variations in frictional resistance; considerably less emphasis has been placed on the causes of the erratic variation in frictional resistance observed within relatively short periods after placement.

OBJECTIVES

The objectives of this research program were

1. To identify the factors that contribute to frictional resistance problems early in a pavement's life;
2. To determine which parts of PennDOT's specifications, design, and construction operation were responsible for producing mixtures with frictional resistance problems;
3. To determine what improvements to current specifications would ensure that only pavements having good frictional resistance characteristics are produced; and
4. To recommend specific changes to existing methods of designing and constructing bituminous surfaces that will correct the existing problems associated with early frictional resistance problems.

SCOPE

Thirteen test sections were selected for evaluation from among four districts in Pennsylvania: 10 with ID-2 surfaces and 3 with ID-3 surfaces. [ID-2 and ID-3 refer to dense-graded wearing courses with 12.5-mm (½-in.) and 25-mm (1-in.) maximum aggregate size, respectively (*1*).] Eight of the 10 ID-2 pavements and 2 of the 3 ID-3 pavements were identified by district materials engineers as exhibiting frictional resistance problems within 1 year after placement. The other sections were identified as sections exhibiting good performance.

RESEARCH METHODS AND MATERIALS

Research Approach

Available materials, construction, and performance information were obtained for selected pavement sections. Each pavement section was also cored and skid tested. Cores obtained from both within and between the wheel track were carefully analyzed for voids, density, overall composition, and variation in properties. Material samples (aggregate and asphalt) were obtained from project sources to perform laboratory tests on mixtures produced using the job-mix formula. The materials were obtained during the course of this study, not during construction. Therefore, the potential exists for some differences between laboratory and field specimens. Results of laboratory investigations were used to determine problems related to mixture design and evaluation methods and to identify procedures that will help identify problem or sensitive mixtures in the future.

Selection of Field Test Sections

A summary of the 13 field test sections selected for evaluation is presented in Table 1. Five of the 10 ID-2 sections were composed

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TABLE 1 Summary of Field Test Sections

District	Section Number	Traffic ADT	Traffic ADTT	Age at Sampling (Years)	Visual Observations	Skid Number[a]	% Air Voids[b]
ID-2 Mixtures							
2	2-1	2,125	361	4.8	Slick Appearance	30.3	3.2
	2-2	2,125	361	4.8	Bleeding in general, with severe localized bleeding	30.5	3.1
	2-3	4,960	298	0.9	Bleeding in general, with severe localized bleeding	27.9	3.2
	2-4	13,663	1435	1.0	Light Bleeding	26.2	1.9
9	9-1	17,720	1595	2.7	Bleeding	30.5	3.1
	9-2	17,720	1595	1.9	Good Performance	39.9	5.6
	9-3	10,015	N/A	1.0	Bleeding in general, with severe localized bleeding	32.0	2.1
11	11-1	18,710	N/A	1.0	Bleeding	35.7	3.2
	11-2	8,000	N/A	1.0	Good Performance	34.4	3.4
	11-3	11,500	N/A	1.0	Bleeding	33.5	2.2
ID-3 Mixtures							
8	8-1	12,000	240	3.2	Light Bleeding	54.6	2.8
	8-2	5,000	300	3.1	Light Bleeding	34.2	2.3
	8-3	17,000	1360	3.1	Good Performance	42.1	3.1

[a] Skid number determined using ASTM method E-274 (SN_{40}), tested in September 1991.

[b] Determined from wheel path cores obtained in May 1991, using the average of maximum specific gravities measured by PennDOT and PTI on mixture recovered from field cores.

of mixtures designed according to PennDOT's special provision for minimizing rutting in bituminous concrete (*2*). The poorly performing sections had excessive asphalt on the surface and resulting loss of texture. It should be noted that problems with these test sections were observed during the first summer after construction. The district engineers' assessments of the performance of these test sections were verified through visual observations. Rutting was not observed on any of the test sections.

Average daily traffic (ADT) and truck traffic (ADTT) levels varied from 2,000 to 19,000 ADT (300–1,600 ADTT) on the ID-2 sections and from 5,000 to 17,000 ADT (240–1,360 ADTT) on the ID-3 sections. Some of the higher traffic levels were reported on the good performing sections (9-2, 11-2, and 8-3), indicating that high traffic level and frictional resistance problems were unrelated.

Project and Material Information

Detailed information on job mix formulas, original master mixture designs, quality control and assurance test results, aggregate data, and asphalt cement data were obtained for each of the projects. The information is available from PennDOT (*3*).

Field Cores

Ten cores of 152.4-mm (6-in.) diameter were obtained from 305-m (1,000-ft) test strips within each of the 13 test sections. Five cores were obtained from within the wheel path (which was identified by visual observation), and five cores were obtained from between wheel paths. The outer lane was sampled on four-lane facilities. Two cores were obtained from within each of five 61-m (200-ft) subsections. Specific sampling locations were selected at random by marking off 1.5 m (5 ft) from the start of each 61-m (200-ft) subsection.

The surface mixture was sawn from the cores and bulk density measurements were made. Material from three between–wheel path specimens was then broken down for maximum specific gravity measurements. The same three specimens were then sent to PennDOT's Materials and Testing Division (MTD) laboratories for maximum specific gravity measurements. MTD made two maximum specific gravity determinations for each specimen. PennDOT's MTD also performed extractions on all cores to determine asphalt contents and to perform gradation analyses. Results were used to determine mixture air-void content (VTM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). Aggregate recovered from cores was used for three purposes: (*a*) to perform gradation analysis for comparison to the job-mix formula, (*b*) to determine the crush count of the coarse aggregate, and (*c*) to analyze size distribution and determine free asphalt on the material passing the no. 200 sieve.

Frictional Resistance Measurements

Skid number (SN_{40}) was determined using ASTM E274 (ribbed tire). Tests were performed on 305-m (1,000-ft) test strips within each of the test sections. Five replicate measurements were obtained from within each 61-m (200-ft) subsection of each project investigated. The standard deviation of SN_{40} for all 13 test sections was between 0.58 and 2.22 (most had a standard deviation less than 1.0). The tests were performed in October, which is generally considered to be the time of year when skid numbers are at their lowest.

Reproduction of Asphalt Mixtures in Laboratory

Three compaction procedures were used to produce mixtures in the laboratory: Marshall (Asphalt Institute Manual Series 2), Texas gyratory (ASTM D4013-81), and modified Texas gyratory. The modified Texas gyratory procedure intended to simulate the Strategic Highway Research Program (SHRP) gyratory compaction procedure, which had not yet been standardized by ASTM, AASHTO, or the Asphalt Institute when this work was done. The procedure used a 1-degree angle of gyration and a constant vertical pressure of 618 kPa (89.7 psi) during compaction. The mixture was continuously gyrated for 200 revolutions (60 rpm).

ANALYSIS OF FACTORS AFFECTING FRICTIONAL RESISTANCE

Based on literature review and discussions with district material engineers and other PennDOT personnel, five main categories of factors were targeted for detailed evaluation:

- Mixture type (ID-2 versus ID-3) and characteristics,
- Material characteristics,
- Mixture designs,
- Plant and construction control, and
- Mixture design procedures.

Analyses and findings related to factors in each of these categories are presented in the following sections.

Mixture Type and Characteristics

Figure 1 illustrates that, for both ID-2 and ID-3 mixtures, lower frictional resistance was observed when mixture air-void contents fell below some critical level. Figure 1a indicates that significantly lower skid numbers resulted for ID-2 mixtures when air-void levels fell below about 3.4 percent, whereas for ID-3 mixtures, Figure 1b shows that skid numbers appeared to be significantly lower when air voids were less than about 2.8 percent. These observations appeared to be rational, since low air-void mixtures are known to be susceptible to flushing and bleeding, conditions which are likely to reduce frictional resistance.

Results of statistical analyses (Comparisons 1 through 5 in Table 2) confirmed that both the differences in air-void levels between groups and the difference in skid numbers between high and low air-void groups were significant at relatively high levels of confidence (low probability of error). Because of the relatively small sample sizes involved in this study, the Student *t*-statistic was used for hypothesis testing. Bartlett's test for equality of variances (*4*) indicated that variances of different air-void groups were significantly different, but that variances of skid numbers within different groups were not significantly different (5 percent probability of error). Therefore, a pooled variance was used to test hypotheses relating to differences in skid numbers.

Given the results of these analyses, the effect of mixture type on skid number was evaluated within specific air-void ranges. Figure 2a shows that ID-3 sections having wheel path air voids greater than 2.5 percent and less than 3.4 percent had higher skid numbers than ID-2 sections with comparable air voids. Statistical analysis (Comparison 6 in Table 2) confirmed this difference to be significant with low probability of error. It appears that larger aggregates in ID-3 mixtures result in more coarse aggregate exposed to the surface, which results in better micro- and macrotexture. The better texture of the ID-3 sections was clearly observed in the field.

Figure 2b shows that for lower air-void contents (2.3 percent and less), the ID-3 mixture offers little, if any, advantage over the ID-2 mixture. Apparently, the surface texture of both mixture types is essentially lost below some critical air-void level. Visual observations in the field, and of cores taken from the field, confirmed that there was little difference in surface texture for these mixtures. Statistical analysis (Comparison 7 in Table 2) also confirmed that there was no significant difference between skid numbers for the two mixture types at low air-void levels.

Since higher skid numbers were observed for both mixture types when air-void levels remained above some critical level, the rest of the investigation was aimed at determining which factors led to mixtures having low air-void contents in the field. The results presented above indicate that ID-2 mixtures should maintain a minimum air-void level of 3.4 percent in the field, whereas ID-3 mixtures should maintain an air-void level of 2.8 percent. However, 3.0 percent is generally considered the accepted minimum by most conventional design procedures.

Materials

An evaluation of reported and measured material properties and characteristics indicated that there were no apparent deficiencies in the materials used in any of the mixtures investigated.

All materials appeared to meet or exceed existing PennDOT specifications for materials to be used in dense-graded surface course mixtures. All coarse aggregates had PennDOT skid resistance level (SRL) ratings (*5*) of good (G) to excellent (E) and crush counts either exceeded or were very close to 85 percent. No differences were observed in the grain size distribution of the fines that would account for the differences observed in the performance of the mixture. The dust/asphalt ratio of all mixtures was less than 0.5 as recommended by the National Asphalt Pavement Association (*6*). Asphalt cement properties measured on recovered asphalt cements revealed nothing unusual.

Mixture Designs

An extensive evaluation of the job-mix formulas, master mix designs, and tests performed on mixture designs reproduced in the laboratory indicated that all mixtures investigated met all relevant specifications for surface course mixtures (*3*). However, other findings appear to indicate that PennDOT's methods of selecting optimum asphalt content and of acceptance of mixture designs were at least partially responsible for the low frictional resistances observed.

The primary problem with the conventional (non-heavy-duty) mixtures appears to be the design asphalt cement content, which, according to the master mixture designs, results in air-void contents

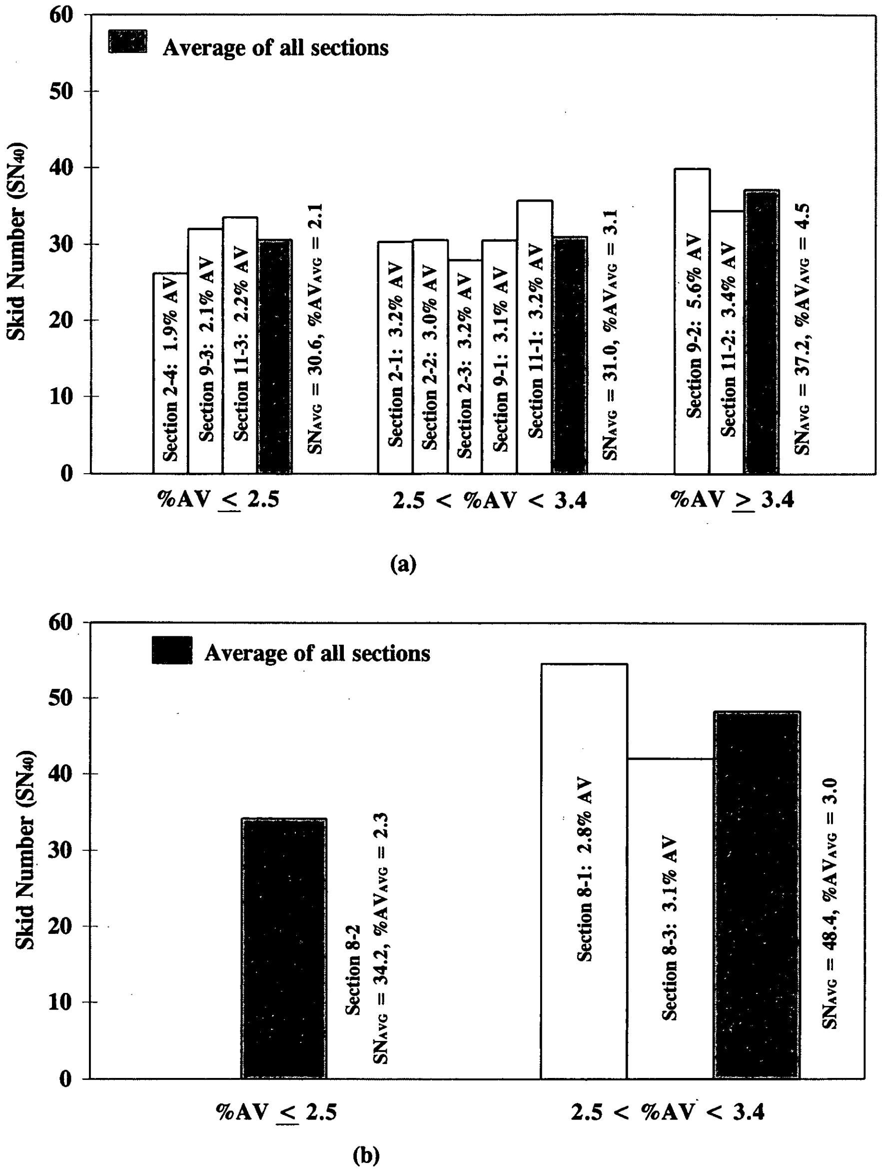


FIGURE 1 Effect of air-void level on skid number: (*a*) ID-2 mixtures; (*b*) ID-3 mixtures.

below 4 percent and in many cases close or equal to 3 percent for the ID-2 mixtures investigated. Table 3 shows the design asphalt contents and corresponding air voids for each mixture as determined from the master designs using PennDOT's procedures for conventional (non-heavy-duty) mixtures. The design air-void content is less than or equal to 4 percent for all ID-2 mixtures and below 3.3 percent for three of the seven ID-2 mix designs.

There are three reasons for the selection of these high asphalt contents: (*a*) lack of prior knowledge that air-void contents below 3.4 percent would likely result in frictional resistance problems for ID-2 mixtures, (*b*) the use of maximum density in selecting the optimum asphalt content, and (*c*) the fact that Marshall compaction does not simulate field densification under traffic. Table 3 clearly shows that higher asphalt contents are consistently required to achieve maximum density than are required to achieve 4 percent air-void content. Given that PennDOT uses only the asphalt content for maximum density and the asphalt content required for 4 percent air voids to determine optimum asphalt content, this guarantees that design asphalt contents will lead to laboratory-compacted mixtures with air-void contents below 4 percent for conventional (non-heavy-duty) mixtures.

Design asphalt cement contents as determined from the master design charts were not a problem with the ID-3 sections (8-1, 8-2, and 8-3). As shown in Table 3, design asphalt contents were selected such that mixtures had 4.0 percent air-void content, which is well above the 2.8 percent value required for suitable performance. The reason 4.0 percent was selected was that the maximum density versus asphalt content relationship never reached a peak for these mixtures, so the optimum asphalt content was selected strictly on the basis of air-void content.

The primary problem with the ID-3 sections appeared to be that Marshall compaction was particularly ineffective in compacting

TABLE 2 Results of Statistical Analyses

Comparison Number	Reference	Null[a] Hypothesis (H_O)	Alternative Hypothesis (H_A)	Student t-Statistic	Result	Probability of Type I Error (α)
1	Figures 1	$\%AV_{<2.5} = \%AV_{>2.5;<3.4}$	$\%AV_{<2.5} < \%AV_{>2.5;<3.4}$	-10.245	Accept H_A	< 0.01
2	Figure 1a	$\%AV_{>2.5;<3.4} = \%AV_{>3.4}$	$\%AV_{>2.5;<3.4} < \%AV_{>3.4}$	-2.899	Accept H_A	< 0.02
3	Figure 1a	$SN_{40}(\%AV_{<2.5}) = SN_{40}(\%AV_{>2.5;<3.4})$	$SN_{40}(\%AV_{<2.5}) < SN_{40}(\%AV_{>2.5;<3.4})$	-0.127	Accept H_O	< 0.01
4	Figure 1a	$SN_{40}(\%AV_{>2.5;<3.4}) = SN_{40}(\%AV_{>3.4})$	$SN_{40}(\%AV_{>2.5;<3.4}) < SN_{40}(\%AV_{>3.4})$	-3.128	Accept H_A	< 0.02
5	Figure 1b	$SN_{40}(\%AV_{<2.5}) = SN_{40}(\%AV_{>2.5;<3.4})$	$SN_{40}(\%AV_{<2.5}) < SN_{40}(\%AV_{>2.5;<3.4})$	-2.620	Accept H_A	< 0.14
6	Figure 2a	$SN_{40}(ID\text{-}2) = SN_{40}(ID\text{-}3)$	$SN_{40}(ID\text{-}2) < SN_{40}(ID\text{-}3)$	-4.708	Accept H_A	< 0.01
7	Figure 2b	$SN_{40}(ID\text{-}2) = SN_{40}(ID\text{-}3)$	$SN_{40}(ID\text{-}2) < SN_{40}(ID\text{-}3)$	-0.713	Accept H_O	< 0.01

[a] The parameters should be interpreted as per the following examples:

$\%AV_{>2.5;<3.4}$: Average air void content of specimens with air void contents greater than 2.5% and less than 3.4%.

$SN_{40}(\%AV_{>2.5;<3.4})$: Average skid number of sections included in referenced figure with air void contents greater than 2.5% and less than 3.4%.

$SN_{40}(ID\text{-}2)$: Average skid number of ID-2 sections included in referenced figure.

these coarser mixtures (see *Specimen Preparation Methods* later in the report). This resulted in mixtures with fictitiously high laboratory-compacted air-void contents relative to the field and, consequently, excessively high asphalt cement contents were selected.

The sensitivity of both ID-2 and ID-3 mixtures to changes in air-void content, with relatively small changes in asphalt content, was found to be a potential problem. Table 4 shows the effect of acceptable variability in asphalt content in the field on compacted air-void content, according to the master mix designs. The table shows that for the design asphalt cement contents selected, acceptable variability in asphalt cement content resulted in unacceptably low air-void content for most of the mixtures investigated.

TABLE 3 Asphalt Cement and Air-Void Contents from Master Designs

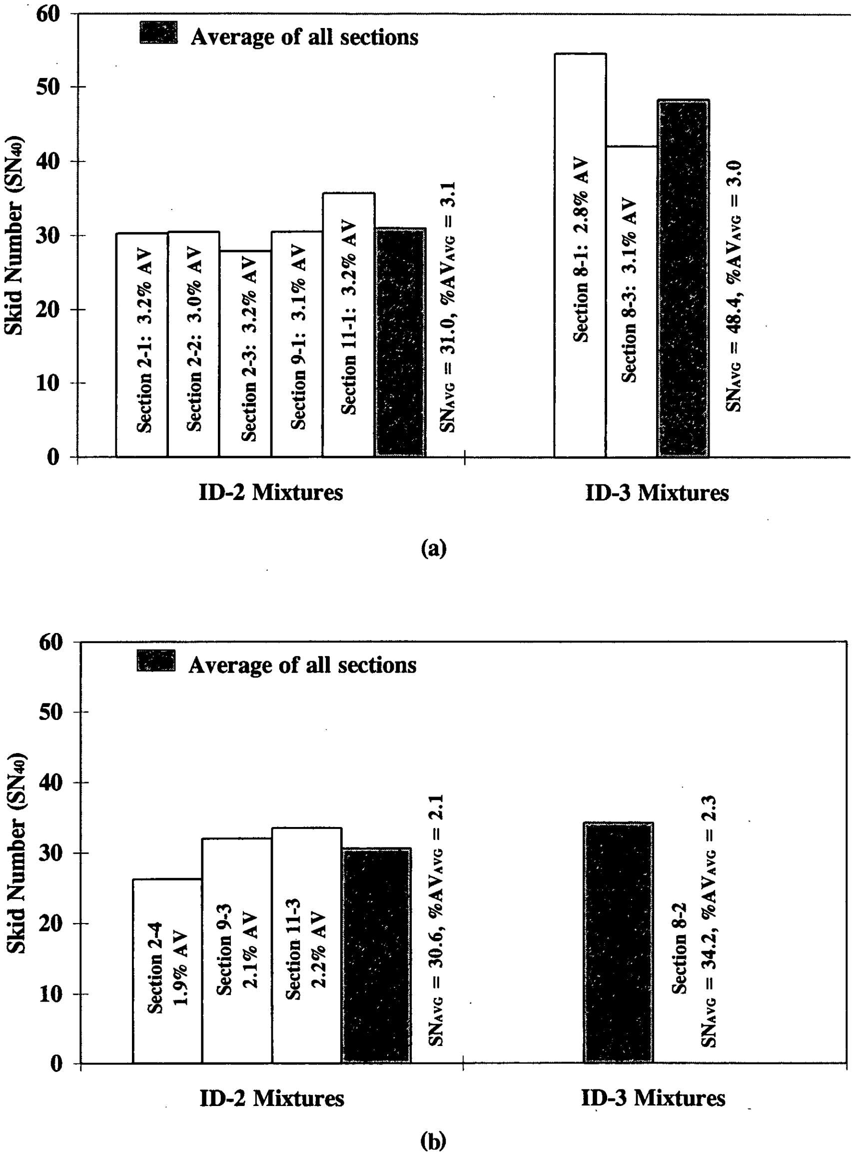
Section	Asphalt content from design charts		Design[a]	
	Maximum Density[b]	4% Air Voids[c]	% Asphalt Content	% Air Voids
2-1	6.0	5.7	5.9	3.2
2-2	6.7	5.8	6.2	3.2
2-3, 2-4	6.4	6.1	6.2	3.7
9-1	6.5	6.1	6.3	3.5
9-2	6.6	6.1	6.3	3.6
9-3	6.5	6.1	6.3	3.0
11-1, 11-2, 11-3	7.0	6.4	6.7	3.6
8-1	-[d]	4.8	4.8	4.0
8-2, 8-3	-	5.4	5.4	4.0

[a] Design optimum asphalt content using PennDOT procedure for conventional (non-heavy-duty) mixtures: Maximum density and 4 percent air-void content.

[b] Asphalt content at peak of density versus asphalt content relationship.

[c] Asphalt content at 4 percent air-void content.

[d] No peak on the design curves for these mixtures.



(a)

(b)

FIGURE 2 Effect of mixture type on skid number: (*a*) sections with air voids between 2.5 and 3.4 percent; (*b*) sections with air voids less than 2.5 percent.

Plant and Construction Control

Gradation and Asphalt Content

Plant control of gradation and asphalt content appeared to be very good on these projects. It was found that gradations were consistently on the fine side of the acceptable range, which agrees with the findings of the study conducted for PennDOT by Kandhal et al. (*7*). However, whether or not slightly fine gradations are a problem is a mixture specific issue. Therefore, instead of imposing tighter controls on gradation limits for all mixtures, a better approach is to impose tighter controls on air-void content of laboratory-compacted, plant-produced mixtures. Table 5 shows that for all but one (ID-3 Section 8-2 was low in asphalt content) of the test sections investigated, asphalt contents measured on samples of field mixtures were within ±0.4 percent of the design asphalt content. In general, it appears that contractors can control asphalt content within ±0.3 percent or better. No penalty points were assigned to any of these jobs.

Another reason to impose tighter air-void controls on laboratory-compacted, plant-produced mixtures is there are always differences between job-mix formulas produced in the laboratory and plant-produced mixtures, even when gradations and asphalt contents are identical. Figure 3 shows that, even though gradation and asphalt content were well controlled on these projects, there were significant differences in laboratory-compacted air-void contents between mixtures composed of laboratory-produced job-mix formulas and plant-produced mixtures. The point is that existing controls on asphalt content and gradation may not be enough to guarantee that suitable mixtures will be produced in the field. Tighter controls on mixture properties and characteristics of laboratory-compacted, plant-produced mixtures are probably needed.

TABLE 4 Sensitivity of Mixture Air-Void Content to Changes in Asphalt Content

Section	Design Asphalt Content[a]		Design Asphalt Content +0.2%		Design Asphalt Content +0.4%	
	%AC[b]	%AV[c]	%AC	%AV	%AC	%AV
2-1	5.9	3.5	6.1	3.1	6.3	2.7
2-2	6.2	3.3	6.4	2.9	6.6	2.8
2-3, 2-4	6.2	3.7	6.4	3.4	6.6	3.0
9-1	6.3	4.0	6.5	3.5	6.7	3.3
9-2	6.3	3.7	6.5	3.3	6.7	3.0
9-3	6.3	3.5	6.5	2.7	6.7	2.7
11-1, 11-2, 11-3	6.7	3.4	6.9	2.7	7.1	2.5
8-1	4.8	4.0	5.0	3.5	5.2	3.0
8-2, 8-3	5.4	3.9	5.6	3.6	5.8	3.0

[a] Design asphalt content from master designs for conventional (non-heavy-duty) mixtures.
[b] Percent asphalt content.
[c] Percentage air-void content.

Mixture Acceptance Criteria

Figures 6 and 7 illustrate how natural variation in maximum specific gravity of a given mixture may result in inaccurate determination of mixture air-void content, which can lead to acceptance of unsuitable mixtures. Figure 4 shows that in four of seven poor performing sections for which data were available, the air-void content of laboratory-compacted, plant-produced mixtures fell well below 3.0 percent when maximum specific gravities determined from recovered field cores were used to compute voids. The air-void contents of the same mixtures were all equal to or greater than 3.0 percent when maximum specific gravities reported by the plant were used to compute voids.

TABLE 5 Average Asphalt Contents of Multiple Specimens

Section	AC Limits[a]		MTD[b]	Plant[c]	PTI[d]
	±0.2%	±0.4%			
2-1	5.7-6.1	5.5-6.3	6.1	5.9	5.7
2-2	6.0-6.4	5.8-6.6	6.1	6.2	6.5
2-3	6.0-6.4	5.8-6.6	6.0	6.0	5.9
2-4	6.0-6.4	5.8-6.6	-[e]	6.3	6.0
9-1	6.1-6.5	5.9-6.7	6.4	-	6.6
9-2	5.8-6.2	5.6-6.4	5.7	6.2	5.9
9-3	6.0-6.4	5.8-6.6	6.1	6.4	6.0
11-1	6.2-6.6	6.0-6.8	6.3	6.3	6.6
11-2	6.2-6.6	6.0-6.8	6.5	-	6.1
11-3	6.2-6.6	6.0-6.8	-	-	6.2
8-1	4.8-5.2	4.6-5.4	4.9	4.8	5.3
8-2	5.2-5.6	5.0-5.8	5.5	5.4	4.8
8-3	5.2-5.6	5.0-5.8	5.4	5.1	5.1

[a] Design asphalt content ±0.2 percent and ±0.4 percent respectively.
[b] Average of asphalt contents from extractions run by MTD on loose mixture during construction.
[c] Average of asphalt contents from extractions run at the plant on loose mixture during construction.
[d] Average of asphalt contents from extractions run by MTD on cores taken by PTI.
[e] No report available for these tests.

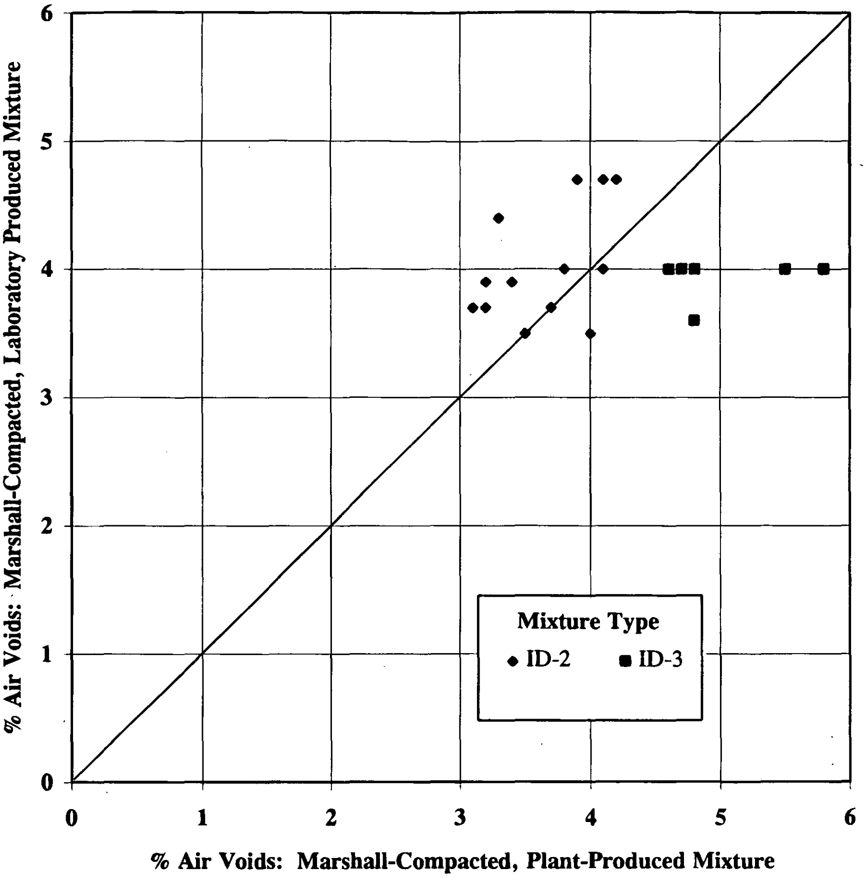


FIGURE 3 Comparison of air voids for laboratory- and plant-produced specimens.

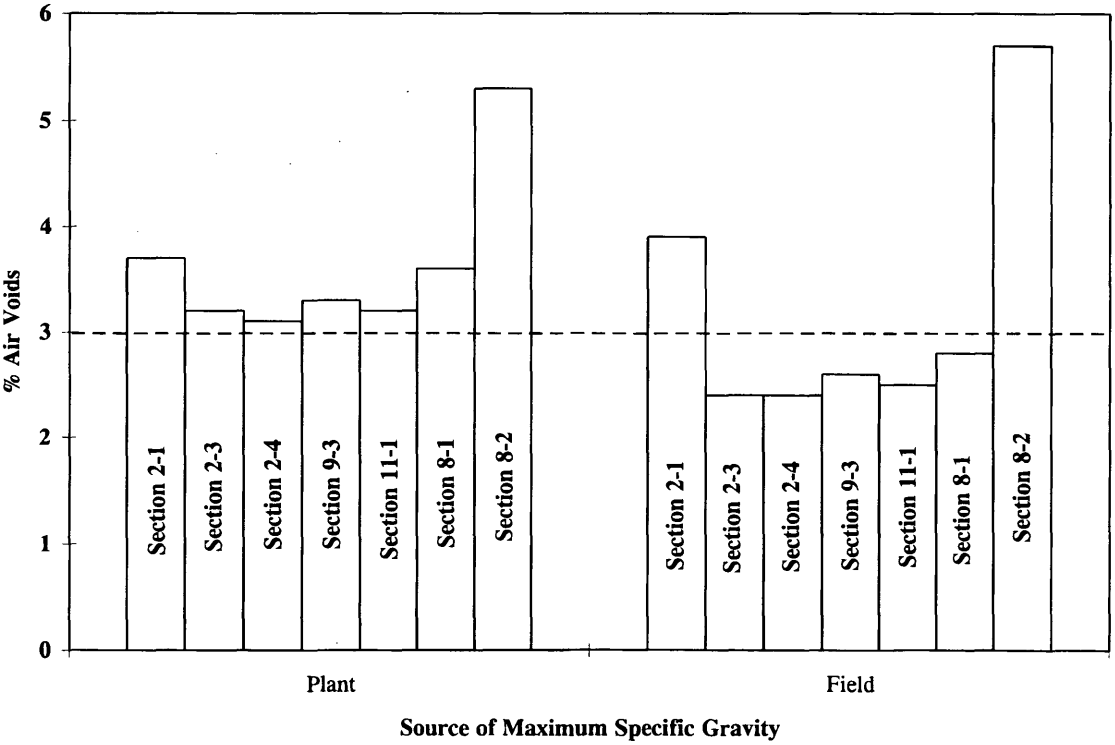


FIGURE 4 Effect of maximum specific gravities from different sources on air-void content of Marshall-compacted, plant-produced mixtures.

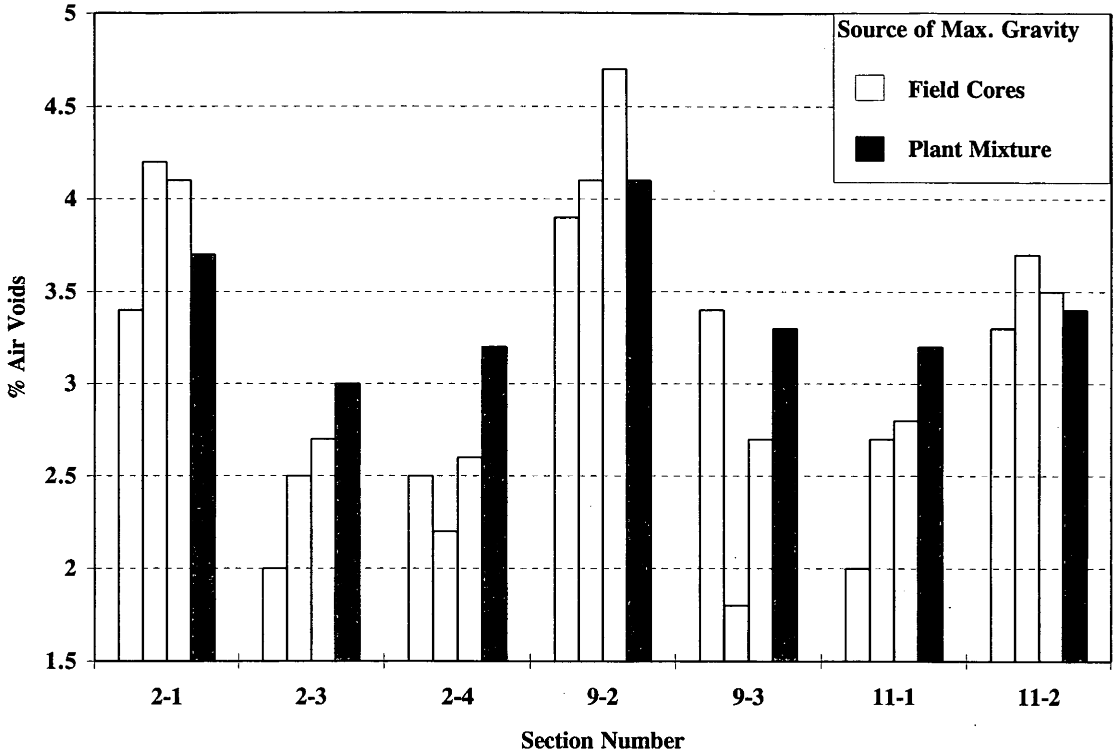


FIGURE 5 Effect of maximum specific gravities from different specimens within 1,000-ft section on air-void content of Marshall-compacted, plant-produced ID-2 mixtures.

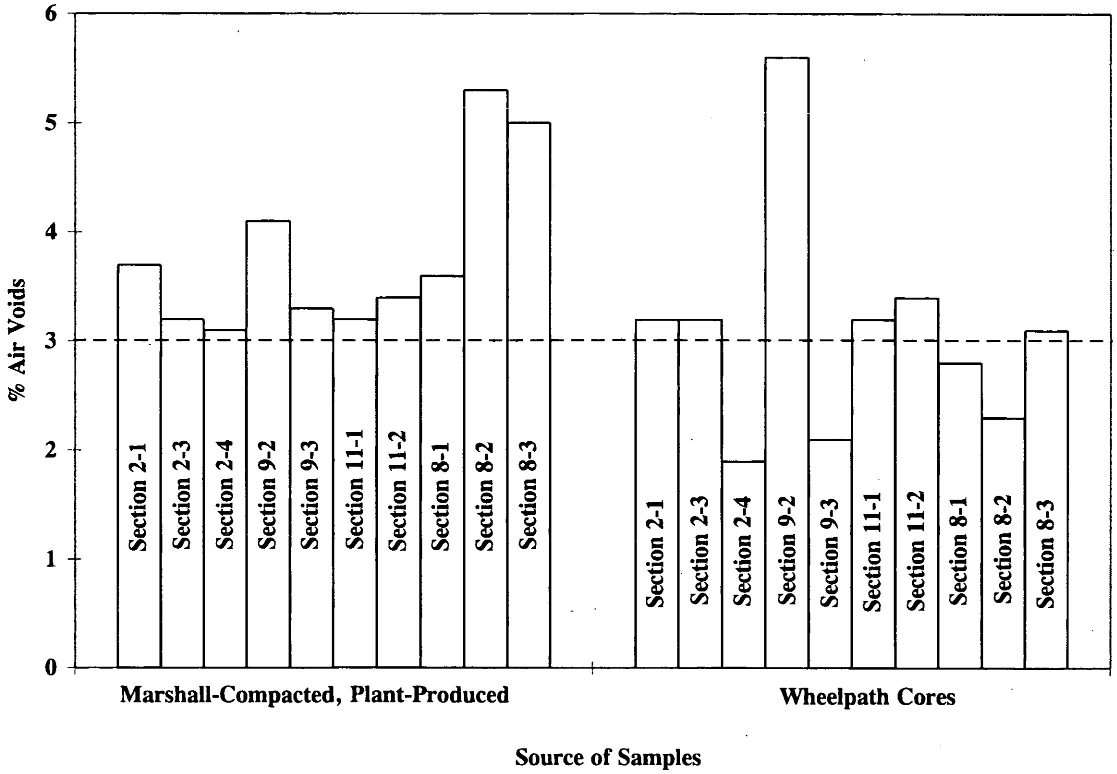


FIGURE 6 Comparison of air-void contents between Marshall-compacted, plant-produced specimens and wheel path cores.

The reason for this is not that the maximum specific gravities reported by the plants were determined incorrectly, but rather that the value may not be representative of the average maximum specific gravity for the mixture being produced on any given day. Figure 5 shows the variability in air-void content of laboratory-compacted, plant-produced ID-2 mixtures resulting from the variability in maximum theoretical densities determined from three field cores obtained from within each of seven 305-m-long (1,000-ft-long) test sections for which data were available. As seen in the figure, variations in air-void content as great as 1.5 percentage points were computed for the same reported bulk density when maximum specific gravities determined from different specimens of the same mixture were used. The repeatability of the measurements clearly indicated that this was not a repeatability problem with the determination of maximum specific gravity (*3*). Plant records also indicated significant daily and weekly variation in maximum specific gravity measurements, which could result in differences in computed air-void contents of as much as 1 percentage point, depending on which maximum specific gravity is used in the computations.

Mixture Design Procedures

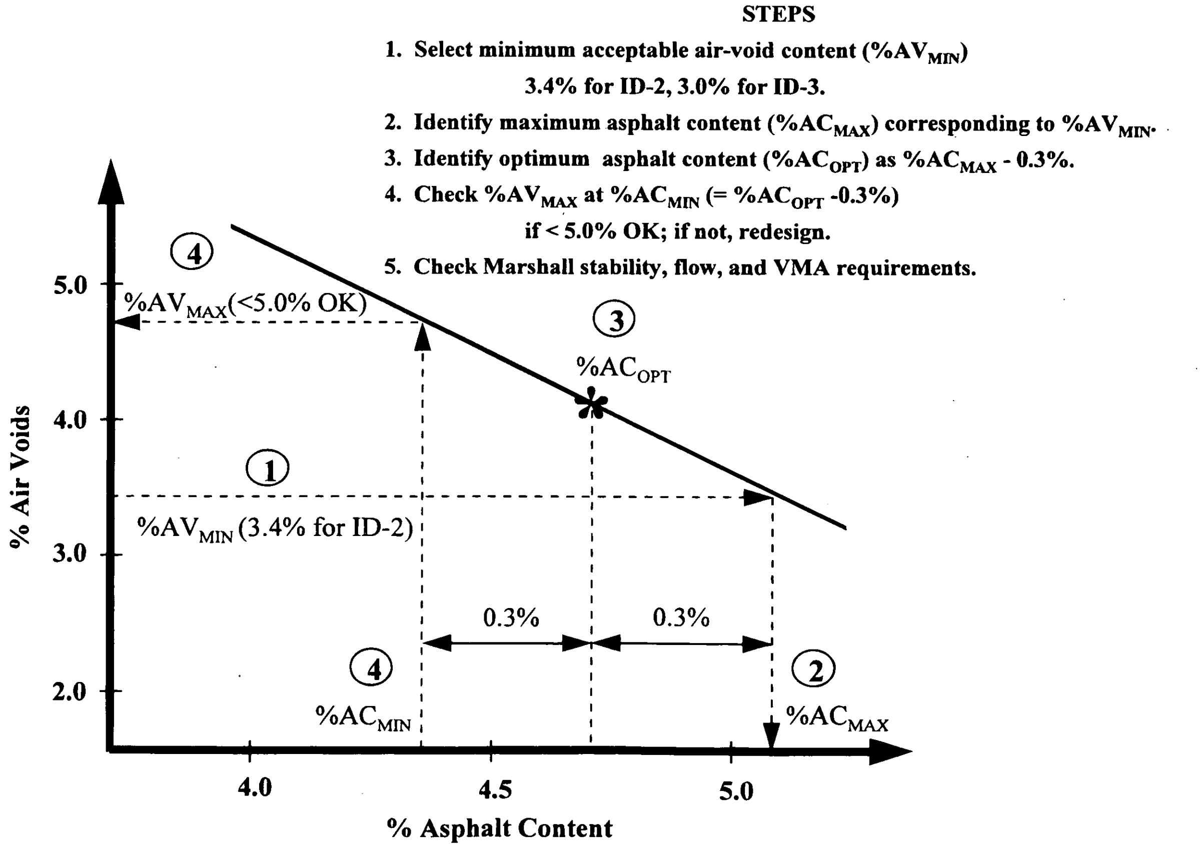
Materials Selection

As discussed previously, correspondence between gradations of plant-produced mixtures and design job-mix formulas was generally very good. Although in most cases, field mixtures were slightly finer than the job-mix formula, gradations of field mixtures were within acceptable limits of the job-mix formula. In general, it appears that existing procedures to adjust laboratory blends to match actual gradations of plant-produced mixtures are adequate.

Specimen Preparation Methods

Figure 6 shows that in 4 of 10 sections for which data were available, mixtures compacted to less than 3.0 percent air voids under the action of traffic. Not one of the same 10 mixtures compacted to less than 3.0 percent air voids when the Marshall method was used to compact the plant-produced mixtures. As shown in Figure 6, Marshall particularly undercompacted the ID-3 mixtures (Sections 8-1 to 8-3). Air-void contents of both Marshall-compacted, plant-produced mixtures and Marshall-compacted laboratory-produced job-mix formula were generally higher than air voids measured on field cores obtained from the wheel paths of test sections composed of the same mixtures.

Laboratory tests performed on mixtures produced according to the job-mix formula indicated that Texas gyratory shear compaction (ASTM D4013-81) overcompacted these mixtures relative to the compaction induced by traffic in the field. Without exception, all mixtures investigated in this study compacted to 0.0 percent air voids when standard Texas gyratory compaction was used. This obviously indicates that the shearing action induced by the 6-degree angle of gyration, and pressures associated with standard Texas gyratory compaction method, were far too severe for these mixtures.



STEPS

1. **Select minimum acceptable air-void content (%AV_{MIN}) 3.4% for ID-2, 3.0% for ID-3.**
2. **Identify maximum asphalt content (%AC_{MAX}) corresponding to %AV_{MIN}.**
3. **Identify optimum asphalt content (%AC_{OPT}) as %AC_{MAX} - 0.3%.**
4. **Check %AV_{MAX} at %AC_{MIN} (= %AC_{OPT} -0.3%) if < 5.0% OK; if not, redesign.**
5. **Check Marshall stability, flow, and VMA requirements.**

FIGURE 7 Proposed procedure to determine optimum asphalt content and evaluate mixture sensitivity.

Materials obtained from asphalt plants were also used to produce asphalt mixtures using the compaction protocol as similar as possible to the one selected for use in the new SHRP mixture design and analysis system. Air-void contents achieved with the modified Texas gyratory procedure were generally closer to air voids measured in the wheel path than were air voids achieved by the Marshall compaction method. However, the laboratory-compacted air-void levels were generally higher than field air-void levels. Clearly, further investigation is required to identify a suitable compaction procedure.

Mixture Evaluation

A procedure was developed for mixture evaluation and determination of optimum asphalt content that addresses the problems of excessively low air voids and sensitivity to changes in asphalt cement content. The procedure selects optimum asphalt content on the basis of the following findings, which were presented earlier:

- The fact that a minimum of 3.4 percent air voids is needed for adequate frictional resistance for ID-2 mixtures and a minimum of 3.0 percent air voids is needed for ID-3 mixtures (actually, 2.8 percent was determined to be acceptable, but 3.0 percent was used for design).
- The fact that contractors appear to be able to control asphalt content in the field within ±0.3 percent. This is illustrated in Table 5, which shows measured differences in asphalt contents between the field and the job-mix formula for each of the test sections investigated.
- The fact that, as shown in Table 3, the sensitivity of air-void-content changes to changes in asphalt-cement content may vary significantly from mixture to mixture.

The procedure, which is illustrated in Figure 7, was used to determine optimum asphalt content for each of the test sections investigated. The results are summarized in Table 6, which compares optimum asphalt content and design air-void content for the existing and proposed procedures. As shown in the table, for all ID-2 mixtures, the proposed method resulted in lower optimum asphalt cement contents and significantly higher design air-void contents than were obtained using the existing procedure. The procedure should help to minimize frictional resistance problems early in the lives of ID-2 mixtures. Note that the mixture used in Section 9-3 would have to be redesigned because it is too sensitive to changes in asphalt content. Very little difference in optimum asphalt content and design air-void content was observed between existing and proposed procedures for the ID-3 mixtures. The reason is that optimum asphalt contents for these sections were selected as the asphalt content corresponding to 4.0 percent air-void content because the maximum density versus asphalt content relation never reached a peak. As mentioned earlier, the primary problem with these mixtures is that Marshall compaction severely undercompacts these coarser mixtures relative to the compaction levels induced by traffic in the field.

CONCLUSIONS AND RECOMMENDATIONS

The primary conclusion of this investigation is that frictional resistance problems early in the lives of surface course mixtures would be reduced if the mixtures were designed and produced in the field such that field air-void contents do not fall below 3.4 percent for 12.5-mm (½-in.) maximum aggregate size (ID-2) mixtures and below 2.8 percent for 25.4-mm (1-in.) maximum aggregate size (ID-3) mixtures. A secondary conclusion is that coarser ID-3 mixtures provide an added margin of safety against early loss in fric-

TABLE 6 Optimum Asphalt Contents for Existing and Proposed Methods

Section	Existing Method[a]		Proposed Method[b]	
	Optimum Asphalt Content (%)	% Air Voids	Optimum Asphalt Content (%)	% Air Voids
2-1	5.9	3.2	5.7	4.1
2-2	6.2	3.2	5.8	4.2
2-3, 2-4	6.2	3.7	6.1	4.1
9-1	6.3	3.5	6.3	4.0
9-2	6.3	3.6	6.1	4.2
9-3	6.3	3.0	6.0[c]	4.8
11-1, 11-2, 11-3	6.7	3.6	6.3	4.2
8-1	4.8	4.0	4.7	4.1
8-2, 8-3	5.4	4.0	5.3	3.9

[a] Design asphalt content and air voids content from master design charts using existing PennDOT's procedure for conventional, non-heavy-duty mixtures.

[b] Design asphalt content and air voids content using proposed method.

[c] This mixture was identified as a sensitive mixture with the proposed design method.

tional resistance over ID-2 mixtures when both are compacted to the same air-void level in the field.

The following developments and recommendations would minimize frictional resistance problems early in the lives of surface course mixtures:

- Whenever possible, ID-3 mixtures should be used in high traffic areas where a larger margin of safety against low frictional resistance may be required.
- Optimum asphalt content should be selected using the procedure presented in this report.
- Additional work should be undertaken to identify and/or validate a laboratory compaction procedure that results in compaction levels representative of those induced by traffic in the field.
- Possible ways to improve field control of laboratory-compacted, plant-produced mixtures should be investigated.
- Field quality control and quality assurance testing requirements should ensure that maximum specific gravities of plant-produced mixtures are determined accurately in the field. A specific procedure to achieve this control is presented by Roque et al. (*3*), but its presentation is beyond the scope of this paper.

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