NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 441

Segregation in Hot-Mix Asphalt Pavements

Transportation Research Board
National Research Council

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Segregation in Hot-Mix Asphalt Pavements

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report presents recommended methods and specifications to detect and measure segregation of hot-mix asphalt (HMA) using infrared thermography or ROSAN$_v$ laser surface texture measurements. It will be of particular interest to materials and construction engineers in state highway agencies, as well as contractor personnel responsible for construction of HMA paving projects. Further, the report contains criteria for classifying the severity of segregation with these measurement techniques and for correlating segregation to rutting potential, loss of fatigue life, permeability, and several other performance-related HMA properties.

Three types of HMA segregation have been identified. *Gradation segregation* is the nonuniform distribution of coarse and fine aggregate materials in the finished HMA mat introduced at one or several points in the HMA production, hauling, and placement operations. Localized mat areas rich in coarse aggregate are typically associated with high air voids and low asphalt contents; these conditions can lead to moisture damage as well as to durability-related pavement distresses such as fatigue cracking, pothole formation, and raveling. Conversely, mat areas rich in fine aggregate are associated with low air voids and high asphalt contents, making them susceptible to rutting and flushing. *Temperature segregation* occurs as the result of differential cooling of portions of the mix on the surface of the mix in the haul truck, along the sides of the truck box, and in the wings of the paver. The third type, *aggregate-asphalt segregation,* is common in stone-matrix asphalts (SMAs).

HMA segregation is a common problem throughout the United States; numerous studies have been conducted to identify and mitigate its causes. Because most identification methods involve subjective, visual interpretations of the appearance of the surface of the HMA pavement, numerous disagreements between contracting parties occur that could be resolved by objective, standardized procedures for identifying and measuring segregation and for evaluating its effects on performance.

Under NCHRP Project 9-11, "Segregation in Hot-Mix Asphalt Pavements," the National Center for Asphalt Technology at Auburn University was assigned the responsibility of developing procedures for defining, locating, and measuring segregation and for evaluating its effects on HMA pavement performance. The research team conducted the following:

- A review of relevant domestic and foreign literature on causes and detection of segregation;
- A survey of current methods and technology for detecting and measuring segregation;
- An extensive field investigation to test and validate several promising, nondestructive and destructive detection methods;

- Development of recommended test methods and specifications for the use of the most promising techniques of infrared thermography and $ROSAN_v$ laser surface texture measurement to identify the occurrence of segregation and estimate its level of severity; and
- A comprehensive laboratory testing program to develop criteria correlating a given level of segregation, as measured by the two selected techniques, with the increased potential for future pavement distress.

This NCHRP report includes a general discussion of the entire research effort, a summary of relevant results from the field and laboratory test programs, and conclusions and significant findings. The appendixes present the main deliverables of the project in the form of four proposed recommended AASHTO specifications:

- A test method for using infrared thermography to identify segregation in HMA during paving operations;
- A test method for using $ROSAN_v$ laser surface texture measurements to identify segregation in HMA pavements;
- A specification for using infrared thermography to detect and measure segregation; and
- A specification for using $ROSAN_v$ surface texture measurements to detect and measure segregation.

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AUTHOR ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of Mr. Dennis Sixby, of the Federal Highway Administration, for arranging for the loan of the ROSAN$_v$ equipment, and Mr. Scott Clements, of Surfan Engineering and Software, Inc., for the analysis software and technical support throughout this project. The authors also would like to thank Scott and Harry Seaman, of Seaman Nuclear Corp., and Robin Moss, of Troxler Electronic Laboratories, Inc., for their extensive support and assistance in completing the nuclear density testing for this project. The support of Dr. Soheil Nazarian of the University of Texas, El Paso, in evaluating the portable seismic pavement analyzer (PSPA) for the purpose of detecting and measuring segregation is also greatly appreciated.

A special thank you is extended to the state agencies that hosted the research teams and provided the field support necessary for the successful completion of this project.

SEGREGATION IN HOT-MIX ASPHALT PAVEMENTS

SUMMARY

The objectives of this research were to develop procedures for defining, detecting, and measuring segregation and to evaluate the effects of segregation on hot-mix asphalt (HMA) pavement performance. Nondestructive technologies capable of evaluating the characteristics of the entire mat during construction were considered the most desirable methods. The best candidate technologies were expected to produce measurements strongly correlated with changes in key performance-related mixture properties.

Two types of segregation were identified in the initial literature review: gradation segregation and temperature segregation (i.e., temperature differential). Gradation segregation is the most commonly seen type and can occur as the result of aggregate stockpiling and handling, production, storage, truck loading practices, construction practices, and equipment adjustments. Temperature segregation was identified in the literature as occurring as the result of differential cooling of portions of the mix on the surface of the mix in the haul truck, along the sides of the truck box, and in the wings of the paver. An additional type, aggregate-asphalt segregation, common in stone-matrix asphalts (SMAs), was also suggested. Segregation may be defined as a lack of homogeneity in the HMA constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es). “Constituents” should be interpreted to mean asphalt cement, aggregates, additives, and air voids.

A total of 14 projects (7 recently constructed, 7 during construction) were evaluated with nondestructive and destructive approaches to determine the ability of each method to detect and measure both types of segregation. Initially, visual observations were used to designate areas in each 150-m test section as having no, low, medium, or high levels of segregation. Infrared thermography was used to determine temperature differentials in these areas. The ROSAN$_v$ laser surface texture measurement system was used to determine the changes in surface texture with the various levels of segregation. A rolling nuclear density and moisture gauge was used to evaluate the change in density and asphalt content via hydrogen counts. A prototype nuclear thin-lift asphalt content gauge and the portable seismic pavement analyzer were also evaluated.

Once the nondestructive testing was complete, cores were obtained and air voids, mix stiffness, tensile strength, gradation and asphalt content were determined. Cores were taken from the same areas evaluated with the nondestructive methods. Laboratory

testing of both cores and laboratory-prepared samples resulted in the development of definitions of levels of segregation based on expected changes in key mixture properties. A summary of the changes in mixture properties resulting from segregation is shown in Table S-1. In addition to these percent changes in properties, air voids were also found to increase with increasing levels of segregation. Air voids were between 0 and 4 percent higher than nonsegregated areas at low levels of segregation, 2 to 6 percent at medium levels, and greater than 4 percent at high levels.

Based on these data, the following definitions of the levels of segregation were developed:

- Areas with **no segregation,** assuming that proper mix design and compaction is attained, will have acceptable air voids, greater than 90 percent of the anticipated mix stiffness. The asphalt content will be within 0.3 percent of the job mix formula, and there will be no statistical difference in the percent passing any of the coarse sieve sizes.
- Areas with **low-level segregation** will have a mix stiffness of between roughly 70 and 90 percent of the nonsegregated areas and increased air voids of between 0 and about 4 percent. If gradation segregation is present, at least one sieve size will be at least 5 percent coarser and there will be a corresponding decrease in asphalt content between 0.3 and 0.75 percent.
- Areas with **medium-level segregation** will have a mix stiffness of between about 30 and 70 percent of the nonsegregated areas and increased air voids of between 2 and 6 percent. If gradation segregation is present, at least two sieve sizes will be

TABLE S-1 Summary of the influence of segregation on mixture properties

Mixture Property	Percent of Non-Segregated Mix Property by Level of Segregation			
	Fine	Low	Medium	High
Permeability	Increased slightly	Increasing with level of coarse segregation		
Resilient Modulus	Little or slightly increasing stiffness	80 to 90%	70 to 80%	50 to 70%
Dynamic Modulus	Little or slightly increasing stiffness	80 to 90%	70 to 80%	50 to 70%
Dry Tensile Strength	110%	90 to 100%	50 to 80%	30 to 50%
Wet Tensile Strength	80 to 90%	75%	50%	30%
Low-Temperature Tensile Stress	No conclusions due to test method difficulties			
Loss of Fatigue Life when Segregation in Upper Lifts, %	Not Estimated	38%	80%	99%
Rutting Potential	Not strongly influenced by gradation segregation			Mixed Results

at least 10 percent coarser and there will be a corresponding decreased asphalt contents between 0.75 and 1.3 percent.

- Areas with **high-level segregation** will have a mix stiffness of less than 30 percent of the nonsegregated areas and increased air voids of more than 4 percent. If gradation segregation is present, at least three sieve sizes will be at least 15 percent coarser and there will be a corresponding decreased asphalt content of greater than 1.3 percent. Cores will have a tendency to fall apart upon coring or cutting.

Pavement conditions in six states were surveyed. Pavements showed various levels of distress resulting from segregated mixtures. Little rutting was seen, except when temperature segregation (i.e., poor compaction) was the primary problem. In these cases, the high air void areas showed evidence of rutting from 5- to 13-mm deep.

These surveys agreed well with the laboratory results. That is, the primary form of distress, in addition to raveling, was either fatigue or longitudinal cracking, followed by the formation of potholes. This type of cracking is associated with both low mix stiffness and low tensile strengths. A survey of the agency staff indicated that they believed that they were losing between 2 and 7 years of an anticipated life of about 15 years because of segregation.

A life cycle cost analysis estimated that the agency cost because of segregation was approximately 10 percent of the original cost of the HMA for a low level of segregation and about 20 percent for medium levels of segregation. High levels of segregation resulted in additional costs of close to 50 percent.

This research showed that of all of the technologies evaluated, both the infrared thermography and the $ROSAN_v$ laser surface texture measurements, are the best for detecting and measuring segregation. Table S-2 presents the range of temperatures seen with the infrared camera, which are indicative of each level of segregation as defined above.

Table S-3 shows the limits for those texture changes associated with each level of segregation. The predicted estimated texture depth (ETD) is calculated using information from the mixture being produced (i.e., maximum size aggregate and gradation characteristics).

TABLE S-2 Identification of a discrete segregated area using infrared thermography

No Segregation	Low-Level Segregation	Medium-Level Segregation	High-Level Segregation
Area in the mat with temperatures 10°C or less of a difference between coldest and hottest temperatures	A discrete area in the mat with a mean temperature between 11 and 16°C cooler than the surrounding area	A discrete area in the mat with a mean temperature between 17 and 21°C cooler than the surrounding area	A discrete area in the mat with a mean temperature more than 21°C cooler than the surrounding area

TABLE S-3 Identification of a segregated area using $ROSAN_v$ surface texture measurements

No Segregation	Low-Level Segregation	Medium-Level Segregation	High-Level Segregation
Textures between 0.75 (Predicted ETD) and 1.15 (Predicted ETD)	Textures between 1.16 (Predicted ETD) and 1.56 (Predicted ETD)	Textures between 1.57 (Predicted ETD) and 2.09 (Predicted ETD)	Textures greater than 2.09 (Predicted ETD)

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Historically, segregation has been defined to mean localized areas of coarse materials in some areas and fine materials in others in the finished mat (*1*). Coarse-aggregate-rich regions typically have high air voids and low asphalt contents that can accelerate moisture- and durability-related pavement distresses such as pothole formation and raveling (*2*). Previous research has shown that very coarsely segregated materials also have substantially reduced tensile strengths and fatigue life (*3*). Fines-rich materials commonly have low voids with high asphalt contents, which can lead to localized depressions (i.e., permanent deformation) and flushing.

Traditionally, visually identified areas of nonuniform surface texture have been classified as segregated mix. Because such evaluation is subjective, inspectors and contractors have difficulty agreeing about what is and is not segregation. Results of testing of these suspect areas sometimes show gradation and density changes. In other cases, only density changes are found (*3*).

Both segregation and low density can significantly increase the occurrence of localized pavement distresses. Therefore, a nonuniform surface texture may be indicative of compositional or volumetric nonuniformities of both, which can lead to accelerated pavement distresses. A methodology for measuring segregation needs to be developed so that the total percent of nonuniformity in the mat can be estimated. The effect of nonuniformity on pavement performance and pavement life is needed so that the cost of segregation to agencies can be estimated. Only then can a reliable, statistically viable specification for detecting and measuring segregation be developed.

Many causes of segregation produce repetitive patterns of nonuniformity; therefore, standard quality control/quality assurance (QC/QA) procedures that randomly define sampling locations would have a low probability of adequately identifying this problem. Ideally, some type of longitudinal pavement profile using one or more nondestructive measurements at selected transverse locations can be identified. An alternative methodology is needed to address random but localized areas of nonuniformity.

1.2 RESEARCH PROBLEM STATEMENT

Hot-mix asphalt (HMA) segregation is a common reoccurring problem throughout the United States, and a number of studies have been conducted to identify its causes. However, little work has been done to systematically develop the following:

- Definitions of segregation,
- Procedures to detect segregation, and
- Evaluations of the effect of segregation on mixture properties and pavement performance.

Most identification methods have consisted of subjective, visual interpretations of the HMA pavement surface appearance. This has led to many disagreements between contracting parties as to what is and is not segregated HMA. These conflicts could be resolved by establishing quantitative procedures for detecting, measuring, and evaluating the effects of segregation.

1.3 OBJECTIVES

The objectives of this research were to develop procedures for defining, detecting, and measuring segregation and to evaluate the effects of segregation on HMA pavement performance. Nondestructive technologies capable of evaluating the characteristics of the entire mat during construction were considered the most desirable methods. The best candidate technologies would produce measurements strongly correlated with changes in key performance-related mixture properties. This would allow for the development of sound, statistically based specifications that could be linked to the anticipated costs associated with the loss of pavement life as as result of segregation.

1.4 RESEARCH APPROACH

The focus of this research was to identify and use innovative technologies for the nondestructive measurement of segregation. These measurements were directly correlated with key performance-related HMA mixture properties. Estimates of the loss of life and hence increased costs as a result of segregation were made using a series of pavement condition surveys of highways exhibiting a range of segregation-related distresses. This information was then used to develop preliminary specifications for detecting and measuring segregation. The following is a list and brief description of the tasks included in the work plan:

- **Task 1—Literature Review.** Conduct a literature search to identify and evaluate ongoing and previously completed research on HMA pavement segregation.
- **Task 2—Current Methods for Detecting, Defining, and Measuring Segregation and Its Effects on HMA Pavement Performance.** Conduct a survey to identify current methods of detecting, defining, and measuring segregation and evaluating its effect on HMA pavement performance.
- **Task 3—Interim Report.** Prepare a report that presents the following:
  —A summary of information gathered in Tasks 1 and 2,
  —Recommendations for defining and measuring HMA pavement segregation,
  —A proposed methodology for evaluating the effects of segregation on HMA pavement performance, and
  —A revised work plan for remaining tasks.
- **Task 4—Validation of Methods of Measurement.** Validate the measurement methods.
- **Task 5—Development of Procedures To Locate Segregated Areas.** Develop procedures to detect segregated areas in HMA. Validate these procedures in at least three states using the measurement methodology or methodologies from Task 4.
- **Task 6—Correlation Between Segregation and Pavement Performance.** Based on the methodology or methodologies from Task 3, correlate segregation severity to pavement performance in different environmental zones.
- **Task 7—Test Methods and Specifications in AASHTO Format.** Based on the results of Tasks 4, 5, and 6, develop a test method or methods and specifications in an AASHTO format to define, locate, measure, and evaluate HMA segregation. The specifications should include guidance in identifying areas of potential conflict and recommendations for resolving those conflicts.
- **Task 8—Final Report.** Prepare a final report that documents the research and findings. The recommended test method or methods and specifications shall be included as stand-alone documents in separate appendixes to the final report.

This report presents and documents the results of all of the work conducted for this project, as well as all data analyses, interpretations, preliminary specifications, and recommendations for further study.

CHAPTER 2

FINDINGS

2.1 SUMMARY OF LITERATURE REVIEW

Highlights of relevant research, as well as critical evaluations of selected literature, are included in this chapter. Previously determined relationships between segregation and pavement distress are also included. The information is organized as follows:

- Detection of segregation;
- Measurement of segregation;
- Influence of segregation on pavement performance; and
- Innovative technologies for locating, measuring, and defining segregation.

2.1.1 Detection of Segregation

Three nondestructive methods have been used. These include the following: (1) visual identification, (2) sand patch testing, and (3) nuclear density gauges. Each will be discussed briefly in the following sections.

2.1.1.1 Visual Identification

Historically, visual identification of nonuniform surface texture has been used to locate segregation (*4*). This is a subjective approach, which can lead to disagreements between agency and contractor representatives. To achieve a level of consistency in this approach, some agencies have formed a select group of experienced individuals who are available for surveys should segregation be suspected. One example of this is South Carolina's "Golden Eye" team (*5*). The Ontario DOT uses a pavement-distress manual concept, which provides inspectors with guidelines and photographic examples of different levels of segregation (*6*).

In all the literature reviewed, visual detection of nonuniform areas was used as the baseline against which any quantitative approach was compared. However, several field studies showed that a nonuniform surface texture was, in reality, an indication not only of coarse aggregate segregation, but also of localized areas of low density (*7, 8*). To a much lesser extent, minor surface defects (e.g., from hand work) and aggregate breakage during compaction (*3*) also contribute to nonuniform surface textures.

For example, Cross et al. (*3*) studied four Kansas field projects with suspected segregation problems. Five areas that were visually identified as segregated and another three classified as acceptable were evaluated for each project. Cores were taken and areas with a change in gradation of more than 5 percent on the 4.75 mm sieve were considered to be segregated. This limit was selected because it was used for acceptance during construction. For one project using a gradation above the maximum density line, only two of the five coarsely textured areas proved to be segregated. Two other projects that were evaluated were constructed with gradations below the maximum density line. All five of five coarsely textured areas for one project and three of five for the other project were measurably segregated. An examination of the cores from the fourth project showed that the coarse surface texture resulted from aggregate breakage during construction and was eliminated from further study.

Conclusions from these studies include that visual observations are better able to identify segregation in mixtures with larger maximum size aggregate and coarser (below the maximum density line) gradations. It is difficult to identify segregation visually for mixtures with smaller sized aggregates and finer gradations.

2.1.1.2 Sand Patch Testing

The sand patch test has been used to quantify visual observations of differences in the surface macrotexture (*6, 8*). The ASTM E965 (*9*) test method indicates that the precision of the test method is approximately 1 percent of the measured depth in millimeters and the between operator variation is about 2 percent.

Good agreement was consistently reported between visual observations of nonuniform textured areas and the sand patch test results for measuring surface macrotexture. An examination of the data from areas visually considered acceptable and confirmed by testing of cores indicates that if a maximum limit of 0.300 mm was placed on macrotexture, 88 percent of the areas with either voids greater than 10 percent from undercompaction or segregated mix would be identified. However, limits on surface texture will be mix-specific. That is, an SMA is expected to have a higher mean surface texture than a fine, dense-graded mix. Limits probably will have to be defined as texture differences between uniform and nonuniform areas.

2.1.1.3 Nuclear Density Gauges

Attempts have been made to use rolling density gauges to identify segregated areas by profiling the longitudinal density of the pavement mats. The assumption is that segregation will be seen as low density. Seaman Nuclear and Troxler both offer roller gauges but use different methods for mounting and operating the gauges. A rolling drum contains the radioactive source, a G-M detector, and a distance-measuring sensor. A speed of 1 km/h (½ mph) with one reading per meter over a 100-m-long section for three longitudinal paths at transverse quarter points is suggested. Seaman demonstrated this gauge for National Center for Asphalt Technology (NCAT) staff in the fall of 1996 on a project in Wisconsin. In general, density decreased with increasing surface texture.

Researchers at Michigan State University recently completed a study, on behalf of the Michigan DOT, that used discrete nuclear density measurements to detect segregation (*10*). The emphasis of this research was the detection of linear pattern segregation; random segregation was not extensively considered. Wolff et al. recommended that the Michigan DOT use linear nuclear density profiles for quality control procedures. They noted that there will be a continuation of the study to further refine testing recommendations. Although these researchers had reasonably good success with this method of detecting segregation, they also noted that there were several test sites that visually appeared segregated but did not show a significant change in density.

The Kansas DOT has also recently adopted the use of nuclear density measurements to detect segregation (*11*). This method requires a minimum of four longitudinal nuclear density profiles. Segregation is detected as a range of densities greater than 5 pcf. There is an additional requirement that the difference between the mean and lowest density value not be more than 2.5 pcf. Kansas DOT staff noted that there appears to be a significant reduction in segregation problems with the implementation of this requirement. However, because the method takes about 1 hour to complete one profile, the testing is time consuming.

A Missouri Transportation and Highway Department study investigated a golf-cart-mounted Troxler 4545 nuclear density gauge (air gap method) (*12*). Both a laboratory and field study were conducted. The laboratory study showed that gauge variability was sensitive to the height of the air gap as well as the type of aggregate. Increasing gap height increased the gauge's variability. Limestone aggregates produced significantly higher variability than did gravels. While there was limited correlation between gauge readings, visual observations, and core densities, the Missouri Transportation and Highway Department concluded the concept of profiling the pavement density as a means of detecting segregation was worth pursuing.

Two reasons can be presented to account for the erratic success in using these gauges for detecting segregation. First, the common assumption for using these gauges is that density decreases with increasingly coarse aggregate segregation. However, this assumption does not consider the relationship of the gradation to the maximum density line. If the job mix formula (JMF) begins above this line, separation of the coarse aggregate in this type of mix may result in a higher density as the gradation shifts toward the maximum density line. Second, different types of aggregates have different effects on gauge variability. Limestone, a commonly used aggregate source, substantially increases testing variability. Gravels on the other hand have much less of an effect on variability. If a mixture is composed of coarse limestone and fine gravel stockpiles, the resulting change in testing variability in coarse aggregate-rich and fine aggregate-rich areas may make it difficult to adequately detect or measure segregation or both.

2.1.1.4 Summary

Based on the information presented in this section, the following can be concluded:

- Visual observations of changes in the pavement surface texture can be quantified using the sand patch test. However, this test is time consuming and would not be practical for daily use by DOTs.
- There is a greater probability that nuclear density gauges can be used to determine segregation in coarse gradations than in fine (above maximum density) gradations.
- Concentrations of different aggregate types can have a significant effect on the nuclear density gauge testing variability. If variability is increased, it may become difficult to distinguish changes in density because of segregation.

2.1.2 Measurements of Segregation

Areas suspected of being segregated are first identified using one of the methods discussed above. The next step is to confirm this suspicion using either nondestructive or destructive (cores) testing (most commonly used to date). Nondestructive measurements include (1) permeability, (2) density (nuclear density gauges, which were discussed above), and (3) a combination of asphalt content and density (nuclear density/asphalt content gauges). Testing of cores includes measuring changes in (1) asphalt content, (2) gradation, (3) densities, and (4) air voids.

2.1.2.1 Nondestructive Measurements

Permeability measurements can be made using either air (ASTM D3637, [*9*]) or water methods. Results reported in the literature suggest that permeability testing might only be applicable for establishing various levels of coarse aggregate segregation. This is because test results depend more on the interconnected nature of void volume rather than simply the percent of voids. Fine dense-graded mixtures have sufficiently low permeability that, even when moderately segregated, there is little to no statistical difference in permeability measurements (*13, 14*).

Disadvantages to this test for evaluating in-place segregation include unsaturated flow and complex flow patterns; no differentiation can be made between horizontal or vertical flow. Most of these disadvantages can be eliminated by taking a core, sealing the outer edges, and conducting a standard falling head permeability test, such as that recently implemented by the Florida DOT in 1997. In addition, measurements of different permeabilities in fine-graded mixtures can be enhanced if a constant vacuum pressure is used to pull the water through the sample (*15, 16*).

Nuclear density/moisture content gauges have been used experimentally to confirm segregation exists in areas with a coarser surface texture than most of the pavement surface. The nuclear moisture measurement portion of these gauges measures hydrogen content, which is used to indicate the asphalt cement content.

Williams et al. (*14*) used combined nuclear moisture/density gauge measurements to define segregation. If, on a plot of percent of JMF density versus difference in asphalt content (from moisture reading), a point falls below the 90 percent probability line, the mix is segregated.

Several limitations should be noted when using these gauges. First, measurements will also factor in properties of underlying materials, because the gauges are not specifically designed to concentrate on the upper few centimeters of the pavement mat. Second, the presence of moisture may be a limitation; however, the researchers assumed that changes in asphalt content in segregated areas will be much larger than changes in moisture content. Brown et al. (*13*) reported decreases in asphalt content from 1 to 2 percent in the coarsely segregated areas of 16 Georgia projects. Although some moisture content is typically allowed in HMA, it is usually limited to less than 0.5 percent immediately after placement. This suggests that moisture will have some effect on measurements made immediately after placement but the changes in the asphalt content should be sufficiently large in segregated areas to be measurable. Substantial problems are anticipated if testing is attempted after a rainfall.

2.1.2.2 Destructive Testing (Cores)

Asphalt content and **gradations** after either extraction or an ignition oven have been used to measure segregation. A decrease in asphalt content with an increase in coarseness was the single constant factor reported in all of the research on segregation measurements (*4, 17*). Bryant's results (*4*) showed that a change of 10 percent in the percentage of aggregate passing the 4.75 mm sieve corresponded to a change of about 0.75 percent in asphalt content. Brown and Brownfield (*8*) reported asphalt content for segregated areas in 16 Georgia projects was from 1 to 2 percent lower than in the nonsegregated areas. Cross et al. (*3*) suggested that for the four Kansas projects evaluated, a change in asphalt content of 0.28 percent indicated a 5 percent change in the material passing the 9.5 and retained on the 4.75 mm sieve.

Changes in coarser aggregate gradation fractions were also commonly used to measure segregation. Several reasons for selecting a specific aggregate size to evaluate segregation can be found. Bryant's original work on the subject of segregation used changes on the 4.75 mm sieve to identify segregation and other researchers have continued to use this parameter (*4*). Other reasons are (1) that this was a control sieve size used in the original acceptance plan and (2) that the most substantial changes were observed for this sieve size. These two reasons were also given for selecting the 2.36 mm sieve size in other research projects (*18*). Khedaywi and White (*19, 20*) used the screen (e.g., sieve size varied) that had approximately 50 percent passing to separate fine aggregate-rich and coarse aggregate-rich mixtures.

The Alabama DOT has recently adopted a testing program, based on asphalt content and gradation measurements, to quantify segregation. Briefly, cores are taken from areas with a nonuniform surface texture, and the asphalt content and gradations are determined. The area is considered segregated if the asphalt content is below a threshold value and the gradation on key sieves (which vary based on mix type) are outside of pre-established ranges (*21*).

Definitions of "significant" segregation varied among researchers. Cross et al. (*3*) defined "significant" based on allowable QC/QA specification ranges for 4.75 mm sieve. Because various agencies have a wide range of specification limits and control sieves, this definition of "significant" would be interpreted differently by each agency. Identification of a statistical difference (95 percent confidence interval) between a number of samples in the uniform areas and a similar number of samples from a nonuniform area has also been used. Brown and Brownfield (*8*) suggested that a change in the percent passing the 2.36 mm sieve of more than 10 percent from the JMF defined a significantly segregated mix because it represented a substantial change in properties such as Marshall stability and voids.

Because different types of HMA will have considerably different gradations (e.g., SMA, large-stone mixtures), selecting one sieve size on which to base a definition of segregation may not be reasonable. One method used by Khedaywi and White (*19, 20*), which separated the mix on a sieve which is closest to 50 percent passing, might be a better basis for defining segregation.

Density measurements are commonly reported and used in the calculation of air voids. Because the density of cores will be influenced by the same changes in aggregate gradations as noted in the discussion on nuclear density gauges, density measurements by themselves should not be used to detect segregation.

Air voids increased with increasing segregation for JMF gradations starting below the maximum density line. This volumetric parameter is calculated using both the bulk and maximum specific gravity test results. Because the proportions of the HMA constituents in segregated areas will be significantly different than those in nonsegregated areas, bulk and maximum specific gravities need to be determined for each area, if an accurate measurement of voids is needed.

2.1.2.3 Summary

Nondestructive testing has the potential for detecting and measuring segregation with the following limitations:

- Permeability testing will only be able to detect segregation in coarse gradations with interconnected, high void contents.
- Although nuclear density/moisture gauges have some potential for measuring segregation once a suspect area is identified, the use of these gauges is not desirable because measurements are made discretely and are technician-time intensive. If these types of gauges can be vehicle-mounted and operated at a reasonable speed to provide accurate results, it may be possible to profile HMA parameters with this technology. Results will be highly dependent upon changes in the moisture content of the pavement.

Using traditional destructive tests, segregation has been quantifiably defined as a statistically significant change in the following:

- Changes in surface texture can be used to identify segregated areas. It is possible that a difference or ratio in surface texture between nonuniform and uniform areas would be a better parameter than just individual texture measurements. This will also need to be explored during the field trials.
- Percent passing the sieve size, which corresponds to the first JMF control sieve larger than that which 50 percent passes (based on JMF). "Statistically significant" has been defined as the limits used for acceptance testing. The next coarser sieve size above the 50 percent size was selected, because results presented in the literature indicate segregation is easier to identify as changes in the coarser fractions.
- Asphalt content in the segregated areas related to the asphalt content in adjacent nonsegregated areas. Again, "statistically significant" was defined as the limits used for acceptance testing. An in-place reference for asphalt content changes was selected rather than the JMF value, since asphalt contents can change substantially from the JMF during construction. This happens when the contractor begins to adjust plant controls to obtain the required densities.
- Determining changes in asphalt content, gradation, and air voids for cores can be used to measure segregation. However, this approach is destructive and time consuming and is not recommended for daily use by state agencies.

2.1.3 Influence of Segregation on Pavement Performance

Cross and Brown (*2*) used sand patch test results as a measure of raveling caused by a combination of segregation and traffic. A single value used to represent the level of segregation for this analysis was selected as a change in the percent passing the 4.75 mm sieve. The final regression equation relating the levels of traffic and segregation to raveling was reported as

$$P = 0.0346 + 0.0718(T) + 0.00265(P_{4.75})^2$$

where:

P = difference in the macrotexture between segregated and nonsegregated areas,
T = traffic in millions,
$P_{4.75}$ = difference in the percent passing the 4.75 mm sieve.

Several other studies (*20, 22, 23*) have used performance-related mixture properties to estimate relative changes in performance characteristics. These properties included tensile strength, the effect of moisture on tensile strength, diametral and beam fatigue testing, and the rate of rutting from laboratory wheel-track testing devices. Cross et al. (*3*) found an increase of 5 percent in coarseness, measured as a change in the percent retained on the 4.75 mm sieve, corresponded to about an 11 percent decrease in tensile strength. These measurements were also strongly correlated with air voids. This suggests that any correlation between tensile strength measurements and pavement performance should include both a measure of the degree of segregation and air voids.

Cross et al. (*3*) found that the diametral fatigue life of cores from segregated areas decreased about 50 percent with only a 10 percent increase in the percent retained on the 4.75 mm sieve. Testing of laboratory-prepared mixtures showed similar results. In the case of laboratory-prepared samples, increasing coarseness also corresponded with increasing moisture sensitivity. However, this finding was also strongly correlated with changes in voids.

Khedaywi and White (*19, 20*) tested laboratory-simulated segregated mixtures in the PURWheel tracking device. Results showed that limited coarsening of the gradation resulted in somewhat improved rut resistance when compared with the JMF. Either fine or very finely segregated mixtures showed some increase in rutting potential. However, all of these mixtures substantially out-performed the very coarsely segregated mixtures. Conducting the test in a wet environment showed that coarse segregation increased moisture damage under the simulated traffic loadings.

2.1.3.1 Summary

Segregation can be expected to substantially

- Decrease fatigue life in coarse-aggregate-rich areas,
- Increase moisture sensitivity when segregation results in an increase in air voids,
- Increase rutting in both fine-aggregate-rich and coarse-aggregate-rich areas (pavement performance appears to be more severely affected by coarse- rather than fine-aggregate-rich segregation), and
- Increase raveling and is accelerated with increasing traffic volumes.

2.1.4 Innovative Technologies for Locating, Measuring, and Defining Segregation

Five new or alternative uses for existing technologies have been identified as having at least some potential for selectively identifying HMA segregation. These are as follows:

- Thermal imaging,
- Ground-penetrating radar (a permittivity measurement),
- Thin-lift nuclear asphalt content/density gauges,
- Laser surface texture measurements, and
- Seismic pavement analyzers.

The major criterion for identifying innovative technologies for possible use in this research was an ability to measure quantifiably in a rapid, repeatable, nondestructive manner at least one key mixture property that will change because of segregation. Key properties include voids, density, asphalt content, gradation, and permeability. Another requirement was that there was a reasonable expectation of the equipment being commercially available in at least some form at the end of this research. Ideally, the technology should be able to map (profile) the HMA mat property or properties in order to identify segregation. Additionally, the ability of the technology to be vehicle-mounted and to operate at highway speeds was considered desirable. However, this type of technology is usually expensive ($100,000 to $200,000) and might only be useful to state agencies for acceptance testing of finished projects. For day-to-day construction control and inspection, a smaller and more affordable scale of the technology, which can be operated at typical construction speeds, is preferable.

2.1.4.1 Thermal Imaging

All objects emit infrared radiation in the form of heat, which can be detected by an infrared scanner. These natural impulses are converted into electrical pulses and then processed to create a visual image of the object's thermal energy. The colors used to represent the thermal imaging can be user-selected to represent surface temperature changes, such as blue for colder regions and red for warmer regions (*24, 25*).

The primary component of any thermal imaging system is an optical scanner. This unit is used to detect radiation in the infrared spectrum. Other essential components are a display monitor, videocamera, and computer and software for data acquisition, analysis, and storage. The area surveyed by the camera is determined by minimum resolution requirements and the height of the equipment above the surface. A full-lane width can be surveyed at one time (*26*) with an appropriately placed camera. Weil and Haefner (*25*) noted that liquid-nitrogen-cooled scanners provide improved resolution over other methods of cooling. Although current technology is vehicle-mounted, operation at highway speeds (>80 kph [50 mph]) tends to blur the image. Resolution is improved substantially by operating the equipment at slower than highway speeds (<60 kph [38 mph]).

Current Use of Infrared Technology. Thermal changes have been used to determine the location and extent of bridge deck delamination, concrete defects (e.g., voids, cracks, and scaling), and asphalt overlay debonding (*24, 25, 27*). For example, vehicle-mounted infrared technology is marketed for evaluating bridge deck delamination (*27, 28*).

In current pavement applications, solar heating of the surface is the source of thermal energy. This means that on cloudy days or after sundown thermal differences are minimized. The best results are obtained when used at a time of day when the rate of heating or cooling of the pavement is most rapid (*25*). Other weather conditions, such as ambient temperature, wind speed, humidity, surface moisture, and surface texture, can greatly influence results. In the case of surface texture, emissivity largely depends on surface texture with rough textures showing higher emissivity than smooth textures.

Testing with this type of equipment is described in ASTM D4788 *Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography* (*9*). A limited precision statement in this method indicates that interoperator testing with the same equipment on the same day on the same location will have about a ±5 percent variation in the areas identified as damaged. No calibration procedure for the equipment is included in this test method.

New Uses of Technology. New applications of this technology have identified temperature differentials during paving operations. In some instances, the temperature difference results from a more rapid cooling of the mix along the uninsulated sides of haul trucks or the collecting (and cooling) of the mix in paver wings. This has been referred to as "temperature segregation" by Brock and Jakob (*29*).

Other researchers (*30, 31*) have indicated that coarse-aggregate-rich areas will have a greater percentage of air voids around the particles—this will promote faster cooling of the mix in these areas. Conversely, denser and more finely packed asphalt-rich and fine-aggregate-rich areas will retain heat longer. These temperature differentials will then be a measure of the degree of segregation.

A Swedish company, CA Konsult, has refined the equipment, data collection, and analysis of these types of images for the specific purpose of detecting and measuring segregation (*32*). There are three parts to the data acquired with this technology: (1) the color thermal scan of the full lane width (3.6 m [12 ft]) by approximately 330-m (100-ft) long, (2) a single transverse temperature profile (line scan), and (3) a bar graph of the percent area of the mat at a given temperature. This source of information also notes that a standard deviation of 3°C is common for projects with no visual signs of segregation.

Based on this information, infrared thermography appears to have excellent potential for locating, defining, and measuring segregation. Data obtained from this type of testing can be used for process control as well as for setting specification limits. Several U.S. sources of the basic infrared thermal imaging equipment have been identified: Inframetrics, Inc., WaveTech, Inc., and Infrasense, Inc. CA Konsult also offers the complete sensor and analysis package under the name of Global Positioning Thermography (GPT), which incorporates fixed positioning capabilities as well as data acquisition.

The **advantages** to using this technology include the following:

- The thermal characteristics of the entire mat surface can be mapped.
- Technology can be used during construction, which will allow the contractor to remedy problems immediately as they occur.
- Sophisticated software already exists that appears readily adaptable to assessing the percent unacceptable material during construction.
- This same software would provide process control charts (maps) that could be used by agencies for acceptance or identifying areas that need more extensive testing to determine the type and level of segregation.

Some **disadvantages** are as follows:

- Only surface or near-surface defects are evident.
- Both temperature and gradation segregation will appear as "cold" areas. A secondary testing program will be needed to define the type of segregation more accurately.
- Data need to be obtained prior to the first pass of the roller, because compaction of the mat alters the surface thermal characteristics.
- The use of this technology for after-construction surface evaluations is doubtful. This technology depends on solar gain to highlight differences. Differences in the heat loss, Q, is the value of interest:

$$Q = UA(T_S - T_A)$$

where:

U = overall heat transfer coefficient,
A = area of heat transfer,
$(T_S - T_A)$ = difference between the surface and ambient temperature.

This last term suggests this technology would not be sensitive to small differences between ambient and mat surface temperatures.

- A calibration procedure is needed to ensure that different cameras are recording differential temperatures to the same magnitude and sensitivity.
- A means of locating the position of nonuniform areas for further testing is needed if the Swedish equipment and software is not used.

2.1.4.2 Ground-Penetrating Radar (Permittivity)

The basic theory used in GPR is a measurement of the dielectric constant, E, (or permittivity). A material is said to be dielectric if it can store energy when exposed to an electrical field (*33*). In highway applications, this property is seen as a peak in the reflected wave amplitude at each layer interface (*34, 35, 36, 37*). The pulse travel time through the structure can then be used to compute the layer thickness (*38, 39*). Rmeili and Scullion (*40*) also found that anomalies in the reflected wave forms between peaks could be used to evaluate density and moisture content. Saarenketo and Scullion (*41*) used this approach with reasonable success for detecting underlying moisture damaged (stripped) areas in several field projects.

GPR Equipment. Systems have four major components: (1) a pulse generator that produces a radar energy signal at a given frequency and power, (2) an antenna that transmits the pulse into the sample being evaluated, (3) a recorder that stores the reflected signals, and (4) computer hardware and software for quantifying selected wave amplitudes (*40, 41, 42*).

Two types of antennae have been used. The air-launched antenna is operated about 0.3 m (12 in.) above the surface, and the depth of penetration of the signal depends on the frequency of the signal. At 1 GHz, the most commonly used frequency, layer information can be obtained for the upper 0.5 m (20 in.). Higher resolution of the near surface can be obtained by increasing the frequency to 2.5 GHz (*43*). Deeper penetration (but less upper layer resolution) can be obtained using a 500 MHz frequency. These antennae can be operated at typical highway speeds (*44*).

The ground-coupled antenna also operates over a range of frequencies (80 to 1,000 MHz), but must remain in near-contact with the surface. This type of antenna can only be operated at slow speeds (typically less than 10 kph [6 mph]) and has some unresolved problems with surface coupling and antenna ringing. These drawbacks make this type of antenna the least desirable for highway applications.

The Texas Transportation Institute (TTI) (*41*) has developed six specification tests for purchasing air-launched GPR equipment. TTI found that, if a unit passes all six of these tests, it can be used to compute layer properties reliably. In fact, several manufacturers have already adopted these tests for calibrating units prior to sale.

The ASTM D4748 *Standard Test Method for Determining the Thickness of Bound Pavement Layers Using Short-Pulse Radar* (*9*) also provides a calibration and standardization procedure. This is based on a calibration time constant established for the radar system by measuring the time interval between reflections from two precisely spaced metal plates. The precision of this unit for thickness measurements is ±5.08 mm (0.2 in.) for between-operator testing.

Sensitivity to Layer Properties. A field project in Ylinampa, Finland, used GPR technology to measure pavement thickness. However, reductions in dielectric values were noted at the end of each truck load and other places where the paver had problems (*44*). Although the intention of the study was to measure thickness, it was apparent that this methodology might also be useful in measuring segregation.

Typically reported values of the real part of the dielectric constant are as follows:

- Water: 81
- Ice: 3.5 to 3.8
- Air: 1
- Aggregates (dry): 4.5 to 6.5
- Asphalt: 2.6 to 2.8

The large influence of water on the test results makes it easy to see why this method has been used successfully to identify moisture in the pavement structure. However, it also suggests that even a small percentage of moisture in the HMA will have a significant affect on test results.

Rmeili and Scullion (*40*) used an air-launched antenna (1 GHz) operated at highway speeds to evaluate moisture-damaged areas of I-45 in the Bryan District in Texas. Comparison of GPR results with a visual examination of more than 60 cores showed that subtle differences in between-layer wave peaks can be used to discern “good” sections from sections with stripping at the bottom of the asphalt layer, mid-depth, or close to the surface. Given that stripping and migration of asphalt and fines produce changes in the aggregate gradation, density, and asphalt content, it is reasonable to conclude that this method has the potential for determining changes in these mix properties resulting from segregation.

Saarenketo noted during a presentation at the 1998 Transportation Research Board meeting that three Finnish pilot projects will use a roller-mounted GPR horn to establish the numbers of passes needed to achieve density (*40*). Saarenketo showed that dielectric constant decreased nonlinearly with increasing air voids.

However, researchers have noted that GPR measurements are not sensitive to changes in asphalt content (*41*). This can be confirmed by estimating the change in the dielectric constant resulting from a change in the asphalt content (holding other volumetric parameters the same). Using the average values shown above and assuming a change in asphalt content from 5.6 percent to 4 percent and holding air voids constant, the dielectric constant would change by only 0.1.

Williams et al. (*14, 23*) conducted a laboratory study using this technology. Results from laboratory testing using a fine, dense-graded control gravel mixture with different levels of segregation showed values for the real part of permittivity were around 4.5 for both the very finely segregated and control mixtures but decreased to about 4.0 for very coarse segregation. When testing a coarser, dense-graded control mixture with different levels of segregation, the real part was approximately 5.0 for both the very finely segregated and control mixtures. The real part of permittivity decreased to around 4.0 for very coarse segregation and the results became very erratic at higher testing frequencies. These results imply this method may only be capable of detecting coarse segregation. This will need to be fully investigated in the preliminary laboratory and/or field trials.

In summary, it appears it will be difficult to quantify changes in measurements for purposes other than those for which the current software is written. It also appears that this method is only a density (or moisture) measurement. Therefore, it has a low probability of being useful in detecting segregation by itself.

Some **advantages** to using this technology include the following:

- This technology is already being used by several state agencies for thickness design and for evaluating underlying moisture in the pavement structure.
- Sophisticated data acquisition and analysis software already exists.
- There is some evidence that this technology can evaluate changes in the pavement layer properties.
- The technology is adaptable for use both during and after construction.
- The equipment can be vehicle-mounted and operated at construction or highway speeds.

Several **disadvantages** need to be considered:

- There appears to be little sensitivity to changes in the asphalt-aggregate proportions. Given that these key mix properties change because of segregation, this would

imply that this test method would not be able to detect segregation.
- Changes in dielectric constant appear to be primarily sensitive to changes in air voids in fresh mix (i.e., limited moisture). This appears to be another form of density measurement.
- The software is only written to evaluate dielectric constant changes that occur at layer interfaces. A time-intensive subjective analysis by the technician would be required to assess changes of the properties within each layer.

On the basis of these disadvantages, it appears that this technology would be a poor candidate for quantifiably detecting and measuring segregation.

2.1.4.3 Combined GPR and Infrared Thermography Technologies

Some research has been completed that combines these two technologies. GPR provides an assessment of the material properties with depth, while the infrared thermography aids in detecting and defining the extent of segregation. Using both technologies may provide the best possible three-dimensional look at HMA mat properties.

Manning and Holt (*27*) found that this approach took advantage of the complimentary nature of these two technologies. GPR only produces data along grid lines scanned by the antenna. Therefore, either multiple passes or multiple antennas are needed. On the other hand, infrared thermography produces a "map" of the entire pavement surface. The combination of technologies could enhance the usefulness of each.

2.1.4.4 Thin-Lift Nuclear Density/Asphalt Content Gauge

Troxler has developed a prototype thin-lift asphalt content/density gauge intended to be used like the traditional density gauges for measuring in-place HMA properties. This gauge should be an improvement over using the moisture content gauges given that the depth of measurement will be limited to the upper layer of the pavement and will help eliminate variability resulting from changes in the underlying layers. A different source of radiation [Californium 252 (Cf 252)] is used in order to increase the sensitivity of the readings. Very limited preliminary laboratory studies indicate that there is a good relationship between gauge readings and asphalt content. Given that the readings will be dependent upon the volume of voids in the HMA, the prototype gauge will have a means of compensating for different densities as well.

The **advantages** of using this technology include the following:

- The asphalt content can be determined in place. This measurement is needed in addition to density measurements to determine the percentage of the nonuniform area that is poorly compacted and that results from gradation or asphalt-aggregate separation.
- The hand-held use of the unit makes it useful for secondary testing once nonuniform areas have been identified by another means.

Disadvantages associated with this technology include the following:

- Moisture content in the HMA will influence the gauge readings. This limits the use of these gauges to applications during construction only. The variability in moisture contents of the pavement mat after construction will make the reliability of the results questionable.
- Concurrent density measurements are needed in order to fully use the data. At the current time, this requires the use of two gauges per test.
- Only discrete measurements can be obtained.
- In its current form, the use of the gauges is time intensive.

Unknowns that still need to be evaluated include determining the effect of underlying layers and aggregate sources on results.

2.1.4.5 Laser Surface Texture Measurements

This type of technology has been used in various forms for several years for measuring surface macrotexture. The technology uses a rapidly pulsing semiconductor laser to produce infrared light that is projected onto the pavement surface. The light is scattered off of the surface and a receiving lens focuses this scattered light onto a linear array of photodiodes. The diode receiving the most light corresponds to the distance to the surface. Texture is determined from a series of these measurements, and data are output as a printout.

Research consistently indicates a strong correlation (R^2 of 0.89) between laser measurements and the sand patch texture depths, which ranged from about 0.20 to 4.25 mm (*45, 46*). These results are consistent with those reported by Roadware, which report an R^2 of 0.94. However, correlations between the sand patch and laser measurements will depend on the roughness of the surface texture. In the case of very rough surface textures, the laser may tend to underestimate the texture as the laser light cannot penetrate deeper air voids that can be filled with sand (*47*).

Calibration and correction factors were found to be essential to reduce variability in test results from different gauges (*45*). After calibration on a specially designed textured rubber mat, these researchers found that the repeatability and reproducibility of these systems were 0.6 and 0.10 mm, respectively.

Various commercially available laser profilometers already incorporate at least one of these sensors in their measurement systems. Roadware also markets a combination of this technology as the ARAN profilometer. The Australian Road Research Board (ARRB) Transport Research organization has also developed a vehicle-mounted multilaser profilometer (MLP) system (*48, 49*).

The location of the sensor on these types of multipurpose units depends on the intended use of the data. For example, the MLP laser sensors in this system are placed to measure flushing in wheel paths and, as a result, one texture sensor system is mounted over each wheel path. To report texture, 40 data points are taken per 280 mm and fit with a second order polynomial to account for the effect of tire bounce on measurements. As with the GPR equipment, these lasers can be operated at typical highway speeds (>80 kph [50 mph]).

The FHWA has developed a single portable laser sensor unit and data acquisition system that can be mounted to the bumper of any vehicle. This product is marketed under the brand name of ROSAN (*50*). Preliminary research showed a potential for identifying localized areas with noticeably different surface textures. Areas with obviously higher surface texture were linked to visually identifiable coarse-aggregate-rich areas.

There are numerous **advantages** to using this technology for detecting and measuring segregation:

- Continuous longitudinal surface texture profiles can be obtained quickly because the technology can be operated at normal highway speeds.
- This technology provides a quantifiable measurement that corresponds to visual observations of nonuniform surface texture.
- The equipment is portable and reasonably affordable and can be mounted to any vehicle.
- The equipment and analysis software is easy to use and can provide a statistical analysis of the data obtained at the time of testing.

Disadvantages include the following:

- The technology measures only surface defects. No information about the depth of the nonuniformity through the pavement layer can be obtained. This means that a secondary testing program may be needed to further define the type and level of segregation in nonuniform areas.
- Slower speeds are needed for better resolution.
- A dry pavement surface is needed. Wet surfaces will alter the deflection of the laser beam.
- It is possible that any statistics will be mix type-dependent. This needs to be evaluated in any testing program using this equipment.

2.1.4.6 Seismic Pavement Analyzer

The seismic pavement analyzer (SPA), developed for SHRP, uses four wave analysis techniques: spectral analysis of surface waves (SASW), ultrasonic body waves, impact echo technique, and impulse response (*51, 52*). SASW is used for evaluating layer moduli and thickness. Ultrasonic body waves and impact echo technique are used in conjunction to obtain Young's modulus and the layer thickness of the surface course. The impulse response component is used to obtain information about the shear modulus of the subgrade for the overall system. The information obtained for surface courses would be the most likely to be useful in identifying the effect of segregation on pavement performance caused by changes in mixture stiffness with changes in composition and density.

The full-scale SPA unit is large (approximately the same size as a falling weight deflectometer) and would not be useful in investigating small, nonuniform areas. However, there is a portable SPA (PSPA) hand-held unit. This unit would be better suited to evaluating the change in material properties once areas of nonuniformity have been identified using other techniques. The following types of information can be obtained from this unit: (1) the thickness of the top layer (impact echo), (2) the shear modulus of the top layer (ultrasonic surface waves), and (3) Young's modulus (ultrasonic body waves).

Advantages to using this technology as a secondary test method include the following:

- Changes in performance-related material properties can be measured in place.
- Information for relating the anticipated effects of types and levels of segregation can be obtained.

Disadvantages include the following:

- Results will be dependent on the pavement temperature at the time of testing. Therefore, information on the change of properties with temperature will be needed to normalize the data collected. This will require laboratory testing of either behind-the-paver mixtures or cores.
- The influence of the underlying pavement layers is unknown.

2.1.4.7 Proposed Methodologies for Detecting and Measuring Segregation

Based on the information presented in the preceding sections, it appears likely that a combination of technologies will be needed in order to detect and measure different types and levels of segregation. The first step will be to use technologies that can provide a quantifiable measurement of surface or near-surface characteristics (e.g., infrared thermography and laser surface texture measurements). Either infrared thermography or laser surface texture measurements can be used as a preliminary means of mapping the pavement properties. In the case of the laser surface texture measurements, mapping would take the form of a property grid, while thermography might be able to provide a complete surface evaluation. The second step will be to evaluate key properties, specifically within areas identified as nonuniform, and compare these to those in uniform areas. Technologies that would be applicable for use in this step include nuclear density and asphalt content measurements and the portable seismic pavement analyzer (PSPA).

Table 1 summarizes the information presented in the previous sections. Visual observations can be quantified nondestructively by using the sand patch test, laser macrotexture measurements, or thermography. Both laser and infrared thermography measurements of surface texture can be used either by themselves or in conjunction with other nondestructive tests (e.g., nuclear asphalt/density gauges) to identify, classify, and quantify segregation.

Nuclear technologies, GPR, and PSPA have the potential for nondestructively evaluating the upper HMA layer. Of the test methods and technologies identified to date, only the GPR and PSPA might be able to evaluate the entire depth of the HMA. However, laboratory GPR tests using the same general technology indicated that this method would probably only be able to evaluate density changes. Any results will be strongly influenced by any moisture present. Because nuclear density gauges are more commonly available and more economical, they would be preferable for measuring density changes.

Field use of permeability tests can only identify coarse types of segregation or areas with high voids (>8 to 10 percent). Given that segregated areas may not always have high voids, this method might not identify all areas. If the assumption is made that limiting water and air intrusion will significantly decrease the potential for accelerated pavement distress, then this method may be useful.

TABLE 1 Estimate of ability of methods to measure segregation

Test Method	Type of Mix				Depth of Measurement		
	Fine Gradations	Dense Gradations	SMA	Misc. (OGFC, LSM, etc.)	Surface Only	Depth of Lift	Full AC Mat Depth
Visual Observations	Yes	Yes	Yes	Yes	Yes	No	No
Laser Sensors	Yes	Yes	Yes	Yes	Yes	No	No
Nuclear Density Gauge	Gradation Dependent	Gradation Dependent	Yes	Gradation Dependent	No	Yes	No
Nuclear Asphalt & Density Gauge	Yes	Yes	Yes	Yes	No	Yes	No
Permeability	No	Coarse Seg.	Yes	Gradation Dependent	No	Yes	No
GPR	Unknown	Unknown	Unknown	Unknown	No	Yes	Yes
Infrared Thermography	Unknown	Unknown	Unknown	Unknown	Yes	Thin Lift	Unknown
PSPA	Unknown	Unknown	Unknown	Unknown	No	Yes	Yes

Destructive testing (i.e., taking cores and determining asphalt content, gradation, and volumetrics) can only be conducted for a few discrete locations. This testing will be used during this project to validate nondestructive measurements of segregation. These results will also be used to set ranges for degrees of segregation.

2.2 SUMMARY OF CURRENT PRACTICES

A questionnaire, designed by Purdue researchers, has been circulated to states, and responses have already been tabulated. The same questions have been asked of contacts. Responses from U.S. agencies and the international contacts are summarized below.

2.2.1 U.S. Questionnaire Summary

Williams et al. (*14, 23*) surveyed the states about current segregation specifications and guidelines, training in the recognition and control of segregation, methods of quantifying the degree of segregation, moisture sensitivity testing (a problem assumed to be accentuated by coarse segregation), and future interest in training materials related to minimizing segregation. A summary of this survey follows.

1. Does your agency have any specifications or guidelines for the prevention of segregation in hot mix asphalt (HMA) during the phases of production and placement?

   Yes: 30 No: 13

   General comments included with "yes" answers:
   - Extracted asphalt content and gradation (random—not specifically for visually segregated areas),
   - Contractor requirement to prevent and correct segregation,
   - Inspectors located at HMA plant and paving sites and inspector training,
   - Specifications (Standard operating procedures, guidelines, and checklists),
   - Require or eliminate specific equipment and construction practices,
   - Pay factor for density (in development),
   - Change to smaller top size aggregate gradations,
   - Stockpiling requirements, and
   - General statements that "segregation of the mixture will not be acceptable" or "roadway must be uniform and smooth."
2. Does your agency train technicians in any troubleshooting procedures to minimize segregation in the production and placement of quality HMA?

   Yes: 37 No: 6

   General comments included with "yes" answers:
   - Both state and contractor technicians trained to minimize segregation during production, hauling, and placement;
   - Intermittent workshops conducted by consultants;
   - Various asphalt plant and paving technician certification courses;
   - On-the-job training; and
   - District-level training sessions.
3. Does your agency make any attempts to quantify the degree of segregation (i.e., testing, visual evaluation) when it is known to exist?

   Yes: 26 No: 17

   General comments included with "yes" answers:
   - Visual evaluation only (most frequent response);
   - Selective sampling and testing for density, asphalt content, and/or gradation; and
   - Visual plus nuclear gauge readings.
4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

   Yes: 3 No: 39

   General comments included with the "yes" answers:
   - Lottman-type testing during mix design, and
   - Raveled sections after construction removed and replaced at contractor's expense.
5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

   Yes: 33 No: 6 Possibly: 4

   General comments included with the "no" answers:
   - Segregation has not been a problem, and
   - Already offer various courses.

2.2.1.1 Summary of Supplemental Information Provided by Survey Respondents

The Georgia DOT proposed one method for detecting segregation using comparative nuclear density gauge measurements. The process starts with a visual identification of potentially segregated areas. The mat density is determined using the nuclear density gauge in backscatter mode. The surface voids are then filled with a slurry of water, fine sand, and cement and then covered with plastic wrap and retested. If the difference between the readings is greater than 163 kg/m^3 (10 pcf), the area is considered to be segregated.

The Georgia DOT proposed a second method using these gauges. With this method, if the voids in a visually nonuniform area are greater than 9 percent, then the area is segregated. Neither method has been adopted because of a lack of data supporting a good correlation between in-place voids (as determined with the nuclear gauges) and the degree of segregation. After much consideration, the Georgia DOT went to identifying segregation by visual inspection and then verifying the observations with extracted core results. If the cores are within the mixture control limits, the mixture is not considered segregated. If changes in the gradation exceed the tolerance, corrective action is to be taken by the contractor.

If results deviate by more than 10 percent from the JMF, the mix may be required to be removed and replaced at the contractor's expense.

The Virginia DOT used a thin-lift nuclear gauge placed on a calibration plate to determine the density of a visually nonuniform surface area. A second reading with the gauge in the surface void mode was then taken. If the difference was more than 146.8 kg/m^3 (9 pcf), the area was considered segregated.

The Colorado DOT submitted a method for detecting segregation using nuclear gauges, based on density variations in the pavement mat. If density measurements in a visually nonuniform mat differed from a uniform area by more than 81.6 kg/m^3 (5 pcf), it was considered segregated. The Colorado DOT has never used this method as a specification.

The Kansas DOT, Michigan DOT, and the Missouri Transportation and Highway Department are all exploring using nuclear density profiles to identify segregation.

2.2.1.2 Overall Summary of Section

Based on this information, the following general statements can be made:

- Most state agencies recognize the importance of controlling segregation in the finished pavement.
- Visual identification is, by far, the most common means of identifying potentially segregated areas. However, the subjectivity of this approach leads to continual debates between agencies and contractors as to what is and is not a uniform surface texture.
- The subjective evaluation of the quality of the final product seems to be the reason that several states specify "good construction practices," such as use of material transfer devices to prevent segregation so that the states do not have to measure segregation.
- Several states would like to have a reliable measurement test method or a specified series of tests that would objectively identify areas of substantial segregation. This is evidenced by the number of states conducting field trials that explore various methods for measuring segregation.
- The lack of adoption of any of these methods also reflects agencies' frustration with the lack of correlation of test results from various tests with segregation.

2.2.2 International Survey

International government agencies, paving associations, and research organizations were contacted in order to obtain a comprehensive view of segregation problems, methods of detection, and current research (see Table 2). The information obtained from this survey is summarized in the following sections.

TABLE 2 Countries and agencies contacted

Country	Agency, Association, or Organization
Australia	Australian Asphalt Pavement Association South Australia Department of Transportation
Belgium	Belgium Road Research Center
Canada	University of Waterloo Roadware Saskatchewan Highways and Transportation
Denmark	Danish Road Institute
Finland	VTT (Finnish Materials Research Lab)
France	LCPC
Germany	German Asphalt Paving Association Superflos
The Netherlands	SHRP - NL
New Zealand	BCA (Asphalt Paving Association)
Norway	Civil Aviation Administration
Portugal	APORBET (Asphalt Paving Association)
South Africa	CSIR Sabita
Sweden	WTI (Swedish Transportation Institute)
Switzerland	EMPA Swiss Federal Labs
United Kingdom	University of Nottingham SWK Pavement Engineering

2.2.2.1 *Australia*

Visual identification is used to specify the quality of the pavement surface (i.e., uniform texture). The use of mixtures that are prone to segregation is minimized; the typical maximum size of aggregate is less than 20 mm. There is some use of large stone mixtures, which tend to segregate. In this case, *NCHRP Report 386* (*7*) and the National Asphalt Pavement Association (NAPA) document on the causes and cures for HMA segregation (*1*) offer procedures for minimizing this problem.

If segregation appears to be a problem, then the State Road Authorities (SRA) will specify the use of a material transfer device. An improvement in the surface smoothness is considered to reflect a reduction in segregation problems.

Testing for segregation is limited to density measurements and a tensile strength ratio minimum of 70 percent for cores obtained from areas with a nonuniform surface texture.

2.2.2.2 *Scandinavian Countries, Switzerland, and Denmark*

Some problems with segregation have been identified. As early as 1991, Swedish researchers noted that infrared thermography seemed useful for identifying segregation during construction (*29, 30*). These researchers hypothesized that coarse-aggregate-rich areas tended to have larger air pockets around them in the loose mix. This was seen in infrared thermographs as cooler regions. Finnish researchers have also been exploring the use of GPR for identifying segregation during construction (see the preceding section for further information on this subject).

2.2.2.3 *England, Belgium, the Netherlands, and France*

Sources from these countries reported similar information. Segregation is not considered a big problem in these countries. This is a direct result of minimizing or limiting aggregate gradations that tend to exhibit this problem. In most cases, the maximum size aggregate is less than 20 mm, and discontinuous gradations are avoided. Limited problems with segregation in SMAs were reported by some sources.

When segregation is considered a problem, "best practices" construction procedures are required. Surface friction measurements generally are used to define the percent defective of the overall surface.

The SHRP respondent for the Netherlands reported that a laboratory test to be used during the mix design stage to evaluate the segregation potential of the mix is being explored. This test method involves preparing loose mix and subjecting it to handling that would allow segregation. Various portions of the mixture are tested. If the asphalt content and gradations are not consistent between the portions, the mix is considered prone to segregation and, therefore, the gradation is unacceptable.

2.2.2.4 *New Zealand*

Segregation is not considered a significant problem because of the predominance of thin surface courses and the small maximum aggregate sizes typically being used. Where segregation appears to be a problem, "best practices" construction techniques are specified (ISO9002). Testing is limited to using nuclear density gauges to establish differences between uniform and nonuniform textured areas. A quick subjective test that was noted involved wetting the pavement surface. Areas with segregation problems will hold water and, therefore, are easily identified.

2.2.2.5 *South Africa*

Segregation is a problem with their large stone base mixtures (LAMBs). Guidelines for addressing this problem are predominately based on a "best practices" construction approach.

2.3 FIELD EVALUATIONS

The literature review identified potentially useful nondestructive technologies, which were summarized in Table 2 (preceding section). Based on this information, GPR and field permeability testing were eliminated from the testing program because these technologies had the lowest likelihood of detecting and measuring segregation.

The preliminary field testing of these technologies was completed for two test sections in each of two states. Projects 1-1 and 2-1 were recently constructed and projects 1-2 and 2-2 were evaluated during construction. The projects evaluated for this research program will be identified by project number and a general classification of geographic location.

Once the preliminary testing was completed, an additional 10 projects (5 recently constructed, 5 during construction) in different areas of the country were evaluated. The work and test results obtained for each set of projects (one recently constructed, one during construction for each state) are detailed in Appendixes A through G (not published herein, but are available, for a limited time for loan or purchase, on request to NCHRP). These test results are summarized in this section.

General project information is summarized in Table 3. A wide range of aggregate sizes and gradations, asphalt grades, and lift thicknesses were included in the testing program. Although most projects were intermediate lifts of medium to high traffic volume facilities, in some cases, a shoulder or a thick leveling lift was tested because of safety considerations.

TABLE 3 Summary of project information

Project	Weather	Paving Information	Max. Size Agg. mm	Asphalt Content %	Asphalt Grade	Lift Thick. mm
Southeast						
1-1	Sunny, hot, humid	NA	25.0 mm	4.1	AC 30	50
1-2	Sunny, hot, humid	Paver - haul truck Daytime paving	25.0 mm	5.0	AC 30	45
4-1	Sunny, hot, humid	NA	12.5 mm	5.3	PG 67-22	50
4-2	Sunny, hot, humid	Material transfer device Daytime paving	19.0 mm	4.4	AC 30	60
5-1	Sunny, hot, humid	NA	19.0 mm SMA	5.8	PG 76-22	50
5-2	Warm, humid, thunderstorms	Paver - haul truck Nighttime paving	19.0 mm SMA	5.8	PG 76-22	55
Northwest						
2-1	Overcast, cool, breezy with an occasional light drizzle	Paver equipped with a re-mixer in hopper	12.5 mm	4.8	AR 4000W	60
2-2	Overcast, cool, breezy with an occasional light drizzle	Paver - haul truck Daytime paving	12.5 mm	4.8	AR 4000W	70
Upper Midwest						
3-1	Sunny, warm, clear	NA	12.5 mm	5.4	NR	30
3-2	Sunny, warm, clear	Windrow Daytime paving	12.5 mm	5.4	NR	60
South						
6-1	Sunny, hot, clear	NA	37.5 mm	3.7	AC 20	105
6-2	Sunny, hot, clear	Windrow paving Daytime paving	37.5 mm	3.7	AC 20	105
Northeast						
7-1	Clear, cool (< 25°C), dry	NA	19.0 mm	5.4	NR	50
7-2	Clear, cool (< 25°C), dry	Paver - haul truck Nighttime paving	19.0 mm	5.4	NR	77

NR: Information not reported

NA: Not applicable

2.3.1 General Testing Program

2.3.1.1 Field Testing

The length of test sections varied somewhat for each test section. Most sections were between 150 and 160 m long, but several were limited to between 80 and 100 m. The length chosen depended on safety, weather, and construction issues. Safety considerations such as a safe stopping distance (for a truck with laser), sight distance for the driving public, and the availability of traffic control were primary factors in determining the length. In one case, a thunderstorm halted construction and, therefore, abbreviated the testing. In another instance, the contractor changed lanes earlier than anticipated.

Infrared testing was conducted from the back of the paver during construction and from standing in the center of the lane for recently constructed sections at 10-m intervals. Nonuniformity could be seen to some extent in the recently constructed pavements, but results were highly dependent on the presence of shadows, clouds, and time of day.

Testing of the finished mat started with marking three longitudinal paths at transverse quarter points, which were used as sight lines for the truck driver (laser) and the rolling nuclear gauge operators. The preliminary testing was used to reduce the number of variables in the laser testing program to one speed (30 kph) for safety reasons, a base length of 500 mm for averaging data, and two replicates along each longitudinal line.

Visual observations of the surface texture were noted. Areas with various levels of segregation (e.g., none, low, medium, and high) were noted on pavement condition survey forms. Generally, a two-person NCAT research team performed this work; however, when the state DOT representatives had selected a project based on their perception of the level of segregation, their classifications were taken into account.

Visual observations were also used to identify between 10 and 20 discrete test locations for additional nondestructive testing. The number of locations varied based on the number of levels of segregation seen and the willingness of the host agency to core a new pavement. Testing included traditional thin-lift nuclear density, a Troxler prototype asphalt content gauge, and the PSPA estimates of stiffness (preliminary projects only). Cores were taken after the nondestructive testing was completed.

2.3.1.2 Laboratory Testing

The standard testing sequence used for determining the properties of each core is briefly described below.

- Bulk specific gravity was determined (cores were dried overnight at 50°C).
- Resilient modulus (stiffness) was determined at three temperatures (4°C, 25°C, and 40°C).
- Cores were sorted on the basis of visual observations of segregation.
- Tensile strength, dry (unconditioned), was determined for one-half of the cores in each group.
- Tensile strength, wet (moisture conditioned), was determined for the remaining cores.
- Cores were dried again, broken up, and the cut faces removed. The theoretical maximum specific gravity was then determined for each core.
- All material was retained from the theoretical maximum specific gravity testing, dried, and used to determine asphalt content and gradations.

Initial testing of cores attempted to include a measurement of permeability in the testing program; however, membranes would not seal around the cores without the use of either epoxy or grease. Because either of these methods would damage the cores, this testing was eliminated.

Potential problems with the ignition oven were avoided by burning a core from a nonsegregated area and then comparing the results to the JMF reported by the agency. If a close agreement was obtained for both the asphalt content and aggregate gradation, then the ignition oven was used to determine the asphalt content. If there appeared to be a problem, at least two cores were used to determine the asphalt content and gradation with traditional solvent extraction methods. This information was used to develop correction factors for both the asphalt content and aggregate gradation on a per sieve basis.

2.3.2 Summary of Laboratory Test Results

The first step in the analysis was to determine if the visually identified nonuniformity was a function of gradation segregation. Two sieve sizes were arbitrarily selected (9.5 and 4.75 mm) for examination. These were selected on the basis of the information presented in the literature review, which suggested that a change of more than 10 percent passing one or the other of these sieves, based on the JMF, was an indication of a significant (high) amount of segregation.

The percent passing each of these sieves was graphed versus the corresponding asphalt content. In most cases, there was a good correlation between changes in the asphalt cement content and gradation changes. When this was the case, the project was considered to exhibit gradation segregation. In some cases, the asphalt content changed noticeably without a change in gradation. These projects were considered to have plant-related mixing problems and were eliminated from the field evaluation of the new technologies.

The good correlation between asphalt content and gradation changes implies that this mix parameter can be used as a single variable to represent gradation changes. This conclusion was used to classify each core statistically as having a no, low, medium, or high levels of segregation. Cores with asphalt contents near the JMF were grouped together first. Natural breaks in the data were then used to further separate the data into different levels of segregation. Statistics were developed for each group formed, and an F-test was used to determine if the variances were statistically different. A means test (95-percent confidence level) for two independent samples with an unknown standard deviation and small sample size was then used to determine if the means were different. This same process was used to define the remaining levels of segregation.

Table 4 summarizes the JMF information for each project, while Tables 5 through 8 present the laboratory results associated with each level of segregation. Tables 9 through 12 present the standard deviations associated with each grouping of cores. The standard deviations associated with the percent passing each sieve was less than 2 percent. This value increased slightly (as expected) with the coarser sieve sizes.

The classification based on significant changes in asphalt content was confirmed by evaluating each gradation for a corresponding significant change in one or more sieves. Project 3-1 showed that the asphalt content changes were plant-related; this project was eliminated from the analysis. The SMA project (5-1) showed significant visual evidence of flushing, but the core results indicated this was the result of a significantly finer gradation than the JMF being used while keeping the asphalt content at the JMF. The contractor on Project 6-2 used a great deal of manual labor to place very fine material from the hopper over coarsely segregated areas. This tended to bias both the asphalt content and overall gradations for cores obtained from this project. That is, the gradations and asphalt content showed less change because of the additional fine aggregate. This also significantly affected the asphalt content because of the high surface area and the high asphalt content of the fine material.

Table 13 presents a general summary of the changes in gradations associated with each level of segregation. In

TABLE 4 Summary of job mix formula information

Properties	Project									
	1-1	1-2	2-2	3-1 & 3-2	4-1	4-2	5-1	5-2	6-1 & 6-2	7-1 & 7-2
Cumulative % Passing										
37.000 mm	100	100							100	
25.000 mm	99	100				100	100		88*	100
19.500 mm	91	95	100		100	99	99	100	77*	98
12.500 mm	76	79	94	100	99	80	56	89	62	92
9.500 mm	63	69	84	89	84	65	35	70	55*	74
4.750 mm	48	52	51*	47	60	45	24	28	38	55
2.360 mm	41	42	31*	28	45	33	19	18	25*	42
1.180 mm	30	34	24*	21*	32	24	15	16	18*	33*
0.600 mm	20	25	19*	15*	21	19	14	14	13*	28*
0.300 mm	12	14	16*	11*	17	14	12	13	8*	24
0.150 mm	7	8	9*	7*	10	9	11	11	5*	15
0.075 mm	4.5	5.1	5.1	3.0	6.0	5.0	8	10	3.8	5
Asphalt Cement Content, %	4.1	5.0	4.8	5.4	5.3	4.4	5.8	5.8	3.7	5.4

*Values approximated from gradation chart

TABLE 5 Summary of laboratory test results for cores identified as having no segregation

Properties	Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
Cumulative % Passing													
37.000 mm										100	100		
25.000 mm	100	100					100			89.4	85.4		
19.500 mm	95.4	96.3	100			100	98.8	100		75.8	77.4	100	100
12.500 mm	76.5	83.7	97.1	100	100	95.9	81.8	70.2		59.0	61.7	97.5	99.3
9.500 mm	66.8	73.0	85.3	87.7	89.8	82.1	68.0	52.8		53.1	55.9	88.9	73.7
4.750 mm	50.4	57.0	52.8	43.7	50.0	69.8	43.5	33.8	Too Few Samples	26.5	39.7	62.1	55.7
2.360mm	39.4	45.0	34.2	28.3	34.8	49.9	32.5	27.8		24.6	26.7	47.1	43.3
1.180 mm	32.3	36.3	23.2	21.3	25.8	35.6	24.3	23.6		17.1	18.4	39.8	33.7
0.600 mm	23.6	26.9	16.5	16.7	19.8	26.3	20.3	20.8		12.8	13.8	29.8	25.7
0.300 mm	14.7	16.0	12.2	11.3	13.0	19.6	16.0	18.0		9.8	10.2	17.5	18.3
0.150 mm	9.4	10.3	8.9	7.0	9.3	13.9	11.0	14.6		6.8	7.0	8.9	11.7
0.075 mm	6.1	6.6	6.2	4.3	4.2	8.9	6.7	10.3		5.2	5.2	5.5	7.5
Asphalt Cement Content, %	4.25	5.23	4.70	5.75	5.65	5.50	4.50	6.0		3.3	4.02	6.70	5.8
Air Voids, %	9.5	6.5	13.5	11.51	11.3	7.4	7.2	1.7		9.2	8.4	4.2	7.0
Resilient Modulus, MPa 25°C	2,668	2,186	1,167	TS	TS	3,039	2,647	2,264		3,769	3,255	1,291	1,524
Tensile Strength, kPa, 25°C	NA	NA	320	32	TS	996	776	370		946	1,150	734	557
Number of Cores	8	3	13	5	6	11	4	7		3	2	8	3

TS: Too soft or too thin to test
NA: Data not available

TABLE 6 Summary of laboratory test results for cores identified as having low segregation

Properties	Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
Cumulative % Passing													
37.000 mm											100		
25.000 mm	100	100					100				87.9		
19.500 mm	92.8	96.4	100				98.0				77.6		
12.500 mm	71.4	77.8	95.0	100	100		78.5				62.4		100
9.500 mm	61.4	69.6	78.5	87.7	86.5		61.3				57.4		72.8
4.750 mm	45.6	55.0	44.0	42.0	45.3	None	39.8	None	Too Few Samples	None	40.8	None	51.0
2.360 mm	36.2	43.6	28.5	28.0	31.0		29.5				28.0		32.3
1.180 mm	30.4	33.8	20.5	21.0	24.0		22.8				19.7		30.3
0.600 mm	23.0	26.8	15.0	16.3	19.3		19.0				14.6		23.8
0.300 mm	14.8	17.0	11.0	11.0	12.8		15.3				11.1		16.8
0.150 mm	10.4	11.0	8.2	7.3	7.0		10.5				8.0		6.5
0.075 mm	2.5	7.0	5.3	4.4	4.3		6.3				6.2		5.3
Asphalt Cement Content, %	3.78	4.79	4.19	6.04	5.04		3.56				3.40		5.30
Air Voids, %	10.7	11.8	13.0	10.7	13.0		9.1				7.8		10.6
Resilient Modulus, MPa 25°C	2,415	1,320	596	TS	TS		2,772				3,609		2,069
Tensile Strength, kPa, 25°C	NA	NA	NA	396	NA		645				1,084		448
Number of Cores	5	5	2	4	4		4				5		4

TS: Too soft or too thin to test
NA: Data not available

TABLE 7 Summary of laboratory test results for cores identified as having medium segregation

Properties	Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
Cumulative % Passing													
37.000 mm										100	100		
25.000 mm	100	100					100			82.2	86.4		
19.500 mm	91.8	97					95	100		65.3	74.2		
12.500 mm	62.4	71		100			74	70.6		45.8	57.2		
9.500 mm	51.6	61		91			52	52.3		40.0	50.9		
4.750 mm	37.0	47	None	46	None	None	31	33.1		27.4	35.9	None	None
2.360 mm	28.8	38		30			21	27.1		19.4	25.1		
1.180 mm	24.0	32		23			19	23.1		14.5	18.1		
0.600 mm	18.4	25		17			16	20.4		11.8	13.4		
0.300 mm	11.8	16		13			13	17.9		9.4	10.5		
0.150 mm	7.8	11		8			9	14.3		7.1	7.6		
0.075 mm	5.1	6.9		5.6			5.1	10.3		5.2	5.6		
Asphalt Cement Content, %	3.20	4.23		6.4			3.19	5.7		2.3	2.9		
Air Voids, %	12.8	13.0		9.5			11.8	2.2		9.7	8.5		
Resilient Modulus, MPa 25°C	1,687	1,400		TS			1,166	2,193		NA	2,181		
Tensile Strength, kPa, 25°C	NA	NA		NA			NA	712		NA	787		
Number of Cores	6	1		1			1	5		3	3		

TS: Too soft or too thin to test
NA: Data not available

TABLE 8 Summary of laboratory test results for cores identified as having high segregation

Properties	Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
Cumulative % Passing													
37.000 mm													
25.000 mm	100												
19.500 mm	87												
12.500 mm	42			100									
9.500 mm	33			89.3									
4.750 mm	23	None	None	45.3	None	None	None	None	Too Few Samples	None	None	None	None
2.360 mm	18			30.0									
1.180 mm	16			21.0									
0.600 mm	13			15.7									
0.300 mm	9			10.7									
0.150 mm	6			7.0									
0.075 mm	3.8			4.2									
Asphalt Cement Content, %	2.4												
Air Voids, %	19.6												
Resilient Modulus, MPa 25°C	NA												
Tensile Strength, kPa, 25°C	NA												
Number of Cores	1												

NA: Data not available

TABLE 9 Summary of standard deviations for laboratory test results for cores identified as having no segregation

Properties	Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
Cumulative % Passing									Too Few Samples				
37.000 mm										0	0		
25.000 mm	0	0					0			1.7	1.4		
19.500 mm	1.3	1.7	0			0	1.0	0		4.1	1.4	0	0
12.500 mm	1.5	4.2	1.3	0	0	0.8	3.3	1.3		5.4	0.7	1.2	1.2
9.500 mm	2.1	3.1	2.1	1.5	2.9	2.1	3.8	1.3		4.3	0.0	1.1	4.0
4.750 mm	2.8	3.3	3.0	1.2	4.2	2.4	2.7	1.1		3.7	1.4	0.9	3.2
2.360 mm	2.3	2.5	1.9	2.3	3.0	1.7	2.1	0.7		2.0	0.0	0.7	2.9
1.180 mm	2.0	1.7	0.9	3.2	2.2	4.2	1.3	1.1		1.5	0.7	0.5	2.3
0.600 mm	1.7	1.4	0.7	3.5	1.5	1.2	1.0	0.9		0.6	0.7	0.5	1.5
0.300 mm	1.3	1.4	0.6	2.5	1.2	1.4	0.8	4.5		0.6	0.7	0.5	1.5
0.150 mm	0.9	1.8	0.5	1.0	1.0	0.8	0.8	0.9		0.3	0.0	0.4	1.5
0.075 mm	0.6	0.8	0.4	0.8	0.6	0.5	0.4	0.6		0.5	0.4	0.2	0.9
Asphalt Cement Content, %	0.14	0.09	0.13	0.11	0.14	0.15	0.19	0.07		0.20	0.35	0.14	0.24
Air Voids, %	0.9	1.3	1.4	2.4	0.7	0.8	1.2	0.8		0.6	0.9	2.1	2.7
Resilient Modulus, MPa 25°C	167	147	295	TS	TS	1,465	641	209		222	156	189	281
Tensile Strength, kPa, 25°C	NA	NA	76	NA	NA	83	NA	42		NA	NA	62	18
Number of Cores	8	3	13	5	6	11	4	7		3	2	8	3

TS: Too soft or too thin to test
NA: Data not available

TABLE 10 Summary of standard deviations for laboratory test results for cores identified as having low segregation

Properties	Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
Cumulative % Passing													
37.000 mm											0		
25.000 mm	0	0					0				1.8		
19.500 mm	1.9	3.9	0				0.8				1.3		0
12.500 mm	1.8	2.4	2.8	0	0		2.9				1.6		1.3
9.500 mm	3.4	3.2	2.1	2.1	2.1		4.7				2.1		2.1
4.750 mm	3.4	4.5	0.0	2.0	2.1	None	5.0	None	Too Few Samples	None	1.9	None	3.6
2.360 mm	3.0	3.7	0.7	2.7	5.1		3.9				1.5		2.6
1.180 mm	3.3	5.9	0.7	2.7	2.9		2.5				1.6		1.9
0.600 mm	3.4	2.6	0.0	2.3	2.2		1.6				1.8		1.0
0.300 mm	3.4	2.1	0.0	4.7	1.9		1.3				2.2		1.0
0.150 mm	3.7	4.6	0.2	0.6	1.4		0.6				2.8		0.6
0.075 mm	3.3	1.7	0.3	0.2	0.9		0.5				3.0		0.5
Asphalt Cement Content, %	0.04	0.22	0.06	0.07	0.08		0.06				0.10		0.04
Air Voids, %	1.5	1.7	0.4	2.2	0.6		1.0				1.2		3.0
Resilient Modulus, MPa 25°C	506	490	239	TS	TS		1,012				336		267
Tensile Strength, kPa, 25°C	NA	NA	NA	96	NA		172				308		NA
Number of Cores	5	5	2	4	4		4				5		4

TS: Too soft or too thin to test
NA: Data not available

TABLE 11 Summary of standard deviations for laboratory test results for cores identified as having medium segregation

Properties	Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
Cumulative % Passing													
37.000 mm										0	0		
25.000 mm	0									0.6	4.6		
19.500 mm	2.6							0		4.6	4.9		
12.500 mm	4.9							1.3		6.6	2.3		
9.500 mm	3.4							1.3		6.5	2.5		
4.750 mm	2.9	Only One Sample	None	Only One Sample	None	None	Only One Sample	0.7	Too Few Samples	5.3	2.1	None	None
2.360 mm	2.1							0.7		4.1	1.0		
1.180 mm	1.6							0.7		3.3	0.0		
0.600 mm	0.9							0.5		2.7	0.6		
0.300 mm	1.1							0.9		2.4	1.0		
0.150 mm	0.8							0.5		2.3	1.2		
0.075 mm	0.4							0.4		1.6	0.8		
Asphalt Cement Content, %	0.11							0.06		0.40	0.11		
Air Voids, %	1.0							0.8		TS	0.6		
Resilient Modulus, MPa 25°C	478							123		NA	677		
Tensile Strength, kPa, 25°C	NA							25		NA	310		
Number of Cores	6							5		3	3		

TS: Too soft or too thin to test
NA: Data not available

TABLE 12 Summary of standard deviations for laboratory test results for cores identified as having high segregation

Properties	Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
Cumulative % Passing													
37.000 mm													
25.000 mm	100												
19.500 mm	87												
12.500 mm	42			100									
9.500 mm	33			89.3									
4.750 mm	23	None	None	45.3	None	None	None	None		None	None	None	None
2.360 mm	18			30.0									
1.180 mm	16			21.0									
0.600 mm	13			15.7									
0.300 mm	9			10.7									
0.150 mm	6			7.0									
0.075 mm	3.8			4.2									
Asphalt Cement Content, %	2.4												
Air Voids, %	19.6												
Resilient Modulus, MPa 25°C	NA												
Tensile Strength, kPa, 25°C	NA												
Number of Cores	1												

TABLE 13 Summary of number of sieves that differ from the JMF

Difference Between JMF and Percent Passing	Number of Sieves with Given Difference in Percent Passing Project												
	1-1	1-2	2-2	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	7-2
No Segregation													
>5.0%	0	0	0	0	1	1	0	7	Too Few Samples	0	0	2	0
>10.0	0	0	0	0	0	0	0	3		0	0	1	0
>15.0	0	0	0	0	0	0	0	0		0	0	0	0
>20.0	0	0	0	0	0	0	0	0		0	0	0	0
Low Segregation													
>5.0%	1	0	2	1	1	None	1	None	Too Few Samples	None	1	None	1
>10.0	0	0	0	0	0		0				0		0
>15.0	0	0	0	0	0		0				0		0
>20.0	0	0	0	0	0		0				0		0
Medium Segregation													
>5.0%	6	4	None	0	None	None	None	4	Too Few Samples	2 (4)	1 (2)	None	None
>10.0	5	0		0				3		3 (3)	0		
>15.0	2	0		0				0		1	0		
>20.0	0	0		0				0		0	0		
High Segregation													
>5.0%	7	None	None	0	None	None	None		Too Few Samples	None	None	None	None
>10.0	6			0									
>15.0	4			0									
>20.0	4			0									

Note: Numbers in parenthesis indicate difference from JMF estimated from gradation chart.

general, the percent passing any sieve difference was less than 5 percent for the nonsegregated cores. There was at least one sieve with a change of more than 5 percent at the low level of segregation; there were at least two sieves with a change of more than 10 percent at the medium level; and there were more than three sieves with a change of more than 15 percent at the high level.

This method of sorting the cores by level of segregation ranked the segregation at the same level as did the visual observations about 60 percent of the time. When there was a difference, the visual observations usually overestimated the level of segregation by one level.

2.3.3 Summary of Field Test Results

After the preliminary field evaluation, the nondestructive field testing concentrated on three technologies: rolling nuclear densities/asphalt contents gauges, infrared thermography, and the measurement of mean texture depths with the ROSAN$_v$ laser.

2.3.3.1 Rolling Nuclear Density Gauges

Both the Troxler and Seaman nuclear density gauges were initially used on projects 1-1 and 1-2. The preliminary evaluation of the data showed that the Seaman nuclear gauge provided the best results. This probably resulted from the slower speed and the differences in how the software reported the average densities for the given time interval. These preliminary results are shown in Appendix A (not published herein). Based on this conclusion, the remainder of the nuclear density testing was completed with the Seaman nuclear gauges, which were operated by Seaman Nuclear Corporation staff.

The visual evaluations of the levels of segregation were used to sort the Density On the Roll (DOR) results into four individual sets of data (i.e., none, low, medium, and high). The mean and standard deviation were calculated for each level of visually identified segregation and longitudinal path for each project. The standard deviation, regardless of the level of segregation, was approximately 52.8 kg/m^3 (3.3 pcf) for projects 1-1, 1-2, 3-1, and 3-2. This increased to about 72 kg/m^3 (4.5 pcf) for projects 6-1 and 6-2 and probably is a

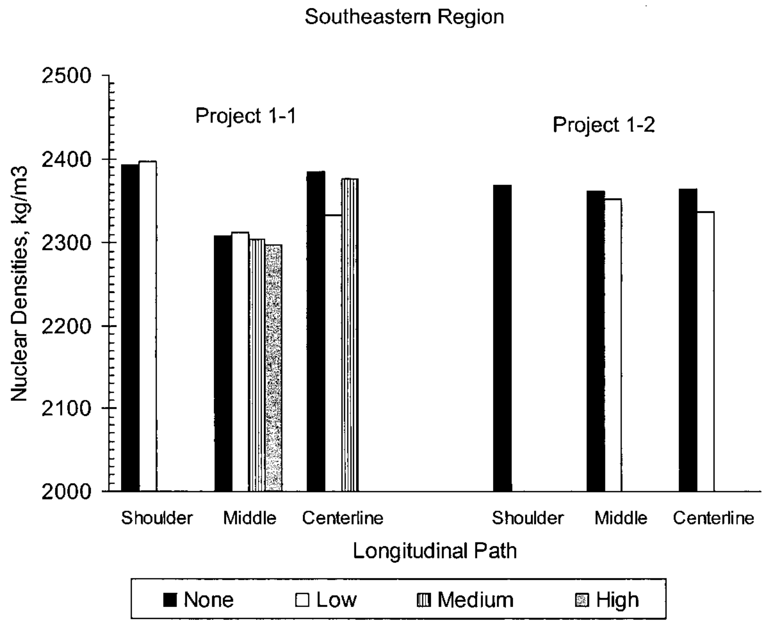

Figure 1. Mean DOR densities for each longitudinal path and level of segregation (projects 1-1 and 1-2).

function of the larger maximum size aggregate and the accompanying very coarse surface texture.

Figure 1 presents the mean densities for each longitudinal path and level of segregation for projects 1-1 and 1-2. There is a statistically significant difference between the nonsegregated areas in the path nearest the shoulder compared with the middle of the pavement. Although there is a general trend in decreasing density with increasing levels of segregation, the differences within a longitudinal path are not significant.

Figure 2 shows that the core air voids increased (i.e., density decreases) with the level of segregation, but there is only a limited statistical difference in air voids because of the standard deviations associated with this test (Tables 9 through 12). These results suggest that the ability of the nuclear density gauge to detect gradation segregation has had variable success, as noted by previous researchers, not because the gauge fails to detect changes in density because of segregation, but because this particular parameter is not the best for identifying this problem.

The differences seen in the surface texture of the fine mixtures for projects 3-1 and 3-2 (Appendix C—not published herein) resulted from a wide range of asphalt contents, but not changes in gradation. Areas with higher asphalt contents appeared more uniformly finely textured, while areas with lower asphalt contents tended to have an apparently coarser texture. Figure 3 shows that the DOR results agreed with this conclusion (i.e., areas with the lowest asphalt content tended to have lower densities while the asphalt-rich areas had the highest values). The DOR also indicated that there were differences in the densities between the paths nearest the shoulder and nearest the centerline for Project 3-1.

Figure 4 shows a consistent trend of decreasing density with the increasing level of segregation for Project 6-1. Nevertheless, these are not statistically significant differences because of the large standard deviation, 64 kg/m^3 (>4 pcf), for this project. Figure 5 shows that the air voids in the cores for Project 6-1 follow the same trend; they are also not statistically different between the no and medium levels of segregation. The air voids are only statistically lower in the fine-aggregate-rich areas of Project 6-1.

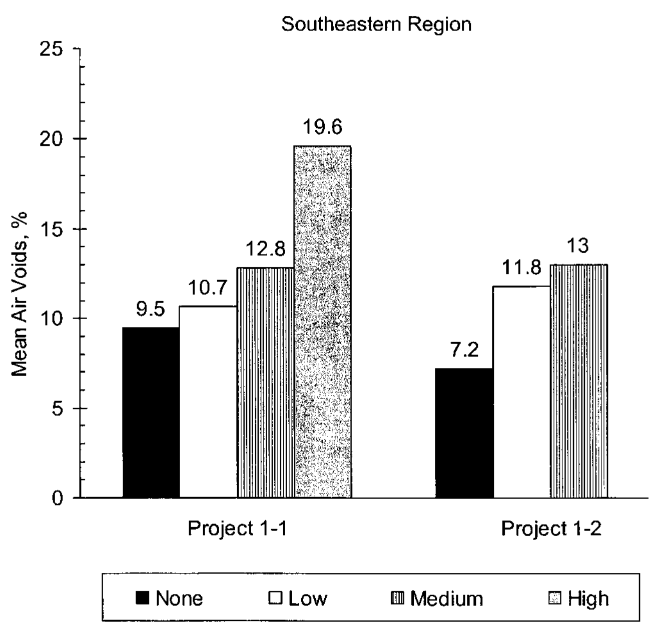

Figure 2. Mean air voids for cores (projects 1-1 and 1-2).

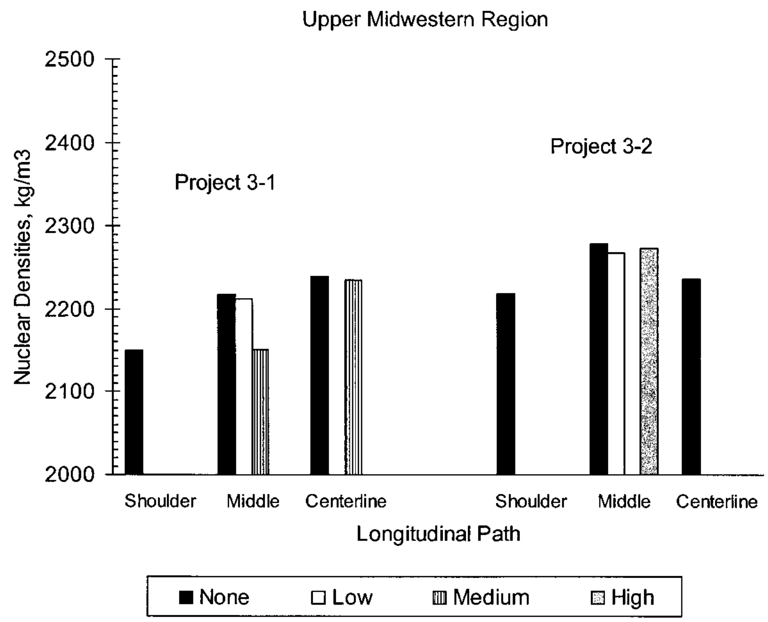

Figure 3. Mean DOR densities for each longitudinal path and level of segregation (projects 3-1 and 3-2).

The extensive handwork by the contractor on Project 6-2 resulted in erratic DOR results and no difference in the core air voids.

Figure 6 shows the estimated asphalt content profiles from the moisture content readings from the nuclear gauge for Project 1-1. The areas of low asphalt content were not well correlated with the areas with medium to high levels of segregation. Given that this was a recently constructed pavement, it is possible that the variable moisture content from both humidity and intermittent showers the week before biased the results.

Figure 7 shows a similar set of profiles for Project 1-2, which was evaluated during construction when the moisture

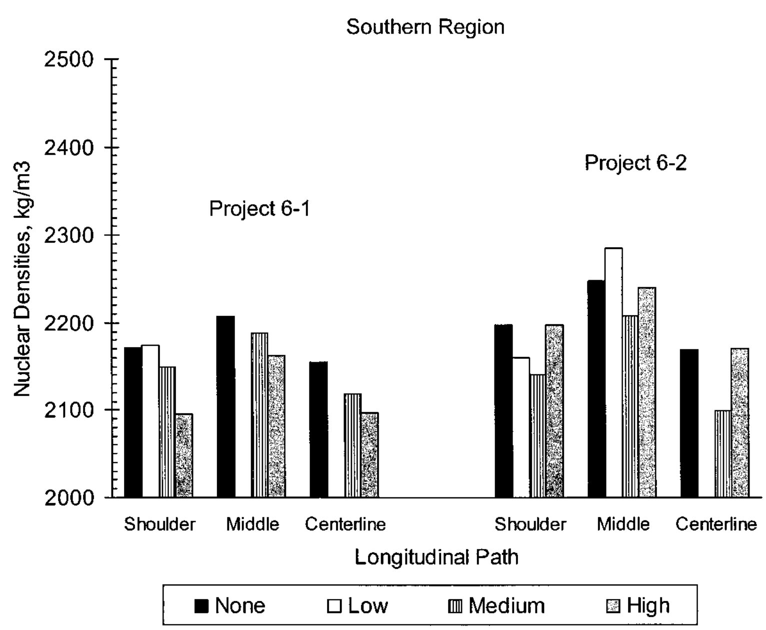

Figure 4. Mean DOR densities for each longitudinal path and level of segregation (projects 6-1 and 6-2).

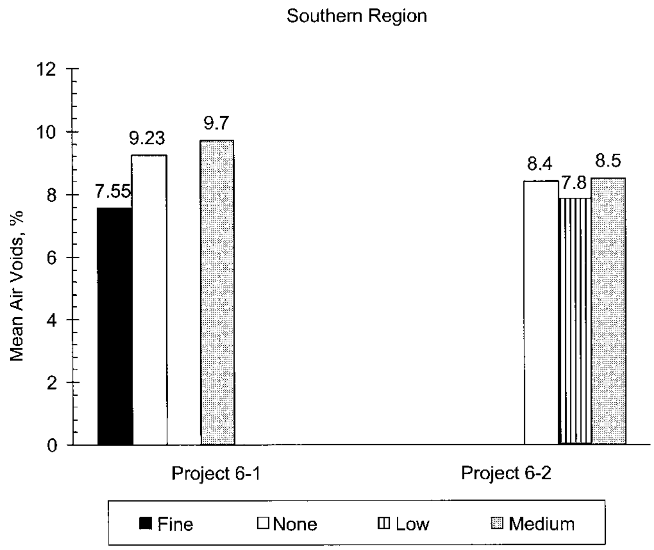

Figure 5. Mean air voids for cores (projects 6-1 and 6-2).

in the HMA is expected to be both low and uniform. Although there are periodic areas of low asphalt content, these regions do not correlate with any of the core results or construction variables. The high variability in the results, even when using a moving average of 10 to smooth the data, makes the usefulness of this approach for estimating differences in asphalt content questionable. These results and conclusions were typical of the other projects.

The following conclusions can be drawn from these data:

1. Both the DOR and conventional measurements of air voids have difficulty in showing statistically different densities between adjacent levels of segregation. Density by itself is not the best parameter for detecting and measuring gradation segregation.
2. Although trying to detect various levels of gradation segregation with the DOR does not appear to be a good use of this gauge, it can be used to assess overall differences in both the transverse and longitudinal densities in the mat.
3. Estimates of asphalt content using the nuclear moisture content gauge did not provide a good correlation with core results. The measurements were highly variable even after a moving average of 10 was used to smooth the data.

2.3.3.2 Infrared Thermography

Recently Constructed Projects. Using infrared thermography on recently constructed pavements requires solar gain to highlight anomalies in the pavement mat. In the case of recently constructed pavements, areas with higher voids are seen as warmer areas. This is because air voids act as insulators and trap warmer air near the surface. Conversely, densely packed areas are good thermal conductors and help conduct the cooler base temperature to the surface.

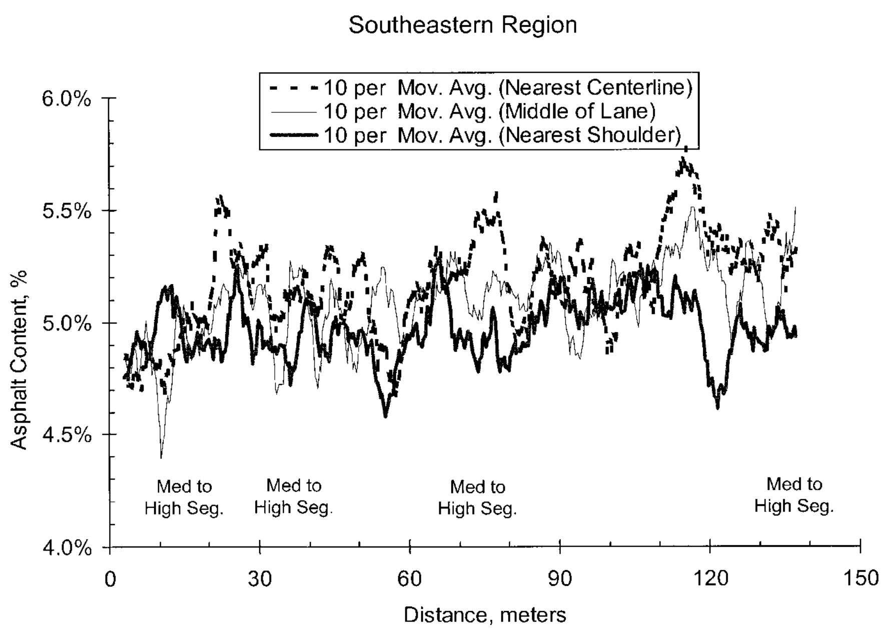

Figure 6. DOR asphalt content estimates for each path for Project 1-1.

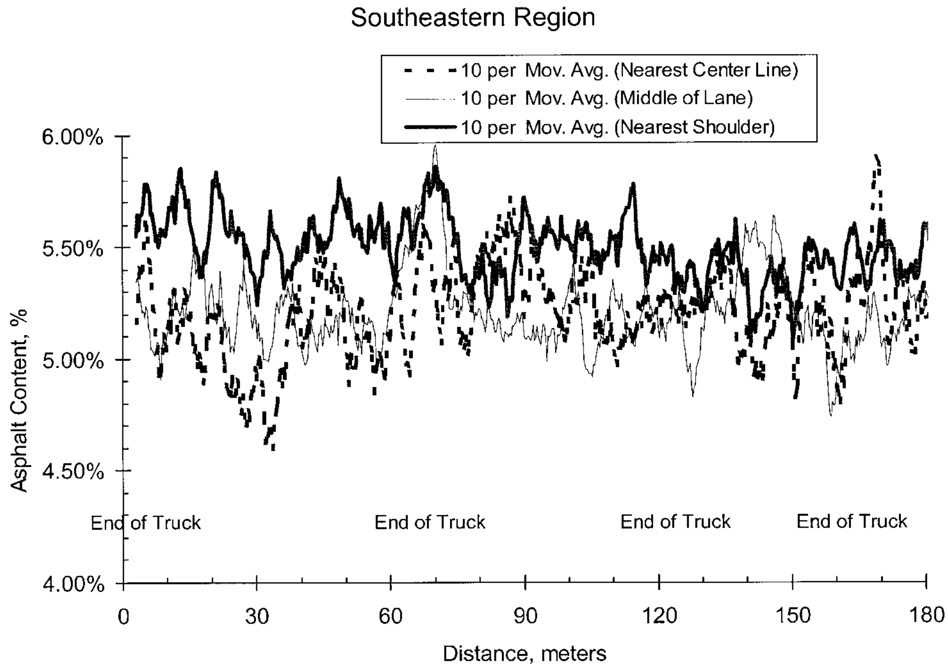

Figure 7. DOR asphalt content estimates for each path for Project 1-2.

A range of temperatures can also be found in uniform (nonsegregated) areas. This results from intermittent shading from surrounding vegetation and cloud cover. Inability to obtain consistently comparable absolute values of temperatures throughout a test section made it impossible to use this technology to do more than mark areas for further testing (i.e., destructive coring).

Because of the results with recently constructed pavements, no attempt was made to use infrared thermography technology to relate absolute temperatures throughout a test section to mixture properties. The bulk of the research concentrated on using this technology during construction where the temperature differential was highly dependent on mix properties that govern the rate of cooling.

During Construction. When a thermal photograph is taken during construction of an area with uniform temperature, the area in the foreground of the thermal photograph, which does not include the edges of the pavement mat, is converted to temperatures per pixel without any normalization of data. Typically, at about 5 m behind the paver, the full width of the pavement will be seen in the photograph, but this area will have a trapezoidal shape because of the focal length of the lens. Temperatures in the trapezoidal region can then be normalized to a standard pavement width of 3.6 m (12 ft) and converted to an ASCII data file of temperatures 123-lines long by 23-data points wide. This approach weights the temperatures near the paver heavier than those in the last half of the area. For analysis purposes, the assumption is made that the data obtained from each image will have this same bias. Therefore, changes in the temperature histogram developed for each image would be relative to any other image given that the camera location is fixed and the images were obtained at incremental (10-m) distances.

These data were then used to develop temperature histograms for each photograph. An examination of the histograms shows that there are three general types of temperature profiles (Figure 8): (1) single mode, narrowly distributed; (2) single mode, widely distributed; and (3) bimodal. The single-mode, narrowly distributed histogram indicates a uni-

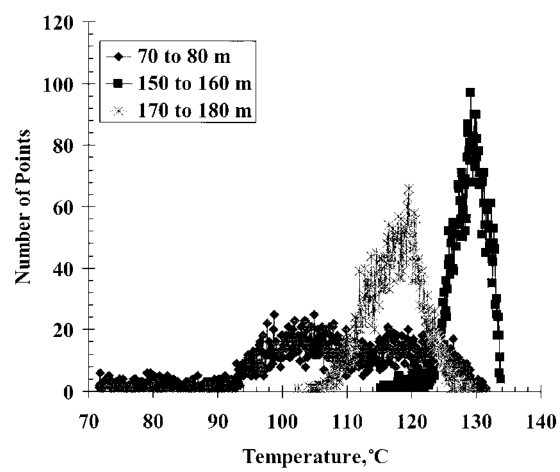

Figure 8. Three types of histograms typically seen in all infrared temperature distributions.

form mat temperature. The single-mode but widely distributed histogram results from localized cooler areas associated with flipping the paver wings. Normally, two populations with different characteristics would be seen as a bimodal histogram. However, in this case, the mean temperatures of each population are not so different as to make them easily distinguishable. The bimodal distribution occurs when the paver has been stopped for a length of time and there is a significant area of the mat that is cooler. Two distinct histogram areas with a wide distribution indicate the cooler area resulting from end-of-truck load changes, flipping the paver wings, and the newer/hotter mix.

The simplest way to represent the width of the spread of any distribution is to use the range. For any given photograph, the cumulative percent of the mat in a 10-m length that was cooler than the maximum temperature in each photograph minus 10°C, 15°C, 20°C, 25°C, and 30°C was calculated from each histogram. Figure 9 shows this distribution for Project 1-2. Construction processes expected to produce areas of segregated mix are also noted on this figure. This figure shows that there was a wide range of temperatures both before and after haul trucks were changed and after paver stops to adjust the equipment. In between these points, less than 10 percent of the mat was cooler than the maximum temperature minus 10°C (second set of bars from the back of figure).

An examination of the thermal photographs revealed that the wide distribution of temperatures in front of the stopped paver were the result of flipping the paver wings. The Seaman DOR longitudinal density data (Figure 10) shows that the wider range of temperatures immediately behind the paver produced a localized region of very low density. This is because, while the roller operator was working close to the back of the paver, it could not roll 100 percent of the mat behind the paver because the equipment was in the way.

These results suggest that there are two types of temperature segregation. The first type of temperature segregation, noted by Brock and Jakob (*29*), results from localized cold or gradation segregated mix in the truck or hopper. The second results from a paver stop long enough to result in a temperature differential of more than 20°C.

Figure 11 shows the same representation of the analysis for Project 3-2. This project used windrow paving to place a tapered 40- to 70-mm first course of Superpave mix over a portland cement concrete pavement. The uniformity of the temperature profile can be attributed to a continuous and consistent windrow paving operation. However, the breadth of the histogram indicates a wide range of temperatures throughout the new lift. This figure shows that between 40 and 60 percent of the mat is more than 20°C cooler than the maximum temperature. This may reflect a combination of moderate ambient temperatures and the tapered lift thickness (i.e., thinner lifts cool more quickly). This condition may also result from cooling of long windrows placed well in advance of the paver.

This project had generally high voids, which may reflect the high percentage of cooler mat. Although there did not appear to be a direct relationship between a given level of the percent of the mat cooler than the maximum temperature and air voids, there did appear to be a direct relationship between the asphalt content and air voids. That is, the voids decrease as the asphalt content increases. This agrees with the previous observation in both projects 3-1 and 3-2, which were experiencing a plant problem and not a segregation problem.

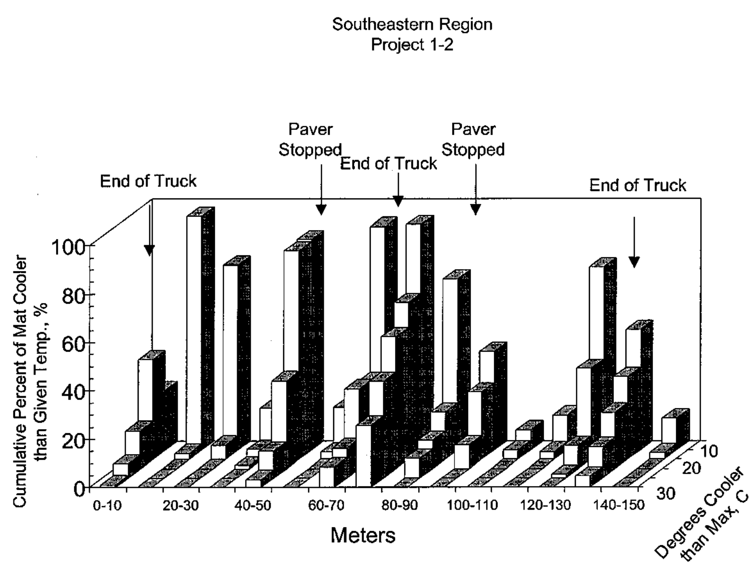

Figure 9. Cumulative frequency distribution for Project 1-2 (Southeastern Region).

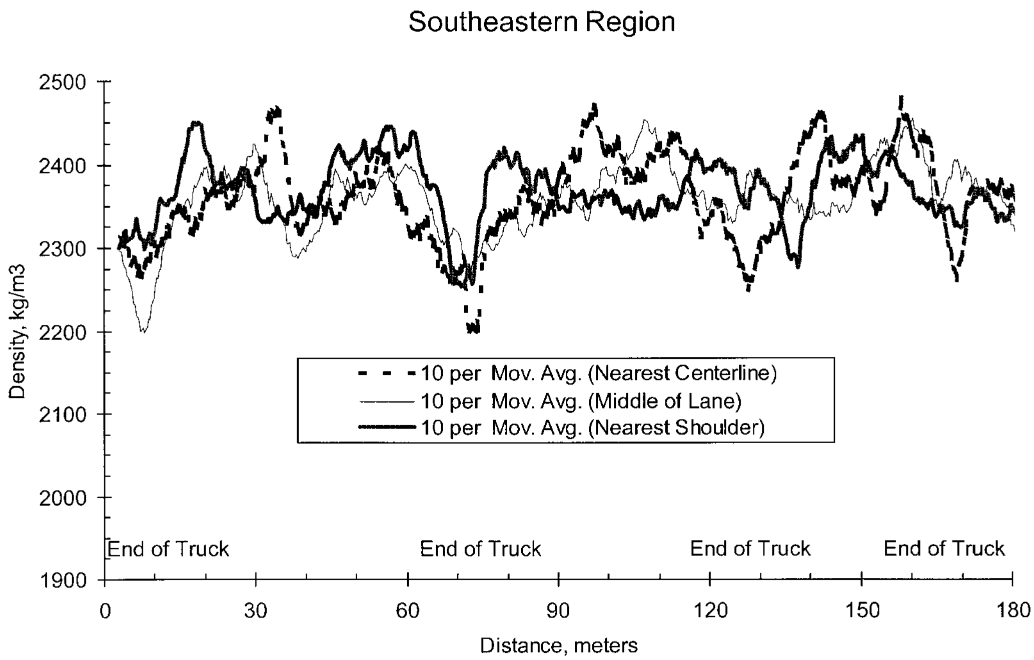

Figure 10. DOR densities for Project 1-2.

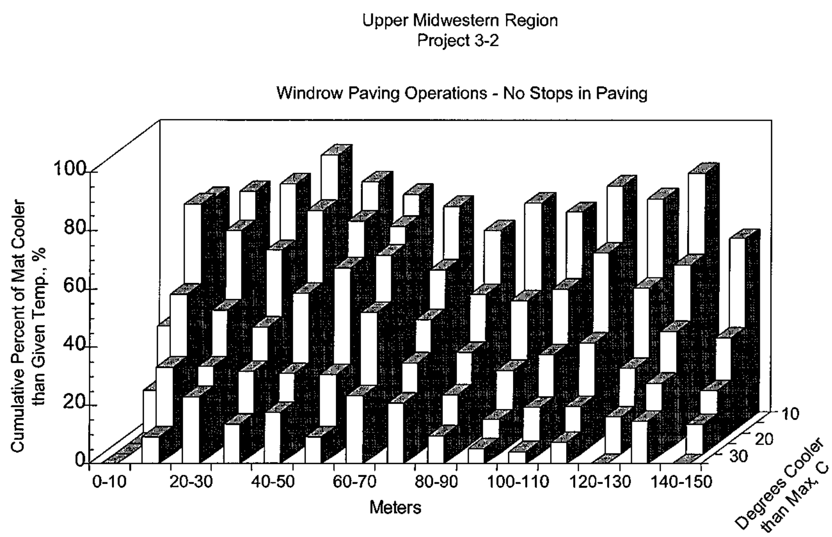

Figure 11. Cumulative frequency distribution for Project 3-2 (Upper Midwestern Region).

Figure 12 shows the temperature profile for Project 4-2. This project used a material transfer device, but experienced problems with haul trucks not arriving in time to prevent the paving operation from stopping. As with Project 1-2, every time a paver stoppage was noted, there was wider temperature distribution behind the paver. Even though there was a surge bin in the hopper and the wings could not be flipped, there was occasionally a wider range of temperature in front of the paver stoppage. This would suggest that the material in the surge bin was cooling sufficiently so that this temperature change was apparent once paving started again. The large temperature range at the end of the test section was the result of an extended delay in the arrival of the haul truck.

Laboratory results indicated there was a strong correlation between asphalt content and gradation changes. The JMF asphalt content was 4.4 percent, so the low asphalt content cores at the beginning of the test section indicate that a low level of segregation was found in areas with the greater temperature differentials.

Figure 13 shows the temperature distribution for the one SMA project evaluated during construction (Project 5-2). At the start of this project, the plant operator had the mixing temperature set very high to compensate for the higher viscosity polymer-modified binder being used. Initial mix temperatures behind the paver were around 180°C ("smoking" of the mix was obvious). Individual infrared photographs indicated that there might be some initial auger problems (i.e., longitudinal segregation); this conclusion is based on the longitudinally cooler areas in the mat. As these longitudinal anomalies began to disappear, the temperature differentials decreased.

Only three cores could be taken because of an approaching thunderstorm. Coring locations were selected so that transverse properties of the test section at about the mid-point were obtained. Air voids were 5.3, 4.2, and 4.7 percent at quarter points transversely across the lane. The 4.2 percent voids correspond with the higher temperature area.

Figure 14 shows the temperature distribution for Project 6-2. This project used windrow paving, but, routinely, there was a 20- to 50-min wait for the next haul trucks. Sometimes three haul trucks would arrive at the same time; only one would arrive at other times. The contractor had assigned two workers to take fine mix out of the hopper periodically and use it to cover the coarser textured areas behind the paver. All of these construction factors (except the time intervals between haul trucks) are identified in Figure 14.

As with projects 1-2 and 4-2, there is a noticeable increase in the percent of the mat 20°C cooler than the maximum temperature immediately behind the paver. The Seaman DOR data shown in Figure 15 confirms that these broader temperature ranges correspond with localized areas of low density, although the areas are not always as obvious as in other projects. This may result from the artificially altered surface texture caused by the hand work of the contractor (i.e., nuclear density measurements tend to vary with changes in the coarseness of the surface texture).

Figure 16 shows the temperature distribution for the last project (7-2). The length of this project was shortened as the

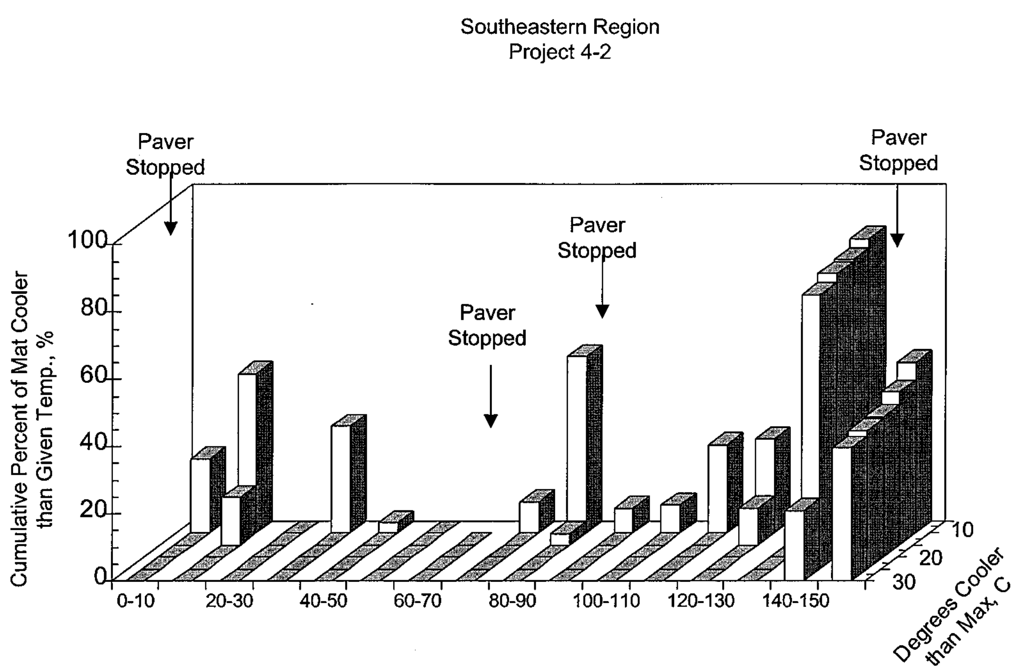

Figure 12. Cumulative frequency distribution for Project 4-2 (Southeastern Region).

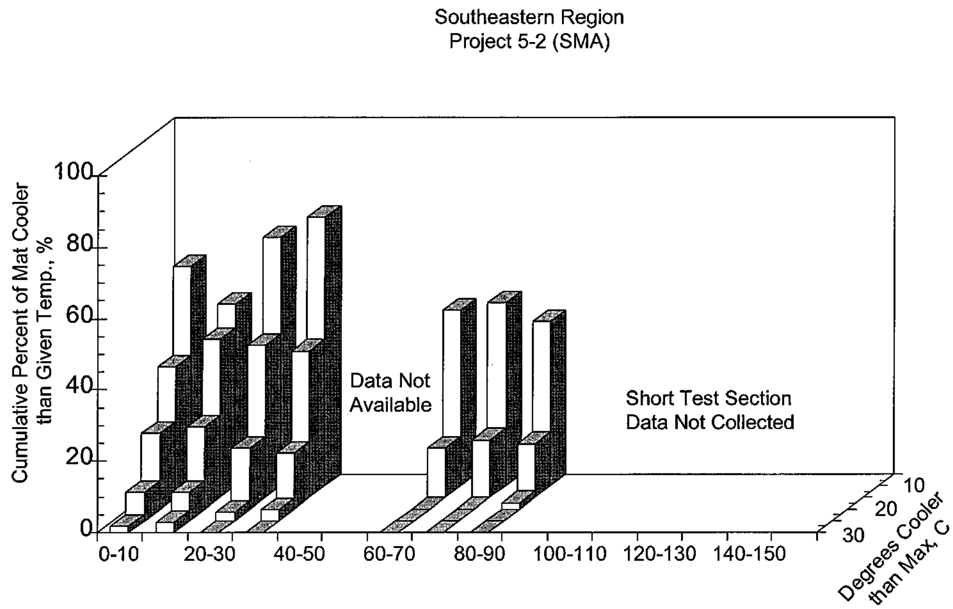

Figure 13. Cumulative frequency distribution for Project 5-2 (SMA, Southeastern Region).

result of the contractor deciding to pave less of the lane prior to dropping back and placing the adjacent lane. Laboratory test results of cores only indicated a limited level of low gradation segregation, but there was a good relationship between cold spots and localized areas of low density. These results support the conclusion that both gradation and temperature segregation were found on this nighttime paving job.

2.3.3.3 ROSAN$_v$ Laser Surface Texture Measurements

Each test site was longitudinally marked by hand every 10 m at transverse quarter points (0.9, 1.8, and 2.7 m from the shoulder). These marks were used as sight lines for the driver; cores were also taken at selected points along these lines. Two passes at three speeds (15, 30, and 45 kph) were

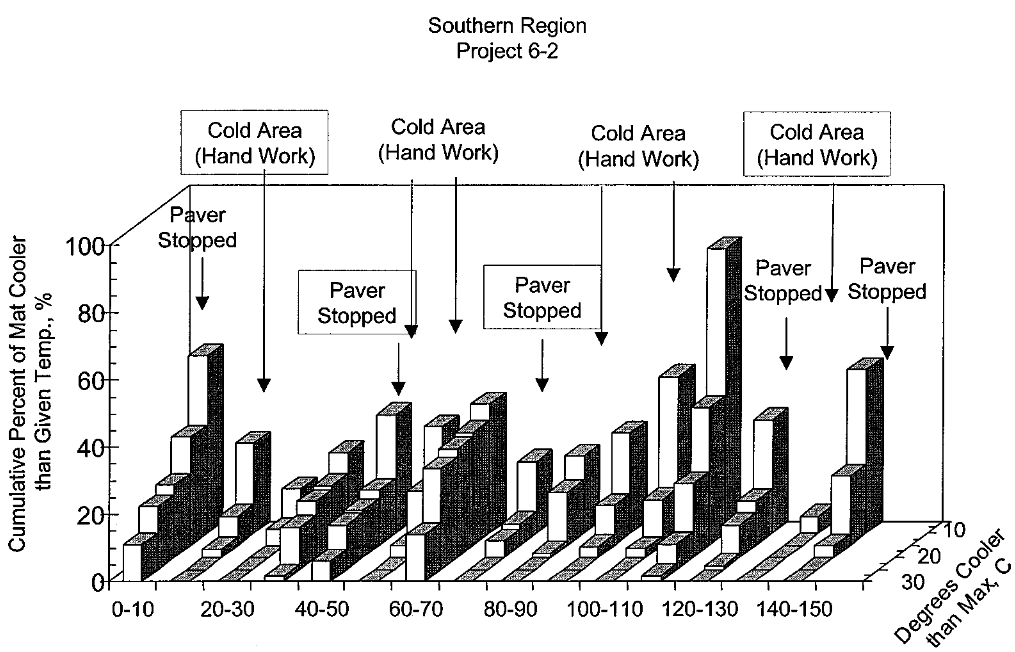

Figure 14. Cumulative frequency distribution for Project 6-2 (Southern Region).

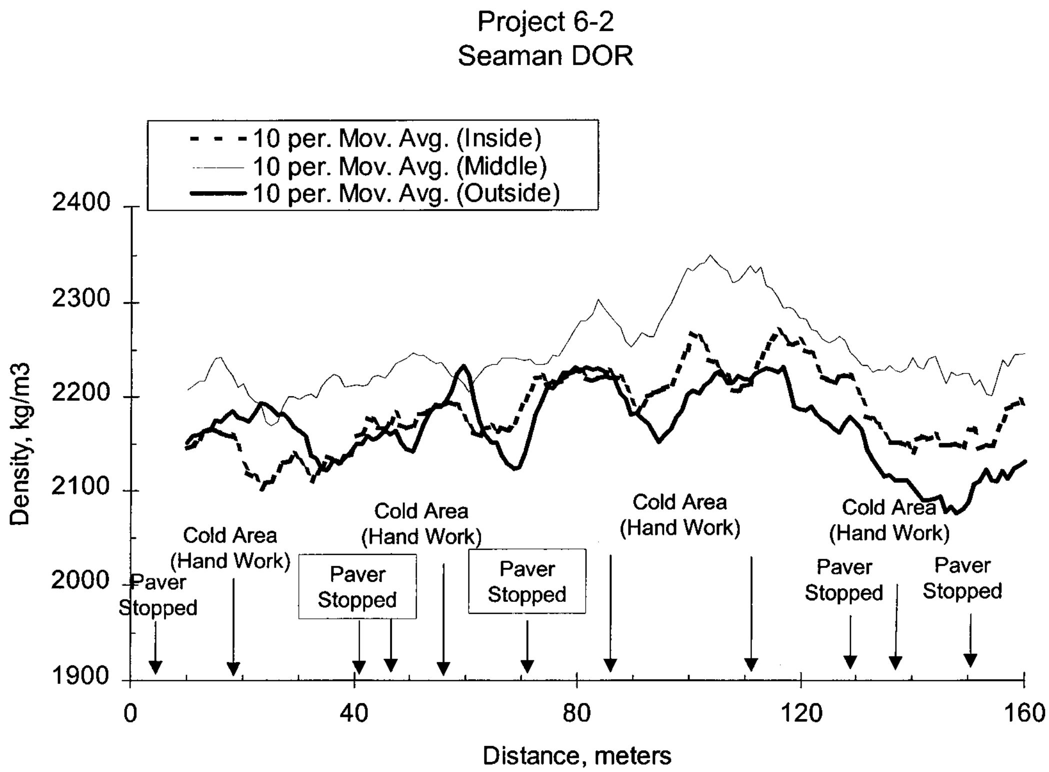

Figure 15. Seaman DOR longitudinal density profiles for Project 6-2 (Southern Region).

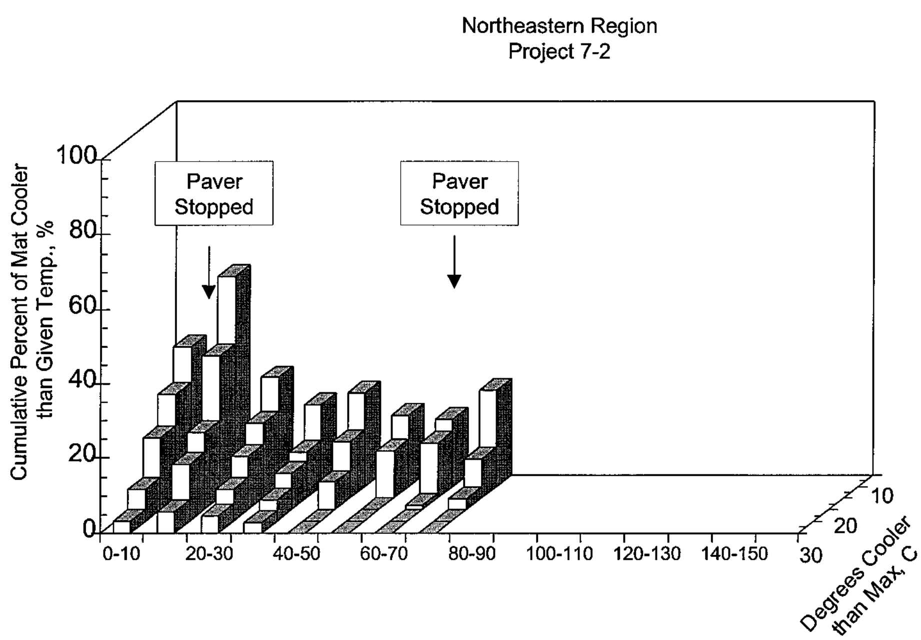

Figure 16. Cumulative frequency distribution for Project 7-2 (Northeastern Region).

made over each line during the preliminary evaluation of the technology. Texture depths and the distance corresponding with each measurement were recorded once per millimeter. The software determined the sampling rate needed to keep this factor constant based on the speed of the truck.

The $ROSAN_v$ software includes two options for distance measurements. The first is to hard-wire a distance encoder into the vehicle's computer speedometer control system. The second is to enter the steady operating speed of the vehicle into the software. This second method was used because of conflicts between the distance encoder and the electronic anti-locking brake systems on the vehicle used. The accuracy of this method of measuring distance was verified by placing optical triggers (strips of hose) at the beginning and end of the test sections. The known distance between the markers was compared between the distance estimated by the software. The agreement was very good in all cases.

The software also allows the user to choose texture equations for the data. Because several previous research efforts showed that laser surface texture measurements were well correlated with the sand patch test (*8*), the mean profile depth (MPD), a two-dimensional measurement correlated with the three-dimensional estimated texture depth (ETD) measurement in ASTM E1845 (*9*), was selected. This relationship, in metric units, is

$$ETD = 0.2 + 0.8\,MPD$$

This ETD should be close to the mean texture depth (MTD) determined volumetrically from the sand patch test (*9*).

Because of the wide range of visually identifiable differences in surface texture, the longitudinal line closest to the centerline of Project 1-1 was used for the initial evaluation of the laser data.

The base length distance was selected as 500 mm, because it was the closest to bracketing the typical diameters of the sand patch circle. Using 100 cm^3 of sand as a standard volume of material, a circle with a diameter of 150 mm was obtained for a surface texture of 1.2 mm and 584 mm for an MTD of 0.38 mm. Table 14 shows that this longitudinal distance also provided the lowest standard deviation, regardless of the vehicle speed used for testing. This distance was selected as the standard distance for the remainder of this study.

TABLE 14 Selection of distance over which to average data (0.9 m from centerline, Project 1-1)

Laser Variable		Statistics	MPD for Various Levels of Segregation, mm			
Speed	Distance over which Date is Average		None	Low	Medium	High
15 kph	100 mm (4 in)	Mean	0.2724	0.3020	0.5701	1.0117
		Std. Dev.	0.1850	0.2637	0.3973	0.6321
		No. of Data Pts.	564	445	308	61
	500 mm (20 in)	Mean	0.3265	0.4812	0.7097	1.2820
		Std. Dev.	0.0913	0.1475	0.2199	0.3401
		No. of Data Pts.	113	91	60	13
30 kph	100 mm (4 in)	Mean	0.2523	0.3788	0.5357	0.9654
		Std. Dev.	0.1925	0.2777	0.3929	0.594
		No. of Data Pts.	746	546	130	41
	500 mm (10 in)	Mean	0.2978	0.4487	0.7306	1.2630
		Std. Dev.	0.1055	0.1819	0.2560	0.3516
		No. of Data Pts.	152	110	26	9
45 kph	100 mm (4 in)	Mean	0.2997	0.4854	0.6064	1.2769
		Std. Dev.	0.2270	0.3251	0.3771	0.6929
		No. of Data Pts.	942	134	148	17
	500 mm (20 in)	Mean	0.3169	0.6201	0.8037	1.1740
		Std. Dev.	0.1399	0.2209	0.2191	0.1370
		No. of Data Pts.	190	36	27	6

Next, the dependency of the test results on vehicle speed was evaluated. The results obtained for each of three longitudinal paths at each of three speeds (15, 30, and 45 kph) were compared statistically using a paired *t*-test (Table 15). This evaluation showed that, in most cases, there was a statistical difference because of speed. However, it was thought that it may be the ability of the driver to track over the same path at increasingly faster speeds that may cause the statistical difference—not the ability of the laser system to replicate measurements.

To explore this hypothesis, two floor mats with widely different but consistent textures over about a 2,000-mm length and 75-mm width were tested at each of three speeds. The consistency of the textures over both the width and length should remove any dependency of the measurements at different speeds on minor deviations in the longitudinal path followed by the driver. These results are shown in Table 16, along with the relevant statistical analysis results. In all cases, there was no statistical difference in the results because of changes in speed. This confirms the initial hypothesis that the

TABLE 15 *T*-Test for evaluating the influence of vehicle speed on test results

Level of Segregation	Statistics*								
	15 vs. 30			15 vs. 45			30 vs. 45		
	t_{calc}	t_{table}	Diff?	t_{calc}	t_{table}	Diff?	t_{calc}	t_{table}	Diff?
Longitudinal Path: 2.7 m from Shoulder									
None	7.40	1.96	yes	6.40	1.96	yes	0.81	1.96	no
Low	0.41	1.96	no	3.52	1.97	yes	3.19	1.96	yes
Medium	1.60	1.99	no	1.16	1.99	no	2.39	2.00	yes
High	3.91	2.06	yes	3.7	2.08	yes	0.21	2.16	no
Longitudinal Path: 1.8 m from Shoulder									
None	2.43	1.96	yes	7.73	1.96	yes	0.74	1.96	no
Low	5.45	1.96	yes	3.42	1.96	yes	1.61	1.96	no
Medium	6.30	1.99	yes	2.78	1.99	yes	1.51	2.00	no
High	3.61	2.05	yes	1.90	2.02	no	1.71	2.00	no
Longitudinal Path: 0.9 m from Shoulder									
None	7.37	1.96	yes	4.45	1.96	yes	2.02	1.96	yes
Low	0.11	1.96	no	0.05	1.96	no	0.15	2.00	no
Medium	These levels of segregation not seen for this longitudinal path.								
High									

* 95% confidence level

TABLE 16 Influence of speed when testing areas with a uniform texture

Statistics*	Fine Textured Pad			Coarse Textured Pad		
	15 vs. 30	15 vs. 45	30 vs. 45	15 vs. 30	15 vs. 45	30 vs. 45
Mean Profile Depth, mm	0.31 vs. 0.24	0.31 vs. 0.27	0.24 vs. 0.27	2.16 vs 2.26	2.16 vs. 2.37	2.26 vs. 2.37
t_{calc}	1.384	1.370	-0.563	-0.368	-0.663	-0.345
t_{table}	2.306	2.306	2.228	2.12	2.12	2.12

* 95% confidence level

statistically different results from vehicle speed when testing actual pavement surfaces are caused by variations in the longitudinal path followed by the driver, which is affected by the driver's ability to transverse the same path at increasingly higher speeds.

Further confirmation can be found in replicate texture measurements at one speed (30 kph). Table 17 shows that, in all but three cases, replicate measurements were not statistically different. This indicates that at this speed, the driver can accurately repeat the testing of a particular longitudinal path. The 30 kph speed was selected for this testing because it was the fastest speed that could be safely used. Safety considerations included starting and stopping sight distances and work zone speed requirements.

Figure 17 shows the average texture depths for every 500 mm of pavement length at the top of a map of visually identified areas of segregation. This figure shows that there is a good agreement between the measured (averaged over 500 mm) and observed pavement texture. Using this information, the longitudinal lengths of each texture profile were separated into four populations. That is, texture depths for the length of each profile were grouped as those in visually identified areas with no, low, medium, and high levels of segregation.

Figure 18 shows an example of a histogram of these data groups. Although the entire histogram shows a skewed distribution, overlaying the total distribution with the histograms for the various levels of segregation shows that it is, in fact, the sum of four normally distributed data bases. There is a fair amount of overlap between the no and low segregation populations and the low and medium segregation populations. This probably results from the variability of the surface texture within each of the general areas shown in Figure 17 and the subjective visual rating. For instance, in a given area designated as having no segregation, there were, in reality, localized areas with a low segregation appearance. However, given that most of the area appeared to have no segregation, the entire area was mapped as such. The means and standard deviations for each longitudinal pass and each level of segregation are shown in Table 18.

2.4 LABORATORY STUDY OF THE INFLUENCE OF SEGREGATION ON MIXTURE PROPERTIES

Although a wide range of mixture properties for all levels of segregation was determined for each of the preceding field

TABLE 17 *T*-Test for assessing ability to repeat test results (30 kph)

Level of Segregation	Replicate a			Replicate b			Statistics*		
	Mean Profile Depth, mm	Standard Deviation	No. of Data Pts.	Mean Profile Depth, mm	Standard Deviation	No. of Data Pts.	t_{calc}	t_{table}	Diff?
Longitudinal Path: 2.7 m from Shoulder									
None	0.2978	0.1055	152	0.2969	0.1187	147	0.07	1.96	no
Low	0.4487	0.1819	110	0.4508	0.1749	53	0.07	1.96	no
Medium	0.7306	0.2560	26	0.6129	0.3158	73	1.71	1.99	no
High	1.263	0.3516	9	0.6605	0.2628	15	4.79	2.06	yes
Longitudinal Path: 1.8 m from Shoulder									
None	0.4924	0.1508	96	0.4151	0.1969	152	0.06	1.96	no
Low	0.6605	0.1678	137	0.5902	0.2030	130	3.09	1.96	yes
Medium	0.8509	0.1698	44	0.9023	0.2681	17	0.89	2.00	no
High	1.3530	0.2287	18	1.1986	0.3178	19	1.69	2.03	no
Longitudinal Path: 0.9 m from Shoulder									
None	0.2456	0.0758	278	0.2266	0.0738	246	3.62	1.96	yes
Low	0.3192	0.0798	12	0.3149	0.0978	44	0.14	2.00	no
Medium	These levels of segregation not seen for this longitudinal path.								
High									

* 95% confidence level

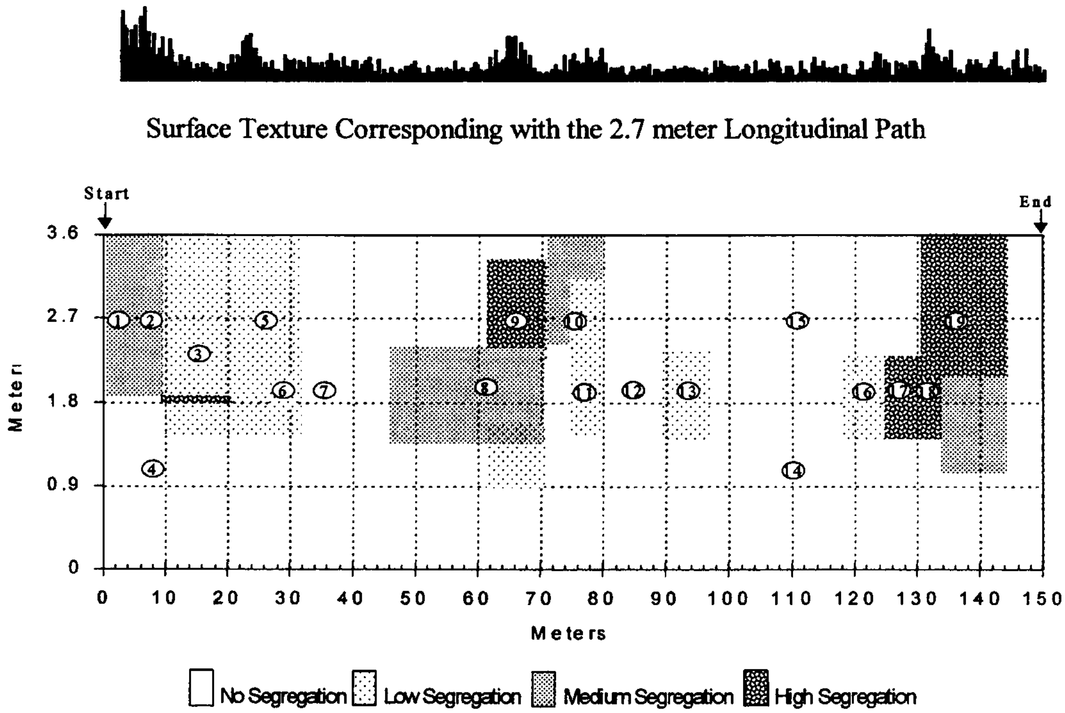

Figure 17. Surface texture measurements overlaid on visual survey of levels of segregation.

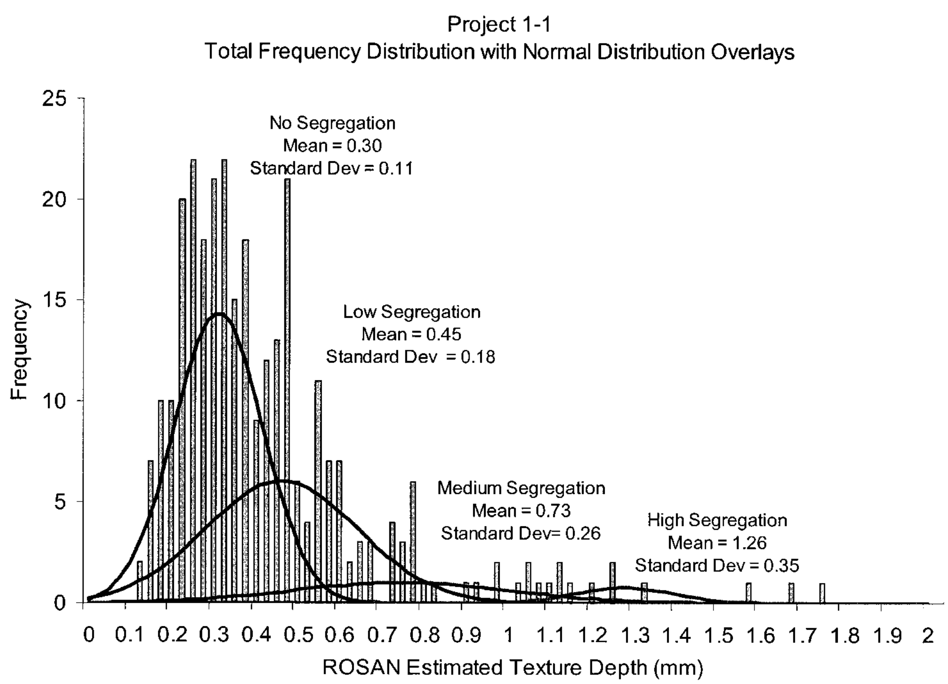

Figure 18. Typical histogram of laser texture depth measurements.

TABLE 18 Mean texture depths

Project	Dist. from Centerline, Meters	MPD for Various Levels of Segregation, mm			
		No	Low	Medium	High
Project 1-1	0.9	0.2974	0.4487	0.7306	1.2630
	1.8	0.4928	0.6605	0.8509	1.3530
	2.7	0.2361	0.3149		
Project 1-2	0.9	0.2213	0.3271		
	1.8	0.1134	0.2069		
	2.7	0.1867	0.2621		
Project 2-1	0.9	0.4717			
	1.8	0.4781			
Project 2-2	0.9	0.5693			
	1.8	0.5078	0.6638		
	2.7	0.4533	0.6331		
Project 3-1	0.9	0.4178			
	1.8	0.6473	0.9565		
	2.7	0.8192	1.1886		
Project 3-2	0.9	0.2889	0.4570		
	1.8	0.2937	0.3548		
	2.7	0.3046	0.3990		
Project 4-1	0.9	0.2028			
	1.8	0.2126			
	2.7	0.2492	0.3214		
Project 4-2	0.9	0.7721	0.9937		
	1.8	0.4939	0.6568		
	2.7	0.5139	0.6788		
Project 6-1	0.9	0.9168	1.0613	1.5251	2.2736
	1.8	0.6675	0.9321	1.1499	1.4334
	2.7	1.0330	1.2167	1.5974	2.2541
Project 6-2	0.9	0.9640	1.2057	1.5923	
	1.8	0.6884	0.9502	1.1748	
	2.7	1.0088	1.3732	1.7510	2.9384
Project 7-1	0.9	0.3665	0.4419		
	1.8	0.3472	0.4181		
	2.7	0.2736	0.3895		
Project 7-2	0.9	0.3858	0.4046		
	1.8	0.2984	0.4133		
	2.7	0.2698	0.3850		
SMA Projects					
		Coarsely Texture	No Flushing	Low Flushing	Med. Flushing
SMA Project 5-1	0.9	1.2174	0.6881	0.4364	0.2141
	1.8	1.4799	0.7279	0.4060	0.2518
	2.7	1.1983	0.8854	0.6514	0.3940
SMA Project 5-2	0.9		1.4057		
	1.8		1.3070		
	2.7		1.1193		

projects, there were several limitations to this laboratory testing program. First, determining the mixture properties of cores with a high level of segregation was often impossible because the cores fell apart either during coring or cutting the sample into lifts. Second, some desired test results required destructive tests that would have further limited testing of cores. Third, required specimen geometry such as a 2 : 1 height-to-width ratio for dynamic and triaxial testing could not be obtained from field cores.

A laboratory testing program was designed that used the data from two of the field projects to simulate segregated mixtures in the laboratory. Projects were selected so that the aggregate gradations would reflect one passing above and one passing below (S-shaped) the maximum density line. Raw materials were obtained and the field test results were used to define the gradations, asphalt contents, and air voids for no, low, medium, and high segregation.

The laboratory tests were selected so that data would be available to estimate the influence of various levels of segregation on (1) temperature susceptibility, (2) moisture sensitivity, (3) rutting potential, (4) thermal cracking, and (5) fatigue cracking. This section will detail the laboratory test results only. The influence of segregation on anticipated pavement performance will be covered in Chapter 3.

2.4.1 Material Properties

Projects 1-1 and 6-1 were selected for use in this phase of the research because they showed the widest range of segregation, differed in gradations above and below the maximum density line, had larger maximum size aggregates (usually prone to segregation problems), and used similar grades of asphalt (to minimize the contribution of binder differences on mix properties).

2.4.1.1 Aggregates

The properties of the as-received individual stockpiles are shown in Tables 19 and 20.

2.4.1.2 Asphalt Cements

The Superpave binder properties for both unmodified binders used in this study are shown in Table 21. Although there are noticeable differences between the binders, both are graded as PG 64-22.

2.4.1.3 Mixtures

Table 22 shows the gradations, asphalt contents, and target air voids used to simulate segregation. The gradations are shown in Figures 19 and 20. The levels of segregation differed somewhat between the projects. The core properties for Project 1-1 indicated that the levels of segregation seen in the field project were none, low, medium, and high. For Project 6-1, there were finely segregated areas and areas with no and medium levels of coarse segregation. A gradation that would simulate a high level of segregation was arbitrarily selected so that at least three of the larger sieve sizes had more than 10 percent coarser material than the medium level.

Superpave mix design procedures and gyratory compaction were used to prepare all samples. The numbers of gyrations were varied to obtain the desired air void levels for each mixture and level of segregation. Although the high level of segregation samples could be produced for the Project 1-1 materials, few samples survived handling and testing; data for these samples could not be obtained reliably.

2.4.2 NCAT Testing Program

Laboratory testing was a combined effort of the NCAT laboratory and Purdue University. Testing conducted at the NCAT facility included (1) permeability; (2) resilient and dynamic modulus at various temperatures; (3) tensile strengths before and after moisture conditioning; (4) triaxial testing to obtain Mohr-Coulomb failure criteria parameters of cohesion, C, and angle of internal friction, ϕ; (5) low temperature indirect tensile creep testing; and (6) estimates of loss of life because of fatigue using the Asphalt Institute's DAMA software program (*53*).

2.4.2.1 Permeability

Permeability increased with levels of segregation for Project 1-1 (Table 23, Figure 21). For Project 6-1, the nonsegregated samples had the lowest permeability. Finely segregating the mixture increased the permeability slightly. Coarsely segregating the mixture resulted in a noticeable increase in the ability of water to move through the mix.

2.4.2.2 Resilient and Dynamic Modulus

This testing was used to assess the influence of segregation on mixture stiffness over a wide range of temperatures (i.e., temperature susceptibility). The test results are shown in Table 23. A ratio of the stiffness for the segregated mixtures to that of the nonsegregated mixture was used to estimate the percent of mix stiffness lost because of segregation. Figure 22 shows that a low level of segregation had little effect on mixture stiffness (i.e., the ratio of modulus for low-level segregation to modulus of nonsegregated areas was 100 percent or higher. The test temperature did not appear to affect this conclusion. At the medium level of

TABLE 19 Aggregate properties for Project 1-1

Properties	Stockpile			
	No. 57 Limestone	No. 78 Limestone	Coarse Sand	M-10 Granite
Percent of Mix	30	27	20	22
Cumulative Percent Passing, %				
37.500 mm	100	100	100	100
25.000 mm	99	100	100	100
19.000 mm	72	99	100	100
12.500 mm	19	78	100	100
9.500 mm	8	51	100	100
4.750 mm	1	14	98	99
2.360 mm	<1	4	88	83
1.180 mm		3	67	65
0.600 mm		2	33	50
0.300 mm		2	6	35
0.150 mm		2	1	23
0.075 mm		1.5	<1	13.9
Bulk Specific Gravity, Dry	2.818	2.828	2.593	2.608
Bulk Specific Gravity, SSD	2.832	2.842	2.604	2.649
Apparent Specific Gravity	2.858	2.868	2.619	2.710
Absorption Capacity, %	0.5	0.5	0.4	1.4
Sand Equivalent			96	51
Fine Aggregate Angularity, %			45.12	46.70
Flat and Elongated, %	5:1 2.0% 3:1 15.9% 2:1 52.4%	5:1 2.5% 3:1 22.9% 2:1 63.9%		

TABLE 20 Aggregate properties for Project 6-1

Properties	Stockpile					
	Type A	Type B	Type D	Type F	Man. Sand	RAP[1]
Percent of Mix	20	22	10	10	18	20
Cumulative Percent Passing, %						
37.500 mm	100	100				
25.000 mm	98	100				100
19.000 mm	17	77	100			94
12.500 mm	3	8	99			85
9.500 mm		4	70	100		70
4.750 mm			5	64	100	57
2.360 mm				6	100	34
1.180 mm				2	94	21
0.600 mm					63	15
0.300 mm					42	11
0.150 mm					27	9
0.075 mm					17	7
					10.9	6
Bulk Specific Gravity, Dry	2.470	2.465	2.517	2.499	2.519	Max. Spec. Gravity 2.449
Bulk Specific Gravity, SSD	2.523	2.526	2.571	2.562	2.583	
Apparent Specific Gravity	2.608	2.624	2.660	2.665	2.691	
Absorption Capacity, %	2.2	2.5	2.1	2.5	2.5	
Sand Equivalent				100	81.4	
Fine Aggregate Angularity, %				41.46	40.86	
Flat and Elongated, %	5:1 0.0% 3:1 3.1% 2:1 33.5%	5:1 1% 3:1 13.1% 2:1 57.6%	5:1 0% 3:1 6.7% 2:1 46.1%			

[1]RAP stockpile split on 4.75 mm sieve for testing

TABLE 21 Asphalt cement properties for Projects 1-1 and 6-1

Properties	Project 1-1	Project 6-2
PG Grade	PG 64-22	PG 64-22
Brookfield Viscosity at 135°C, cP	525	363
G*/sin δ on Original, kPa	1.925	1.169
G*/sin δ on RTFO Aged, kPa	5.622	2.438
G*sin δ on RTFO and PAV Aged, kPa	2,096	3,097
Creep Stiffness, MPa at -12°C	114	222
Slope, m at -12°C	0.304	0.349

TABLE 22 Gradations, asphalt content, and target air voids for laboratory-simulated segregated mixtures

Property	Project 1-1				Project 6-1			
	None	Low	Medium	High	Fine	None	Medium	High
Cumulative Percent Passing, %								
37.500 mm	100	100	100	100	100	100	100	100
25.000 mm	100	100	100	100	90	90	82	75
19.000 mm	95	92	92	87	79	76	65	55
12.500 mm	77	71	62	42	64	59	46	33
9.500 mm	67	61	52	33	58	53	40	27
4.750 mm	50	46	37	23	41	37	27	18
2.360 mm	39	36	29	18	27	25	19	14
1.180 mm	32	30	24	16	19	17	15	12
0.600 mm	24	23	18	13	14	12	12	11
0.300 mm	15	15	12	9	11	10	9	9
0.150 mm	9	10	8	6	7	7	7	7
0.075 mm	6.1	7.5	5.1	3.8	5.5	5.2	5.2	5.2
Asphalt Content, %	4.25	3.78	3.20	2.40	3.68	3.30	2.28	1.70
Air Voids, %	9.5	10.7	12.8	19.6	7.6	9.2	9.7	10.8

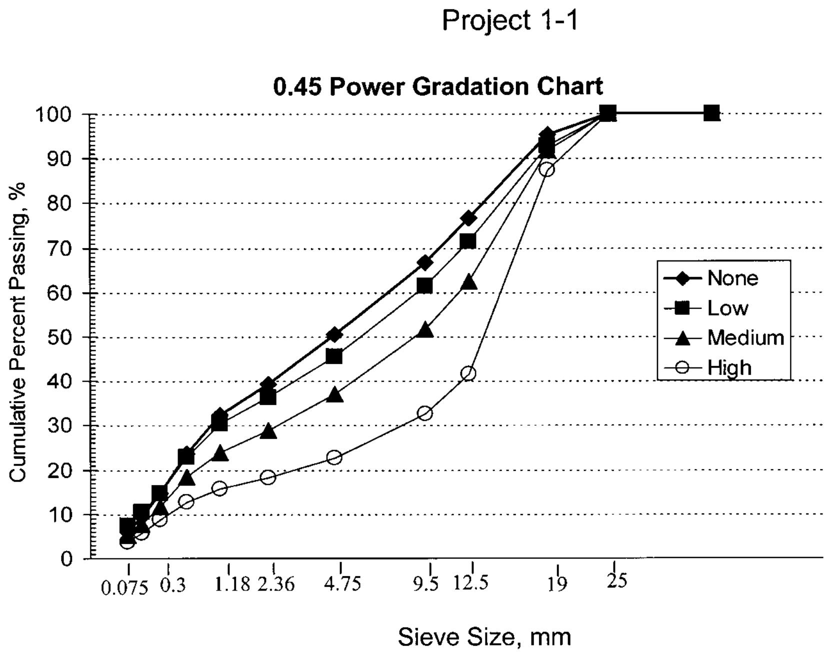

Figure 19. Gradations used to simulate segregation in laboratory study (Project 1-1).

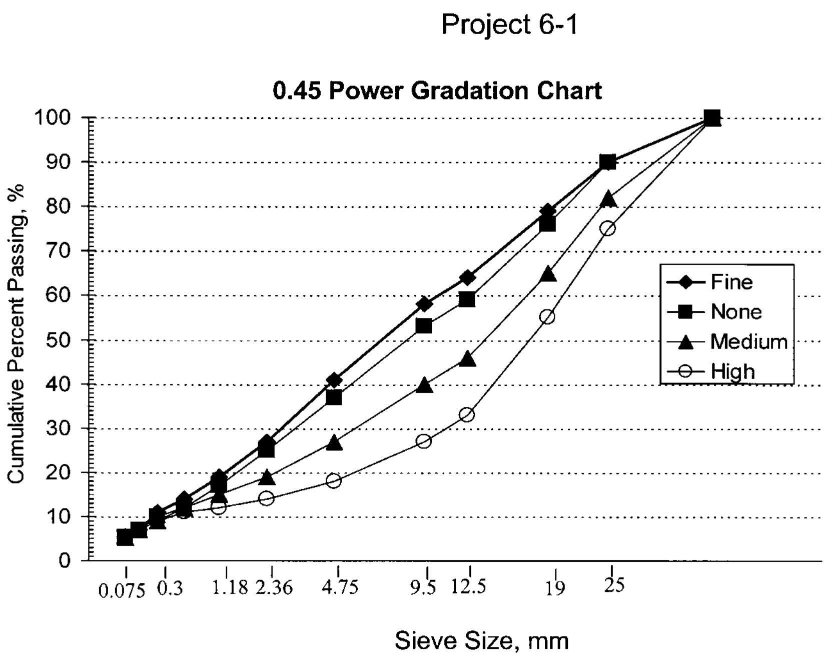

Figure 20. Gradations used to simulate segregation in laboratory study (Project 6-1).

TABLE 23 Influence of segregation on mix properties

Test	Project 1-1				Project 6-1			
	None	Low	Medium	High	Fine	None	Low	Medium
Permeability, cm/sec	0.03	0.06	0.17	0.59	0.13	0.10	1.13	0.63
Tensile Strength, kPa								
Dry, 25°C	923	887	812	464	960	899	514	316
Wet, 25°C	680	609	493	376	605	735	366	148
Resilient Modulus, MPa								
4°C	8,162	9,330	10,599	5,934	9,887	9,147	6,711	5,035
25°C	4,211	3,268	3,486	3,500	4,169	4,507	3,549	2,218
40°C	1,620	1,901	1,570	1,218	1,017	2,077	1,507	775
Dynamic Modulus, MPa								
4°C								
25°C	14,248	12,556	11,809		14,218	17,204	11,761	7,718
64°C	4,239	3,063	2,528	NA	5,176	5,232	3,275	2,570
	1,056	1,408	1,021		944	880	846	789
Mohr's Circle								
C, kPa	352	528	352		862	586	345	528
ϕ, degrees	54.0	53.8	53.0	NA	41.2	45.7	45.0	26.6
τ_{oct}, kPa	1,200	1,284	1,123		2,446	2,151	1,515	1,067

NA: not available - samples fell apart prior to testing

segregation, there was little change in stiffness at 4°C. However, as the temperature increased, so did the influence of segregation. The higher segregated mixtures had only 80 percent of the stiffness of the nonsegregated mixtures at all temperatures. These results do not show as great a loss in mixture stiffness as was seen for the cores tested for this project. A hypothesis for this difference is provided in the following section. The dynamic modulus test results follow similar trends (Table 23).

For Project 6-1, fine segregation had the least effect on modulus at any given temperature (Figure 23). Medium segregation reduced the mix stiffness by 30 percent and high segregation by about 50 percent. These results are similar to those seen for the cores tested for this project.

2.4.2.3 Tensile Strengths

The dry tensile strengths for Project 1-1 followed a similar trend as those for the resilient modulus (Figure 24). That is, there is only a slight decrease in strength because of the medium-level segregation. The wet strengths, however, show a slight but continual decrease in tensile strengths after moisture conditions with increasing levels of segrega-

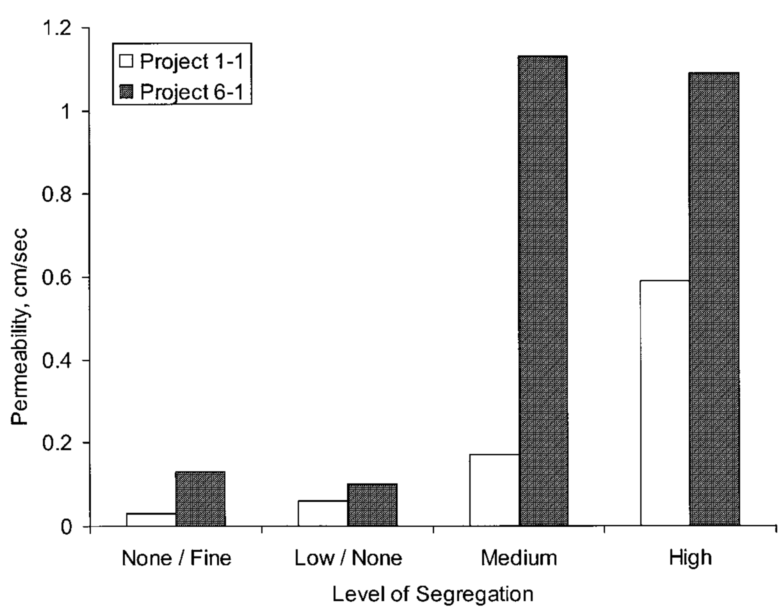

Figure 21. Influence of level of segregation on permeability.

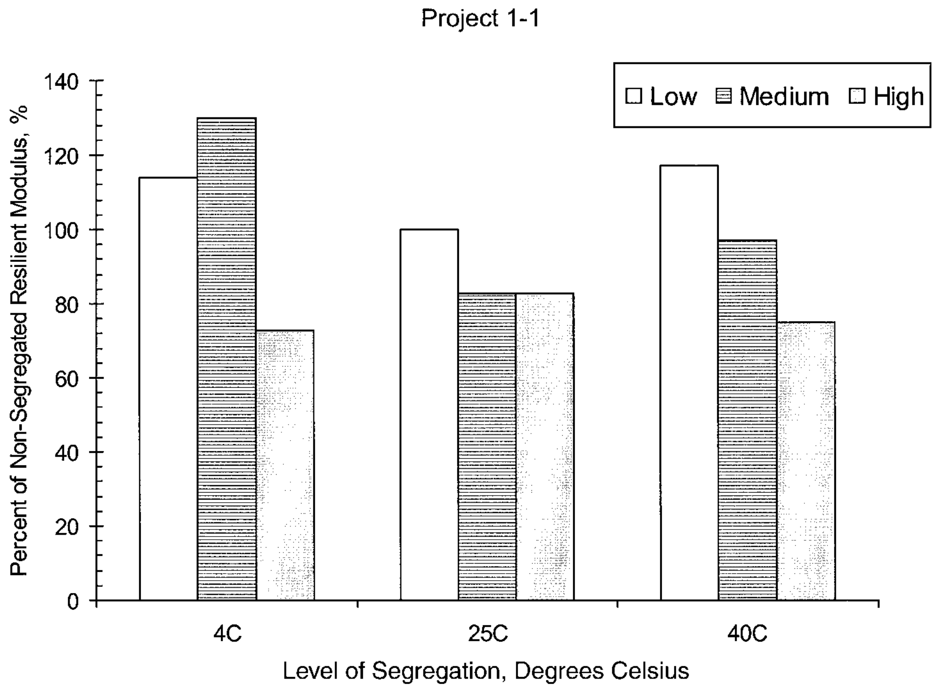

Figure 22. *Percent loss of stiffness with increasing levels of segregation (Project 1-1).*

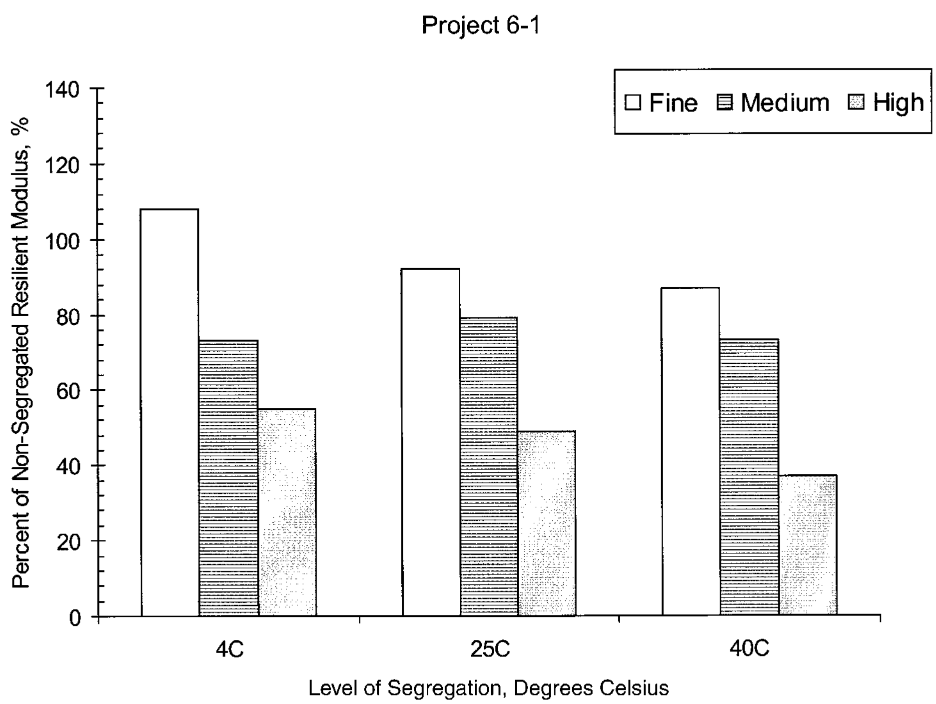

Figure 23. *Percent loss of stiffness with increasing levels of segregation (Project 6-1).*

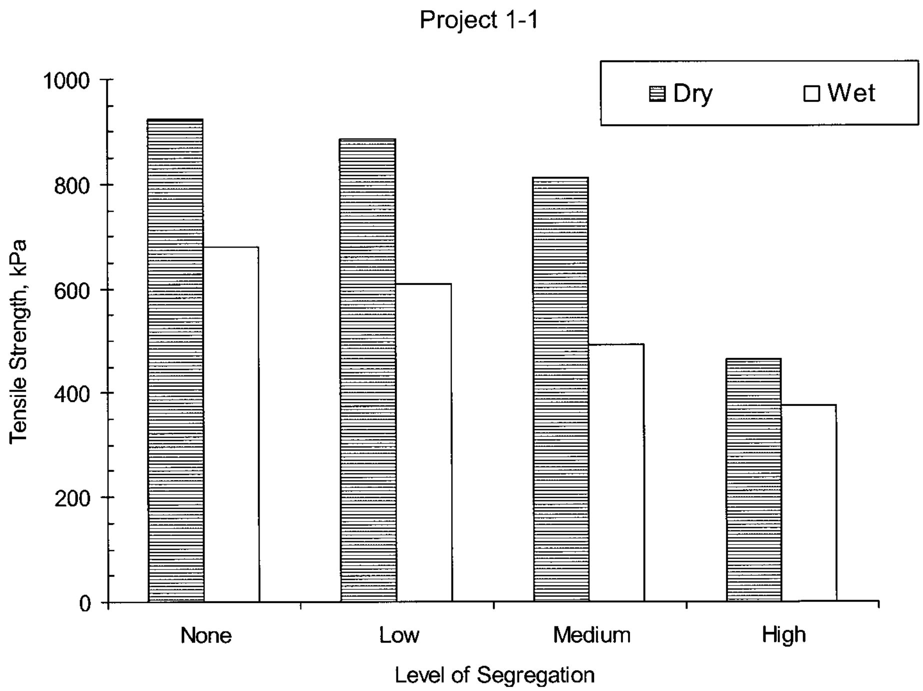

Figure 24. Influence of segregation on tensile strengths (Project 1-1).

tion. This is probably a combined effect of air voids, air voids interconnectivity, and, possibly, differences in film thickness.

The lack of a substantial decrease in either the modulus or dry tensile strength with increasing levels of segregation did not agree well with the loss of stiffness and strength seen in the cores. The hypothesis is that even poor quality mixtures can be fabricated more uniformly in the laboratory than during construction. Only after environmental exposure (moisture conditioning) did the influence of segregation become apparent in the laboratory-produced segregated samples.

For Project 6-1, the dry tensile strengths of the finely segregated and nonsegregated mixtures were similar (Figure 25).

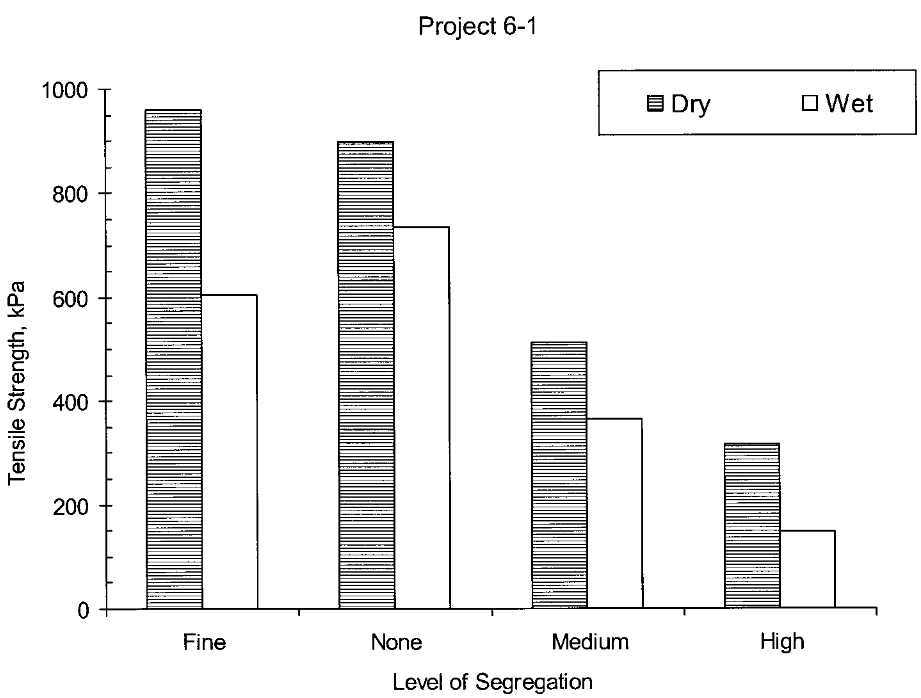

Figure 25. Influence of segregation on tensile strengths (Project 6-1).

The loss of dry strength increases with increasing levels of coarse segregation. After moisture conditioning, the nonsegregated samples have the highest wet strengths. There is a decrease in wet tensile strengths in the finely segregated samples as well as a decrease in dry tensile strength because of increased coarse segregation. These differences can be seen clearly in the tensile strength ratios for each level of segregation for each project (Figure 26).

2.4.2.4 Mohr-Coulomb Failure Criteria

Cohesion, *C*, and the angle of internal friction, φ, values are shown in Table 23. Cohesion is primarily a function of the binder—this explains the decrease in *C* with the decreasing asphalt contents associated with the increasing levels of segregation. The angle of internal friction is relatively constant, regardless of the level of segregation for Project 1-1. At a high level of segregation for Project 6-1, *C* increases slightly, but there is a significant decrease in the angle of internal friction. This would indicate the loss of internal aggregate interlock because of the limited aggregate-to-aggregate contact between the larger particles. That is, there are few fines to fill the large voids between aggregates.

The octahedral shear stress, τ_{oct}, can be used to define the influence of the nine three-dimensional stresses at a specific point in the pavement:

$$\tau_{oct} = 0.942\left[\frac{\sigma_3 \sin\varphi}{1-\sin\varphi} + \left(\frac{1+\sin\varphi}{1-\sin\varphi}\right)^{1/2}\right]$$

where:

σ_3 = minor principle stress

The data for Project 1-1 showed little dependency of the maximum octahedral shear stress on the level of gradation segregation. Using the data for Project 6-1 and assuming a constant horizontal confining pressure of 300 kPa for a given point in a pavement structure, the octahedral shear stress that can be tolerated by each mix (Table 23) decreases with increasing segregation. There is a small decrease because of low segregation. However, there is about a 40 and 60 percent lower shear stress at a medium and high level of gradation segregation, respectively. These results suggest that the effect of segregation on the rutting potential should be mix specific and that, in some cases, more severe levels of segregation should result in rutting.

The effect of temperature segregation (i.e., decreases in density) on rutting potential is already well documented and was not included in this study.

2.4.2.5 Low Temperature Indirect Tensile Creep Testing

Analysis software that follows the Superpave analysis procedure was provided by Dr. Don Christensen at Pennsylvania State University (*54*). It was anticipated that the critical pavement temperature could be estimated using this software. However, the data were exceptionally erratic for these large aggregate mixtures; this made a comprehensive

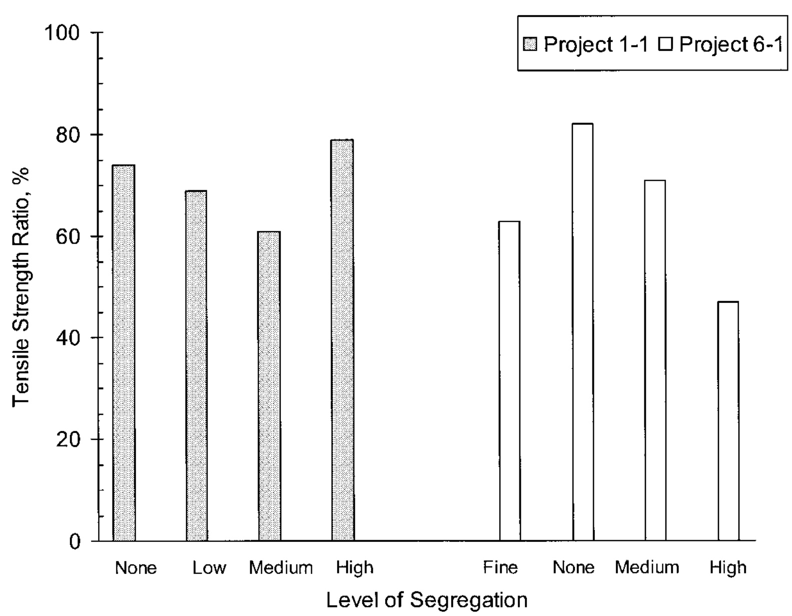

Figure 26. Influence of segregation on tensile strength ratios.

evaluation of the data impossible. The limited data that could be obtained after 100 sec of loading are shown in Table 24. There is some indication that the compliance of the mixtures increases with the level of segregation, but this may simply be reflecting the increased variability across the narrow gauge length over which the strain data are collected. Although the data for the medium and high segregation levels were tested, the data were consistently and exceptionally poor.

The slope of the compliance versus time relationship also follows expected trends. That is, the slope increases both with temperature and with the level of segregation. Again, because of the erratic data, no firm conclusions can be drawn.

Because of the problems with the data, no further analysis was completed. This testing suggests that substantial revisions are needed to the testing protocol to accommodate larger sized aggregate mixtures.

2.4.2.6 Fatigue Cracking

The Asphalt Institute's DAMA program was used to estimate the effect of segregation on fatigue life (*53*). This program uses inputs of mean monthly high temperatures (Table 25), key aggregate and asphalt properties (Tables 26 and 27), and pavement structure information (also Tables 26 and 27). The temperature information was collected from the National Weather Service (NWS) database. This information is used in conjunction with other data to estimate the modulus of asphalt concrete in different seasons. Structural information shown in these tables was obtained from the construction records for each of the projects evaluated.

The DAMA program was run assuming that a given level of segregation would occur in only one lift at a time. The individual mixture inputs for each level of segregation were obtained from the laboratory testing of the cores from each project.

Table 28 shows the anticipated loss of pavement life for each lift because of segregation. For Project 1-1, segregation in the wearing course primarily affects the life of only that lift. When there is a high level of segregation, the failure mode shifts from fatigue to compression (i.e., rutting) in the next lift down (binder 1). When the intermediate lift has either low or medium levels of segregation, there is little influence on the life of the wearing course. In this case, most of the loss of life is in the lift with the segregation. At a high level of segregation, there is a noticeable loss of fatigue lift of the wearing course as well as the upper binder course. Segregation in the lower lift shifts the mode of failure in the upper layers from fatigue to compression. Similar analysis trends are seen for Project 6-1.

These results suggest that a low level of segregation will reduce the fatigue life of the lift in which the segregation occurs with a minimal effect on lifts above the affected one. A medium level of segregation will result in a large decrease in fatigue life, while a high level will have a pronounced affect on all of the pavement lifts.

TABLE 24 Indirect tensile creep results at 100 seconds

Project	Test Temperature °C	Compliance versus log Time Parameters at Various Levels of Segregation			
		None	Low	Medium	High
Compliance, E^{-7}, 1/ psi					
1-1	-20	3.736	5.175		
	-10	3.828	5.850		
	0	13.406	12.378		
6-1	-20	4.388	7.034		
	-10	7.230			
	0	7.134	27.306		
Slope, m					
1-1	-20	0.1376	0.1802		
	-10	0.2260	0.3322		
	0	0.4235	0.4853		
6-1	-20	0.1130	0.2157		
	-10	0.2299			
	0	0.3468	0.4931		

Shaded areas indicate tests that were completed but in which the data were not useful.

TABLE 25 Temperature data used for DAMA input

Month	Mean Average Air Temperatures, °F	
	Project 1-1	Project 6-1
January	41.0	49.6
February	47.5	53.8
March	53.3	61.8
April	61.4	69.6
May	69.1	75.7
June	76.0	81.6
July	78.7	84.4
August	78.0	84.2
September	72.6	79.3
October	62.3	70.4
November	53.1	60.4
December	44.5	52.4

TABLE 26 Structure, mixture, and binder values used for DAMA input for Project 1-1

Pavement Structure		Mix Properties					Binder Properties	
Lift	Level of Segregation	Poisson's Ratio	Lift Thickness	Air Voids, %	% Pass 0.075 mm	%AC (wt. of mix)	Viscosity 60°C, P	Viscosity 135°C, cSt
Wearing Course	None	0.35	75 mm	9.5	6.1	4.25	1,925	525
	Low			10.7	7.5	3.78		
	Medium			12.8	5.1	3.20		
	High			19.6	3.8	2.40		
Binder Course 1	None	0.35	75 mm	9.5	6.1	4.25		
	Low			10.7	7.5	3.78		
	Medium			12.8	5.1	3.20		
	High			19.6	3.8	2.40		
Binder Course 2	None	0.35	75 mm	9.5	6.1	4.25		
	Low			10.7	7.5	3.78		
	Medium			12.8	5.1	3.20		
	High			19.6	3.8	2.40		
Base		0.35	400 mm					
Subgrade		0.45	NA					

TABLE 27 Structure, mixture, and binder values used for DAMA input for Project 6-1

Pavement Structure		Mix Properties					Binder Properties	
Lift	Level of Segregation	Poisson's Ratio	Lift Thickness	Air Voids, %	% Pass 0.075 mm	%AC (wt. of mix)	Viscosity 60°C, P	Viscosity 135°C, cSt
Wearing Course	None	0.35	50 mm	7.0	5.0	5.25	1,169	363
Binder Course 1	None	0.35	100 mm	9.23	5.2	3.30		
	Medium			9.7	5.2	2.28		
	High			10.8	5.2	1.70		
Binder Course 2	None	0.35	100 mm	9.23	5.2	3.30		
	Medium			9.7	5.2	2.28		
	High			10.8	5.2	1.70		
Base		0.35	400 mm					
Subgrade		0.45	NA					

TABLE 28 Influence of segregation on fatigue life using output from DAMA software

Lift	Percent Loss of Life Due to a Given Level of Segregation in a Given Lift, %		
	Low	Medium	High
Project 1-1			
Segregation in Wearing Course			
Wearing	38	81	99
Binder 1	3.2	0	(compression)
Binder 2	0	0	0
Segregation in Binder 1 Course			
Wearing	8	0	29
Binder 1	57	79	95
Binder 2	0	0	0
Segregation in Binder 2 Course			
Wearing	2	(compression)	11
Binder 1	(compression)	15	74
Binder 2	50	50	50
Project 6-1			
Segregation in Binder 1 Course	Not Evaluated		
Wearing		19	25
Binder 1		84	98
Binder 2		0	0
Segregation in Binder 2 Course			
Wearing		(compression)	(compression)
Binder 1		(compression	(compression)
Binder 2		50	50

2.4.3 Purdue University Testing Program

2.4.3.1 PURWheel Testing

This section describes laboratory tests conducted using the Purdue University laboratory wheel track test device, PURWheel (Appendix H, not published herein, provides individual test results), which was designed to test compacted HMA slab specimens under conditions associated with both rutting and stripping. These conditions include high moisture, high temperature, and moving wheel loads. Tests can be conducted on laboratory-compacted specimens as well as specimens taken from in-service pavements. An associated linear compactor was designed and fabricated to produce laboratory-compacted slab specimens for PURWheel testing.

Two specimens can be tested at the same time in this device. The test environment can be either hot/wet or hot/dry. Typical highest temperatures range from 55°C to 60°C, although the test temperature can vary from room temperature to 65°C. Specimen dimensions are typically 290-mm wide and 310-mm long. Specimen thickness can be up to 102 mm and varies, depending on the nominal maximum aggregate size of the mixture being tested. A pneumatic tire is loaded to achieve a gross contact pressure of about 620 kPa with a tire inflation pressure of 793 kPa. The wheel velocity can be set from 200 mm/sec to 400 mm/sec. In current tests, wheel velocity was selected to be 330 ± mm/sec. Typical test criteria are 20,000 wheel passes or 20 mm of deformation in the wheel path, whichever comes first. All of the individual test results are shown in Appendix H (not published herein).

Figure 27 shows a summary of the PURWheel test results. Because several samples failed prior to the 20,000 cycles, the data for 10,000 cycles are shown. There was little influence of segregation levels on the rutting potential, regardless of

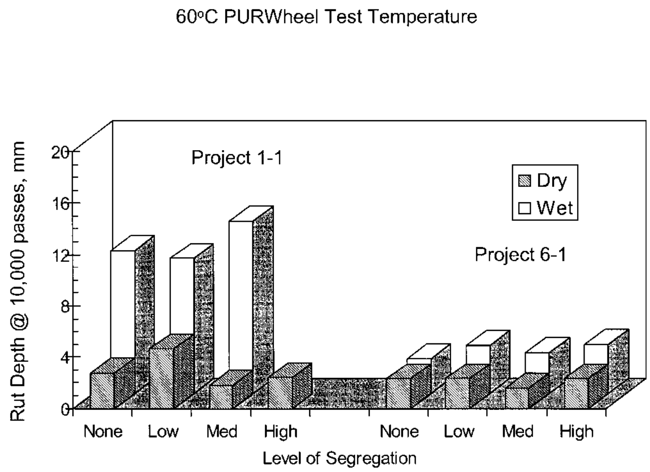

Figure 27. PURWheel rut depths after 10,000 cycles.

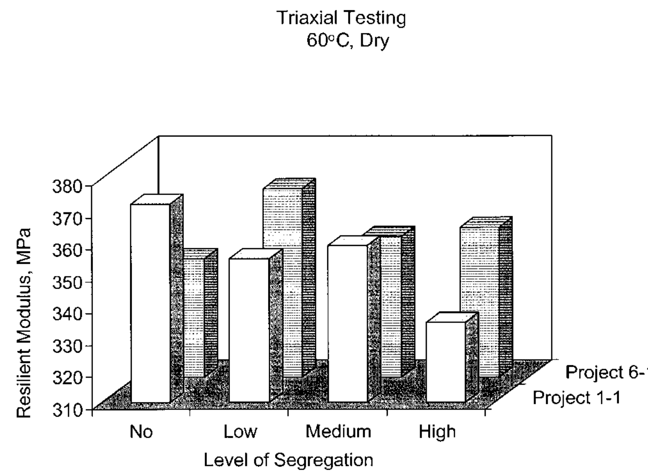

Figure 28. Resilient modulus results (dry, 60°C, axially loaded).

whether the samples were tested wet or dry. However, the Project 1-1 aggregates appear to have a greater stripping potential than the Project 6-1 aggregates. Testing under hot/wet conditions produced about three times the rut depth for the no, low, and medium levels of segregation. The high level of segregation for Project 1-1 samples failed before 10,000 cycles.

2.4.3.2 Resilient Modulus Testing

A Superpave gyratory compactor was used to prepare samples with a height of between 110 and 130 mm and a diameter of 150 mm for this testing. Axially loaded, dry resilient modulus tests were conducted at 60°C and a 138 kPa confining pressure. The resilient modulus was determined after 200 applications of a 275 kPa deviator stress applied at a rate of 1Hz. The seating load for the test was 0.8 kn (approximately 10 percent of the expected maximum loading).

Testing was also conducted after the specimen was saturated. Both the undrained and drained conditions were evaluated. Saturation was accomplished by placing the specimen between two porous stones, preheating the water to 60°C, then using a vacuum pressure to pull the water into the sample. The back pressure was held until the pore pressure was the same as the back pressure and no water was flowing into the sample. Further testing details can be found in Appendix H (not published herein).

The dry resilient modulus test results are shown in Figure 28. There is a general trend of decreasing modulus with increasing levels of segregation for the Project 1-1 mixtures. The no level of segregation has the lowest modulus of the Project 6-1 mixtures.

Figure 29 shows the resilient modulus results for both the wet, undrained and the wet, drained testing conditions. There appears to be little influence of drainage on the test results. There is a general trend for the Project 6-1 mixtures to be slightly stiffer than the Project 1-1 mixtures. This is consistent with results from other test methods.

2.4.3.3 Triaxial Testing

Traditional triaxial testing was conducted immediately after the resilient modulus testing was completed. This testing was conducted at a loading rate of 1.25 mm/min with a confining pressure of 138 kn and at a test temperature of 60°C (see Figures 30 through 33). Project 6-1 mixtures consistently have a higher strength than the Project 1-1 mixes. The higher strengths for the wet condition probably reflect the reaction of pore water pressure. There is little difference in mix strength until the level of segregation approaches the high level. This is consistent with all of the test results previously shown. These results also indicate that a high level of segregation is needed before the permanent deformation of these coarse aggregate gradations will experience noticeable changes in rutting potential.

2.4.4 Summary

The influence of segregation on mixture properties is summarized in Table 29. These results agree with previous laboratory testing reported in the literature review. These laboratory results agree well with the results obtained for the cores (Section 2.3).

2.5 PAVEMENT CONDITION SURVEYS

Existing pavements showing signs of segregation-related pavement distresses were identified in six states: Alabama, Washington, Minnesota, Georgia, Texas, and Connecticut. Pavement condition surveys were conducted from the shoul-

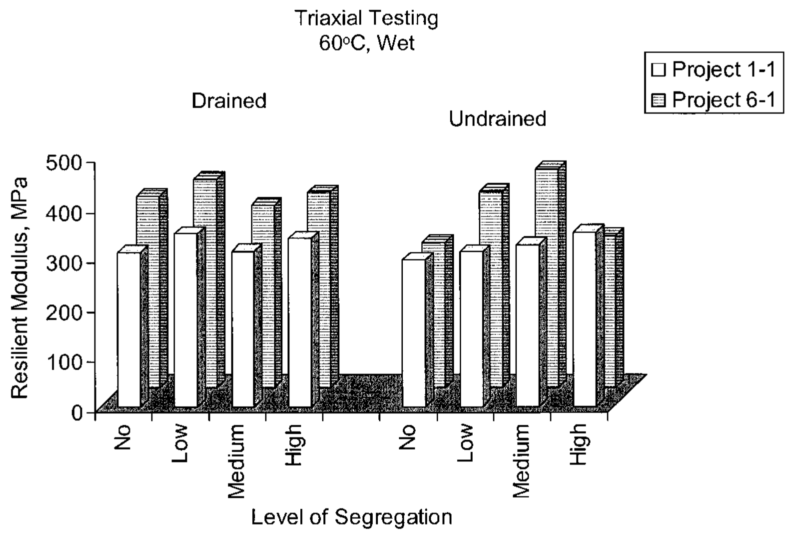

Figure 29. Resilient modulus results for wet, undrained and wet, drained conditions (60°C).

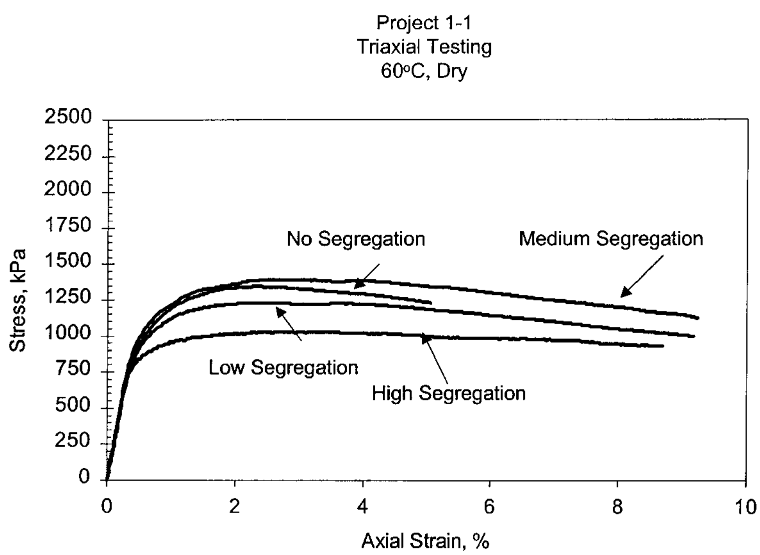

Figure 30. Triaxial test results (dry, 60°C; Project 1-1).

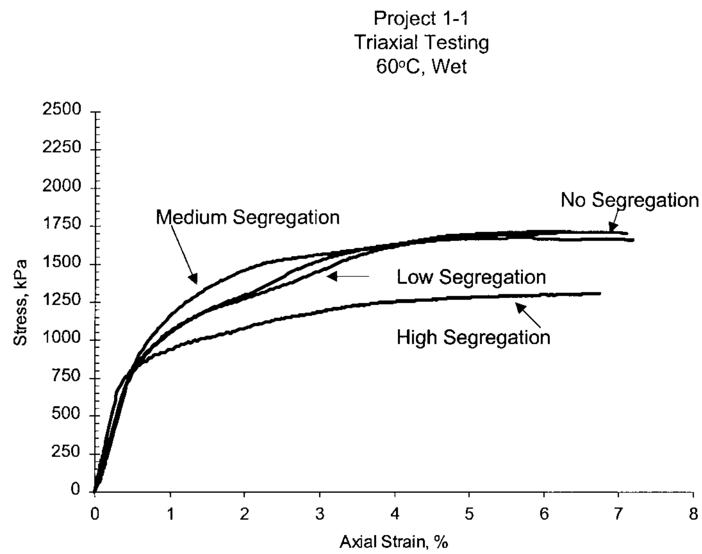

Figure 31. Triaxial test results (wet, 60°C; Project 1-1).

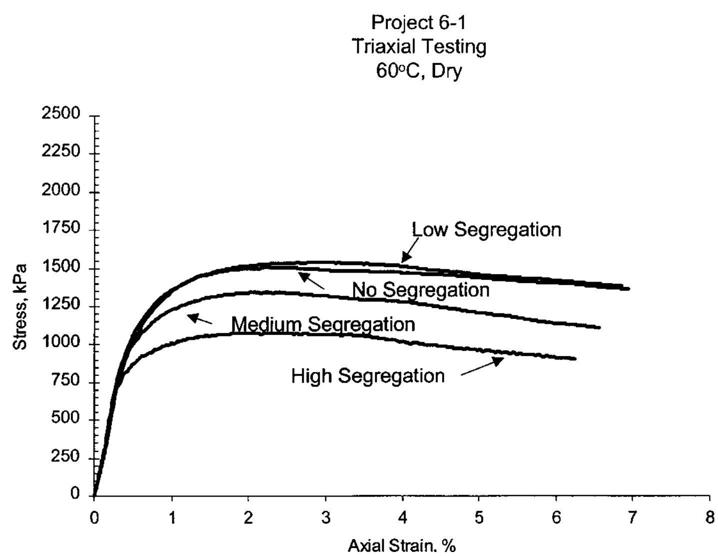

Figure 32. Triaxial test results (dry, 60°C; Project 6-1).

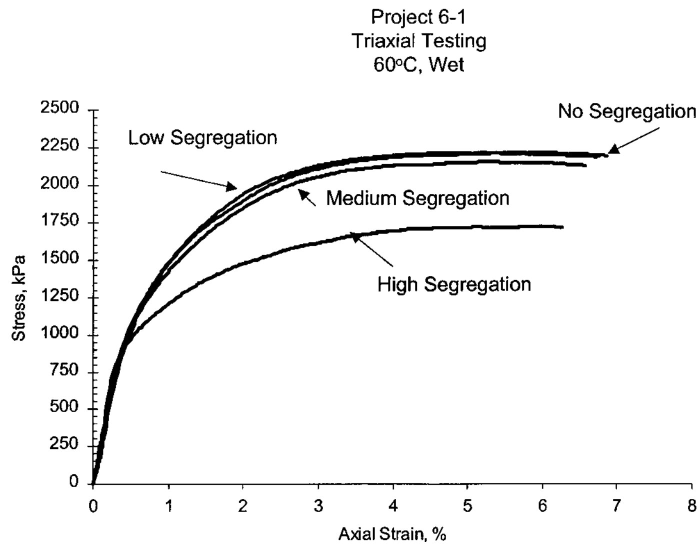

Figure 33. Triaxial test results (wet, 60°C; Project 6-1).

TABLE 29 Summary of the influence of segregation on mixture properties

Mixture Property	Percent of Non-Segregated Mix Property by Level of Segregation			
	Fine	Low	Medium	High
Permeability	Increased slightly	Increasing with level of coarse segregation		
Resilient Modulus	Little or slightly increasing stiffness	80 to 90%	70 to 80%	50 to 70%
Dynamic Modulus	Little or slightly increasing stiffness	80 to 90%	70 to 80%	50 to 70%
Dry Tensile Strength	110%	90 to 100%	50 to 80%	30 to 50%
Wet Tensile Strength	80 to 90%	75%	50%	30%
Low Temperature Tensile Stress	No conclusions due to test method difficulties			
Loss of Fatigue Life when Segregation in Upper Lifts, %	Not Estimated	38%	80%	99%
Rutting Potential	Not strongly influenced by gradation segregation until a high level of segregation is seen			

ders of the roadways by a two-person survey team to determine the type and extent of distresses associated with this construction problem. Table 30 indicates the survey locations and general construction and traffic information as provided by the respective DOTs.

2.5.1 Alabama Pavement Condition Surveys

The location and general condition of the nonsegregated and segregated areas are summarized in Table 31. In all cases, the segregation seen was cyclic in nature throughout the entire length of the section evaluated.

2.5.2 Washington Pavement Condition Surveys

The results of the surveys are summarized in Table 32. The survey team noted that when driving along pavements with evidence of segregation, there was also a decided dip in roadway profile. In order to investigate this change in ride quality, the Washington State DOT (WashDOT) provided a profile of one of the sections surveyed. These results are shown in Figure 34. Transverse depressions from 3 to 18 mm in depth occurred every time the condition survey noted segregation-related pavement distresses.

Previous work by both WashDOT and University of Washington researchers indicated that temperature segregation was

TABLE 30 Background information for pavements surveyed for segregation-related distresses

Location	Date of Construction of Surface	Traffic	Thickness of Top Lift	Type of Mix	Nominal Max. Size Agg.	Underlying Structure	Date of Original Construction
Alabama							
I 85 MP 57 to 62	1989	24,000[1]	NR	416-B	12.5[1] mm	NR	NR
I 65 MP 315 to 319	1989	24,000[1]	NR	416-B	12.5[1] mm	NR	1966
I 65 KMP 316 to 319	1985	24,000[1]	NR	416-B	12.5[1] mm	NR	NR
Washington							
SR 5 MP 224 to 220	1997	25,000 ADT 12% Truck	0.15 ft	Cl A	12.5 mm	0.35 ft AC, 0.45 ft ATB 0.45 ft Base	1969 to 1974
SR 5 MP 115 to 124	1995	46,000 ADT 12% Truck	0.15 ft	Cl A	12.5 mm	0.25 ft, 0.65 ft ATB, 0.10 ft Base	PCC 1950's
SR 16 MP 8.51 to 11.19	1997	35,000 ADT 5.3% Truck	0.15 ft	Cl A	12.5 mm	0.25 ft, 0.35 ft ATB, 0.40 ft Base	1980's
Minnesota							
TH 23 south of Clara	Information Not Available						
TH 169 from TH 19 to MP 101	1987	15,000[1]	0.25 ft	2341	12.5 mm	PCC (Crack and Seat)	1955

(continued on next page)

TABLE 30 (*Continued*)

Location	Date of Construction of Surface	Traffic	Thickness of Top Lift	Type of Mix	Nominal Max. Size Agg.	Underlying Structure	Date of Original Construction
Georgia							
SR 20	1993	24,900 ADT	40 mm	Type E	12.5 mm	Existing AC Pavement	NR
I 85 from Exit 10 to 12	1988	21,100 ADT	40 mm (E) 16 mm (D)	Type E RAP and Type D	12.5 mm	Existing AC Pavement	NR
Texas							
Loop 1	1993	9,000 ADT	50 mm	Type C	19 mm	300 mm Base	1993
Loop 360	1988	18,000 ADT	50 mm	Type D	NR	300 mm Flexible Base	NR
I 35	1993	25,300 ADT	76 mm	Type C	19 mm	Existing AC Pavement	NR
Connecticut							
Route 11	1995	6,734 ADT	75 mm	Cl 1	12.5 mm	50 mm AC, 200 mm Base and Binder 100 mm Chlor. Stab. Base 250 to 430 mm Subbase	1972
Route 395 between Exits 77 and 83	1995	40,000 ADT	125 mm	Cl 1 and Cl 2	12.5 mm	125 mm AC, 75 mm Macadam 100 mm Crushed Stone 250 to 430 mm Subbase	1958

NR: Not reported
[1]Values estimated from information provided by the DOT.

TABLE 31 Summary of pavement condition (Alabama)

Location	Condition of Area without Segregation	Condition of Area with Segregation
I 85 MP 57 to 62	Slight raveling, dry-looking surface	Longitudinal cracking Some potholes starting to form Moderate to severe raveling Cyclic: covers about 15 meters out of every 40 to 50 meters
I 65 MP 315 to 319	Slight raveling	Longitudinal cracking Numerous potholes of varying sizes Moderate to severe raveling Cyclic: covers about 15 meters out of every 40 to 50 meters
I 65 KMP 316 to 319	Slight raveling	Longitudinal cracking Some potholes starting to form Moderate to severe raveling Cyclic: covers about 15 meters out of every 40 to 50 meters

TABLE 32 Summary of pavement condition survey (Washington)

Location	Condition of Area without Segregation	Condition of Area with Segregation
SR 5 MP 224 to 220	Slight raveling, dry-looking surface	Intermittent longitudinal cracking Low to moderate raveling Cyclic: covers between 5 and 10 meters out of every 25 to 35 meters Accompanied by transverse ruts in segregated areas
SR 5 MP 115 to 124	Slight raveling, dry-looking surface	Intermittent longitudinal cracking Moderate to severe raveling Cyclic: covers between 5 and 10 meters out of every 25 to 35 meters Accompanied by transverse ruts in segregated areas
SR 16 MP 8.51 to 11.19	Slight raveling, dry-looking surface	Intermittent longitudinal cracking Mostly moderate raveling Cyclic: covers between 5 and 10 meters out of every 25 to 35 meters Accompanied by transverse ruts in segregated areas

the primary problem in this part of the country. These researchers also found that the air voids in segregated areas were approximately 5 percent higher than in nonsegregated areas. That is, if the air voids were 7 percent in nonsegregated areas, then the voids in the temperature-segregated areas were roughly 12 percent. This would explain the associated depressions in pavements with this type of construction problem. Although the freshly finished surface is smooth, differential densification of the pavement mat over time because of traffic loadings is producing localized areas of rutting.

WashDOT staff estimated the loss of pavement life caused by segregation to be between 3 and 7 years for a pavement that would normally perform well for about 15 years if segregation was not present.

2.5.3 Minnesota Pavement Condition Surveys

The results of the pavement condition surveys are shown in Table 33. Most of the segregation found in these surveys was of a longitudinal nature rather than cyclic, as seen in previous surveys. Higher levels of pavement distresses were observed in some areas.

2.5.4 Georgia Pavement Condition Surveys

The condition surveys are summarized in Table 34. Pavement distresses seen on these projects were of a nature similar to those found in Alabama.

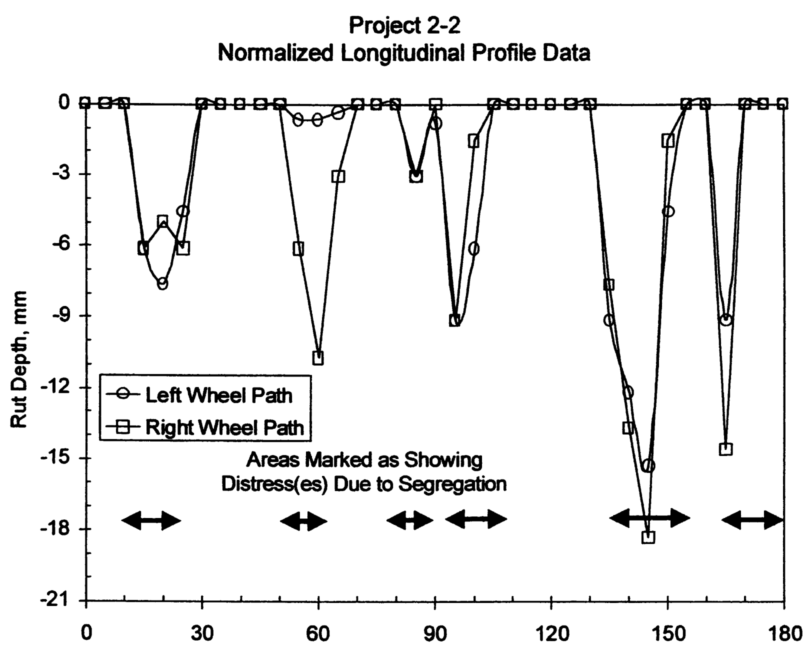

Figure 34. Relationship between pavement profile and segregated areas.

TABLE 33 Summary of pavement condition survey (Minnesota)

Location	Condition of Area without Segregation	Condition of Area with Segregation
TH 23 south of Clara	Good condition	Slight to moderate raveling Distress appears to be accelerated by moisture damage Cyclic: covers about 5 meters out of every 40 to 50 meters
Highway 169 from Highway 19 to MP 101	Thermal cracking Slight to moderate raveling around cracks	Moderate to severe raveling longitudinally Occurs intermittently throughout test section Some pothole formation

TABLE 34 Summary of pavement condition survey (Georgia)

Location	Condition of Area without Segregation	Condition of Area with Segregation
SR 20	Good condition	Slight to moderate raveling Cyclic: covers about 5 to 10 meters out of every 40 to 50 meters
I 185 from Exit 12 to 13	Milled surface Dry with slight raveling and some longitudinal cracking	Frequent large potholes Severe raveling Intermittent longitudinal cracking
I 85 from Exit 10 to 12	Fair condition Slight raveling	Slight to moderate raveling Limited number of potholes starting Cyclic: covers about 10 meters every 40 to 50 meters

2.5.5 Texas Pavement Condition Surveys

The results are shown in Table 35. In areas of the pavement without segregation, the surface showed some signs of raveling and looked dry, but it was generally in good shape. Most segregated areas showed a high severity of longitudinal cracking, raveling, and pothole formation.

DOT staff estimated the loss of pavement life caused by segregation to be between 4 and 7 years compared with an anticipated life of between 12 and 15 years for a pavement without segregation problems.

2.5.6 Connecticut Pavement Condition Surveys

The results are summarized in Table 36. Typical distresses were similar to those shown for Alabama.

TABLE 35 Summary of pavement condition survey (Texas)

Location	Condition of Area without Segregation	Condition of Area with Segregation
Loop 1	Good condition	Slight raveling Random but looks like typical end-of-truck problems when it occurs Covers approximately five 10-m-long areas out of a 170-m section
Loop 360	Generally good condition Slight raveling, dry looking surface	Moderate to severe raveling Some potholes starting to form (appears to be starting from longitudinal cracking) Somewhat cyclic: covers about a total of 40 out of 170 meters
I 35 near Exit 161	Generally good condition	Slight to moderate raveling Slight raveling Random but looks like typical end-of-truck problems when it occurs Covers approximately 40 out of a 170-m section

TABLE 36 Summary of pavement condition survey (Connecticut)

Location	Condition of Area without Segregation	Condition of Area with Segregation
Route 11	Thermal cracks every 20 meters	Moderate raveling Noticeable dip/bump when driving Cyclic: covers about 25 out of 170 meters
Route 395 between Exits 77 and 83	Good condition Looks slightly dry	Limited moderate to severe raveling Cyclic: covers about 20 out of 150 meters

2.5.7 Summary

The following conclusions can be drawn from these surveys:

1. Temperature segregation results in periodic rutting because of the initially low density in segregated areas. Increased longitudinal and fatigue cracking distresses are also seen in these areas.
2. Gradation segregation results in similar increases in raveling and longitudinal and fatigue cracking in segregated areas. Unlike temperature segregation, no appreciable depressions caused by traffic densification are seen.
3. DOT staff estimate subjectively the loss of pavement life caused by segregation (either temperature or gradation) to be between 3 to 7 years, depending on severity, from an anticipated pavement life of between 12 and 15 years for pavements with no evidence of segregation. The obviously lower pavement distresses noted in the pavement distress surveys agree with these DOT observations.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATION

3.1 INTRODUCTION

This chapter presents the interpretation, appraisal, and application of three nondestructive technologies that have the potential for detecting and measuring segregation. These are as follows:

1. DOR nuclear gauge,
2. Infrared thermography, and
3. ROSAN$_v$ surface texture measurements.

Initial findings (Chapter 2) showed that the nuclear density and asphalt content (i.e., moisture) measurements were not sufficiently sensitive for the detection and measurement of segregation. However, overly cold areas, such as after long paver stoppages, will result in localized, poorly compacted areas. Although this problem is not considered a part of the traditional meaning of segregation, it does fit with the definition developed for this research program. That is, segregation is the lack of homogeneity of the HMA constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress. Localized areas of poor compaction are expected to accelerate pavement distresses. The influence of localized cold area on density will be discussed in the infrared thermography section.

The last section in this chapter will discuss the influence of segregation on the life cycle cost of a typical HMA pavement.

3.2 INFRARED THERMOGRAPHY

3.2.1 Research Program

The objectives were to evaluate the potential for using infrared thermography for detecting and measuring segregation and to relate infrared measurements to performance-related mixture properties.

3.2.2 Analysis

Key mixture properties (i.e., stiffness, air voids, and asphalt content) shown in Tables 5 through 8 were correlated with the average mean temperature for each level of segregation (Table 37). These relationships were used to define a range of temperature differences that will indicate the various levels of segregation.

3.2.2.1 Air Voids

Because air void levels in nonsegregated areas depend on the overall compactive effort by the contractor, a difference in air voids between those in the segregated areas and those in the nonsegregated areas was used. This removes any job-specific dependency of the average voids in the nonsegregated areas. That is, air voids in the nonsegregated areas associated with paving a driving lane were between 6 and 8 percent but between 10 and 12 percent for shoulder paving jobs. Using the difference allows for a direct comparison of the results, regardless of the type of project.

Figure 35 shows that an increasing difference in air voids is well correlated with increasing temperature differences. There are also natural breaks in the data between the changes in air voids that result from the different levels of segregation. Suggested temperature difference limits, which can be used to detect and measure the level of segregation, are shown in this figure.

A pavement mat with no segregation will have temperature differences of less than 10°C throughout the mat and air voids within about 2 percent of average air voids in the nonsegregated areas. Areas with temperature changes between 10°C and 16°C will exhibit an increase in air voids when compared with the nonsegregated areas of between 2 and 4.5 percent at a low level of segregation. Medium segregation will have an increase in air voids from about 4.5 to 6.5 percent and temperature differences between 16°C and 21°C. Areas with temperature changes above this will be highly segregated and have air voids greater than 6.5 percent.

3.2.2.2 Asphalt Cement Content

Asphalt content was used as a single variable representation of significant changes in gradation. The difference in asphalt content between the nonsegregated and segregated areas was again used to remove any job-specific parameters from the analysis.

Figure 36 shows the relationship between changes in the asphalt content and corresponding temperature differences. The temperature differences suggested for the identification of change in air voids can be applied to this relationship as well. Areas of the pavement mat with no segregation will have temperature differences of 10°C or less and asphalt content changes of less than about 0.3 percent from those asphalt

TABLE 37 Mean infrared temperature difference from the maximum for each level of segregation

Level of Segregation	Southeastern Region			Southern Region	Upper Midwestern Region	Northeastern Region
	Mean Infrared Temperature Difference for Project No.:					
	1-2	4-2	5-2 (SMA)	6-2	3-2	7-2
Fine	6.5				4	
None	8.9	5.2	9	24.5	5.9	3.5
Low	12.8	11.4	20	19.7	18.2	18.8
Medium	16	18.8		27.2		
High						

contents in the nonsegregated areas. Areas with temperature changes between 10°C and 16°C will have a reduction in asphalt content of between roughly 0.3 and 0.8 percent. Medium segregation is indicated by a temperature differential between 16°C and 21°C and indicates a reduction in asphalt content of 0.8 and 1.3 percent. Areas with temperature changes above this will be highly segregated.

3.2.2.3 Resilient Modulus

Resilient modulus measurements (stiffness) have a strong dependency on the stiffness of the binder used for each mixture and, given that most projects used different grades of asphalt cement, a single parameter was needed so that all of the data could be compared at once. The hypothesis used to develop this parameter was that, although the magnitude of the stiffness is dependent on the asphalt grade, the change in stiffness resulting from segregation should be proportional. Therefore, the ratio of the stiffness of the segregated to the nonsegregated mix was used.

Figure 37 shows that this parameter did a good job of providing a correlation between the level of segregation and the mean temperature difference determined from the infrared thermography. Two outliers are circled; both of these are from Project 6-2, which was the project with all of the contractor hand work. There are two values not shown (highly

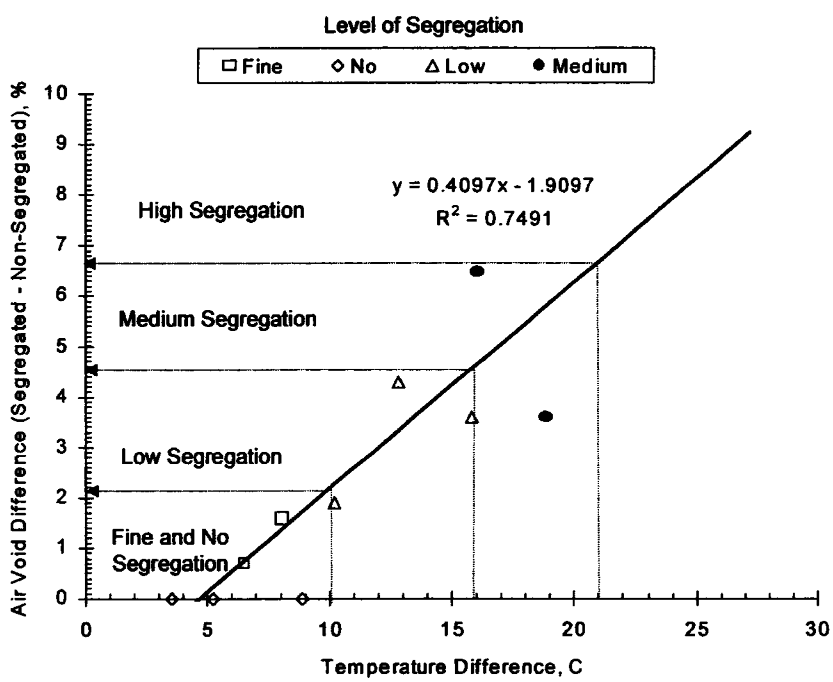

Figure 35. Relationship between temperature differences and changes in air voids.

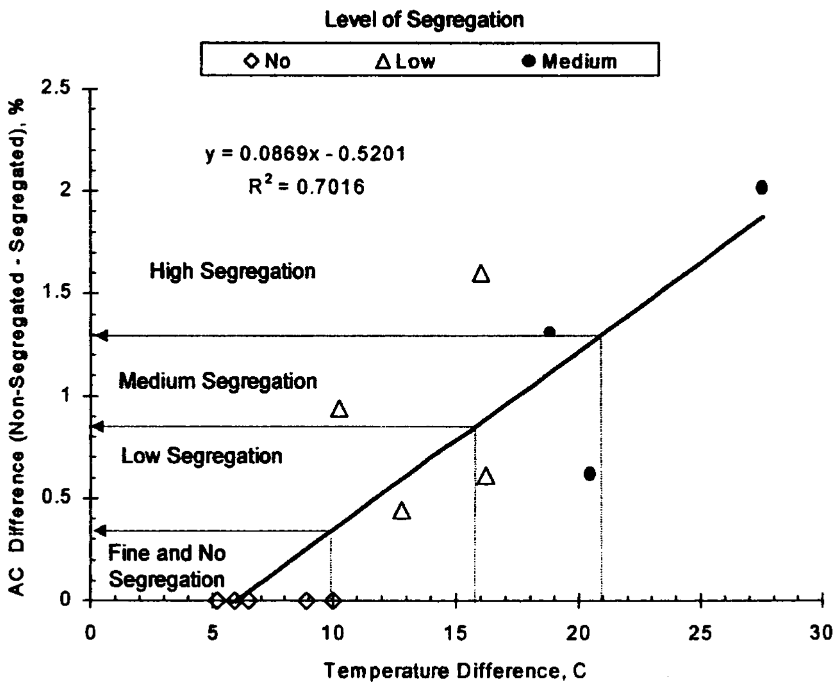

Figure 36. Estimated infrared temperature difference for a given level of asphalt content.

segregated areas) that signified their low stiffness by falling apart upon coring. These cores had temperature differences greater than 25°C. This figure shows that areas with fine or no segregation typically had resilient modulus ratios of 90 percent or greater and temperature differences of 10°C or less. Areas with low and medium segregation had stiffness values between 70 to 90 percent and 50 to 70 percent of the nonsegregated areas, respectively. These changes in stiffness agree with the information presented in the Background section (Chapter 2), which suggested that there was a loss of about 50 percent of stiffness with a 10 percent change in the percent passing coarser sieve size(s). This level of gradation change would correspond with the designation of "medium" segregation.

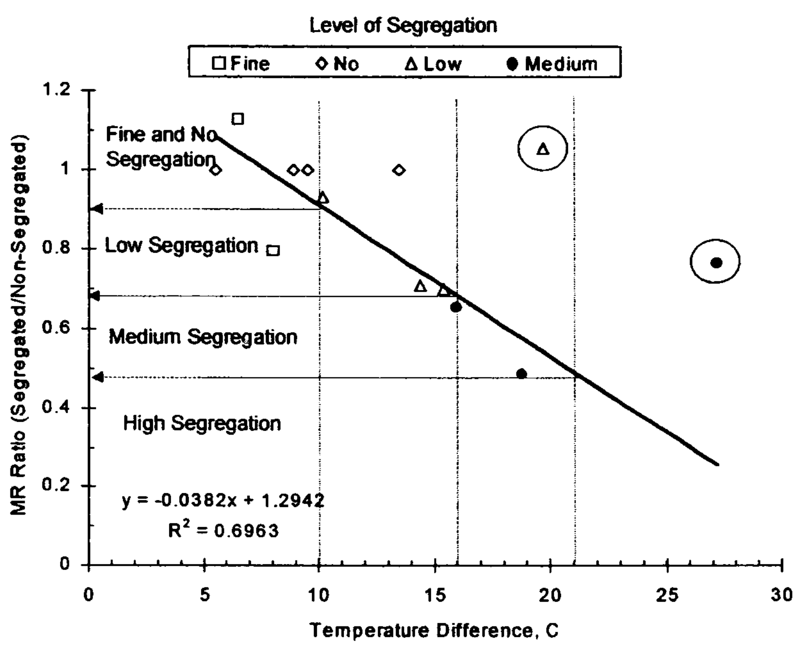

Figure 37. Correlation between infrared temperature differences and loss of stiffness due to segregation.

Temperature differences between 10°C and 16°C indicate a low level of segregation, while a difference between 17°C and 21°C is associated with a medium level of segregation. Mixtures with changes greater than 21°C signify highly segregated mixtures. For this relationship, the levels of segregation include both gradation and temperature segregation, because either type will influence mixture stiffness.

3.3 LASER SURFACE TEXTURE MEASUREMENTS

3.3.1 Research Program

The objectives of this portion of the research were to

- Evaluate ROSAN$_v$ laser surface texture measurements as a means of quantifying segregation and
- Confirm that changes in surface texture correspond with changes in key performance-related volumetric and mixture properties.

3.3.2 Analysis

The macrotexture of a pavement surface will depend primarily on the maximum size of aggregate, the aggregate shape (e.g., crushed or rounded), and the gradation (e.g., percent of fines). Therefore, the expected nonsegregated texture should vary between projects given that all of these factors will also differ, at least somewhat. In order to compare all of the field project data, a parameter independent of the mix properties was needed. After an examination of all of the data, the assumption was made that, although the texture may vary, the change in texture caused by segregation should be proportional. That is, the ratio of texture for a given level of segregation to that in the nonsegregated areas should be consistent.

Table 38 shows these ratios for all of the projects tested. The average ratio for low-to-no segregation is 1.36, and 1.76 and 2.59 for medium-to-no and high-to-no segregation, respectively. The standard deviations associated with each ratio are 0.15, 0.22, and 0.42, respectively. A t-test shows that these means are statistically different, and an F-test shows that the standard deviations between adjacent levels of segregation are not different. They are, however, different between low-to-no and high-to-no segregation.

3.3.2.2 Air Voids

The difference in air voids between each level of segregation and the voids in the nonsegregated areas is used as a single project-independent parameter. Figure 38 shows using an upper limit of 1.36 plus two standard deviations for the low-to-no texture ratio limit corresponding with an increase in air voids resulting from segregation of about 2.5 percent. An upper limit of 2.2 for the medium-to-no texture ratio shows the air voids are expected be mostly between 2.5 and 5.5 percent higher. There is only a limited amount of data for the voids in the highly segregated areas because these cores usually fell apart upon coring.

3.3.2.2 Asphalt Cement Content

Asphalt content decreases with increasing levels of segregation. This agrees with the findings of other researchers, who found that if the HMA is properly mixed, segregation will be seen as a change in asphalt content (*8, 17*). This results from the decrease in aggregate surface area with increasing coarseness. Decreasing percent passing the coarse 12.5- and 9.5-mm sieves showed a strong correlation with decreasing asphalt content for all projects with segregation problems. Consequently, decreases in asphalt content were used to represent statistically significant decreases in at least one of the coarse sieve sizes. The average asphalt content was determined for each level of segregation and the difference in asphalt content between nonsegregated and segregated areas was used as the single project-independent parameter to represent increasing levels of coarseness.

Figure 39 also uses the same limits of 1.6 and 2.2 for the upper low-to-no and medium-to-no texture ratios as suggested by the change in air voids. This figure shows that asphalt content in areas with low segregation is expected to be as much as 0.75 percent lower than the asphalt content in the nonsegregated areas. The asphalt content will be between 0.75 and 1.4 percent lower in areas with medium segregation.

3.3.2.3 Resilient Modulus

Resilient modulus (mix stiffness) is expected to be highly dependent on the binder stiffness and, to a lesser extent, the aggregate gradation. The assumption was that, although the magnitude may be project-dependent, the relative change in modulus because of segregation should be consistent. Therefore, a ratio of stiffness in the segregated areas to that in the nonsegregated area was used as a single project-independent parameter.

Figure 40 shows that the same upper limits of 1.6 and 2.2 texture ratios for separating low and medium levels of segregation also separated mix stiffness (25°C) ratios very well. Mixtures with low levels of segregation should have a mix stiffness of between roughly 65 and 100 percent of the nonsegregated stiffness. Medium segregation results in a mix stiffness of only about 25 to 65 percent of the nonsegregated stiffness. Pavement areas with high levels of segregation indicated their very low stiffness by falling apart.

These initial limits were adjusted so that there is a reasonable sharing of buyer's (accepting segregated material) and seller's (rejecting acceptable material) risk. Figure 41 shows normal distributions for the no, low, medium, and high levels of segregation for Project 1-1. A texture ratio of 1.17 evenly shares the buyer's and seller's risk with each having a possibility of accepting 30 percent low segregation or rejecting about 30 percent of acceptable material. Ratios of 1.56 and 2.09 similarly split the risk at about 36 and 27 percent for the upper limits for low and medium segregation, respectively.

Figure 41 also shows limited distributions obtained from one SMA project. Although the laboratory evaluation of cores from this project did not indicate the flushing observed on this

TABLE 38 Ratios of mean texture depths

Project	Dist. from Centerline, Meters	MPD for No Segregation, mm	Ratio of Texture: Segregated Areas to No Segregation		
			Low : No	Medium : No	High : No
Project 1-1	0.9	0.2974	1.512	2.286	3.234
	1.8	0.4928	1.269	1.779	2.589
	2.7	0.2361	1.343		
Project 1-2	0.9	0.2213	1.478		
	1.8	0.1134	1.824		
	2.7	0.1867	1.404		
Project 2-1	0.9	0.4717			
	1.8	0.4781			
Project 2-2	0.9	0.5693			
	1.8	0.5078	1.307		
	2.7	0.4533	1.397		
Project 3-1	0.9	0.4178			
	1.8	0.6473	1.462		
	2.7	0.8192	1.290		
Project 3-2	0.9	0.2889	1.582		
	1.8	0.2937	1.208		
	2.7	0.3046	1.310		
Project 4-1	0.9	0.2028			
	1.8	0.2126			
	2.7	0.2492	1.155		
Project 4-2	0.9	0.7121	1.292		
	1.8	0.4939	1.329		
	2.7	0.5139	1.315		

TABLE 38 ***(Continued)***

Project	Dist. from Centerline, Meters	MPD for No Segregation, mm	Ratio of Texture: Segregated Areas to No Segregation		
			Low : No	Medium : No	High : No
Project 6-1	0.9	0.9168	1.157	1.664	2.480
	1.8	0.6675	1.396	1.723	2.147
	2.7	1.0330	1.178	1.546	2.182
Project 6-2	0.9	0.9640	1.251	1.652	
	1.8	0.6884	1.380	1.707	
	2.7	1.0088	1.361	1.736	2.913
Project 7-1	0.9	0.3665	1.206		
	1.8	0.3472	1.204		
	2.7	0.2736	1.424		
Project 7-2	0.9	0.3858	1.416		
	1.8	0.2984	1.385		
	2.7	0.2698	1.427		

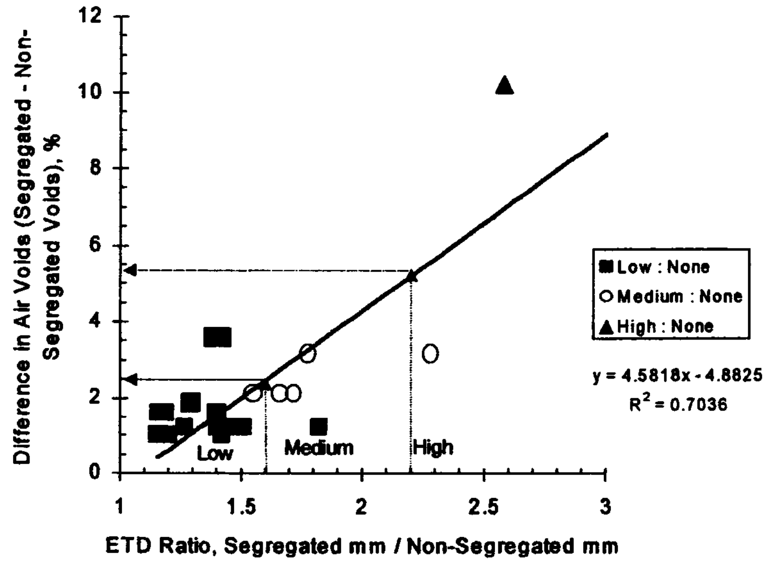

Figure 38. Relationship between changes in air voids and texture ratios.

project resulted from any type of segregation, it did allow a preliminary definition of limits for flushing. Tentative texture ratio limits were set at 0.74 and 0.28 for the upper limits of low and medium levels of flushing. These limits need further field testing before they should be used in any specification.

3.3.3 Comparison of Findings with Ministry of Ontario Specification

The Ministry of Ontario recently implemented an amended specification, OPSS 313 (Special Provision 103S38, April 1999), which used a ratio of surface textures as determined by the sand patch test to identify segregated areas of the pavement (*6*). Table 39 compares the results from this research project with those being used in Canada. The texture ratios from both sources are very close and provide an independent confirmation of both the findings for using the ROSAN$_v$ for detecting and measuring segregation and the specification limits in use by the Ministry of Ontario.

Major advantages to using the ROSAN$_v$ laser system instead of the sand patch test include reduced testing time

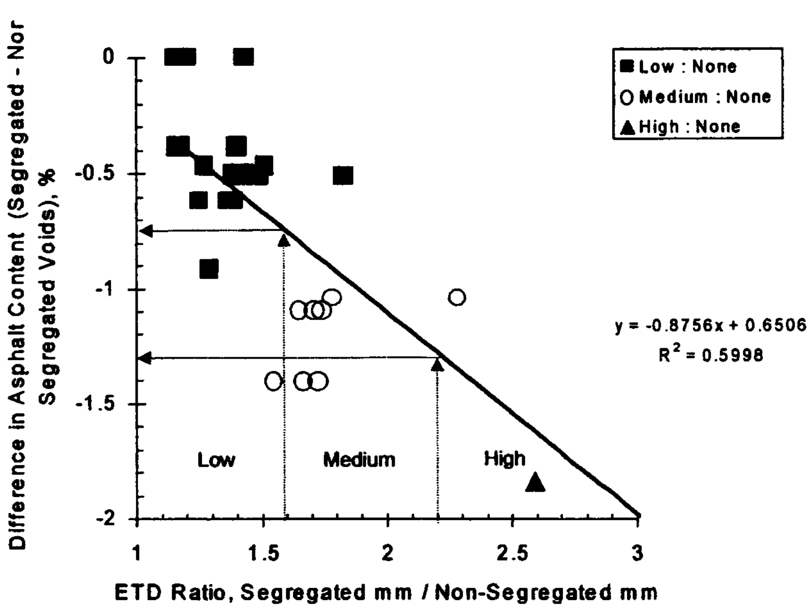

Figure 39. Relationship between changes in asphalt content (used to represent changes in coarse sieve sizes) and texture ratios.

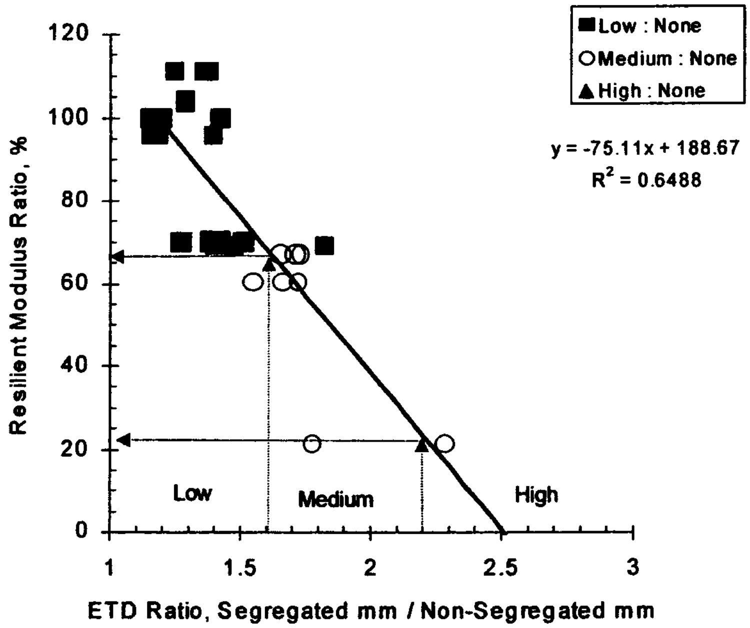

Figure 40. Relationship between stiffness and texture ratios.

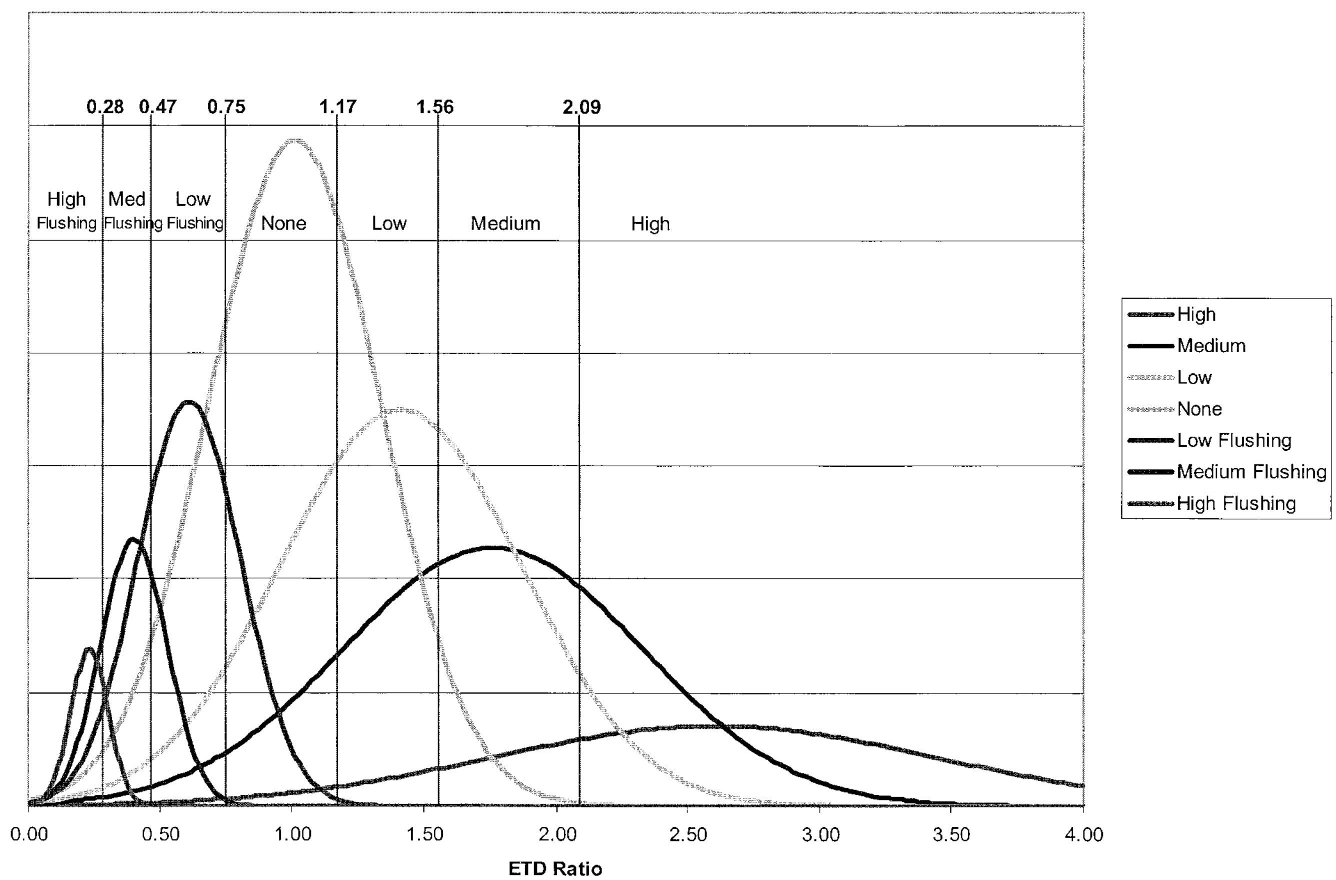

Figure 41. Assessment of buyer's and seller's risk.

TABLE 39 Comparison of NCHRP 9-11 Findings and OPSS 313

Mix Type	Texture Ratios		
NCHRP 9-11			
	Low : No	Medium : No	High : No
Applicable for All Mixes	1.17 to 1.56	1.57 to 2.02	> 2.02
OPSS 313 Special Provision No. 103S38 (Ministry of Ontario)			
	Slight Segregation	Med. Segregation	Severe Segregation
HL Mixes (except HL 1 in.) RHM, MDBC	< 1.9	1.9 to 2.5	> 2.5
HDBC	<1.8	1.8 to 2.6	> 2.6
DFC / HL 1 in.	<1.6	1.6 to 2.2	> 2.2

through automation of data collection and analysis, reduced costs because lane closures are not needed for testing, and improved worker safety.

3.3.4 Practical Application of Ratios

Although these ratio ranges are well correlated with changes in air voids, gradation (asphalt content), and mix stiffness, developing the data used to set these limits was time consuming. All of the individual databases for each longitudinal path had to be hand sorted and the visual observations used to confirm the data groupings. This analysis approach is not very useful for day-to-day use of this technology, so a simpler methodology was developed.

The development of a simplified method started with calculating an equation for predicting the anticipated texture for the nonsegregated areas from JMF gradation information. Several single and multiple linear regressions (forward step-wise) were conducted for predicting texture. Parameters included the maximum size of aggregate, the percent passing the 4.75 mm sieve, the coefficient of curvature, the coefficient of uniformity, and the log transformed coefficients of curvature and uniformity. Table 40 shows selected results from these analyses. The final equation ($r^2 = 0.65$) selected to predict the mean texture was

$$ETD = 0.01980\ (\text{Max. agg. size}) - 0.004984\ (\%\ \text{passing 4.75 mm}) + 0.1038\, C_c - 0.004861\, C_u$$

where:

C_c = Coefficient of curvature
C_u = Coefficient of uniformity

Once the ratio limits have been set, on the basis of a predicted texture depth, the analysis of the data can be handled completely by the software (with minor programming changes) rather than having to process the data manually. Suggested changes to the software would process the raw data files as follows:

1. The first screen would require that the aggregate information be input along with the other $ROSAN_v$ requirements. This will be used to predict the texture in the nonsegregated areas.
2. The limiting ratios for low (1.17 ≤ to ≤ 1.56), medium (1.57 ≤ to ≤ 2.02), and high (>2.20) levels of segregation will be used to set the ranges of textures for these levels of segregation.
3. The operator would collect texture measurements over the desired section of pavement using a baseline of 500 mm.
4. The software will then determine the number of data points within each range. The number of data points divided by the total number of points provides an estimate of the percentage of the longitudinal path with no, low, medium, and high levels of segregation.

TABLE 40 Results of single and multiple linear regressions

Regression Equation	Regression Constants				
	a_1	a_2	a_3	a_4	r^2
Max. Size	0.01174				0.07
% Pass. 4.75 mm	-0.01868				0.39
C_c	0.0616				0.42
C_u	0.004827				0.27
Max. Size, % Pass. 4.75 mm	-0.018128	0.00938			0.44
Max. Size, C_c	0.01963	0.0672			0.55
Max. Size, % Pass. 4.75 mm, C_c	-0.009281	0.01418	0.0502		0.62
Max. Size, % Pass. 4.75 mm, C_c, C_u	-0.004984	0.01980	0.1038	0.004861	0.65

Figure 42 shows an example using this approach with the data obtained from testing the longitudinal path nearest the centerline of Project 1-1. The predicted ETD for the nonsegregated areas was 0.35. The ratios of 1.17, 1.56, and 2.09 were used to set upper limits on textures of 0.41, 0.55, and 0.73 mm for no, low, and medium levels of segregation. A lower texture ratio limit of 0.75 was also set. In this example, 30 percent of the longitudinal path has no segregation. Twenty-two percent has a low level of segregation, while there is about 10 percent each of medium and high segregation. Twenty-seven percent of the pavement has a fine texture. This is reasonable given that the fine material missing in the segregated areas would have to be concentrated somewhere else.

These results agree very well with the visual observations. Figure 17 shows that about 20 and 26 percent of this path should have high and medium levels of segregation, respectively. Although these percentages are higher than those estimated with the $ROSAN_v$ system, the research indicated visual observations tended to overestimate the level of segregation. Therefore, the $ROSAN_v$ analysis appears to be reasonable.

According to the $ROSAN_v$ another 7 percent should have low segregation, while there will be about 47 percent of the mat with no segregation. Given that the visual observations did not distinguish between no segregation and finely segregated mix, it is assumed that the visual observations of “no segregation” will also include the finely segregated mix.

An alternative approach would be to identify an area of the pavement with visually acceptable textures and then use the $ROSAN_v$ equipment to determine the average texture. This value could then be entered as the nonsegregated value for calculating ratios.

3.4 AGENCY COST OF SEGREGATION

This section presents an example of how the agency cost of segregation can be estimated. In the preceding section, agency staff from each of the host state agencies were asked to estimate the loss of pavement life caused by segregation. Responses varied from 2 to 7 years’ reduction in an anticipated 15-year life. A subjective observation of this small survey suggests that segregation in the finer mixtures has less of an effect on the pavement life than areas with coarser, larger top-size aggregate mixtures. Life cycle cost analyses for various alternatives were conducted to assess the cost to the agency as the result of segregation. *All calculations are based on a per lane-mile basis.*

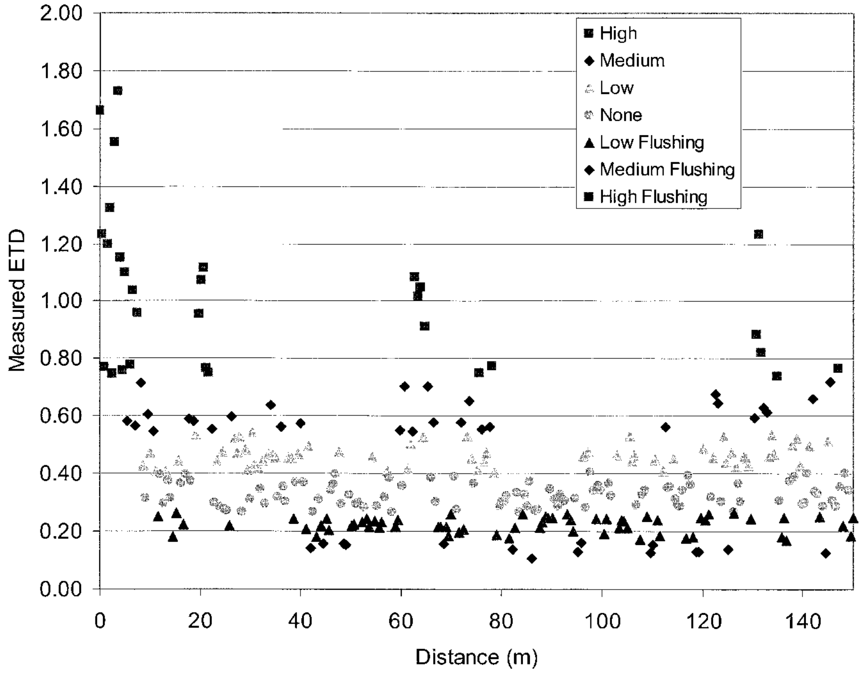

Figure 42. Example of how data would be sorted using ratio-determined texture limits.

3.4.1 Initial Construction Assumptions

The original construction was a 100-mm (4-in.)-thick 12.5-mm Superpave overlay placed on a two-lane section of highway with an ADT of 20,000. The cost of the HMA was set at $38/ton and traffic control and user costs were arbitrarily set at $10,000.

3.4.2 Rehabilitation Strategies

Because of the severity and frequency of the distresses and the moderately high traffic volumes, only two strategies were considered: (1) mill and replace and (2) full-depth patching with a new overlay.

3.4.2.1 Mill and Replace with HMA

The distressed 50-mm overlay will be milled ($5/yd^2) and replaced with the same mix as originally used. The original traffic costs (i.e., $7,500) will increase because of the longer time needed for the additional step of milling ($10,000).

3.4.2.2 Patch and Overlay with HMA

Full-depth (50-mm) patches will be used to repair the distressed areas. The area of each patch is assumed to be the full lane width and 30 ft in length. Segregation-related distressed areas occur every 150 ft for a total of 35 patches per mile. The cost of patching is assumed to be $1.50/ft^2. The original traffic costs (i.e., $7,500) will increase because of the longer time needed for the additional step of cutting and patching ($10,000).

3.4.3 Comparison of Strategies

A present-worth analysis using a discount rate of 4 percent and an analysis period of 15 years was used to estimate the cost of segregation (shown in Tables 41 and 42). Given that 2 years was the lowest decrease in pavement life caused by segregation estimated by any state agency, it is assumed that this would correlate with a low level of segregation. The effect on the present worth cost for this level of segregation can then be estimated as an increase of 8 to 13 percent of the cost of the original HMA (no segregation option), depending on the rehabilitation strategy. If medium segregation is assumed to result in about a 5-year loss of pavement life, then the agency cost is an increase of between 22 and 30 percent of the original cost. The cost is between 37 and 46 percent assuming a high level of segregation relates to a 7-year loss of pavement life.

3.4.4 Suggested Pay Factors

The pavement condition survey and discussions with state agency staff indicated that when segregation leads to a loss of pavement life, localized maintenance strategies (e.g., patch-

TABLE 41 Cost of segregation (assuming mill and replace strategy)

Work to Be Performed	PW Information		No Segregation		2-Year Loss of Life		5-Year Loss of Life		7-Year Loss of Life	
	Time, yr.	$1/(1+i)^n$	Cost	PW	Cost	PW	Cost	PW	Cost	PW
Overlay	0	1	$58,468	$58,468	$58,468	$58,468	$58,468	$58,468	$58,468	$58,468
Traffic Control	0	1	$7,500	$7,500	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000
Mill	7	0.760	0	0	0	0	0	0	$70,400	$53,498
Overlay	7	0.760	0	0	0	0	0	0	$58,468	$44,430
Traffic Control	7	0.760	0	0	0	0	0	0	$10,000	$7,599
Mill	10	0.676	0	0	0	0	$70,400	$47560	0	0
Overlay	10	0.676	0	0	0	0	$58,468	$39,499	0	0
Traffic Control	10	0.676	0	0	0	0	$10,000	$6,755	0	0
Mill	13	0.601	0	0	$70,400	$42,280	0	0	0	0
Overlay	13	0.601	0	0	$58,468	$35,114	0	0	0	0
Traffic Control	13	0.601	0	0	$10,000	$6,005	0	0	0	0
Mill	14	0.577	0	0	0	0	0	0	0	0
Overlay	14	0.577	0	0	0	0	0	0	0	0
Traffic Control	14	0.577	0	0	0	0	0	0	0	0
Mill	15	0.555	$70,400	$39,090					0	
Overlay	15	0.555	$58,468	$32,450					0	
Traffic Control	15	0.555	$10,000	$5,550					0	
Salvage	15	0.555	($68,468)	($38,000)	($59,338)	($32,949)	($45,645)	($25,345)	($36,516)	($20,276)
Sum of Present Worth Cost for Each Case				$105,059		$118,920		$136,937		$153,720

TABLE 42 Cost of segregation (assuming patch and overlay strategy)

Work to Be Performed	PW Information		No Segregation		2-Year Loss of Life		5-Year Loss of Life		7-Year Loss of Life	
	Time, yr.	$1/(1+i)^n$	Cost	PW	Cost	PW	Cost	PW	Cost	PW
Overlay	0	1	$58,468	$58,468	$58,468	$58,468	$58,468	$58,468	$58,468	$58,468
Traffic Control	0	1	$7,500	$7,500	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000
Patch	7	0.760	0	0	0	0			$38,016	$28,889
Overlay	7	0.760	0	0	0	0			$58,468	$44,431
Traffic Control	7	0.760	0	0	0	0			$10,000	$7,599
Patch	10	0.676	0	0	0	0	$38,016	$25,682	0	0
Overlay	10	0.676	0	0	0	0	$58,468	$39,499	0	0
Traffic Control	10	0.676	0	0	0	0	$10,000	$6,755	0	0
Patch	13	0.601	0	0	$38,016	$22,831	0	0	0	0
Overlay	13	0.601	0	0	$58,468	$35,114	0	0	0	0
Traffic Control	13	0.601	0	0	$10,000	$6,005	0	0	0	0
Patch	14	0.577	0	0	0	0	0	0	0	0
Overlay	14	0.577	0	0	0	0	0	0	0	0
Traffic Control	14	0.577	0	0	0	0	0	0	0	0
Patch	15	0.555	$38,016	$21,953	0	0	0	0	0	0
Overlay	15	0.555	$58,468	$33,761	0	0	0	0	0	0
Traffic Control	15	0.555	$10,000	$5,775	0	0	0	0	0	0
Salvage	15	0.555	0	0	($59,338)	($32,949)	($45,645)	($25,345)	($36,516)	($20,276)
Sum of Present Worth Cost for Each Case				$94,477		$99,471		$115,060		$129,111

ing) are not used; pavements are overlaid or reconstructed. Therefore, payment for any lot with evidence of segregation should be on the basis of the properties of the segregated areas **only**, because these areas will control the life of the entire lot. Alternatively, the contractor can opt to remove and replace the segregated areas.

Based on the life cycle cost estimates, a pay factor of 90 percent, which represents an average of both strategies, for pavements with a low level of segregation would be reasonable. One of the expected properties of areas with low levels of segregation is an average increase in air voids of 2 percent. Although density-based pay factors cover a wide range of values, 90 percent pay for pavements with 10 percent voids is not unusual. This would agree with the recommended pay factor for low levels of segregation.

An appropriate pay factor for a medium level of segregation would be 80 percent. The increase in air voids for this level of segregation is expected to be an average of 4 percent. Although this pay factor represents an extreme value, it is not inconsistent with pay factors for pavements with 12 percent air voids. Areas of pavement with a high levels of segregation should be removed and replaced.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 DEFINITIONS

Two types of segregation were identified in the initial literature review: gradation segregation and temperature segregation. Gradation segregation is the most commonly identified type and can occur as the result of aggregate stockpiling and handling, production, storage, truck loading practices, construction practices, and equipment adjustments. Temperature segregation was identified in the literature as occurring as the result of differential cooling of portions of the mix on the surface of the mix in the haul truck, along the sides of the truck box, and in the wings of the paver. An additional type, aggregate-asphalt segregation, common in SMAs, was also suggested. Segregation is defined as a lack of homogeneity in the hot-mix asphalt constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es). "Constituents" should be interpreted to mean asphalt cement, aggregates, additives, and air voids.

Laboratory testing of both cores and laboratory-prepared samples resulted in the development of definitions of levels of segregation based on expected changes in key mixture properties:

- Areas with *no segregation,* assuming that proper mix design and compaction are attained, will have the following: acceptable air voids; at least 90 percent of the anticipated mix stiffness; an asphalt content within 0.3 percent of the JMF; and no statistical difference in the percent passing any of the coarse sieve sizes.
- Areas with low-level segregation will have a mix stiffness of between about 70 and 90 percent of the nonsegregated areas and increased air voids of between 0 and roughly 4 percent. If gradation segregation is present, at least one sieve size will be at least 5 percent coarser and there will be a corresponding decrease in asphalt content between 0.30 and 0.75 percent.
- Areas with a medium-level segregation will have a mix stiffness of between roughly 30 and 70 percent of the nonsegregated areas and increased air voids of between 2 and 6 percent. If gradation segregation is present, at least two sieve sizes will be at least 10 percent coarser and there will be corresponding decreased asphalt contents between 0.75 and 1.30 percent.
- Areas with high-level segregation will have a mix stiffness of less than 30 percent of the nonsegregated areas and increased air voids of more than 4 percent. If gradation segregation is present, at least three sieve sizes will be at least 15 percent coarser and there will be corresponding decreased asphalt contents of greater than 1.3 percent. Cores will tend to fall apart upon coring or cutting.

4.2 CONCLUSIONS FOR TECHNOLOGIES

4.2.1 Rolling Nuclear Density Measurements

Changes in density with levels of segregation tend to be variable and only statistically significantly different when the level of segregation is medium or high. This means that technologies that only measure density changes will also have difficulty in discerning differences between each level of segregation. Testing with the Seaman DOR nuclear density gauge confirmed this conclusion.

In evaluating field test sections during construction, this technology proved useful in identifying a second, construction-process-produced cause of temperature segregation. When the paver stops for an extended time, the mix immediately behind the screed cools. Even if the roller operator is staying close to the paver, the mat in this area cannot be rolled because the paver is in the way. Once the paver starts to move again, the roller operator compacts this cool region with the same amount of effort as the fresh, hot mix. The end result is a transverse strip of very low density.

In summary, the DOR gauge is not generally useful for detecting and measuring all levels and types of segregation; however, it is very well suited for developing a longitudinal density profile that can then be used to identify a specific category of temperature segregation.

4.2.2 Infrared Thermography

This technology can be used to detect and measure each level of segregation; however, it cannot distinguish between gradation and temperature segregation types.

This technology can be used to survey each lot. In any lot of HMA, several repeated, but not necessarily cyclically occurring, areas having a temperature differential of 11°C to 16°C, constitute evidence of low levels of segregation, and pay adjustments should be made accordingly. Any lot with several repeated, but not necessarily cyclically occurring, areas having a temperature differential of 17°C to 20°C has a medium level of segregation, and the entire lot should be paid for accordingly. Isolated areas with temperature differentials (either low or medium levels of segregation) should be repaired or removed and replaced if full pay is expected. Areas with temperature differentials greater than 20°C should be removed and replaced. If a definition of the type of segregation is desired, cores can be taken from each of the temperature regions and tested to determine changes in air voids, asphalt content, and aggregate gradations.

This technology can also be used to estimate the percent and level of segregation in a given area of the pavement mat. At this time, this approach requires two people and a rigorous software analysis of each infrared thermal photograph. While useful for research purposes, use of the technology needs further equipment and automation development before it is ready and affordable for general implementation.

This technology could be used to develop a percent uniformity measurement for each lot—assuming that a continuous method of estimating the temperature differentials during construction can be developed. For example, an infrared sensor bar (discrete sensors rather than image presentation) mounted roughly 150 mm behind the paver screeds could be used to determine the temperature every 150 mm transversely and every 300 mm longitudinally. The temperature readings could be collected and displayed on a computer mounted next to the paver operator. This would provide agencies with a record of the uniformity of the entire construction project. It would also provide a means of process control for contractors during construction.

4.2.2.1 Recommendations

This technology can be used to inspect the uniformity of the mat during construction or to estimate the percent of the mat that is at a particular level of segregation.

Inspection. The immediate use for this technology is in the during-construction inspection of a paving project. The infrared camera should be used to survey the pavement mat behind the paver. Areas of the mat with temperatures between 10°C and 16°C, 17°C and 21°C, and greater than 21°C cooler than the maximum temperature seen in the photograph should be marked as areas from which to obtain cores. Laboratory testing of the cores should be used to determine the type and extent of the segregation.

Materials in these areas have properties that are statistically different than most of the mat and should not be included in the normal random sampling plan for acceptance testing. Samples from each temperature group should be considered a separate population. Differences in mix properties for each group should be compared with the appropriate specification limits (i.e., density, voids, gradation, and asphalt content) and pay factors for these areas set accordingly.

Estimates of Levels of Segregation. Two people are required to obtain the data for this type of analysis. One person is located on the back of the paver deck with the infrared camera. The second person is positioned on the ground immediately behind the paver with a distance measurement device. This person signals the camera operator to take an infrared photograph every 10 m (33 ft). At the end of the testing, the infrared camera software is used to convert the mat area in each photograph into temperatures per pixel. A spreadsheet analysis program can then be used to normalize the data, so that there are an equal number of temperatures per row, and then to develop the histogram of the temperatures. This histogram can be used to determine the percent of each photograph with no, low, medium, and high levels of segregation. An Excel macro program developed by NCAT staff can be used for this analysis. The code for this macro can be can be obtained from NCAT.

4.2.3 ROSAN$_v$ Surface Texture Measurements

This technology can be used to detect and measure each level of gradation segregation and aggregate-asphalt segregation, because both of these types alter the surface texture characteristics of the pavement. This technology cannot be used to detect any of the types of temperature segregation.

Ratios of the texture in segregated areas to that in nonsegregated areas were set on the basis of statistically different key mixture properties. Texture ratios between 0.75 and 1.15 indicate no segregation, between 1.16 and 1.56 are associated with a low level of segregation, and between 1.57 and 2.09 are associated with medium segregation. Ratios above 2.09 indicate high levels of segregation. Ratios indicating various levels of flushing were also suggested, but the limited amount of data available for evaluating this type of segregation precluded any firm limits being set.

A practical approach for using a spreadsheet program to analyze the raw ROSAN$_v$ laser data was developed to help reduce the amount of time and subjectivity of the analysis. The result of this methodology is an estimate of the percentage of the longitudinal path with each level of segregation. This technology and analysis approach is ready to be implemented immediately by state agencies.

4.3 SPECIFICATIONS

Two technologies can be used to detect and measure various levels of segregation: infrared thermography and ROSAN$_v$ surface texture measurements. Proposed specification formats for each are shown in Appendixes I and J. The test methods

TABLE 43 Summary of specification limits and expected corresponding mixture changes

Mixture Property	Percent of Non-Segregated Mix Property by Level of Segregation			
	None	Low	Medium	High
Range of Temperature Differences, °C	<10	10 to 16	17 to 21	> 21
Surface Texture Ratios	< 1.16	1.16 to 1.56	1.57 to 2.09	> 2.09
Change in Mix Properties Expressed as a % of the Properties in the Non-Segregated Areas				
Permeability	Increased slightly	Increasing with level of coarse segregation		
Resilient Modulus[1]	Little or slightly increasing stiffness	70 to 90%	50 to 70% (infrared) 30 to 80% (laser)	< 50% (infrared) < 30% (laser)
Dynamic Modulus	Little or slightly increasing stiffness	80 to 90%	70 to 80%	50 to 70%
Dry Tensile Strength	110%	90 to 100%	50 to 80%	30 to 50%
Wet Tensile Strength	80 to 90%	75%	50%	30%
Low Temperature Tensile Stress	No conclusions due to test method difficulties			
Loss of Fatigue Life when Segregation in Upper Lifts, %	Not Estimated	38%	80%	99%
Rutting Potential	Not strongly influenced by gradation segregation until a high level of segregation is seen			
Difference in Values Between Segregated and Non-Segregated Areas				
Gradations Minimum number of sieve sizes that are given % coarser	NA	1 sieve > 5%	2 sieves > 10%	4 sieves > 15%
Change in Air Voids, %	NA	2.5 to 4.5% (infrared) 0 to 2.5% (laser)	4.5% to 6.5% (infrared) 0 to 2.5% (laser)	> 6.5% (infrared) > 4% (laser)
Change in Asphalt Content, %	NA	-0.3 to -0.75%	-0.75 to -1.3%	> 1.3%

[1]Reflects results from testing both cores and laboratory-prepared samples

required for each specification are presented in AASHTO format in Appendixes K and L. Table 43 summarizes the proposed specification limits for both technologies and the corresponding changes in key mixture properties that can be expected at a given level of segregation.

4.4 RECOMMENDATIONS FOR CONTINUED RESEARCH

Recommendations are as follows:

- Further field testing is recommended of SMA pavements so that the lower limits for low, medium, and high levels of flushing can be set for the $ROSAN_v$ surface texture measurement specification.
- Further field testing is recommended of SMA pavements so that the applicability of the infrared technology to detect asphalt rich areas can be confirmed.
- Infrared thermography is an excellent inspection tool for identifying anomalous areas that require additional conventional testing. Further development is needed before infrared thermography can be used as a reliable specification. The development of a temperature sensor bar with a distance measurement system and a real-time computer output for the paver operator's use would greatly enhance the acceptance of this approach to detecting and measuring segregation.

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APPENDIXES A THROUGH H

UNPUBLISHED MATERIAL

Appendixes A through H contained in the research agency's final report are not published herein. For a limited time, these appendixes will be available on a loan basis or for purchase ($30.00) on request to NCHRP, Transportation Research Board, Box 289, Washington, D.C., 20055.

Appendix A: Projects 1-1 and 1-2

Appendix B: Projects 2-1 and 2-2

Appendix C: Projects 3-1 and 3-2

Appendix D: Projects 4-1 and 4-2

Appendix E: Projects 5-1 and 5-2

Appendix F: Projects 6-1 and 6-2

Appendix G: Projects 7-1 and 7-2

Appendix H: Purdue University Test Results

APPENDIX I

EXAMPLE SPECIFICATION FOR USING INFRARED THERMOGRAPHY TO DETECT AND MEASURE SEGREGATION

Section 1. Definitions.

Segregation: is the lack of homogeneity in the hot-mix asphalt constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es).

Constituents: include asphalt, aggregate, and air voids.

Temperature segregation: refers to portions of the mix with significantly different temperatures. This type of segregation can occur as the result of the surface of the mix cooling in the haul truck, cold mix in the paver wings getting raised immediately prior to the addition of fresh hot mix, and any anomalies in the paving operations that result in areas with significantly different temperatures.

Gradation segregation: is the separation of the coarse and fine aggregate fractions.

Sieves: Gradation results are based on using the following sieves in the analysis: 37.5, 25, 19, 12.5, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15 and 0.072 mm.

Low-level segregation: will have mix stiffness (resilient modulus) of between 70 and 90 percent of the mix in the nonsegregated areas; air voids will be up to 4 percent higher. When gradation segregation is present, there will be one or more sieves that are at least 5 percent coarser than the nonsegregated area with a corresponding decrease in asphalt content of between 0.3 and 0.75 percent.

Medium-level segregation: will have mix stiffness (resilient modulus) of between 30 and 70 percent of the mix in the nonsegregated areas; air voids will be between 2 and 6 percent higher. When gradation segregation is present, there will be two or more sieves that are at least 10 percent coarser than the nonsegregated areas with a corresponding decrease in the asphalt content of between 0.75 and 1.3 percent.

High-level segregation: will have mix stiffness (resilient modulus) of less than 30 percent of the mix in the nonsegregated areas; air voids will be more than 5 percent higher. When gradation segregation is present, there will be three or more sieves that are at least 15 percent coarser than the nonsegregated areas with a corresponding decrease in the asphalt content of more than 1.2 percent.

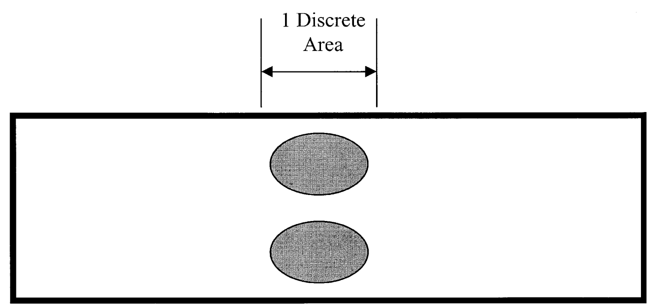
Section 2. Identification of Segregated Areas.

Discrete segregated areas (Figure I-1) will show up in infrared images taken immediately behind the paver during construction as obviously cooler areas when compared with the majority of the mat. The level of segregation will be defined as the difference in temperature between the area of interest and the average maximum temperature seen in the majority of the mat. These differences are shown in Table I-1.

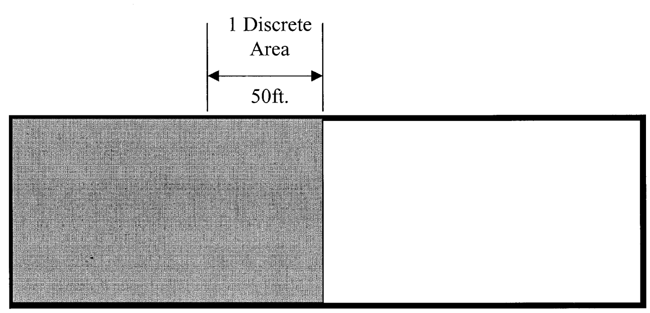
Section 3. Pay Factors and/or Correction of Segregation.

Areas with a low level of segregation will be assessed a pay adjustment factor at the discretion of the agency.

Areas with a medium level will either have a pay adjustment factor assessed, or the contractor will be required either to repair or to remove and replace the area. The choice of remedial action will be at the agency's discretion. When the choice is to remove the segregated area(s), the segregated areas(s), as well as 50 feet on either side of these areas, will be removed and replaced.



Patterns in Segregated Areas
(Typical of End-of-Paver)



Patterns in Segregated Areas
(Typical of Behind-the-Paver Low Density)

Figure I-1. Areas to test when significant temperature differentials are observed.

TABLE I-1 Identification of a discrete segregated area

No Segregation	Low Level Segregation	Medium Level Segregation	High Level Segregation
Area in the mat with temperatures 10°C or less of a difference between coldest and hottest temperatures	A discrete area in the mat with a mean temperature between 11 and 16°C cooler than the surrounding area	A discrete area in the mat with a mean temperature between 17 and 21°C cooler than the surrounding area	A discrete area in the mat with a mean temperature of more than 21°C cooler than the surrounding area

Areas with a high level of segregation will be removed and replaced. The areas to be removed and replaced will be the segregated areas and a minimum of 50 feet on either side of each area.

Section 4. Disputes.

Areas suspected of having a level of segregation other than "no segregation" can be marked during paving for additional testing. Each area marked shall be identified with the suspected level of segregation. Marked areas shall be grouped by the anticipated level of segregation for further testing. The inspector shall determine the number of cores to be taken from each group. Standard testing to determine density, air voids, asphalt content, and gradation shall be used to confirm the level and extent of segregation.

If the level of segregation indicated by the infrared measurements is confirmed by the laboratory testing of the cores, the cost of the coring and testing shall be paid by the contractor.

APPENDIX J

EXAMPLE SPECIFICATION FOR USING ROSAN$_v$ SURFACE TEXTURE MEASUREMENTS TO DETECT AND MEASURE SEGREGATION

Section 1. Definitions.

Segregation: is the lack of homogeneity in the hot-mix asphalt constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es).

Constituents: include asphalt, aggregate, and air voids.

Temperature segregation: refers to portions of the mix with significantly different temperatures. This type of segregation can occur as the result of the surface of the mix cooling in the haul truck, cold mix in the paver wings getting raised immediately prior to the addition of fresh hot mix, and any anomalies in the paving operations that result in areas with significantly different temperatures.

Gradation segregation: is the separation of the coarse and fine aggregate fractions.

Sieves: Gradation results are based on using the following sieves in the analysis: 37.5, 25, 19, 12.5, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15 and 0.072 mm.

Low-level segregation: will have mix stiffness (resilient modulus) of between 70 and 90 percent of the mix in the nonsegregated areas; air voids will be up to 4 percent higher. When gradation segregation is present, there will be one or more sieves that are at least 5 percent coarser than the nonsegregated area with a corresponding decrease in asphalt content of between 0.3 and 0.75 percent.

Medium-level segregation: will have mix stiffness (resilient modulus) of between 30 and 70 percent of the mix in the nonsegregated areas; air voids will be between 2 and 6 percent higher. When gradation segregation is present, there will be two or more sieves that are at least 10 percent coarser than the nonsegregated areas with a corresponding decrease in the asphalt content of between 0.75 and 1.3 percent.

High-level segregation: will have mix stiffness (resilient modulus) of less than 30 percent of the mix in the nonsegregated areas; air voids will be more than 5 percent higher. When gradation segregation is present, there will be three or more sieves that are at least 15 percent coarser than the nonsegregated areas with a corresponding decrease in the asphalt content of more than 1.2 percent.

Section 2. Identification of Segregated Areas.

Segregated areas will have textures either statistically coarser or finer than the texture in a nonsegregated area. The units for texture measurements shall be the estimated texture depth (ETD) as defined in ASTM E1845. This value uses the ROSAN$_v$ mean profile depth (MPD) to estimate the texture depth (i.e., ETD) obtained with the sand patch test (ASTM E965).

Section 2.1. Setting Limits for No, Low, Medium, and High Levels of Segregation.

Visually identify and mark an area of the mat with acceptable textures. Use the ROSAN$_v$ equipment to determine the average texture depth in this area. This value can be used to compute the texture ratios in the test sections. Alternatively the anticipated texture in a nonsegregated area can be estimated using information on the maximum aggregate size, percent passing the 4.75 mm sieve, and the coefficients of curvature and uniformity:

$$\text{Predicted ETD} = 0.01980\,(\text{max. agg. size}) - 0.004984\,(\%\text{ pass. } 4.75\text{ mm}) + 0.1038\,(C_c) - 0.004861\,(C_u)$$

Where:

Predicted ETD = estimated texture depth from sand patch test in mm
Max. Agg. Size = smallest sieve size with 100 percent passing.
% pass. 4.75 mm = the percent passing the 4.75 mm sieve
C_c = coefficient of curvature = $(D_{30})^2/(D_{10}\,D_{60})$
C_u = coefficient of uniformity = $D_{60}\,/\,D_{10}$
D_{10} = the sieve size, in mm, associated with 10 percent passing
D_{30} = the sieve size, in mm, associated with 30 percent passing
D_{60} = the sieve size, in mm, associated with 60 percent passing

Upper and lower texture limits used to detect and measure low, medium, and high levels of segregation are obtained by multiplying either the measured nonsegregated area texture or the predicted ETD by the appropriate factor from Table J-1. For example, a pavement surface will be considered to have

TABLE J-1 Factors for the predicted ETD for detecting and measuring various levels of segregation

Limit	Fine Level Segregation	No Segregation	Low Level Segregation	Medium Level Segregation	High Level Segregation
Lower	< 0.75	0.75	1.16	1.57	> 2.09
Upper	None	1.15	1.56	2.09	None

no segregation if all texture measurements are between 0.75 and 1.15 times the predicted texture.

Section 3. Extent of Each Level of Segregation.

One lot shall be 5,000 feet of one lane width. Each lot shall be subdivided into ten 500 foot sublots. Three sublots shall be randomly selected for testing. The MPD will be measured longitudinally at quarter points for lanes 12 feet and wider for each sublot tested (Figure J-1). The MPD will be measured longitudinally at third points for lanes less than 12 feet wide for each sublot tested. The modified $ROSAN_v$ software will determine the number of MPD measurements that fall within the limits for each level of segregation. The percent of each level of segregation in each sublot will be

$$\% \text{ Segregation} = \frac{\text{Number of data points within segregation limits}}{\text{Total number of data points}} \times 100$$

The number of data points at any given level of segregation will be the sum of the data points collected for all longitudinal passes conducted for each sublot. The percent of each level of segregation for the lot will be the average of sublot percentages for each level of segregation.

Section 4. Pay Factors and/or Correction of Segregation.

Areas with a low level of segregation or higher will be assessed a pay adjustment factor at the discretion of the agency.

Areas with a medium level either will have a pay adjustment factor assessed, or the contractor will be required either to repair or to remove and replace the area. The choice of remedial action will be at the agency's discretion. When the choice is to remove the segregated area(s), the segregated areas(s), as well as 50 feet on either side of these areas, will be removed and replaced.

Any areas with a high level of segregation will be removed and replaced. The areas to be removed and replaced will be the segregated areas and a minimum of 50 feet on either side of each area.

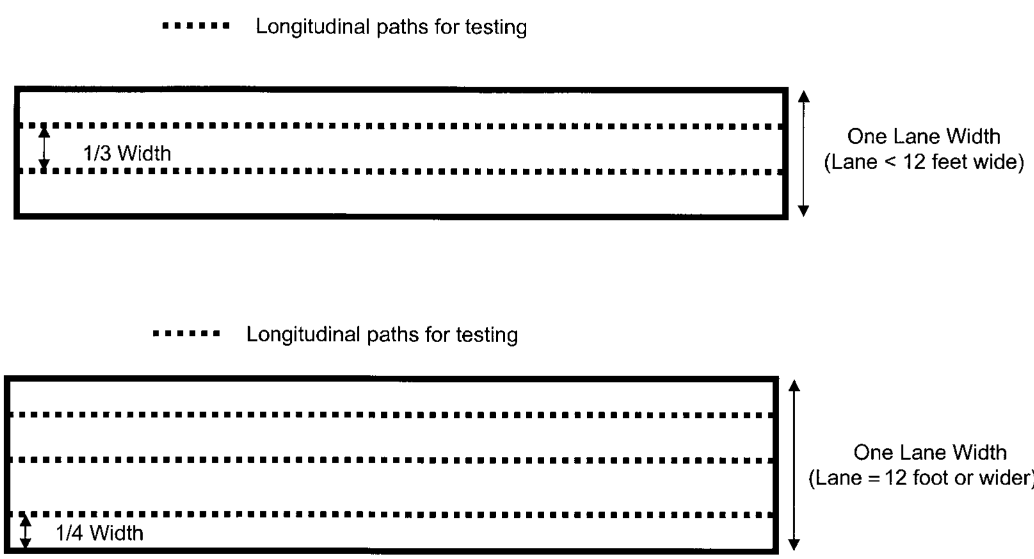


Figure J-1. Longitudinal paths for measurement for each sublot.

Section 5. Disputes.

All areas suspected of having a level of segregation other than “no segregation” shall be marked for additional testing. Each area marked shall be identified with the suspected level of segregation. Marked areas shall be grouped by the anticipated level of segregation for further testing. The inspector shall determine the number of cores to be taken from each group. Standard testing to determine density, air voids, asphalt content, and gradation shall be used to confirm the level and extent of segregation.

If the level of segregation indicated by the texture measurements is confirmed by the laboratory testing of the cores, the cost of the coring and testing shall be paid by the contractor.

APPENDIX K

PROPOSED DRAFT AASHTO PROVISIONAL STANDARD

STANDARD TEST METHOD FOR USING INFRARED THERMOGRAPHY TO IDENTIFY SEGREGATION IN HOT-MIX ASPHALT DURING PAVING OPERATIONS

MAY 1999

1. SCOPE

1.1 This test method covers the identification of areas of segregated hot-mix asphalt in a pavement mat immediately behind the screed. This test method is intended for use during construction.

1.2 This test method uses an imaging infrared camera capable of capturing thermal photographs to detect localized areas of cooler mix.

1.3 Infrared thermography can be used to mark non-uniform areas during construction for coring and testing. In conjunction with software analysis programs, it can be used to estimate the percent of low, medium, and high levels of segregation.

1.4 The values stated in degrees Celsius are to be regarded as the standard.

1.5 *This standard may involve hazardous materials, operations, and equipment. It does not purport to address all of the safety problems associated with its use. It is the responsibility of anyone using this practice to consult and establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.*

2. REFERENCED DOCUMENTS

2.1 AASHTO Standards

- T166 Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens
- T168 Sampling Bituminous Paving Mixtures
- T209 Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
- T269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures

2.2 ASTM

- ASTM PS 90 Asphalt Content of Hot Mix Asphalt by the Ignition Oven Method
- ASTM D4123 Indirect Tension Test for Resilient Modulus of Bituminous Mixtures

3. SIGNIFICANCE AND USE

3.1 *Inspection and marking of non-uniform areas.*

3.1.1 The inspector uses the infrared camera to identify areas in the mat that are more than 10°C cooler than the typical maximum temperature of the majority of the mat. When these areas are found, the inspector marks the area for coring and testing.

3.1.2 The type and degree of segregation in these is determined based on the laboratory testing of the cores.

3.2 *Estimating the extent of segregation.*

3.2.1 A person using a hand-held infrared camera with a wide-angle lens is positioned on the back of the paver deck. The camera is aimed so that the bottom of the viewfinder is positioned approximately 3 meters from the back of the screed. A second person on the ground uses a "fifth wheel" to mark off the distance traveled by the paver. Every 10 meters, the person on the ground signals the camera operator to take a thermal photograph of the paving operation.

3.2.2 When the camera operator notes an area in the viewfinder with a temperature more than 10°C cooler than the warmest temperature seen in the remainder of the image, he/she will signal the person on the ground to mark the area for further testing (coring). One or more of the following properties will be statistically different in these areas: air voids, asphalt content, aggregate gradation.

3.2.3 Given that these cooler areas will have statistically different properties, they should be excluded from standard random sampling plans that assume that materials are being collected from a single population.

3.2.4 Thermal images are processed with manufacturer-supplied software so that a record of the temperature per pixel is obtained. An analysis of the histogram of these data, normalized to account for focal length, can be used to estimate the level and extent of segregation in a given thermal photograph.

4. DEFINITIONS

4.1 *Segregation:* is the lack of homogeneity in the hot-mix asphalt constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es).

4.2 *Constituents:* include asphalt, aggregates, and air voids.

4.3 *Gradation segregation:* is the separation of the coarse and fine aggregate fractions.

4.4 *Temperature segregation:* refers to portions of the mix with significantly different temperatures. This type of segregation can occur as the result of the surface of the mix cooling in the haul truck, cold mix in the paver wings being flipped into the hopper immediately prior to the addition of fresh hot mix, and any anomalies in the paving operations that result in areas with significantly different temperatures.

4.5 *Low-level segregation:* will have temperatures between 10°C and 16°C cooler than non-segregated areas. It is anticipated that these areas will have mix stiffness (resilient modulus) of between 70 and 90 percent of the mix in the non-segregated areas; air voids will be up to 2 percent higher. When gradation segregation is present, there will also be a decrease in the asphalt content of between 0.3 and 0.75 percent and a statistically measurable decrease in the percent passing at least one coarse sieve.

4.6 *Medium-level segregation:* will have temperatures between 17°C and 21°C cooler than non-segregated areas. It is anticipated that these areas will have mix stiffness (resilient modulus) of between 50 and 70 percent of the mix in the nonsegregated areas; air voids will be between 2 and 6 percent higher. When gradation segregation is present there will also be a decrease in the asphalt content of between 0.75 and 1.3 percent and a statistically measurable decrease in the percent passing at least one coarse sieve.

4.7 *High-level segregation:* will have temperatures greater than 21°C cooler than non-segregated areas. It is anticipated that these areas will have mix stiffness (resilient modulus) of less than 50 percent of the mix in the non-segregated areas; air voids will be more than 5 percent higher. When gradation segregation is present there will also be a decrease in the asphalt content of greater than 1.3 percent and a statistically measurable decrease in the percent passing at least one coarse sieve.

5. APPARATUS

5.1 *Infrared camera*—A battery-operated imaging infrared camera capable of storing images to a PCMCIA card for retrieval by camera software. The camera should have a temperature measurement range of −10°C to 450°C, an imaging sensitivity of 0.07°C, color imaging capabilities, and a movable pointer that can be used to display the temperature at any single point in the camera viewfinder. The camera shall be equipped with a lens with a field of vision of at least 16 deg. A lens with a field of vision of 32 deg is needed if the analysis detailed in Section 3.2 is to be conducted.

5.2 *Infrared camera software*—that can convert the color thermal images into temperatures per pixel.

5.3 *Battery charger and extra battery*—for the infrared camera.
5.4 *PCMCIA card for portable computer*—A portable computer Flash card that is compatible with the infrared camera.
5.5 *Portable computer*—A portable computer capable of running Windows 98, an available PCMCIA port, and a disk drive for storing processed images and data files.
5.6 *Distance measuring device*—Any measurement device that can be used to mark off distance in meters.
5.7 *Miscellaneous*—paint or chalk for marking the pavement.

6. PROCEDURES

6.1 Inspection.
6.1.1 Turn the camera on and allow it to complete its startup procedures.
6.1.2 The inspector shall walk along side of the paving project immediately behind the paver.
6.1.3 When the inspector finds an area in the pavement mat that is more than 10°C cooler than the majority of the mat, he/she shall mark these areas in such a way that they can be found once paving is completed.
6.1.4 Marked areas will be excluded from the normal random sampling program.
6.1.5 Cores will be obtained per AASHTO T168 at the discretion of the inspector.
6.1.6 Testing will include determining the density (AASHTO T166), maximum specific gravity (AASHTO T209), air voids (AASHTO T269), and asphalt content and gradation (ASTM PS90) of each core. If possible, the resilient modulus (ASTM D4123) of the cores will also be determined
6.1.7 The level of segregation will be defined based on these laboratory results.
6.2 *Estimation of Segregation from Infrared Photographs.*
6.2.1 One person equipped with the infrared camera and extra battery will position himself/herself on the paver deck. Turn the camera on and allow it to complete its start-up routine (takes about 10 minutes).
6.2.2 A second person with a distance measurement device shall walk along behind the paver about 3 meters (10 feet) from the screed. Every 10 meters (33 feet), this person shall signal the camera operator to take an infrared photograph by holding the measurement device over the pavement mat at the designated distance and within the field of vision of the camera operator.
6.2.3 The camera operator shall position the viewfinder so that the measurement device is at the bottom of the image. An infrared photograph will be taken immediately.
6.2.4 This process shall be repeated for the desired length of the paving project.
6.2.5 Analysis of data.
6.2.5.1 Remove the PCMCIA disk from the camera, insert it in the portable computer, and load the first photograph into the manufacturer's analysis software program.
6.2.5.2 Use this software to mark off the trapezoidal area of the photograph that is the pavement mat. Save this portion of the photograph to a spreadsheet-accessible data file.
6.2.5.3 Open the data file in a spreadsheet program. Normalize the data to account for focal length. That is, each line of temperature data needs to be adjusted so that there are the same number of data points per line throughout the file.
6.2.5.4 Once the data file has been normalized to account for the focal length of the camera lens, use the spreadsheet function to develop a histogram of the data. Bin sizes for the histogram shall be 1°C increments.
6.2.5.5 Estimates of the percent of the photograph with a given level of segregation can be determined from the histogram. The percent of the mat with temperatures between 10°C and 16°C has a low level of segregation, between 17°C and 21°C has a medium level of segregation, and greater than 21°C has a high level of segregation.

7. REPORT

7.1 The report shall include the following information:
7.1.1 Paving date, location, and description.
7.1.2 If used for inspection:
7.1.2.1 Location of area.
7.1.2.2 Square foot of each area marked as being segregated.
7.1.2.3 The number of cores to be taken from each area.
7.1.3 If used for estimating segregation:
7.1.3.1 The starting location of the testing.
7.1.3.2 Number of photographs saved.
7.1.3.3 The percent of each level of segregation seen in each photograph.

8. PRECISION AND BIAS

8.1 The nature of this test method does not allow for a round-robin testing program. Consequently, the precision and bias of this test method are unknown at this time.

APPENDIX L

PROPOSED DRAFT AASHTO PROVISIONAL STANDARD

STANDARD TEST METHOD FOR USING ROSAN$_V$ LASER SURFACE TEXTURE MEASUREMENTS TO IDENTIFY SEGREGATION IN HOT-MIX ASPHALT PAVEMENTS

MAY 1999

1. SCOPE

1.1 This test method covers the identification of areas of segregated hot-mix asphalt in a finished pavement mat.
1.2 This test method uses the $ROSAN_v$ high-frequency laser sensor system to measure the texture depth of a longitudinal profile of a pavement section.
1.3 Statistically based limits can be used to determine the percent of the profile with none, low, medium, and high levels of gradation segregation.
1.4 The values stated in millimeters are to be regarded as the standard.
1.5 *This standard may involve hazardous materials, operations, and equipment. It does not purport to address all of the safety problems associated with its use. It is the responsibility of anyone using this practice to consult and establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.*

2. REFERENCED DOCUMENTS

2.1 AASHTO Standards
T166 Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens
T168 Sampling Bituminous Paving Mixtures
T209 Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
T269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures
2.2 ASTM
ASTM PS 90 Asphalt Content of Hot Mix Asphalt by the Ignition Oven Method
ASTM D4123 Indirect Tension Test for Resilient Modulus of Bituminous Mixtures

3. SIGNIFICANCE AND USE

3.1 The estimated texture depth (ETD) is determined for a baseline of 500 mm using the $ROSAN_v$ laser surface texture measurement system. The distance measurements corresponding with the measurements can be obtained either from a digital distance encoder or by using the optical trigger option.
3.2 Either an average texture in a non-segregated area or mix design information is used to determine an anticipated texture depth in the non-segregated areas. Mix information used includes the maximum size of aggregate, the percent passing the 4.75 mm sieve, and the coefficients of curvature and uniformity.
3.3 This estimated non-segregated area texture and texture ratios that define the limits between none, low, medium, and high segregation can then be used to sort the raw $ROSAN_v$ data. The number of data points in each segregation level divided by the total number of data points provides an estimate of the percent of each level of segregation present.

4. DEFINITIONS

4.1 *Segregation*: is the lack of homogeneity in the hot-mix asphalt constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es).
4.2 *Constituents*: include asphalt, aggregates, and air voids.
4.3 *Gradation segregation:* is the separation of the coarse and fine aggregate fractions.
4.4 *Temperature segregation:* refers to portions of the mix with significantly different temperatures. This type of segregation can occur as the result of the surface of the mix cooling in the haul truck, cold mix in the paver wings being flipped into the hopper immediately prior to the addition of fresh hot mix, and any anomalies in the paving operations that result in areas with significantly different temperatures.
4.5 *Texture ratios:* are the ratios of textures in segregated areas to those in non-segregated areas.
4.6 *Low-level segregation*: will have texture ratios between 1.16 and 1.56. It is anticipated that these areas will have mix stiffness (resilient modulus) of between 70 and 90 percent of the mix in the non-segregated areas; air voids will be up to 2 percent higher. There will also be a decrease in the asphalt content of between 0.3 and 0.75 percent and a statistically measurable decrease in the percent passing at least one coarse sieve.
4.7 *Medium-level segregation:* will have texture ratios of between 1.57 and 2.09. It is anticipated that these areas will have mix stiffness (resilient modulus) of between 50 and 70 percent of the mix in the non-segregated areas; air voids will be between 2 and 6 percent higher. When gradation segregation is present, there will also be a decrease in the asphalt content of between 0.75 and 1.3 percent and a statistically measurable decrease in the percent passing at least one coarse sieve.
4.8 *High-level segregation:* will have texture ratios greater than 2.09. It is anticipated that these areas will have mix stiffness (resilient modulus) of less than 50 percent of the mix in the non-segregated areas; air voids will be more than 5 percent higher. When gradation segregation is present, there will also be a decrease in the asphalt content of greater than 1.3 percent and a statistically measurable decrease in the percent passing at least one coarse sieve.

5. APPARATUS

5.1 *$ROSAN_v$ hardware* which consists of:
5.1.1 Selcom laser sensor head optocator model number 2008.
5.1.2 Selcom probe processing unit (PPU).
5.1.3 Selcom OIM-II signal conditioner and box.
5.1.4 Carrying case for sensor and equipment.
5.1.5 National Instruments DAQCard-AI-16E-4.
5.1.6 National Instruments PCMCIA adapter 183569A-01.
5.1.7 National Instruments 2M Calbe 182419B-02.
5.1.8 National Instruments Terminal Block CB68LP.
5.1.9 Notebook computer.
5.2 Software.
5.2.1 *$ROSAN_v$-TMR software* for collecting, storing, and processing laser data.
5.3 *Digital distance encoder*-which works off of the vehicle speedometer and can be wired into the $ROSAN_v$ data collection system.
5.4 *Optical triggers*-3-meter lengths of rubber hose with a diameter of about 25 mm (1 inch) can be used for optical triggers in place of the digital distance encoder or speed option in the software. A minimum of one hose is needed at beginning and end of the test section.
5.5 *Miscellaneous*-include such items as duct tape for securing the hose to the pavement, paint, and markers.
5.6 *Bumper Bracket*-for mounting the laser sensor to the vehicle.

6. PROCEDURES

6.1 Mount the bumper bracket on the vehicle bumper so that the desired transverse path can be evaluated.
6.2 Attach the laser sensor so that the sensor lens is 15.3 inches above the surface of the pavement. Remove the sensor lens cover.
6.3 Attach the cabling that connects the sensor to the data collection system inside the vehicle.
6.4 Attach the cable from the $ROSAN_v$ system to the computer.
6.5 Provide 12-volt power from the vehicle to the $ROSAN_v$ system.
6.6 Turn on the $ROSAN_v$ system and check to see that the green lights are lit in about the middle of the light display. This provides a check that the sensor is mounted at the correct height. If the lights show yellow, adjust the sensor height.
6.7 Boot the computer and start the $ROSAN_v$ software.
6.8 Enter data as requested on software window.
6.9 Once the software is ready for data collection, position the vehicle in the lane to be tested and operate it at the speed entered into the software. Start the data collection when the vehicle is both in position and at the appropriate speed.
6.10 Stop the data collection after the desired length of section has been tested by clicking on the left-mouse button. Data should not be collected for more than 15 seconds at a time. This will ensure that the data files are of a manageable size for storing and data analysis.
6.11 Check to see that data was actually collected by reviewing data per software supplier instructions.

7. CALCULATIONS

7.1 Develop the texture limits for each level of segregation for a given project.
7.1.1 If the non-segregated area texture is to be estimated
7.1.1.1 Estimated texture depth, ETD, in the non-segregated areas using the maximum size of aggregate, the percent passing the 4.75 mm sieve and the coefficients of curvature and uniformity:

$$ETD = 0.01980\,(\text{max. agg. size}) - 0.004984\,(\%\text{ pass. }4.75\text{ mm}) + 0.1038(C_c) - 0.004861(C_u)$$

Where:

ETD = estimated texture depth in mm
Max. Agg. Size = smallest sieve size with 100 percent passing
% pass. 4.75 mm = the percent passing the 4.75 mm sieve
C_c = coefficient of curvature = $(D_{30})^2 / (D_{10}\, D_{60})$
C_u = coefficient of uniformity = D_{60} / D_{10}
D_{10} = the sieve size, in mm, associated with 10 percent passing
D_{30} = the sieve size, in mm, associated with 30 percent passing
D_{60} = the sieve size, in mm, associated with 60 percent passing

7.1.2 Calculate the limits for none, low, medium, and high levels of segregation:
7.1.2.1 No segregation limits, in mm:

$$\text{Upper ETD Limit}_{no} = \text{Non-segregated area ETD} * 1.15$$

$$\text{Lower ETD Limit}_{no} = \text{Non-segregated area ETD} * 0.7$$

Note 1: Although a lower limit on texture is set, this limit has not been verified with laboratory testing

7.1.2.2 Upper low segregation limit, in mm:

$$\text{Upper ETD Limit}_{low} = ETD * 1.56$$

7.1.2.3 Upper medium segregation limit, in mm:

$$\text{Upper ETD Limit}_{medium} = ETD * 2.02$$

7.1.3 Import the $ROSAN_v$ data file into any spreadsheet program.
7.1.3.1 Divide each data point by the ETD for the non-segregated area.
7.1.3.2 Sort the data so that the number of data points can be counted with textures between the:
Lower and upper ETD_{no} limits (no segregation),
Upper ETD_{no} and upper ETD_{low} limits (low segregation),
Upper ETD_{low} and upper ETD_{medium} limits (medium segregation), and
Greater than upper ETD_{medium} limit (high segregation).
7.1.3.3 The estimated percent of the longitudinal path tested with a given level of segregation can be obtained dividing the number of data points in each level of segregation by the total number of data points.

8. REPORT

8.1 The report shall include the following information:
8.1.1 How the distance was measured.
8.1.2 Whether the non-segregated area ETD was measured and averaged or estimated from mix properties.
8.1.3 The starting point of the measurements.
8.1.4 The lane designation, the transverse position in the lane, and the reference point (e.g., centerline) from which the transverse location was measured.
8.1.5 The predicted ETD, the upper and lower limits for ETD_{no}, and the upper limits for ETD_{low} and ETD_{medium}.
8.1.6 The percent of the data within each level of segregation.
8.1.7 The corresponding locations of each data point in the medium and high levels of segregation.

9. PRECISION AND BIAS

9.1 The nature of this test method does not allow for a round-robin testing program. Consequently, the precision and bias of this test method are unknown at this time.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation