Development and Analysis of Laboratory Techniques for Simulating Segregation

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Objectives of this research were to develop laboratory techniques for simulating asphalt mixture segregation and determine mixture compactibility and physical properties. Segregation in asphalt concrete pavements occurs as a result of nonuniform distribution of the mixture components such as aggregate and asphalt. Mixture segregation can lead to premature pavement distress. Factors and steps in the production, transportation, and placement of asphalt mixtures associated with segregation include material type, mixture design, stockpiling and handling, plant type and operation, surge silos, truck loading and unloading, and laydown. Materials used in the study included gravel, natural sand, and an AC-20 asphalt cement. Aggregates were selected to meet the Indiana Department of Transportation specification for a No. 8 binder with a maximum aggregate size of 25.0 mm (1 in.). In order to simulate various degrees of segregation of the coarse and fine fractions, four artificially segregated asphalt mixtures were prepared in addition to the control asphalt mixture. As part of the study, specimens were compacted for the fine mixtures using the U.S. Corps of Engineers gyratory testing machine to determine the stability and compactibility indexes. Specimens were also prepared and tested using the indirect tensile test method. Slabs of the five mixtures were compacted using a laboratory linear compactor. Subsequently, these slabs were tested using the Purwheel tracking device to determine their rutting potential and moisture susceptibility. Results indicate that segregation affects the residual asphalt content, gradation, stability index, compatibility index, air voids, unit weight, indirect tensile strength, rutting potential, and moisture susceptibility of asphalt concrete mixtures.

Asphalt concrete mixture segregation in pavements occurs as a result of nonuniform distribution of the mixture components such as asphalt and aggregate. Segregation in pavements leads to premature distress such as cracking, rutting, raveling, and stripping. These distresses will affect the performance, serviceability, and structural capacity of the pavement (*1*). Segregation may result from one or a combination of the following factors: aggregate type, mixture design, stockpiling and handling, plant type and operation, truck loading and unloading, and laydown operations.

Asphalt content and gradation have a significant effect on potential for segregation. For example, a gap-graded mixture with low asphalt content is prone to segregation. Brock (*2*) described a gap-graded mixture as one that has a gradation making an S across the maximum density line.

Bryant (*3*) studied the variation of asphalt content as a result of segregation. He concluded that there was a relationship between the degree of segregation and the percentage of extracted asphalt and recommended an effort to reduce segregation because of its potential effects on asphalt mixture characteristics. Brown et al. (*4*) concluded that segregated areas are generally 8 to 15 percent coarser than nonsegregated areas on the No. 8 sieve; the voids are typically 3 to 5 percent higher; and the asphalt content is often 1 to 2 percent lower.

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LABORATORY WORK

A laboratory study has been conducted to measure the effect of various degrees of segregation on the physical and mechanical characteristics of asphalt mixtures. A description is provided of materials and tests.

Materials

Asphalt Cement

One asphalt cement (AC-20) was used in the study which was obtained from a storage tank at Fauber Construction Company, Inc., West Lafayette, Indiana. Test results characterizing this asphalt are presented in Table 1.

Aggregate

Aggregates used in the study were gravel and sand meeting Indiana Department of Transportation (INDOT) specifications. The aggregate stockpiles were blended to meet an INDOT #8 binder gradation with a maximum aggregate size of 25.4 mm (1 in.). The gravel and sand were obtained from Vulcan Materials Company and Fairfield Builders Supply Corporation, respectively, of West Lafayette, Ind. Properties and the gradations of the aggregate are given in Tables 2 and 3.

Samples for mix design purposes were compacted using 75 blows on each side with the Marshall manual hammer. An optimum asphalt content of 4.5 percent was selected at 6 percent air voids. This is the current INDOT criterion for selecting optimum asphalt content.

Five mixes with varying degrees of segregation were evaluated in the laboratory. A mixture with a median gradation according to the specifications for INDOT #8 binder gradation and at 4.5 percent asphalt content was used as one degree of segregation (mix design). This heated mixture was sieved over a 10-mm (⅜-in.) sieve creating coarse (retained) and fine (passing) mixtures representing the extremes of segregation. Two other mixtures with intermediate degrees of segregation were produced by combining percentages of the coarse and fine material as shown (1 mm = 0.04 in.):

Mix. No.	Segregation Classification	Percentage of Material + 10 mm	Percentage of Material − 10 mm
1	Very fine	0.0	100.0
2.	Fine	24.0	76.0
3	Mix design	48.3	51.7
4	Coarse	74.0	26.0
5	Very coarse	100.0	0.0

Mixtures 1 and 5 have visible segregation. The five mixtures are shown in Figure 1.

Sample Gradation

Gradations of the extracted aggregate were determined for each segregated mixture in accordance with ASTM C 1 36. Gradations are shown in Figure 2.

Extracted Asphalt Content

Three extraction tests (ASTM D2172, Method B) were performed on each of the five segregated mixtures. The asphalt content is expressed as the mass percentage of moisture-free mixture. Figure 3(*a*) shows the extracted asphalt versus degree of segregation.

Tests

Gyratory Test

The US Corps of Engineers gyratory testing machine (GTM) was used to compact and test the five mixtures. Segregated specimens were proportioned for an approximate total weight of 1200 g. For example, a batch weight of 1275 g for Mix 2 would be proportioned as 0.24 × 1275 = 306 g of +10-mm (+3⁄8-in.) material and 0.76 × 1,275 = 969 g of −10 mm (−3⁄8 in.) material.

Each mixture combination was weighed into a separate mixing bowl. The bowls were placed in an oven and heated to a temperature between 135°C (275°F) and 149°C (300°F). When the mixture was heated, the bowl was removed from the oven and the mixture was mixed by hand with a trowel. The entire batch was placed in the GTM mold and spaded with a heated spatula 15 times around the perimeter and 10 times over the interior. The surface was smoothed to a slightly rounded shape. Temperature of the mixture immediately before compaction was not less than 135°C (275°F). The mold assembly was placed in the GTM.

Specimens were compacted and tested according to ASTM D3387. Three specimens were prepared for each mixture using a 1380-kPa (200-psi) vertical pressure, 1-degree angle of gyration, and 30, 60, and 120 revolutions. After compaction, samples were

TABLE 2 Properties of Aggregate Used

Type of Aggregate	ASTM Test Designation	Bulk Specific Gravity	Apparent Specific Gravity	Water Absorption (percent)
Gravel	C127	2.61	2.66	1.88
Sand	C128	2.60	2.72	1.77

TABLE 3 Aggregate Gradation Used

Sieve Size	Percentage Passing	Specification Limits*
25.00 mm	100	100
19.00 mm	92.5	80-98
12.50 mm	68.0	56-80
9.50 mm	51.2	43-68
No. 4	33.4	25-40
No. 8	28.0 1	4-40
No. 16	20.6	8-32
No. 30	12.8	5-24
No. 50	4.5	2-16
No. 100	0.8	0-10
No. 200	0.3	0-3

25.4 mm=1 inch

*Indiana Department Of Transportation Specification Limits

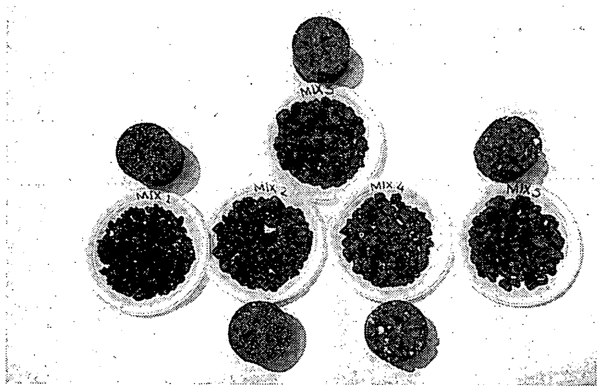


FIGURE 1 Samples from prepared mixes and specimens.

TABLE 1 Properties of Asphalt Used

Property	ASTM Test Designation	Test Result
Penetration (0.1 mm) at 25°C, 100 gm, 5 sec	D5	75
Ductility (cm) at 25°	CD113	100+
Specific gravity at 25°	CD70	1.026
Softening point (°C) (ring and ball)	D36	48
Flash point (°C)	D92	325

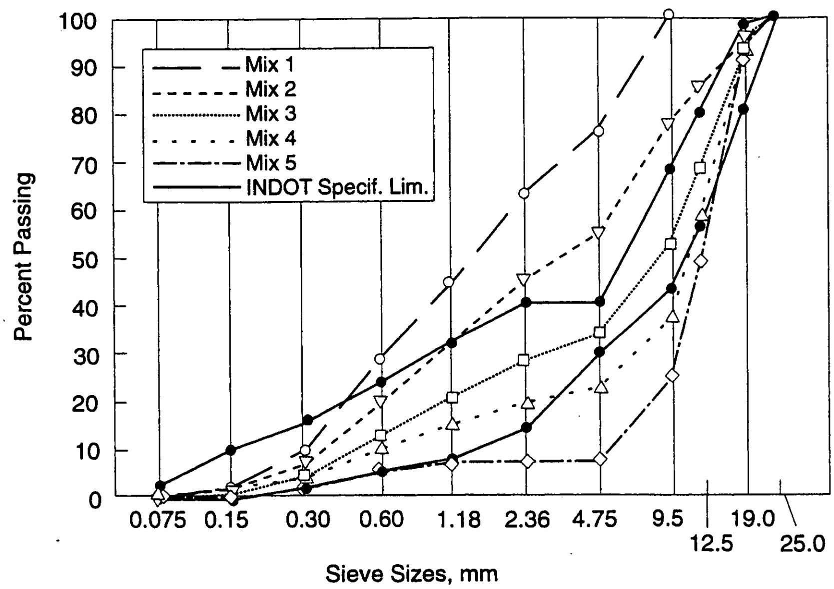


FIGURE 2 Aggregate gradations after extraction test.

removed from the mold and allowed to cool for at least 2 hr before handling.

Subsequently, the following determinations were made:

1. Unit weight (total mix),
2. Gyratory stability index (GSI):

$$\text{GSI} = \frac{\text{Minimum gyrograph band width}}{\text{Minimum intermediate gyrograph band width}} \tag{1}$$

3. Gyratory compactibility index (GCI)

$$\text{GCI} = \frac{\text{Unit weight at 30 revolutions}}{\text{Unit weight at 60 revolutions}} \tag{2}$$

4. Percent air voids of total mix.

Figures 3(*b*), 4, and 5(*a*) present the results of the above determinations.

Indirect Tensile Test

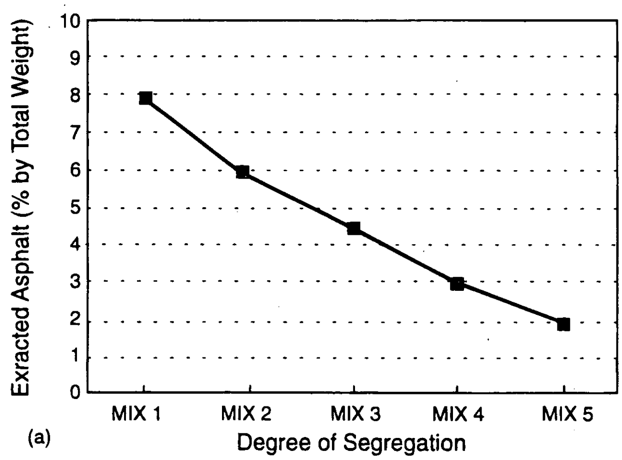
Indirect tensile tests were conducted on specimens prepared with the GTM. The compressive load was applied through a steel loading strip 12.7 mm (0.5 in.) wide with a radius equal to that of the specimen (*5*). The tensile strength was calculated using the following equation.

$$S_t = 2P/\pi tD \tag{3}$$

where:

S_t = tensile strength (kPa),
P = maximum load (kg),
t = specimen height immediately before tensile test (mm), and
D = specimen diameter (mm).

Figure 5(*b*) shows the indirect tensile test results.



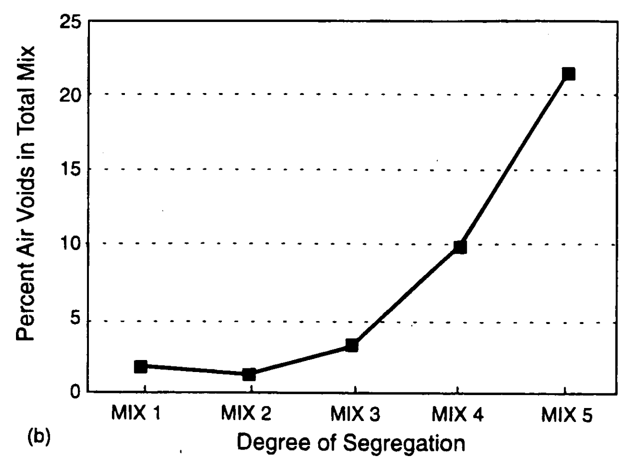


FIGURE 3 (*a*) Extracted asphalt versus degree of segregation, (*b*) percent air voids versus degree of segregation.

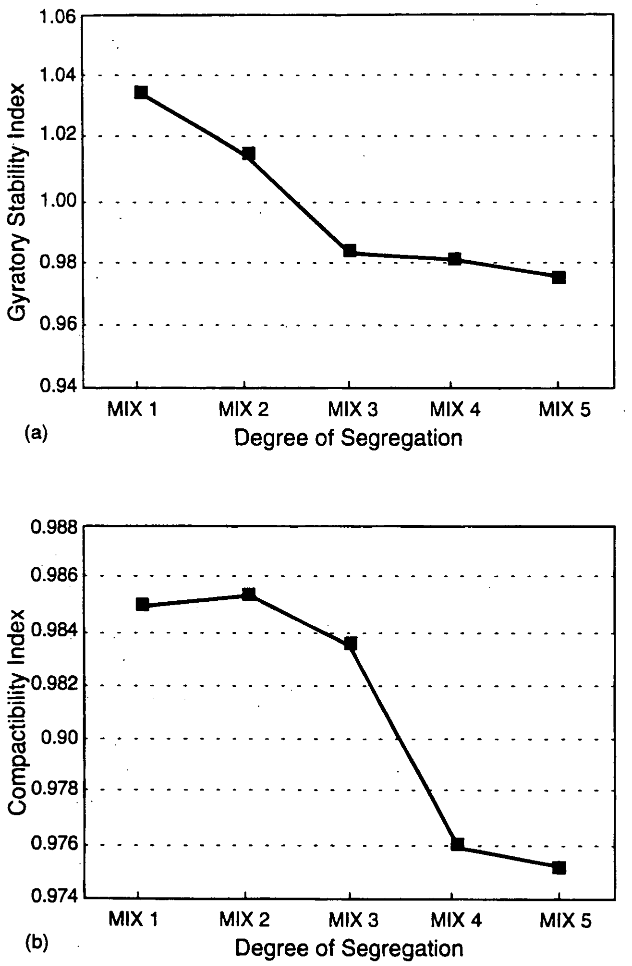


FIGURE 4 **(*a*) Stability index versus degree of segregation, (*b*) compactibility index versus degree of segregation.**

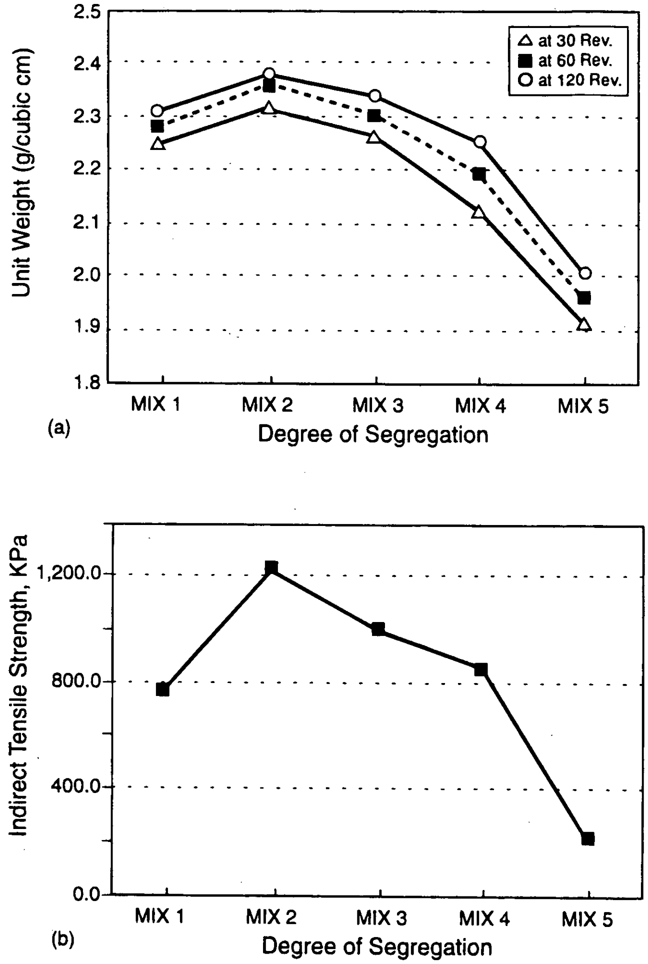


FIGURE 5 **(*a*) Unit weight versus degree of segregation, (*b*) indirect tensile strength versus degree of segregation.**

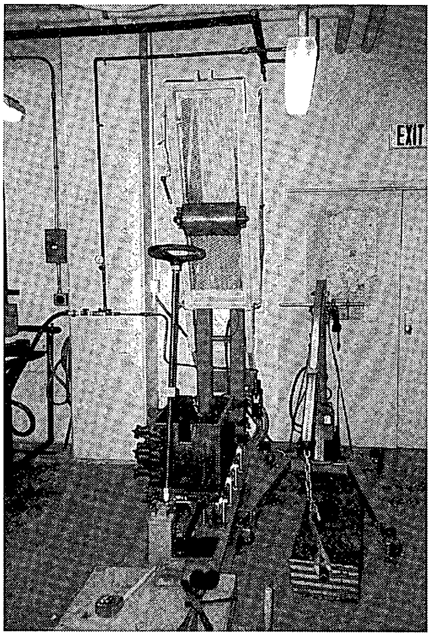
Purwheel-Tracking-Device Test

Segregated asphalt mixture resistance to permanent deformation and moisture damage was evaluated using the Purwheel tracking device (*6*).

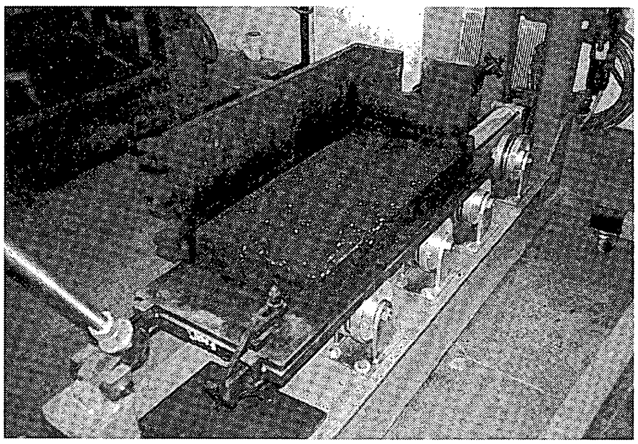
Mixture Preparation Figure 3(*a*) was used to determine the asphalt content for each degree of segregation. An amount of aggregate and asphalt to produce a compacted slab 622.3 mm (24.5 in.) long, 304.8 mm (12.0 in.) wide, and approximately 76.2 mm (3 in.) deep was weighed into three mixing bowls. The total weights of aggregate for test mixtures 1 through 5 were 30.082 kg (66.481 lb), 31.295 kg (69.162 lb), 30.774 kg (68.011 lb), 29.695 kg (65.626 lb), and 25.625 kg (56.631 lb), respectively. Corresponding asphalt contents were 7.87, 5.87, 4.50, 2.93, and 1.87 percent. Target densities for the slabs were determined from specimens compacted with a 75-blow Marshall manual compaction effort. The mixing bowls with aggregate were placed in the oven and heated to a temperature between 135°C (275°F) and 149°C (300°F). When the aggregate was heated, asphalt was added and the combination was mixed with a mechanical mixer.

Slab Compaction For this study, slabs were compacted with a linear compactor (Figure 6). Before compaction, a filter paper was placed in the bottom of the mold. Once the aggregate and asphalt were mixed, the entire batch was placed in the compactor mold and spaded vigorously with a heated spatula. The surface of the mix was leveled and another piece of filter paper was placed on top of the mixture. Forty-nine vertical steel plates, each 12.7 mm (0.5 in.) thick, were placed vertically on top of the mix in the mold. The roller was lowered to contact the top of the steel plates. As the mold assembly moved back and forth horizontally the roller was cranked down. Moving the mold back and forth under the roller simplified keeping the roller motion parallel to the mix surface. After compaction, the steel plates were removed and the slab was allowed to cool in air. Half of the mold was detachable to facilitate removal of the slab. Subsequently, the slab was moved to a smooth, level surface until testing began. The unit weights of slabs made from Mixes 1 through 5 were 2.308 (144.0), 2.314 (144.3), 2.292 (143.0), 2.168 (135.2), and 1.929 (120.3) g/cm^3 (lb/ft^3), respectively. Corresponding air voids were 2.94, 5.51, 8.65, 14.88, and 27.45 percent.

The compacted slabs were tested with the Purwheel tracking device (Figure 7) which was fabricated in the Purdue University Central Machine Shop. Two sets of slabs were tested in replicate. The first set of slabs was tested using a steel wheel 50.8 mm (2 in.)



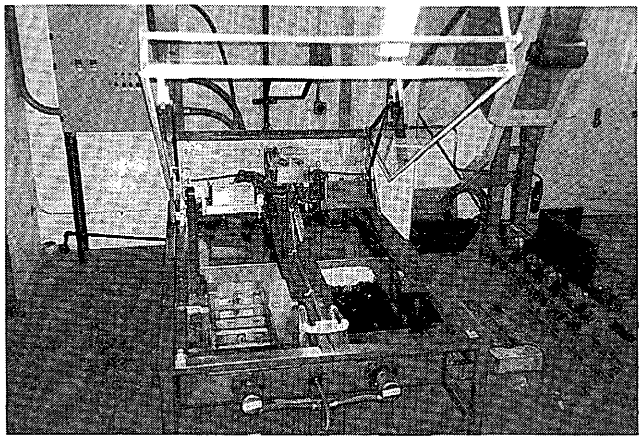
(*a*)



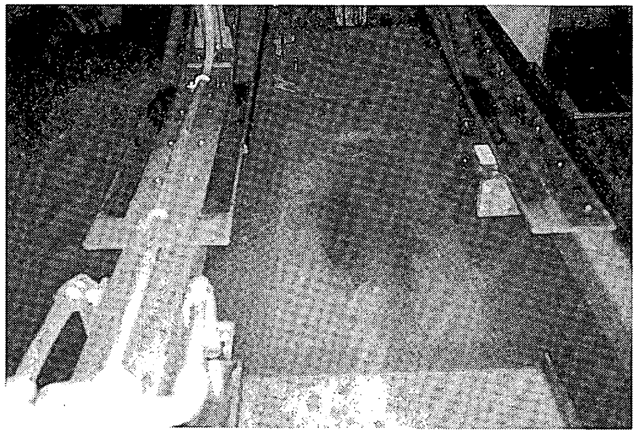
(*b*)

FIGURE 6 Purdue linear kneading compactor: (*a*) prepared for compaction; (*b*) after compaction.

wide, and the second set was tested using a steel wheel 76.2 mm (3 in.) wide. Both steel wheels were loaded to have an initial contact pressure of 827.6 kPa (120 psi). Tracking tests were conducted with the slabs submerged in water at 50°C (122°F). The wheels tracked over the slab at a velocity of 34 cm/sec (1.1 ft/sec). A software program controlled all test parameters. The vertical deformation was measured to the nearest 0.01 mm (0.00039 in.) with a linear variable differential transformer. Deformation was stored for five equally spaced points along the specimen during each pass of the wheel. The resulting deformation was displayed during the test. Tests were run for 20,000 passes, or until the average rut depth reached 25.4 mm (1 in.). Figure 8 shows slabs ready for testing and one slab after testing. Figures 9 through 15 show results of the Purwheel-tracking-device tests.



(*a*)



(*b*)

FIGURE 7 Purwheel tracking device: (*a*) prepared for testing; (*b*) after testing.

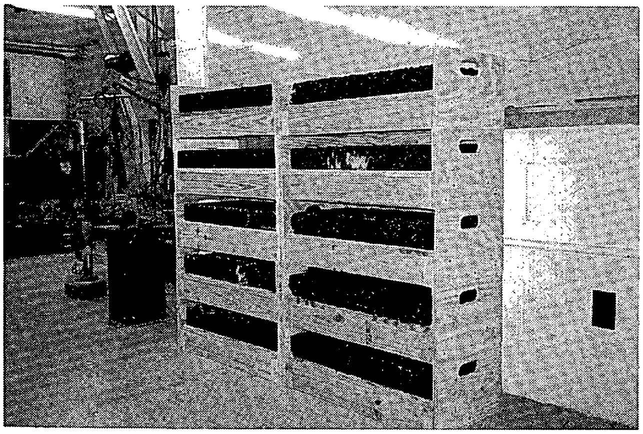
ANALYSIS OF RESULTS AND DISCUSSION

A number of sample preparation techniques and test procedures have been utilized in this study. The results of applying these techniques and tests are discussed.

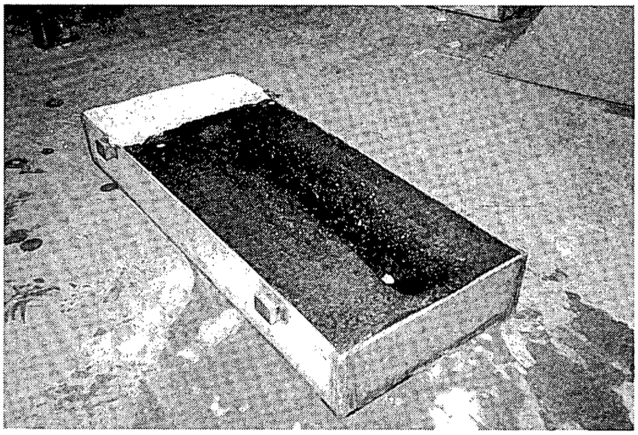
Extracted Asphalt

Asphalt content varies with the degree of segregation as shown in Figure 3(*a*). A lower asphalt content occurs with a coarse fraction, because the larger aggregates have a smaller surface area for asphalt to coat than the fine aggregate fraction. In addition to the larger surface of the fine aggregate fraction, the fine aggregates tend to agglomerate into a mastic, which holds more asphalt.

The combination of smaller aggregate sizes and high asphalt content in Mixes 1 and 2 creates an increase in the potential for rutting. The combination of large aggregate and low asphalt content in Mixes 4 and 5 creates a potential for fatigue, raveling, thermal cracking, and stripping.



(*a*)



(*b*)

FIGURE 8 (*a*) Slabs ready for testing; (*b*) slab after testing.

Gradation of Extracted Aggregate

The gradations of the five segregated asphalt mixtures are shown in Figure 2. INDOT gradation limits for the #8 binder are also plotted in Figure 2 for comparison. The percentages retained on the 10-mm (3/8-in.) sieve were 0, 22.5, 48.3, 63.1, and 75.2 for Mixes 1, 2, 3, 4, and 5, respectively. A wide range of segregation was achieved by proportioning the plus and minus 10-mm (3/8-in.) fractions.

Air Voids

Air voids for each of the five mixes are presented in Figure 3(*b*). The air voids are low for Mixes 1 and 2 and increase dramatically for Mixes 4 and 5.

Gyratory Stability Index

A GSI value in excess of unity indicates a progressive increase in plasticity during densification (ASTM D3382). Since the compaction effort can be varied to simulate pavement loading conditions, an increase in this index indicates instability of the hot mix asphalt for a given loading. Figure 4(*a*) shows the effect of segregation on the GSI values of mixes in this study. There is considerable loss in stability for Mixes 1 and 2 as compared with Mixes 4 and 5, which means that the finer mixes are more plastic.

Gyratory Compactibility Index

The GCI is an indicator of the compactibility of asphalt mixtures. The closer this index approaches unity, the easier the mix is to compact. Figure 4(*b*) presents the effect of segregation on the GCI values of the five mixes; it can be seen that the GCI value decreases with an increase of coarse aggregate in the mix.

Unit Weight

Figure 5(*a*) shows the relationship between degree of segregation and unit weight of the mixes. The unit weights at 120 revolutions for the five mixtures are 2.313 (144.3), 2.381 (148.5), 2.342 (146.1), 2.248 (140.2), and 2.010 (125.4) g/cm^3 (lb/ft^3), respectively. Figure 5(*a*) also shows that the unit weight increases with increasing number of revolutions or compactive effort.

Indirect Tensile Test

The change in indirect tensile strength with degree of segregation is shown in Figure 5(*b*). It can be seen that the tensile strength increases to a maximum value and then decreases. This result is directly correlated to density.

Purwheel-Tracking-Device Test

Purwheel-tracking-device tests were carried out on all five mixes described in the section on laboratory work. When samples are tested in hot water the Purwheel tracking device measures mixture potential for permanent deformation and stripping. The advent of stripping is usually accompanied by a sudden increase in the rate of deformation; free, stripped asphalt; and flushing of the fine aggregate fraction from the mixture (7). A typical rutting curve (Figure 9) is divided into four regions: postcompaction, creep slope, stripping inflection point, and stripping slope. These regions have been described by Hines (7). Results are shown in Figures 10 through 15 for each of the five mixtures tested with both the 50.4-mm (2-in.) and 76.2-mm (3-in.) wide wheels. Table 4 shows observations of stripped and flushed fines for the five mixes.

In general, the linear compactor produced specimens with increasing and then decreasing density for different degrees of segregation starting with the very fine segregated mixture (Mix 1). Also, the air voids for the total mix show results corresponding to those for density; that is, they first decrease and then increase. Specifically, the slab densities were close to the gyratory-compacted core densities at 30 revolutions. Air voids of the slabs were higher than the gyratory cores. The maximum difference occurred for the coarse mixture (Mix 5), where the air voids were approximately 22 and 27 percent for the gyratory cores and linear compactor slabs, respectively. The slabs prepared with the linear compactor show the same relative magnitude of density and air voids as those of the gyratory-compacted cores. Results of the tests

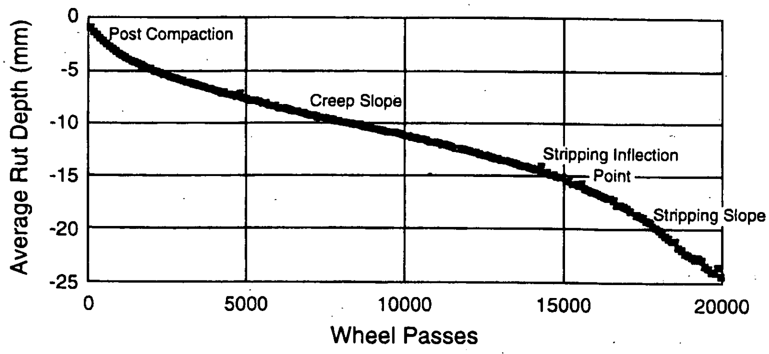


FIGURE 9 Rutting characteristics.

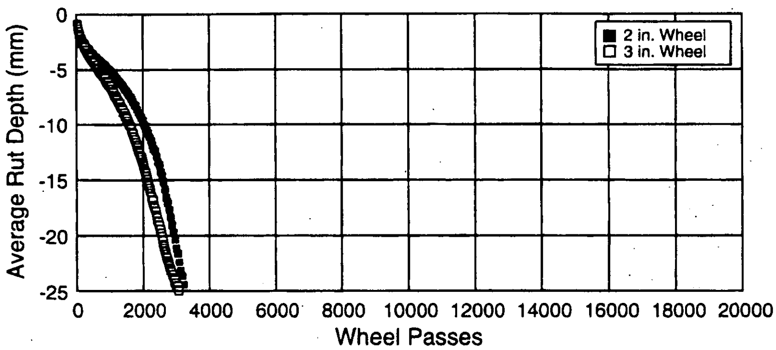


FIGURE 10 Relationship between average rut depth and number of wheel passes for Mix 1.

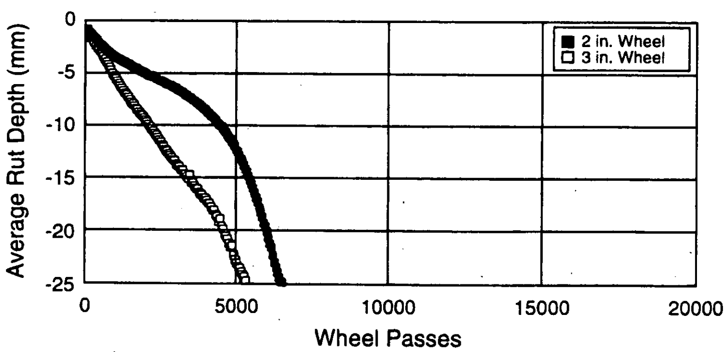


FIGURE 11 Relationship between average rut depth and number of wheel passes for Mix 2.

may be affected by the difference, but for a given test the relative results are considered to be significant.

Inverse Creep Slope

The inverse creep slope is derived from the rate of deformation in the linear region of the deformation curve, after post compaction effects have ended and before the onset of stripping (*6*). The inverse creep slope is reported in passes per millimeter. Therefore, the higher this value, the more resistant the mix is to permanent deformation.

The influence of degree of segregation on the inverse creep slope is shown in Figure 15. The inverse creep slope increases with increasing amount of coarse aggregate for Mixes 1 through 4 but is much lower for Mix 5. Figure 15 also shows that, in

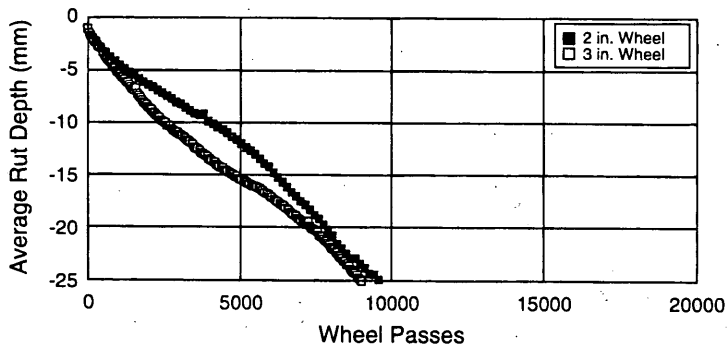


FIGURE 12 Relationship between average rut depth and number of wheel passes for Mix 3.

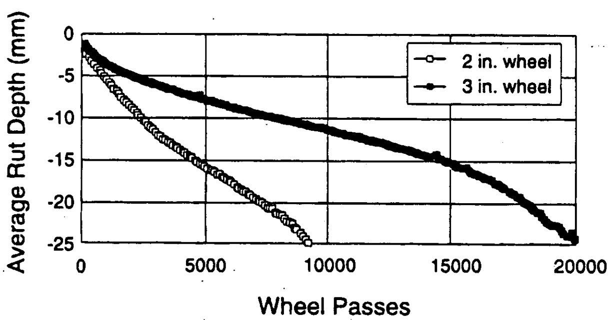


FIGURE 13 Relationship between average rut depth and number of wheel passes for Mix 4.

general, Mixes 1, 2, and 5 are more sensitive to rutting than Mixes 3 and 4.

Stripping Inflection Point

The stripping inflection point is the number of passes at the intersection of the creep slope and the stripping slope. The stripping inflection point is related to the amount of mechanical energy required to produce stripping under the test conditions. A lower stripping inflection point indicates a mixture that is likely to strip (*6*).

The influence of degree of segregation on the stripping inflection point is shown in Figure 15(*b*). The stripping inflection point first increases and then decreases with increasing amount of coarse aggregate. Mixes 1, 2, and 5 have higher potential for stripping than Mixes 3 and 4.

Inverse Stripping Slope

The inverse stripping slope is the rate of deformation in the linear region of the deformation curve after stripping begins and until the end of the test. The inverse stripping slope is related to the severity of moisture damage. The lower the inverse stripping slope, the more severe the moisture damage (*6*).

Figure 15(*c*) shows the influence of degree of segregation on the inverse stripping slope, which first increases and then decreases with increasing amount of coarse aggregate in the mix. The plot shows that Mixes 1, 2, and 5 have lower resistance to moisture damage than Mixes 3 and 4.

Summary

Figure 15 shows that for coarse Mix 4 [63.1 percent retained on 10-mm (3/8-in.) sieve] and very coarse Mix 5 [75.2 percent retained on 10-mm (3/8-in.) sieve], the values of inverse creep slope, stripping inflection point, inverse stripping slope, and passes at a 25-mm (1-in.) rut depth with the 50.4-mm (2-in.) wheel are lower than those

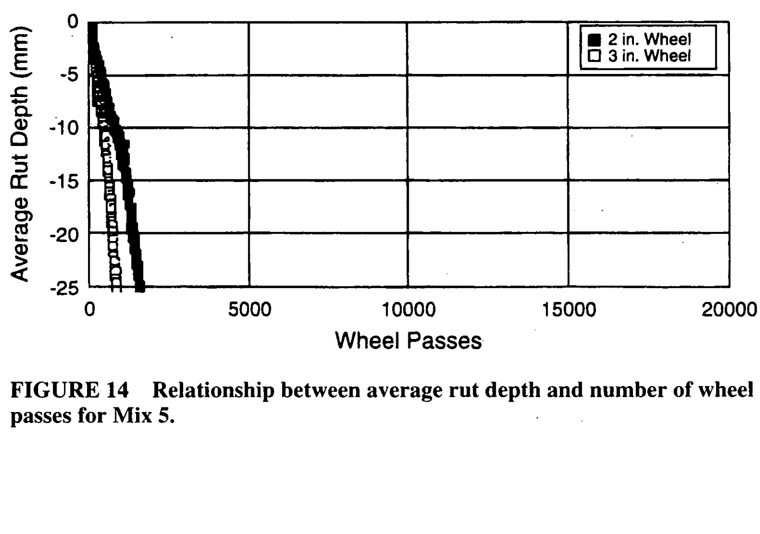


FIGURE 14 Relationship between average rut depth and number of wheel passes for Mix 5.

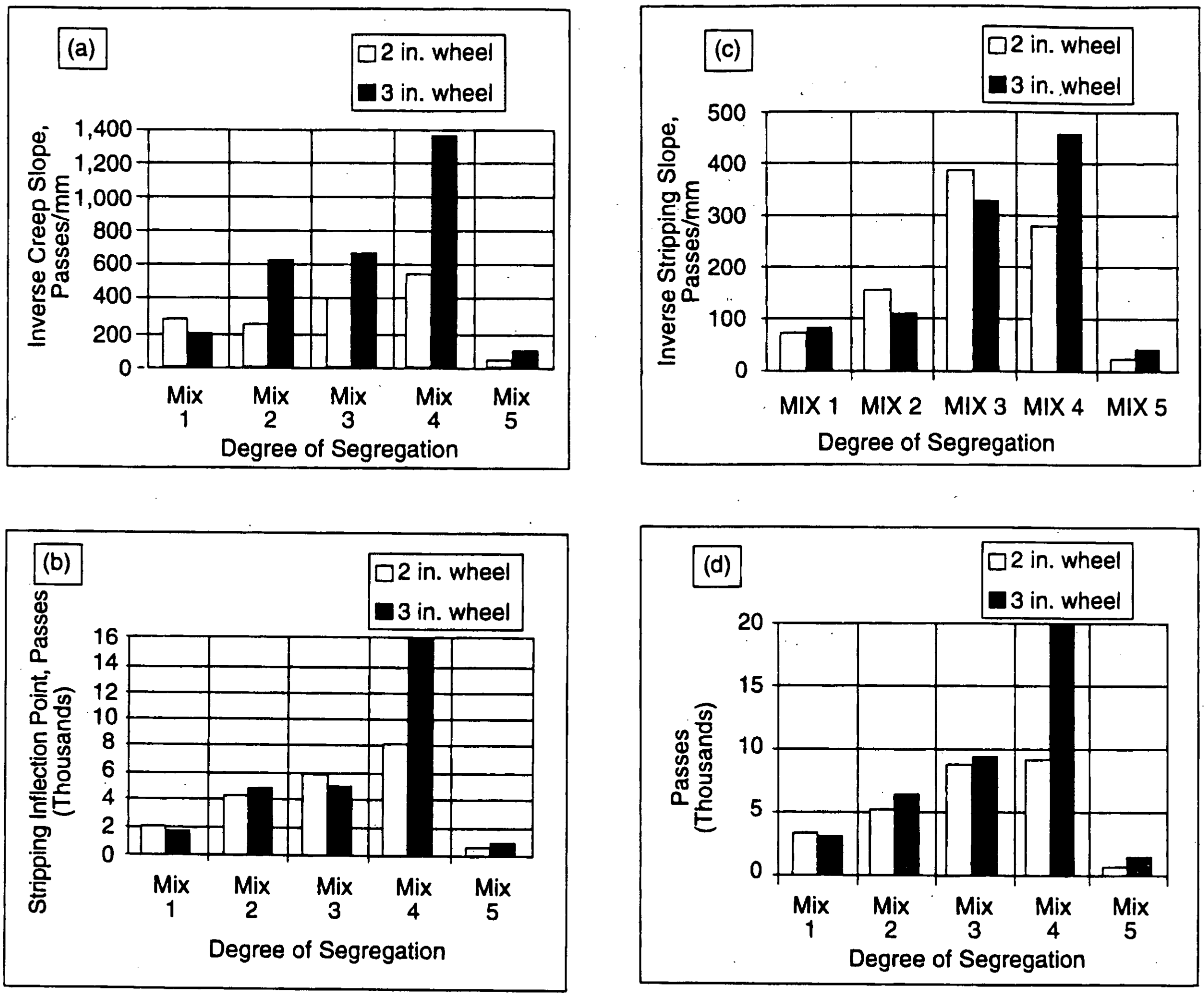


FIGURE 15 *(a)* **Creep slope versus degree of segregation;** *(b)* **stripping inflection point versus degree of segregation;** *(c)* **stripping slope versus degree of segregation;** *(d)* **passes at 2.5-mm rut depth versus degree of segregation.**

TABLE 4 Observations of Stripped Asphalt and Flushed Fines

	Free Asphalt		Flushed Fines	
Mix No.	Yes	No	Yes	No
1	x		x	
2	x		x	
3	x		x	
4	x		x	
5		x		x

values obtained with the 76.2-mm (3-in.) wheel. This result suggests that the aggregate interlock is being compromised sooner with the 50.4-mm (2-in.) wheel even though the initial contact pressure is adjusted to be the same.

The following are observations made during the Purwheel-tracking-device tests:

1. Mix 5 performed so poorly that little information could be obtained about the test or the relative merits of the 50.4-mm (2-in.) versus 76.2-mm (3-in.) wheels.
2. Mixes 1, 2, and 3 showed similar characteristics for both the 50.4-mm (2-in.) and 76.2-mm (3-in.) wheels.
3. The greatest difference in results between the 50.4-mm (2-in.) and 76.2-mm (3-in.) wheels was for Mix 4. In this case the 76.2-mm (3-in.) wheel appeared to accentuate Mix 4 characteristics. As pointed out above, any benefit was completely lost in testing Mix 5.
4. It appeared that the 76.2-mm (3-in.) wheel would be more effective in testing this type of mixture (gravel/natural sand) with a gradation as coarse as Mix 4.
5. Ultimately, a correlation with field performance of mixtures will be needed.
6. Additional tests of mixtures with other aggregates should be made and are planned.

CONCLUSIONS

On the basis of the laboratory testing performed in this study, the following conclusions were drawn:

1. As a result of segregation, the combination of fine material and excess of asphalt created a potential for rutting.
2. Laboratory samples were effectively prepared representing a wide range of potential segregation.
3. The gyratory stability index and the compactibility index decreased with increasing amount of coarse aggregate.
4. Air voids were low for segregated fine material and high for segregated coarse material.
5. Indirect tensile strength increased and then decreased with increasing amount of coarse aggregate.
6. Inverse creep slope, stripping inflection point, and inverse stripping slope increased and then decreased with increasing amount of coarse aggregate.
7. Results of Purwheel-tracking-device tests showed that for segregated bituminous mixtures containing an excess of coarse aggregate, the 50.8-mm (2-in.) wheel was more severe than the 76.2-mm (3-in.) wheel.
8. The Purdue linear compactor did not fracture the aggregate and compacted slabs to a predetermined density.

ACKNOWLEDGMENT

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