Test Method to Determine the Existence of Segregation in Bituminous Mixtures

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PRCE

Michigan State University
Pavement Research Center of Excellence

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Abstract

Segregation in asphalt concrete pavements is a construction-related problem that has been of concern for many years. However, no quantitative methods to assess segregation are found in any standard specifications. This report shows the progress of a research project to develop an expedient test for segregation. Nuclear density measurements were evaluated as possible indicators of segregation. Two spreadsheet-based programs, MBITSEG1 and MBITSEG2, were developed to perform statistical tests to access the presence of segregation based on differences in density measurements. With this approach, the presence of segregation can be expediently detected and the paving operation can be adjusted. To verify and calibrate the expedient test, seven test sites were selected exhibiting various types and degrees of segregation. Nuclear density measurements, laboratory density measurements and aggregate gradation tests were made at these sites and statistical patterns were analyzed using the programs. Results indicated that the observed trends for air-dry laboratory density and the percent passing No.4 and No.8 sieves are generally similar to those for nuclear measured density. Regression analyses show that nuclear-measured density values are not strongly correlated to lab values, but one-minute nuclear density measurements correlate most closely with air-dry lab density measurements for the surface course.

Key Words : segregation, nuclear density, asphalt pavements, statistical methods, quality control, bituminous mixtures

Conversion Factors

English	Metric
1 inch, in	2.544×10^{1} mm = 2.544 cm = 2.544×10^{-2} m
1 foot, ft	30.48×10^{1} mm = 30.48 cm = 30.48×10^{-2} m
1 yard, yd	91.44×10^{1} mm = 91.44 cm = 91.44×10^{-2} m
I mile (U.S.)	1.609×10^{3} m = 1.609 km
1 mil	0.0254 mm = 2.54×10^{-5} m = 25.4 μm
1 inch square, in^2	6.472×10^{2} mm^2 = 6.472 cm^2 = 6.472×10^{-4} m^2
1 foot square, ft^2	929.03×10^{2} mm^2 = 929.03 cm^2 = 929.03×10^{-4} m^2
1 yard square, yd^2	8361×10^{2} mm^2 = 8,361 cm^2 = 8361×10^{-4} m^2
I mile square (U.S.)	2.5889×10^{6} m^2 = 2.5889 km^2
1 pound mass, lbm or lb	0.4536 kg = 0.4536×10^{3} g
1 ton = 2000 lb	907.2 kg = 907.2×10^{3} g
1 slug	14.59 kg = 14.59×10^{3} g
1 pound-force, lbf	4.448 N = 4.448×10^{-3} kN
1 ton-force	8,896 N = 8.896 kN
1 pound per square inch, psi	6,895 Pa = 6.895 kPa
1 kip per square inch, ksi	6,895,000 Pa = 6.895 Mpa
1 pound-force/square foot, psf	47.88 Pa = 47.88×10^{-3} kPa
1 pound-mass per cubic foot, pcf	16.018 kg/m^3
For asphalt overlays	
100 pounds per square yard	about 1 in
170 pounds per square yard	about 1.5 in

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Chronology

1995

Aug. 3	First Technical Activities Group meeting
Sep. 11	Nuclear density was measured at the St. John's site
Sep. 13	The definition of bituminous segregation was given by MDOT.
Oct. 5-10	Nuclear density was measured at the Muskegon (uniform) site.
Oct. 9-10	Nuclear density was measured at the Muskegon (random) site.
Oct.	Spreadsheet template was developed.
Nov.	Lab density tests for samples obtained at the St. John's site
Dec. 19	Second Technical Activities Group meeting
Dec.	Lab density tests for samples obtained at the St. John's site

1996

Jan.	Lab density tests for samples obtained at the Muskegon (uniform) site
Feb.	Sieve analyses for samples obtained at the St. John's site
	Lab density tests for samples obtained at the Muskegon (uniform) site
March	Sieve analyses for samples obtained at the St. John's site
	Lab density tests for samples obtained at the Muskegon uniform and random site
April 9	Third Technical Activities Group meeting
April	Lab density tests for samples obtained at the Muskegon (random) site
	Sieve analyses for samples obtained at the Muskegon (uniform) site
May	Sieve analyses for samples obtained at the Muskegon (uniform) site
June	Improvement of spreadsheet template
	Sieve analyses for samples obtained at the Muskegon (random) site
July 8	Nuclear density was measured at the M-99 site
July 14	Fourth Technical Activities Group meeting
July 18	FWD tests at the M-123 site
July 19	Nuclear density was measured at the M-123 site.
July	Lab density tests for samples obtained at the M-99 site
	Sieve analyses for samples obtained at the Muskegon (random) site
Aug. 12	Nuclear density was measured at the old U.S. 27 site.
Aug.	Sieve analyses for samples obtained at the Muskegon (random) site
Oct. 7	Fifth Technical Activities Group meeting
Oct.	Lab density tests for samples obtained at the old U.S. 27 site
	Sieve analyses for samples obtained at the Muskegon (random) site

Nov.	Lab density tests for samples obtained at the old U.S. 27 site
	Sieve analyses for samples obtained at the M-99 site
Dec.	Lab density tests for samples obtained at the old U.S. 27 site
	Lab density tests for samples obtained at the M-123 site
	Sieve analyses for samples obtained at the M-99 site

1997

Jan. 21	Sixth Technical Activities Group meeting
Jan.	Sieve analyses for samples obtained at the old U.S. 27 site
Feb.	Sieve analyses for samples obtained at the old U.S. 27 and M-123 site
March	Sieve analyses for samples obtained at the M-123 site
April 7	Seventh Technical Activities Group meeting
April	Spreadsheet template for two-sample comparison was developed.
	Two software were named MBITSEG1.xls and MBITSEG2.xls separately.
June 4	FWD tests at the Lansing state police facility site
June 16	Eighth Technical Activities Group meeting
	Draft report was submitted.
June 19	Nuclear density was measured at the Lansing state police facility site.
Aug. 15	Final draft report was submitted.

Executive Summary

Segregation of hot-mix asphalt concrete pavements is a matter of potential dispute between construction contractors and the highway agency. Its presence and severity is a matter of visual observation and judgment, and no quantitative measures or tests are defined in specifications to address these matters. Furthermore, if assessed by performing comparative gradation tests on aggregate extracted from cores of placed pavements, the time required for testing is too long to adjust the construction operation to remedy the problem.

This report summarizes the findings of a two-year research study to develop an expedient field test to detect segregation, based on statistical variation of density values measured using a nuclear density device. For this study, MDOT provided the following definition of segregation:

> *Areas of non-uniform distribution of coarse and fine aggregate particles in a bituminous pavement that are visually identifiable or can be determined by other methods.*

The premise of the study was that segregated areas will have regions of statistically significant differences in nuclear density values, which correspond to significantly different lab density and gradation parameters indicative of segregation. These nuclear-measured density differences may occur for two reasons:

- With everything else taken equal, coarser-graded zones in a pavement tend to have lower density than nearby finer-graded zones.
- In addition to actual density differences, coarser-graded zones may have nuclear-measured density values even lower than actual density values due to surface voids and rough texture.

The original and primary focus of the study was the detection of *linear segregation*, segregated areas aligned in the direction of the pavement and paver travel. To detect segregation, nuclear density measurements are made over a rectangular sampling grid of six rows by six columns. To perform the statistical analyses and provide various visual displays of density differences, a spreadsheet template, MBITSEG1.xls was developed. MBITSEG1.xls performs an analysis of variance (ANOVA) to test for significant differences among the columnwise data. Three different multiple comparison tests (Tukey test, paired test and 6 of 6 test) are also performed to assist locating the specific columns where the significant differences occur.

Seven field test sites were selected for nuclear density measurements, and core samples were taken at six of the seven sites. An extensive program of laboratory density and gradation testing was performed. The same software was used to perform extensive analyses of lab density and gradation parameters to verify the hypothesized correlations.

Later in the study, as other (e.g., random) segregation patterns were observed, a second spreadsheet, MBITSEG2.xls, was developed. This spreadsheet performs a simple Student's-t test on two samples of three to ten values each, but provides the user with a variety of information in an easy-to-follow graphical format.

Three primary conclusions were drawn from the study:

I. ***Statistical differences in nuclear-measured density values are promising as an expdient indicator of segregation*** and correlate with statistically significant gradation differences. This occurs because voids due to separation of coarse and fine materials in asphalt mixtures and surface roughness are taken into account. In fact, nuclear density readings may have an amplifying effect on measured density differences.

II. ***The spreadsheets MBITSEG1.xls and MBITSEG2.xls can provide a user-friendly means to efficiently perform the required analyses*** by an engineer or technician with a basic familiarity with spreadsheet software and some elementary training in statistics.

III. Due to the limited number of sites invesigated, and the variety of conditions encountered at those sites, ***additional studies should be performed before finalizing and implementing specifications and payment provisions related to segregation***. These include beta-testing by MDOT personnel at actual sites, identification and evaluation of additional sites by MSU PRCE personnel, and further methodology and program refinements, especially directed at random segregation.

A number of more detailed conclusions are noted in the main report.

Furthermore, three recommendations were made:

1. As described in Chapter 7, ***MDOT should begin implementation of a pilot project to phase in quality control procedures for segregation***, by systematically gathering data on new pavements using the developed procedures and software. Initially, this data should be gathered for information purposes, until such time sufficient confidence is developed with the procedures to implement segregation-related specifications.

2. In conjunction with the recommended pilot program, ***additional research should be performed to further calibrate the developed methodology and software*** to determine the appropriate magnitudes of statistical measures (e.g. p-values and coefficients of variation) that correspond to unaccepatable degrees of segregation that will impact pavement performance. Although the present study showed that segregation can be detected by density statistics, the variety of conditions encountered over the relatively small number of sites precluded led to a database of insufficient size to set specification criteria with confidence.

3. ***New project specifications and payment provisions should be developed to control segregation.*** These will need to be written in the context of significant variations in gradation and density within rather short distances and localized areas, as opposed to the current specifications which are written in the context of average values of samples representing the average condition of large areas of pavement. Suggested preliminary wording was provided in Chapter 7; however, the quantitative criteria in those specifications should be set based on the further studies described in recommendation 2.

1. Introduction

1.1 Background

In the summer of 1995, personnel of the Michigan Department of Transportation (MDOT) discussed with pavement researchers of the Pavement Research Center of Excellence (PRCE) at Michigan State University (MSU) their experiences with segregation of bituminous pavements on newly-paved roads. Segregation is a potential matter of dispute between a construction contractor and the agency as its presence and severity is a matter of visual observation and judgment; no quantitative measures or tests are defined in project specifications to determine presence or severity. Furthermore, if it were assessed by performing comparative gradation tests on aggregate extracted from cores of placed pavements, the time required for testing would be too long to adjust the paving operation to remedy the problem. MDOT personnel desired a quick and accurate test to determine the presence of segregation.

In response, the principal investigators, under the auspices of the newly-formed MDOT-MSU PRCE, prepared a proposal for the research effort reported herein, and the project was funded for a two-year effort, September 1, 1995 through August 30, 1997.

1.2 Objectives

The objectives of the project were to:

- **Review the literature** regarding the nature, causes, and effects of segregation of hot-mix bituminous pavement materials.

- Visit and **inspect segregated pavements**.

- Develop a **research hypothesis** leading to an expedient test for segregation.

- Select **test sites** exhibiting various types and degrees of segregation, for development and calibration of the expedient test.

- Perform **destructive and non-destructive tests** on pavements at the test sites, for verification and calibration of the developed procedures.

- **Develop and recommend a test procedure** for expedient evaluation of the presence of segregation.

1.3 Research Hypotheses and Tasks

The hypotheses developed for this research are stated as follows:

- Pavement segregation can be correlated with differences in nuclear density measurements.
- Statistical differences in nuclear density measurements are indicators of pavement segregation.
- Given a rectangular grid of nuclear density measurement, linear segregation can be assessed by performing statistical tests to compare differences in measured values from column to column in the grid.
- The required statistical tests can be easily performed by highway engineers using a spreadsheet-based software package.

To test these hypotheses, the following tasks were performed;

1. Seven **test sites** were identified.
2. **Nuclear density measurements** were made at 108 locations for each site, triplicate adjacent samples in a six row by six column grid.
3. **Cores** were obtained at the same 108 locations for each of the six sites.
4. **Laboratory density** measurements were made on the surface course and leveling course layers of the cores.
5. Aggregates were separated from the cores by incineration and **gradation tests** were made on the surface course layers.
6. A **spreadsheet program** was developed to test for linear segregation by columnwise comparison of data (nuclear density, lab density, percent passing a sieve size) within a test grid.
7. **Statistical tests** were performed to determine column differences in **nuclear density values** which may be an indicator of segregation.
8. **Statistical tests** were performed to determine column differences in **lab density values** which may be an indicator of segregation.
9. **Regression analyses** were performed to compare the results of the **nuclear and lab density** values; it was concluded early on that the nuclear density readings correlated primarily to the surface course layer.
10. **Statistical tests** were performed to determine column differences in **percent passing** various sieve sizes which may be an indicator of segregation.

11. The indicated **column differences for lab density, field density, and gradation parameters were reviewed** to assess the degree to which the field density analyses would lead to the same conclusions as the lab density and gradation analyses.

The emphasis on statistically testing for column differences was based on the fact that the original proposal and considered problem was the determination of *linear segregation*, which leads to similarities in pavement characteristics in the longitudinal (or column) direction, and variation from column to column. Once the sampling and testing was underway, it became apparent that detection of other types of segregation would be of interest. Hence, a limited amount of effort was redirected to the assessment of segregation in general.

1.4 Scope of This Report

Chapter 2 of this report provides a literature review of the aspects of bituminous pavement segregation relevant to the research, including definition, types and causes, indicators, and effects on pavement performance. As the theoretical and operational principles of density measurements using nuclear devices are also relevant to the work, these topics are also reviewed. In Chapter 3, MDOT's practice for specification and quality assurance of bituminous pavements are reviewed.

Chapter 4 describes the field and laboratory investigations made in support of the study, and Chapter 5 describes the software developed to perform the statistical analyses. Based on these two items, Chapter 6 summarizes the detailed analyses performed to make the comparisons in sections 6,7,8, 10 and 11 in the preceding section.

In Chapter 7, the recommended expedient determination of segregation is described, and in Chapter 8, a project summary, conclusion, and recommendations are provided.

There are eight appendices to this report. The first, Appendix A, provides a user's manual for the developed software. The remaining seven, Appendices B through H, contain the detailed project data analyses for the seven test sites.

2 . Literature Review

2.1 Definition of Segregation

Segregation is the separation of coarse and fine aggregate particles in an asphalt mix. Several definitions of segregation can be found in the literature. Brock et al. (1996) stated that segregation causes non-uniform asphalt mixtures and changes the original job mix formula in gradation of asphalt content. This results in poor structural and textural characteristics of pavements. Kennedy et al. (1987) explained that "segregation in asphalt mixtures is non-uniform distribution of aggregate with differing sizes and also involves a concentration of coarse materials in a specific area and fines in another area."

For this study, MDOT provided the following Department definition of segregation:

> *Areas of non-uniform distribution of coarse and fine aggregate particles in a bituminous pavement that are visually identifiable or can be determined by other methods.*

Segregation may result in non-uniform distributions of density and asphalt content in the pavement section. On visual inspection, segregated pavement areas display rough surface texture. Kennedy et al. (1987) stated that segregated areas of pavement can easily be seen in wet conditions or in low-angle sunlight. Where segregation is present, pavement performance can be impaired due to the relatively greater amount of voids and related potential for absorption of moisture. Therefore, some types of pavement distress can be expected, including raveling, stripping, cracking and rutting.

2.2 Causes and Types of Segregation

The segregation mechanism is based on the motion of aggregates. Whenever aggregates are moved, there is a tendency for segregation to occur. Kennedy et al. (1987) explained the fundamental mechanism that causes segregation by a simple demonstration: When graded aggregates fall, the coarser particles travel a greater distance than the finer ones. Therefore, the coarse aggregates are separated from the fine aggregates. In general, there are four major causes of segregation:

- problems with the mix design,
- problems with the design or operation of the hot asphalt mix plant,
- improper handling and transportation, and
- improper paver characteristics and operation.

These are described in the following paragraphs.

2.2.1 Mix Design Considerations

The proper design of bituminous paving mixtures is very important to reducing the likelihood of segregation. Elton (1989) stated that the best mix design uses a well-graded aggregate gradation that plots just above or below the maximum density line (A-line), as shown in Figure 2.1. It is not desirable to use a gradation with a curve that coincides with the A-line because such a gradation results in low air voids and low asphalt content which may cause flushing and raveling. Brock et al. (1996) suggested a gradation curve located between two and four percent above the A-line if a fine texture is desired and two to four percent below the A-line if a coarse texture is desired. An S-shaped gradation curve that crosses the A-line indicates a gap-graded mixture with high segregation potential.

The amount of asphalt also influences the segregation potential of the mix. To minimize segregation potential, the asphalt content should be high enough for the asphalt to coat the aggregate. However, a thick asphalt film causes rutting. Brock (1986) mentioned that a slight increase in asphalt content can often reduce segregation significantly. Two percent increase in asphalt content was recommended.

2.2.2 Hot Mix Asphalt Plant

At the hot mix asphalt plant, aggregate segregation can occur during the various steps of the plant operation. These are summarized below.

1. Stockpiling. Production of hot-mix asphalt begins with the stockpiles of aggregates that are to be processed through the plant. In general, a minimum of three stockpiles are required (Kennedy et al., 1987) which are coarse stone, fine stone, and sand. Since a range of sizes are contained in each stockpile, segregation may occur during the stockpiling operation. If large stockpiles are created or aggregates of large sizes are combined with smaller sizes, the large aggregates tend to roll down to the outside of the pile as shown in Figure 2.2. In the case of truck-dumped stockpiles, the discharge should be handled as rapidly as possible and the dropped stream should be kept vertical. For the construction of stockpiles, Brock et al. (1996) suggested using horizontal or gently sloping layers to avoid segregation.

It can be expected that if segregation occurs during the stockpiling, the segregated materials will be delivered to the hot-mix asphalt (HMA) facility. In drum mix plants, segregation can get worse because there is no screening unit to re-integrate aggregate of different sizes. Therefore, care must be taken in the stockpiling procedure to ensure uniform materials are fed to the hot mix plant.

2. Cold-feed Bins. When aggregates are moved using a front-end loader from stockpiles to cold-feed bins, segregation can occur if the loader operator scoops up the side of the stockpile instead of pushing the bucket directly into the pile (Kennedy et al, 1987). As mentioned above, the large size aggregates tend to roll down the face of the stockpile. Therefore, scooping along the face of the stockpile forces the larger particles gathered into the bucket and hence, into the cold feed bins. The opening configuration of the cold feed bins may also cause segregation, see Figure 2.3. Brock et al. (1996) suggested that segregation potential can be decreased by using a self-relieving opening with a trapezoidal bottom rather than a rectangular opening. Elton (1989) explained that " if the wide end of the trapezoid is on the downstream edge of the opening, the material will flow more freely from all areas of the bins."

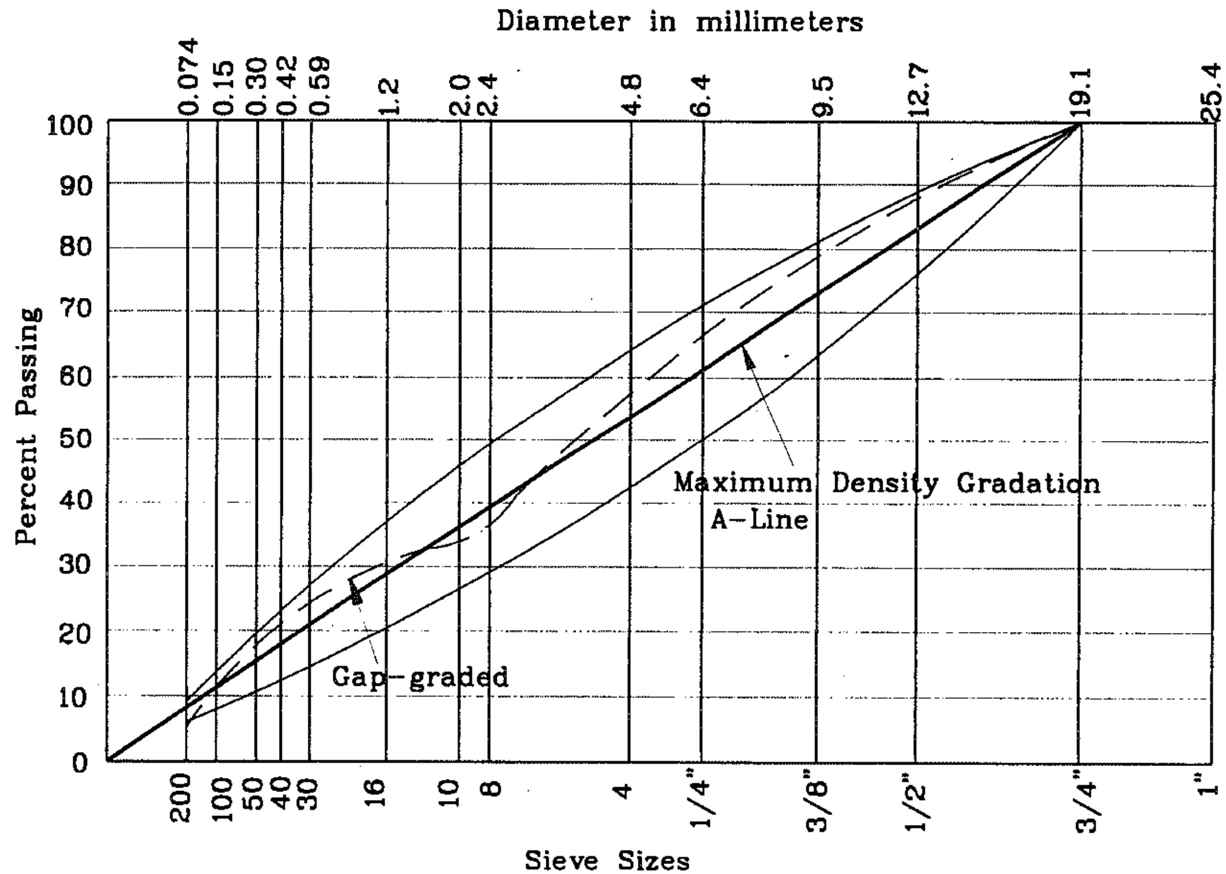


Figure 2.1 Gradation Plot Showing A-line

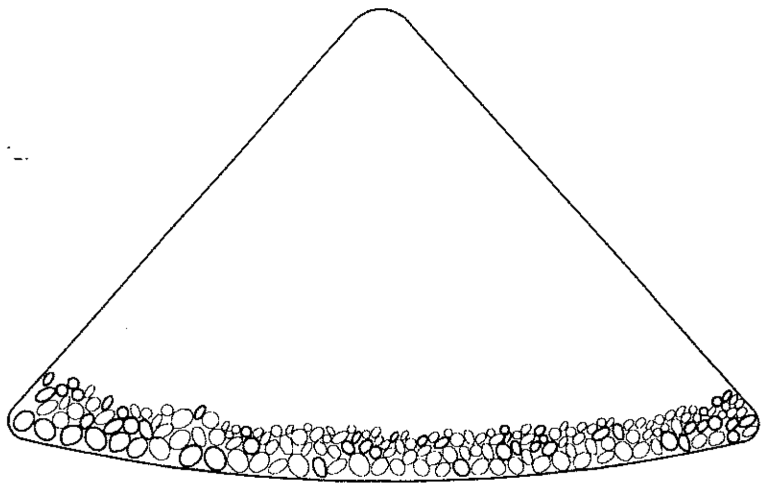


Figure 2.2 Segregated Stockpile

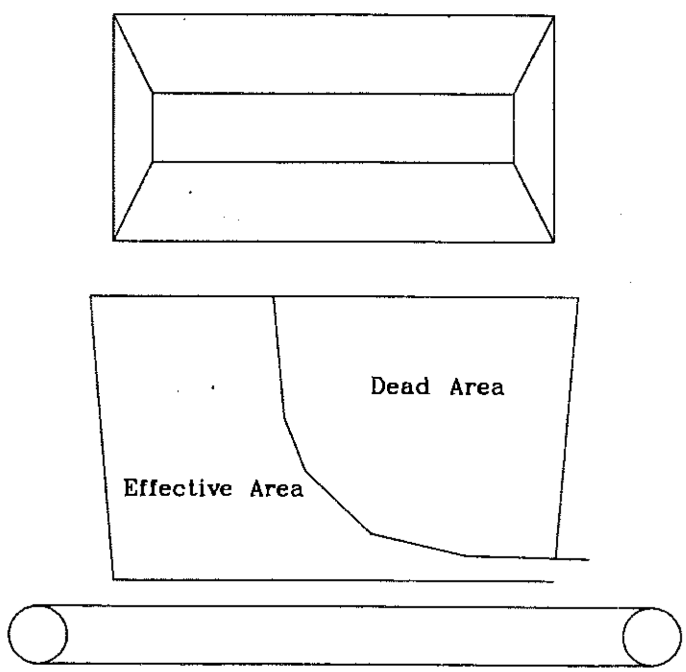


Figure 2.3 Cold-feed Bins with Rectangular Opening

3. Hot Bins on Batch Plants. In batch plants, the aggregates are moved on conveyer belts and discharged onto screens that are designed to separate the materials into a number of sizes. After screening the aggregates, they are collected in hot bins. Unfortunately, segregation often occurs, especially in the No. 1 hot bin, due to a greater size variation in the materials (Brock et al., 1996). Moreover, the fine materials that fall directly through the screen accumulate on the side of the hot bin. When the level of material becomes low, the fines, which are stuck on the wall of the hot bin, will break loose. This results in an unacceptable segregated ultra-fine batch.

4. Drum Mixer. In drum mixers, the segregation of well-graded aggregates during continuous process is not a major concern. However, gap-graded mixes are prone to segregate because the particles may not become thoroughly coated with a uniform asphalt film. Brock et al. (1996) stated that, if a large amount of fine particles are used, the resulting affinity for asphalt causes the film thickness around the coarse materials to decrease, potentially resulting in segregation.

5. Surge and Storage Silos. The purpose of silos is to keep an asphalt mix plant operating continuously. Once the truck-loading process is interrupted, the mixtures can be stored in silos. Brock et al. (1996) and Kennedy et al. (1987) reported that the most important cause of segregation is related to the improper use of surge or storage silos. Before the hot mixes are fed into the silo, they are transported by a drag conveyor. Segregation can occur in a drag conveyor due to "hydroplaning," in which the fine material accumulates along the high friction surface and the coarse material goes over top.

Instead of dropping the mix directly from the drag conveyor into the silo, two devices are usually used to prevent segregation, a batcher and a rotating chute. However, using these two devices does not guarantee the elimination of segregation. Brock (1986) suggests that, for a batcher, at least 5000 pounds of mix should be kept and discharged into the silo with a quick motion. The discharge from a batcher should be located in the center of the silo, otherwise, the coarse particles tend to run down to the walls of the silo. During discharge, the batcher should never be completely emptied. If the batcher is empty, which means that the interval of the gate opening is too long, segregation could occur because the materials can fall directly into the silo. The level of materials within a silo also have a great effect on segregation potential. If the silo is too full, the material dropped from a batcher may not have enough momentum to form a flat surface. Thus, a cone-shaped surface will be generated, resulting in accumulations of coarse particles near the silo walls. For a rotating chute, the flow of the asphalt mixture is continuous. However, segregation still can occur by poor maintenance of this equipment. Since the vertical portion of the chute is subject to the impact from the mix and becomes worn out, this causes the coarse materials roll to the center of the silo and the fine materials to the outside of the silo.

2.2.3 Handling and Transportation

When the mix is delivered to trucks from the bottom of a silo, it was suggested by FAA (1991) that the cone angle needs to be steep enough, and the gate opening large enough, to assure that the mass flow is uniform without rolling of coarse aggregates into the center of the cone. If the mix is deposited into the center of the truck bed as a single drop, as shown in Figure 2.4, coarse aggregate will mostly accumulate in the front and back of the truck. The proper solution is to place the mix in the truck with three separate drops. The first drop should be loaded near the front of the truck bed, the second drop near the tailgate and the third drop in the middle of the truck bed. The reason was given by Kennedy et al. (1987) that the first and second drop in the back and front of the truck bed can reduce the rolling potential of coarse aggregates and the third drop helps coarse aggregates to re-mix with nonsegregated materials.

When mix is unloaded to a paver hopper, it is necessary to allow a mass of mix to be discharged without any coarse aggregate rolling to the tailgate first. Elton (1989) pointed out that a smooth truck bed is preferred because mix can slide instead of roll out from a truck bed.

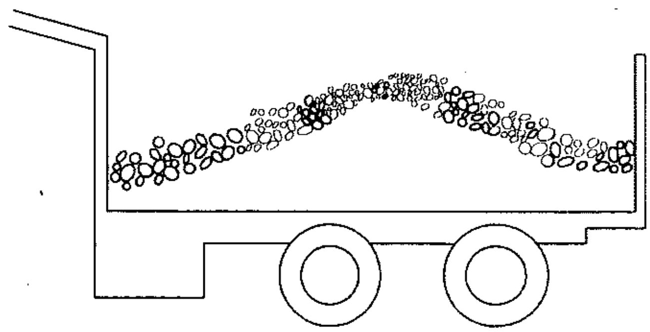


Figure 2.4 Incorrect Truck Loading

2.2.4 Paver Characteristics and Operation

A number of aspects of the paver and its operation can lead to segregation. These are summarized in the following paragraphs. The linear segregation which was the focus of this study is typically related to the paver and its operation.

1.Hopper Operation. The function of a hopper is to hold the asphalt mix after unloading from the truck. Since the coarse material from each side of the truck bed is mostly deposited in the wings of the hopper, it is not good practice to dump the hopper wings after each truck load. Both Brock et al. (1996) and Kennedy et al. (1987) suggested that wings be dumped as seldom as possible. Another cause of segregation due to hopper operation is related to the hopper being empty. If segregated materials are laid down from the wings into an empty hopper, there is seldom a chance to re-mix with fine materials before they go to the slat conveyor.

2.Auger Operation. It is very important to run the auger continuously. If the distribution of the mix being sent to the auger is inadequate, because of a small hopper gate opening, slow slat conveyor and/or empty hopper, the coarse material will be transported to each side of the auger. Brock et al. (1996) stated that if the speed of the auger is too fast, the center of the mat will be deficient of material and a coarse strip will results. Kennedy et al. (1987) stated that if the speed of the auger is too slow, periodic edge segregation can occur. Further, if the width of the pavement is larger than the auger and if auger extensions are not used on both sides of the auger, edge segregation will occur. For a proper paving operation (assuming no segregation has taken place), the gate opening, auger speed, paver speed, and material supply must be calibrated in a systematic movement.

As previously mentioned before, there are many sources to cause segregation problems. Since the cause of segregation is associated with the type of segregation that is present, it is important to identify possible sources of these segregation patterns. Based on Kennedy et al. (1987) and Brock (1986), there are five major types of segregation which are listed below and illustrated in Figure 2.5:

- Random Segregation
- Systematic Both Sides Segregation
- Continuous Both Sides Segregation
- Systematic One Side Segregation
- Center Line Segregation

The *Segregation Diagnostic Chart* written by Brock et al. (1996) provides information to find the potential causes of segregation, which is summarized in Table 2.1.

2.3 Indicators of Segregation

The following subsections review various methods that have been proposed to test for or quantify segregation. From the literature review, it is apparent there is no consensus regarding a method of test or measurement. If a visual inspection indicates that the pavement section appears segregated, some quantitative measure would be useful to support this observation. This would distinguish between the segregated and nonsegregated areas based on some measured properties of the in-place pavement.

2.3.1 Macrotexture

According to ASTM E965, pavement macrotexture is defined as " the deviation of a pavement surface from a true planar surface with the characteristic dimensions of wavelength and amplitude from 0.5 mm up to those that no longer affect tire-pavement interaction."

Cross and Brown (1993) applied the concept of macrotexture to indirectly develop a rating scheme based on the amount of segregation or raveling. Segregation was rated relative to five levels, with level one indicating segregation with raveling, up to level five, representing best pavements that do not exhibit segregation and raveling or exhibit just a little segregation. They also provided a visual estimation of the rating levels for five pavement sites in Alabama. Their rating scheme is summarized in Table 2.2.

The results are shown in Figure 2.6, where the difference in macrotexture is determined between segregated cores and the average of random samples. A relationship between the difference in macrotexture (Y) and change in gradation on No. 4 sieve (X) was also developed as :

$$Y = 0.2065 + 0.00275\,X^2$$

with $R^2 = 0.83$

Finally, the conclusion was drawn that if a difference in macrotexture exceeds 0.50 mm, segregation or raveling can be observed.

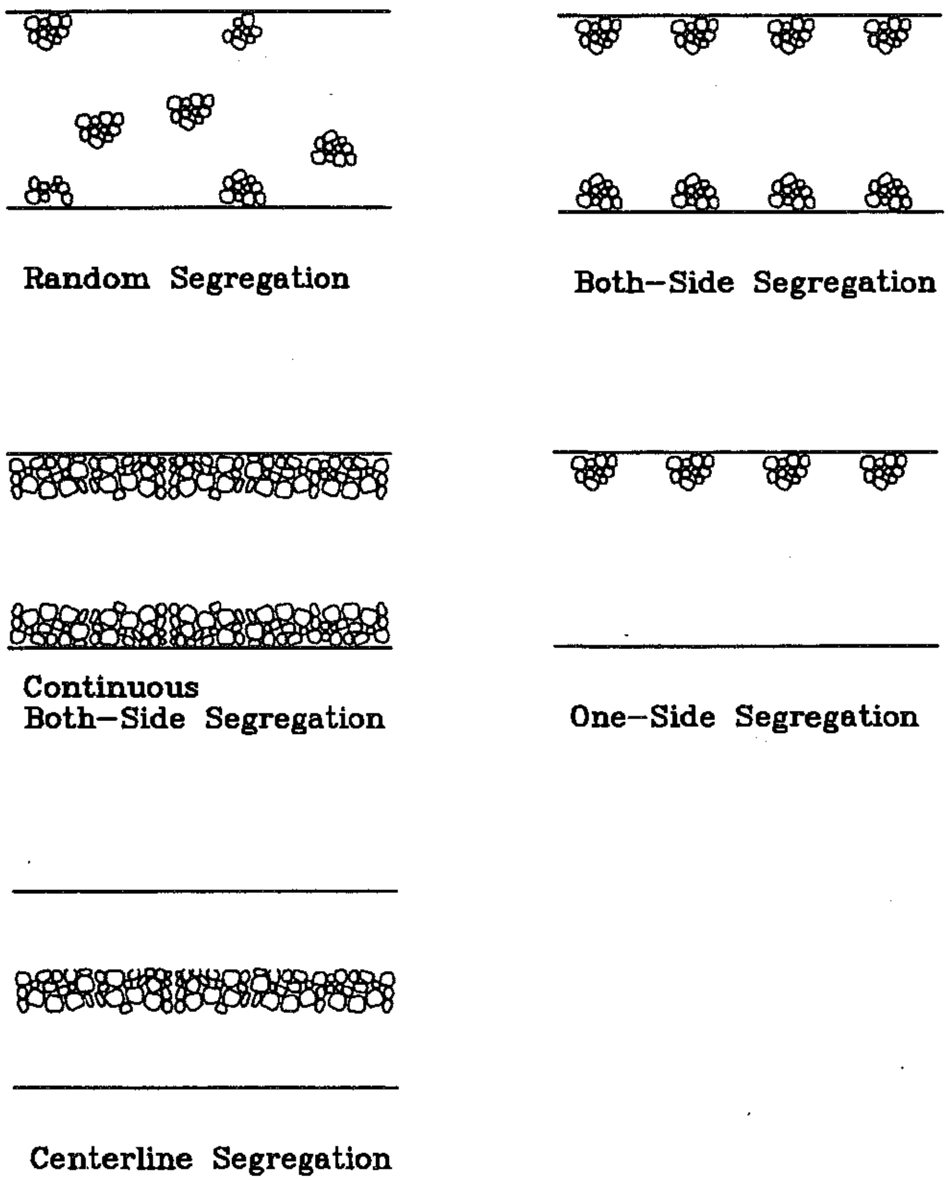


Figure 2.5 Segregation Patterns

Table 2.1 Sources for Various Types of Segregation

		Type of Segregation				
		Random	**Systematic Both Sides**	**Center Line**	**Continuous Both Sides**	**Systematic One Side**
Mix Design	Gap Graded	●	●	●	●	●
	Single Aggregate Mix	●				
Plant	Stockpiling	●				
	Cold-feed Bins	●				
	A Batch Plant	●(1)				
	A Drum Mix Plant					●(2)
	Partially Mixed	●	●			
Silos	Level of Materials	●	●			
	Hydroplaning in Drag Conveyor	●				
	Rotating Chute : stop turning	●	●			
	Rotating Chute : edge worn out	●	●	●		
	Rotating Chute : drop with a angle	●	●			
	Batcher : gate opening	●	●			●
	Batcher : partial filling		●			
	Batcher : off-set drop		●			
Transportation	Truck Loading		●			
Paver	Auger	●			●	
	Dumped Wings		●			
	Auger Gear			●		

Notes (1) : including hot bins, a hole in screen and in the dividing walls between bins
(2) : related to gravity discharge

Table 2.2 Cross and Brown's Rating Scheme

Rating	Location	Description	Deterioration
1	site 1	segregation and raveling through the whole section	moisture-related damage, stripping and raveling of the surface aggregates
2	site 4	segregation with spot raveling	absorbing of moisture, stripping and raveling
3	site 5	segregation with slight raveling	absorbing of moisture, stripping and raveling
4	site 2	some segregation without raveling	absorbing slight amount of moisture, no stripping and raveling
5	site 3	slight segregation without raveling	absorbing slight amount of moisture, no stripping and raveling

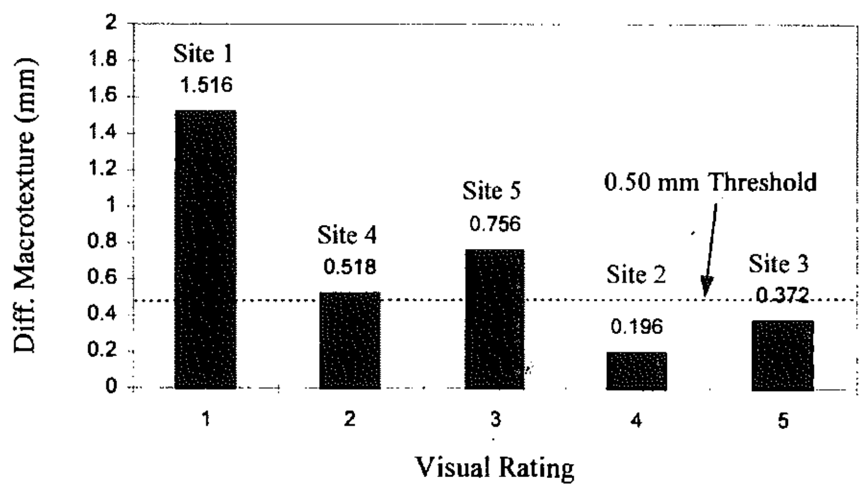


Figure 2.6 Difference in Macrotexture for Sites of Different Rating (Cross and Brown, 1993)

2.3.2 Unit Weight

It is well known that segregated areas exhibit low unit weights or densities because of their open texture. Brown et al. (1989) state that a nuclear density gauge might be useful in identifying segregated areas. Furthermore, the conclusion was drawn that any segregated area with a density four to five pounds per cubic foot lower than adjacent nonsegregated material should be removed or replaced. Based on laboratory samples prepared to simulate segregation, Khedaywi and White (1995) demonstrated that increasing the degree of segregation causes a decrease in unit weight of asphalt mixtures. Another term, *relative compaction*, was used by Cross and Brown (1993). It is defined as :

$$\text{Relative Compaction (\%)} = \frac{\text{unit weight of the HMA}}{\text{average unit weight of the random samples from that site}}$$

Similarly, their results showed that as the amount of segregation increases, the relative compaction decreases.

2.3.3 Asphalt Content

In segregated pavements, coarse and fine aggregate materials are separated. Thus, the measured asphalt content can be affected significantly. As the coarser aggregates would hold less asphalt due to their smaller total surface areas compared to the fine particles, segregation can be measured by variation in extracted asphalt content. Bryant (1967) performed a laboratory experiment to determine the relationship between the extracted asphalt content and the extracted aggregate gradation. Before starting the test, four percent asphalt was added to an aggregate with the gradation listed in Table 2.3. Four additional samples were prepared with different degrees of segregation. The results indicated that the asphalt content is less than four percent for the coarser mixtures.

Table 2.3 Gradation of Bryant's Test Aggregate

Sieve Size	3/4"	1/2"	3/8"	No. 4	No. 10	No. 20	No. 50	No. 100	No. 200
Percent Retained	0	1	4	22	61	73	78	86	92

Kandhal and Cross (1993) collected field data to study the correlation between asphalt content and gradation. It was reported that a strong correlation exists between asphalt content and the percent passing No. 4 and No. 8 sieves for the segregated binder mix. Their regression models are:

$$AC = 2.186 + 0.060\ P_4$$
$$AC = 2.025 + 0.084\ P_8$$

where AC = asphalt content

P_4 = percent passing No. 4 sieve by weight
P_8 = percent passing No. 8 sieve by weight

A study reported by Khedaywi and White (1995) also concluded that the amount of extracted asphalt decreases with increasing degree of segregation. Brown et al. (1989) concluded that the asphalt content is 1 to 2 percent lower for segregated areas.

2.3.4 Aggregate Gradation

As mentioned early, segregation involves the separation of coarse and fine materials in asphalt mixtures. Thus, it is apparent that gradation plays an important role to evaluate segregation. Based on Khedaywi and White's study (1995), as shown in Figure 2.7, mix number 5 was prone to segregation because of its large percentage of coarse aggregates.

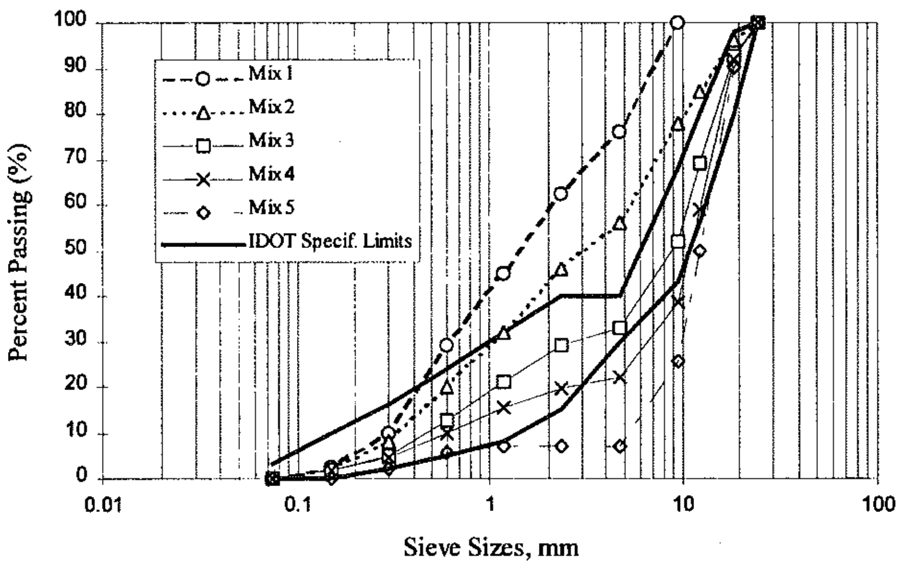


Figure 2.7 Aggregate Gradations Measured by Khedaywi and White after Extraction Tests

In general, the amount of segregation can be related to variation in the percent passing No. 4 or No. 8 sieves. Cross and Brown (1993) showed that a variation in the percent passing No. 4 sieve greater than 8 to 10 percent corresponds to segregation.

2.3.5 Permeability

Permeability tests also can be used to detect segregation. As the number of voids increases with increasing degree of segregation, higher permeability values would be expected in segregated areas. Brown et al. (1989) used water permeability tests and found that permeability increases dramatically with the degree of segregation. However, Whilliams et al. (1996) stated that the measurement of air permeability is more suitable than water permeability because turbulent flow occurring in a water permeability test will increase the risk of volume change. The results of their tests showed that air permeability correlated with level of segregation for a coarse gravel surface mixture, but not for a dense fine-graded mix.

2.4 Effects on Pavement Performance

Segregation can reduce pavement durability and hence affect long-term pavement performance. Some types of pavement distress due to segregation are briefly discussed below:

1. Raveling. In segregated areas, some fine material or binder is absent and the surface texture becomes rough; this results in raveling. According to Roberts et al. (1991), raveling of an HMA pavement surface is usually caused by one or a combination of the following factors :

- Deficient asphalt content
- Insufficient amount of fine aggregate to hold the coarse aggregate particles together
- Lack of compaction (high air voids)
- Excessive aging

The first three of these four factors are related to segregation.

2. Moisture-Related Damage. Water enters the pavement surface through air voids in segregated pavement surfaces. As a result, damage occurs. Based on Huang (1993), the influence of moisture on pavements can be summarized as follows :

- Reduced strength of unbound granular materials and roadbed soils
- Pumping of fine materials in the base course of flexible pavements
- Stripping of asphalt mixture with resulting loss of adhesive bond
- Frost heave susceptibility

Both Brown et al. (1989) and Cross et al. (1993) mentioned that moisture is easily absorbed in segregated pavements due to open texture of coarse spots.

In the state of Michigan, some of the asphalt pavement network shows different degrees of segregation. On some roads where linear segregation is observed under the middle or the side of the paver screed, strip raveling was noted within two to five years after construction.

3. Cracking. Indirect tensile tests were performed by Brown et al. (1989) and Khedaywi et al. (1995). The results indicated that the tensile strength reaches a maximum value and then decreases dramatically with increasing degree of segregation. As the critical tensile stress in a pavement occurs at the bottom of the AC course, if segregated mixtures do not provide adequate asphalt-aggregate adhesion because of a thin film on the coarse aggregates, cracks can originate from the bottom of the AC layer and propagate to the surface.

4. Rutting Potential. For fine segregated materials with high asphalt contents, there is a potential for rutting due to shear deformation associated with the asphalt binder between particles. This point was supported by Khedaywi and White (1995). However, for coarse segregated materials, the rutting potential is strongly influenced by characteristics of the aggregate. Since extracted aggregate gradations have large voids and less contact areas between particles, it can be expected that there is more permanent deformation in a coarse open-graded mixture.

2.5 Evaluation of Nuclear Density Measurements

The research hypothesis for this project is that differences in nuclear density measurement are potential indicators of segregation and that the nuclear gauge and statistical software can therefore form the basis of an expedient test. An advantage of this approach is that nuclear density measurements can be obtained in a very brief time after finishing compaction of an asphalt pavement, the paving operation can be adjusted to avoid further segregation and the approach becomes potentially suitable for acceptance testing.

Given the reliance on the nuclear gauge measurements, the fundamental principles of nuclear gage measurement and its accuracy were reviewed.

2.5.1 Operating Principle of the Nuclear Density Gauge

In a typical nuclear density device operated in backscatter mode on a pavement surface, gamma rays are emitted from a source located at the bottom of the device. Some of these rays are absorbed by the pavement, and some backscattered radiation reaches the detector toward the front of the gauge, as shown in Figure 2.8. Regimand (1987) stated that the gamma ray scattering is governed by two interactions, photoelectric effect and Compton scattering. The photoelectric effect is related to low energy gamma rays and Compton scattering is related to intermediate-energy gamma rays. In general, gamma radiation is treated as a wave motion and the basic radiation attenuation law is given as :

$$I_x = I_0 \, e^{-\mu\rho}$$

where I_x = gamma radiation intensity at x (counts/min)
I_0 = incident intensity of gammas
μ = material mass attenuation coefficient
ρ = density of the medium

For photoenergy within the range of 0.5 to 2 Mev, the material mass attenuation coefficient is constant for most cases of soils having a low organic content, hence gamma radiation intensity is dependent on density based on the theoretical consideration. The plot of $\ln(I_x/I_0)$ versus density is shown in Figure 2.9. The straight lines passing through the origin for different materials indicate that a constant μ value is a valid assumption.

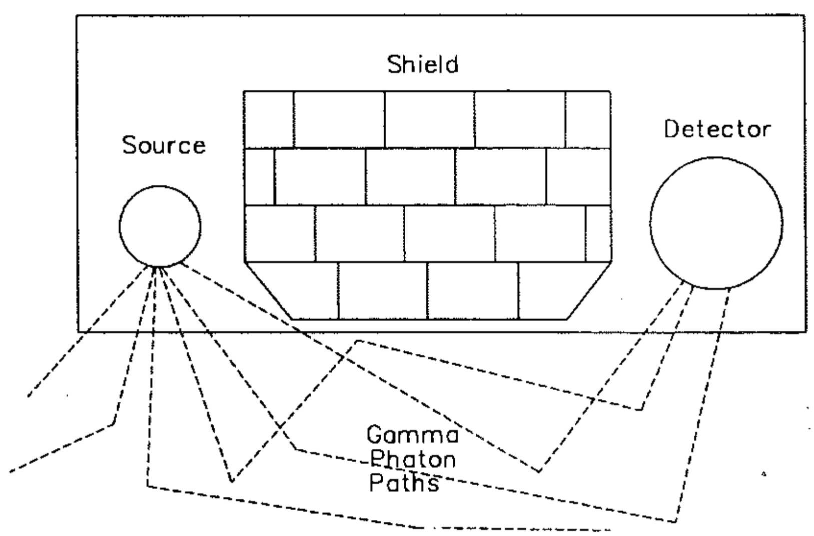


Figure 2.8 Schematic of Backscatter Nuclear Density

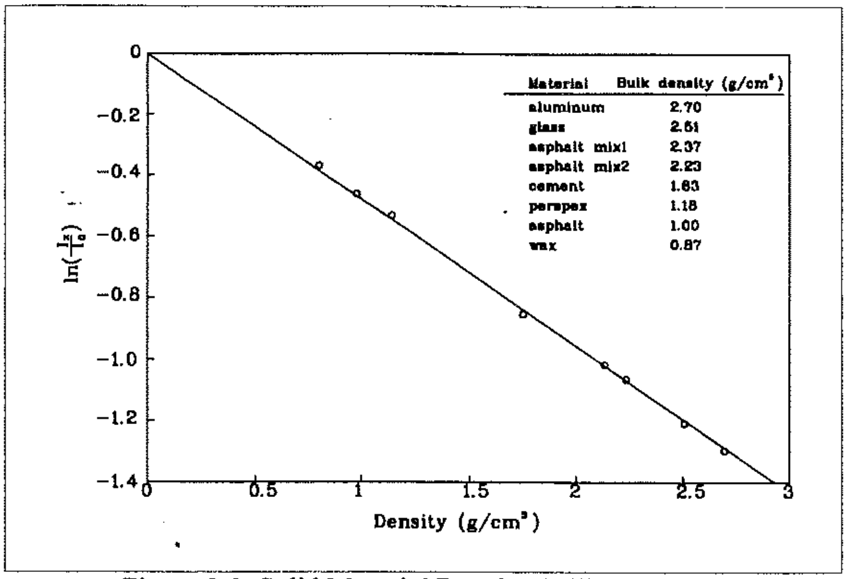


Figure 2.9 Solid Material Density Calibration Line

2.5.2 Influence of Voids

Due to the heterogeneity of asphalt mixtures, variation of nuclear gauge readings is a major concern regarding the accuracy of the results. Contributors to asphalt concrete heterogeneity include surface roughness, voids and irregularities. Lal (1979) studied the effects of gravel concentration on the nuclear count ratio in a sand-gravel mixture. For dry sand, the slope μ of the regression lines relating dry density to nuclear count ratio generally decreased with increasing gravel content. Ballard and Gardner (1965) stated that the nuclear gauge is very sensitive to the material directly beneath the gauge. Therefore, a small void space directly beneath the source or detector causes a change of gauge response, resulting in a high back-scattering count ratio and indicating a low density. They suggested using fine sand for surface smoothing to avoid this kind of error. Tan and Fwa (1991) investigated the effects of voids on nuclear gauge readings. They used aluminum to simulate soil materials in lab because the atomic number of aluminum (13) is close to the atomic number of soil components. The experimental results for aluminum specimens with concentric voids indicated that a plot of density against $\ln(I_X / I_0)$ lay above the solid's calibration line; for aluminum specimens with peripheral voids, the plot lay below the solid's calibration line. However, when the bulk density was calculated based on the gamma-ray path geometry of the particular source-detector arrangement, the calibration lines are identical with that for solid materials. They also studied density calibration for dry sands and gravels. The plot of $\ln(I_X / I_0)$ versus density for sand specimens showed good agreement with the solid's line. However, for coarse gravel specimens (13~25 mm) having more voids at center, the calibration line was not linear and was far away from the solid's line. It is evident that nonuniform void distribution has a great effect on the calibration between nuclear count ratio and the overall bulk density of soil-gravel mixture.

2.5.3 Thickness of Measured Layer

It is also important to know the depth of penetration of the energy photons, or in practical terms, what is the effective thickness over which nuclear gauge is indicating the density. Preiss (1966) found that, for a back-scattering density gauge, the effective depth is 4 inches at a density of 140 lb/ft^3 and the effective depth is inversely proportional to density. His experimental work also showed that the effective depth is independent of the source energy and the distance between the source and the detector.

Regimand (1987) proposed the principle of a thin-layer backscatter density gauge which can be used to measure the density of the surface course of an existing pavement. It is desired that the measurement should be independent of the density and composition of the bottom layer. His modified theory is based on a gauge geometry using two detectors at different distances from the source. The density of the top layer D_T is given as :

$$D_T = \frac{k_2 D_{G1} - k_1 D_{G2}}{k_1 - k_2}$$

where D_{G1} and D_{G2} are the bulk density measured by two different detectors and k_1 and k_2 are constants. According to Regimand, k value can be determined as a function of top layer thickness, and then, D_T can be evaluated. In a report published by FHWA (1991), the depth sensitivity was thoroughly studied using 8 different nuclear density instruments. A new criterion was also established to determine the suitability of each gauge for measuring the top layer density. This criterion is given by the term "95-percent depth," which means that 95 percent of the gauge reading is contributed by the density of the top layer material and five percent is contributed by the density of the base material. The comparison for each gauge is shown in Table 2.4.

Table 2.4 Depth Sensitivity for Several Nuclear Gauges

Gauge	95 % Depth (inches)
CPN MC-3 BS Source Position	1.9
CPN MC-3 AS Source Position	1.4
Seman C-200 Touchable Position	1.7
Humboldt 5001p	2.9
Troxler 3401	2.7
Troxler 4640	1.1
Troxler 4640 (Surface voids mode)	1.9
Troxler 4545	2.6
CPN DND FD Source Position	2.1
CPN DMD TL Source Position	1.7
Seman DOR-1000	1.5

(after FHWA ,1991)

2.5.4 Comparison of Nuclear and Core Density Measurements

As used in the field, nuclear density may be used only as a predictor of core-density measurements, or the nuclear readings themselves may be used for acceptance testing. Given the desire to rely on the nuclear measurements, several research studies have compared nuclear-gauge density with core-density measurements. Most concluded that the nuclear density is lower than core density. Hence, use of the gauge readings for acceptance testing would tend to be somewhat inaccurate but conservative. Alexander and Doty (1984) found that there is 1.5 to 5 percent difference between density measured by nuclear and water displacement methods. They also pointed out that the difference is mainly contributed by the backscatter nuclear gauge due to the irregularities in the asphalt concrete and nuclear gauge calibration. Burati and Elzoghbi (1987) investigated two runway paving projects to study the correlation between nuclear and core densities. Statistical analysis showed that the readings of nuclear gauge are significantly different from the core density. Furthermore, data also indicate that the nuclear densities have a higher variation than core densities. Kennedy et al. (1989) performed regression analysis and the corresponding equation is given as follows:

$$\text{Core Density} = (66\sim108) + (0.27\sim 0.55) \times \text{Nuclear Density} \quad \text{with } R^2 = 0.18\sim0.55$$

Schmitt (1996) gave the regression equation as :

$$\text{Core Density} = 48 + 0.667 \times \text{Nuclear Density}$$

It is of interest to note that a perfect correlation would yield an equation of the form

$$\text{Core Density} = 0 + 1.00 \times \text{Nuclear Density}$$

which has a slope of zero and an intercept of unity. The regresion equations have an intercept on the order of one-third to two-thirds the density and slopes on the order of one-third to two-thirds the variation. Also, the correlation coefficients are not strong. Similar results were found in this study and are reported in Section 6.7.

3. MDOT Practice for Asphalt Mixtures

3.1 Introduction

The implementation of an expedient test for determining segregation requires some changes in the existing MDOT specifications and payment procedures. This chapter reviews MDOT's existing practices.

3.2 MDOT Specifications for Asphalt Mixtures

For asphalt mixtures, the current MDOT specifications include aggregate gradations, asphalt contents, and mix design criteria for ten asphalt mixtures. The mix design criteria specify the voids in mineral aggregate (VMA), the percent air voids, the fine/binder ratio mix, the minimum fine aggregate angularity, the flow, the percent Los Angeles abrasion loss, the maximum percent of soft particles, and the minimum Marshall stability. Some of these specifications which have direct impacts on segregation are discussed below.

3.2.1 Aggregate Gradation

According to the Asphalt Institute (1989), the amount of mineral aggregate in asphalt mixtures is 90 to 95 percent by weight of total mix or 75 to 85 percent by volume. Therefore, aggregates play an important role in an asphalt mixture. In general aggregate mixes are described by their gradation using the following terms:

- dense-graded
- open-graded
- coarse-graded
- fine-graded
- gap-graded

For asphalt aggregate mixtures, aggregates are usually classified as:

- coarse aggregate
- fine aggregate
- mineral filler

It was shown in Chapter 2 that aggregate gradation may cause segregation in the compacted asphalt mixtures. For example, a gap-graded aggregate is an inherently segregated aggregate mix.

To provide economical mix design for a range of applications, MDOT specifies aggregate gradations and asphalt contents for ten asphalt mixes as shown in Table 3.1. The range of the MDOT specified aggregate gradation for 4C mixes is shown in Figure 3.1 along with the maximum-density gradation line. Figure 3.1 also shows a gap-graded aggregate mix. This mix satisfies the MDOT gradation specification and yet it is a segregated mix.

3.2.2 Asphalt Content

The MDOT specification of asphalt contents for 10 asphalt mixtures is also listed in Table 3.1. Asphalt content is defined as the ratio of the mass of asphalt to the total mass of the asphalt-aggregate mixture. Higher asphalt contents improve workability to permit efficient placement of the mix without segregation. However, too high an asphalt content causes bleeding (flushing) of the asphalt cement and leads to a loss of skid resistance on asphalt concrete surfaces.

In general, finer aggregate mixes require higher asphalt contents to coat the surface of the particles because of the high aggregate surface area. On the other hand, coarser mixes (have higher voids in mineral aggregate and lower surface area that finer mixes) require lower asphalt contents to coat the aggregate. In practice, the asphalt content of coarser aggregate mixes is increased to provide enough binder to decrease segregation potential.

3.2.3 Mix Design Criteria

Table 3.2 also provides a list of the parameters defined in the MDOT specified mix design criteria. These include: the voids in mineral aggregate (VMA), the percent air voids (AV), the fine/binder ratio mix, the minimum fine aggregate angularity, the flow, the percent Los Angeles abrasion loss, the maximum percent of soft particles, the minimum Marshall stability. In this section, only the VMA and AV specifications are addressed. These two parameters have direct impact on the aggregate gradation and asphalt contents listed in Table 3.1.

Voids in Mineral Aggregate. The VMA is defined as the ratio of the total volume of air between the aggregate particles of a compacted aggregate-mineral filler mix to the total volume of the mix.

Air Voids. The AV is defined as the ratio of the volume of air in a compacted hot-mix asphalt concrete (HMAC) to the total volume of the mix.

The importance of the AV and VMA relative to the performance of asphalt concrete mixes was discussed by Hunter (1994). He stated that the aggregate structure should have enough VMA to:

1. Furnish the necessary space for the addition of a sufficient amount of binder to provide durability of the mix.

2. Provide a sufficient volume of air voids to avoid problems with plastic deformation and bleeding of the mix.

The MDOT specifications relative to VMA and AV (see Table 3.1) effectively limit the acceptable range (band) of aggregate gradation. After examination of the aggregate gradation data of Table 3.1 and the aggregate gradation band for 4C mix shown in Figure 3.1, one may

Table 3.1 MDOT Standard Asphalt Mixtures

Mixture Type		2B	2C	3B	3C	4B	4C	13	13A	11A	36A
Binder %		4.0-6.0	4.0-6.0	4.5-7.5	4.5-7.5	5.0-8.0	5.0-8.0	5.0-8.0	5.0-8.0	4.0-6.0	5.5-8.0
Percent Passing Indicated Sieve											
1 ½ inch	37.5 mm	100	100							100	
1 inch	25.0 mm	99 -100	99 -100	100	100					90 - 100	
¾ inch	19.0 mm	90 max.	90 max.	99 -100	99 -100	100	100	100	100	70 - 95	
½ inch	12.5 mm	78 max.	78 max.	90 max.	90 max.	99 -100	99 - 100	75 - 95	75 - 95	55 - 85	100
3/8 inch	9.5 mm	70 max.	70 max.	77 max.	77 max.	90 max.	90 max.	60 - 90	60 - 90	40 - 80	92 - 100
No.4	4.75 mm	52 max.	52 max.	57 max.	57 max.	67 max.	67 max.	45 - 80	45 - 80	25 - 65	65 - 90
No.8	2.36 mm	15 - 40	15 - 40	15 - 45	15 - 45	15 - 52	15 - 52	30 - 65	30 - 65	15 - 50	55 - 75
No.16	1.18 mm	30 max.	30 max.	33 max.	33 max.	37 max.	37 max.	20 - 50	20 - 50	10 - 40	
No.30	600 mm	22 max.	22 max.	25 max.	25 max.	27 max.	27 max.	15 - 40	15 - 40	7 - 32	20 - 50
No.50	300 mm	17 max.	17 max.	19 max.	19 max.	20 max.	20 max.	10 - 25	10 - 25	5 - 20	
No.100	150 mm	15 max.	15 max.	15 max.	15 max.	15 max.	15 max.	5 - 15	5 - 15	4 - 12	
No.200	75 mm	3 - 6	3 - 6	3 - 6	3 - 6	3 - 6	3 - 6	3 - 6	3 - 6	3 - 6	3 - 10
Cruched Min %		50	90	50	90	50	90	0	25	25	60

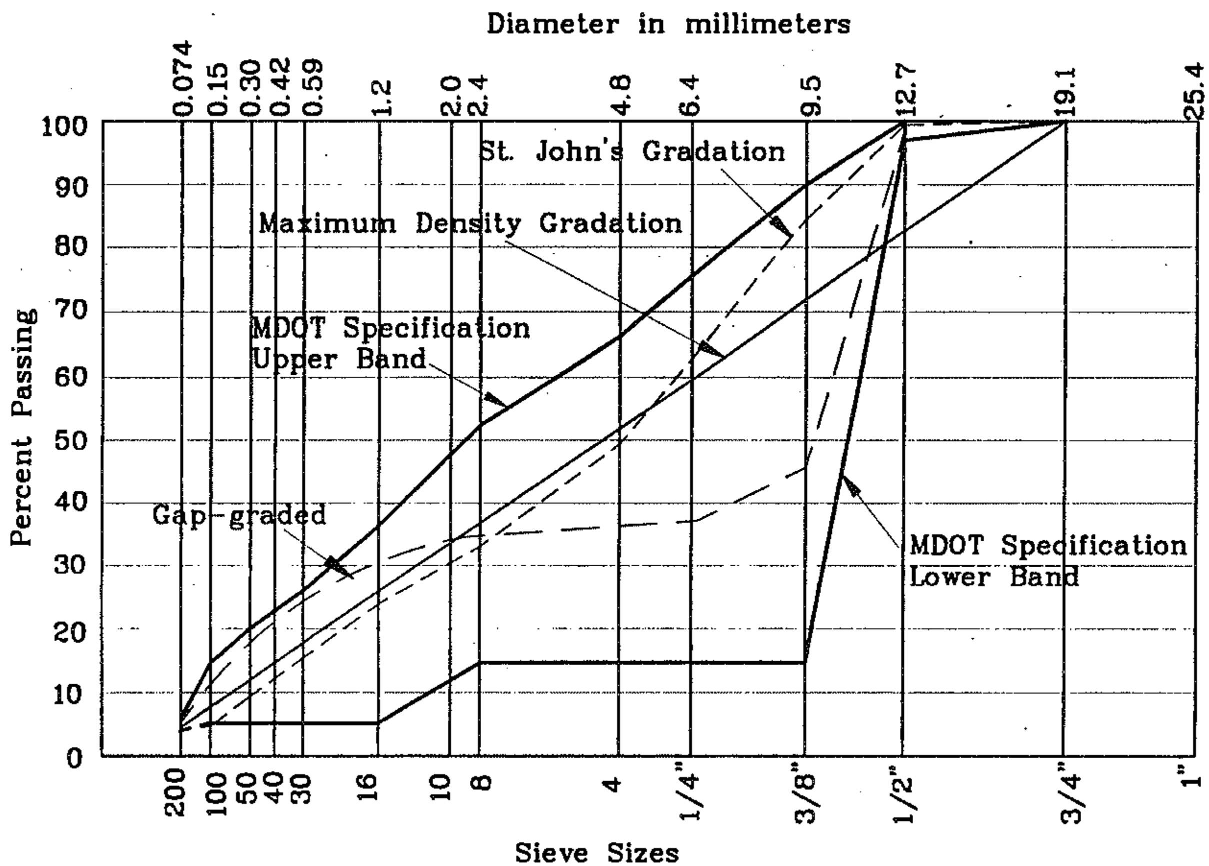


Figure 3.1 Aggregate Gradation for MDOT Specification (Mixture Type 4C)

have the impression that, given the wide range of aggregate gradation specifications, a contractor may deliver any gradation within the gradation band. This is not the case. For a typical job, most of the area within the gradation band of the aggregate mix in question will provide an aggregate mix that will not meet the MDOT mix design criteria relative to VMA and AV. Hence, in reality, the gradation range is much narrower than it may be seen in Figure 3.1. For example, for a 4C mix, if one uses an aggregate gradation located near the lower or the upper band of Figure 3.1 along with the specified asphalt content, then the mix design criteria relative to VMA or AV cannot be met. The point here is that the MDOT aggregate gradation specification provides a very wide gradation band, but the asphalt content and the mix design criteria effectively restrict that band. Such restriction however, is not based on the segregation potential of the mix. Within the given gradation band, asphalt content, and mix design criteria, one can still find a high number of aggregate gradations that satisfy the gradation specification, the asphalt content, and the design criteria and yet will have high segregation potential.

Further, if a contractor delivers an asphalt mix that meets the gradation specifications, the asphalt content, and the mix design criteria, and the segregation potential of the mix is very low, these should not imply that a segregation-free pavement will result. Segregation in the pavement depends not only on the original mix specifications regarding gradation, asphalt content, and the mix design criteria, but also on the resulting variation of the aggregate gradation from one point to another after the paving operation. This implies that, for segregation control, the aggregate gradation should be checked at three points in time as follows:

1. The contractor bid which includes the type and gradation of the aggregate to be used on the job (aggregate gradation specifications).

2. The end results of the asphalt mix design process conducted by the contractor (loose asphalt mixture specifications).

3. The as-constructed pavement (the mix design criteria).

Current MDOT practices address the above three items. However, the specifications for the last item (as-constructed pavement) are ill suited to prevent segregation. New specifications, or modifications of the existing specifications, concerning the differences in aggregate gradation between various points along the project are crucial to the success of segregation control and the implementation of an expedient test for determining segregation. Such specifications must address the differences in gradation between several points along the project relative to the aggregate gradation that was accepted in the bidding and asphalt mix design phases of the job in question.

3.3 MDOT Quality Control and Quality Assurance Procedures

Quality control (QC) and quality assurance (QA) are designed and implemented to ensure good quality of the final products (the compacted asphalt mixtures). QC is referred to the tests which can be conducted and the test results which can be used to control a product or to determine the quality of products. QA is related to the tests which can be used as an acceptance of a product. As stated above, the current MDOT QC/QA procedures provide methods for controlling the following three characteristics of asphalt mixtures; blended aggregate, loose asphalt mixtures, and compacted asphalt mixtures. One of these procedures however, need to be modified to minimize the segregation potential. The three procedures and the shortcomings are addressed below.

3.3.1 Blended Aggregate

As stated in the *Standard Specifications for Construction* (MDOT, 1996b), in the process of mixture production, aggregates are required to be stockpiled to minimize segregation potential. The following tests are required in MDOT specifications:

- Gradation (ASTM C136, ASTM C117)
- Crushed Particle Content (MTM 117)
- Deleterious Particle Content (MTM 110)
- Fine Aggregate Angularity Index (MTM 118)

Since aggregate gradation has a direct influence on segregation potential, only the gradation control test is discussed below.

The MDOT specifications require that the gradation of at least one sample be tested per production day. The problem is where to sample? Segregation or separation of coarse and fine aggregate in a stockpile typically occur at the bottom of the pile and/or during the entire mixing and paving process. It was recommended by MDOT (1988) that the pattern of segregation be taken into consideration when obtaining a representative sample. The specifications suggest general sampling locations for blended aggregates from rail cars, trucks, and stockpiles. The results of gradation analysis of the representative sample(s) are then checked against pre-specified target values of the percent passing certain sieve sizes (see Table 3.1).

The above scenario implies that if the gradation of the representative sample satisfies the specifications, the results should not be interpreted as the stockpile being segregation free. In certain areas of the stockpile, the aggregate may be segregated.

3.3.2 Loose Bituminous Mixture

The following quality control tests are typically conducted for loose bituminous mixture:

- theoretical maximum density (TMD);
- Marshall density;
- air voids;
- voids in mineral aggregate (VMA); and
- composition of the mixture which includes the following five options:

Option I :	asphalt binder content, blended aggregate gradation, and crushed particle content.
Option II :	asphalt binder content, crushed particle content, and blended aggregate gradation.
Option III :	asphalt binder content using the effective specific gravity, crushed particle content, and blended aggregate gradation.

Option IV :	asphalt binder content based on plant recording system, crushed particle content, and blended aggregate gradation.
Option V :	asphalt binder content determined by the incineration method, crushed particle content, and blended aggregate gradation.

Sampling loose bituminous mixtures is specified by MTM 313. The sampling materials are to be obtained at different time during the mixing and paving operations as follows:

- the conveyor belt;
- truck transports or paver hoppers;
- roadway prior to compaction;
- the skip conveyor delivering mixture to bin storage;
- funnel device feeding a conveyor for mixture delivery to storage; and
- the roadway after compaction.

The number of samples to be taken depends on the variation of the aggregate materials being used (MTM 313). Sufficient amount of materials need to be obtained for routine tests. If the samples are taken in place, according to the *Standard Specifications for Construction* (MDOT, 1996b), a minimum of three sublots need to be sampled for any one mixture type. The target values for the properties of loose asphalt mixtures are shown in Table 3.2.

3.3.3 Compacted Bituminous Mixture

Immediately after pavers lay down the loose asphalt mixtures, they are compacted at or near the specified compaction temperature. Several roller types can be used such as a smooth drum roller, vibrator, or rubber-tire roller. Rolling of the loose asphalt mixtures is accomplished in special pattern as to minimize shearing action in the asphalt mat. The purposes of compaction include (Hughes, 1989):

1. Reduce the air void contents to acceptable levels.
2. Improve the strength and durability of the asphalt mat.
3. Enhance the resistance to deformation under loads.
4. Decrease the asphalt permeability to minimize water damage.

In order to ensure sufficient compaction, the as-compacted asphalt mat and core densities are specified by MDOT. The specifications require that the as-compacted density of the asphalt mat meets certain percentages of the control density. According to the *Special Provision for Bituminous Mixture and Pavement Density Acceptance* (MDOT, 1996a), for projects with quality control/quality assurance (QC/QA) testing, the value of the control density is based on the value of the theoretical maximum density (TMD).

For a typical asphalt pavement project, the project is divided into lots. Each lot consists of five continuous sublots where a sublot is defined as a variable increment of mixture production (MDOT, 1996a). In the case of end-of-job production, if one or two sublots are remaining, they will be added to the previous lot. If there are 3 or more sublots remaining, they will be considered as a separate lot. Nevertheless, the density of the compacted asphalt mat is measured

Table 3.2 Mix Design Criteria

Mixture Type	**2B**	**2C**	**3B**	**3C**	**4B**	**4C**	**13**	**13A**	**11A**	**36A**
VMA Min. %	13.5	13.5	15	15	16	16	15.5	15.5	13.5	16.5
Air Voids % Target	3	3	3.5	3.5	3.5	3.5	3	3	3	3
Fines/Binder Ratio Max.	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Fine Agg. Angularity Min.	3	4	3	4	3	4	2	2.5	2.5	3
Flow (mm)	2.0 - 4.0	2.0 - 4.0	2.0 - 4.0	2.0 - 4.0	2.0 - 4.0	2.0 - 4.0	2.0 - 4.0	2.0 - 4.0	2.0 - 4.0	2.0 - 4.0
L.A. Abrasion max. % Loss	40	40	40	40	40	40	40	40	50	40
Soft Particle Max. %	12	12	12	12	8	8	8	8	12	8
Stability Min.	5.3 kN	5.3 kN	5.3 kN	5.3 kN	5.3 kN	5.3 kN	4.0 kN	4.0 kN	4.0 kN	4.0 kN

Table 3.2 (continued) Mix Design Criteria

Data based on June 10, 1996

	Shoulder Only	**Com. ADT *1 0-250**		**Com. ADT 251-1000**		**Com. ADT 1001-3500**	**Com. ADT >3500**
TOP	**13** 18.4 lb/ft^2 *2 & 3 to 28.7 lb/ft^2	**13A** 18.4 lb/ft^2 to 28.7 lb/ft^2	**36A** 12.3 lb/ft^2 to 18.4 lb/ft^2	**4B** 18.4 lb/ft^2 to 28.7 lb/ft^2	Local Agency Use Only **36B** 12.3 lb/ft^2 to 18.4 lb/ft^2	**4C** 18.4 lb/ft^2 to 28.7 lb/ft^2	
LEVEL	**13** 18.4 lb/ft^2 to 28.7 lb/ft^2	**13A** 18.4 lb/ft^2 to 28.7 lb/ft^2	**36A** 12.3 lb/ft^2 to 18.4 lb/ft^2	**3B** 24.6 lb/ft^2 to 36.9 lb/ft^2	Local Agency Use Only **36B** 12.3 lb/ft^2 to 18.4 lb/ft^2	**3C** 24.6 lb/ft^2 to 36.9 lb/ft^2	Request Recommendations from Bituminous Technical Service Unit of C & T Division
BASE	**13** 18.4 lb/ft^2 to 28.7 lb/ft^2 OR If total base >28.7 lb/ft^2 then must use **11A** 30.7 lb/ft^2 to 55.3 lb/ft^2	**13A** 18.4 lb/ft^2 to 28.7 lb/ft^2 OR If >28.7 lb/ft^2 then must use **11A** 30.7 lb/ft^2 to 55.3 lb/ft^2 OR **2B** 30.7 lb/ft^2 to 50.3 lb/ft^2		**3B** 24.6 lb/ft^2 to 36.9 lb/ft^2 OR If >36.9 lb/ft^2 then use **2B** 38.9 lb/ft^2 to 55.3 lb/ft^2		**3C** 24.6 lb/ft^2 to 36.9 lb/ft^2 OR If >36.9 lb/ft^2 then use **2C** 38.9 lb/ft^2 to 55.3 lb/ft^2	

*1: Selection is based on commercial ADT in one direction in the design lane (average the present and future ADT. On multi lane: 90% in right lane.

*2: Bituminous application rates shown in the table above are the required minimum and maximum rates to be used for specified mixes. Pavement designs requiring bituminous mix thicknesses greater than specified maximum will require multiple lifts of the leveling and/or base mixes.

*3: Application rate 12.3 lb/ft^2 per one inch thickness.

by using a nuclear density gauge. For each lot, several density readings are obtained and the average density per lot is calculated. Further, for each lot, several pavement cores are extracted and the density of each core is determined in the laboratory. The compacted asphalt mat along a lot will be accepted if the average density of that lot satisfies the following two conditions:

1. The average density of the compacted asphalt mix in a lot is equal to or greater than 94.0%, but less than or equal to 96.0%.

2. The densities of the pavement cores satisfy the conditions listed in the density core table (Table 3.3).

Table 3.3 Pavement Density Core Table (MDOT,1996a)

Number of Lot Cores	6% Bituminous Quality Initiative		10% Negative Adjustment	25% Negative Adjustment
Criteria	Minimum Number of Cores 94% ≤ Density ≤ 96%	Minimum Number of Cores 92% ≤ Density ≤ 97%	Minimum Number of Cores Density < 92% Denisty > 97%	Minimum Number of Cores Density < 91%
3	2	2	2	2
4	2	3	2	2
5	3	4	2	2
6	4	4	3	2
7	4	5	3	2
8	5	6	3	2
9	6	7	3	2
10	6	8	3	3
11	7	8	4	3
12	8	9	4	3
13	8	10	4	3
14	9	11	4	3
15	10	12	4	4

For projects with small tonnage, the density of the compacted asphalt mixtures is measured along six randomly selected locations. The TMD is obtained from the job mix formula (JMF). If the average of the six nuclear density values is equal to or greater than 92.0%, but less than 97.0% of the control density, then the compaction is acceptable.

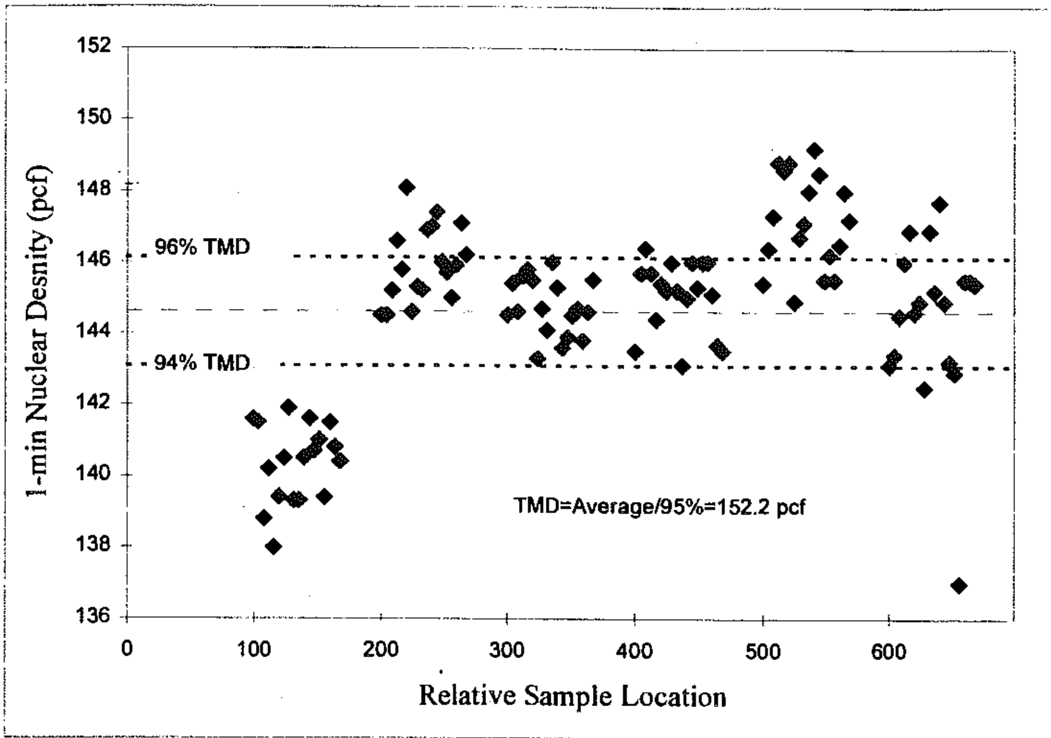
For those projects which are not mentioned above, the nuclear density gauge will be used to determine the field density. A minimum of 97 percent of the control density is required. Although such density specifications address the average quality of compaction, they do not address the problem of segregation. To illustrate this point, consider the data presented in Figures 3.2a and 3.2b. Figure 3.2a depicts the as-constructed nuclear density data obtained from the St. John's bypass (Site 1, a heavily segregated pavement). The data was obtained from a stretch of the road about 150 feet long. If one assumes that 152 pcf represents the control density (nuclear density measurement is typically lower than lab density), then the pavement is acceptable because the average measured density (144.7 pcf) is within specifications (96 to 94 percent of the control density). Similarly, if one assumes that the lab control density is 155 pcf, then the laboratory determined core density data is acceptable because the average of 149.5 pcf is within the specifications. It can be seen from both figures that some of the nuclear and some of the laboratory density data along the relative location 100 (column 1) are significantly below the 94 percent, while the data along location 500 (column 5) is significantly above the specification limit of 96 percent. Those two relative locations were found to be heavily segregated. Once again, based on the average density value, the pavement is acceptable. Similar data were also obtained from M-99 South of the City of Lansing and it is shown in Figures 3.3a and 3.3b

3.3.4 Other MDOT Specified Limits

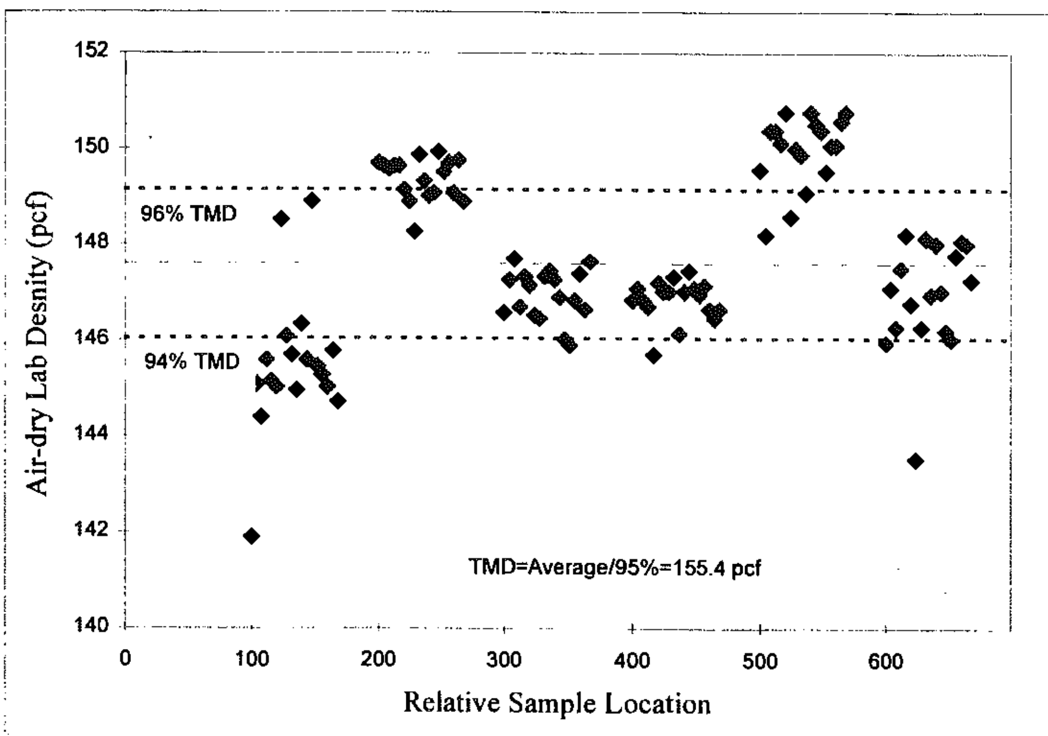
In addition to density of the as-compacted asphalt mixtures, tolerance limits for other parameters are also specified by MDOT. Although such limits do not have a direct impact on segregation, for completeness purposes, they are listed in Table 3.4 for projects with QC/QA or with small tonnage and in Table 3.5 for projects without the bituminous mixture and pavement density acceptance special provision.

Table 3.4 Tolerances of Mixture Properties

Parameter	Tolerance
Voids in Mineral Aggregate	± 1.20 %
Theoretical Maximum Density	± 19.22 kg/m^3
Marshall Air Voids	± 1.00 %
Asphalt Binder Content	± 0.50 %
Crushed Particles	± 15 %

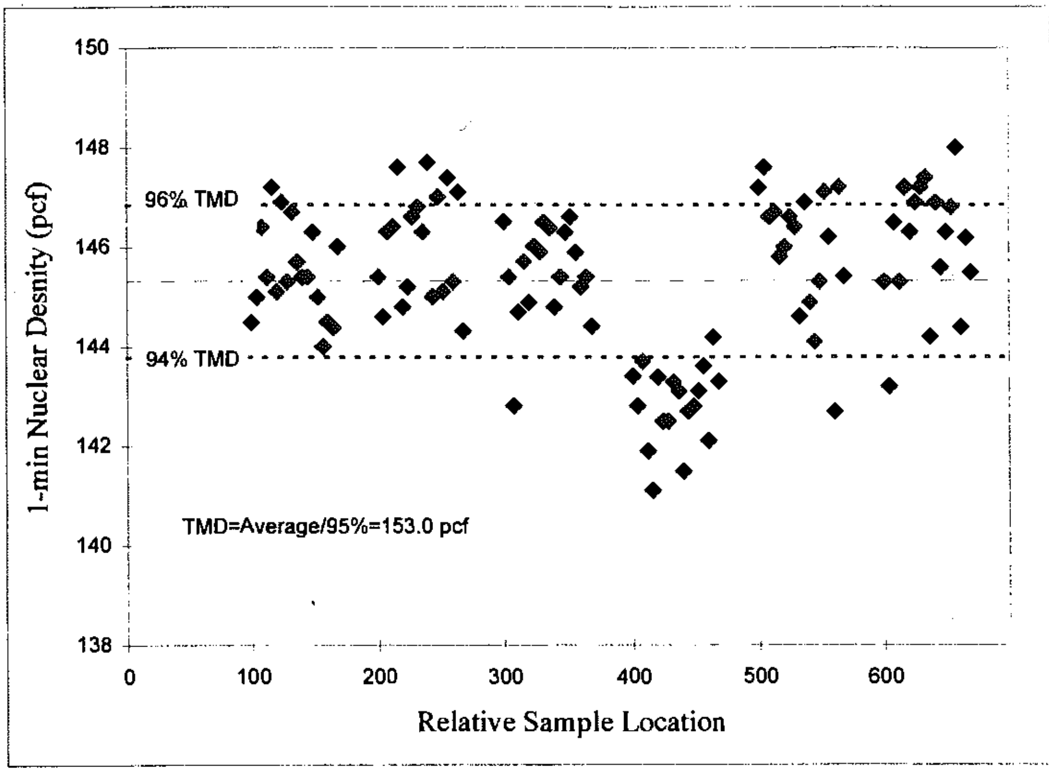


(a.) 1-min Nuclear Density

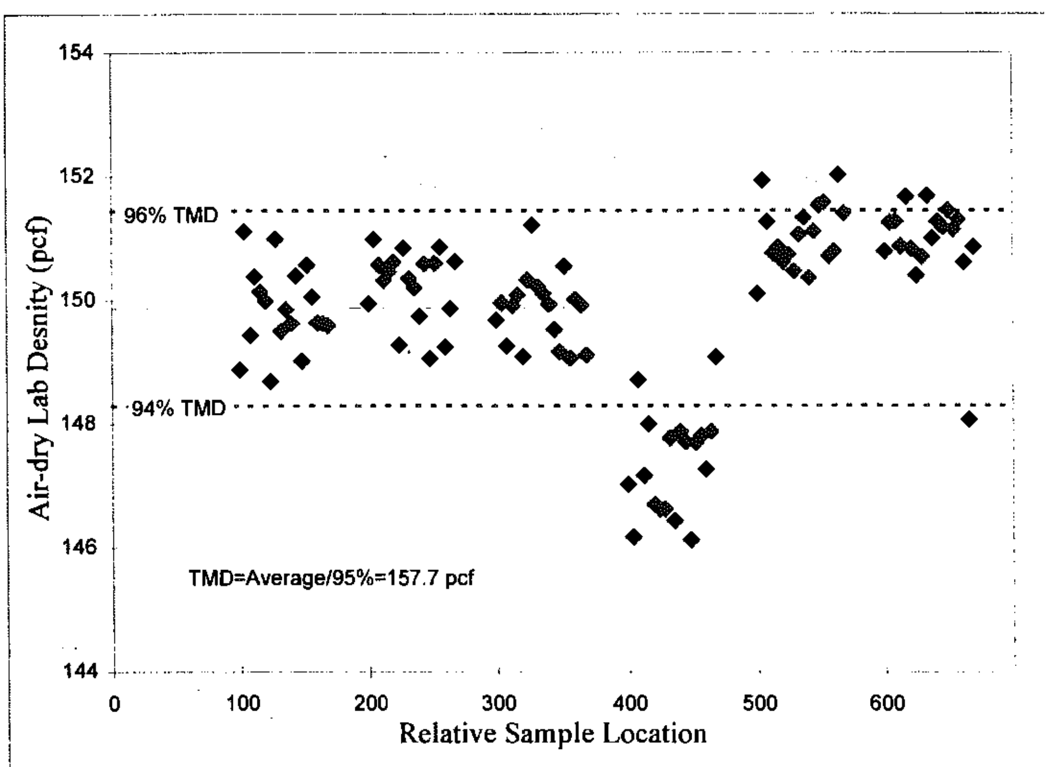


(b.) Lab Air-Dry Density

Figure 3.2 Desnity Variation with Control Bands at Site 1 - St. John's



(a.) 1-min Nuclear Density



(b.) Lab Air-Dry Density

Figure 3.3 Density Variation with Control Bands at Site 4 - M-99

Table 3.5 Uniformity Tolerances Limits for Projects Without the Bituminous Mixture and Pavement Density Acceptance Special Provision

Course	Range *	Percentage Passing Sieve Size				Asphalt Content
		all sizes ≥ 4.75 mm	2.36 mm	600 µm	75 µm	
Top and Leveling	Range 1	± 5.0	± 5.0	± 4.0	± 1.0	± 0.40
Top and Leveling	Range 2	± 8.0	± 8.0	± 6.0	± 2.0	± 0.50
Base	Range 1	± 7.0	± 7.0	± 6.0	± 2.0	± 0.40
Base	Range 2	± 9.0	± 9.0	± 9.0	± 2.0	± 0.50

* This range allows for normal mixture and testing variations. The mixture shall be proportioned to test as closely as possible to the JMF.

NOTE: In general, the aggregate gradation and asphalt content should be maintained within the range 1 uniformity tolerance limits. As mentioned by MDOT (1996), if two consecutive aggregate gradations on one sieve or asphalt contents are outside range 1 but within range 2 tolerance limits, the contractor shall suspend all operations.

4. Field and Laboratory Investigations

As described in Chapter 1, the development of an expedient test for segregation depends on correlating density differences to observed segregation. To investigate such correlations, an extensive field and laboratory testing programs were conducted. These include:

- Selection of seven test sites.
- Field determination of pavement density using a nuclear device.
- Field coring at six of the sites.
- Laboratory determination of density of the pavement courses within the cores.
- Laboratory determination of aggregate gradation of the pavement courses.

In addition, falling-weight deflectometer data was obtained at two of the sites (M-123 and Lansing state police facility) to find any possible correlation between deflection and nuclear density.

4.1 Site Selection

The field test sites were jointly selected by MSU researchers and MDOT engineers. Although the emphasis was on pavements exhibiting various degrees and types of segregation, some non-segregated areas were included. In order to avoid aging effects, recently-constructed sites were favored. The seven sites are shown in Table 4.1. The locations of the seven sites are shown in Figure 4.1.

4.2 Sampling Grid

As described in Chapters 1 and 5, the primary emphasis of this project was the detection of linear segregation by comparing differences in parameter statistics representing the properties of longitudinal strips or stripes running in the direction of paving. Sample locations at each test site were thus obtained based on a six-by-six sampling grid, with columns oriented in the longitudinal direction (parallel to the direction of paving) and rows oriented in the transverse direction (across the paved width) as shown in Figure 4.2 To mark test locations, the grid was painted on pavement surface at each test site. Each circle (location) in Figure 4.2 designated the locations of three 6-inch diameter circles. Each circle designate a sample. Hence, the three circles were considered a triplicate. The reason for the triplicate is to obtain enough materials for laboratory testing. Each circle (sample) was designated by a 3-digit number xyz, where x is the row number, y is the column number, and z is the number of sample in a triplicate. For example, sample 242 designates the second sample of a triplicate located at the intersection of row 2 and column 4.

Table 4.1 Test Sites

Site	Basis for Selection	Pavement Age (year)
1. St. John's Bypass, U.S. 27	notable linear segregation	0.75
2. Muskegon, U.S. 31	linear segregation	0.5
3. Muskegon (random), U.S. 31	random segregation	0.5
4. Lansing, M-99	believed unsegregated	1
5. Gaylord, Old US 27	extensive segregation	0.1
6. St. Ignace, M-123	mix of linear and random segregation	3
7. Lansing State Police Facility	slight segregation	0.6

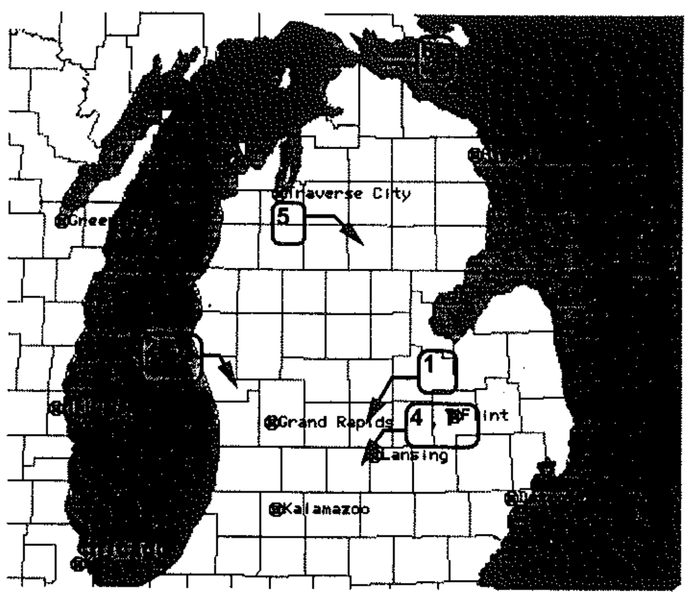


Figure 4.1 Location of Test Sites

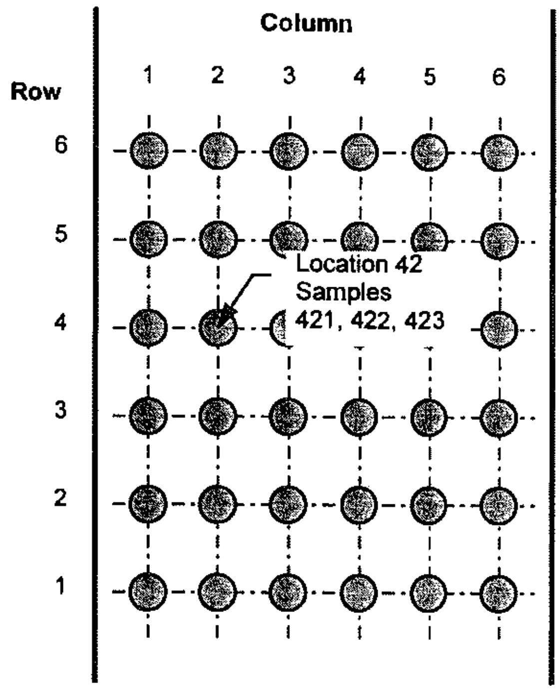


Figure 4.2 Sampling Grid

Six columns were used to provide comparative data along a number of pavement areas, e.g., sides, near-center, and intermediate strips. Six rows were provided to provide as large a sample size in each column as practical to permit reasonably confident statistical comparisons while minimizing the volume of data.

It should be noted that the distances between rows and between columns need not be equal, nor be any fixed dimension. Furthermore, columns need not be straight. Where linearly segregated areas were observed, some sample columns were laid out to follow the segregated areas; remaining columns were defined along apparently unsegregated areas. Columns were aligned to follow areas of apparently similar degree of segregation. If randomly segregated areas were identified, then sample locations were adjusted to fall in observed segregated areas, such as the Muskegon random site. If no segregation was apparent from visual inspection, the distances between columns were made equal.

Rows were spaced to uniformly cover the length of pavement for which a segregation evaluation was to be made. The total length of a test area was made short enough that similar conditions were expected, but long enough that the six measurements in each columns could be considered independent. Row spacings were typically 25 to 50 inches, except Site 5. Too short a row spacing would lead to correlation (non-independence) of samples within a column; too long a row spacing may lead to lack of similarity over the length of a column. The basic idea is that some columns may be areas of linear segregation and others may not be; and that there should be a sufficient number of measurements in each column to do meaningful statistical tests.

Following this approach, a unique sampling grid was developed for each of the seven sites. These are shown in Figures 4.3 through 4.9.

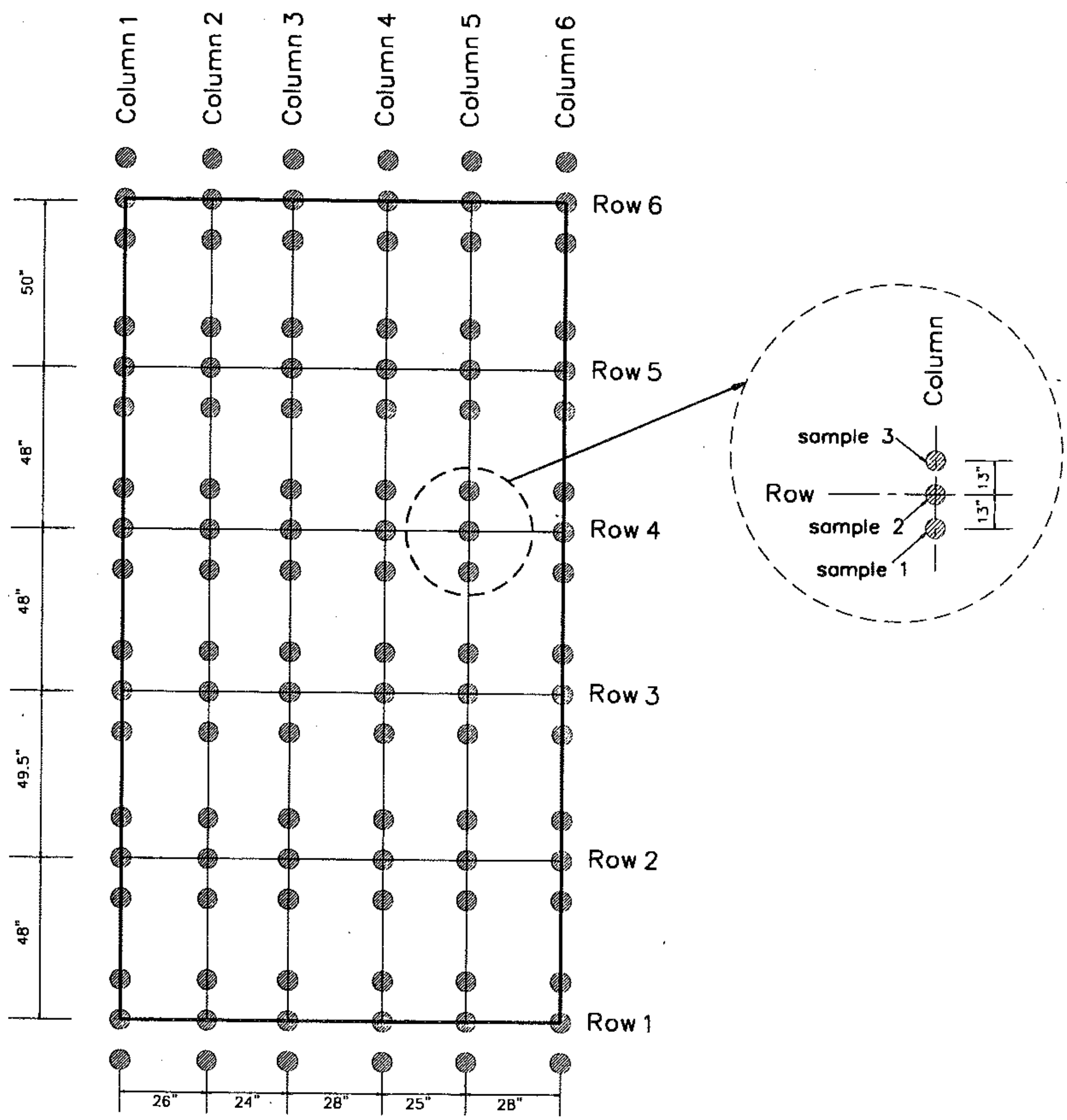


Figure 4.3 Layout of Sampling Grid at Site 1 - St. John's

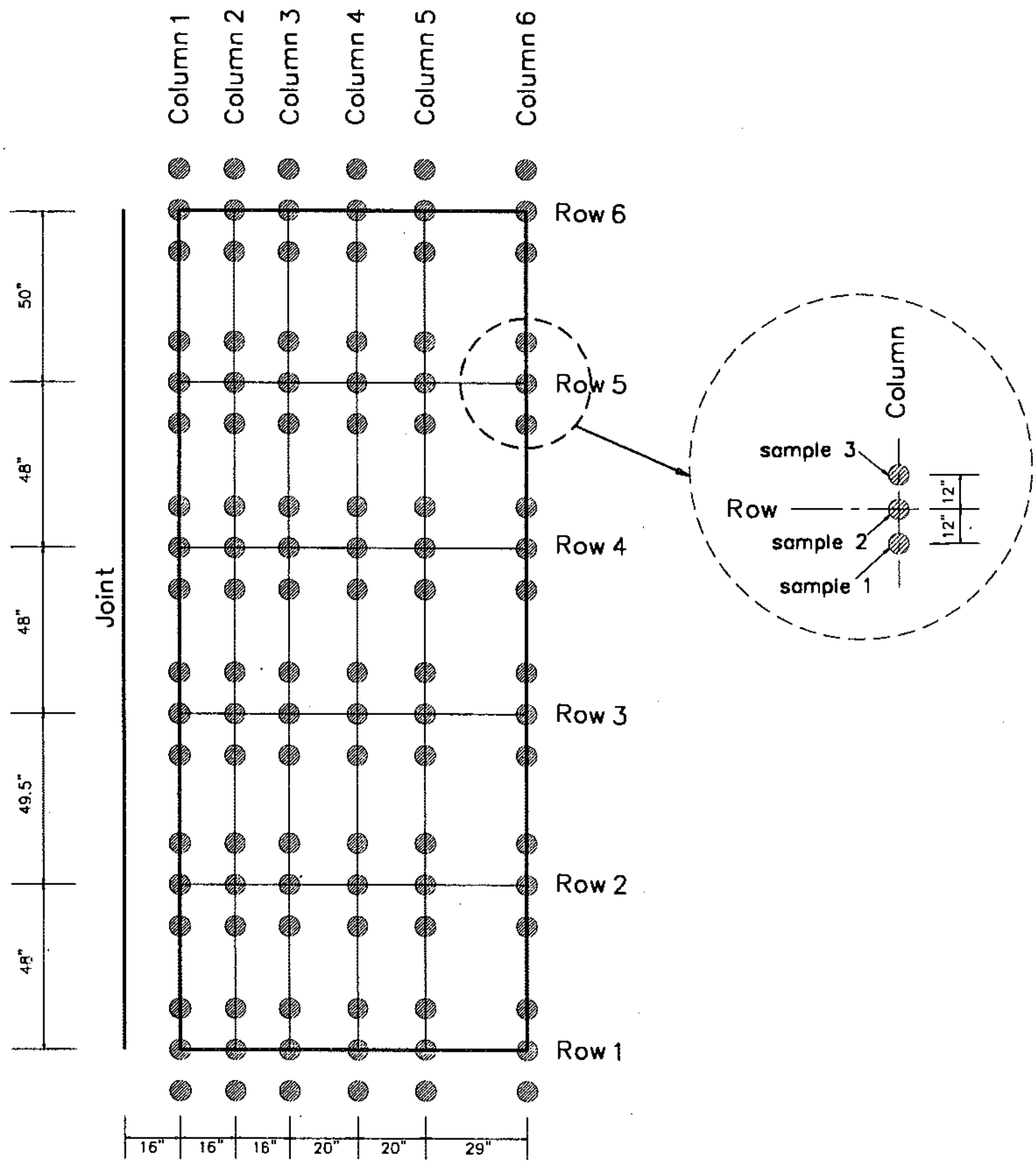
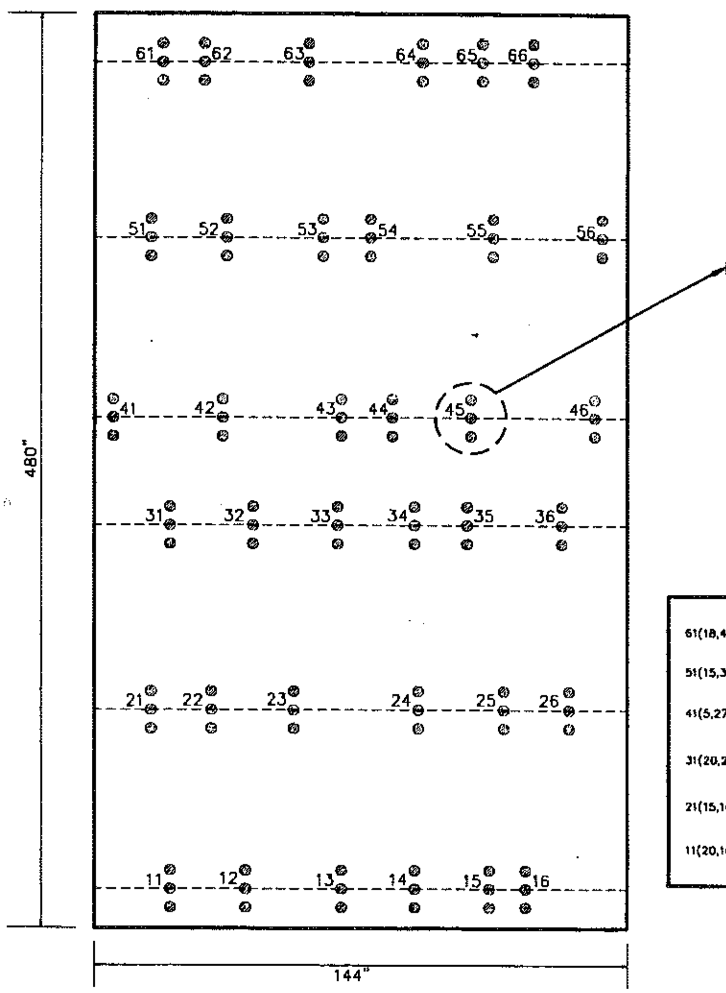
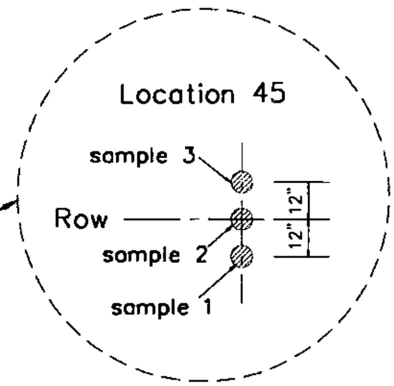


Figure 4.4 Layout of Sampling Grid at Site 2 - Muskegon (uniform)





Coordinate for Each Location

61(18,454)	62(29,454)	63(57,454)	64(88,454)	65(104,454)	66(118,454)
51(15,360)	52(35,360)	53(61,360)	54(74,360)	55(107,360)	56(137,360)
41(5,273)	42(34,273)	43(66,273)	44(80,273)	45(101,273)	46(135,273)
31(20,205)	32(42,205)	33(65,205)	34(88,205)	35(100,205)	36(126,205)
21(15,106)	22(31,106)	23(53,106)	24(87,106)	25(110,106)	26(128,106)
11(20,10)	12(40,10)	13(66,10)	14(88,10)	15(108,10)	16(116,10)

Figure 4.5 Layout of Sampling Grid at Site 3 - Muskegon (random)

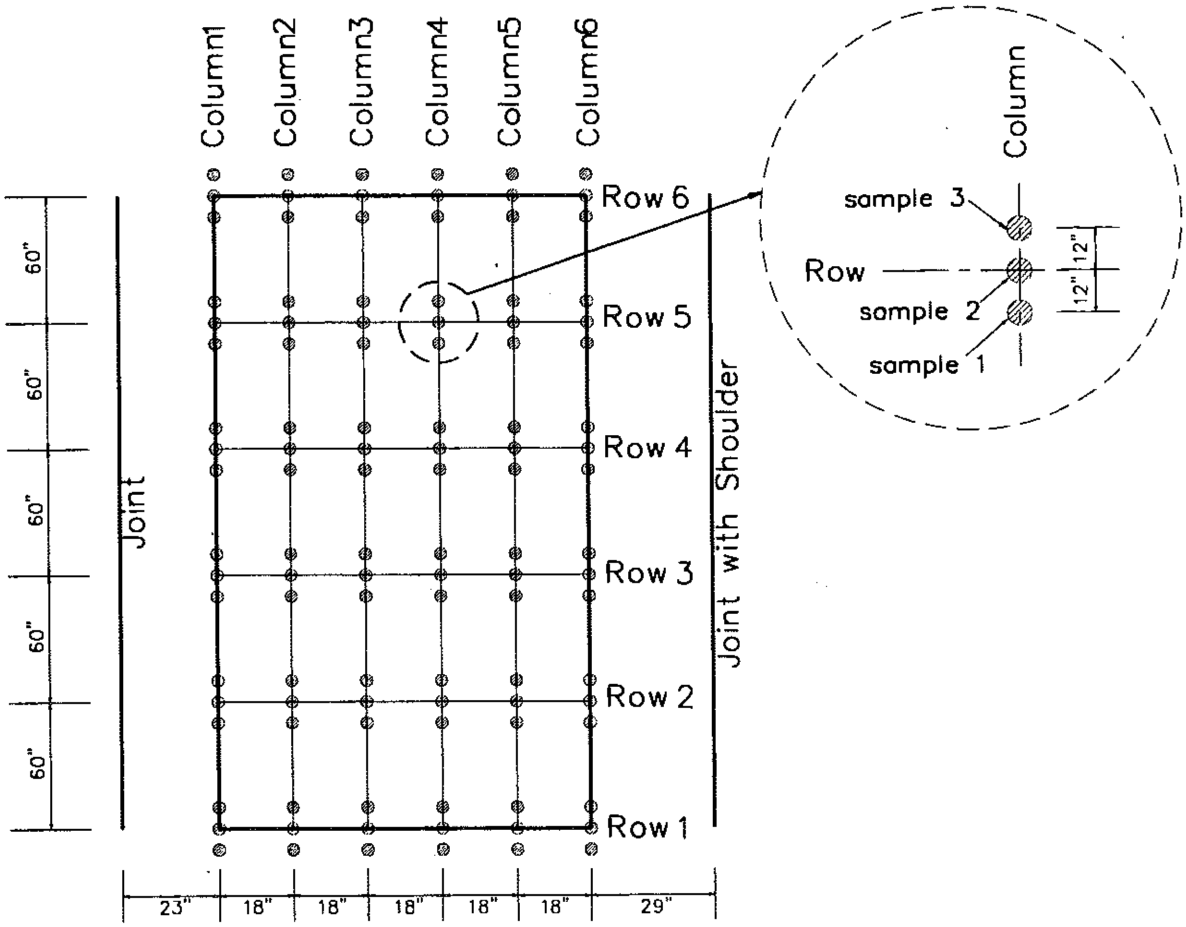


Figure 4.6 Layout of Sampling Grid at Site 4 - M-99

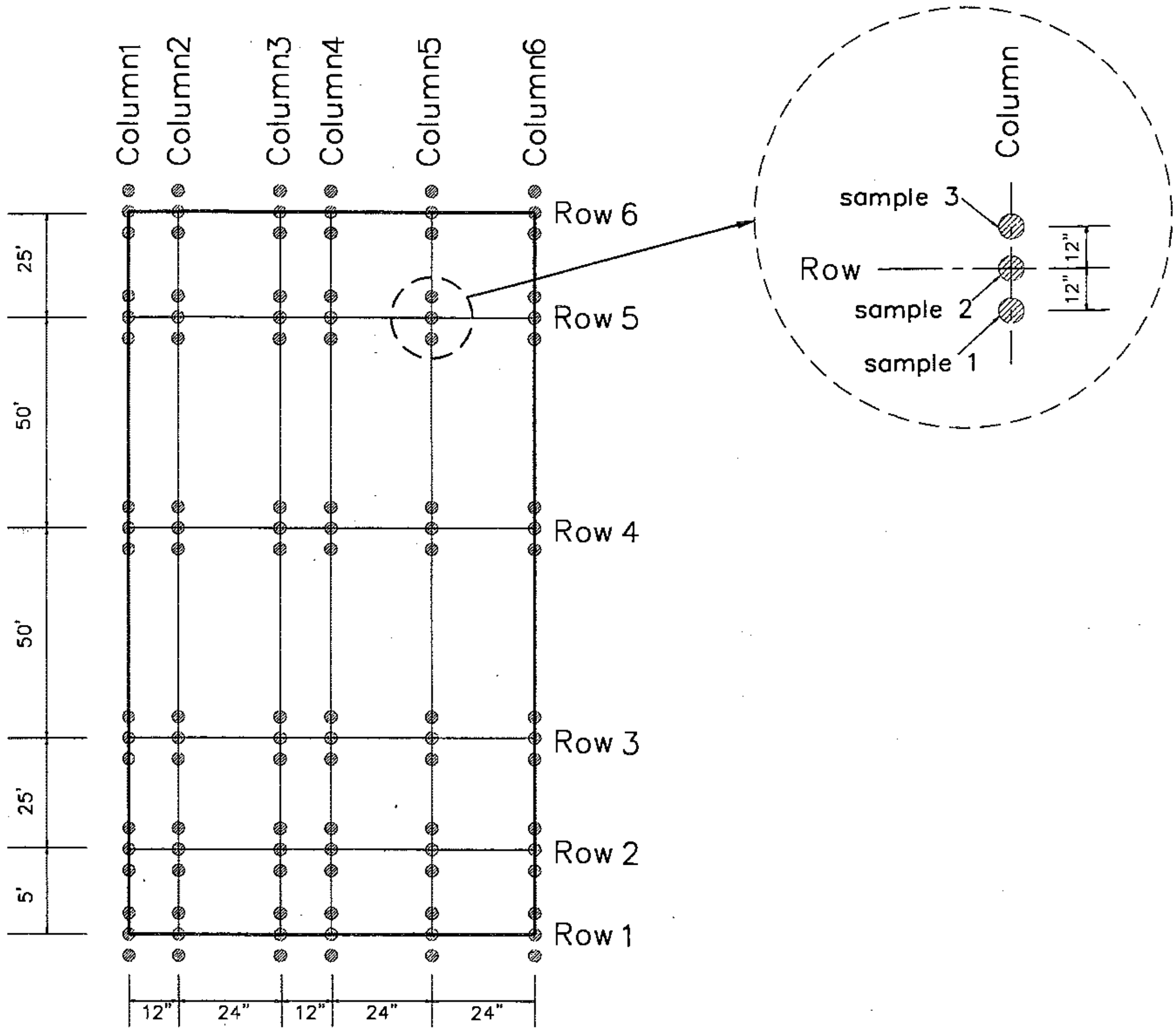


Figure 4.7 Layout of Sampling Grid at Site 5 - Old U.S. 27

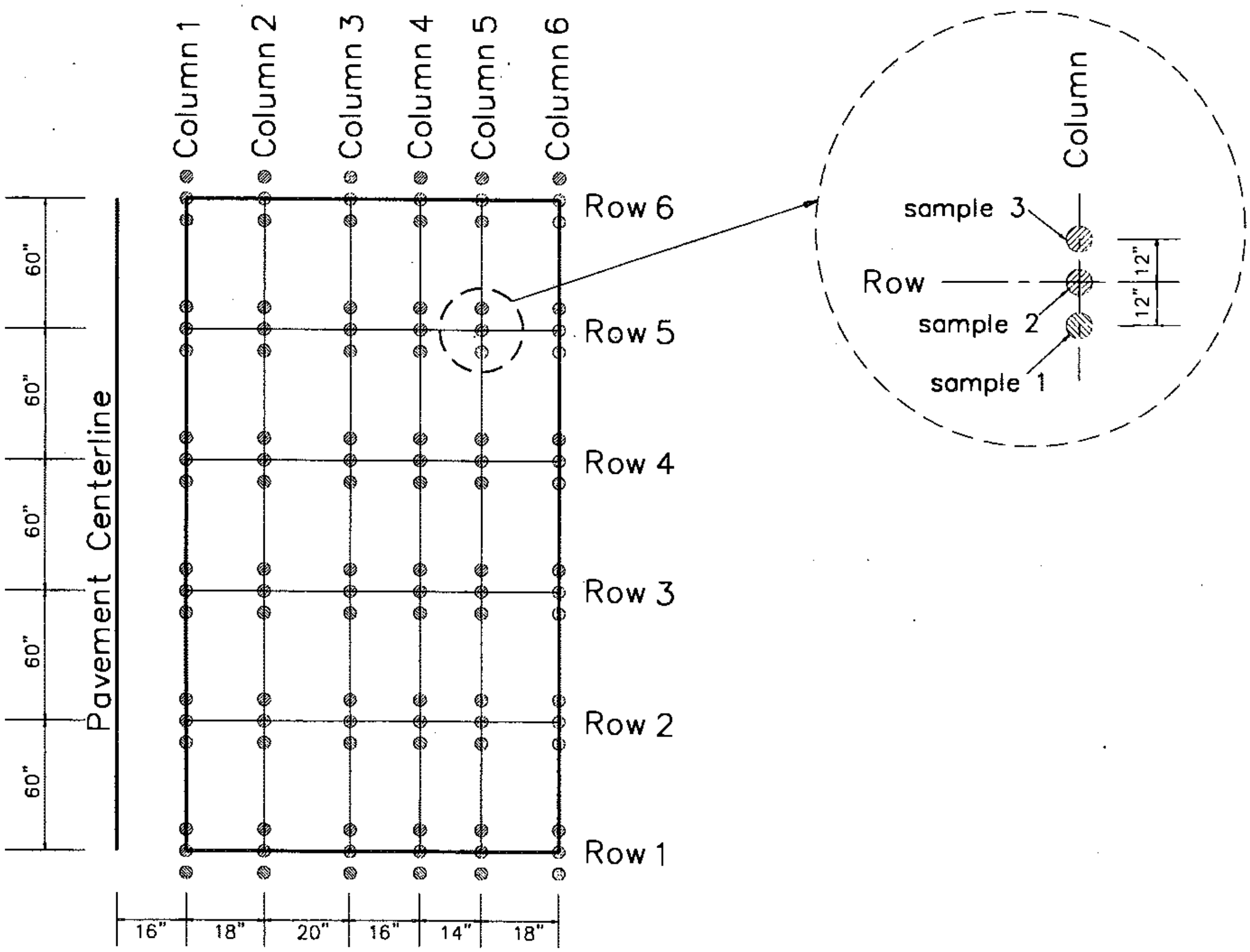


Figure 4.8 Layout of Sampling Grid at Site 6 - M-123

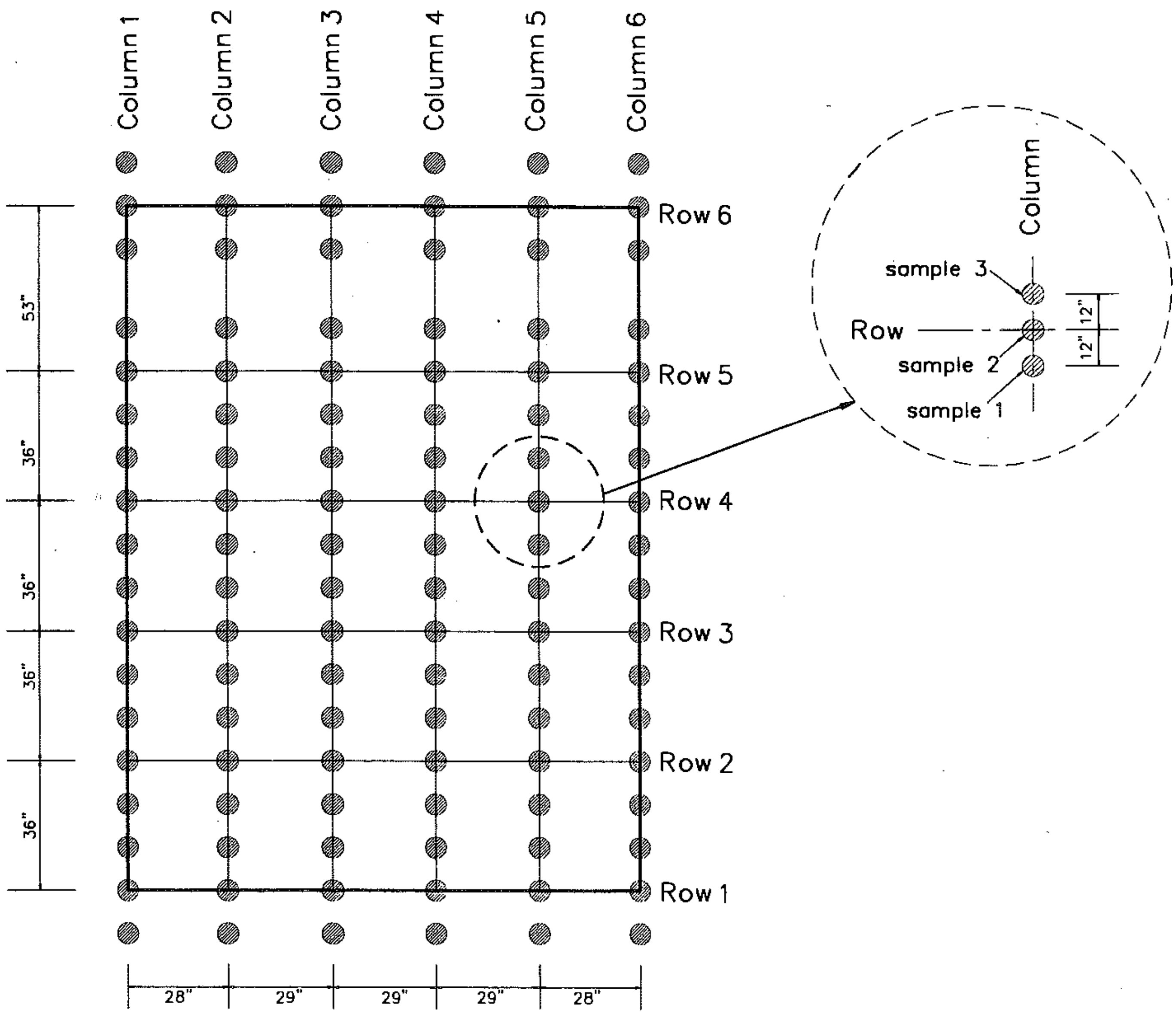


Figure 4.9 Layout of Sampling Grid at Site 7 - Lansing State Police Facility

4.3 Segregation Mapping

Where differences in segregation across a site were visually notable, the segregation was mapped and qualitatively described using the following terms: heavy, medium, and light.

4.4 Field Testing

4.4.1 Nuclear Density Testing

After MSU personnel marked the sampling grid on each test site, MDOT personnel obtained measurements using a nuclear density gauge. At each core location (36 sample locations times 3 cores = 108 measurements) the gauge was placed over the proposed core location (at the center of a 6-inch circle that was painted on the pavement surface) to obtain count readings indicating total density and moisture content. At sites 2, 3 and 4, both one-minute and four-minute counts were obtained; at the remaining sites, only one-minute counts were obtained. The count readings were directly converted to values of density and asphalt content based on the internal calibration circuitry of the nuclear gauge. This requires that the gauge calibration procedure (using a block of standard, known density) is performed each day of testing.

The nuclear gauges used at each test site are listed in Table 4.2.

Table 4.2 Nuclear Gauges Used at Test Sites

Site	Duration of reading	Model	Gauge No.
Site 1: St. John's	1 min.	Troxler 3411	93060
Site 2: Muskegon Uniform	1 min.	Troxler 4640	101234
	4 min.	Troxler 3440	102079
Site 3: Muskegon Random	1 min.	Troxler 3440	102079
	4 min.	Troxler 4640	101234
Site 4: M-99	1 min.	Troxler 3440	102234
	4 min.	Troxler 3440	102234
Site 5: Old US 27	1 min.	Troxler 3411	89748
Site 6: M-123	1 min.	Troxler 3440	102082
Site 7: Lansing State Police Facility	1 min.	Troxler 3440	102081

4.4.2 Falling-Weight Deflectometer Testing

Non-destructive deflection tests using MDOT's KUAB falling weight deflectometer (FWD) were also performed at sites 6 and 7 by MDOT personnel. In these tests, an impulse force (load) is created by dropping a set of two weights from specific heights. The load is transmitted to the pavement through a circular loading plate with a 5.91 inch radius. Pavement surface deflections were recorded using nine sensors, set at distances of 0, 8, 12, 18, 24, 36 and 60 inches behind the loading plate and 12 inches left and front of the plate. The configuration of sensors is shown in Figure 4.10. At each FWD test location, four drops were made; the first drop was for seating purposes and the deflections from the other three drops were averaged at each measuring point to obtain the average shape of the deflection basin caused by the impact. The purpose of the tests was to determine whether or not segregated areas have different deflection magnitude and shape than unsegregated areas.

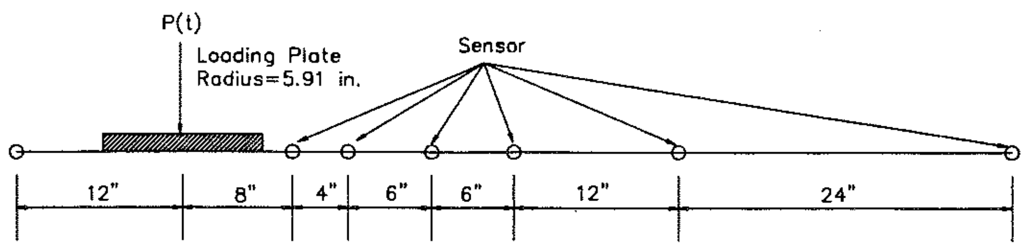


Figure 4.10 Configuration of FWD Sensors

4.5 Laboratory Testing

4.5.1 Sample Preparation

After field tests were completes at six sites, cores were obtained by MDOT personnel using a power rotary drill with a 6-inch coring bit. Each core was numbered as previously described. One-hundred-eight cores were taken at each test site and they were transported to MSU, where they were sawed to separate the base course, leveling course and surface course. The surface and leveling course specimens were used for laboratory density measurements, after which the asphalt binder was extracted and aggregate gradation analyses were performed.

4.5.2 Laboratory Density

For sites 1, 2, and 3, the air dry and the saturated surface dry (SSD) densities were measured for each of the surface and the leveling courses. For sites 4, 5, and 6, the two densities of the surface course only were measured.

Air-Dry Density. The air-dry density tests were conducted according to Michigan Test Method (MTM) 306. In this method, the actual specific gravity is defined as the ratio of the mass of a bituminous mixture to its volume divided by the density of water. The test consists of two steps: first, the mass of the specimen in air was recorded ; second, the apparent mass of the specimen while completely submerged in water was measured. Given these values, the actual specific gravity can be calculated as:

$$\text{Actual specific gravity} = \frac{A}{A - B}$$

where A = mass of the dry specimen in air
B = mass of the specimen in water

The specific gravity was multiplied by the unit weight of water, 62.4 lb/ft^3, to obtain the air-dry unit weight (density) in pounds per cubic foot.

Saturated Surface-Dry Density. The SSD density tests were conducted according to ASTM standard test D-2726 and MTM 315 to determine the bulk specific gravity using saturated surface-dry (SSD) specimens. The mass of the specimen is determined while immersed in a water bath at 25°C. After the mass is measured, the specimen is taken out from the water bath, blotted quickly with a damp towel, and weighed in air. The difference of the two mass measurements is taken as the mass of an equal volume of water at 25°C. The calculation to determine the bulk specific gravity of the saturated surface-dry specimen can be expressed as follows:

$$\text{Bulk Specific Gravity} = \frac{A}{B - C}$$

where A = mass of the dry specimen in air (g) obtained from the air-dry density test ;
B = mass of the saturated surface-dry specimen in air (g) ; and
C = apparent mass of the specimen in water (g).

The specific gravity was multiplied by the unit weight of water, 62.4 lb/ft^3, to obtain the SSD unit weight (density) in pounds per cubic foot.

4.5.3 Extraction of Asphalt Binder

Extraction of Asphalt Binder by High Temperature Oven Burning. After all the density tests were completed, the asphalt binder was extracted from the aggregate of the surface and leveling courses in accordance with the MTM 319. This permitted the remaining aggregate to be used for sieve analysis.

The extraction was performed at the MDOT laboratory by MSU personnel using a forced air ignition furnace preheated to 480°C. Each sample was simply placed evenly distributed within a basket which was placed in the furnace and burned until the stable light and audible indicated that the extraction process was complete. The aggregate was then retrieved and subjected to sieve analysis.

4.5.4 Gradation Tests

Once the aggregate and fine material left from the extraction process was cooled, the particle size distribution was determined by sieve analysis according to ASTM C136 and MTM 117. The sieve sizes used and the corresponding sieve opening sizes are listed in Table 4.3.

Table 4.3 Sieve and Opening Sizes Used in Gradation Tests

Sieve Size	Opening (mm)
0.75″	19
0.50″	12.5
0.375″	9.5
No. 4	4.75
No. 8	2.37
No. 16	1.18
No. 30	0.60
No. 50	0.30
No. 100	0.15
No. 200	0.075

5. Statistical Analyses and Software

5.1 Introduction

This chapter summarizes the statistical tests used for expedient assessment of pavement segregation, and describes two custom-designed spreadsheet templates for performing those tests and visualizing the associated data. Appendices A and B provide user's manuals for these spreadsheets, which contain lesser detail regarding the statistical procedures and greater detail regarding hands-on use of the spreadsheets.

5.2 Software

Two software products, each a custom-designed Excel™ spreadsheet, were developed for this project:

- MBITSEG1.XLS performs a set of comprehensive statistical analyses oriented toward detecting statistical differences among column data in the 6 by 6 test grid described in Chapter 4. Such differences are taken to be indicators of linear segregation. A key part of the research effort was to perform extensive analyses using MBITSEG1.XLS to analyze field density data, lab density data, and aggregate gradation data obtained from the seven test sites.

- MBITSEG2.XLS is a simplified spreadsheet intended for use in field construction. It performs statistical comparisons of two samples of up to 10 data points each, but requires the data sets be selected in the field based on visual selection of a presumed segregated area and a control area.

5.3 MBITSEG1.XLS

MBITSEG1.XLS is a spreadsheet template developed to evaluate the presence of linear segregation in hot-mix asphalt pavement. Given input data regarding properties of pavement materials (e.g. nuclear-measured density, lab-measured density, or percent passing some sieve) arranged in a 6 by 6 grid format, the spreadsheet performs a series of statistical tests to evaluate whether the differences in column statistics are significant. The main hypotheses is that areas of linear, longitudinal segregation will have statistically significant differences in properties of pavement materials than adjacent non-segregated areas.

Three-dimensional graphs are displayed by the spreadsheet to assist visualizing the variation of material properties across the grid and confirm whether the input data are correct. These plots may also be useful to asses the presence of a pattern of segregation in the testing pavement section

System requirements for running MBITSEG1.XLS are as follows:

- Windows^{TM}-version 3.1 or higher
- Excel^{TM} version 5 or higher

MBITSEG1 is arranged as a series of "sheets," each with its own function to enter data, display results, or perform statistical tests. These sheets, and the underlying statistical theory, are described in paragraphs 5.3.1 through 5.3.9.

5.3.1 Data Entry Sheet

MBITSEG1 has 11 tabs at the bottom of the screen, each representing a worksheet. When loaded, MBITSEG1 opens in the Data Entry sheet, show in Figure 5.1. This spreadsheet includes the following features:

- An *identification block* near the top left, wherein one can enter location, date and other Descriptive Information.

- A *data entry block* in the left center, consisting of a six by six matrix corresponding to the six by six test grid

- Some *user buttons*, to the right of the data entry block

- Displayed *results*, below and to the right of the data entry block.

Pavement Segregation Analysis Spreadshee T.F. Wolff
Michigan State University - Pavement Research Center of Excellence July 1996

Location: Sample Data -- from St. John's, samples xx1
Date: 9/11/95
Description: Samples xx1, unit weight

(updated 11/15/96)

Enter measured unit values in grid below

Column / Row	1	2	3	4	5	6
6	141.6	144.5	144.5	143.5	145.4	143.1
5	141.5	144.5	145.4	145.7	146.4	143.4
4	138.8	145.2	144.6	146.4	147.3	144.5
3	140.2	146.6	145.6	145.7	148.8	146.0
2	138.0	145.8	145.8	144.4	148.6	146.9
1	139.4	148.1	145.5	145.4	148.8	144.6
Edge						Edge
Tukey test	DIFF !	--	--	--	DIFF !	--
paired t tests	DIFF !	--	--	--	DIFF !	--
6 of 6 test	DIFF !	--	--	--	DIFF !	--

Clear — *Clears everything for a new proble Enter data, or press a key below.*

Example — *Enters example segregated data*

Random — *Enters a random sample*

YES ! <-- significant column differences?

Figure 5.1 Data Entry Sheet

The identification block and data entry block on the data entry sheet are the only areas where users can enter data. The remainder of the data entry sheet and the remaining worksheets are write-protected to prevent unintentional corruption of the formulas and other content.

Identification Block. In the identification block the user may enter information regarding the location where the data were obtained, (... the Job No. and control section...) the date, and other descriptive information. No calculations or database operations are performed from this data, it is strictly for identification. It is, however, automatically copied to the other worksheets.

Data Entry Block. In the data entry block, the user enters 36 data values on which columnwise statistical analyses are to be performed. For field use in evaluating linear segregation, these would normally be nuclear density values. However, in the research effort, these have also been lab density values, and percentages passing various sieves. They may be any quantitative data upon which it is desired to perform columnwise comparisons. These data are used by the other worksheets in performing graphing and statistical tests.

User Buttons. To the right of the data entry block are three user buttons:

Clear	Clicking on this button clears the data entry block for a new problem.
Example.	Clicking this button automatically fills the data entry block with example data from a segregated site.
Random.	Clicking this button fills the data entry block with a set of randomly generated nuclear density values. As these are random, they will usually not exhibit columnwise differences (indicating linear segregation) but occasionally will.

The latter two buttons are provided for training purposes, to easily get data onto the worksheet and demonstrate the program features.

Displayed Results. As data are input, statistical analyses are performed automatically on other sheets and results are reported back to the data entry sheet. An analysis of variance (ANOVA) is performed first, as described in section 5.3.6. The analysis of variance tests to see if any statistically significant columnwise differences are present in the data, and the final result is shown in the boxed cell to the right of row 1. A displayed **YES!** indicates there are statistically significant differences among mean values of columns and **NO!** indicates there are not.

If the box displays a **YES!** , it remains to be determined which columns are different from which. A set of statistical tests, namely the Tukey multiple comparison test, the Student t test, and the 'six-of-six" test are performed comparing each column to each, a set of fifteen possible comparisons The details of these tests are described in Sections 5.3.7 through 5.3.9. The tests are performed on separate worksheets and automatically reported back to the data entry sheet. If the statistics for any column are found to be statistically different from those of at least three other columns, the notation **DIFF !** is displayed below the data for that column. For the example data from the St. John's site, shown in Figure 1, columns 1 and 5 are each found to be significantly different, and all three statistical tests yield the same conclusion.

If the analysis of variance display box displays **NO**, the overall differences among column means are insufficient to suggest significant differences, and displayed **DIFF !** should generally be ignored.

5.3.2 Parameter Statistics Sheet

The second tab at bottom of screen is named "unit weight statistics." It is shown in Figure 5.2. However, its purpose is to calculate basic statistics on row and column data from the preceding data entry sheet, whether that data be unit weight values, percent passing a sieve size, or any other data. Basic statistics calculated include average (or mean) value, standard deviation and coefficient of variation of the entire set of 36 input values as well for the six values in each column and row.

User-input data from the data entry sheet is automatically copied to the parameter statistics sheet. Remaining features are described below.

Pavement Segregation Analysis Spreadsheet T. F. Wolff June 1996
Michigan State University - Pavement Research Center of Excellence

Location: *Sample Data – from St. John's, samples xx1*
Date: *12/6/96*
Description: *Samples xx1, Unit weight*

Color 1 — *Color Above and Below Average*
Clear Color

Column	1	2	3	4	5	6		Average	Standard Deviation	Coeff of Variation
Row										
6	141.6	144.5	144.5	143.5	145.4	143.1		143.77	1.338	0.93%
5	141.5	144.5	145.4	145.7	146.4	143.4		144.48	1.793	1.24%
4	138.8	145.2	144.6	146.4	147.3	144.5		144.47	2.981	2.06%
3	140.2	146.6	145.6	145.7	148.8	146.0		145.48	2.846	1.96%
2	138.0	145.8	145.8	144.4	148.6	146.9		144.92	3.665	2.53%
1	139.4	148.1	145.5	145.4	148.8	144.6		145.30	3.330	2.29%
Average	139.92	145.78	145.23	145.18	147.55	144.75	144.74	**144.74**	2.659	1.84%
Std. Dev.	1.457	1.391	0.547	1.050	1.431	1.471	1.224		**2.64285**	
Coeff. of Var.	1.04%	0.95%	0.38%	0.72%	0.97%	1.02%	0.85%			**1.83%**

Figure 5.2 Unit Weight Statistics Data Sheet

Average Values. The *average value* is a measure of central tendency. Average values of row and column data are displayed to the right of and below row and column data, respectively. The average value of the data in row or column j is calculated as:

$$\bar{x}_j = \frac{\sum_{i=1}^{n} x_{ij}}{n} \tag{5.1}$$

where n = 6.

With the example data shown in Figure 5.2, it can be noted that the average unit weight measured in column 1 (139.92 lb/ft^3) appears significantly lower than the average unit weights of other columns, suggesting segregation may be present. Similarly, the average unit weight of column 5 is somewhat high. The statistical significance of such low or high averages is further tested by the statistical tests described later.

Standard Deviations. The *standard deviation* is a measure of the dispersion of the data about the mean. The standard deviation of the population of all possible values in row or column j is estimated from the measured values as:

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)^2}{n-1}} \qquad (5.2)$$

where n = 6.

Standard deviations of row and column data are displayed to the right of an below the respective average values.

The standard deviation of each column or row is a measure of the variability in sets of six data values; higher values indicate greater variability. In an unsegregated pavement, density values would be expected to vary randomly. In a linearly-segregated pavement, columns would tend to have consistently low, intermediate, or high density values, with little variation in value within a column, and rows would tend to have greater variability as they are mixes of density values from different regions of the segregated pavement, see Figure 5.3. In the example in Figure 5.2, it can be seen that the row data has notably larger standard deviations than the column data, suggesting linear segregation.

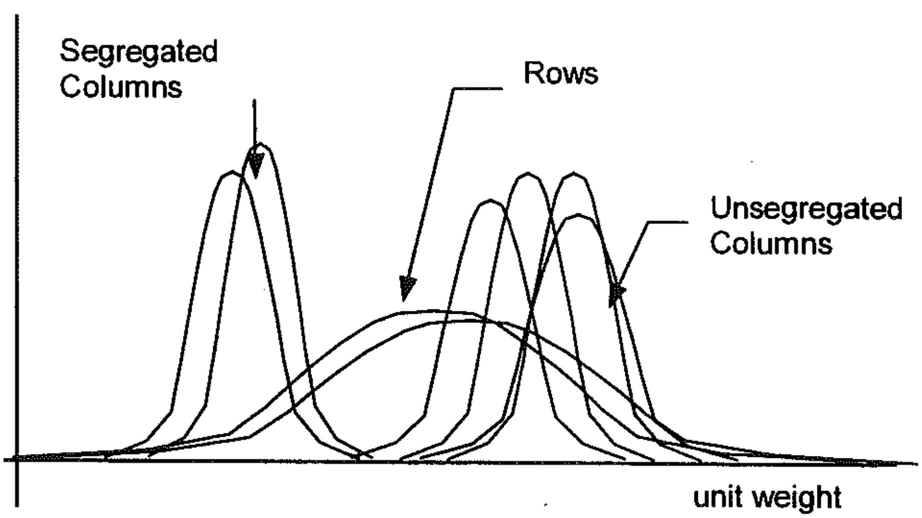


Figure 5.3 Expected Statistical Distributions

Coefficients of Variation. The *coefficient of variation* is the ratio of the standard deviation to the average or mean:

$$V_{x(j)} = \frac{\sigma_j}{\bar{x}_j} \tag{5.3}$$

The coefficient of variation provides a convenient dimensionless measure of variability. Values are reported to the right of and below the respective standard deviation values.

For the example segregated data, it can be noted that row values are generally larger than column values, providing a similar indication of linear segregation as that for standard deviation values.

Global Statistics. A similar procedure is used to find the global average, standard deviation and coefficient of variation of the entire set of 36 data vales. These are reported in boldface in the lower right portion of the sheet, at the intersection of the row and column values.

User Buttons for Color-Coding Data. The statistics sheet contains two user buttons to the right of the identification block. Clicking on the button marked **Color 1** colors cells with values below the average in yellow and those with values above the average in blue. This also provides a visual indication of correlated patterns of high or low density. Clicking on the button marked **Clear Color** erases the coloring and provides a clear background.

5.3.3 Parameter Graphs Sheet

The third tab on MBITSEG1.XLS is titled "unit wt graph." Clicking on it opens a worksheet that provides two three-dimensional graphs of the data entered on the data entry worksheet, usually unit weight (density) data. Figure 5.4 shows these graphs representing the data in the previous two figures. These two charts are identical in content, and differ only in the chart type, with one representing the data as row-wise ribbons and the other as a connected surface. Such charts, which are similar to topographical maps, permit a visualization of the degree of correlation of low or high density values within a sampled column at a suspected segregated site. For the segregated site shown, the previously indicated statistical differences in average column unit weight in columns one and five are notably apparent. Rather than observing values above and below the average randomly throughout the test grid, the values within each column are highly correlated with each other, but exhibit little correlation to values within other columns. This strongly suggests that the differences in unit weight are related to some aspect of the paving operation, such as the paver placing a material with different characteristics (e.g., gradation or quantity per area) near the edge of the paved lane (columns 1and 6) than at the next adjacent sample point along the auger (columns 2 and 5).

5.3.4 Standardized Statistics Sheet

Clicking on the fourth tab in MBITSEG1.XLS, titled "Std Data," opens the standardized statistics sheet shown in Figure 5.5. This sheet provides an alternative representation of the parameter statistics sheet where all values are transformed to *standardized values*, dimensionless quantities in a format commonly used in statistical analysis.

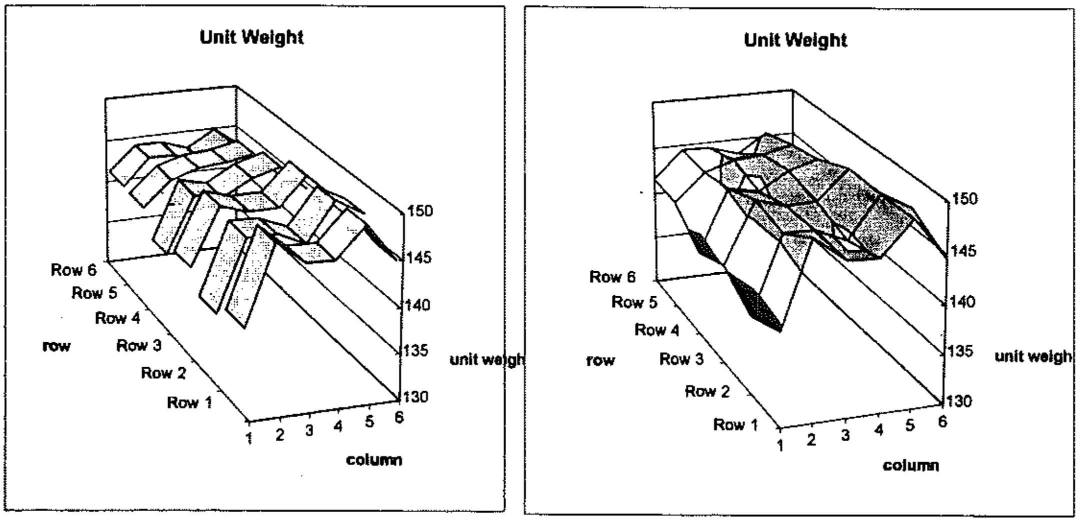


Figure 5.4 Unit Weight Graphs

It is sometimes helpful to examine the distribution of observations in a data set relative to their mean value and standard deviation rather than their absolute values. For example, it permits easy identification of "outliers," values that are unusually far above or below the mean. Standardized values, denoted by the variable z, simply measure the distance that a data value x_i, lies from the mean $\overline{x}$ in units of the standard deviation σ_x. Standardized values are calculated as :

$$z_i = \frac{x_i - \overline{x}}{\sigma_x} \tag{5.4}$$

where z_i is the standardized value
x_i is the data value
$\overline{x}$ is the mean (of all 36 data points in this case)
σ_x is the standard deviation (of the 36 data points)

For such standardized data, the global mean will be 0.00 and the global standard deviation will be 1.00. The standardized value z_i is a dimensionless quantity as the numerator and denominator are in the same units of measure. Hence, a value of -2.02 indicates that the associated data value is 2.02 standard deviations below the mean value.

The data displayed in Figure 5.5 is again that from the example segregated site shown in the preceding figures. In column one, it can be observed that all values are below average, as the signs are all negative, and further that all values are more than one standard deviation below the average. If the density variations were all merely random as opposed to being related to segregation, it would be expected that about half would be above the average and half would be below, with more values near zero. The average values for columns one and five are -1.82 and 1.06, respectively. This also implies segregation, as average z values within columns for a uniformly variable in-place property should generally be much closer to 0.0, as are the remaining columns and the row values.

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Location: *Sample Data -- from St. John's, samples xx1*
Date: *12/6/96*
Description: *Samples xx1, Unit weight*

Color 1 — *Color Above and Below Average*
Clear Color

Standardized Values

Column / Row	1	2	3	4	5	6		Average	Standard Deviation
6	-1.19	-0.09	-0.09	-0.47	0.25	-0.62		-0.37	0.506
5	-1.22	-0.09	0.25	0.36	0.63	-0.51		-0.10	0.678
4	-2.25	0.18	-0.05	0.63	0.97	-0.09		-0.10	1.128
3	-1.72	0.71	0.33	0.36	1.54	0.48		0.28	1.077
2	-2.55	0.40	0.40	-0.13	1.46	0.82		0.07	1.387
1	-2.02	1.27	0.29	0.25	1.54	-0.05		0.21	1.260
Average	-1.82	0.40	0.19	0.17	1.06	0.01	0.00	0.00	1.006
Std. Dev.	0.551	0.526	0.207	0.397	0.541	0.556	0.463		1.00

Figure 5.5 Standardized Statistics Sheet

5.3.5 Standardized Graphs Sheet

Clicking on the fifth tab in MBITSEG1.XLS, titled "Std Graph" opens the standardized statistics sheet shown in Figure 5.6. These are similar to the parameter graphs previously described, but are based on the standardized data on the previous sheet. As the global mean of any standardized data set is 0.00, it can be easily visualized where column values are consistently and substantially above or below the mean value. In Figure 5.6, the significant characteristics of columns 1 and 5 can again be readily observed.

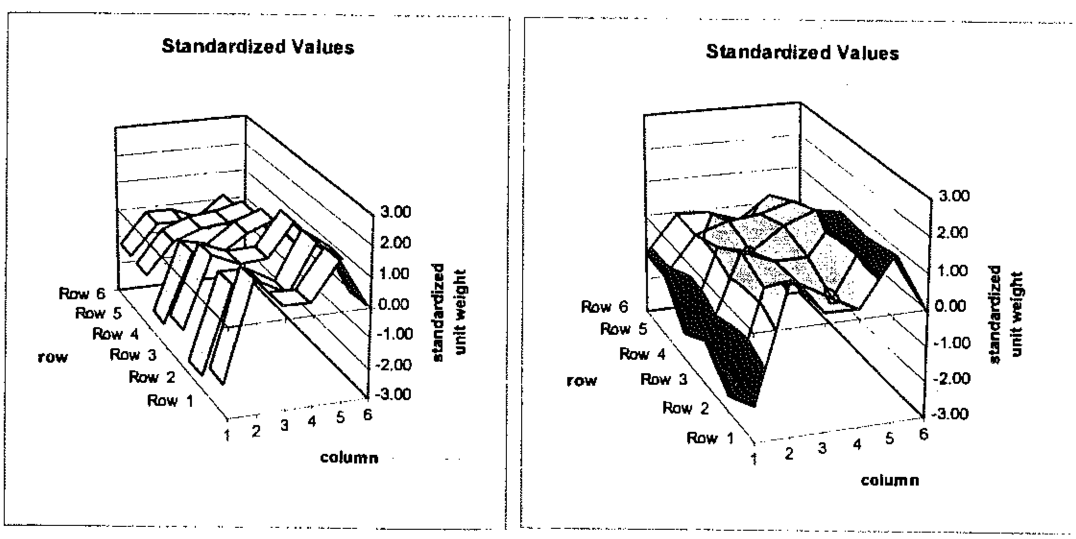

Figure 5.6 Standardized Graphs

5.3.6 ANOVA Sheet

As discussed in Section 5.3.1, the first and primary displayed result on the data entry sheet is the result of a one-way analysis of variance (ANOVA) on the column data. The calculations to support this result are performed on the ANOVA sheet, shown in Figure 5.7.

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One-way analysis of variance on column data

Column	Average	Diff from grnd mean	Diff ^2	sigma	Variance
1	139.92	-4.82	23.227	1.457	2.122
2	145.78	1.05	1.097	1.391	1.934
3	145.23	0.50	0.247	0.547	0.299
4	145.18	0.45	0.200	1.050	1.102
5	147.55	2.81	7.918	1.431	2.047
6	144.75	0.01	0.000	1.471	2.163
sum			32.689		9.666
all data	144.74			2.64285	6.9847

	Sum Sq	df	Variance	F	Fcrit	Prob
between columns:	196.134722	5	39.227	24.35028	2.533554	9.973E-10
within columns:	48.3283333	30	1.611			
Total:	244.463056					

Different ? | 1 | YES!

Figure 5.7 ANOVA Sheet

Analysis of variance is a technique to determine whether or not statistically significant differences exist among the means of data sets, in this case, the six columns. Despite its name and use of variances, the hypothesis of an ANOVA is that there is no difference in mean values among the six data sets. If there are no significant differences, the values in each subset of six as well as the entire set of 36 will be randomly distributed in a similar fashion, and hence the variances of the subsets and the entire set will be similar. If significant differences exist, the variance of the entire data set will be significantly larger than those of the subsets. The ANOVA procedure assumes that each column of data is a random sample from a normal distribution and that the population variance is constant among the 6 columns.

The technique is described in many statistical texts (e.g., Berthouex and Brown, 1994). For convenience of the reader, the application in MBITSEG1.xls is briefly summarized below. The analyzed data is from the xx1 nuclear density values at the St. John's site as shown in Figure 5.1.

Column and Global Averages. First the column and grand (or global) average (or mean) values are automatically copied from the parameter statistics sheet to the ANOVA sheet, as seen in the second column of Figure 5.7. Then the differences of the column means from the grand mean (144.74) are calculated in the third column of the spreadsheet. The next step is to calculate variances and standard deviations of the subsets and the entire data set. These could be calculated using the differences from the means in the third column, but the standard deviations have already been calculated on the parameter statistics sheet. Hence, they are directly copied from there and entered in the fourth column, and then squared to obtain the variances in the fifth column.

Sums of Squared Deviations. The *total sum of squares* is a measure of the variability in the total data set and is calculated as the sum of the squared deviations from the grand mean, and is denoted SSTO.

$$SSTO = \Sigma\Sigma(X_{ij} - \overline{\overline{X}})^2 \qquad (5.5)$$

where X_{ij} refers to the ith value in column j.

The greater the total variability in the data X_{ij}, the larger is SSTO. In the example shown, the total sum of squares is 244.46.

The *error sum of squares* separates out the variability component that is present within data subsets (columns on the pavement sample grid). Hence the deviations are taken about the column means $\overline{X}_j$ and are of the form $X_{ij} - \overline{X}_j$. Therefore,

$$SSE = \sum_j \sum_i \left(X_{ij} - \overline{X}_i\right)^2 \qquad (5.6)$$

In the example shown, the error sum of squares, listed as "within columns," is 48.33.

The difference between the total sum of squares and the error sums of squares is called the *treatment sum of squares* and is denoted by SSTR.

$$SSTR = SSTO - SSE \qquad (5.7)$$

If the column means $\overline{X}_j$ are nearly equal, SSE will be close to SSTO, and SSTR will be small. If the $\overline{X}_j$ are not close to each other, SSTR will be larger. Alternatively, SSTR is actually a sum of squares of the deviations of the subset means $\overline{X}_j$ around the grand mean $\overline{\overline{X}}$:

$$SSTR = \sum n_j\left(X_j - \overline{\overline{X}}\right)^2 \qquad (5.8)$$

In the example shown, the treatment sum of squares, listed as "between columns," is 196.13.

Degrees of Freedom. Each sum of squares for the single-factor ANOVA model has associated with it a number of degrees of freedom. SSTO has $n_T - 1$ degrees of freedom. There are n_T deviations $(X_{ij} - \overline{\overline{X}})$, but these are subject to one constraint that is $\Sigma\Sigma(X_{ij} - \overline{\overline{X}}) = 0$.
SSTR has r-1 degrees of freedom, where r indicates the number of columns. There are r deviations $(X_i - \overline{\overline{X}})$, but those are subject to one constraint, namely, $\sum n_j\left(X_i - \overline{\overline{X}}\right) = 0$.

Finally, SSE has n_T-r degrees of freedom. Since the degrees of freedom are additive, then we can find the following relationship:

$$(n_T - 1) = (r - 1) \quad + \; (n_T - r) \qquad (5.9)$$

For the six by six sample grid used in MBITSEG1.XLS, SSTO always has 35 degrees of freedom, SSTR always has five, and SSE always has 30.

Mean Squares. Treatment mean square (MSTR) and error mean square (MSE) are obtained by dividing the respective sums of squares by their associated degrees of freedom. These are essentially variances, one of the data about their subset means and one of the subset means about the grand mean:

$$MSTR = \frac{SSTR}{r-1} \qquad (5.10)$$

$$MSE = \frac{SSE}{n_T - r}. \qquad (5.11)$$

In the example shown, these are 39.23 and 1.611, respectively.

F-test for Equality of Column Means. To test the equality of column means, the null hypothesis is formulated as:

$$H_0: \quad \mu_1 = \mu_2 = \ldots = \mu_r$$

The alternative hypothesis H_1 is that at least two column means differ. To test this hypothesis, the F-statistic or F ratio is calculated, which is the ratio of MSTR to MSE:

$$F = \frac{MSTR}{MSE} \qquad (5.12)$$

Large values of the F ratio support H_1 ; i.e, that significant differences exist among the data subsets. Neter et al. (1992) explained that MSTR tends to be larger than MSE when H_1 holds, whereas the two mean squares tend to be of the same magnitude when H_0 holds. In constructing the decision rule, the F ratio is compared to the critical value F_{crit} for the desired confidence level α and the number of degrees of freedom as summarized below.

$$\text{If } F^* \le F(1-\alpha;\ r-1, n_T - r), \text{ conclude } H_0$$
$$\text{If } F^* > F(1-\alpha;\ r-1, n_T - r), \text{ conclude } H_1$$

For the example data shown (from the St. John's site) the F ratio is 24.53, a huge value in statistical terms. Taking 1-α at the 95 percent confidence level (5 percent risk), with $r - 1 = 5$ and $n_T - r = 30$, the value of F_{crit} is 2.53. In other words, where there is no significant difference in mean values, 95 out of 100 times sampled, the calculated F ratio would be 2.53 or less.

The spreadsheet also takes the F value and degrees of freedom and calculates the probability (or percent of the time) that such a measured F ratio would be found in sampling a statistically homogeneous population without differences among column means. For the example shown, this is 9.973 x 10^{-10}, or about one in one billion. Obviously there are very significant column differences at the tested site, which is consistent with the observed segregation.

5.3.7 t-Test Sheet

Description. Following the ANOVA sheet is the Tukey test sheet; however the next sheet, the t-test sheet, will be described first as it is more basic and the Tukey test can be considered a refinement of the t-test. The t-test sheet is shown in Figure 5.8. It consists of two matrices; in the first, the probability values (risk of concluding a difference when there is not a difference) corresponding to the differences in column means are calculated and displayed. In the second matrix, a value of 1 or 0 is generated depending on whether the probability is value is less than or greater than 0.05, respectively.

As 15 paired comparisons can be made among six column means, and the five percent significance level used corresponds to a probability of one in twenty, it would be expected that at least a few significant differences would be found much of the time. Furthermore, two columns with sigficantly different means would each score a "one" in the second matrix. Hence, a more stringent criteria is applied to identify significantly different columns; only when a column mean is significantly different than at least three other column means the indication **DIFF!** is displayed on the data entry sheet. These determinations are made in the two columns to the left of the lower matrix.

t-tests
two sample, equal variance, homoscedastic

Col vs Col	1	2	3	4	5	6
1		0.0000	0.0000	0.0000	0.0000	0.0002
2	0.0000		0.3884	0.4186	0.0553	0.2396
3	0.0000	0.3884		0.9196	0.0041	0.4679
4	0.0000	0.4186	0.9196		0.0085	0.5699
5	0.0000	0.0553	0.0041	0.0085		0.0075
6	0.0002	0.2396	0.4679	0.5699	0.0075	

Fail t-test at 0.05 level?

Col vs Col	1	2	3	4	5	6	Sum	Diff ?
1		1	1	1	1	1	5	1
2	1		0	0	0	0	1	0
3	1	0		0	1	0	2	0
4	1	0	0		1	0	2	0
5	1	0	1	1		1	4	1
6	1	0	0	0	1		2	0

Figure 5.8 t-Test Sheet.

Background of the t-test. The t-test is a well-known statistical test to compare the mean of a small sample and the mean of a population, or the means of two small samples. In the former case, the test statistic t is defined as the ratio of the difference between the sample mean and population mean to the standard error of the mean:

$$t = \frac{\bar{x} - \mu}{s / \sqrt{n}} \tag{5.13}$$

where $\bar{x}$ is the sample mean
μ is the population mean
s is the sample standard deviation
n is the sample size

Hence, t represents the number of standard errors by which the sample mean differs from the population mean. For small n, the sample mean is distributed around the population mean according to the t distribution, which depends on the number of degrees of freedom n – 1. One would expect t to be small, and large values of t (greater than t critical) suggest statistically significant differences.

As interest is in sample means that are either significantly above or below the population mean, a two-sided test is used. The decision rule for the two-sided test is constructed as follows :

Null hypothesis H_0: $\mu = \mu_0$
Alternative hypothesis H_1: $\mu \neq \mu_0$

The critical t value $t_{\alpha/2}$ corresponds to the points cutting off an area of $\alpha/2$ in the upper and lower tails of the t-distribution with n-1 degrees of freedom. If the absolute value of the calculated t test statistic is greater than the critical t value, then H_0 is rejected and significant differences are considered present.

As the data subset in each pavement column represents an independent sample, the sample size is n = 6. Taking the significance level α as 0.05, the critical t value with 5 degrees of freedom is $t_{\alpha/2} = 2.571$. Using the St. John's sample xx1 data, a t test can be performed comparing each subset of column data to the observed global mean 144.74 lb/ft^3. The results are shown in Table 5.1

Table 5.1 t Tests for Column Means and Global Mean, St. John's xx1 Data

Column	Mean	Standard Deviation	t	t_{crit} $\alpha/2$	Significant ?
1	139.92	1.457	8.105	2.571	**Yes**
2	145.78	1.391	1.845	2.571	No
3	145.23	0.547	2.229	2.571	No
4	145.18	1.050	1.044	2.571	No
5	147.55	1.431	4.818	2.571	**Yes**
6	144.75	1.471	0.023	2.571	No

To further illustrate, the 95 percent confidence interval for the mean value for each data subset (column) is shown graphically in Figure 5.9. The endpoints of the confidence intervals correspond to:

$$x = \bar{x} \pm t_{\alpha/2} \frac{s}{\sqrt{n}} \tag{5.14}$$

These are compared to the global mean unit weight, 144.74 lb/ft^3, and it is seen that, for columns one and four, the confidence interval on the estimated mean lies outside the global mean of the data set. For example, in the first column $\bar{x}$ = 139.92 and s = 1.457, so the interval is from 138.39 to 141.45.

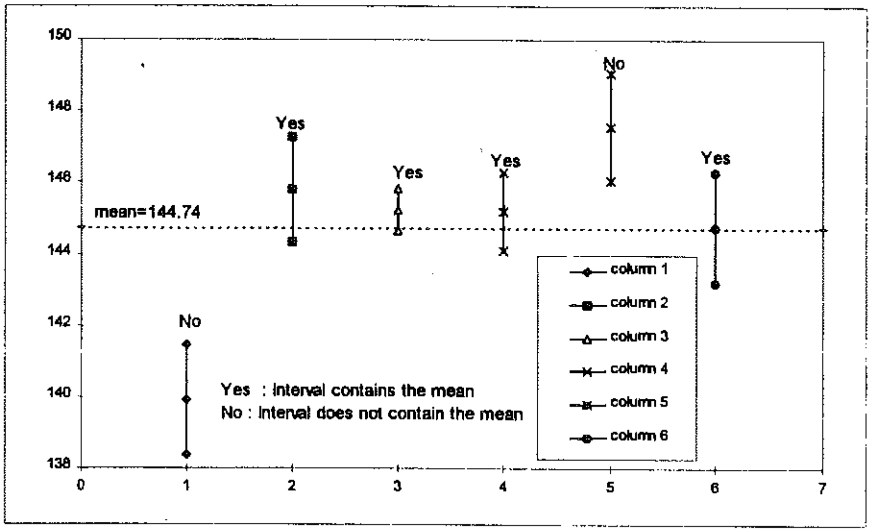

Figure 5.9 Confidence Intervals Based on the t-distribution

Difference of Column Means. In testing for linear pavement segregation, it is of interest to test whether the mean of any column is significantly different from the mean of any other column. The test of columns against the global mean shown in Figure 5.9 does not do so as the global mean includes some of the data in the column being tested. To make pairwise column comparison, it is assumed that each column represents a sample from its own population, and the difference of the two population means, $\mu_1 - \mu_2$ is tested for significance. Assumptions inherent in the procedure include the following:

- The two populations with means μ_1 and μ_2 are normally distributed.
- The population variances σ_1^2 and σ_2^2 are equal.
- The two populations are independent.

The decision rule is taken as:

Null hypothesis H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis: $\mu_1 - \mu_2 \neq 0$

The test statistic employed is:

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{S_{pooled}\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{5.15}$$

where $\bar{x}_1$ and $\bar{x}_2$ are the sample means corresponding to population 1 and 2.
$(\mu_1 - \mu_2)$ is the difference in population means (taken as zero), and
n_1 and n_2 are the sample sizes

The pooled estimator S_{pooled} of the common standard deviation σ, is taken as

$$S_{pooled} = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \tag{5.16}$$

where s_1^2 and s_2^2 are the sample variances of the two samples.

The critical t value gives the distance in standard errors from the estimated mean to the points on the upper and lower tail on the t distribution of the mean. For a two-tailed test with 95 percent confidence and $n_1 + n_2 - 2 = 10$, it can be computed as $t_{\alpha/2} = t(1 - \frac{0.05}{2}; 6 + 6 - 2) = 2.228$. If the calculated t value is larger than this critical $t_{\alpha/2}$ value, the null hypothesis H_0 is rejected, and a significant difference in mean values is indicated.

As previously stated, the actual calculation of t and comparison to t-critical is automatically performed by built-in spreadsheet functions in the t-test sheet upper matrix. Results of the α risk (significance level) are presented in shown in the upper matrix (Figure 5.8).

5.3.8 Tukey Multiple Comparison Test Sheet

Description. As stated in the preceding section, if all 15 possible comparisons are made among six column means, at the $\alpha = 5$ percent level (or 95 percent confidence level), some significant differences would inevitably be found as this level implies the magnitude of difference that would be found one in twenty times in a homogeneous but random data set. Stated in simple terms, if one makes many multiple comparisons of means sampled from a normally distributed population, one is bound to find some significant differences. The Tukey multiple comparison test (Tukey, 1949; Berthouex and Brown, 1994) circumvents this problem by adjusting the critical value of the test statistic to achieve the desired confidence level over the set of all possible comparisons may be made.

The Tukey test sheet in MBITSEG.XLS is shown in Figure 5.10. The upper matrix contains the difference in column means. The second matrix contains the critical values for the difference in column means, calculated as described below. These two values are compared and a result is generated in the third (lowermost) matrix, with "1" indicating a significant difference and "0" indicating no significant difference. As was the case for the simple t-tests, a column mean must be significantly different from three other column means for the conclusion **DIFF!** to be displayed on the data entry sheet.

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Tukey's paired comparison test

Difference of means

Columns	1	2	3	4	5	6
1		-5.87	-5.32	-5.27	-7.63	-4.83
2	-5.87		0.55	0.60	-1.77	1.03
3	-5.32	0.55		0.05	-2.32	0.48
4	-5.27	0.60	0.05		-2.37	0.43
5	-7.63	-1.77	-2.32	-2.37		2.80
6	-4.83	1.03	0.48	0.43	2.80	

Critical Values

Columns	1	2	3	4	5	6
1		2.74	2.12	2.45	2.78	2.82
2	2.74		2.04	2.37	2.72	2.76
3	2.12	2.04		1.61	2.09	2.14
4	2.45	2.37	1.61		2.42	2.46
5	2.78	2.72	2.09	2.42		2.80
6	2.82	2.76	2.14	2.46	2.80	

Critical ?

Columns	1	2	3	4	5	6
1		1	1	1	1	1
2	1		0	0	0	0
3	1	0		0	1	0
4	1	0	0		0	0
5	1	0	1	0		1
6	1	0	0	0	1	
Sum	5	1	2	1	3	2
Different?	1	0	0	0	1	0

Figure 5.10 Tukey Test Sheet

Background. It has been shown by Tukey (1949) that the desired confidence intervals are given by:

$$(\bar{\mu}_i - \bar{\mu}_j) \pm \frac{q_{k,v,\alpha/2}}{\sqrt{2}} S_{pooled} \sqrt{\frac{1}{n_i} + \frac{1}{n_j}} \qquad (5.17)$$

where $q_{k,v}$ is the appropriate upper significance level for the studentized range for k means and v is the number of degrees of freedom in the estimate S^2_{pooled} of variance σ^2.

The pooled estimate of the common σ^2 is obtained as :

$$S^2_{pooled} = \frac{(n_i - 1)s_i^2 + (n_j - 1)s_j^2}{n_i + n_j - 2} \qquad (5.18)$$

For the six by six test grid in this study, k = 6 and ν = 30; then $q_{k,\nu}$ with α risk 5% is determined as 4.72. This value is taken from tables (Berthouex and Brown, 1994) and programmed directly into the spreadsheet; it is not calculated internally.

As n_i and n_j are fixed at 6; the confidence interval for the difference in two means can be simplified as

$$(\bar{\mu}_i - \bar{\mu}_j) \pm \frac{4.72}{2\sqrt{3}}\sqrt{S_i^2 + S_j^2} \qquad (5.19)$$

and the difference in population means $\mu_1 - \mu_2$ is assumed to be zero.

The decision rule is:

Null hypothesis H_0: $\mu_i = \mu_j$

Alternative hypothesis H_1: $\mu_I \neq \mu_j$

The test statistic employed is :

$$(\bar{x}_i - \bar{x}_j) \geq \frac{4.72}{2\sqrt{3}}\sqrt{S_i^2 + S_j^2} \qquad \text{significant difference}$$

$$(\bar{x}_i - \bar{x}_j) < \frac{4.72}{2\sqrt{3}}\sqrt{S_i^2 + S_j^2} \qquad \text{no significant difference}$$

5.3.9 Six of Six Test

The "six of six" test is a very simple statistical test developed for this study. Assuming that the sample data is symmetrically distributed about the global mean, any single value is above or below the mean with probability p = 0.5. The expected number of samples in any column above or below the mean are 3 and 3, respectively. However, other distributions (4 and 2, 2 and 4 etc., are not be uncommon. If the values in a column are assumed independent, the number of values in a column (sample of six) above and below the global mean follows a binomial distribution. The probability for each combination is shown in Table 5.2.

As seen in Table 5.2, if the test data are truly random, there is only a 3.2 percent chance of all six values in a column being above or below the global mean in a sample. Therefore, if all 6 values in a column are above or below the global mean, it can be concluded that a real difference exists at the 3.2 percent significance level.

The "six of six" test is performed on the six of six data sheet shown in Figure The output of 6 of 6 test is arranged is shown in Figure 5.11. The data array is transformed to a value of "1" for values above the mean and "0" for values below the mean. For the data at the St. John's test site, columns 1 and 4 are found to have significant differences, which corresponds well with the findings of the multiple comparison tests.

Table 5.2 Probability of a Number of Values in a Column Exceeding the Mean

Number of Values Above Mean	Number of Values Below Mean	Probability
0	6	0.016
1	5	0.094
2	4	0.234
3	3	0.312
4	2	0.234
5	1	0.094
6	0	0.016

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Above Average? 1= true, 0 = false

0	0	0	0	1	0
0	0	1	1	1	0
0	1	0	1	1	0
0	1	1	1	1	1
0	1	1	0	1	1
0	1	1	1	1	0
0	4	4	4	6	2

Figure 5.11 Spreadsheet of 6 of 6 test

5.4 MBITSEG2.XLS — Segregation Analysis for Two Samples

After an extensive set of analyses were performed, a second spreadsheet template, intended to be more simplified and tailored for filed use, was developed later in the research study. This spreadsheet, titled MBITSEG2.XLS, performs a t-test to check the statistical significance of the difference in means of two data sets, where one is a candidate for being considered segregated, and the other is considered an unsegregated control site.

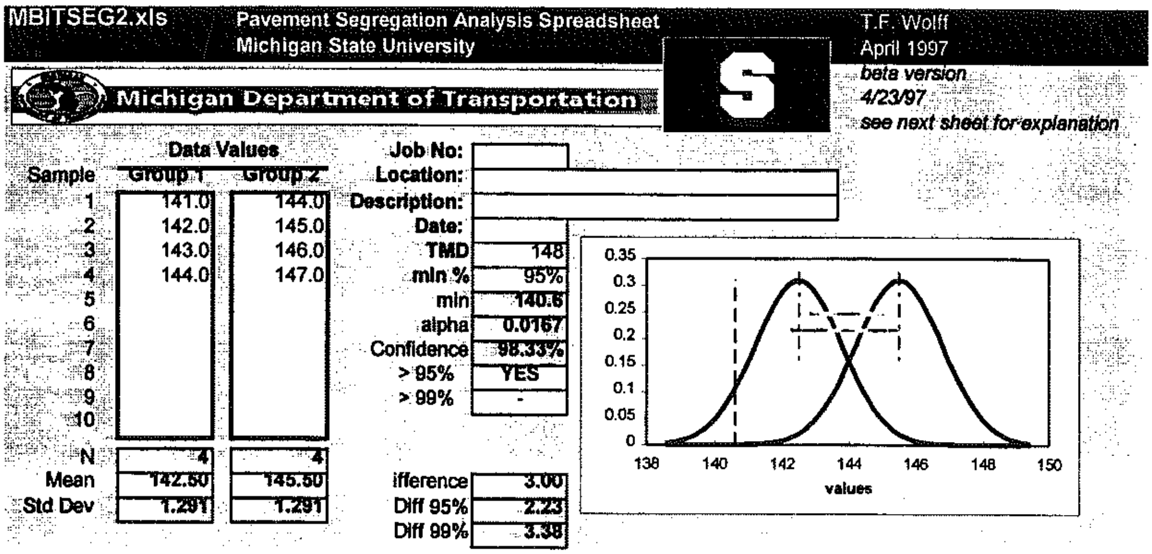


Figure 5.12 First Sheet of Spreadsheet MBITSEG2.XLS

The first sheet of MBITSEG2.XLS is shown in Figure 5.12. It provides for both data entry and textual and graphic display of results. The second sheet of MBITSEG2.XLS provides a very brief overview of the program. It is shown in Figure 5.13. Use of MBITSEG2.XLS is described below.

Identification Data Block. At the top center of the sheet are provided blank spaces where the user may enter descriptive information to identify the site tested and other information. These are labeled Job No., Location, Description, and Date. These are solely for identification and no calculations or database operations are performed on this data.

Data Entry Blocks. To the left of the sheet are two column blocks, labeled Group 1 and Group 2 in which the user may enter up to ten data values per group. The number of data values in each group need not be equal. Typically, these would be nuclear-measured density values; however, any numerical data may be entered. As data are entered, the number of samples, mean values and standard deviations for each group are automatically updated and displayed in the boxes below the data entry cells. Increasing the number of data values in a group tends to narrow the confidence bands on the mean value, increasing the ability to conclude whether significant differences in mean value exist.

The two sets of four data values shown in Figure 12 were synthesized to illustrate the spreadsheet capabilities

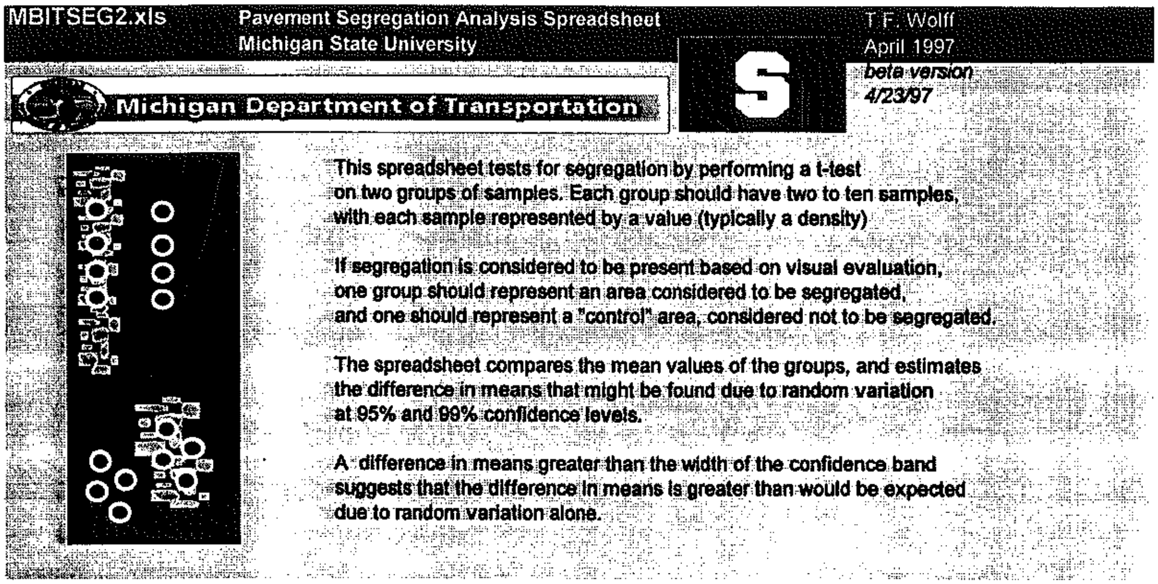


Figure 5.13 Second Sheet of Spreadsheet MBITSEG2.XLS

Control Density Block. The spreadsheet also permits the user to enter the theoretical maximum density (TMD) value for the asphalt mixture at the site and a minimum percentage of TMD (min %) which is considered acceptable. These are multiplied to obtain the minimum acceptable density, which is displayed in the block marked "min" and also displayed on the graphic display discussed below. In the example shown, 95 percent of TMD = 148 lb/ft^3 leads to a minimum acceptable density value of 140.6 lb/ft^3.

Statistical Results. Statistical comparisons are made using the t-test comparison of two means described in Section 5.3.7 and accomplished using built-in spreadsheet functions. Results of statistical calculations are displayed in the lower center portion of the sheet. The value of "alpha," shown as 0.0167, is the risk level associated with rejecting the null hypothesis of no difference in mean values. In other words, for the data shown, if one concluded that the two groups of data values came from populations with different mean values, there is a probability of 0.0167 (or about one in sixty) that such a conclusion is in error.

The "confidence" value, shown as 98.33%, is simply the complement of the alpha value.

Below the confidence value are two blocks labeled >95% and >99%, respectively. If the confidence value exceeds these values, **YES** is displayed in the adjacent cell.

6. Data Analysis

6.1 Overview

This chapter summarizes the detailed analyses performed in support of this study. Using the field and laboratory data acquired as described in Chapter 4 and the statistical software and tests described in Chapter 5, differences in nuclear-measured field density, direct-measured lab density, and gradation parameters at the seven test sites were assessed for statistical significance, and relative degrees of statistical significance for the various parameters were compared. Based on these comparisons, the adequacy of using nuclear density measurements and statistical analysis to assess segregation is investigated.

In addition, several related and supporting analyses were performed, including investigations of the effects of testing time on nuclear-measured density and the relationship between laboratory and field-measured density values.

6.2 Nuclear Density Testing Time

In practice, MDOT and others have used both one-minute and four-minute measurement periods with nuclear devices. Given the number of measurements to be made over the testing grid (36) and the goal of using the test in real-time construction, maintaining testing time as short as possible was an issue of concern early in the study. At test sites 2, 3 and 4 both one-minute and four-minute nuclear density readings were taken in order to assess the efficacy of using the shorter testing time.

Linear regression analyses were performed to investigate the relationship between 1-min and 4-min nuclear density readings. The details of regression analysis are described in most standard statistical texts. The results of the regression analysis between 1 min. and 4 min. nuclear reading for the three sites are listed in Table 6.1. The regression plots are shown in Figures 6.1, 6.2 and 6.3.

In Table 6.1, the coefficient of determination (square of the correlation coefficient) is a measure of the overall fit of the data to the best-fit equation. The standard error is the standard deviation of the residual differences of the data points from the fit line, and is a measure of the magnitude of error still left around the fitted relationship. It can be seen that the correlations between one and four minute readings are not as strong as might be expected; R^2 is in the range 0.40 to 0.66. Likewise, the standard error values were as high as 3.8 lb/ft^3. In order to further compare the density values determined by the two test durations, a set of paired t-test was also made and a 99 percent significance level was chosen as the criterion. Results are given in Table 6.2.

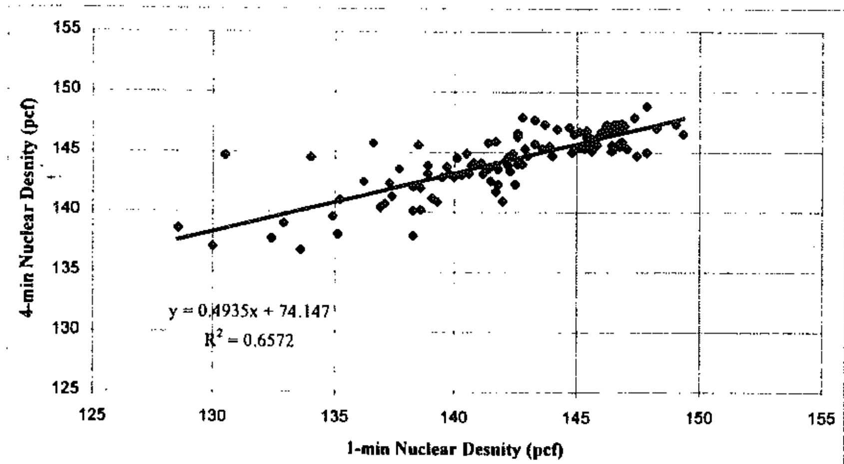


Figure 6.1 Regression Line for 1-min versue 4-min Nuclear Density at Site 2 - Muskegon (uniform)

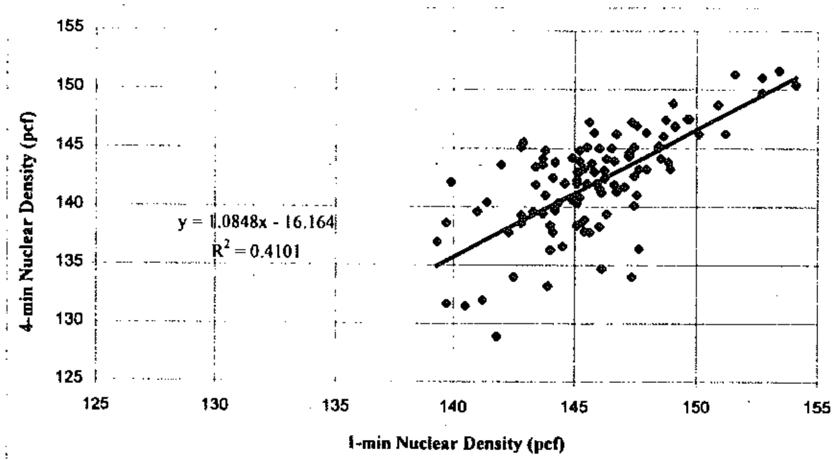


Figure 6.2 Regression Line for 1-min versue 4-min Nuclear Density at Site 3 - Muskegon (random)

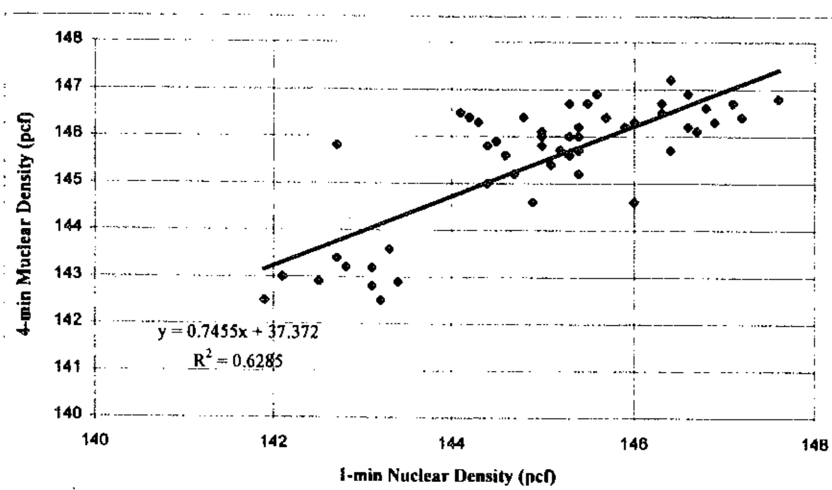


Figure 6.3 Regression Line for 1-min versue 4-min Nuclear Density at Site 4 - M-99

Table 6.1 Regression Analysis of One Minute and Four-Minute Nuclear Density Values

Site	Regression Equation (lb/ft^3)	Coefficient of Determination R^2	Standard Error, σ (lb/ft^3)	Observations N
2. Muskegon (uniform)	$\gamma_{4min} = 0.494\gamma_{1min} + 74.147$	0.657	1.598	108
3. Muskegon (random)	$\gamma_{4min} = 1.085\gamma_{1min} - 16.164$	0.410	3.789	108
4. M-99	$\gamma_{4min} = 0.746\gamma_{1min} + 37.372$	0.629	0.810	54

Table 6.2 Results of Paired t-tests for One and Four Minute Nuclear Density Values

Site	Calculated t	Critical t value	Conclusion
2. Muskegon (uniform)	-8.570	2.623	difference
3. Muskegon (random)	10.426	2.623	difference
4. M-99	-3.858	2.672	difference

These results indicate that, for measurement of density, the one minute values are not very good predictors of four-minute values. However, the emphasis of this study was not absolute measurement of density, but rather detection of patterns of relative differences in density values. In this regard, numerous comparisons were made of the results of grid analysis using MBITSEG1, for both one and four minute measurement times, and these almost always led to similar conclusions regarding the presence or absence of segregation. Hence, the remaining work and primary analyses of the study were based on one-minute readings.

6.3 Assessment of Linear Segregation Based on Nuclear-Measured Density

6.3.1 Procedures

Nuclear density measurements were obtained at each of the seven field testing sites. At each site, measurements were made at 108 locations, corresponding to the triplicate core locations centered on the 36 test grid locations. (No cores were taken at Site 7, but the same nuclear measurement scheme was used). As the MBITSEG1 software input is set for 36 values at the grid locations, four separate data sets were developed for each site; the sample 1, sample 2, and sample 3 values for each grid point, and the average value of the three samples at each grid point. There were an additional four data sets for those sites with four-minute readings.

As mentioned in Section 5.3.6, a one-way ANOVA is performed in MBITSEG1.xls to determine whether the column means are significantly different, with the testing hypothesis controlled at the 95 percent significance level. As the number of data points and columns are fixed at each site, the critical F value can be determined and is:

$$F(1-\alpha; r-1; n_T - r) = F(0.95,\ 5,\ 30) = 2.534$$

If the calculated F value is greater than $F_{crit} = 2.534$, the null hypothesis of no column difference should be rejected with 95 percent confidence, or alternatively stated, if $F > 2.534$,

- At least ninety-five percent of the time, a random sample from a homogeneous set of values would have less variation than that observed, and

- No more than five percent of the time, a random sample from a homogeneous set of values would have more variation than that observed.

The spreadsheet ANOVA routines, however, not only determine acceptance or rejection at a specified level of significance, but also provide the actual probability level corresponding to making a Type I error of rejecting the null hypothesis (no difference). This is termed the p-value and $p = 1 - \alpha$. If, for example, $p = 0.001$, only one time in one thousand would the differences observed occur due to chance, and concluding that the observed differences are significant involves taking a risk of only one in one thousand.

The p-values provide a convenient measure to compare findings at various sites in a more robust manner than just "no difference / difference" at a selected level. If $p < 0.05$, the significance level exceeds 95 percent, if $p < 0.01$, the significance level exceeds 99 percent, etc. Table 6.3 summarizes the obtained p-values for nuclear density readings using the four data sets considered at the seven sites. p-values below 0 05 are italicized, and those below 0.01 are bold italicized. It should be noted that some of the sites exhibit exceedingly low p-values, ranging from around one in a thousand to less than one in a billion, suggesting almost certainty that differences in density are not due to chance, but rather have some cause such as differences in gradation.

6.3.2 Site 1 - St. John's

This site was chosen as a site of notable linear segregation. This selection is well-supported by the ANOVA; the resulting p-values in Table 6.3 are extremely low, some less than one in a billion. The reason is apparent on the surface plot for the average of three samples (one-minute) shown in Figure 6.4. The values in column 1 are consistently very low; the values in column 5 are consistently high within their respective rows.

6.3.3 Site 2 - Muskegon (uniform)

This site was chosen as a site of linear segregation. As seen in Table 6.3, for one-minute readings, the ANOVA for the number 2 samples did not support a conclusion of segregation at

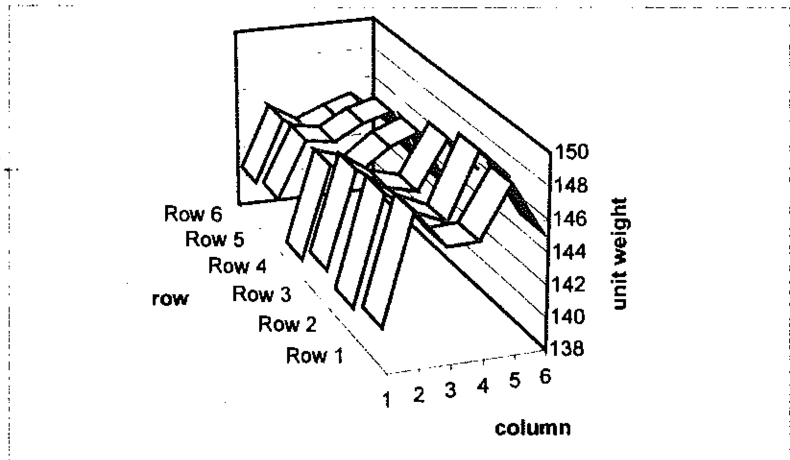


Figure 6.4 Surface Plot for Average of 1-min Nuclear Density at Site 1 - St. John's

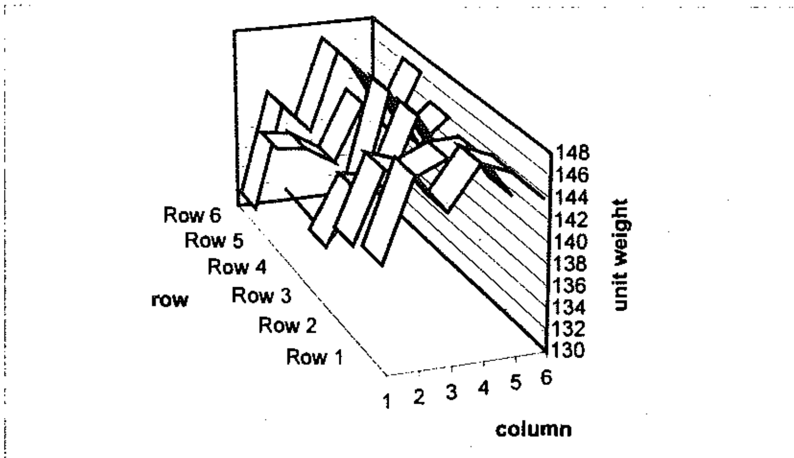


Figure 6.5 Surface Plot for Average of 1-min Nuclear Density at Site 2 - Muskegon (uniform)

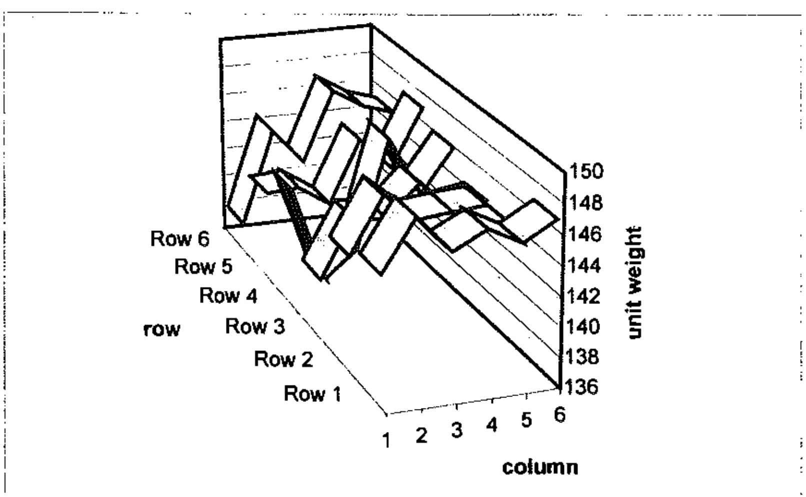


Figure 6.6 Surface Plot for Average of 4-min Nuclear Density at Site 2 - Muskegon (uniform)

95 percent significance level, but would if the 90 percent level was selected. The remaining sample sets for one-minute measurements indicate significant density differences. Differences in four-minute readings are not as strong (as measured by p-value), but one of the three primary data sets is significant at a 94 percent level, and one is significant at the 98 percent level, with the triplicate average values significant at the 95 percent level. The surface plot for the average of three samples is shown in Figure 6.5 for one-minute readings, and in Figure 6.6 for four-minute readings. Some trend is evident, with low densities in column 1 and high densities in column 4.

Table 6.3 p-values for Nuclear Density Evaluation

Site	Duration of reading	Sample 1	Sample 2	Sample 3	Average of three samples
1. St. John's	1 min	***9.97×10^{-10}***	***1.88×10^{-8}***	***3.26×10^{-6}***	***6.28×10^{-11}***
2. Muskegon (uniform)	1 min	*2.72×10^{-5}*	0.0818	***0.0048***	***0.0004***
	4 min	0.0635	***0.0083***	0.2376	*0.0364*
3. Muskegon (random)	1 min	*0.0190*	***0.0025***	***0.0004***	***0.0011***
	4 min	0.4550	***0.0060***	*0.0435*	*0.0463*
4. M-99	1 min	***2.87×10^{-5}***	*5.75×10^{-7}*	***0.0009***	***1.33×10^{-8}***
5. Old US 27	1 min	0.7896	0.2468	0.3925	0.3106
6. M-123	1 min	0.4393	*0.0212*	***0.0015***	***0.0015***
7. Lansing state police facility	1 min	0.0799	*0.0279*	***0.0001***	***0.0007***

6.3.4 Site 3 - Muskegon (random)

As described in Section 4.1, this is a site of random segregation, and the sampling grid columns were shifted somewhat from linear to provide an element of randomness to the sampling pattern. However, due to limited width of lane to obtain cores, lateral deviations were not great, and column analysis could still be performed to see how much column difference was captured by the sampling. For the one-minute readings, the ANOVA indicates significant variation among columns, with all data sets significant at the 95 percent level and most significant at levels greater than 99 percent. However, multiple comparison statistical tests are inconclusive as to which columns are different than which. The surface plot is shown in Figure 6.7. Some prominent low spots are evident, indicative of random segregation.

For the four-minute readings, sample 1 exhibited a large variation with the overall coefficient of variation being 4.20%, but significant column differences were not detected in the ANOVA. In the remaining three sample sets, the ANOVA indicated significant density differences at the 95

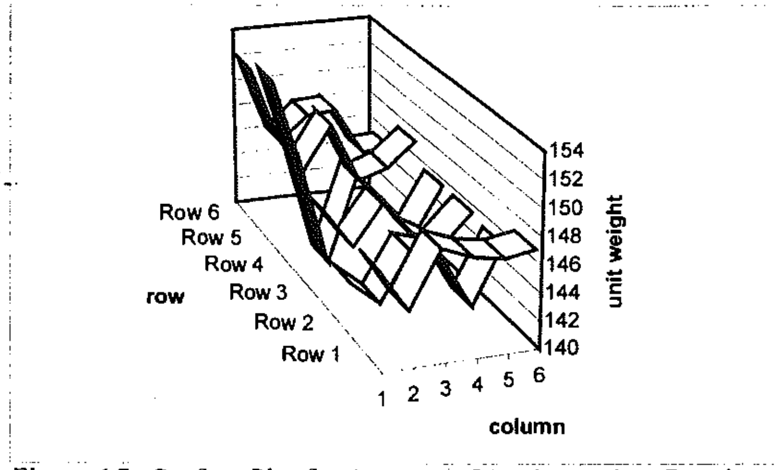


Figure 6.7 Surface Plot for Average of 1-min Nuclear Density at Site 3 - Muskegon (random)

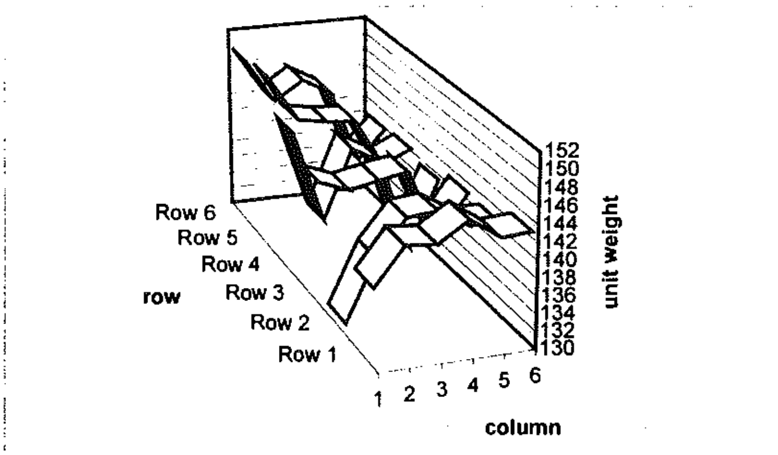


Figure 6.8 Surface Plot for Average of 4-min Nuclear Density at Site 3 - Muskegon (random)

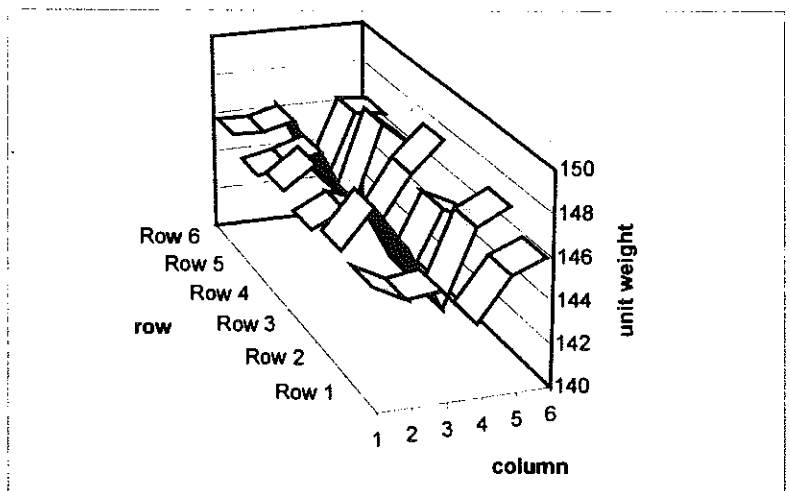


Figure 6.9 Surface Plot for Average of 1-min Nuclear Density at Site 4 - M-99

percent significance level. The surface plot for four-minute readings (Figure 6.8), for the most part, indicates a similar trend that for one-minute readings.

6.3.5 Site 4 - M-99

This site was originally chosen as a "control" site without notable segregation; however, the MSU research team noted slight segregation in mapping the site. The ANOVA found strong column differences for all four data sets, with p-values in the range 10^{-5} to 10^{-8}, leaving no doubt that significant differences are present in mean column density. The surface plot in Figure 6.9 clearly indicates the reason for the noted difference; the density values in column 4, while only typically 2 to 4 lb/ft^3 less than others, are very consistently so; all of the low density values at the site occur in column 4.

6.3.6 Site 5 - Old US 27

This site was chosen as a site of extensive segregation, although it was not observed to occur in linear patterns. The ANOVA and multiple comparison statistical tests did not indicate any significant differences in column statistics. The surface plot in Figure 6.10 provides some insight to the reason; there is an overall general trend of decreasing density from row 6 toward row 2, superimposed with "pockets" of low density values; however, the variation is not aligned in a linear fashion corresponding to the columns.

A notable finding at this site was that all the nuclear density measurements are substantially lower (124 to 137 lb/ft^3) than usually encountered in asphalt concrete pavements. This suggests that the observed surface voids have a significant effect on the accuracy nuclear density measurements. The gauge readings are not in considered in error (in the sense of equipment defects), but rather are responding to the zero-density surface voids near the detector.

Because of the pattern of segregation, the rows and columns were transposed and a second analysis was performed using MBITSEG to look for row differences. However, results of row analyses did not show significant differences.

6.3.7 Site 6 - M-123

This site was chosen as one exhibiting a mix of linear and random segregation. Three of the four data sets indicated significant column differences, with p values in the range 0.0015 to 0.02, suggesting segregation. For reasons that are not apparent, no significant differences were noted in the number 1 samples. This may be due to the physical location of these samples relative to the segregated area. The surface plot in Figure 6.11 shows obvious linear trends, with consistent peaks and valley oriented in a columnwise direction. Although column differences are significant, multiple comparison statistical tests did not give consistent results in identifying specific columns.

6.3.8 Site 7 - Lansing State Police Facility

The Lansing State Police facility was a second site first chosen in an attempt to sample an "unsegregated" site, but for which minor or slight segregation could be noted. As was the case for the M-99 site, the ANOVA indicated significant column differences, in this case in three of

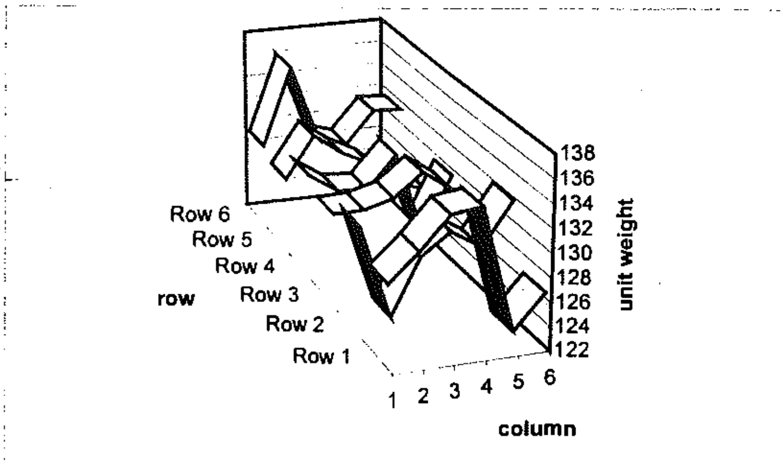


Figure 6.10 Surface Plot for Average of 1-min Nuclear Density at Site 5 - Old U.S. 27

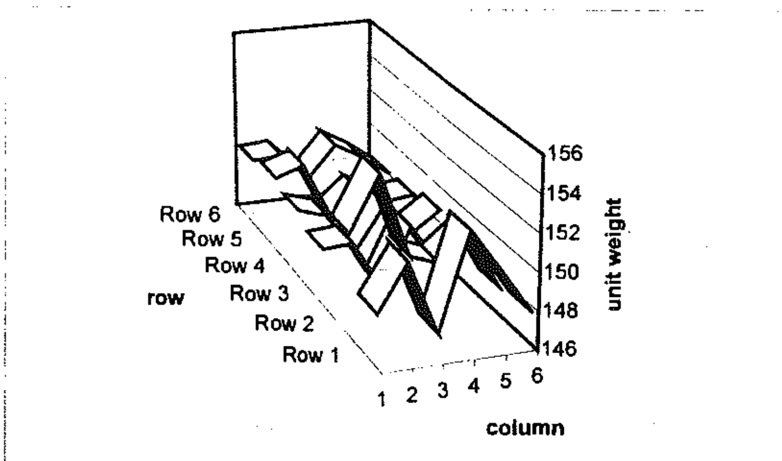


Figure 6.11 Surface Plot for Average of 1-min Nuclear Density at Site 6 - M-123

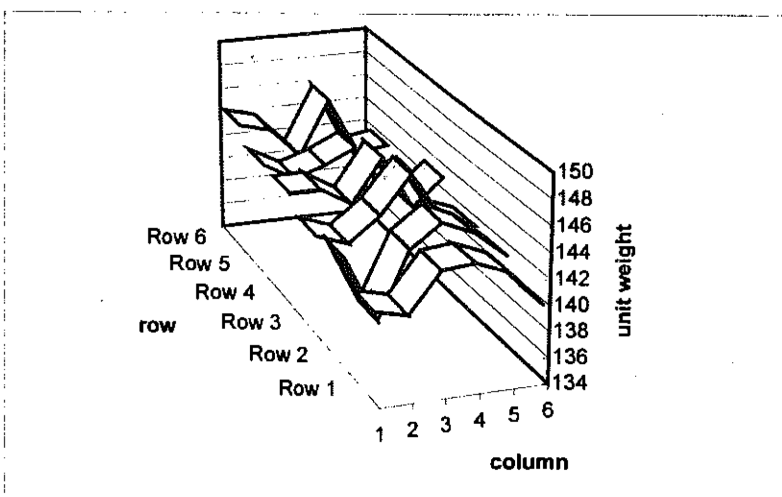


Figure 6.12 Surface Plot for Average of 1-min Nuclear Density at Site 7 - Lansing State Police Facility

the four sample sets. The fourth set (sample 1) would be found significant if the significance level were lowered to 90 percent.

For sample 1, paired t-tests and 6 of 6 tests found that density values in column 4 are different from that in other columns. In sample 2, ANOVA analysis indicated significant column differences and multiple statistical comparison tests found that density values in column 4 is consistently high. In sample 3, beside high density values in column 4, density values in column 6 were found to be somewhat low. For the average of three samples, the ANOVA indicated that there is significant column difference with consistently high density values in column 4. The surface plot is shown in Figure 6.12, and the trend of linear peaks and valleys is evident.

6.3.9 Comparison to Visual Observations

The indicated degrees of segregation based on visual observations and based on analysis using nuclear density values with MBITSEG1.xls are compared in Table 6.4.

Table 6.4 Comparison between Results of MBITSEG1 and Site Inspection

Site	Duration of reading	Observation	MBITSEG1 for nuclear density evaluation
1. St. John's	1 min	linear segregation	linear segregation
2. Muskegon (uniform)	1 min 4 min	linear segregation	linear segregation light linear segregation
3. Muskegon (random)	1 min 4 min	random segregation	linear segregation light linear segregation
4. M-99	1 min	slight segregation	linear segregation
5. Old US 27	1 min	extensive segregation	no linear segregation in column direction
6. M-123	1 min	mix of both linear and random segregation	linear segregation
Lansing State Police Facility	1 min	slight segregation	linear segregation

6.3.10 Coefficients of Variation of Nuclear-Measured Density

Where columnwise linear segregation is present, one would expect to find greater variation along rows (across columns) than within columns. A convenient measure of variability is the coefficient of variation, the ratio of the standard deviation to mean value. Values of the average coefficients of variation for column data, row data, and complete sample at each of the seven sites are shown in Table 6.5. In a statistically homogeneous data set, these would all be expected

Table 6.5 Coefficient of Variation for Nuclear Density

Site	Duration of readings	Sample	Coefficient of variation (%)		
			Column	Row	Overall
1. St. John's	1 min	sample 1	0.85	1.84	1.83
		sample 2	0.89	1.75	1.71
		sample 3	0.85	1.69	1.69
		average of three samples	0.66	1.66	1.61
2. Muskegon (uniform)	1 min	sample 1	1.89	3.03	2.98
		sample 2	2.81	2.98	3.29
		sample 3	2.50	2.96	3.23
		average of three samples	2.00	2.67	2.80
	4 min	sample 1	1.50	1.58	1.83
		sample 2	1.53	1.91	1.99
		sample 3	1.69	1.62	1.86
		average of three samples	1.43	1.58	1.77
3. Muskegon (random)	1 min	sample 1	1.57	1.66	1.92
		sample 2	1.46	1.68	1.94
		sample 3	1.47	2.04	2.12
		average of three samples	1.32	1.60	1.83
	4 min	sample 1	3.40	3.77	4.20
		sample 2	2.33	3.06	3.14
		sample 3	2.38	2.86	2.93
		average of three samples	2.23	2.85	3.02
4. M-99	1 min	sample 1	0.75	1.14	1.11
		sample 2	0.62	1.11	1.08
		sample 3	0.76	0.97	1.02
		average of three samples	0.45	0.93	0.91
5. Old U.S. 27	1 min	sample 1	2.25	2.18	2.31
		sample 2	3.01	3.04	3.47
		sample 3	2.44	2.27	2.48
		average of three samples	1.94	2.09	2.12
6. M-123	1 min	sample 1	1.21	1.02	1.32
		sample 2	0.99	1.25	1.39
		sample 3	1.08	1.34	1.41
		average of three samples	0.78	0.96	1.06
7. Lansing State Police Facility	1 min	sample 1	1.41	1.45	1.62
		sample 2	1.20	1.38	1.38
		sample 3	0.90	1.50	1.43
		average of three samples	0.88	1.26	1.24

to be equal at a site. It can be observed that, at the sites where linear segregation was identified, the average column values are consistently lower than average row values or overall values, with the magnitude of differences generally corresponding to the degree of segregation.

Another view of the overall variation in density and its frequency distribution at the sites can be obtained from viewing histograms, shown in Figure 6.13, which shows values from each site with equal horizontal axes to permit easy comparison. Most of the sites exhibit either a second histogram peak on the low side (St. John's, M-99, Old US 27), low values separated from the remaining data values (Muskegon uniform, Muskegon random, Old US 27, and Lansing state police facility), or both. The only exception is the M-123 site, which has one separated high value.

Among the seven sites, the data at the Muskegon (uniform) site had the highest overall coefficient of variation (2.8 percent); for the M-99 and M-123 sites, the coefficients of variation were as low as 1.0 percent.

6.4 Assessment of Linear Segregation Based on Lab-Measured Density

6.4.1 Procedure

Air-dry and saturated surfaced dry (SSD) lab density measurements were available for both leveling course and surface course samples at the first six sites. (No cores were obtained at Site 7, the State Police facility). As will be discussed in Section 6.7, the lab density measurements from air-dry surface course samples were found to have the strongest correlation with nuclear density measurements. Therefore, these were used to perform a companion set of statistical tests to those described in the previous section, i.e. ANOVA and multiple comparison tests using MBITSEG1.xls. It should be noted that the laboratory samples were taken shortly after measuring nuclear density at the same location. p-values from these analyses are summarized in Table 6.6. Once again, p values less than 0.05 (>95 percent significance) are shown in italics, p values less than 0.01 (>99 percent significance) are shown in bold italics.

6.4.2 Site 1 - St. John's

For the ANOVA, all four data sets showed extremely low p-values, in the range 10^{-7} to 10^{-14}, similar to the results found for nuclear-measured density values. This is consistent with the conclusion from the nuclear density values. The surface plot of lab density (Figure 6.14) is very similar in pattern to that for nuclear density (Figure 6.4). The density values columns 2 and 5 are consistently high, and those in columns 1 and 6 are consistently low.

6.4.3 Site 2 - Muskegon (uniform)

At the Muskegon (uniform) site, the ANOVA results indicated significant differences for all four data sets. This agrees well with the results of nuclear density tests, which showed significance for three or four data sets. Multiple comparison statistical tests indicated that lab density measurements are consistently high in column 4, somewhat high in column 6, and somewhat low in column 1. The "peak and valley" trends of the surface plot (Figure 6.15) are also very similar to those for the nuclear data (Figure 6.5). Therefore, the trends or data pattern for both are almost identical.

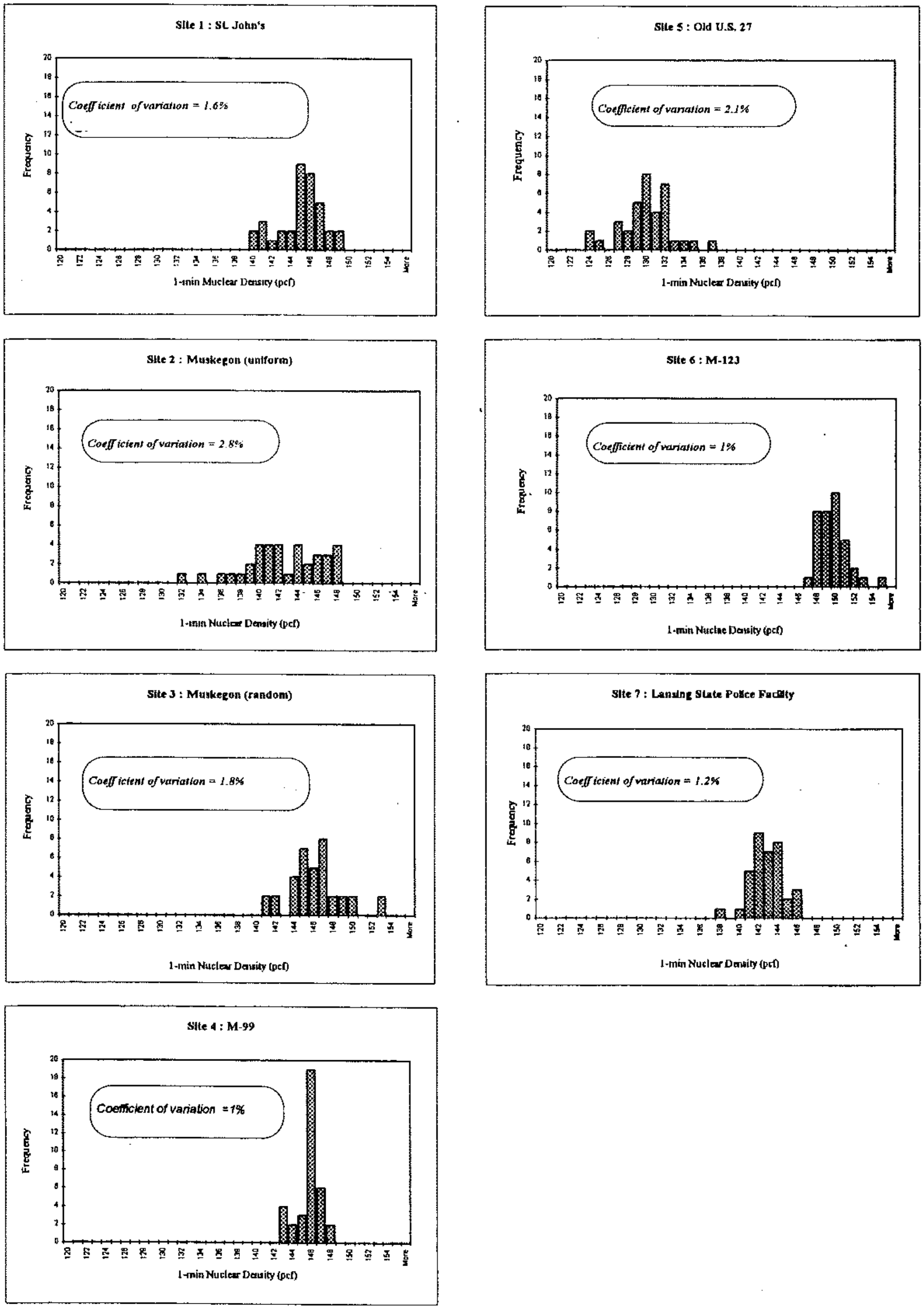


Figure 6.13 Histograms for Average of 1-min Nuclear Density

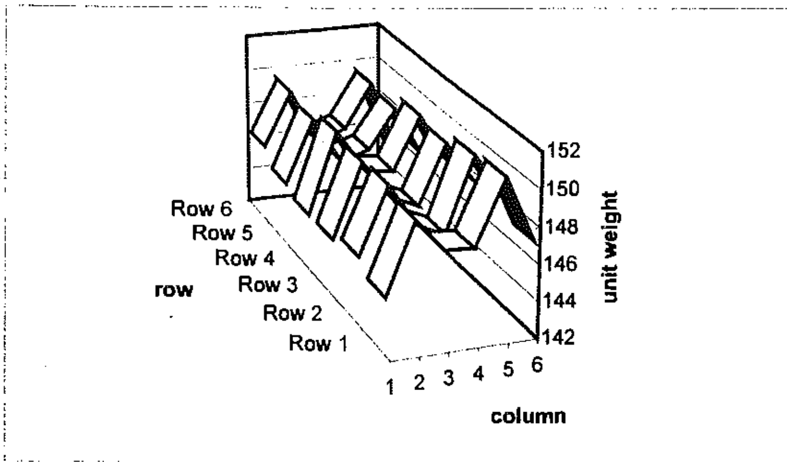


Figure 6.14 Surface Plot for Average of Air-dry Density (surface course) at Site 1 - St. John's

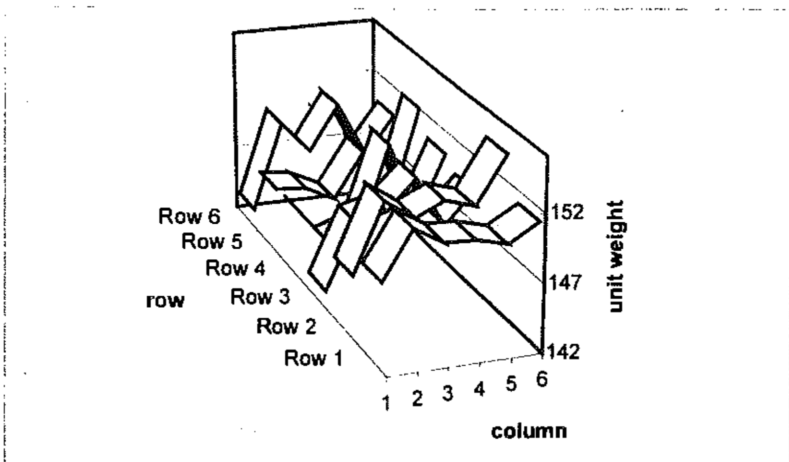


Figure 6.15 Surface Plot for Average of Air-dry Density (surface course) at Site 2 - Muskegon (uniform)

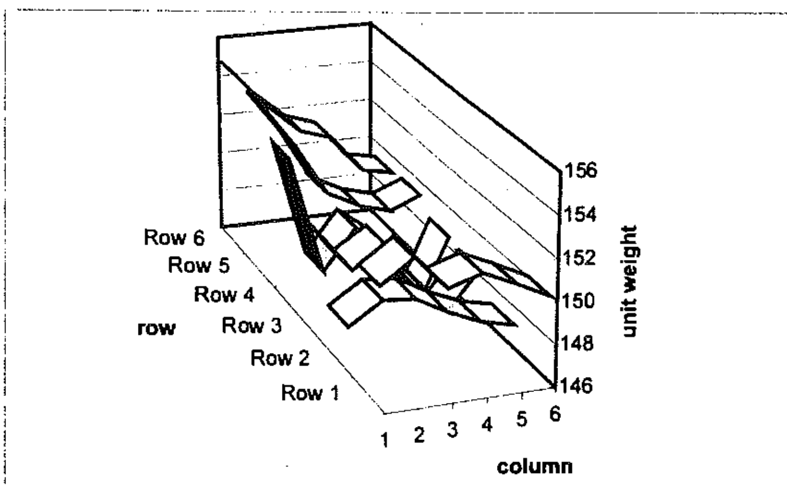


Figure 6.16 Surface Plot for Average of Air-dry Density (surface course) at Site 3 - Muskegon (random)

Table 6.6 p-values for Lab Density Evaluation (Air-dry Surface Course)

Site	Sample 1	Sample 2	Sample 3	Average of three samples
1. St. John's	***4.92×10-12***	***6.92×10-7***	***4.49×10-10***	***3.14×10-14***
2. Muskegon (uniform)	***0.0056***	***0.0062***	*0.0125*	***0.0015***
3. Muskegon (random)	***0.0013***	***0.0135***	*0.0208*	***0.0064***
4. M-99	***4.63×10-11***	***1.77×10-11***	***4.91×10-7***	***1.01×10-12***
5. Old US 27	0.5722	0.4860	0.4021	0.4846
6. M-123	***2.72×10-6***	***0.0002***	***3.88×10-5***	***3.19×10-7***

6.4.4 Site 3 - Muskegon (random)

Despite the visually apparent random segregation and somewhat random sampling configuration, linear segregation analysis using MBITSEG1.xls still revealed significant column differences for all four data sets, with p values on the order or 0.02 or less. However, multiple comparison statistical tests were not consistent in identifying specific columns that differed significantly from others. There may be two reasons for this:

- The results of multiple comparison statistical tests depend on the number of paired-columns studies and the selected confidence level.
- The scattered spots of segregation are not oriented perfectly along the longitudinal direction.

The surface plot for the average of three samples is shown in Figure 6.16. The pattern is generally similar to that for the one and four-minute nuclear density values previously shown in Figures 6.7 and 6.8, with a sharp decline in density from high values in column 1 to low values in column 2, with general trend to decrease in the direction of increasing column number.

6.4.5 Site 4 - M-99

The ANOVA analysis indicated significant column differences for all four data sets, with extremely low p-values (10^{-6} to 10^{-10}, as seen in Table 6.6). This matches the findings from nuclear density values.

Multiple comparison tests found the lab density values in column 4 are consistently low, the same result obtained from nuclear density grid analysis. However, for samples 1 and 2, the t-test found all columns different from each other. For sample 3, instead of consistently low values in column 4, values in column 5 were identified as consistently high.

The surface plot of the average of three samples is shown in Figure 6-17. It is a very good match in pattern shape to the corresponding plot for nuclear density (Figure 6.9).

6.4.6 Site 5 - Old US 27

The ANOVA finds no significant differences in column values, which matches the conclusion for the nuclear density values. Unlike the unrealistically low nuclear-measured density values, lab density values all seem to be within a reasonable range except perhaps two the lab density measurements at location 11 and 16 with the value 141.3 lb/ft^3 and 142.5 lb/ft^3 which appear low. This can be seen from the surface plot shown in Figure 6.18. The general shape of the surface plots for lab and nuclear density values are not as similar as at other sites, which is likely due to the unusually-low nuclear values.

As MBITSEG1.xls did not find any significant column differences at this site using either nuclear or lab density measurements, a problem is raised by the fact that extensive segregation was in fact identified by visual inspection. One explanation is that the segregation was not in a linear pattern, as MBITSEG1.xls is designed to look for.

6.4.7 Site 6 - M-123

The ANOVA found significant column differences for all four data sets, with small p-values, in the range 10^{-4} to 10^{-7}. This is reasonably similar to the results for nuclear density values, where three of four data sets showed significant differences, but with larger p-values. Multiple comparison tests consistently showed lab density values are high in column 2, but gave mixed results regarding other columns. The surface plot for lab density values, shown in Figure 6.19, shows more overall variability than that for nuclear density values. The reason may be that nuclear density readings account for surface voids of the asphalt mixture, but air-dry density considers the volume of the specimen excluding any surface voids.

6.4.8 Coefficients of Variation of Lab-Measured Density

The average coefficients of variation for row and column data, as well as overall coefficients of variation, are shown in Table 6.7. As was the case for nuclear density values, at sites where linear segregation was identified, the average column values are consistently lower than average row values or overall values, with the magnitude of differences generally corresponding to the degree of segregation.

The frequency distribution of lab density measurements are also presented using histograms, shown in Figure 6-20. All seven sites, to some extent, exhibit multiple peaks, and all exhibit low or high values separated from the remaining data values. As was the case for nuclear density, the data at the Muskegon (uniform) site had the highest overall coefficient of variation (1.8 percent); and the M-99 and M-123 sites had the lowest coefficients of variation (0.9 percent).

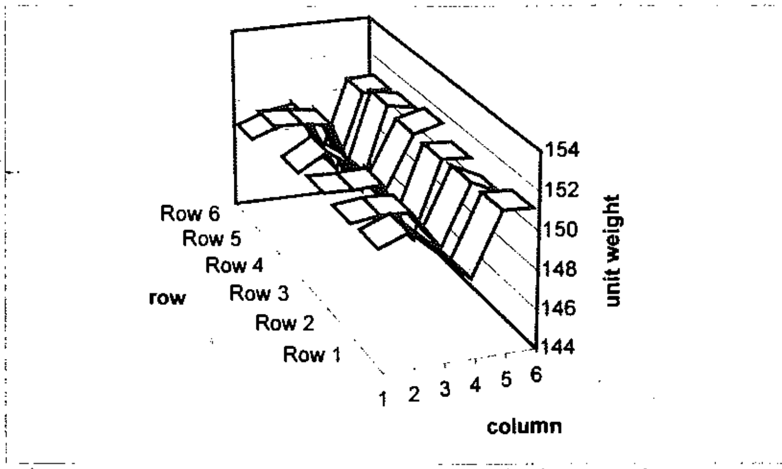


Figure 6.17 Surface Plot for Average of Air-dry Density (surface course) at Site 4 - M-99

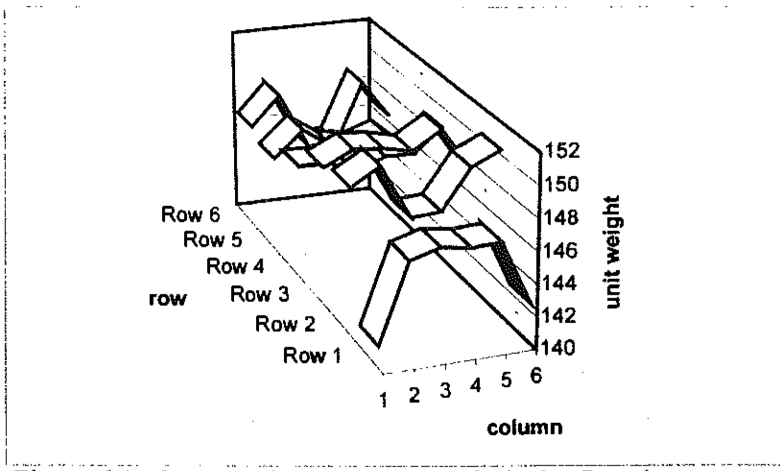


Figure 6.18 Surface Plot for Average of Air-dry Density (surface course) at Site 5 - Old U.S. 27

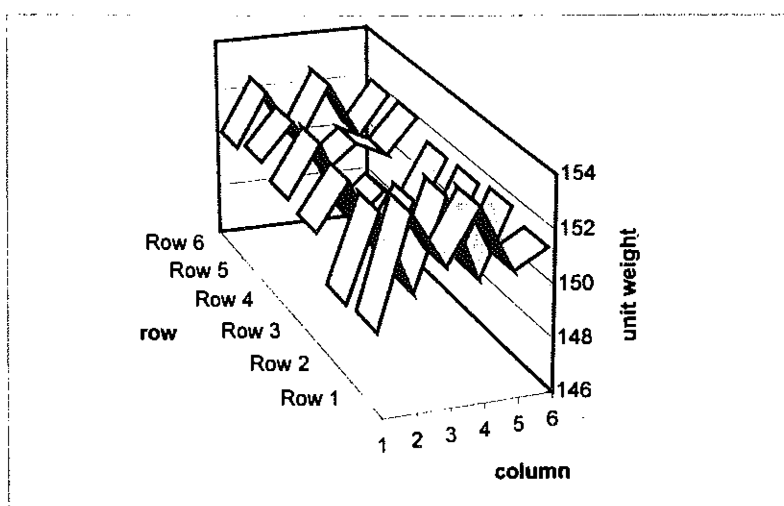


Figure 6.19 Surface Plot for Average of Air-dry Density (surface course) at site 6 - M-123

Table 6.7 Coefficient of Variation for Air-dry Lab Density

Site	Sample	Coefficient of variation (%)		
		Column	Row	Overall
	sample 1	0.48	1.41	1.35
1. St. John's	sample 2	0.59	1.15	1.10
	sample 3	0.49	1.28	1.20
	average of three samples	0.40	1.07	1.00
	sample 1	1.25	1.47	1.63
2. Muskegon	sample 2	1.79	2.08	2.40
(uniform)	sample 3	1.50	1.71	1.86
	average of three samples	1.35	1.62	1.79
	sample 1	1.10	1.26	1.45
3. Muskegon	sample 2	1.31	1.21	1.60
(random)	sample 3	1.24	1.24	1.54
	average of three samples	1.17	1.18	1.48
	sample 1	0.38	0.97	0.94
4. M-99	sample 2	0.38	0.98	0.94
	sample 3	0.52	0.94	0.92
	average of three samples	0.31	0.91	0.88
	sample 1	1.47	1.03	1.54
5. Old U.S. 27	sample 2	1.31	0.90	1.35
	sample 3	1.24	1.01	1.32
	average of three samples	1.30	0.93	1.36
	sample 1	0.53	0.86	0.87
6. M-123	sample 2	0.67	1.04	1.04
	sample 3	0.65	0.95	0.97
	average of three samples	0.48	0.86	0.86

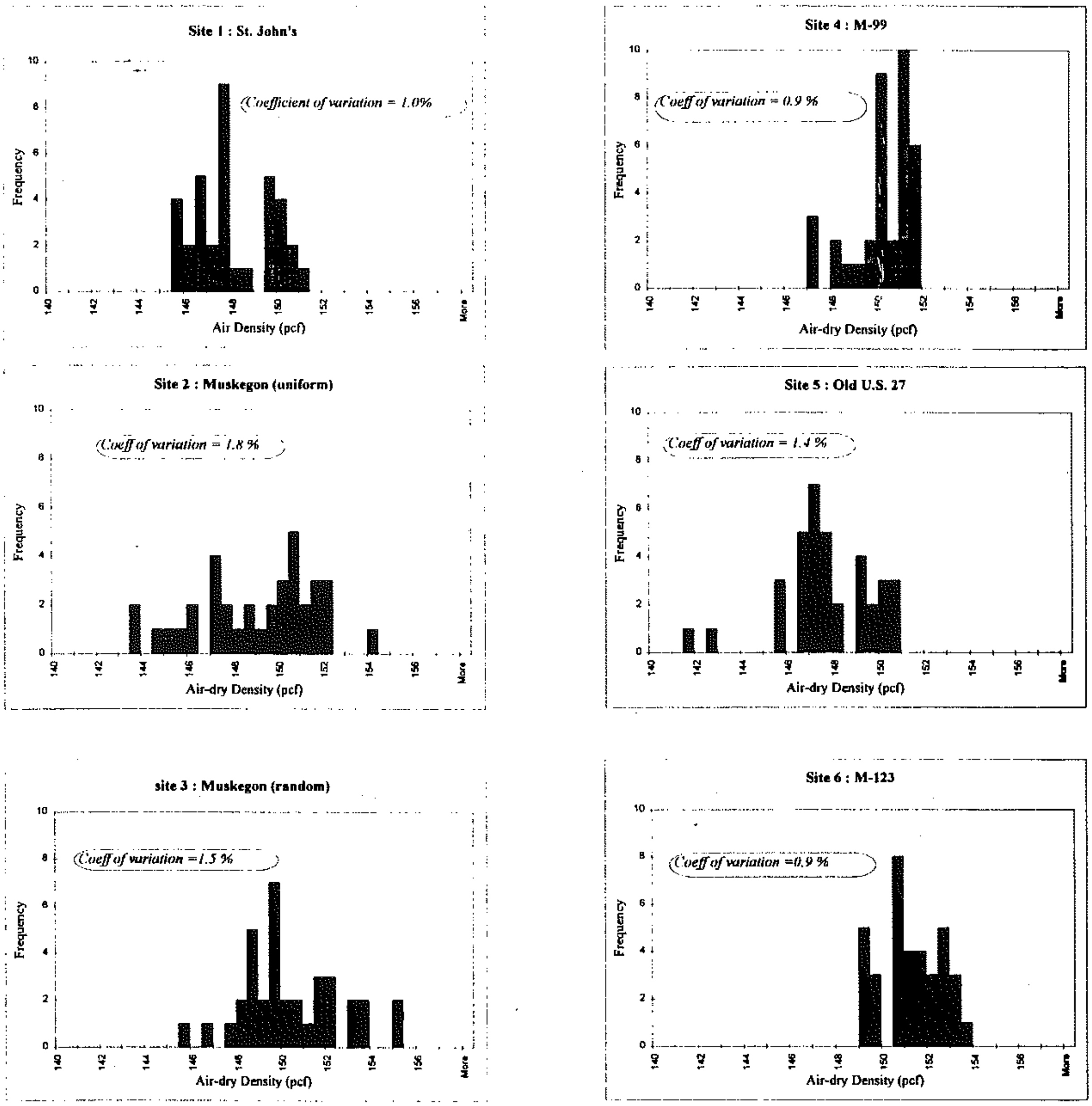


Figure 6.20 Histograms for Average of Air-dry Density on Surface Course

6.5 Assessment of Liner Segregation Based on Gradation Analysis

6.5.1 Overview

Segregation refers to the phenomena of physical separation of coarse and fine materials in an asphalt mixture; up to this point, significant differences in density have been hypothesized to correlate with actual physical differences in gradation. To check for differences in grain size, the percents passing three different sieve sizes, 3/8", No. 4 and No. 8 were used as data values in yet another series of grid analyses using MBITSEG1.xls. The resulting p-values are shown in Table 6.8. Again, p-values less than 0.05 are shown in italics, and those less than 0.01 are shown in bold italics.

Table 6.8 p-values for Gradation Evaluation

Site	Percent passing 3/8"	Percent passing No.4	Percent passing No.8
1. St. John's	0.1610	***1.45×10^{-5}***	***2.90×10^{-6}***
2. Muskegon (uniform)	0.1321	0.3100	0.2199
3. Muskegon (random)	0.0514	0.0748	0.0564
4. M-99	***0.0009***	***2.80×10^{-6}***	***1.80×10^{-7}***
5. Old US 27 (columns)	0.3502	0.7686	0.8073
5. Old US 27 (row)	***4.48×10^{-5}***	***6.83×10^{-10}***	***1.53×10^{-11}***
6. M-123	***6.38×10^{-5}***	***5.20×10^{-7}***	***2.96×10^{-7}***

In general, p-values are not as small as those obtained for nuclear or lab density values. Nevertheless, the sites with the strongest indication of density differences (Sites 1, 4, and 6) also have the strongest indication of gradation differences, and the site with the least indication (Site 5) of density difference corresponds to the least indication of gradation difference. The Muskegon sites (2 and 3), which had significant density differences, would only show significant gradation differences if the significance level were reduced to about 70 percent (p=0.3), which is not very conclusive in statistical terms.

Based on the comparison of p-values alone, a preliminary conclusion can be drawn:

For sites where gradation differences were significant with very low p-values (say < 10^{-3}), p-values for density differences were also very low.

Details of specific sites are described in the following paragraphs.

6.5.2 Site 1 - St. John's

The ANOVA found strong column differences for percents passing the No. 4 and No. 8 sieves, but not for the percent passing the 3/8" sieve. Multiple comparison tests for all three data sets found the percents-finer to be low in column 2, suggesting a coarser-than-average gradation. The surface plots for all three percents-finer is shown in Figure 6.21. Although they are strongly correlated to each other, they do not appear similar in pattern to either the lab or nuclear density values.

6.5.3 Site 2 - Muskegon (uniform)

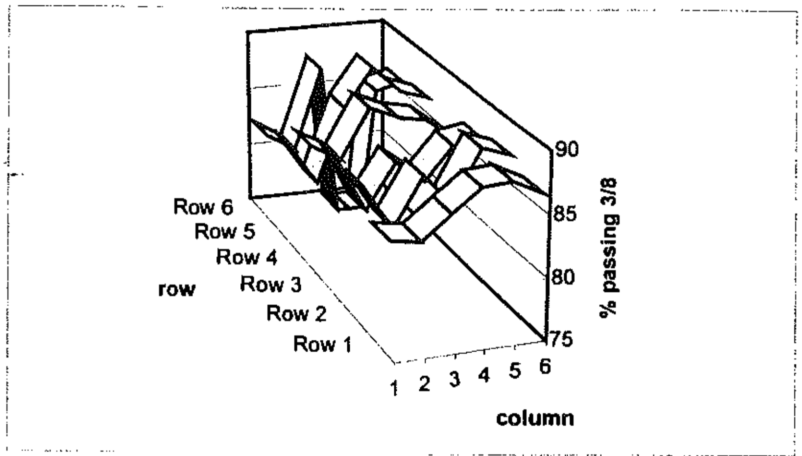
The ANOVA did not find significant differences (at the 95 percent level or better) for any of the three sieve sizes, which differs from the conclusion for density evaluations. There is a seemingly large variation in the percents passing various screen sizes, with the difference between the most and least percent passing among the 36 cores being 6.32 percent, 7.49 percent and 6.25 percent for the 3/8", No. 4 and No.8 sieves, respectively. The surface plots for the percents passing the three sieve sizes are shown in Figure 6.22. The variation is most apparent for the percent passing the No. 8, even though the percent passing the 3/8" sieve had the lowest p-value. When the density surface plots are compared to the gradation surface plots, some similarities can be noted in column one, where low measured density values apparently correspond to low percents passing, or a coarser-than-average gradation.

6.5.4 Site 3 - Muskegon (random)

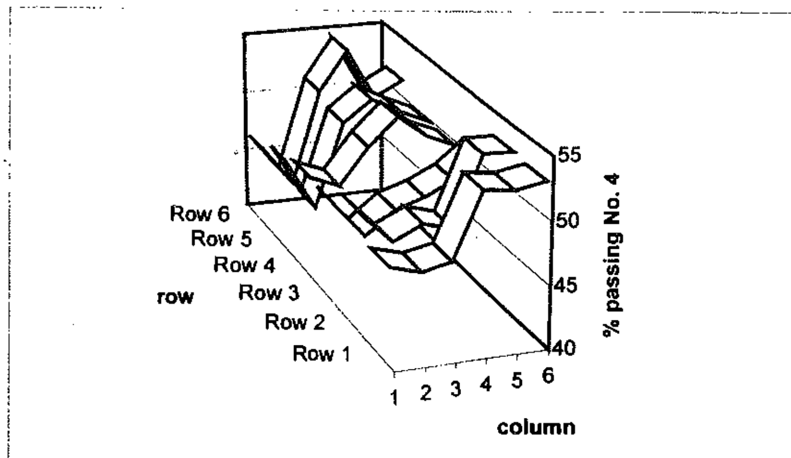
The ANOVA did not find any significant column differences at the 95 percent significance level; however, several were close and all would be significant at the 92 percent confidence level. This again suggests that nuclear density measurement tends to find differences at greater significance levels than they are present in terms of gradation. The overall variation is relatively high, with the coefficients of variation (for percent passing) at 7.33 percent, 9.67 percent and 8.16 percent for the percent passing 3/8", No. 4 and No. 8 sieve respectively. The surface plots are shown in Figure 6.23 and are similar in shape to each other. It is difficult, however, to find similarities in the gradation surface plots and density surface plots.

6.5.5 Site 4 - M-99

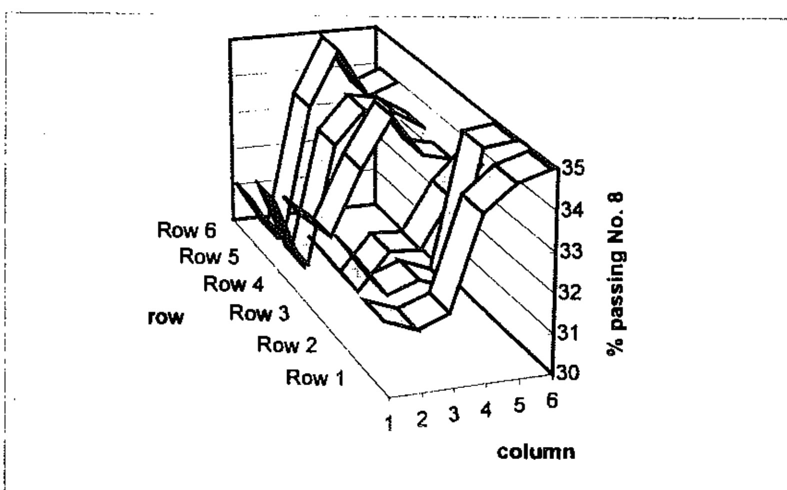
Recall that the M-99 site was originally chosen as a candidate for an "unsegregated" site, but field inspection indicated slight segregation and ANOVA's for both nuclear and lab density found a strong linear trend of low density in column four with very high statistical significance. The gradation analyses agree well at this site with the density analyses. The ANOVA found significant column differences for all three sieve sizes considered. For the percent passing 3/8" sieve, multiple comparison statistical tests indicated low values in column 5; for the percent passing No. 4 and No.8, consistently low values are found in both column 4 and column 5. The low density values are indicative of a linear strip in the pavement that is relatively deficient in fines. The surface plots for gradation data are shown in Figure 6.24. They are generally similar to each other and reasonably similar to the density plots. The overall variation is not as large as that observed at previous sites; the coefficients of variation are 2.66%, 3.23% and 3.41% for percent passing 3/8", No.4 and No.8 sieve respectively.



(a) Percent Passing 3/8" Sieve

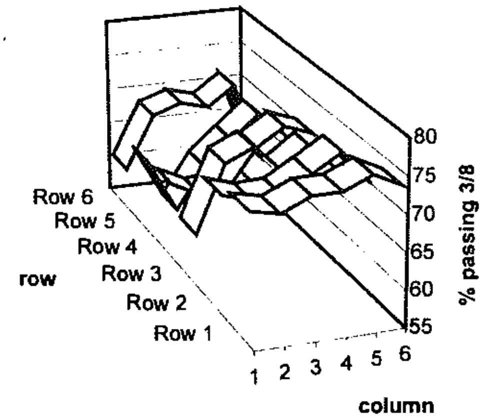


(b) Percent Passing No.4 Sieve

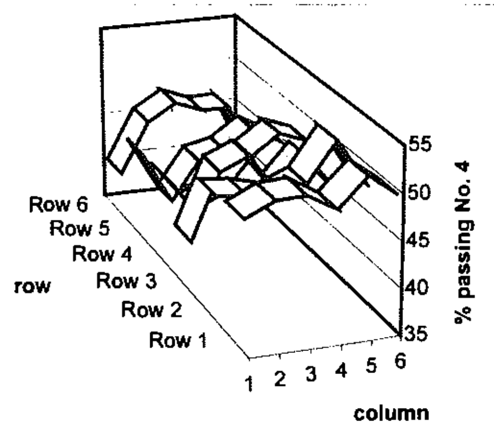


(c) Percent Passing No.8 Sieve

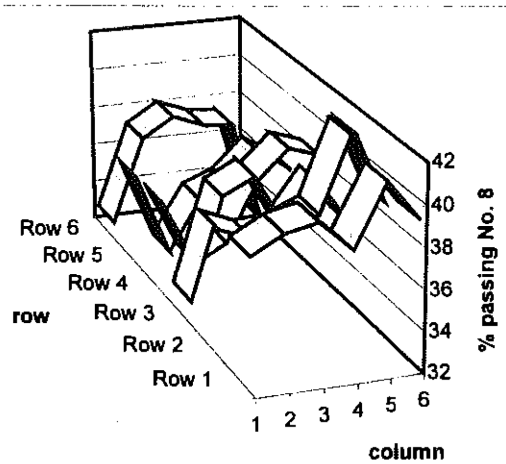
Figure 6.21 Surface Plots for Gradation at Site 1 - St. John's



(a) Percent Passing 3/8" Sieve

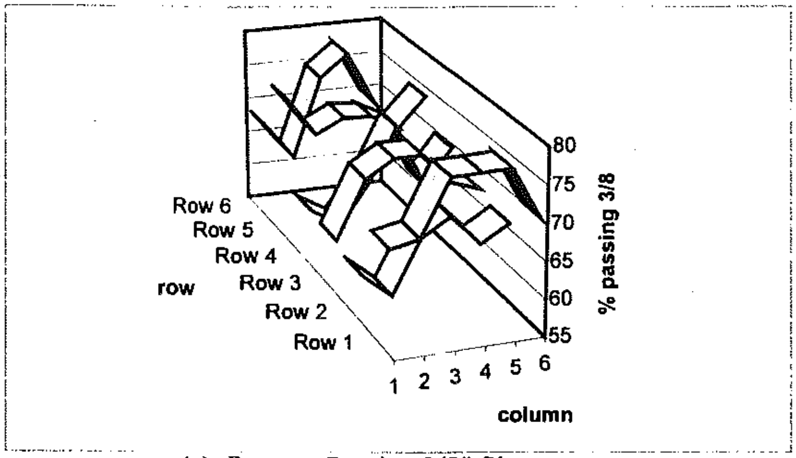


(b) Percent Passing No.4 Sieve

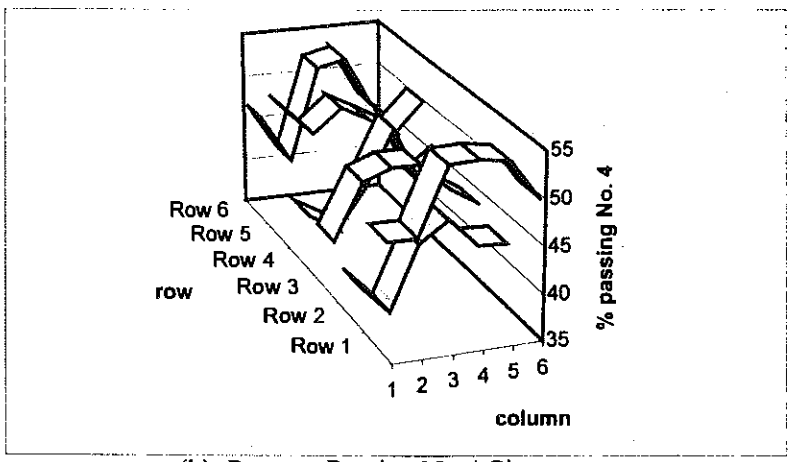


(c) Percent Passing No.8 Sieve

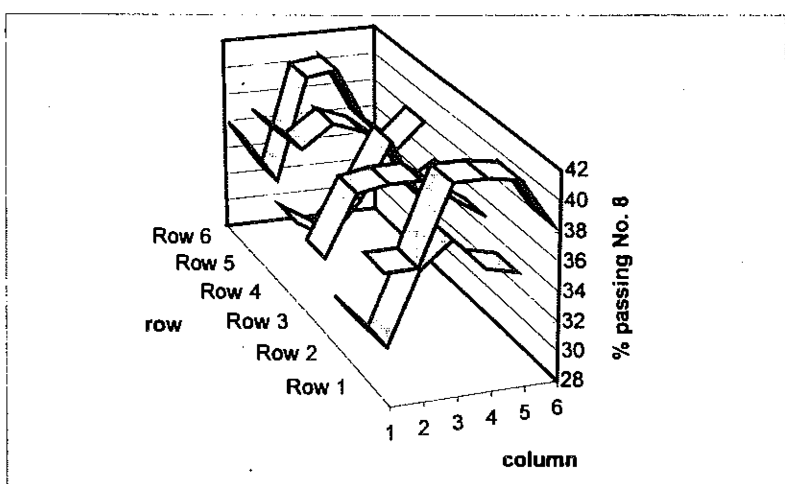
Figure 6.22 Surface Plots for Gradation at Site 2 - Muskegon (uniform)



(a) Percent Passing 3/8" Sieve

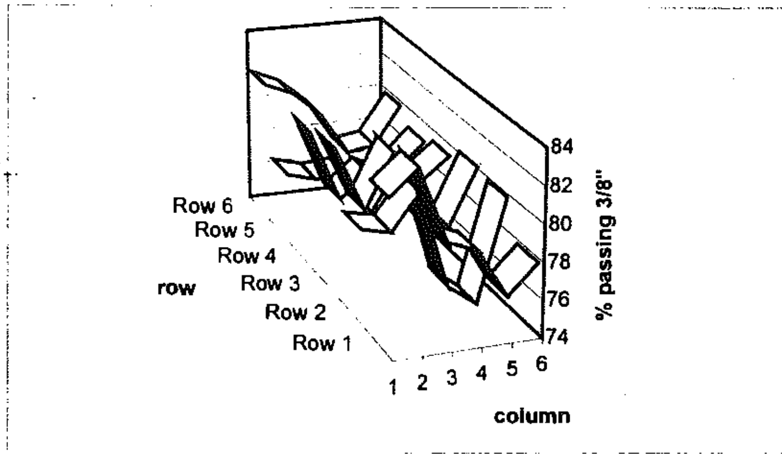


(b) Percent Passing No.4 Sieve

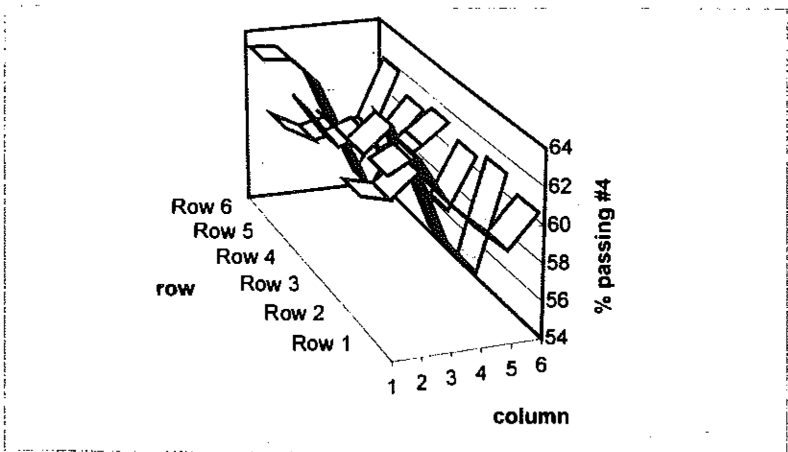


(c) Percent Passing No.8 Sieve

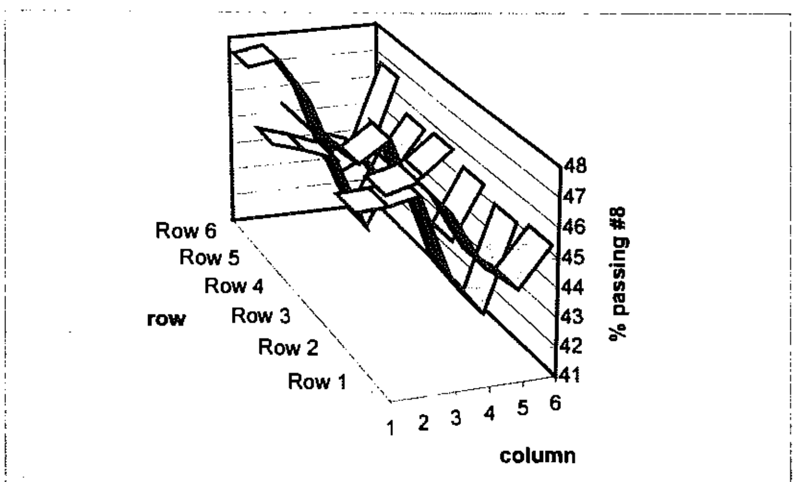
Figure 6.23 Surface Plots for Gradation at Site 3 - Muskegon (random)



(a) Percent Passing 3/8" Sieve



(b) Percent Passing No.4 Sieve



(c) Percent Passing No.8 Sieve

Figure 6.24 Surface Plots for Gradation at Site 4 - M-99

6.5.6 Site 5 - Old US 27

No significant column differences were found either from ANOVA analysis or multiple comparison statistical tests. As seen in Table 6.9, the p-values are quite high, indicating no statistical significance, a similar results to that for density evaluation, but still at odds with the visual observation in field, i.e., a site with severe segregation. A clue was obtained when the surface plots (Figure 6.25) were viewed; these consistently show a strong trend of different percents passing, but oriented along *rows* rather than columns. This is believed to be evidence of "end-of-job" segregation, where coarse materials left in the hopper are discharged into the augers, producing a uniformly increasing percent of coarse materials near the end of the paving. These patterns may be somewhat similar to, but are not strongly correlated with, the patterns of the density plots.

Because of the notable variations from row-to-row, a second round of ANOVA analysis and multiple comparison statistical tests were applied to find row differences, by switching rows and columns in MBITSEG1.xls. Strong row differences were found for all three sieve sizes, and p-values were in the range 10^{-5} to 10^{-11}. Furthermore, multiple comparison tests found that all row means are concluded as different for the percent passing No.4 and No.8. The overall variation is quite large for the percent passing No.4 and No.8 with the coefficients of variation at 7.64 percent and 9.29 percent respectively.

6.5.7 Site 6 - M-123

The ANOVA indicated the presence of linear segregation, with p-values on the order of one in a million. This agrees well with the results of both density evaluations, nuclear and lab. Multiple comparison tests indicated that the percents passing in column 3 were consistently low, indicating coarser-than-average aggregate gradations in column 3. Surface plots are shown in Figure 6.26. The three gradation plots are similar to each other and to the laboratory density plot. The nuclear density plot is generally similar in pattern, but less sharp and pronounced in its variation. Once again, lower percents passing, or coarser gradations, correlated with lower density values.

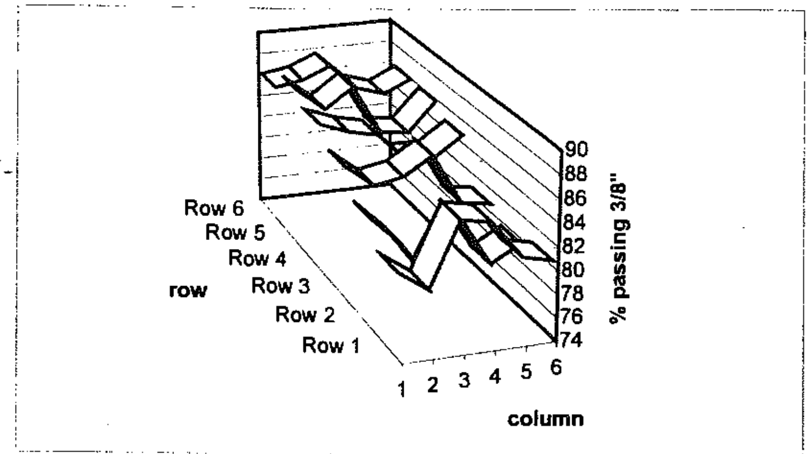
6.5.8 Coefficients of Variation of Percent Passing

The values of coefficient of variation for both row and column data and for the overall sites are presented in Table 6.9. Once again, the three sites for which strong indications of segregation are present based on low p-values (St. John's, M-99 and M-123) have average coefficients of variation for columns that are much lower than those for rows or for the entire data set. Also, the row averages for the Old US 27 site are much lower than the column averages or global averages, which is consistent with the observed end-of-job segregation pattern.

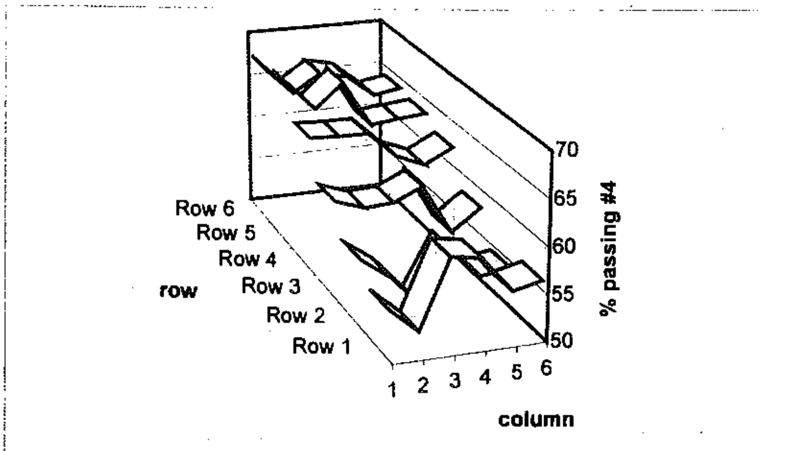
The frequency distribution of percents passing the No. 4 and No. 8 sieves are presented using histograms, in Figures 6.27 and 6.28. Similar to the case for density measurements, most or the sites exhibit multiple peaks, isolated high or low values separated from the remaining data, or both.

Table 6.9 Coefficient of Variation for Gradation Data

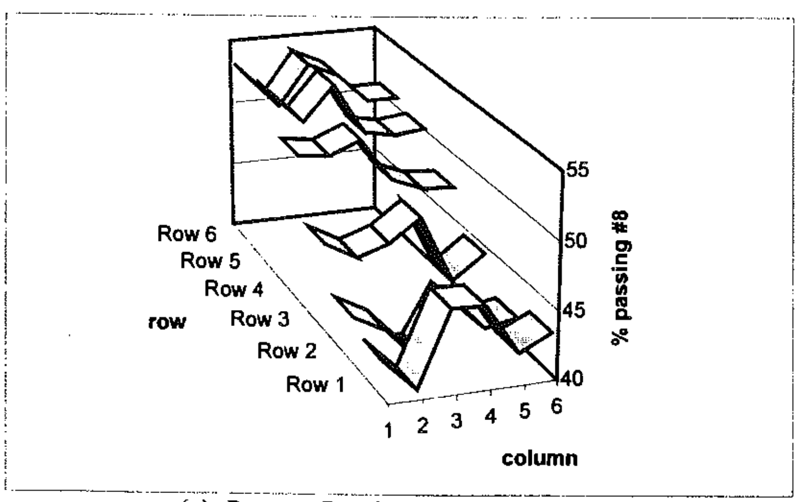
Site	Sample	Coefficient of variation (%) Column	Row	Overall
1. St. John's	percent passing 3/8"	2.96	3.68	4.62
	percent passing No.4	3.46	5.49	5.44
	percent passing No.8	2.60	4.49	4.38
2. Muskegon (uniform)	percent passing 3/8"	5.74	4.83	6.32
	percent passing No.4	7.18	5.62	7.49
	percent passing No.8	5.87	5.18	6.25
3. Muskegon (random)	percent passing 3/8"	6.56	5.79	7.33
	percent passing No.4	8.86	6.98	9.67
	percent passing No.8	7.36	6.04	8.16
4. M-99	percent passing 3/8"	1.98	2.51	2.66
	percent passing No.4	1.94	3.17	3.23
	percent passing No.8	1.93	3.38	3.41
5. Old U.S. 27	percent passing 3/8"	3.19	2.29	3.36
	percent passing No.4	7.72	3.61	7.64
	percent passing No.8	9.50	3.86	9.29
6. M-123	percent passing 3/8"	2.32	3.38	3.43
	percent passing No.4	3.39	6.41	6.24
	percent passing No.8	3.09	5.88	5.67



(a) Percent Passing 3/8" Sieve

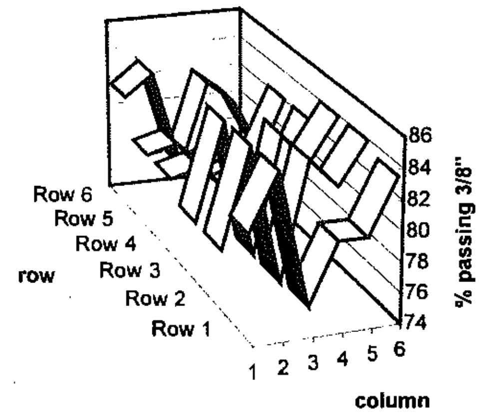


(b) Percent Passing No.4 Sieve

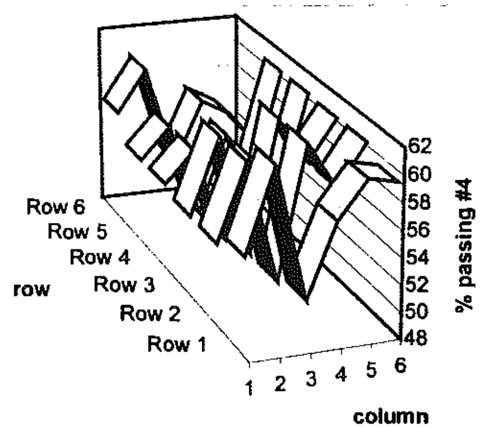


(c) Percent Passing No.8 Sieve

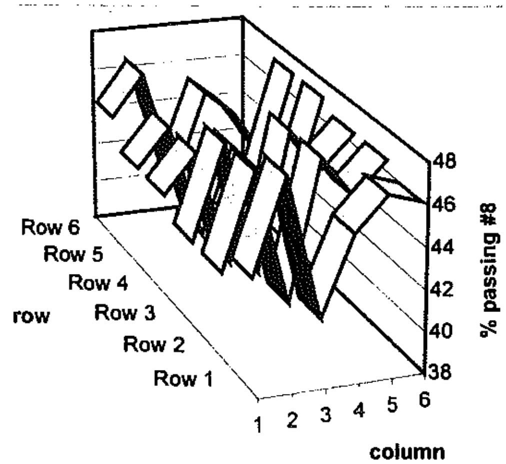
Figure 6.25 Surface Plots for Gradation at Site 5 - Old U.S. 27



(a) Percent Passing 3/8" Sieve



(b) Percent Passing No.4 Sieve



(c) Percent Passing No.8 Sieve

Figure 6.26 Surface Plots for Gradation at Site 6 - M-123

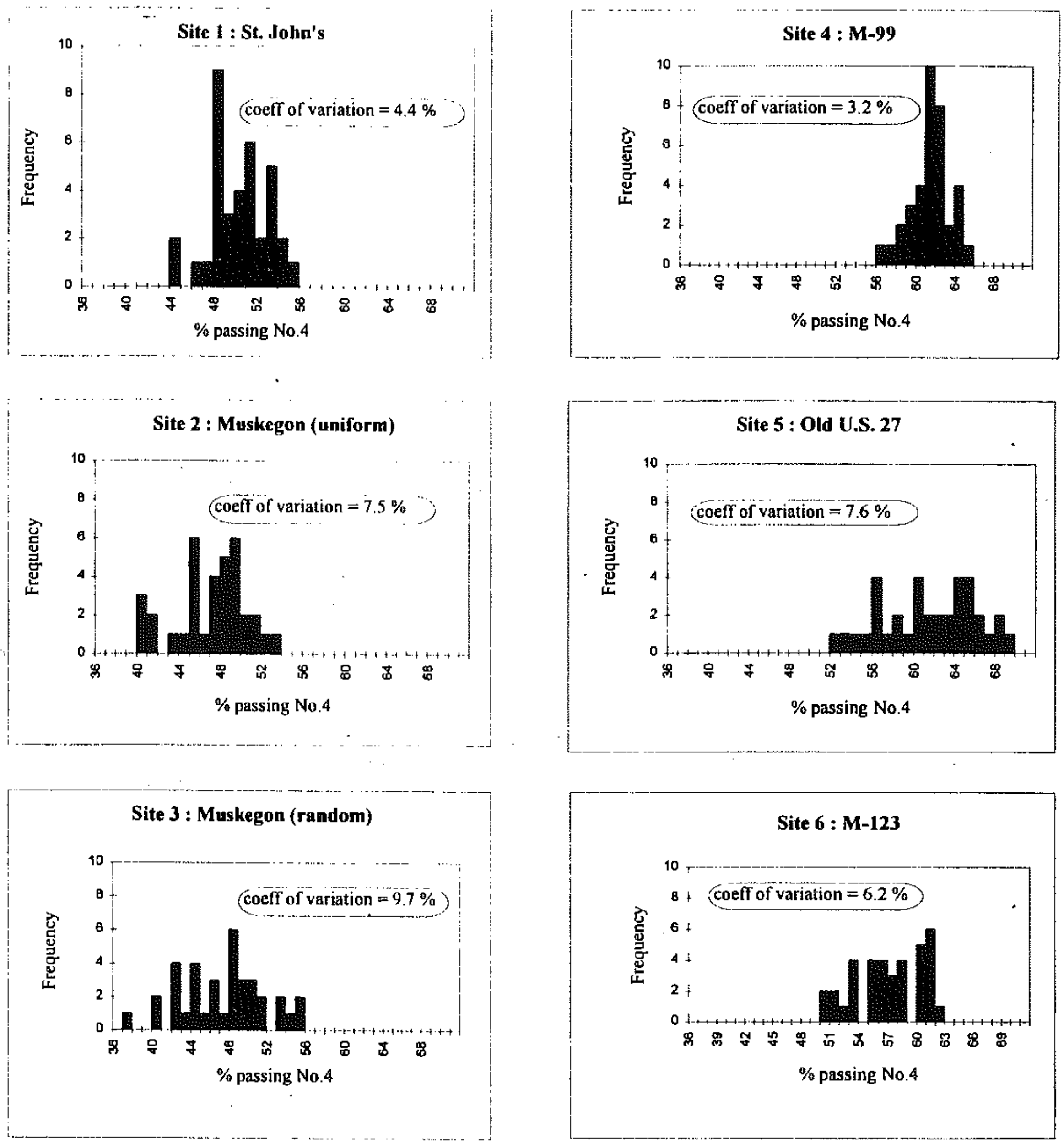


Figure 6.27 Histograms for Percent Passing No.4 Sieve

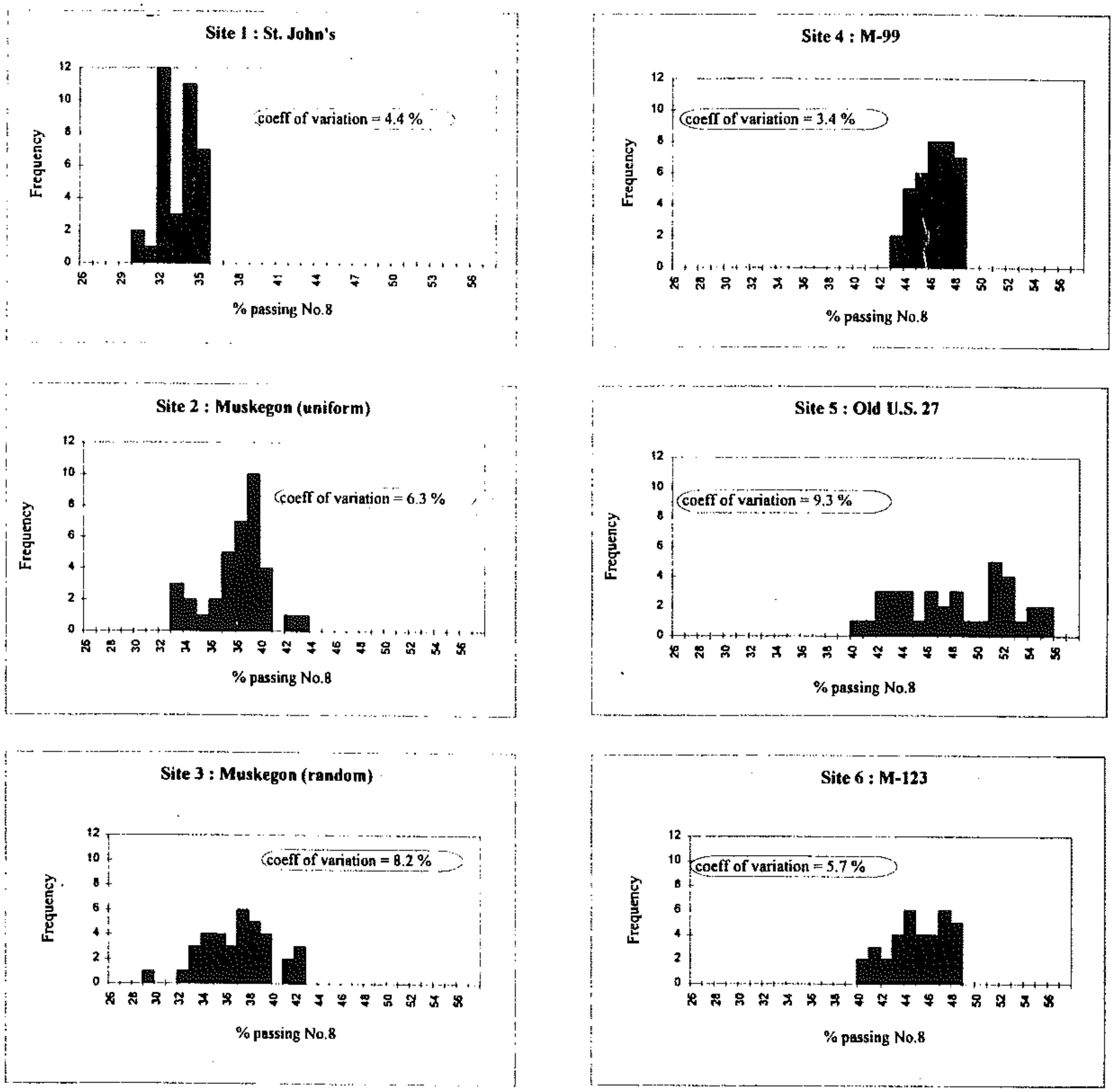


Figure 6.28 Histrograms for Percent Passing N0.8 Sieve

6.6 Assessment of Linear Segregation Using Nondestructive Deflection Testing

A set of nondestructive deflection tests (NDT) using the MDOT falling weight deflectometer (FWD), was made at the M-123 site and the Lansing State Police site to investigate possible correlation between these measures and the existence of segregation. As large voids deficient in fine materials can easily be observed in a segregated area, higher deflections might be expected, which would give an alternative way to identify and quantify segregation in the existing pavement. Work with FWD by others also demonstrated that cracking of pavements can have a great effect on deflection data. Maestas and Mamlouk (1992) selected the particular pavement surface with extent of cracking for the overlay analysis to minimize errors associated with deflection testing of variable cracking pavement. Claessen et al. (1976) compared FWD data on various pavement sections and concluded that the difference of deflection values measured in and between the wheel tracks is caused by cracks in the wheel crack. Furthermore, Newcomb et al. (1989) compared the results between the laboratory and field estimates of moduli. Considerable differences were found between the two test sites. They concluded that it is due to fatigue cracking on the pavement.

6.6.1 Using MBITSEG1.xls for Deflection Evaluation

As mentioned before, deflection data may indicate the existence of segregation. From the previous data analysis, it is also known that segregated areas result in a low density asphalt mixture because of the open texture of pavements. Therefore, it is also reasonable to perform statistical tests for the deflection data. The hypothesis is made as follows:

Segregated areas either with accumulation of coarse particles or fine materials can lead to a high deflection, provided that the material properties beneath the AC layer are homogeneous.

Therefore, an unsegregated asphalt mixture should be expected to have a low deflection value because the smaller particles occupy the void spaces between the larger ones, thus increasing the resistance to relative particle translation when subjected to a falling weight.

Deflection data were collected at the M-123 site and Lansing state police facility site. As mentioned in Section 4.4, there were nine sensors set at distances of 0, 8, 12, 18, 24, 36 and 60 in. behind the loading plate and both 12 in. left and front of the plate. The corresponding deflections are named D_0, D_8, D_{12}(behind), D_{18}, D_{24}, D_{36}, D_{60}, D_{12}(left) and D_{12}(front), respectively. In each testing location, four drops were made; the first drop was for seating purposes and the average deflection from the other drops was selected to represent an actual basin.

Site 6 - M-123. ANOVA found significant column differences for all data sets (sample 1, sample 2, sample 3, and average of three samples) at the center location D_0 as well as locations D_8 and $D_{12(behind)}$. The p-values obtained from ANOVA analysis are given in Table 6.10. Multiple comparison statistical tests indicated higher deflections in column 6 and lower deflections in column 2 for sample 1. For samples 2 and 3, t-tests indicated that all paired columns are different with each other, but Tukey and six of six tests did not support the same conclusion. The surface plot for the average of three samples at the D_0 location is shown in Figure 6.29. Although significant differences are found in column data, the overall pattern does not appear to have any similarity to those for nuclear or lab-measured density.

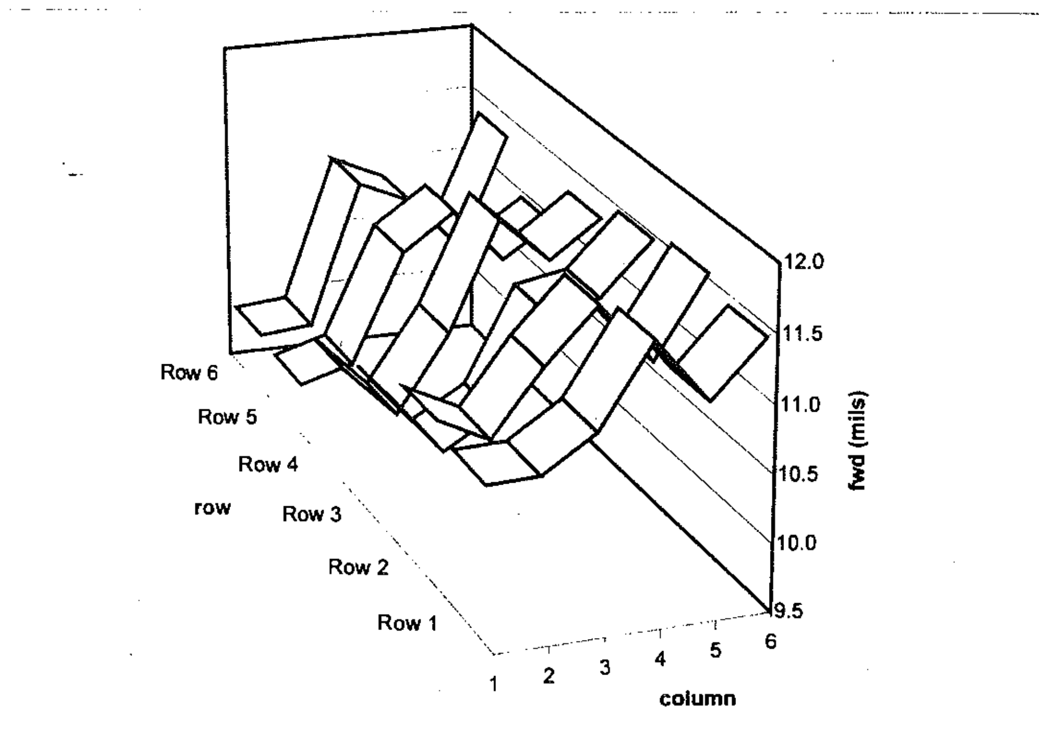


Figure 6.29 Surface Plot for Deflection Data (D0) at Site 6 - M-123

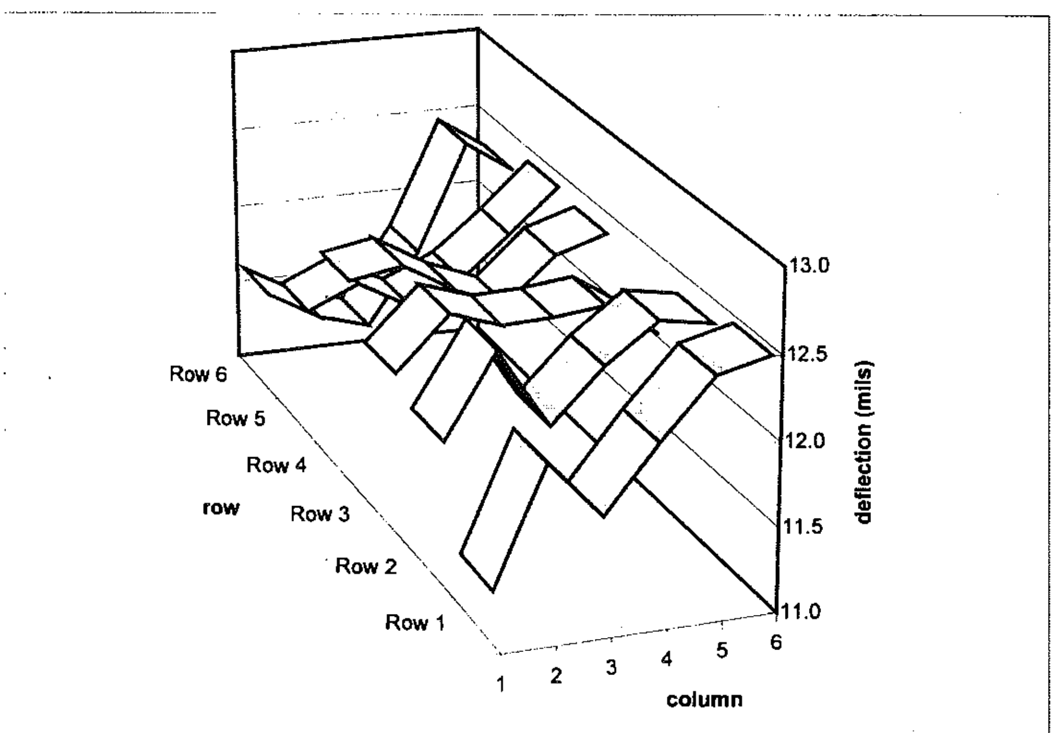


Figure 6.30 Surface Plot for Deflection Data (D12, behind) at Site 7 - Lansing State Police Facility

Table 6.10 p-values for Deflection Evaluation at Site 6 - M-123

Sensor Location	Sample 1	Sample 2	Sample 3	Average of three samples
D_0	***0.0066***	***0.0036***	***0.0035***	***0.0030***
D_8	***0.0096***	***0.0092***	***0.0074***	***0.0080***
D_{12}(behind)	*0.0256*	*0.0268*	*0.0240*	*0.0241*
D_{18}	0.0531	0.0684	0.0602	0.0567
D_{24}	0.1067	0.0967	0.0993	0.0977
D_{36}	0.1768	0.1511	0.1571	0.1565
D_{60}	0.6371	0.7532	0.7152	0.7005

For the deflection data of D_0, D_8, D_{12}(behind), MBITSEG1 software showed that there are column differences and multiple comparison tests indicated that the deflection values in column 6 are consistently high. According to the hypothesis, this could be an indication of segregation. However, the high deflection cannot be expected to correlated strongly with higher or lower values of nuclear density, as the measure of nuclear density is not only influenced by the amount of surface voids but also by the specific gravity of aggregates.

For the deflection data recorded at D_{18}, D_{24}, D_{36} and D_{60}, MBITSEG1 did not indicate any significant column differences. As these sensors are away from the center of the loading plate, the magnitude of deflection data are relatively small compared to the deflection data recorded by the sensors close to the center.

Site 7 - Lansing State Police Facility. p-values obtained from the ANOVA are shown in Table 6.11. Very significant column differences were found for deflection data recorded at D_0, D_8, D_{12}, D_{18}, D_{24}, and D_{36}. It is interesting to note that the p-values for deflection evaluation at D_{12}(behind) are not as low as that at other sensor locations. From the surface plot for deflection data at D_{12}(behind), see Figure 6.30, only column 5 with high deflection is different from other columns.

Furthermore, coefficient of variation for average of three samples is 2.60%, which shows there is not much variation. The values of coefficient of variation for deflection data at each sensor location are shown in Table 6.12.

Table 6.11 p-values for Deflection Evaluation at Site 7 - Lansing State Police Facility

Sensor Location	Sample 1	Sample 2	Sample 3	Average of three samples
D_0	*2.37×10^{-12}*	*5.84×10^{-13}*	*3.43×10^{-11}*	*7.63×10^{-13}*
D_8	***8.97×10^{-11}***	***1.44×10^{-10}***	***8.33×10^{-10}***	***3.30×10^{-11}***
D_{12}(behind)	***0.0009***	*0.0242*	*0.0144*	***0.0027***
D_{18}	***1.09×10^{-9}***	***3.30×10^{-11}***	***1.46×10^{-10}***	***1.57×10^{-11}***
D_{24}	***1.25×10^{-11}***	***4.22×10^{-14}***	***5.55×10^{-14}***	***5.83×10^{-14}***
D_{36}	***1.16×10^{-09}***	***1.62×10^{-11}***	***1.13×10^{-11}***	***8.38×10^{-12}***
D_{60}	0.1215	0.3936	0.0858	0.1320

Table 6.12 Coefficient of Variation at Site 7 - Lansing State Police Facility

Sensor Location	Sample 1	Sample 2	Sample 3	Average of three samples
D_0	12.27	12.42	13.33	12.56
D_8	7.24	7.06	7.24	7.08
D_{12}(behind)	2.78	2.68	2.84	2.60
D_{18}	6.19	6.37	6.51	6.25
D_{24}	10.72	10.17	10.68	10.43
D_{36}	13.56	12.30	13.04	12.78
D_{60}	5.84	6.26	7.58	6.29

6.6.2 Relation between Deflection and Nuclear Density

As mentioned before, deflection data may indicate the existence of segregation. From previous data analysis, it is also known that segregated areas exhibit low density values because of open texture of pavements. Therefore, it is reasonable to attempt to correlate deflection data with 1-min nuclear density.

The direct plots of 1-min nuclear density versus deflection at each sensor location are shown in Figure 6.31 and 6.32 for the M-123 and Lansing state police facility site respectively. Obviously, there is a lot of scatter and hence, no relation can be found.

The next effort was made to adjust peak deflection to a single reference temperature. For the pavements tested for this study, the temperature on the surface of AC layer was monitored during deflection testing and ranged from 65.0 °F to 74.3 °F. Since this temperature variation could affect deflection measurements, the deflection data must be corrected to a standard temperature, usually 68 °F. The AASHTO guide (1993) has a graph for temperature corrections of the peak deflection to this standardized temperature. Since the temperature adjustment factor is also a function of total asphalt thickness, then, information regarding asphalt thickness is required. In this case, pavements have an average AC thickness of 3.96 in. which is measured from asphalt concrete cores. The relationship between the peak deflection with temperature adjustment and one-minute nuclear density value is shown in Figure 6.33. No correlation is apparent.

Obviously, deflection readings are also affected by pavement layer thickness. Rwebangira et al. (1987) concluded that the backcalculated layer moduli are more sensitive to AC thickness than base layer thickness. Due to the variation of AC thicknesses in the construction process, AC thicknesses were measured from the 108 core samples taken from the field. The adjustment factor is based on the normalization of AC thickness :

$$\text{Adjustment Factor} = \frac{\text{AC thickness}}{\text{average of AC thickness}}$$

The plot of peak deflection with AC thickness adjustment versus 1 min. nuclear density is shown in Figure 6.34. Still, no clear pattern can be observed.

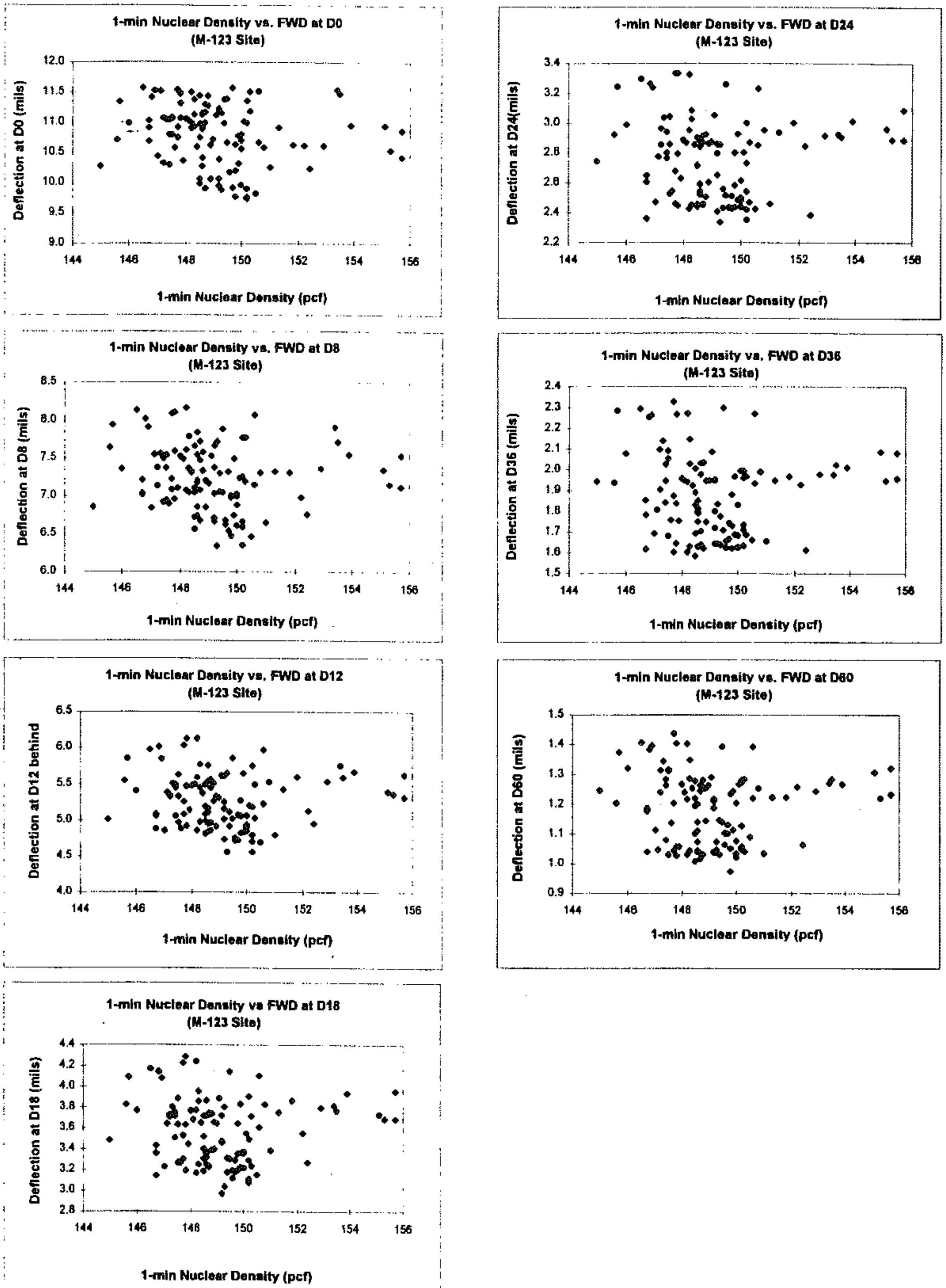


Figure 6.31 Scatter Plots between Deflection and Nuclear Density at Site 6 - M-123

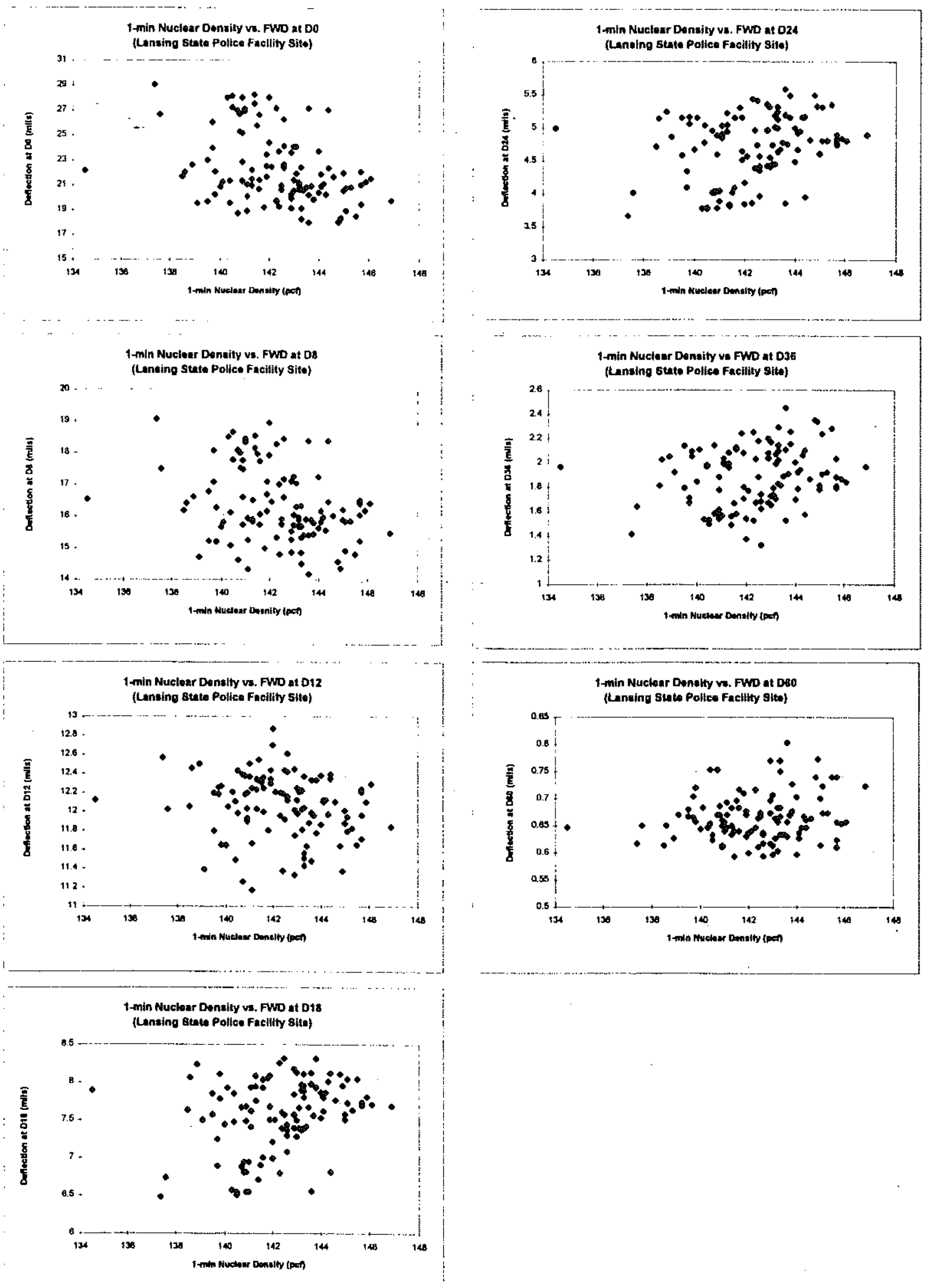


Figure 6.32 Scatter Plots between Deflection and Nuclear Density at Site 7 - Lansing State Police Facility

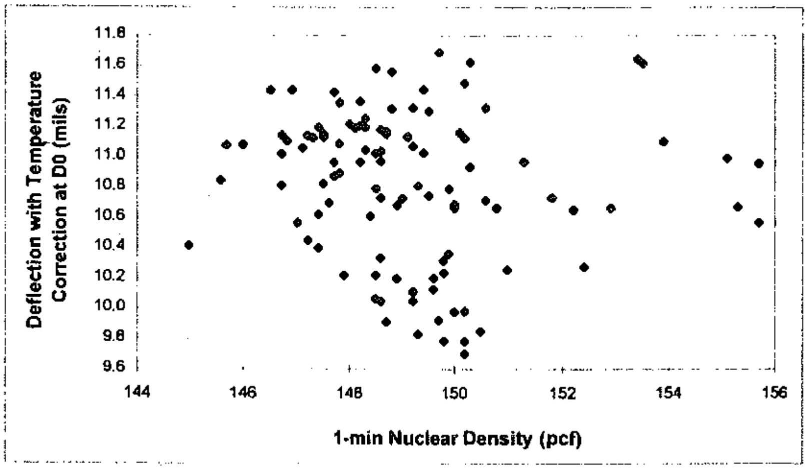


Figure 6.33 Scatter Plot between Deflection with Temperature Correction and Nuclear Density at Site 6 - M-123

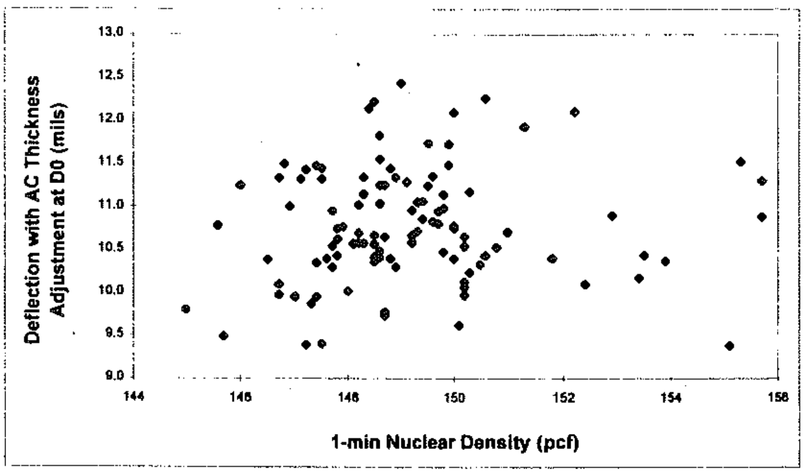


Figure 6.34 Scatter Plot between Deflection with AC Thickness Adjustment and Nuclear Density at Site 6 - M-123

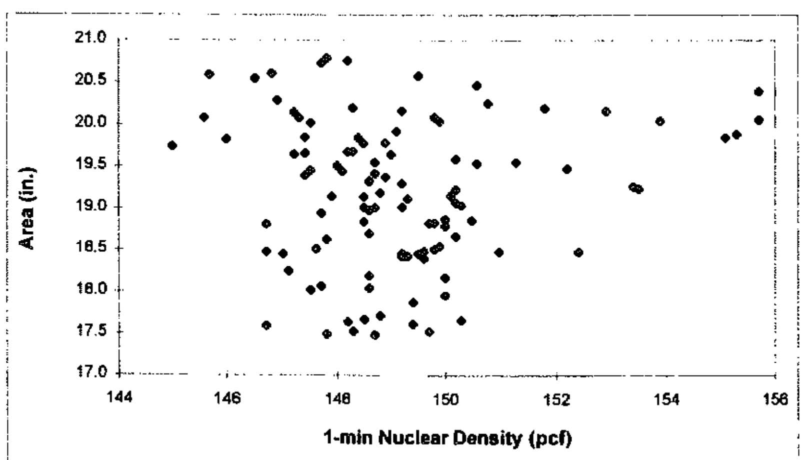


Figure 6.35 Scatter Plot between Area and Nuclear Density at Site 6 - M-123

6.6.3 Relation between FWD Parameters and Nuclear Density

Hoffman and Thompson (1982) proposed the AREA to characterize the deflection basin of FWDs. The AREA of the deflection basin was originally defined as :

$$\text{AREA} = 6 \times \left[1 + 2(\frac{D_{12}}{D_0}) + 2(\frac{D_{24}}{D_0}) + (\frac{D_{30}}{D_0}) \right]$$

where D_0 is the maximum deflection at the center of the load plate.

D_{12}, D_{24} and D_{36} are the deflections at 12, 24 and 36 in. from the plate center.

According to Hall and Mohseni (1991), each term in the expression of AREA is normalized with respect to D_0 in order to remove that different load levels and to restrict the range of values obtained. Furthermore, it was mentioned that AREA and D_0 become two independent parameters in the backcalculation process. Based on the configuration of sensors in the M-123 site, AREA is redefined as the following expression :

$$\text{AREA} = \left[4(\frac{D_0}{D_0} + \frac{D_8}{D_0}) + 2(\frac{D_8}{D_0} + \frac{D_{12}}{D_0}) + 3(\frac{D_{12}}{D_0} + \frac{D_{18}}{D_0}) + 3(\frac{D_{18}}{D_0} + \frac{D_{24}}{D_0}) + 6(\frac{D_{24}}{D_0} + \frac{D_{36}}{D_0}) + 12(\frac{D_{36}}{D_0} + \frac{D_{60}}{D_0}) \right]$$

The results of AREA versus 1 min. nuclear density is shown in Figure 6.35.

Another parameter named *deflection ratio* is also calculated. The concept of the deflection ratio is based on the elastic layer theorem with known layer thickness and characterized moduli and Poisson's ratio. When a load is applied over a plate with 5.91 in. in radius, deflections are created at some distance from the center of the loaded area. It is normally assumed that the load spreads through the pavement system with 2 vertical to 1 horizontal distribution. Deflection D_8 at distance 8 in. from the center of plate is only due to the elastic compression of the layer beneath the AC layer. Therefore, deflection ratio is defined as :

$$Q_r = \frac{D_r}{D_0}$$

where r = 8, 12, 18, 24, 36 and 60 in. from the center of loading plate
D_0 = the deflection at the center of the plate

Results of deflection ratio versus nuclear density are shown in Figures 6.36.

The surface curvature index is also applied here. McCullough and Taute (1982) explained that this parameter has been often correlated to layer stiffness for asphalt pavements. This parameter is expressed as :

$$\text{SCI (Surface Curvature Index)} = D_0 - D_{12}$$

The plot of SCI versus 1 min. nuclear density is shown in Figure 6.37.

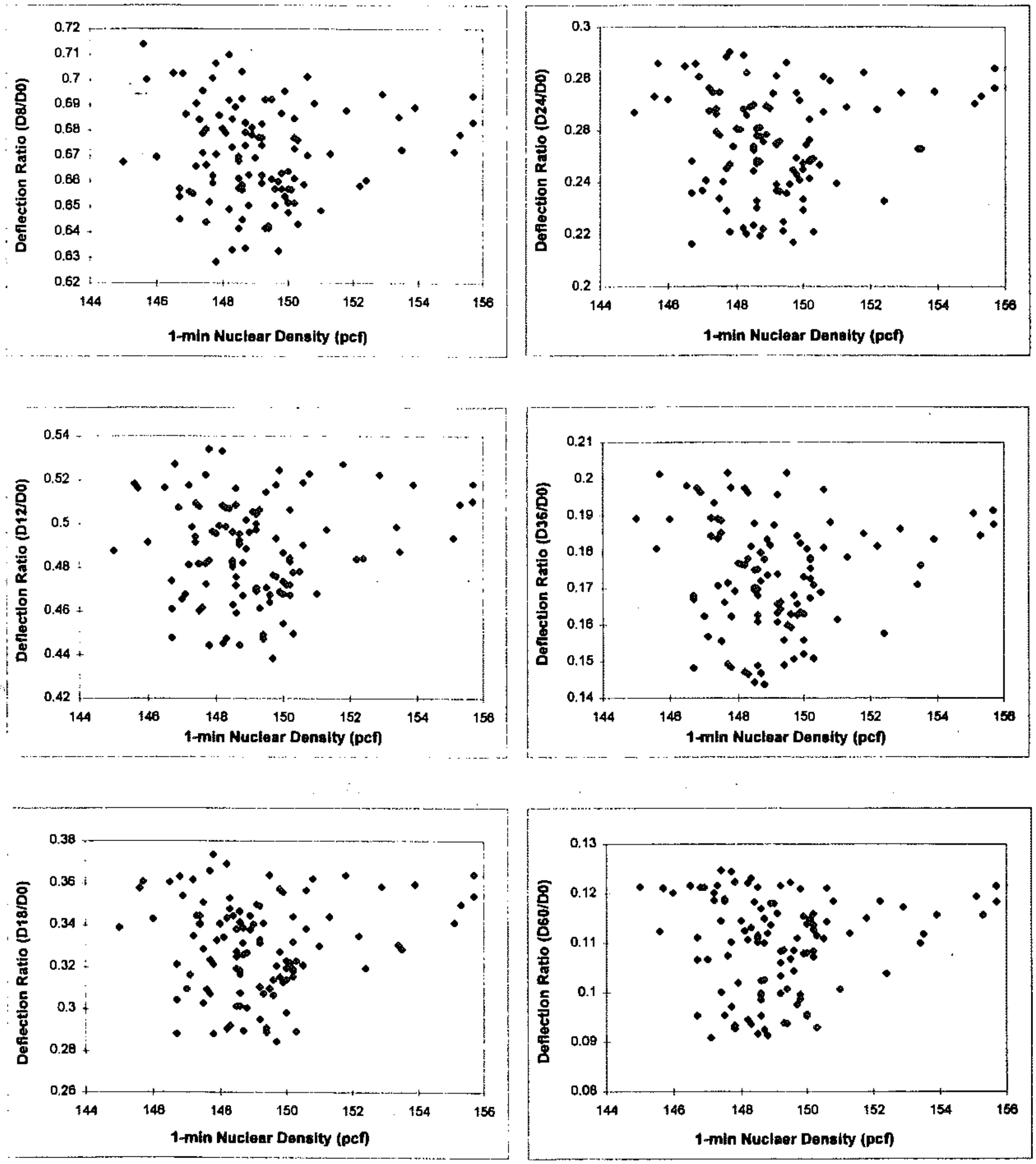


Figure 6.36 Relation between Deflection Ratio and Nuclear Density
at Site 6 - M-123

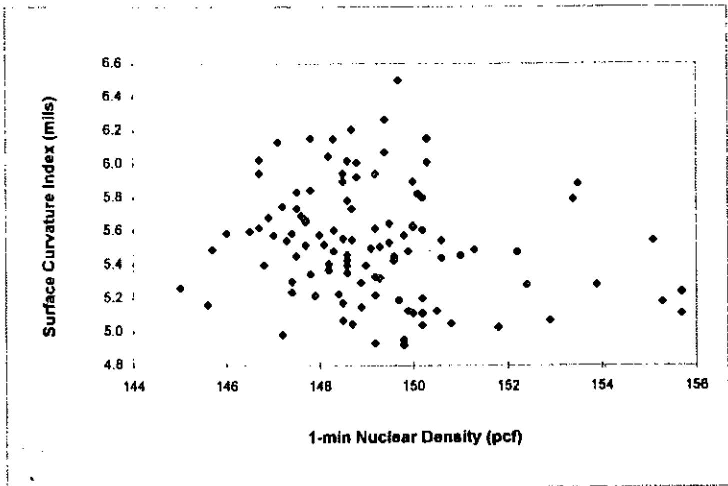


Figure 6.37 Relation between SCI and Nuclear Density at Site 6 - M-123

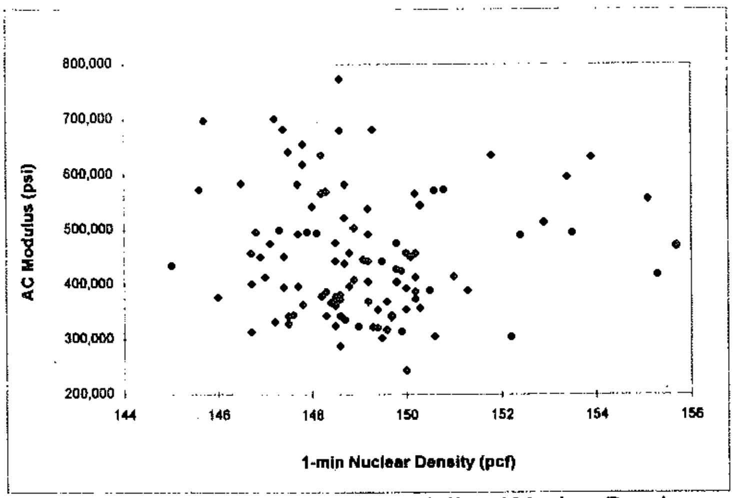


Figure 6.38 Relation between AC Moduli and Nuclear Density at Site 6 - M-123

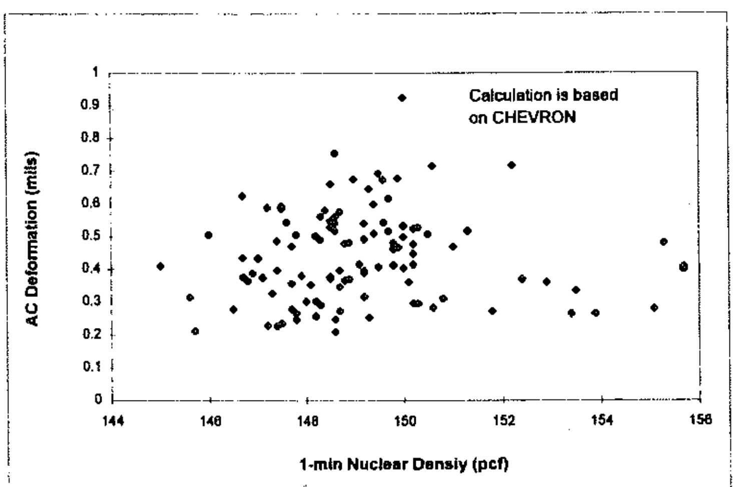


Figure 6.39 Relation between AC Deformation and Nuclear Desnity at Site 6 - M-123

6.6.4 Relation between AC Moduli and Nuclear Density

One major application of FWD deflection is to backcalculate material property of pavements. The methodology of backcalculation is to resolve the response of surface loading to determine the layer moduli given the surface deflections. The MICHBACK program developed by Harichandran et al. (1994) was used to determine the AC moduli. This program reads the FWD measurement file created by the KUAB FWD device automatically. The required input data are given in Table 6.13.

Table 6.13 Required Input for MICHBACK

Pavement Layer	Thickness	Poisson's ratio
AC layer	obtained from core measurement	0.30
Base layer	18 in.	0.40
Subgrade	semi-infinite	0.45

The calculated AC moduli are plotted with respected to nuclear density in Figure 6.38. As we know, modulus is a mechanistic material property, but density is a physical property. It seems there is no direct relation between these two properties. However, for the same material, the resilient modulus values are expected to increase proportionally to the sample density. Due to imhomegenous material properties of asphalt mixture, no correlation can be found.

6.6.5 Relation between AC Deformation and Nuclear Density

According to Yolder and Witczck (1975), the peak deflection of FWD is mainly contributed by the vertical strain in the roadbed soil which is 75 ~ 90 %. Therefore, it is necessary to compute the deformation in the AC layer and then, try to correlate the one-minute nuclear density with the deformation in AC layer. The CHEVRON program based on elastic multi-layer theorem was used to calculate the difference between deflections on the pavement surface and at the bottom of the AC layer. Relation between the AC deformation and 1 minute nuclear density is provided in Figure 6.39.

When analyzing FWD data, some assumptions have to be made (Ullidtz and Coetzee, 1995) :

- the pavement system is in equilibrium
- the materials are continuous and remain continuous under deformation
- the materials are elastic, isotropic and homogeneous

However, for segregated pavements, the materials are not continuous anymore. The assumption for homogeneity is also violated. These could be the reasons that there is no relation between FWD data and nuclear density for asphalt mixture. Two suggestion are provided here:

- Using an alternative method developed by Jung and Stolle (1992) : The concept is cited here " this new approach uses differences between the real problem and the idealized problem, to estimate a weighted average of in situ properties and to obtain other information on the integrity and the state of deterioration of layer materials."

- Testing an adjacent unsegregated pavements : If the error of backcalculation is only associated with the discontinuity of asphalt mixture, then we can use backcalculation of unsegregated pavement to verify the accuracy of base and subgrade moduli in the segregated pavement. Based on the information of the base and subgrade moduli obtained from the unsegregated pavement, it is possible to recalculate the AC modulus in the segregated pavement.

A limited analysis involving nuclear density and deflection was made at Site 7, also without encouraging results; hence more detailed analyses (as above) were not performed.

6.7 Comparison between Nuclear-Measured and Lab-Measured Density Values

This study involved the acquisition of hundreds of paired values for nuclear-measured and lab-measured density; hence it afforded an opportunity to compare values obtained from these two methods. Furthermore, some basic understanding of exactly what the nuclear gauge is measuring is important to a proper application of the nuclear gauge in segregation assessment. For both of these reasons, an extensive set of linear regression analyses were performed to investigate correlation between nuclear-measured and lab-measured field values.

It has been previously noted (Kennedy, et al., 1989) and confirmed by this study that the nuclear gage generally indicates lower density values than those measured in the lab by the water displacement method. The most important difference is the way to volume is accounted for in the procedures. Lab density measurements, using either saturated surface-dry specimens or air-dry specimen, exclude any surface voids from the volume measurement. However, nuclear density measurement includes the response of any surface voids in the volume of influence. Therefore, the density obtained from nuclear gauge is related to the average bulk density of the total mass in the volume of influence, including both permeable and impermeable voids. According to ASTM D 2950, the density values obtained by nuclear methods are relative. If actual density is desired, a conversion factor must be developed by taking nuclear density measurements and companion core densities at randomly selected locations.

The ASTM procedure further recommend that notable surface voids be filled with fine sand before placing the nuclear device over the measurement point. This was *not* done for this study, as it was desired to use the lower-than-average values associated with surface voids as an indicator of segregation.

After nuclear gauge density measurements were made, one-hundred-eight 6-inch diameter cores were cut from each of the first six field sites. These cores were sawed horizontally into two segments representing the surface course and leveling course. The densities of each segment were determined by weighing in air and water. Six different lab density measurements were considered for regression analysis:

- Surface course, SSD
- Surface course, air-dry
- Leveling course, SSD
- Leveling course, air-dry
- Average of surface and leveling course, SSD
- Average of surface and leveling course, air-dry

The mean, standard deviation and coefficient of variation for both nuclear and lab density measurements at each test site are summarized in Table 6.14. In all cases, mean values of nuclear density measurements are lower than that of lab density measurements. Furthermore, for the surface course (which is what is being measured, as will be shown) the variation of nuclear density measurements is greater than that of lab density measurements.

6.7.1 Regression Analysis

To investigate the relationships between nuclear gauge densities for both one and four-minute readings and core densities for the six measures of lab density, linear regression analysis were performed. Nuclear density was chosen as the independent variable and core density was chosen as the dependent variable. Essentially, the regression analyses measure the ability of the nuclear device to predict lab density. Results are shown in Table 6.15 for all sites and comparisons.

From the table, nuclear-measured density is not as strongly correlated with lab density as might be expected. Both one-minute and four-minute readings are best correlated with lab density measurements of the surface course core segments at Sites 2 (Muskegon uniform), 3 (Muskegon random) and 4 (M-99). In general, the coefficients of determination (R^2) ranged between 0.40 and 0.70. As the R^2 values increase closer to unity, the greater is the degree of linear statistical relation between nuclear and lab densities. These moderately low correlation coefficients are indicative of the scatter in the measurements.

A second means of comparison is the values of the slope of the fitted equation. The expected slope is 1.00, implying a unit change in nuclear-measured density indicates a unit change in lab-measured density. The fitted slopes for the air-dry surface course at sites 1 through 4 were in the range 0.39 to 0.59, indicating that a 2 lb/ft^3 variation in nuclear density corresponds to only about 1 lb/ft^3 variation in lab density. The slopes for sites 5 and 6 were very low, as were R^2 values, indicating virtually no variation.

Based on the regression analysis, the following inferences are drawn regarding correlation of nuclear density results with core densities:

- Both one-minute and four-minute density values moderately correlated with lab density of the surface course at four of six sites. For the old US 27 and M-123 sites, there is essentially no correlation (R^2 is as low as 0.04). At the old US 27 site, this is very likely due to the large amount of observed surface voids, which also led to significantly low nuclear density values (5 to 25 lb/ft^3 lower than lab values). At the M-123 site, the small R^2 value appears to be due to the fact that the one-minute nuclear density values at sample locations 21, 22, 23 and 25 being larger than the lab density values, which is an unusual situation. This may be due to some aggregate materials with high specific gravity unduly influencing the nuclear count.

- Nuclear density is, for practical purposes, uncorrelated with lab density of the leveling course materials. The reason, already given in Section 2.5.3, is that the nuclear gauge reading is mostly contributed by the top 2-in. of pavement material depending on the type of gauge used.

Table 6.14 Summary of Overall Mean, Standard Deviation and Coefficient of Variation at Each Site

Site		1-min nuclear	4-min nuclear	Surface course, SSD	Surfaec course, air-dry	Leveling course, SSD	Leveling course, air-dry
1. St. John's	Overall mean	144.62		147.18	147.60	143.97	145.78
	Standard deviation	2.507		2.935	1.789	8.336	6.793
	Coefficient of variation	1.733 %		1.994 %	1.212 %	5.790 %	4.660 %
2. Muskegon (uniform)	Overall mean	141.90	144.18	148.27	148.66	146.97	147.44
	Standard deviation	4.462	2.716	3.142	2.963	1.257	1.237
	Coefficient of variation	3.144 %	1.884 %	2.119 %	1.993 %	0.855 %	0.839 %
3. Muskegon (random)	Overall mean	145.82	142.03	149.53	149.92	149.60	150.03
	Standard deviation	2.898	4.910	2.452	2.276	1.581	1.494
	Coefficient of variation	1.988 %	3.457 %	1.640 %	1.518 %	1.057 %	0.995 %
4. M-99	Overall mean	145.32	145.48	149.74	149.86		
	Standard deviation	1.542	1.317	1.418	1.390		
	Coefficient of variation	1.061 %	0.905 %	0.947 %	0.928 %		
5. Old US 27	Overall mean	129.64		147.14	147.32		
	Standard deviation	3.625		2.218	2.058		
	Coefficient of variation	2.796 %		1.507 %	1.397 %		
6. M-123	Overall mean	149.17		150.57	150.86		
	Standard deviation	2.040		1.487	1.440		
	Coefficient of variation	1.368 %		0.988 %	0.955 %		

Table 6.15 Summary of Regression Analysis between Nuclear and Lab Density

	1. St. John's	2. Muskegon (uniform)	3. Muskegon (random)	4. M-99	5. OLD US 27	6. M-123
$\gamma_{SC,AIR}$ vs. γ_{NUC1}	R^2=0.47 Std Err= 1.30 lb/ft^3 $\gamma_{SC,AIR}=0.49\gamma_{NUC1}+76.47$	R^2=0.45 Std Err= 2.22 lb/ft^3 $\gamma_{SC,AIR}=0.44\gamma_{NUC1}+85.74$	R^2=0.52 Std Err=1.59 lb/ft^3 $\gamma_{SC,AIR}=0.56\gamma_{NUC1}+67.62$	R^2=0.43 Std Err=1.06 lb/ft^3 $\gamma_{SC,AIR}=0.59\gamma_{NUC1}+64.83$	R^2=0.034 Std Err=2.03 lb/ft^3 $\gamma_{SC,AIR}=0.10\gamma_{NUC1}+133.74$	R^2=0.09 Std Err=2.14 lb/ft^3 $\gamma_{SC,AIR}=0.21\gamma_{NUC1}+119.98$
$\gamma_{SC,SSD}$ vs. γ_{NUC1}	R^2=0.28 Std Err= 2.50 lb/ft^3 $\gamma_{SC,SSD}=0.62\gamma_{NUC1}+57.69$	R^2=0.48 Std Err=2.29 lb/ft^3 $\gamma_{SC,SSD}=0.49\gamma_{NUC1}+79.38$	R^2=0.54 Std Err=1.67 lb/ft^3 $\gamma_{SC,SSD}=0.62\gamma_{NUC1}+58.62$	R^2=0.42 Std Err=1.08 lb/ft^3 $\gamma_{SC,SSD}=0.59\gamma_{NUC1}+63.49$	R^2=0.039 Std Err=2.18 lb/ft^3 $\gamma_{SC,SSD}=0.12\gamma_{NUC1}+131.43$	R^2=0.09 Std Err=2.15 lb/ft^3 $\gamma_{SC,SSD}=0.22\gamma_{NUC1}+118.37$
$\gamma_{LC,AIR}$ vs. γ_{NUC1}	R^2=0.04 Std Err = 6.76 lb/ft^3 $\gamma_{LC,AIR}=0.54\gamma_{NUC1}+67.33$	R^2=0.01 Std Err=1.24 lb/ft^3 $\gamma_{LC,AIR}=0.03\gamma_{NUC1}+143.23$	R^2=0.009 Std Err=1.67 lb/ft^3 $\gamma_{LC,AIR}=0.05\gamma_{NUC1}+142.77$	X	X	X
$\gamma_{LC,SSD}$ vs. γ_{NUC1}	R^2=0.08 Std err = 8.01 lb/ft^3 $\gamma_{LC,SSD}=0.92\gamma_{NUC1}+11.36$	R^2=0.03 Std Err=1.25 lb/ft^3 $\gamma_{LC,SSD}=0.05\gamma_{NUC1}+140.51$	R^2=0.012 Std Err=1.56 lb/ft^3 $\gamma_{LC,SSD}=0.06\gamma_{NUC1}+141.01$	X	X	X
$\gamma_{AVG,AIR}$ vs. γ_{NUC1}	R^2=0.13 Std err = 3.34 lb/ft^3 $\gamma_{AVG,AIR}=0.52\gamma_{NUC1}+71.90$	R^2=0.39 Std Err = 1.29 lb/ft^3 $\gamma_{AVG,AIR}=0.23\gamma_{NUC1}+115.32$	R^2=0.36 Std Err=1.20 lb/ft^3 $\gamma_{AVG,AIR}=0.31\gamma_{NUC1}+105.20$	X	X	X
$\gamma_{AVG,SSD}$ vs. γ_{NUC1}	R^2=0.18 Std Err= 4.16 lb/ft^3 $\gamma_{AVG,SSD}=0.77\gamma_{NUC1}+34.52$	R^2=0.44 Std Err = 1.32 lb/ft^3 $\gamma_{AVG,SSD}=0.26\gamma_{NUC1}+110.77$	R^2=0.39 Std Err=1.24 lb/ft^3 $\gamma_{AVG,SSD}=0.34\gamma_{NUC1}+99.81$	X	X	X
$\gamma_{SC,AIR}$ vs. γ_{NUC4}	X	R^2=0.58 Std Err = 1.94 lb/ft^3 $\gamma_{SC,AIR}=0.83\gamma_{NUC4}+29.31$	R^2=0.42 Std Err=1.74 lb/ft^3 $\gamma_{SC,AIR}=0.30\gamma_{NUC4}+106.99$	R^2=0.67 Std Err=0.84 lb/ft^3 $\gamma_{SC,AIR}=0.89\gamma_{NUC4}+20.79$	X	X
$\gamma_{SC,SSD}$ vs. γ_{NUC4}	X	R^2=0.61 Std Err = 1.97 lb/ft^3 $\gamma_{SC,SSD}=0.90\gamma_{NUC4}+17.96$	R^2=0.46 Std Err=1.82 lb/ft^3 $\gamma_{SC,SSD}=0.34\gamma_{NUC4}+101.65$	R^2=0.67 Std Err=0.85 lb/ft^3 $\gamma_{SC,SSD}=0.90\gamma_{NUC4}+18.57$	X	X
$\gamma_{LC,AIR}$ vs. γ_{NUC4}	X	R^2=0.01 Std Err = 1.24 lb/ft^3 $\gamma_{LC,AIR}=0.04\gamma_{NUC4}+141.52$	R^2=0.016 Std Err = 1.56 lb/ft^3 $\gamma_{LC,AIR}=0.04\gamma_{NUC4}+144.35$	X	X	X
$\gamma_{LC,SSD}$ vs. γ_{NUC4}	X	R^2=0.02 Std Err = 1.25 lb/ft^3 $\gamma_{LC,SSD}=0.06\gamma_{NUC4}+137.82$	R^2=0.024 Std Err = 1.55 lb/ft^3 $\gamma_{LC,SSD}=0.05\gamma_{NUC4}+142.75$	X	X	X
$\gamma_{AVG,AIR}$ vs. γ_{NUC4}	X	R^2=0.49 Std Err = 1.18 lb/ft^3 $\gamma_{AVG,AIR}=0.43\gamma_{NUC4}+85.92$	R^2=0.32 Std Err=1.24 lb/ft^3 $\gamma_{AVG,AIR}=0.17\gamma_{NUC4}+125.67$	X	X	X
$\gamma_{AVG,SSD}$ vs. γ_{NUC4}	X	R^2=0.54 Std Err = 1.20 lb/ft^3 $\gamma_{AVG,SSD}=0.48\gamma_{NUC4}+78.30$	R^2=0.36 Std Err= 1.27 lb/ft^3 $\gamma_{AVG,SSD}=0.19\gamma_{NUC4}+122.20$	X	X	X

X : not performed

- The correlation of lab density with one-minute or four-minute nuclear density values does not indicate any significant, differences. Therefore, four-minute nuclear density readings were not used at the St. John's, old US 27 and M-123 sites.

- The study of average values of the surface and leveling course lab densities was made to see if the correlation was better, which could occur if the nuclear gauge influence zone was thicker than the surfaces course. This was not found to be the case. It can be seen from Table 6.15 that the values of R^2 decrease when the two lab densities were averaged.

Based on these results, all remaining studies were focused on the one-minute nuclear density values and air-dry lab density values in the surface course. The scatter plots of these relationships are illustrated in Figure 6.40 through 6.45.

6.7.2 Pairwise Comparison Tests

A second easy way to compare nuclear density and lab density values is to define a new variable D which is the deviation of nuclear and lab density measurement.

D = lab density measurement - nuclear density measurement

It is clear that the larger the difference, the lower is the accuracy of the nuclear gauge for measuring actual density. However, it should be noted that nuclear gauge may still give a good indication of segregation because unusually low nuclear values may be due to the large amount of voids, which is a characteristic of segregated pavements. Figure 6.46 shows differences between one-minute nuclear density and air-dry density of the surface course for the first six sites. It is seen that the magnitude of difference is as much as 6 lb/ft^3 at the St. John's, M-99 and M-123 sites, 12 lb/ft^3 at the Muskegon uniform and random sites.

The paired t-test was used to compare means and the F-test was used to compare variances of the nuclear-measured and lab-measured densities. The hypothesis for testing the mean was:

Null hypothesis, H_0: $\mu_1=\mu_2$
Alternative hypothesis, H_1: $\mu_1\neq\mu_2$

The hypothesis for variance testing was:

Null hypothesis, H_0: $\sigma_1^2 = \sigma_2^2$
Alternative hypothesis, H_1 : $\sigma_1^2 \neq \sigma_2^2$

Results are summarized in Table 6.16. The means of nuclear density and lab density are statistically different with significance levels greater than 99 percent. Concerning the variance, the conclusion is that, if the significance level is set at 99 percent, there is no significant difference for variance at the Muskegon uniform (4-min readings) and M-99 sites.

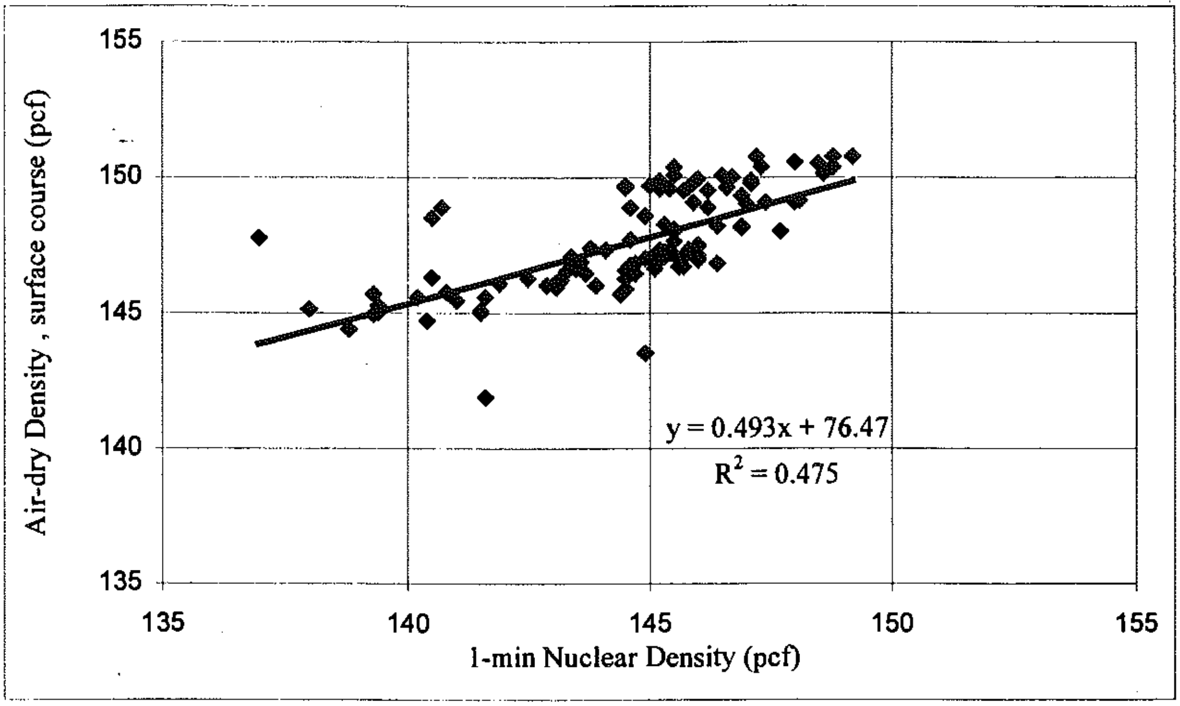


Figure 6.40 Regression Line for 1-min Nuclear Density versus Air-dry Density at Site 1 - St. John's

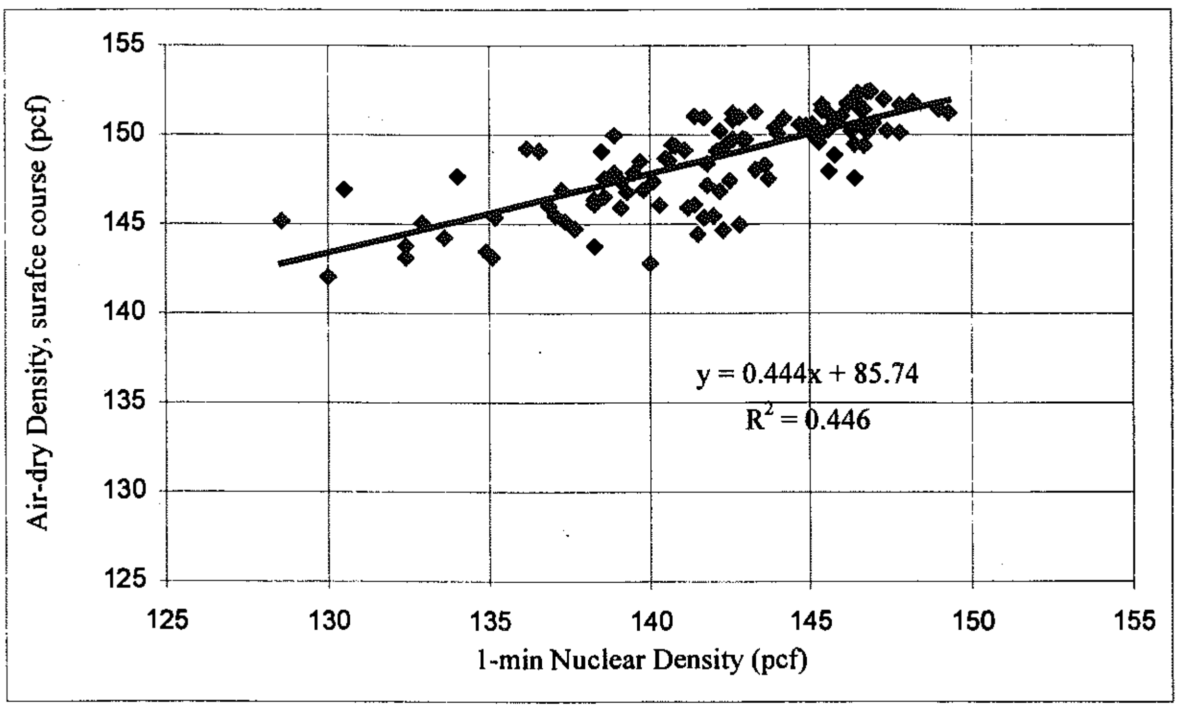


Figure 6.41 Regression Line for 1-min Nuclear Density versus Air-dry Density at Site 2 - Muskegon (uniform)

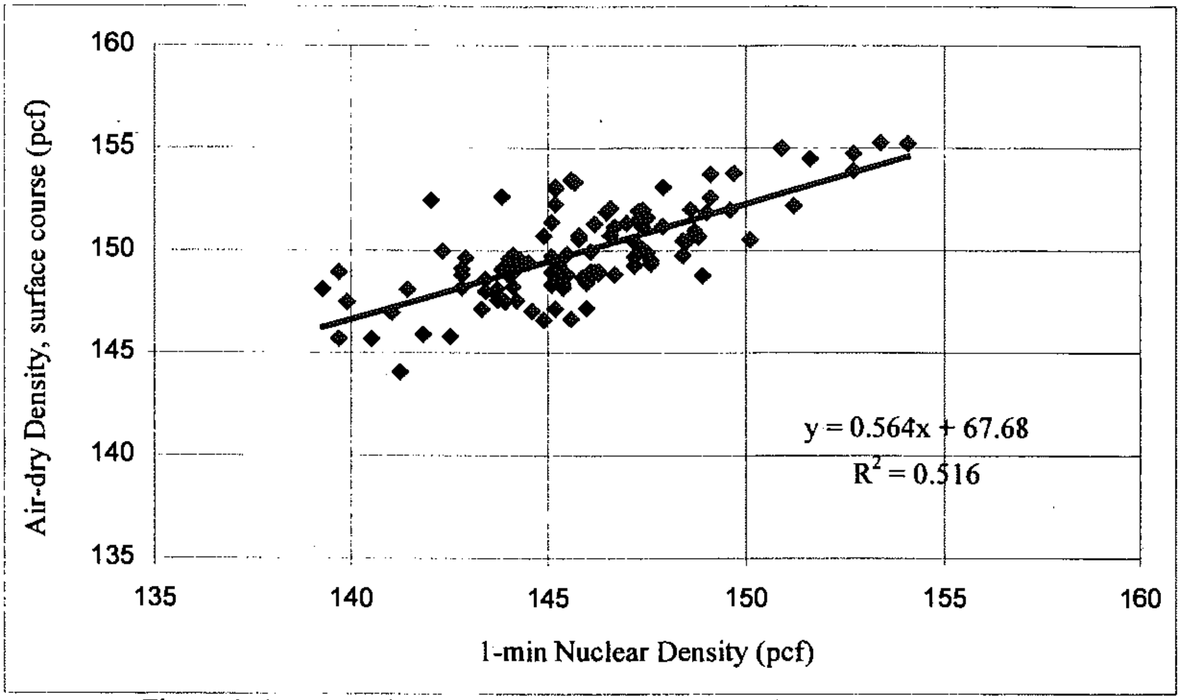


Figure 6.42 Regression Line for 1-min Nuclear Density versus Air-dry Density at Site 3 - Muskegon (random)

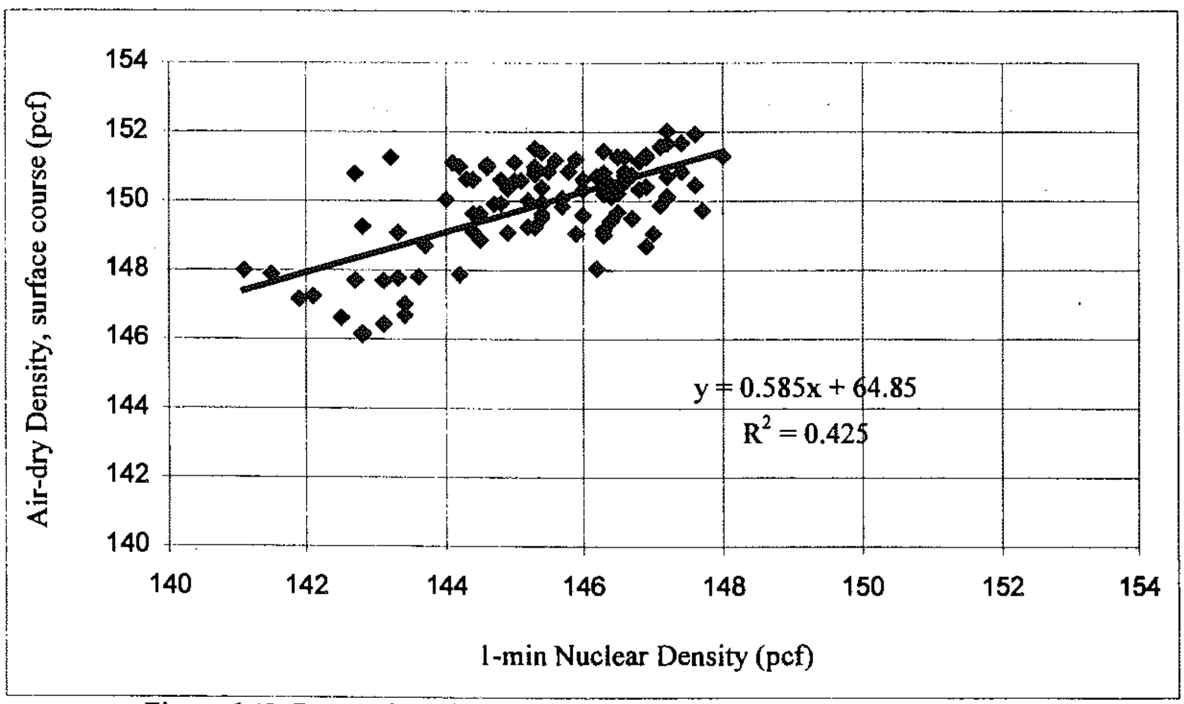


Figure 6.43 Regression Line for 1-min Nuclear Density versus Air-dry Density at Site 4 - M-99

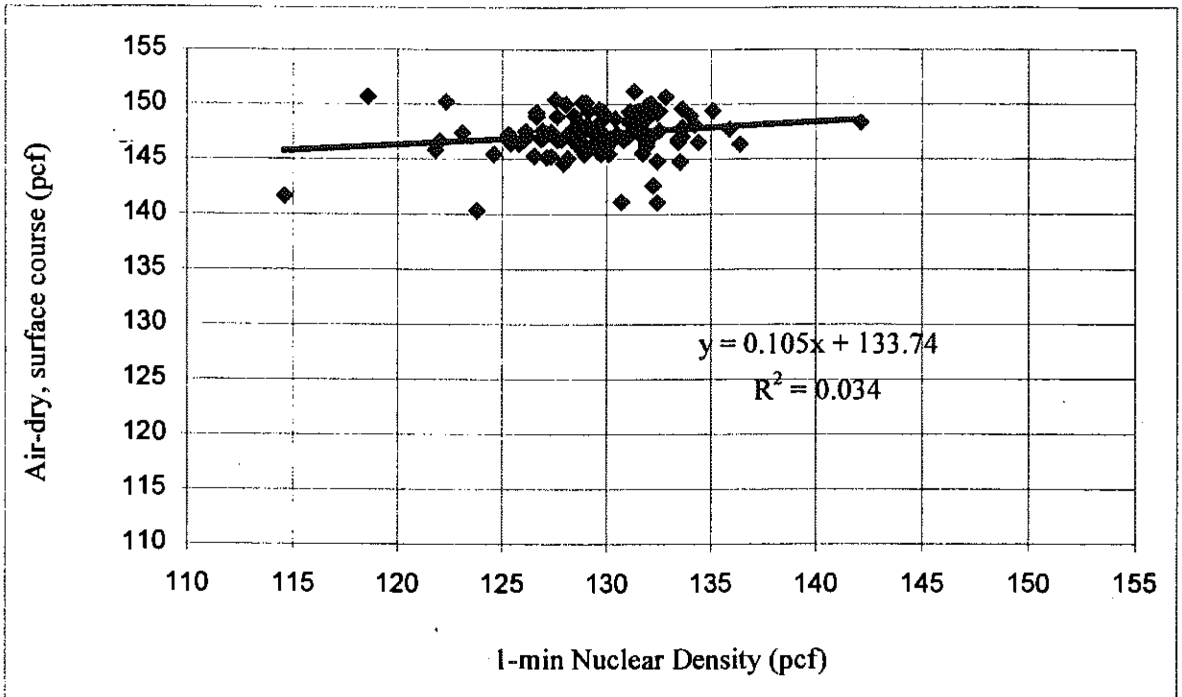


Figure 6.44 Regression Line for 1-min Nuclear Density versus Air-dry Density at Site 5 - Old U.S. 27

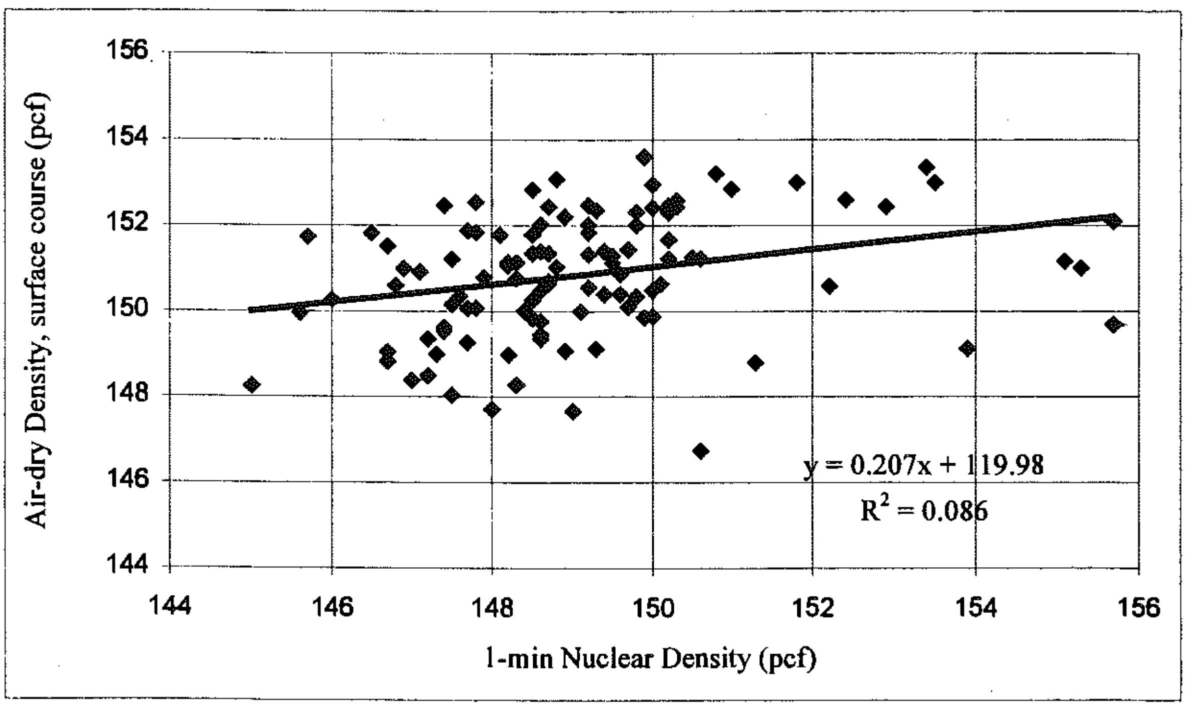


Figure 6.45 Regression Line for 1-min Nuclear Density versus Air-dry Density at Site 6 - M-123

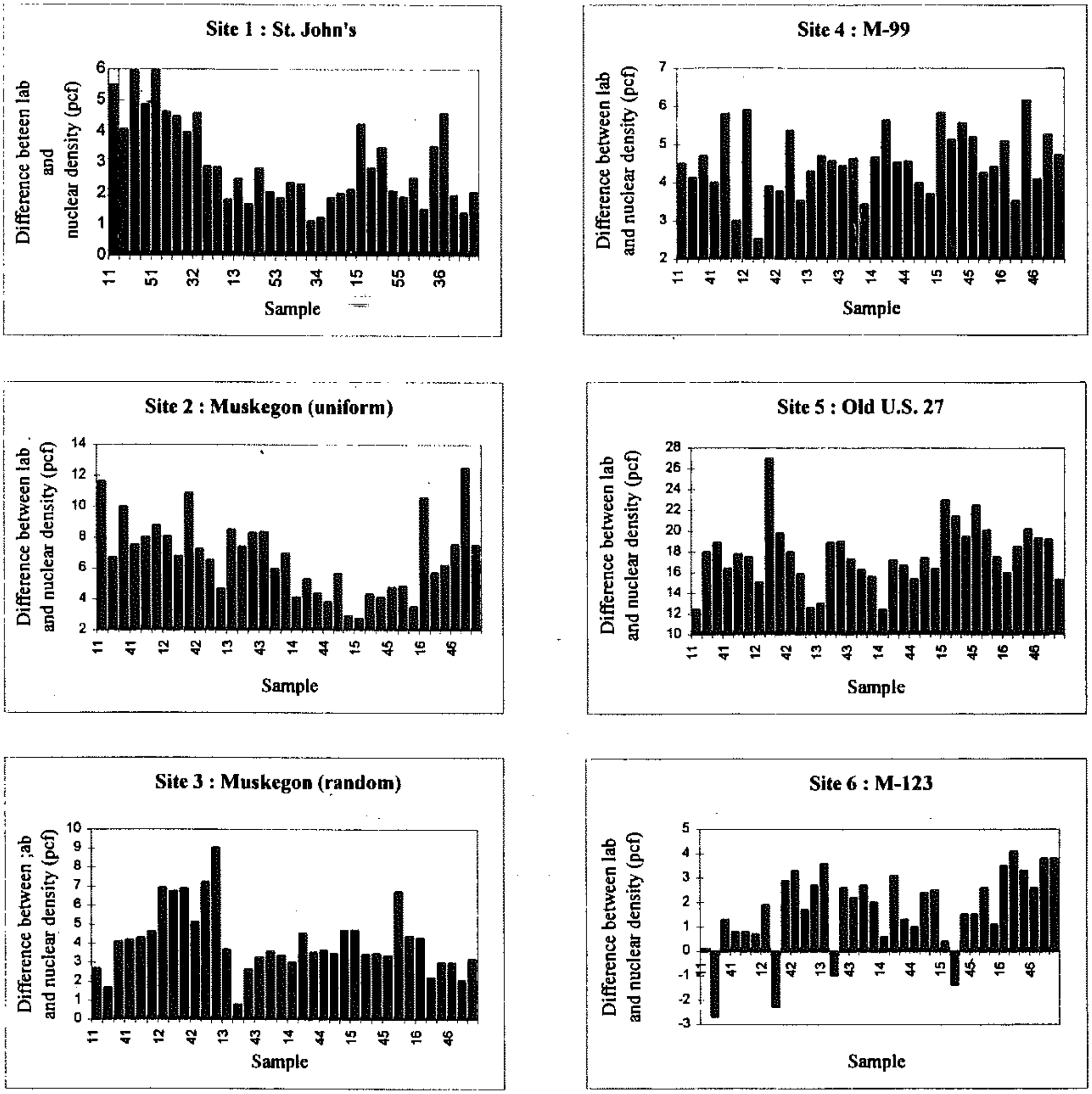


Figure 6.46 Differences between Lab and Nuclear Desnity

Table 6.16 Results of Hypothesis Tests for Pairwise Comparisons between Nuclear and Lab Density Measurements

Site	Duration of Nuclear Density Reading	t-statistic	p-value	F-statistic	p-value
St. John's	1-min	11.64	*2.76×10^{-32}*	1.27	***0.0003***
Muskegon (uniform)	1-min	21.15	*5.09×10^{-40}*	2.27	***1.53×10^{-5}***
	4-min	23.46	*5.51×10^{-44}*	0.84	0.8146
Muskegon (random)	1-min	21.01	*9.17×10^{-40}*	1.62	***0.0065***
	4-min	21.37	*2.11×10^{-40}*	4.65	***1.62×10^{-14}***
M-99	1-min	38.06	*1.22×10^{-63}*	1.24	0.1333
old US 27	1-min	47.60	*6.78×10^{-73}*	3.10	***8.46×10^{-9}***
M-123	1-min	8.26	*4.17×10^{-13}*	2.01	***0.0002***

6.8 Comparison between Density Values and Gradation Parameters

Asphalt mixtures in segregated areas have gradation curves varying from their as-mixed gradations. Where segregation is present, different proportions of coarse and fine aggregates would be expected in different areas of a pavement. Where there is an accumulation of coarse aggregates, the case usually associated with visually-identified segregated areas, low nuclear density values are expected because voids are present among aggregate particles instead of fine materials, and surface voids in particular are know to lead to low nuclear density readings Where there is an accumulation of fine materials, which should occur nearby when the segregation is paver-related, comparatively higher nuclear density values are expected because voids are filled with fine materials.

It should be emphasized that there are other factors, such as particle size, arrangement, and specific gravity that may also have a great influence on nuclear density measurements. Nevertheless, the hypothesis of this study was that gradation differences due to segregation should have sufficient influence on nuclear density readings to permit finding a correlation. In this regard, this section provides a site-by-site evaluation of the similarities and differences of statistical findings regarding nuclear density, lab density and gradation obtained using MBITSEG1.xls.

To facilitate comparison, a tabular format was devised, and Tables 6.17 through 6.24 show the summary data for Sites 1 through 6. In each table, statistics for the following five parameters are presented:

- Nuclear-measured density, average of triplicate samples.
- Lab-measured density, air-dry, for surface course.

Table 6.17 Comparisons between Nuclear Density Measurements, Lab Density Measurements and Gradation Data at Site 1 - St. John's

1-min Nuclear Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	144.62	140.36	145.94	144.75	145.07	147.15	144.45
Coefficient of variation	1.61%	0.58%	0.65%	0.34%	0.46%	0.85%	1.08%
p-value	*6.28E-11*						
Tukey test		DIFF !	--	--	--	DIFF !	--
t-test		DIFF !	--	DIFF !	--	DIFF !	--
6 of 6 test		DIFF !	DIFF !	--	--	DIFF !	--

Air-dry Lab Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	147.60	145.52	149.37	146.95	146.84	149.98	146.94
Coefficient of variation	1.13%	0.35%	0.17%	0.27%	0.22%	0.37%	0.68%
p-value	*3.14E-14*						
Tukey test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	--
t-test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	DIFF !
6 of 6 test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	--

Percent passing 3/8"	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	84.92	84.73	82.20	86.64	82.89	86.86	86.22
Coefficient of variation	4.62%	1.91%	1.96%	1.23%	10.49%	1.14%	1.01%
p-value	0.1610						
Tukey test		--	DIFF !	--	--	--	--
t-test		DIFF !	DIFF !	--	--	--	--
6 of 6 test		--	DIFF !	DIFF !	--	DIFF !	--

Percent passing No.4	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	49.35	47.97	45.59	49.11	51.19	51.03	51.24
Coefficient of variation	5.44%	2.10%	4.06%	3.39%	5.46%	2.90%	2.85%
p-value	*1.45E-05*						
Tukey test		--	DIFF !	--	--	--	--
t-test		DIFF !	DIFF !	--	--	--	DIFF !
6 of 6 test		--	DIFF !	--	--	--	DIFF !

Percent passing No.8	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	32.74	31.88	30.80	32.50	33.42	33.87	33.99
Coefficient of variation	4.38%	1.49%	2.65%	2.59%	4.44%	2.19%	2.23%
p-value	*2.89E-06*						
Tukey test		--	DIFF !	--	--	--	--
t-test		DIFF !	DIFF !	DIFF !	--	DIFF !	DIFF !
6 of 6 test		DIFF !	DIFF !	--	--	DIFF !	DIFF !

Table 6.18 Comparisons between Nuclear Density Measurements, Lab Density Measurements and Gradation Data at Site 2 - Muskegon (uniform)

1-min Nuclear Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	141.90	137.19	141.42	140.37	146.30	143.42	142.72
Coefficient of variation	2.80%	2.27%	3.34%	2.08%	0.97%	1.58%	1.73%
p-value	***0.0004***						
Tukey test		DIFF !	--	--	--	--	--
t-test		DIFF !	--	--	DIFF !	--	--
6 of 6 test		DIFF !	--	--	DIFF !	--	--

Air-dry Lab Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	148.67	145.97	148.80	147.98	150.68	147.48	151.08
Coefficient of variation	1.79%	1.44%	1.96%	1.51%	0.57%	1.50%	1.14%
p-value	***0.0015***						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	DIFF !	--	DIFF !
6 of 6 test		DIFF !	--	--	DIFF !	--	DIFF !

Percent passing 3/8"	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	68.80	66.16	67.06	68.98	69.95	72.57	68.07
Coefficient of variation	6.32%	7.18%	8.10%	6.22%	3.55%	2.78%	6.63%
p-value	0.1321						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	DIFF !	--

Percent passing No.4	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	46.29	44.63	45.37	46.77	46.48	49.03	45.45
Coefficient of variation	7.49%	8.54%	9.86%	6.92%	4.09%	5.68%	8.00%
p-value	0.3100						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Percent passing No.8	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	37.12	36.00	36.37	37.30	37.19	39.17	36.67
Coefficient of variation	6.25%	6.74%	7.49%	5.78%	2.82%	5.28%	7.10%
p-value	0.2199						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	DIFF !	--

Table 6.19 Comparisons between Nuclear Density Measurements, Lab Density Measurements and Gradation Data at Site 3 - Muskegon (random)

1-min Nuclear Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	145.82	148.70	143.74	147.40	145.63	143.69	145.78
Coefficient of variation	1.83%	2.34%	1.49%	0.84%	1.08%	1.50%	0.65%
p-value	***0.0011***						
Tukey test		--	--	--	--	--	--
t-test		--	--	DIFF !	--	--	--
6 of 6 test		--	--	--	--	--	--

Air-dry Lab Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	149.92	152.29	150.72	150.28	149.45	148.03	148.74
Coefficient of variation	1.48%	1.67%	1.57%	0.67%	1.05%	1.37%	0.66%
p-value	***0.0064***						
Tukey test		--	--	--	--	--	--
t-test		DIFF !	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Percent passing 3/8"	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	69.04	66.63	65.31	71.28	73.42	68.92	68.66
Coefficient of variation	7.33%	8.13%	8.22%	6.63%	4.98%	7.01%	4.37%
p-value	0.0514						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	DIFF !	--	--
6 of 6 test		--	--	--	--	--	--

Percent passing No.4	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	46.41	44.44	43.20	48.67	49.93	46.42	45.80
Coefficient of variation	9.67%	9.97%	11.25%	9.27%	6.63%	8.93%	7.12%
p-value	0.0748						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Percent passing No.8	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	36.28	35.00	34.16	37.85	38.70	36.28	35.66
Coefficient of variation	8.16%	7.67%	9.82%	7.92%	5.52%	7.50%	5.71%
p-value	0.0564						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	DIFF !	--	--
6 of 6 test		--	--	--	--	--	--

Table 6.20 Comparisons between Nuclear Density Measurements, Lab Density Measurements and Gradation Data at Site 4 - M-99

1-min Nuclear Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	145.32	145.51	146.05	145.49	142.83	145.96	146.07
Coefficient of variation	0.91%	0.21%	0.68%	0.36%	0.33%	0.46%	0.63%
p-value	*1.33E-08*						
Tukey test		--	--	--	DIFF !	--	--
t-test		--	--	--	DIFF !	--	--
6 of 6 test		--	--	--	DIFF !	--	--

Air-dry Lab Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	149.86	149.85	150.22	149.83	147.36	151.03	150.90
Coefficient of variation	0.88%	0.44%	0.35%	0.31%	0.44%	0.12%	0.23%
p-value	*1.01E-12*						
Tukey test		DIFF !	--	DIFF !	DIFF !	DIFF !	DIFF !
t-test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	DIFF !
6 of 6 test		--	--	--	DIFF !	DIFF !	DIFF !

Percent passing 3/8"	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	78.84	80.76	79.49	79.66	77.09	76.75	79.27
Coefficient of variation	2.66%	2.26%	2.99%	1.71%	1.99%	1.85%	1.06%
p-value	*0.0009*						
Tukey test		--	--	--	--	DIFF !	--
t-test		--	--	--	DIFF !	DIFF !	--
6 of 6 test		--	--	--	--	DIFF !	--

Percent passing No.4	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	60.59	62.40	61.63	61.56	58.51	58.38	61.04
Coefficient of variation	3.23%	2.07%	2.77%	1.46%	2.13%	2.41%	0.80%
p-value	*2.80E-06*						
Tukey test		--	--	--	DIFF !	DIFF !	--
t-test		DIFF !	--	--	DIFF !	DIFF !	DIFF !
6 of 6 test		DIFF !	--	--	DIFF !	DIFF !	--

Percent passing No.8	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	45.49	46.96	46.65	46.22	43.78	43.73	45.60
Coefficient of variation	3.41%	1.89%	2.16%	1.82%	2.31%	2.19%	1.23%
p-value	*1.80E-07*						
Tukey test		--	--	--	DIFF !	DIFF !	--
t-test		DIFF !	DIFF !	--	DIFF !	DIFF !	DIFF !
6 of 6 test		DIFF !	--	--	DIFF !	DIFF !	--

Table 6.21 Comparisons between Nuclear Density Measurements, Lab Density Measurements and Gradation Data at Site 5 - Old US 27 (column analysis)

1-min Nuclear Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	129.58	129.76	130.29	130.18	130.96	127.57	128.74
Coefficient of variation	2.12%	0.87%	3.22%	1.53%	1.69%	2.46%	1.90%
p-value	0.3106						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Air-dry Lab Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	147.29	146.59	148.35	146.86	146.87	148.24	146.82
Coefficient of variation	1.36%	1.93%	1.03%	1.01%	0.93%	1.04%	1.87%
p-value	0.4846						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Percent passing 3/8"	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	83.78	85.30	83.84	84.63	84.11	81.90	82.89
Coefficient of variation	3.36%	3.02%	3.69%	4.55%	1.58%	2.81%	3.51%
p-value	0.3502						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Percent passing No.4	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	60.65	62.34	60.24	61.71	61.36	58.63	59.63
Coefficient of variation	7.64%	8.77%	9.13%	9.76%	4.80%	7.12%	6.76%
p-value	0.7686						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Percent passing No.8	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	47.37	48.56	46.90	48.63	48.19	45.69	46.28
Coefficient of variation	9.29%	10.25%	10.63%	11.94%	6.84%	9.22%	8.09%
p-value	0.8073						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Table 6.22 Comparisons between Nuclear Density Measurements, Lab Density Measurements and Gradation Data at Site 5 - Old US 27 (row analysis)

1-min Nuclear Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	129.58	129.68	128.69	130.19	129.23	128.72	130.98
Coefficient of variation	2.12%	3.22%	2.39%	1.26%	1.90%	1.68%	2.10%
p-value	0.7001						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Air-dry Lab Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	147.29	146.59	148.35	146.86	146.87	148.24	146.82
Coefficient of variation	1.36%	1.93%	1.03%	1.01%	0.93%	1.04%	1.87%
p-value	0.4846						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Percent passing 3/8"	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	83.78	81.94	80.31	83.45	84.95	85.78	86.25
Coefficient of variation	3.36%	2.70%	2.90%	2.52%	1.94%	2.45%	1.25%
p-value	***4.48E-05***						
Tukey test		--	DIFF !	--	--	--	--
t-test		DIFF !	DIFF !	--	--	--	DIFF !
6 of 6 test		--	DIFF !	--	--	--	DIFF !

Percent passing No.4	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	60.65	56.38	54.88	59.15	63.10	65.12	65.29
Coefficient of variation	7.64%	4.91%	3.99%	3.36%	3.00%	3.82%	2.56%
p-value	***6.83E-10***						
Tukey test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	DIFF !
t-test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	DIFF !
6 of 6 test		DIFF !	DIFF !	--	--	DIFF !	DIFF !

Percent passing No.8	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	47.37	43.25	42.01	45.49	49.63	51.68	52.18
Coefficient of variation	9.29%	5.04%	3.59%	3.92%	3.96%	3.79%	2.89%
p-value	***1.53E-11***						
Tukey test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	DIFF !
t-test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	DIFF !
6 of 6 test		DIFF !	DIFF !	--	DIFF !	DIFF !	DIFF !

Table 6.23 Comparisons between Nuclear Density Measurements, Lab Density Measurements and Gradation Data at Site 6 - M -123

1-min Nuclear Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	149.17	149.77	150.71	147.76	149.93	148.79	148.04
Coefficient of variation	1.06%	0.61%	1.27%	0.78%	0.86%	0.87%	0.29%
p-value	***0.0015***						
Tukey test		--	--	--	--	--	--
t-test		--	--	DIFF !	--	--	DIFF !
6 of 6 test		--	--	--	--	--	DIFF !

Air-dry Lab Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	150.86	149.93	152.42	149.76	151.74	149.74	151.56
Coefficient of variation	0.86%	0.60%	0.25%	0.57%	0.68%	0.54%	0.22%
p-value	***3.19E-07***						
Tukey test		--	DIFF !	DIFF !	--	DIFF !	DIFF !
t-test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	DIFF !
6 of 6 test		DIFF !	DIFF !	--	--	DIFF !	DIFF !

Percent passing 3/8"	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	80.24	79.52	82.74	76.43	80.92	79.77	82.08
Coefficient of variation	3.43%	1.91%	2.83%	1.58%	2.66%	1.83%	3.12%
p-value	***6.38E-05***						
Tukey test		--	--	DIFF !	--	--	--
t-test		--	DIFF !	DIFF !	--	--	--
6 of 6 test		--	--	DIFF !	--	--	--

Percent passing No.4	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	56.25	54.89	59.20	50.80	57.84	55.87	58.92
Coefficient of variation	6.24%	1.69%	3.08%	1.76%	3.95%	4.87%	4.99%
p-value	***5.20E-07***						
Tukey test		--	--	DIFF !	--	--	--
t-test		DIFF !	DIFF !	DIFF !	--	--	--
6 of 6 test		--	DIFF !	DIFF !	--	--	--

Percent passing No.8	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	44.12	43.05	46.34	40.17	45.28	44.07	45.80
Coefficient of variation	5.67%	2.02%	2.48%	1.96%	3.35%	4.07%	4.67%
p-value	***2.96E-07***						
Tukey test		--	--	DIFF !	--	--	--
t-test		DIFF !	DIFF !	DIFF !	--	--	--
6 of 6 test		--	DIFF !	DIFF !	--	--	--

Table 6.24 Results of Nuclear Density Measurements for Each Column at Site 7 - Lansing State Police Facility

1-min Nuclear Density	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	142.32	142.68	141.22	142.39	144.76	141.63	141.23
Coefficient of variation	1.24%	0.87%	1.64%	0.54%	0.71%	0.82%	0.74%
p-value	*0.0007*						
Tukey test		--	--	--	DIFF !	--	--
t-test		--	--	--	DIFF !	--	--
6 of 6 test		--	--	--	DIFF !	--	--

- Percent passing 3/8 inch sieve.
- Percent passing No. 4 sieve
- Percent passing No. 8 sieve.

The statistics presented include:

- Mean values and coefficients of variation for the values at the thirty six grid points.
- p-values from the MBITSEG1.xls analysis of variance (ANOVA) which indicate the significance of differences among column data (lower value indicates increasing significance)
- Columnwise results from the three multiple-comparison tests. (DIFF! indicates column values were significantly different from three or more other columns)

The results for the five parameters are vertically aligned to permit easy comparison across parameters at each site.

6.8.1 Site 1 - St. John's

This site was originally selected as a site of notable linear segregation. The statistical analysis confirm this. Results are summarized in Table 6.17. The ANOVA results indicate very significant column differences for nuclear density, lab density, and percent passing the No.4 and No.8 sieves. The extremely low p-values indicate that the differences in values from one column to another could almost never occur due to random variation within a statistically homogeneous set of values, and hence there must be some real differences related to the processes that led to values, in this case the asphalt mixture and its placement. Although the percent passing 3/8" sieve was not found to have significant column differences, detailed investigation of the data found an unreasonably low percent passing in sample location 64. If this number is adjusted to 85%, the p-value would be at the order of 10^{-5}, consistent with other results.

The multiple comparison test results for nuclear density values strongly support statistical differences in columns 1 and 5, whereas those for gradation parameters strongly support statistical differences in column 2. The lab density values find virtually all columns different from at least three others. For all of the comparisons in this section, it should be kept in mind that the display of the conclusion **DIFF!** does not indicate that the data in a specific column itself is "high" or "low" but rather that it is statistically different from three other columns. At Site 1, review of the column mean values will indicate that materials in columns 1 and 2 are generally coarser (smaller percents passing a sieve) than columns 3 through 6, but this is primarily reflected in the nuclear density reading by low values in column 1. Both support the conclusion of segregation along the left edge of test section. Similarly, but less strongly, the results data suggest an asphalt mixture rich in fines along the right edge (columns 5 and 6) of the test section.

6.8.2 Site 2 - Muskegon (uniform)

This site was chosen as a site of linear segregation, but was not perceived to be as strongly segregated as Site 1. Results are summarized in Table 6.18. The statistical analyses of this site provide mixed results. The ANOVA found significant column differences for nuclear density and lab density, but the not for gradation parameters. The multiple comparison tests identified columns 1 and 4 as the locations of significant difference for nuclear density (and less strongly, columns 4 and 6 for lab density) but with two minor exceptions, likewise find no significant differences for gradation parameters. However, if the column mean values are reviewed, it can be noted that the percents passing various sieves are consistently lowest in column 1, suggesting a coarse mix, and high in column 5, suggesting a fine mix, but not different enough to be statistically significant (gradation differences in column 5 are found by the six-of-six test in two cases).

In general, these finding agrees with the hypothesis that coarse segregated mixtures have comparatively low density values and fine segregated materials have high density values. However, if the nuclear density differences are to be used as predictors of significant gradation differences, the latter are not present here with sufficient strength to support a conclusion.

Two possible approaches are suggested by these results:

- Downward adjustment of the p-value for nuclear density, if one is to predict p-values for gradation difference, and
- Consideration of overall variability (coefficient of variation) as a second candidate indicator of segregation.

In the first case, one might require the p-value for nuclear density to be as low as 10^{-5} or 10^{-6} to be reasonably confident that the p-value value for gradation differences would be as low as 0.05. In the second case, it is noted that the coefficient of variation of the nuclear density values (2.8%) at Site 2 was considerably higher than that observed at other sites (0.9 to 2.1%). This degree of variability may also be correlated with the visually observed degree of segregation.

6.8.3 Site 3 - Muskegon (random)

This site was chosen as an example of random segregation. As MBITSEG1.xls and the study hypothesis was focused on linear segregation, this site was somewhat of an experiment. A quasi-random sampling pattern was used by fixing row locations, but adjusting column points within the rows in a random pattern. In the field, the random locations were further adjusted within the row to coincide with visually-apparent segregated and unsegregated areas. In hindsight, only the latter should have been done, to produce column-wise sets that tended to be visually segregated or unsegregated.

Results are summarized in Table 6.19. The statistical analyses of this site again provide mixed results. The ANOVA found significant column differences for nuclear density and lab density, but the not for gradation parameters. However, the gradation parameter differences would be found significant if the significance level were lowered somewhat, from 95 percent to 92 - 94 percent. This again supports the first refinement listed for the previous site, downward adjustment of the threshold p-value.

Multiple comparison tests find differences in column 3 for nuclear density, and column 4 for gradation, but only the t-test finds differences, not the more robust Tukey test. The random pattern of the observed segregation apparently had much less influence on column parameters than that for linear segregation.

6.8.4 Site 4 - M-99

This site was originally proposed as an example "control" site without segregation, but at the time of sampling was classified by the MSU researchers as slightly segregated. Statistical results are summarized in Table 6.20, and lead to the conclusion of strong linear segregation. The ANOVA found very significant column differences for nuclear density, lab density, and all gradation parameters. Nevertheless, and as previously observed, the p-values for nuclear and lab density tend to be several orders of magnitude smaller than those for gradation parameters.

Multiple comparison tests for nuclear density values locate differences in column 4, while those for gradation parameters find them in columns 4 and 5, and to a lesser extent, column 1. As was the case for Site 1, analysis of lab density finds a large number of differences. The indication of differences strengthens with decreasing grain size, being the strongest for percent passing the No. 8. Once again, the tendency for low nuclear values is generally aligned with the tendency for coarser-than-average gradation.

The significance of the results for this site can be stated as follows:

The extremely low p-values and consistency of identified columns (4 and 5 for the various tests and parameters) clearly indicate the presence a linear construction feature, i.e, a significantly coarser-than-average strip of asphalt mixture in the direction of paver travel, even though it is not strongly apparent on the ground.

This suggests a possibility of testing for segregation even where it is not visually apparent, but also opens up the possibility that such testing may find much more segregation than is presently noted in practice. If a statistical criteria were implemented for construction quality control, it would be advisable to obtain much more background data to evaluate just how consistently paving operations can be controlled to produce and place uniform mixes..

6.8.5 Site 5 - Old US 27

This site was originally selected as an extensively segregated site, but one not exhibiting a linear pattern. Statistical analyses by MBITSEG1.xls are summarized in Table 6.21, and find no evidence of segregation, by either ANOVA or multiple comparison analysis, when analyzed in the conventional row format.

However, two other unusual findings were made at this site. As previously discussed in Section 6.3, the nuclear density values were unrealistically low, and as previously discussed in Section 6.5, surface plots of the gradation analyses visually showed a strong trend of differences from row to row, with similarities from column to column. Because of the latter point, a second set of analyses was performed with rows and columns switched. The results are shown in Table 6.22. The small p-values in range of 10^{-5} to 10^{-11} indicated strong row difference for percent passing 3/8", No.4 and No.8 sieves, but not in the case of row analyses for density data

Also noteworthy at this site is the fact that the coefficient of variation of nuclear density values (2.1 percent) was relatively high, supporting the concept of identifying segregation using some measure of absolute variability in conjunction with some criterion of column differences.

6.8.6 Site 6 - M-123

This site was originally selected as one exhibiting a mix of linear and random segregation. Statistical tests made using MBITSEG1.xls are summarized in Table 6.23. As was the case for sites 1 and 4, extremely low p-values were obtained from the ANOVA's for all parameters, nuclear density, lab density, and three gradation parameters. This is a consistent indication of segregation.

The multiple comparison test results are less strong in pointing out the location of the segregation. Results for the nuclear density tests weakly identify columns 3 and 5, while results for the gradation parameters strongly point to column 3 and less so to column 1 and 2. Studying column mean values, however, once again shows that the coarsest materials correspond to the zone of lowest nuclear-measured density value.

The p-values for gradation differences at this site are lower (stronger) than those for nuclear density, which is different from the case at other sites.

6.8.7 Site 7 - Lansing State Police Facility

Like Site 4, this site was originally chosen as a "control" site, presumed to be unsegregated. However, the MSU research team identified it as lightly segregated, and after nuclear density measurements were made, the project Technical Advisory Group (TAG) also mapped the sight and reported various descriptions of light segregation. No cores were taken at this site and hence no gradation analyses were performed.

The results of the MBITSEG1.xls analyses on nuclear density are shown in Table 6.24. The very low p-value (0.0007) indicates significant column differences, and the multiple comparison tests identify column 4. Checking the density of column 4, however, shows it to be statistically heavy rather than statistically light. A review of the TAG members mapping showed varying patterns of segregation at areas other than column 4.

6.9 Assessment of Linear Segregation - Asphalt Content

When an asphalt mixture segregates, the asphalt content is normally higher for the finer material and lower for the coarser aggregate. Hence, an alternative method to find identify segregation may be to relate the degree of segregation to asphalt content. The field asphalt content was measured using the nuclear gauge over the same sampling grid and at the same time as the density evaluation. Advantages of using a nuclear gauge to measure asphalt content include:

- it is a non-destructive method
- it is faster and safer compared to ignition method

The principle of using the nuclear gauge to measure asphalt content is briefly explained here. According to Alattar and Al-Qadi (1996), high-energy neutrons can be slowed down by the presence of hydrogen which exists in the AC. Therefore, hydrogen content (AC content) is a function of the neutron interaction in the asphalt mixture. They also investigated the effect of various parameters on the asphalt content calibration, which are aggregate type and gradation, total specimen weight, and level of moisture content. Finally, the conclusion was drawn that there is a strong correlation between AC content and number of counts using a 3241-C Troxler nuclear gauge based on statistical methods.

Table 6.25 summarizes the results of statistical analysis on asphalt content using MBITSEG1.xls.

At Site 1, p-values are very low, similar to the case for other parameters. Multiple comparison tests, however, show scattered indications of where the significant differences lie.

At Site 2, the ANOVA yields finds significant column differences and yields a low p-value, similar to the case for nuclear and lab density. The multiple comparison tests point to column 6 as having the lowest asphalt content. There is no apparent correlation of this finding to those for the density or gradation analyses.

At Site 3, the ANOVA also indicated significant column differences, as was the case for nuclear and lab density, but not for gradation. The multiple comparison tests found indications of differences scattered throughout the six columns and three tests. Again, there is no clear correlation.

At Site 4, the ANOVA found strong column differences, consistent with all other measured parameters. Multiple comparison pointed out columns 1 and 2 as different, whereas gradation tests had pointed to 3 and 4. Comparison of the mean values are inconclusive regarding whether coarser mixes are correlated with lower asphalt contents.

At Site 5, the ANOVA did not find significant column differences for samples 1, 2 and 3, but did find column differences for average of three samples. The p-value was 0.043, which is close to the threshold of significance or non-significance. This is in conflict with the results found for other parameters. Multiple comparison tests did not locate any specific columns with differences, which is consistent with other analyses.

At Site 6, no significant column differences were found in any of the four samples, which is a different conclusion from analyses of nuclear density values and gradation parameters.

In summary, analyses of nuclear-measured asphalt content sometimes supported other analyses, and sometimes did not. It did not appear to be a promising line of attack, and was dropped from further consideration.

6.10 Expedient Analyses of Segregation Using Two Samples and MBITSEG2.xls

In the last six months of the project, after all seven test sites had been sampled and analyzed using MBITSEG1.xls, interest was expressed in developing a more streamlined program. It was decided by the TAG and MSU researchers that, if an apparently segregated area could be visually identified in the field (say by a chalk circle) together with an apparently unsegregated (or control) area, expedient testing could be performed using only these two sample sets, without the need for obtaining six columns of data. Furthermore, the methodology could apparently be easily adapted to other types of segregation, such as random segregation and "chevron shaped" segregation patterns.

Table 6.25 Results of Asphalt Content Analysis

Site 1 : St. John's

Asphalt Content	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	6.04	6.21	5.91	6.20	5.96	6.06	5.88
Coefficient of variation	2.72%	2.39%	2.01%	0.59%	1.57%	1.79%	1.63%
p-value	*4.77E-06*						
Tukey test		DIFF !	--	DIFF !	--	--	--
t-test		DIFF !	DIFF !	DIFF !	--	DIFF !	DIFF !
6 of 6 test		--	--	DIFF !	--	--	DIFF !

Site 2 : Muskegon (uniform)

Asphalt Content	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	5.85	5.93	6.03	5.87	5.66	6.13	5.48
Coefficient of variation	6.07%	4.16%	6.53%	5.97%	3.22%	5.37%	3.88%
p-value	*0.0061*						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	DIFF !
6 of 6 test		--	--	--	--	--	DIFF !

Site 3 : Muskegon (random)

Asphalt Content	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	5.94	5.52	6.27	5.77	6.14	6.23	5.69
Coefficient of variation	6.28%	7.12%	3.55%	2.07%	1.59%	5.16%	3.42%
p-value	*1.24E-05*						
Tukey test		DIFF !	DIFF !	--	DIFF !	--	DIFF !
t-test		DIFF !	DIFF !	DIFF !	DIFF !	DIFF !	DIFF !
6 of 6 test		--	DIFF !	--	DIFF !	--	--

Site 4 : M-99

Asphalt Content	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	6.24	6.83	6.69	5.92	6.05	6.07	5.86
Coefficient of variation	7.15%	3.63%	3.22%	3.52%	5.52%	3.83%	3.73%
p-value	*6.08E-08*						
Tukey test		DIFF !	DIFF !	--	--	--	--
t-test		DIFF !	DIFF !	--	--	--	--
6 of 6 test		DIFF !	DIFF !	--	--	--	--

Site 5 : Old U.S. 27

Asphalt Content	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	6.54	6.77	6.72	6.77	6.40	6.42	6.16
Coefficient of variation	6.45%	8.01%	4.07%	3.69%	5.38%	5.25%	7.30%
p-value	*0.0430*						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Site 6 : M-123

Asphalt Content	Overall	column 1	column 2	column 3	column 4	column 5	column 6
Mean	7.18	7.21	7.13	7.25	7.06	7.20	7.24
Coefficient of variation	2.42%	2.37%	2.41%	1.86%	2.66%	1.31%	3.35%
p-value	0.4057						
Tukey test		--	--	--	--	--	--
t-test		--	--	--	--	--	--
6 of 6 test		--	--	--	--	--	--

Consequently, the second software package, MBITSEG2.xls, was developed as described in Section 5.4. MBITSEG2.xls provides a convenient, user-friendly tool with graphic display to perform simple t-tests to assess the significance of the difference of two sample means.

To provide a preliminary verification of MBITSEG2.xls, candidate segregated and unsegregated areas were selected from existing sites, based on both previous analyses using MBITSEG1.xls and visual segregation mapping performed during site layout. Numerous pairs of samples, one segregated and one unsegregated in each pair, were then analyzed using MBITSEG2.xls. Detailed findings are discussed in the paragraphs following.

6.10.1 Site 1 - St. John's

Field observations were used to allocate samples among four levels of segregation:

- none apparent,
- light,
- moderate, and
- heavy

The locations of samples and assigned degrees of segregation are shown in Figure 6.47. Sample sizes, n_1 and n_2, were both chosen as 6. Results of comparisons using MBITSEG2.xls for both one-minute nuclear density and air-dry lab density on surface course samples are shown in Table 6.26.

For nuclear-measured density, it can be seen that MBITSEG2.xls was used to compare "heavy" segregation areas from the other three (less severe) categories, significance levels were generally greater than 99 percent. However, when comparing "moderate" or "light" areas to less severe areas, results were less strong.

Results for air-dry lab density on surface course also indicated that the mostly significant differences are between heavily segregated samples and other samples with a lesser degree of segregation.

6.10.2 Site 2 - Muskegon (uniform)

Figure 6.48 shows the sampling configuration at this site. It was recognized that column 1 was located approximately at the edge of the auger during the paving operation. Samples in column 4 also segregated with accumulation of fine materials because it was located near the middle of the auger. Samples in column 6 appeared to have heavy segregation. Remaining samples were taken to be unsegregated. Thus, one-hundred-eight samples were grouped with respect to four categories of segregation:

- edge of auger,
- middle of auger,
- heavy, and
- none.

Samples from the "none" category were randomly chosen for testing against other samples. Results (in terms of significance levels) for two-sample comparisons for both nuclear and lab

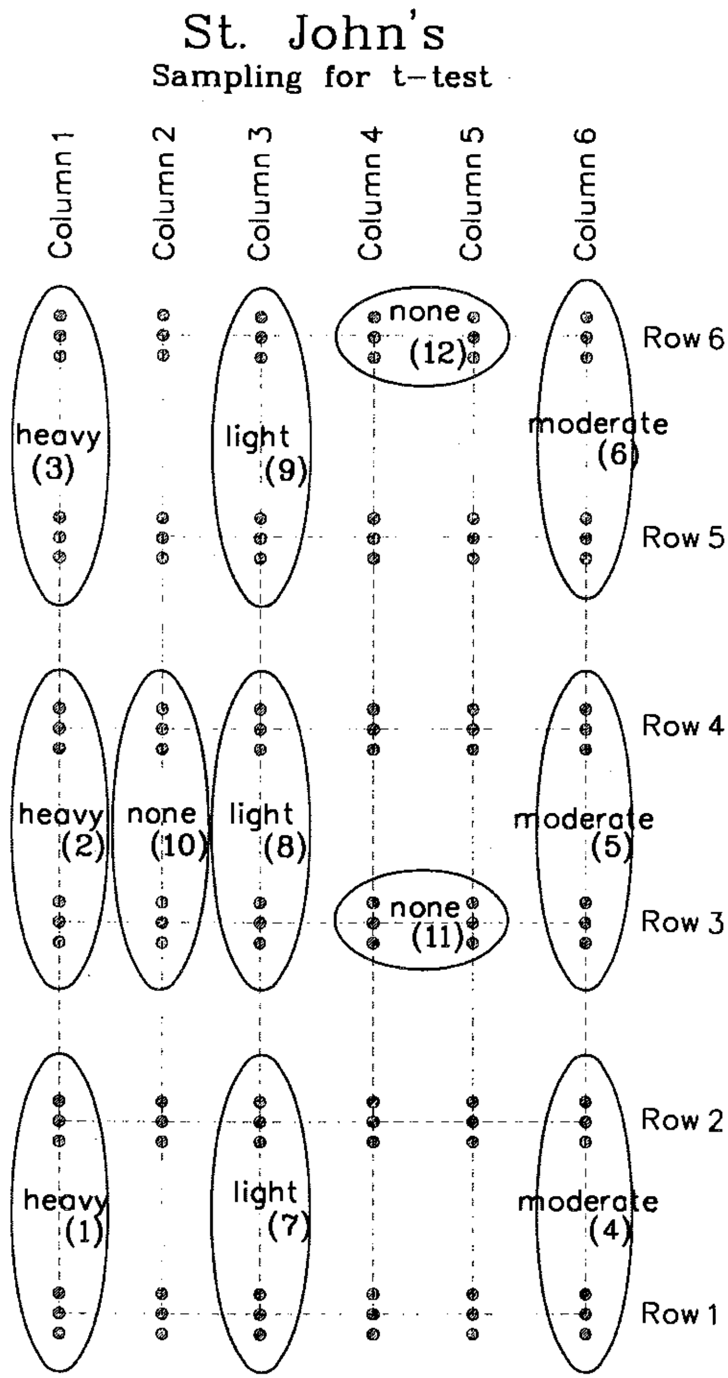


Figure 6.47 Sampling for Two-sample Comparison at Site 1 - St. John's

Table 6.26 Results of Two-sample Comparison Using MBITSEG2.xls at Site 1 - St. John's

(a.) Nuclear Density Evaluation

	heavy			moderate			light			none
		41.62								
heavy		91.82								
		99.03								
	100.00	***100.00***	***100.00***		68.66					
moderate	*97.38*	*98.43*	92.68		***99.81***					
	99.96	***100.00***	***99.96***		41.37					
	100.00	***100.00***	***100.00***	78.21	42.11	***99.53***		38.51		
light	***100.00***	***100.00***	***100.00***	88.23	30.76	*98.73*		83.62		
	100.00	***100.00***	***100.00***	*96.99*	10.33	*95.95*		61.95		
	100.00	***100.00***	***100.00***	4.38	69.06	***99.96***	86.03	93.73	***99.09***	33.33
none	***99.99***	***100.00***	***99.98***	28.55	73.81	***99.00***	76.81	84.55	93.17	90.77
	100.00	***100.00***	***100.00***	83.57	38.60	***99.51***	14.26	27.40	80.23	80.24

(b.) Lab Density Evaluation

	heavy			moderate			light			none
		59.90								
heavy		38.89								
		54.90								
	99.90	***100.00***	82.38		18.71					
moderate	***99.97***	***99.99***	79.42		*98.87*					
	53.52	77.63	9.80		*98.15*					
	99.99	***100.00***	70.57	80.35	62.05	*97.15*		29.62		
light	***99.99***	***100.00***	73.60	68.75	47.11	*97.75*		*98.27*		
	99.21	***99.91***	33.13	***99.37***	*98.14*	72.54		*98.83*		
	100.00	***100.00***	***99.30***	***100.00***	***99.99***	***100.00***	***100.00***	***100.00***	***100.00***	88.03
none	1.97	6.58	18.07	60.43	58.35	14.81	51.75	53.69	33.39	93.36
	99.84	***99.93***	90.82	68.23	72.66	*98.78*	88.58	85.70	*98.02*	71.96

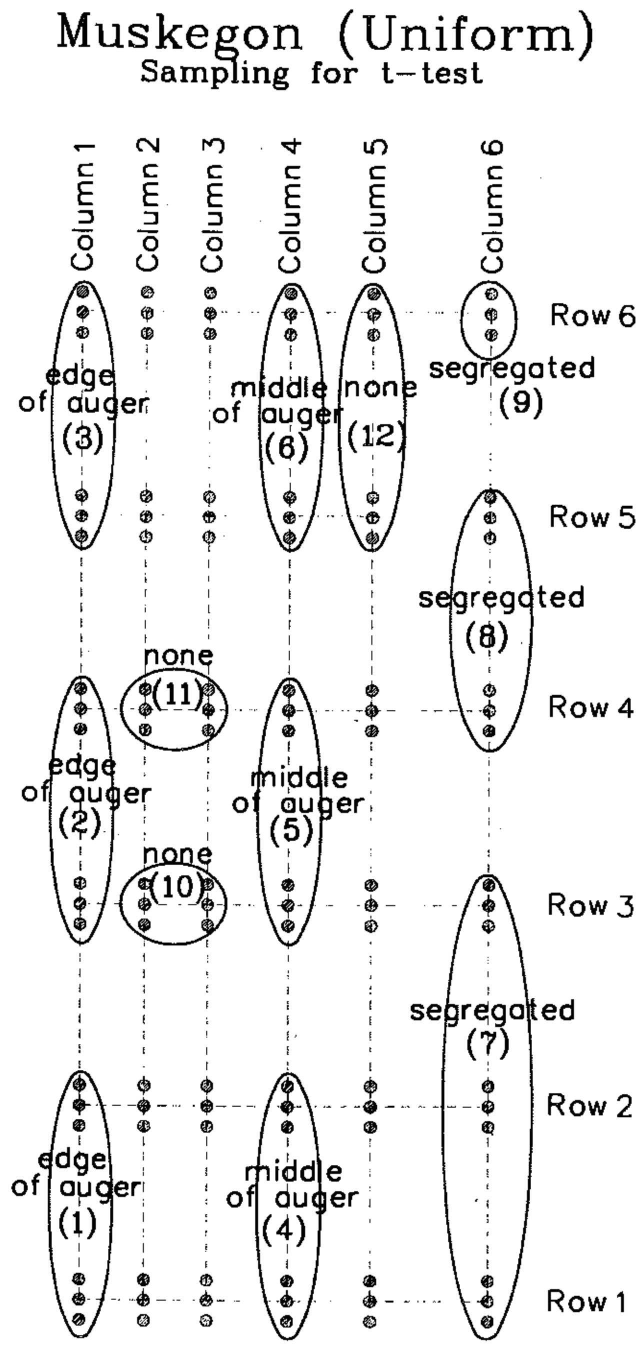


Figure 6.48 Sampling for Two-sample Comparison at Site 2 - Muskegon (uniform)

density are shown in Table 6.27. For nuclear density, high significance levels (> 99 percent) are observed for

- Middle of auger vs. edge of auger
- Middle of auger vs. none

Somewhat less significant differences (> 95 percent) were found for

- Middle of auger vs. segregated.

This supports the finding that that samples at middle of the auger have higher density values. For lab density, high levels of significance are found for:

- Edge of auger vs. middle of auger
- Edge of auger vs. segregated
- Middle of auger vs. none
- Segregated vs. none.

6.10.3 Site 4 - M-99

At the M-99 site, selection of sample groups was based on the previous results in Section 6.3 and 6.4 that density values are always low in column 4. Therefore, three samples (numbered one through three) were chosen in column 4 and compared to six other samples (numbered four through nine) were randomly selected from none-segregated areas. The sampling configuration is shown in Figure 6.49. Results of comparisons presented in Table 6.28. It is clear that nuclear density values for segregated samples (1-3) are significantly different from that for unsegregated samples (4 - 9) with significance levels consistently more than 99 percent. Comparisons based on lab density give similar results. One exception involved sample 9, which had an extremely high lab density with mean around 150.9 lb/ft^3.

6.10.4 Site 5 - Old US 27

Based on site inspection, one-hundred-eight samples were regrouped to 12 samples with five different levels of segregation:

- heavy,
- medium,
- slight,
- little-to-none, and
- none,

Sample locations and classification are shown in Figure 6.50. Results of two-sample comparisons are shown in Table 6.29. For nuclear density evaluation, results were generally not good, with only the "slight" category exhibiting much differences from others. However, it should be recalled that this was the site of unreasonably low nuclear-measured density values.

For lab density evaluation, results are as-expected. Lab density values in heavily segregated samples are significantly different from those with lesser degrees of segregation. Similar results were also found in the comparisons between medium segregated samples and samples with

Table 6.27 Results of Two-sample Comparison at Site 2 - Muskegon (uniform)

(a.) Nuclear Density Evaluation

	edge of the auger			middle of the auger			segregated			none
edge of the auger		71.46								
		77.06								
		12.77								
middle of the auger	***99.96***	***99.95***	***99.95***		57.81					
	99.99	***99.98***	***99.97***		65.36					
	99.72	***99.81***	***99.82***		88.06					
segregated	98.19	***99.63***	***99.7***	***99.97***	***100***	*98.77*		*99.27*		
	99.82	***99.84***	***99.85***	78.71	*95.98*	9.38		*95.85*		
	2.32	58.64	63.79	***99.80***	***99.95***	*98.65*		***99.22***		
none	52.38	86.55	89.01	***99.18***	***99.66***	*96.47*	72.67	*96.83*	39.46	*96.14*
	91.97	39.67	25.90	***100***	***100***	***99.98***	***99.98***	***99.98***	83.12	59.13
	92.38	*97.72*	*98.06*	***99.25***	***99.84***	93.43	0	94.64	84.75	99.66

(b.) Lab Density Evaluation

	edge of the auger			middle of the auger			segregated			none
edge of the auger		94.03								
		94.93								
		6.15								
middle of the auger	***99.98***	***99.98***	***99.99***		52.78					
	99.98	***99.99***	***99.99***		74.94					
	99.66	***99.92***	***99.93***		88.68					
segregated	94.78	***99.20***	***99.27***	29.14	13.83	53.27		15.10		
	99.98	***99.99***	***99.99***	48.74	4.31	87.51		47.71		
	97.36	*98.67*	*98.8*	88.67	92.73	33.92		91.95		
none	67.11	*97.55*	*97.88*	*98.50*	***99.14***	91.34	86.65	***99.07***	71.26	***99.66***
	99.50	34.09	27.29	***100***	***100***	***100***	***99.61***	***100***	***99.92***	*97.23*
	92.66	40.62	46.53	***100***	***100***	***99.97***	*98.83*	***100***	***99.49***	78.05

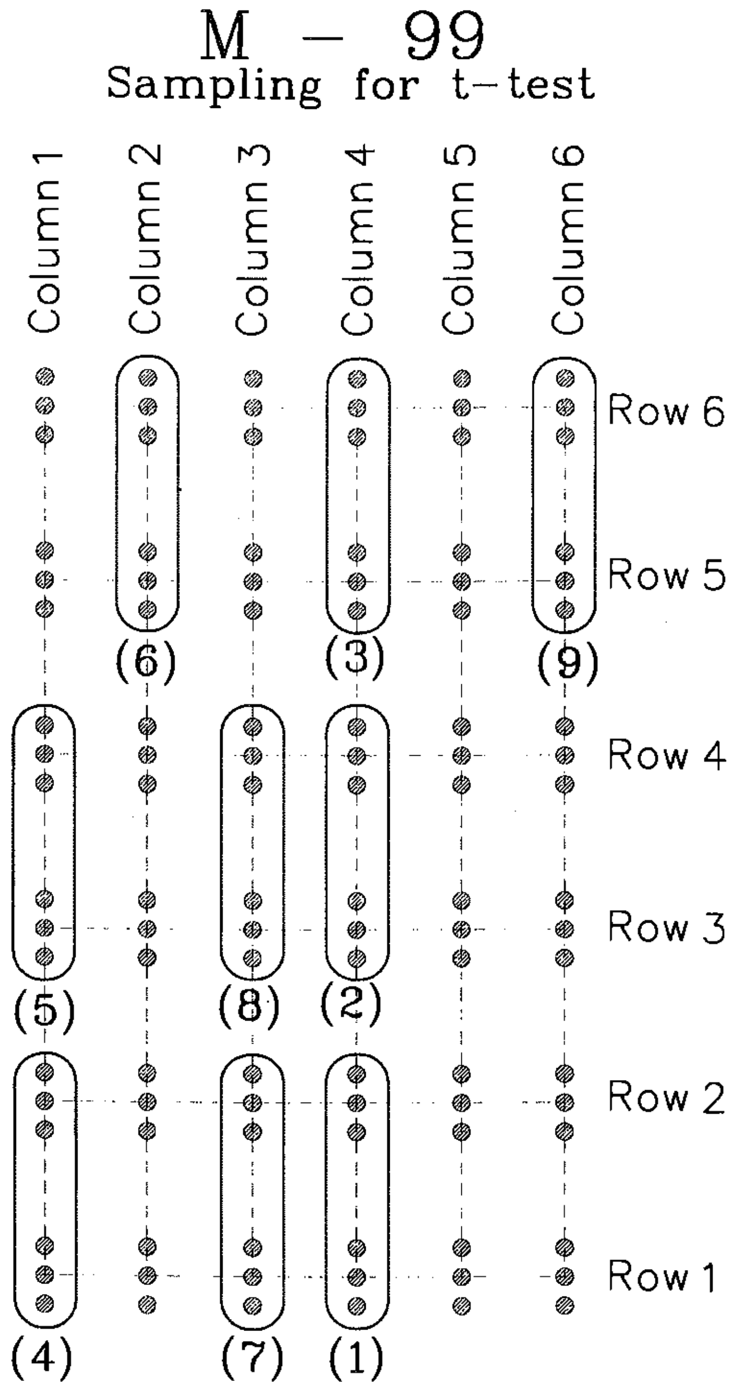


Figure 6.49 Sampling for Two-sample Comparison at Site 4 - M-99

Table 6.28 Results of Two-sample Comparison at Site 4 - M-99

Nuclear	sample 1	sample 2	sample 3	sample 4	sample 5	sample 6	sample 7	sample 8	sample 9
sample 1	x								
sample 2	32.50	x							
sample 3	22.60	22.20	x						
sample 4	***99.91***	***99.96***	***99.99***	x					
sample 5	***99.83***	***99.92***	***99.98***	17.78	x				
sample 6	***99.92***	***99.97***	***100.00***	9.51	26.47	x			
sample 7	***99.90***	***99.98***	***100.00***	70.86	52.42	76.99	x		
sample 8	***99.34***	***99.48***	***99.79***	36.27	21.59	42.87	19.26	x	
sample 9	***99.80***	***99.86***	***99.94***	37.58	48.05	31.30	78.35	57.86	x

Lab	sample 1	sample 2	sample 3	sample 4	sample 5	sample 6	sample 7	sample 8	sample 9
sample 1	x								
sample 2	55.19	x							
sample 3	*98.60*	93.50	x						
sample 4	***99.95***	***99.99***	***100.00***	x					
sample 5	***99.98***	***99.99***	***100.00***	24.14	x				
sample 6	***99.94***	***99.98***	***100.00***	43.48	58.06	x			
sample 7	***99.93***	***99.98***	***100.00***	69.66	59.18	48.90	x		
sample 8	***99.96***	***99.99***	***100.00***	32.44	13.88	61.41	42.84	x	
sample 9	***100.00***	***100.00***	***100.00***	***99.88***	***99.97***	*95.18*	***99.98***	***99.92***	x

Note : sample 1 , 2 and 3 are segragated

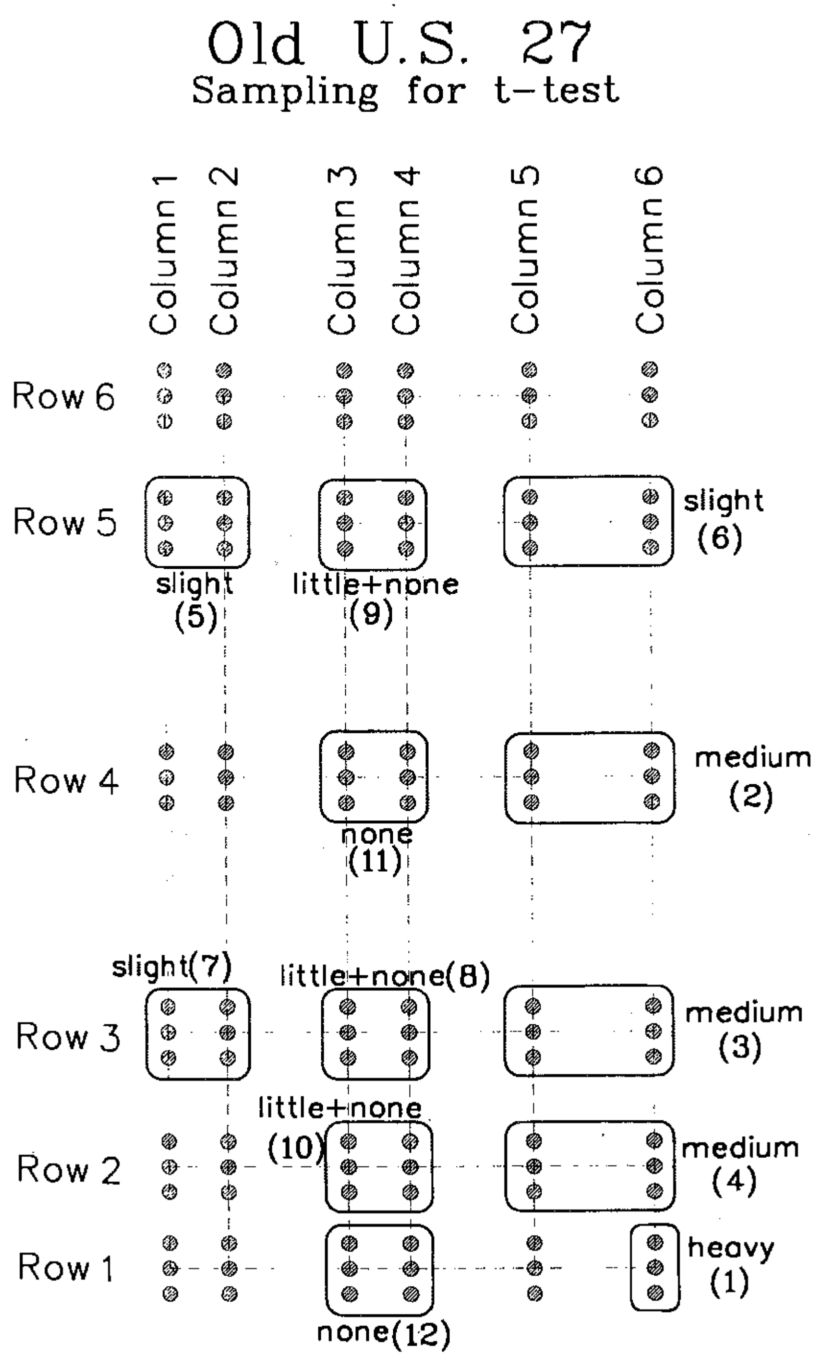


Figure 6.50 Sampling for Two-sample Comparison at Site 5 - Old U.S. 27

Table 6.29 Results of Two-sample Comparison at Site 5 - Old U.S. 27

(a.) Nuclear Density Evaluation

	heavy	medium	slight	little+none	none
heavy	x				
medium	10.74 45.10 57.52	71.50 87.95 42.44			
slight	59.73 0.65 58.26	89.13 50.05 13.00 32.39 94.67 ***99.24*** 90.22 45.05 3.53	***99.08*** 18.08 ***99.85***		
little+none	75.49 52.64 43.72	*98.27* 91.01 81.03 83.54 23.88 24.63 73.19 14.37 64.89	70.38 ***99.99*** 90.17 35.46 ***99.00*** 25.85 69.69 *98.91* 74.29	90.89 *98.64* 47.17	
none	64.75 88.92	93.89 66.78 34.18 ***99.78*** ***99.29*** *98.86*	18.70 ***99.85*** 44.16 *97.86* ***100.00*** ***99.59***	66.76 57.45 87.02 94.06 ***99.48*** ***99.91***	*98.35*

(b.) Lab Density Evaluation

	heavy	medium	slight	little+none	none
heavy	x				
medium	***99.94*** ***99.92*** ***99.99***	81.97 ***99.80*** 80.73			
slight	***99.81*** ***99.33*** ***99.99***	88.52 *97.84* ***99.99*** ***99.42*** ***99.76*** ***100.00*** *97.94* 31.90 85.11	88.98 ***99.90*** ***99.99***		
little+none	***99.99*** ***99.83*** ***99.93***	*99.33* 44.56 86.05 ***99.68*** ***99.80*** ***100.00*** *97.26* ***99.20*** ***100.00***	***99.97*** ***100.00*** 22.23 84.51 53.44 ***100.00*** 16.20 94.30 ***100.00***	***100.00*** ***100.00*** *98.18*	
none	***99.86*** ***99.78***	*97.11* ***99.22*** ***100.00*** *97.93* ***99.39*** ***100.00***	37.77 84.62 ***99.99*** 56.89 70.98 ***99.99***	***100.00*** 78.52 39.39 ***100.00*** 48.74 64.57	31.48

lesser degree of segregation. In general, for two-sample comparisons at this site, lab density evaluation gave more reasonable results than nuclear density evaluation.

6.10.5 Site 3 - Muskegon (random) and Site 6 - M-123

At these sites, segregation was recognized by visual inspection, but no categorical description regarding the degree of segregation was mapped. Therefore, criteria to choose samples at these sites were based on surface plots from nuclear density data. Several adjacent points within a similar pattern, i.e., low spots, high spots or middle areas were grouped together. The sampling configurations are shown in Figures 6.51 and 6.52; results of comparisons are shown in Tables 6.30 and 6.31. For the adjacent-sample comparison at the Muskegon (random) site, sample 1 has consistently significant density differences from the surrounding samples (2, 3 and 4). Samples 2, 5, 6, 11, 12, and 13 also show similar results. It can be concluded that the samples mentioned above are the random segregated spots in this pavement grid. The corresponding patterns are shown in Table 6-32.

Table 6.32 Patterns of Selected Samples

Selected Sample	Description of Pattern
Sample 1	low
Sample 2	flat
Sample 5	high
Sample 6	low
Sample 11	high
Sample 12	low
Sample 13	flat

At the M-123 site, the indication of random segregation is not clear. Only samples 2 and 9 showed a significant density difference from the surrounding samples. This matches the field observation that linear and random segregation are mixed in this site.

6.10.6 Alternative verification

An alternative way to verify the MBITSEG2.xls spreadsheet is to compare two samples with similar patterns. Three types of pattern are defined as low, flat, and high. The corresponding samples are listed in Table 6.32. In general, and as expected, comparisons for two samples with similar pattern did not indicate significant difference for density values. However, some exceptions were also found in comparison between sample 2 and sample 10, and comparison for lab density from those samples with low spots.

6.10.7 Site 7 - Lansing State Police Facility

At this site, three levels of segregation were defined, light segregation, little segregation and none. The sampling configuration is shown in Figure 6.53. Using a random selection technique, three samples for each level of segregation were chosen. Results of two-sample comparison are presented in Table 6.33. It can be seen that most paired comparisons did not indicate significant

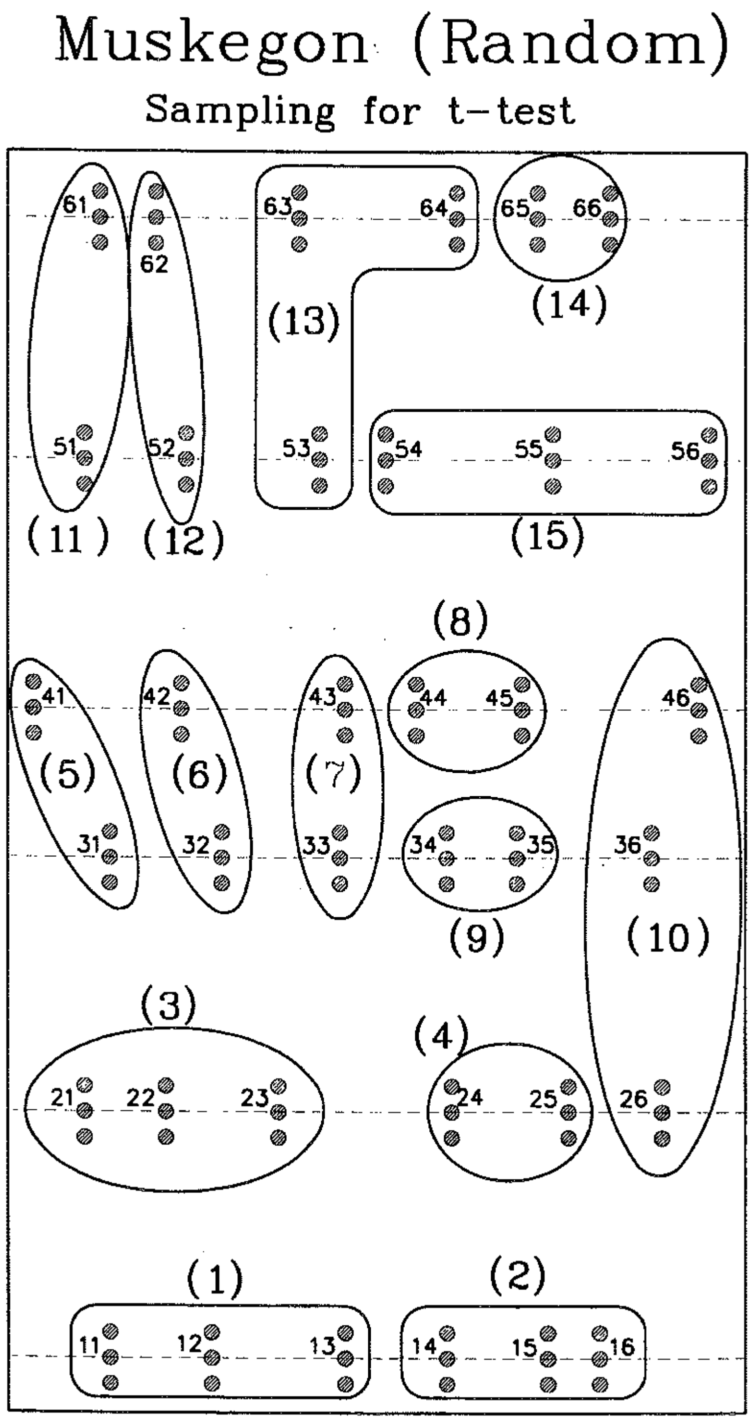


Figure 6.51 Sampling for Two-sample Comparison at Site 3 - Muskegon (random)

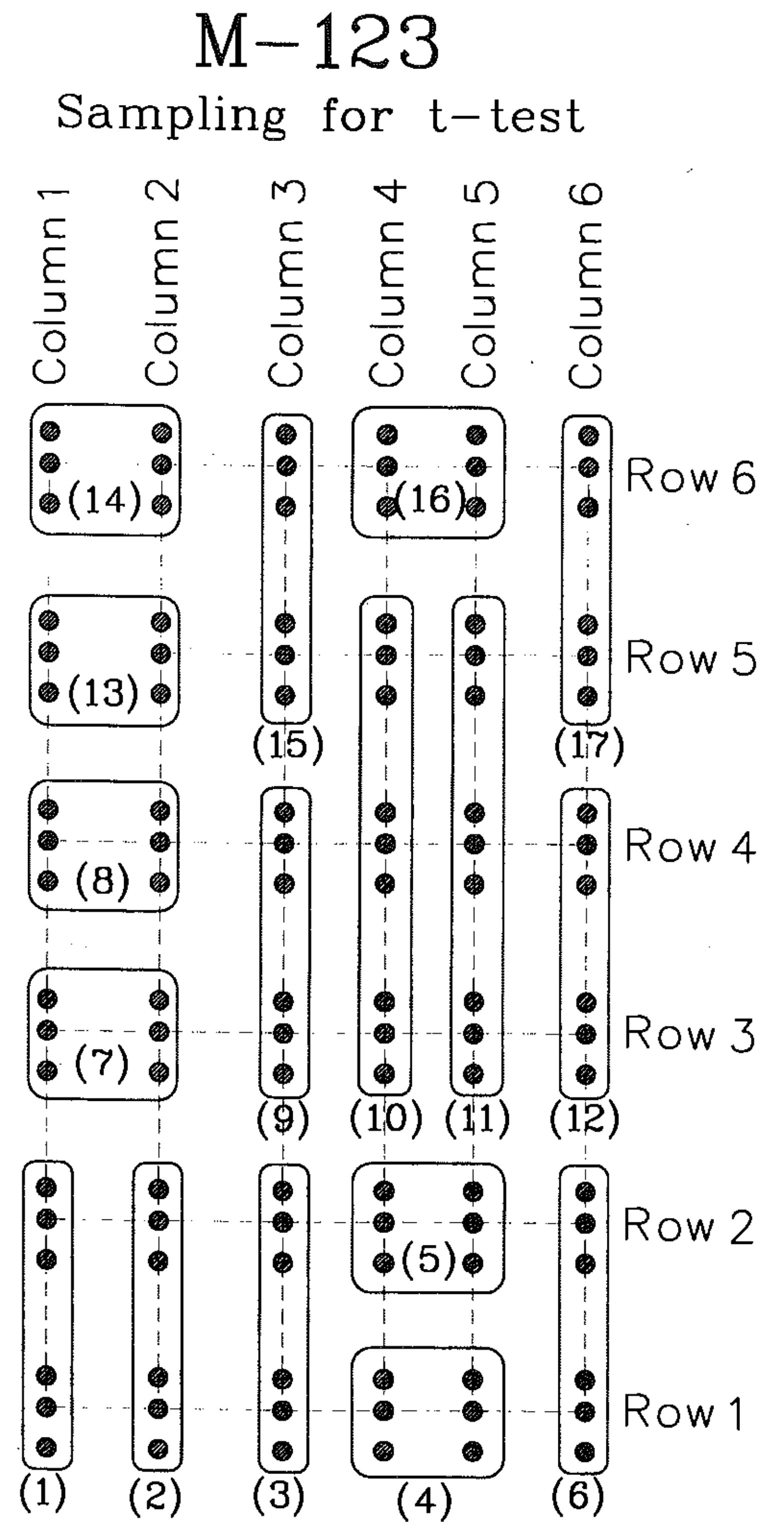


Figure 6.52 Sampling for Two-sample Comparison at Site 6 - M-123

Table 6.30 Results of Two-sample Comparison at Site 3 - Muskegon (random)

		Nuclear	Lab.
		confidence (%)	
sample 1 vs.	2	46.80	*97.24*
	3	*96.78*	***100.00***
	4	*98.69*	***100.00***
sample 2 vs.	1	46.80	*97.24*
	3	***99.51***	***99.98***
	4	***99.79***	***100.00***
sample 3 vs.	1	*96.78*	***100.00***
	2	***99.51***	***99.98***
	4	58.69	*95.43*
	5	***99.91***	***100.00***
	6	73.07	54.82
	7	***99.19***	*98.76*
sample 4 vs.	1	*98.69*	***100.00***
	2	***99.79***	***100.00***
	3	58.69	*95.43*
	9	57.42	66.75
	10	*98.83*	27.68
sample 5 vs.	3	***99.91***	***100.00***
	6	***99.93***	***99.94***
	11	***99.97***	***99.82***
	12	*98.04*	64.67
sample 6 vs.	3	73.07	54.82
	5	***99.93***	***99.94***
	7	***99.69***	*96.87*
	11	***100.00***	***100.00***
	12	***99.26***	***100.00***
	13	***99.99***	***99.90***
sample 7 vs.	6	***99.69***	*96.87*
	8	***99.65***	***99.57***
	9	*98.89*	***99.97***
	12	75.66	***100.00***
	13	91.65	*96.62*
	15	87.01	***99.17***
sample 8 vs.	7	***99.65***	***99.57***
	9	31.61	39.18
	10	*98.60*	87.37
	15	*98.12*	***99.35***
sample 9 vs.	4	57.42	66.75
	7	*98.89*	***99.97***
	8	31.61	39.18
	10	93.58	83.81
sample 10 vs.	4	*98.83*	27.68
	9	93.58	83.81
	8	*98.60*	87.37
	15	39.96	***99.37***
sample 11 vs.	5	***99.97***	***99.82***
	6	***100.00***	***100.00***
	12	***100.00***	***99.98***
sample 12 vs.	11	***100.00***	***99.98***
	5	*98.04*	64.67
	6	***99.26***	***100.00***
	7	75.66	***100.00***
	13	***99.44***	***99.75***
sample 13 vs.	12	***99.44***	***99.75***
	6	***99.99***	***99.60***
	7	91.65	*96.62*
	15	***99.86***	***99.49***
	14	***99.98***	***99.65***
sample 14 vs.	13	***99.98***	***99.65***
	15	77.03	62.65
sample 15 vs.	13	***99.86***	***99.99***
	14	77.03	62.65
	7	87.01	***99.17***
	8	*98.12*	***99.35***
	10	39.96	***99.37***

Table 6.31 Results of Two-sample Comparison at Site 6 - M-123

		Nuclear	Lab.
		confidence (%)	
sample 1 vs.	2	*95.71*	***99.97***
	7	81.38	***99.15***
sample 2 vs.	1	*95.71*	***99.97***
	3	*98.13*	***99.66***
	7	***99.53***	96.37
sample 3 vs.	2	*98.13*	***99.66***
	4	83.61	94.93
	5	52.98	54.42
	7	35.95	89.57
	9	81.45	67.98
	10	57.08	91.84
sample 4 vs.	3	83.61	94.93
	5	54.13	70.22
	6	*95.93*	40.49
sample 5 vs.	3	52.98	54.42
	4	54.13	70.22
	6	84.89	61.37
	10	35.79	23.80
	11	93.99	81.82
	12	69.31	59.08
sample 6 vs.	4	*95.93*	40.49
	5	84.89	61.37
	11	13.31	***99.84***
	12	66.64	12.10
sample 7 vs.	1	81.38	***99.15***
	2	***99.53***	*96.37*
	3	35.95	89.57
	9	***99.93***	***99.62***
	8	60.21	33.41
sample 8 vs.	7	60.21	33.41
	9	***99.98***	***99.72***
	13	88.59	13.66
	15	***99.68***	93.13

		Nuclear	Lab.
		confidence (%)	
sample 9 vs.	3	81.45	67.98
	5	*95.55*	88.36
	7	***99.93***	***99.62***
	8	***99.98***	***99.72***
	10	***100.00***	***99.98***
	15	*95.64*	*95.81*
sample 10 vs.	5	35.79	23.80
	9	***100.00***	***99.98***
	11	***100.00***	***99.60***
	15	***99.82***	89.32
	16	67.02	76.29
sample 11 vs.	5	93.99	81.82
	10	***100.00***	***99.60***
	12	89.91	***99.83***
	16	***100.00***	***99.06***
	17	74.42	***99.97***
sample 12 vs.	6	66.64	12.10
	11	89.91	***99.83***
	17	38.16	90.97
sample 13 vs.	8	88.59	13.66
	14	66.95	12.14
	15	***99.88***	*97.01*
sample 14 vs.	13	66.95	12.14
	15	***99.82***	90.54
sample 15 vs.	13	***99.88***	*97.01*
	14	***99.82***	90.54
	9	*95.64*	*95.81*
	10	***99.82***	89.32
	16	***99.87***	90.21
sample 16 vs.	15	***99.87***	90.21
	10	67.02	76.29
	11	***100.00***	***99.06***
	17	***99.46***	53.37
sample 17 vs.	16	***99.46***	53.37
	11	74.42	***99.97***
	12	38.16	90.97

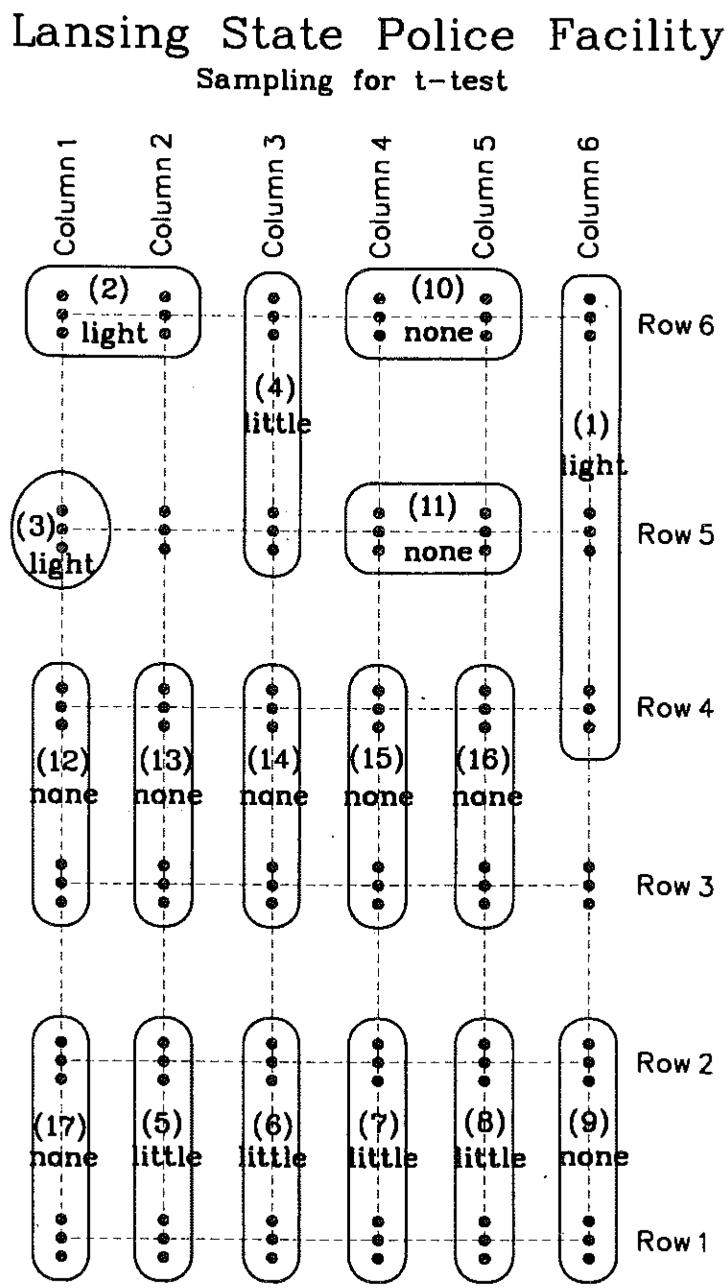


Figure 6.53 Sampling for Two-sample Comparison at Site 7 - Lansing State Police Facility

Table 6.33 Results of Two-sample Comparison at Site 7 - Lansing State Police Facility

Two Samples	Condidence Level	Two Samples	Condidence Level	Two Samples	Condidence Level
9 vs. 10	*96.34*	10 vs. 11	61.72	11 vs. 12	28.93
9 vs. 11	76.46	10 vs. 12	53.22	11 vs. 13	3.91
9 vs. 12	*96.62*	10 vs. 13	69.16	11 vs. 14	15.74
9 vs. 13	91.45	10 vs. 14	62.82	11 vs. 16	30.74
9 vs. 14	94.74	10 vs. 16	86.13	11 vs. 17	14.41
9 vs. 16	83.58	10 vs. 17	75.24		
9 vs. 17	78.38				

Two Samples	Condidence Level	Two Samples	Condidence Level	Two Samples	Condidence Level
12 vs. 13	35.8	13 vs. 14	17.11	14 vs. 16	65.82
12 vs. 14	20.45	13 vs. 16	50.53	14 vs. 17	37.77
12 vs. 16	77.62	13 vs. 17	23.76		
12 vs. 17	51.73				

Two Samples	Condidence Level
16 vs. 17	18.65

differences. Comparing samples with light segregation to that without segregation, only 2 of 9 paired comparisons have confidence levels more than 95 %. This fact reveals that this is a site having a relatively uniform density distribution. For the comparison between samples with little segregation and samples without segregation, no confidence levels are over 95 %. Again, this supports the above statement that this is a "uniform" site without much density variation.

None of the comparisons included column 4, where density values were previously found to be high.

7. Implementation of an Expedient Test Method for Detecting Segregation

7.1 Introduction

Based on the findings of the research effort previously described, this chapter summarizes a plan for the preliminary implementation of a test procedure for expedient determination of segregation, and provides suggested wording that could be used as a starting point for a new specification provision to limit segregation in constructed pavements.

The study involved a limited number of sites and the research had somewhat mixed results within those sites; nevertheless, the developed methodology shows considerable promise as an expedient quantitative tool for identifying segregated areas. Hence, it is strongly recommended that MDOT implement a pilot program of using the developed tests for the purposes of information and acquiring experience, prior to the implementation of any specification or payment provisions related to the test.

7.2 Test Procedure

7.2.1 Six-by-Six Grid Test for Linear Segregation

Although two-sample test described in the next section is more expedient, the six-by-six grid test should be used during the pilot program wherever significant linear segregation is apparent. The six-by-six grid provides considerable additional data that will be useful in further developing and calibrating the procedures. The steps in the six-by-six grid test are as follows:

Step 1: Lay out testing grid. The testing grid should be laid out as described in paragraph A.3, *Field Sampling, of Appendix A: User's Manual for Program MBITSEG1.xls*. As noted in the user's manual, the testing grid size is not fixed but is laid out to capture segregated and unsegregated areas. A sketch should be made of the actual test locations, as well as the location and condition of any apparently segregated areas.

Step 2: Obtain one-minute nuclear density measurements at the 36 locations.

Step 3. Enter the site information and nuclear density values in MBITSEG1.xls

Step 4. Save the file under a unique name.

Step 5. Interpret results. A description of the results displayed by MBITSEG1.xls is provided in Appendix A, and additional details are provided in Chapter 5. If significant column differences are present at the 95 percent significance level, **YES!** will be displayed in the box to the right of row 1, and if certain columns can be identified as meeting various criteria for significant differences, they are displayed at the bottom of the sheet. As the segregated sites studied in the current research typically had significance levels much greater than 95 percent (p-values much lower than 0.05), it is not yet certain if the 95 percent threshold is sufficiently high for application in practice. Collection of data files for additional sites will assist in this determination. The actual p-value can be found on the ANOVA worksheet of the program.

The visual displays also provide a good indication of linear segregation. Where present, the density plots will show notable linear peaks and valleys. Where not present, the plots will show a random high and low points.

7.2.2 Two-Sample Expedient Test for Segregation

Where a segregation pattern of any type is visually apparent, the two-sample expedient test can be performed using MBITSEG2.xls. Details of the program are described in Appendix B and Chapter 5. The steps are as follows:

Step 1. Lay out test area. The boundary of an apparently-segregated area should be outlined on the pavement in chalk or paint and test locations should be uniformly distributed over the area. Apparently-segregated areas will usually be those which appear relatively coarse and deficient in fines. The test area should be sufficiently large to permit five to ten nuclear density tests, each representing two to ten square feet; hence a typical test area might be 10 to 100 square feet. The area should be large enough that segregation of areas of such size is of concern; it should be small enough as to represent a contiguous area of apparent segregation that can be visually differentiated from another area. The greater the number of tests in the sample, the greater the confidence that can be associated with the test results.

Step 2. Lay out control area. A control area of similar size should be outlined and a similar number of test locations marked. The control area should be visually different from the presumed segregated area, and will correspond to either a "normal" area, or an area that is rich in fines that have been removed from the coarser area. Care should be taken not to mix these conditions if possible.

Step 3. Obtain nuclear density measurements at the marked locations.

Step 4. Enter data in MBITSEG.xls Details are provided in Appendix B, the user's manual, and in Chapter 5.

Step 5. Interpret Data. Details are provided in Appendix B, the user's manual, and in Chapter 5. MBITSEG2.xls performs a Student's t-test to assess whether the difference in the mean nuclear density values is statistically significant. It determines whether these differences are significant at the 95 and 99 percent levels, and also displays the actual significance level. For the segregated sites evaluated in the research, very high (> 99.9 percent) significance levels were noted. Very high significance levels are considered to be strong indicators of segregation. Where significance levels are high but not "very high" (i.e. 95 to 99.9 percent) segregation is likely to be present, but additional data and experience are necessary before recommendations for action can be made for these cases.

7.3 Specification Revisions

As the developed procedures find their way into practice, contract specification language, matched to the test procedure, is ultimately required to provide a system to minimize segregation in pavement construction.

Although density controls are a part of the existing specification and quality control practice, the samples obtained for density control are sparse and scattered, and the control is based on the average of multiple readings. As discussed in Chapter 3, it is quite possible to construct pavements which meet specifications with average density values within specified limits, that still in fact have significant areas of low or high density. Where segregation is present, there will likely be localized contiguous areas with density values outside the control density limits, as well as significant variations in density over short distances. Both have been observed in this study.

Likewise, segregated areas may have gradations that fall entirely within specifications, but are consistently different in fines content from other nearby areas.

Hence, specifications must address consistency of gradation from point to point on the pavement, and indicate that consistency of density will be taken as an indicator of segregation.

Recommended preliminary specification wording is provided below:

Segregation. *Segregation is defined as a condition of inconsistent aggregate gradation from point-to-point in a pavement. The contractor shall monitor and control all procedures in the mixing, transportation, and placement of HMA to prevent the occurrence of segregation and to result in a pavement with a consistent aggregate gradation from point to point in the completed pavement.*

Consistency of Aggregate Gradation. *Consistency of aggregate gradation shall be determined as follows: Ten cores shall be obtained, five each in two designated areas. Each area shall encompass 20 to 100 square feet, and core locations shall be uniformly distributed over the area. The mean (average) percent passing the (No. 4)(No. 8) sieve for each of the two areas shall be determined using the five samples from each respective area. These two mean values shall be compared using a standard Student's t-test for the difference of two means. If the difference is found significant at the 95 (99) percent significance level, the placed materials shall be determined to be segregated.*

Expedient Test for Segregation. *Significant differences in average nuclear density values is an expedient indicator of likely segregation. An expedient test for segregation shall be performed as follows. Two areas shall be defined as described above, and ten one-minute nuclear density measurements shall be taken in each area. The mean value for each area shall be determined as the average of the ten measured values. The two mean values shall be compared using a standard Student's t-test for the difference of two means. If the difference is found significant at the 99 (99.9) percent significance level, the placed materials shall be determined to be segregated unless found otherwise based on gradation testing of core samples as described in the preceding paragraph.*

8. Summary, Conclusions and Recommendations

8.1 Summary

A research study was conducted to develop and test an expedient field method to assess the presence of segregation in hot-mix asphalt concrete pavements and make recommendations regarding its implementation in practice. The proposal and working hypothesis for the study was limited to linear-pattern segregation, but some effort was later directed at other (i.e. random) segregation patterns.

For the purposes of the study, segregation was defined by MDOT as

> *Areas of non-uniform distribution of coarse and fine aggregate particles in a bituminous pavement that are visually identifiable or can be determined by other methods.*

The hypothesis of the study was that segregated areas will have subareas with statistically significant differences in nuclear density values, which correspond to significantly different gradation parameters indicative of segregation. These nuclear-measured density differences may occur for two reasons:

- With everything else taken equal, coarser-graded zones in a pavement tend to have lower density than nearby finer-graded zones.
- In addition to actual density differences, coarser-graded zones may have nuclear-measured density values even lower than actual density values due to surface voids and rough texture.

To test for the presence of segregation, statistical comparison tests are performed on a number of measured density values. The primary focus of the study, linear segregation, was investigated using grids of thirty-six (triplicate) samples arranged in a rectangular grid of six columns and six rows. A follow-on effort to test for any segregation pattern used two samples of four to ten values each. Seven field tests sites, with different degrees and patterns of segregation, were investigated.

To perform the statistical analyses and provide various visual displays of density differences, two spreadsheet templates, MBITSEG1.xls and MBITSEG2.xls were developed. These automate the statistical assessments, and require only that the user enter the data and be familiar with the general operation of Excel™ spreadsheet software in the Windows™ operating system. MBITSEG1.xls performs an analysis of variance (ANOVA) to test whether any significant differences occur among the six samples (columns) of six values each. Three different multiple comparison tests are also performed to assist locating the specific columns where the significant differences occur. MBITSEG2.xls performs a simple Student's-t test on two samples of three to ten values each , but provides the user with a variety of information in an easy-to-follow graphical format. User's guides were prepared for both spreadsheets.

To verify that the nuclear-measured density differences in fact correlate to segregation, cores were taken and gradation analyses performed. Statistical tests for significant gradation differences were also performed using MBITSEG1.xls.

Lab density measurements were made on the two pavement courses within the cores and an extensive set of statistical analyses were made to assess the interrelationships among lab and nuclear-measured density values, and gradation parameters. These included both regression analyses and statistical comparisons using MBITSEG1.xls. Finally, falling-weight deflectometer (FWD) measurements were made at two sites and analyzed using MBITSEG1.xls to determine if any relationships were evident between segregation and FWD deflection.

8.2 Conclusions

The primary conclusions from the study can be drawn from reviewing Tables 6.17 through 6.24 in Section 6.7, where MBITSEG1.xls results for nuclear-measured density, lab density, and gradation parameters are compared for each test site. These conclusions are:

1. ***Where linear segregation was identified*** (Sites 1 and 2), or where grid columns were aligned to coincide with observed segregated and unsegregated zones (Sites 3 and 6), ***the statistical analyses showed highly significant differences in one-minute nuclear density values***, with p-values varying in the range 10^{-3} to 10^{-11}. The p-value is the probability that the observed differences would occur by chance, for example if two sets of six values were randomly drawn from a large set of normally-distributed values. Although the significance level in MBITSEG1.xls was set at 95 percent ($p < 0.05$) for all studies in the project, the resulting p-values for areas pre-identified as having segregated zones were generally much lower.

2. ***At two of the four sites noted above*** (Sites 1 and 6), ***significant differences in gradation were also found.*** At a third site (Site 3) significant differences would be concluded if the significance level were lowered from 95 percent to 92 percent.

3. ***At two sites*** (Sites 4 and 7) ***where segregation was not considered to be excessive, significant linear segregation was nevertheless found***, with p-values for nuclear density differences in the range 10^{-3} to 10^{-8}. Some segregation was, however, noted by the research team at these sites. ***At Site 4, the segregation was confirmed by highly significant differences in gradation parameters.*** At Site 7, no cores were taken and no gradation parameters could be analyzed.

4. Based on conclusions 1 through 3, it can be concluded that ***highly significant differences in nuclear-measured density are indicators of likely-significant differences in gradation, i.e. segregation.*** Site 2 is an exception, and gradation differences were not found significant. In general, but not in all cases (Site 6 is an exception), the p-value was higher (significance lower) for gradation differences than for nuclear-measured density differences.

5. At one site (Site 5) extensive segregation was observed, but the statistical analyses did not reveal any significant columnwise differences in density or gradation. However, nuclear-measured density values at this site were exceptionally and unreasonably low and uncorrelated to lab values. This confirmed the observation that ***surface roughness lowers the nuclear-measured density value***, and suggested ***that extremely low nuclear-measured density values might also be taken as indicators of segregation.***

6. ***Reanalysis of the data from Site 5 indicated that highly significant differences in gradation parameters were found when row-wise comparisons were made, supporting the visual observation of segregation.*** A similar conclusion could not be made for the nuclear density values as the magnitude of the low values overshadowed any differences in the values.

7. ***Analyses of FWD data and its correlation with segregation were inconclusive for the*** *limited data sets considered.*

Some additional conclusions follow from the above and from general trends noted in pursuing the research:

8. Comparison of one-minute and four-minute nuclear density measurements did not show good statistical correlation, but the two approaches led to consistent trends and conclusions when used in the developed procedures (MBITSEG1.xls) to assess segregation. Hence, ***one-minute readings are considered adequate for assessing segregation..***

9. Regression lines fit to relate nuclear and lab-measured density values do not have zero intercepts and slopes near 1.0 as would be expected, but rather have significant intercepts and slopes much different than 1.0. ***A two pound per cubic foot difference in nuclear density may correspond to only about one pound per cubic foot difference in lab density.*** Part of this difference may be attributable to surface roughness effects in segregated areas.

10. Nuclear-density values at segregated sites tended to have larger overall coefficients of gradation than unsegregated sites, and suggest that ***overall variability might provide still another criteria for assessing segregation***, especially for areas with random segregation.

11. ***Statistically significant differences in gradation may not correspond to large-magnitude differences in per finer than a given sieve size.*** Many of the statistically significant differences were on the order of 5 to 8 percent difference in percent passing a given sieve. However, the statistical differences reflect consistency in gradation within a segregated zone and non-consistency in gradation from one zone to another. For example in a segregated area, one region may have 45 percent passing the No. 4 sieve and another may have 51 percent passing the No. 4; but six samples in the former will all have values statistically "close" to 45 percent and six in the latter will have values statistically close to 51 percent.

12. The conclusion above has important implications to construction practice and quality control: ***Materials in segregated areas may be relatively close in gradation and meet all applicable gradation specifications, but segregation may produce two zones of consistently graded materials that are perhaps 5 to 8 percent different in fines content from one to the***

other. To reduce segregation, specifications will need to limit such differences within the paved width, or limit deviations from a target gradation, regardless of the overall acceptability of the gradation.

13. As the p-values for nuclear density comparisons at segregated sites were extremely low, and those for gradation parameters were low but generally not as low as for nuclear density, ***the significance criterion used in this study (95 percent, $p < 0.05$) should be set much more restrictive, perhaps at 99.9 percent ($p < 0.001$) for nuclear density values.*** This will ensure that segregated areas, as determined by nuclear testing, will have a high likelihood of accurately predicting segregated areas, and minimize the occurrence of "false positive" errors. This will, however, increase "false negative" errors where segregation is not detected.

Finally, these lead to three summary conclusions:

I. ***Statistical differences in nuclear-measured density values are promising as an expdient indicator of segregation*** and correlate with statistically significant gradation differences. This occurs because voids due to separation of coarse and fine materials in asphalt mixtures and surface roughness are taken into account. In fact, nuclear density readings may have an amplifying effect on measured density differences.

II. ***The spreadsheets MBITSEG1.xls and MBITSEG2.xls can provide a user-friendly means to efficiently perform the required analyses*** by an engineer or technician with a basic familiarity with spreadsheet software and some elementary training in statistics.

III. Due to the limited number of sites invesigated, and the variety of conditions encountered at those sites, ***additional studies should be performed before finalizing and implementing specifications and payment provisions related to segregation.*** These include beta-testing by MDOT personnel at actual sites, identification and evaluation of additional sites by MSU PRCE personnel, and further methodology and program refinements, especially directed at random segregation.

8.3 Recommendations

Based on the results and conclusions of the research, three primary recommendations are made:

1. As described in Chapter 7, ***MDOT should begin implementation of a pilot project to phase in quality control procedures for segregation***, by systematically gathering data on new pavements using the developed procedures and software. Initially, this data should be gathered for information purposes, until such time sufficient data are acquired and sufficient confidence is developed with the procedures to implement segregation-related specifications.

2. In conjunction with the recommended pilot program, ***additional research should be performed to further calibrate the developed methodology and software*** to determine the appropriate magnitudes of statistical measures (e.g. p-values and coefficients of variation) that correspond to unaccepatable degrees of segregation that will impact pavement performance. Although the present study showed that segregation can be detected by density

statistics, the variety of conditions encountered over the relatively small number of sites precluded led to a database of insufficient size to set specification criteria with confidence.

3. ***New project specifications and payment provisions should be developed to control segregation.*** These will need to be written in the context of significant variations in gradation and density within rather short distances and localized areas, as opposed to the current specifications which are written in the context of average values of samples representing the average condition of large areas of pavement. Suggested preliminary wording was provided in Chapter 7; however, the quantitative criteria in those specifications should be set based on the further studies described in recommendation 2.

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Test Method to Determine the Existence of Segregation in Bituminous Mixtures

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Appendix A

User's Manual for Program MBITSEG1.xls

A.1. Introduction

This appendix provides an overview of MBITSEG1.xls, an Excel™-based spreadsheet template developed to evaluate the presence of linear segregation in hot-mix asphalt pavement. When the user input data from measured properties of pavement materials (e.g. nuclear-measured density) arranged in a 6 by 6 grid format, the spreadsheet performs a set of statistical tests to evaluate whether there are statistically significant differences in average values from one column to another.

In research studies at Michigan State University, statistically significant differences in nuclear-measured unit weight were found to have some correlation with difference in aggregate gradation indicative of segregation.

In addition to performing statistical tests, the spreadsheet displays three-dimensional graphs to assist visualizing the variation of material properties across the grid and confirm whether the input data are correct. These plots, especially when they show columnar trends or low unit weight or density values, may also be useful to assess the presence of a pattern of segregation in the tested pavement section.

By using a spreadsheet-based approach, it is not necessary for the user to learn any program-specific details regarding file operations, printing, etc., as these are common to all Excel applications. Rather, the user need be concerned with the engineering details of how the input data and results are processed and displayed.

A.2. Linear Segregation

The Michigan Department of Transportation (MDOT) defines segregation as:

> *Areas of non-uniform distribution of coarse and fine aggregate particles in a bituminous pavement that are visually identifiable or can be determined by other methods.*

More detail regarding segregation and its effects can be found in the main report. Linear segregation, which the spreadsheet MBITSEG1.xls was developed to detect, is characterized by coarse or rough-appearing "stripes" running in the longitudinal direction, parallel to the direction of paver travel. It can be categorized into three types, which may present in combinations.

- Systematic both-sides segregation
- Systematic one-side segregation
- Center Line segregation

Such segregated areas often exhibit significantly low density values when measured with a nuclear device. This may occur for two reasons:

- The field density values are in fact lower in the segregated area
- Near-surface voids in segregated areas may cause the nuclear device to read even lower than the actual density

A.3. Field Sampling

Where a significant degree of linear segregation is present, nuclear-measured density values in the segregated area may be expected to be significantly lower than in adjacent, unsegregated areas. To check for such differences, thirty-six values are measured over a six-by-six sampling grid. The configuration of the field sampling grid is shown in Figure A.1. Six columns are laid out in the direction of paver travel, and six rows are laid out across the width of the paved lane. The distance between each row or each column need not necessarily be the same, or be any fixed dimension. Columns should be aligned to follow areas appearing to have similar degrees of segregation or absence of segregation; rows should be generally be spaced to uniformly cover the length of pavement for which a segregation evaluating is to be made. No specific length of pavement need be covered in the distance between Row 1 and 6; the total length of the grid should be at least as long as the length of pavement for which a segregated area would be of concern, and also sufficiently short that the six rows are taken within a length of pavement for which other variables (other changes in the paving operation) would not influence results. A recommended range for total length is 15 ft (3 ft between rows) to 50 feet (10 ft between rows). The typical width of the grid would be 10 ft (2 ft between columns) to 12 feet (1.2 ft between columns).

Measurement locations are referred to by a two-digit scheme, rc, where r is the row number and c is the column number. For example, measurement 42 would be located at the intersection of row 4 and column 2.

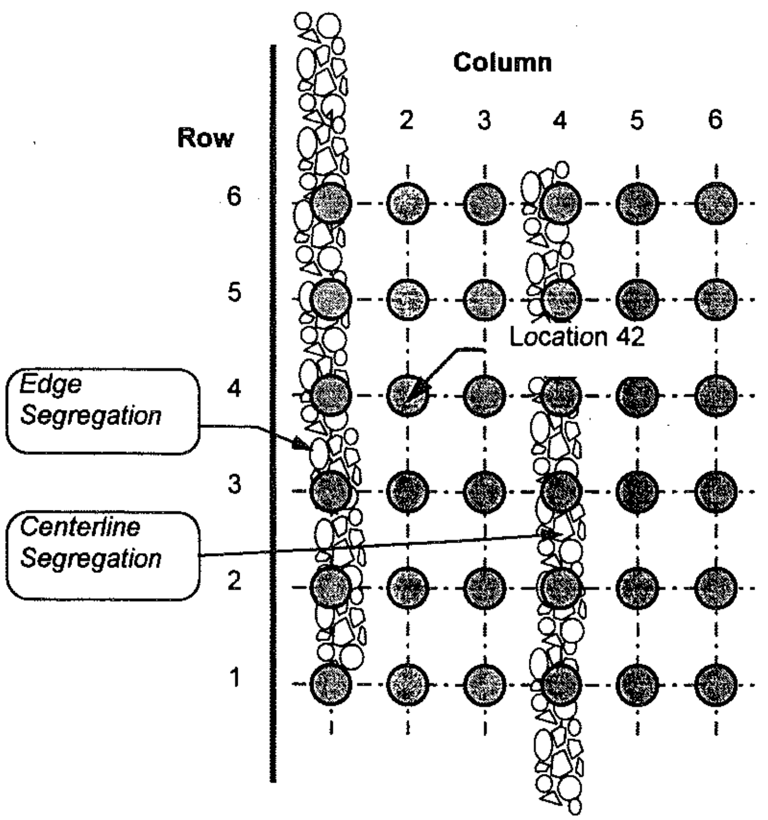


Figure A.1 Sampling Grid

A.4 Starting MBITSEG1.xls

A.4.1 System Requirements

System requirements for running MBITSEG1.xls are as follows:

- Windows™ version 3.1 or higher, or Windows 95™
- Excel™ version 5 or higher

Prior to using MBITSEG1.xls, the file should be copies from the diskette to a new directory (e.g. **c:\mbitseg**) on the hard drive.

A.4.2 Opening Excel

MBITSEG1.xls is a spreadsheet template developed to run in the spreadsheet program Excel ™. Before MBITSEG1.xls can be loaded, Excel must be open. Excel can be opened in several ways. To open Excel with a blank spreadsheet, follow these steps:

Windows 3.1

- If Windows is not running, start Windows 3.1 from the DOS prompt by typing **win** and pressing Enter.
- Select the group window that contains Excel. Usually the Excel icon is in the Microsoft Office group window. Then, by clicking this group window, the Excel application icon is available.
- Start Excel by double-clicking the Excel application icon.

Windows 95

- Windows 95 automatically starts if computer is on.
- Click on the **Start** Button and move the mouse pointer to the item labeled **Programs**.
- Find **Excel** through **Programs** submenu.
- Click on **Excel**. If a shortcut to Excel is already on desktop, just double-click the shortcut to access Excel.

A.4.3 Starting MBITSEG1.xls from Excel

To open the MBITSEG1.xls once Excel has been opened:

1. Click the **File, Open** command and the **Open** dialog box will appear.
2. Select (double-click) the directory where MBITSEG1.xls resides (e.g., **c:\mbitseg**)
3. Select (click) MBITSEG1.xls
4. Choose **OK** in Windows 3.1 or **Open** in Windows 95

A.4.4. Opening Excel and MBITSEG1.xls Concurrently

The file MBITSEG1.xls may be accessed directly, and will open Excel in the process.

Windows 3.1

- Open File Manager and set it to occupy part of the screen with Program Manager showing on the other part.
- Drag the File Manager listing of MBITSEG1.xls onto an open group window in Program manager; an icon will appear labeled MBITSEG1.xls.
- From now on, double-clicking on this icon will open the program.

Windows 95

- Open Windows Explorer, locate MBITSEG1.xls and right-click on it.
- Select **Create Shortcut**. A shortcut icon will appear in the directory list.
- Drag this icon to the desktop.
- From now on, double-clicking on this icon will open the program.

A.4.5 Setting the Display

The worksheet screen in MBITSEG1.xls were designed to fill a 480×600 pixel video display; however, there may be some variations in display for different graphic configurations (such as whether the Windows 95 Task Bar is being displayed). To fit the worksheets of MBITSEG1.xls to the screen, Excel's **View, Zoom** command can be used. This command magnifies or reduces the amount of worksheet on screen. 100 percent is the default setting. A custom zoom from 10 percent to 400 percent is available from the Zoom dialog box. Another way to change displays is to select the range and choose the **Fit Selection** option in the Zoom dialog box; the selected range will expand or contract to fit within Excel's boundary. Once a display size has been found that is preferred for a specific computer and graphic display settings, the user may perform a **File, Save** operation to permanently save the settings.

A.5 Data Entry Sheet

MBITSEG1 is arranged as a series of *worksheets* or simply *sheets*, each with its own function to enter data, display results, or perform statistical tests. The sheets of interest to users in road construction are described in the following paragraphs. Additional information and details regarding the remaining sheets and their underlying statistical theory are described in the main report.

MBITSEG1 has 11 tabs at the bottom of the screen, each representing a worksheet. When loaded, MBITSEG1 opens in the *Data Entry sheet*, show in Figure A.2. This spreadsheet includes the following features:

- An *identification block* near the top left, wherein one can enter Location, Date, (Job Number, Control Block ?) and other Descriptive Information.

- A *data entry block* in the left center, consisting of a six by six matrix corresponding to the six by six test grid

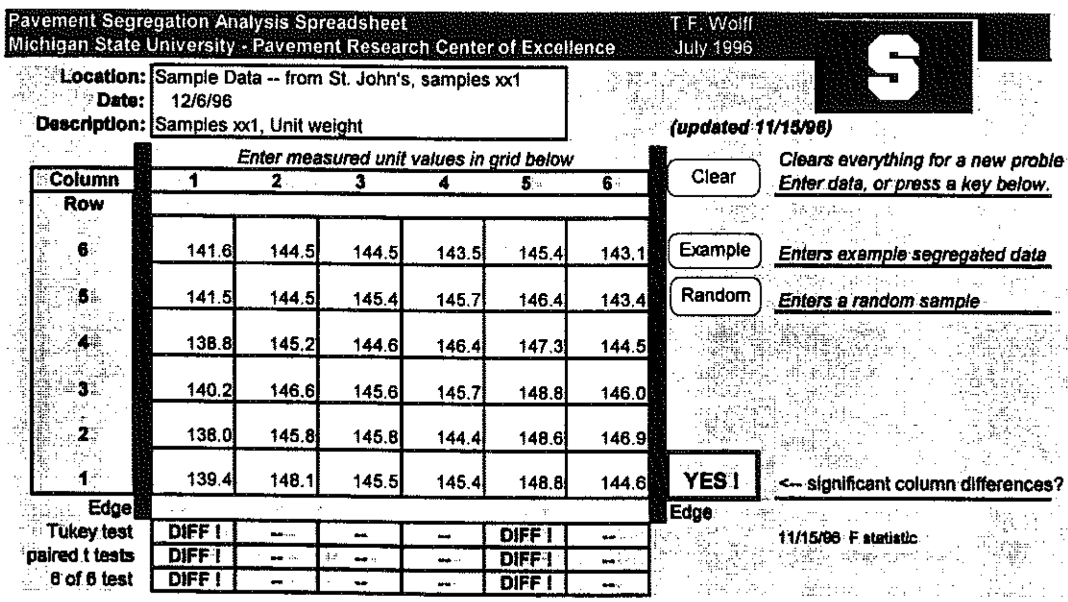
- Some *user buttons*, to the right of the data entry block

- Displayed *results*, below and to the right of the data entry block.

The identification block and data entry block on the data entry sheet are the only areas where users can enter data. The remainder of the data entry sheet and the remaining worksheets are write-protected to prevent unintentional corruption of the formulas and other content.

Identification Block. In the identification block the user may enter information regarding the location where the data were obtained, (... the Job No. and control section...) the date, and other descriptive information. No calculations or database operations are performed from this data, it is strictly for identification. It is, however, automatically copied to the other worksheets.

Data Entry Block. In the data entry block, the user enters 36 data values on which columnwise statistical analyses are to be performed. For field use in evaluating linear segregation, these would normally be nuclear density values obtained at the grid locations previously described. However, they may be any quantitative data upon which it is desired to perform columnwise comparisons. These data are used by the other worksheets in performing graphing and statistical tests.


Pavement Segregation Analysis Spreadsheet
Michigan State University - Pavement Research Center of Excellence
T.F. Wolff
July 1996
Location: Sample Data -- from St. John's, samples xx1
Date: 12/6/96
Description: Samples xx1, Unit weight
(updated 11/15/96)
Enter measured unit values in grid below

Column / Row	1	2	3	4	5	6
6	141.6	144.5	144.5	143.5	145.4	143.1
5	141.5	144.5	145.4	145.7	146.4	143.4
4	138.8	145.2	144.6	146.4	147.3	144.5
3	140.2	146.6	145.6	145.7	148.8	146.0
2	138.0	145.8	145.8	144.4	148.6	146.9
1	139.4	148.1	145.5	145.4	148.8	144.6
Edge						
Tukey test	DIFF !	--	--	--	DIFF !	--
paired t tests	DIFF !	--	--	--	DIFF !	--
6 of 6 test	DIFF !	--	--	--	DIFF !	--

Clear — Clears everything for a new proble
Enter data, or press a key below.
Example — Enters example segregated data
Random — Enters a random sample
YES ! <-- significant column differences?
Edge
11/15/96 F statistic

Figure A.2 Data Entry Sheet

User Buttons. To the right of the data entry block are three user buttons:

Clear Clicking on this button clears the data entry block for a new problem.

Example. Clicking this button automatically fills the data entry block with example data from a segregated site to illustrate operation of the program.

Random. Clicking this button fills the data entry block with a set of randomly generated nuclear density values. As these are random, they will usually not exhibit columnwise differences (indicating linear segregation) but occasionally will.

The latter two buttons are provided for training purposes, to easily get data onto the worksheet and demonstrate the program features.

Displayed Results. As data are input, statistical analyses are performed automatically on other sheets and results are reported back to the data entry sheet. Once all identification data and 36 numeric values have been entered, the user may view the results. An analysis of variance (ANOVA) is performed first, as described in section 5.3.6 of the main report. The analysis of variance tests to see if any statistically significant columnwise differences are present in the data, and the final result is shown in the boxed cell to the right of row 1. A displayed **YES!** indicates there are statistically significant differences among mean values of columns and **NO!** indicates there are not.

If the box displays a **YES!**, it remains to be determined which columns are different from which. A set of statistical tests, namely the Tukey multiple comparison test, the Student t test, and the 'six-of-six" test are performed comparing each column to each other, a set of fifteen possible comparions. The details of these tests are described in Sections 5.3.7 through 5.3.9 of the main report. The tests are performed on separate worksheets and automatically reported back to the data entry sheet. If the statistics for any column are found to be statistically different from those of at least three other columns, the notation **DIFF!** is displayed below the data for that column. For the example data shown in Figure A.2, columns 1 and 5 are each found to be significantly different, and all three statistical tests yield the same conclusion.

It should be noted that the display of **DIFF!** in a column does not always indicate that that particular column is segregated, but only that it is significantly different in mean value from at least three other columns. Hence, there could be segregation with accompanying low density values in three or more columns, and the display of **DIFF!** may appear in the "unsegregated," denser column, as the segregated columns are similar in density and exhibit no significant difference.

Furthermore, the three statistical tests may not always lead to the same conclusion. In general, the Tukey multiple comparison test is "stricter" than the t-test. The more tests that indicate a statistically significant difference, the stronger the conclusion may be drawn regarding segregation.

If the analysis of variance display box displays **NO**, the overall differences among column means are insufficient to suggest significant differences, and displayed **DIFF !** should generally be ignored.

A.6 Saving and Printing Results

Saving. Once all data have been entered, the user may save the results using any valid file name, by clicking the **File, Save As** menu item in Excel, and specifying the file name. In Excel 5 running under Windows 3.1, this must be in the conventional "8.3" name.ext format. If the user is running a Windows 95 version of Excel, long file names are permitted. File names should be selected that will provide one to easily locate any data set of interest.

Caution: The user should always specify a new file name using the File, Save As option. Saving with File, Save will overwrite the previous data. It is suggested that the a backup copy of MBITSEG1.xls be made named MBITSEG1.bak and stored in the same directory in the event that the original program file ever becomes corrupted.

Printing. Any of the sheets in MBITSEG1.xls can be printed by selecting that sheet using the tabs at the bottom of the display, and clicking on **File, Print** from the menu display. **The File, Print Preview** command followed by a click on the **Setup** button will permit the user to set margins, scale the printout to the page, and otherwise control how the sheets are printed.

The user is referred to Excel manuals and program help screens for additional details regarding file operations and printing.

A.7 Unit Weight Statistics Sheet

The second tab in MBITSEG1.xls is named "unit weight statistics." It is shown in Figure A.3. Basic statistics calculated include average (or mean) value, standard deviation and coefficient of variation of the entire set of 36 input values as well for the six values in each column and row.

User-input data from the data entry sheet is automatically copied to the parameter statistics sheet. Remaining features are described below.

Average Values. The *average value* is a measure of central tendency. Average values of row and column data are displayed to the right of and below row and column data, respectively. The average value of the data in column j is calculated as:

$$\bar{x}_j = \frac{x_1 + x_2 + \ldots + x_6}{6} \qquad (A.1)$$

With the example data shown in Figure A.3, it can be noted that the average unit weight measured in column 1 (139.92 lb/ft^3) appears significantly lower than the average unit weights of other columns, suggesting segregation may be present. Similarly, the average unit weight of column 5 is somewhat high. The statistical significance of such low or high averages is further tested by the other statistical tests previously mentioned.

Pavement Segregation Analysis Spreadsheet T. F. Wolff June 1996
Michigan State University - Pavement Research Center of Excellence

Location: *Sample Data -- from St. John's, samples xx1*
Date: *12/6/96*
Description: *Samples xx1, Unit weight*

Color 1 — *Color Above and Below Average*
Clear Color

Column	1	2	3	4	5	6		Average	Standard Deviation	Coeff of Variation
Row										
6	141.6	144.5	144.5	143.5	145.4	143.1		143.77	1.338	0.93%
5	141.5	144.5	145.4	145.7	146.4	143.4		144.48	1.793	1.24%
4	138.8	145.2	144.6	146.4	147.3	144.5		144.47	2.981	2.06%
3	140.2	146.6	145.6	145.7	148.8	146.0		145.48	2.846	1.96%
2	138.0	145.8	145.8	144.4	148.6	146.9		144.92	3.665	2.53%
1	139.4	148.1	145.5	145.4	148.8	144.6		145.30	3.330	2.29%
Average	139.92	145.78	145.23	145.18	147.55	144.75	144.74	**144.74**	2.659	1.84%
Std. Dev.	1.457	1.391	0.547	1.050	1.431	1.471	1.224		**2.64285**	
Coeff. of Var.	1.04%	0.95%	0.38%	0.72%	0.97%	1.02%	0.85%			**1.83%**

Figure A.3 Unit Weight Statistics Data Sheet

Standard Deviations. The *standard deviation* is a statistical measure of the dispersion of the data about the mean. The standard deviation of the population of all possible values in row or column j is estimated from the measured values as:

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)^2}{n-1}} \qquad \text{(A.2)}$$

where n = 6.

Standard deviations of row and column data are displayed to the right of an below the respective average values.

The standard deviation of each column or row is a measure of the variability in sets of six data values; higher values indicate greater variability. In an unsegregated pavement, density values would be expected to vary randomly. In a linearly-segregated pavement, columns would tend to have consistently low, intermediate, or high density values, with little variation in value within a column, and rows would tend to have greater variability as they are mixes of density values from different regions of the segregated pavement. In the example in Figure A.3, it can be seen that the row data has notably larger standard deviations than the column data, suggesting linear segregation.

Coefficients of Variation. The *coefficient of variation* is the ratio of the standard deviation to the average or mean:

$$V_{x(j)} = \frac{\sigma_j}{\bar{x}_j} \tag{A.3}$$

The coefficient of variation provides a convenient dimensionless measure of variability. Values are reported to the right of and below the respective standard deviation values.

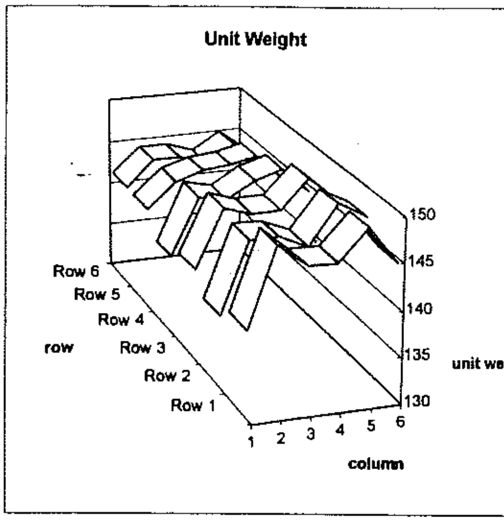
For the example segregated data, it can be noted that row values are generally larger than column values, providing a similar indication of linear segregation as that for standard deviation values.

Global Statistics. A similar procedure is used to find the global average, standard deviation and coefficient of variation of the entire set of 36 data vales. These are reported in boldface in the lower right portion of the sheet, at the intersection of the row and column values.

User Buttons for Color-Coding Data. The statistics sheet contains two user buttons to the right of the identification block. Clicking on the button marked **Color 1** colors cells with values below the average in yellow and those with values above the average in blue. This also provides a visual indication of correlated patterns of high or low density. Clicking on the button marked **Clear Color** erases the coloring and provides a clear background.

A.8 Unit Weight Graphs Sheet

The third tab on MBITSEG1.XLS is titled "unit wt graph." Clicking on it opens a worksheet that provides two three-dimensional graphs of the data entered on the data entry worksheet, usually unit weight (density) data. Figure A.4 shows these graphs representing the data in the previous two figures. These two charts are identical in content, and differ only in the chart type, with one representing the data as row-wise ribbons and the other as a connected surface. Such charts, which are similar to topographical maps, permit a visualization of the degree of correlation of low or high density values within a sampled column at a suspected segregated site. For the segregated site shown, the previously indicated statistical differences in average column unit weight in columns one and five are notably apparent. Rather than observing values above and below the average randomly throughout the test grid, the values within each column are highly correlated with each other, but exhibit little correlation to values within other columns. This strongly suggests that the differences in unit weight are related to some aspect of the paving operation, such as the paver placing a material with different characteristics (e.g., gradation or quantity per area) near the edge of the paved lane (columns 1and 6) than at the next adjacent sample point along the auger (columns 2 and 5).



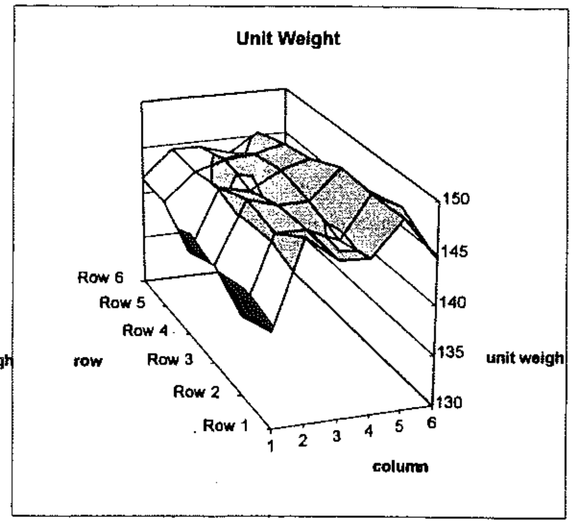


Figure A.4 Unit Weight Graphs

A.9 Standardized Statistics Sheet

Clicking on the fourth tab in MBITSEG1.XLS, titled "Std Data," opens the standardized statistics sheet shown in Figure A.5. This sheet provides an alternative representation of the parameter statistics sheet where all values are transformed to *standardized values*, dimensionless quantities in a format commonly used in statistical analysis.

It is sometimes helpful to examine the distribution of observations in a data set relative to their mean value and standard deviation rather than their absolute values. For example, it permits easy identification of "outliers," values that are unusually far above or below the mean. Standardized values, denoted by the variable *z*, simply measure the distance that a data value x_i, lies from the mean $\overline{x}$ in units of the standard deviation σ_x. Standardized values are calculated as :

$$z_i = \frac{x_i - \overline{x}}{\sigma_x} \qquad \text{(A.4)}$$

where z_i is the standardized value
x_i is the data value
$\overline{x}$ is the mean (of all 36 data points in this case)
σ_x is the standard deviation (of the 36 data points)

For such standardized data, the global mean will be 0.00 and the global standard deviation will be 1.00. The standardized value z_i is a dimensionless quantity as the numerator and denominator are in the same units of measure. Hence, a value of -2.02 indicates that the associated data value is 2.02 standard deviations below the mean value.

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Location: *Sample Data – from St. John's, samples xx1*
Date: *12/6/96*
Description: *Samples xx1, Unit weight*

Color 1 — *Color Above and Below Average*
Clear Color

Standardized Values

Column / Row	1	2	3	4	5	6		Average	Standard Deviation
6	-1.19	-0.09	-0.09	-0.47	0.25	-0.62		-0.37	0.506
5	-1.22	-0.09	0.25	0.36	0.63	-0.51		-0.10	0.678
4	-2.25	0.18	-0.05	0.63	0.97	-0.09		-0.10	1.128
3	-1.72	0.71	0.33	0.36	1.54	0.48		0.28	1.077
2	-2.55	0.40	0.40	-0.13	1.46	0.82		0.07	1.387
1	-2.02	1.27	0.29	0.25	1.54	-0.05		0.21	1.260
Average	-1.82	0.40	0.19	0.17	1.06	0.01	0.00	**0.00**	1.006
Std. Dev.	0.551	0.526	0.207	0.397	0.541	0.556	0.463		**1.00**

Figure A.5 Standardized Statistics Sheet

The data displayed in Figure A.5 is again that from the example segregated site shown in the preceding figures. In column one, it can be observed that all values are below average, as the signs are all negative, and further that all values are more than one standard deviation below the average. If the density variations were all merely random as opposed to being related to segregation, it would be expected that about half would be above the average and half would be below, with more values near zero. The average values for columns one and five are -1.82 and 1.06, respectively. This also implies segregation, as average z values within columns for a uniformly variable in-place property should generally be much closer to 0.0, as are the remaining columns and the row values.

A.10 Standardized Graphs Sheet

Clicking on the fifth tab in MBITSEG1.XLS, titled "Std Graph" opens the standardized statistics sheet shown in Figure A.6. These are similar to the unit weight parameter graphs previously described, but are based on the standardized data on the previous sheet. As the global mean of any standardized data set is 0.00, it can be easily visualized where column values are consistently and substantially above or below the mean value. In Figure A.6, the significant characteristics of columns 1 and 5 can again be readily observed.

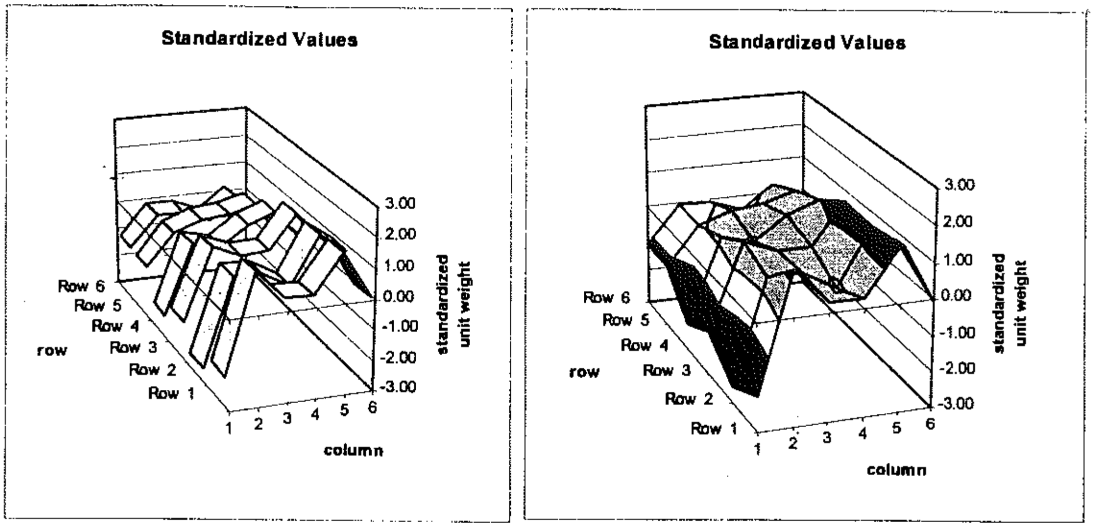

Figure A.6 Standardized Graphs

The standardized graphs included in the "Std Graph" sheet may provide a better visualization of the variation of data from the sample grid. Since the global mean is 0.00, it can be found that surface plot is surrounding with the surface of mean equal to zero, see Figure 6. It can again be observed that column 1 is relatively low and column 5 is high.

A.11 Remaining Sheets

The remaining sheets are used to perform the statistical tests and obtain the results displayed on the data entry sheet. They are described in detail in Chapter 5 of the main report.

Test Method to Determine the Existence of Segregation in Bituminous Mixtures

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PRCE

Michigan State University
Pavement Research Center of Excellence

Appendix B

User's Manual for Program MBITSEG2.xls

B.1. Introduction

This appendix provides an overview of MBITSEG2.xls, an Excel™-based spreadsheet template developed to evaluate the presence of segregation in hot-mix asphalt pavement. When a highway engineer wishes to assess density differences in two pavement areas, one with apparent segregation and one taken as a control area, he or she may enter up to ten nuclear-measured density values from each, and MBITSEG2.xls will perform a t-test to assess whether the differences in the mean or average values of the two data sets are greater than would be expected from normal, random variation.

In addition to performing statistical tests, the spreadsheet displays graphs of fitted normal distributions to the two samples to assist visualizing the variation of material properties.

A third feature of the program is the capability to enter a theoretical maximum density (TMD) value for the paving mixture and a minimum percent of TMD that is contractually acceptable. The program then calculates the minimum acceptable density and displays it on the graph with the distributions to provide a visual comparison of the data and the density requirement.

By using a spreadsheet-based approach, it is not necessary for the user to learn any program-specific details regarding file operations, printing, etc., as these are common to all Excel applications. Rather, the user need be concerned with the engineering details of how the input data and results are processed and displayed.

B.2. Segregation

The Michigan Department of Transportation (MDOT) defines segregation as:

> *Areas of non-uniform distribution of coarse and fine aggregate particles in a bituminous pavement that are visually identifiable or can be determined by other methods.*

More detail regarding segregation and its effects can be found in the main report. The companion spreadsheet, MBITSEG1.xls, was developed specifically to assess *linear* segregation, and contains a number of additional tests designed to detect statistical differences in samples from lines oriented parallel to a paving operation. Linear segregation is characterized by coarse or rough-appearing "stripes" running in the longitudinal direction, parallel to the direction of paver travel. It can be categorized into three types, which may present in combinations.

- Systematic both-sides segregation
- Systematic one-side segregation
- Center Line segregation

The term *random segregation* will be used to refer to any other segregation not occurring in a linear, longitudinal direction. Two common manifestations are

- an *irregular zone*, where a mass of previously segregated material is discharged into the paver hopper or cleaned from the hopper sides and subsequently placed, or

- an *angled or chevron shaped area*, where a smaller mass of previously segregated material is deposited in this shape by the combined outward movement of the auger and forward movement of the paver.

Segregated areas often exhibit significantly low density values when measured with a nuclear device. This may occur for two reasons:

- The field density values are in fact lower in the segregated area
- Near-surface voids in segregated areas may cause the nuclear device to read even lower than the actual density

B.3. Field Sampling

Where a significant degree of segregation is present, nuclear-measured density values in the segregated area may be expected to be significantly lower than those in adjacent, unsegregated areas. To check for such differences using MBITSEG2.xls, the field engineer should mark the outline of the apparently segregated area and similarly outline an adjacent control area of similar dimensions. Examples are shown in Figure B.1.

No specific area of need be tested; however it should be large enough that segregation over that large an area is of concern and large enough to obtain a reasonable number of samples. It should be small enough to be considered a contiguous segregated area.

The number of measurements in each sample is permitted to vary, and the number need not be equal for the two samples. The greater the number of samples, the narrower will be the confidence bands on the statistical tests, which will lead to a greater degree of certainty if indeed segregation is present. It is recommended that at least five values be obtained for each of the two samples.

B.4 Starting MBITSEG2.xls

B.4.1 System Requirements

System requirements for running MBITSEG1.xls are as follows:

- Windows™ version 3.1 or higher, or Windows 95™
- Excel™ version 5 or higher

Prior to using MBITSEG2.xls, the file should be copies from the diskette to a new directory (e.g. **c:\mbitseg**) on the hard drive.

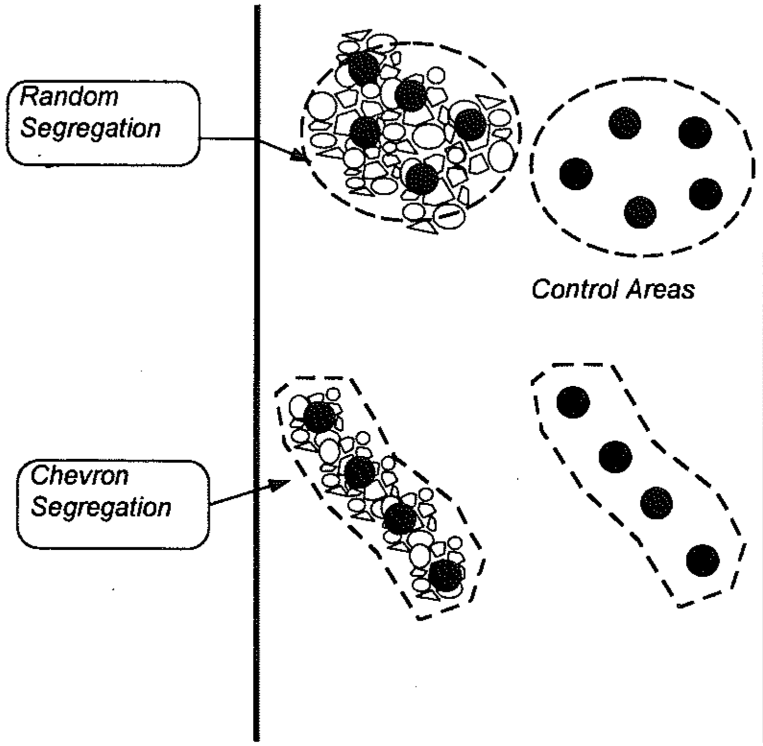


Figure B.1 Sampling Scheme

B.4.2 Opening Excel

MBITSEG2.xls is a spreadsheet template developed to run in the spreadsheet program Excel TM. Before MBITSEG2.xls can be loaded, Excel must be open. Excel can be opened in several ways. To open Excel with a blank spreadsheet, follow these steps:

Windows 3.1

- If Windows is not running, start Windows 3.1 from the DOS prompt by typing **win** and pressing Enter.
- Select the group window that contains Excel. Usually the Excel icon is in the Microsoft Office group window. Then, by clicking this group window, the Excel application icon is available.
- Start Excel by double-clicking the Excel application icon.

Windows 95

- Windows 95 automatically starts if computer is on.
- Click on the **Start** Button and move the mouse pointer to the item labeled **Programs.**
- Find **Excel** through **Programs** submenu.
- Click on **Excel.** If a shortcut to Excel is already on desktop, just double-click the shortcut to access Excel.

B.4.3 Starting MBITSEG2.xls from Excel

To open the MBITSEG2.xls once Excel has been opened:

1. Click the **File, Open** command and the **Open** dialog box will appear.
2. Select (double-click) the directory where MBITSEG2.xls resides (e.g., **c:\mbitseg)**
3. Select (click) MBITSEG2.xls
4. Choose **OK** in Windows 3.1 or **Open** in Windows 95

B.4.4. Opening Excel and MBITSEG2.xls Concurrently

The file MBITSEG2.xls may be accessed directly, and will open Excel in the process.

Windows 3.1

- Open File Manager and set it to occupy part of the screen with Program Manager showing on the other part.
- Drag the File Manager listing of MBITSEG2.xls onto an open group window in Program manager; an icon will appear labeled MBITSEG2.xls.
- From now on, double-clicking on this icon will open the program.

Windows 95

- Open Windows Explorer, locate MBITSEG2.xls and right-click on it.
- Select **Create Shortcut**. A shortcut icon will appear in the directory list.
- Drag this icon to the desktop.
- From now on, double-clicking on this icon will open the program.

B.4.5 Setting the Display

The worksheet screen in MBITSEG2.xls were designed to fill a 480×600 pixel video display; however, there may be some variations in display for different graphic configurations (such as whether the Windows 95 Task Bar is being displayed). To fit the worksheets of MBITSEG1.xls to the screen, Excel's **View, Zoom** command can be used. This command magnifies or reduces the amount of worksheet on screen. 100 percent is the default setting. A custom zoom from 10 percent to 400 percent is available from the Zoom dialog box. Another way to change displays is to select the range and choose the **Fit Selection** option in the Zoom dialog box; the selected range will expand or contract to fit within Excel's boundary. Once a display size has been found that is preferred for a specific computer and graphic display settings, the user may perform a **File, Save** operation to permanently save the settings.

B.5 MBITSEG2.xls Spreadsheets

The first sheet of MBITSEG2.XLS is shown in Figure B.2. It provides for both data entry and textual and graphic display of results. The second sheet of MBITSEG2.XLS provides a very brief overview of the program. It is shown in Figure B.3. Use of MBITSEG2.XLS is described below.

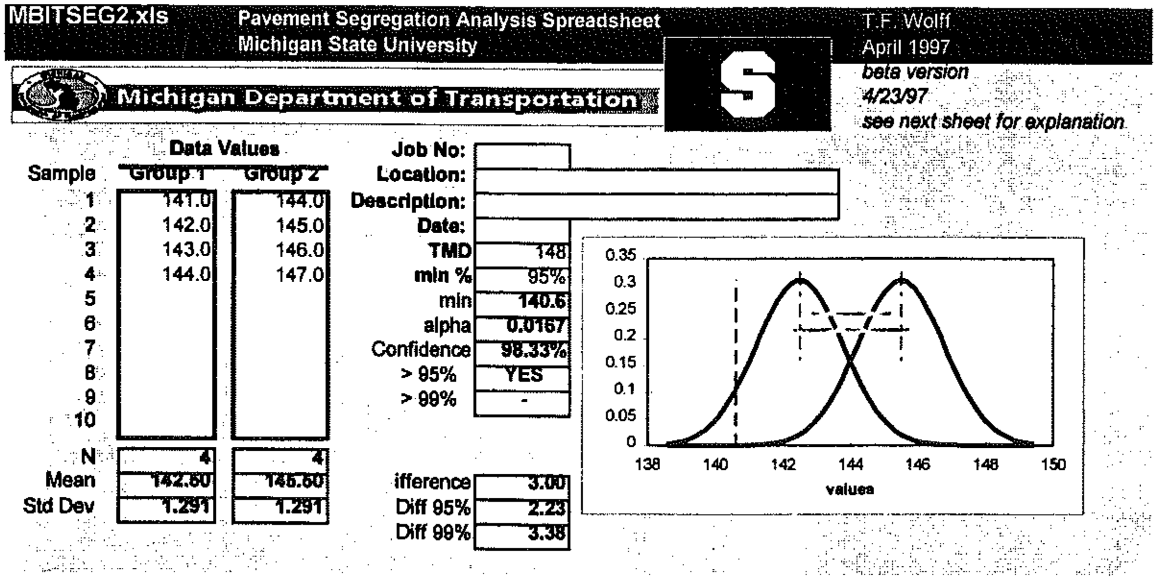


Figure B.2 First Sheet of Spreadsheet MBITSEG2.XLS

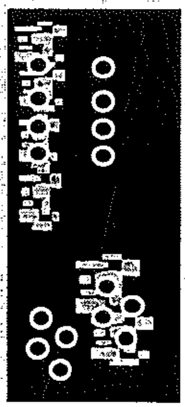
Identification Data Block. At the top center of the sheet are provided blank spaces where the user may enter descriptive information to identify the site tested and other information. These are labeled Job No., Location, Description, and Date. These are solely for identification and no calculations or database operations are performed on this data.

Data Entry Blocks. To the left of the sheet are two column blocks, labeled Group 1 and Group 2 in which the user may enter up to ten data values per group. The number of data values in each group need not be equal. Typically, these would be nuclear-measured density values; however, any numerical data may be entered. As data are entered, the number of samples, mean values and standard deviations for each group are automatically updated and displayed in the boxes below the data entry cells. Increasing the number of data values in a group tends to narrow the confidence bands on the mean value, increasing the ability to conclude whether significant differences in mean value exist.

The two sets of four data values shown in Figure B.2 were synthesized to illustrate the spreadsheet capabilities

MBITSEG2.xls | Pavement Segregation Analysis Spreadsheet
Michigan State University | T.F. Wolff
April 1997
beta version
4/23/97

Michigan Department of Transportation



This spreadsheet tests for segregation by performing a t-test on two groups of samples. Each group should have two to ten samples, with each sample represented by a value (typically a density)

If segregation is considered to be present based on visual evaluation, one group should represent an area considered to be segregated, and one should represent a "control" area, considered not to be segregated.

The spreadsheet compares the mean values of the groups, and estimates the difference in means that might be found due to random variation at 95% and 99% confidence levels.

A difference in means greater than the width of the confidence band suggests that the difference in means is greater than would be expected due to random variation alone.

Figure B.3 Second Sheet of Spreadsheet MBITSEG2.XLS

Control Density Block. The spreadsheet also permits the user to enter the theoretical maximum density (TMD) value for the asphalt mixture at the site and a minimum percentage of TMD (min %) which is considered acceptable. These are multiplied to obtain the minimum acceptable density, which is displayed in the block marked "min" and also displayed on the graphic display discussed below. In the example shown, 95 percent of TMD = 148 lb/ft^3 leads to a minimum acceptable density value of 140.6 lb/ft^3.

Statistical Results. Statistical comparisons are made using the t-test comparison of two means described in Section 5.3.7 of the main report and accomplished using built-in spreadsheet functions. Results of statistical calculations are displayed in the lower center portion of the sheet. The value of "alpha," shown as 0.0167, is the risk level associated with rejecting the null hypothesis of no difference in mean values. In other words, for the data shown, if one concluded that the two groups of data values came from populations with different mean values, there is a probability of 0.0167 (or about one in sixty) that such a conclusion is in error.

The "confidence" value, shown as 98.33%, is simply the complement of the alpha value.

Below the confidence value are two blocks labeled >95% and >99%, respectively. If the confidence value exceeds these values, **YES** is displayed in the adjacent cell.

The group of three blocks in the lower center of the sheet display the actual difference in mean values and the critical differences in mean values corresponding to the 95 and 99 percent confidence levels. In the example shown, the actual difference in mean values is 3.00 lb/ft^3. At the 95 percent confidence level, the critical difference is 2.23. Tthis means that, for identical populations with the same characteristics as those here, the difference in mean values for two random samples would be expected to differ by more than 2.23 lb/ft^3 only five percent of the time, and the risk associated with concluding a significant difference in these circumstances is five percent. Similarly, the critical difference in mean values at the 99 percent confidence level or one percent risk level is 3.38. Concluding that the actual difference of 3.00 lb/ft^3 is not significant carries a risk greater than 1 percent but less than 5 percent.

Graphic Display. On the right side of the spreadsheet is a graphic display with a variety of information. The two **bell-shaped curves** represent normal distributions fit to the means and standard deviations of the two samples; if the measured values were unbiased, random samples from normally distributed populations, these curves represent the relative frequency of measuring various values. It can be noted from relative location alone that there are significant differences; the central (maximum frequency) portion of each curve lies above a tail of the other. For samples from the same population, considerable overlap would be expected.

The **mean values** are represented by **vertical centerline markings** through the peak of each curve. The 95 and 99 percent **confidence bands for the mean values** are represented by the narrower and wider (respectively) **horizontal red shaded bands**. If both mean values cross both bands, no significant difference can be concluded. If the mean values cross one band but not the other, as is the case in the figure shown, the confidence level is between 95 and 99 percent. If both means lie outside both confidence bands, there is greater than 99 percent confidence, and it is highly probable that the differences are not random, but have an associated cause such as segregation.

The **vertical dashed line**, usually to the left of the normal curves, marks **the minimum acceptable density** calculated from the TMD and minimum acceptable percentages. If an area of either tail extends to the left of this line, it suggests that a portion (corresponding to the relative area) of the material likely may not meet minimum density requirements, suggesting further verification. Note that it does not prove this is the case as the plotted distributions are estimated from the data and extend beyond the actual data.

B.6 Saving and Printing Results

Saving. Once all data have been entered, the user may save the results using any valid file name, by clicking the **File, Save As** menu item in Excel, and specifying the file name. In Excel 5 running under Windows 3.1, this must be in the conventional "8.3" name.ext format. If the user is running a Windows 95 version of Excel, long file names are permitted. File names should be selected that will provide one to easily locate any data set of interest.

Caution: The user should always specify a new file name using the File, Save As option. Saving with File, Save will overwrite the previous data. It is suggested that the a backup copy of MBITSEG2.xls be made named MBITSEG2.bak and stored in the same directory in the event that the original program file ever becomes corrupted.

Printing. Either of the sheets in MBITSEG2.xls can be printed by selecting that sheet using the tabs at the bottom of the display, and clicking on **File, Print** from the menu display. **The File, Print Preview** command followed by a click on the **Setup** button will permit the user to set margins, scale the printout to the page, and otherwise control how the sheets are printed.

The user is referred to Excel manuals and program help screens for additional details regarding file operations and printing.