Michigan Department of Transportation

DETECTING AND QUANTIFYING SEGREGATION IN BITUMINOUS PAVEMENTS AND RELATING ITS EFFECT TO CONDITION

Final Report

Michigan State University
Pavement Research Center of Excellence
Department of Civil and Environmental Engineering
East Lansing, Michigan 48824-1226

TESTING AND RESEARCH SECTION
CONSTRUCTION AND TECHNOLOGY DIVISION
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Detecting and Quantifying Segregation in Bituminous Pavements and Relating Its Effect to Condition

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Abstract

This report describes a follow-up project to the previous project titled "Test Method to Determine the Existence of Segregation in Bituminous Mixtures". To better correlate nuclear-measured density with segregation, procedures were developed to incorporate mapping of apparently segregated areas and apparently non-segregated control areas. Statistical comparison tests were then performed on data from both segregated and non-segregated areas to assess whether there were significant differences in nuclear-measured density and gradation parameters.

It was found that statistically significant differences in nuclear density will usually be present where medium or heavy segregated areas are identified visually and these areas have aggregate gradation differences from non-segregated areas. The proposed criteria were the nuclear density differences with p-values less than 10^{-3}. The criteria were further verified by the gradation differences of p-values less than 10^{-2}. The conditional probability of finding medium or heavy segregation based on visual identification and nuclear density measurements is approximately 86%; the conditional probability of finding light through medium segregation drops to 63%.

The occurrence of segregation deteriorates pavements. Raveling and cracking were the most common distresses at segregation sites. Growth rate of distresses depends on the degree of segregation.

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

Conversion Factors

English	Metric
1 inch, in	25.44 mm = 2.544 cm = 0.0254 m
1 foot, ft	304.8 mm = 30.48 cm = 0.3048 m
1 yard, yd	914.4 mm = 91.44 cm = 0.9144 m
1 mile (U.S.)	1,609 m = 1.609 km
1 mil	0.0254 mm = 0.0000254 m = 25.4 micron
1 inch square, in^2	645.2 mm^2 = 6.45 cm^2 = 6.452 m^2
1 foot square, ft^2	0.0929 m^2 = 929.03 cm^2
1 yard square, yd^2	0.836 m^2 = 8361.3 cm^2
1 square mile (U.S.)	2.590 km^2
1 pound mass, lbm or lb	0.4536 kg
1 ton = 2000 lbm	907.2 kg
1 slug (1 lb-force/ft/s^2)	14.59 kg
1 pound-force, lbf	4.448 N
1 ton-force	8.896 x 10^3 N = 8.896 kN
1 pound per square inch, psi	6.895 kPa = 6.895 x 10^3 Pa
1 kip per square inch, ksi	6896 kPa = 6.895 x 10^6 Pa
1 pound-force/square foot, psf	47.88 Pa
1 pound-mass per cubic foot, pcf	16.018 kg/m^3
For asphalt overlays	
100 pounds per square yard ≅ 0.9 in	54.25 kg/m^2 ≅ 23.1 mm
170 pounds per square yard ≅ 1.5 in	92.22 kg/m^2 ≅ 39.2 mm

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EXECUTIVE SUMMARY

This project is the second phase of a segregation study, which started in 1995. Both phases have the objective of developing an expedient field test to verify and quantify segregation in hot-mix bituminous pavements. The problems related to segregation and the advantages of having a quantitative expedient field test, were presented and discussed in detail in the final report of the Phase I study. This report defines three degrees of segregation, light, medium and heavy. It is shown that nuclear density testing can form the basis of an expedient field quality-control test to verify and quantify the existence of medium and heavy degrees of segregation in hot-mix bituminous pavements. Statistical differences in nuclear density values are shown to be good predictor of actual aggregate gradation differences and are correlated to visual observations of medium and heavy degrees of segregation.

Nuclear density values may differ from the norm in segregated areas for two reasons:

- Coarse-graded zones in a pavement, consisting of materials that have been separated from their accompanying fines, tend to have lower actual densities than nearby finer-graded zones. In addition, nuclear density values obtained in these coarser-graded zones may be even lower by an additional increment due to the effects of surface voids and rough texture.
- Differences in compaction during construction are affected by the number of roller passes, by the compaction temperature and/or temperature segregation. After construction, the density of the asphalt mat may vary across the pavement due to the effect of traffic.

The primary focus of the earlier study was the detection of *linear segregation*– segregated areas aligned in the direction of the pavement and paver travel. To test for differences in nuclear density, measurements were made over a rectangular sampling grid of six rows by six columns. To perform the statistical analyses and provide visual displays of density variations, a spreadsheet template, mbitseg1.xls was developed. Mbitseg1.xls performs a variety of statistical multiple comparison tests. Nuclear density measurements were taken at seven field-test sites, 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 analyze lab density and gradation parameters.

As the first study progressed, other (e.g., random) segregation patterns were encountered. To accommodate more general segregation patterns a second spreadsheet, mbitseg2.xls, was developed. This spreadsheet performed a simple Student's-t test on two samples of three to ten values each, and provided the user with a variety of information in an easy-to-follow graphical format.

The first project concluded that ***statistical differences in nuclear-measured density values are promising as an expedient indicator of segregation*** and may correlate with statistically significant gradation differences. The basis of the methodology is that voids due to separation of coarse and fine materials in asphalt mixtures and surface roughness lead to different (generally lower) nuclear density values. However, a follow-up project was recommended before adopting any field test. The reasons for this follow-up study included the following:

1. The first project involved only seven sites, and proof testing of the procedure using "good," or non-segregated sites, had not been accomplished.

2. The emphasis of the first project on linear segregation and statistical analysis led to a "blind" approach, wherein it was hoped that quantitative measurements in fixed patterns alone could detect segregation without operator assistance. However, experience and discussions made it apparent that the varied nature of segregation patterns, gave more promise to a "confirmatory approach." In this approach, an area is selected as potentially segregated, and field tests were made to compare this area to a selected "control" area.

3. In addition to verifying the existence of segregation, the effects of segregation on pavement distress was studied by several periodic observations of the test sites.

The Phase II study involved 20 test sites. At each site, a joint MSU and MDOT team mapped pavement segregation in detail before data gathering. Before any field mapping, a training session was conducted among the field mapping team to ensure consistency of terminology. Two of the sites were selected as non-segregated "good" sites.

Once a consensus was reached on the presence, areas and degrees of segregation at the test sites, six to twelve sample locations were painted on the pavement. The locations were chosen to reflect consistent descriptions of light, medium or heavy segregation, as well as non-segregated "control" areas. Extensive nuclear density measurements were made at each site, and about half the locations were cored for laboratory tests. For the core samples, the surface course was sawed from the remainder and laboratory density and gradation tests were performed.

Extensive statistical analyses of nuclear density data, lab density data, gradation data and their relationship to visual mapping indicated the following:

1. ***Eighty-six percent of visually identified medium and heavy segregated areas exhibited nuclear density values significantly lower and aggregate gradations significantly coarser than nearby "control" areas.***

2. ***Differences in nuclear density values themselves, without significant consideration of other variables, do not necessarily predict the presence of segregation.*** Such differences are affected by compaction variables (roller, traffic, and discontinuities in the asphalt mat such as concrete curbs and/or joints). Significant nuclear density differences were measured at good (not segregated) pavement sites and even on a cold and uncompacted asphalt mat.

3. ***Statistical comparisons of nuclear density values provide good indication of segregation, when:***

    a. ***Areas of medium or heavy segregation are visually identified.***

    b. ***Areas of non-segregation are visually selected from the same truck load during construction and at the same distance from the pavement edge as the segregated area.***

The results of the study provided extensive and insightful information regarding density variations in pavements. Procedures were refined to correlate both visual observation and nuclear density measurements. As a result, the capability to predict the presence of segregation (actual gradation differences) is strengthened by use of the modified criteria which includes both the p-value from nuclear density comparisons and visual classification as medium or heavy.

It is proposed that nuclear density measurements, when used in conjunction with visual observations be used in a quality-control framework at the time of construction. A first-draft implementation specification is provided in Chapter 8 of the report. The spreadsheet mbitseg2.xls was converted to Quattro Pro format as mbitseg2.wb3 to facilitate the required statistical calculations in the field.

Another objective of the study was to relate the degree of segregation to pavement condition. Distress surveys were conducted periodically. Two types of segregation-related distress, raveling and cracking, were identified. The rate of deterioration was determined at those sites exhibiting distress. During the two-year study, it was found that heavy segregation causes a minimum of 50 percent reduction in the pavement service life.

CHAPTER 1
INTRODUCTION

1.0 BACKGROUND

The project described herein is a follow-up effort to a preceding MDOT–MSU PRCE study, *Test Method to Determine the Existence of Segregation in Bituminous Mixtures* reported by Wolff, Baladi and Chang (1997). Both the previous and current studies focus on the application of nuclear density measurements and statistical comparison tests to verify segregation for construction quality control purposes. In addition, the current study investigates the relationships among segregation, its severity, and pavement distress.

Segregation refers to the uneven distribution of coarse and fine particles from one point to another in a bituminous mix, due to some deficiency in the mixing, transportation, or placement operations.

For the purposes of the prior and present study, a working definition of segregation was furnished by MDOT:

> *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 is a matter of potential dispute between construction contractors and highway agencies as its presence and severity is a matter of visual observation and judgment. Although specifications require asphalt mixes not to be segregated, no quantitative measures or tests for segregation are defined. Furthermore, assessing segregation by comparative gradation tests on aggregate extracted from cores would incur extensive time delays to adjust the paving operation to remedy the problem.

Where segregation is present, pavement performance can be impaired due to the relatively greater amount of voids and related potential for moisture absorption. Therefore, some types of pavement distress can be expected, including raveling, stripping, cracking and rutting.

For these reasons, MDOT desired a timely and accurate test to quantitatively determine the presence of segregation during the paving process.

2.0 SEGREGATION APPEARANCE AND PATTERNS

Most references and pavement engineers consider segregated areas to be those relatively deficient in fine aggregate; however, when such conditions exist, there may also be areas deficient in coarse aggregate, a phenomenon sometimes referred to as *flushing*. Areas deficient in coarse aggregate may be more difficult to visually determine, although they tend to be smooth-looking. On visual inspection, segregated pavement areas that are deficient in fines display a rough surface texture. Kennedy et al. (1987) stated that such areas can easily be seen in wet conditions or in low-angle sunlight. Various patterns of segregation have been categorized in different manners by McGennis and Kennedy (1986); Kennedy, et al. (1987); the Federal Aviation Administration (1991), and others. A widely-cited and used pamphlet and diagnostic chart has been developed by Brock (1986). These are further discussed and compared in Section 2.0 of Chapter 2. Two recent references, Williams, et al. (1996) Cross, e. al. (1998), also provide general discussion for segregation in hot mix asphalt pavements.

3.0 PREVIOUS MSU—MDOT STUDY

The prior study for MDOT (Wolff, et. al., 1997) originally focused on what Brock termed centerline and each-side segregation, which exhibit continuous, fines-deficient linear areas in the direction of paver travel which appear as longitudinal "strips." The working hypothesis of the study was that segregated areas would exhibit nuclear density values statistically different from non-segregated areas, which could be distinguished by statistical comparison tests from one longitudinal strip to another. Fines-deficient segregated areas were noted to generally have nuclear density values statistically lower than non-segregated areas or site averages.

Seven field test sites were selected, exhibiting various degrees and patterns of segregation. At these sites, nuclear density measurements were made on a six-by-six test grid (Figure 1.1) of 36 locations, with triplicate measurements made at each location, for a total of 108 measurements per test site. At six of the seven sites, cores were obtained, the asphalt binder removed by incineration, and gradation tests performed.

A spreadsheet template, mbitseg1.xls, was developed to perform statistical analysis on data arranged in a six-by-six grid, with columns aligned in the longitudinal direction of the pavement and rows arranged in the transverse direction. The first screen of mbitseg1.xls is shown in Figure 1.2. The spreadsheet performs a series of multiple comparison tests on the gridded data, to test for differences among columns and from column-to-column. Analyzed data included nuclear-measured density values, lab density values, and percent finer than various sieve openings.

The emphasis of the previous study was to look for statistical patterns in the column-wise data and see if they correlated to observed segregation patterns. By the time the third site was analyzed, it became apparent that other segregation patterns, particularly random segregation, was present at some sites, instead of or in addition to the linear patterns that mbitseg1.xls was designed to test for. A second spreadsheet template, mbitseg2.xls (Figure 1.3), was developed to perform t-test comparisons on two selected samples of up to twelve values each. Limited analyses were also performed using mbitseg2.xls on selected subsets of the available data.

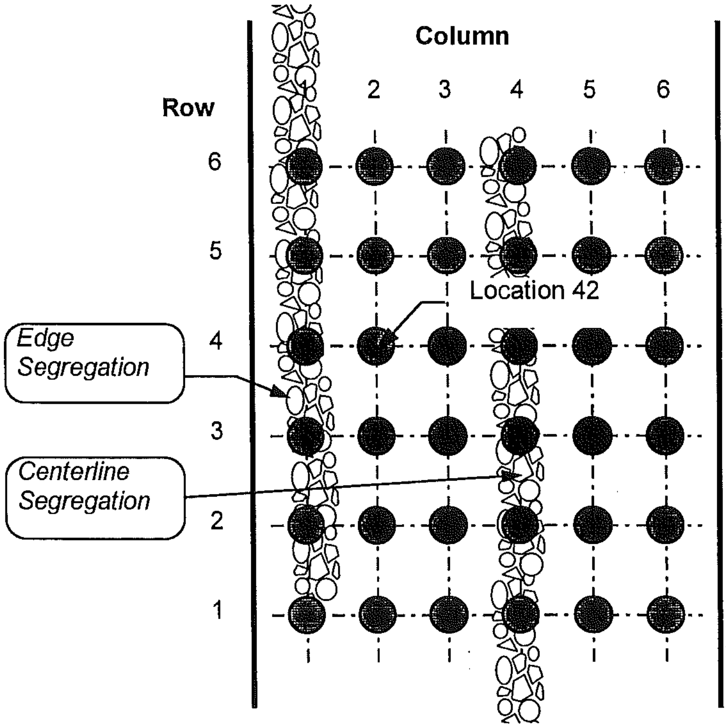
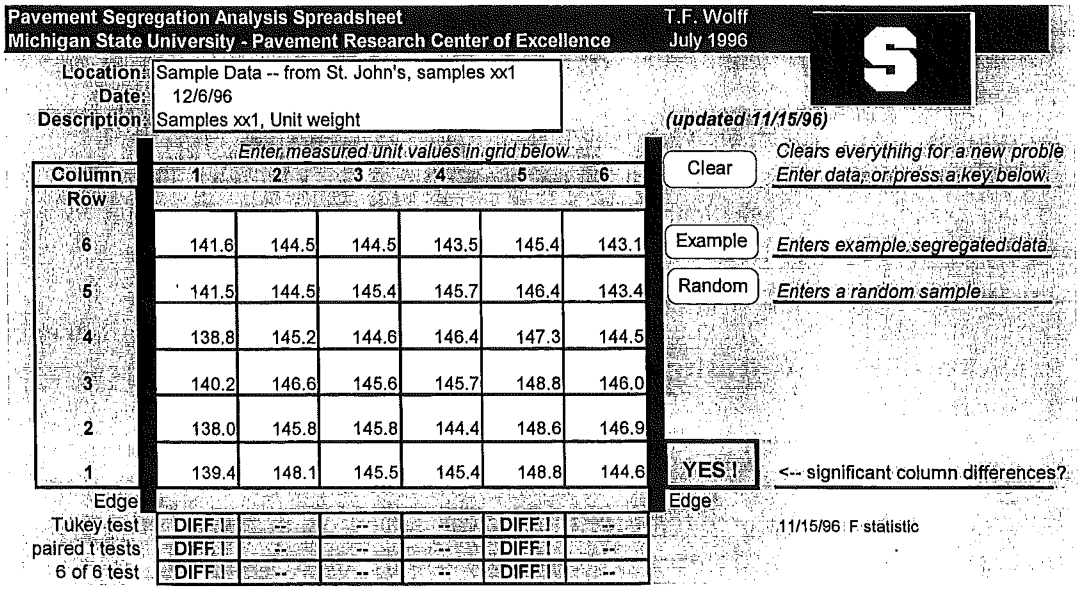


Figure 1.1 Test Grid for Previous Study



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	1	2	3	4	5	6
Row						
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 !	--

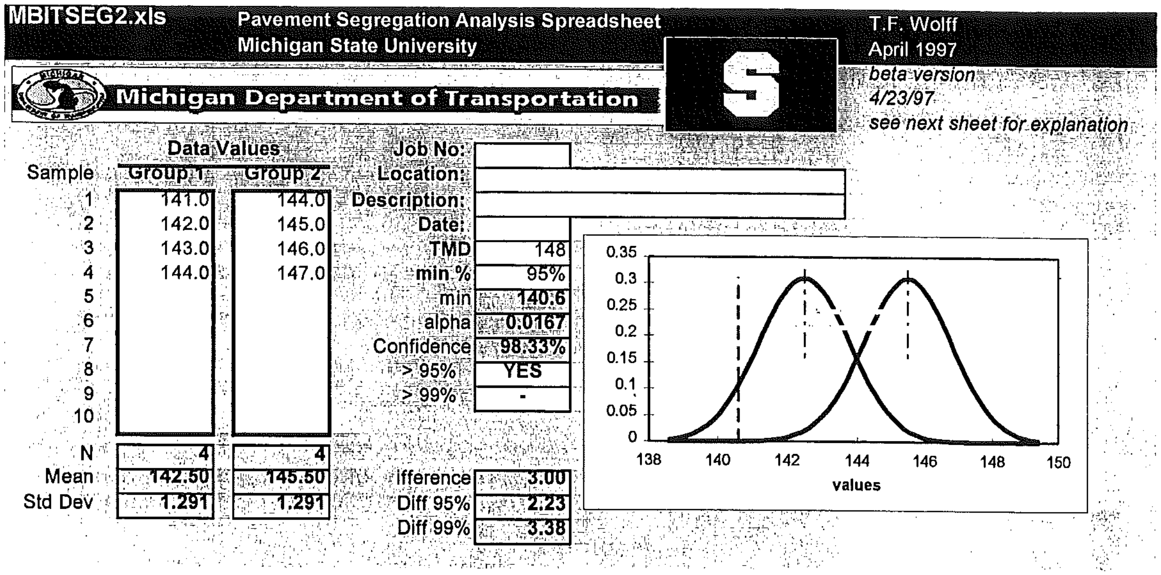
Clears everything for a new proble
Enter data, or press a key below.
Enters example segregated data.
Enters a random sample

YES ! <-- significant column differences?

Edge

11/15/96 F statistic

Figure 1.2 Spreadsheet Template mbitseg1.xls



MBITSEG2.xls

Pavement Segregation Analysis Spreadsheet
Michigan State University

T.F. Wolff
April 1997
beta version
4/23/97
see next sheet for explanation

Michigan Department of Transportation

Sample	Group 1	Group 2
1	141.0	144.0
2	142.0	145.0
3	143.0	146.0
4	144.0	147.0
5		
6		
7		
8		
9		
10		
N	4	4
Mean	142.50	145.50
Std Dev	1.291	1.291

Job No:
Location:
Description:
Date:
TMD 148
min % 95%
min 140.6
alpha 0.0167
Confidence 98.33%
> 95% YES
> 99% -
lfference 3.00
Diff 95% 2.23
Diff 99% 3.38

Figure 1.3 Spreadsheet Template mbitseg2.xls

The general **conclusions of the previous study** can be summarized as follows:

1. **Where linear segregation patterns were pre-identified** (two of the seven sites), or where sample locations were aligned to coincide with observed segregated and non-segregated zones (two more sites) the **statistical analyses showed very highly significant differences in one-minute density values.**

At two of the four sites noted above, statistical analysis of gradation data also showed a highly significant difference, but not as great as that for nuclear density values. A third site would be found significant if the criteria were relaxed somewhat.

2. **At two sites where segregation was not considered excessive, statistically significant differences in nuclear density value were nevertheless found.** At one of these, statistically significant differences in gradation parameters were also found. At the other, no cores were taken and this analysis could not be made.

3. Based on conclusions 1 through 3, it was found **that highly significant differences in nuclear-measured density are indicators of likely-significant differences in gradation, i.e. segregation.** In all but one case, the statistical significance of nuclear-measured density values was greater than that for gradation parameter differences.

4. Surface roughness appeared to lower the nuclear density values, suggesting **that extremely low nuclear density values might also be taken as indicators of segregation.**

4.0 OBJECTIVES OF THE PRESENT STUDY

The primary objectives of the study reported herein were:

- To **develop and validate an expedient procedure to quantify segregation in the field**, building upon the findings of the previous study, and
- to **relate the severity of observed segregation to potential pavement distress**.

The original proposal for the study listed five objectives:

1. Develop criteria to identify the degree of segregation based on visual inspection.
2. Calibrate and verify the recently-developed procedures for detecting linear segregation (using mbitseg1.xls) by obtaining data and performing analyses at a number of additional (to the previous seven) asphalt pavement sites , exhibiting linear and random segregation patterns and a range of mix types and other variables. The purpose of the calibration is to match the program threshold criteria for degrees of segregation to the developed visual methods (Objective 1).
3. Based on the calibration and verification, recommend revised specification criteria (threshold values), based on expedient testing, regarding the detection of the degree of segregation. Preliminary specifications were proposed in Chapter 7 of the report for the previous segregation project; this would revise the quantitative measures in that wording or equivalent wording developed in consultation with MDOT.
4. Using the additional sites in Objective 1, investigate and develop relationships expressing the effects of the degree of segregation on pavement conditions such as raveling, cracking, stripping, and/or rutting. Verify the developed relationships on a third group of sites.
5. Based on the verified relationships between segregation and condition (from Objective 4), revise as necessary the recommended acceptance thresholds for the degree of segregation (Objective 3).

To achieve these objectives, the following hypotheses were developed and tasks were performed.

5.0 RESEARCH HYPOTHESES AND TASKS

The **primary hypotheses** developed for this research are stated as follows:

- Pavement segregation, as evidenced by both visual appearance and gradation analysis, can be correlated with differences in nuclear-measured density values.

- Pavement distress can be correlated with severity of segregation.

Detailed hypotheses following from these are identified and tested in Chapters 5 and 6.

The present study capitalized on the experiences of the previous study by obtaining additional data and providing a more focused inquiry. In particular, it was assumed that the test procedure would begin with the visual pre-identification of areas of apparent segregation in the field, along with apparent non-segregated control areas. Statistical tests would focus on checking for significant differences in nuclear density values between these areas and confirming them by testing for differences in gradation parameters. Figure 1.4 shows an example.

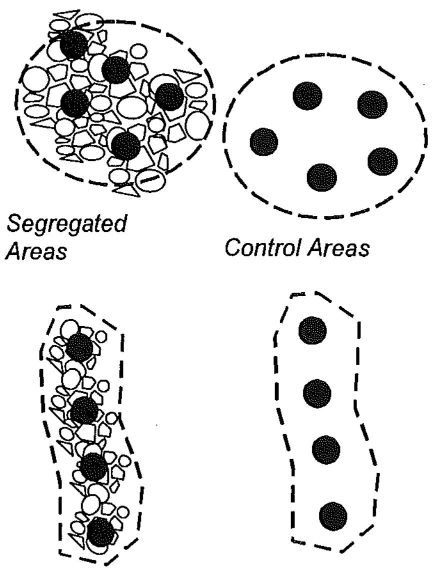


Figure 1.4 Example Field Test Site

To investigate and test the hypotheses, the study progressed as a series of tasks as listed below:

- Twenty-one candidate test sites were pre-selected by MDOT.

- **Segregation** pattern and severity at the test sites **were visually mapped** by a joint team of MDOT and MSU personnel.
- Apparent non-segregated **control areas** were selected at the test sites.
- **Nuclear density testing** was performed at each test site.
- Coring, lab density testing and gradation analyses were performed at the selected test sites.
- Analysis focused on investigating differences in parameter values between the localized, visually-mapped segregated areas and non-segregated control areas.
- **Pavement distress** was monitored and mapped at the test sites over the duration of the project.

6.0 SCOPE OF THIS REPORT

Chapter 2 of this report provides a description of the test sites and criteria for their selection. Chapters 3 and 4 describe the field and laboratory testing performed for the study respectively. In Chapter 5, the development and testing of statistical criteria to relate nuclear density differences to visually observed segregation are described. Statistical studies to relate gradation differences to nuclear-measured density differences are described in Chapter 6. The studies regarding the relationship of segregation and pavement distress are described in Chapter 7. An implementation plan is provided in Chapter 8, and a summary, conclusions, and recommendations are provided in Chapter 9.

CHAPTER 2
SITE SELECTION AND SEGREGATION TERMINOLOGY

1.0 SITE SELECTION CRITERIA

The first task of the research was to identify a set of suitable field test sites. The primary criterion for site selection was the presence of visually observable segregation. It was also desired that the sites exhibit a range of characteristics regarding other factors, such as pavements of different ages, average daily traffic, and mix type. However, recently constructed sites were preferred because effects of traffic compaction would be reduced. In addition, it was desired to identify some control sites where segregation was not present, to validate the test procedure.

2.0 CLASSIFICATION OF SEGREGATION AND DISTRESS

Table 2.1 provides a summary of typical segregation patterns as described by a number of references. Depending on the reference, segregation patterns have been subdivided into as many as six categories and as few as three. Based on a review of the various terminology, segregation patterns can be grouped into three general categories:

- Random
- Continuous
- Systematic or spot

The latter two of these, in turn can be subdivided by location, e.g. centerline, or along one or both edges. These classifications and subdivisions can be used as diagnostic tools to determine the likely cause of the segregation (see, e.g., Brock, et.al., 1996); however, the emphasis of the team classification exercise was merely to attempt to obtain some consistency in describing the segregation in the test areas.

Once a pattern of segregation has been identified, its severity can be described. Table 2.2 summarizes a classification scheme reported by Korgemagi and Lynch (1988). Their paper reported on segregation problems with public roads in Ontario in the mid-1980's which led to a visual criteria by which pavement would be required to be replaced, if severely segregated, or a reduction in price could be imposed, where medium segregation is present.

In this study, the terms *heavy segregation, medium segregation*, and *light segregation* were adopted, to correspond to the definitions of severe, medium and slight given by Korgemagi and Lynch. Before the joint team visited the initial 14 sites, a short meeting and training session was held to define the terminology to be used to map segregation patterns and severity, and also distress type and severity.

Table 2.1 Segregation Pattern Terminology

	Reference				
Pattern type	McGennis and Kennedy (1986)	Brock (1996) Roberts et. al. (1996)	Kennedy et. al. (1987)	FAA (1991)	Korgemagi and Lynch (1988)
Random	Random Segregation	Random Segregation	Random Segregation	Rock Pockets and Random Segregation	Random Segregation
Continuous	Continuous segregation both sides	Each side segregation (continuously)	Continuous segregation both sides	Side-to-side segregation	Two streaks in the wheel paths parallel to centerline
	Continuous segregation one side		Continuous segregation one side		
	Continuous segregation center of mat	Centerline segregation	Continuous segregation center of mat		
Systematic or spot	Systematic spot segregation both side	Each side segregation (systematic)	Systematic spot segregation both side	Truckload-to-truckload segregation	Truck-load segregation
	One side segregation (systematic)	One side segregation (systematic)			

Table 2.2 Degree of Segregation

Degree of Segregation		Description	Action Taken by Ontario Ministry (Korgemagi and Lynch, 1988)
This Study	Korgemagi and Lynch (1988)		
Heavy	Severe	stone against stone, little or no matrix	subject to removal
Medium	Medium	lack of surrounding matrix, significantly more stone than surrounding mat	allowed to remain in place, subject to price adjustment
Light	Slight	matrix in place, more stone than surrounding mat	considered not to be a problem

Distress mapping at the test sites was performed according to the criteria in Table 2.3, adapted from SHRP (1993) and Baladi and Snyder (1990). Two groups of distress categories were considered:

- Raveling and stripping
- Longitudinal and transverse cracking

Each of these was subdivided into three levels of distress, low, moderate or high, based on the criteria in the Table.

3.0 INITIAL SITES (SITE 1 THROUGH 14)

In December 1997, MDOT proposed fourteen sites for initial consideration. Two joint field trips with MDOT and MSU personnel were made in December 1997 to finalize site selection and visually map the extent and severity of segregation and pavement distress. Nine investigators participated in the first trip, which visited sites 1 through 8. Seven investigators were involved in the second trip, to sites 9 through 14. For both trips, the air temperature was slightly above freezing, at 33 to 35°F. Based on the field inspections, two of the sites (4 and 12) were dropped as they appeared to be the result of a thin surface layer where new pavement was feathered out to meet old. The remaining twelve sites were carried forward for further study.

At each of the twelve initial sites, the following was done:

- A 12 ft by 36 ft reference grid was established on the pavement
- Segregation was mapped by each member of the inspection team using the form shown in Figure 2.1. Patterns and degree of segregation were noted and distress was recorded by location and severity level.
- The resulting individual maps were analyzed to develop a composite, consensus map of segregation location and severity

The summary results of the visual observations regarding segregation made at each site are summarized in Table 2.4. The locations of each site are illustrated in Figure 2.2.

Table 2.3 Severity Level of Distress

Distress Mode	Severity Level	Description
Raveling and Stripping	Low	aggregate or binder has started to wear away, but not progressed significantly
	Moderate	aggregate or binder has worn away and the surface texture becomes moderately rough and pitted
	High	aggregate or binder has worn away, and the surface texture is very rough and pitted
Longitudinal or Transverse Cracking	Low	a crack with a mean width ≤ 6 mm (0.25 in.)
	Moderate	a crack with a mean width > 6 mm (0.25 in.) and ≤ 19 mm (0.75 in.); or a crack with a mean width ≤ 19 mm (0.75 in.)and adjacent low severity random cracking
	High	a crack with a mean width > 19 mm (0.75 in.); or a crack with a mean width ≤ 19 mm (0.75in.) and adjacent moderate to high severity random cracking

Sources: SHRP (1993), Distress Identification Manual for the Long-Term Pavement Performance Project,
Baladi and Snyder (1990), Highway Pavement Training Course

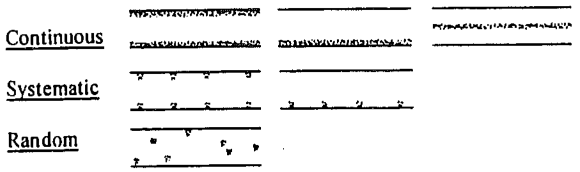
Segregation Survey

Date of Survey:
Weather:

Surveyor: ______________________ (your name)
Control Section Number:________________Route:____________Direction:______________.
Region:__________________________Mile Post: from ____________to____________.
Section Number:________________Test Site Number:________________ADT:__________.

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.

Type of Segregation:



Degree of Segregation
Heavy: stone against stone, little or no matrix (fine)
Medium: lack of surrounding matrix (fine),significantly more stone than surrounding mat
Light: matrix (fine) in place, more stone than surrounding mat

Distress to be Identified

1. Raveling

☐ Low ☐ Moderate ☐ High

Low: aggregate or binder has started to wear away, but not progressed significantly
Moderate: aggregate or binder has worn away, and the surface texture becomes moderately rough and pitted; loss particles generally exist; loss of fine aggregate and some loss of coarse aggregate
High: aggregate or binder has worn away, and the surface texture is very rough and pitted; loss of coarse aggregate

2. Cracking

☐ Low ☐ Moderate ☐ High

Low: a crack with a mean width ≤ 0.25 in.
Moderate: a crack with a mean width > 0.25 in. and ≤ 0.75 in.; or any crack with a mean width ≤ 0.75 in. and adjacent low severity random cracking
High: any crack with a mean width ≥ 0.75 in.; or any crack with a mean width ≤ 0.75 in. and adjacent moderate to high random cracking

3. Rut Depth

4. Flushing

☐ Low ☐ Moderate ☐ High

Low: an area of pavement surface discolored relative to the remainder of the pavement by excess asphalt
Moderate: an area of pavement surface that is losing surface texture due to excess asphalt
High: excess asphalt gives the pavement surface a shiny appearance; the aggregate may be obscured by excess asphalt; tire marks may be evident in warm whether

COMMENTS

Segregation Map

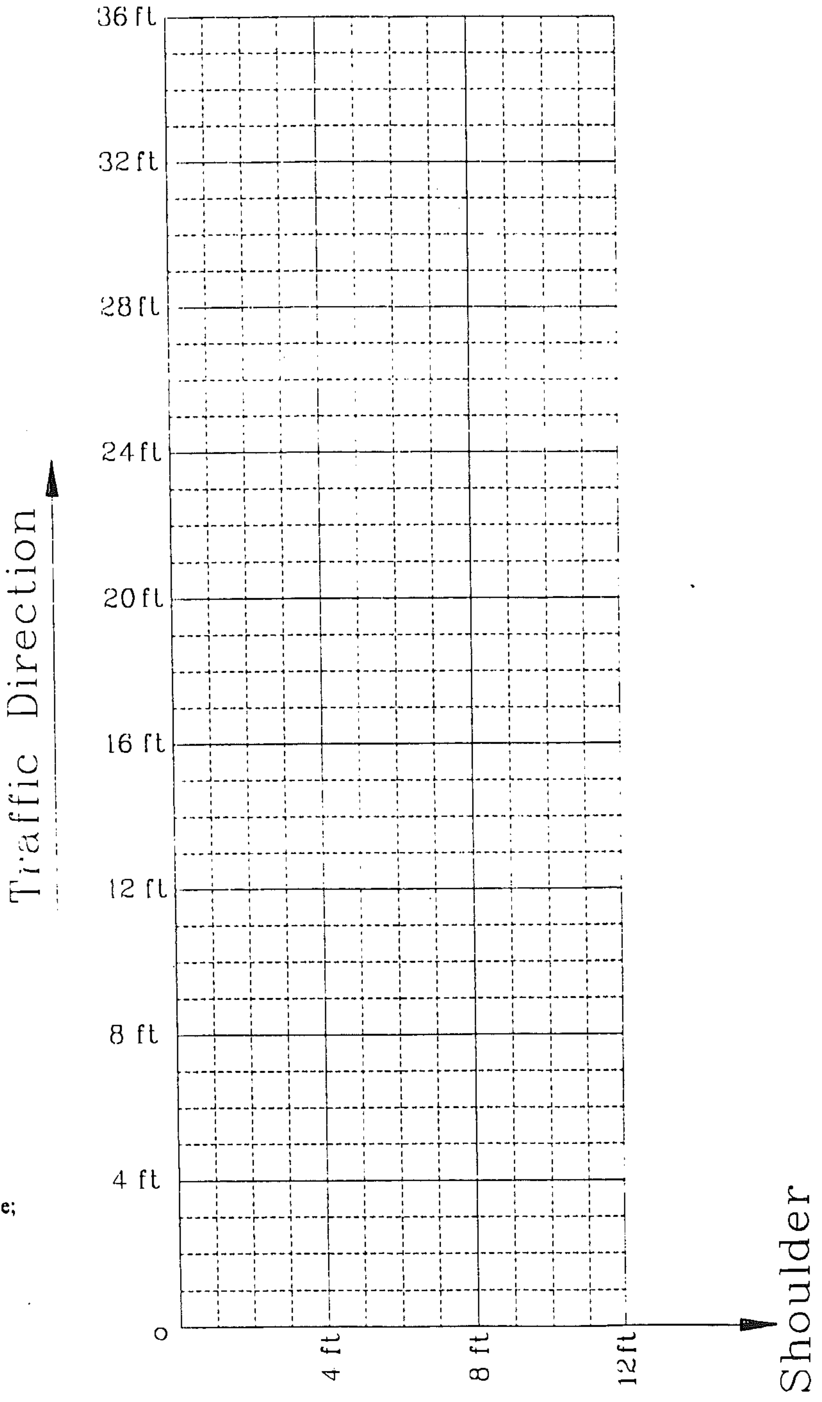


Figure 2.1 Pavement Mapping Form

Table 2.4 Initial Test Sites

Site	Mixture Type	ADT	Date of Paving	Segregation / Comments
1. Parking lot of MDOT special crews building, Jackson	1300T	service yard	1995	• Continuous segregation • Centerline segregation rated heavy • Right edge segregation ratings vary light to medium • Raveling apparent
2. Michigan Avenue (I94 BL) westbound (in front of Foote Hospital), Jackson	4C	19,000	1997	• Continuous, systematic, and random segregation • Heavy to medium in far left side • Heavy on near end • Mixed description in middle left side • Light to none on right side • Flushing / rich on right side
3. Michigan Avenue (I94 BL) eastbound, Jackson	4C	19,000	1997	• Centerline segregation • Medium to light
4. Not used (intersection in Moscow MI)				(thin section at end of paving)
5. US-12 westbound (west of Moscow Road), Hillsdale County	4B	5,100	1997	• Segregated area (heavy) across width of pavement beyond joint at 28 ft • Continuous segregation, right side, medium to light • Some random segregation on left side, inconsistent description

Table 2.4 Initial Test Sites (continued)

Site	Mixture Type	ADT	Date of Paving	Segregation / Comments
6. Sterling Road westbound, (300 ft west of Knowles Road), Hillsdale County	13A	—	1997	• Random and systematic segregation • Heavy to medium segregated spots on far left • Segregated spot in middle left; inconsistent classification • Heavy to medium in lower right area
7. Sterling Road eastbound (300 ft west of Knowles Road), Hillsdale County	13A	—	1997	• Prominent centerline segregation • Heavy to medium in far center area • Medium to light in near center area • Some flushing noted • Some raveling and cracking noted
8. Sterling Road eastbound (2000 ft west of Knowles Road), Hillsdale County	13A	—	1997	• Center line segregation • Inconsistently rated – light to heavy • One additional light spot in near left
9. Canal Road northbound (in front of Delta Center School), Eaton County	4B	—	1996	• Centerline segregation • Left edge segregation • Both light to medium
10. Canal Road southbound (150 ft south of Westshire Road), Eaton County	4B	—	1996	• Centerline segregation • Left edge segregation • Both medium to light

Table 2.4 Initial Test Sites (continued)

Site	Mixture Type	ADT	Date of Paving	Segregation / Comments
11. M-100 northbound (south of M-43), Eaton County	13A	20,000	1996	• Continuous centerline segregation • Continuous left edge segregation • Continuous right edge segregation noted by some • All segregation mapped as light • No pavement distress noted
12. Not used				(thin section at end of paving)
13. M-50 northbound (350ft north of Round Lake road), Eaton County	4B	1,700	1997	• Random and continuous segregation • Light continuous segregation right of centerline • One heavy spot adjacent to above • Several spots in near part of section, mixed descriptions, light to medium • Some cracking evident
14. M-50 S. Bound (1437 ft north of Allegan road), Eaton County	4B	1,700	1997	• Two strips of segregation near left edge, light to medium, depending on location • Some mapped heavy to medium spot near far left corner • Cracking noted • Raveling noted by some

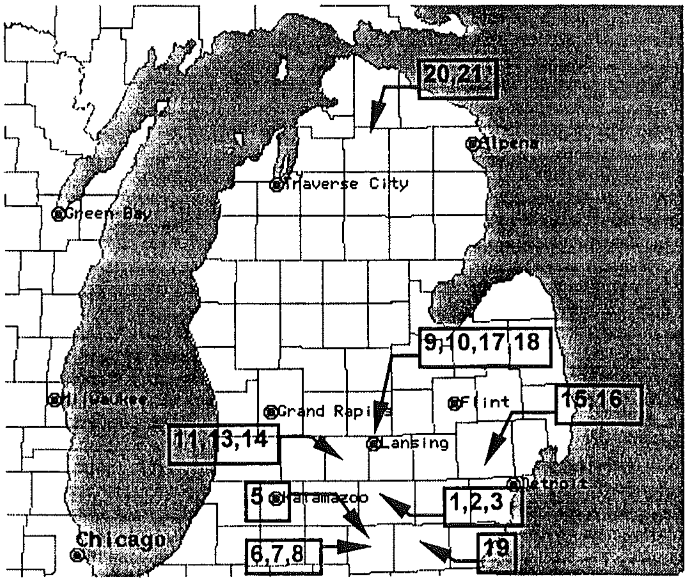


Figure 2.2 Locations of Test Sites

4.0 ADDITIONAL SITES (SITE 15 THROUGH 22)

The additional eight sites were selected between July 1998 and June 1999. One joint field trip was made to visit sites 15 to 18 in the end of July 1998. Seven investigators including MDOT, MAPA (Michigan Asphalt Paving Association) and MSU personnel are involved in this trip. Sites 17 and 18 were selected as control sites having a uniform asphalt mix without segregation present. Another joint trip was made to visit and test site 19 in September 1998. Five investigators from MDOT, MAPA and MSU were involved. The air temperature in the first trip was around 75°F; 60 °F in the second trip. At each of the sites 15 to 19, the following was done:

- A sampling grid was established (4 ft by 36 ft grid at site 15, 12 ft by 36 ft grid at sites 16~18, and 15 ft by 36 ft grid at site 20).
- Segregation was mapped by each member of the inspection team using the form shown in Figure 2.1.
- The severity level of segregation and pavement distress were recorded.

Site 20 and 21 were selected by MDOT and surveyed by MSU research team in the end of October 1998. The air temperature at the date testing site 20 was around 35°F and 60°F at the date testing site 21. For each of the sites 20 and 21, several separate sections of segregation were selected at interval along the road. There are six sections in site 20 and three sections in site 21. Location and severity of segregation were recorded.

Site 22 was visited in the end of June 1999. It was an uncompacted asphalt pavement placed at a mix plant facility to get some idea regarding the variation in nuclear density behind a paver before compaction. MDOT, MAPA and MSU personnel were involved. The sampling grid was established with 20 ft in the longitudinal direction and 12 ft in the transverse direction. The air temperature at the date testing site 22 was approximately 80 °F.

The summary results of the visual observations regarding segregation made at each site are summarized in Table 2.5. The locations of the additional sites are also illustrated in Figure 2.2.

Table 2.5 Additional Test Sites

Site	Mixture Type	ADT	Date of Paving	Segregation / Comments
15. US-23 North Bound (Milepost 63.5), Brighton	1500 MOD T RP	18,500 (main-lane)	1992	• Segregation on shoulder • Random segregation • Various segregation ratings from light to heavy • Raveling apparently associated with heavy segregation
16. US-23 South Bound (Ramp Exit 60B to I-96), Brighton	1500 MOD T RP	18,500 (main-lane)	1992	• Continuous segregation • Heavy to medium in the right side • Mixed description in middle left side • Moderate raveling apparent
17. Bus. 69 West Bound (Saginaw Highway) near Hagadorn Road, East Lansing	SuperPave 5E3	—	1997	• No segregation (control site)
18. M-99 (Logan Street) North Bound across Berten Street	SuperPave 4C	19,000	1998	• No segregation (control site)
19. US-223, North Bound, near Rome Center	SuperPave 3E3	7,600	1998	• Continuous and systematic segregation • End-of-load segregation apparent • Medium to heavy in the right side • Medium on lower left side

Table 2.5 Additional Test Sites (continued)

Site	Mixture Type	ADT	Date of Paving	Segregation / Comments
20. I-75, South Bound, near Rondo overpass	SuperPave 4E3	6,000	1997	• Random and systematic segregation • Continuous segregation in section 6 • Mixed heavy and medium in sections 1~5 • Mixed description in middle right side in section 6
21. I-75, South Bound, near Vanderbilt interchange	SuperPave 4E10	6,500	1998	• Systematic segregation (every 240 ft) • Light to medium segregation
22. Capital Excavating and Paving Co. Mason	1100 T	—	1999	• Demonstration project • Loose asphalt mix behind paver without compaction

CHAPTER 3
FIELD INVESTIGATIONS

This chapter summarizes the various field investigations undertaken for this project. These include

- Mapping of segregation at the selected sites
- Nuclear density measurements in segregated areas and control areas
- Obtaining cores from a more limited number of segregated areas and control areas
- Distress mapping

1.0 SAMPLING GRID

Visual mapping and sample locations at each test sites were referenced to a sampling grid, 12 ft along the transverse direction and 36 ft along the traffic direction, as shown in Figure 2.1. However, the width of sampling grid was adjusted in field to match the width of traffic lane or lane with shoulder. It varied from 4 ft to 15 ft. The sample number is based on the sampling grid. Each sample was designated by a four-digit number XXYY, where XX is the number along x-axis in the transverse direction and YY is the number along the y-axis in the longitudinal direction. For example, sample 0716 indicates that the location is seven feet away from the origin in the x-direction and 16 ft from the origin in the y direction. An example of sampling grid established in the field is illustrated in Figure 3.1. The sampling grids for each site are shown in Appendix A.

2.0 MAPPING SEGREGATION

Locations of segregation in the sampling grid were identified by each member attending the field trips and the associated degrees of segregation noted as heavy, medium or light in accordance with Table 2.2. The location of segregation and the severity of segregation associated were precisely marked on the segregation survey sheet as shown in Figure 2.1.

The participants at each site are listed in Table 3.1. After the segregation maps were collected, the data regarding the location and severity of segregation from each member was evaluated. The procedure to establish the summarized segregation maps was based on the areas of segregation and the number of severity level assigned by the surveyors. Then, the segregation sample areas, shown in Appendix A, were determined in term of location and associated severity level.

In addition to segregated areas, several non-segregated areas were also selected to be used as control samples compared to the segregated samples.

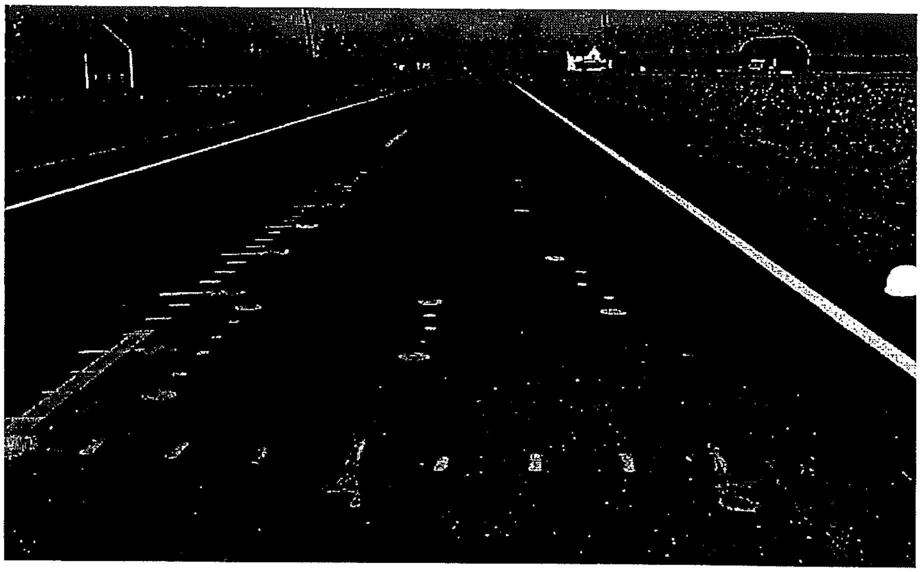


Figure 3.1 Sampling Grid at Site 13

Table 3.1 Participants for Visual Mapping at Each Site

Site	Date	Participant
Sites 1~3 Sites 5~8	Dec. 3, 1997	Frankhouse, Bradley, Ziegler, Mayes, Smiley, Winkler, Wolff, Baladi, Chang
Sites 9~11 Sites 13~14	Dec. 9, 1997	Ziegler, Frankhouse, Smiley, Winkler, Wolff, Baladi, Chang
Sites 15~18	July 31, 1998	Ziegler, Bradley, Smiley, Wolff, Baladi, Chang
Site 19	October 16, 1998	Ziegler, Bradley, Click, Baladi, Chang
Site 20	October 21, 1998	Baladi and Chang
Site 21	October 28, 1998	Baladi and Chang
Site 22	June 25, 1999	Frankhouse, Ziegler, Smiley, Click Wolff, Baladi, Chang

3.0 NUCLEAR DENSITY TESTING

After MSU personnel marked the sampling grid and the sample locations at each site, MDOT personnel obtained measurements using a nuclear density gauge. At each location of data points, the gauge was placed over the proposed location to obtain count readings indicating total density. One-minute counts were obtained. The count readings were directly converted to values of density based on the internal calibration circuitry of the nuclear gauge. This required that the gauge calibration procedure (using a block of standard, known density) be performed each day of testing. A troxler model 3440 nuclear gauge was used for testing at all sites. A photo of the nuclear density gauge is shown in Figure 3.2. The nuclear gauge number used at each test site is listed in Table 3.2.

4.0 CORING

After nuclear density tests were completed at each site, cores were obtained by MDOT personnel using a power rotary drill with a 6-inch coring bit, as shown in Figure 3.3. Each core was numbered as previously described in Section 3.0. Not all of the nuclear density locations were cored; approximately half were cored. The coring locations for each site are shown in the maps of sampling grids in Appendix A.

5.0 DISTRESS SURVEY

Distress surveys were conducted on dates shown in Table 3.3. Four types of distresses that are related to segregation (raveling, cracking, flushing and rutting) were based on its extent and severity level. The procedure to record distress data was based on SHRP (1990).

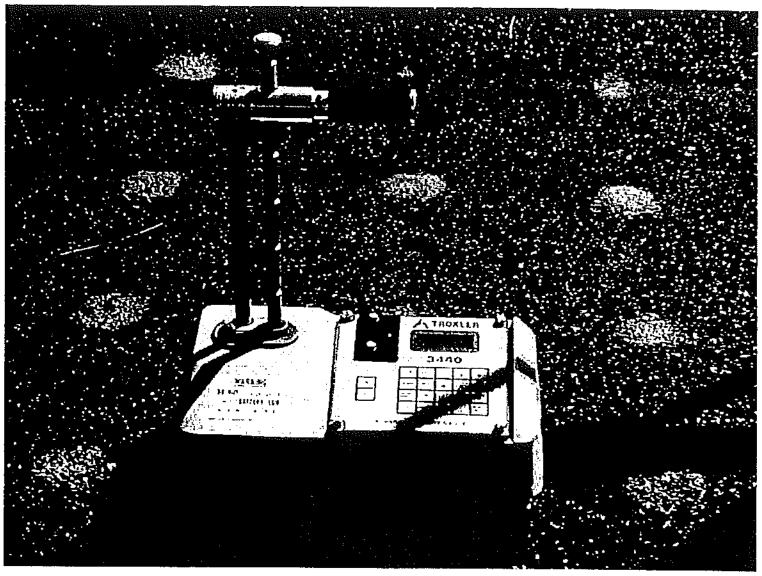


Figure 3.2 Nuclear Density Gauge

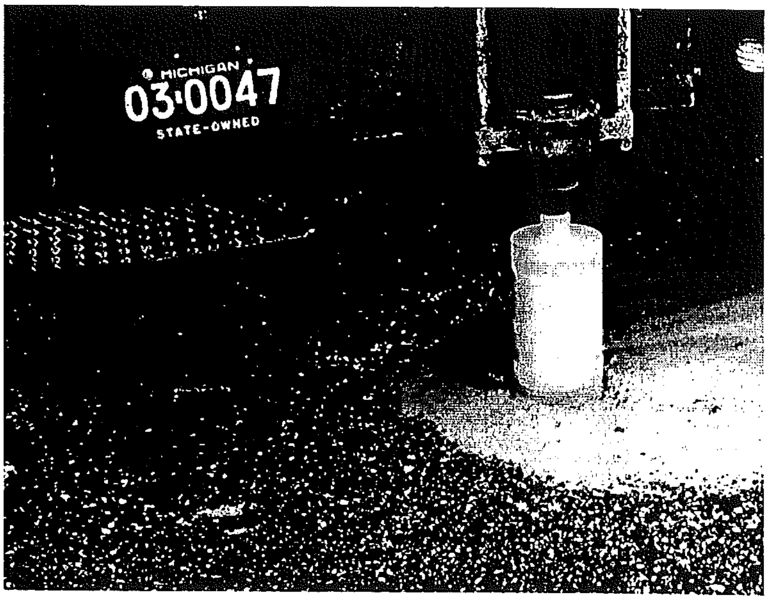


Figure 3.3 Coring Process

Table 3.2 Summary of Nuclear Testing and Coring

Site	Date of Nuclear Testing	No. of Nuclear Measurements	Gauge No.	Date of Coring	No. of cores
1	Jan. 16 & April 9, 1998	98	99398 101953	April 9, 1998	33
2	Jan. 16, 1998	57	99398	X	X
3	Jan. 16 & April 9, 1998	65	99398	April 9, 1998	24
5	Jan. 30 & April 14, 1998	81	99398 101953	April 14, 1998	39
6	Jan. 30, 1998	58	99398	X	X
7	Jan. 30, 1998	35	99398	X	X
8	Jan. 30, 1998	48	99398	X	X
9	Feb. 13, 1998	43	102420	X	X
10	Feb. 13 & April 16, 1998	78	102420 101953	April 16, 1998	30
11	Feb. 13, 1998	30	102420	X	X
13	Feb. 13 & April 16, 1998	84	102420 101953	April 16, 1998	30
14	Feb. 13, 1998	42	102420	X	X
15	Aug. 11, 1998	54	102835	Aug. 11, 1998	26
16	Aug. 11, 1998	108	102835	Aug. 11, 1998	57
17	Aug. 12, 1998	72	102835	Aug. 12, 1998	16
18	Aug. 12, 1998	72	102835	Aug. 12, 1998	16
19	Oct. 16, 1998	71	102835	Oct. 16, 1998	23
20	Oct. 21, 1998	82	102835	Oct. 21, 1998	59
21	Oct. 28, 1998	66	102835	Oct. 28, 1998	42
22	June 25, 1999	85	102933	June 25, 1999	9
	Total	1329			404

CHAPTER 4
LABORATORY INVESTIGATIONS

Laboratory investigations consisted of density measurements and gradation analyses on the surface course portion of the cores described in Chapter 3.

1.0 SAMPLE PREPARATION

Obtained cores from the field were transported to MSU. They were sawed to separate the surface course from the base course. The surface course specimens were used for laboratory density measurements, after which the asphalt binder was extracted and aggregate gradation analyses were performed. A cored and sawed specimen is shown in Figure 4.1.

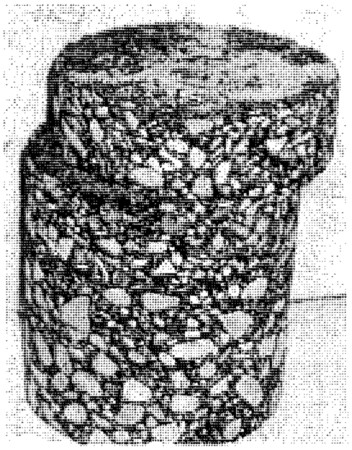


Figure 4.1 Cored Specimen

2.0 DENSITY MEASUREMENTS

For the surface course portion from each core, the air dry and the saturated surface dry (SSD) densities were measured.

Air-Dry Density. The air-dry density tests were conducted according to Michigan Test Method (MTM) 306. In this method, the 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 air-dry density can be calculated as:

$$\text{Air-dry density (g/cm}^3\text{)} = 0.997 \times \frac{A}{A - B}$$

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

Saturated Surface-Dry Density. The SSD density tests were conducted according to MTM 315 (which is similar to ASTM standard test D-2726) to determine the 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 density of the saturated surface-dry specimen can be expressed as follows:

$$\text{SSD density (g/cm}^3\text{)} = 0.997 \times \frac{A}{B - C}$$

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).

Although laboratory density values would not be used directly in any proposed field procedure, the measurements were made to aid understanding of the relationship between nuclear density and gradation.

3.0 INCINERATION OF ASPHALT BINDER

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

The extraction operations were initially performed by MSU personnel at the MDOT laboratory. Later, they were performed at the MSU laboratory using a forced air ignition furnace (Figure 4.2) preheated to 538°C. Each sample was simply placed evenly distributed within a basket which was placed in the furnace and burned until a stable light indicated that the extraction process was complete. The aggregate was then retrieved and subjected to sieve analysis.

4.0 GRADATION TESTS

Once the aggregate and fine material left from the extraction process were cooled, the particle size distribution was determined by sieve analysis according to MTM 117 (which is similar to ASTM C136). The sieve sizes used and the corresponding sieve opening sizes are listed in Table 4.1.

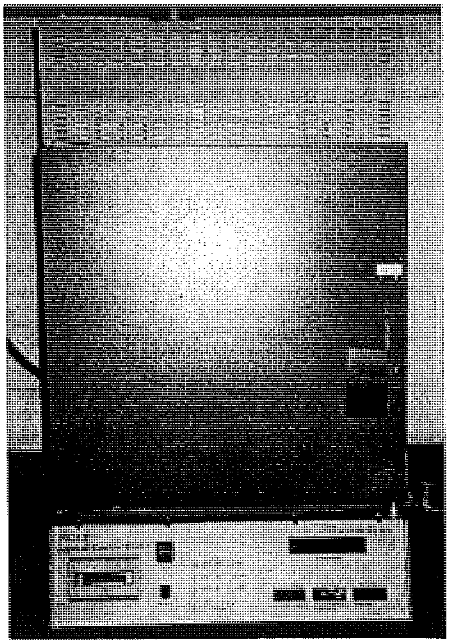


Figure 4.2 Incineration Oven

Table 4.1 Sieve and Opening Sizes Used in Gradation Tests

Sieve Size	Opening (mm)	Opening Power 0.45 (mm)
0.75″	19	3.76
0.50″	12.5	3.12
0.375″	9.5	2.75
No. 4	4.75	2.02
No. 8	2.37	1.47
No. 16	1.18	1.08
No. 30	0.60	0.79
No. 50	0.30	0.58
No. 100	0.15	0.43
No. 200	0.075	0.31

CHAPTER 5
DEVELOPMENT OF TEST AND CRITERIA

1.0 OVERVIEW

This chapter describes studies to relate differences in nuclear density values to differences in visually-mapped degree of segregation severity. Data are summarized and graphed in a variety of manners. Nuclear-measured density values were compared to lab density results through regression analyses. An extensive number of t-tests were performed for the data obtained at each site. These are discussed in detail including location of samples, degree of segregation from visual observation and confidence level of significant difference. Criteria were established relating three variables: degree of segregation, absolute nuclear density difference and statistical difference in term of p-value. Conditional probability was introduced regarding the chance of segregation being present given different nuclear density criteria. Verification of these criteria using gradation properties is discussed in Chapter 6.

2.0 CHARACTERISTICS OF NUCLEAR DENSITY MEASUREMENTS

At each site, one-minute nuclear density measurements were made at selected sample areas visually mapped as light, medium, heavy segregation, or control (non-segregated). Each sample consisted of 3 to 12 nuclear density measurements. The mean and standard deviation of nuclear density values were computed for each sample. These are summarized in Table 5.1. For each sample, the number of nuclear density readings is also listed. The total number of samples analyzed was 173, involving a total of 1171 one-minute nuclear density readings for sites 1 through 22.

2.1 Pattern of Nuclear Density Variation at Each Site

Nuclear density values are plotted as a function of location along the longitudinal direction in Figure 5.1. This format was used to visualize the consistency of values along areas of similar degrees of segregation, and the difference in values among samples with different severity levels of segregation. It can be observed that at most sites heavy and medium segregation samples correspond to lower nuclear density values. However, some exceptions are found. At sites 2 and 5, the "outside grid" control sample had relatively low density values and the heavy segregation sample had relatively high nuclear density values. As both these samples (control and heavy) were located across joints from the main sampling grid and not in the same mat, it is possible that the variation of placing operation dominated properties governing the nuclear density readings, not the occurrence of segregation. At site 10, one additional control sample located at the right edge of the driving lane (close to concrete curb) had low density values. At this location, it is believed that a lower degree of compaction may have been achieved during the construction process because the compressive force of the roller was partially sustained by the concrete curb. At site 11, nuclear density measurements may have been affected by mud on the pavement surface from the residential construction site near by.

Table 5.1 Statistical Summary of Nuclear Density Values

Site	**Sample** by increasing degree	**Mean** (lb/ft^3)	**Standard Deviation** (lb/ft^3)	**Sample Size**
Site 1	2. Control	140.0	1.46	12
	5. Control	138.8	1.26	9
	Outside. Control	138.1	1.20	10
	7. Additional Control	135.7	1.84	9
	1. Light	136.0	0.76	9
	4. Medium	132.2	1.24	9
	3. Heavy	133.3	1.22	12
	6. Heavy	131.8	0.96	9
Site 2	Outside. Control	138.3	2.05	10
	3. Light (fine)	146.3	0.87	10
	1. Medium	136.6	2.92	10
	4. Medium	135.9	2.68	9
	2. Heavy	138.5	1.15	10
	5. Heavy	139.5	3.94	8
Site 3	1. Control	147.0	1.59	9
	5. Control	143.0	0.73	9
	2. Light	143.7	1.03	9
	3. Medium	142.4	0.91	9
	4. Medium	142.4	0.86	9
Site 5	Outside. Control	141.6	0.99	10
	Transverse. Control	145.6	3.97	12
	3. Light	140.6	1.91	9
	2. Light (fine)	146.4	1.51	10
	4. Medium	140.6	1.67	9
	5. Medium	137.9	1.00	9
	1. Heavy	143.3	1.71	10
Site 6	3. Control	146.9	0.71	9
	5. Control	147.1	0.81	9
	4. Light-Medium	144.1	1.70	6
	1. Heavy	141.7	3.54	4
	2. Heavy	142.8	1.41	6
	6. Heavy	141.0	3.08	6
	7. Heavy	139.1	1.86	8
Site 7	1. Control	145.9	1.43	9
	4. Control	146.0	0.77	9
	3. Light-Medium	138.0	1.51	8
	4. Medium-Heavy	133.3	2.11	9

Table 5.1 Statistical Summary of Nuclear Density Values (continued)

Site	Sample by increasing degree	Mean (lb/ft^3)	Standard Deviation (lb/ft^3)	Sample Size
Site 8	1 & 4. Non-segregated	147.5	1.37	6
	5. Non-segregated	144.8	1.59	6
	6. Non-segregated	149.1	0.86	6
	8. Non-segregated	145.0	0.72	6
	9. Non-segregated	144.9	1.08	6
	10. Non-segregated	147.8	0.65	6
	2 & 3. Segregated	140.8	1.98	6
	7. Segregated	141.1	3.17	6
Site 9	2. Control	143.8	3.30	6
	6. Control	140.7	1.43	6
	1. Light	145.0	0.68	6
	4. Light	142.9	1.13	6
	5. Light	141.4	1.65	6
	3. Light +	142.5	0.53	6
	7. Light +	142.5	0.47	6
Site 10	A. Control	146.7	0.52	6
	B. Control	148.1	0.82	6
	C. Additional Control	146.5	0.91	6
	D. Additional Control	138.6	0.84	6
	2. Light	140.3	1.37	7
	5. Light	141.7	2.80	7
	1. Light-Medium	144.4	1.07	6
	3. Light-Medium	143.1	0.93	6
	4. Medium	141.2	2.81	6
Site 11	3. Control	142.1	1.26	6
	5. Control	145.3	1.02	6
	1. Light	144.7	0.93	6
	2. Light	145.0	0.78	6
	4. Light	144.9	1.16	6
Site 13	3. Control	142.3	1.10	9
	7. Additional Control	140.3	0.92	6
	8. Additional Control	143.5	1.42	6
	2. Light	136.9	1.38	9
	1. Light-Medium	138.9	0.73	6
	4. Light-Medium	139.9	0.77	6
	5. Medium	135.0	4.40	5
	6. Heavy	136.0	1.65	5

Table 5.1 Statistical Summary of Nuclear Density Values (continued)

Site	Sample by increasing degree	Mean (lb/ft^3)	Standard Deviation (lb/ft^3)	Sample Size
Site 14	4. Control	147.1	0.53	6
	7. Control	144.6	0.64	6
	2. Light	143.8	0.71	6
	6. Light	141.9	0.82	6
	3. Light-Medium	139.3	1.99	6
	1. Medium	139.2	1.04	6
	5. Medium	138.0	0.68	6
Site 15	2. Control	144.1	1.24	5
	4. Control	142.5	1.01	7
	7. Control	142.3	1.87	7
	8. Control	143.2	1.54	8
	9. Control	138.6	3.14	4
	1. Light	142.2	1.44	6
	3. Light	141.2	1.80	5
	5. Light	137.2	3.13	4
	6. Medium-Heavy	129.3	4.07	9
Site 16	1. Control	144.0	1.06	6
	2. Control	145.4	0.73	6
	5. Control	145.8	2.14	6
	6. Control	142.5	2.72	6
	8. Control	144.5	3.64	11
	9. Control	145.2	0.86	11
	11. Control	142.8	2.56	11
	12. Control	146.1	0.99	11
	4. Light	143.4	0.57	6
	3. Light-Medium	140.6	0.88	6
	6. Light-Medium	142.5	2.72	6
	10. Light-Medium	142.6	1.36	11
	13. Medium	142.1	1.20	11
	7. Heavy-Medium	140.6	1.59	6
Site 17	1. Non-segregated	139.7	1.51	6
	2. Non-segregated	144.1	1.48	6
	3. Non-segregated	142.6	1.69	6
	4. Non-segregated	142.9	1.55	6
	5. Non-segregated	145.7	0.39	6
	6. Non-segregated	143.6	0.71	6
	7. Non-segregated	140.0	0.75	6
	8. Non-segregated	143.9	1.03	6
	9. Non-segregated	142.3	0.92	6
	10. Non-segregated	142.7	0.82	6
	11. Non-segregated	145.5	1.56	6
	12. Non-segregated	141.9	1.14	6

Table 5.1 Statistical Summary of Nuclear Density Values (continued)

Site	Sample by increasing degree	Mean (lb/ft^3)	Standard Deviation (lb/ft^3)	Sample Size
Site 18	1. Non-segregated	138.6	1.15	6
	2. Non-segregated	142.6	0.84	6
	3. Non-segregated	138.8	0.88	6
	4. Non-segregated	140.0	1.45	6
	5. Non-segregated	141.3	1.23	6
	6. Non-segregated	141.0	1.80	6
	7. Non-segregated	139.2	0.84	6
	8. Non-segregated	144.2	0.74	6
	9. Non-segregated	138.6	0.68	6
	10. Non-segregated	139.3	1.00	6
	11. Non-segregated	140.8	1.16	6
	12. Non-segregated	141.0	1.15	6
Site 19	1. Control	147.1	0.83	4
	2. Control	147.3	2.22	8
	7. Control	148.7	0.92	8
	3. Medium	141.8	3.26	6
	5. Medium	137.7	2.56	6
	6. Medium-Heavy	140.0	2.40	7
	4. Heavy	133.0	1.27	6
	8. Heavy	137.9	4.47	6
Site 20				
Section 1	3. Control	146.8	0.25	3
	1. Heavy	142.3	1.59	3
	2. Heavy	140.1	1.69	3
Section 2	5. Control (fine)	147.2	0.15	3
	4. Heavy	139.7	1.18	3
Section 3	8. Control	145.6	0.61	3
	6. Medium-Heavy	139.2	1.08	3
	7. Medium-Heavy	140.2	2.60	3
Section 4	11. Control	146.7	1.07	3
	10. Control (fine)	146.4	0.78	3
	9. Heavy	142.0	1.15	6
Section 5	13. Control	147.0	0.49	3
	12. Heavy	141.7	0.90	3
Section 6	15. Control	145.8	1.29	10
	14D. Light-Medium	142.1	0.90	4
	14C. Medium	141.6	1.46	5
	14B. Medium-Heavy	140.3	1.30	5
	14A. Heavy	138.9	0.66	4

Table 5.1 Statistical Summary of Nuclear Density Values (continued)

Site	**Sample** by increasing degree	**Mean** (lb/ft^3)	**Standard Deviation** (lb/ft^3)	**Sample Size**
Site 21				
Section 1	2. Control	142.3	0.54	5
	1. Light-Medium	140.7	0.74	9
Section 2	4. Control	140.6	0.32	5
	3. Light-Medium	138.5	1.13	5
Section 3	7. Control	141.0	0.64	5
	8. Control	142.2	0.56	5
	5. Light-Medium	138.6	0.97	5
	6. Light-Medium	138.8	1.32	3
Site 22	Sample 1	127.9	1.11	6
	Sample 2	127.8	0.85	6
	Sample 3	123.9	1.85	6
	Sample 4	121.5	0.83	6
	Sample 5	125.5	0.79	6
	Sample 6	128.8	0.68	6
	Sample 7	129.9	1.15	6
	Sample 8	127.6	1.22	6
	Sample 9	125.4	0.91	6
	Sample 10	123.6	1.66	6
	Sample 11	124.7	1.27	6
	Sample 12	127.0	0.57	6

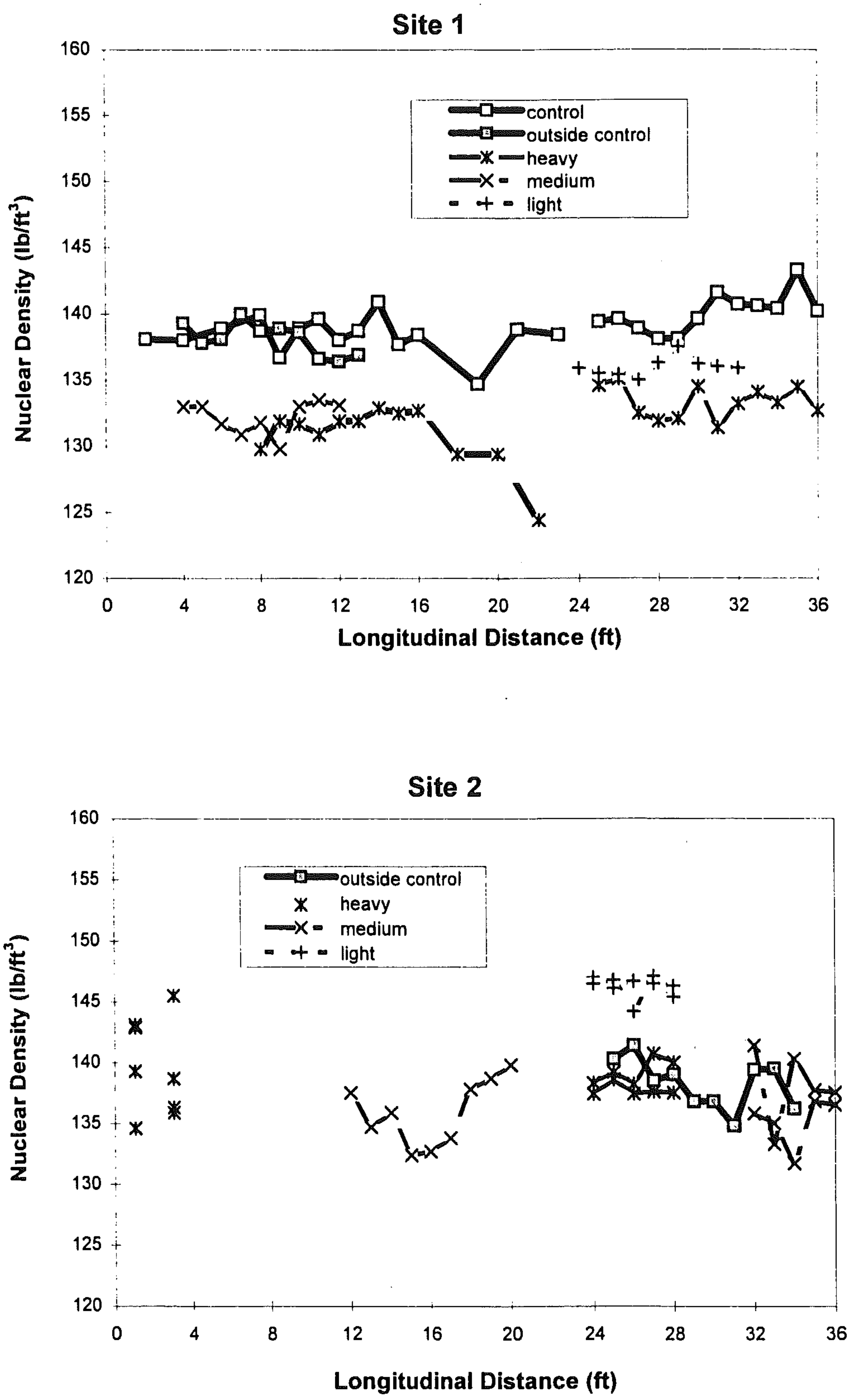
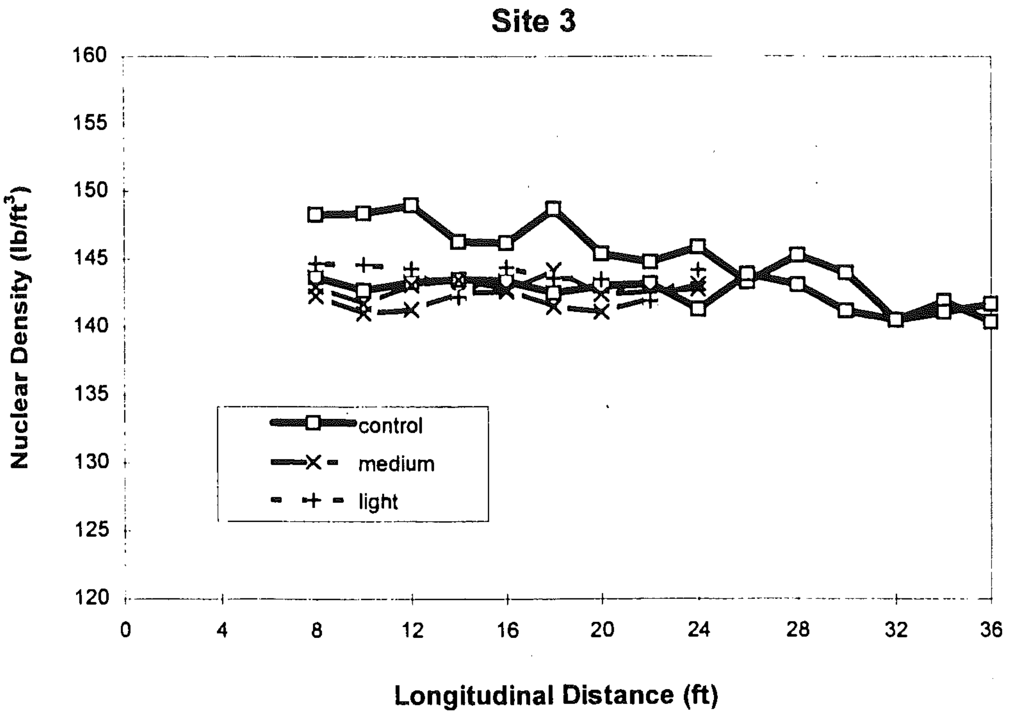


Figure 5.1 Distribution of Nuclear Density



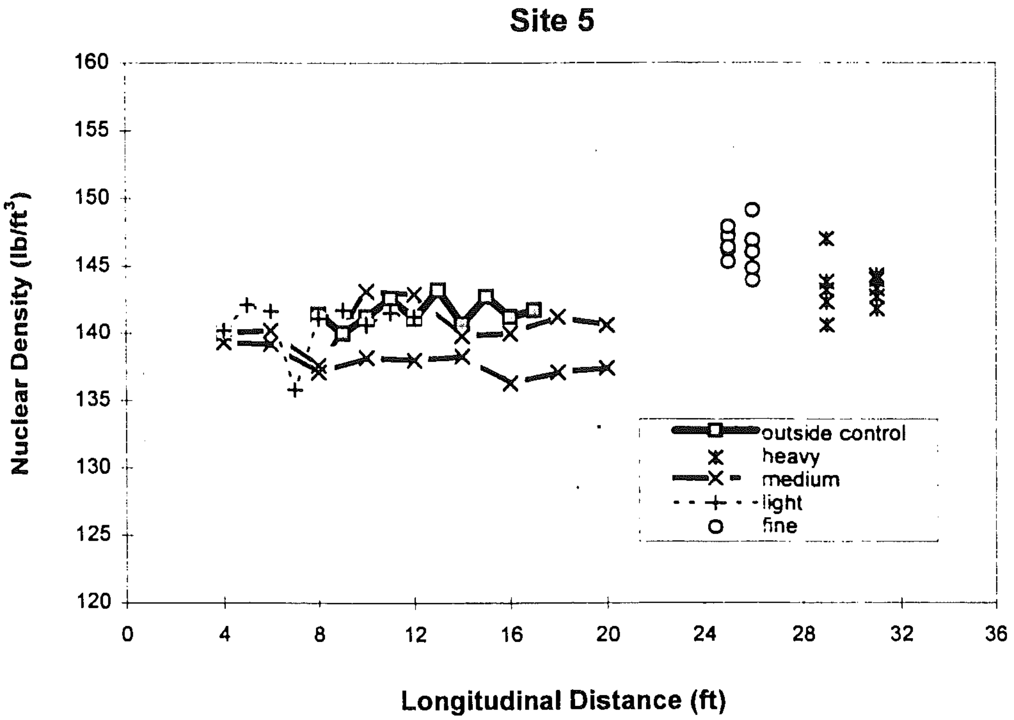
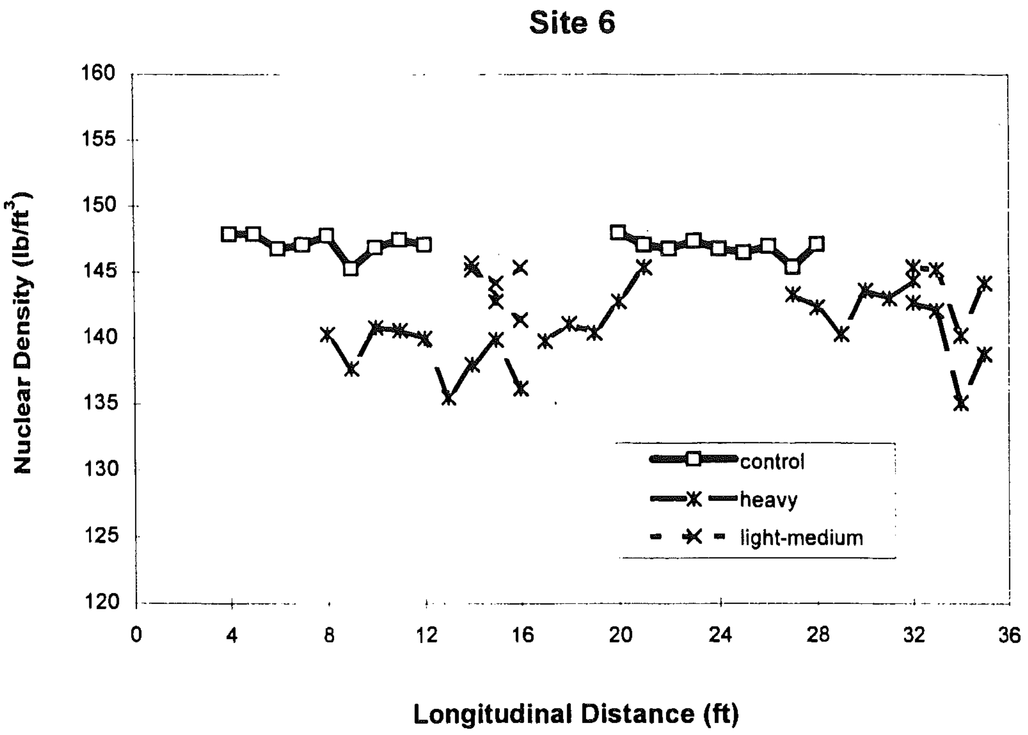


Figure 5.1 (continued) Distribution of Nuclear Density



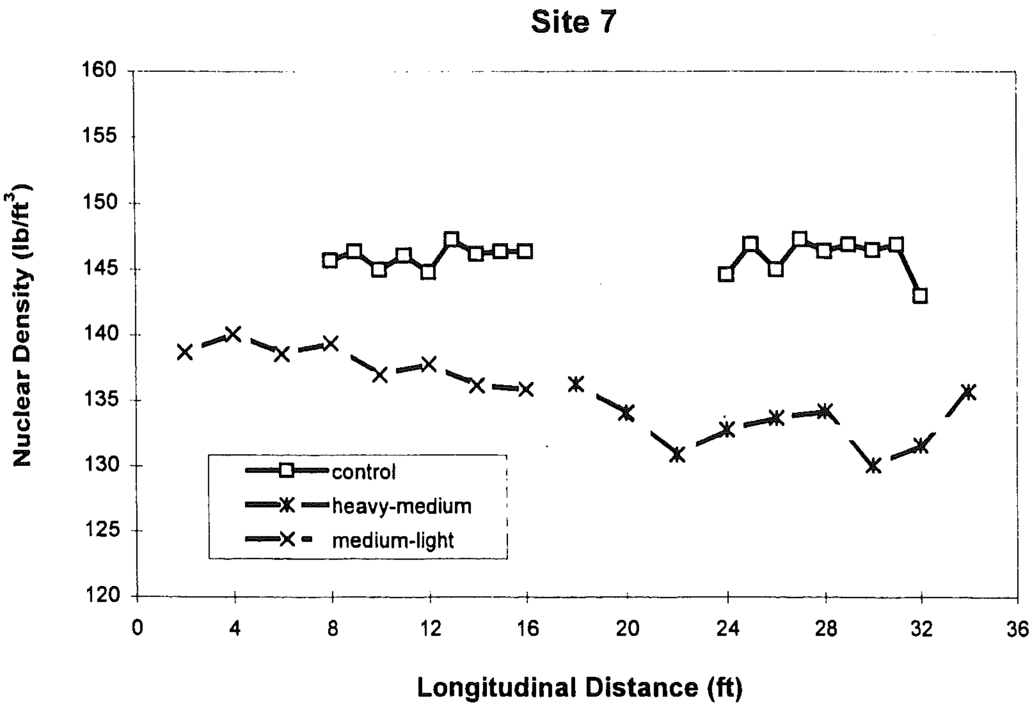
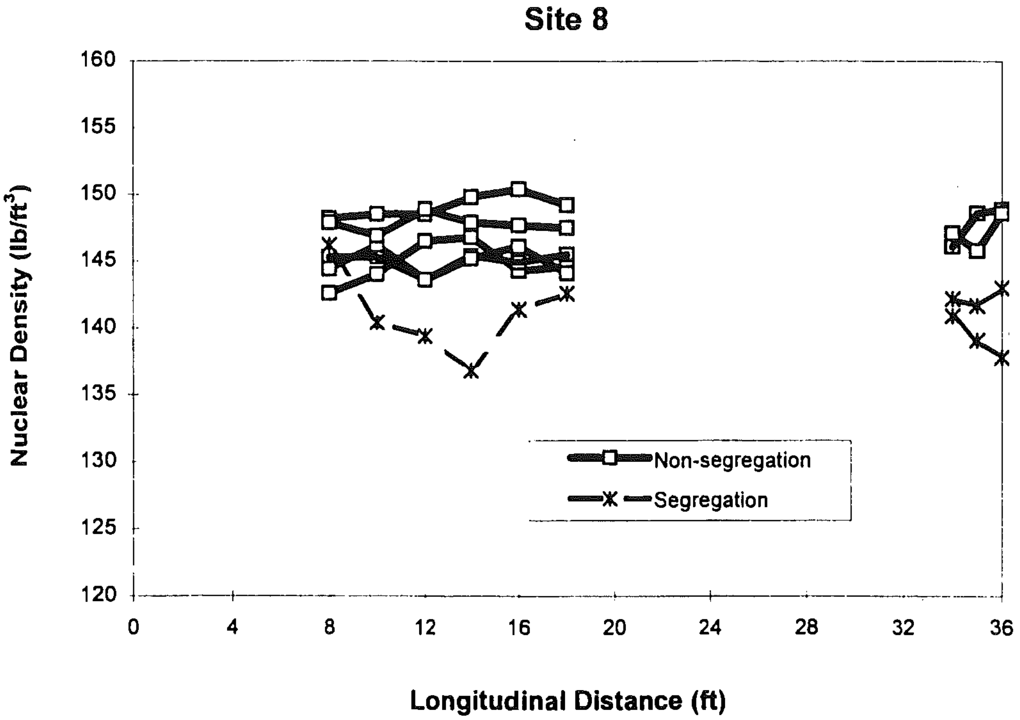
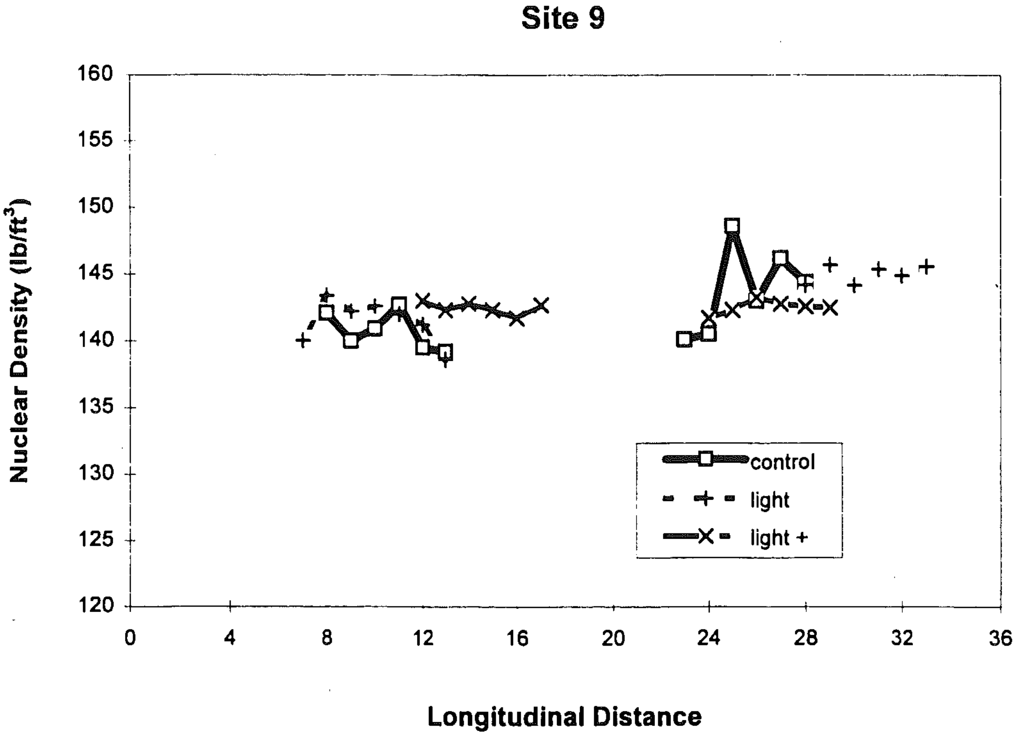


Figure 5.1 (continued) Distribution of Nuclear Density





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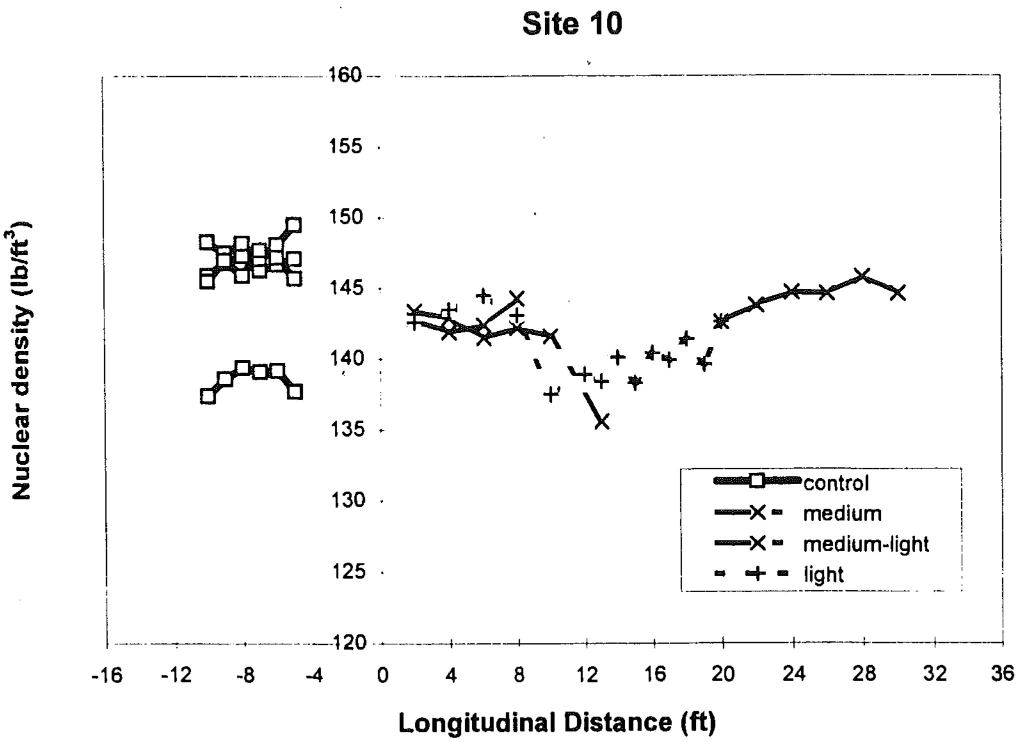

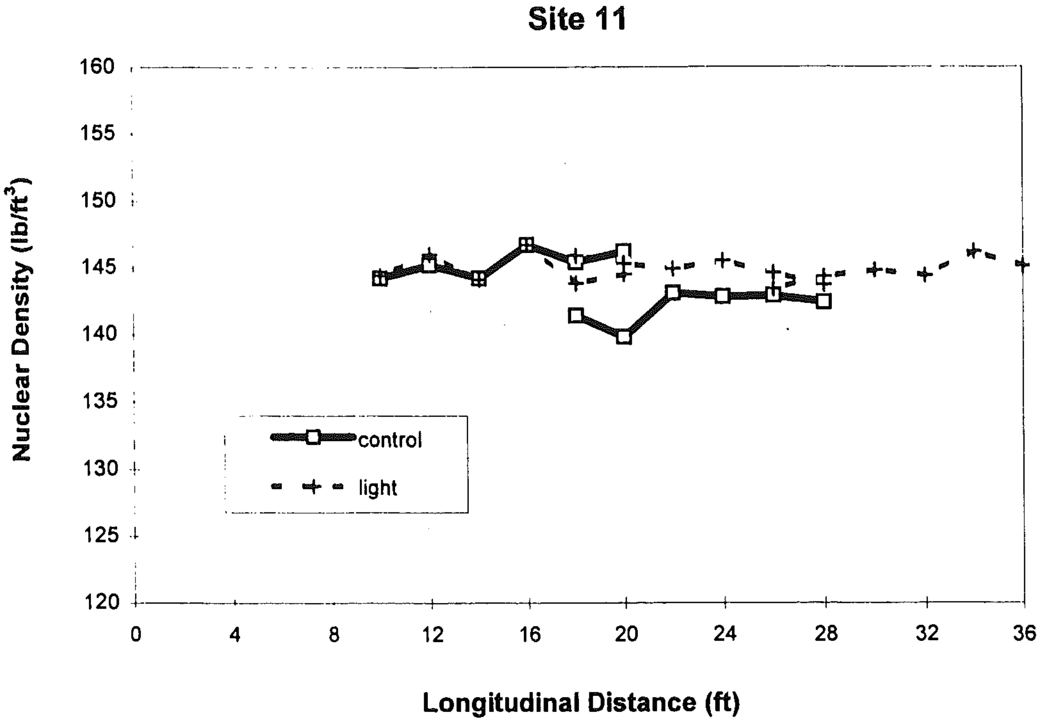

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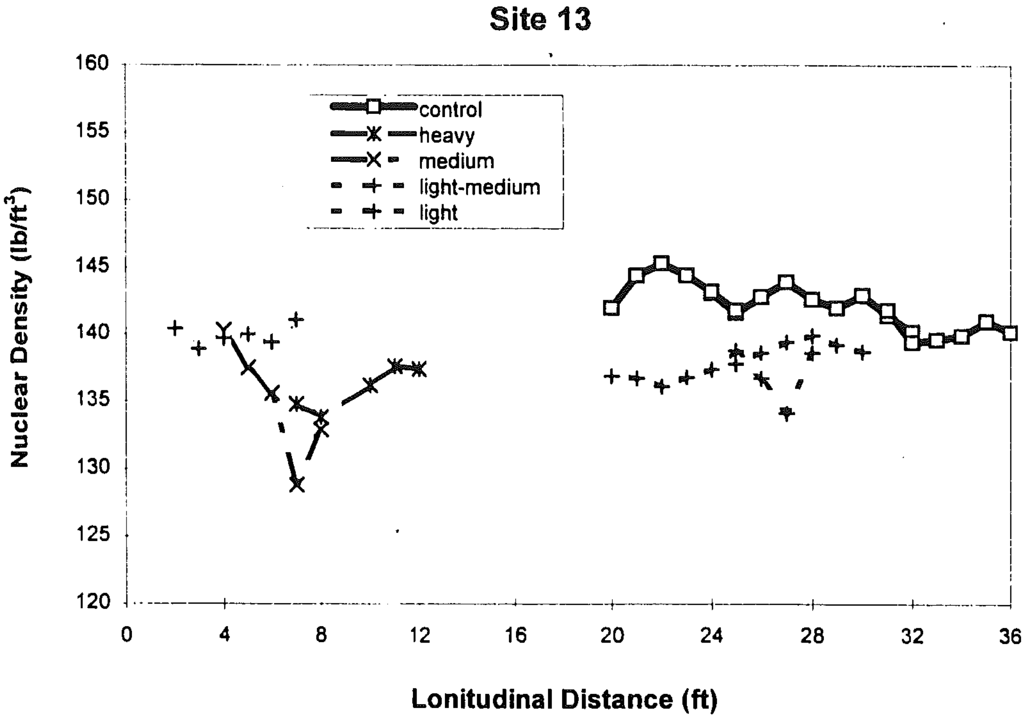


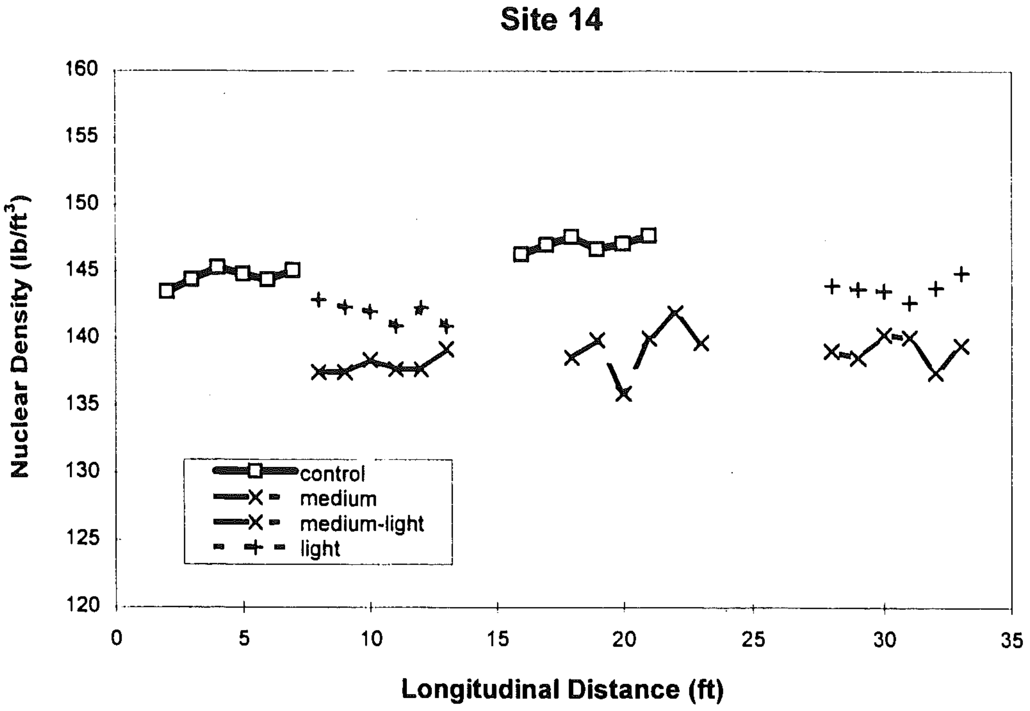
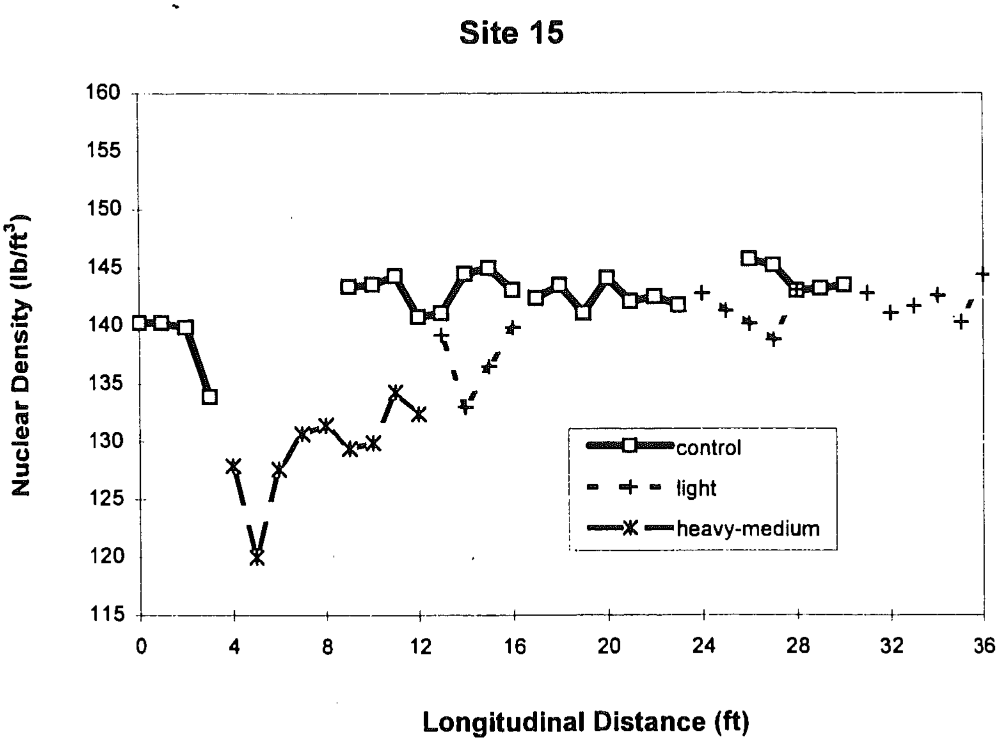


Figure 5.1 (continued) Distribution of Nuclear Density



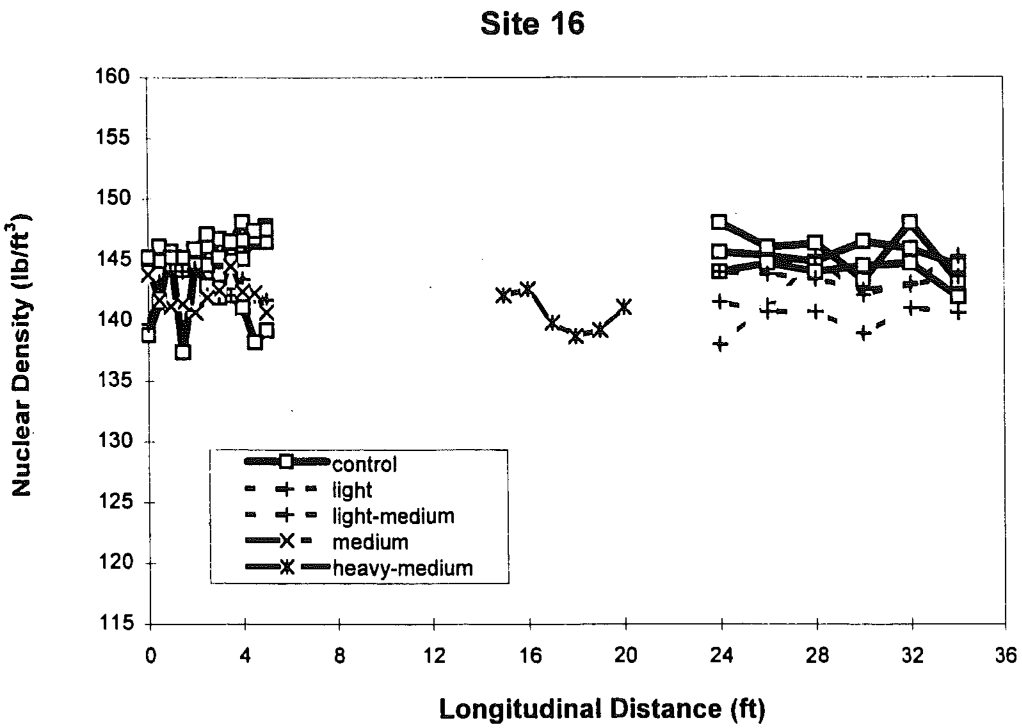
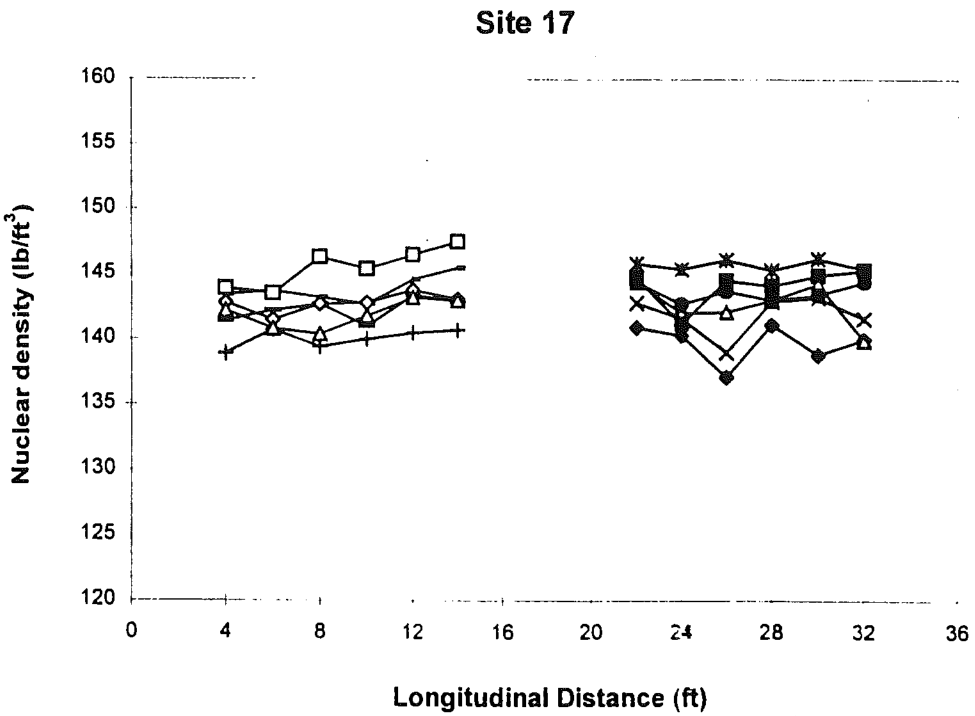


Figure 5.1 (continued) Distribution of Nuclear Density



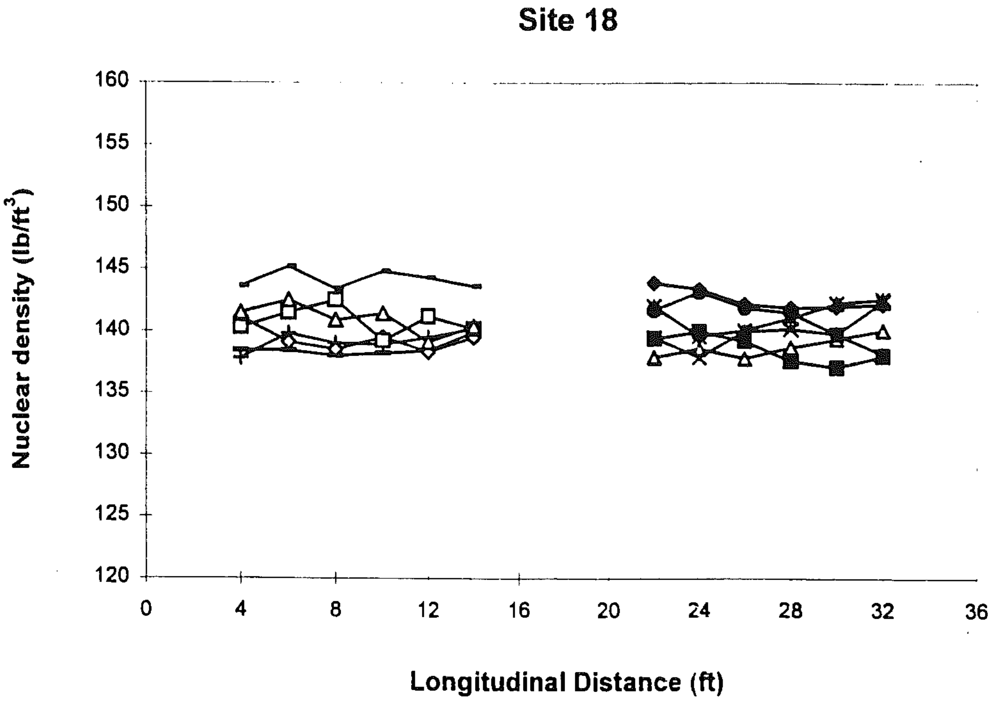
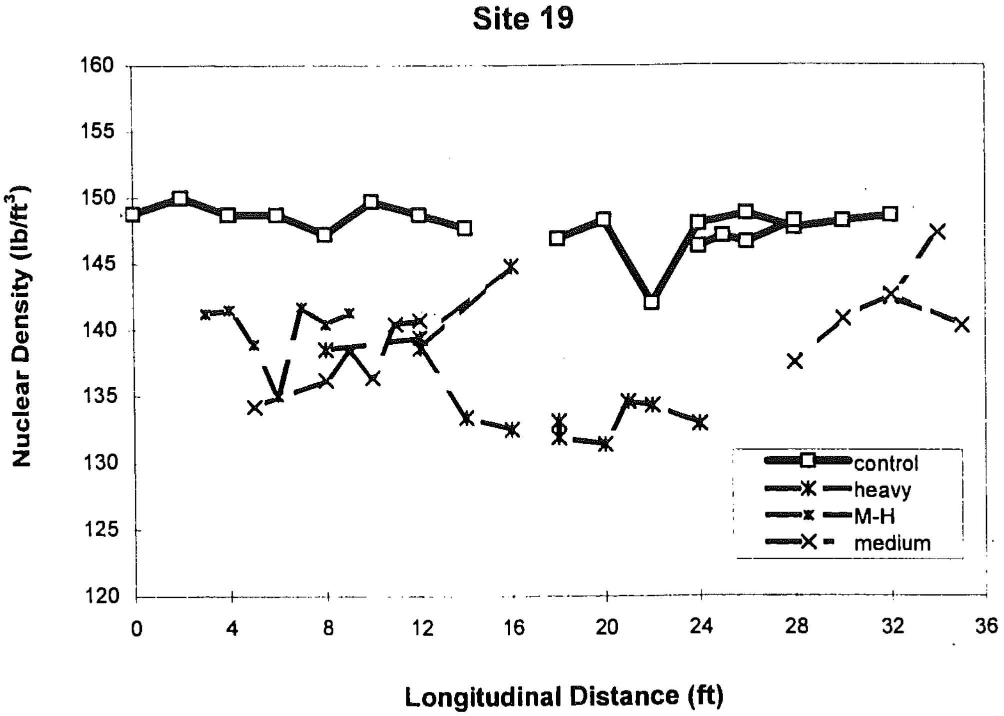


Figure 5.1 (continued) Distribution of Nuclear Density



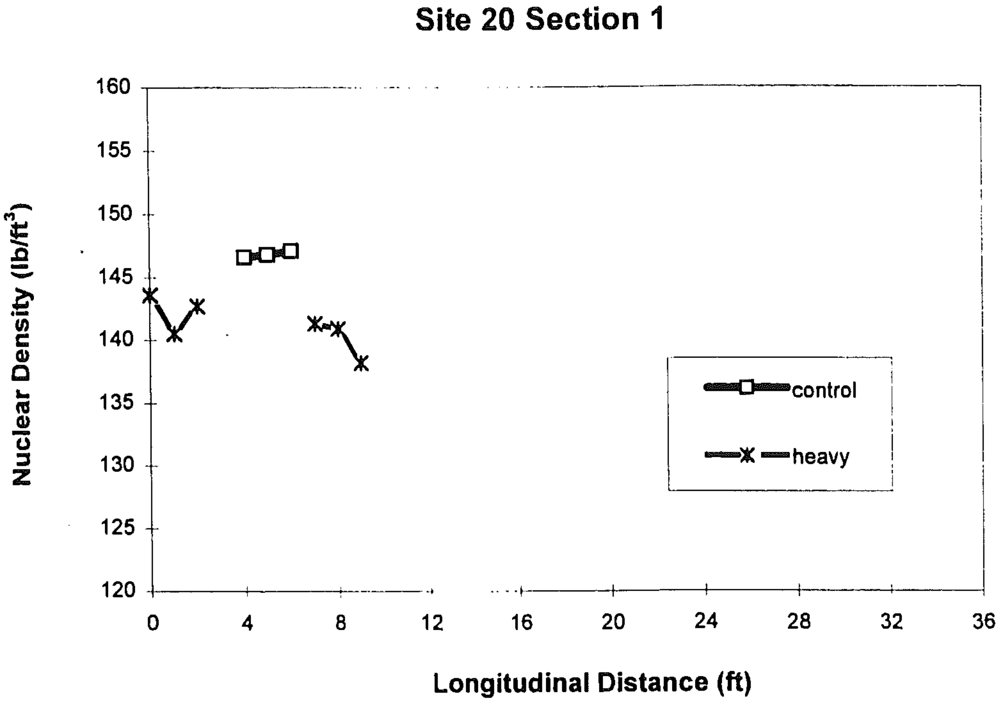
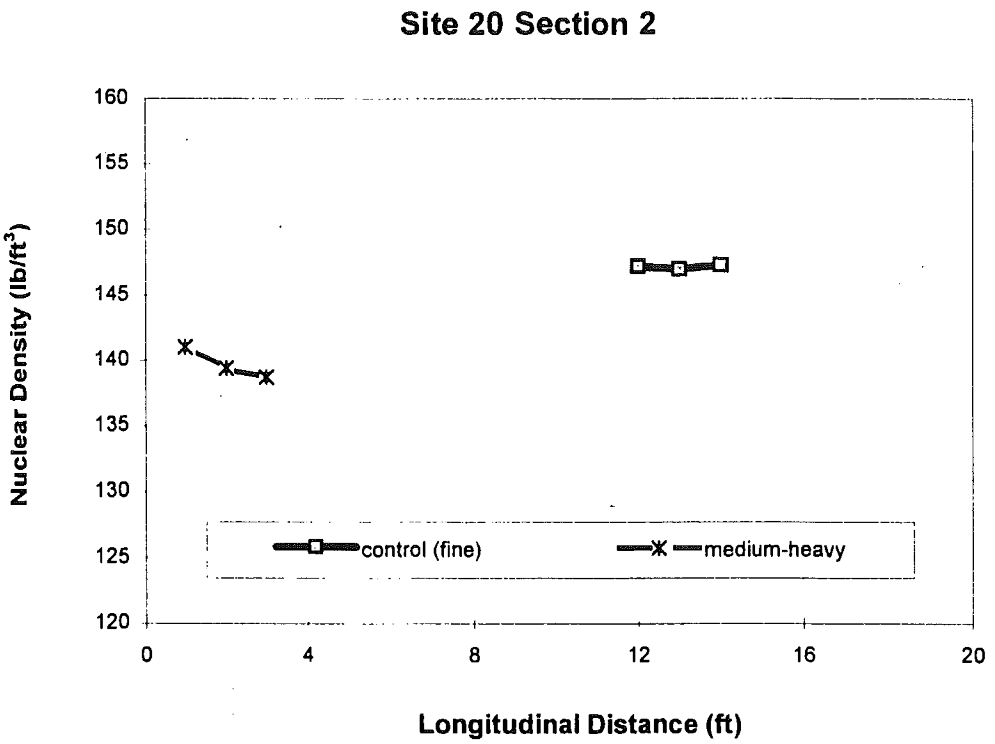


Figure 5.1 (continued) Distribution of Nuclear Density



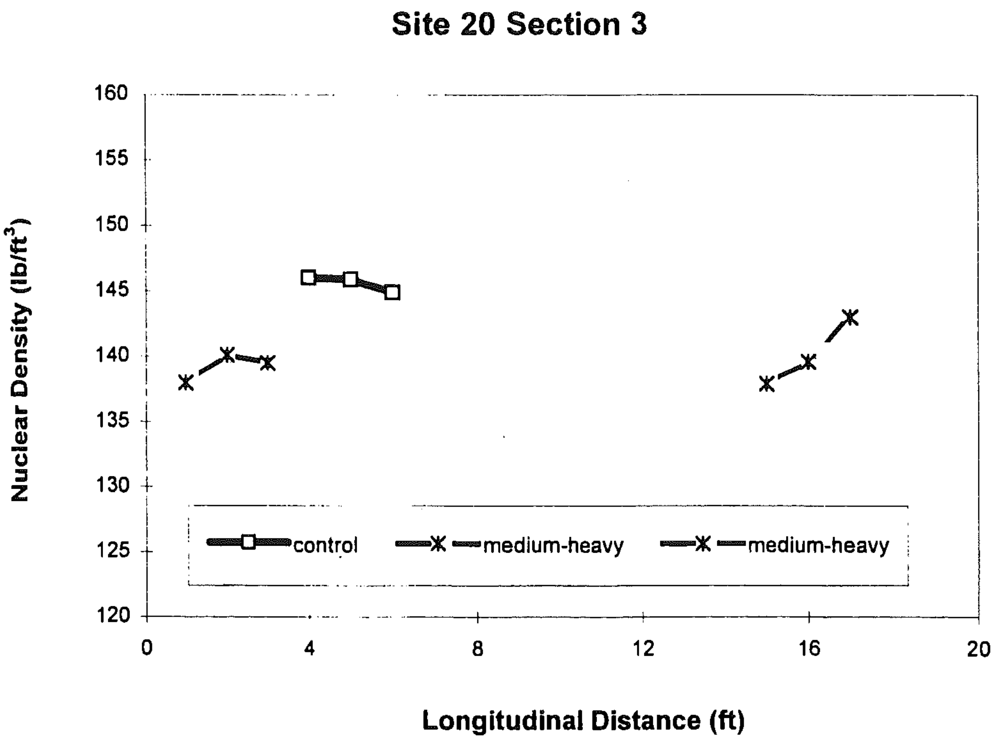
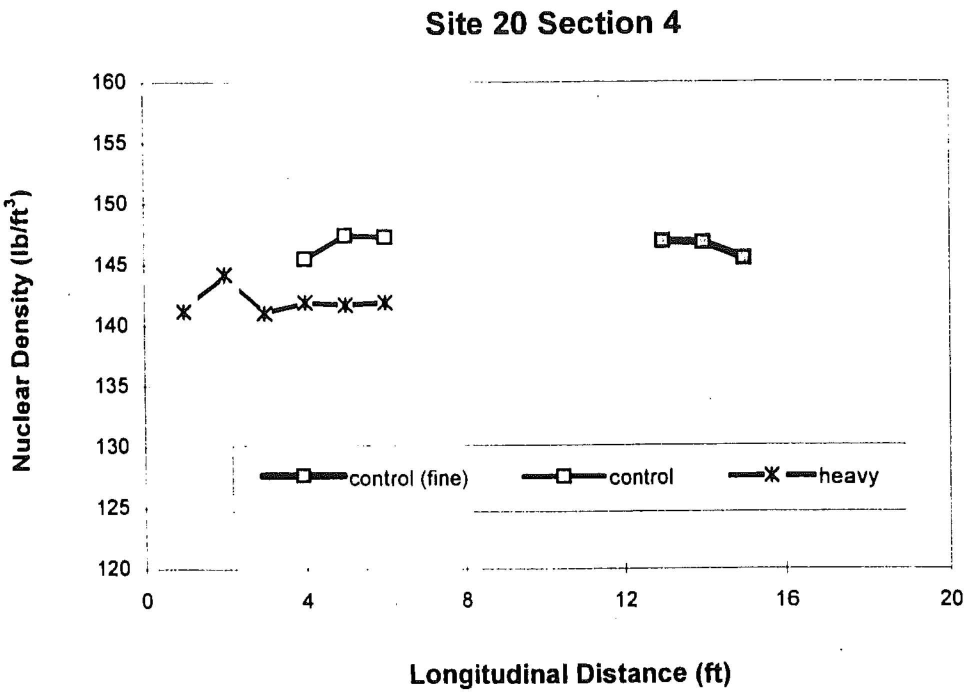


Figure 5.1 (continued) Distribution of Nuclear Density



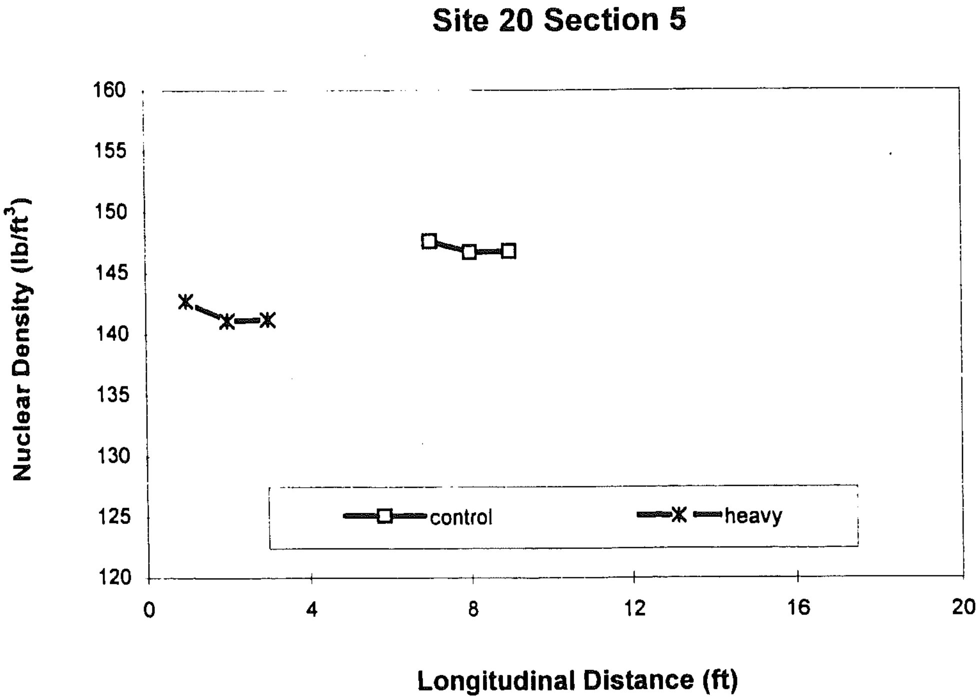
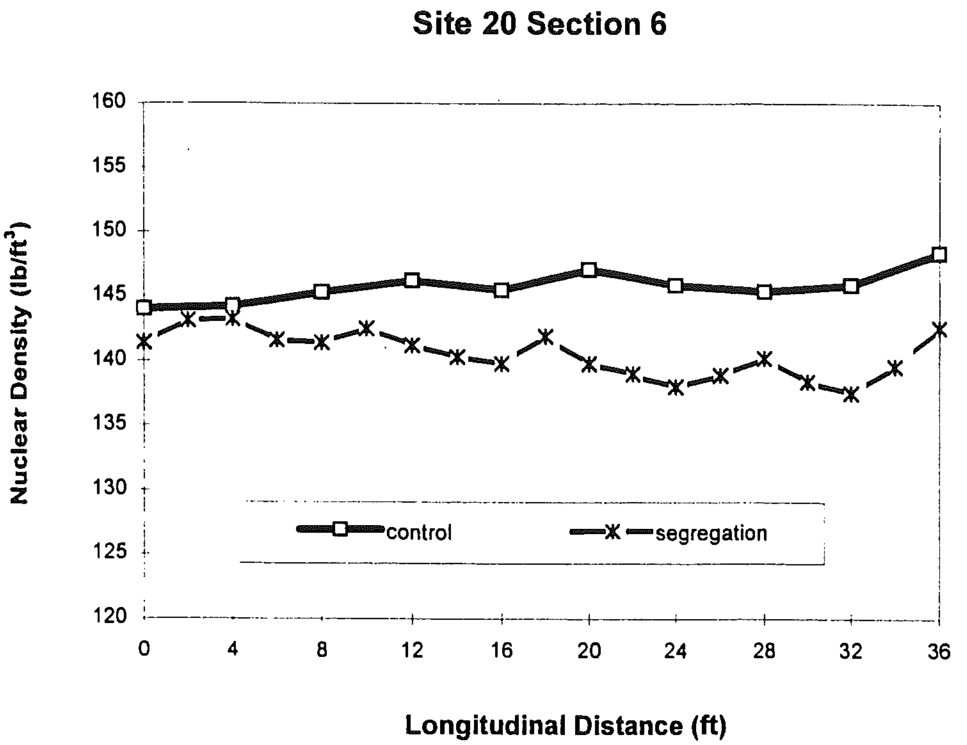


Figure 5.1 (continued) Distribution of Nuclear Density



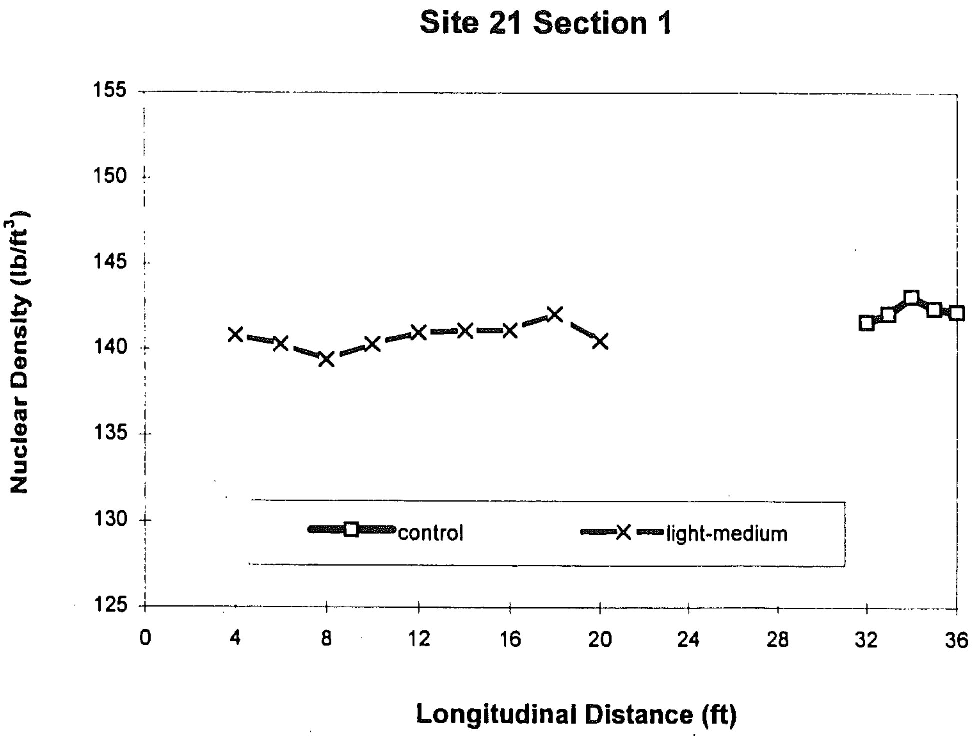
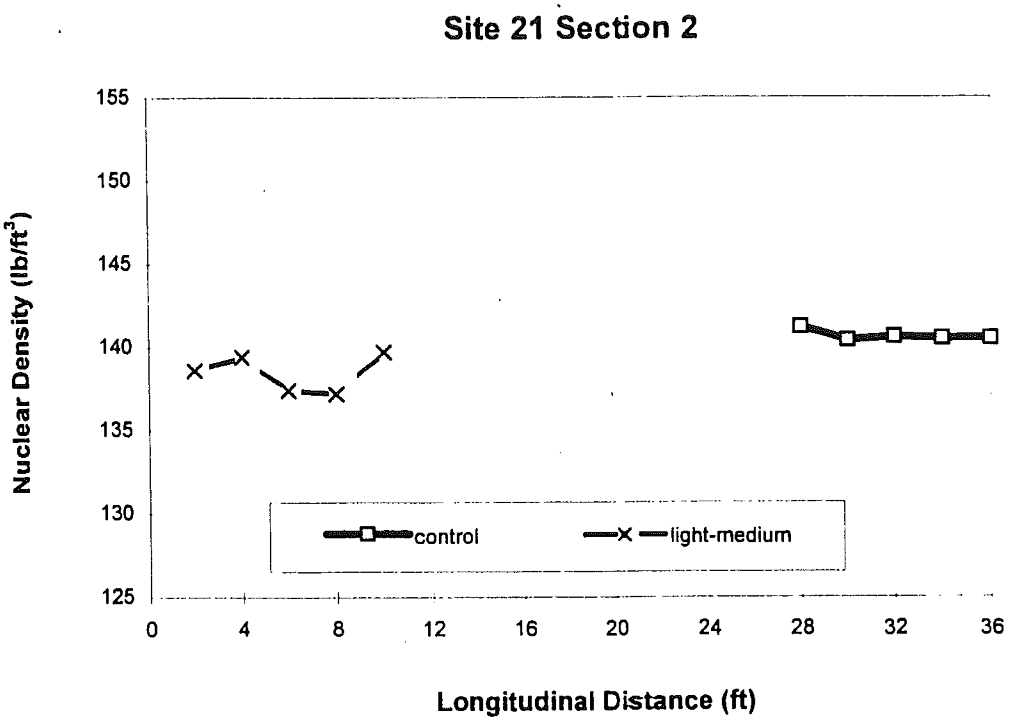


Figure 5.1 (continued) Distribution of Nuclear Density



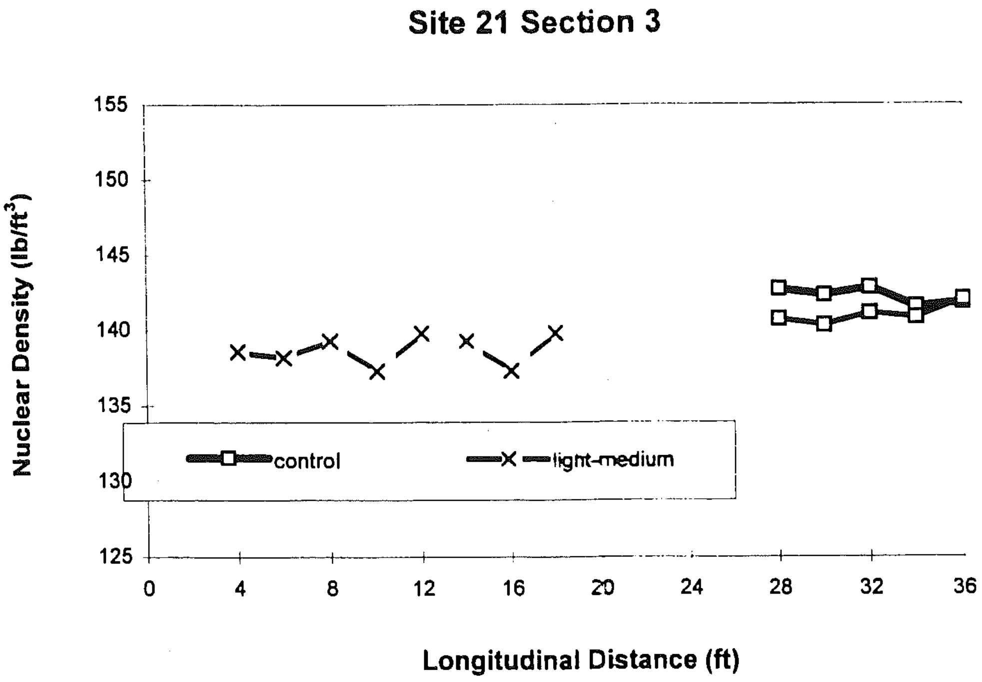


Figure 5.1 (continued) Distribution of Nuclear Density

Nuclear density measurements were taken along the transverse direction at 8 sites. Figure 5.2 shows the distribution of density values along the transverse direction. In general, the peak density values occur at the transverse distance of y=4 and y=10 ft; low density values at y=6. This reflects the effects of traffic loading compaction on density distribution along the transverse direction of pavements.

In summary, while it is evident that segregation can result in low density values, other factors such as compaction efforts provided by roller, traffic load in the wheel paths and placing operations can also lead to systematic variation in nuclear density measurements.

2.2 Variation of Nuclear Density Measurements

When a nuclear density device is 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 materials. and some backscattered radiation reaches the detector toward the opposite end of the gauge. Due to the heterogeneity of asphalt mixtures, variation of nuclear gauge readings is a concern regarding the accuracy of the results. Contributors to asphalt concrete heterogeneity include surface roughness, voids and composition of aggregate particles.

At site 22 where uncompacted asphalt mix was placed for demonstration purposes, replicate nuclear density measurements were taken with the gauge oriented in four different directions. The variation of nuclear density values at two locations is shown in Figure 5.3. It can be seen that the range of density difference at the location 0401 is 4.5 lb/ft^3 and the coefficient of variation is 1.8%. The differences in nuclear density measurements are contributed by the surface roughness. Since the specific surface void areas measured by nuclear density gauge vary for the four different directions (the contact area between gauge and surface), it is expected to have different readings. Another example is given by the location 0209 where the range in density is 1.8 lb/ft^3 for the reading taken from relatively uniform pavement areas. The coefficient of variation is only 0.6%. If nuclear density measurements were taken from smooth and uniform compacted pavement. lower variation would be expected.

The Phase I study concluded that nuclear density measurements have high variation at segregated sites. Therefore, the coefficient of variation, the ratio of the standard deviation to mean value, was compared for samples with different degrees of segregation. Figure 5.4 shows the average coefficient of variation for samples with different degree of segregation using nuclear density values from all 19 sites. It can be seen that two categories exist: one includes control, light and light-to-medium samples with mean coefficient of variation less than 0.9%, the other includes medium, medium to heavy, and heavy segregated samples with the mean coefficient of variation more than 1.3%. This suggests that more severely segregated samples have higher variation in nuclear density measurements.

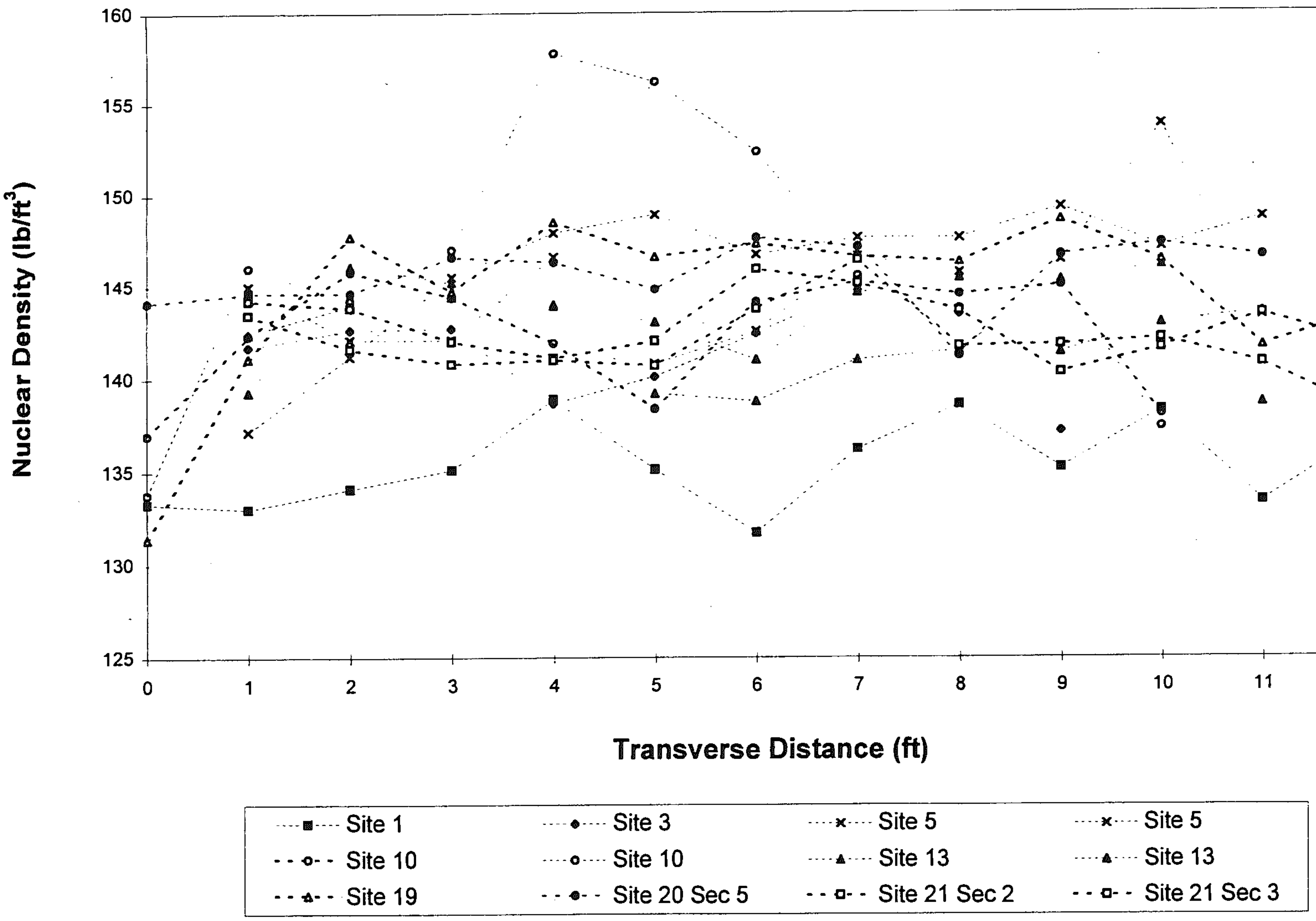
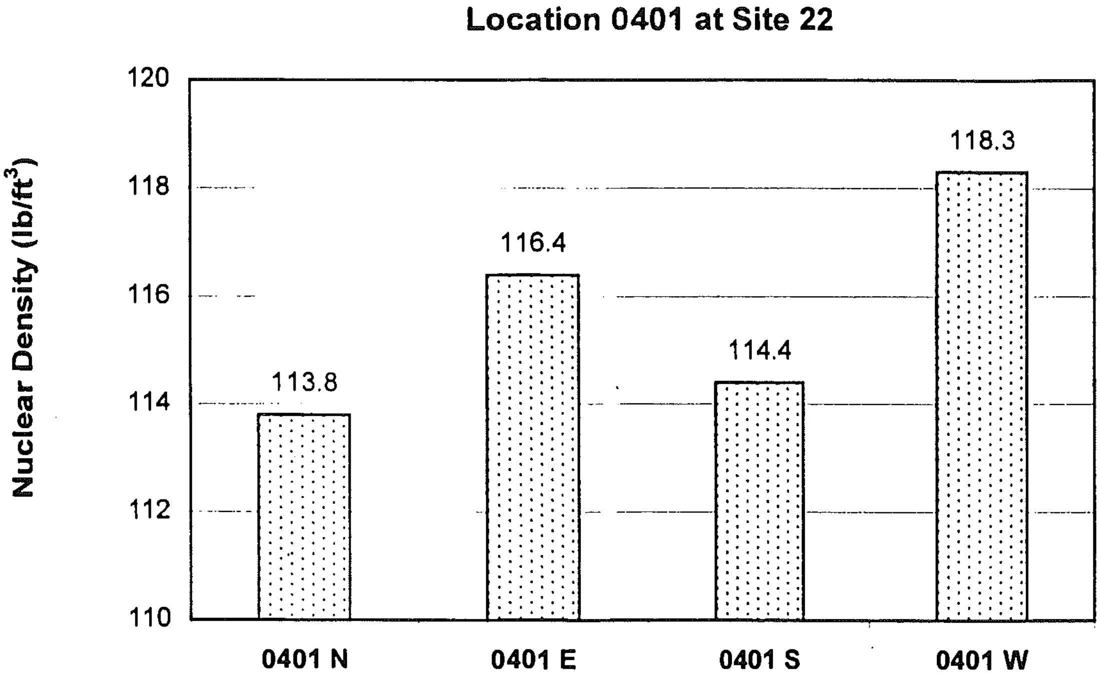


Figure 5.2 Nuclear Density Variation in the Transverse Direction



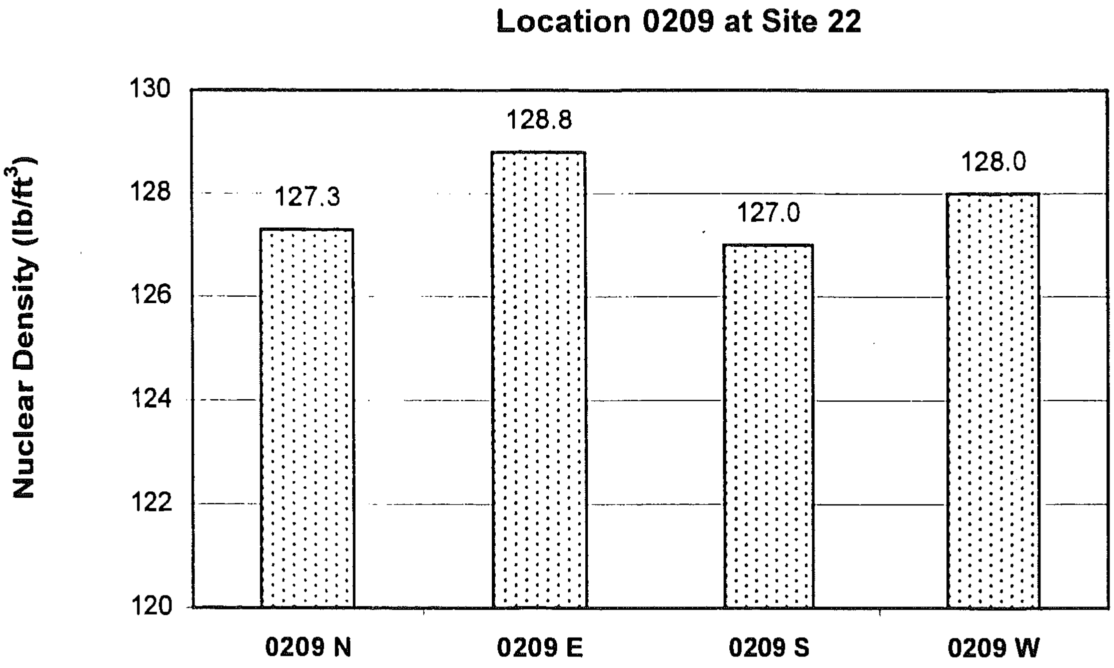


Figure 5.3 Variation of Nuclear Density Values at Site 22
(taken at same spot from four different directions)

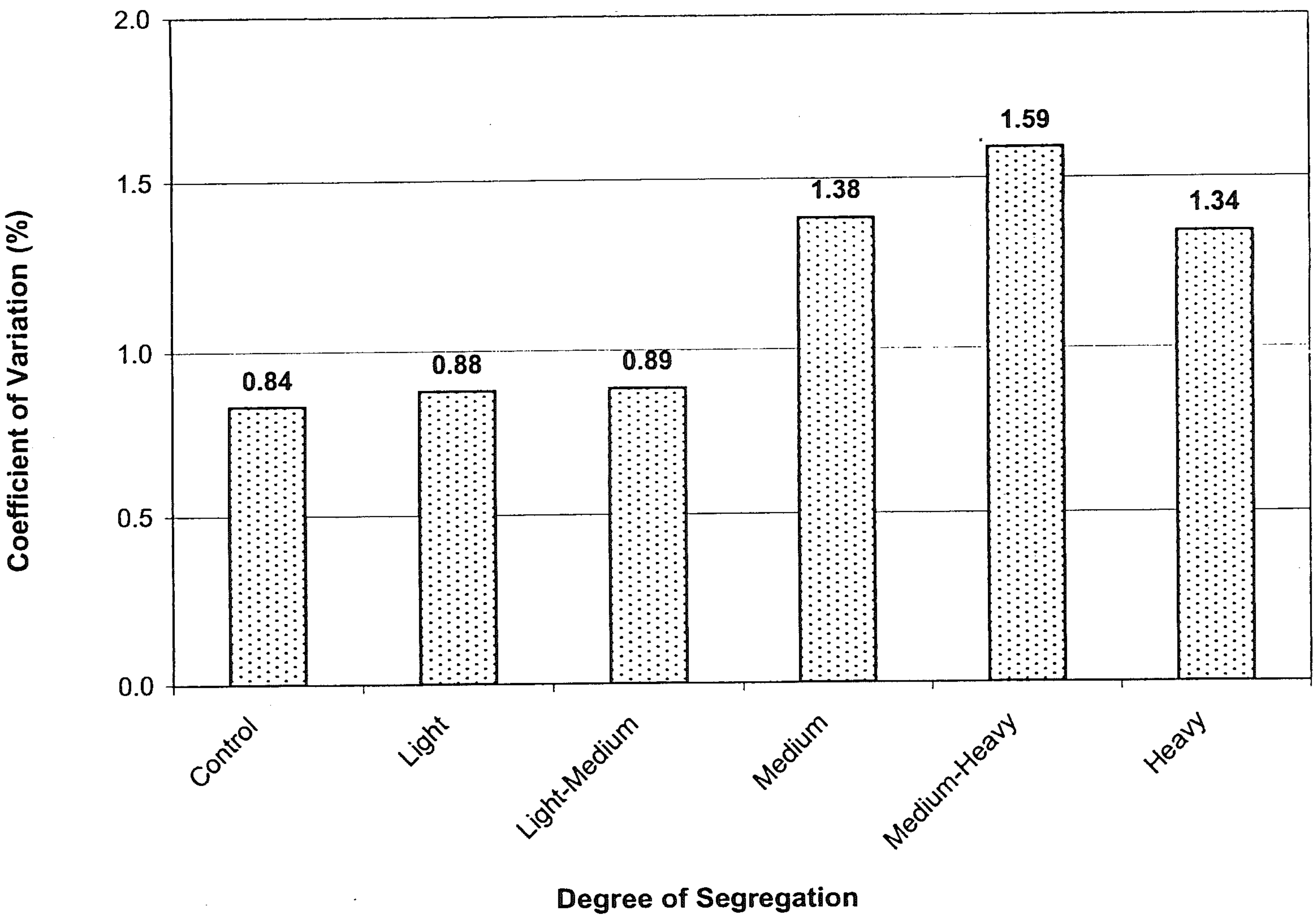


Figure 5.4 Mean Coefficient of Variation of Nuclear Density for Different Degrees of Segregation

2.3 Accuracy of Nuclear-Measured Density Values

The expedient tests to be developed for field use would rely entirely on nuclear-measured density values. To understand the characteristics of segregated areas, it is important to investigate the relationships between nuclear gauge densities and actual core densities. Both air-dry density and SSD density were measured. Linear regression analyses 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 5.2 for all 12 sites where cores were taken.

From the table, nuclear-measured density is not as strongly correlated with lab density as might be expected from one not familiar with previous studies. However, similar trends have been measured by Kennedy et al. (1989), Sander et al. (1994) and Schmitt et al. (1997).

Nuclear density readings were found to be best correlated with SSD lab density measurements of the surface course core segments, different from the conclusion made in the previous project that air-dry density was correlated better with nuclear density. In general, the coefficients of determination (R^2) ranged between 0.50 and 0.70 except sites 15, 16 and 21 where cracks already existed in the specimens. As the R^2 values increase, 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. Scatter plots of the combined data from all sites are illustrated in Figures 5.5 and 5.6 based on 377 data points (cores). The linear regression equations are:

$$\text{SSD Density} = 0.62 \times \text{Nuclear Density} + 57.4 \ (\text{lb/ft}^3)$$

$$\text{Air-dry Density} = 0.50 \times \text{Nuclear Density} + 74.5 \ (\text{lb/ft}^3)$$

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. However, the fitted slopes are less than 1 and on the order of 0.5 to 0.6. This indicates that the decrease in nuclear density in low-density areas is greater than for lab density. A unit decrease in lab densities corresponds to about 1.4 to 1.5 decrease in nuclear density. The conclusion is that very low nuclear density values deviated significantly from low lab density, suggesting that low nuclear values reflect both 1.) low true density obtained from lab tests and 2.) an additional reduction due to surface voids.

3.0 t-TEST ANALYSES ON NUCLEAR DENSITY VALUES

As mentioned before, the main hypothesis for development of an expedient field test for segregation is that a segregated area with an accumulation of coarse aggregates will have more voids that lead to comparatively low actual density values and even lower nuclear density readings than a uniform area, provided the compaction efforts are similar. Therefore,

Table 5.2 Linear Regression Data for Lab Density Predicted by Nuclear Density

	Correlation between air-dry and nuclear	**Correlation between SSD and nuclear**
Site 1	Air-dry=0.35×Nuc+95.2, R^2=0.55	SSD=0.59×Nuc+61.4, R^2=0.73
Site 3	Air-dry=0.71×Nuc+43.6, R^2=0.72	SSD=0.82×Nuc+26.8, R^2=0.76
Site 5	Air-dry=0.64×Nuc+54.7, R^2=0.65	SSD=0.88×Nuc+18.9, R^2=0.76
Site 10	Air-dry=0.42×Nuc+86.6, R^2=0.49	SSD=0.48×Nuc+77.2, R^2=0.55
Site 13	Air-dry=1.07×Nuc-6.6, R^2=0.68	SSD=1.11×Nuc-12.2, R^2=0.69
Site 15	Air-dry=0.20×Nuc+116.3, R^2=0.10	SSD=0.34×Nuc+95.2, R^2=0.27
Site 16	Air-dry=0.47×Nuc+79.4, R^2=0.33	SSD=0.65×Nuc+53.1, R^2=0.43
Site 17	Air-dry=0.99×Nuc+3.9, R^2=0.79	SSD=1.013×Nuc+0.39, R^2=0.78
Site 18	Air-dry=0.51×Nuc+73.1, R^2=0.79	SSD=0.65×Nuc+52.7, R^2=0.81
Site 19	Air-dry=0.37×Nuc+96.7, R^2=0.77	SSD=0.23×Nuc+117.6, R^2=0.60
Site 20	Air-dry=0.49×Nuc+77.7, R^2=0.61	SSD=0.63×Nuc+57.8, R^2=0.68
Site 21	Air-dry=-0.16×Nuc+166.4, R^2=0.06	SSD=0.20×Nuc+113.9, R^2=0.12

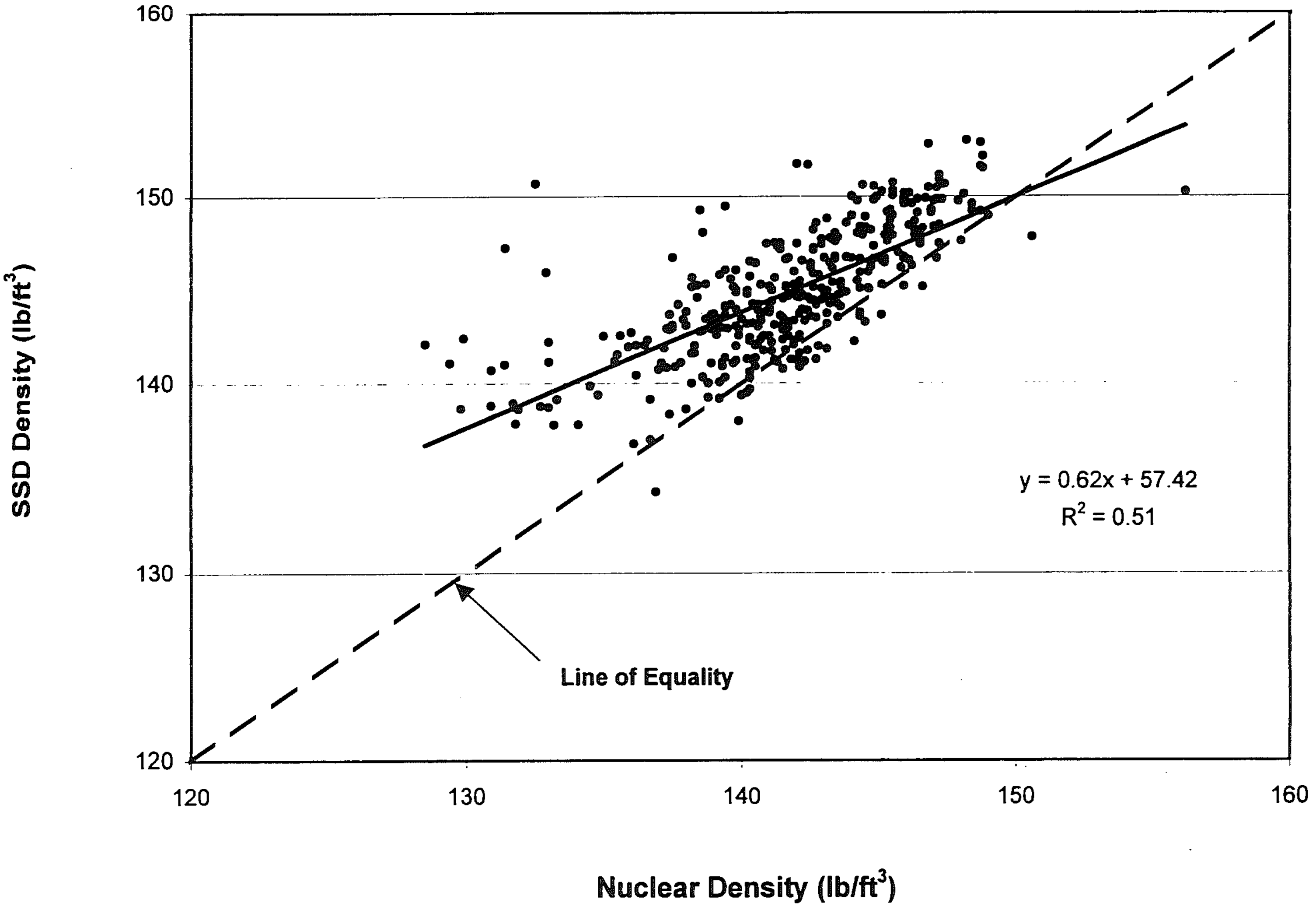


Figure 5.5 Regression Plot between Nuclear Density and SSD Density

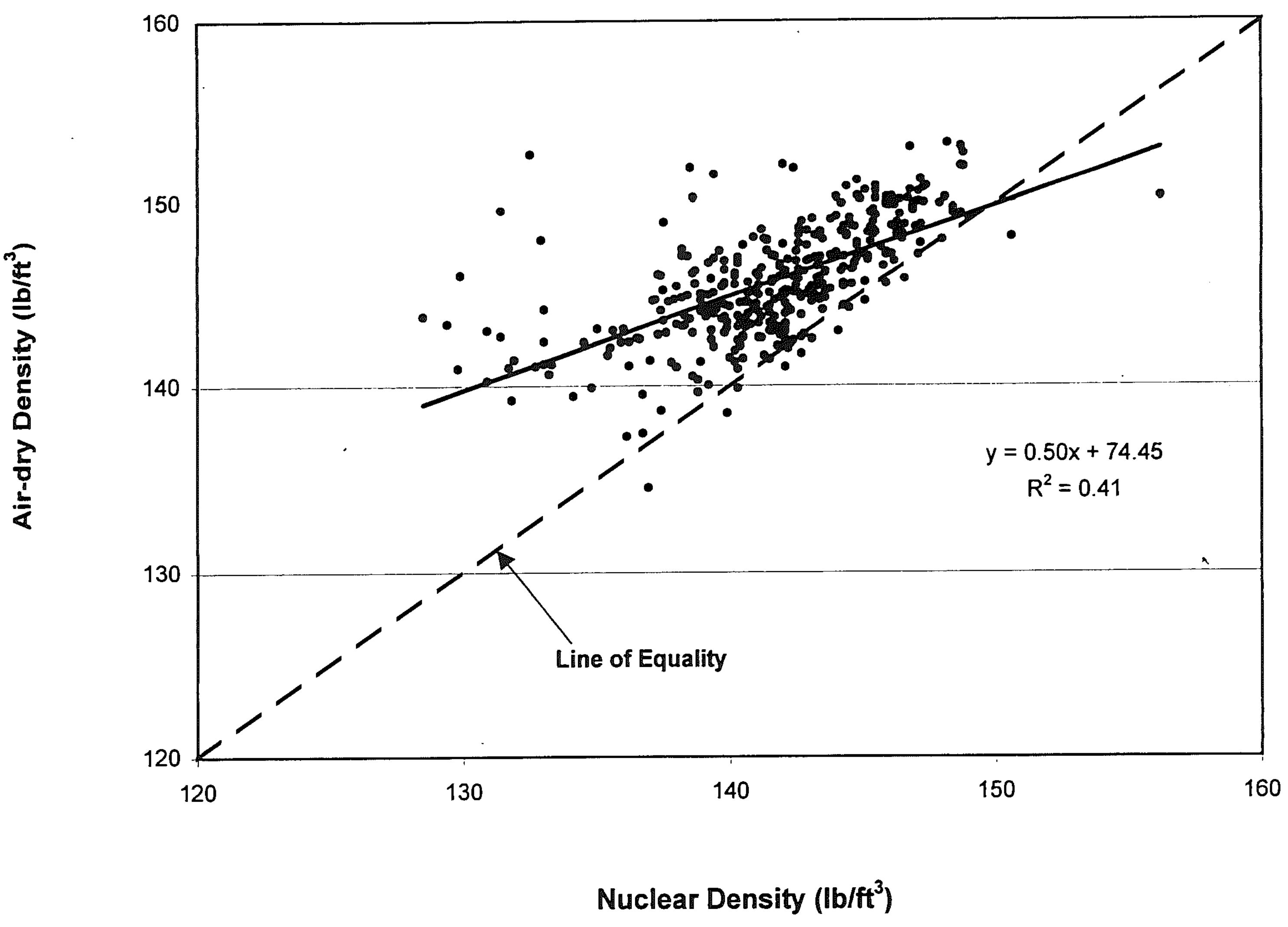


Figure 5.6 Regression Plot between Nucler Density and Air-dry Density

statistical tests performed on the nuclear density data can be used to assess the significance of density differences.

3.1 t-Test and p-Value

The most straightforward statistical test for two-sample comparison is the t-test. Paired samples (sets of measurements) with different visually-mapped severity of segregation are compared. t-tests compare the means of two samples to see if their differences are within the range that would be expected to be found within the realm of chance variation. A null hypothesis H_0 is made, that there is no significant difference in the mean values. The test statistic employed is:

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

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

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

where s_1^2 and s_2^2 are the sample variances of the two samples given by the following expression:

$$s^2 = \frac{\sum (x_i - \bar{x})^2}{n - 1}$$

In the traditional statistical approach, a level of confidence, say 95%, is adopted and two t values are computed, based on the actual data and a “critical" t-value associated with the confidence level and sample size. If the actual t-value exceeds the critical t-value, the observed difference in means is considered “rare”, the null hypothesis is rejected, and a statistically significant difference is concluded.

Using modern spreadsheet programs instead of tables permits one to forego pre-setting confidence level and determine the precise level of confidence at which the change from accepting to rejecting the null hypothesis would occur. The lower the p-value, the greater the statistical confidence in stating the differences are significant. Hence, a 99% confidence level indicates that the differences in sample means ,for random draws from a common population, would be smaller than those observed 99 times out of 100. The p-value is 1 minus confidence level. Hence, for a 99 confidence level, the p-value is 0.01. In other words, p-value is a probability value that measures the extent to which the sample data are consistent with conclusions H_0.

3.2 Results of t-Test Analysis

At each site, the number of possible t-test comparisons is m(m-1)/2 where m is the number of samples. Every possible comparison was made. The results of t-tests for each comparison are presented in term of confidence level, as shown in Figure 5.7. Although actual confidence levels are reported, a minimum of 95% confidence level will be considered as a significant difference for the present discussion.

At **site 1**, there are three control samples: two within the grid and one outside. With 99% confidence, all three control samples are significantly different from all segregated samples (light, medium and heavy). This implies that the nuclear density differences correspond to visual segregation mapping. However, when samples were compared to other samples with the same degree of segregation, i.e., control to control or heavy to heavy, t-tests also, in some cases, indicated significant differences. An example is outside control to sample 2 control. In general, nuclear density comparisons between segregated samples and control samples exhibit significant differences. However, comparisons between two samples with the same severity of segregation also may show differences.

At **site 2**, one control sample was selected in the left turning lane outside the grid; other segregated samples are within the grid. Two samples with medium segregation were selected; however, one did not have a good consistency of visual classification. Two samples with heavy segregation were selected with good consistency of visual inspection. Unfortunately, the density readings for the control sample did not show any significant difference from that for other segregated samples. It was subsequently recognized that the control area should be selected within the same mat as the segregated samples to avoid variation of construction practice. Another sample rich with fine material (mapped as light segregation) had relatively high nuclear density values that were significantly different from other samples.

At **site 3**, the degree of segregation ranged between medium and light, but was not consistent described by visual inspection. For the two-sample comparisons, one in-grid control sample had low density values and did not reveal any significant difference from segregated samples. Another problem at this site was that comparison between two control samples showed a density difference with a confidence level more than 99.95%.

Site number 4 was not sampled (see Chapter 2).

At **site 5**, no significant density difference was found between heavy segregation samples and control samples. This may be because the materials at these samples were not placed in the same day (locations of two samples are in different mats) or received different compaction efforts. The control sample was located across the longitudinal joint outside the grid; the heavy segregation sample was located across the transverse joint from most other samples. Two medium segregation samples were compared with each other; the t-test shows 99.9 % significant difference. This result is not as expected. The sample with more fine materials

Site 1

		Control	Sample 2	Sample 5	Sample 1	Sample 4	Sample 3	Sample 6
		Outside	**Control**	**Control**	**Light**	**Medium**	**Heavy**	**Heavy**
Control	**Outside**							
Sample 2	**Control**	***99.2***						
Sample 5	**Control**	71.7	89.5					
Sample 1	**Light**	***99.9***	***100.0***	***100.0***				
Sample 4	**Medium**	***100.0***	***100.0***	***100.0***	***100.0***			
Sample 3	**Heavy**	***100.0***	***100.0***	***100.0***	***100.0***	91.8		
Sample 6	**Heavy**	***100.0***	***100.0***	***100.0***	***100.0***	54.5	*98.8*	

Site 2

		Control	Sample 3	Sample 1	Sample 4	Sample 2	Sample 5
		Outside	**L (Fine)**	**Medium**	**Medium**	**Heavy**	**Heavy**
Control	**Outside**						
Sample 3	**L (Fine)**	***100.0***					
Sample 1	**Medium**	84.3	***100.0***				
Sample 4	**Medium**	*95.4*	***100.0***	39.3			
Sample 2	**Heavy**	22.9	***100.0***	92.7	*98.7*		
Sample 5	**Heavy**	61.0	***100.0***	91.2	*95.9*	56.8	

Site 3

		Sample 1	Sample 5	Sample 2	Sample 3	Sample 4
		Control	**Control**	**L (Fine)**	**Medium**	**Medium**
Sample 1	**Control**					
Sample 5	**Control**	***100.0***				
Sample 2	**L (Fine)**	***100.0***	90.9			
Sample 3	**Medium**	***100.0***	81.9	*98.8*		
Sample 4	**Medium**	***100.0***	80.7	*98.8*	6.3	

Site 5

		Outside	Transverse	Sample 2	Sample 3	Sample 4	Sample 5	Sample 1
		Control	**Control**	**L (Fine)**	**Light**	**Medium**	**Medium**	**Heavy**
Outside	**Control**							
Transverse	**Control**	***100.0***						
Sample 2	**L (Fine)**	***100.0***	55.0					
Sample 3	**Light**	81.0	***100.0***	***100.0***				
Sample 4	**Medium**	86.6	***100.0***	***100.0***	4.1			
Sample 5	**Medium**	***100.0***	***100.0***	***100.0***	***99.9***	***99.9***		
Sample 1	**Heavy**	*98.7*	***99.9***	***100.0***	***99.5***	***99.7***	***100.0***	

Site 6

		Sample 3	Sample 5	Sample 4	Sample 1	Sample 2	Sample 6	Sample 7
		Control	**Control**	**M-L**	**Heavy**	**Heavy**	**Heavy**	**Heavy**
Sample 3	**Control**							
Sample 5	**Control**	49.5						
Sample 4	**M-L**	***99.9***	***100.0***					
Sample 1	**Heavy**	***99.9***	***100.0***	84.7				
Sample 2	**Heavy**	***100.0***	***100.0***	82.0	51.3			
Sample 6	**Heavy**	***100.0***	***100.0***	94.8	31.9	79.3		
Sample 7	**Heavy**	***100.0***	***100.0***	***100.0***	91.4	***99.8***	81.4	

Note: ***100.0*** implies confidence level ³ *99.95*

Figure 5.7 Results of t-Tests Using Confidence Level

Site 7		Sample 1	Sample 4	Sample 3	Sample 2
		Control	**Control**	**M-L**	**M-H**
Sample 1	**Control**				
Sample 4	**Control**	12.8			
Sample 3	**M-L**	*100.0*	*100.0*		
Sample 2	**M-H**	*100.0*	*100.0*	*100.0*	

Site 8		Sample 2-3	Sample 7	Sample 1-4	Sample 5	Sample 6	Sample 8	Sample 9	Sample 10
		Seg	**Seg**	**None**	**None**	**None**	**None**	**None**	**None**
Sample 2-3	**Seg**								
Sample 7	**Seg**	17.7							
Sample 1-4	**None**	*100.0*	*99.9*						
Sample 5	**None**	*99.7*	*97.0*	*99.0*					
Sample 6	**None**	*100.0*	*100.0*	*96.2*	*100.0*				
Sample 8	**None**	*99.9*	*98.5*	*99.7*	21.5	*100.0*			
Sample 9	**None**	*99.9*	*98.1*	*99.5*	13.2	*100.0*	9.8		
Sample 10	**None**	*100.0*	*99.9*	34.3	*99.8*	*98.5*	*100.0*	*100.0*	

Site 9		Sample 2	Sample 6	Sample 1	Sample 4	Sample 5	Sample 3	Sample 7
		Control	**Control**	**Light**	**Light**	**Light**	**Light +**	**Light +**
Sample 2	**Control**							
Sample 6	**Control**	93.7						
Sample 1	**Light**	59.7	*100.0*					
Sample 4	**Light**	45.9	*98.5*	*99.7*				
Sample 5	**Light**	87.9	56.3	*100.0*	90.8			
Sample 3	**Light +**	62.5	*98.4*	*100.0*	51.3	85.4		
Sample 7	**Light +**	65.0	*98.2*	*100.0*	59.6	83.4	17.8	

Site 10		Control A	Control B	Sample 2	Sample 5	Sample 1	Sample 3	Sample 4
		Control	**Control**	**Light**	**Light**	**M-L**	**M-L**	**Medium**
Control A	**Control**							
Control B	**Control**	*99.5*						
Sample 2	**Light**	*100.0*	*100.0*					
Sample 5	**Light**	*99.8*	*100.0*	72.0				
Sample 1	**M-L**	*99.9*	*100.0*	*100.0*	94.5			
Sample 3	**M-L**	*100.0*	*100.0*	*99.9*	73.8	94.1		
Sample 4	**Medium**	*99.9*	*100.0*	51.6	22.7	*97.1*	85.3	

Site 11		Sample 3	Sample 5	Sample 1	Sample 2	Sample 4
		Control	**Control**	**Light**	**Light**	**Light**
Sample 3	**Control**					
Sample 5	**Control**	*99.9*				
Sample 1	**Light**	*99.8*	70.0			
Sample 2	**Light**	*99.9*	46.2	42.0		
Sample 4	**Light**	*99.8*	46.0	27.1	9.1	

Note: ***100.0*** implies confidence level ≥ ***99.95***

Figure 5.7 (continued) Results of t-Tests Using Confidence Level

Site 13		Sample 3	Sample 7	Sample 8	Sample 2	Sample 1	Sample 4	Sample 5	Sample 6
		Control	**Control**	**Control**	**Light**	**M-L**	**M-L**	**Medium**	**Heavy**
Sample 3	**Control**								
Sample 7	**Control**	*99.7*							
Sample 8	**Control**	92.1	*99.9*						
Sample 2	**Light**	*100.0*	*100.0*	*100.0*					
Sample 1	**M-L**	*100.0*	*98.4*	*100.0*	*99.4*				
Sample 4	**M-L**	*99.9*	56.7	*100.0*	*100.0*	*95.3*			
Sample 5	**Medium**	*100.0*	*98.2*	*99.9*	75.1	94.1	*97.6*		
Sample 6	**Heavy**	*100.0*	*100.0*	*100.0*	72.4	*99.7*	*99.9*	33.3	

Site 14		Sample 4	Sample 7	Sample 2	Sample 6	Sample 3	Sample 1	Sample 5
		Control	**Control**	**Light**	**Light**	**M-L**	**Medium**	**Medium**
Sample 4	**Control**							
Sample 7	**Control**	*100.0*						
Sample 2	**Light**	*100.0*	93.2					
Sample 6	**Light**	*100.0*	*100.0*	*99.8*				
Sample 3	**M-L**	*100.0*	*100.0*	*100.0*	*98.4*			
Sample 1	**Medium**	*100.0*	*100.0*	*100.0*	*99.9*	12.7		
Sample 5	**Medium**	*100.0*	*100.0*	*100.0*	*100.0*	84.9	*95.9*	

Site 15		Sample 2	Sample 4	Sample 7	Sample 8	Sample 9	Sample 1	Sample 3	Sample 5	Sample 6
		Control	**Control**	**Outside**	**Control**	**Control**	**Light**	**Light**	**Light**	**M-H**
Sample 2	**Control**									
Sample 4	**Control**	*96.8*								
Sample 7	**Outside**	91.0	17.9							
Sample 8	**Control**	70.3	69.2	68.1						
Sample 9	**Control**	*99.2*	*98.8*	*96.6*	*99.4*					
Sample 1	**Light**	*96.0*	38.1	13.6	79.1	*96.1*				
Sample 3	**Light**	*98.2*	84.9	65.8	94.3	84.6	62.5			
Sample 5	**Light**	*99.8*	*99.8*	*99.3*	*99.9*	46.3	*99.2*	*95.8*		
Sample 6	**M-H**	*100.0*	*100.0*	*100.0*	*100.0*	*99.8*	*100.0*	*100.0*	*99.4*	

Note: *100.0* implies confidence level ³ *99.95*

Figure 5.7 (continued) Results of t-Tests Using Confidence Level

Site 16		Sample 1	Sample 2	Sample 5	Sample 8	Sample 9	Sample 11	Sample 12
		Control	**Control**	**Control**	**Control**	**Control**	**Control**	**Control**
Sample 1	**Control**							
Sample 2	**Control**	*98.1*						
Sample 5	**Control**	91.0	30.0					
Sample 8	**Control**	9.8	58.1	66.3				
Sample 9	**Control**	*97.0*	61.3	65.5	55.4			
Sample 11	**Control**	55.7	*95.9*	*95.8*	52.9	*97.4*		
Sample 12	**Control**	*99.8*	71.3	12.3	84.3	*95.9*	*99.7*	
Sample 4	**Light**	75.0	*100.0*	*97.7*	38.9	*100.0*	17.3	*100.0*
Sample 3	**L-M**	*100.0*	*100.0*	*100.0*	*96.5*	*100.0*	*97.5*	*100.0*
Sample 6	**L-M**	76.3	*97.2*	*96.0*	65.6	*98.8*	38.9	*99.8*
Sample 10	**L-M**	91.8	*99.9*	*99.6*	74.0	*100.0*	36.5	*100.0*
Sample 13	**Medium**	*99.0*	*100.0*	*99.9*	86.9	*100.0*	70.3	*100.0*
Sample 7	**M-H**	*99.9*	*100.0*	*99.9*	*95.9*	*100.0*	*96.4*	*100.0*

Site 16		Sample 4	Sample 3	Sample 6	Sample 10	Sample 13	Sample 7
		Light	**L-M**	**L-M**	**L-M**	**Medium**	**M-H**
Sample 4	**Light**						
Sample 3	**L-M**	*100.0*					
Sample 6	**L-M**	55.4	86.5				
Sample 10	**L-M**	69.6	*99.5*	19.2			
Sample 13	**Medium**	*95.5*	*99.1*	18.2	58.4		
Sample 7	**M-H**	*99.8*	1.7	82.6	*98.6*	*96.9*	

Site 19		Sample 1	Sample 2	Sample 7	Sample 3	Sample 5	Sample 6	Sample 4	Sample 8
		Control	**Control**	**Control**	**Medium**	**Medium**	**M-H**	**Heavy**	**Heavy**
Sample 1	**Control**								
Sample 2	**Control**	17.2							
Sample 7	**Control**	*98.6*	87.1						
Sample 3	**Medium**	*98.5*	*99.7*	*100.0*					
Sample 5	**Medium**	*100.0*	*100.0*	*100.0*	*96.5*				
Sample 6	**M-H**	*100.0*	*100.0*	*100.0*	72.8	87.7			
Sample 4	**Heavy**	*100.0*	*100.0*	*100.0*	*100.0*	*99.7*	*100.0*		
Sample 8	**Heavy**	*99.6*	*100.0*	*100.0*	88.9	6.2	70.3	*97.1*	

Note: *100.0* implies confidence level ³ *99.95*

Figure 5.7 (continued) Results of t-Tests Using Confidence Level

Site 20

Section 1

		Sample 3	Sample 1	Sample 2
		Control	**Heavy**	**Heavy**
Sample 3	**Control**			
Sample 1	**Heavy**	*99.2*		
Sample 2	**Heavy**	*99.8*	81.3	

Section 4

		Sample 11	Sample 10	Sample 9
		Control	**C (Fine)**	**Heavy**
Sample 11	**Control**			
Sample 10	**C (Fine)**	31.5		
Sample 9	**Heavy**	*99.9*	*99.9*	

Section 2

		Sample 4	Sample 5
		Heavy	**Fine**
Sample 4	**Heavy**		
Sample 5	**Fine**	*100.0*	

Section 5

		Sample 13	Sample 12
		Control	**Heavy**
Sample 13	**Control**		
Sample 12	**Heavy**	*99.9*	

Section 3

		Sample 8	Sample 6	Sample 7
		Control	**M-H**	**M-H**
Sample 8	**Control**			
Sample 6	**M-H**	*99.9*		
Sample 7	**M-H**	*97.6*	41.6	

Section 6

		Sample 14A	Sample 14B	Sample 14C	Sample 14D	Sample 15
		Heavy	**M-H**	**Medium**	**L-M**	**Control**
Sample14A	**Heavy**					
Sample 14B	**M-H**	90.8				
Sample 14C	**Medium**	*98.8*	81.8			
Sample 14D	**L-M**	*99.9*	94.5	42.1		
Sample 15	**Control**	*100.0*	*100.0*	*100.0*	*100.0*	

Site 21

Section 1

		Sample 2	Sample 1
		Control	**L-M**
Sample 2	**Control**		
Sample 1	**L-M**	*99.8*	

Section 2

		Sample 4	Sample 3
		Control	**L-M**
Sample 4	**Control**		
Sample 3	**L-M**	*99.7*	

Section 3

		Sample 7	Sample 8	Sample 5	Sample 6
		Control	**Control**	**L-M**	**L-M**
Sample 7	**Control**				
Sample 8	**Control**	*98.8*			
Sample 5	**L-M**	*99.8*	*100.0*		
Sample 6	**L-M**	*98.2*	*99.8*	15.1	

Note: *100.0* implies confidence level ≥ *99.95*

Figure 5.7 (continued) Results of t-Tests Using Confidence Level

has significant density differences with other samples. The results at site 5 indicated the potential variability of nuclear density values from one mat or day's paving work to another.

Site 6 is a good example of results that fit the hypothesis stated in Chapter 1 Section 5.0. Based on the results of two-sample comparison, control samples indicated significant density differences from segregated samples. Most comparisons among samples with heavy segregation did not show any significant differences from each other. An exception is sample 2 against sample 7.

Site 7 is a site with typical centerline segregation. Two samples were selected along the strip of centerline segregation. One control sample was selected at the left side of the strip; the other at the right side. The results of two-sample comparison are as expected. The main apparent conclusion drawn is segregated and control samples are distinguishable using both nuclear density data and visual observations. However, later analysis of "control" sites without segregation (sites 17 and 18) revealed that density differences in centerline and wheel-path samples could be found in areas without centerline segregation.

Site 8 is also a site with centerline segregation. To relate present studies to observations from the past project, a six by six sampling grid was laid out and 36 nuclear readings were analyzed using MBITSEG1.xls. ANOVA indicated significant column differences with p-value 3×10^{-8}, a very significant result. Multiple comparison tests found that two columns (x=3.5 and x=6.5) have consistently high density values. However, the column (x=4) with segregation was not clearly identified regarding severity of segregation. Twelve more nuclear sampling locations were selected between y=34 and 36 ft. These 12 nuclear readings combined with the previous 36 readings were analyzed again by t-tests. From the matrix shown in Figure 5.7, segregated samples have significant density differences from non-segregated samples. However, if non-segregated samples were compared with each other, the results are mixed. Therefore, it can be seen that even in normal pavements without any visualized segregation, nuclear density values may vary significantly among samples.

At **site 9**, two segregation strips were observed at this site. Three samples were mapped as light segregation; two samples as light + which means more severe than light; and two as control. However, these two control samples did not show significant difference in nuclear density from other light or light + samples. One control sample with mean 143.8 lb/ft^3 had large variation (σ=3.30 lb/ft^3). The other control sample had the lowest average value in nuclear density among all seven samples. Thus, light-segregated strips cannot be identified by t-tests.

Site 10 was recognized as a site with continuous segregation. The degree of segregation was classified as either light or medium. However, visual inspection did not give consistent results for degree of segregation. It can be seen from Table 5.1 that the label of visual segregation is not consistent with the average value of nuclear density readings. The density values for light-medium sample are higher than that for light segregated sample. If the five segregated samples are compared with each other, the interpretation of results based on the significance level is limited because the visual difference in segregation is equal or less than one degree (light, light-medium or medium). If the segregated samples are compared to four control samples, the results indicated significant difference. However, if control samples are compared with each other, significant differences are also found, with the confidence level as high as approximately 99.95%. This implied that a single criterion (significance level) to quantitatively predict the existence of segregation is not enough. Other factors, such as locations of control areas and compaction efforts, would need to be taken into account.

Site 11 was identified as a site with continuous segregation. Based on the visual inspection, the classifications are consistent and find that only light segregation occurs in this site. Three segregated samples and two control samples were selected within the grid. If three light-segregated samples are compared with each other, the confidence level of a difference is below 95 %, and the null hypothesis is accepted. If light-segregated samples were compared to the control samples, results are mixed. Although several comparisons among light-segregated and control samples indicated significant differences, however, values violated the hypothesis the density values in the segregated area are lower than that in the control area. As is the case for site 9, it is difficult to locate light segregation using nuclear density measurements.

Site number 12 was not sampled.

Site 13 was selected as a site of continuous segregation, but was also mixed with several random spots. Based on the results of t-tests, comparisons among control and segregated samples indicated significant differences as expected.

Site 14 was selected as continuous segregation. No heavy segregation was identified by visual inspection. Two control samples showed significant differences from segregated samples with classifications ranging from light to medium. Comparisons between light and medium segregated samples also indicated significant differences. The same problem of finding differences among samples with the same severity of segregation was encountered.

At about this point in the study, it was noted that significant density differences could be present due to wheel-track compaction, as well as roller during construction. Therefore, the sampling locations at the following sites (sites 15 through 21) were selected such that control and segregated samples are located in a common linear strip and subject to similar compaction efforts.

Site 15 was mapped as having random segregation. To eliminate the previously-noted effects of compaction on density readings, comparisons for the samples in the same longitudinal line are considered. First, considering two control samples, two light segregation samples and one medium-heavy segregation sample located in the x=3 column, the medium-heavy segregation sample showed significant differences from both control samples. However, mixed results were obtained for comparisons among light and control samples. Second, considering one light segregation sample and two control samples located at x=0 column; similar findings were obtained that the light segregation sample can not be differentiated from the control samples. Two points are made: (1) if the effects of different compaction are eliminated, t-tests show significant differences between controls and a heavy-medium segregation sample and (2) under the same compaction efforts, light-segregated and control samples are not distinguishable.

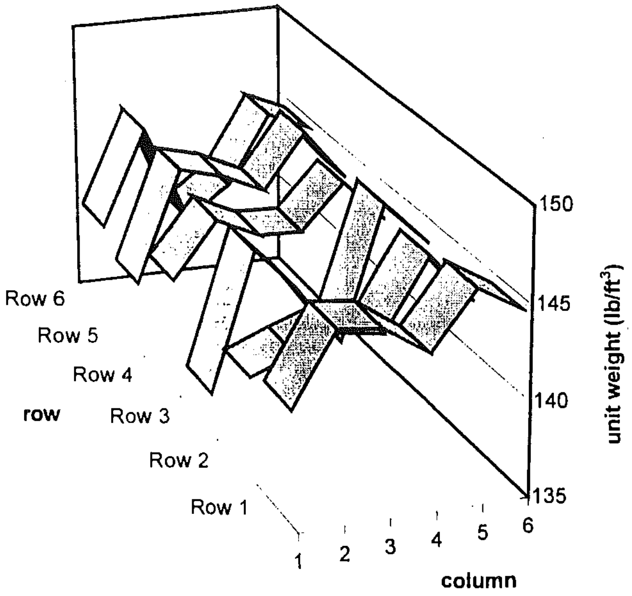
Site 16 was selected as continuous segregation. Seven control samples and six segregated samples ranging from light to heavy segregation were selected. Based on the matrix shown in Figure 5.6, three out of seven control samples have difficulty indicating differences from segregated samples. Among these three control samples, one control at x=6 having a relative low average value of nuclear density may not be a good selection of a control area; the other two control samples located at x=0 were unable to show differences from segregated samples. This is because the variation of nuclear density values within a sample is large. The conclusion of significant differences can not be made although the average density values of control sample is slightly higher than that of segregated samples.

Sites 17 and 18 were selected as *unsegregated* sites where no differences would be expected, to confirm the validity of the method. Each site was sampled with two 6 by 6 sampling grids. 3-D surface plots of density values were present shown in Figure 5.8. Unfortunately, the ANOVA indicated significant density differences. At site 17, results from two sampling grids are similar in that columns 2 and 6, located at x=3 and x=9 respectively, have higher density values. This is apparently because these locations are along the wheel paths and are compacted by traffic loads. At site 18, the nuclear density testing was completed right after overlay construction and before opening to public traffic, but the ANOVA also indicated significant density differences. Column 1 of both grids is close to a concrete curb and has low density values. The low density at column 1 is apparently contributed by lower compaction, similar to that observed at site 10. The findings at these two unsegregated sites again indicated significant density variations may exist in unsegergated pavements due to either roller compaction or traffic loading.

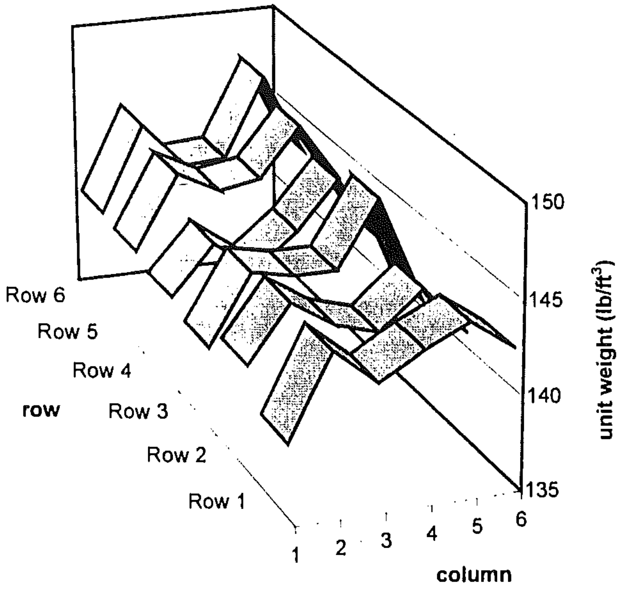
Site 19 was selected as a site with end-of-load segregation. All segregated samples were classified as medium or heavy severity level. Among 15 comparisons between control and segregated samples, t-tests indicated significant differences at 99 percent confidence level for 14 comparisons. The remaining comparison indicated difference at the 95 percent confidence level. In summary, segregated samples are differentiable from control samples. However, if medium-segregated samples were compared to heavy-segregated samples, no consistent results are obtained.

Sites 20 and 21 were divided into several sections spread along the road at distances of several hundred feet. At each section, at least one control and one segregated sample were selected that were laid out in the same strip along the longitudinal direction to avoid the effects of compaction due to roller or traffic loads. As shown in Figure 5.7, the comparisons between the control and segregated samples at each section indicated significant nuclear density difference with the confidence levels at 97 percent or above. These results support the project hypothesis that segregated sample have low nuclear density readings compared to control sample.

Site 22 was as a site specially paved for demonstration purposes to check the density variation behind the paver without compaction. The 3-D surface plots (Figure 5.8) show low

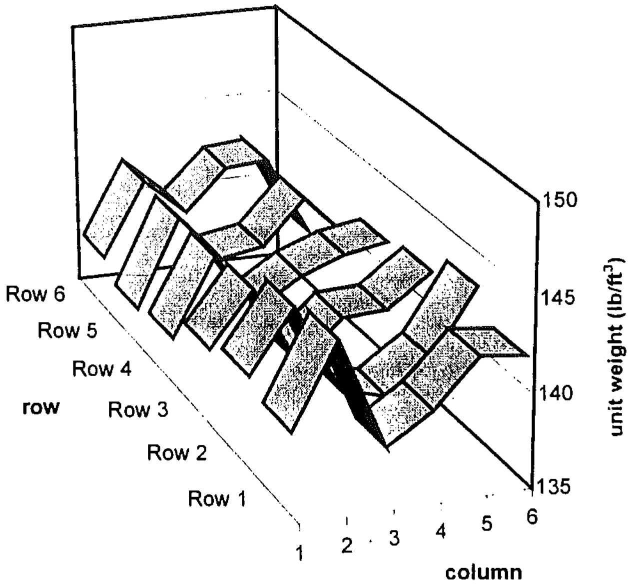


Site 17 (y=22~32)

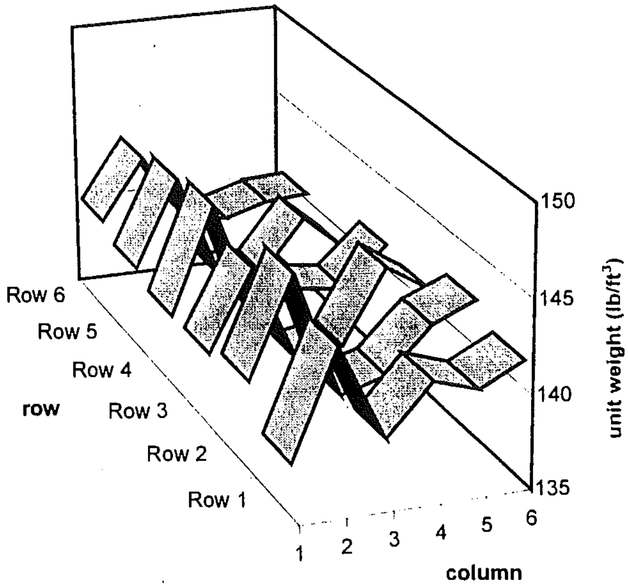


Site 17 (y=4~14)

Figure 5.8 Surface Plots for Nculear Density Values

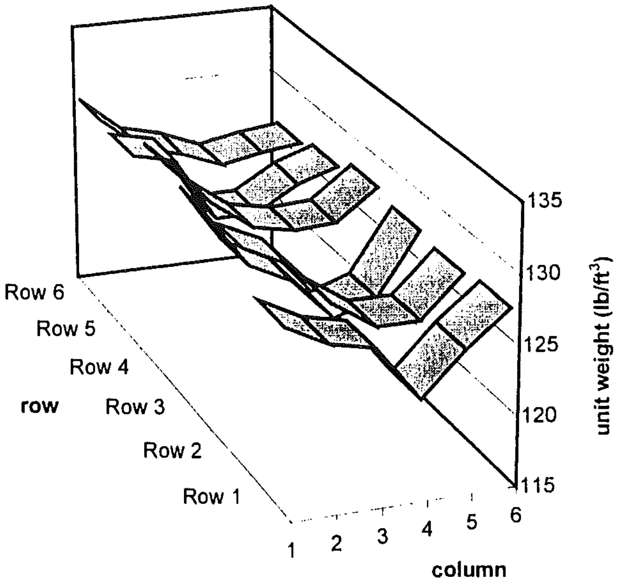


Site 18 (y=22~32)

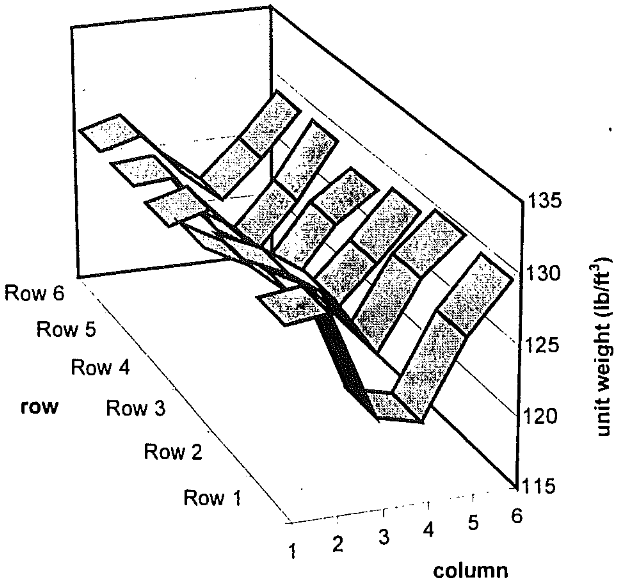


Site 18 (y=4~14)

Figure 5.8 (continued) Surface Plots for Nculear Density Values



Site 22 (y=12~17)



Site 22 (y=4~9)

Figure 5.8 (continued) Surface Plots for Nculear Density Values density values at the center of both grids. This might be contributed by the rough surface found in the path of gear box of the paver. ANOVA analyses indicated significant differences with p-value less than 10^{-8}.

4.0 CRITERIA DEVELOPMENT FOR PREDICTING SEGREGATION BASED ON DIFFERENCES IN NUCLEAR DENSITY

4.1 Visual Difference in Degree of Segregation

Two-sample comparisons were involved in this study. Since the degree of segregation based on visual observation is available for each sample, a numerical value is assigned for each degree as listed in Table 5.3. Using the numerical values, differences between observed degrees of segregation can be assigned values. For example, the visual difference between light and heavy segregation samples is 3−1=2. Note that the scale in Table 5.3 is for mathematical convenience only; heavy segregation is not three times different from light segregation by any mean.

Table 5.3 Descriptive Terms and Numerical Values for Degree of Segregation

Degree of Segregation	
Descriptive	**Numerical**
Heavy	3
Heavy-Medium	2.5
Medium	2
Medium-Light	1.5
Light	1
Non-Segregation	0

The numerical differences between any two degrees of segregation for paired samples provide a variable that can be compared to nuclear density differences (the p-values). The value of the variable expresses differences between various observed degrees of segregation as shown in Table 5.4.

Table 5.4 Difference in the Assigned Numerical Values for Visual Segregation with the Corresponding Paired Samples in Descriptive Terms

Difference in the Numerical Values of the Degree of Segregation	Paired Samples
3	Non-segregation to heavy
2	Non-segregation to medium or light to medium
1	Non-segregation to light, light to medium or medium to heavy
0	Non-segregation to non-segregation, light to light, medium to medium, or heavy to heavy

4.2 Selection of Trial Criteria

As mentioned in Section 3, the results of t-tests can be presented using p-value for the comparison between paired samples. The average of p-values for each numerical difference between the degrees of segregation is shown in Figure 5.9. It should be noted in the figure that the data were obtained from sites 1 through 14 only. Nuclear density data from other sites were used for verification. Based on the data presented in Figure 5.9, three criteria were developed and are stated below.

- An average p-value from t-test about 10^{-2} or larger can be expected in pavement areas having the same visual degree of segregation or in non-segregated areas.
- Where the average p-value is around 10^{-3}, there is at least one degree difference in the numerical values of the degree of segregation.
- Where the average p-value is about 10^{-5} or smaller, there are at least two degrees difference in the numerical values of the degree of segregation.

The absolute difference in nuclear density values is another criterion for assessing the various degrees of segregation. Data were obtained for sites 1 through 14 for the determination of trial criterion selection. Figure 5.10 shows the range of nuclear density differences (average ± one standard deviation) for each degree of difference in the numerical values of the degree of segregation.

Review of Figure 5.10 indicates:

- For a typical non-segregated pavement and/or for a pavement experiencing the same degree of segregation, the absolute difference in nuclear density values could be as high as 2.5 lb/ft^3.
- For pavement areas with at least one degree difference in the numerical values of the degree of segregation, the absolute difference in nuclear density values is about 3 lb/ft^3 or larger.
- For pavement areas with two or three degrees difference in the numerical values of the degree of segregation, the absolute difference in nuclear density values is around 5 lb/ft^3 or larger.

4.3 Probability of Observing Visual Difference, Given Absolute and Statistical Differences in Nuclear Density

Probabilistic concepts were used to derive criteria for predicting segregation and severity using nuclear density measurements. The sample locations are assumed to represent a population of non-segregated areas and segregated areas of varying severity. For example,

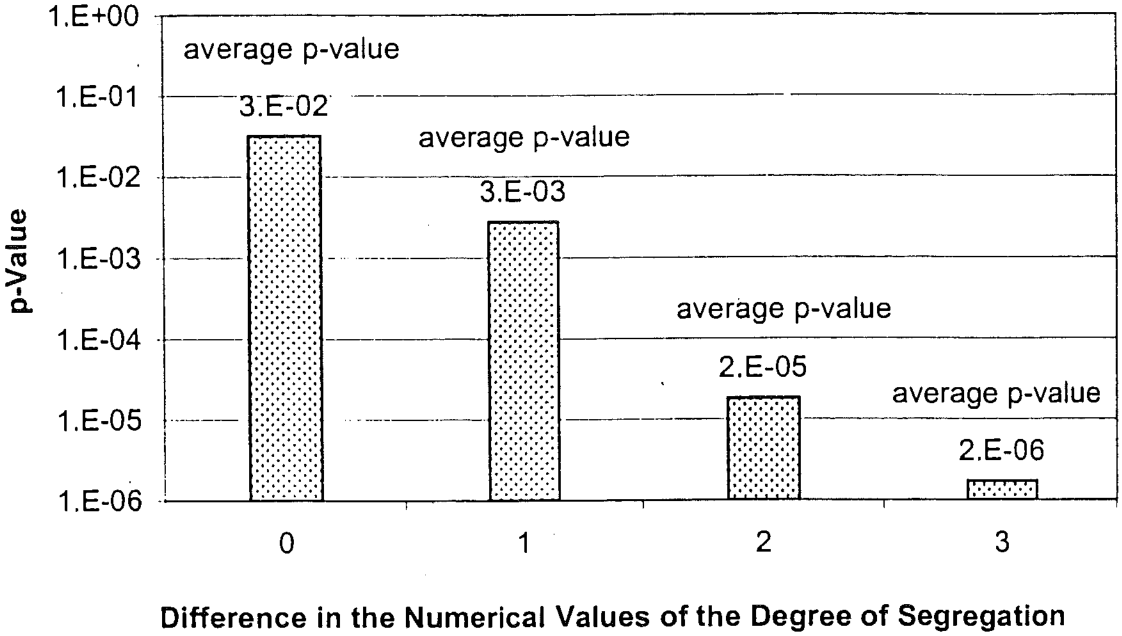


Figure 5.9 Average p-Value for Various Differences in the Numetrical Values of the Degree of Segregation

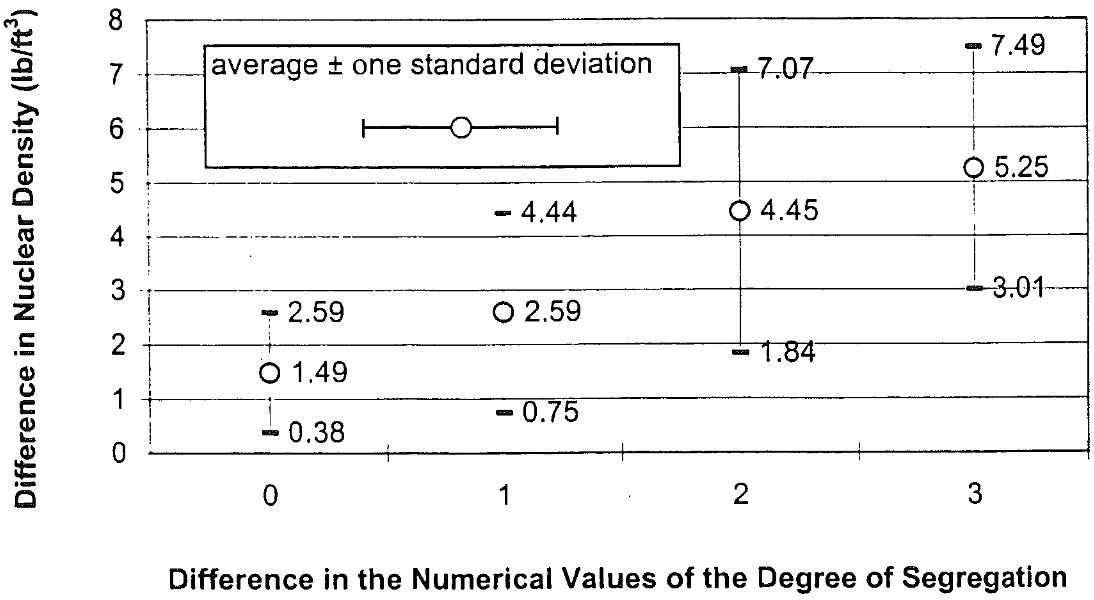


Figure 5.10 Nuclear Density Differences for Various Difference in the Numerical Values of the Degree of Segregation

given a certain p-value or nuclear density difference, the conditional probability that a different degree of segregation would be visually mapped can be determined by counting the number of comparisons that either satisfy or fail the criteria. The data were separated into two sets, one including all two-sample comparisons, another only including comparisons for control to segregated samples. The latter simulates the envisioned field operation to detect segregation. Three variables are involved: degree of segregation based on visual observation, p-value from t-test, and absolute nuclear density difference.

Figure 5.11 shows plots of the conditional probability that two compared samples have a visual difference greater than 1, 2 or 3 degrees, given that $\Delta\gamma \geq 3,5$ or 6.5 lb/ft^3 for all comparisons. Figure 5.12 shows the same for comparisons between control and segregated samples. Both figures are plotted based on nuclear density data from sites 1 through 21. It is seen that large density differences indicate a high likelihood of visual difference. Under the condition of $\Delta\gamma\geq3$ lb/ft^3, the chance of finding at least one degree difference in visual segregation is 87 %. Under the condition of $\Delta\gamma\geq5$ lb/ft^3, the chance of finding at least one degree difference in visual segregation is 96%; finding at least two degree difference (heavy to light or medium to control) is reduced to only 67%. If a more restrictive criterion is selected, such as $\Delta\gamma\geq6.5$ lb/ft^3, the probability that one would observe at least two degrees of difference in visual segregation increases to 76%. Similar findings also apply to the criterion using p-value, as shown in Figure 5.12.

Figure 5.13 shows the conditional probability for the comparisons made between control and segregated samples. It should be noted that the probability for at least one degree difference is always one because the condition that the comparison between control (zero degree) and segregated sample (at least one degree) already is imposed. The conditional probability values are always higher than those obtained based on the data set of all comparisons. For example, the chance of finding at least two degree differences in visual segregation using the criterion $\Delta\gamma\geq5$ lb/ft^3 is 77% compared to 67% based on the data set of all comparisons. The reason for high probability value is that the inconsistency of visual observation for segregation has been reduced with comparisons made between control and segregated samples only. Similar findings were also observed using the p-value criteria, shown in Figure 5.14.

4.4 Combined Criteria Based on Absolute and Statistical Differences in Nuclear Density

If combined criteria using 3 or 5 lb/ft^3 difference in nuclear density and 10^{-3} or 10^{-5} in p-value are considered, the conditional probability values increase slightly. For example, the conditional probability values using the criteria $\Delta\gamma\geq3$ lb/ft^3 and p-value less than 10^{-3} are 0.51 and 0.54 respectively for all comparisons with at least two degrees of differences. When the combined criteria were chosen, the probability value increased to 0.59. The probability values are listed in Table 5.5 and also illustrated in Figures 5.15 and 5.16.

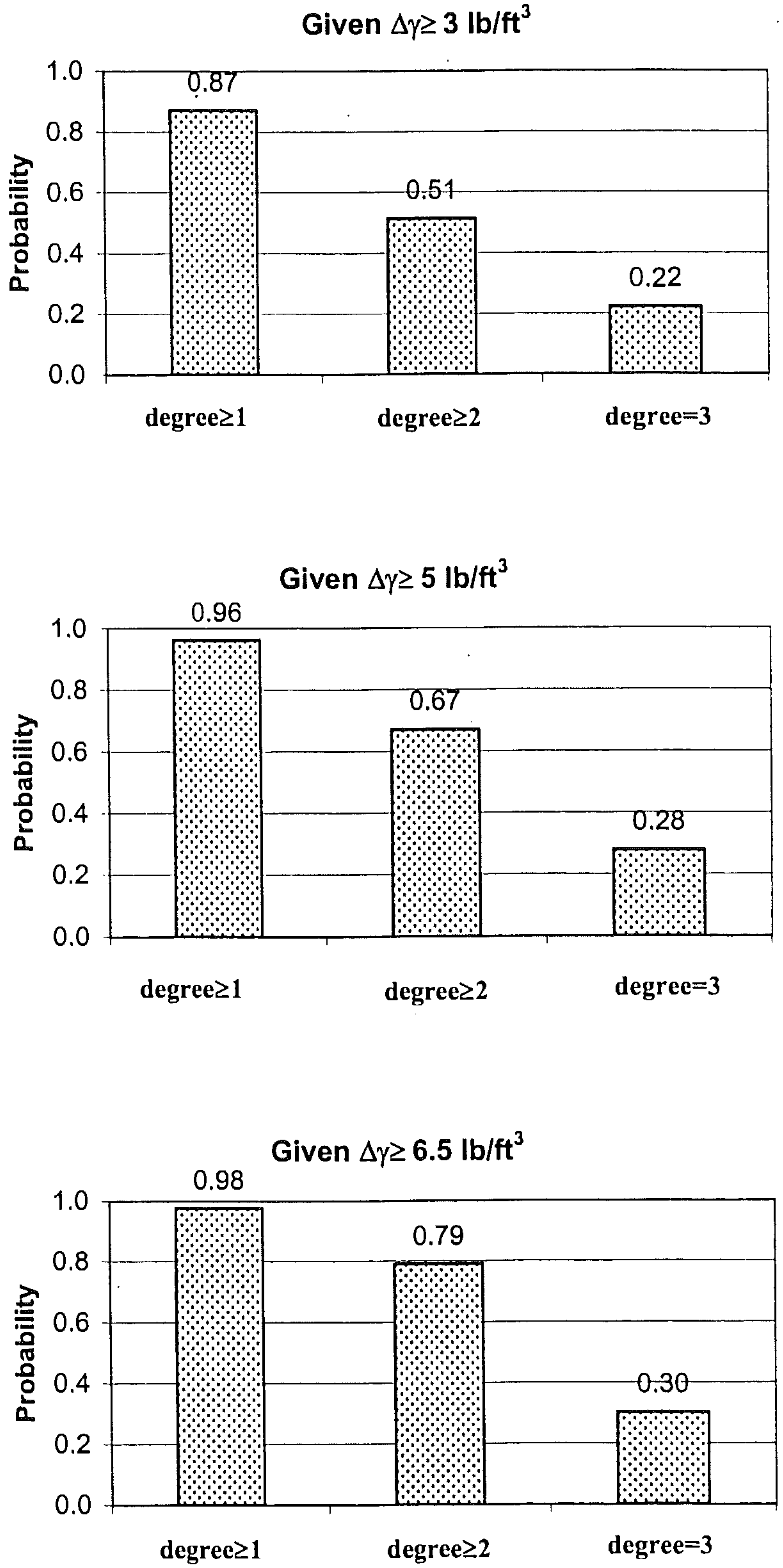


Figure 5.11 Conditional Probability of Degrees of Visual Difference Given $\Delta\gamma$ from Nuclear Density Comparison (All Comparisons)

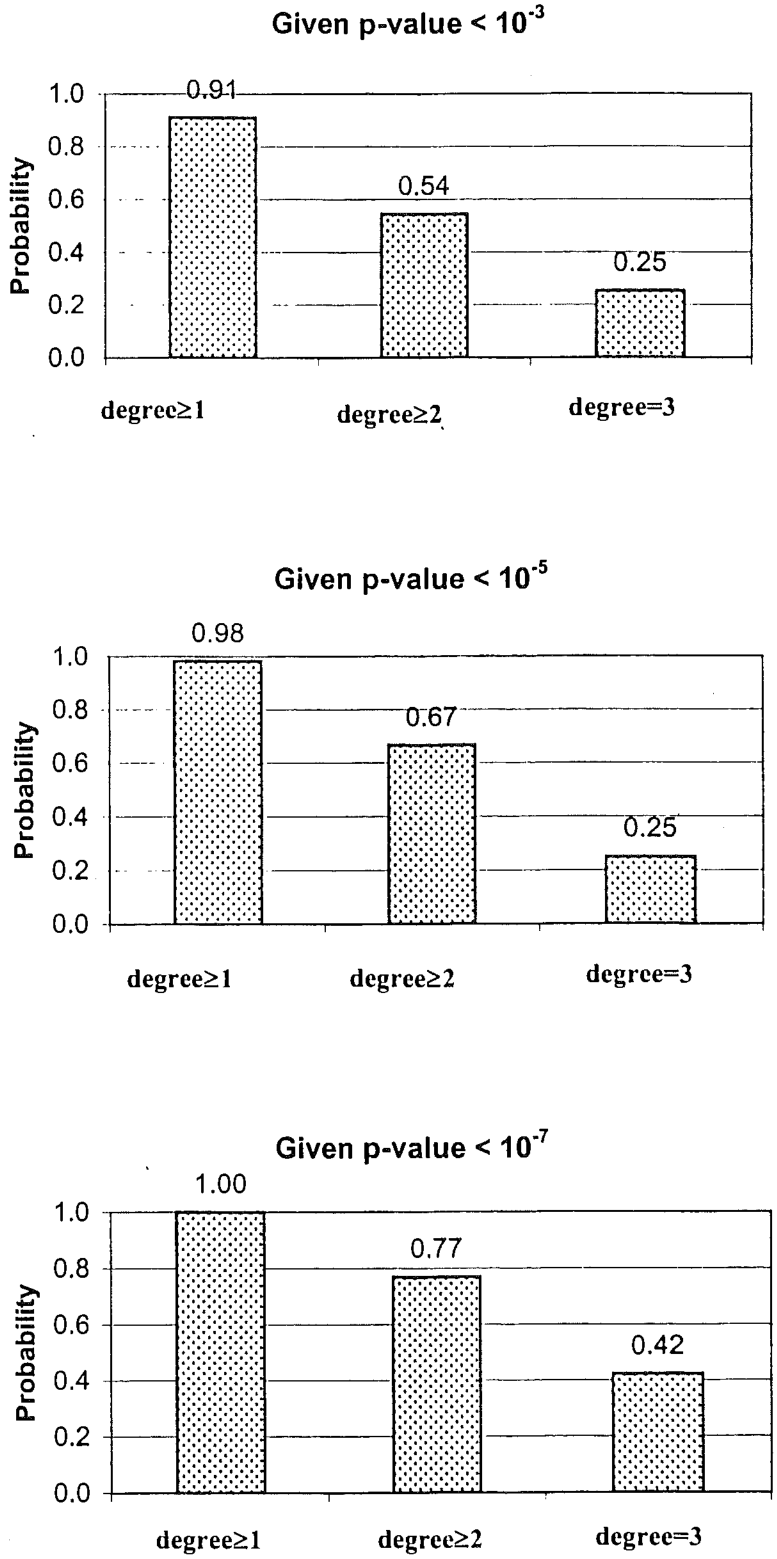


Figure 5.12 Conditional Probability of Degrees of Visual Difference Given p-Value from Nuclear Density Comparison (All Comparisons)

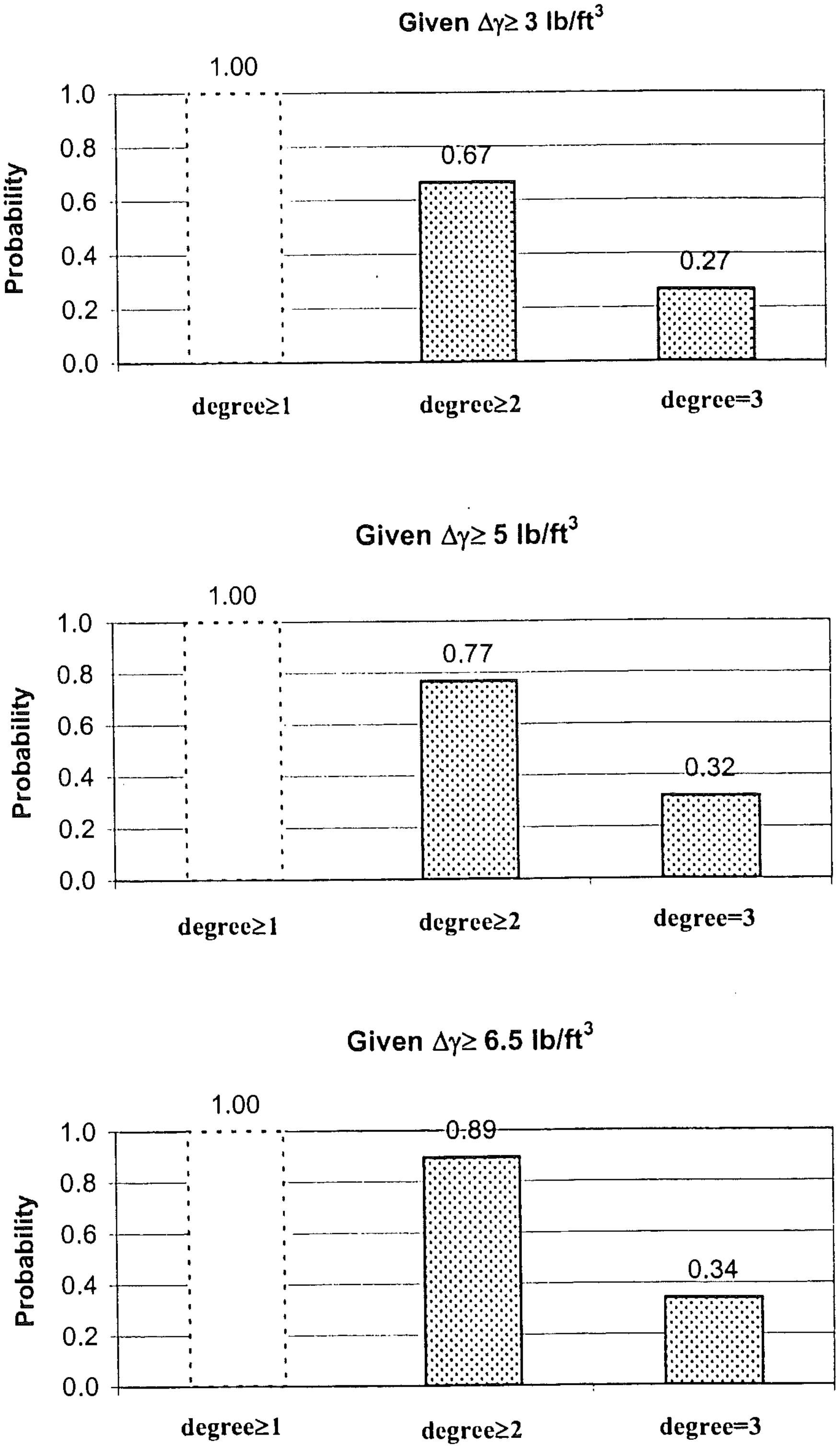
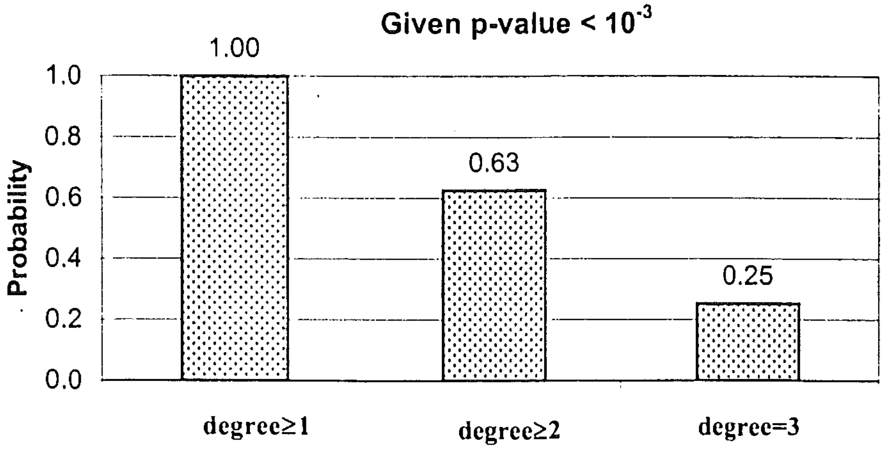
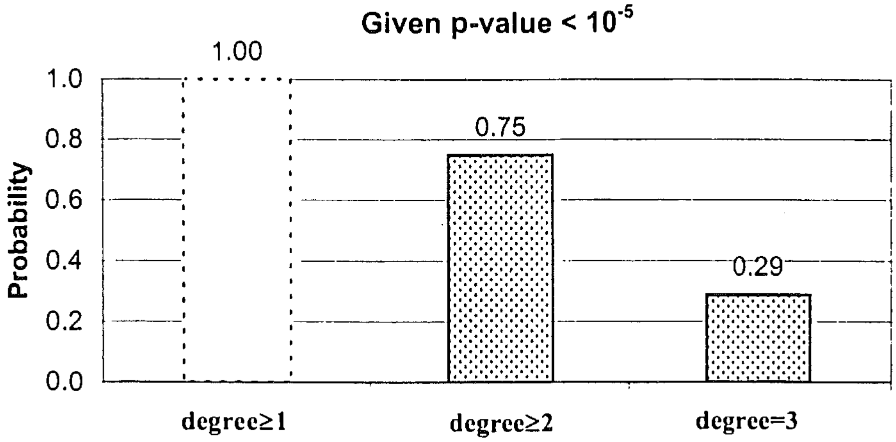


Figure 5.13 Conditional Probability of Degrees of Visual Difference Given Δγ from Nuclear Density Comparisons (Comparisons between Segregated and Control Samples)





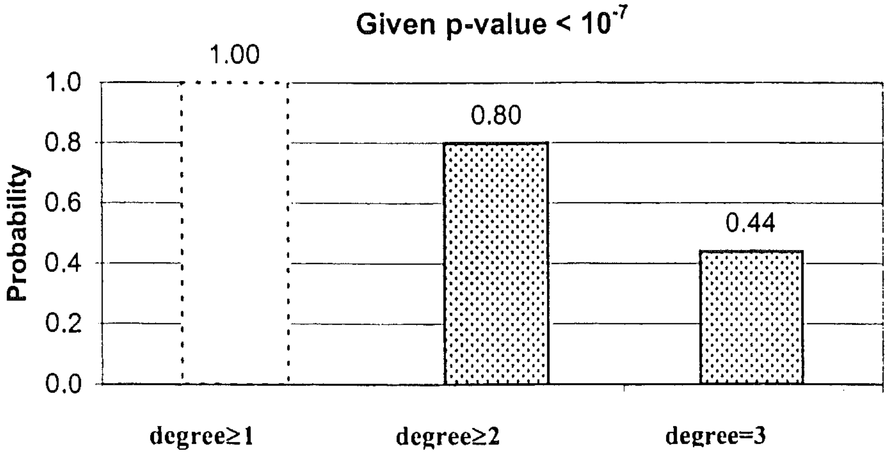
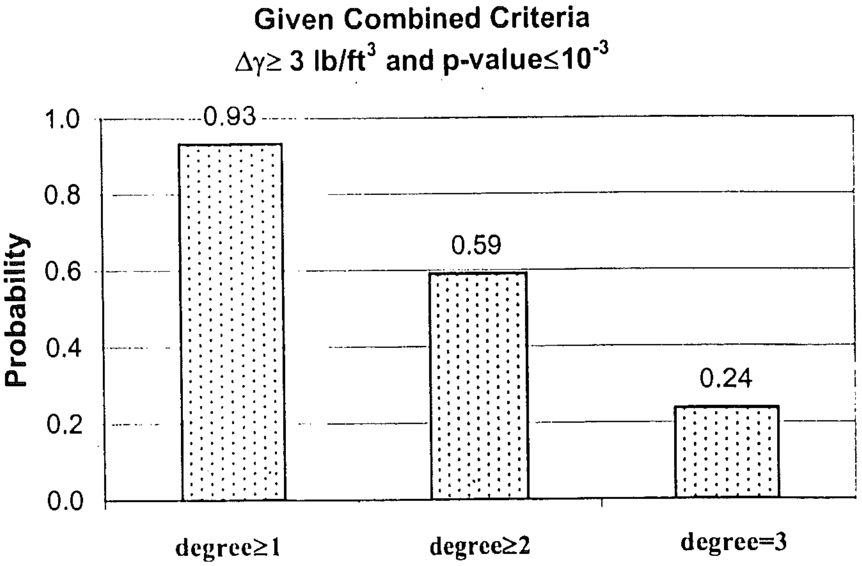


Figure 5.14 Conditional Probability of Degrees of Visual Difference Given p-Value from Nuclear Density Comparisons
(Comparisons between Segregated and Control Samples)



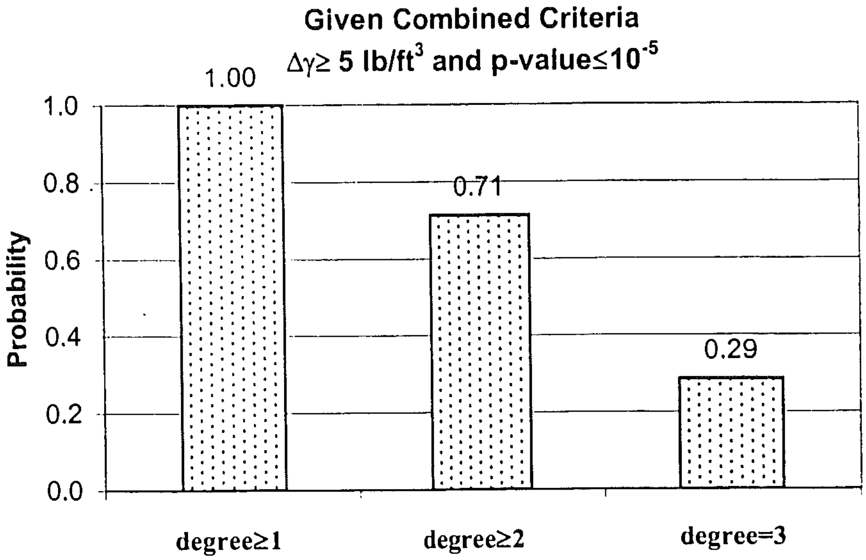
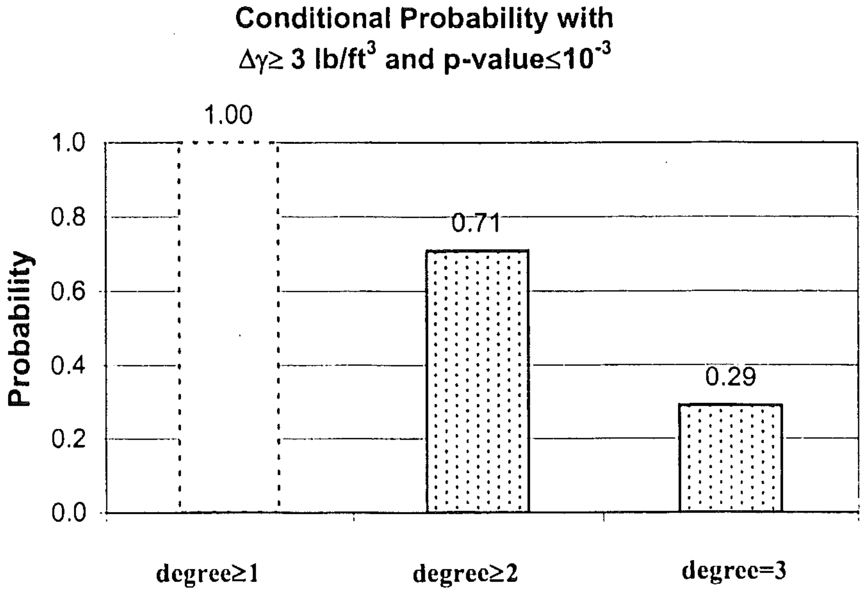


Figure 5.15 Coditional Probability Based on Combined Criteria (All Comparisons)



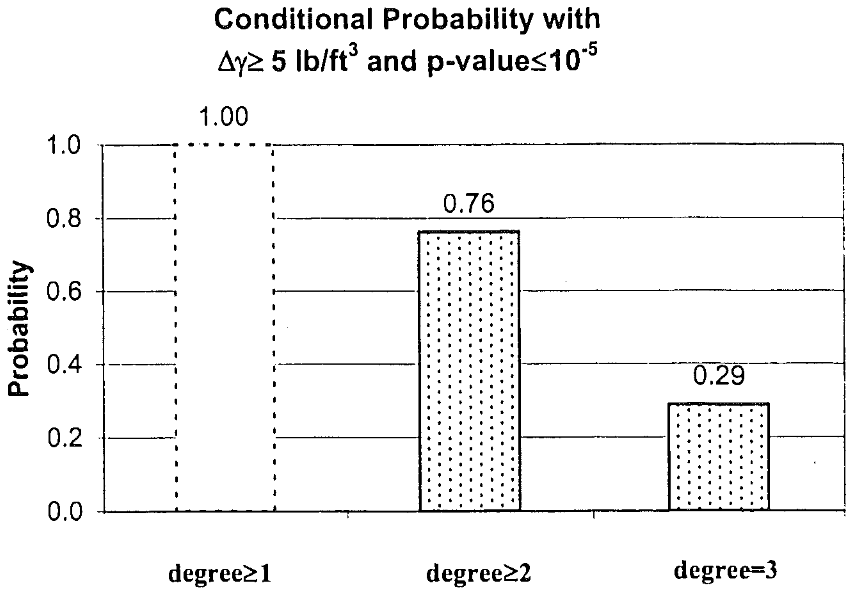


Figure 5.16 Conditional Probability Based on Combined Criteria
(Comparisons between Control and Segregated Sample)

Table 5.5 Conditional Probability for Each Criterion

	All Comparisons			**Control-to-segregated Comparisons**		
	degree≥1	degree≥2	degree≥3	degree≥1	degree≥2	degree≥3
$\Delta\gamma \geq 3$	0.87	0.51	0.22	1.00	0.67	0.27
p-value $< 10^{-3}$	0.91	0.51	0.25	1.00	0.63	0.25
combined	0.93	0.59	0.24	1.00	0.71	0.29
$\Delta\gamma \geq 5$	0.96	0.67	0.28	1.00	0.77	0.32
p-value $< 10^{-5}$	0.98	0.67	0.25	1.00	0.75	0.29
combined	1.00	0.71	0.29	1.00	0.76	0.29

5.0 SUMMARY

Extensive analyses of nuclear density differences and visual differences were performed, as described in detail above. These indicate that

- Segregated areas usually have nuclear density values significantly lower than that obtained from control areas.
- Areas visually classified as medium and heavy segregation are differentiable from control areas in most cases; however this is not true for segregated areas with light segregation.
- Areas visually mapped as the same degree of segregation may indicate statistical density differences, suggesting that either visual mapping is not consistent or other variables, namely compaction, also lead to differences.
- Control areas should be selected in the same longitudinal line with apparently segregated areas to avoid the effects of compaction-induced density differences due to roller, traffic load, or construction.
- Three variables were considered in the development of the criteria: visual difference, absolute nuclear density difference and statistical difference in term of p-value.
- The conditional probability of different degrees of segregation being observed does not differ much whether p-value or absolute difference in nuclear density is taken as the critical variable. The p-value is used because both means and variance of density values are considered.
- For comparisons made for any two samples satisfying the combined criteria of $\Delta\gamma \geq 3$ lb/ft^3 and p-valuel 0^{-3}, the probability of finding at least one degree of segregation is

approximately 90 percent; for at least two degrees of segregation the probability is 65 percent. However the relatively high probabilities are based on samples pre-selected to include a number of segregated areas. At non-segregated sites, similar density differences were observed.

CHAPTER 6
VERIFICATION OF TEST AND CRITERIA

1.0 OVERVIEW

Where segregation is visually mapped, significant gradation differences would be expected when segregated areas and control areas are compared. However, results from the previous study (Wolff,et.al, 1997) showed that such differences may be small. That study used 6 by 6 sample grids; within the sample columns, the degree of segregation was not always of uniform severity. To remedy this difficulty in the present study, the sample areas were individually defined to ensure more uniform visual classification segregation severity, and they were permitted to vary in size, shape and number of data points.

To test and refine the trial criteria proposed in Chapter 5 for predicting the presence of segregation based on nuclear density data, studies using lab density and gradation data (percent passing 3/8″, No.4 and No.8 sieve) were conducted. Lab-measured density values were obtained and analyzed to determine to what extent the observed low nuclear density measurements reflected low actual density, and to what extent they reflected an additional reduction in apparent density due to the coarse surface associated with segregation.

The gradation data were analyzed to determine to what extent the particle size distribution in visually-observed segregated areas actually differs from those in "good" or "control" areas. Relationships between nuclear-measured density values and gradation parameters were assessed by cross-plotting normalized density and lab data and by cross-plotting p-values from density comparisons and gradation parameter comparisons. Further criteria were developed to predict gradation differences based on nuclear density differences by applying the concepts of conditional probability. Finally, a comprehensive conditional probability representation among nuclear density comparisons, gradation comparisons and visually-mapped degree of segregation was developed.

2.0 LAB-MEASURED DENSITY ANALYSIS

Due to traffic and accessibility considerations, not all sites were cored. The twelve sites at which cores were obtained for laboratory tests are listed in Table 6.1, along with the mean and standard deviation for both SSD and air-dry laboratory density. Locations of cores at each site are shown in Appendix A. It should be noted that not all sample locations at which nuclear density measurements were taken were cored; approximately half were cored. The lab density values are plotted versus longitudinal distance in Figure 6.1 for both SSD and air-dry density, similar to that previously shown for nuclear density in Figure 5.1

At **site 1**, two control samples had higher lab density values than the rest of the samples, similar to the findings from nuclear density measurements shown in Figure 5.1. However, the control sample located outside the grid had relatively low lab density values, especially for air-dry density. The heavy segregation samples have the lowest lab density values.

Table 6.1 Summary of Lab-Measured Density

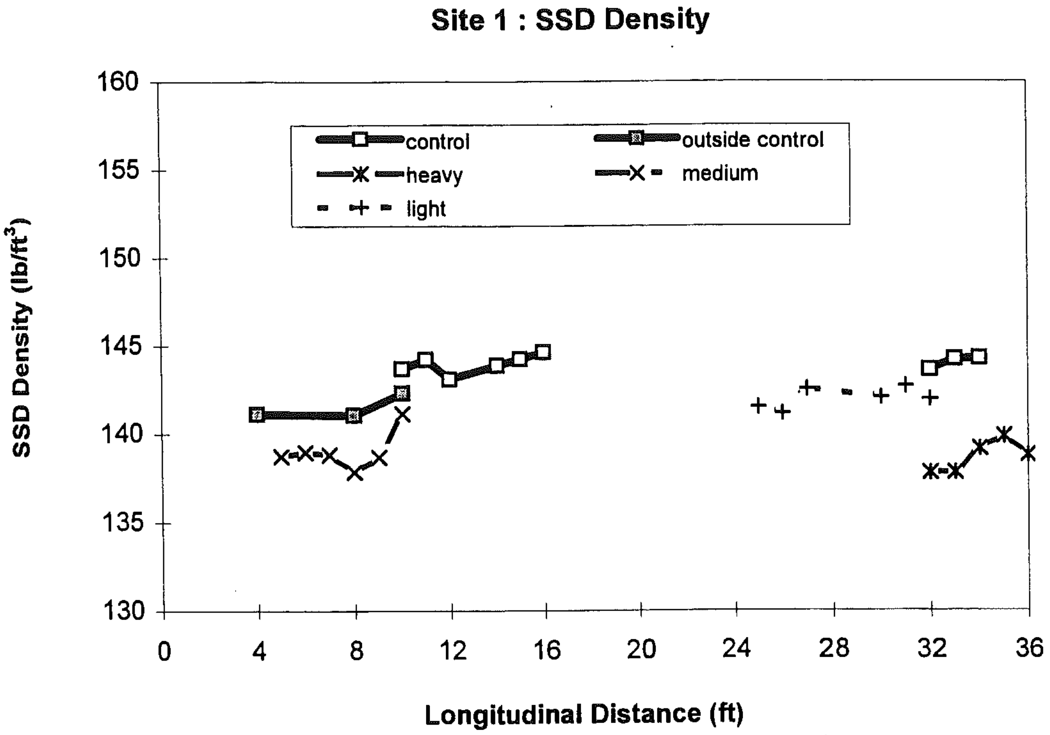
	SSD		Air-dry		
Site	Mean (lb/ft^3)	std.	Mean (lb/ft^3)	std.	# of Cores
Site 1					
2. Control	144.0	0.36	144.2	0.34	3
5. Control	144.0	0.53	144.2	0.54	6
Outside Control	141.5	0.71	141.7	0.72	3
1. Light	142.0	0.58	142.4	0.55	6
4. Medium	139.0	1.10	140.9	1.05	6
3. Heavy	138.7	0.90	140.9	1.04	5
6. Heavy	139.5		142.2		2
Site 3					
1. Control	148.6	0.74	148.8	0.75	6
5. Control	144.4	0.18	145.0	0.23	6
2. Light	143.9	0.98	144.4	0.82	6
4. Medium	144.2	0.99	145.1	0.81	6
Site 5					
Outside Control	143.3	1.29	144.0	0.98	5
2. Light (Fine)	148.5	1.35	148.7	1.27	6
3. Light	143.2	2.02	144.0	1.57	6
4. Medium	142.7	2.14	144.2	1.70	6
5. Medium	140.4	1.05	143.2	1.28	6
1. Heavy	146.0	2.61	146.4	2.46	6
Site 10					
Control C	150.5	0.62	150.6	0.60	3
Control D	143.7	0.30	144.1	0.26	3
2. Light	142.5	1.20	143.2	1.03	3
5. Light	144.5	1.51	145.5	0.71	3
1. Medium-Light	145.8	0.78	146.0	0.76	3
3. Medium-Light	145.5	0.83	145.9	0.76	3
4. Medium	144.5	0.91	144.8	0.85	3
Site 13					
3. Control	147.4	0.17	147.5	0.18	3
8. Control	147.9	0.24	148.0	0.22	6
2. Light	137.5	1.91	137.9	1.91	6
1. Light-Medium	141.2	1.48	141.4	1.46	3
4. Light-Medium	144.0	1.03	144.2	1.02	3
5. Light-Medium	142.8		143.2		2
6. Heavy	140.7	1.49	141.3	1.52	3

Table 6.1 (continued) Summary of Lab-Measured Density

	SSD		Air-dry		
Site	**Mean (lb/ft^3)**	**std.**	**Mean (lb/ft^3)**	**std.**	**# of Cores**
Site 15					
2. Control	147.2	0.64	147.5	0.75	3
4. Control	142.7	2.09	143.1	2.19	3
7. Control	145.0	0.60	145.6	0.48	4
8. Control	146.3	1.66	146.6	1.69	3
9. Control	140.0	2.24	140.5	2.38	3
1. Light	146.9	0.37	147.2	0.42	3
3. Light	140.8	0.70	141.3	0.84	3
5. Light	141.2	1.68	142.2	2.04	3
6. Heavy-Medium	141.5	0.79	144.0	1.75	3
Site 16					
1. Control	147.8	0.92	148.2	0.90	3
2. Control	147.3	0.48	147.6	0.52	3
5. Control	147.8	0.17	148.1	0.15	3
8. Control	150.1	0.30	150.4	0.29	5
9. Control	149.0	1.04	149.4	0.99	5
11. Control	145.7	0.67	146.6	0.40	10
12. Control	147.2	0.72	147.6	0.75	5
4. Light	147.2	0.85	148.0	0.63	3
3. Light-Medium	143.7	0.24	144.7	0.27	3
6. Light-Medium	143.1	0.62	144.1	0.77	3
10. Light-Medium	143.2	1.13	144.6	1.38	5
13. Medium	143.5	0.28	145.1	0.74	4
7. Medium-Heavy	143.5	0.44	145.5	0.70	3
Site 17					
Sample 3	144.8	0.24	145.1	0.21	4
Sample 5	148.4	0.08	148.6	0.11	4
Sample 9	144.0	0.33	144.2	0.33	4
Sample 11	148.3	0.39	148.4	0.41	4
Site 18					
Sample 2	146.0	0.91	146.3	0.88	4
Sample 4	144.2	0.89	144.9	0.61	4
Sample 8	146.7	0.09	146.9	0.08	4
Sample 10	142.6	0.41	143.6	0.34	4
Site 19					
2. Control	151.5	1.66	151.9	1.52	4
7. Control	151.8	0.84	152.1	0.74	4
3. Medium	148.6	2.78	149.7	1.97	3
9. Medium	149.9		150.3		2
4. Heavy	146.6		148.8		2
8. Heavy	149.6	1.05	151.5	0.89	5

Table 6.1 (continued) Summary of Lab-Measured Density

Site	SSD Mean (lb/ft^3)	SSD std.	Air-dry Mean (lb/ft^3)	Air-dry std.	# of Cores
Site 20					
3. Control	148.7	3.05	149.0	2.82	3
5. Control (Fine)	148.9	0.80	149.1	0.74	3
10. Control (Fine)	150.8	1.81	151.0	1.77	3
11. Control	150.7	0.05	150.9	0.06	3
15. Control	149.3	0.54	149.5	0.50	10
14D. Light-Medium	147.6		147.9		2
14C. Medium	146.0	1.76	146.7	1.38	5
14B. Medium-Heavy	145.8	1.21	146.7	0.97	5
1. Heavy	146.8	1.72	147.6	1.38	3
2. Heavy	146.9	1.01	147.8	0.35	3
4. Heavy	145.1	1.16	146.1	0.91	3
9. Heavy	148.9	0.80	149.1	0.74	3
14A. Heavy	143.5		144.7		2
Site 21					
2. Control	141.8	0.48	142.6	0.50	5
4. Control	141.5	0.53	142.4	0.60	5
1. Light-Medium	141.6	0.79	143.2	0.74	9
3. Light-Medium	142.0	0.82	144.8	1.12	5



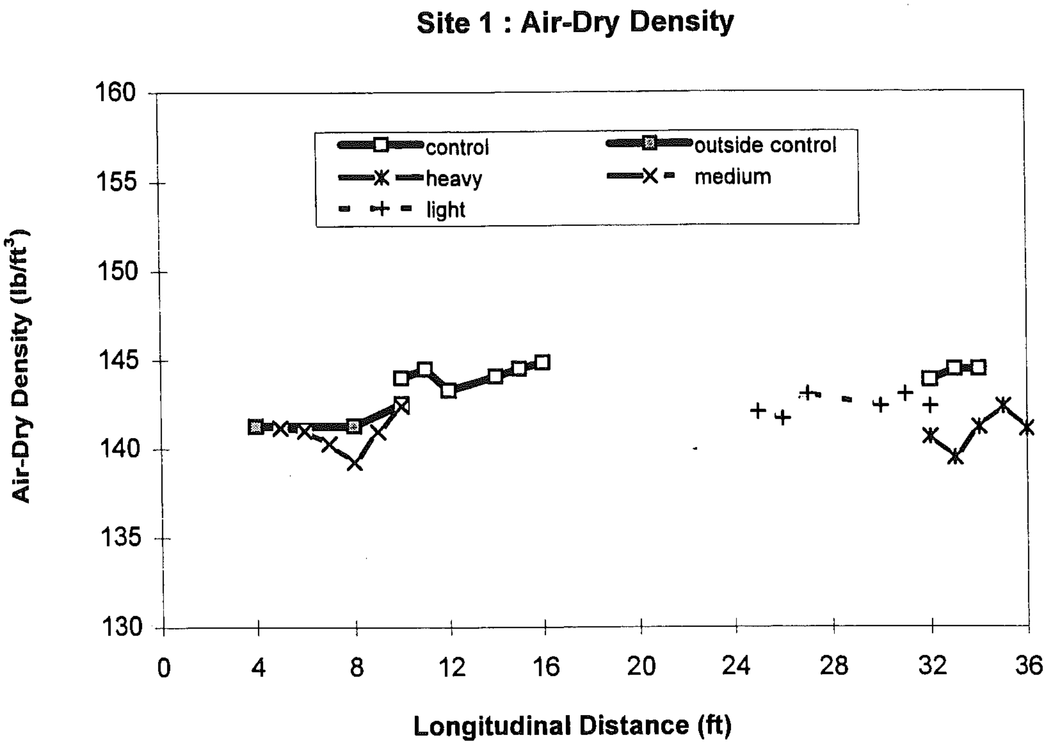
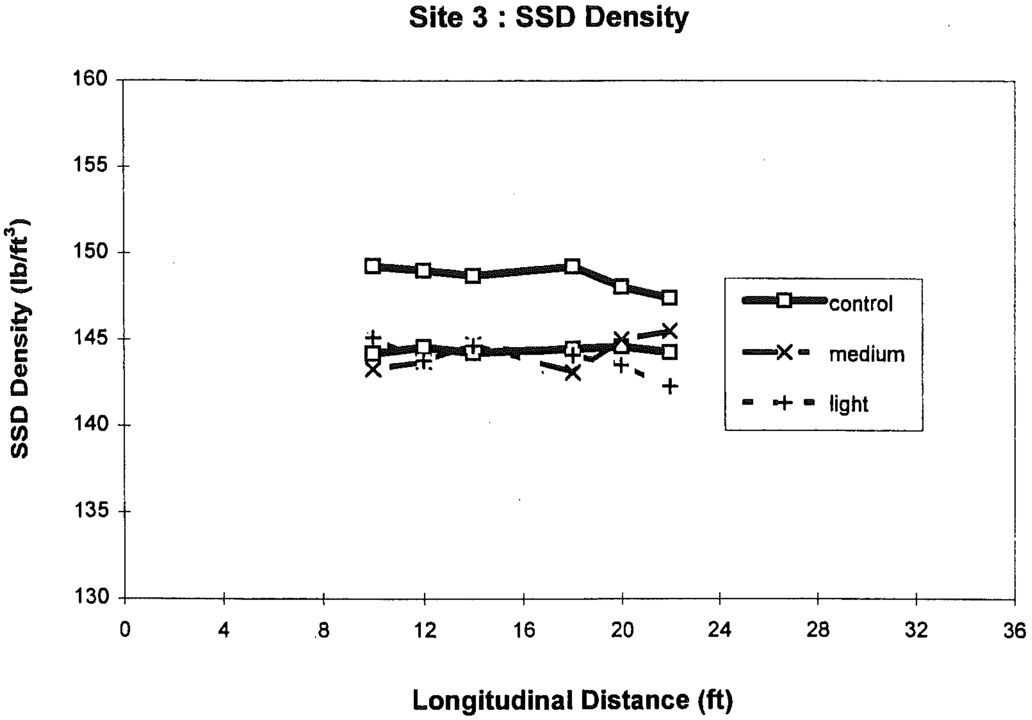
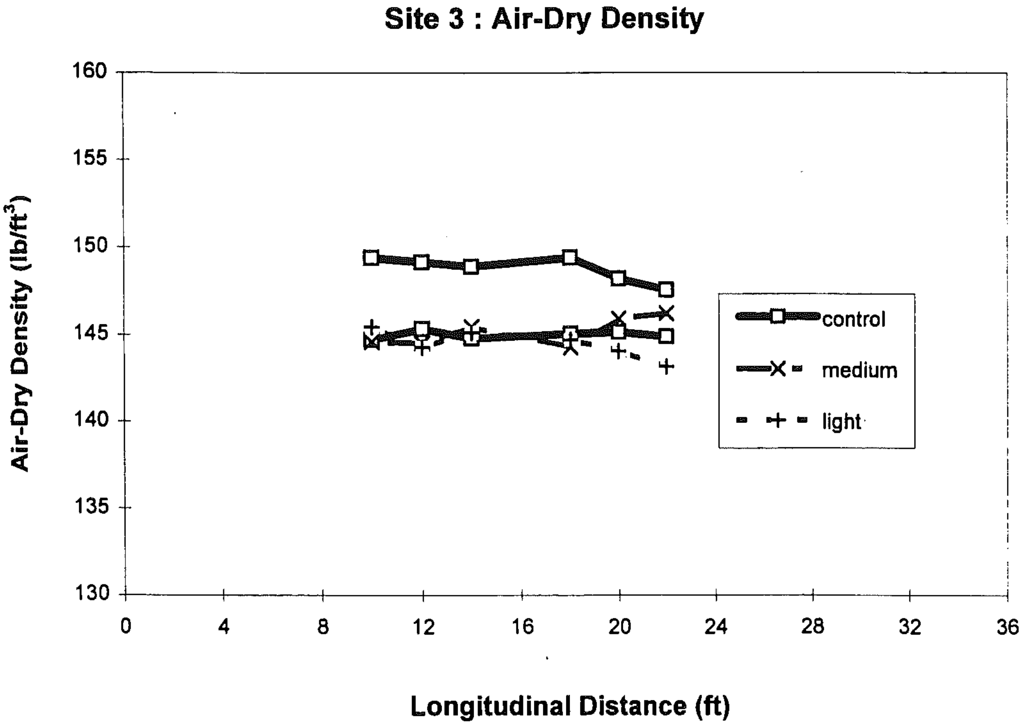


Figure 6.1 Distribution of of Lab Density





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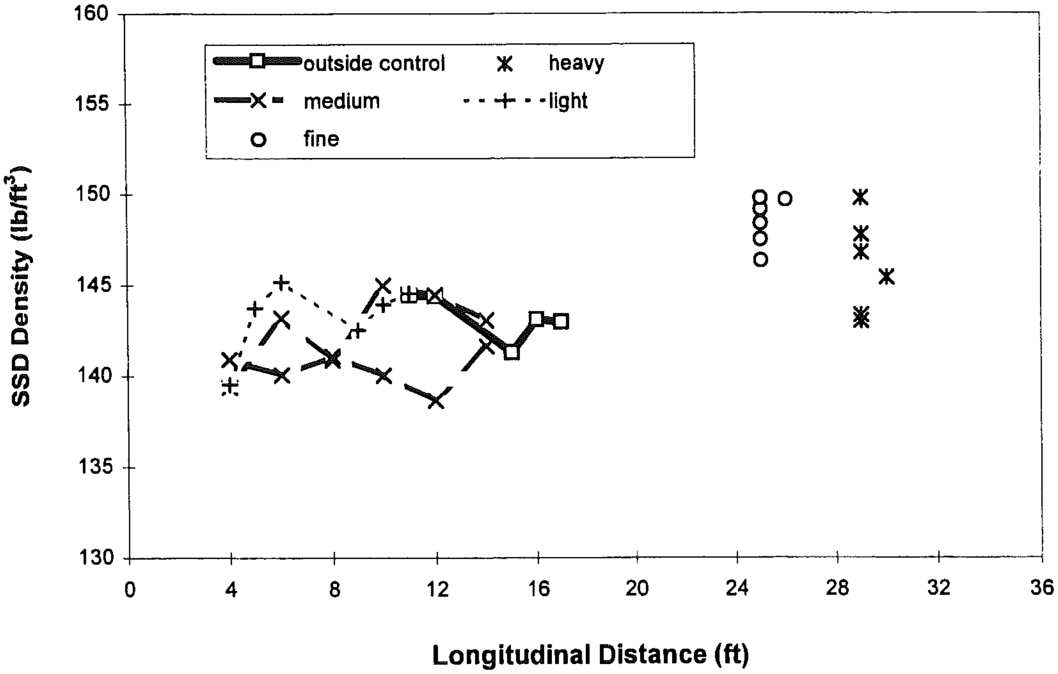

Site 5 : SSD Density

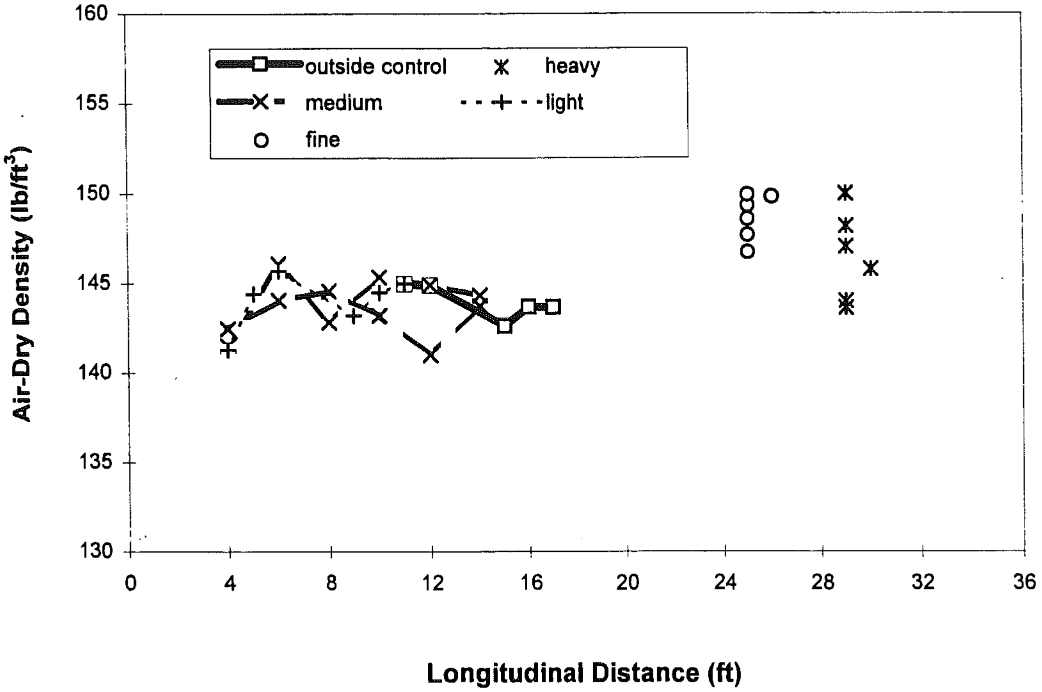
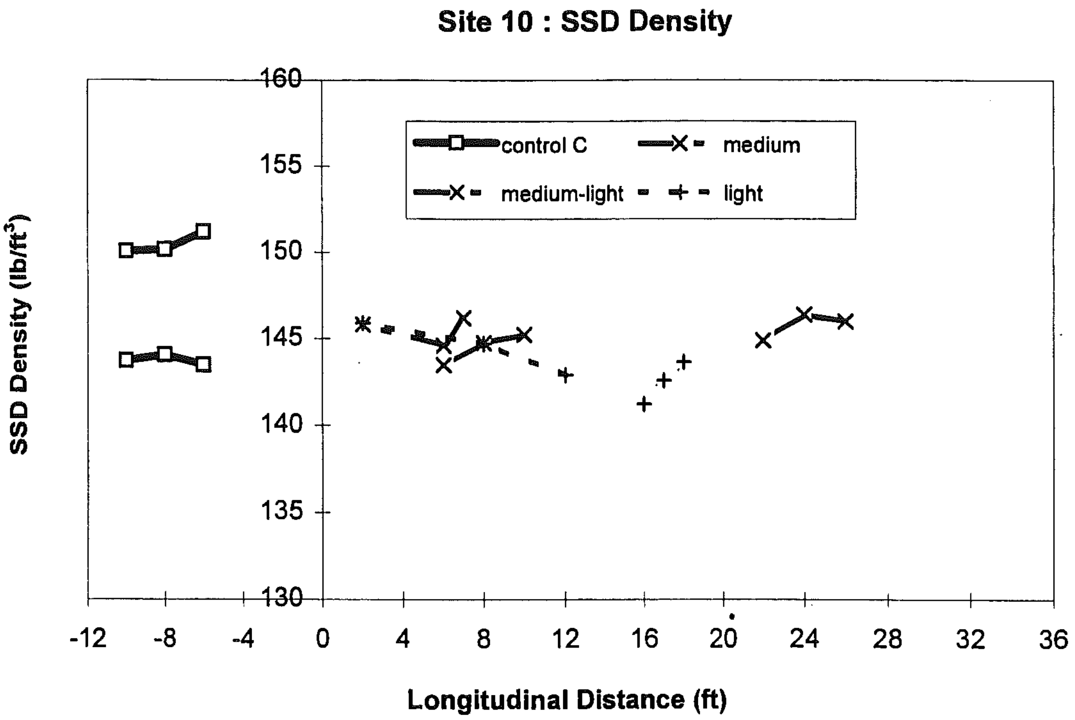

Site 5 : Air-Dry Density

Figure 6.1 (continued) Distribution of Lab Density



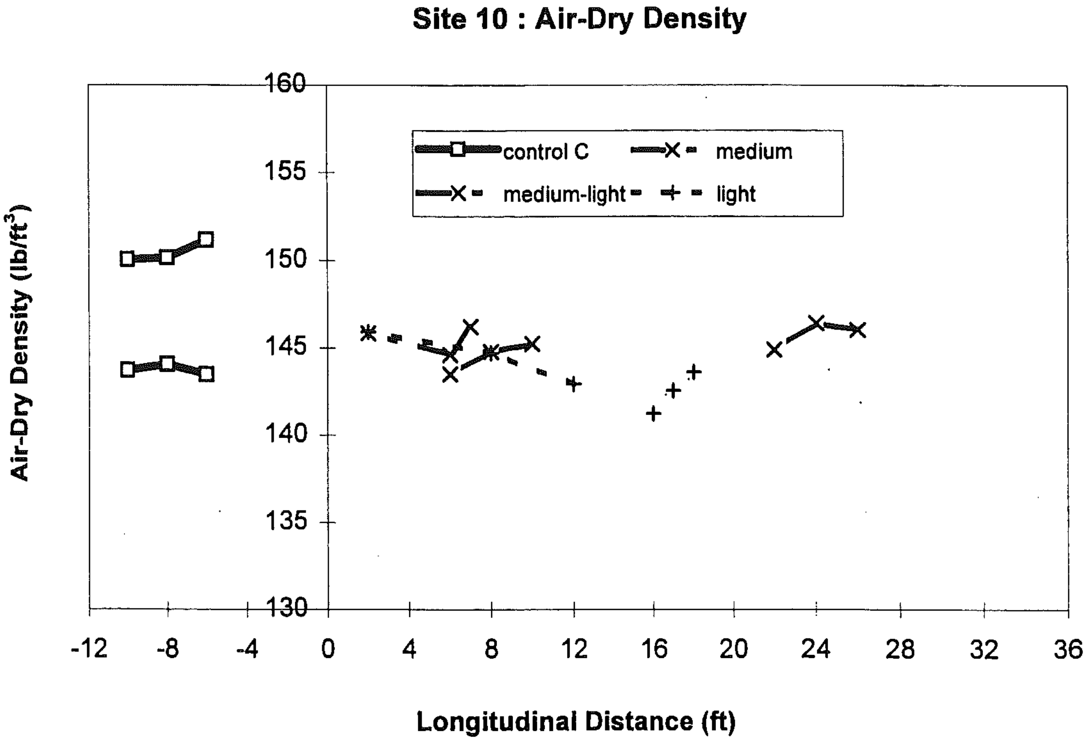
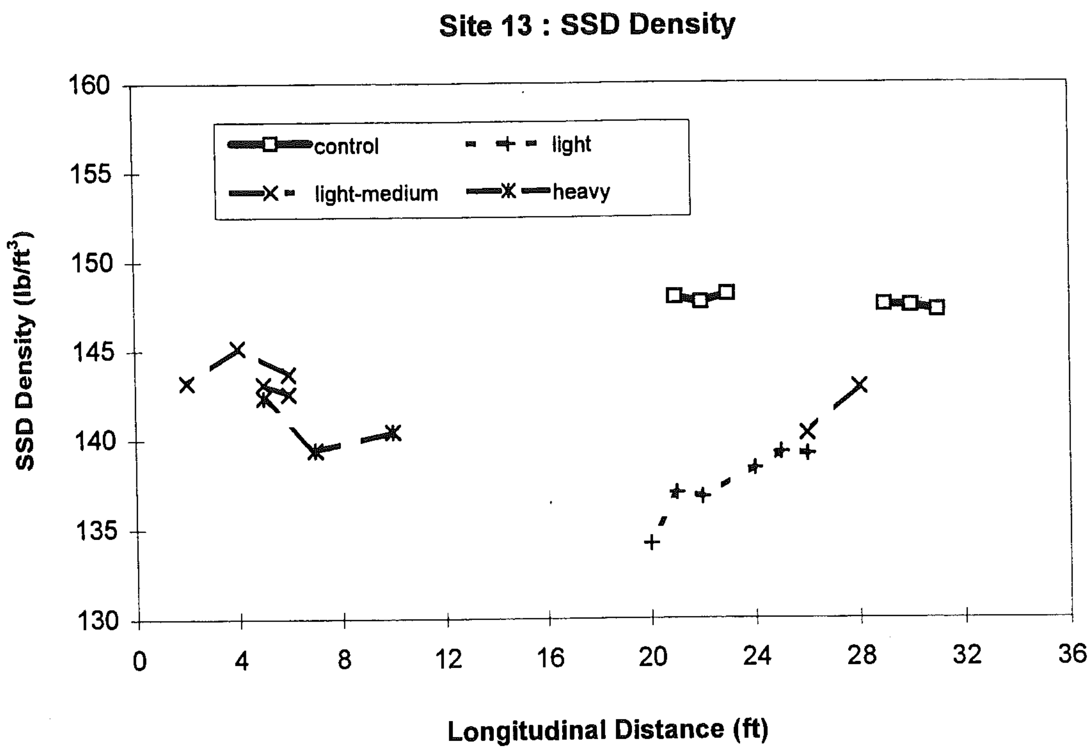


Figure 6.1 (continued) Distribution of Lab Density



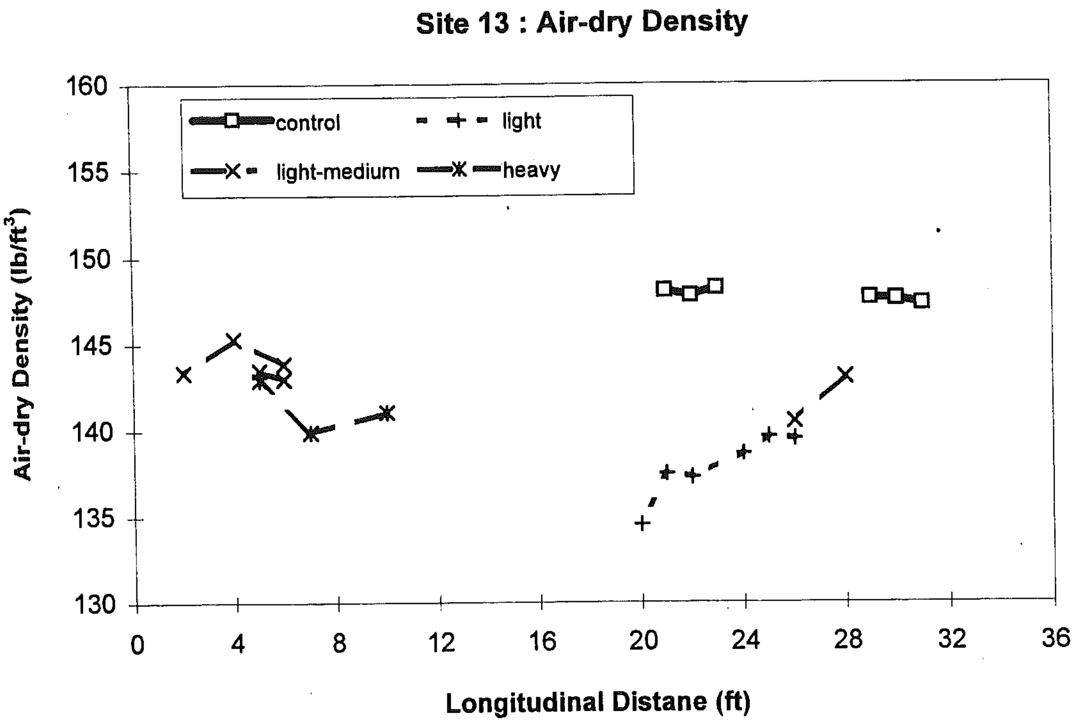
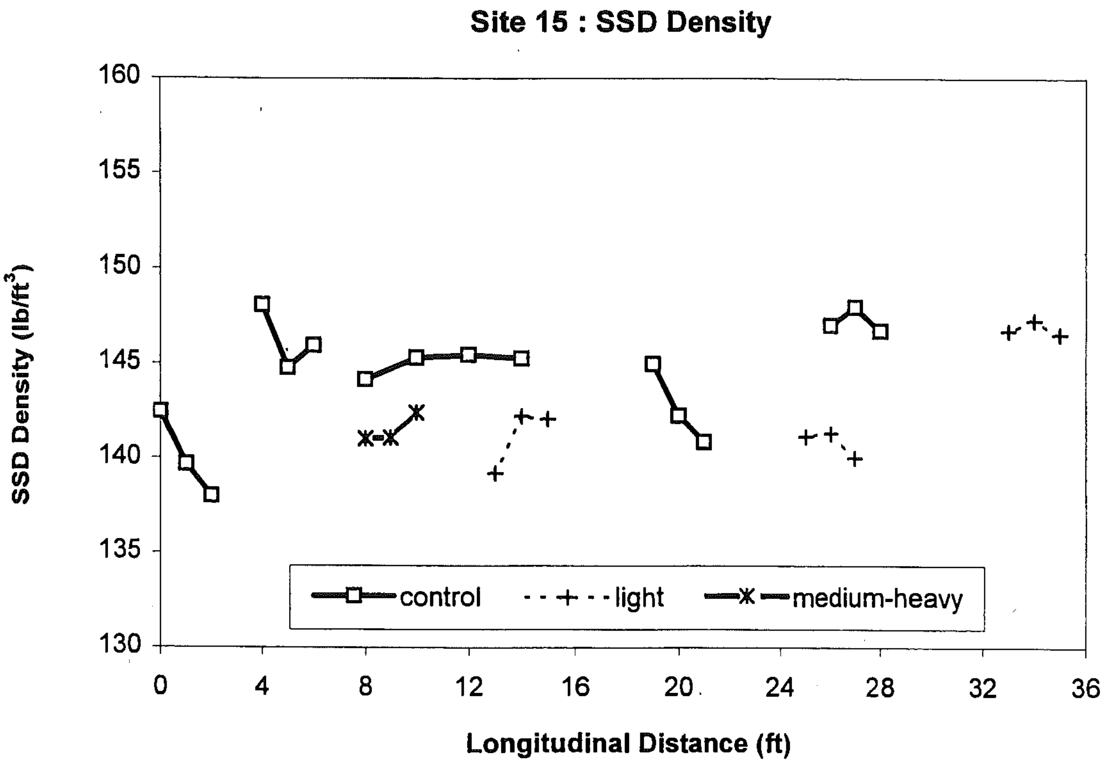


Figure 6.1 (continued) Distribution of Lab Density



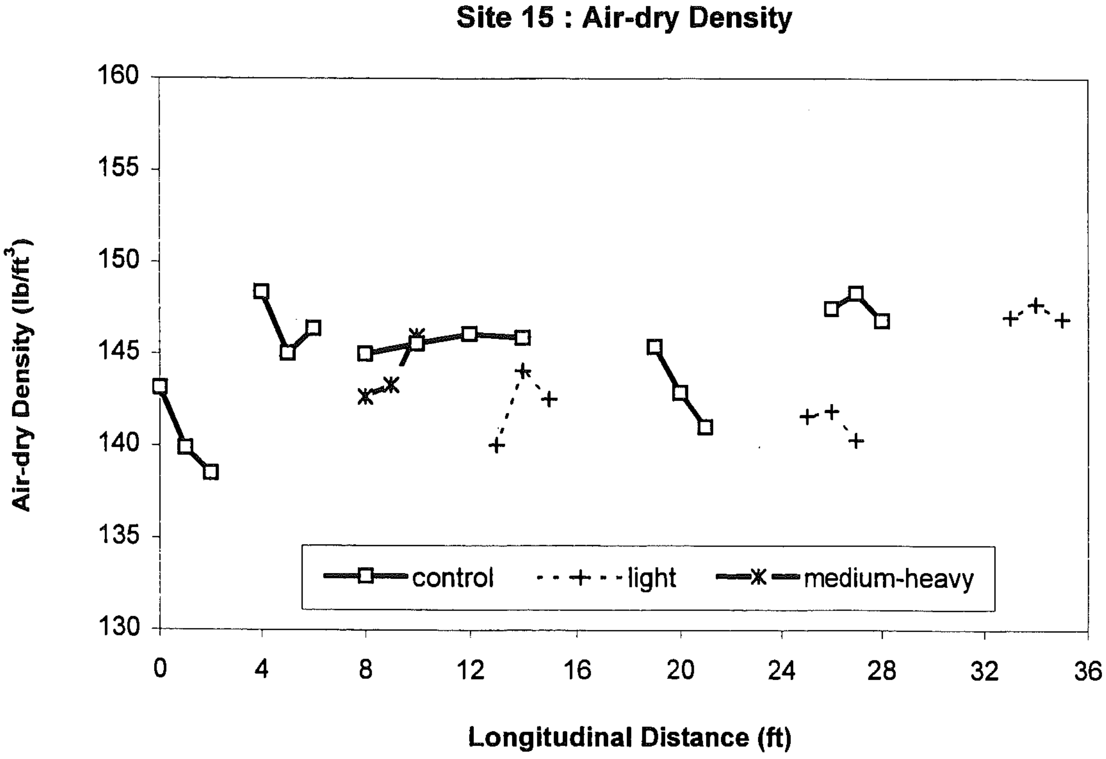
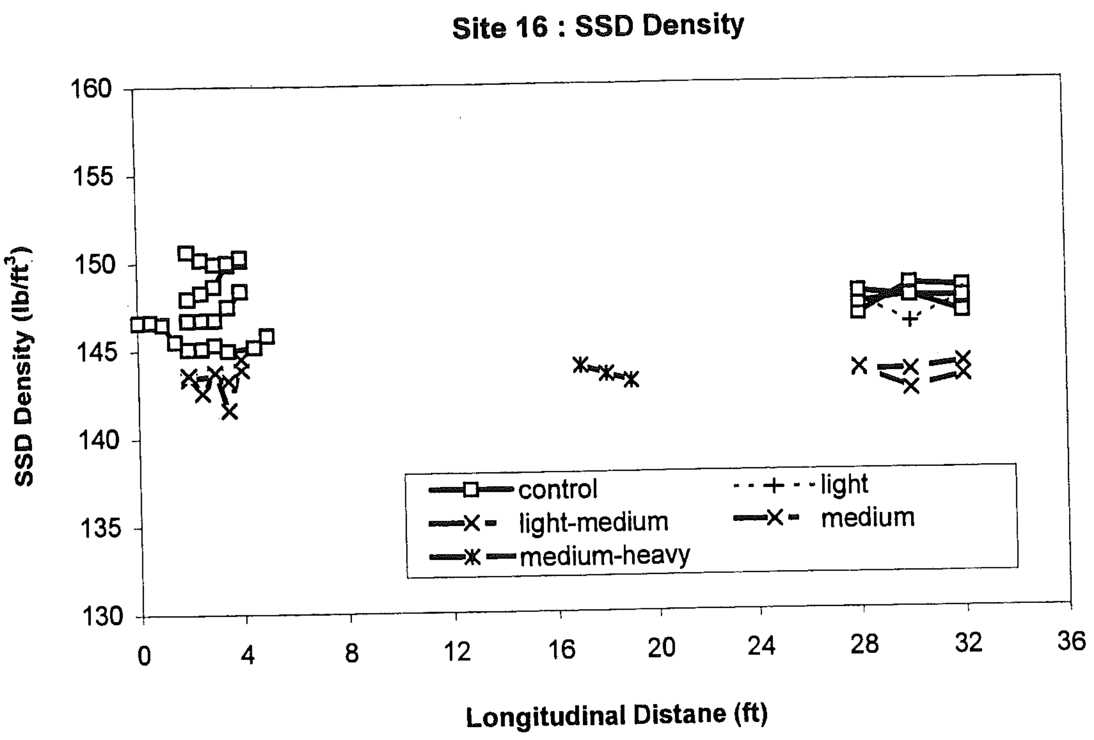


Figure 6.1 (continued) Distribution of Lab Density



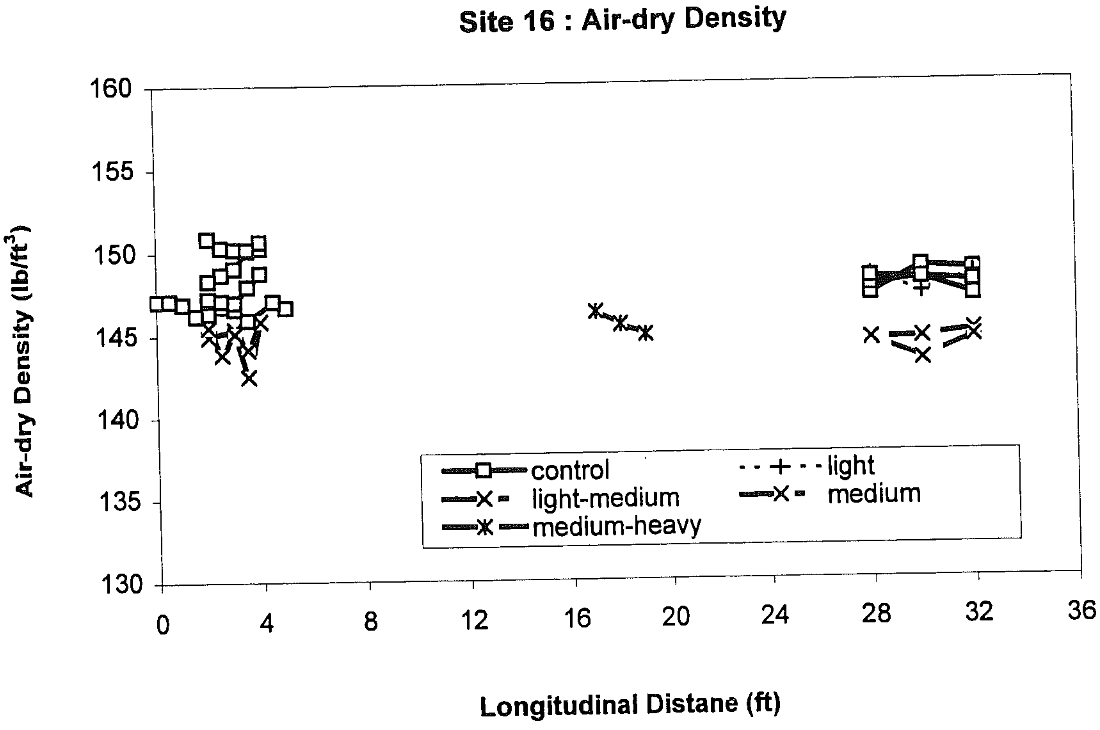
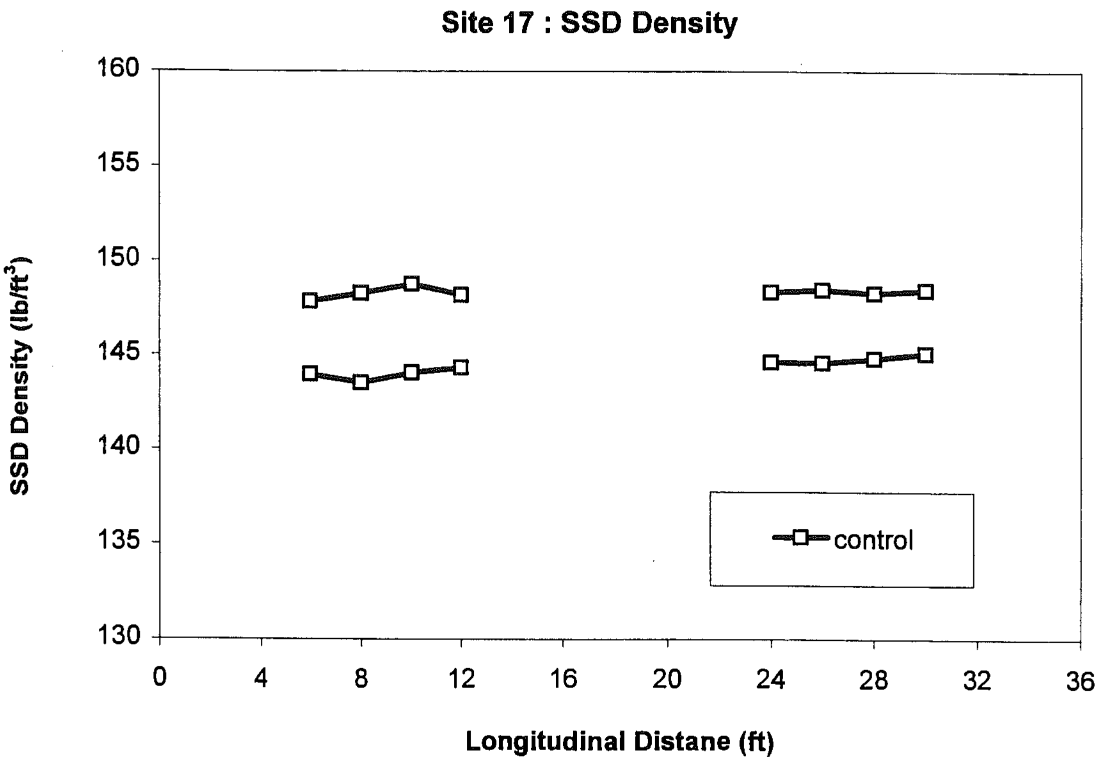


Figure 6.1 (continued) Distribution of Lab Density



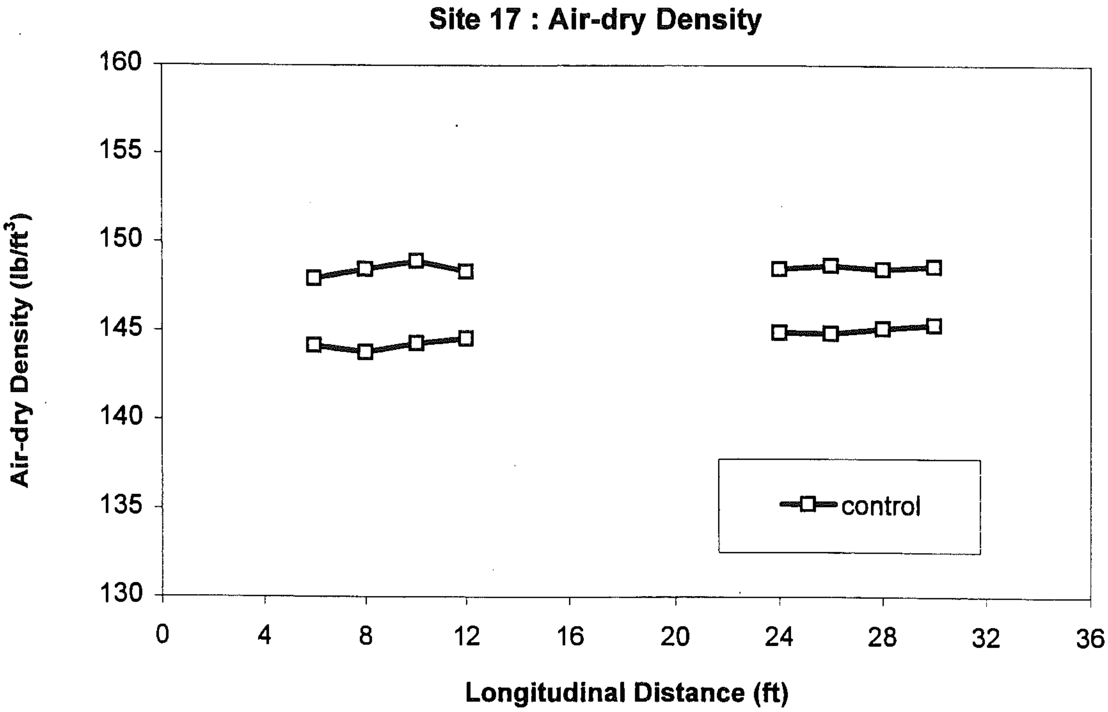
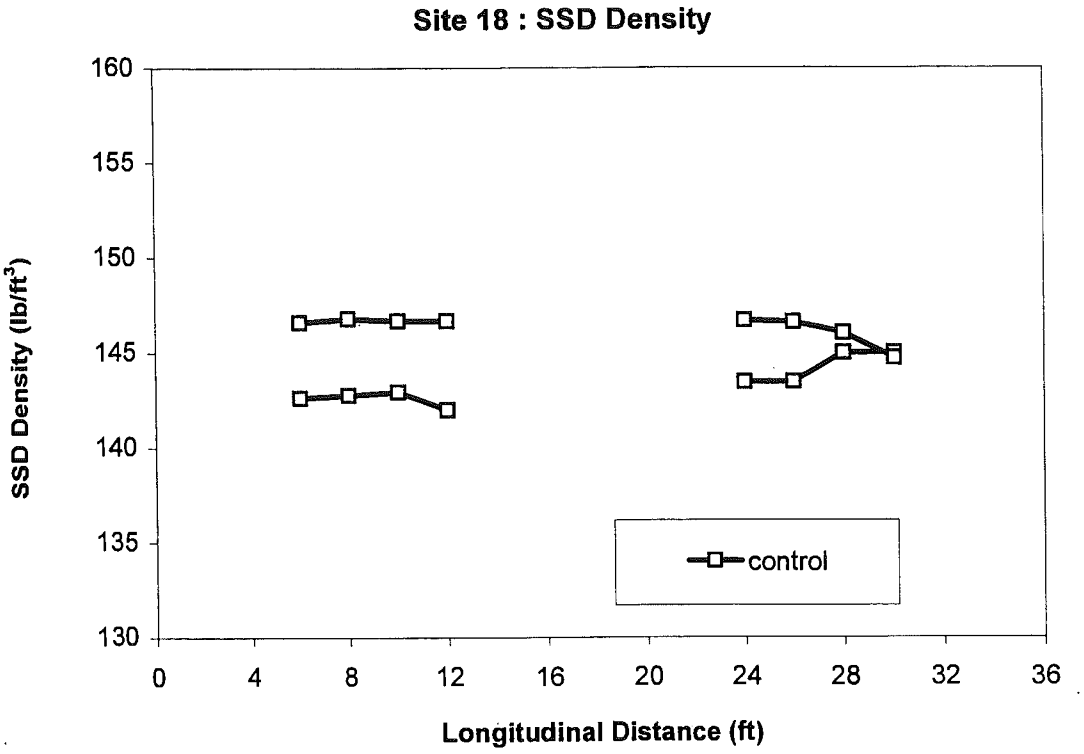


Figure 6.1 (continued) Distribution of Lab Density



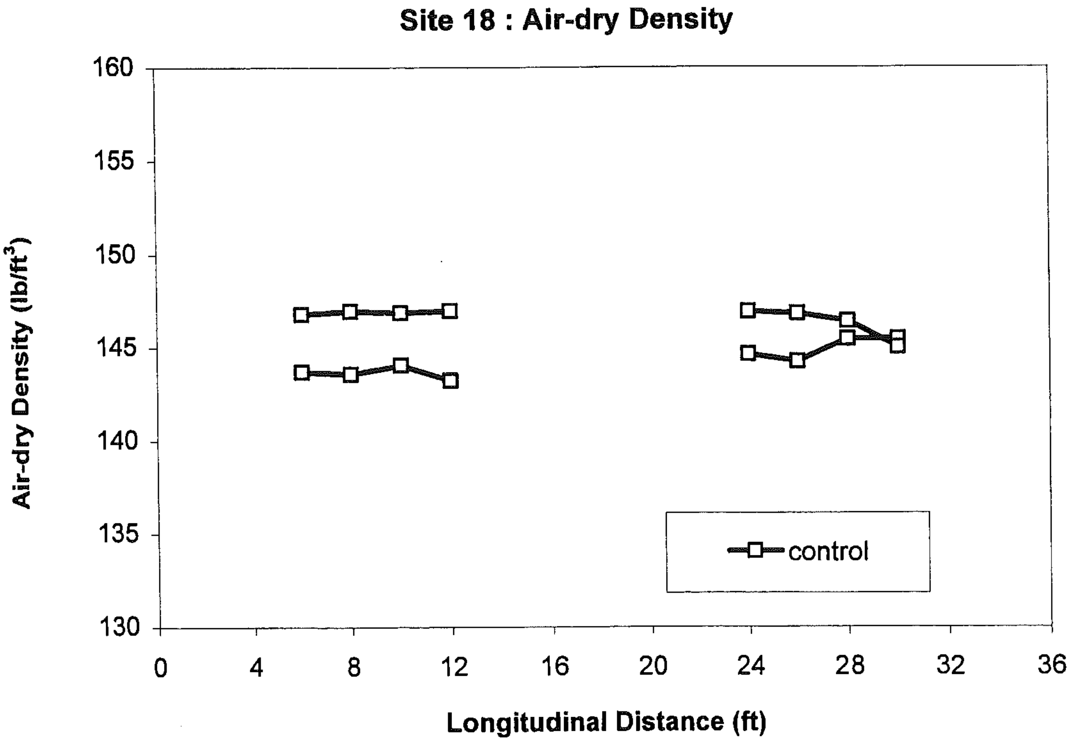
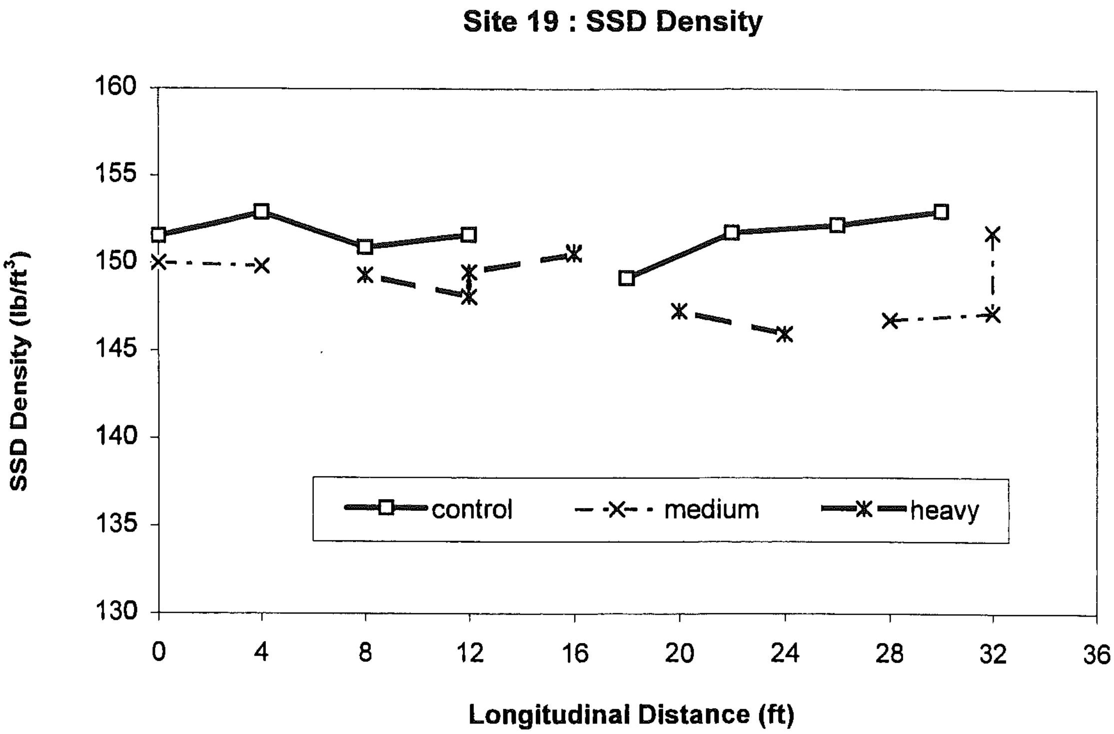


Figure 6.1 (continued) Distribution of Lab Density



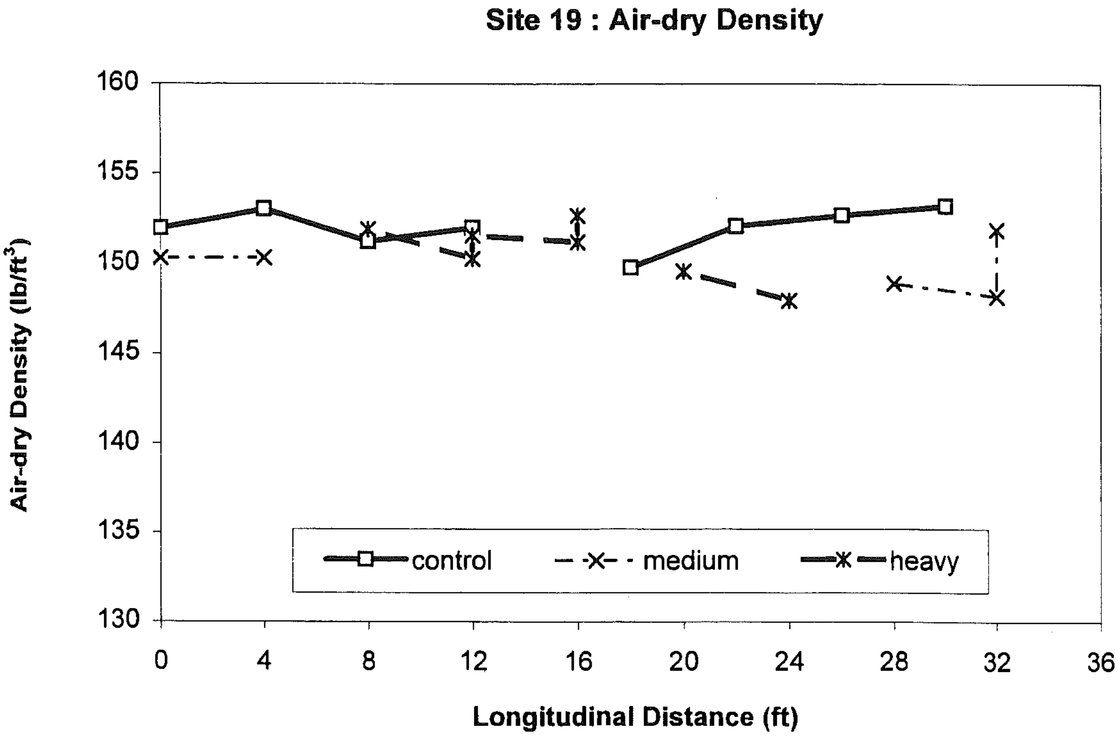
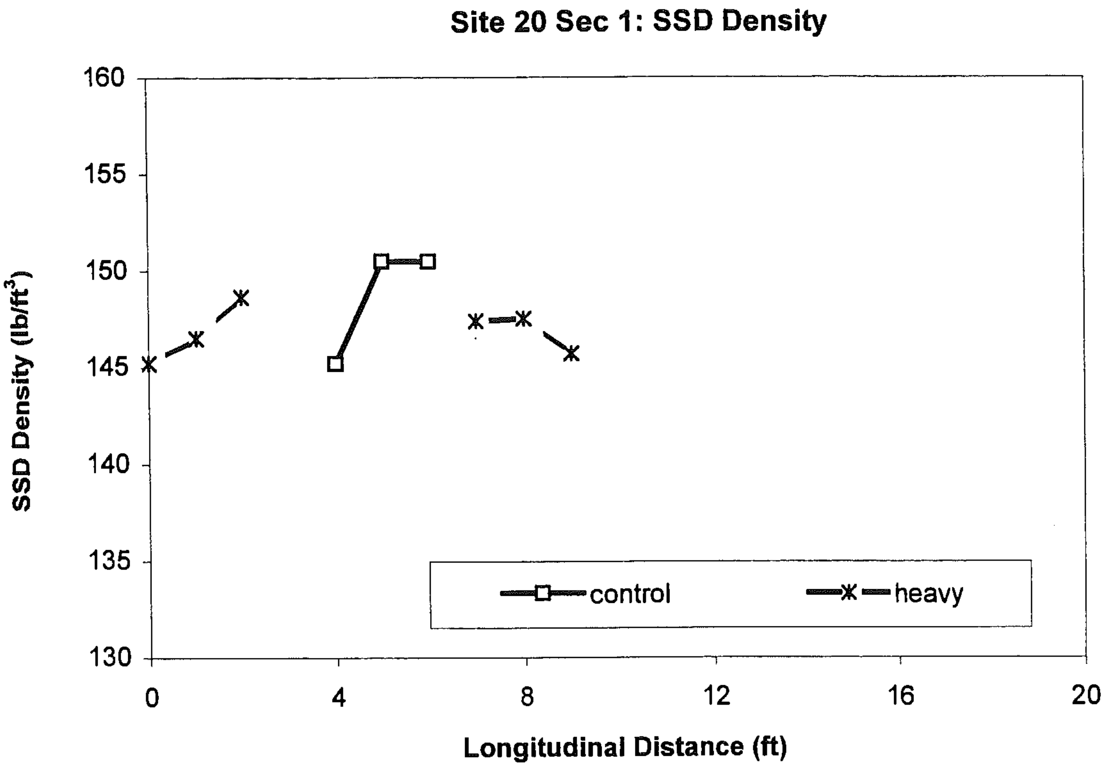


Figure 6.1 (continued) Distribution of Lab Density



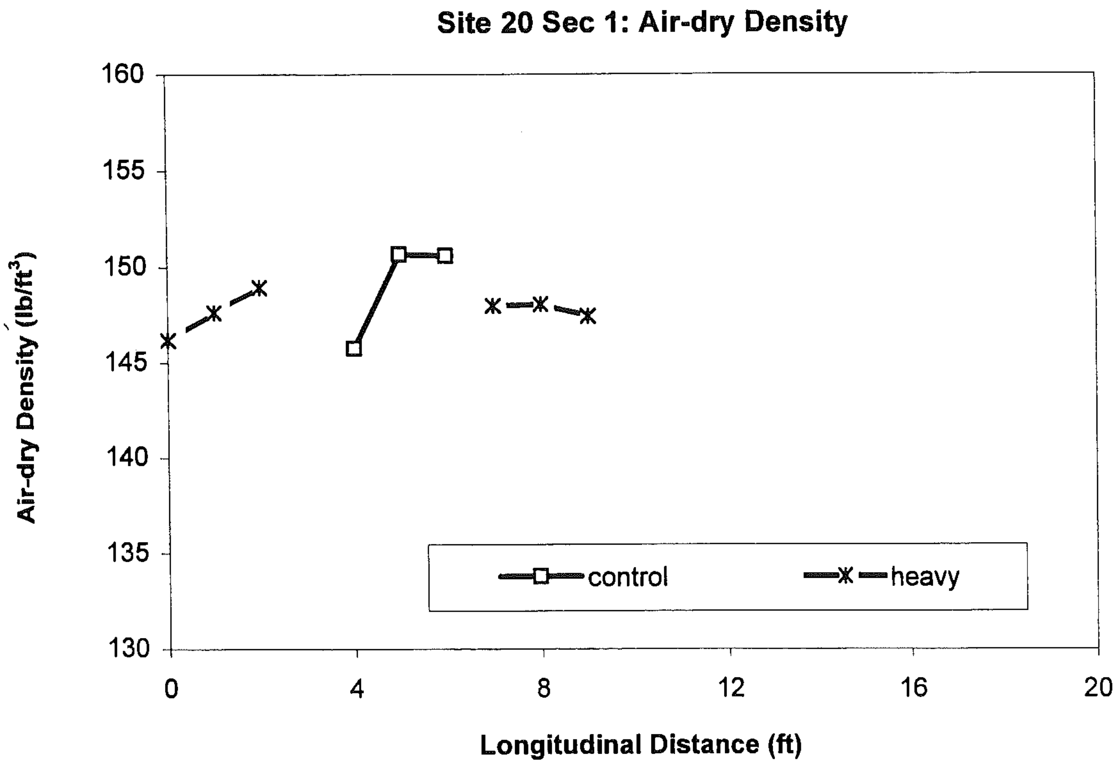
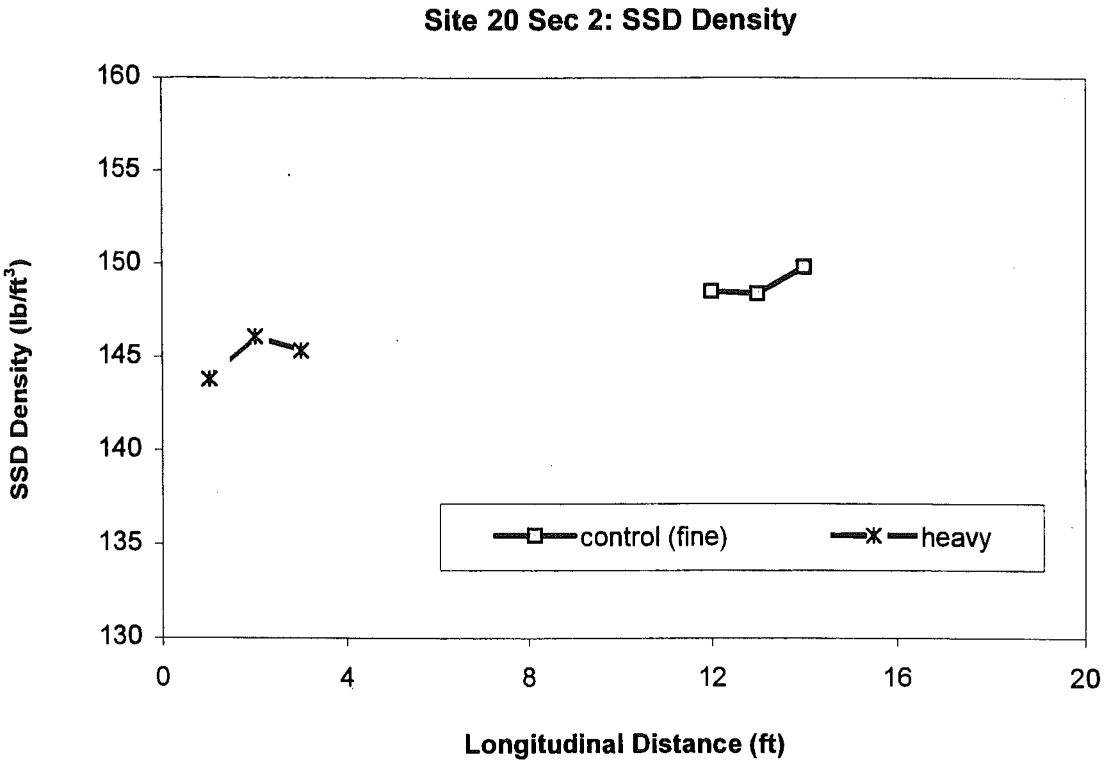


Figure 6.1 (continued) Distribution of Lab Density



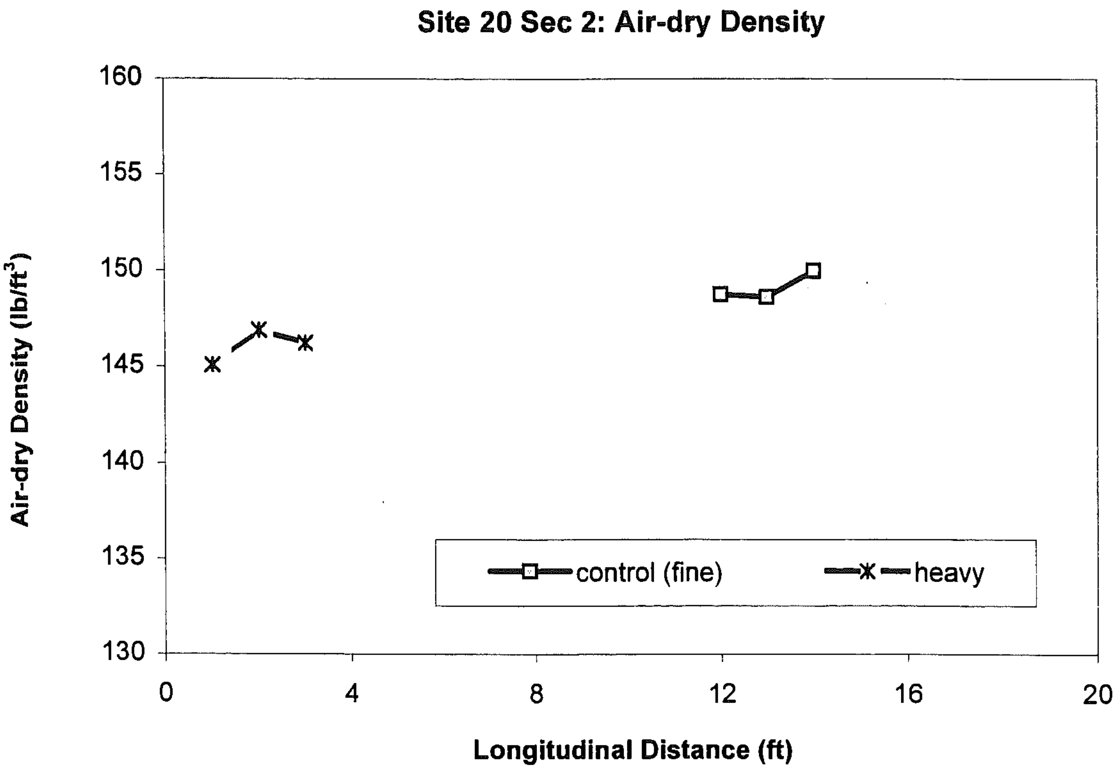
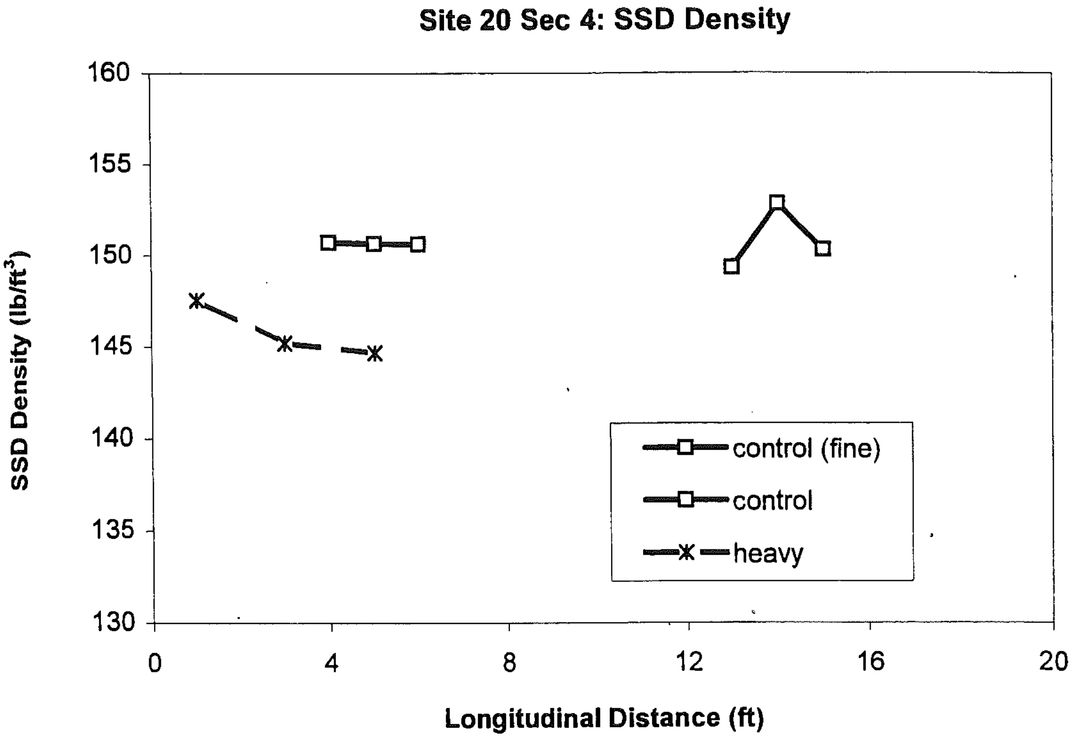


Figure 6.1 (continued) Distribution of Lab Density



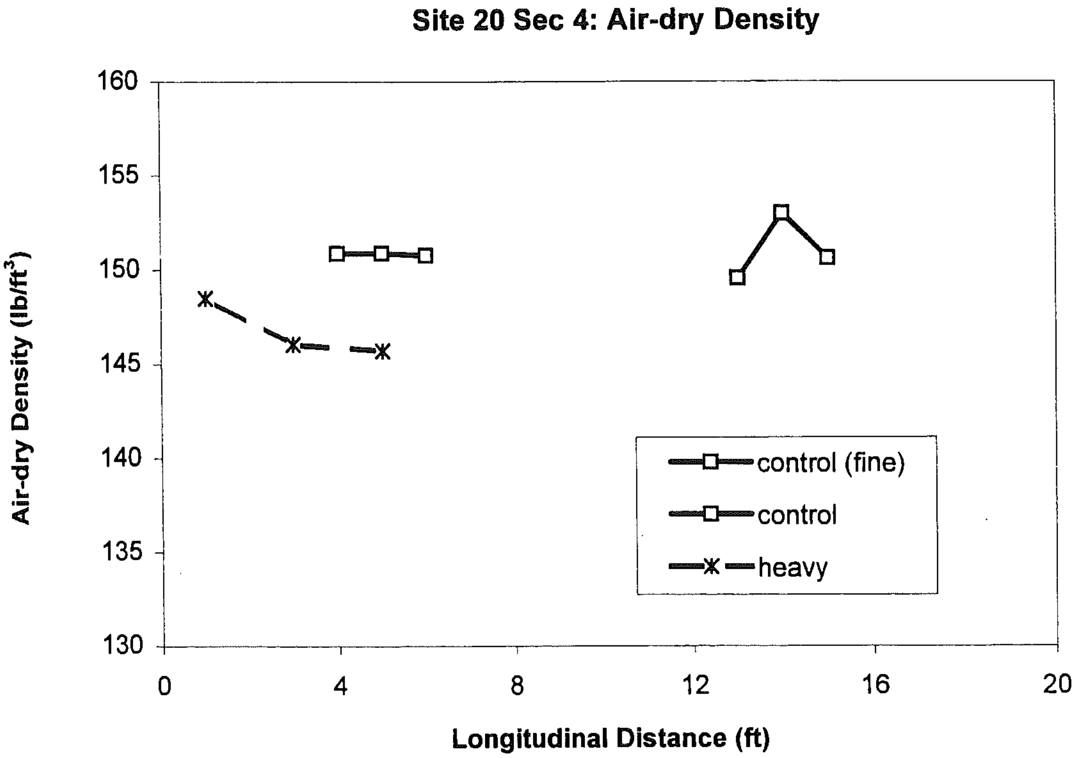
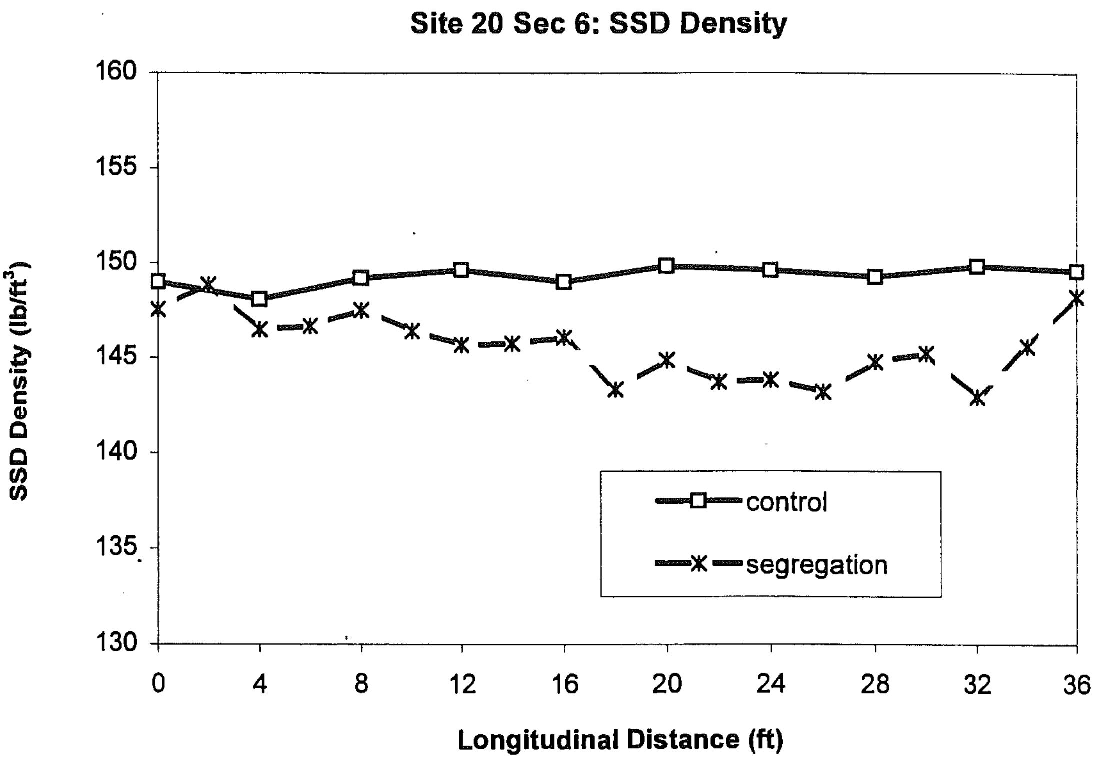


Figure 6.1 (continued) Distribution of Lab Density



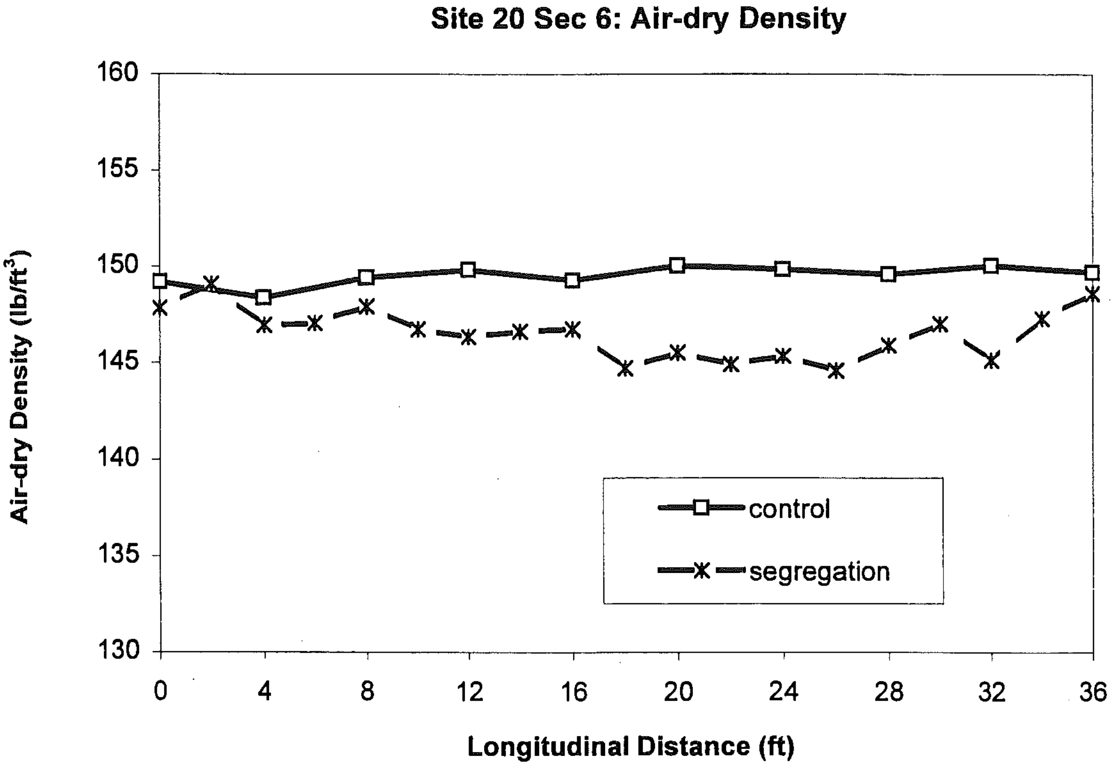
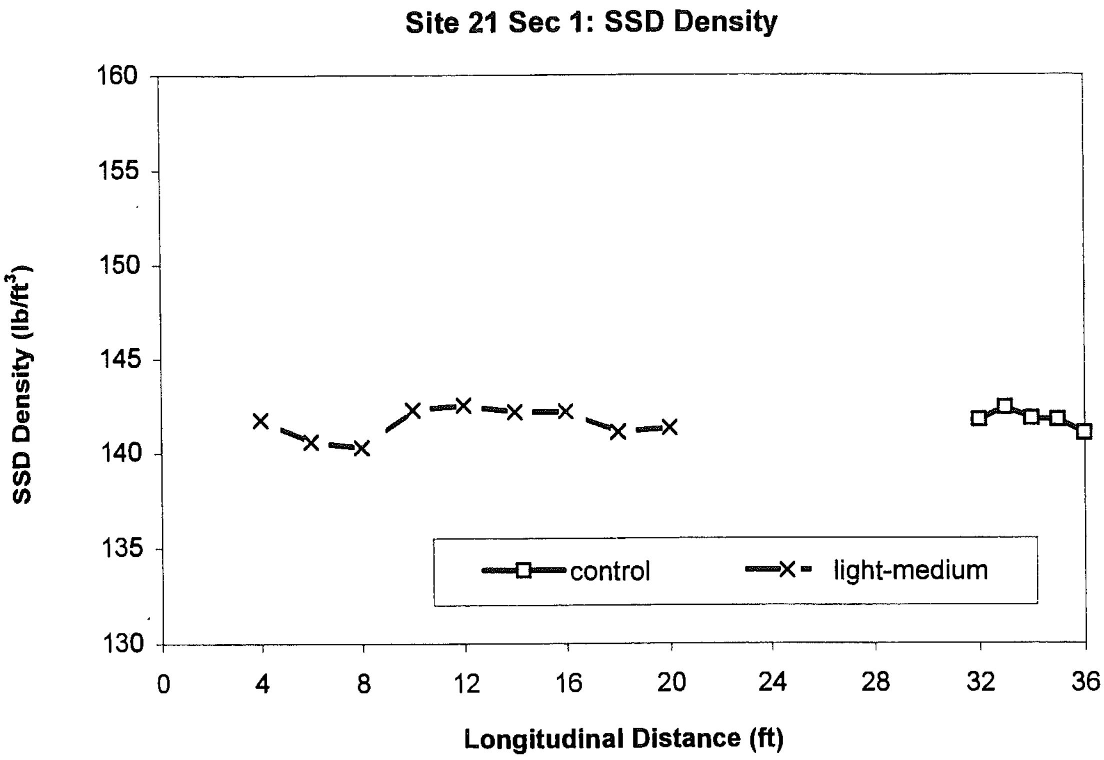


Figure 6.1 (continued) Distribution of Lab Density



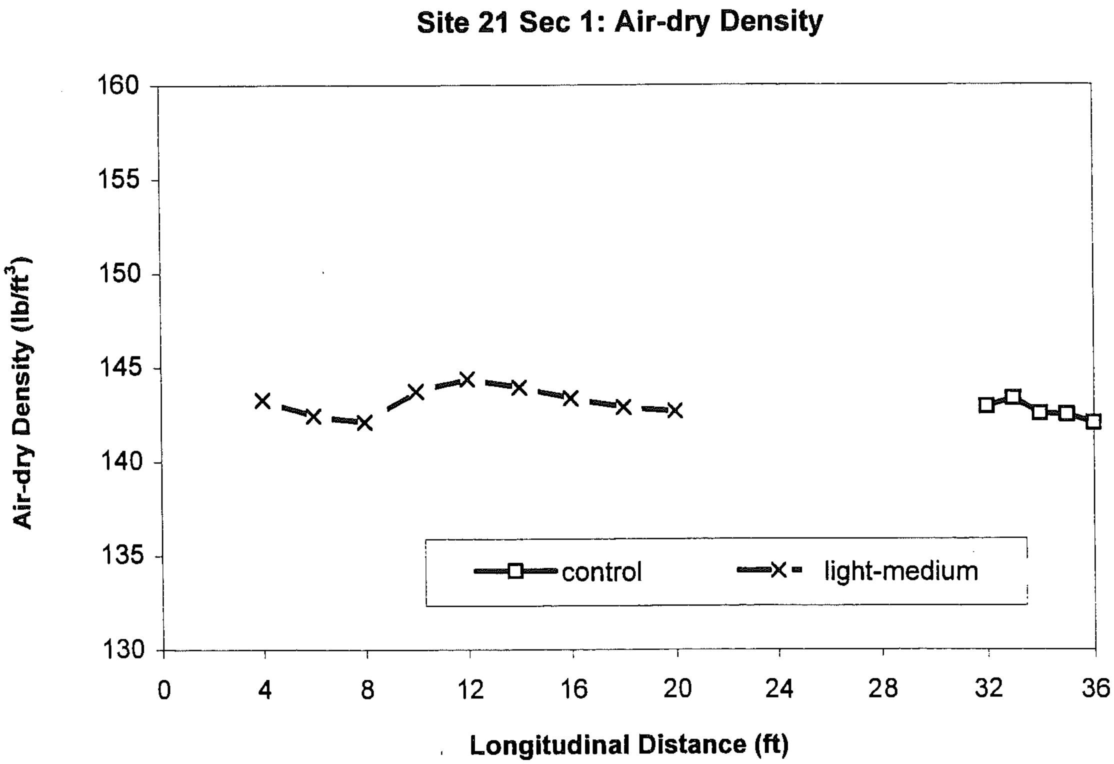
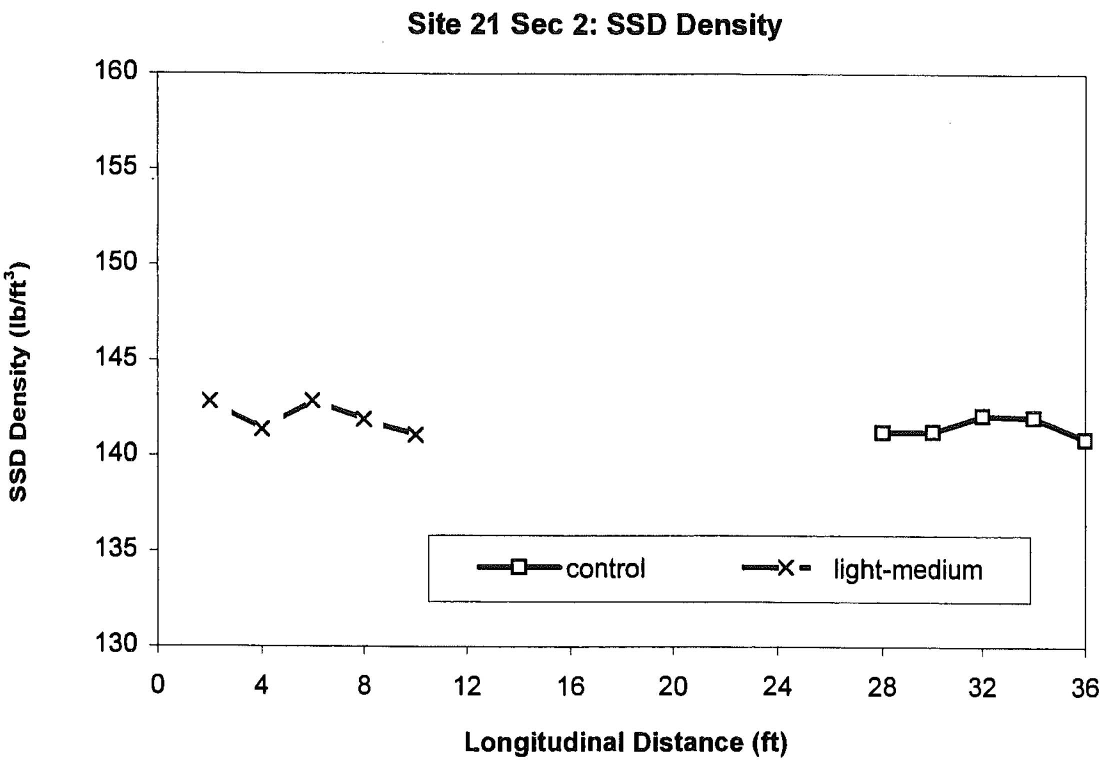


Figure 6.1 (continued) Distribution of Lab Density



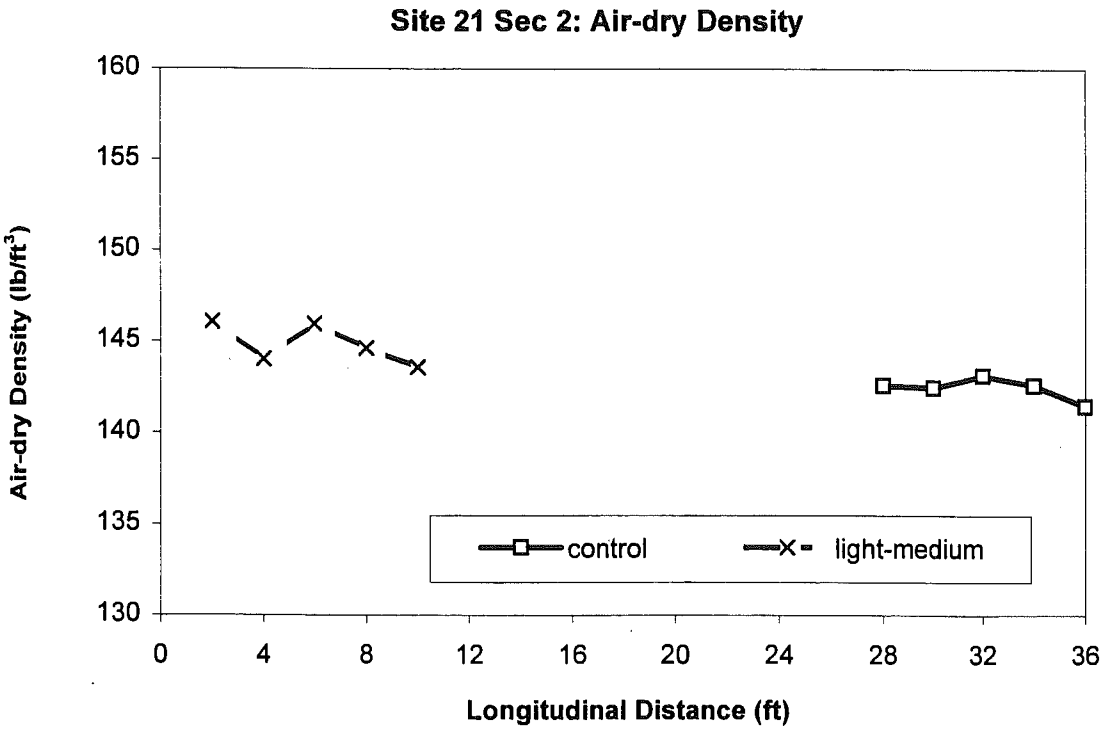
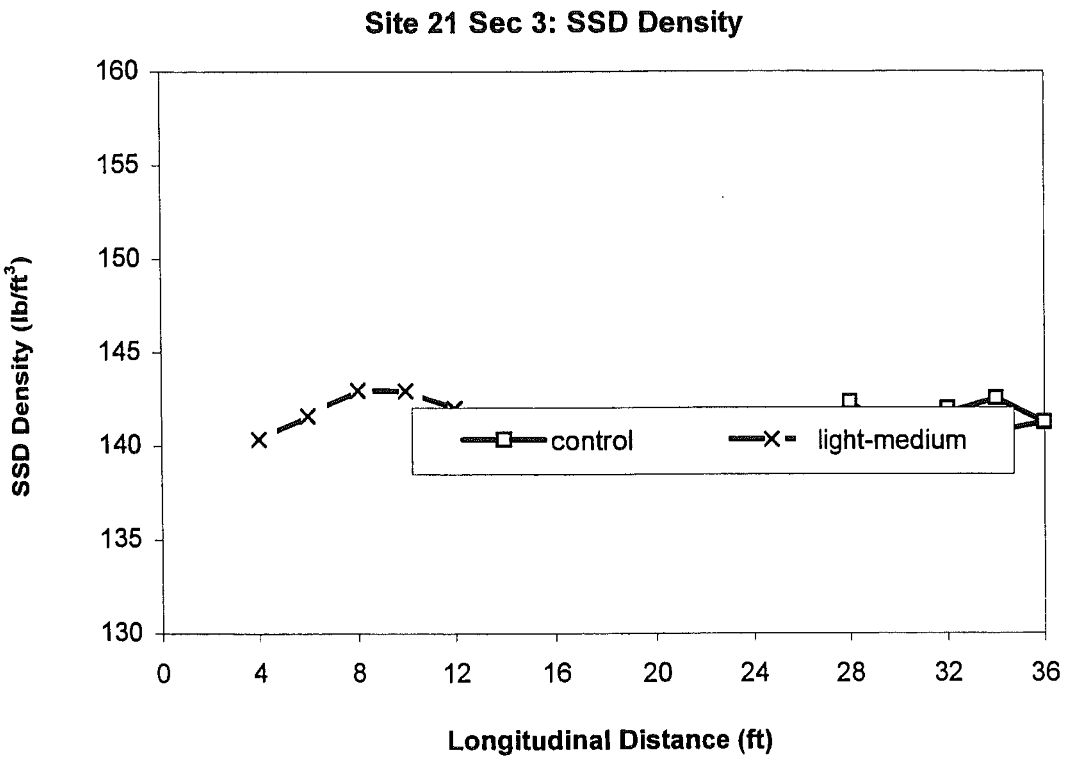


Figure 6.1 (continued) Distribution of Lab Density



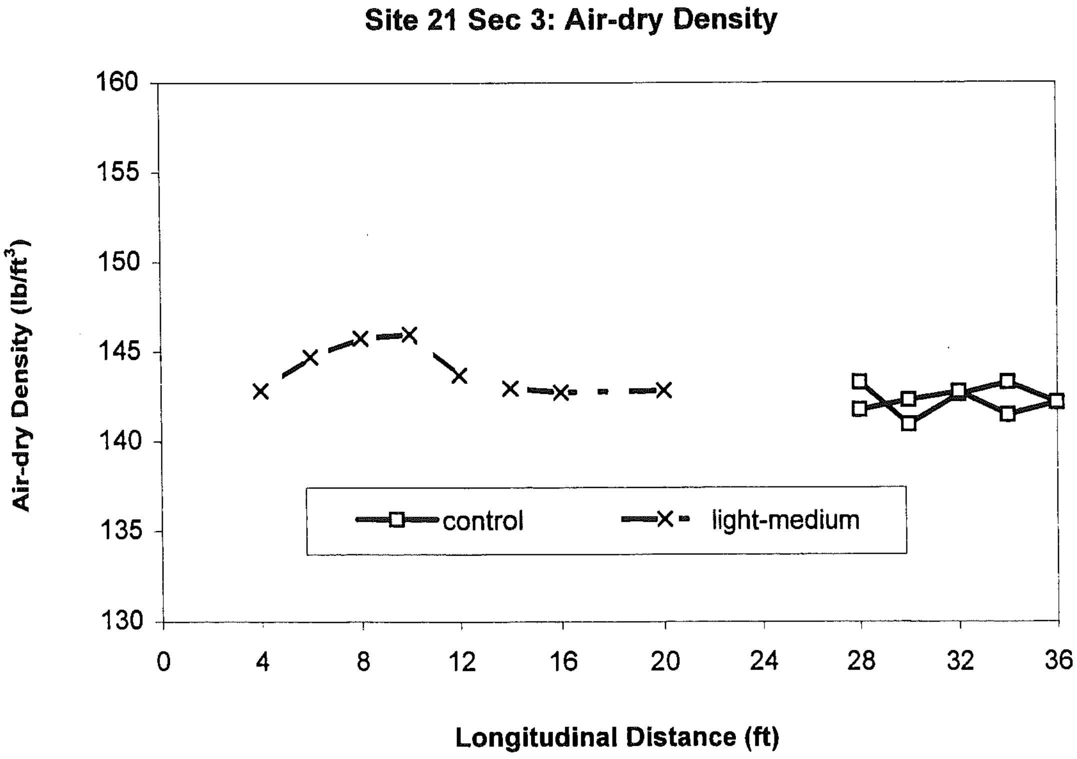


Figure 6.1 (continued) Distribution of Lab Density

At **site 3**, the trends of the lab density measurements are similar to those for nuclear density values: one control has high density values, the other is similar to the segregated samples.

At **site 5**, the control sample located outside the grid has relatively low density values (both SSD and air-dry), similar to that of nuclear density values. The heavy segregation sample located across the transverse joint from the main sample grid has high lab density values.

At **site 10**, the trend of lab density is similar to that of nuclear density measurements. The results for medium or light segregated samples within the grid were mixed as shown in Figure 6.1. One control sample outside the grid showed relatively low density values compared to segregated samples within the grid.

At **site 13**, the density values of control samples are consistently higher for both SSD and air-dry lab density than that of segregated samples. In fact, the difference in lab density between control and heavy-segregated sample is approximately 6 lb/ft^3.

At **site 15**, one control sample has relatively low density values and one light segregated sample has relatively high lab density values. For the rest of segregated samples, the lab density values are less than the control samples, as expected.

At **site 16**, the trend of lab-measured density values is similar to that of nuclear-measured density values. The SSD and air-dry density for segregated samples are lower than that for unsegregated control samples.

Site 17 and 18 were selected as control sites exhibiting no segregation. However, lab density values exhibited differences among samples as great as 4 lb/ft^3, matching the findings from the nuclear density analysis. This confirms that density differences due to compaction (either by traffic or construction differences) can be as large as those associated with segregation.

At **site 19**, lab-measured density values of control samples from SSD and air-dry are greater than 150 lb/ft^3 and higher than that of segregated samples. The density difference between control and heavy segregated samples is as great as 5 lb/ft^3 for SSD density, compared to the 14 lb/ft^3 difference from nuclear density analysis.

At **site 20**, lab density analyses were performed at four sections. At section 1, the density difference between control and segregated samples is less than 2 lb/ft^3. At sections 2, 3 and 6, the expected trend is present: density values from the control sample are higher than that from segregated samples.

At **site 21**, the control and light to medium segregated samples are not differentiable based on SSD or air-dry density values. It is found that the lab density values are approximately 142 lb/ft^3 that is only 92% of the Theoretical Maximum Density (TMD).

In general, the trends of laboratory density values are similar to the trends of nuclear density values. Segregated samples, in most but not all cases, have lower density values than control samples. The difference between lab density (either SSD or air-dry) is not as great as that from nuclear density measurements. This further suggests that the low nuclear density values in segregated areas are contributed by both the voids due to separation of coarse and fine materials and by rough surface texture.

3.0 GRADATION ANALYSIS

Segregation refers to the 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 another series of analyses. Gradation plots for cored samples are shown in Figures 6.2 to 6.19. Each curve represents the mean value of percent passing at different sizes of sieves for each sample. Curves are plotted using grain size raised to the 0.45 power on the x-axis. On this scale, a minimum void-ratio gradation will plot approximately a straight line. Concave curves below a straight maximum density line indicate open-graded mixes with insufficient fines to fill the voids; convex curves above a straight line indicate mixes with excessive fines or "tender mixes," in which larger particles may not be fully in contact. Results of statistical comparisons of gradation parameters will be presented using p-value. The detailed results for all comparisons are presented in Appendix B.

Site 1 had significant density differences, as great as 8 lb/ft^3 for nuclear density values between control and heavy segregated samples. It also has significant gradation differences, as seen in Figure 6.2. The curves for medium and heavy segregation samples are concave, and far below that for the three control samples, which are slightly convex. This implies the segregated samples have a coarser, more open mix. The maximum gradation difference is approximately 25% of the percent passing at the No. 4 sieve. The p-values from comparisons between control and segregated sample approach 10^{-10}, an exceptional value.

At **site 3**, the medium-segregated sample had significant differences from both control samples, for comparisons based on percent passing 3/8", No.4 and No.8 sieves. Figure 6.3 shows the gradation plots along with the job mix formula (JMF) curve. It can been seen that the curve for the medium segregation sample is coarser and more concave than that for control samples. The light segregation sample did not have a significant difference from one control sample; it is close to the curves of JMF and control samples.

At **site 5**, no significant differences were found (at the 99 percent confidence level) between control and segregated samples for percents passing the 3/8″ and No. 4 sieves. Even when segregated samples with different severity levels were compared against each other, most comparisons indicated p-values greater than 0.01. This implies that if the confidence level is set at 99 percent level, no statistically significant difference is found. The mean gradation plots for site 5 are shown in Figure 6.4 with the JMF curve.

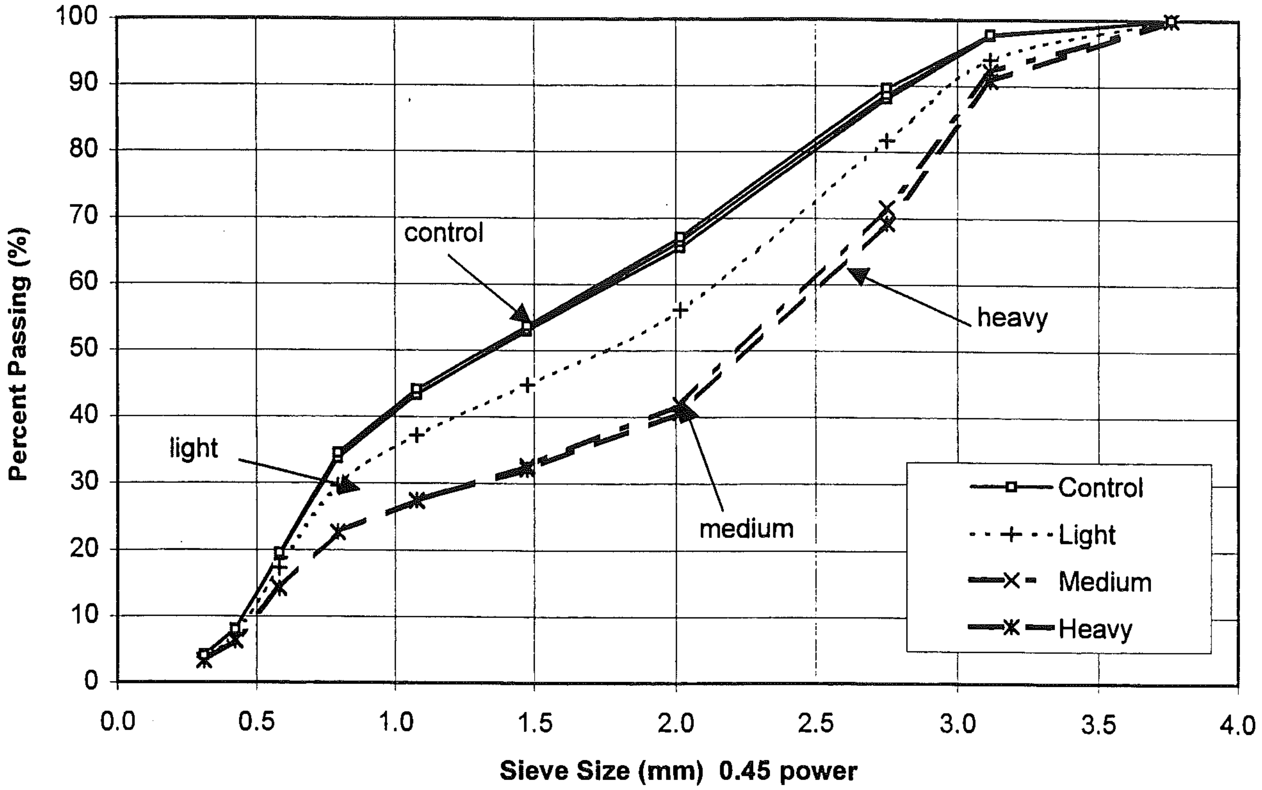


Figure 6.2 Gradation Curves at Site 1

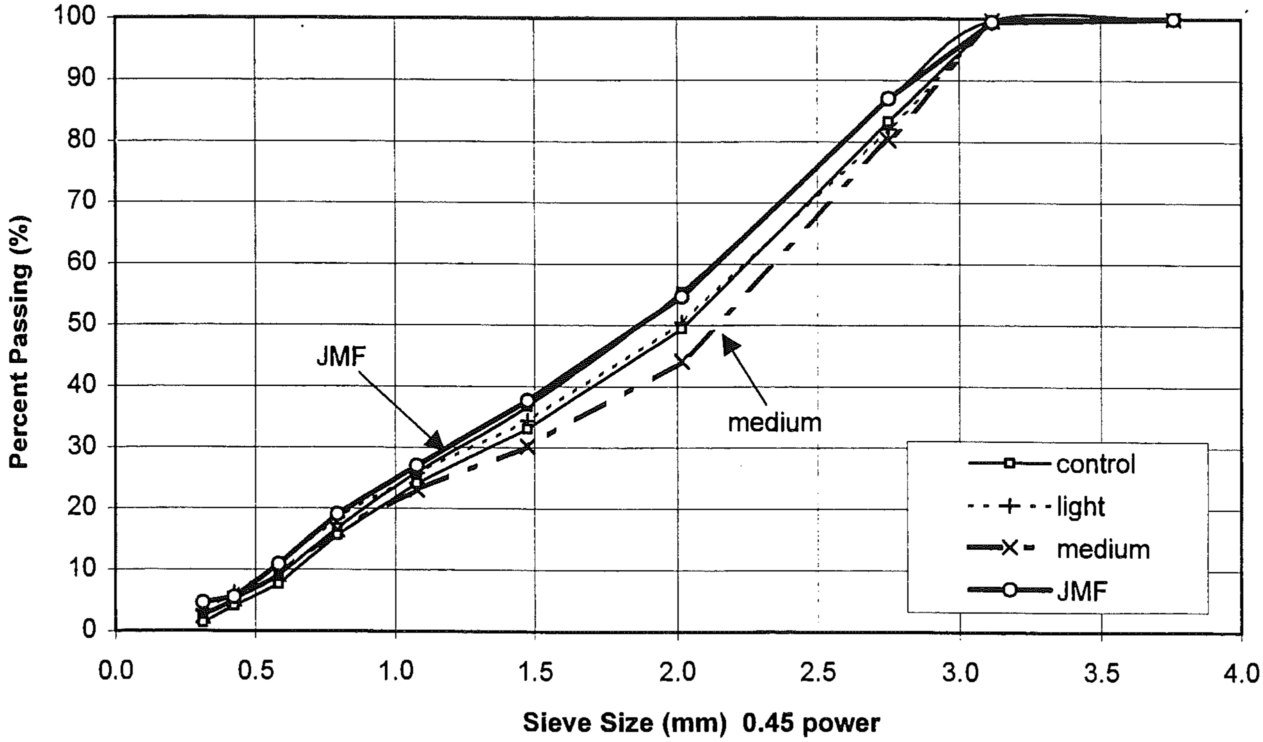


Figure 6.3 Gradation Curves at Site 3

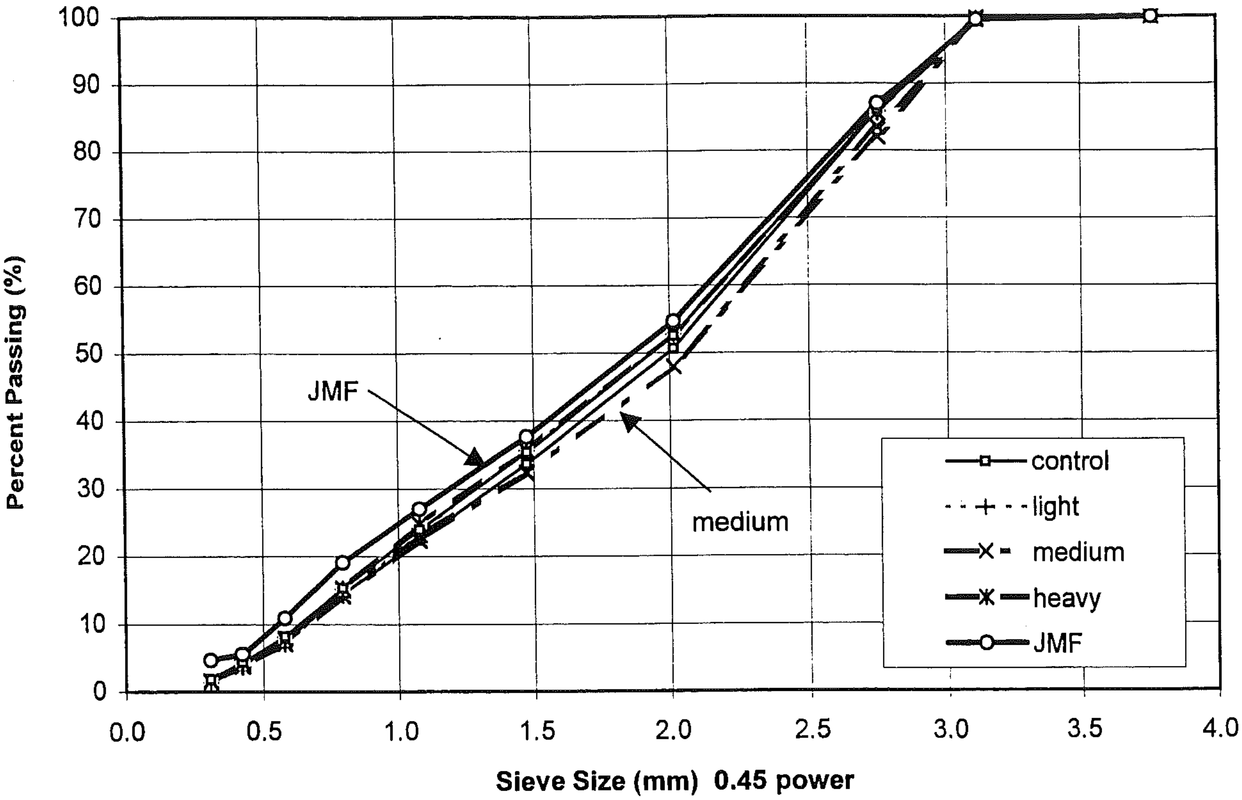


Figure 6.4 Gradation Curves at Site 5

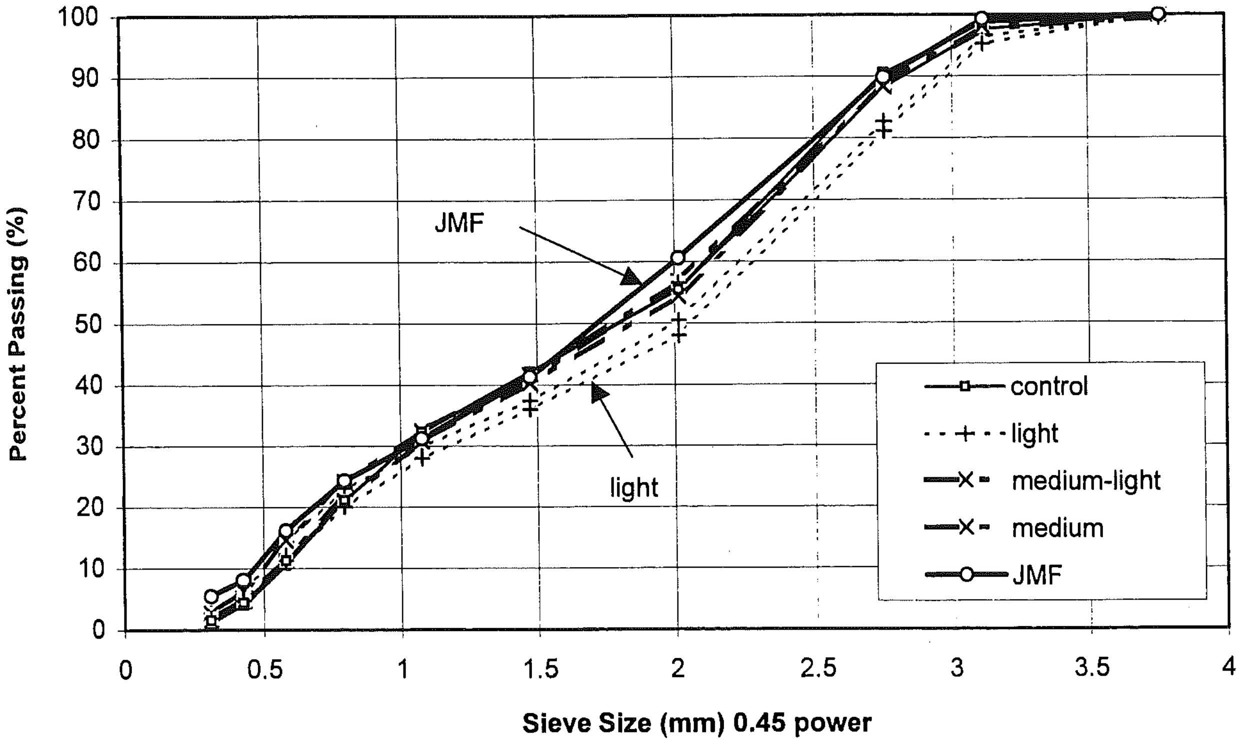


Figure 6.5 Gradation Curves at Site 10

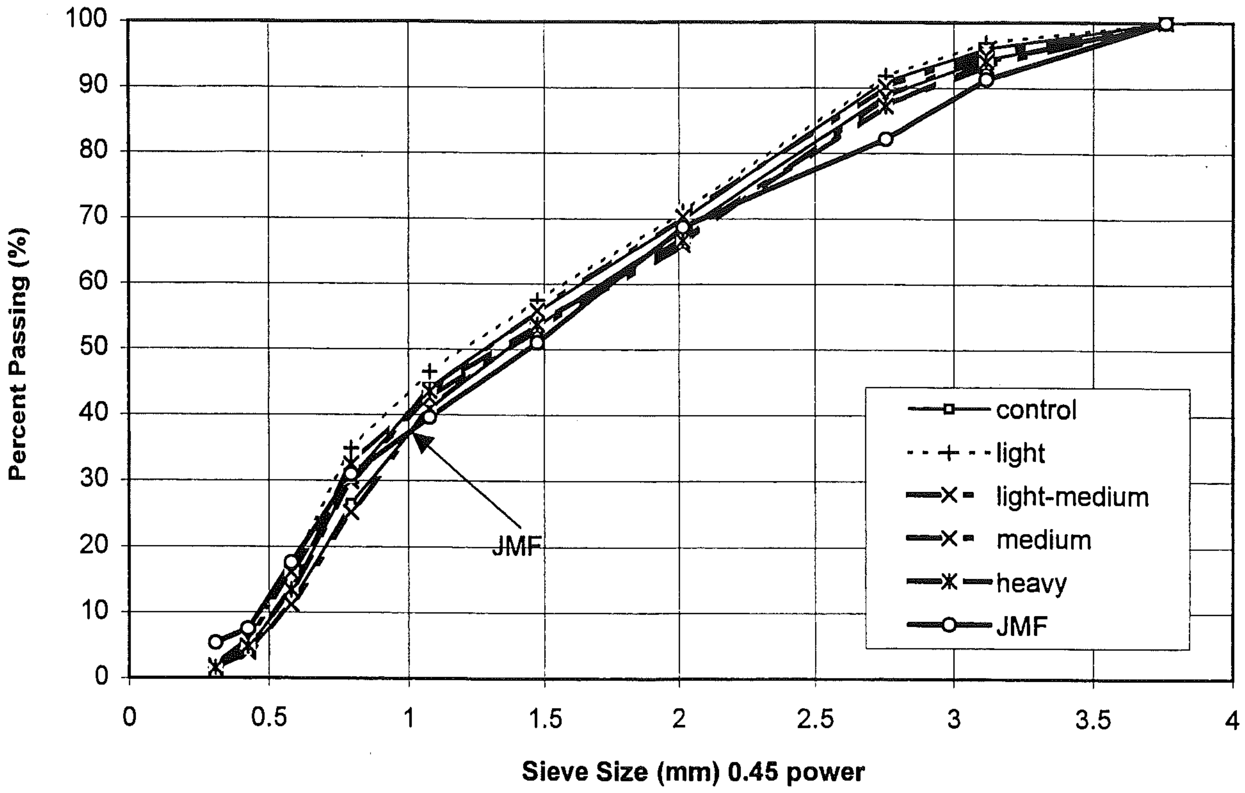


Figure 6.6 Gradation Curves at Site 13

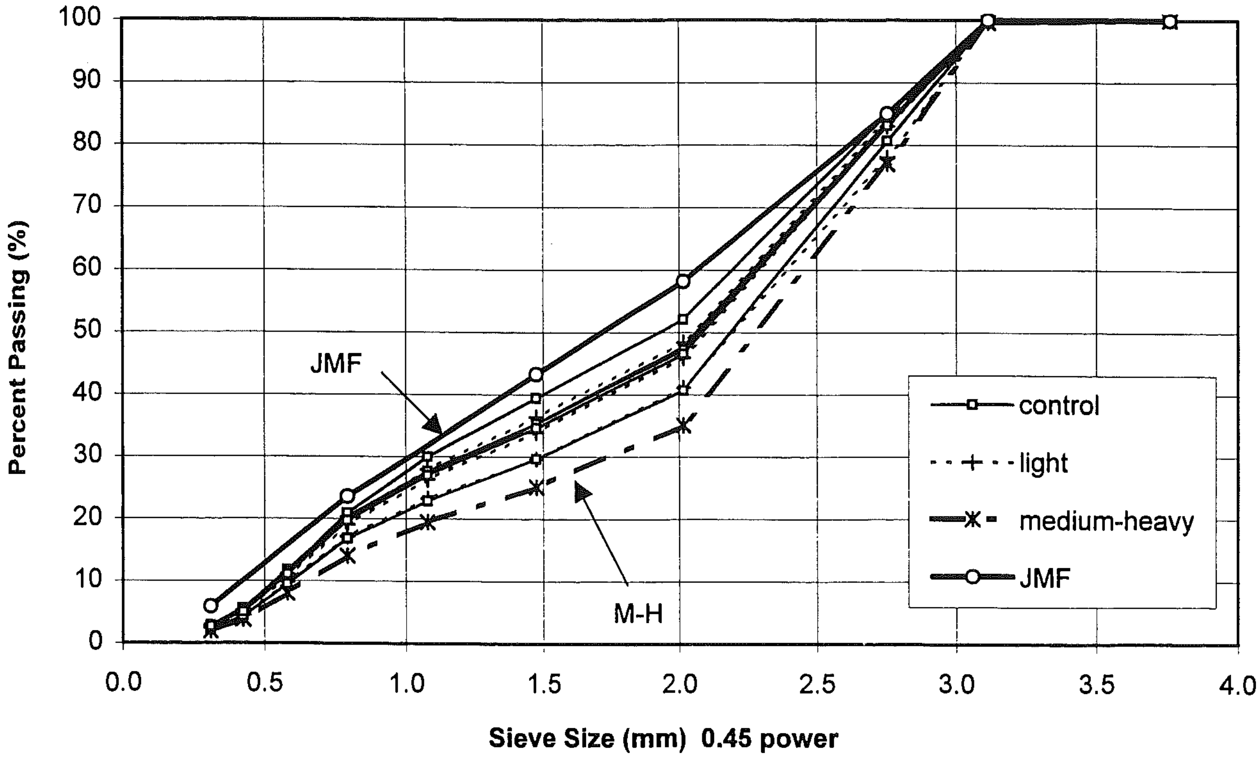


Figure 6.7 Gradation Curves at Site 15

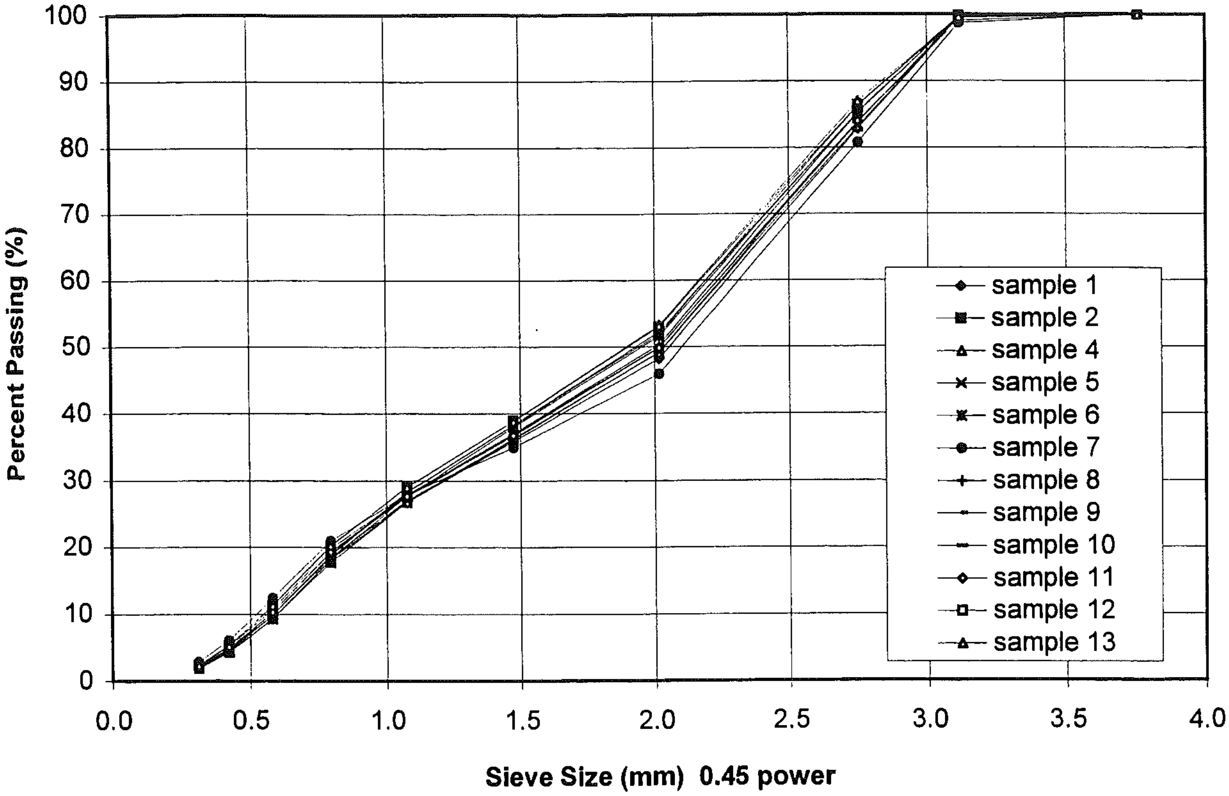


Figure 6.8 Gradation Curves at Site 16

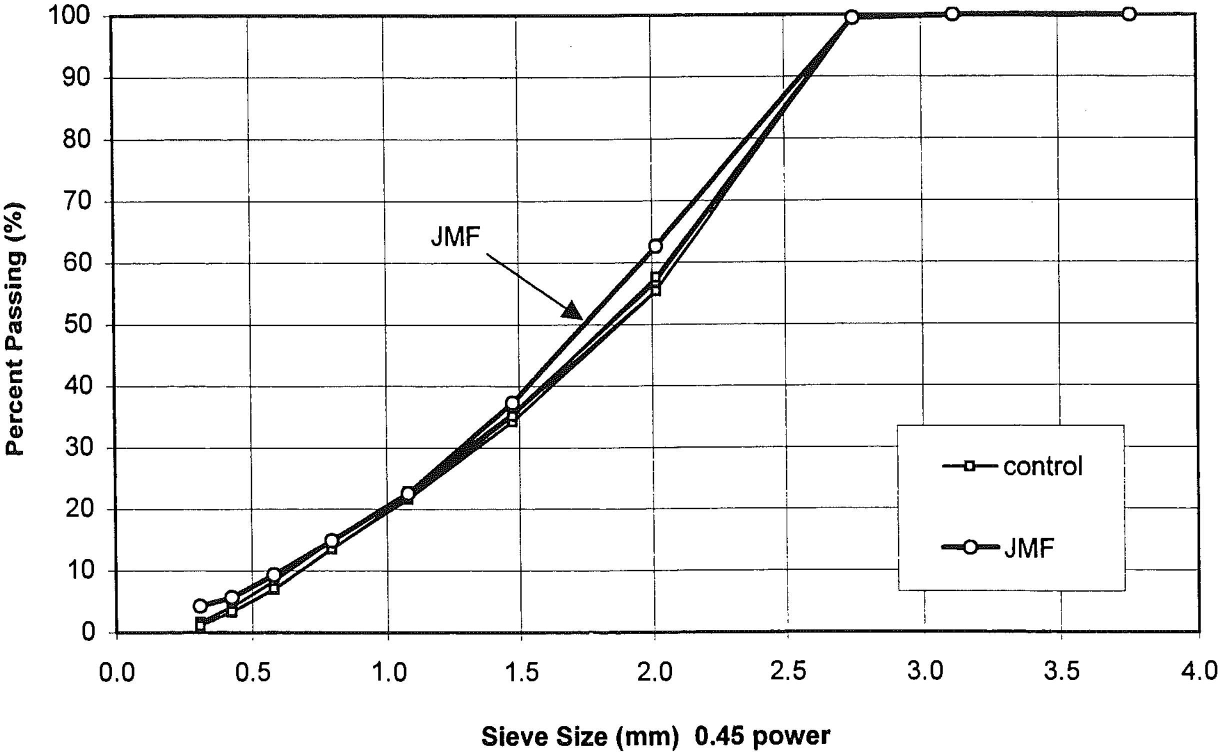


Figure 6.9 Gradation Curves at Site 17

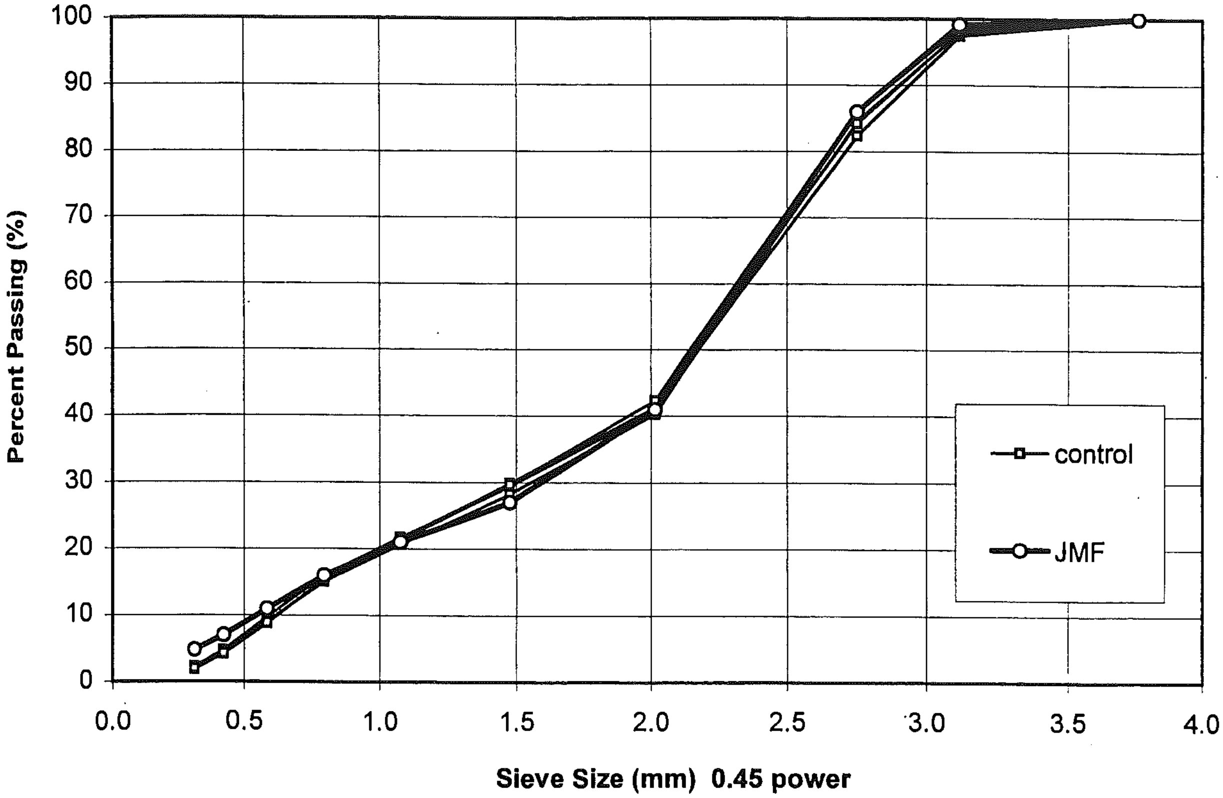


Figure 6.10 Gradation Curves at Site 18

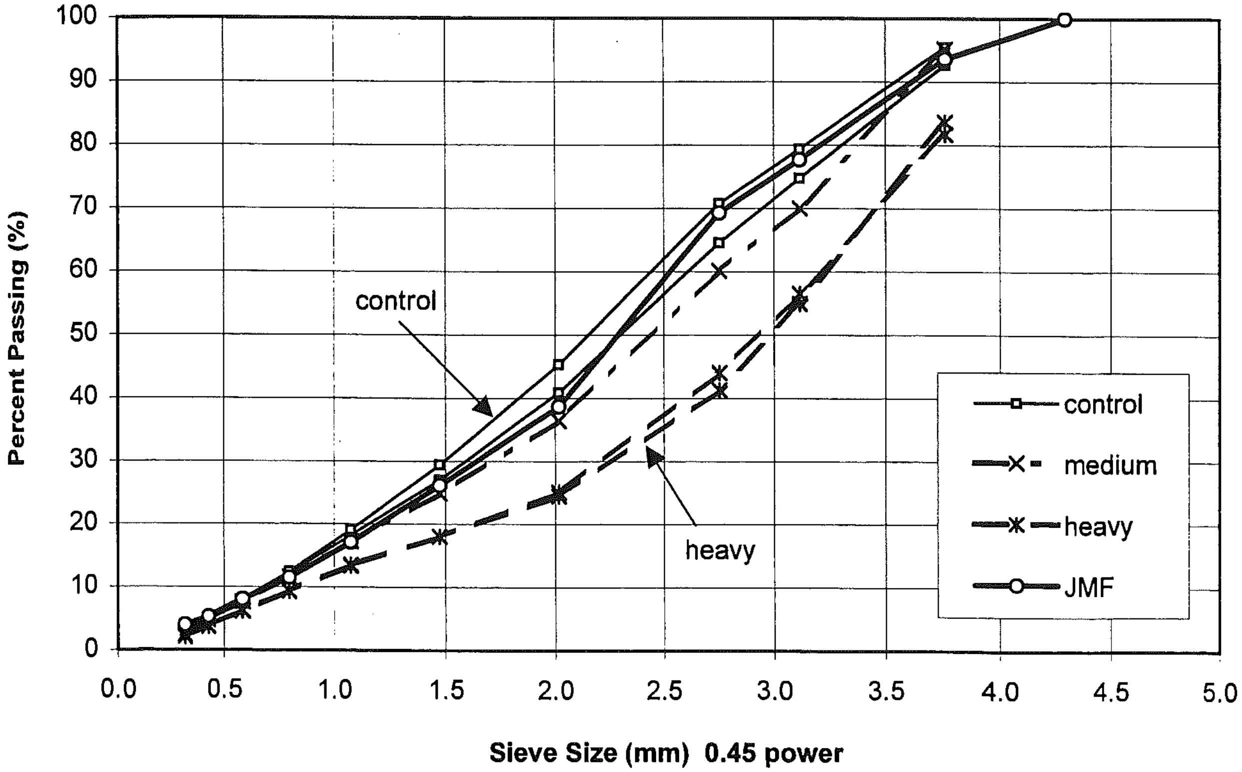


Figure 6.11 Gradation Curves at Site 19

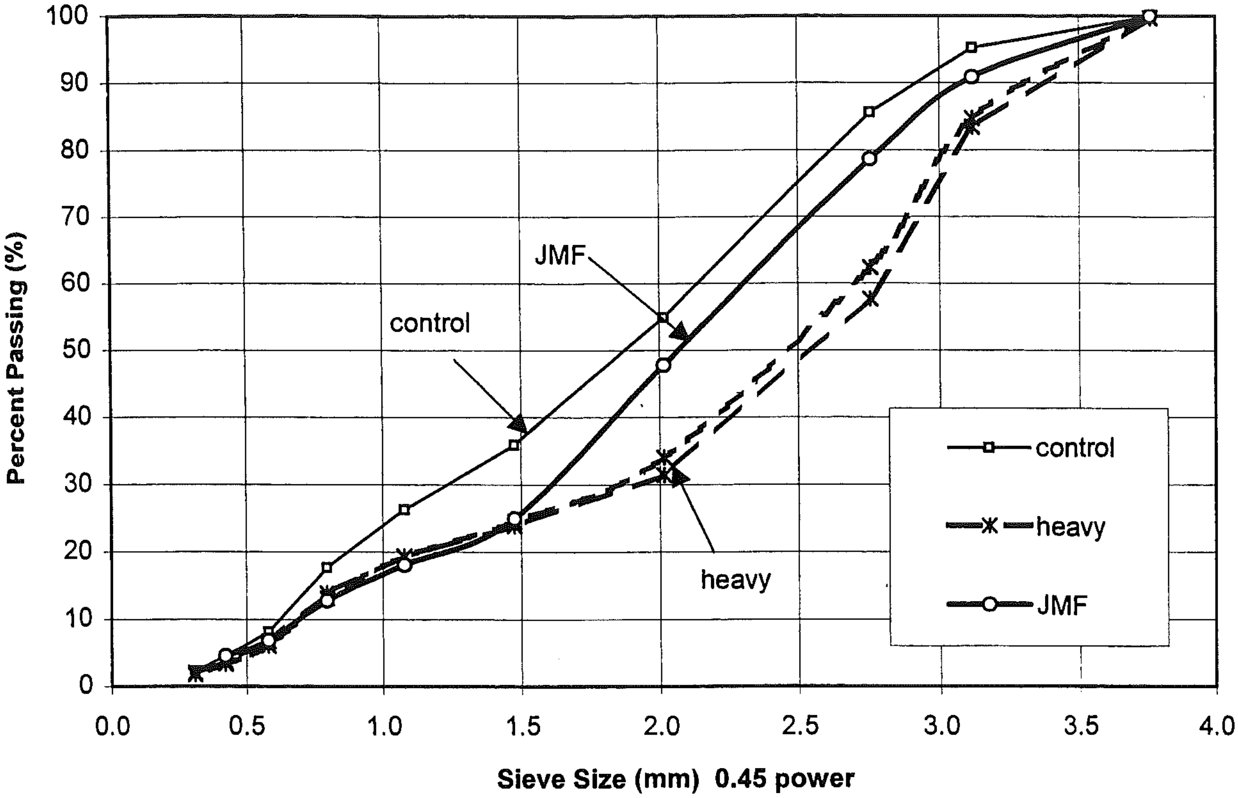


Figure 6.12 Gradation Curves at Site 20 Section 1

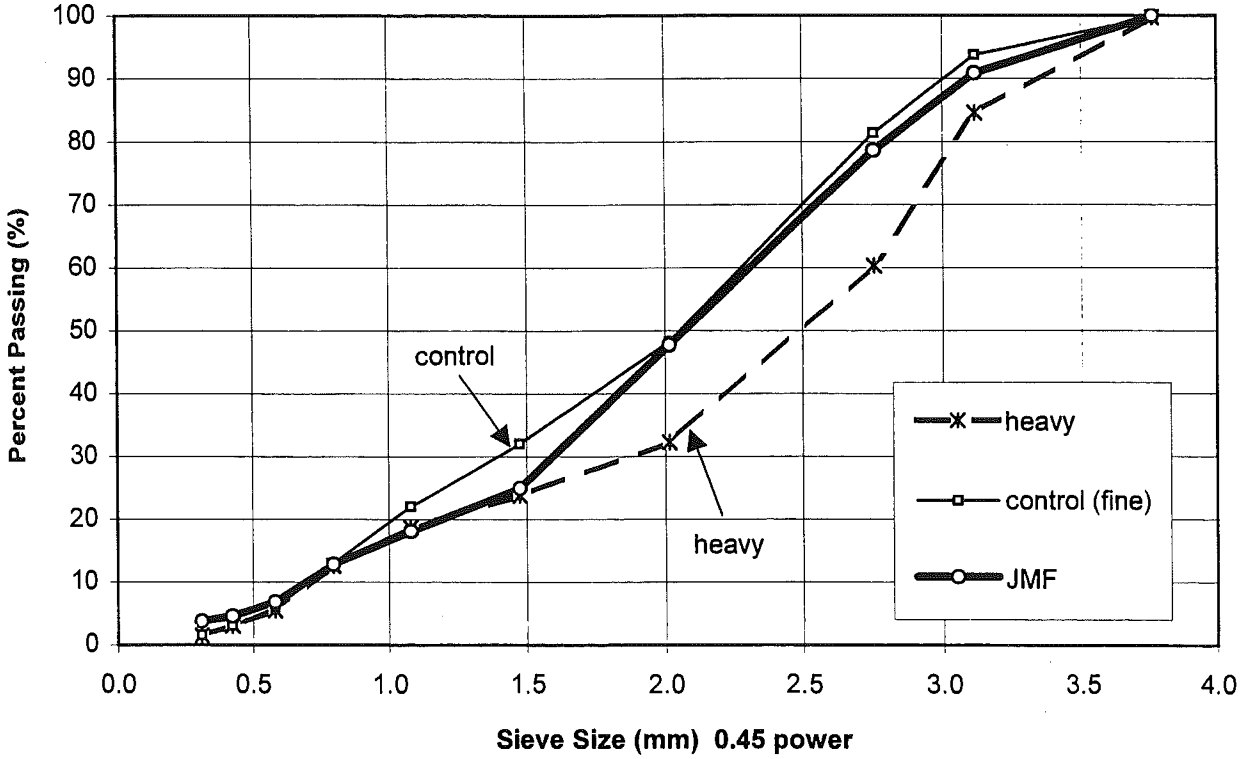


Figure 6.13 Gradation Curves at Site 20 Section 2

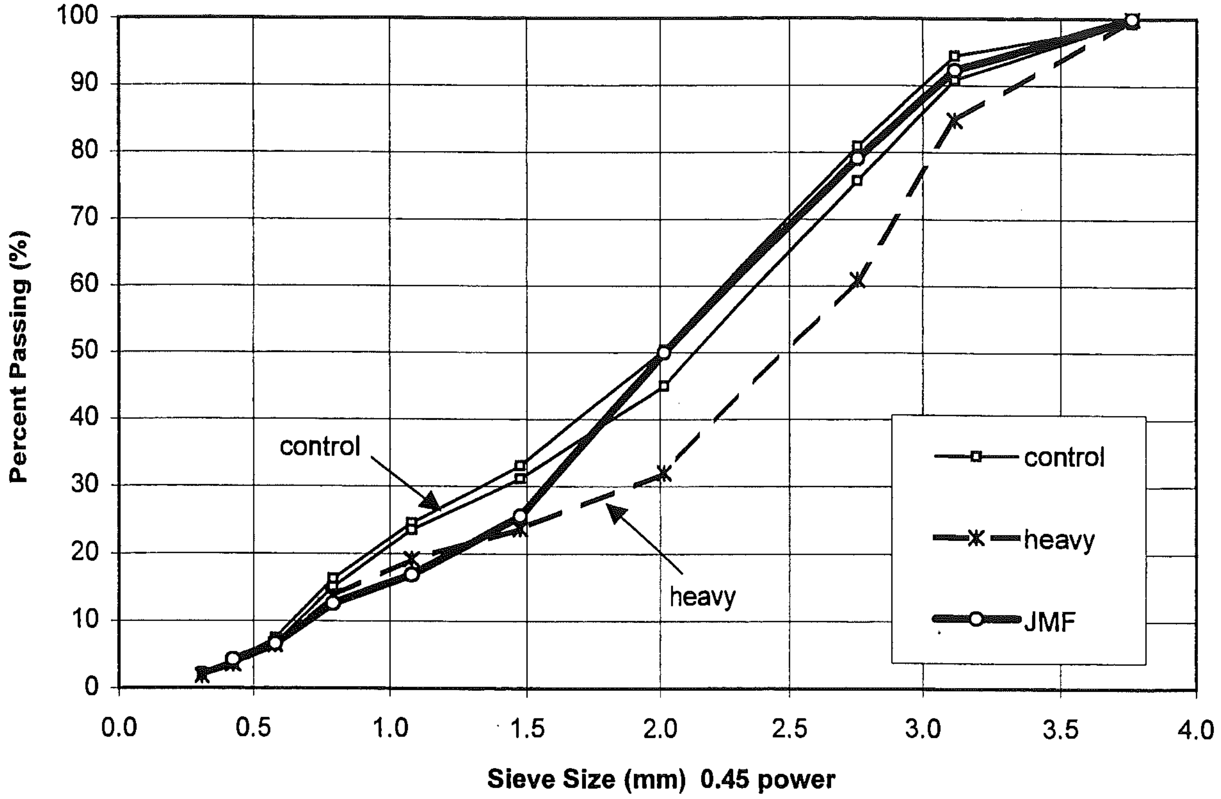


Figure 6.14 Gradation Curves at Site 20 Section 4

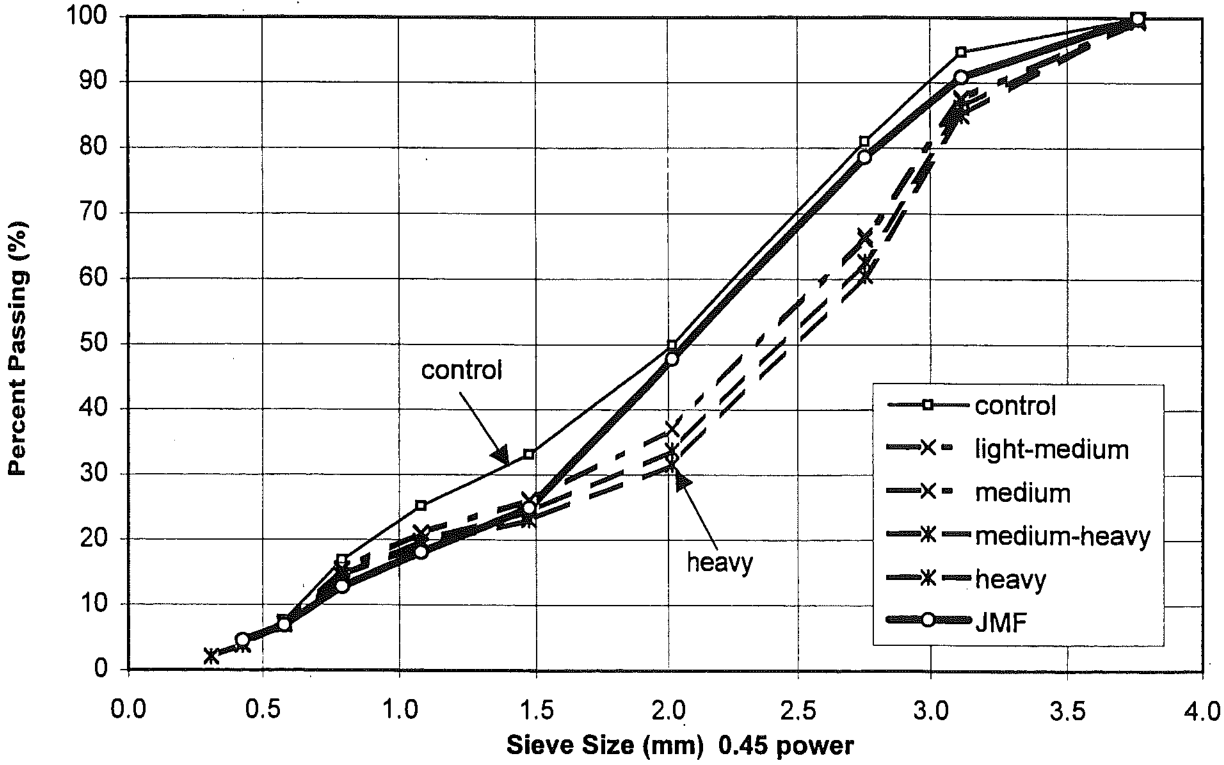


Figure 6.15 Gradation Curves at Site 20 Section 6

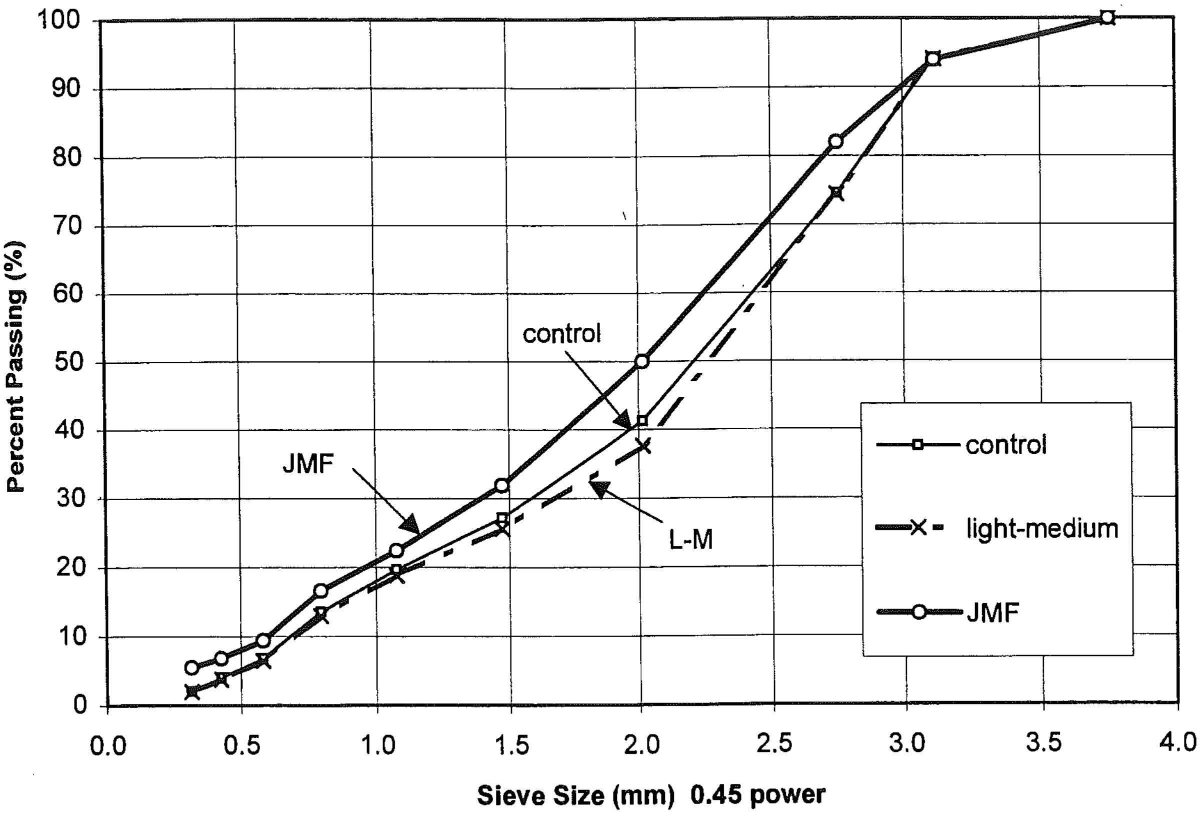


Figure 6.16 Gradation Curves at Site 21 Section 1

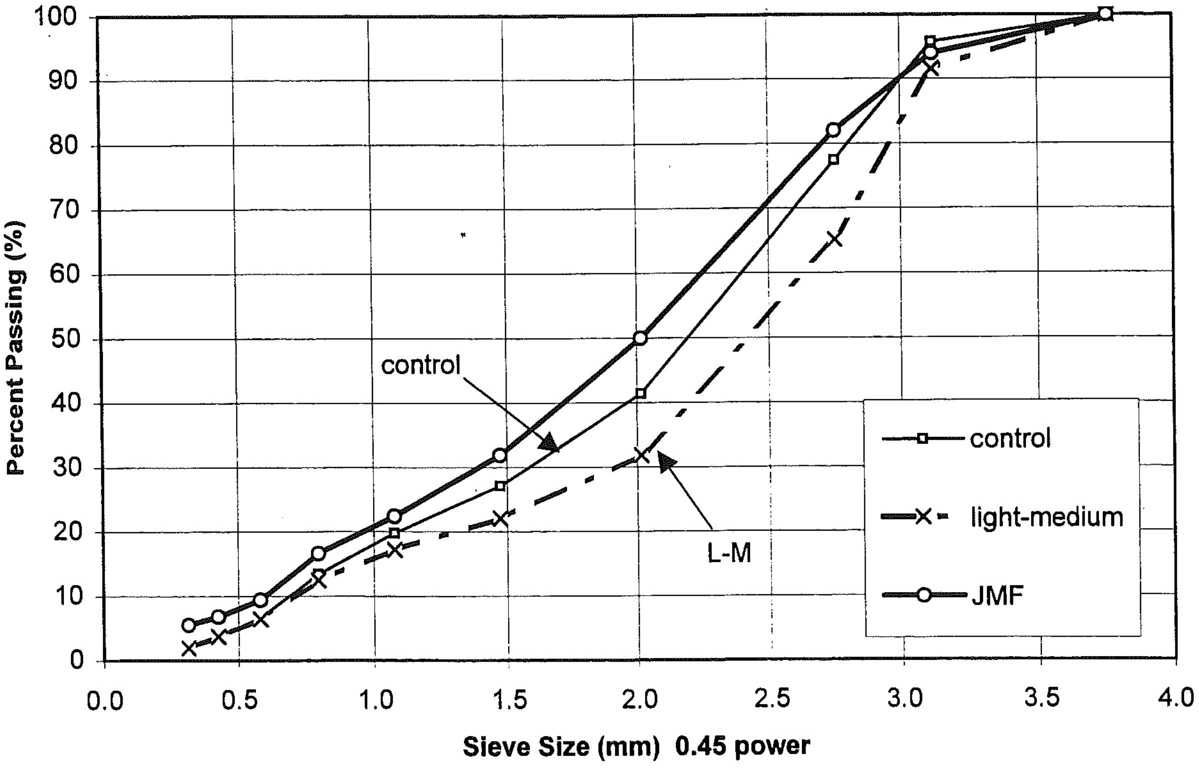


Figure 6.17 Gradation Curves at Site 21 Section 2

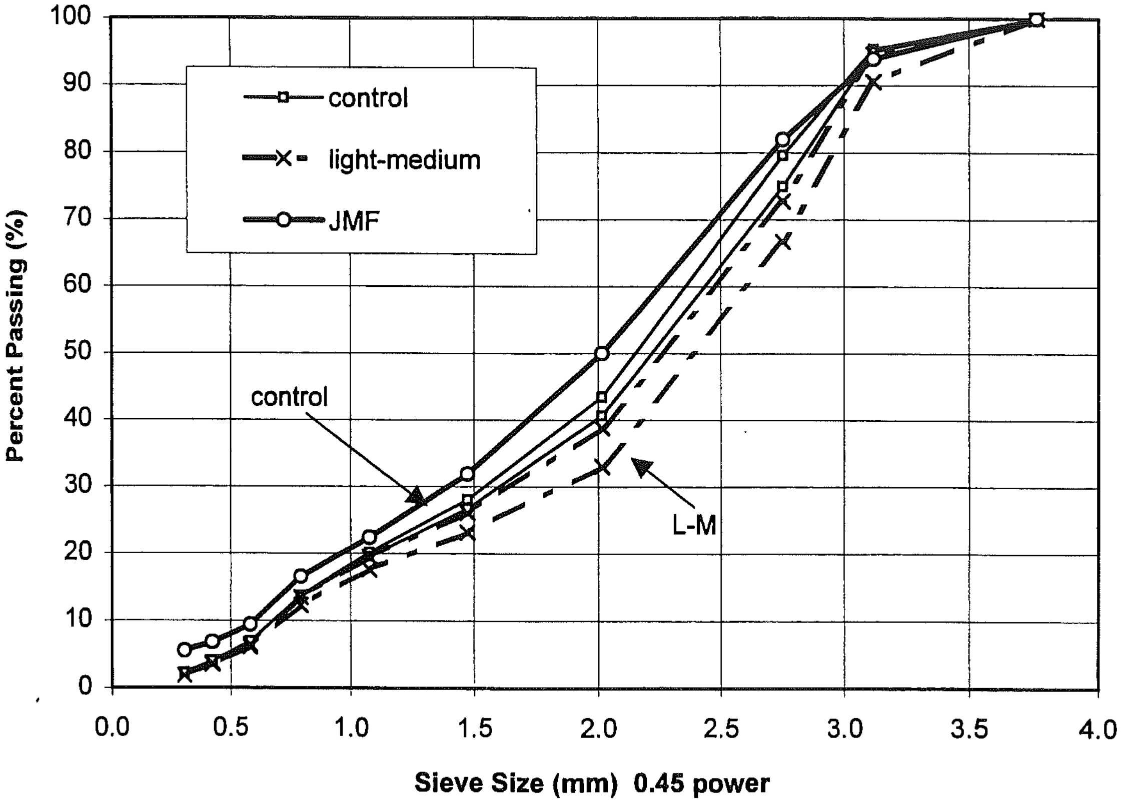


Figure 6.18 Gradation Curves at Site 21 Section 3

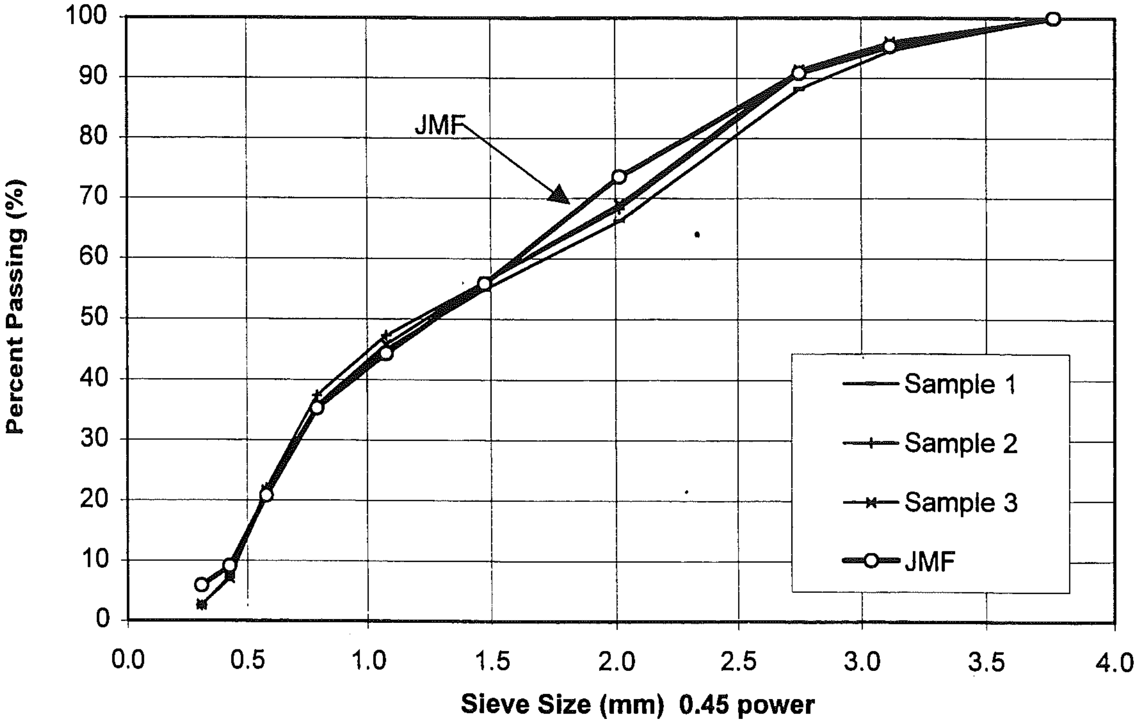


Figure 6.19 Gradation Curves at Site 22

At **site 10**, two light segregation samples showed differences from control and medium segregated samples if the confidence level is reduced to 95 percent. Figure 6.5 indicates that the gradation for both light segregation samples is coarser and more concave than that for other samples. However, light-medium and medium segregation samples were not different from control samples; this differs from the conclusion for nuclear density evaluations.

At **site 13**, based on p-values, no significant gradation differences between control and heavy or between control and medium samples were found. As mentioned in Chapter 5 Section 3.0, nuclear density difference is significant with low p-value, but this is not the case for gradation data. Figure 6.6 shows the gradation plots. The gradation curves for all cores taken from the field are finer than that for JMF. All are convex, and located above the maximum density line, indicating fine mixes.

At **site 15**, segregated samples with medium to heavy segregation have significant gradation differences from all control samples based on the percent passing 3/8", No.4 and No. 8 sieves. The results of t-tests indicated that comparisons between the medium-heavy segregated and control samples have significant differences with confidence levels greater than 99 percent. Figure 6.7 shows the gradation curve for the medium to heavy segregated sample, which is distant from both control and JMF curves. Among the comparisons between light segregated and control samples, results of t-tests are mixed.

At **site 16**, there were seven control, one light, two light-medium, one medium and one medium-heavy segregated samples. Although the visually identified segregation samples can be predicted using nuclear density measurements, results based on gradation data are not supportive. For most comparisons using percent passing 3/8", No.4 and No. 8 sieves, no significant differences were found. The gradation curves are shown in Figure 6.8, and are seen to be close together.

Site 17 and 18 were selected as control sites and the gradation plots are shown in Figure 6.9 and 6.10 respectively. The curves for all samples as well as the job mix formula plot very close. Results of t-tests using gradation data indicate no significant differences for all comparisons. This supports previous findings that differences in nuclear density measurements at these two control sites are related to compaction differences either during construction or by vehicle traffic.

Site 19 was newly reconstructed at the time field testing was conducted. Figure 6.11 illustrates the coarse gradation curves for heavy segregated samples. The medium segregated sample has a significant difference from one control, but not from the other control using percent passing 3/8", No. 4 and No.8 sieves Results of t-tests indicated the heavily segregated samples are significantly different from the controls based on 99 percent confidence level.

Site 20 consists of six different sections. Cores were taken from four sections. Gradation curves are shown in Figures 6.12 through 6.15. Results indicated that segregated samples have significant gradation differences from control and fine samples with the confidence level greater than 99 percent. When comparisons made between samples with similar degree of segregation (control to control, heavy to heavy), t-tests indicated there is no significant difference in gradation parameters.

Site 21 was separated to three different sections. Gradation curves are shown in Figures 6.16 to 6.18. All light to medium segregated samples have a coarser mix than that for control or JMF. Results of t-tests indicated that significant differences based on 95% confidence level between light to medium segregated sample and control sample.

Site 22 was selected as a demonstration site, to determine the variation in density associated with the paver. The nuclear density values were obtained on a placed asphalt mixture allowed to cool overnight without compaction. Materials were collected at nine nuclear density testing locations for sieve analyses. Gradation plots are shown in Figure 6.19. Results of t-tests indicated that there are no significant differences between samples. The observed consistent variations in nuclear density values are due neither to compaction nor gradation difference, but apparently to variations in surface roughness.

In general, gradation curves from medium or heavy segregated samples are usually differentiable from those from control area samples. However, gradation data from sites 13 and 16 were not supportive of the visual observation of segregation, even though nuclear density data do support it. At both sites, gradation curves for segregated samples are close to those for control samples. At site 13, gradation analysis indicated a fine mix and all gradation curves are above the maximum density line. The gradation differences are less than 5%, which is not strong enough to support statistical differences. At site 16, the entire pavement within the grid was badly segregated and cracked. This suggests that the control samples might not be representative of the original uniform mix. Furthermore, results of gradation analysis at the two "good pavement" control sites (sites 17 and 18) indicated no significant difference among all comparisons, even though nuclear density differences were noted. This supports the previous finding that the difference in nuclear density measurements at these two control sites is related to compaction differences in the wheel-tracks of these in-service pavements.

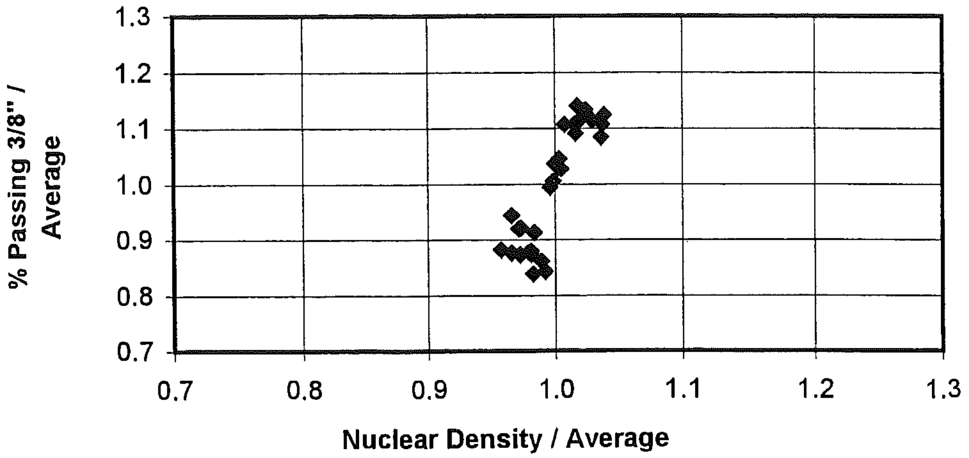
4.0 CROSS-PLOTTING ANALYSIS OF NUCLEAR-MEASURED DENSITY AND GRADATION PARAMETERS

To more clearly view the correlation between gradation and nuclear density, parameters from the former were plotted against the latter as described in the following two sections.

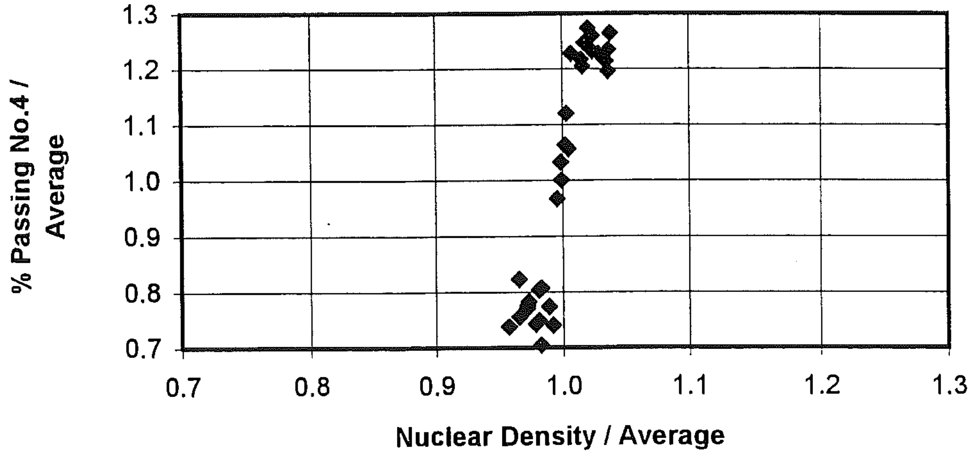
4.1 Normalized Data

Figures 6.20 through 6.29 for each site show plots of normalized gradation parameters versus normalized nuclear density values. These plots correlate individual sample values, not two-sample comparisons. In each case, the individual parameter values are normalized by dividing by the average value in the data set. Gradation parameters used were percent passing 3/8" sieve, percent passing No. 4 sieve and percent passing No. 8 sieve. The same data also could be normalized with respect to several other specific values, such as the theoretical maximum density for nuclear density or the percent passing from JMF for gradation data. The trend of plots would not be affected by the specific value chosen.

Site 1 : Nuclear Density vs. % Passing 3/8"



Site 1 : Nuclear Density vs. % Passing No.4



Site 1 : Nuclear Density vs. % Passing No.8

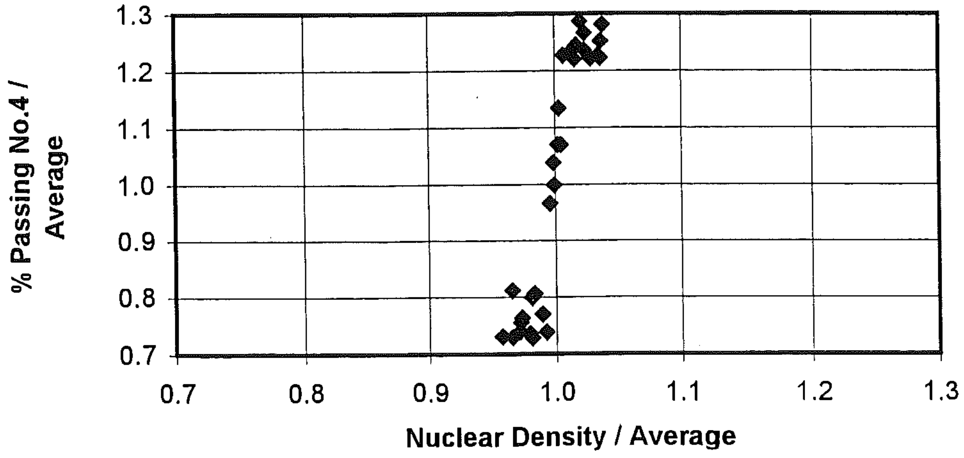
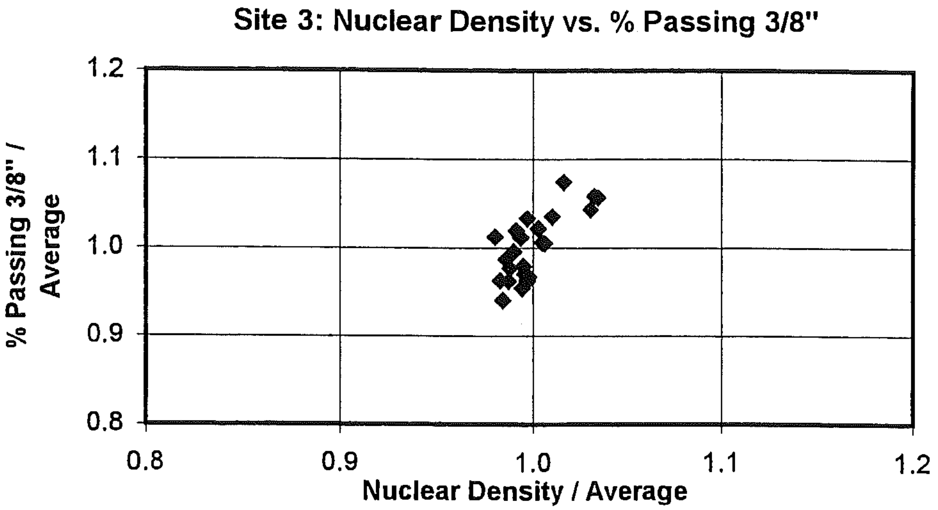
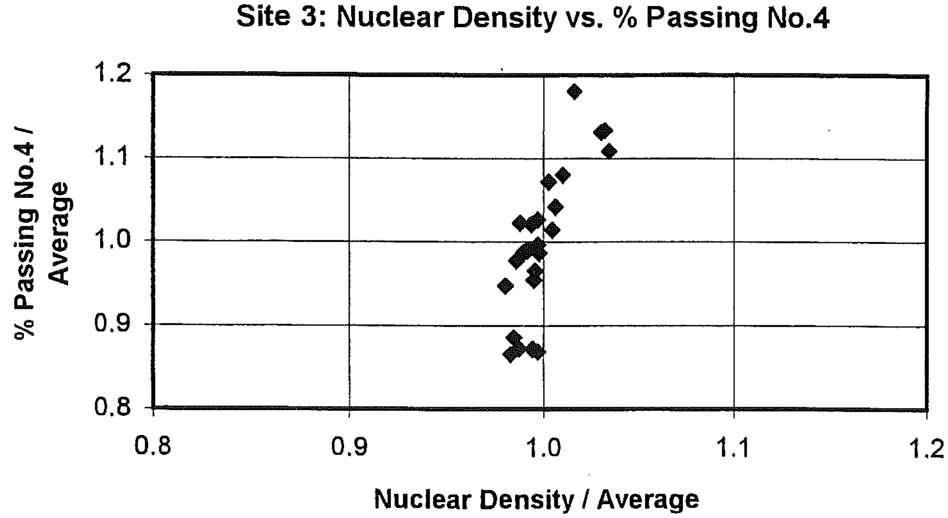


Figure 6.20 Scatter Plots between Normalized Nuclear-Measured Density and Normalized Gradation Parameters at Site 1





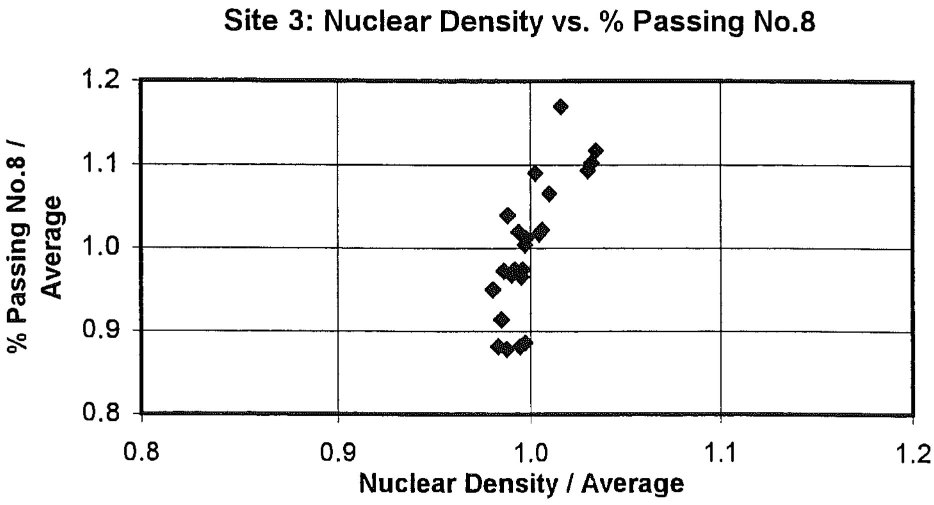
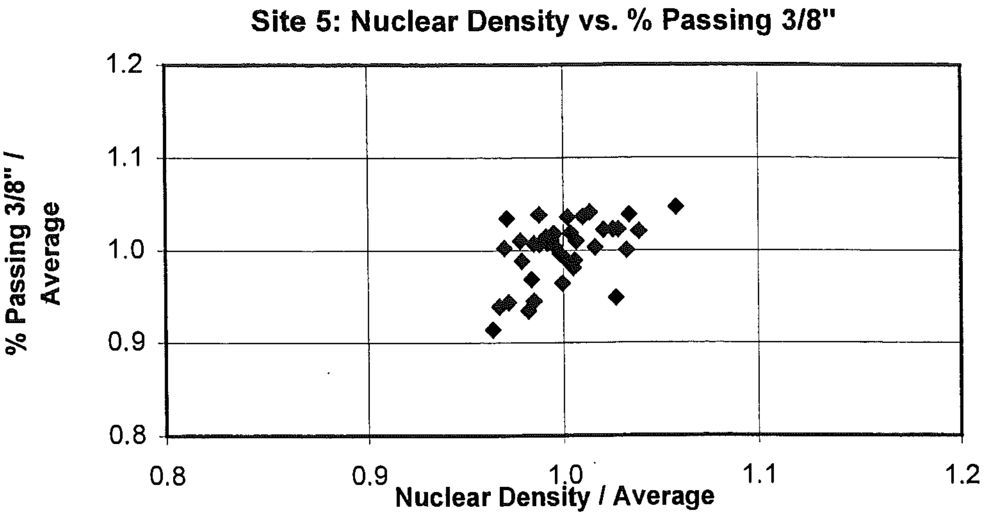
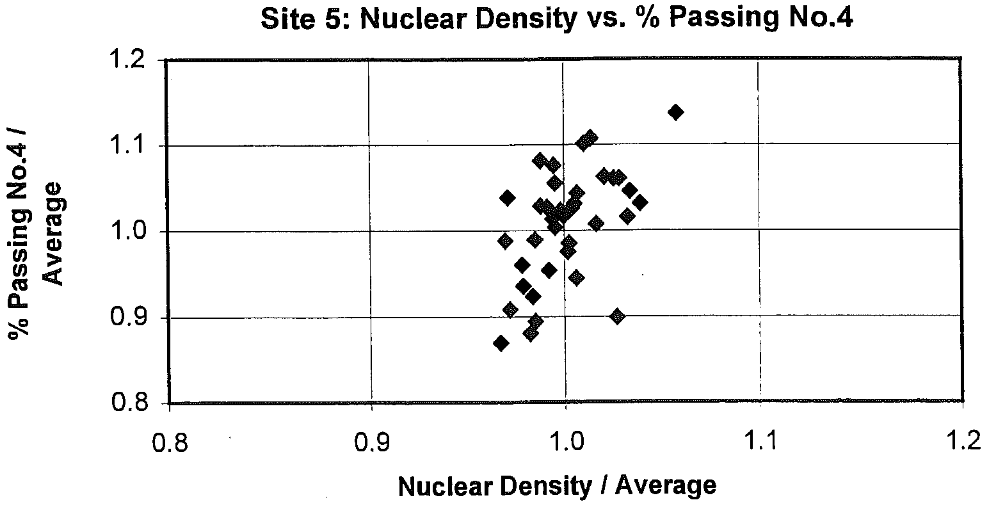


Figure 6.21 Scatter Plots between Normalized Nuclear-Measured Density and Normalized Gradation Parameters at Site 3





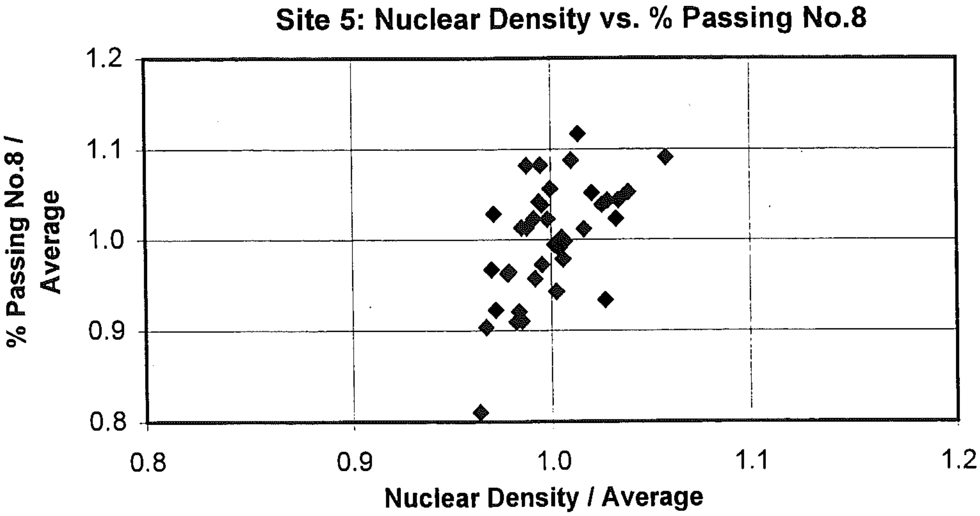
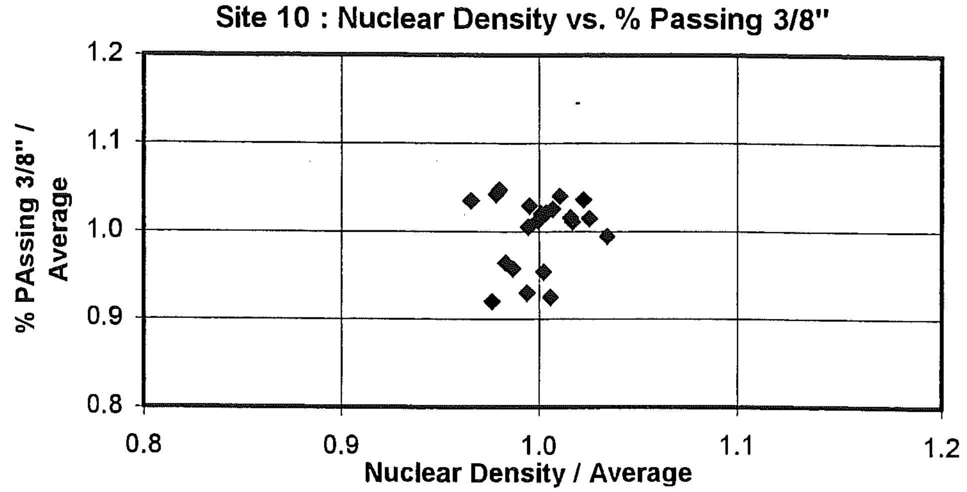
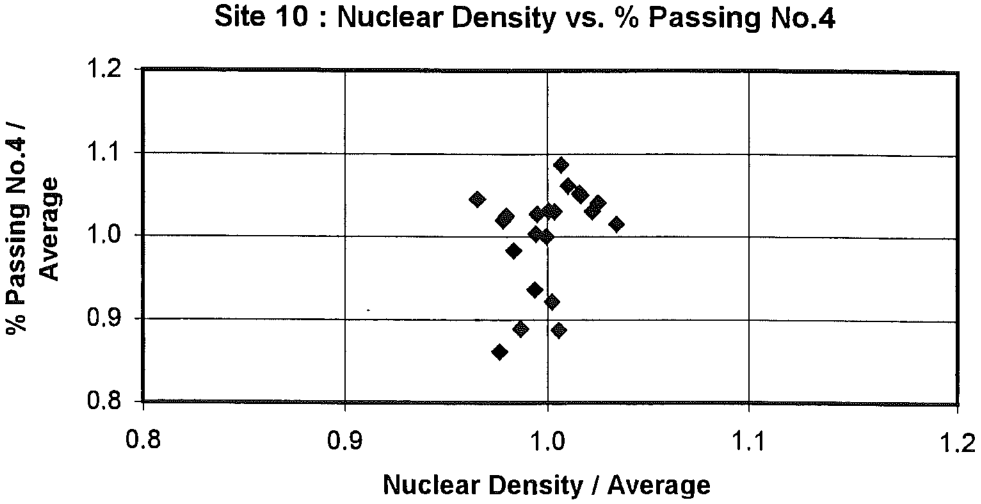


Figure 6.22 Scatter Plots between Normalized Nuclear-Measured Density and Normalized Gradation Parameters at Site 5





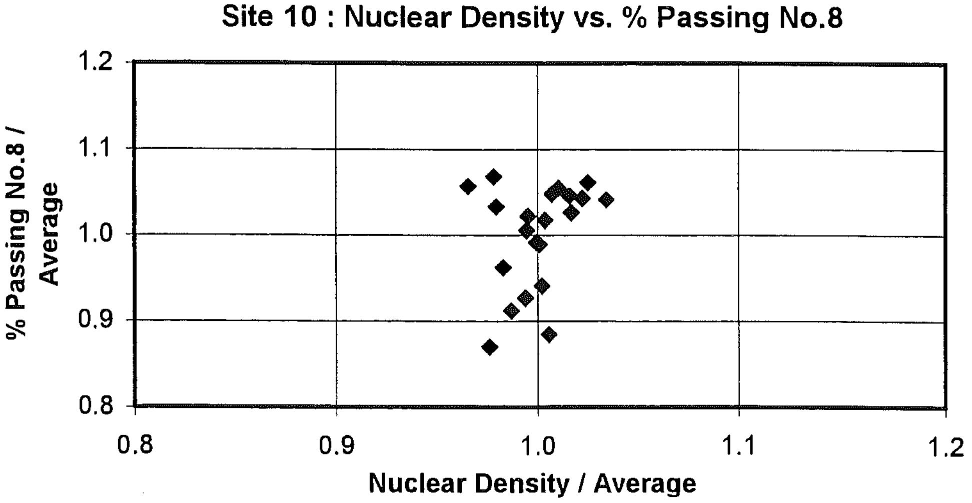
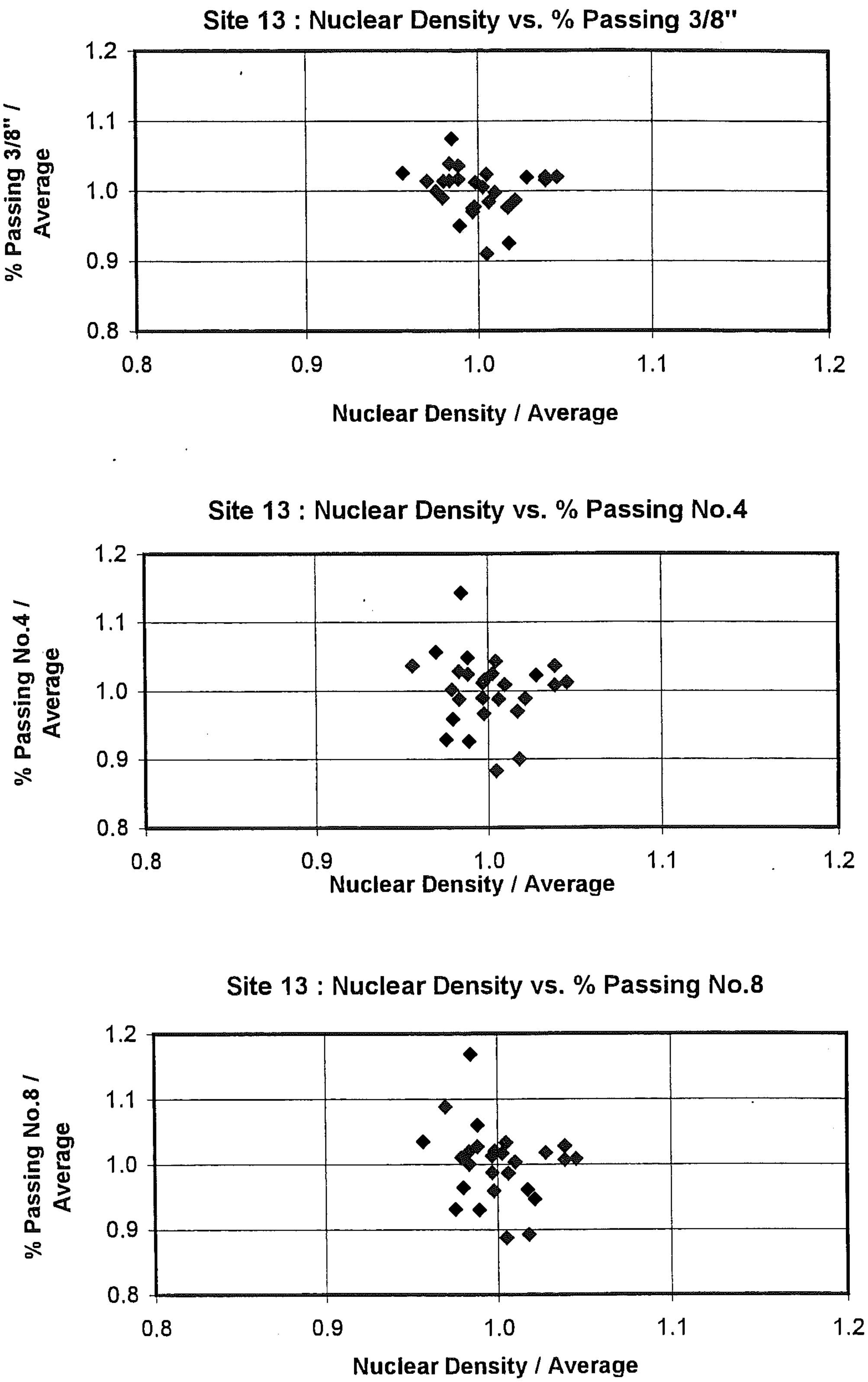


Figure 6.23 Scatter Plots between Normalized Nuclear-Measured Density and Gradation Parameters at Site 10



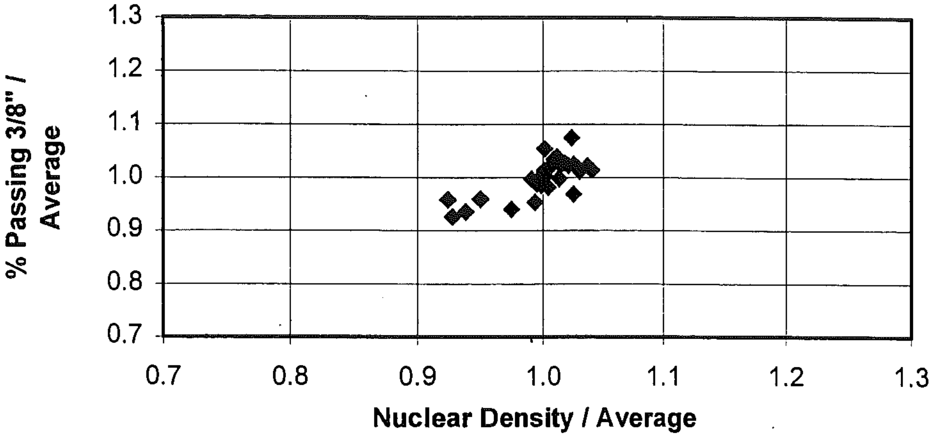
Site 13 : Nuclear Density vs. % Passing 3/8"

Site 13 : Nuclear Density vs. % Passing No.4

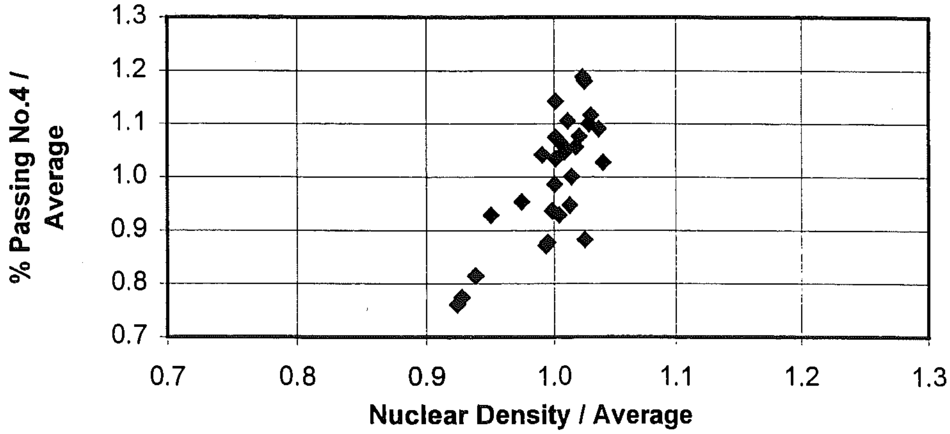
Site 13 : Nuclear Density vs. % Passing No.8

Figure 6.24 Scatter Plots between Normalized Nuclear-Measured Density and Normalized Gradation Parameters at Site 13

Site 15 : Nuclear Density vs. % Passing 3/8"



Site 15 : Nuclear Density vs. % Passing No.4



Site 15 : Nuclear Density vs. % Passing No.8

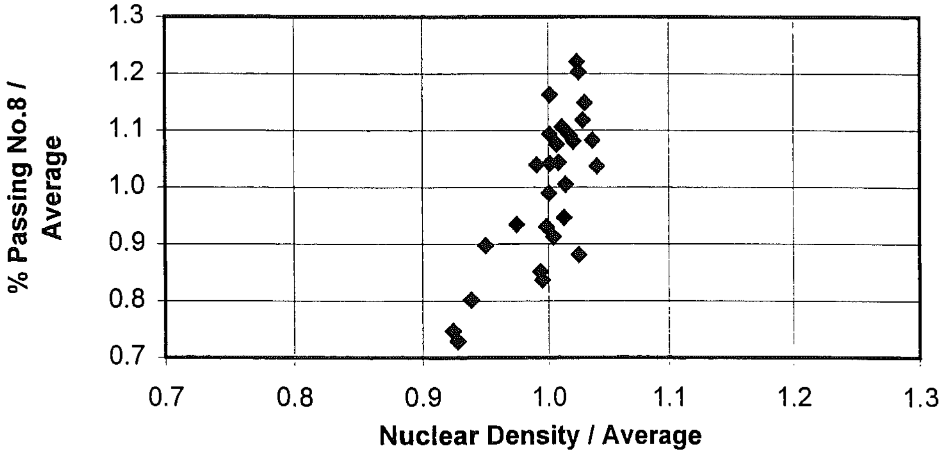
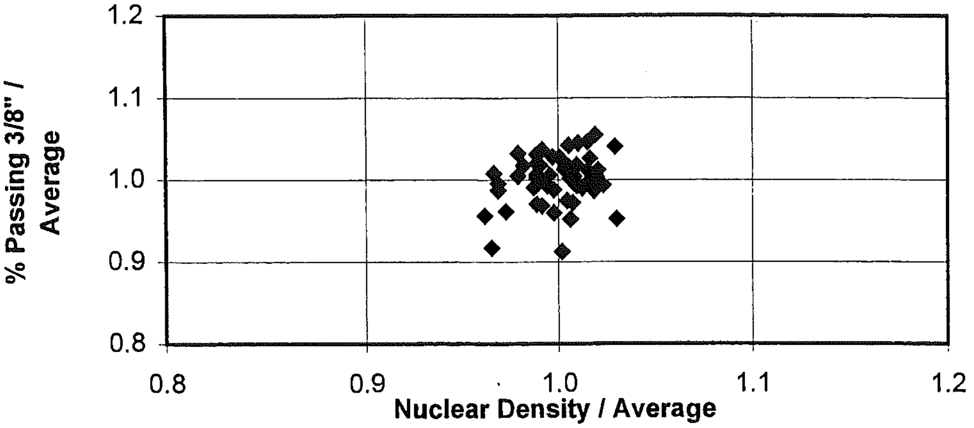
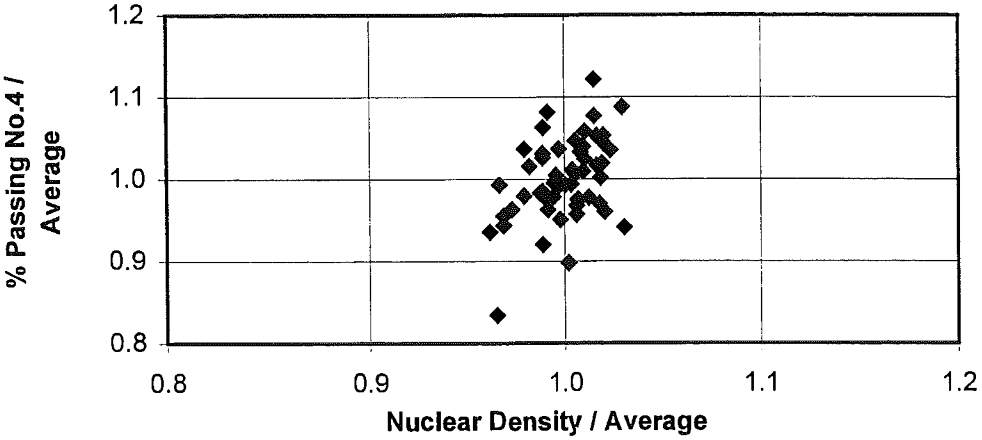


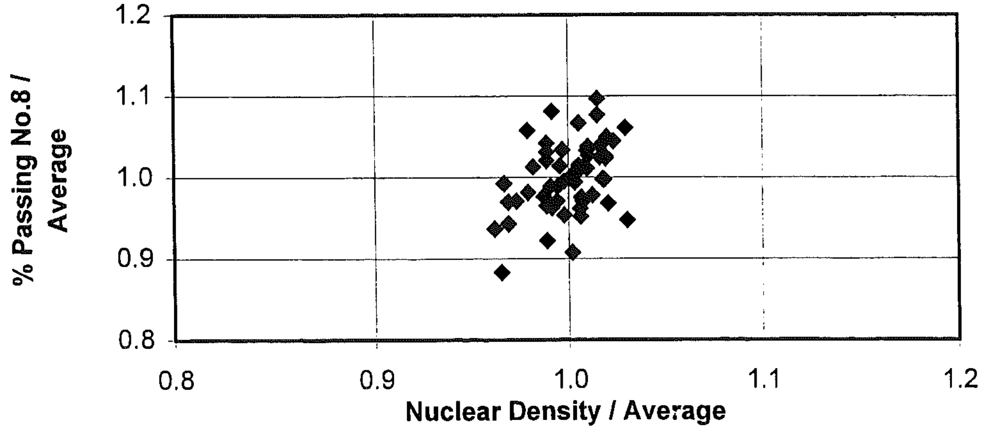
Figure 6.25 Scatter Plot between Normalized Nuclear-Measured Density and Normalized Gradation Parameters at Site 15



Site 16 : Nuclear Density vs. % Passing 3/8"



Site 16 : Nuclear Density vs. % Passing No.4



Site 16 : Nuclear Density vs. % Passing No.8

Figure 6.26 Scatter Plots between Normalized Nuclear-Measured Density and Gradation Parameters at Site 16

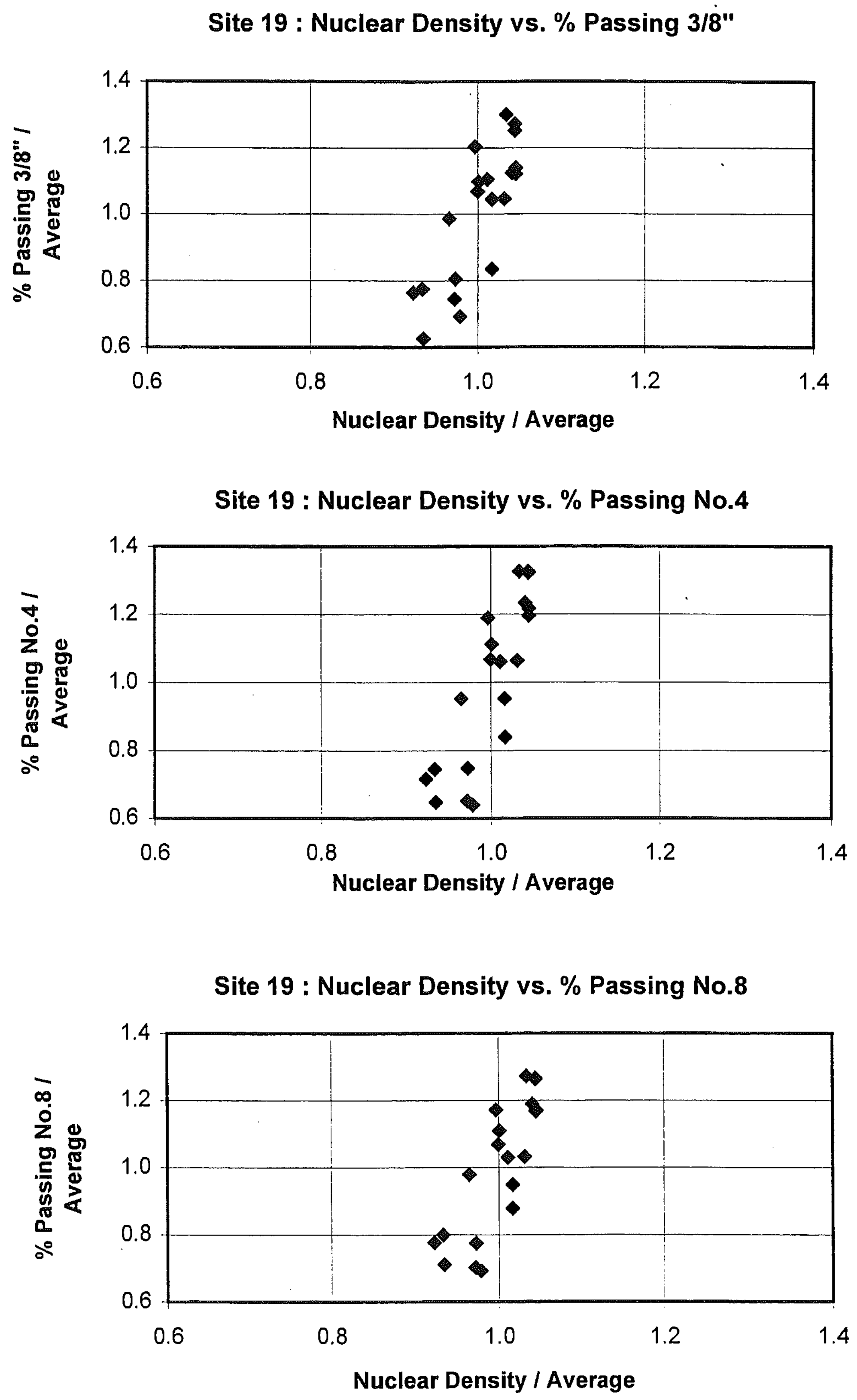
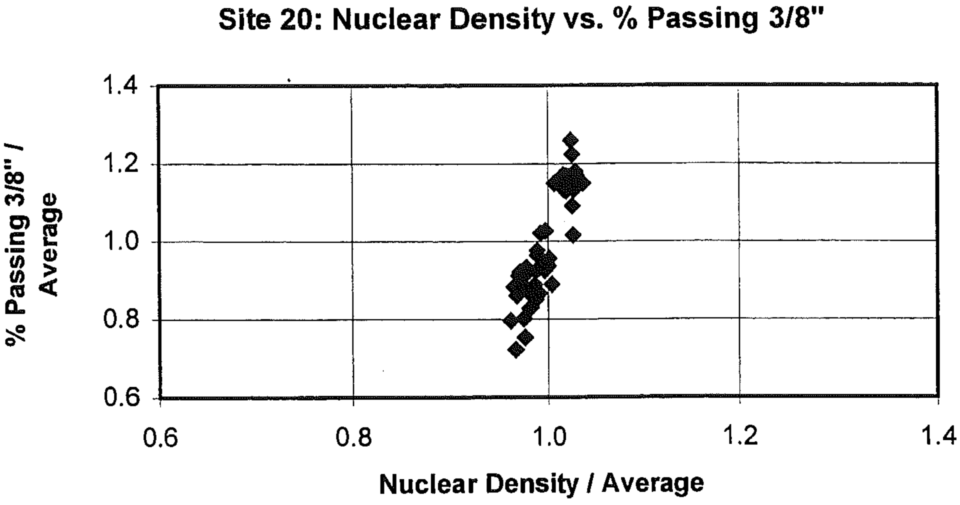
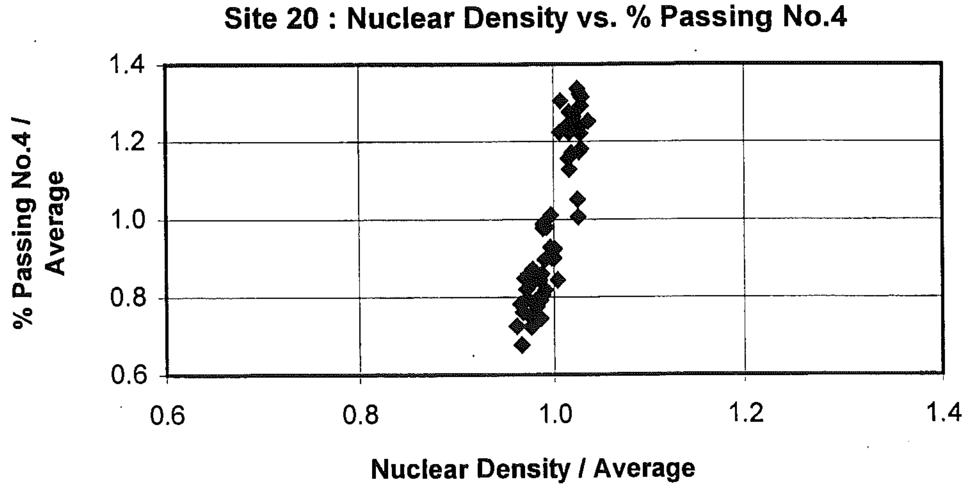


Figure 6.27 Scatter Plots between Normalized Nuclear-Measured Density and Gradation Parameters at Site 19


Site 20: Nuclear Density vs. % Passing 3/8"


Site 20 : Nuclear Density vs. % Passing No.4

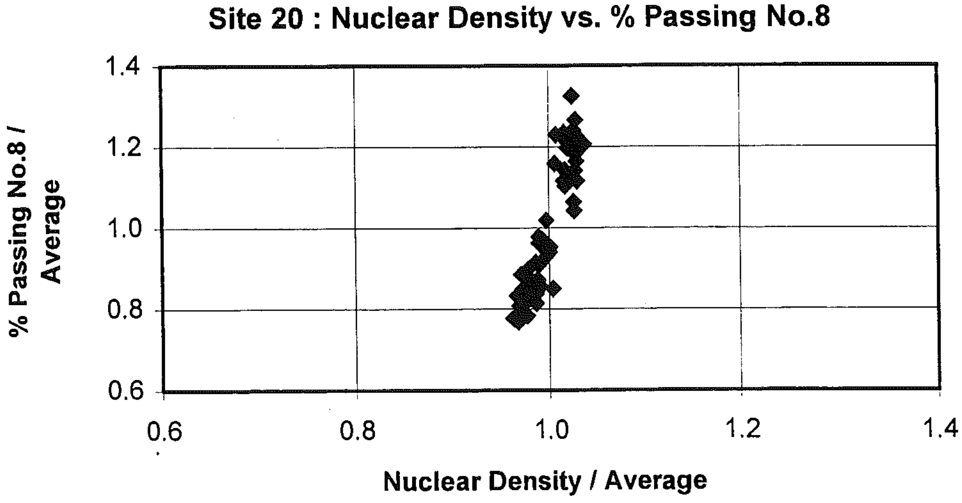

Site 20 : Nuclear Density vs. % Passing No.8

Figure 6.28 Scatter Plots between Normalized Nuclear Density and Grdation Parameters at Site 20

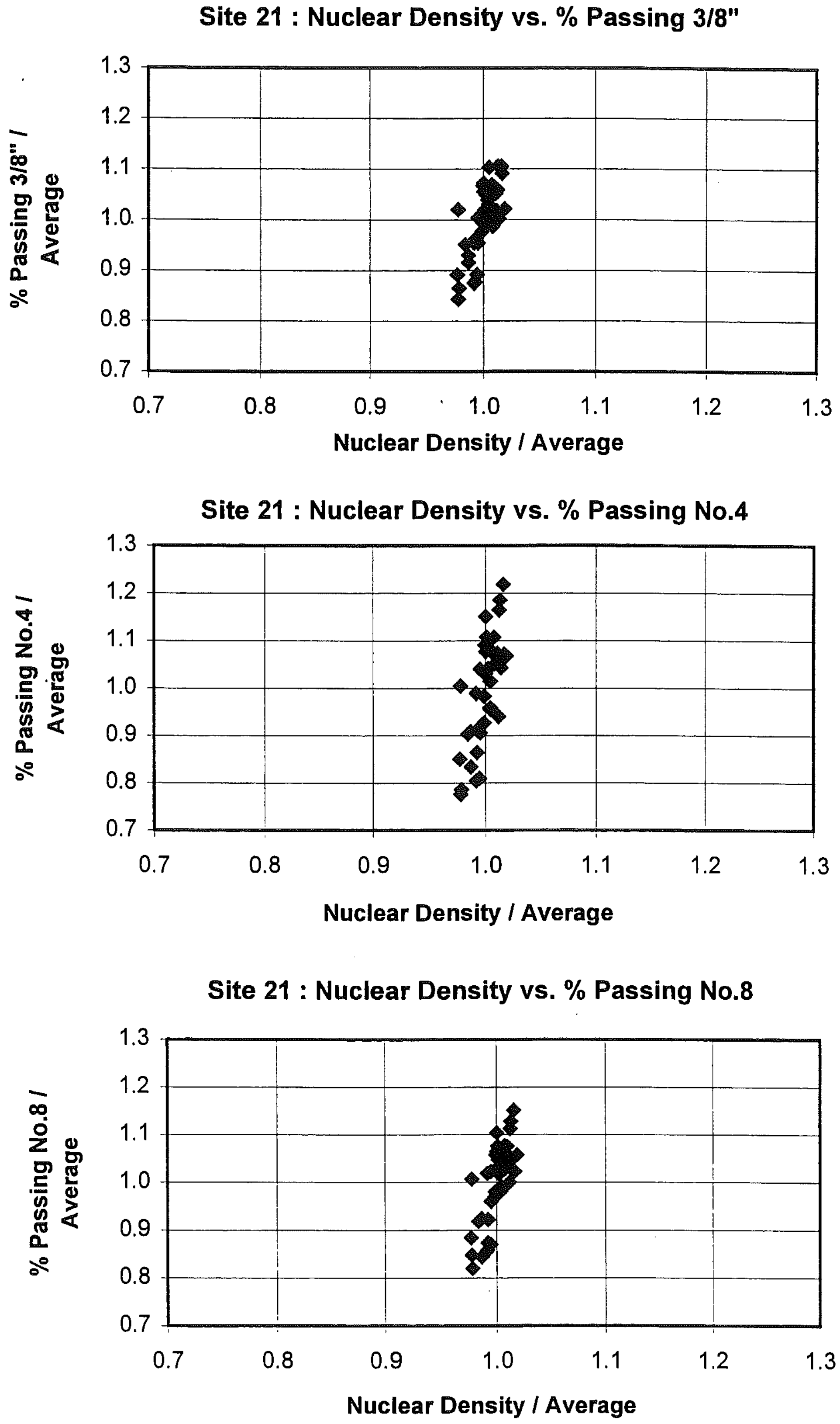


Figure 6.29 Scatter Plots between Normalized Nuclear-Measured Density and Gradation Parameters at Site 21

The results presented indicate the following:

- The expected relation between gradation parameters and nuclear-measured density values is a linear trend. According to the hypothesis, low nuclear density values correspond to low percent passing (3/8", No. 4 and No.8) in sieve analysis and high density values are correspond to high percent passing (more fine material).

- The plots from **sites 1 and 3** showed good agreement between nuclear-measured density and gradation parameters. The normalized nuclear-measured density values decrease as the normalized gradation parameters decrease. It is also noted that the variation in gradation parameters is larger than that in nuclear-measured density. As shown in Figures 6.20 and 6.21, the range of normalized gradation parameters are from 0.7 to 1.3, compared to the range of normalized nuclear-measured density values from 0.95 to 1.05.

- The plots for **sites 15, 19, 20 and 21** similarly indicate a linear trend between the normalized gradation and nuclear density parameters. The range of gradation parameter is between 0.6 and 1.4 for sites 19 and 20; between 0.7 and 1.3 for sites 15 and 21. This shows that relatively large percent changes in normalized gradation corresponds to a smaller percent change in normalized change in normalized nuclear density parameter (0.95 to 1.05).

- The data for **sites 10 and 13** show considerable scatter, as shown in Figure 6.23 and 6.24. No consistent correlation between nuclear-measured density and gradation parameters can be made.

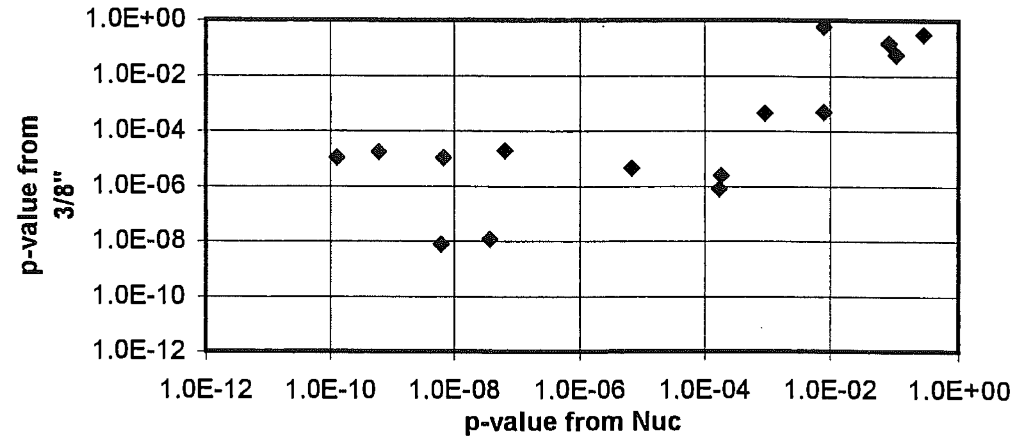
- The data for **sites 5 and 16** exhibit scatter (Figure 6.22 and 6.26 respectively) with some degree of linear trend observed. The range of normalized gradation parameter is between 0.8 and 1.2; the range of normalized nuclear-measured density values is between 0.95 and 1.05.

4.2 p-Values

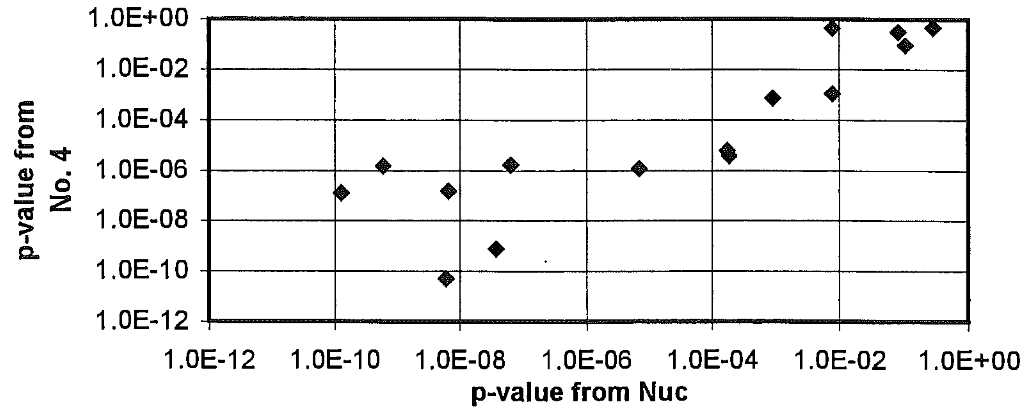
To visualize the correlation of gradation parameter comparisons and nuclear-measured density comparison, p-values from t-tests were cross-plotted. Where two-sample comparisons of nuclear density measurements indicate a significant difference, it is expected that two-sample comparisons of gradation parameters (percent passing 3/8", No.4 and No.8 sieves) would also show a significant difference. For example, it is expected that comparisons between a heavy-segregated sample and a control sample would have small p-values for both nuclear density and gradation parameters, and comparisons between two control samples or samples with similar degrees of segregation would have large (non-significant) p-values. Figures 6.30 through 6.41 site show cross-plotted p-values plot from two-sample comparisons of nuclear density measurements and gradation data for each site.

The following summary is made for these Figures:

Site 1: Nucear Density vs. Gradation 3/8"



Site 1: Nucear Density vs. Gradation No.4



Site 1: Nucear Density vs. Gradation No.8

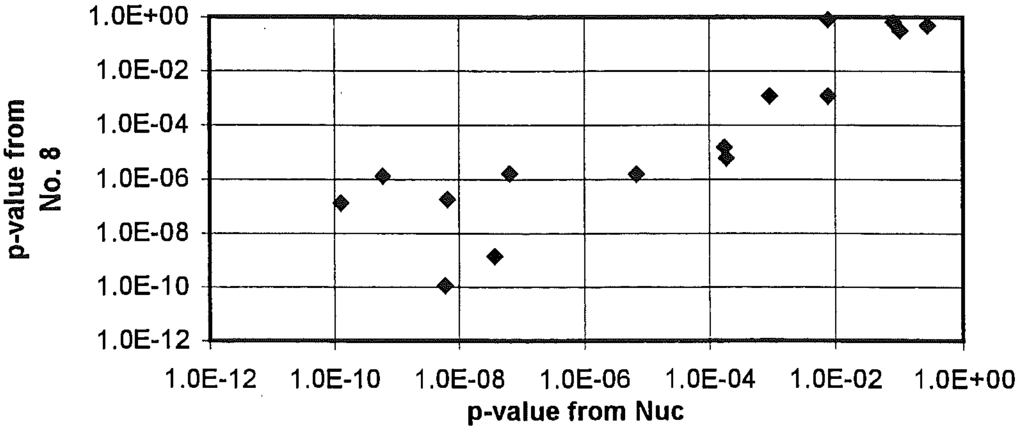
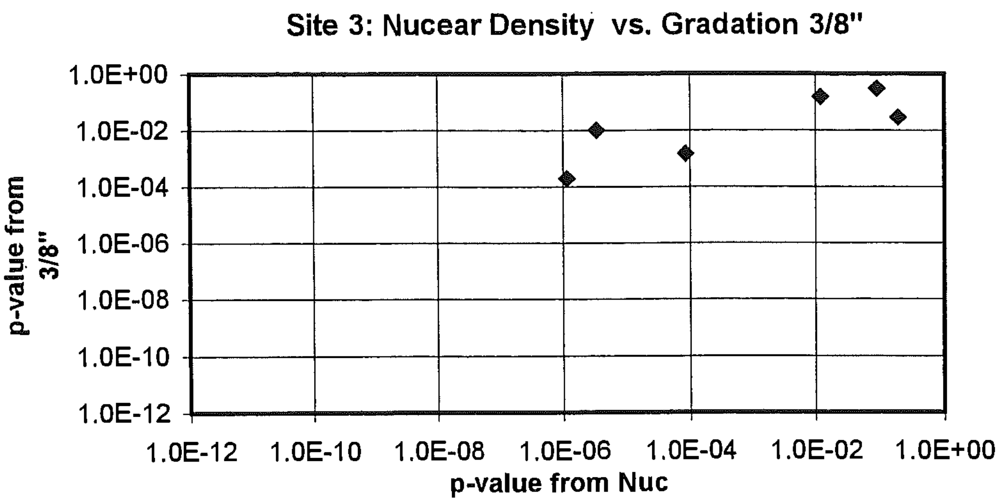
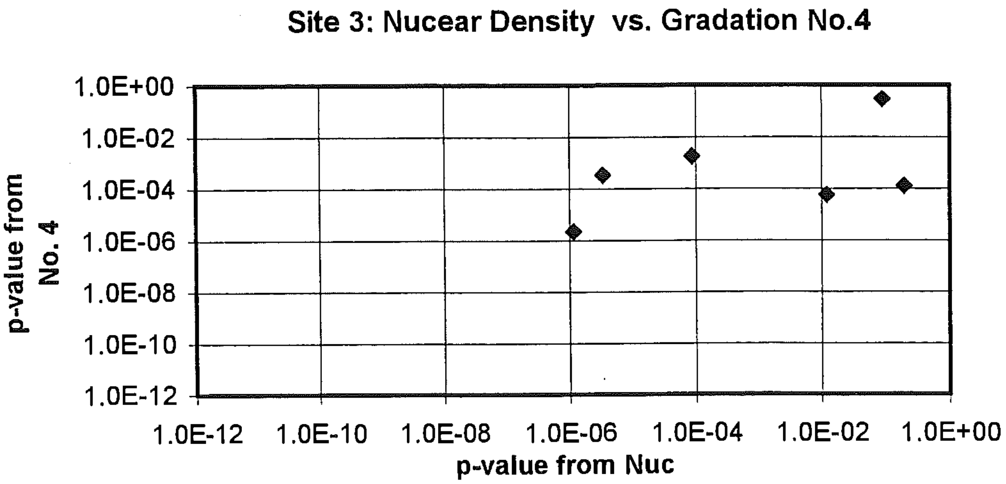


Figure 6.30 p-value Plots at Site 1


Site 3: Nucear Density vs. Gradation 3/8"


Site 3: Nucear Density vs. Gradation No.4

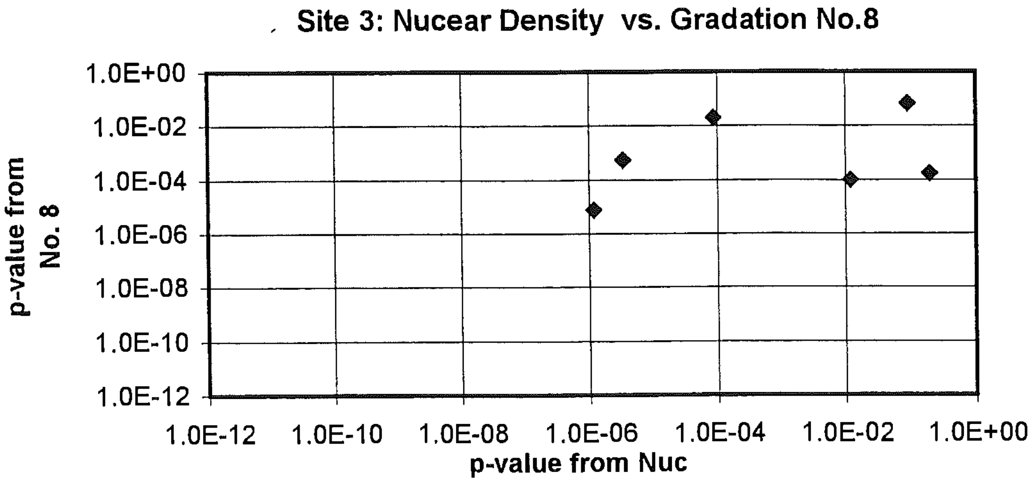
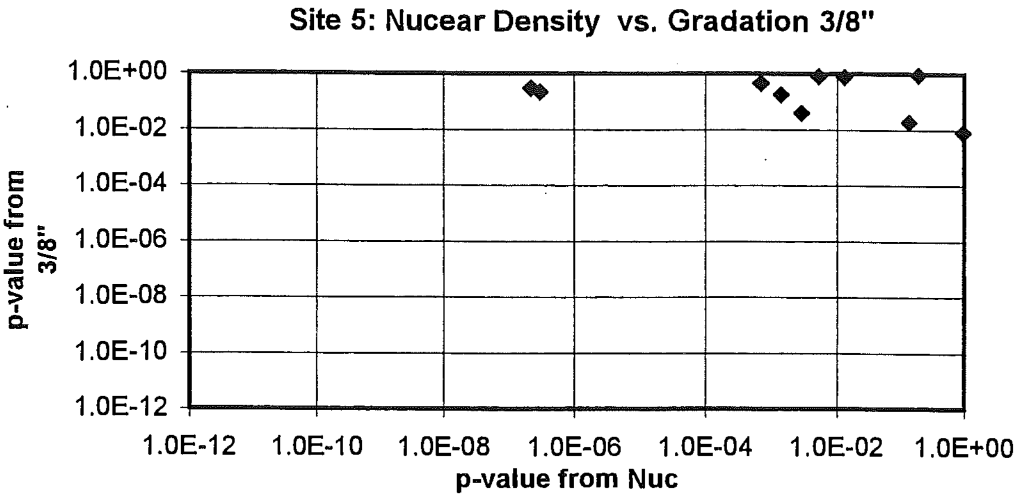
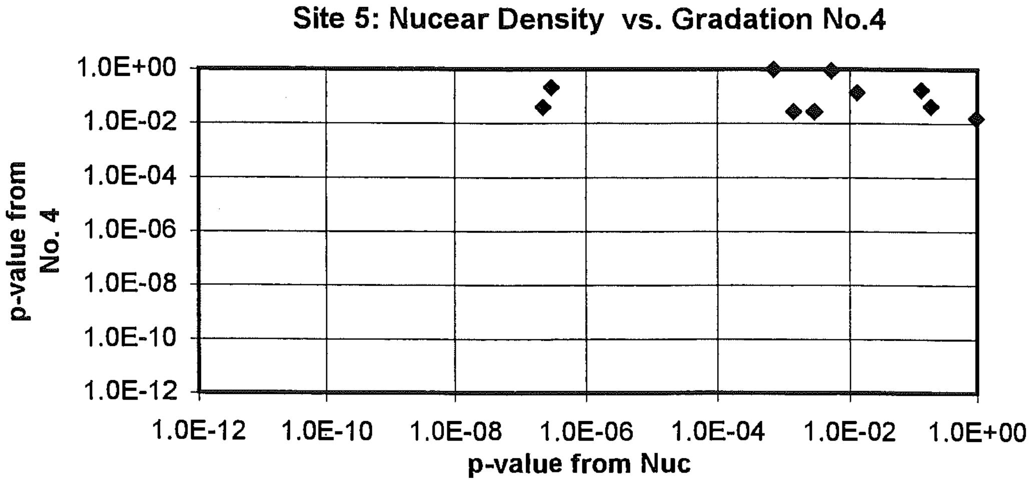

Site 3: Nucear Density vs. Gradation No.8

Figure 6.31 p-value Plots at Site 3





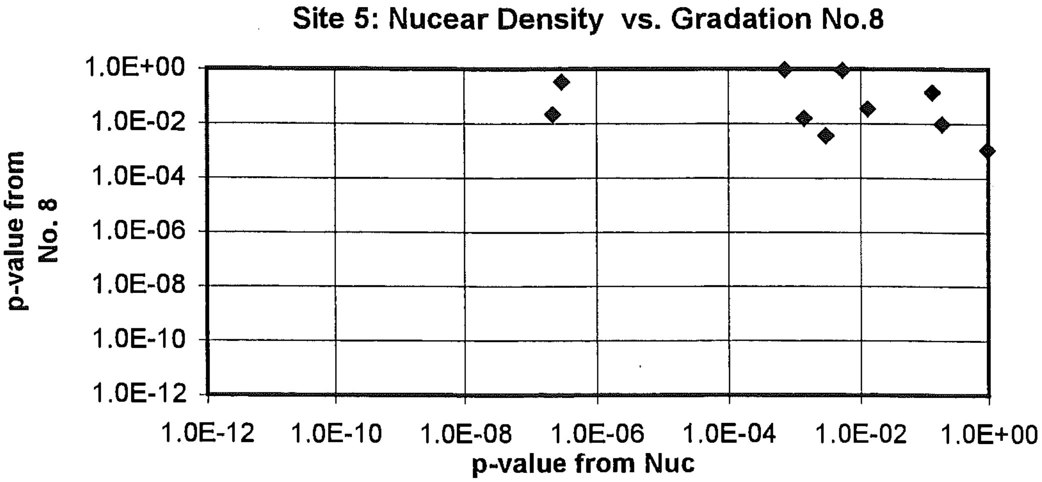
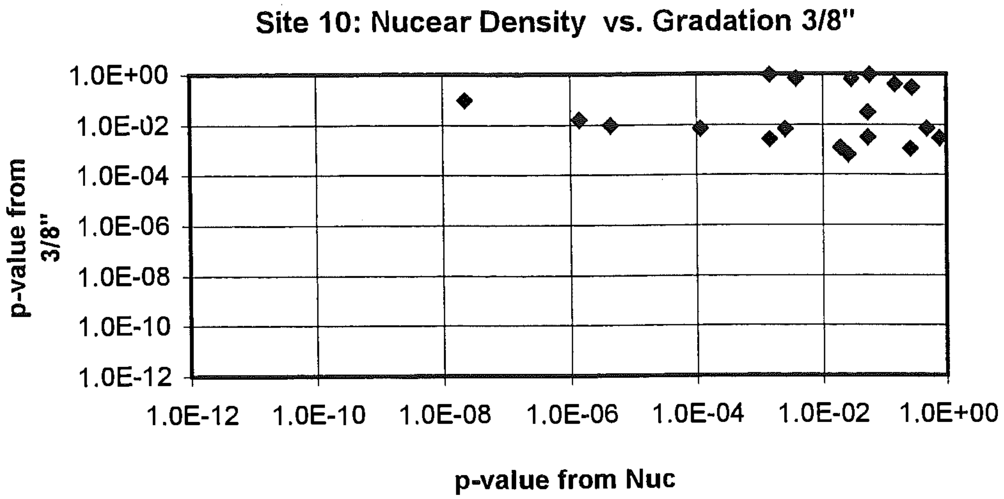
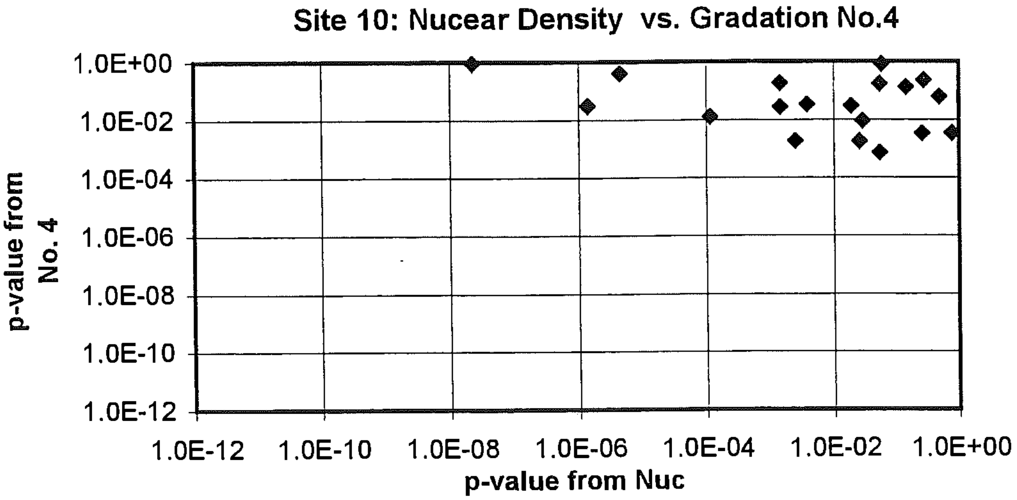


Figure 6.32 p-value Plots at Site 5





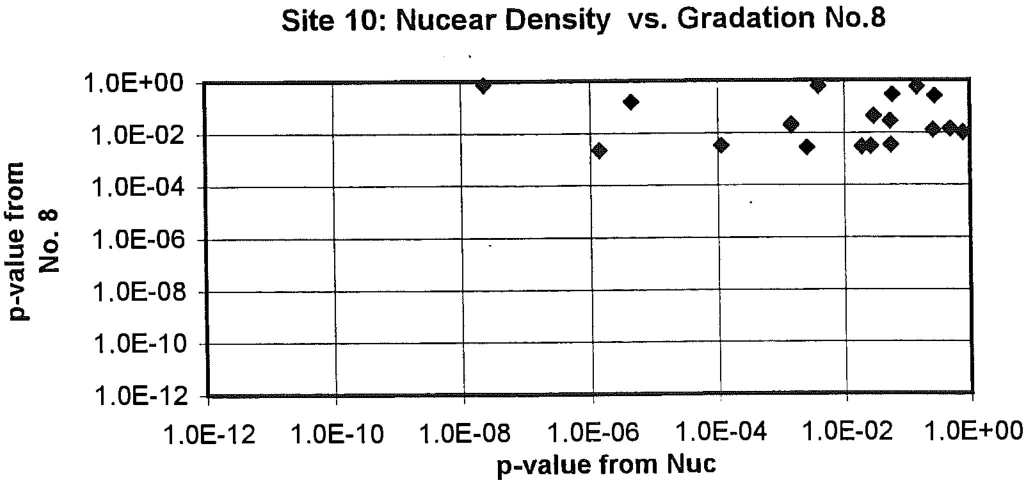
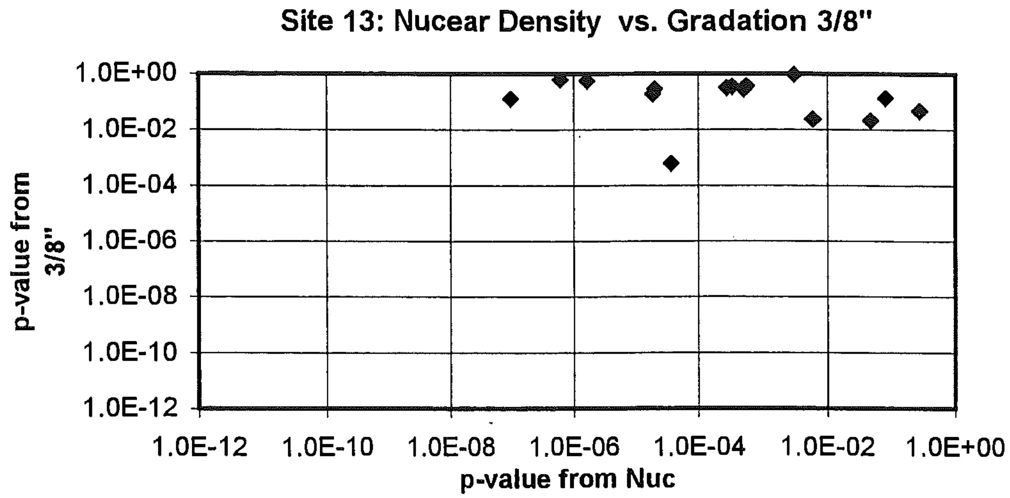
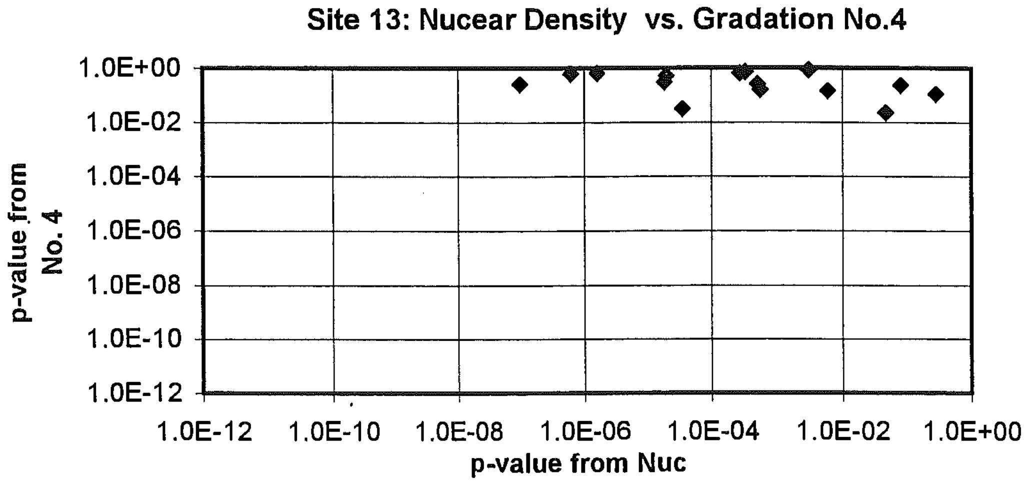


Figure 6.33 p-value Plots at Site 10





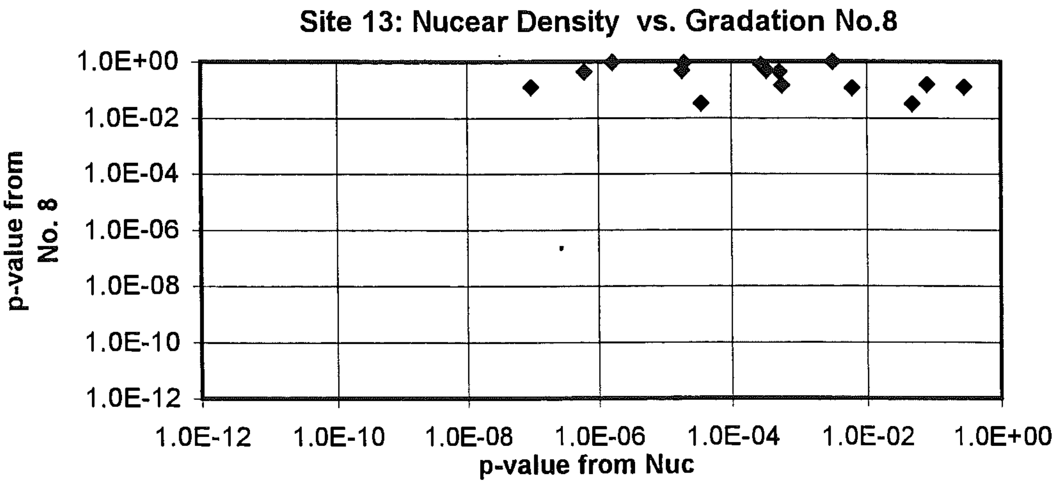


Figure 6.34 p-value Plots at Site 13

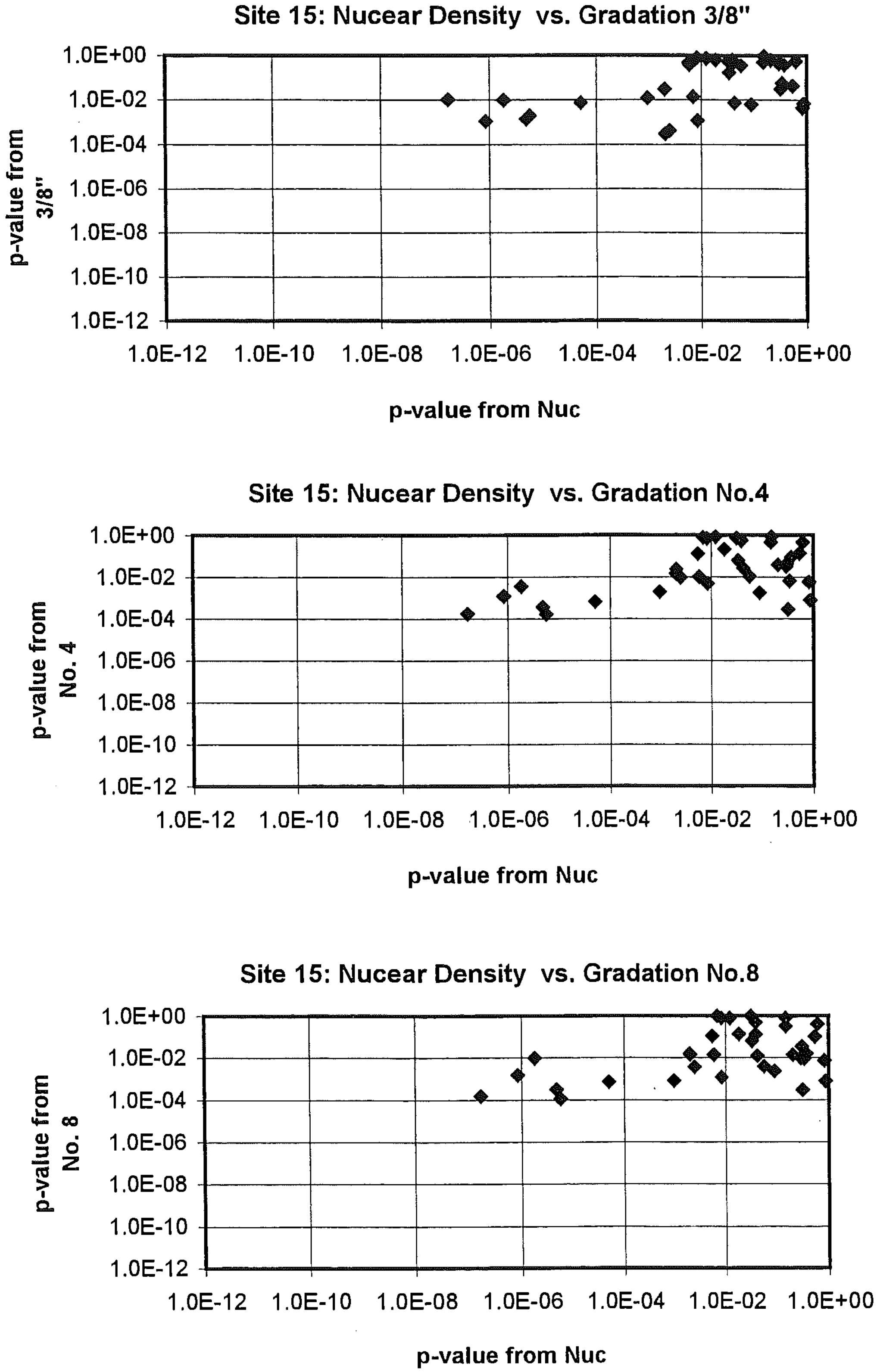
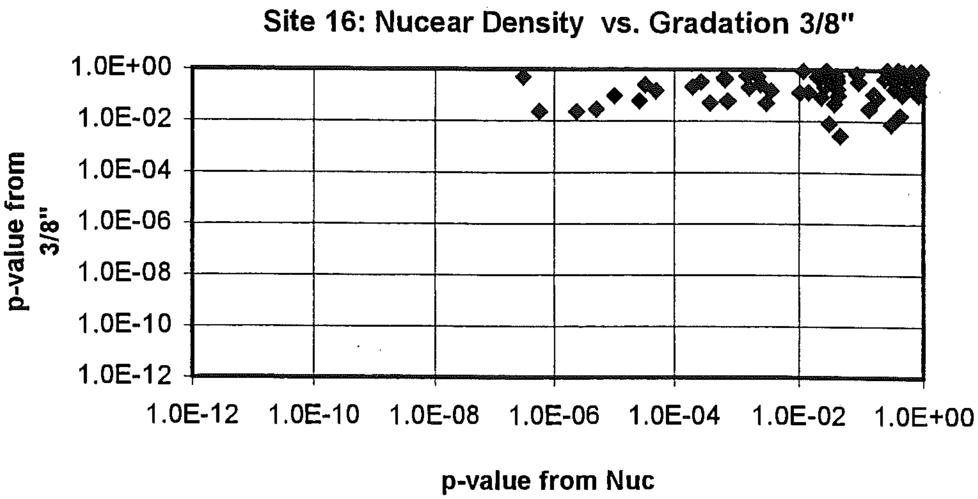
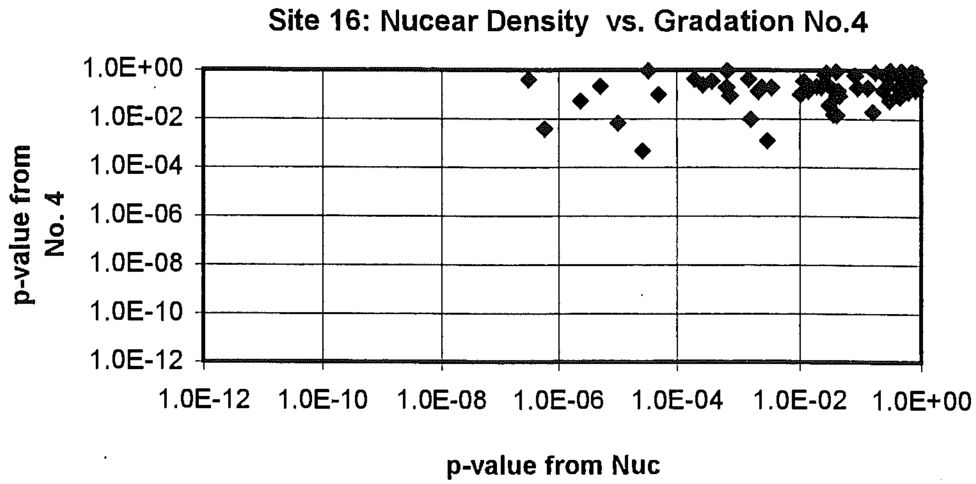


Figure 6.35 p-value Plots at Site 15


Site 16: Nucear Density vs. Gradation 3/8"


Site 16: Nucear Density vs. Gradation No.4

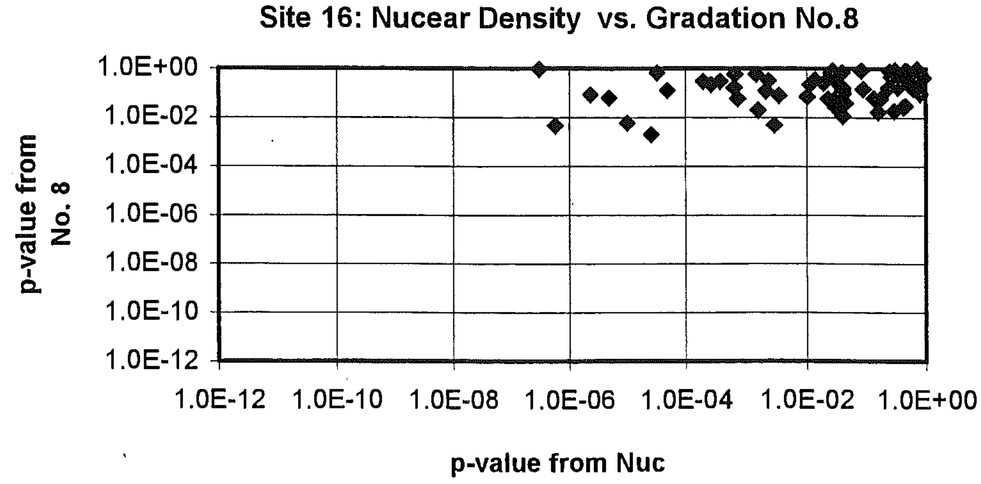
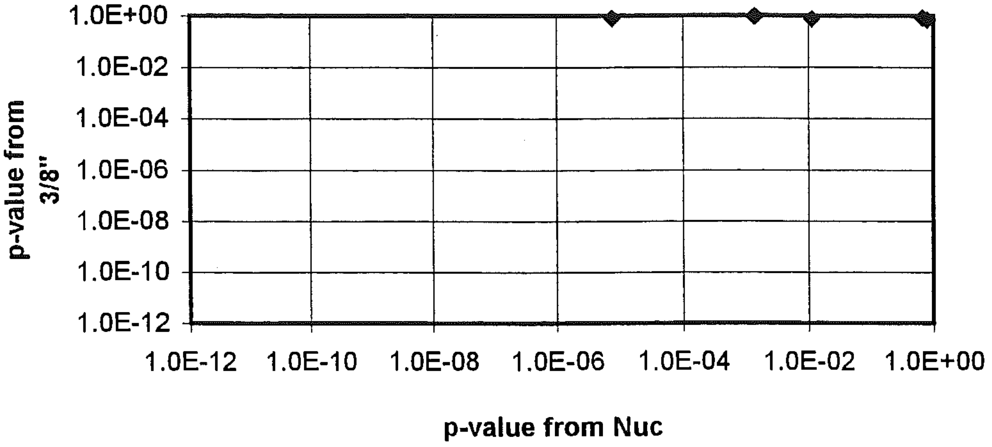
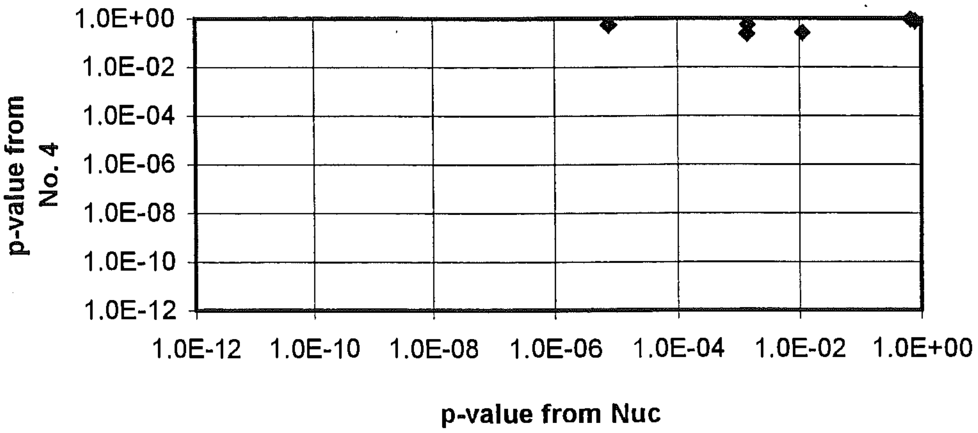

Site 16: Nucear Density vs. Gradation No.8

Figure 6.36 p-value Plots at Site 16

Site 17: Nucear Density vs. Gradation 3/8"



Site 17: Nucear Density vs. Gradation No.4



Site 17: Nucear Density vs. Gradation No.8

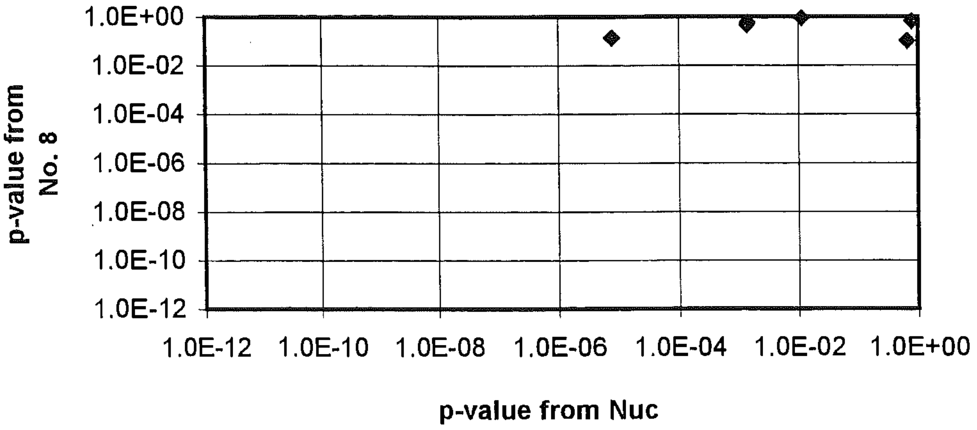
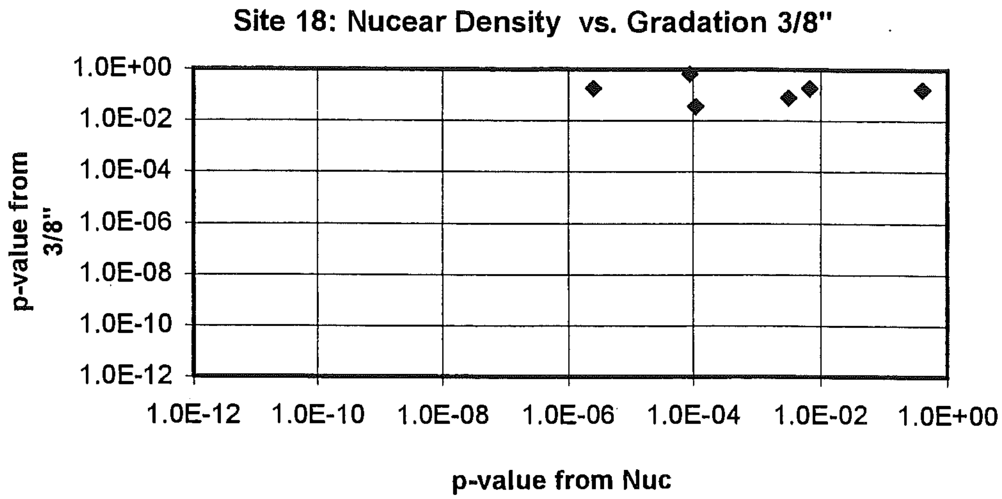
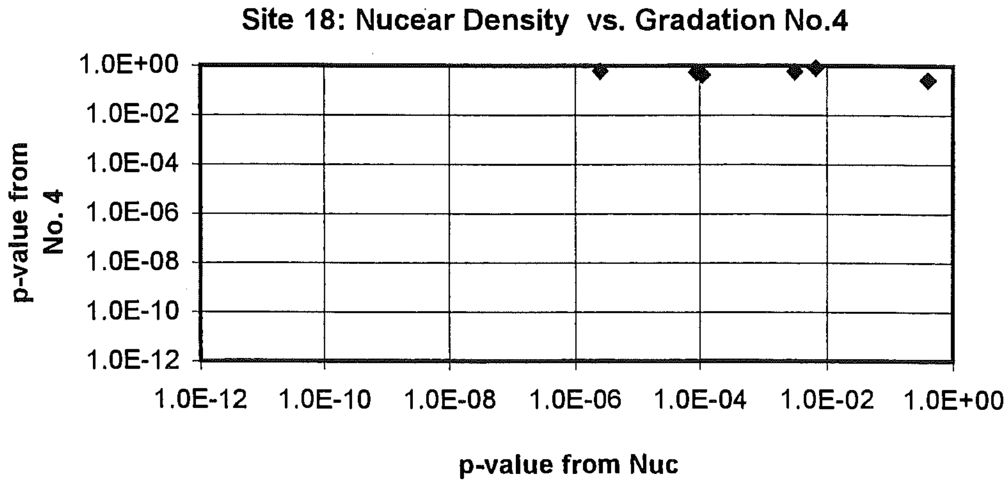


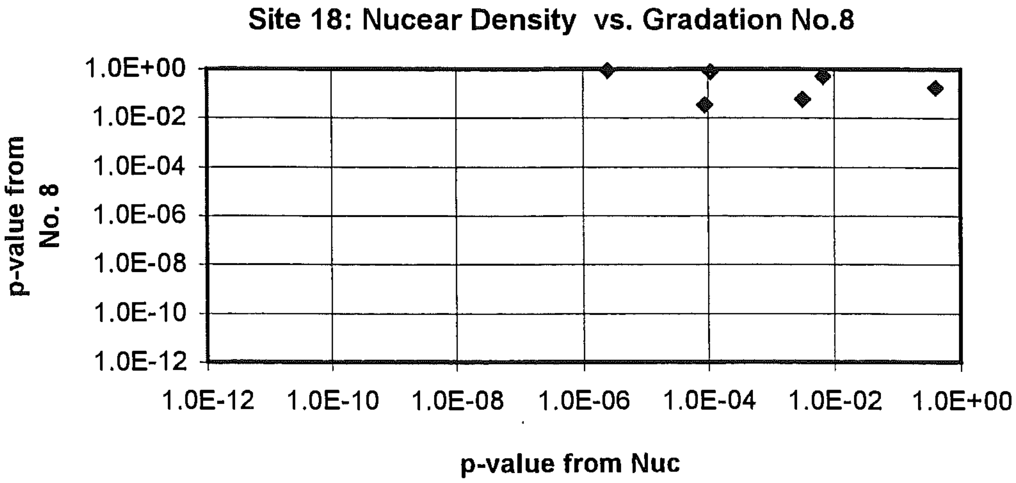
Figure 6.37 p-value Plots at Site 17



Site 18: Nucear Density vs. Gradation 3/8"

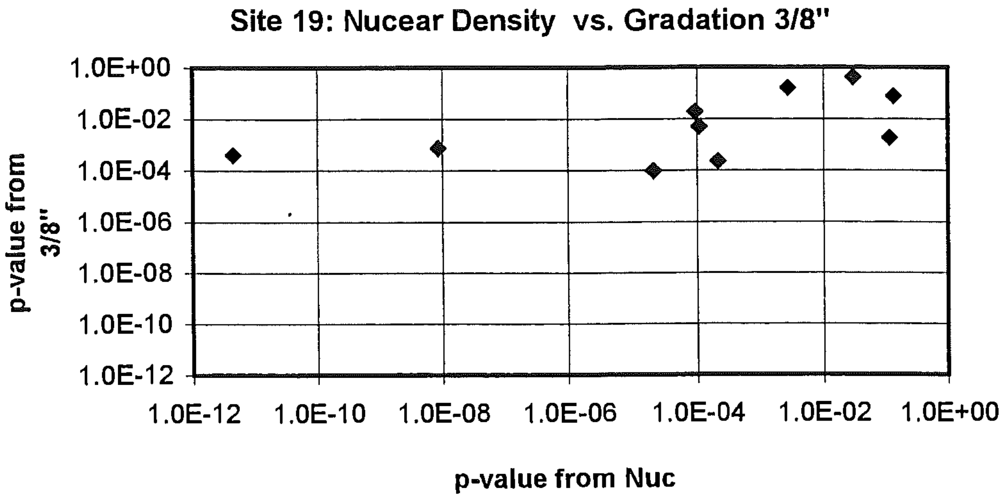


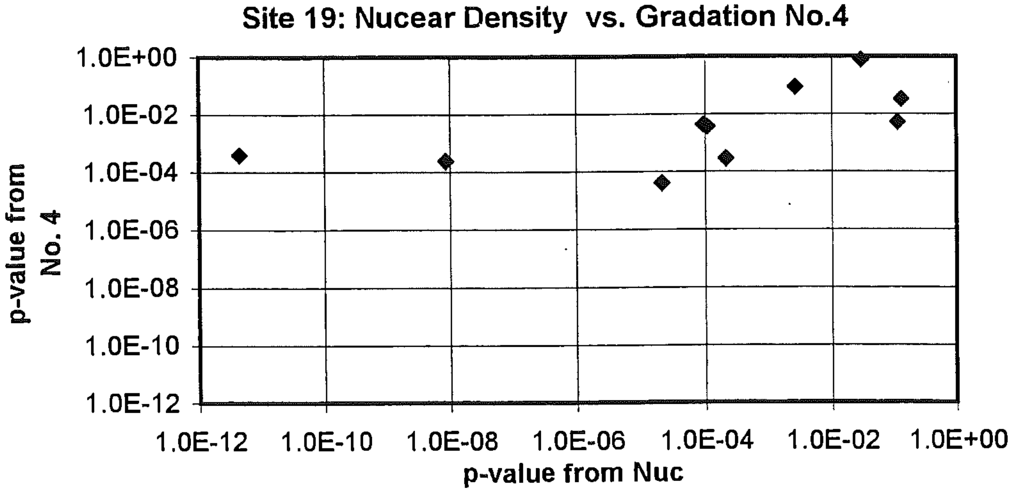
Site 18: Nucear Density vs. Gradation No.4



Site 18: Nucear Density vs. Gradation No.8

Figure 6.38 p-value Plots at Site 18





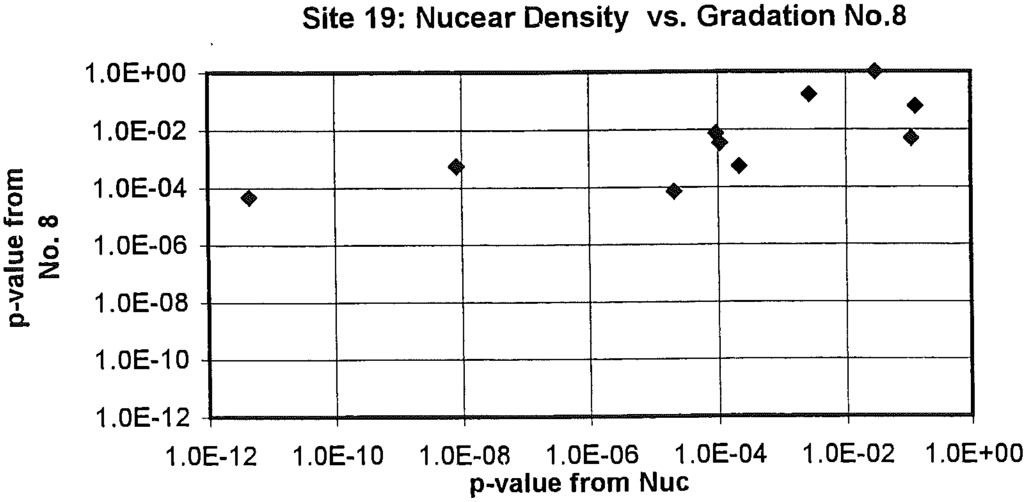
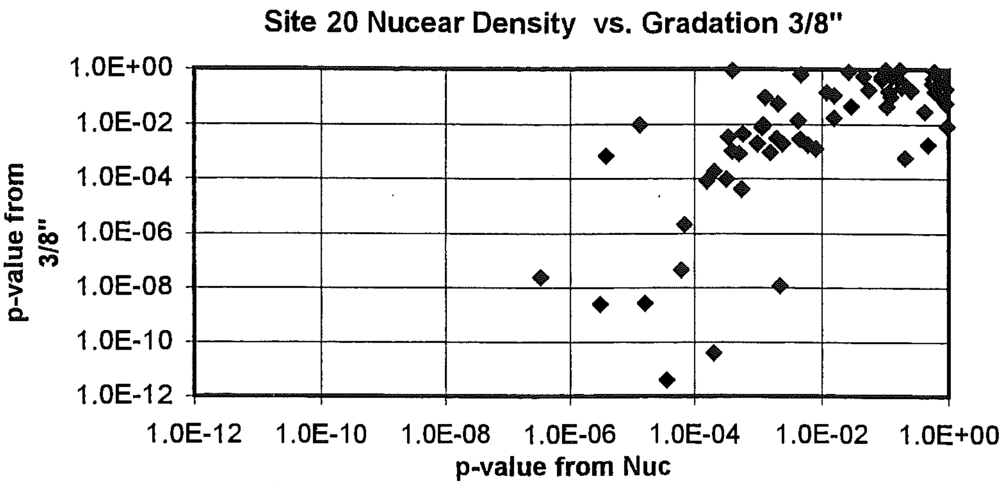
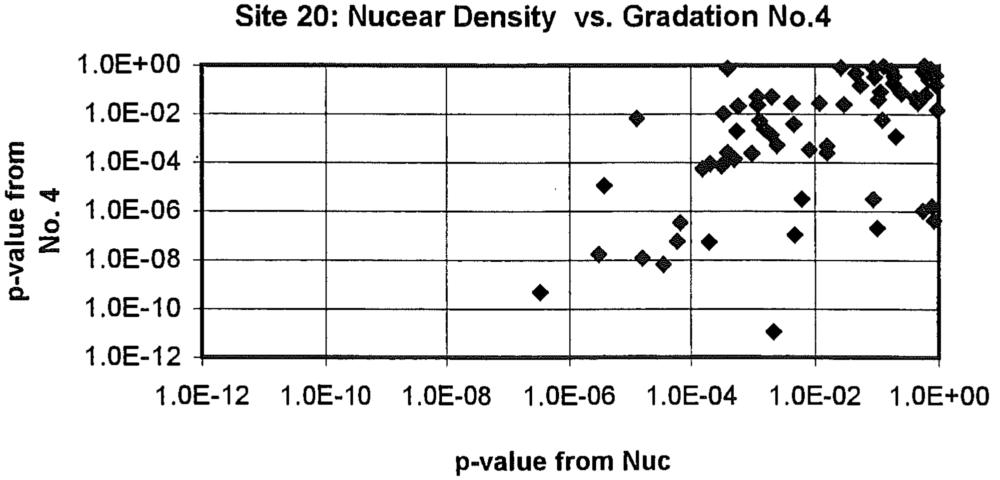


Figure 6.39 p-value Plots at Site 19





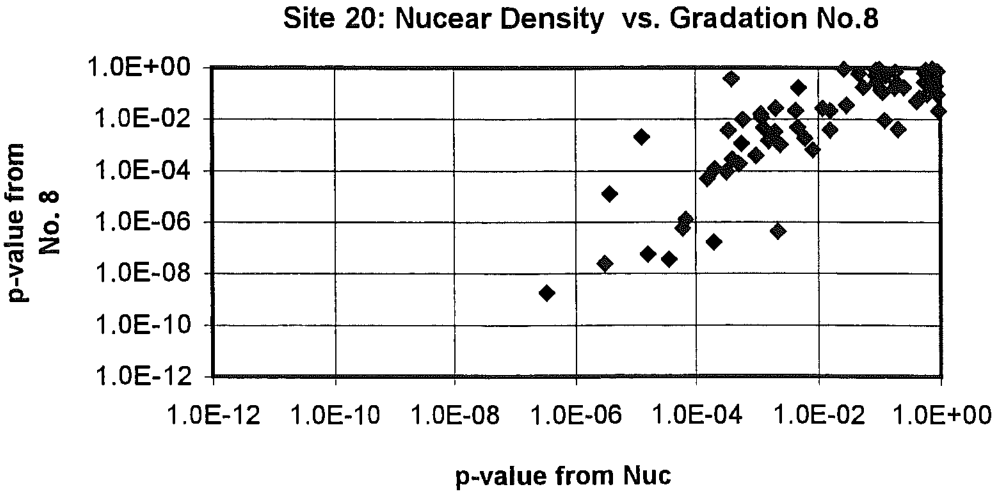


Figure 6.40 p-value Plots at Site 20

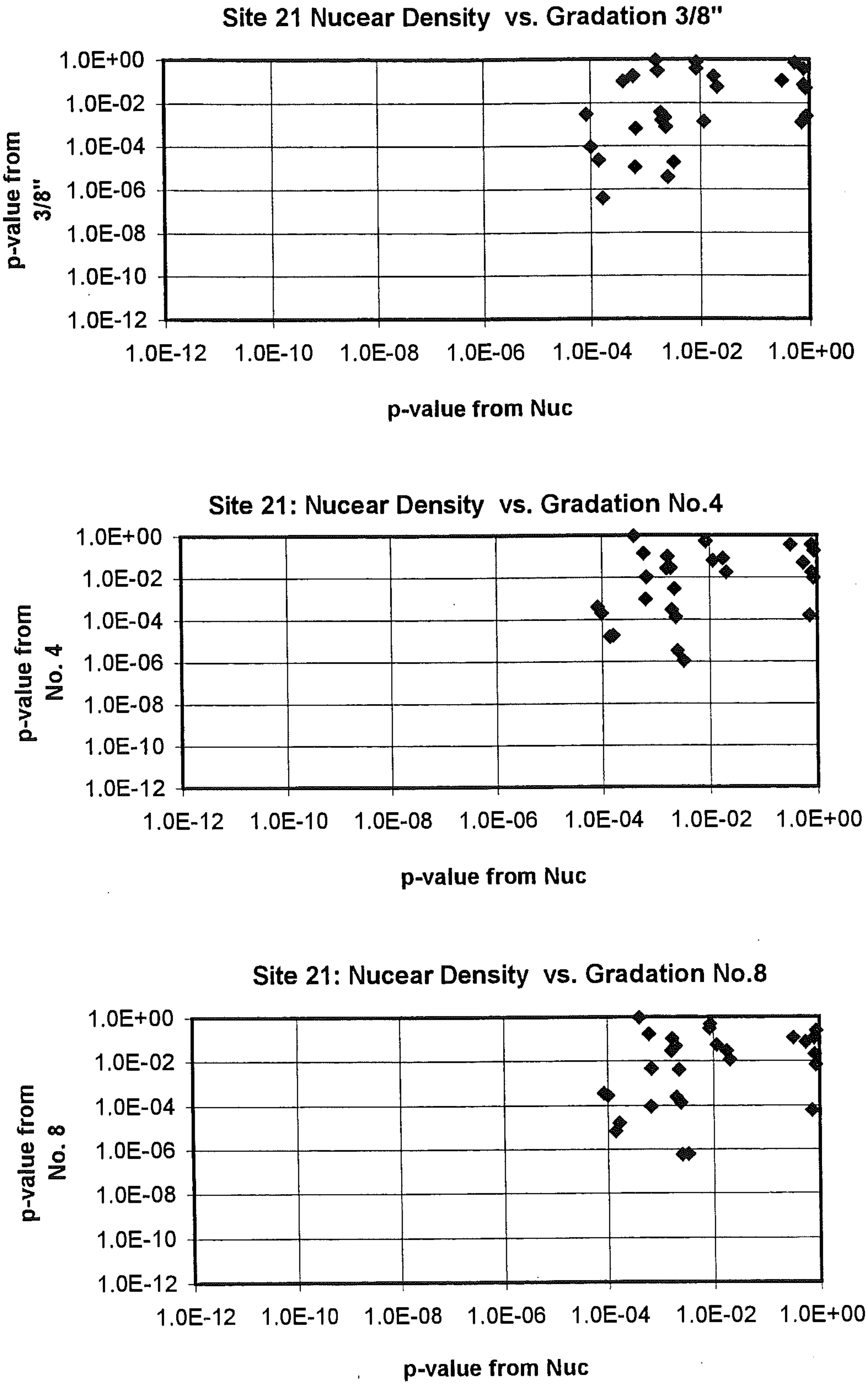


Figure 6.41 p-value Plots at Site 21

The data presented are based on all comparisons at each site. It would be expected to have a linear relationship such that a significant statistical difference in nuclear density values corresponds to a significant statistical difference in gradation.

- The plots from **sites 1, 19, 20 and 21**, as shown in Figures 6.30, 6.39, 6.40 and 6.41 respectively, indicate considerable scatter but a general diagonal trend. Individual p-value could be as small as 10^{-12} for both nuclear density parameter and gradation parameter.
- The plots from **sites 3 and 15** (Figures 6.31 and 6.35) also show scatter. However, a trend can still be found. It is observed that the p-value from nuclear density comparisons can be as low as 10^{-8} , but the p-value from gradation drops only as low as 10^{-4} . This indicates that nuclear density measurements can have greater statistical differences than gradation parameters.
- The plots from **sites 5, 10, 13 and 16** (Figures 6.32 through 6.34 and 6.36) do not show a trend between nuclear density comparisons and gradation comparisons. Although the p-values from nuclear density comparisons are as small as 10^{-8}, most comparisons based on gradation data have p-values greater than 10^{-2}. It is found that the gradation data at these four sites are fine mixes and all gradation curves are close to the maximum density line.
- The plots for the two control sites (**sites 17 and 18**) are shown in Figure 6.37 and 6.38. The nuclear density comparisons, with p-values as low as 10^{-6} , reveals the effects of different compaction efforts. The p-value from gradation data supports no occurrence of segregation for the common statistical criterion of p-value less than 10^{-2} (99 percent confidence level).

5.0 PROBABILISTIC APPROACH TO VERIFY CRITERIA

For the previous analysis of nuclear density measurements in Chapter 5 Section 4.0, trial criteria were established to predict visually-apparent segregation given p-value or absolute density difference ($\Delta\gamma$) from nuclear density comparisons. To further refine a criterion based on the nuclear density measurements, a probabilistic approach was utilized to incorporate gradation parameters. As before, the percent passing the 3/8″, No.4 and No.8 sieves were used to verify the selected criteria.

5.1 Venn Diagram

To visualize the agreement or disagreement of comparisons between paired samples using nuclear density measurements, gradation data and visual observations, a Venn diagram is presented. The diagram shown in Figure 6.42 has three circular main regions where two-sample comparisons indicate significant differences in nuclear density values (top left), gradation data (top right) and visual difference in degree of segregation (bottom center). These three regions can be divided into seven subregions plus one more subregion that is the area outside the circles. The characteristics of each subregion are as follows:

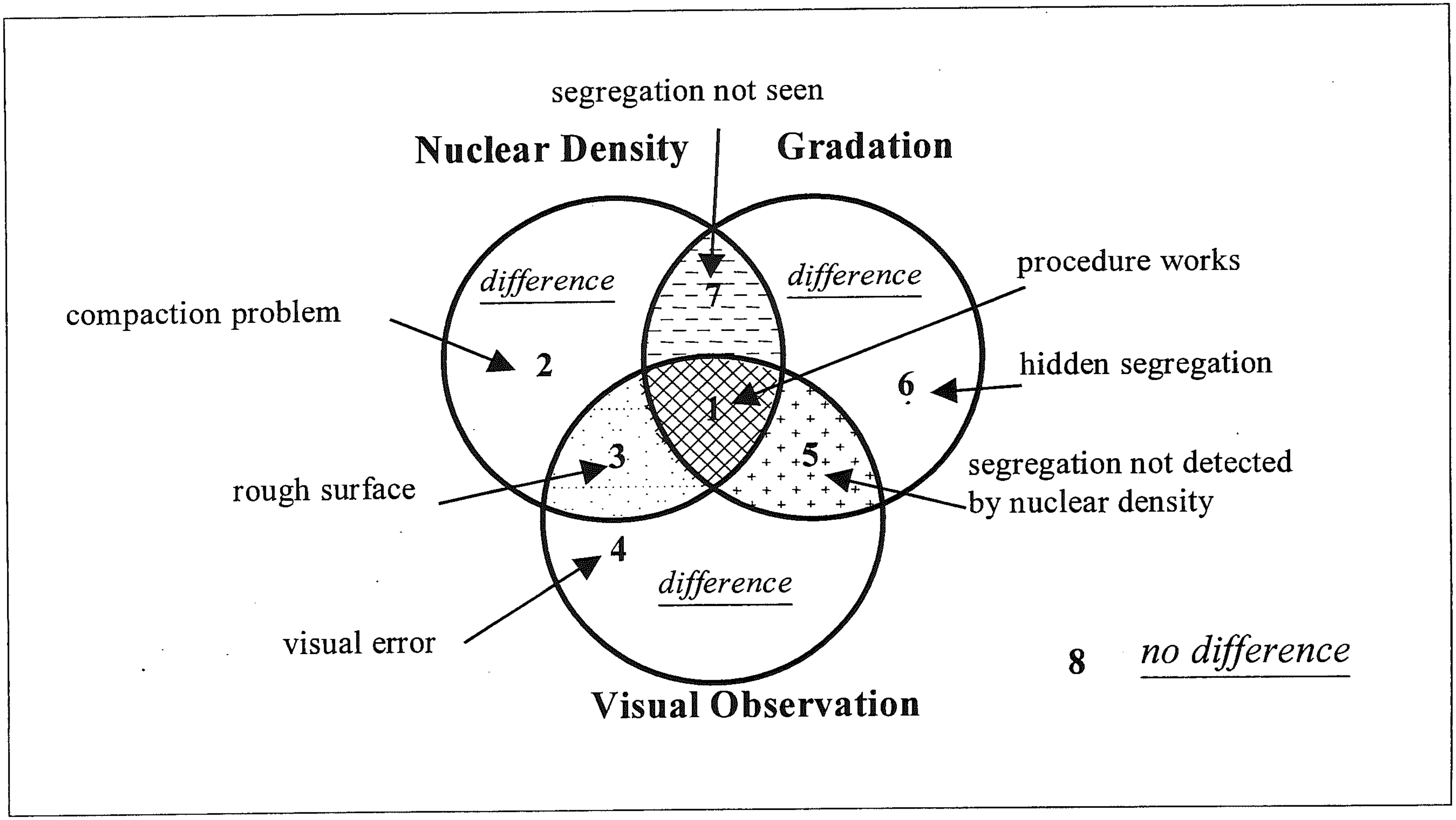


Figure 6.42 Possible Outcomes of Comparisons

Subregion 1 **procedure works**: If all three comparisons plot in this zone, a visually observed difference is identified by nuclear density difference and also supported by a gradation difference. This implies that a comparatively coarse gradation in a visually apparent segregation area is found to have significantly low nuclear density values.

Subregion 2 **compaction problem**: For comparisons plotting in this zone, a nuclear density difference is found, but there is neither a gradation difference nor a visual difference. The nuclear density difference occurs due to a difference in compaction effort.

Subregion 3 **rough surface**: For comparisons plotting in this zone, differences are found based on nuclear density measurements and visual observation of segregation, but no gradation difference is found. This condition appears due to surface voids counted by nuclear gauge and identified by visual observation.

Subregion 4 **visual error**: Comparisons plotting in this zone indicate that a difference is found by visual observation only but not confirmed by nuclear density and gradation differences.

Subregion 5 **hypothesis fails**: Segregation is found by visual observation, and confirmed by gradation tests, but not by nuclear density measurements. A test based on nuclear density differences would not confirm segregation in this case.

Subregion 6 **hidden segregation**: Segregation (based gradation difference) is found. However, the gradation difference is not visually observable nor does it exhibit a nuclear density difference.

Subregion 7 **segregation not seen**: Segregation is detected by both nuclear density measurements and gradation data. The segregated areas do not appear different from uniform control areas.

Subregion 8 **no difference (procedure works)**: In this region fall comparisons of samples from "good" uniform mixes (unsegregated) or comparisons involving similar degrees of segregation where there are no nuclear density differences or gradation differences.

It is desired to adjust the p-value criteria to maximize the number of comparisons located in the heavy shaded intersection area (subregion 1) and outside the circles (subregion 8), and to minimize the number in the other six subregions. The center intersection area indicates a visually observed difference that is identified by nuclear density difference and also supported by a gradation difference; the outside area should correspond to comparisons among unsegregated samples.

5.2 Accuracy of Criteria Based on Gradation Difference p-Value<10^{-3}

Conditional probability analyses using nuclear density comparisons and gradation comparisons were performed using the data obtained from 12 sites (1, 3, 5, 10, 13, 15, 16, 17, 18, 19, 20 and 21). Results are based on the nuclear density criterion of p-value less than 10^{-3} and gradation criterion of p-value less than 10^{-3}. This is a very significant difference in gradation. Under this criteria, the pavement would be considered truly segregated only if the observed gradation difference could be found by chance only 1 in 1000 times.

Since the degree of segregation is one parameter considered in the criteria, the data were divided into two sets, one including all two-sample comparisons, another only including comparisons for control to segregated samples (of any degree). The latter simulated the envisioned field operation, i.e. comparing samples from pre-selected, apparently segregated areas to control areas. Venn diagrams for nuclear density comparisons and gradation comparisons are shown in Figures 6.43 and 6.44 for both data sets. The numbers inside the Venn diagram indicate the number of comparisons that either satisfy or fail the p-value criteria.

Conditional probability values were computed based on the Venn diagram for different gradation parameters (percent passing 3/8", No.4 and No.8 sieves). Three different events are described as follows:

- **Pr(gradation difference given nuclear density difference)** This value represents how accurately the field procedure would work to detect segregation using nuclear density measurements.

- **Pr(nuclear density difference given gradation difference).** If a high probability value is reported, this indicates the hypothesis is accurate that voids in a mix due to separation of coarse and fine materials will give low nuclear density values.

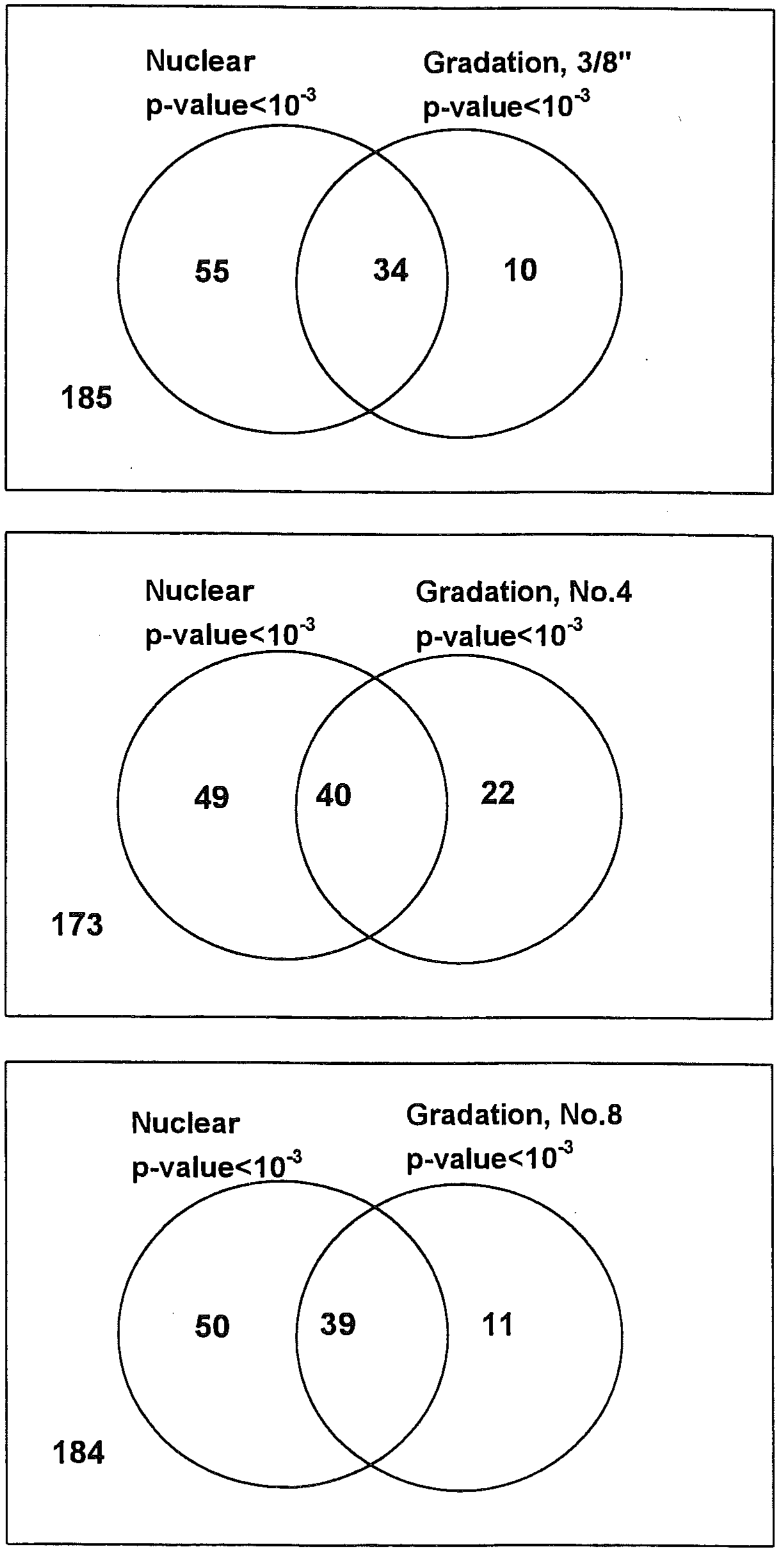
- **Pr(nuclear density consistent with gradation difference) :** Given the entire sample space, this is the probability of either satisfying or failing the criterion for both gradation and nuclear density data. If a high probability value is obtained, this suggests the use of nuclear density measurements would be appropriate for identifying segregation

The conditional probability using nuclear density criterion p-value<10^{-3} and gradation criterion p-value<10^{-3} based on percent passing No. 4 sieve for both data sets is illustrated in Figures 6.45 and 6.46. The computation of probability value for the data set of all comparisons (Figure 6.45) is demonstrated as follows:

- Pr(gradation difference | nuclear density difference)=$\frac{40}{49+40}=0.45$

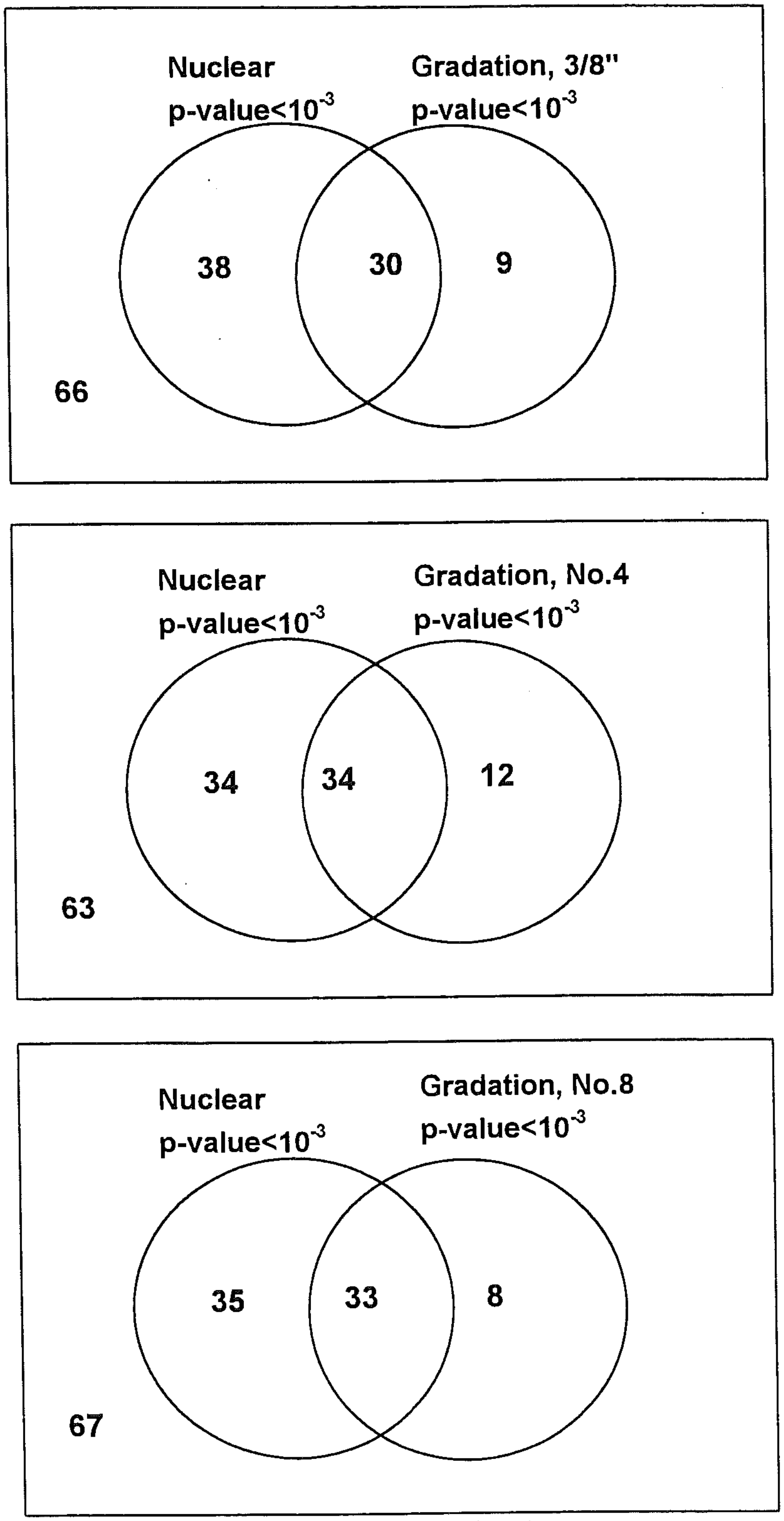
- Pr(nuclear density difference | gradation difference)=$\frac{40}{40+22}=0.65$

- Pr(nuclear density difference consistent with gradation difference)=$\frac{40+173}{49+40+22+173}=0.75$



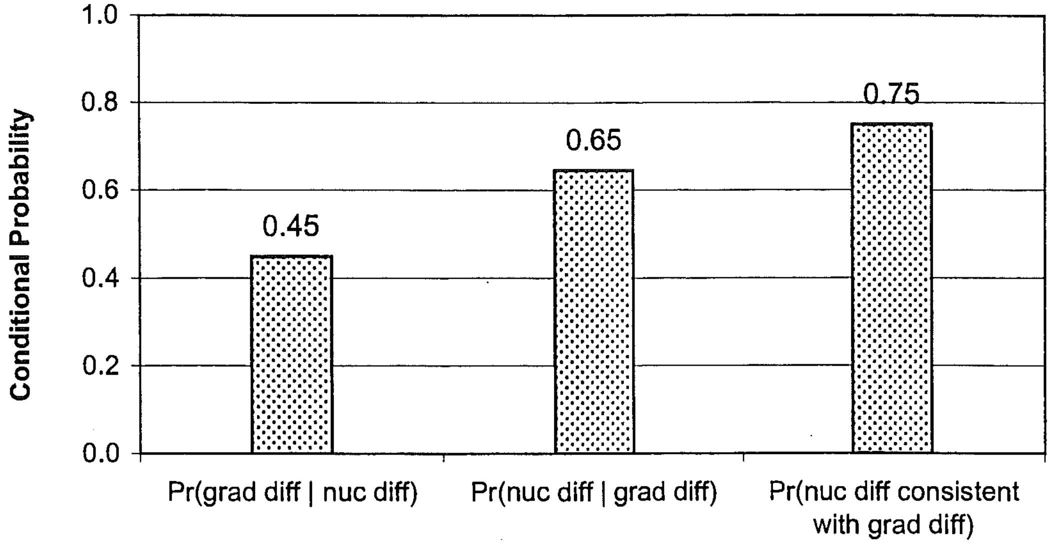
Note: All Comparisons (284 comparisons)

Figure 6.43 Venn Diagrams Using Nuclear Density and Gradation Critera of p-value$<10^{-3}$ Based on the Data Set of All Comparisons



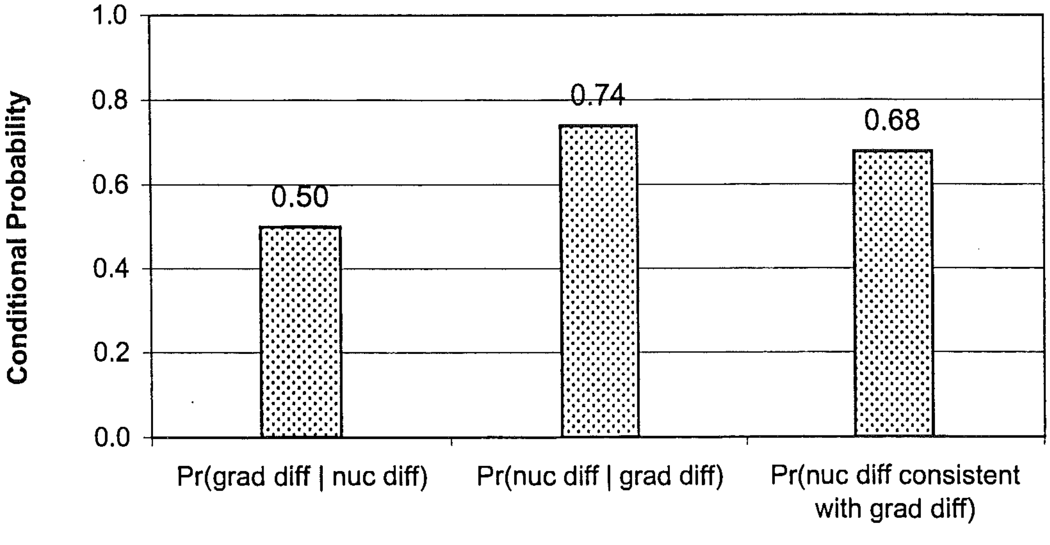
Note: Control to Segregation (143 comparisons)

Figure 6.44 Venn Diagrams Using Nuclear Density and Gradation Criterion of p-value$<10^{-3}$ Based on the Data Set of Control to Segregation Samples



Note : based on all 284 comparisons

Figure 6.45 Conditional Probability Values using Nuclear Density and Gradation of p-value Based on Percent Passing No.4 Sieve for the Data Set of All Comparisons



Note : based on 143 control to segregation comparisons

Figure 6.46 Conditional Probability Values using Nuclear Density and Gradation of p-value Based on Percent Passing No.4 Sieve for the Data Set of Control to Segregatio

Table 6.2 gives the probability values for the different events and different grain-size criteria based on the criteria of gradation difference p-value less than 10^{-3}. Results are summarized as follows:

- Given various criteria for nuclear density difference, the conditional probability for finding a gradation difference is approximately 0.4 to 0.5. In other words, if a difference is found using nuclear density measurements in the field, the chance of verifying segregation based on the gradation difference is only about 50 percent.
- The probability values are not sensitive to the gradation parameter chosen, (percent passing 3/8″, No.4 and No. 8 sieve).
- Given a gradation difference, the conditional probability values for observing a difference in nuclear density measurements are ranged from 0.6 to 0.8.
- The probability of consistent results for both nuclear density difference and gradation difference is approximately 70 percent. The consistent result means satisfying or failing the p-value criterion for both nuclear density difference and gradation difference.

Table 6.2 Conditional Probability using Criteria p-value $<10^{-3}$

	Probability under Different Conditions	3/8″	No.4	No.8
All comparisons	Pr(gradation diff | nuclear diff)	0.38	0.45	0.44
	Pr(nuclear diff | gradation diff)	0.77	0.65	0.78
	Pr(nuclear diff consistent with gradation diff)	0.77	0.75	0.79
Control to segregation	Pr(gradation diff | nuclear diff)	0.44	0.50	0.49
	Pr(nuclear diff | gradation diff)	0.77	0.74	0.80
	Pr(nuclear diff consistent with gradation diff)	0.67	0.68	0.70

5.3 Accuracy of Criteria Based on Gradation Difference p-Value < 10^{-2}

In the previous section, it was found that given the condition of nuclear density difference, the chance of finding a significant gradation difference is only 50%. This may be due to the use of too restrictive a criterion for gradation difference. In common statistical practice, p-value of 0.01 (99% confidence level) is generally considered significant. Therefore, the analyses are repeated based on the gradation difference criterion of p-value less than 10^{-2}. In addition, a new data set is included that is the comparisons between segregated and control samples from all cored sites except site 16 where the testing section was segregated, cracked, and raveled without representative control areas.

Venn diagrams for comparisons of nuclear density values under the criterion of p-value<10^{-3} and comparisons of gradation parameters under the criterion of p-value<10^{-2} for three dada sets are shown in Figures 6.47 through 6.49. It can be seen that the number of comparisons in the intersection area of two circles increases compared to that using gradation criterion of p-value<10^{-3}. The conditional probability values for different conditions using the percent passing No.4 sieve are shown in Figures 6.50 through 6.52. Table 6.3 summarizes a list of conditional probability values under different conditions based on the gradation difference of p-value<10^{-2} and nuclear density difference of p-value<10^{-3}.

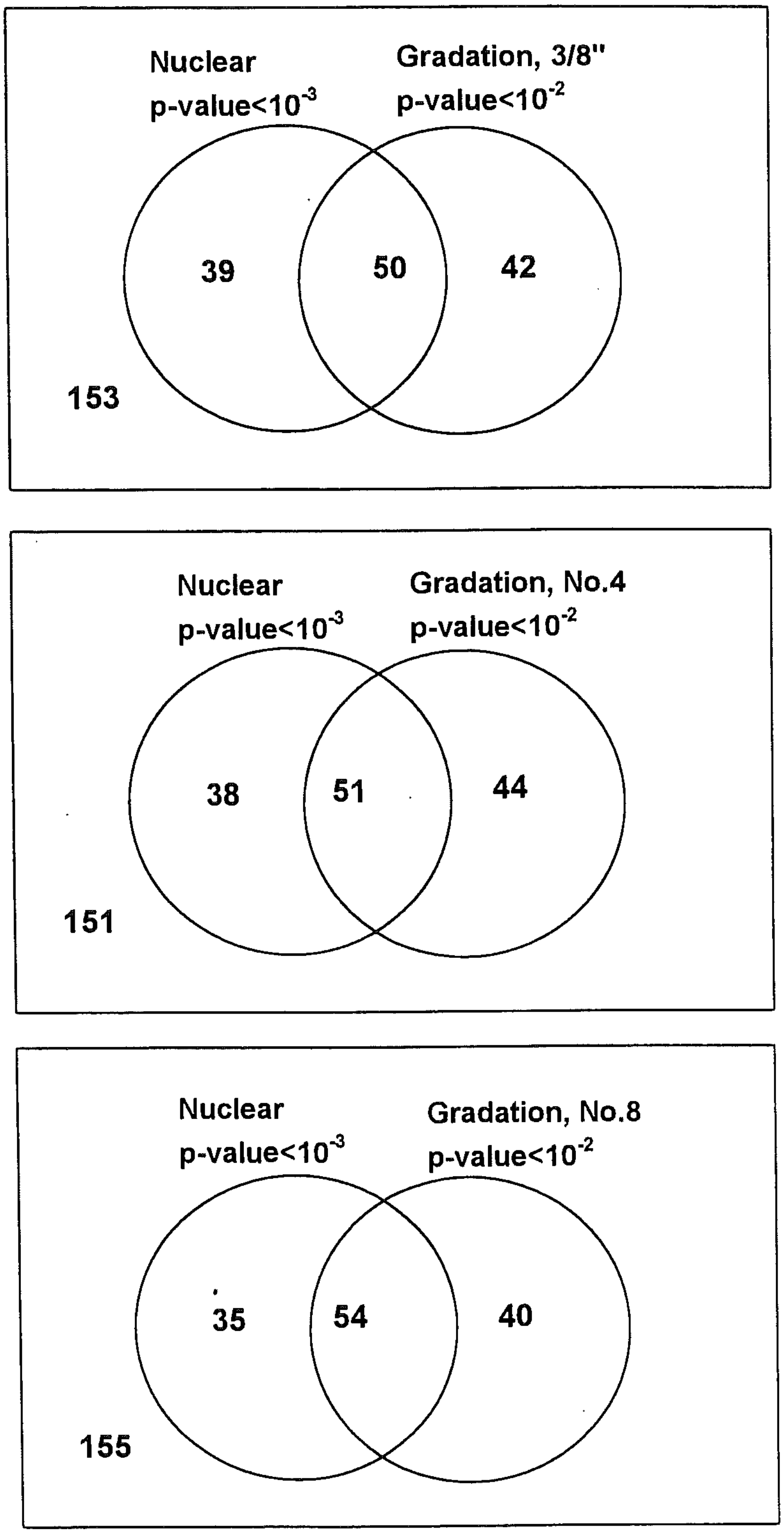
Table 6.3 Conditional Probability using Criteria p-value <10^{-2}

	Probability under Different Conditions	3/8″	No.4	No.8
All comparisons	Pr(gradation diff | nuclear diff)	0.56	0.57	0.61
	Pr(nuclear diff | gradation diff)	0.54	0.54	0.57
	Pr(nuclear diff consistent with gradation diff)	0.71	0.71	0.74
Control to segregation	Pr(gradation diff | nuclear diff)	0.62	0.63	0.66
	Pr(nuclear diff | gradation diff)	0.65	0.67	0.66
	Pr(nuclear diff consistent with gradation diff)	0.66	0.68	0.68
Control to segregation (no site 16)	Pr(gradation diff | nuclear diff)	0.78	0.74	0.78
	Pr(nuclear diff | gradation diff)	0.66	0.66	0.65
	Pr(nuclear diff consistent with gradation diff)	0.69	0.68	0.68

Findings based on the analysis using gradation difference of p-value less than 10^{-2} can be summarized as follows:

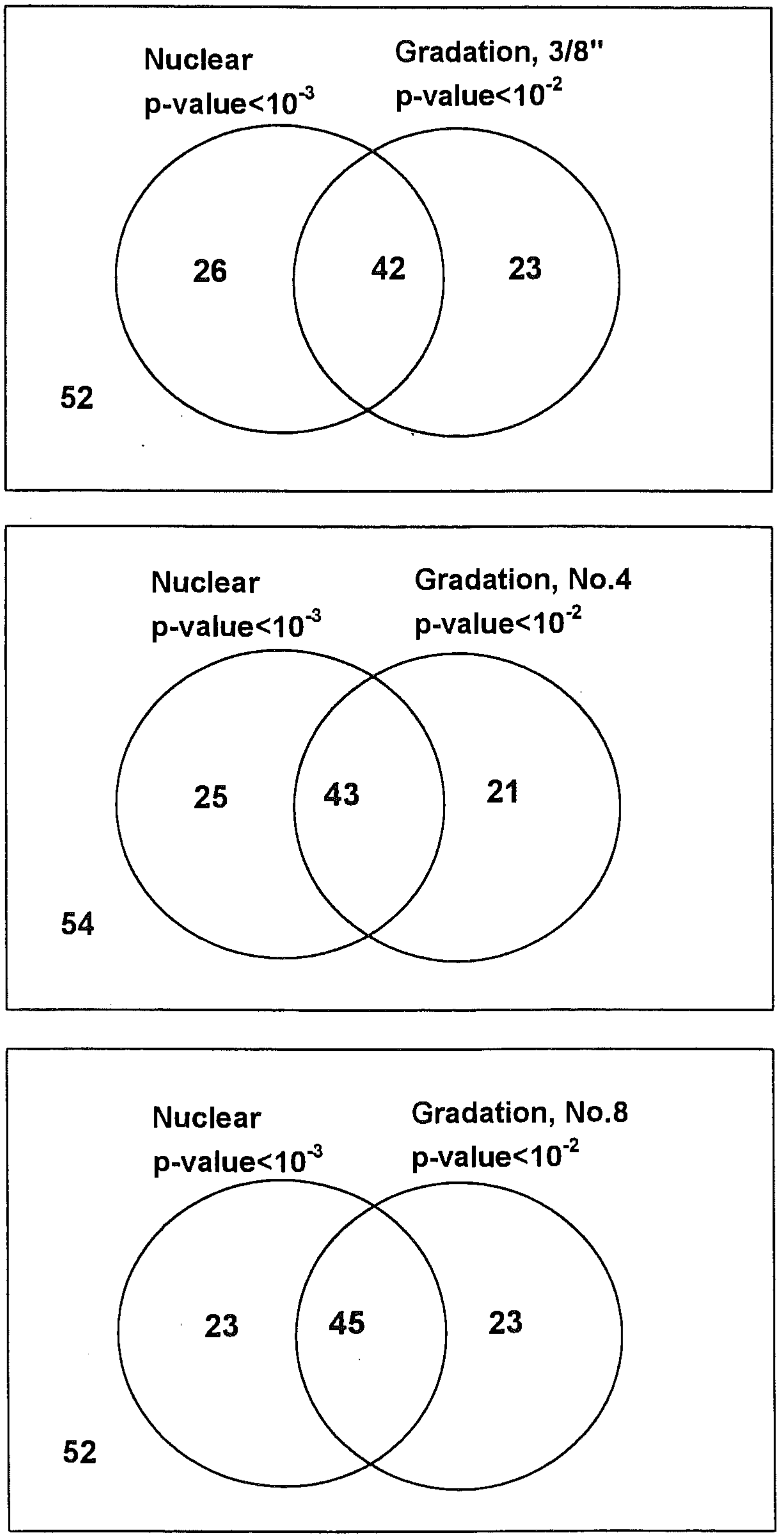
- Given the criterion of p-value< 10^{-3} for nuclear density difference, the conditional probability for finding a gradation difference (under the condition of p-value<10^{-2}) is approximately 0.6 to 0.8, depending on the data set selected. If a difference is found using nuclear density measurements in the field and the data space is chosen as control to segregation comparisons without site 16, the chance of detecting segregation (gradation difference) reaches 77% based on the average probability from three sieve sizes.

- The conditional probability values, Pr(gradation diff | nuclear diff), vary with the data space. If the data space is taken as the set of all comparisons, the conditional probability is approximately 60%. However, if a more narrowly defined data space is considered,



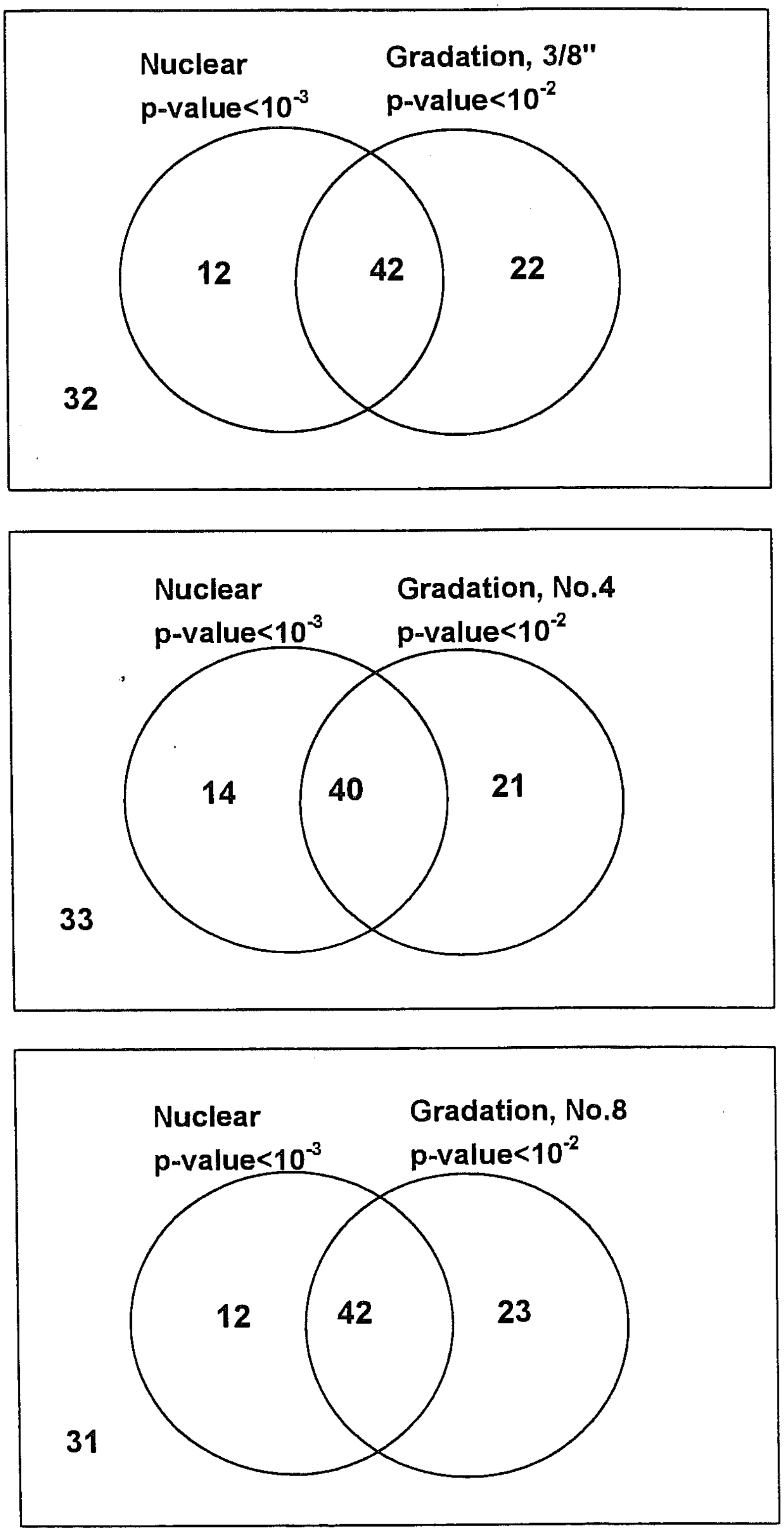
Note: All Comparisons (284 comparisons)

Figure 6.47 Venn Diagrams Using Nuclear Density and Gradation Criterion of p-value$<10^{-2}$ Based on the Data Set of All Comparisons



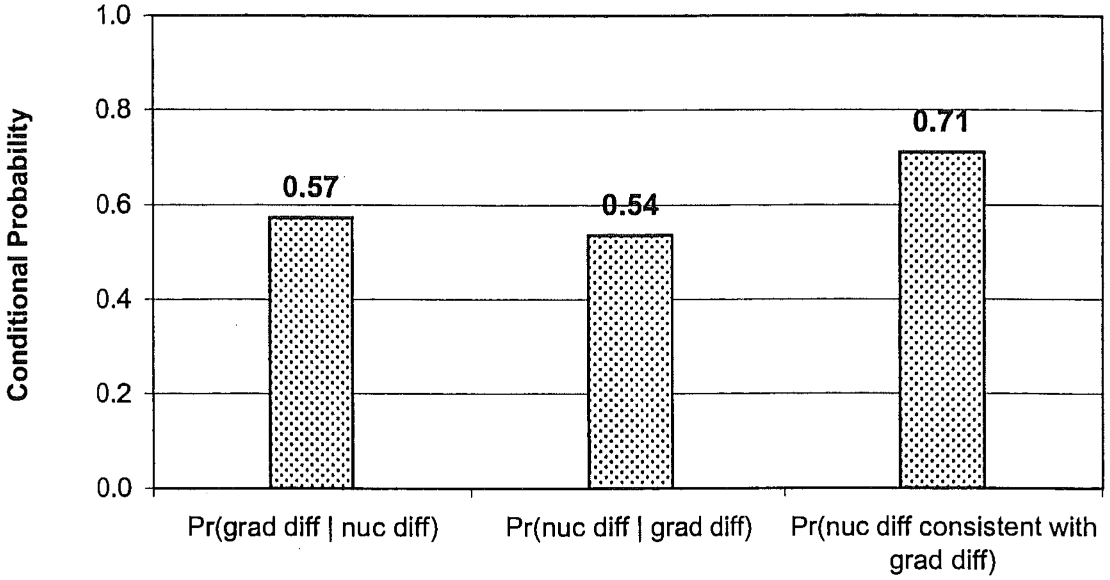
Note: Control to segregation (143 comparisons)

Figure 6.48 Venn Diagrams Using Nuclear Density and Gradation Criterion of p-value$<10^{-2}$ Based on the Data Set of Control to Segregation Samples



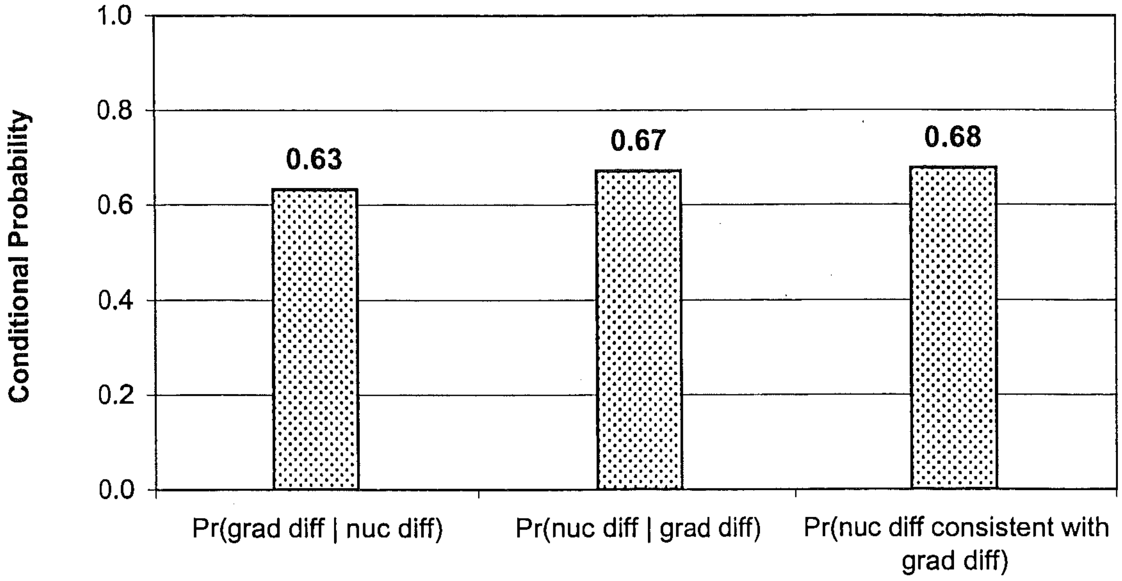
Note: Control to segregation, no site 16 (108 comparisons)

Figure 6.49 Venn Diagrams Using Nuclear Density and Gradation Criterion of p-value$<10^{-2}$ Based on the Data Set of Control to Segregation Samples without Site 16



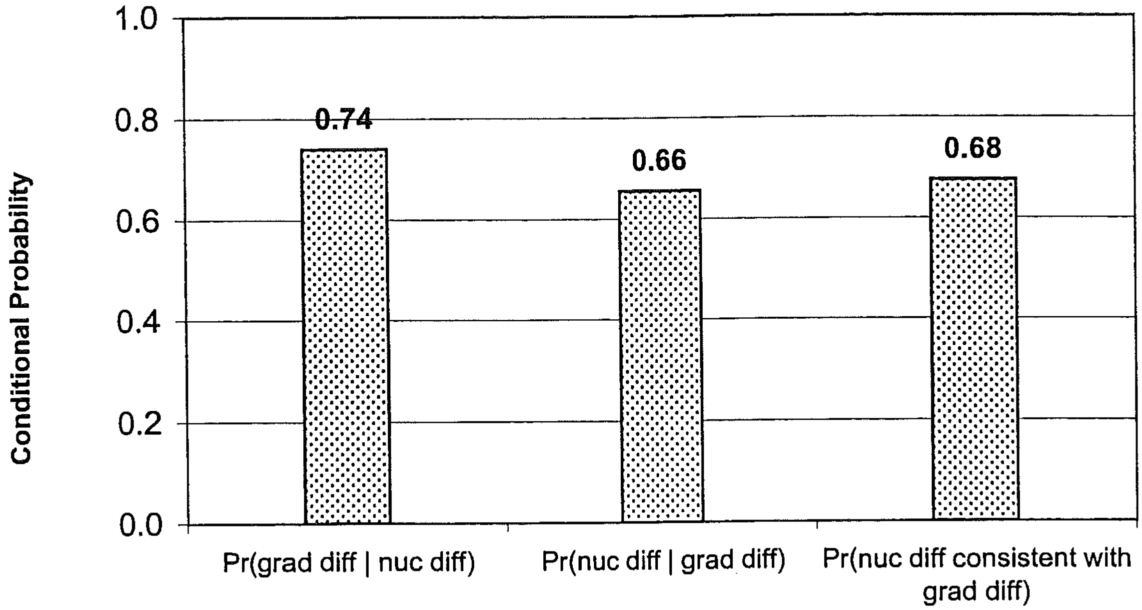
Note : based on all 284 comparisons

Figure 6.50 Conditional Probability Values Using Nuclear Density and Gradation of p-value$<10^{-2}$ Based on Percent Passing No.4 Sieve for the Data Set of All Comparisons



Note : based on 143 control to segregation comparisons

Figure 6.51 Conditional Probability Values Using Nuclear Density and Gradation of p-value$<10^{-2}$ Based on Percent Passing No.4 Sieve for the Data Set of Control to Segregation



Note : based on 108 control to segregation comparisons without site 16

Figure 6.52 Conditional Probability Values Using Nuclear Density and Gradation of p-value<10^{-2} Based on % Passing No.4 Sieve for Control to Segregation without Site 16 i.e., comparisons between control and segregation samples without site 16, the conditional probability increases substantially.

- Given a gradation difference, the conditional probability values for observing a difference in nuclear density measurements ranged from 0.54 to 0.68. The probability of consistent results for both nuclear density difference and gradation difference is approximately 70 percent, which is similar to that based on the gradation difference criterion using p-value<10^{-3} in Chapter 6 Section 5.2.

6.0 CONDITIONAL PROBABILITY FOR VARIOUS NUCLEAR DENSITY CRITERIA

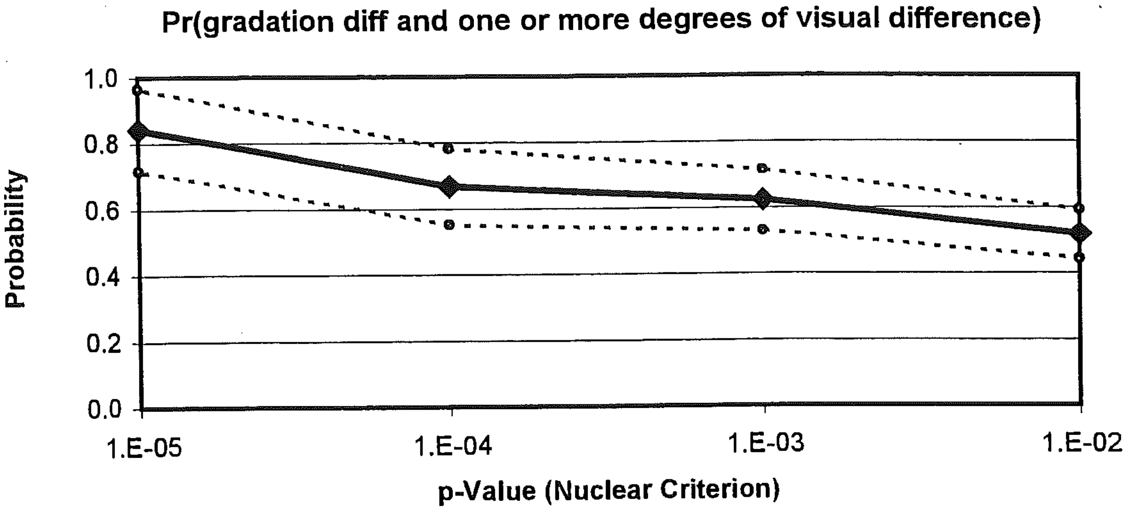
The nuclear density criterion to detect segregation in the previous analysis was taken as a p-value less than 10^{-3}. Using this density criterion, the conditional probability of finding a significant gradation difference (p-value less than 10^{-2}) is approximately 77%. In this section, the conditional probability based on various nuclear density criteria is presented.

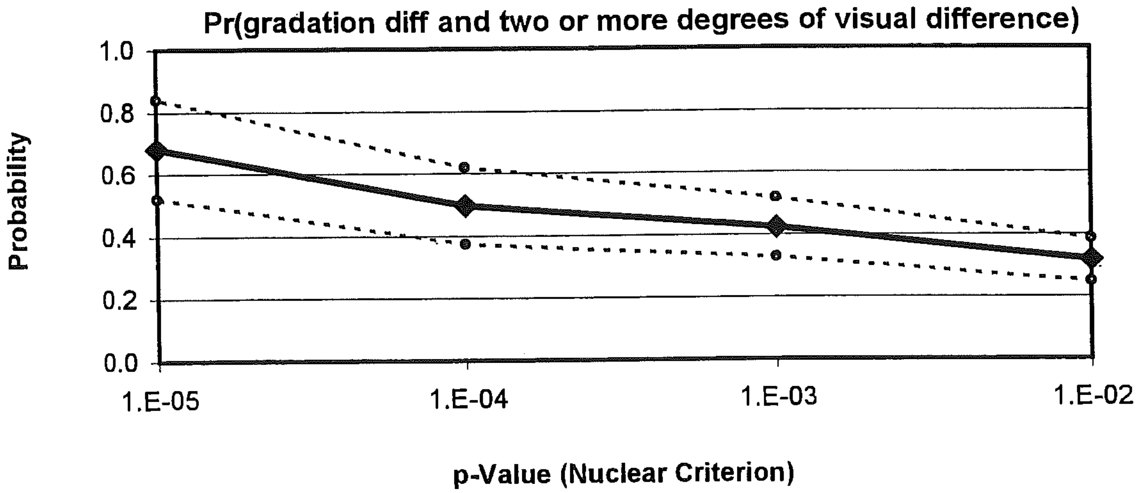
Four trial criteria are chosen, which are p-value from nuclear density comparisons less than 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}. The selection of p-value less than 10^{-2} is more restrictive than the general statistical practice of taking 99% confidence as a significant difference. It is expected that more restrictive criteria may increase the probability of identifying only sites for which there is a gradation difference. Again, the data are separated into two sets, one including all comparisons from both nuclear density and gradation data, the other including the comparisons between control and segregated samples. The comparisons from site 16 are not included in these data sets.

The conditional probabilities of finding a gradation difference and one or more degrees visual difference given a nuclear density difference p-value are shown in Figures 6.53 and 6.54 for both data sets. Detailed values are listed in Tables 6.4 and 6.5. In the figures, the solid line represents the mean probability values from the three conditional probability values based on percent passing 3/8", No.4 and No.8 sieves. Since the small sample size intorduces uncertainty in estimating the conditional probability, a confidence interval is applied to indicate the precision of the estimate. The dashed lines indicate the 90% confidence intervals for the corresponding mean probability value. To obtain confidence limits for the probability (p), the following equation is used (Lapin, 1990):

$$\text{Confidence Interval for Proportion} = p \pm z_{\alpha/2}\sqrt{\frac{p(1-p)}{n}}$$

where p = probability (population proportion)
n = number of samples
$z_{\alpha/2}$= the standardized value of a normal distribution at α confidence level (taken as 90%)





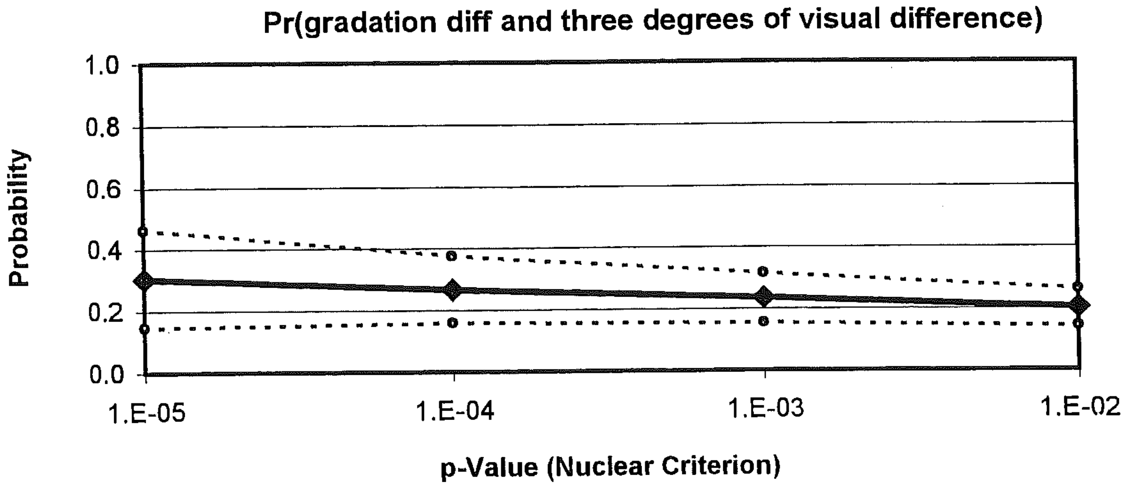
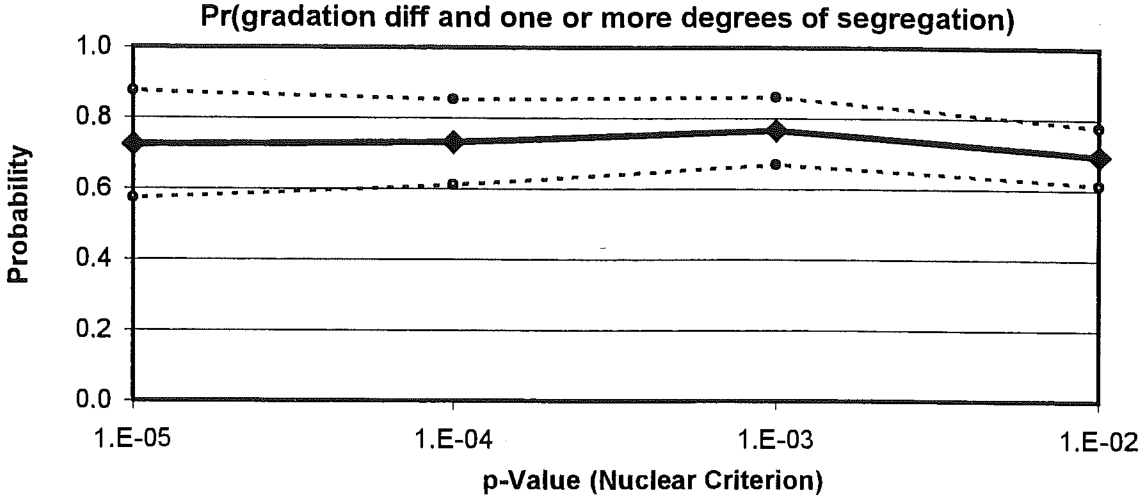
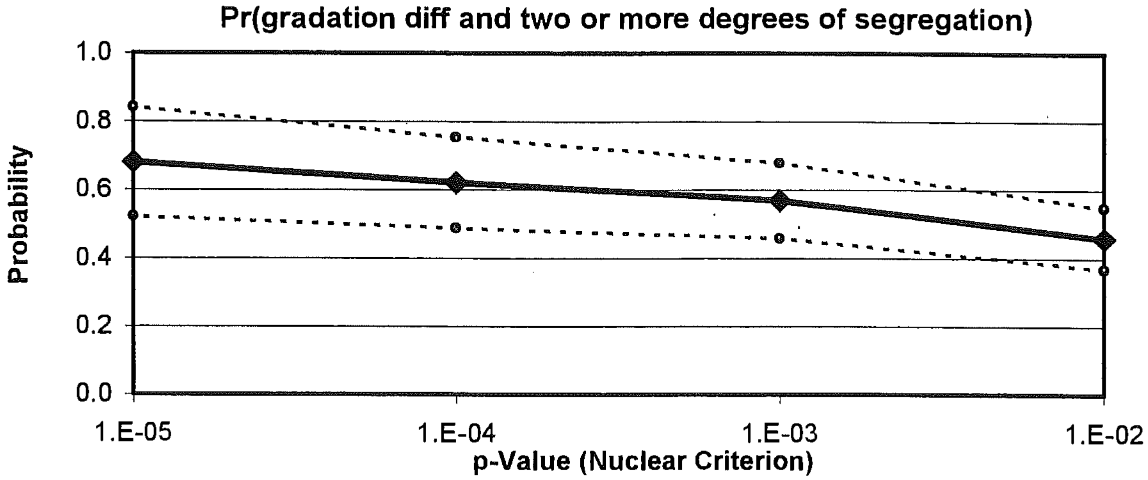


Figure 6.53 Conditional Probability with Various Nuclear Density Criteria Based on the Data Set of All Comparisons without Site 16





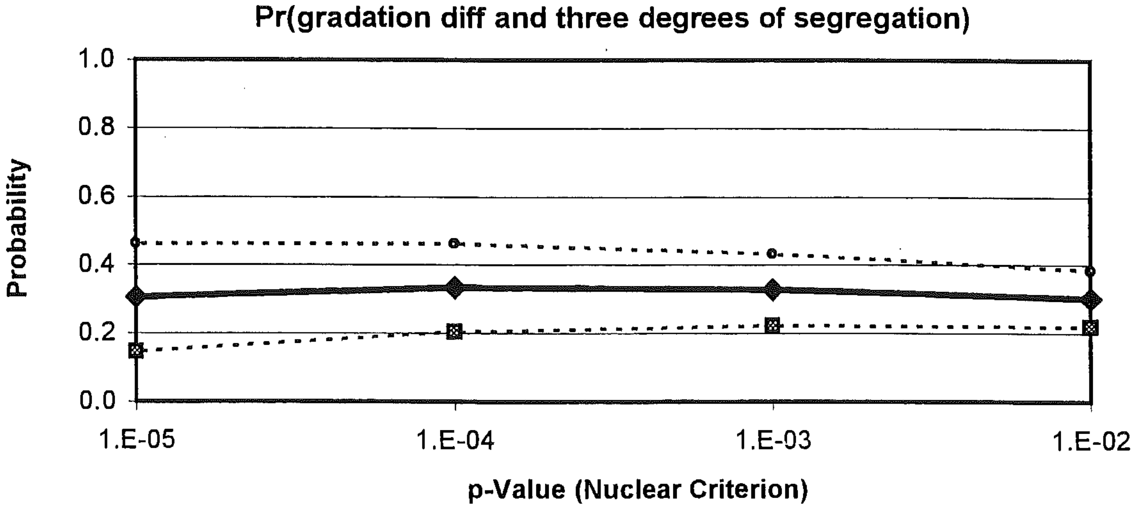


Figure 6.54 Conditional Probability with Various Nuclear Density Criteria Based on the Data Set of Comparisons between Segregated and Control Samples without Site 16

Table 6.4 The Mean Probability and 90% Confidence Interval for Data from All Comparisons

Pr(more than one degree of segregation)

Nuclear Criterion	Mean Probability	Lower Bound	Upper Bound
10^{-2}	0.52	0.44	0.59
10^{-3}	0.62	0.53	0.71
10^{-4}	0.67	0.55	0.78
10^{-5}	0.84	0.72	0.97

Pr(more or equal two degree of segregation)

Nuclear Criterion	Mean Probability	Lower Bound	Upper Bound
10^{-2}	0.32	0.25	0.39
10^{-3}	0.42	0.33	0.52
10^{-4}	0.50	0.37	0.62
10^{-5}	0.68	0.52	0.84

Pr(equal three degree of segregation)

Nuclear Criterion	Mean Probability	Lower Bound	Upper Bound
10^{-2}	0.20	0.14	0.26
10^{-3}	0.24	0.15	0.32
10^{-4}	0.27	0.16	0.38
10^{-5}	0.30	0.15	0.46

Note:

1. Pr(Segregation) is based on the gradation criterion p-value $< 10^{-2}$
2. Degree of segregation is based on visual observation
3. Mean Probability = Average probability using gradation data from 3/8", No.4 and No.8 sieves
4. Lower and upper bond is based on 90% confidence interval
5. All Comparisons (No Site 16) (Total number of comparisons = 218)

Table 6.5 The Mean Probability and 90% Confidence Interval for Data from Control to Segregation

Pr(more than one degree of segregation)

Nuclear Criterion	Mean Probability	Lower Bound	Upper Bound
10^{-2}	0.69	0.61	0.78
10^{-3}	0.77	0.67	0.86
10^{-4}	0.73	0.61	0.85
10^{-5}	0.72	0.57	0.88

Pr(more or equal two degree of segregation)

Nuclear Criterion	Mean Probability	Lower Bound	Upper Bound
10^{-2}	0.46	0.37	0.55
10^{-3}	0.57	0.46	0.68
10^{-4}	0.62	0.49	0.75
10^{-5}	0.68	0.52	0.84

Pr(equal three degree of segregation)

Nuclear Criterion	Mean Probability	Lower Bound	Upper Bound
10^{-2}	0.30	0.22	0.38
10^{-3}	0.33	0.22	0.43
10^{-4}	0.33	0.20	0.46
10^{-5}	0.30	0.15	0.46

Note:

1. Pr(Segregation) is based on the gradation criterion p-value $< 10^{-2}$
2. Degree of segregation is based on visual observation
3. Mean Probability = Average probability using gradation data from 3/8", No.4 and No.8 sieves
4. Lower and upper bond is based on 90% confidence interval
5. Control to Segregation (No Site 16) (Total number of comparisons = 108)

In Figure 6.53, the probability of a gradation difference increases as more restrictive nuclear density criteria are selected. The probability that the two sampled areas vary by one or more degree of visual difference is 62% using p-value<10^{-3} criterion, and increases to 84% if p-value<10^{-5} is chosen. Similar trends are also found for probability of finding two or more degrees of visual difference or l three degrees of visual difference. The relatively low probability values for finding heavy segregation (three degree of visual difference) is because the small proportion of heavy-segregated sample in the entire sample space (32 comparisons between control to heavy out of 218 from all comparisons without site 16).

This suggests that setting a very low p-value criteria, say <10^{-5}, would let one be more confident in identifying segregation from nuclear density testing. The trade-off, however, is that one would also fail to identify more areas of actual segregation with this more restrictive criteria.

In Figure 6.54, the data set of comparisons between segregated and control samples was used. The trend of linear increase with various p-value criteria is not obvious. The probability for finding segregation is between 69% to 77% and does not vary much with different p-value criteria. It can be seen that the probability values from the data set of comparisons between control and segregated samples are higher than that from the data set of using all comparisons. The 90% confidence interval for the estimate of the probability is indicated by the dashed lines. The conditional probability values for finding medium or heavy segregation increase with more restrictive criteria chosen. The conditional probability values for finding heavy segregation is approximately 33%. It is noted that the number of comparisons between control to heavy-segregated sample is only 30% (32 out of 108) of total sample space (comparisons between control and segregated sample).

7.0 ACCURACY OF VISUAL DEGREES OF SEGREGATION

In the previous analyses, the computed probability values are based on the data set of either all comparisons, comparisons between control and segregated samples or the comparisons between control and segregated samples without site 16. The reported probability values are based on a sample space including samples from all degrees of segregation. This eliminates inconsistency of visual observation regarding degree of segregation. In this section, samples from each visual classification are considered separately.

Comparisons between control and segregated samples are separated into five groups by visual degree difference as control to light, control to light-medium, control to medium, control to medium-heavy and control to heavy. The conditional probability values are shown in Figure 6.55 for control to segregated samples from all sites; in Figure 6.56 for control to segregated samples without site 16. It is noted that the gradation parameter used herein is the percent passing No.4 sieve because the probability values do not vary much with different sieve sizes chosen. Four possibilities of conditional probability are reported; each for comparisons between a specific severity level and control sample.

- Pr(gradation difference given nuclear density difference)
- Pr(nuclear density difference given gradation difference)

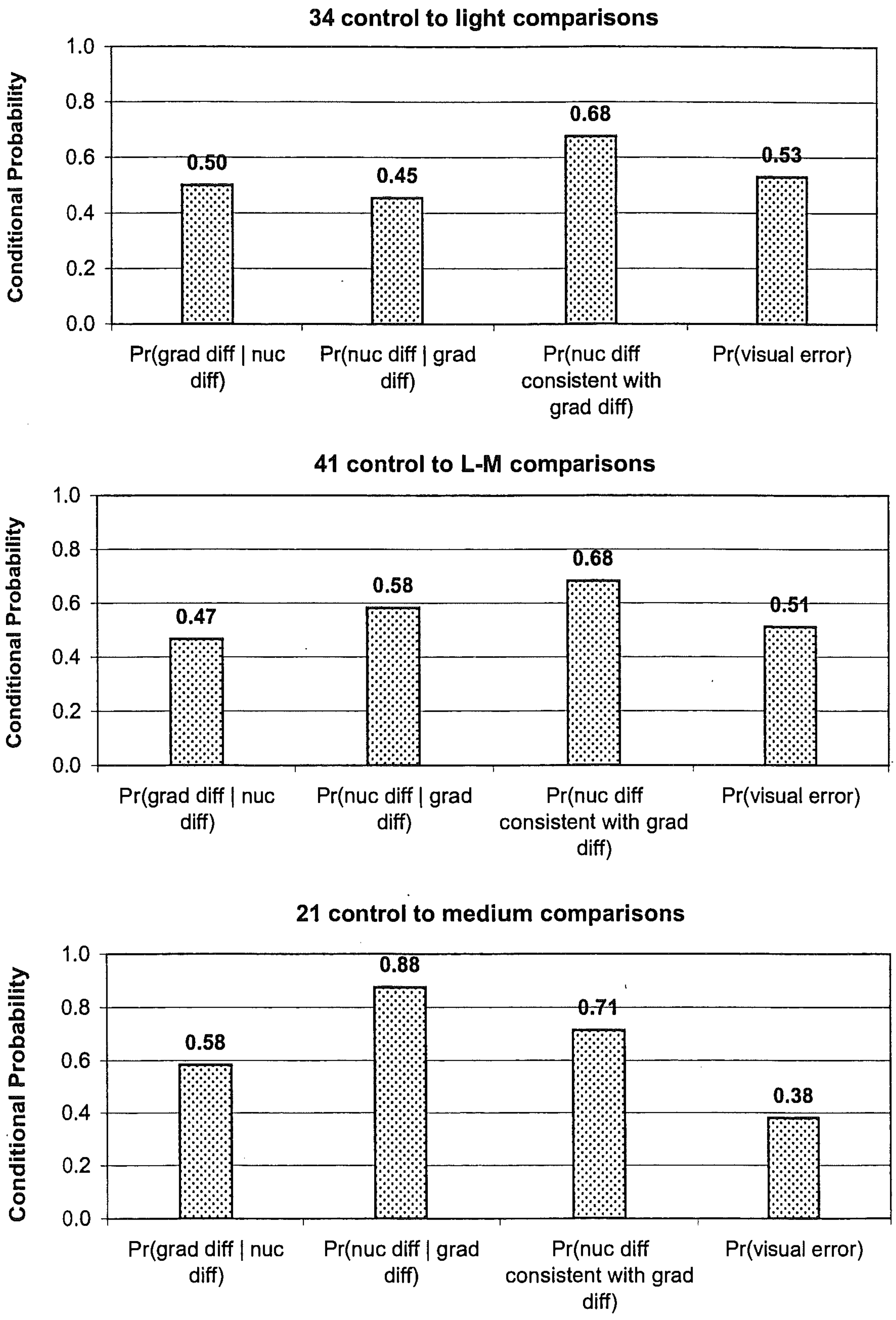
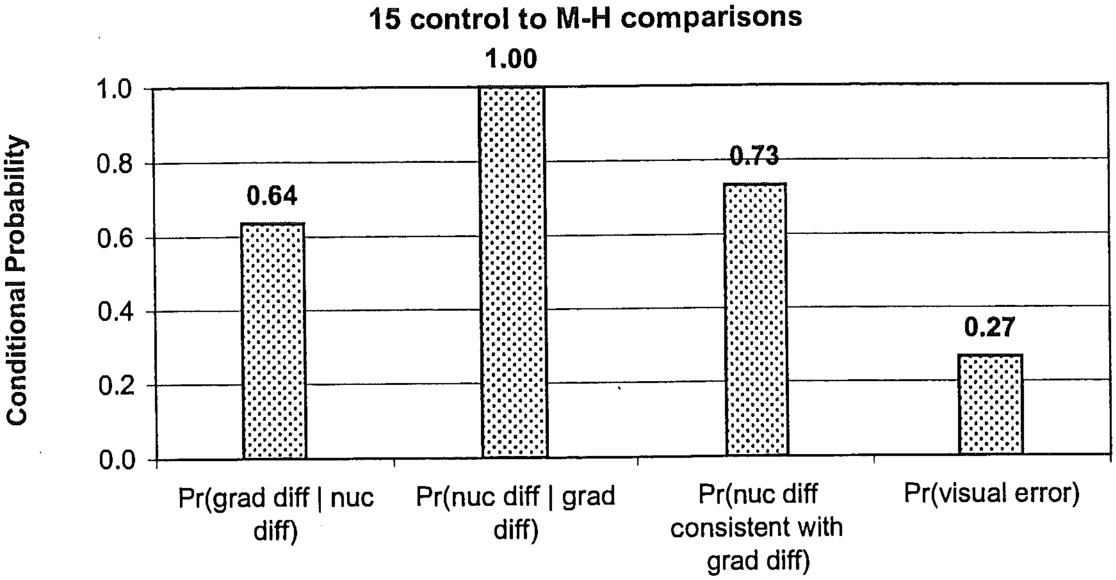


Figure 6.55 Conditional Probability for Each Visual Degree of Segregation



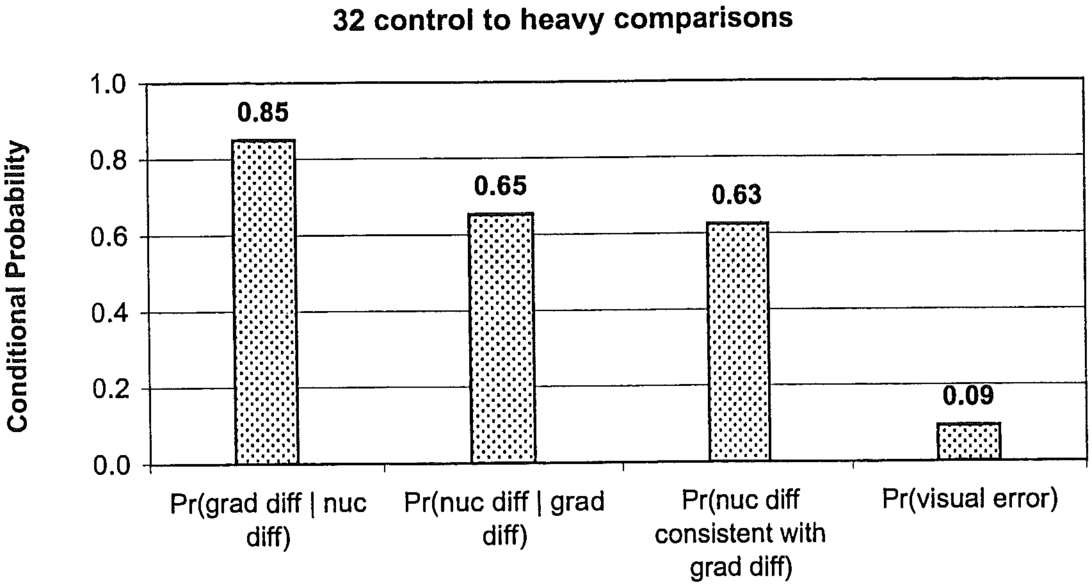


Figure 6.55 (continued) Conditional Probability for Each Visual Degree of Segregation

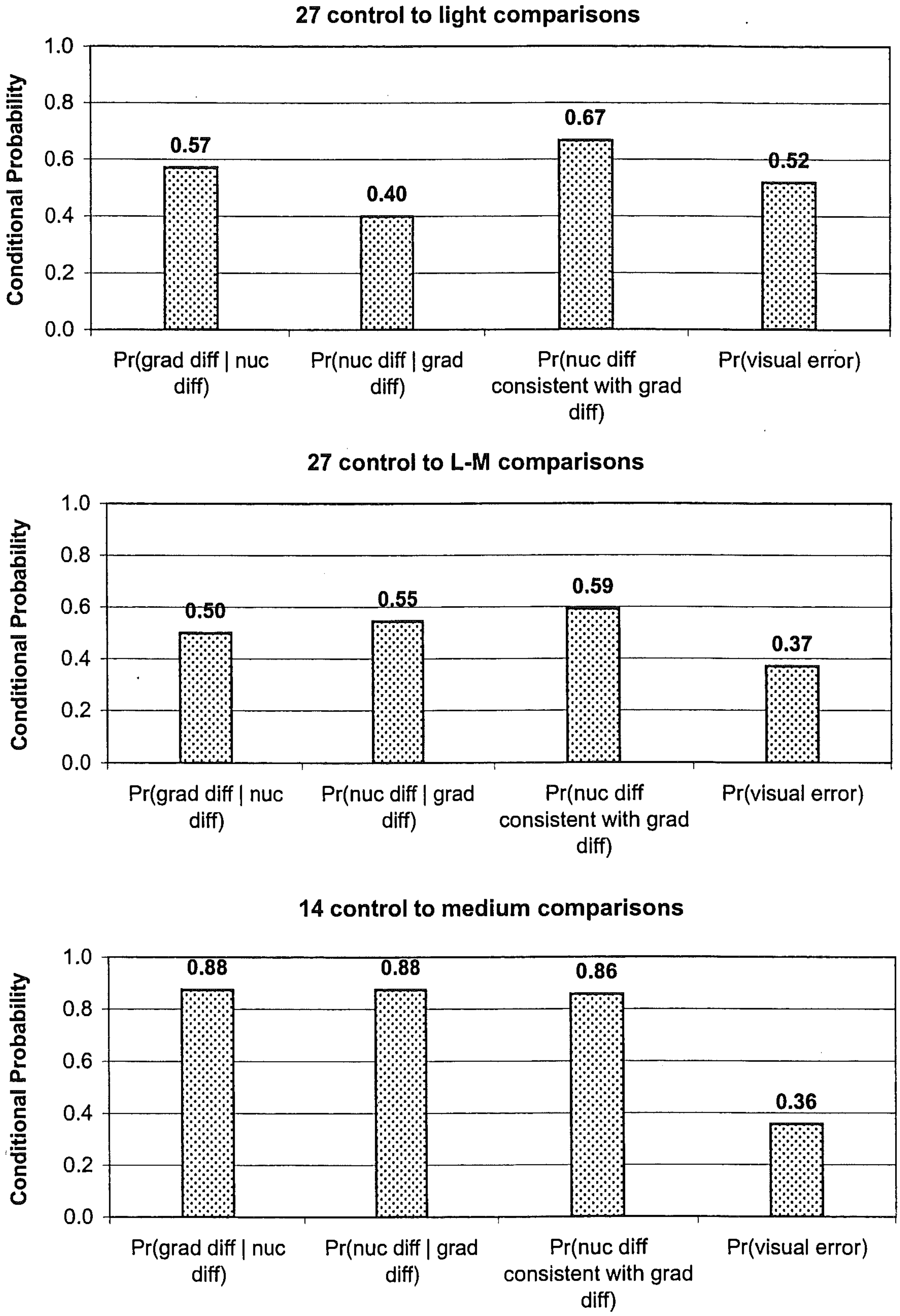
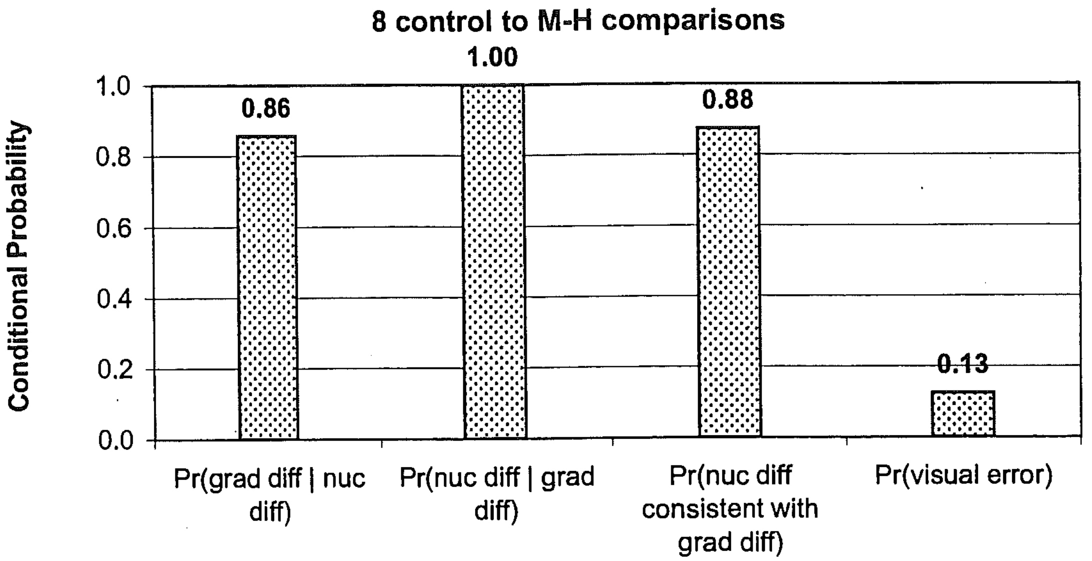


Figure 6.56 Conditional Probability for Each Visual Degree of Segregation without Site 16



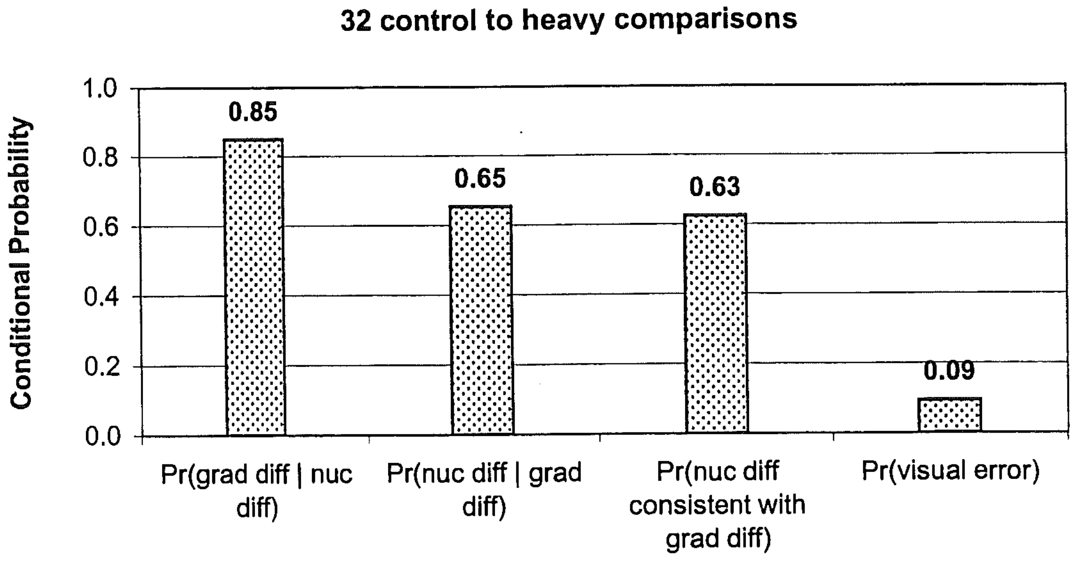


Figure 6.56 (continued) Conditional Probability for Each Visual Degree of Segregation without Site 16

- Pr(nuclear density finding consistent with gradation finding)
- Pr(error of visual observation)

The first three conditional probabilities have been mentioned in Chapter 6 Section 5.2. The fourth probability regarding visual error in determining segregation is computed using the number of comparisons neither satisfying nuclear nor gradation criterion divided by the numbers of sample space, which corresponds to comparisons selected on the basis that segregation differences were visually noted.

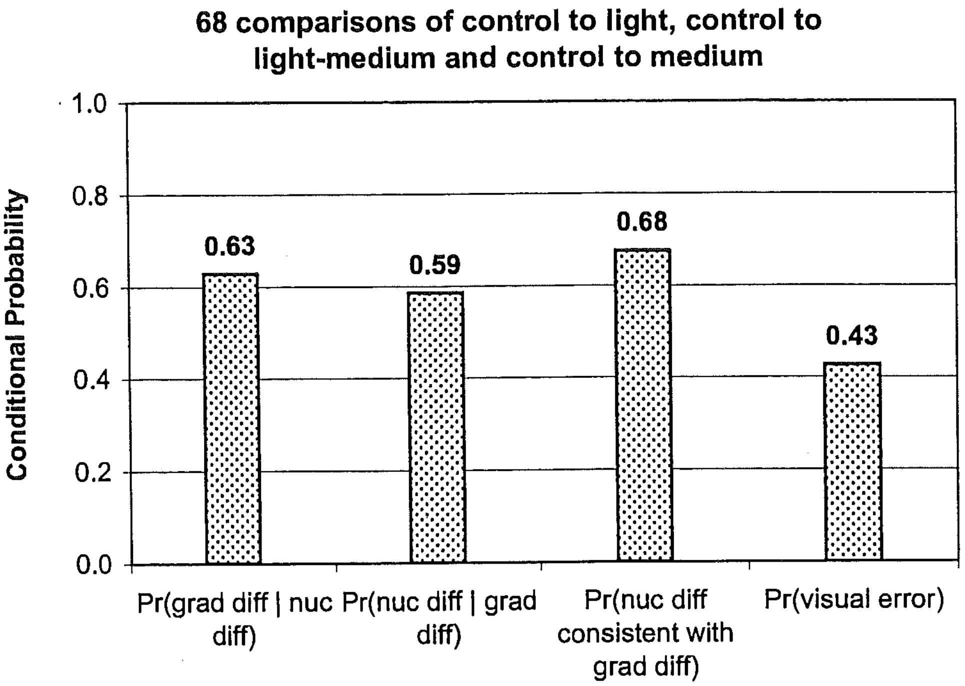
It is noted that likelihood of confirming segregation mapped as medium or heavy is greater than that for light-segregated areas. For example, if light segregated areas are observed visually and nuclear density differences are found, the probability of finding a difference in gradation parameters is approximately 50%. If medium segregated areas are identified and nuclear density differences are found, the chance of finding gradation difference ranges between 58 to 88 % depending on the data set selected. If heavy segregated areas are observed and nuclear density differences are found, the chance of confirming the segregation by gradation tests increases to 85%.

The conditional probability values for observing a difference in nuclear density measurements given a gradation difference also increase with segregation severity level. The probability of nuclear density difference (or no difference) being consistent with a gradation difference (or no difference) has a similar range between 0.6 and 0.7 as discussed in Chapter 6 Section 5.3.

The probability of visual error (finding no nuclear difference and no gradation difference even though segregation was mapped) is high, approximately 50%, for light segregation. For medium, it reduces to 0.38. However, for visually-identified heavy segregation, the chance of visual error reduces significantly, to only 9%. This reveals the accuracy of properly classifying light segregation from visual observation (for the data in this study) is only 50%. If light segregated area is mapped by an expert and nuclear density comparison lead to p-values below 10^{-3}, the chance of a confirming segregation difference is only 50%. For heavy segregation, the accuracy improves significantly to 85%.

The above analyses suggest that segregated areas visually mapped as medium or worse and exhibiting nuclear density differences have a high probability of being confirmed by differences in gradation parameters (percent passing the No. 4 sieve).

These findings are summarized using conditional probability values for two groups of data (Figure 6.57). One group includes the comparisons of control samples to light, light to medium, and medium. The other group includes the comparisons of control samples to medium, medium to heavy and heavy. The conditional probability values are shown using the data set of all comparisons without site 16. Again, the group of samples mapped as medium or worse have an 86% of probability value for Pr(gradation difference | nuclear density difference), which is much better than the 63% for the group mapped between light and medium.



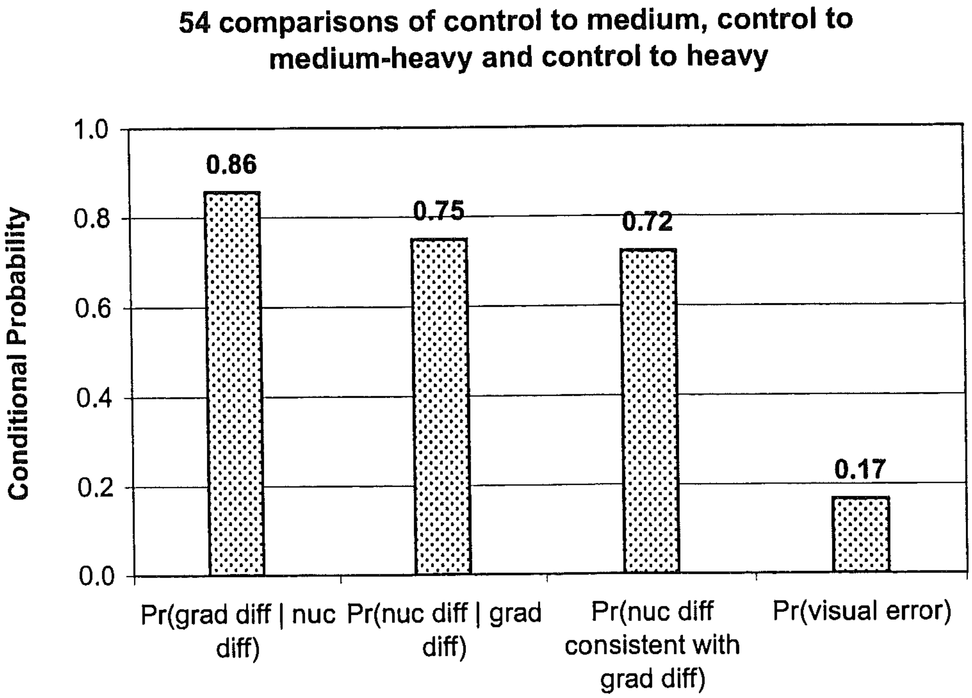


Figure 6.57 Conditional Probability for Combination of Several Visual Degrees of Segregation Based on the Comparisons between Control and Segregated Samples without Site 16

8.0 REVISED CRITERIA BASED ON COMBINATION OF VISUAL OBSERVATION AND NUCLEAR DENSITY MEASUREMENTS

The correlation between visual degree of segregation and nuclear density measurements was studied in Chapter 5 Section 4.0. It was found that given nuclear density differences, the probability that one sample would be visually mapped as segregated is high. In other words, results of nuclear density analyses using statistical comparisons between paired samples were generally consistent with the results of visual observations of segregation.

However, by including gradation data to confirm that segregation is present, the probability of finding "real" segregation by using nuclear density measurements is reduced. This verification was discussed in Chapter 6 Section 5.0. Conditional probability values were computed using various nuclear density criteria based on different p-values.

In Chapter 6 Section 6.0, probability values were reported based on the either the sample space of all comparisons between paired samples or the sample space of comparisons between control and pre-selected segregation samples. An implicit assumption was made that all segregated samples are statistically randomly selected in a manner not dependent on the visual degree of segregation. This procedure implies that if two areas are selected from the pavement section (usually one is mapped as visually segregated, another is unsegregated), the likelihood that segregation would be confirmed, along with the probable visual degree, can be estimated from p-values from nuclear density tests. It should be noted that these probability values are based on the comparisons from the 19 sites in this project.

In Chapter 6 Section 7.0, the accuracy of visual classification of segregation was considered using the nuclear density criterion of p-value less than 10^{-3} and gradation criterion of p-value less than 10^{-2}. The accuracy of visual segregation mapping is improved with increasing segregation severity. ***This suggests visual evaluation and nuclear density measurement provide complementary information for detecting segregation.***

To establish revised criteria combining visual observation, nuclear density measurements and gradation data, the comparisons are divided into two groups:

- Group of comparisons involving medium or below (control to light, control to light-medium and control to medium)
- Group of comparisons involving medium or above (control to medium, control to medium-heavy and control to heavy)

The reason to select these two groups is based on the results in the previous section. The accuracy of confirming light segregation by gradation testing, given visual observation and nuclear difference, is around 50%, for medium is between 60 and 80%, and for heavy is more than 80 percent. This indicates mapping difficulties for light segregated and unsegregated areas. However, visual observation for medium or heavy segregation provides more accurate information. The conditional probability values, Pr(gradation difference | nuclear density difference), were computed using different nuclear density criteria with different p-values at the gradation difference of p-value less than 10^{-2}. These probability values are listed in Tables 6.6 and 6.7 based on different sieve sizes. The following observations are made:

- The conditional probability values, Pr(gradation diff | nuclear diff), are not sensitive to the sieve size chosen.
- Segregation can be accurately predicted using nuclear density measurements if suspicious areas are visually selected with medium or above degree of segregation.
- The probability value does not vary much once the p-value criterion is set at less than 10^{-4} for the group of comparisons with medium or above degree of segregation. The probability actually drops slightly if the criterion of p-value is set less than 10^{-4} for the group of comparisons with medium or below degree of segregation. This is because of the small sample size associated with the more restrictive nuclear density criteria.

9.0 SUMMARY

Based on the laboratory data from the 12 sites at which cores were taken, the criteria using visual observation and nuclear density measurements were verified. Findings include the following:

- In general, the results of statistical comparisons and trends of density distribution using SSD or air-dry density are similar to those based on nuclear density. Segregated areas tend to have lower nuclear density values.
- The gradation difference between the segregated and control areas at sites 1, 15, 19, 10 and 21 could be as large as approximately 20% for the percent passing No.4 sieve. The gradation difference between segregated sample and control sample at sites 3 and 10 is less than 10%. The gradation data at sites 13 and 16 are within a tight range with maximum difference of 4%. It is also found that gradation curves at site 13 and 16 are either close or above the maximum density line that indicates fine mixes.
- Gradation data from sites 17 and 18, which were selected as control sites without segregation, indicate no significant differences. This reveals that the observed nuclear density differences are contributed by the compaction along the wheel paths.
- Based on the normalized nuclear density data and gradation parameters, the expected relation (high normalized density value corresponding to high percent passing) was found at sites 1, 3, 15, 19, 20 and 21. A small change of normalized nuclear density corresponds to a relatively large change in normalized gradation parameters.
- Correlation between nuclear-measured density comparison results and gradation parameter comparison results is presented by cross-plotting p-values. A linear trend showing that a statistical difference in nuclear density values corresponds to a statistical difference in gradation is observed at sites 1, 3, 15, 19, 20 and 21.

Table 6.6 Conditional Probability of the Group with Segregation Light Through Medium

Nuclear Density Criteria	Sieve Size			Average
	3/8"	No.4	No.8	
p-value < 10^{-2}	0.63	0.54	0.54	0.57
p-value < 10^{-3}	0.67	0.63	0.63	0.64
p-value < 10^{-4}	0.65	0.53	0.53	0.57
p-value < 10^{-5}	0.60	0.40	0.50	0.50

Note: 54 comparisons from control to light, control to light-medium and control to medium (no site 16)

Table 6.7 Conditional Probability of the Group with Segregation Medium or Worse

Nuclear Density Criteria	Sieve Size			Average
	3/8"	No.4	No.8	
p-value < 10^{-2}	0.79	0.77	0.81	0.79
p-value < 10^{-3}	0.86	0.86	0.91	0.88
p-value < 10^{-4}	0.81	0.88	0.88	0.86
p-value < 10^{-5}	0.83	0.88	0.88	0.87

Note: 68 comparisons from control to medium, control to medium-heavy and control to heavy (no site 16)

- The proposed criterion using nuclear density measurements was tested using the percent passing 3/8", No.4 and No.8 sieves. It was found that the results were not sensitive to the sieve size chosen. Two data sets were considered, one based on all comparisons and one on comparisons between control and segregated sample.

- If segregation was visually observed and the comparison of nuclear density values found significant differences with the p-value less than 10^{-3}, the probability that segregation would be confirmed by a gradation difference ($p < 10^{-2}$) is around 0.75. The converse indicates 66% chance to find nuclear density difference given gradation difference.

- The conditional probability values were established using various nuclear density criteria with p-value ranged from 10^{-2} to 10^{-5}. In general, probability increases with more restrictive criterion selected. The screen test based on the different p-value filters gives the probability of finding segregation (not degree of segregation).

- The accuracy of visual degree of segregation was verified by both nuclear-measured density with p-value less than 10^{-3} and gradation data with p-value less than 10^{-2}. It was found that the visually-selected heavy segregation is 85% accurate based on the probability of gradation difference given nuclear density difference; approximately 60 to 80% for medium segregation; and only 50 to 56% for light segregation.

CHAPTER 7
EFFECTS OF SEGREGATION ON PAVEMENT CONDITION

1.0 OVERVIEW

The effect of segregation on pavement condition was studied in a four-step process. In the first step, the degrees of segregation were qualified as (heavy, medium and light) based on visual observations. In the second step, the visual degree of segregation was verified based on statistical differences using both nuclear-measured density values and aggregate gradation data. In the third step, the pavement surface condition (distress) was mapped five different times. In the fourth step, the results of steps 1 and 2 were compared to the results of the distress survey.

2.0 VISUAL OBSERVATIONS

MDOT and MSU personnel conducted visual observations of the various pavement sites to map and qualify areas of light, medium, and heavy segregation. The definitions of light, medium and heavy segregation can be found in Table 2.2 of Chapter 2. During the field observation, the terms light-medium and medium-heavy were added for segregated areas with severity level between light and medium or between medium and heavy. Each member of the observation team was given a standard form (see Figure 2.1) to map and label segregated areas. Table 7.1 provides a summary of the various degrees of segregation found at each site. Table 7.1 should be examined with caution. The reason is that the degrees of segregation reported in the table correspond to the opinions of the majority of the visual observation team members. The team members did not agree all the times. Therefore, the letter “x” in the table indicates the majority opinion. For example, at site 13, the majority of the team members found areas of light, light to medium, medium and heavy segregation. On the other hand, the team members unanimously found no segregation at sites 17 and 18.

3.0 QUANTIFYING THE DEGREES OF SEGREGATION

The visual degree of segregation was quantified based on statistical analysis of the differences between the measured nuclear density values. The results of the statistical analysis are included in Chapters 5 and 6. The hypothesis is that the visual degree of segregation could be related to the associated p-value from the comparison between segregated and non-segregated (control) areas. The results of the analysis are detailed in Section 7.0 of Chapter 6. It should be noted that the analysis to establish the degree of segregation using nuclear density measurements are based on visual observations and identifications of the degrees of segregation (see next section). The total sample space that was included in the analysis consists of 43 segregated samples and 34 non-segregated (control) samples. The analysis is based on 143 comparisons between segregated and non-segregated (control) samples at 19 sites. Given the p-value obtained from two-sample comparison, the probability values for finding segregated areas were obtained and are listed in Table 7.2. For example, if a p-value of less than 0.001 is specified, then the probability of

Table 7.1 A Summary of Degrees of Segregation Based on Visual Observation

Site	Degree of Segregation				
	Light	Light-Medium	Medium	Medium-Heavy	Heavy
1	x		x		x
2	x		x		x
3	x		x		
5	x		x		x
6		x			x
7		x		x	
8	x		x		x
9	x				
10	x	x	x		
11	x				
13	x	x	x		x
14	x	x	x		
15	x			x	
16	x	x	x	x	
17					
18					
19			x	x	x
20		x	x	x	x
21		x			

finding segregation is 77 percent. However, if the nuclear density measurements are used to verify the visually identified degrees of segregation, as discussed Section 7.0 of Chapter 6, then the probability values for the accuracy of observing heavy, medium and light segregations are 85, 58 and 50 percent, respectively. If the data from site number 16 is eliminated (potential outliers) then the probability values for the accuracy of observing heavy segregation remains the same at 85 percent while the probability values for the accuracy of observing medium and light segregations increase to 88 and 57 percent, respectively.

4.0 DISTRESS SURVEY

Segregation in the pavement surface may cause early distress and may accelerate the rate of deterioration. In general the four types of segregation-related distress that can be identified are: raveling, cracking, stripping and rutting. The four distress types are briefly discussed below:

Raveling - Raveling is the wearing away of the pavement surface caused by dislodging of aggregate particles due to loss of asphalt binder. Raveling is usually caused by the following three mechanisms:

1. Horizontal shear stresses on the surface from traffic.
2. Water entering the pavement through interconnecting voids and traffic creating high intensity hydrostatic pressure that:
    - Occurs early and decreases with time.
    - Occurs in mixes placed late in the season and cool temperatures.
3. Long term emissions from motor vehicles that act as solvents to the asphalt binder.
4. Segregation in the asphalt mix which is manifested by deficient amount of fine materials, and low in asphalt contents. Hence, the air voids in segregated areas are relatively higher than in adjacent areas. The high air voids in the coarse mix would allow moisture to infiltrate the asphalt mat and to be retained for a longer time period. The hydrostatic pressure from water would weaken the bond between the asphalt binder and the aggregate thereby causing raveling.

Cracking - The lack of fine material in segregated areas combined with high air voids and low asphalt contents cause relatively low tensile strength of the mix. Low tensile strengths imply high cracking potential. Therefore, segregation would increase the development of cracks in pavements subjected to tensile stress due to either cold temperatures or load.

Table 7.2 Probability Values for Accurate Visual Identification of Segregation

Visual degree of segregation	Number of segregated sample	Number of comparisons ( ) Includes site 16 data	Probability of correct observations* ( ) Includes site 16 data	Probability of unsupported observations*
Segregation including Light, Light-Medium, Medium. Medium-Heavy and Heavy	43	108 (143)	77 % (64 %)	23 %
Light	10	27 (34)	57 % (50 %)	43 %
Medium	9	14 (21)	88 % (58 %)	12 %
Heavy	10	32 (32)	85 % (85 %)	15 %
Light, Light-Medium and Medium	30	68 (96)	63 % (51 %)	37 %
Medium, Medium-Heavy and Heavy	22	57 (68)	86 % (72 %)	14 %

Notes *: based on the criteria of p-value $< 10^{-3}$ from nuclear density measurements and p-value $< 10^{-2}$ from gradation data of percent passing the No.4 sieve

Stripping - When water enters the pavement surface through cracks, interconnected voids or by capillary action, stripping may occurs. Two mechanisms cause stripping:

- The breaking of the adhesive bond between aggregate and the asphalt cement due to neutralization of the electric charge of the asphalt binder by moisture.
- Asphalt removal by water and moisture vapor

Stripping starts at the bottom of the asphalt pavement and propagates toward the pavement surface. In pavements, the signature of stripping is a longitudinal crack in the center of the lane. When segregation is presents in the asphalt base course, the action of water to strip the asphalt would be enhanced due to the relatively open texture of the mix and lower asphalt contents.

Rutting Potential - A rut is a surface depression in the wheel paths. It can be caused by consolidation, compaction or lateral movement of the layers beneath the pavement surface due to traffic loads. It also can be caused by compaction or plastic flow of the AC course due to traffic load and high temperatures. In segregated areas that are rich in fines and high in asphalt contents, the rutting potential increases significantly.

To study the effects of segregation on pavement conditions, five distress surveys were performed on 14 sites (1 through 14) and three distress surveys were conducted on the additional 7 sites (15 through 21). During the survey, each type of distress observed on the pavement surface was identified and its severity level and extent were recorded. In general, only two types of segregation-related distress (raveling and cracking) were found at some sites. Other non segregation-related distresses were also observed and recorded. Table 7.3 provides a summary of the types of distress observed at each site and the date of the survey. Once again, during the survey, distressed areas were mapped and measured. These maps are included in Appendix C. The distress measurements consisted of:

1. The total number of square feet of raveled areas.
2. The cumulative lengths of the longitudinal cracks within the test site.
3. The number of transverse cracks.

Tables 7.4 and 7.5 provide a summary of all distress measurements made during the five surveys. When possible, the visually identified degrees of segregation where the distress occurred are also included in the tables. Examination of the data provided in Tables 7.3 through 7.5 indicates that:

1. As of the last survey date of June 22, 1999, no distress was observed on sites 9, 10, 18 and 21. Site 18 has no segregation and the other three sites showed light to medium segregation.

2. No segregation-related distresses were observed on sites 3, 11 and 17. Site 17 has no segregation and the other two sites showed light to medium segregation.

Table 7.3 A Summary of Pavement Distress at Each Site and Dates of Distress Surveys

Site	Distress type	Segregation Related	Date of Survey
1	Continuous raveling and spot raveling	Yes	Feb. 2, May 27, and Oct. 2, 1998 April 5 and June 21, 1999
2	Raveling	Yes	Feb. 2, May 27, and Oct. 2, 1998 April 5 and June 21, 1999
3	Cracking close to curb	No	Feb. 2, May 27, and Oct. 2, 1998 April 5 and June 21, 1999
5	Raveling	Yes	Feb. 2, May 27, and Oct. 2, 1998 April 5 and June 21, 1999
6	Raveling	Yes	Feb. 2, May 27, and Oct. 2, 1998 April 5 and June 21, 1999
7	Raveling	Yes	Feb. 2, May 27, and Oct. 2, 1998 April 5 and June 21, 1999
8	Raveling	Yes	Feb. 2, May 27, and Oct. 2, 1998 April 5 and June 21, 1999
9	No distress		Feb. 25, May 28, and Oct. 2, 1998 April 5 and June 21, 1999
10	No distress		Feb. 25, May 28, and Oct. 2, 1998 April 5 and June 21, 1999
11	Temperature cracking	No	Feb. 25, May 28, and Oct. 2, 1998 April 5 and June 21, 1999
13	Cracking	Yes	Feb. 25, May 28, and Oct. 2, 1998 April 5 and June 21, 1999
14	Cracking	Yes	Feb. 25, May 28, and Oct. 2, 1998 April 5 and June 21, 1999
15	Raveling	Yes	July 31, 1998 April 20 and June 21, 1999
16	Raveling and cracking	Yes	July 31, 1998 April 20 and June 21, 1999
17	Refection cracking (control site)	No	Aug. 12, 1998 April 28 and June 21, 1999
18	No distress (control site)		Aug. 12, 1998 April 28 and June 21, 1999
19	No distress (newly constructed)		Oct. 16, 1998 April 5, 1999
20	Raveling and cracking	Yes	Oct. 21, 1998 April 20 and June 22, 1999
21	No distress		Oct 28, 1998 April 20 and June 22, 1999

Table 7.4 Raveling Areas with Corresponding Degree of Segregation

	Site 1	Site 2	Site 5
Date of Survey	Raveling area (ft^2) due to 168 ft^2 heavy segregated area	Raveling area (ft^2) due to segregation	Raveling area (ft^2) due to 119 ft^2 medium segregated area
Feb. 1998	7.9	0.035	5
May 1998	9.8	0.07	5
Oct. 1998	11.4	0.07	5
April 1999	14.4	3.07	13
June 1999	24	3.07	18.5

	Site 6			
Date of Survey	Raveling area (ft^2) due to 16 ft^2 heavy segregated area	Raveling area (ft^2) due to 40 ft^2 M-H segregated area	Raveling area (ft^2) due to 2 ft^2 medium segregated area	Raveling area (ft^2) not seg related
Feb. 1998	0	8.9	0	0
May 1998	0.8	9.6	0	0
Oct. 1998	0.8	9.6	0	0
April 1999	9.2	22	1.5	0
June 1999	12	46	1.5	12

	Site 7		Site 8
Date of Survey	Raveling area (ft^2) due to 32 ft^2 M-H segregated area	Raveling area (ft^2) due to 40 ft^2 L-M segregated area	Raveling area (ft^2) due to 102 ft^2 segregated areas
Feb. 1998	3.2	0.8	4
May 1998	3.2	0.8	7
Oct. 1998	3.2	0.8	14
April 1999	3.2	1.6	19.5
June 1999	10	8	30.5

	Site 15	Site 16
Date of Survey	Raveling area (ft^2) due to 16 ft^2 heavy segregated area	Raveling area (ft^2) due to 36 ft^2 medium segregated area
July 1998	10	0
April 1999	10	0
June 1999	10	32

	Site 20 Sec 6
Date of Survey	Raveling area (ft^2) due to M-H segregated area
Oct. 1998	0
April 1999	0
June 1999	4

Table 7.5 Summary of Cracking Data

	Site 13		
Date of Survey	Length of longitudinal crack (ft)	Number of transverse tears	Number of transverse cracks
Feb. 1998	20.5	2	0
May 1998	22	2	0
Oct. 1998	22	2	0
April 1999	35.5	2	1
June 1999	45	4	1

	Site 14		
Date of Survey	Length of longitudinal crack (ft)	Number of transverse tears	Number of transverse cracks
Feb. 1998	0	2	0
May 1998	0	2	0
Oct. 1998	0	2	0
April 1999	19	3	0
June 1999	19	3	0

	Site 16		
Date of Survey	Length of longitudinal crack (ft)	Number of transverse tears	Number of transverse cracks
July 1998	103.3	1	0
April 1999	109.8	5	0
June 1999	134.8	10	1

	Site 20 Sec 4		
Date of Survey	Length of longitudinal crack (ft)	Number of transverse tears	Number of transverse cracks
Oct. 1998	0	0	0
April 1999	10	0	0
June 1999	10	0	0

	Site 20 Sec 6		
Date of Survey	Length of longitudinal crack (ft)	Number of transverse tears	Number of transverse cracks
Oct. 1998	0	0	0
April 1999	21	0	0
June 1999	21	0	0

- At site 3, longitudinal cracks were found along the concrete curb. This distress is related to the differential expansion and contraction of the asphalt and concrete.
- At site 11, transverse temperature cracks were observed.
- At site 17, which is a control site, reflective cracks were observed during the second distress survey that is caused by movements in the underlying concrete layer.

3. Raveling was found along 9 sites where segregation was observed (sites 1, 2, 5, 6, 7, 8, 15, 16, and 20). Cracks were also found on sites 16 and 20. Typical examples of cracked and raveled pavements are shown in Figures 7.1 and 7.2. In general, most raveled areas coincided with the segregated areas. More severe raveling was observed along heavily segregated areas and the degree of raveling decreases as the degree of segregation decreases from heavy to medium to light.

4. Longitudinal cracks were observed in segregated areas at sites 13, 14, 16 and 20.

5. Segregation of the leveling course was observed during construction on site 19. The segregated areas were identified and mapped. Unfortunately, before the distress survey was conducted, the surface course was placed and compacted. Hence, all segregated areas were covered. Nevertheless, no distress in the surface course was observed as of June 22, 1999. This should not imply that segregation in the leveling course has no impact on pavement deterioration. Long-term pavement monitoring should be conducted to assess the impact of such segregation.

Table 7.4 provides a tabulation of the nine sites where raveling was observed within segregated areas. The raveled areas that were measured during the various distress surveys. For each degree of segregation, the segregated area is also included in the table. As can be seen, in general, raveling occurred in the areas of heavy or medium segregation and no raveling was observed in areas of light segregation.

On five sites, segregation-related cracks were observed and measured. The data are summarized in Table 7.5. The degree of segregation associated with the cracked areas is not included in the table. The reason is that after a crack is initiated, it tends to grow along the lowest resistance path. Because of this, the length of the crack cannot be broken down to segments along degrees of segregation. Nevertheless, at sites 13, 16 and 20, the degree of segregation ranges from light to heavy. At site 14, the longitudinal cracks occurred along and across areas with light and medium degrees of segregation.

5.0 PAVEMENT RATE OF DETERIORATION DUE TO SEGREGATION

For all types of distress, the length of the pavement section is 36 feet. Hence, the extent of the distress (raveled area, the cumulative length of longitudinal cracks and the number of transverse cracks) reported in the various graphs and tables are based on one lane width (12-feet) and 36-feet long section. Nevertheless, for each distress type (raveling and cracking),

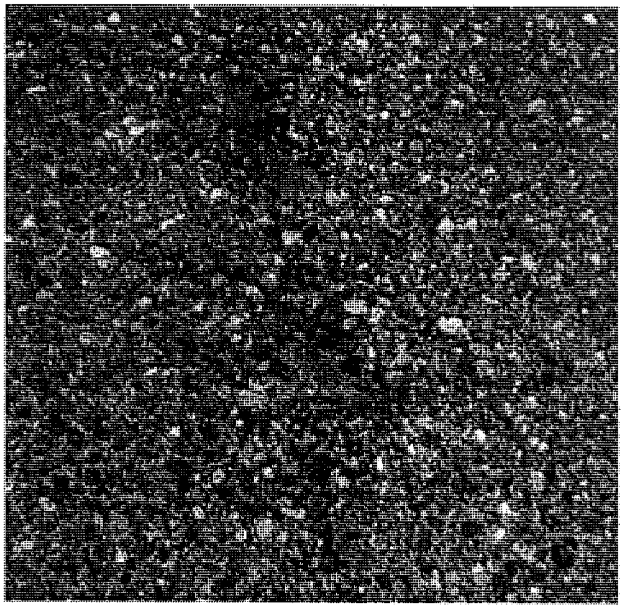


Figure 7.1 A Typical Segregation-Related Raveling at Site 1

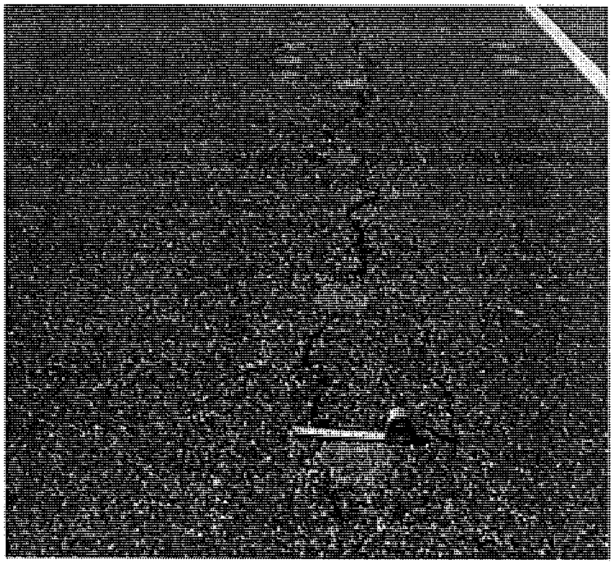


Figure 7.2 A Typical Segregation-Related Cracking at Site 13

the measured distress data were analyzed and the rates of pavement deterioration (rate of increase in raveled areas and rate of crack propagation/growth) were calculated. The results are presented below.

5.1 Raveling

In this study, for each site, raveled areas at each severity level were measured in square feet. The severity levels used are light (few aggregates are dislodged from the pavement surface), medium (a limited matrix of aggregates were dislodged and are missing) and heavy (portions of the pavement surface were raveled and are missing). Raveling could also be continuous or could occur in spots. The term "Spot raveling" indicates that the pavement surface has raveled at limited spots (two to three square inches at a time). Spot raveling makes the measurement of the raveled areas a difficult task. Therefore, for light spot raveling, the identified raveling area was measured and reduced by a factor of 0.2. That is, it was estimated that on the average, the collective areas of spot raveling is about 20 percent of the total affected area. For medium spot raveling, a factor of 0.3 was used. When the raveled area is continuous (more than three square inches), no reduction factor was used.

To study the effects of segregation on the rate of growth of raveled area, the distress data was expressed in percent raveled (PR) as defined by the following equation:

$$\textit{Percent Raveled}\ (PR) = \frac{\textit{Raveled area}}{\textit{The area of a specific degree of segregation}}$$

It should be noted that:

1. The term "the area of a specific degree of segregation" in the above equation is an area on the pavement surface that was measured after it was visually identified as segregated area with the specific degree of segregation, i.e., light, medium or heavy.

2. In some cases, the percent raveled could be more than 100% because the raveling areas have extended beyond the visually identified boundaries of the segregated areas.

The rate of growth of raveled areas was then calculated by simply dividing the difference in the calculated percent raveled areas made in two consecutive distress surveys by the time period (the time lapse) between the two surveys. Table 7.6 provides a list of the calculated growth rates of raveling at six sites along with the degree of segregation and the survey time. Figures 7.3 through 7.8 show the growth of raveling along the segregation areas. It should be noted that the rate of raveling is typically accelerated by traffic loading and by environmental factors such as moisture and freeze-thaw cycles. Examination of the data provided in Table 7.6 indicates that:

1. For most sites, the rate of growth of raveled area (in terms of percent raveled per month) increases with time.

Table 7.6 A Summary of the Rate of Growth of Raveling at the Indicated Time Interval Period (percent raveled per month)

Site Number and Degree of Segregation	Time Interval			
	February-May 1998	May-October 1998	October 1998 - April 1999	April-June 1999
Site 1 Heavy	0.38	0.19	0.30	2.86
Site 5 Medium	0	0	1.04	2.15
Site 6 Heavy	1.67	0	8.75	8.75
Heavy-Medium	0.58	0	1.00	42.50
Medium	0	0	12.50	0
Site 7 Heavy-Medium	0	0	0	10.63
Medium-Light	0	0	0	8.0
Site 8 Segregation	0.98	1.37	0.90	5.39
Site 15 Segregation			0	0

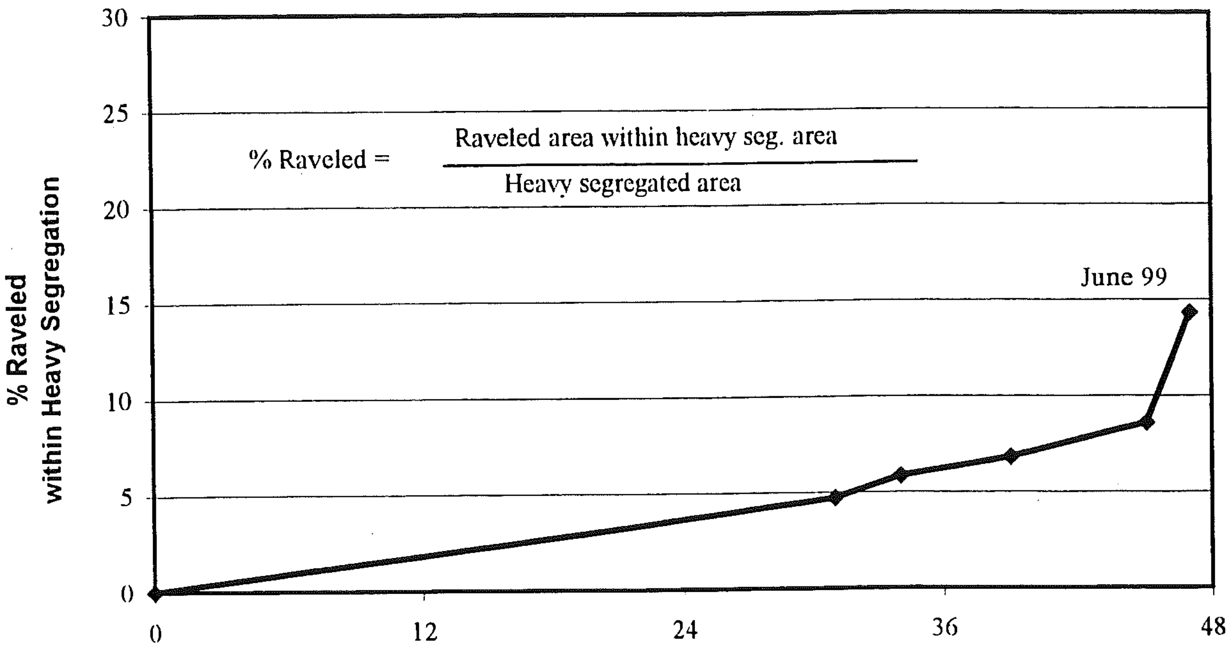


Figure 7.3 Raveling as Percent of Segregation Area vs. Time at Site 1

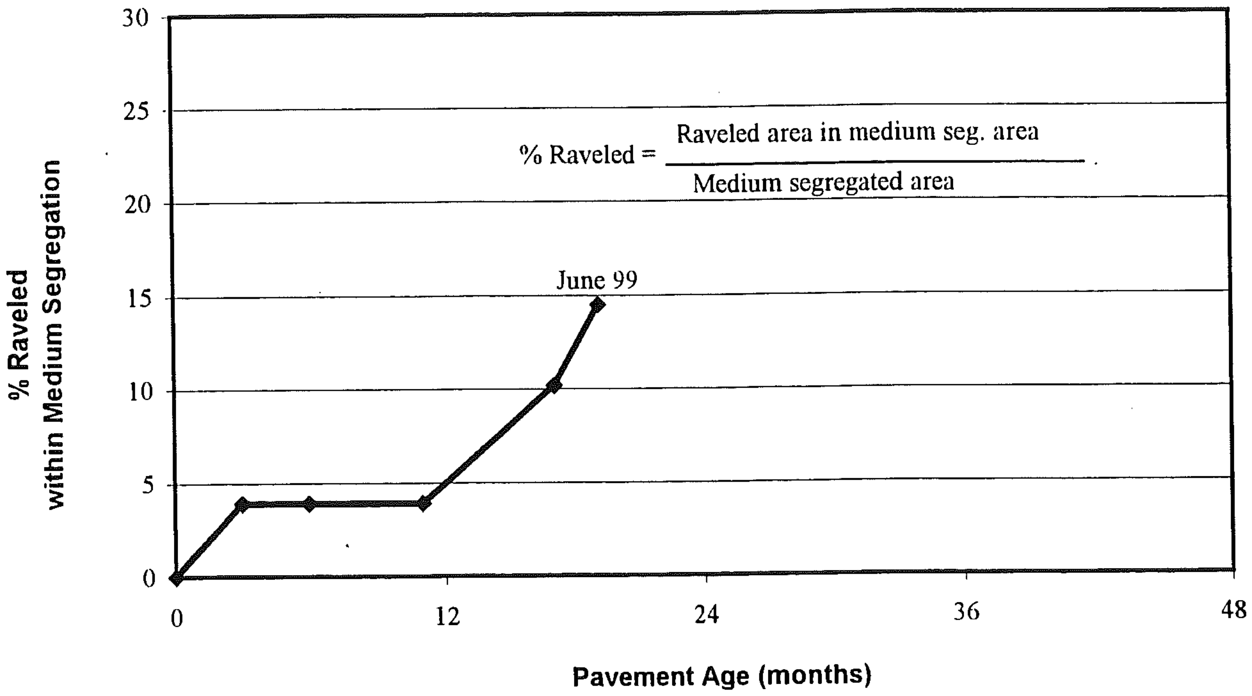


Figure 7.4 Raveling as Percent of Segregation Area vs. Time at Site 5

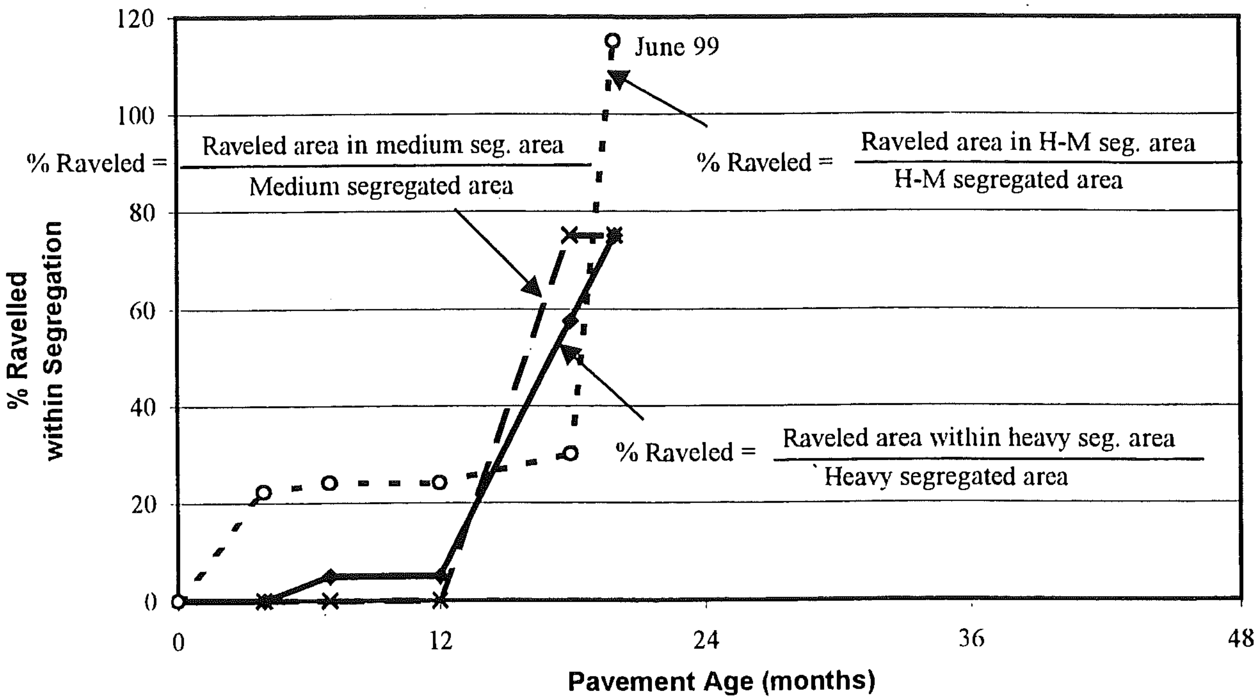


Figure 7.5 Raveling as Percent of Segregation Area vs. Time at Site 6

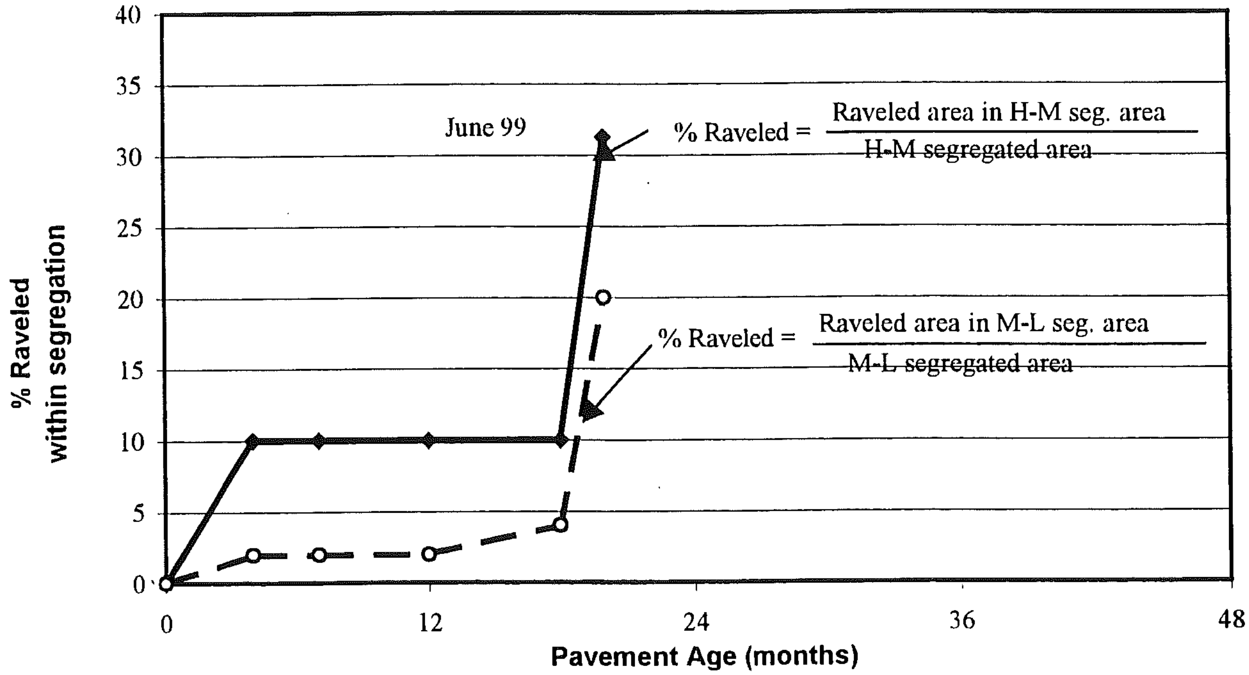


Figure 7.6 Raveling as Percent of Segregation Area vs. Time at Site 7

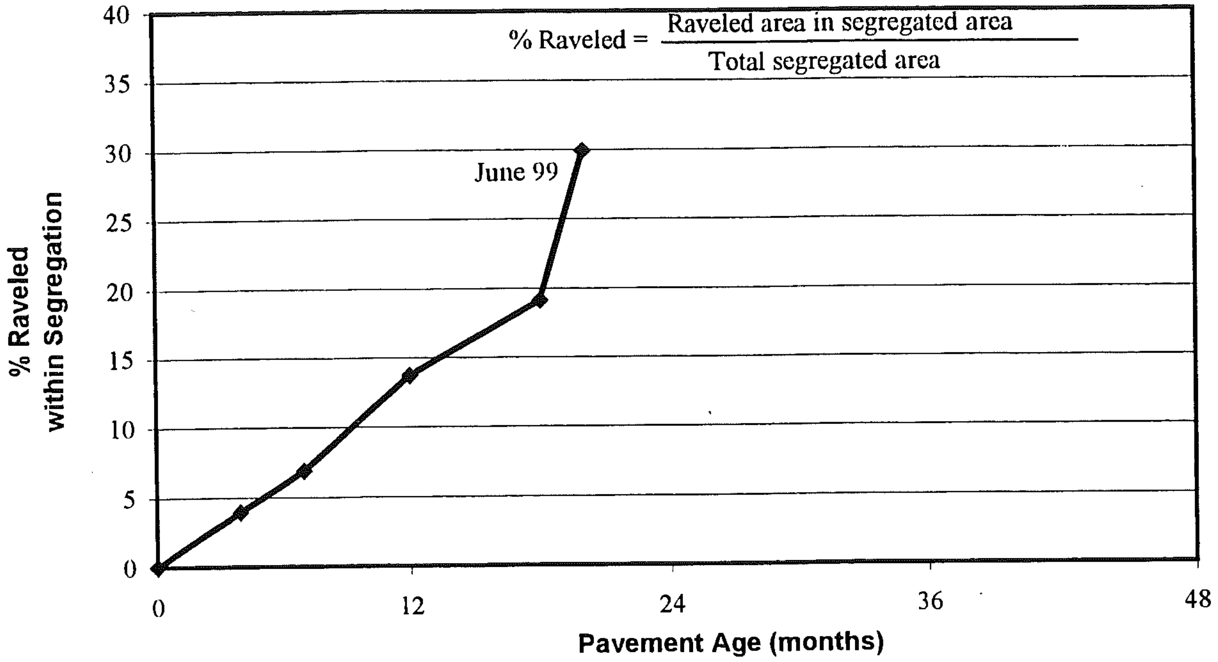


Figure 7.7 Raveling as Percent of Segregation Area vs. Time at Site 8

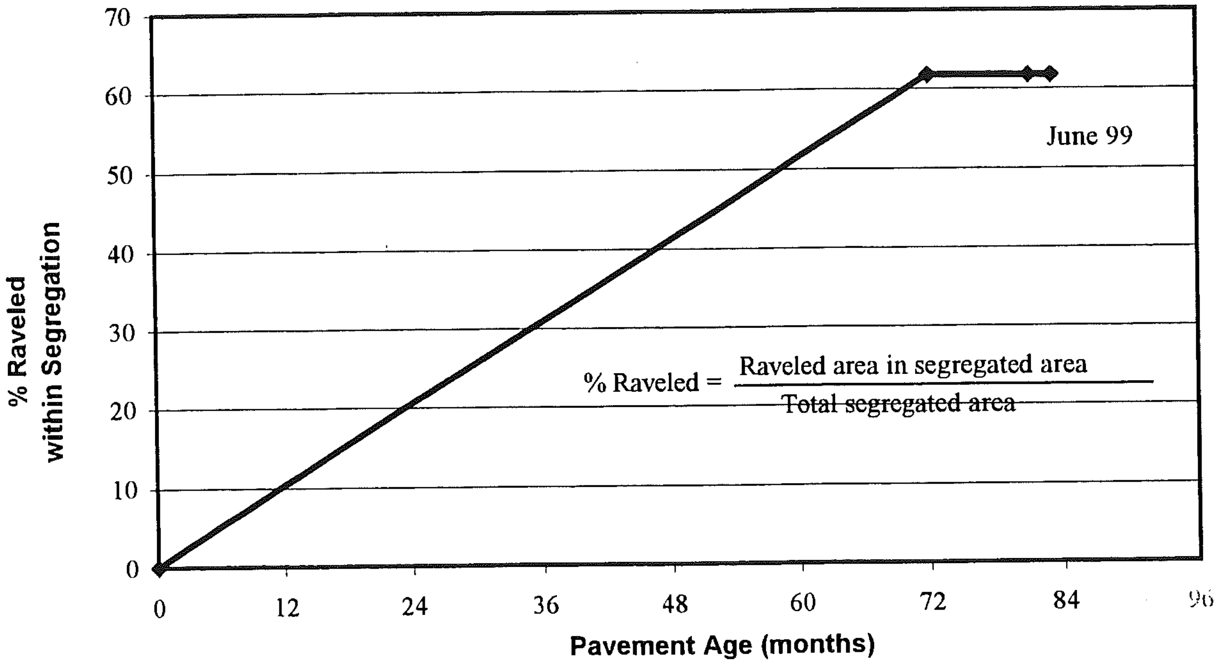


Figure 7.8 Raveling as Percent of Segregation Area vs. Time at Site 15

2. The rate of growth of raveled areas increases as the visually identified degree of segregation increases from light-medium, to medium, to medium-heavy, to heavy.

3. On the average, the rate of raveling decreases during the summer and fall months and increases during the spring thaw period.

4. At site 1, the raveling grew steadily along the heavy segregated areas until April 1999 survey. After that, the rate of raveling increased substantially (see Figure 7.3) and its severity changed from moderate to high.

5. At site 5 (Figure 7.4), low severity raveling occurred along the medium segregation areas. Although the raveled area grew steadily, its severity remained medium. As of June 1999, the raveling reached 15 percent of the medium segregated areas.

6. At site 6, raveling occurred along and across the three degrees of segregation (medium, medium to heavy and heavy). The percent raveled along and across each degree of segregation is plotted in Figure 7.5 as a function of time. It can been seen that the percent raveled along either the medium or the heavy segregated areas reaches 75%, the percent raveled along the heavy-to-medium segregated area is more than 100%.

7. At site 7, the rates of raveling along the medium and medium to light segregation areas are shown in Figure 7.6. As can be seen, the raveling along the heavy to medium area increased rapidly after April 99 and reached 32 percent of the total segregated area compared to only 20% for the medium to light area. This implies that higher degrees of segregation cause higher amount of pavement damage although the last observed raveling rates were the same.

8. At site 8, the percent raveling steadily increased and reached 30% of the total segregated areas within less than two years after construction as shown in Figure 7.7.

9. At site 15 (located on the shoulder of US-23, no traffic), the raveled area that was measured in the June 98 survey did not change as of April 1999 (the last survey) as shown in Figure 7.8. Given that the winter of 1998-1999 was a mild one (fewer freeze-thaw cycles than normal) and that the rate of raveling in previous years was about 15 percent per year, the observation supports the statement made earlier that raveling is accelerated by environmental factors.

5.2 Cracking

Longitudinal and transverse cracks were the second most frequently observed distress on segregated asphalt pavements. During the survey, the cumulative length of the longitudinal cracks (the length of two or more longitudinal cracks were added) and the number of transverse cracks were measured and recorded as shown in Table 7.5. From these data, the rates of increase in the length of the longitudinal cracks (foot per month) and in the number of transverse cracks (crack per month) were calculated and are listed in Tables 7.7 and 7.8,

Table 7.7 A Summary of the Rate of Longitudinal Crack Propagation (length of longitudinal cracks in feet per month)

Site	Time Interval			
	February-May 1998	May-October 1998	October 1998 - April 1999	April-June 1999
Site 13	0.50	0	2.25	4.75
Site 14	0	0	3.17	0
Site 16			0.72 (July 98~April 99)	12.50
Site 20 (Section 6)			3.5	0

Table 7.8 A Summary of the Rate of Increases in the Number of Transverse Tears and Cracks (number of tears and cracks per month)

Site	Time Interval			
	February-May 1998	May-October 1998	October 1998 - April 1999	April-June 1999
Site 13	0	0	0.2	1.0
Site 14	0	0	0.2	0
Site 16			0.4 (July 98~April 99)	3.0

respectively. It was observed that most longitudinal and transverse cracks were initiated in the vicinity of heavily segregated areas and propagated into other areas with various degrees of segregation. Hence, the effects of different degrees of segregation on the rate of cracking could not be determined. Figures 7.9 through 7.12 show the progression of longitudinal and transverse cracks versus time at four sites. Examination of the data provided in Tables 7.5, 7.7 and 7.8 and Figures 7.9 through 7.12 indicates that:

1. At site 13, the length of the longitudinal and the number of transverse cracks steadily increased from May 1997 (end of overlay construction) to the last survey of June 1999 where the total length of longitudinal cracks was measured at 45 ft. Most of the cracks were initiated within heavy segregation area. Approximately 18 percent of the total length crosses heavy segregation areas and the remaining 82 percent crosses light and/or medium segregation areas. As can be seen from Figure 7.9, the growth of longitudinal cracks was halted during the summer season of 1998. However, about one year after construction of the overlay, the cracks started propagating again. It should be noted that, because of the pavement crown, at the center of the lane (near the longitudinal cracks), the thickness of the overlay is less than one inch. This factor may have contributed to the crack propagation. The trend of growth in the number of transverse cracks is similar to that of the longitudinal cracks. The number of transverse cracks was unchanged during the summer season of 1998 after which it increased.

2. At site 14, about 14 months after rehabilitation, nineteen feet of longitudinal cracks were developed within light and medium segregation areas. The growth of the longitudinal cracks was halted during the summer season of 1999 as shown in Figure 7.10. About 6-month after construction, two transverse cracks close to lightly segregated areas were observed. A third one was developed during the spring season of 1999. The first two cracks are likely cold-temperature related. The third one however, could be segregation related crack. At this point in time, the data is not conclusive.

3. Along the 36-feet long section at site 16 where the pavement was overlaid in July 1992, approximately 135 ft of longitudinal cracks were developed as of June 99. Most cracks occurred within the light or medium segregated areas. It is noted that a large amount of longitudinal cracks is also contributed by the traffic load repetitions within seven years. The rate of propagation of the longitudinal cracks (the cracks length increased from about 110 to 135 feet) appears to accelerate during the spring season of 1999 as shown in Figure 7.11. The rate of growth of the number of transverse cracks followed similar trend as that of the longitudinal cracks. All transverse cracks appear to be segregation-related because transverse cracks occurred at the segregated areas where the asphalt was subjected to higher degrees of oxidation and hardening because of high void contents. Hence, harder asphalt binders exhibit brittle behavior and crack at low strain levels.

4. At site 20 section 6, one and half years after rehabilitation, 21 feet long longitudinal crack was developed within medium and heavy segregated areas during the winter of

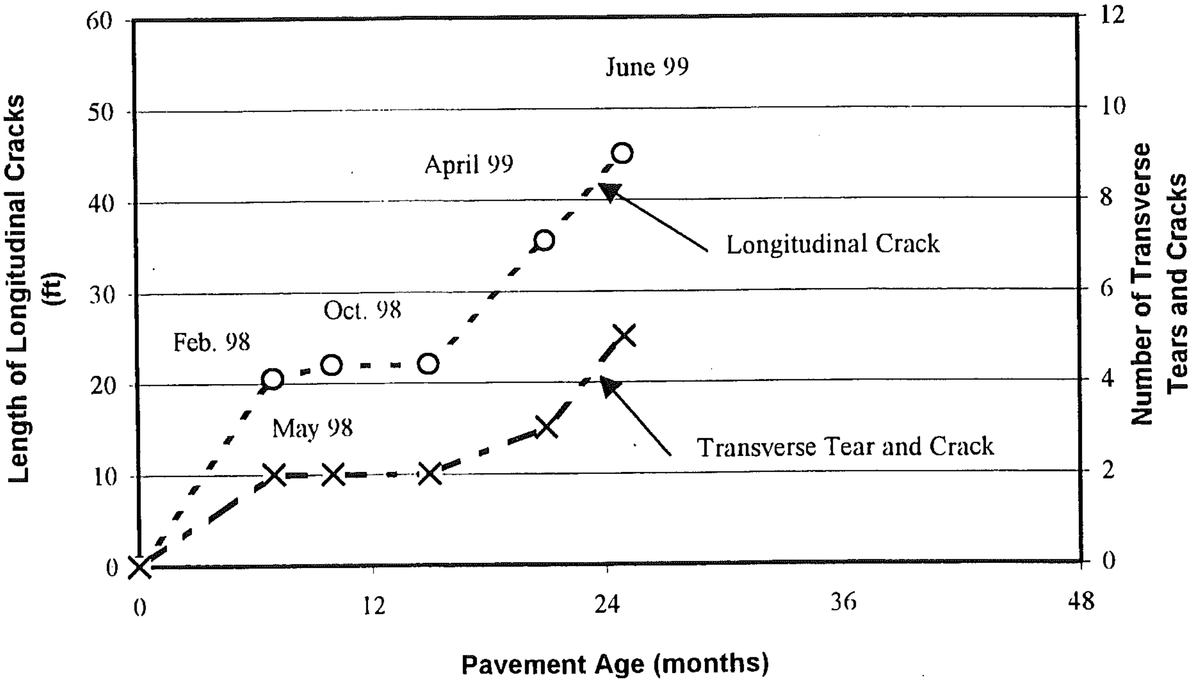


Figure 7.9 Crack vs. Time at Site 13

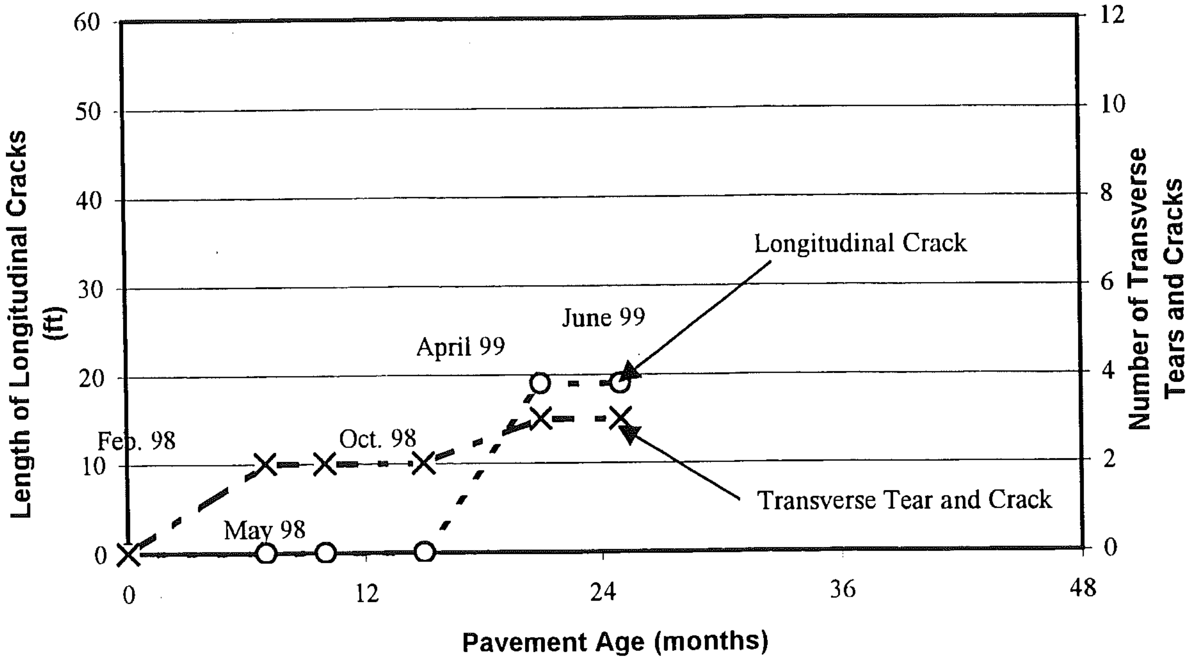


Figure 7.10 Crack vs. Time at Site 14

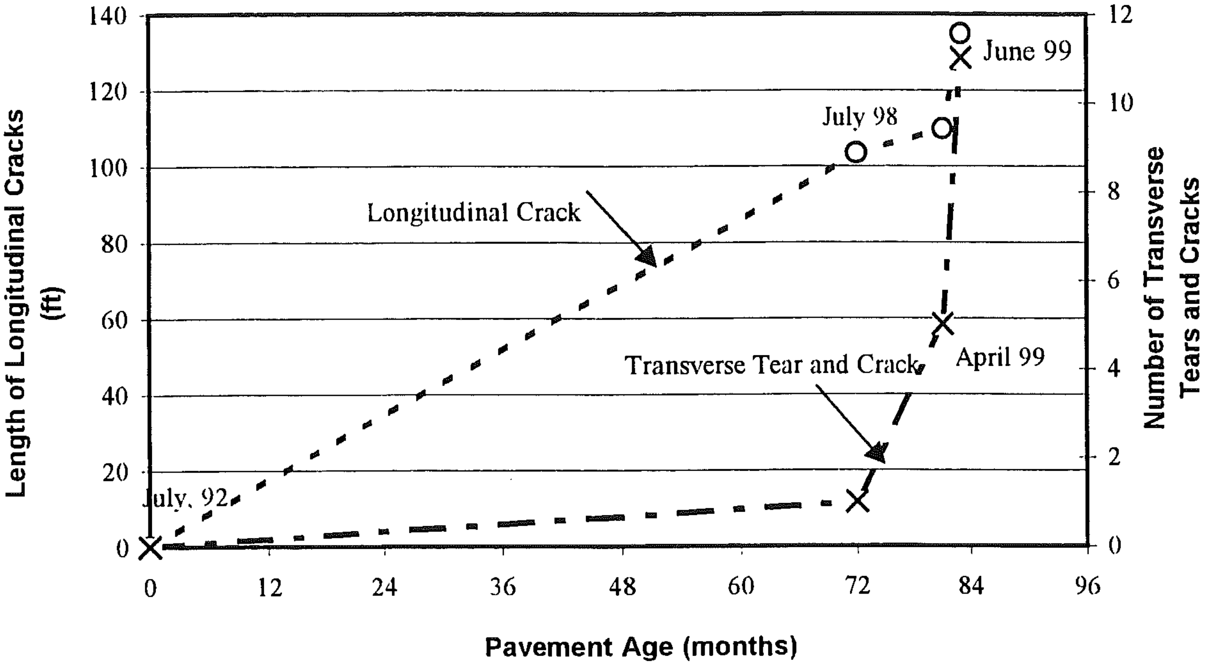


Figure 7.11 Crack vs. Time at Site 16

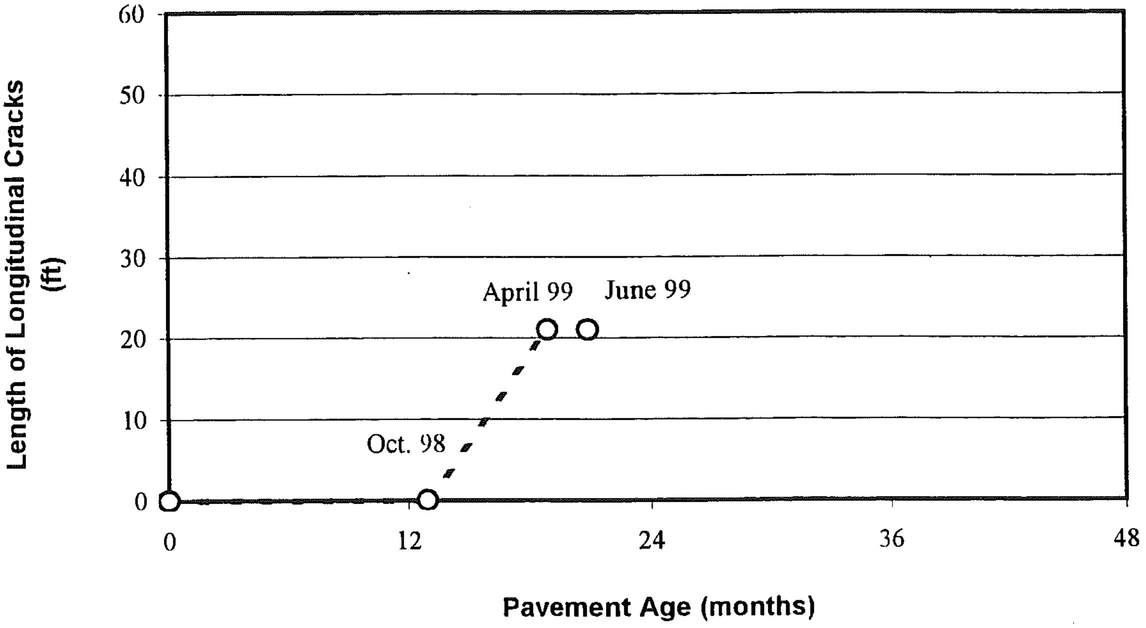


Figure 7.12 Crack vs. Time at Site 20 Section 6

1999 as shown in Figure 7.12. The crack growth appears to be halted between April and June 1999. Given that the crack is not in the wheel path and that the crack is confined only within segregated area, one can conclude that the crack is segregation-related.

6.0 PAVEMENT PERFORMANCE MODEL

For a given pavement section and for each type of distress, the MDOT pavement management system assigns certain distress points based on the severity and extent of the distress and on the degrees of associated distress. A distress index is then plotted against time as shown in Figure 7.13. The curve in the figure is called "a pavement performance model". It should be noted that a pavement performance model could be based on ride quality, distress index or any type of distress. Nevertheless, the MDOT distress index threshold is set at 50-distress point. The area ABC shown in the figure expresses the pavement's performance. Hence, the term "pavement performance" can be defined as the area above the distress index curve and below the distress index threshold line. Therefore, pavement performance expresses how well the pavement serves traffic over time.

Further, several points should be noted in the MDOT pavement management practice, these points includes (Baladi et al., 1998):

1. The distress index is normalized to 0.1-mile (528 feet) pavement section. In this study, the pavement distresses (raveling and cracking) were observed along 36 ft of pavement.
2. Although raveling is a distress included in the MDOT pavement management system, no distress points have been developed yet.
3. Segregation is not considered as pavement distress, it is however considered as a cause of distress.

Given the above three observations, and the limited time (only 2-years) during which the distress data due to segregation were collected, it is not possible at this time to use the MDOT distress point system to determine the exact reduction (insufficient data points) in the pavement performance due to segregation. The reasons are that only four sites showed cracking where distress points could be assigned and the others showed raveling where no distress points have been assigned in the current MDOT distress point system. Certainly, segregation has significant impact on pavement performance and life. For some pavements, such as the US 23 site, this reduction is well over 50 percent of the design life. One may argue that the reduction in pavement performance and life should have been determined for the rate of deterioration that was discussed in the previous section. Although this point is well taken, the data does not support the exercise with a respectable confidence level. At this point, the data support the conclusions that heavy segregation leads to higher damage than medium and light segregation and that segregation adversely affects pavement performance

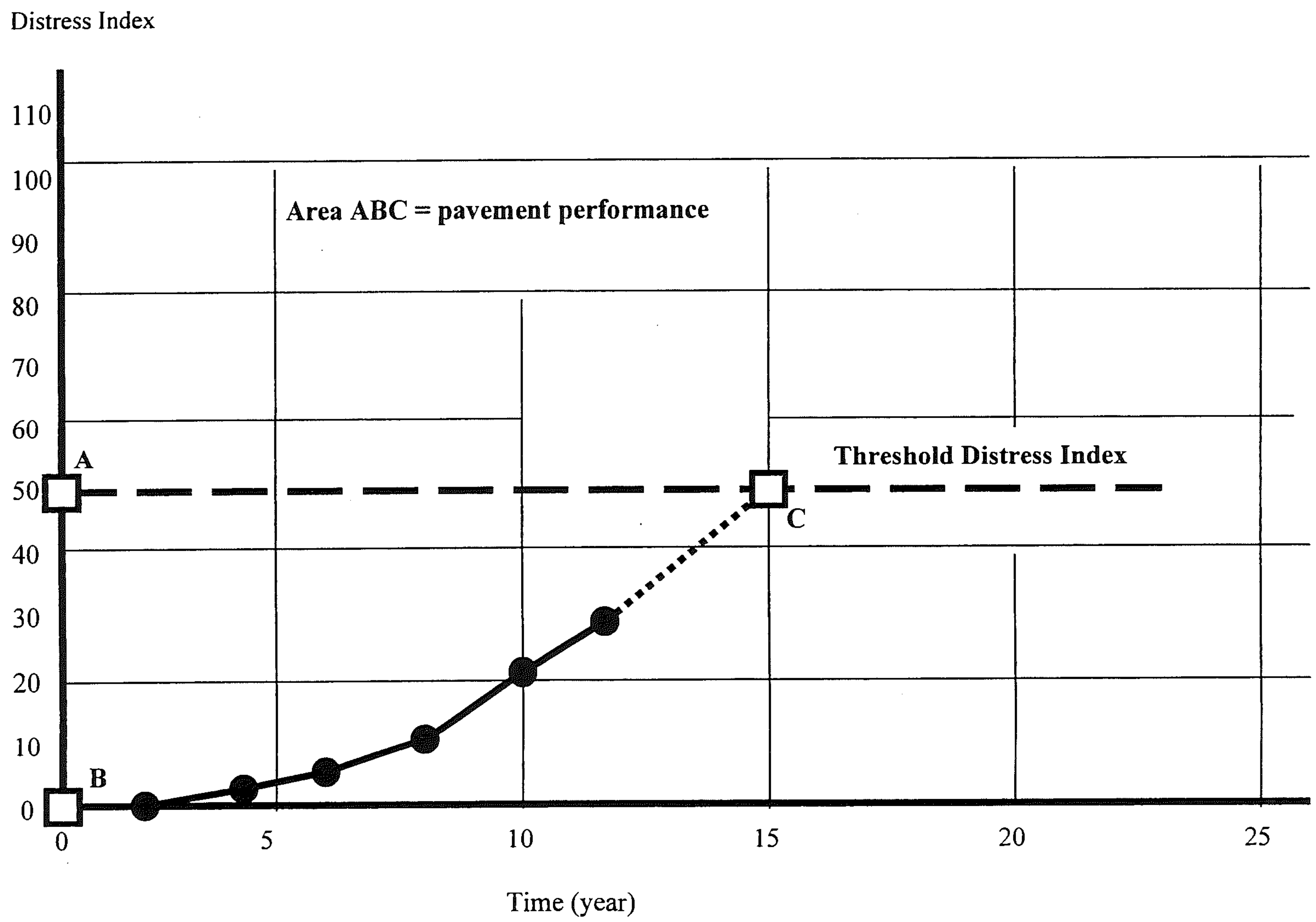


Figure 7.13 Schematic Diagram Showing a Plot of the Distress Index versus Time, the Distress Index Threshold and the Pavement Performance

the problem and to bring the study to solid conclusions, the following steps need to be taken by MDOT:

1. Develop distress points for raveling and flushing (two segregation–related distresses).
2. Monitor the pavement condition once every six months for an additional two-year period. This should allow more accurate determination of the rate of deterioration for heavy, medium and light segregation. This would lead to a relatively accurate determination of the magnitude of reduction in the pavement's performance and life.

If one is to use the pavement distress data and only the distress data that were collected during this study, one can draw three conclusions. These conclusions are not based on the existing MDOT distress point systems or on the MDOT distress index. To reach the conclusions, micro (not macro) analysis must be conducted. For such microanalysis the term "reduction in pavement life" is defined as the reduction in the life of the pavement area showing a specific degree of segregation. Hence, if the area of heavy segregation is 25-ft^2, then the analysis must only address the reduction in life of the 25-ft^2 area. Given such analysis of the distress data, the following three conclusions were reached:

1. Heavy degree of segregation causes a minimum of 50 percent reduction in the life of the heavy segregated area.
2. Medium degree of segregation causes a minimum of 30 percent reduction in the life of the medium segregated area.
3. Light degree of segregation causes no significant reduction in the life of the lightly segregated area.

7.0 SUMMARY

During the course of the study (2-years), the effects of the visually observed heavy, medium and light segregations were studied. These effects can be summarized as follows:

1. Raveling and cracking are the most commonly observed segregation-related distresses.
2. The limited pavement distress data were analyzed as a function of time. It was found that:
    - Three of nine sites have experienced more than 60 percent raveling.
    - Four of nine sites have experienced between 15 to 30 percent raveling.
    - Light raveling was observed on the last two sites.
3. Raveling occurred at the locations where the segregation was rated as heavy or medium. The rate of raveling depends on the degree of segregation.

4. Longitudinal cracks were observed at four sites (sites 13, 14, 16 and 20). They occurred within segregated areas and, in certain cases, propagated to adjacent non-segregated areas.

CHAPTER 8
IMPLEMENTATION

1.0 INTRODUCTION

The practical intent of this research project was to develop an expedient field tool to indicate where segregation was likely present, using statistical comparisons of one-minute nuclear density tests. It was hoped that differences in gradation parameters between segregated and non-segregated areas would be closely correlated to nuclear density differences and visual observations. If this were the case, nuclear tests and a statistical analysis computer spreadsheet would be able to confirm the presence of segregation and predict the degree of segregation that would be mapped by the expert team.

As the study progressed, it was discovered that nuclear density differences alone could not provide a conclusive basis for determining the presence of segregation, and that other factors needed to be taken into account:

- It was found that statistically significant nuclear density differences may occur in non-segregated pavements due to wheel track compaction and variation in compaction at time of construction (i.e., location adjacent to a concrete curb) and the magnitude of the differences due to these factors may be as large as those due to segregation.

- For segregated areas mapped as light-to-medium, significant gradation differences or density differences were not observed as frequently as for those mapped as medium to heavy.

- Significant nuclear density variations were noted at test site 22, where bituminous mix was placed without any compaction effort, even though gradation differences were not observed. This indicates that nuclear density variations may occur due to paver characteristics and/or rough surface features alone.

Hence, the original expectation of developing a test method where segregation could be reliably predicted solely on the basis of nuclear density measurements and analysis was not conclusive.

However, it was found that the combination of visually-mapped segregation of medium or greater degree and nuclear density comparisons with p-values smaller than 10^{-3} lead to a reasonably high probability that segregation would be confirmed if gradation tests were performed. Conclusions from Section 7.0 of Chapter 6 are re-stated below.

> *If medium to heavy segregated areas are identified and nuclear density differences are found, the chance of finding a gradation difference ranges from 64 to 86% depending on the data set selected. If apparently heavy segregated areas are observed and density differences are found, the chance of confirming the segregation by gradation tests increases to 85%.*

2.0 CONSTRUCTION SPECIFICATIONS

Where nuclear density differences and coarse textured appearance are present, there may be cause for concern even where gradation differences may not be significant. The alternative explanation for the observed texture and differences is variation in compaction effort, which may occur due to temperature differences during compaction. MDOT might consider a "uniformity of density specification" that would address both segregation and compaction problems. A first-draft wording is provided below:

> *An area of heavy segregation is defined as one showing stone against stone, with little or no matrix visible. An area of medium segregation is defined as one showing significantly more stone than the surrounding pavement, with a lack of matrix.(Heavy segregation may reduce pavement life on the order of fifty percent).*
>
> *Pavement materials shall be transported, placed, and compacted in such a manner to prevent segregation and to provide uniform gradation and density throughout. Statistically large variations in nuclear density, even with values above the specified minimum, may indicate (medium or heavy) (heavy) segregation or incomplete compaction due to rolling temperature differences.*
>
> *Where the appearance of the pavement surface indicates the presence of (medium or heavy) (heavy) segregation (or non-uniform compaction), a set of six to (twelve)(fifteen) nuclear density measurements shall be made in the area of concern, and a similar set of readings shall be made in a comparison area. The mean density values of the two areas shall be compared using a two-tailed Student's-t test. If the resulting means are found to be significantly different at the 99.9 percent confidence level ($\alpha = 0.001$), the pavement shall be repaired or replaced as directed.*

The above wording in terms of confidence level is in the format used by most statistical texts, where a confidence level is set and the differences are determined to be significant or not. In the spreadsheet solution described in the next section, a calculated p-value less than 10^{-3} corresponds to the determination of a significant difference (rejecting the null hypothesis) for $\alpha=0.001$.

3.0 MBITSEG2.wb3 SPREADSHEETS

The Excel spreadsheet mbitseg2.xls, developed in April 1997, was used for all the p-value calculations in this report. Once these analyses were completed, the spreadsheet was converted to QuattroPro 8 format to be consistent with MDOT practice, and various conditional probability estimations were programmed consistent with the findings of Chapters 6 and 7.

The first sheet of mbitseg2.wb3 is shown in Figure 8.1. It provides a very brief overview of the field testing approach and program and illustration for the three major patterns of segregation.

The second sheet of mbitseg2.wb3 provides for both data entry and textual display of results. It is shown in Figure 8.2. The formulas used in the mbitseg2.wb3 are listed in Appendix D. Functions of mbitseg2.wb3 are described below.

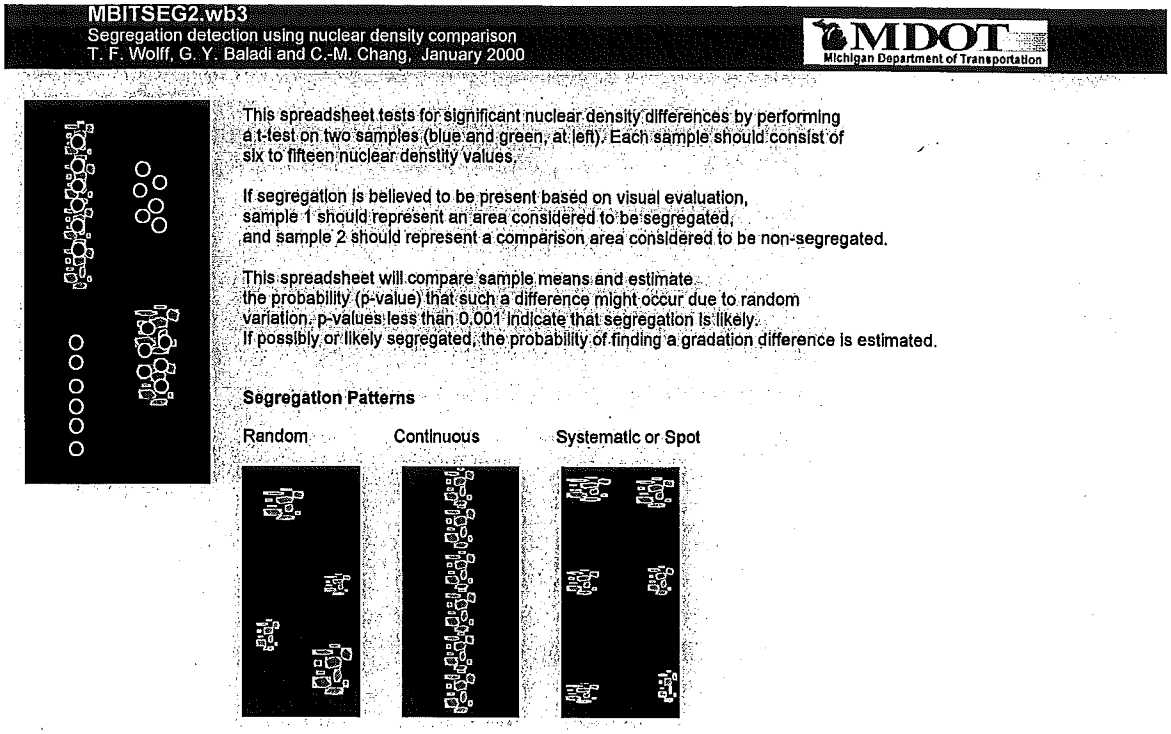
Identification Data Block. At the top right of the sheet are provided blank spaces where the user may enter descriptive information to identify the test site and other information. These are labeled as Site Description, Date and Test By. These are solely for identification and no calculations or database operations are performed on these data.

Data Entry Blocks. To the left of the sheet are two column blocks, labeled Sample 1 (in blue) and Sample 2 (in green) in which the user may enter up to fifteen data values per sample. The number of data values in each sample need not be equal. Typically, these would be nuclear-measured density values; however, other numerical data may be entered to used for a statistical t-test. 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 sample tends to narrow the confidence bands on the mean value, increasing the ability to conclude whether significant differences in mean value exist. It is recommended that a minimum of six readings be obtained to run the spreadsheet.

Control Density Block. The spreadsheet also permits the user to enter the theoretical maximum density (TMD) value for the asphalt mixture at the site. A percentage of TMD, sample mean divided by TMD, for both samples (segregated and non-segregated) is reported.

Statistical Results. Statistical comparisons are made using the t-test comparison of two means described in Section 3.1 of Chapter 5 in the main report and accomplished using spreadsheet functions. Results of statistical calculations are displayed in the lower left portion of the sheet. The sample size, mean, standard deviation, coefficient of variance and variance for both samples are computed below the data entry block. The t-value is also reported based on the pooled variance and difference in two means. The p-value, shown as 1.27×10^{-6} at the right top of the spreadsheet (below the identification block), 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 1.27×10^{-6} that such a conclusion is in error.

Detection of Segregation. Below the reported p-value, occurrence of **Segregation** is described by the following three terms with the corresponding range of p-value:



MBITSEG2.wb3
Segregation detection using nuclear density comparison
T. F. Wolff, G. Y. Baladi and C.-M. Chang, January 2000

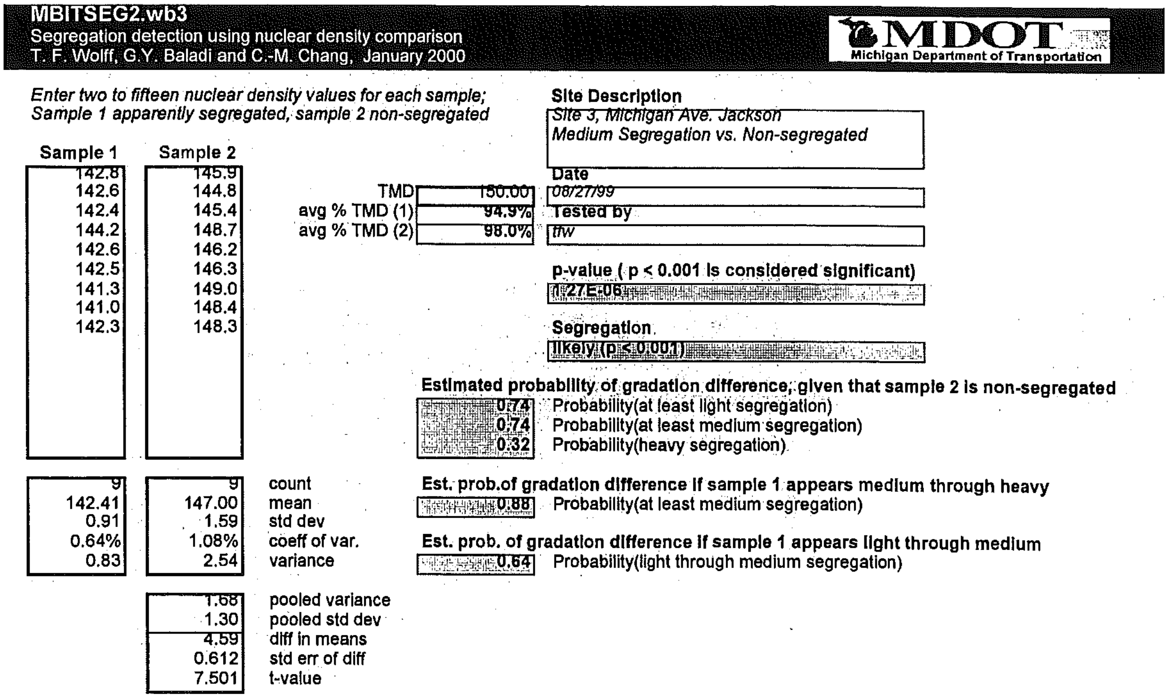
This spreadsheet tests for significant nuclear density differences by performing a t-test on two samples (blue and green, at left). Each sample should consist of six to fifteen nuclear denstity values.

If segregation is believed to be present based on visual evaluation, sample 1 should represent an area considered to be segregated, and sample 2 should represent a comparison area considered to be non-segregated.

This spreadsheet will compare sample means and estimate the probability (p-value) that such a difference might occur due to random variation. p-values less than 0.001 indicate that segregation is likely. If possibly or likely segregated, the probability of finding a gradation difference is estimated.

Segregation Patterns

Figure 8.1 First Sheet of Spreadsheet mbitseg2.wb3



MBITSEG2.wb3
Segregation detection using nuclear density comparison
T. F. Wolff, G.Y. Baladi and C.-M. Chang, January 2000

Enter two to fifteen nuclear density values for each sample;
Sample 1 apparently segregated, sample 2 non-segregated

Sample 1	Sample 2
142.8	145.9
142.6	144.8
142.4	145.4
144.2	148.7
142.6	146.2
142.5	146.3
141.3	149.0
141.0	148.4
142.3	148.3

Sample 1	Sample 2	
9	9	count
142.41	147.00	mean
0.91	1.59	std dev
0.64%	1.08%	coeff of var.
0.83	2.54	variance
	1.68	pooled variance
	1.30	pooled std dev
	4.59	diff in means
	0.612	std err of diff
	7.501	t-value

TMD	150.00
avg % TMD (1)	94.9%
avg % TMD (2)	98.0%

Site Description
Site 3, Michigan Ave. Jackson
Medium Segregation vs. Non-segregated

Date
08/27/99

Tested by
tfw

p-value (p < 0.001 is considered significant)
1.27E-06

Segregation
likely (p < 0.001)

Estimated probability of gradation difference, given that sample 2 is non-segregated

0.74	Probability(at least light segregation)
0.74	Probability(at least medium segregation)
0.32	Probability(heavy segregation)

Est. prob.of gradation difference if sample 1 appears medium through heavy
0.88 Probability(at least medium segregation)

Est. prob. of gradation difference if sample 1 appears light through medium
0.64 Probability(light through medium segregation)

Figure 8.2 Second Sheet of Spreadsheet mbitseg2.wb3

not determined : $10^{-2} \leq$ p-value
possible : $10^{-3} \leq$ p-value $< 10^{-2}$
likely: p-value $< 10^{-3}$

Conditional Probability Value. Below the indication of segregation likelihood, there are three blocks that provide various conditional probability values:

Estimated probability of gradation difference, given that sample 2 is non-segregated. The first block provides three conditional probability values that Sample 1 would be confirmed segregated in the lab and would be mapped as segregated to some degree by an expert observer, given that Sample 2 is a "good" or non-segregated sample. These probabilities are derived from the field data (comparisons between control and segregated samples in Section 6.0 of Chapter 6), and do not incorporate any information regarding the degree of segregation noted by the field technician.

Estimated probability of gradation difference if sample 1 appears medium through heavy. If the field technician identifies Sample 1 as medium, medium-to-heavy, or heavy, this additional information reduces the sample space and generally increases the probability to the values in the next block. These values are based on the analyses conducted in Section 8.0 of Chapter 6.

Estimated probability of gradation difference if sample 1 appears light through medium. If the field technician identifies Sample 1 as light, light-to-medium, or medium, this information likewise leads to revised probability values, which will be lower than those for medium to heavy segregation due to the greater chance for identification error.

Where the p-value is greater than 10^{-2}, and segregation cannot be determined, these lower blocks report "inconclusive."

4.0 APPLICATION IN PRACTICE

Application of the field test for segregation in practice would proceed as follows:

Step 1. Lay out test area. The boundary of an apparent-segregated area should be outlined on the pavement in chalk or paint and test locations should be uniformly distributed over the area. Apparent-segregated areas will usually be those which appear relatively coarse and deficient in fines. The test area should be sufficiently large to permit six to twelve nuclear density tests. 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 non-segregated (or "control") area of similar size should be outlined and a similar number of test locations marked. The non-segregated area should be visually different from the presumed segregated area, and is presumed to be a "normal" area. In fact, the non-segregated area may be an area that is rich in fine materials that have been removed from the coarser area. Note, the non-segregated areas should be selected from the same truck load and at the same distance from the pavement edge as segregated areas (along the same longitudinal line as the segregated areas).

Step 3. Obtain nuclear density measurements at the marked locations. Six to twelve nuclear density values for each sample are recommended, with test locations at least one foot apart. The program provides for as many as fifteen.

Step 4. Enter data in mbitseg2.wb3 Details are provided in the previous section.

Step 5. Interpret Data. mbitseg2.wb3 performs a Student's t-test to assess whether the difference in the mean nuclear density values is statistically significant. Where p-values are greater than 10^{-2}, the degree of statistical significance is not strong enough to reliably predict segregation and the program returns "not determined." In this case, adding additional values to the samples may narrow the confidence bands and lead to a more conclusive finding. Where p-values are between 10^{-3} and 10^{-2}, the program will report "segregation possible," and again it may be desirable to add additional data to the samples. Where the p-value is less than 10^{-3}, there is a reasonably high probability that laboratory tests on core samples would find statistically significant segregation differences. In this case of p-value less than 10^{-3}, the program will report "segregation likely."

CHAPTER 9
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

1.0 SUMMARY

A two-phase research project was sponsored by MDOT to study segregation in asphalt pavements. The Phase I study titled "Test Method to Determine the Existence of Segregation in Bituminous Mixtures" focused on the linear pattern of segregation. In the Phase II study, a sampling technique was developed which can be applied to any segregation pattern; e.g., random, continuous and systematic segregation. The main objective of the Phase II study was to develop and validate an expedient procedure to quantify segregation in the field, and further, to relate the occurrence of segregation to pavement performance.

The definition of segregation used was given 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 with a concentration of coarse aggregate would have higher void contents and lower densities compared to non-segregated areas. Therefore, statistical comparisons of in-place nuclear density measurements could be used as an indicator of segregation. Furthermore, the deterioration in pavement conditions and the reduction in pavement performance were investigated in order to correlate them to various degrees of segregation that were determined from visual observation.

Extensive testing and analyses were conducted at 20 sites; 17 segregated, two non-segregated control sites and one demonstration site involving a loose, uncompacted asphalt mixture. Each site was examined visually to select sampling areas of heavy, medium and light segregation. In addition, non-segregated areas were also identified as control sampling areas. For several test sites where the pattern of segregation was linear strips, the six by six sampling grid pattern developed in the Phase I study was used. In most cases the size and shape of sampling areas was determined in the field to correspond to consistently observed conditions. For each sampling area, a minimum of six one-minute nuclear density readings were obtained. After nuclear density tests were completed, six-inch diameter cores were obtained from some of the same locations where nuclear densities were measured. Cores were sawed to separate the surface course from leveling and base courses. Air-dry and saturated surface-dry (SSD) laboratory density tests were conducted on the surface course. The aggregates were recovered by incinerating the asphalt binder. Sieve analyses were performed to determine the aggregate gradation parameters.

Extensive statistical comparison tests were performed on nuclear density measurements to determine if the variations in visual classifications correspond to statistical differences in nuclear density. For two-sample comparisons between samples with different degrees of segregation, t-tests were performed using the spreadsheet template mbitseg2.

In some cases, it was found that significant nuclear density differences were present even where no segregation was visually observable, or where the degree of segregation appeared similar for two samples. This was determined to be the result of different compaction efforts across the pavement, such as in wheel paths of existing pavements, and near the edge of new pavement. This effect can be minimized by assuring that the compaction efforts of two compared sampling areas are similar, such as by locating them in the same longitudinal line (at the same distance from the pavement edge).

Criteria to detect existence of segregation were developed by relating visual classifications of degree of segregation to the p-values from t-tests using nuclear density measurements. In the field, nuclear density measurements taken from the pre-selected segregation areas were compared to those from non-segregated control areas. Conditional probabilities were computed to arrive at an acceptable criterion; e.g. given a certain p-value from nuclear density comparisons, the conditional probability that different degrees of segregation would be visually mapped was determined. Furthermore, the accuracy of nuclear density measurements was verified by performing regression analyses using lab density data.

To verify the proposed criteria for predicting segregation, aggregate gradation data were used, with the parameters taken as percent passing 3/8", No. 4 and No. 8 sieves. Again, t-tests were performed to determine statistical significance of observed differences. The relationships among the differences between paired samples in degrees of segregation, nuclear density measurements and gradation were established. The criteria were refined to maximize the probability that a visually observed segregation sample that is identified by nuclear density measurements is also supported by gradation data.

Finally, to study the effects of segregation on pavement conditions, distress surveys were periodically conducted and segregation-related distress data were collected based on extent and severity level. The rate of distress deterioration due to different degrees of segregation was determined based on the quantitative distress data.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the analyses of nuclear density, lab density and gradation data on the criteria for detecting segregation and on the effects of segregation on pavement conditions, the following conclusions were made:

1. The sampling procedure presented in Chapter 3 is suitable for any pattern of segregation (random, continuous and systematic segregation).

2. For in-service pavements, compaction due to traffic loads can result in statistically significant differences in nuclear density readings, even where segregation is not visible.

3. Nuclear density values at visually identified heavy or medium-segregated areas have greater coefficients of variation than at light-segregated or non-segregated (control) areas.

4. Statistical differences in nuclear-measured density values can be used as an expedient indicator of visually identified medium and heavy segregation.

5. In visually identified segregation areas, nuclear density differences with p-values less than 10^{-3} confirmed the presence of visual segregation with approximately 90 percent probability.

6. Medium or heavy segregated areas generally have a coarser aggregate mix than that in the control areas to which they were compared.

7. In visually identified medium and heavy segregated areas, the probability that differences in nuclear density values correspond to significant gradation differences is 86 percent.

8. In visually identified light, medium and heavy segregated areas, the probability that differences in nuclear density values correspond to significant gradation differences is 76 percent.

9. A spreadsheet mbitseg2 developed in QuattroPro format is capable of reporting the various conditional probabilities of segregation based on the combination of visual description of segregation and nuclear density values.

10. Raveling and cracking were observed from the periodical distress survey in the segregated sites. Based on the distress data collected within the two-year period, heavy and medium segregation cause minimum of 50 and 30 percent decreases in the pavement service life, respectively.

11. A unit decrease in lab density corresponds to about a 1.4 to 1.5 decrease in nuclear density.

Based on the results of this study, the following recommendations were made:

1. Utilize one-minute nuclear density readings for detection of segregation during pavement construction.

2. Use the user-friendly spreadsheet mbitseg2 to perform the required statistical analyses for predicting segregation.

3. Improve the conditional probabilities by expanding the database with more segregation projects.

4. MDOT should modify and implement the draft construction specifications provided in Chapter 8 for preventing segregation.

5. Use the procedure and application of the field nuclear density test written in Chapter 8 as a management decision tool.

6. Develop distress points for raveling and flushing which are segregation-related distresses.

7. Monitor the pavement condition once every six months for an additional two-year period. This should allow more accurate determination of the rate of deterioration for heavy, medium and light segregation.

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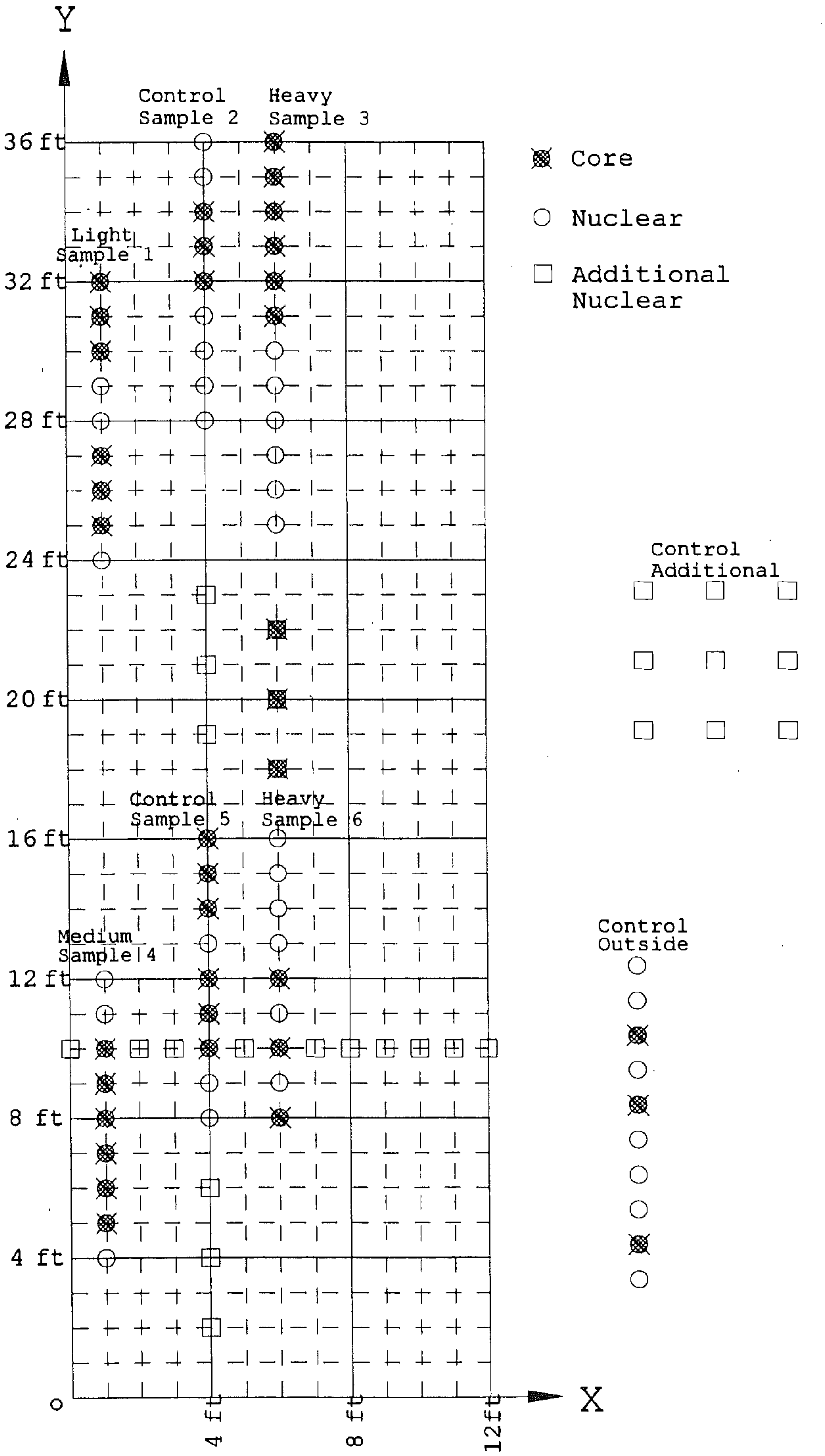
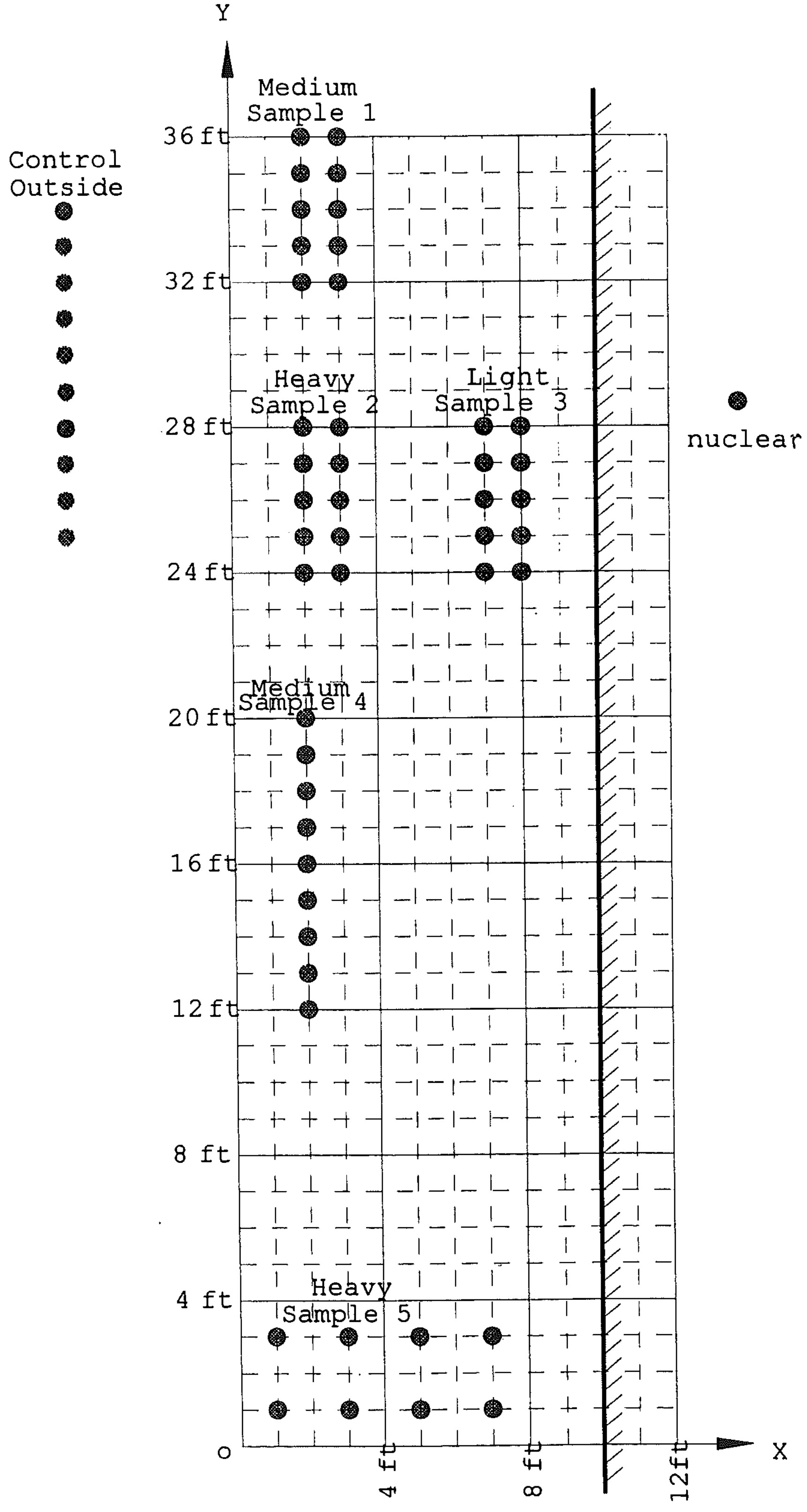
Appendix A

Site 1

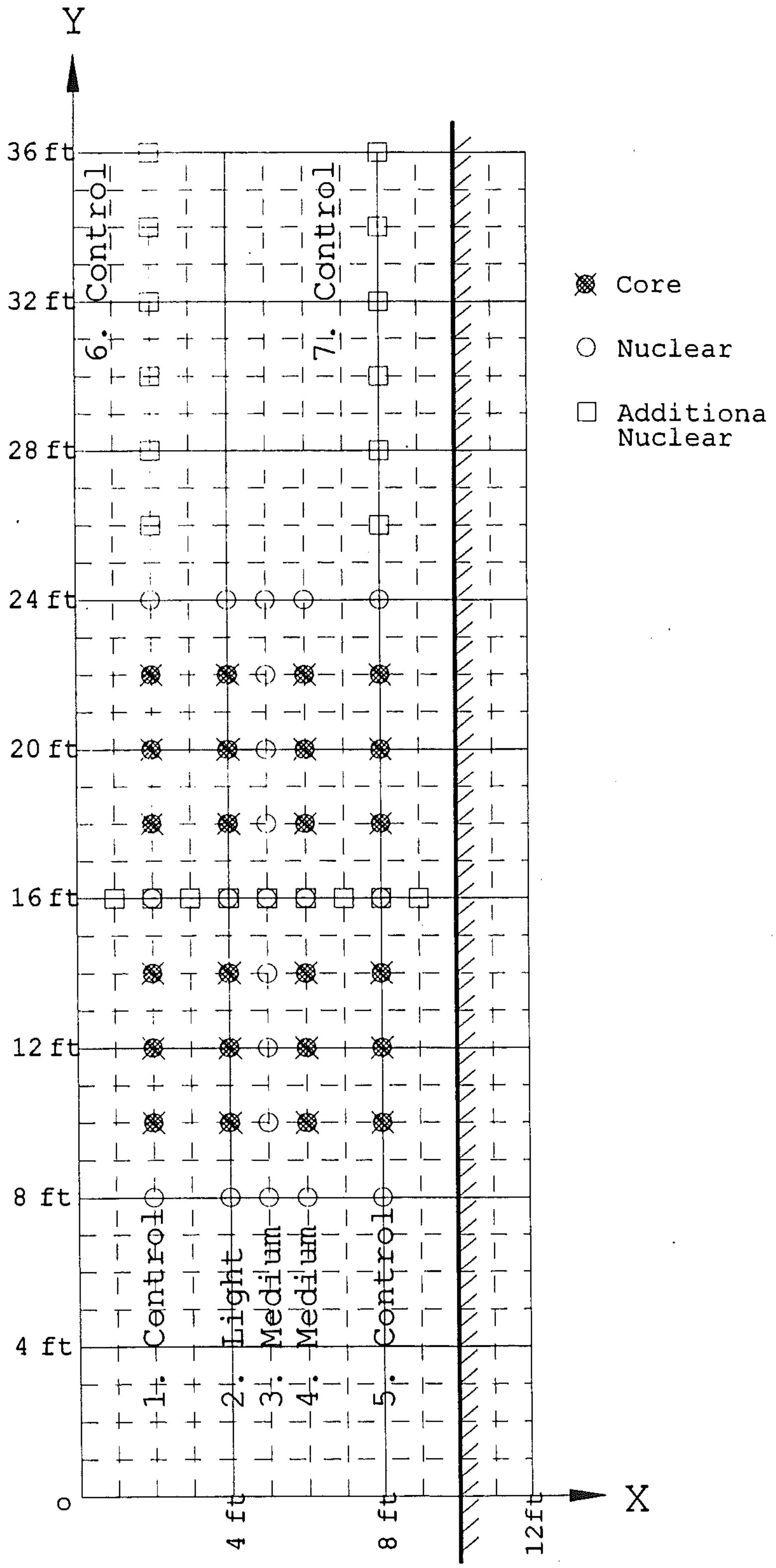


Y
X
Control Sample 2
Heavy Sample 3
Light Sample 1
Control Sample 5
Heavy Sample 6
Medium Sample 4
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
0
4 ft
8 ft
12ft
Core
Nuclear
Additional Nuclear
Control Additional
Control Outside

Site 2

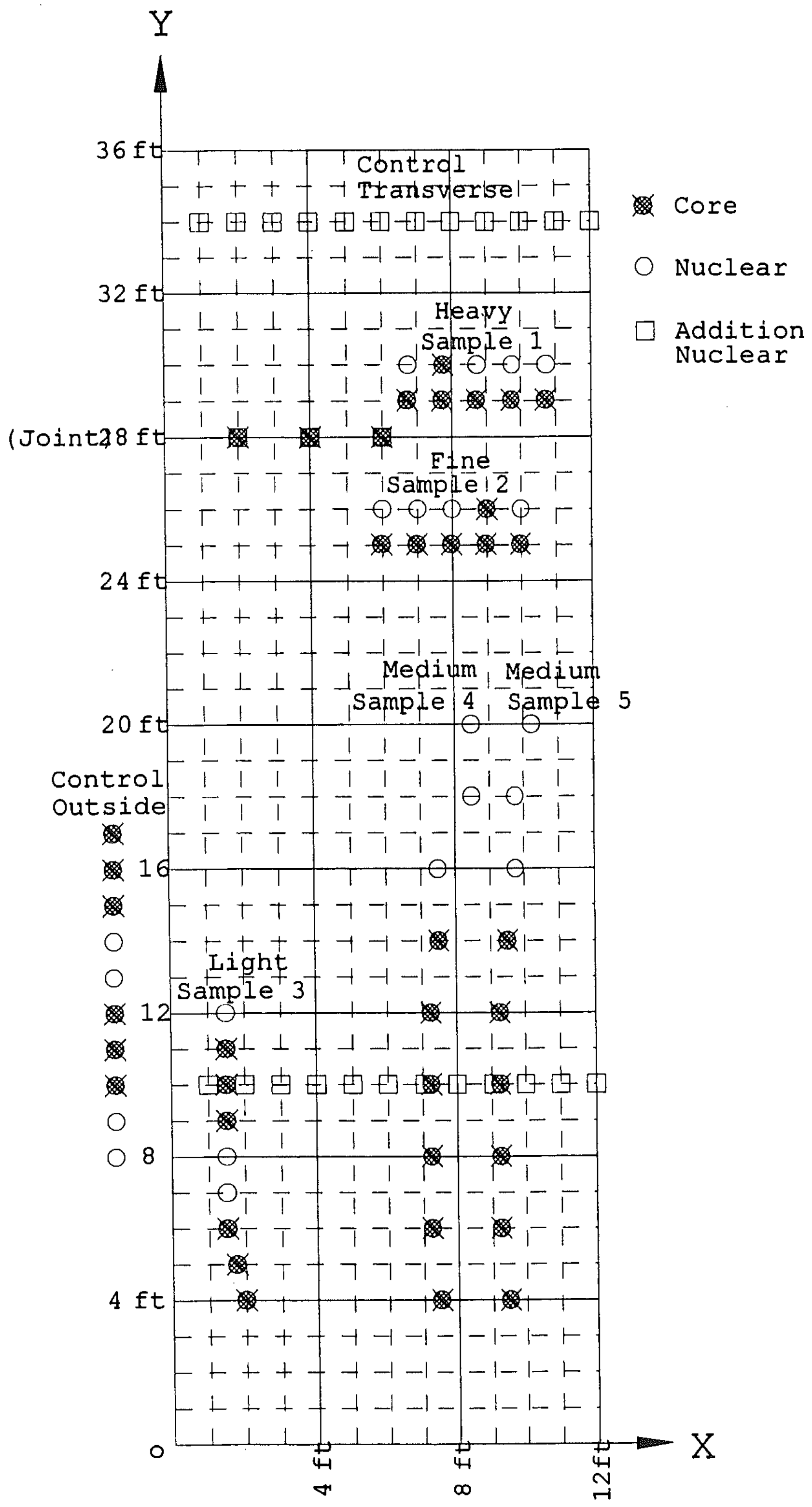

Y
Medium
Sample 1
36 ft
Control
Outside
32 ft
Heavy
Sample 2
Light
Sample 3
nuclear
28 ft
24 ft
Medium
Sample 4
20 ft
16 ft
12 ft
8 ft
4 ft
Heavy
Sample 5
o
4 ft
8 ft
12ft
X

Site 3

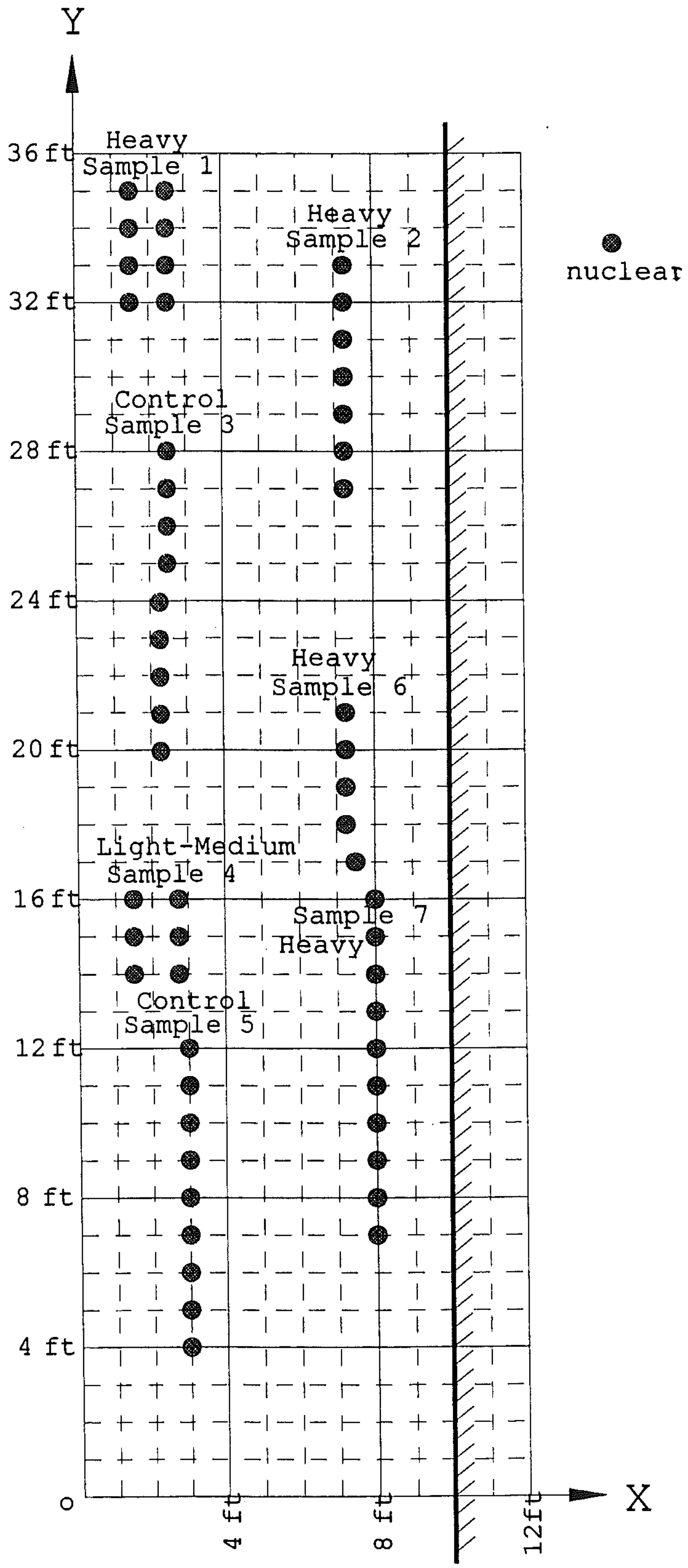


Y
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft
X
6. Control
7. Control
1. Control
2. Light
3. Medium
4. Medium
5. Control
Core
Nuclear
Additiona Nuclear

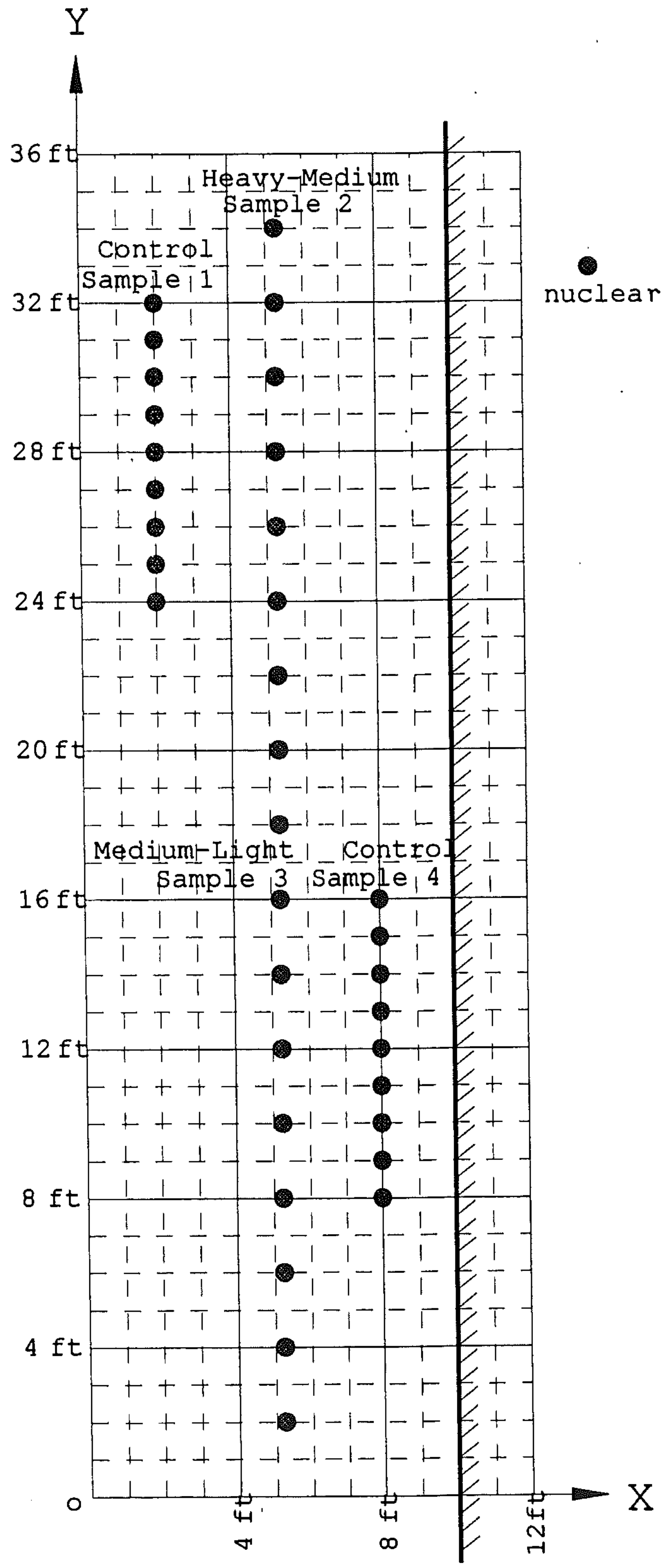
Site 5


Y
X
36 ft
32 ft
(Joint) 28 ft
24 ft
20 ft
16
12
8
4 ft
0
4 ft
8 ft
12ft
Control
Transverse
Heavy
Sample 1
Fine
Sample 2
Medium
Sample 4
Medium
Sample 5
Light
Sample 3
Control
Outside
Core
Nuclear
Addition
Nuclear

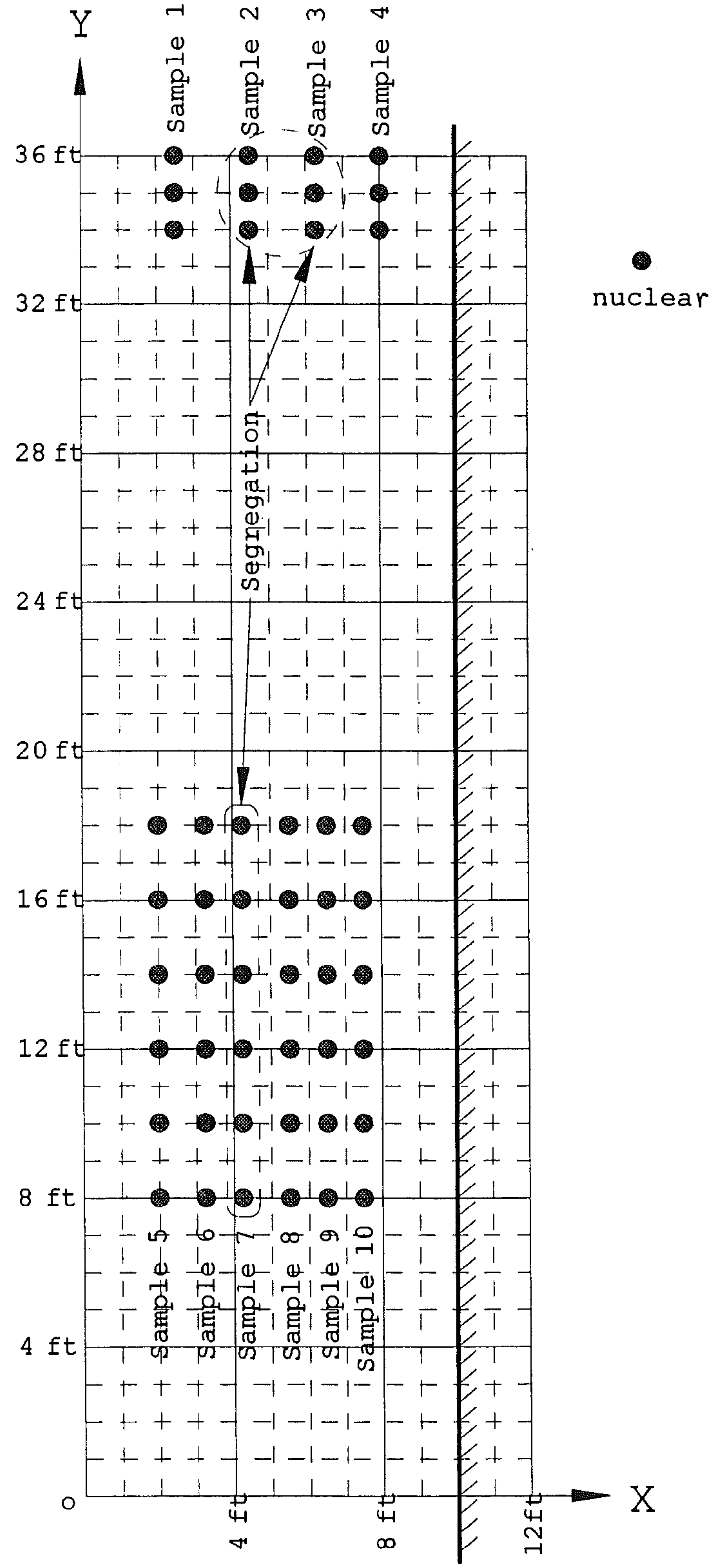
Site 6


Y
X
Heavy
Sample 1
Heavy
Sample 2
nuclear
Control
Sample 3
Heavy
Sample 6
Light-Medium
Sample 4
Sample 7
Heavy
Control
Sample 5
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft

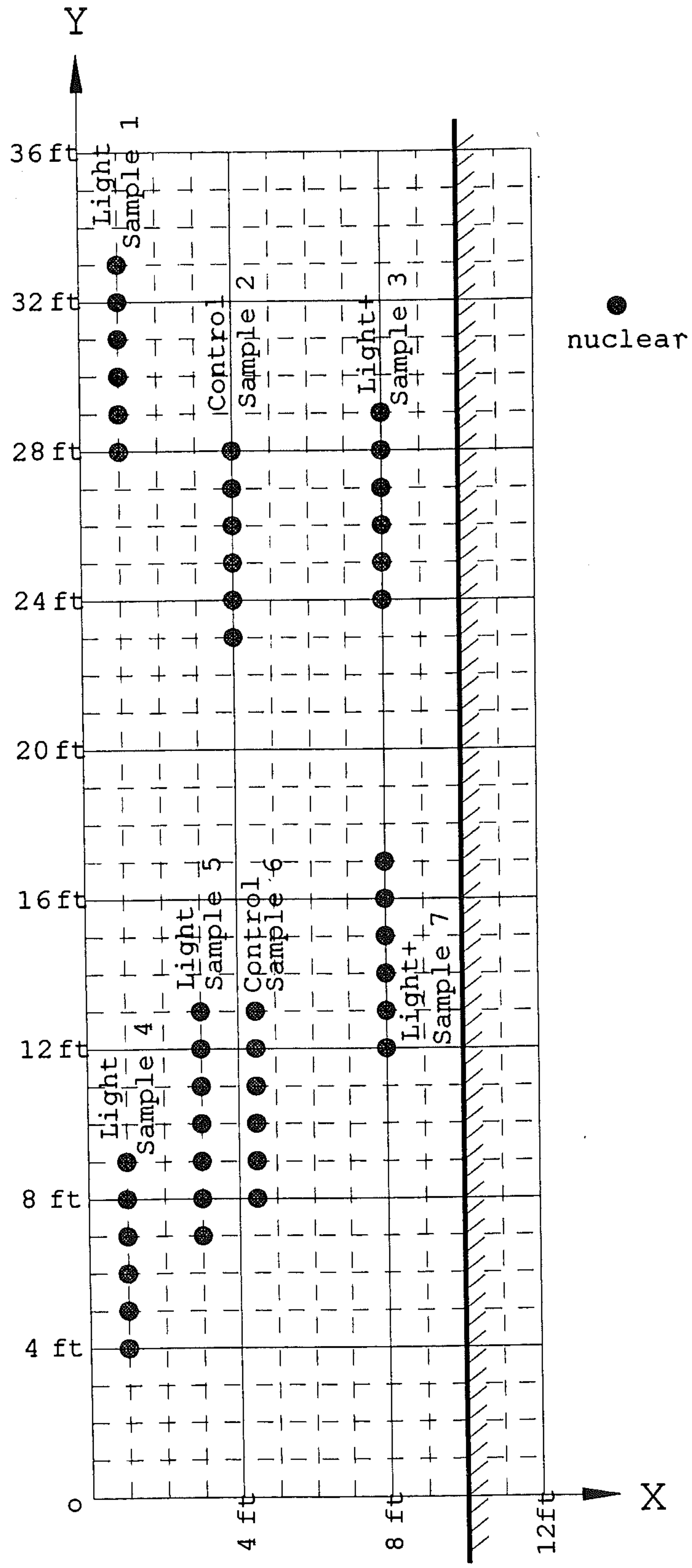
Site 7


Y
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft
X
Heavy-Medium
Sample 2
Control
Sample 1
nuclear
Medium-Light
Sample 3
Control
Sample 4

Site 8

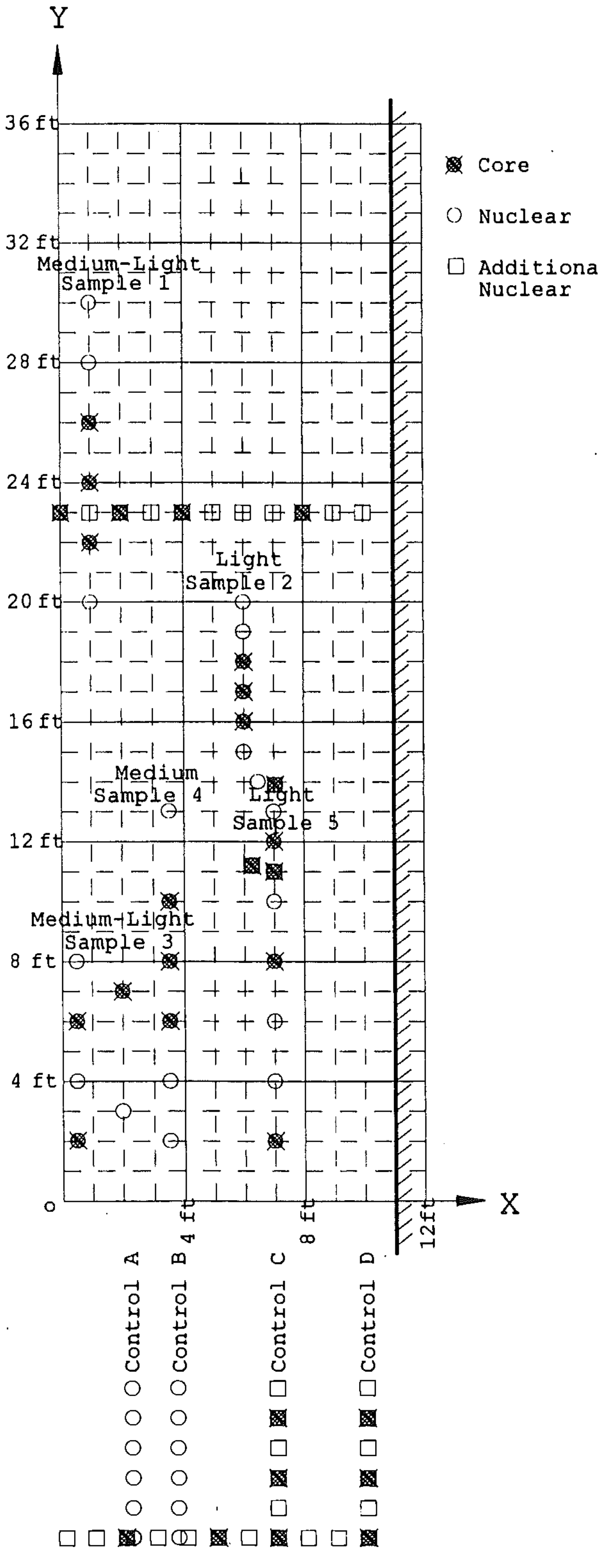

Y
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft
X
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Sample 7
Sample 8
Sample 9
Sample 10
Segregation
nuclear

Site 9

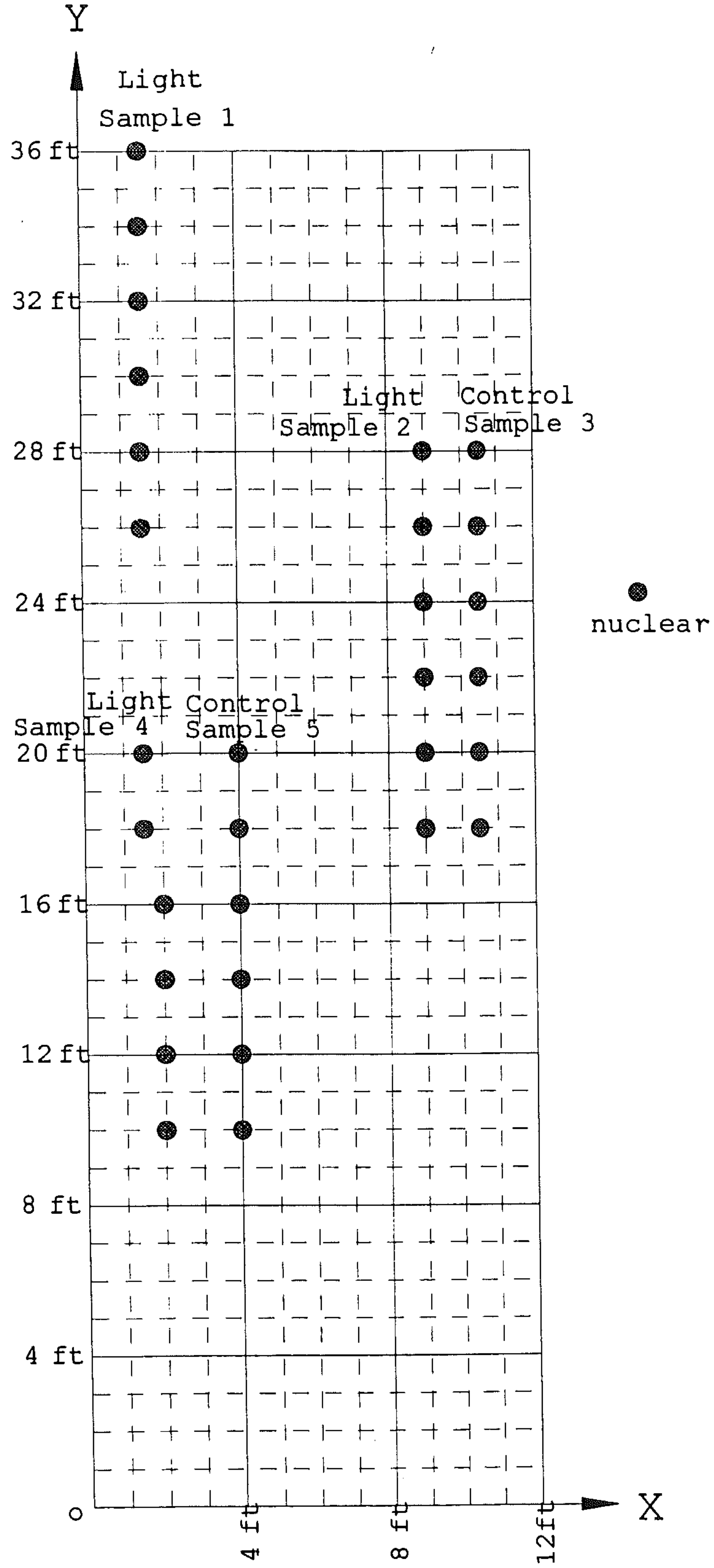


Y
X
0
4 ft
8 ft
12ft
4 ft
8 ft
12 ft
16 ft
20 ft
24 ft
28 ft
32 ft
36 ft
Light Sample 1
Control Sample 2
Light+ Sample 3
Light Sample 4
Light Sample 5
Control Sample 6
Light+ Sample 7
nuclear

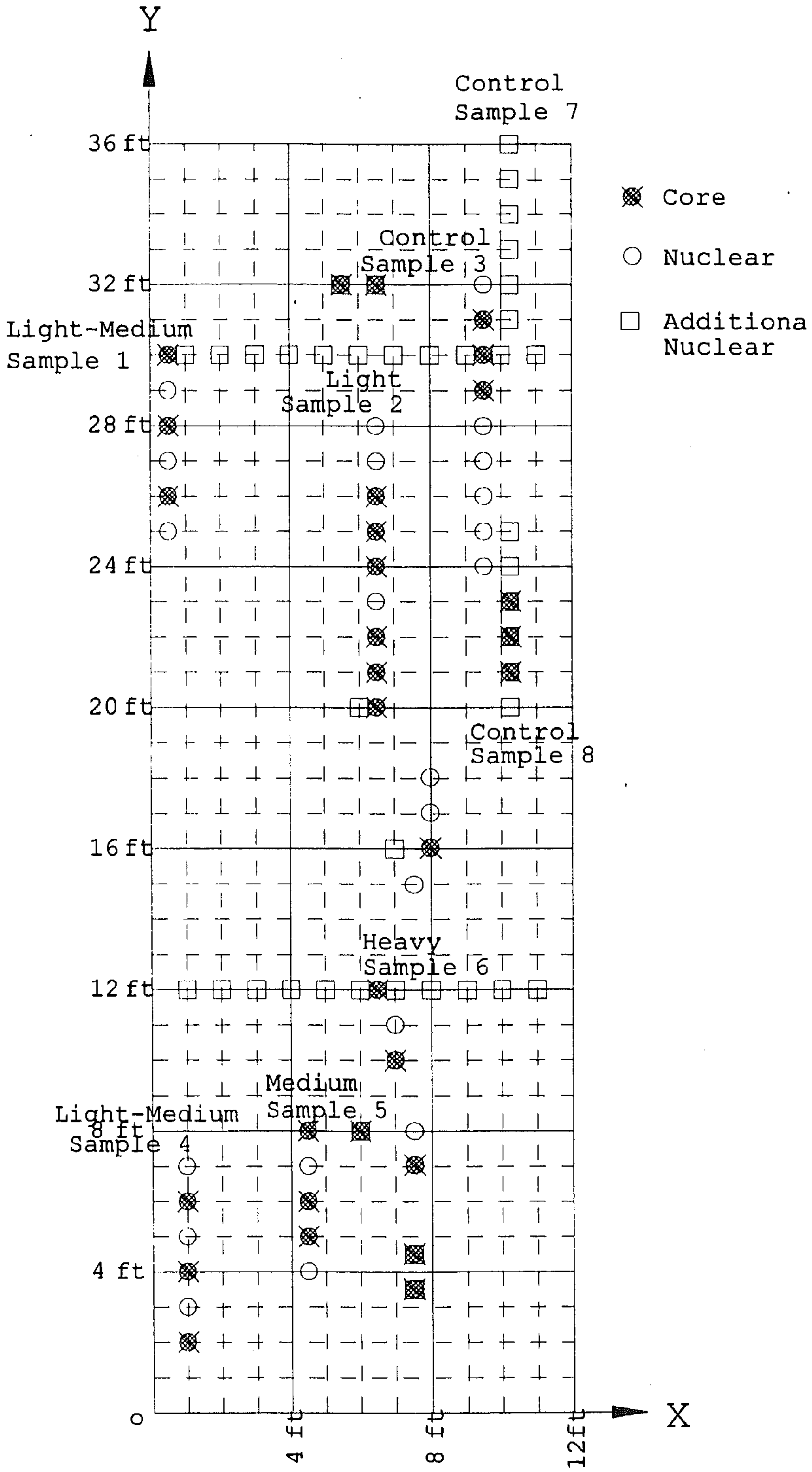
Site 10


Y
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft
X
Medium-Light
Sample 1
Light
Sample 2
Medium
Sample 4
Light
Sample 5
Medium-Light
Sample 3
Control A
Control B
Control C
Control D
▨ Core
○ Nuclear
☐ Additiona
Nuclear

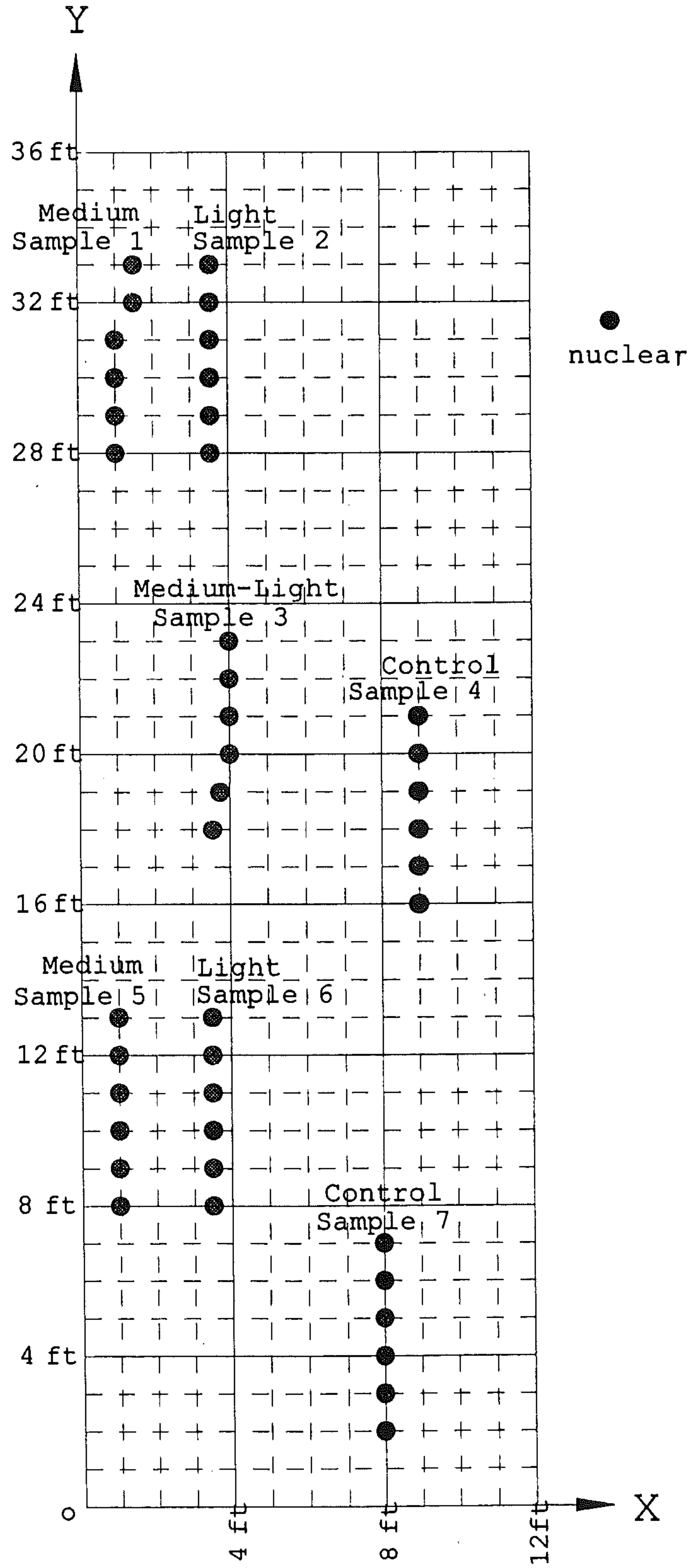
Site 11


Y
Light
Sample 1
36 ft
32 ft
Light
Sample 2
Control
Sample 3
28 ft
24 ft
nuclear
Light
Sample 4
Control
Sample 5
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft
X

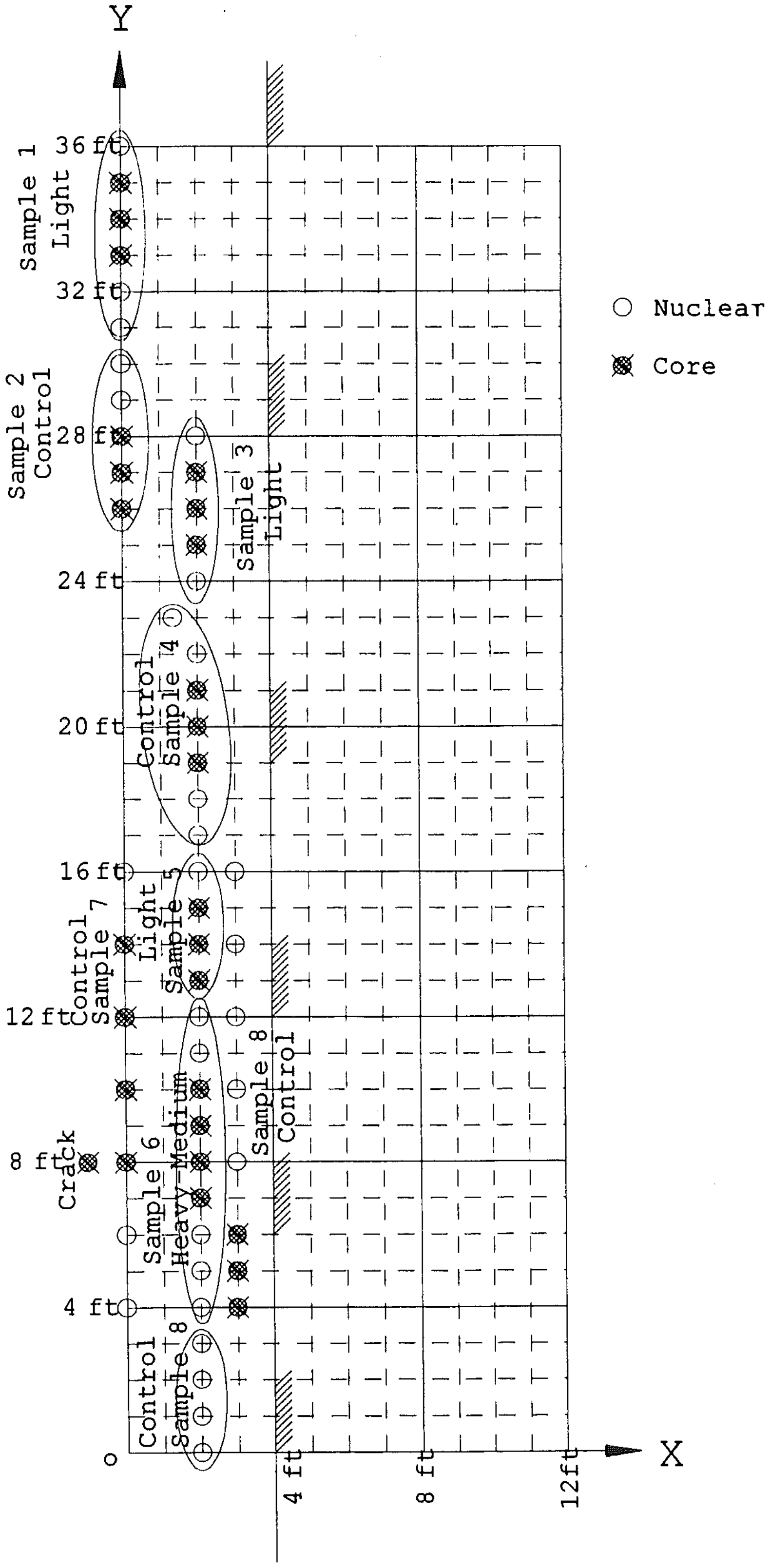
Site 13


Y
Control
Sample 7
36 ft
Core
Nuclear
Additiona
Nuclear
Control
Sample 3
32 ft
Light-Medium
Sample 1
Light
Sample 2
28 ft
24 ft
20 ft
Control
Sample 8
16 ft
Heavy
Sample 6
12 ft
Medium
Sample 5
Light-Medium
Sample 4
8 ft
4 ft
o
4 ft
8 ft
12ft
X

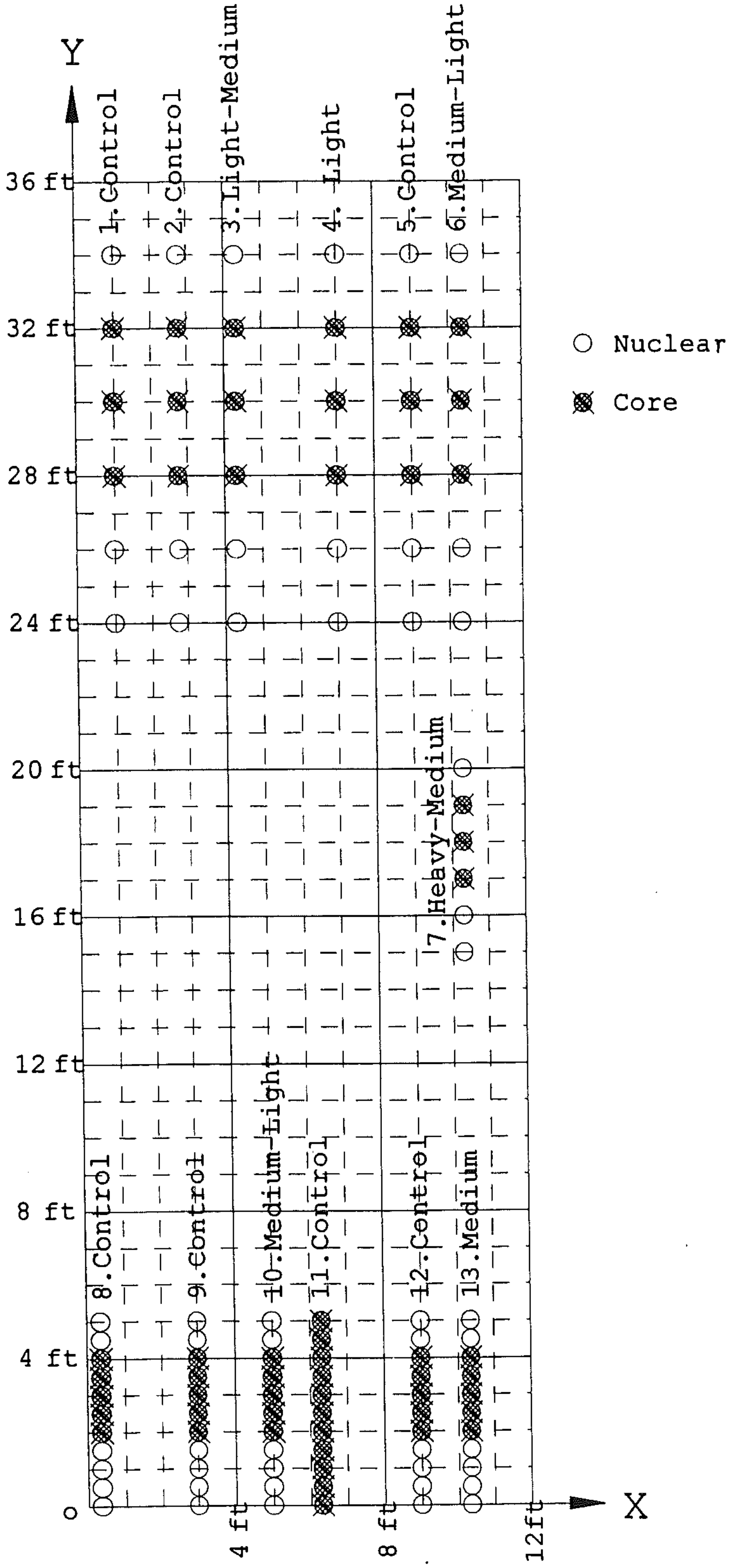
Site 14


Y
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft
X
Medium
Sample 1
Light
Sample 2
Medium-Light
Sample 3
Control
Sample 4
Medium
Sample 5
Light
Sample 6
Control
Sample 7
● nuclear

Site 15

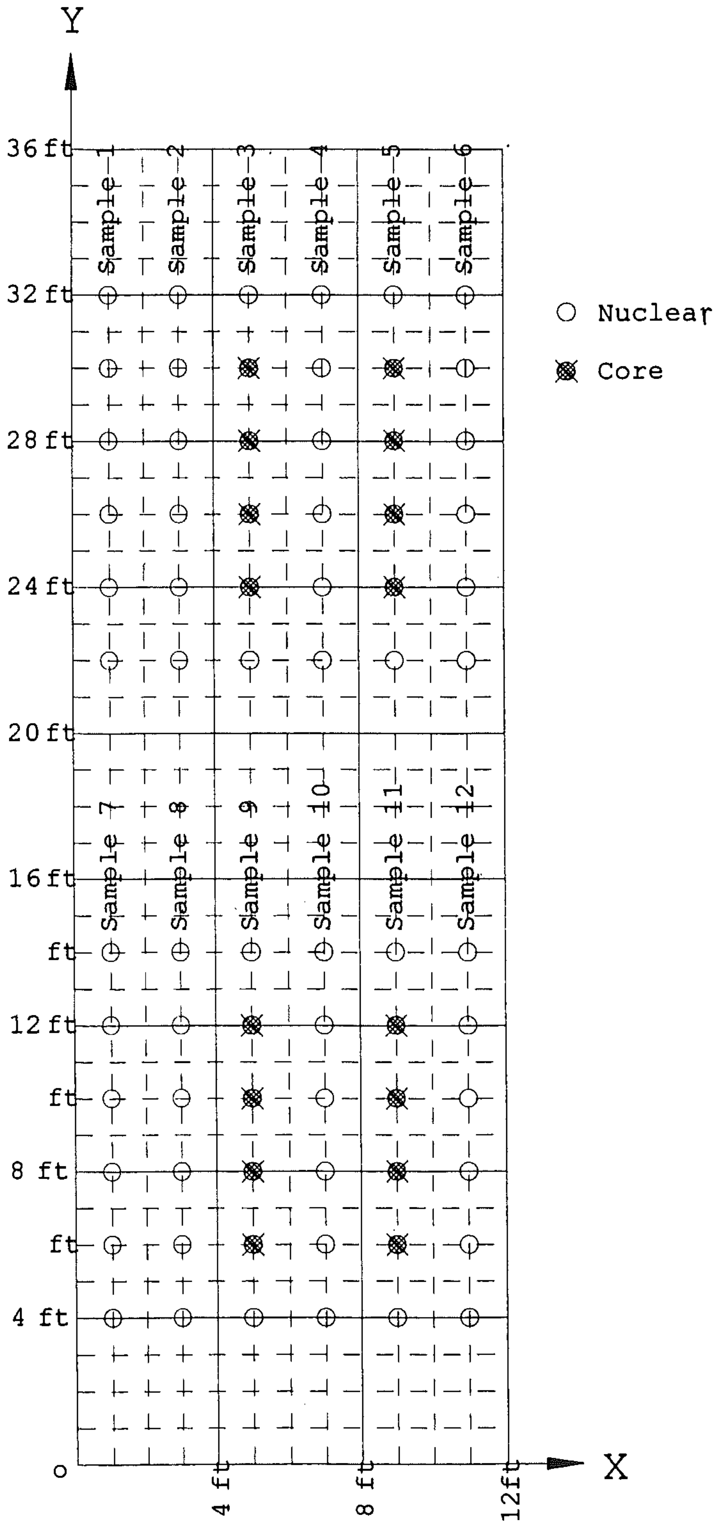

Y
X
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft
Sample 1
Light
Sample 2
Control
Sample 3
Light
Sample 4
Control
Sample 5
Light
Sample 7
Control
Sample 6
Heavy-Medium
Sample 8
Control
Crack
Sample 8
Control
○ Nuclear
⊗ Core

Site 16

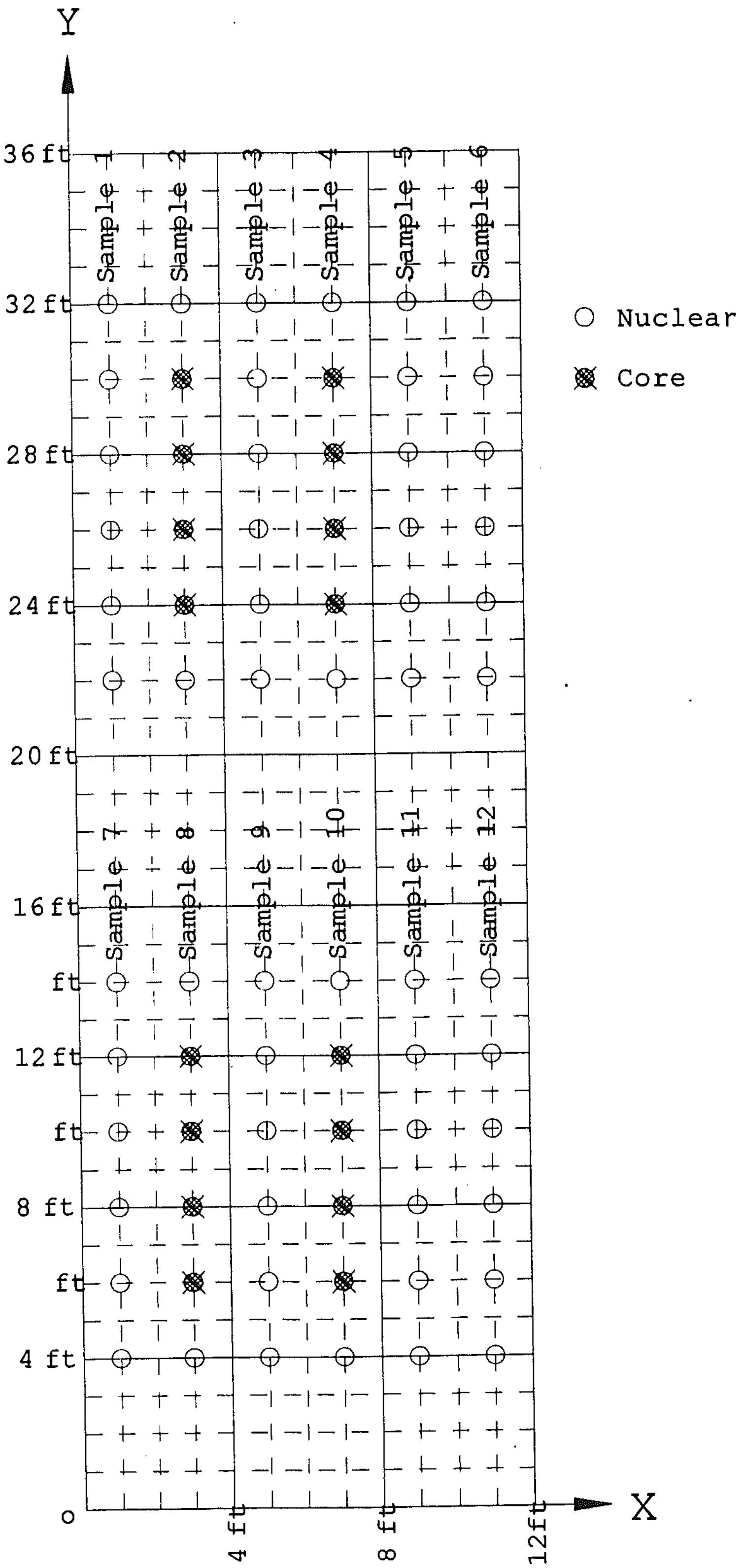


Y
X
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
o
4 ft
8 ft
12ft
1. Control
2. Control
3. Light-Medium
4. Light
5. Control
6. Medium-Light
7. Heavy-Medium
8. Control
9. Control
10. Medium-Light
11. Control
12. Control
13. Medium
○ Nuclear
⊗ Core

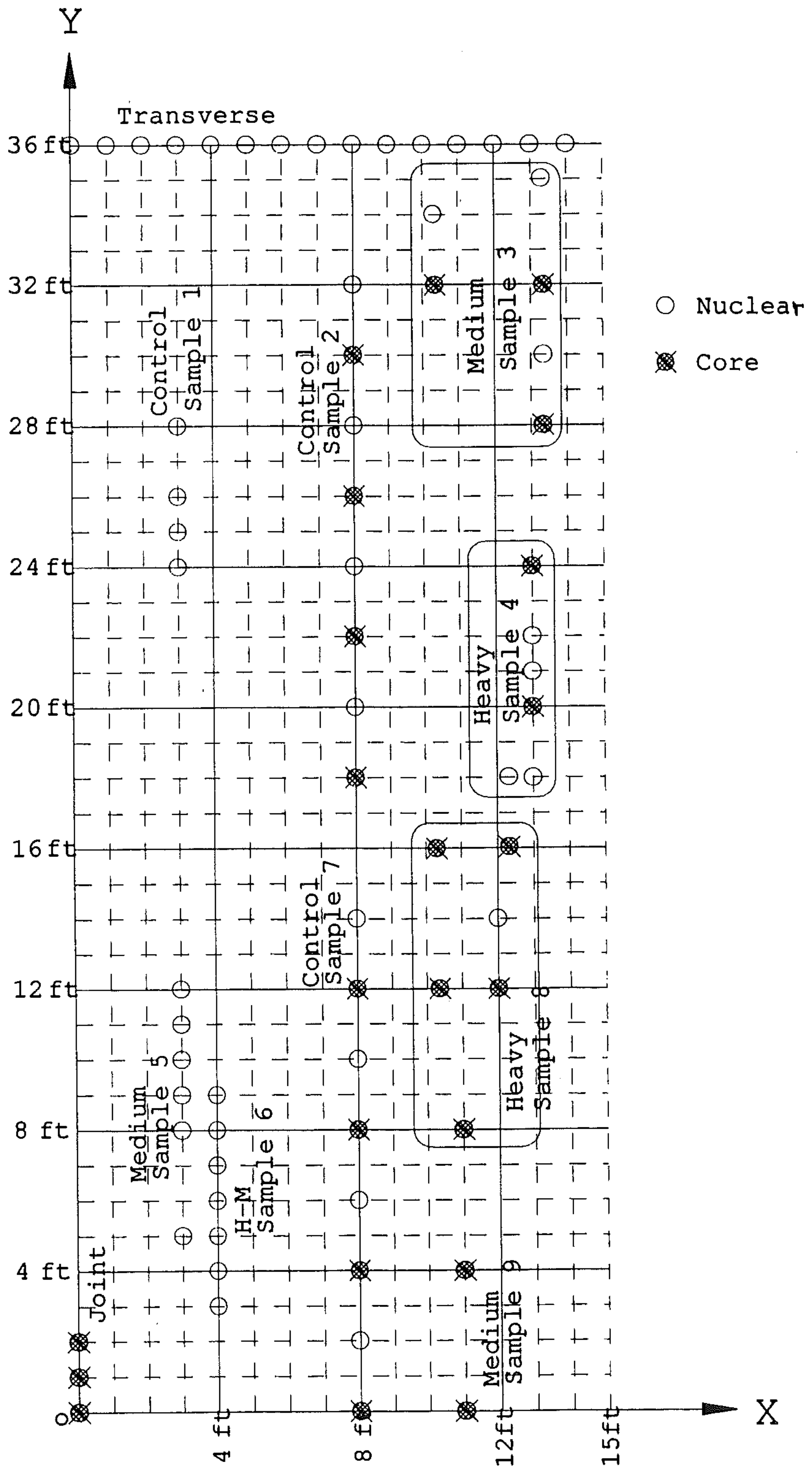
Site 17


Y
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
ft
12 ft
ft
8 ft
ft
4 ft
o
4 ft
8 ft
12ft
X
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Sample 7
Sample 8
Sample 9
Sample 10
Sample 11
Sample 12
○ Nuclear
● Core

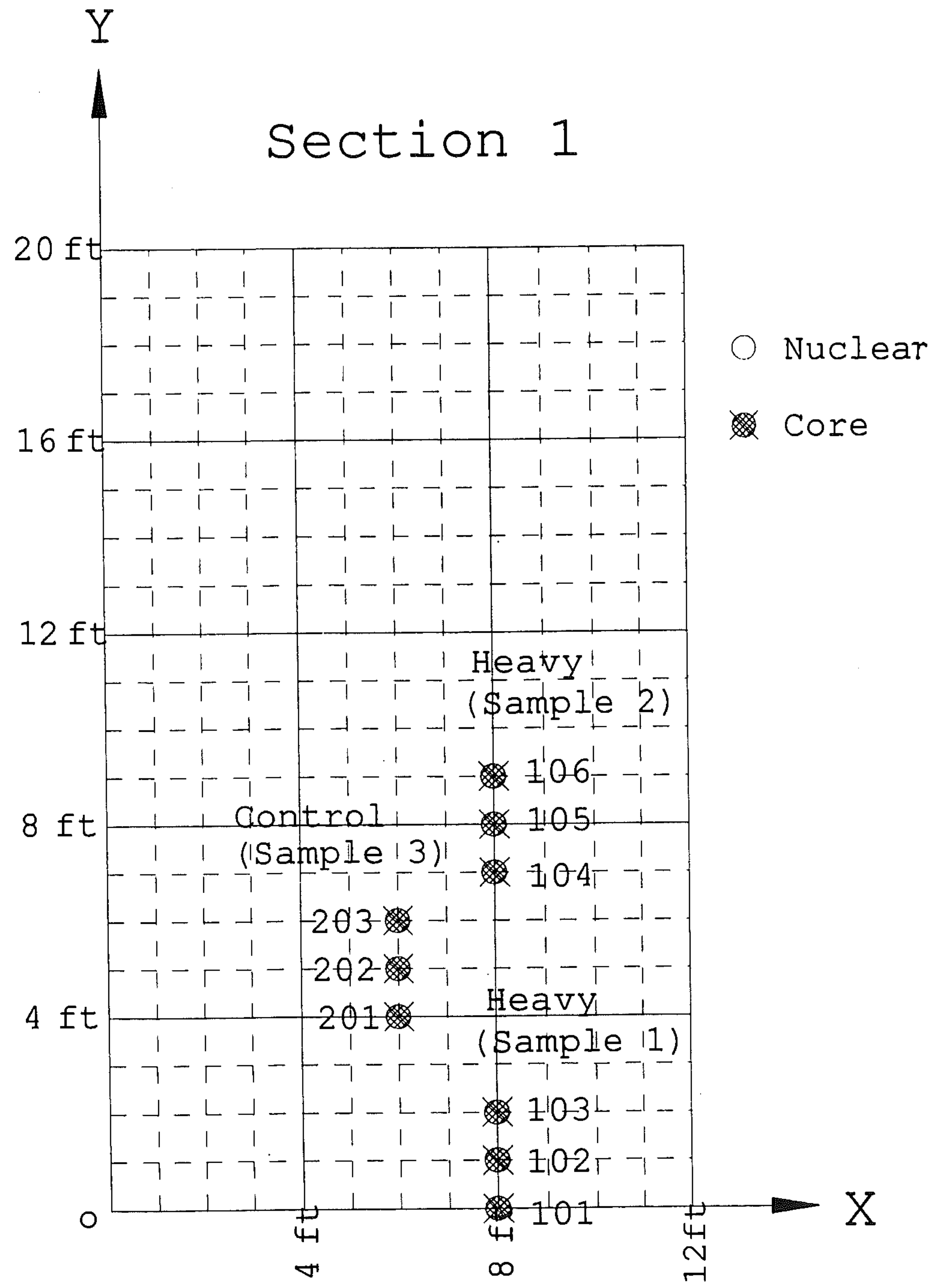
Site 18


Y
X
0
4 ft
8 ft
12ft
16 ft
20 ft
24 ft
28 ft
32 ft
36 ft
ft
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Sample 7
Sample 8
Sample 9
Sample 10
Sample 11
Sample 12
○ Nuclear
⊗ Core

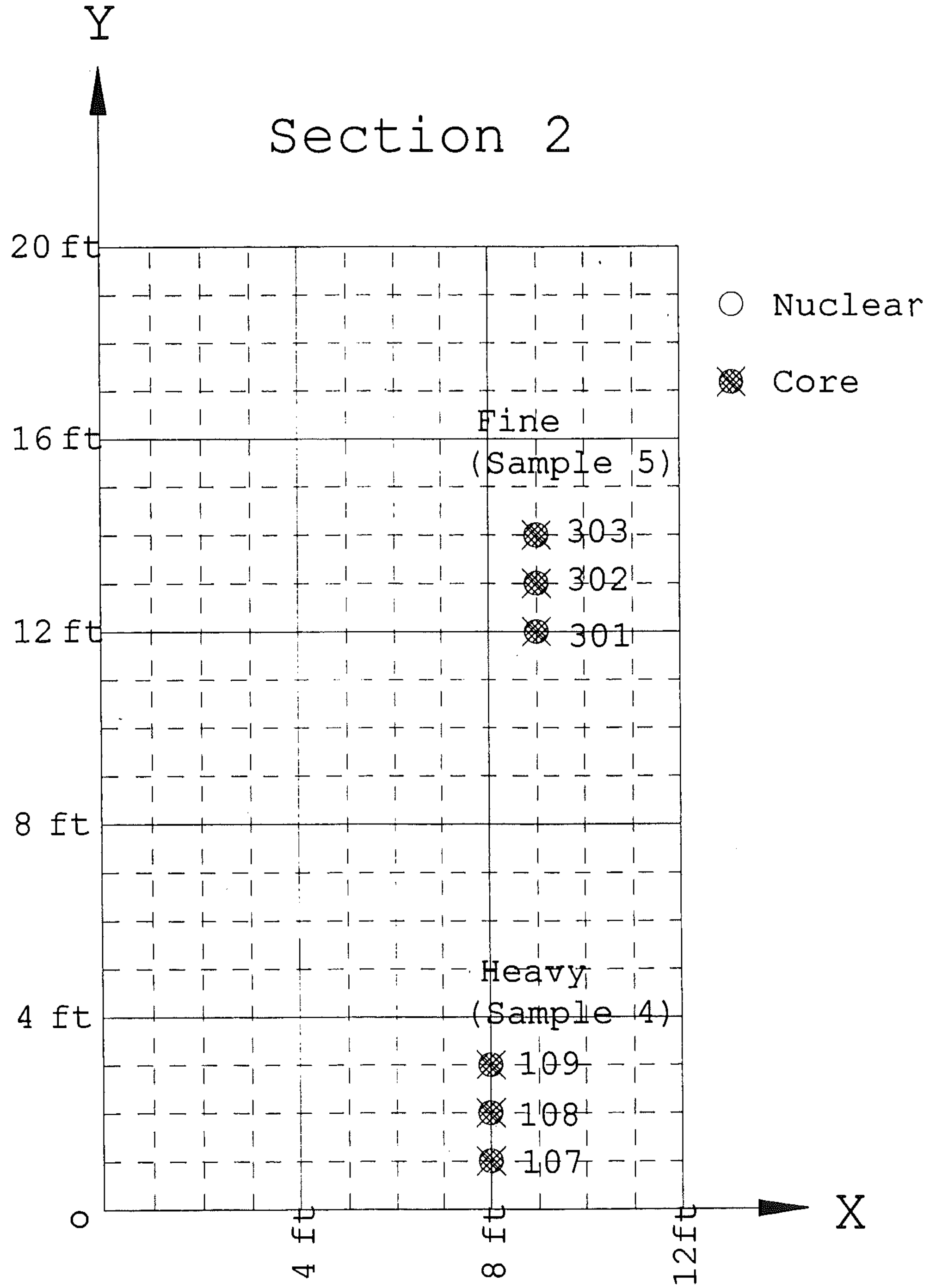
Site 19


Y
X
Transverse
36 ft
32 ft
28 ft
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
0
4 ft
8 ft
12ft
15ft
Control Sample 1
Control Sample 2
Medium Sample 3
Heavy Sample 4
Medium Sample 5
H-M Sample 6
Control Sample 7
Heavy Sample 8
Medium Sample 9
Joint
○ Nuclear
▨ Core

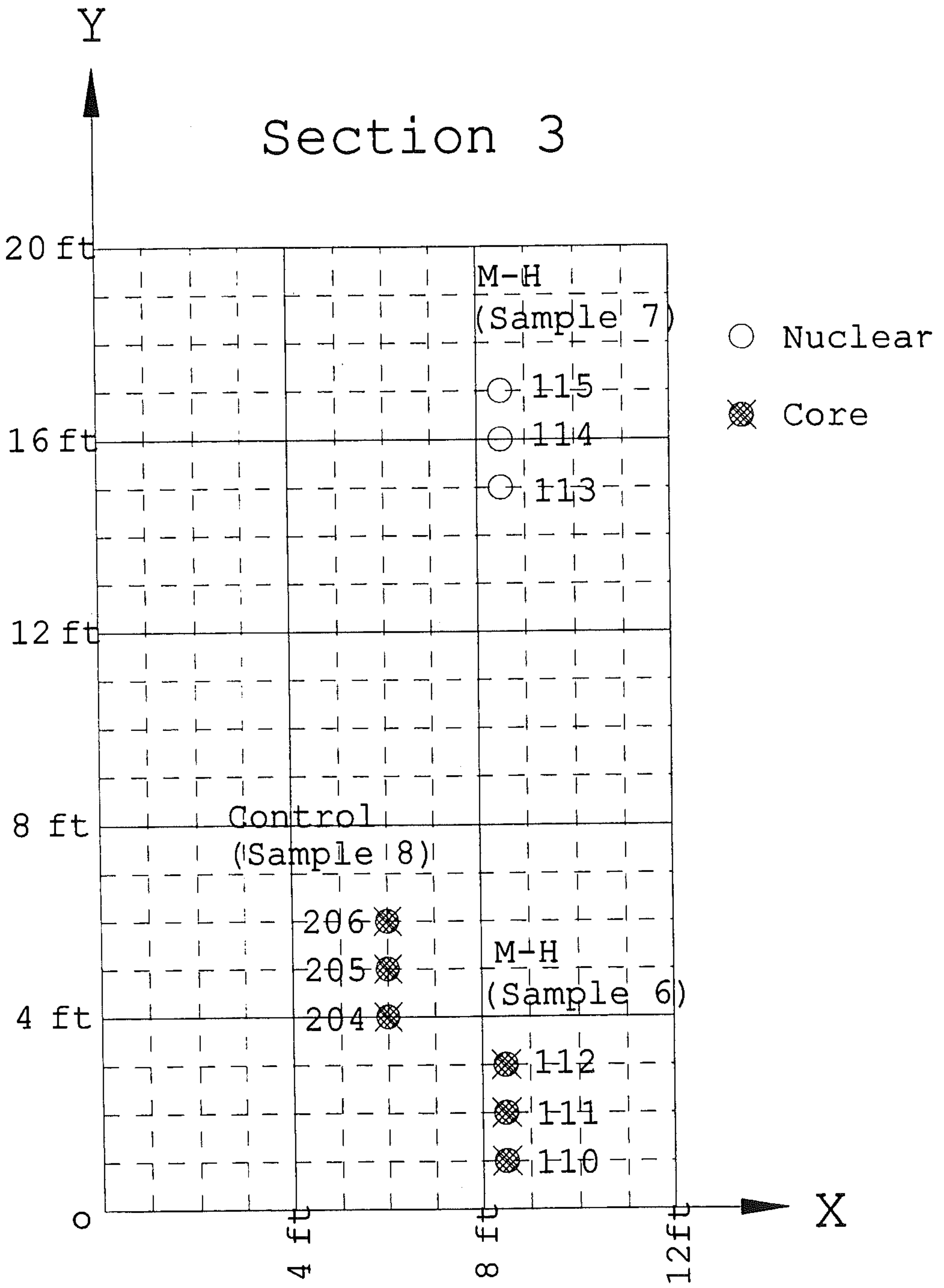
Site 20 Section 1



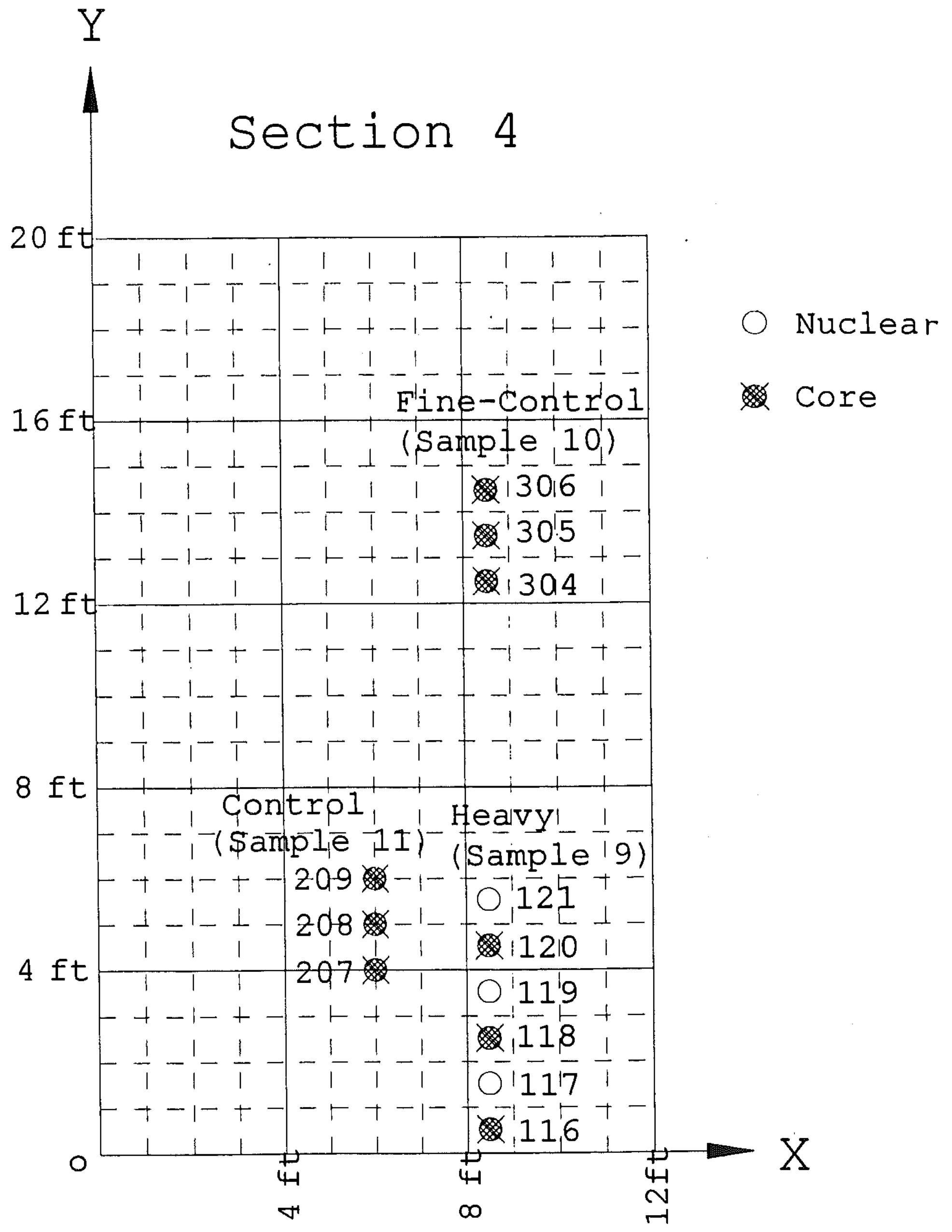
Site 20 Section 2



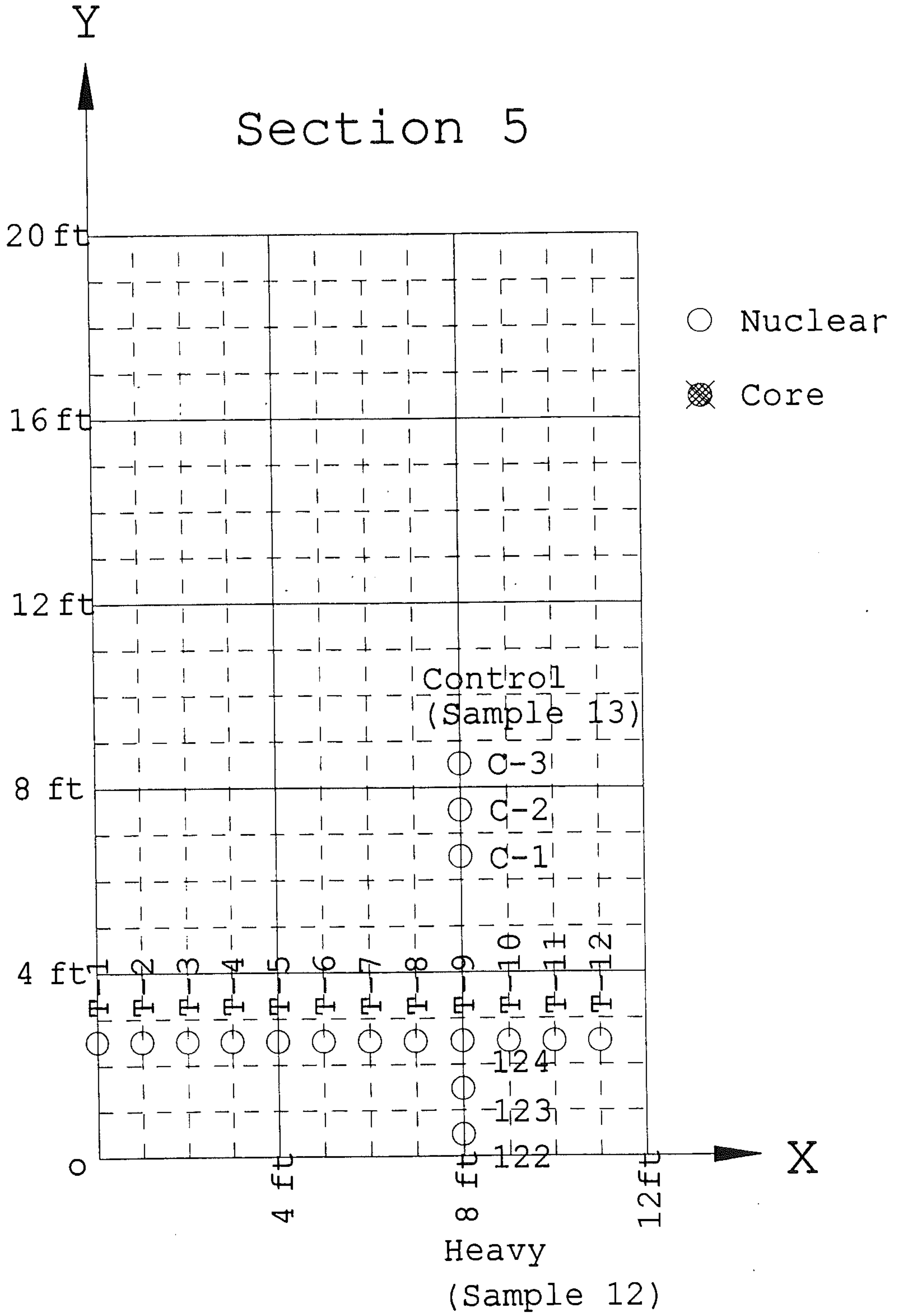
Site 20 Section 3



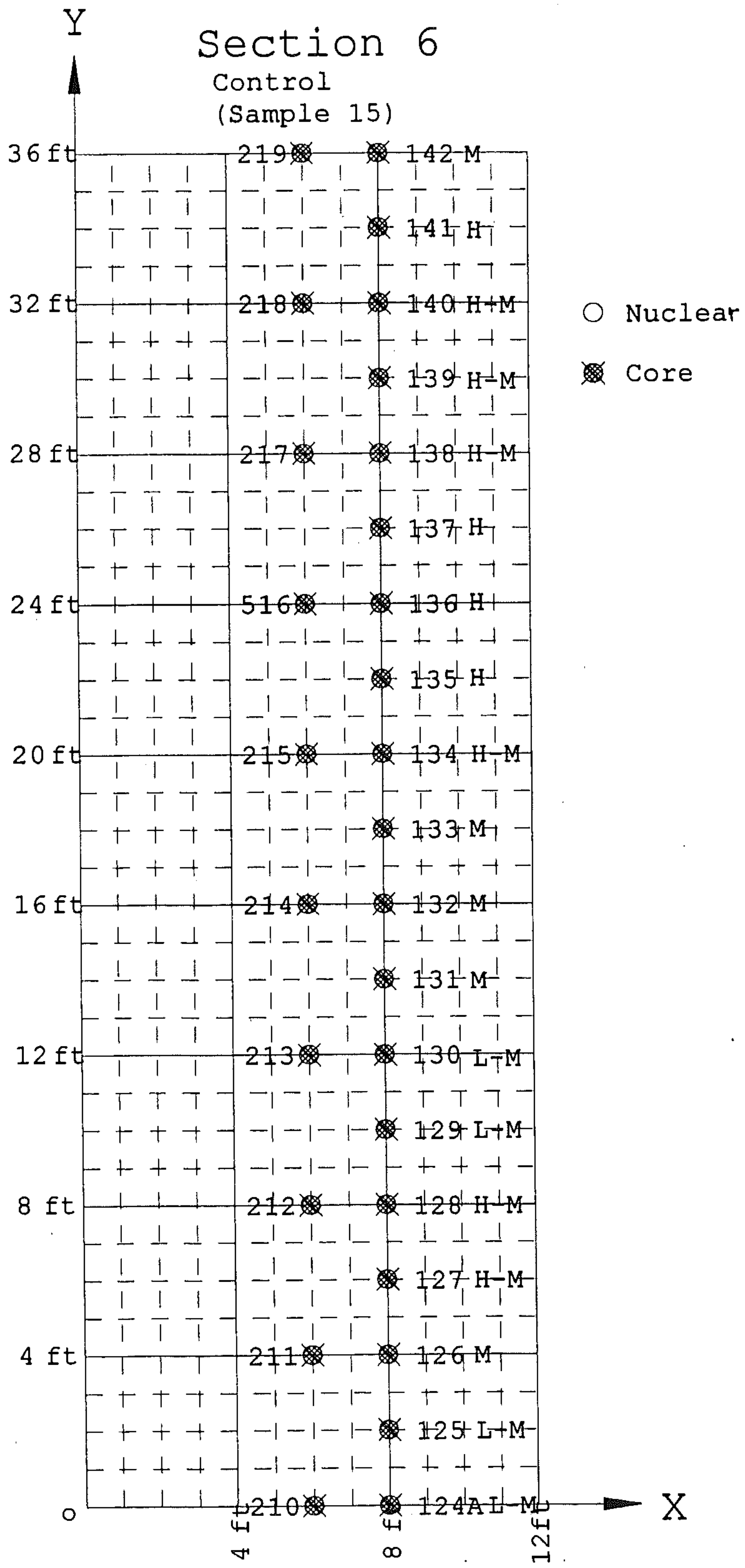
Site 20 Section 4



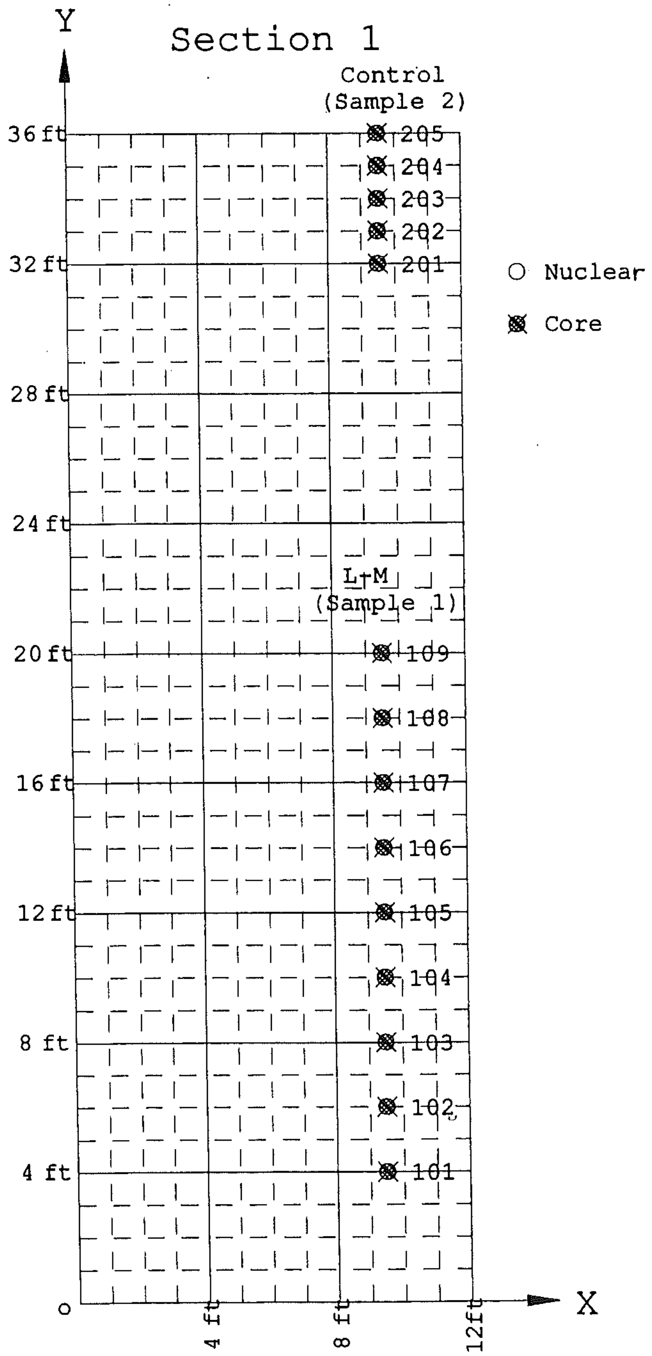
Site 20 Section 5



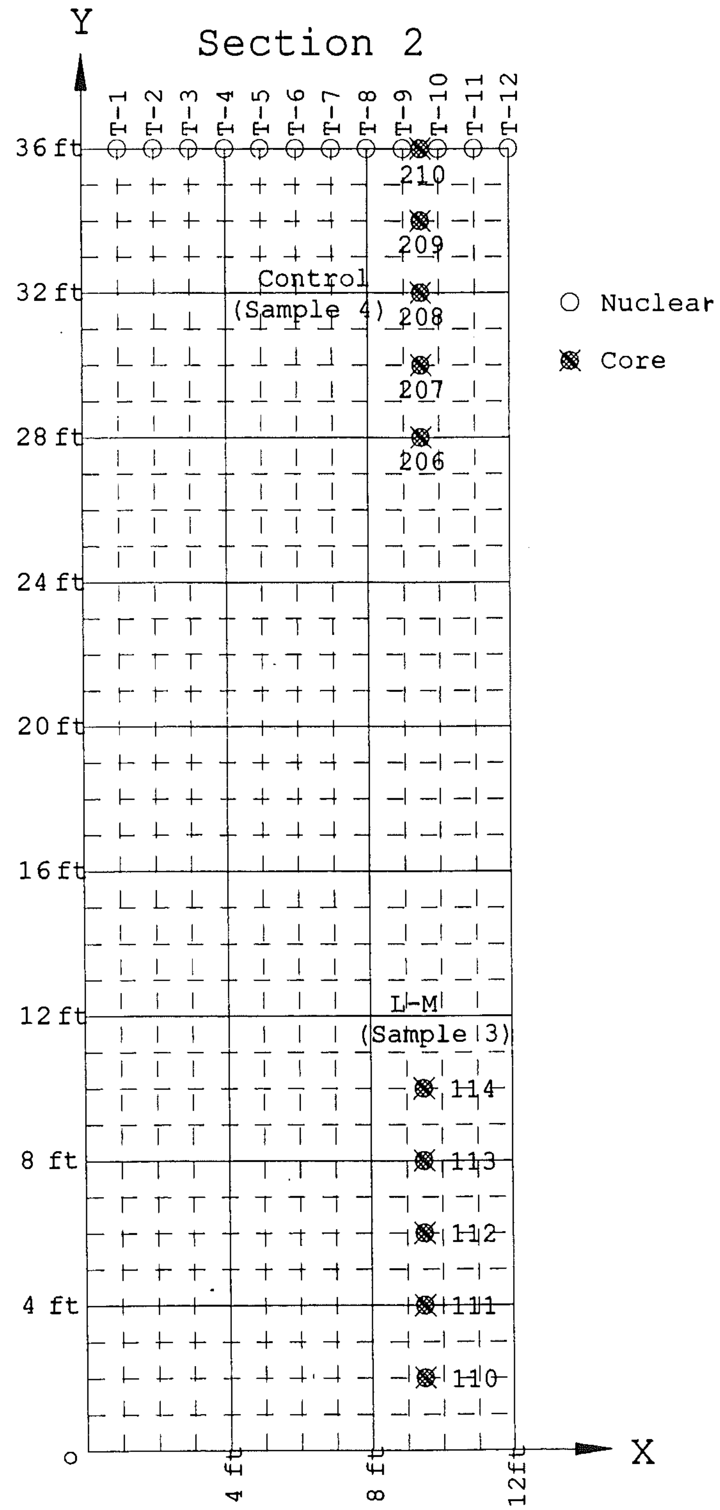
Site 20 Section 6



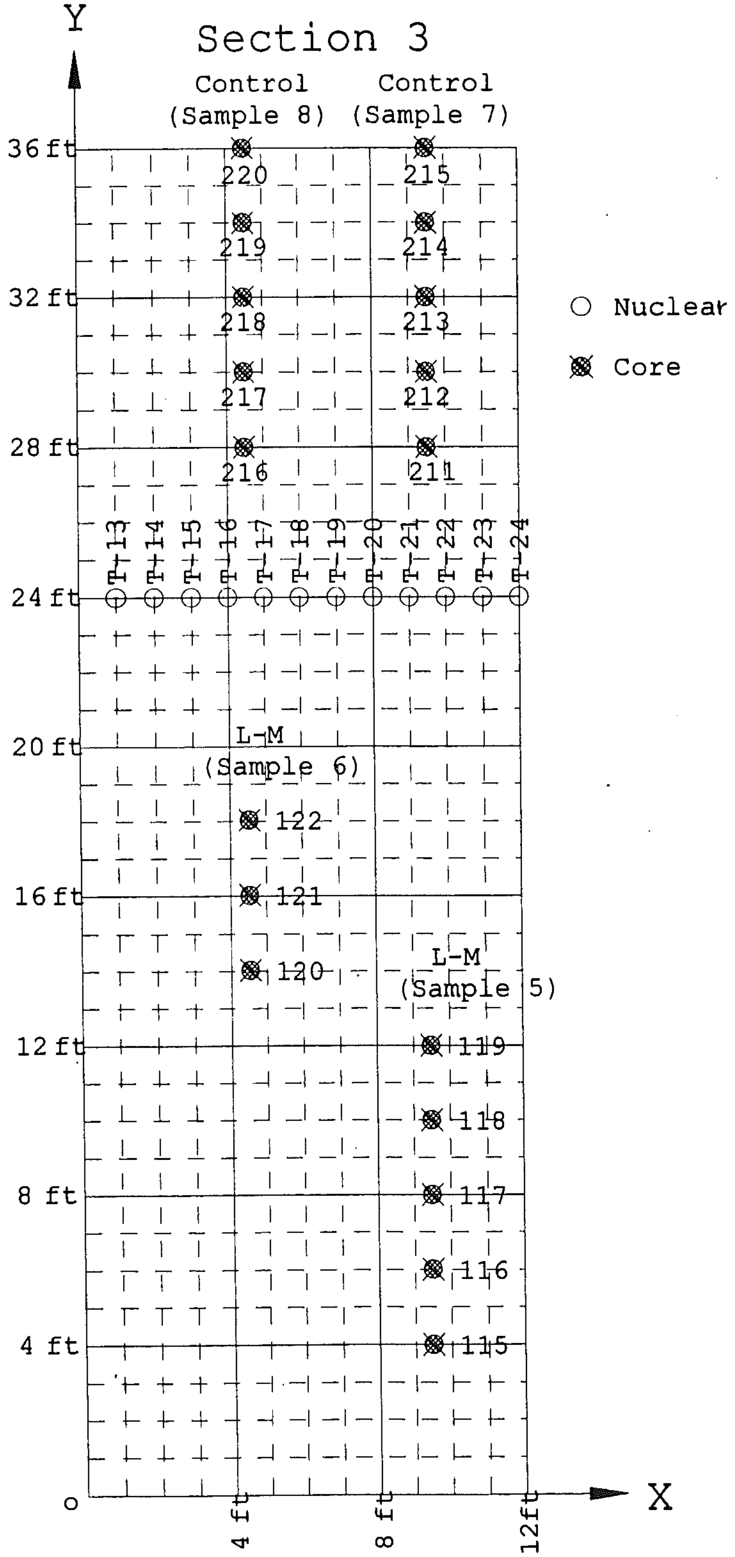
Site 21 Section 1



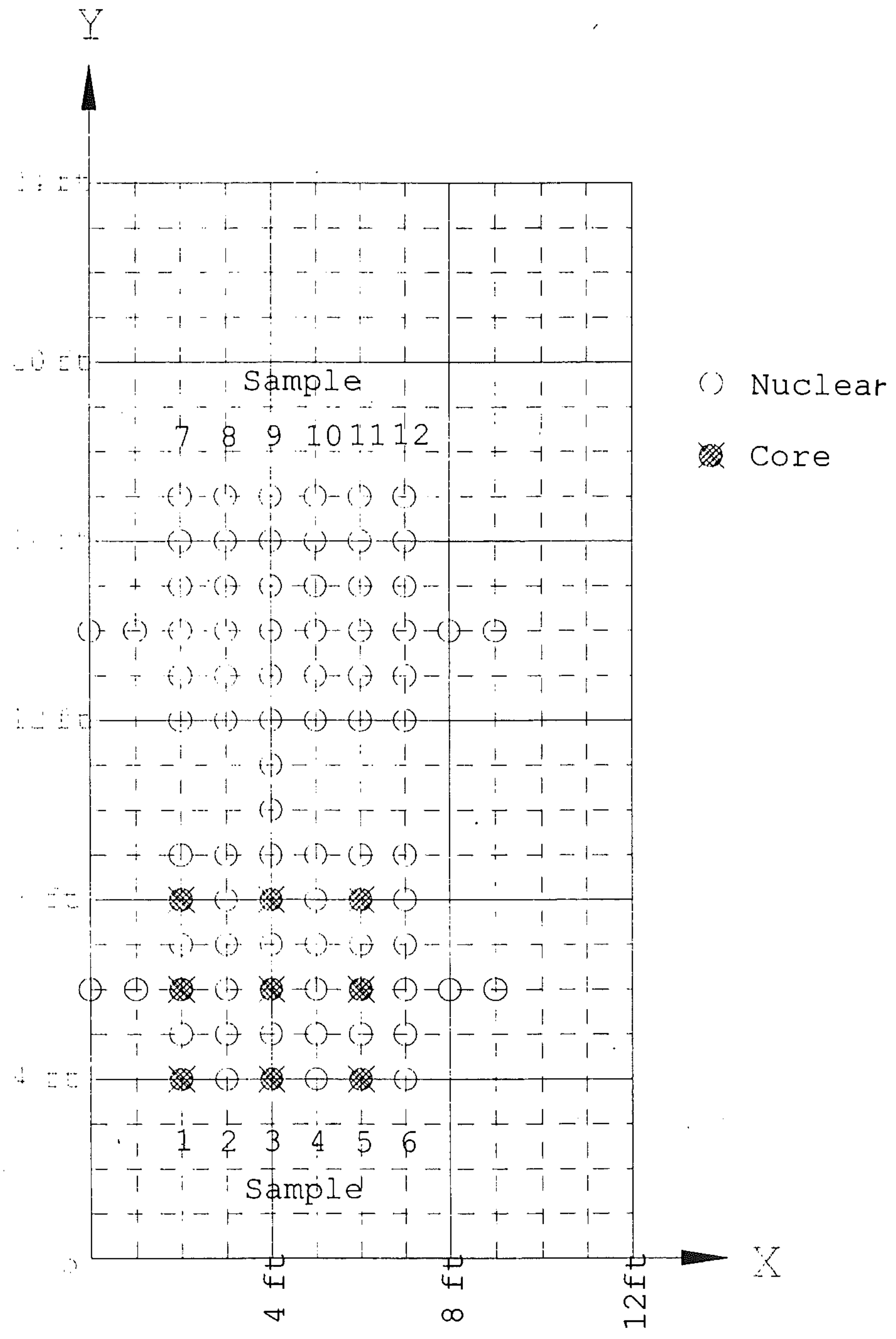
Site 21 Section 2



Site 21 Section 3

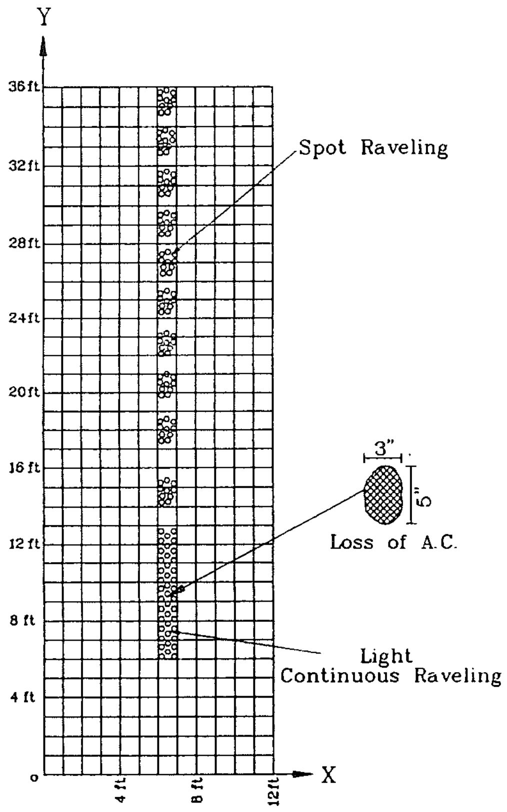


Site 22

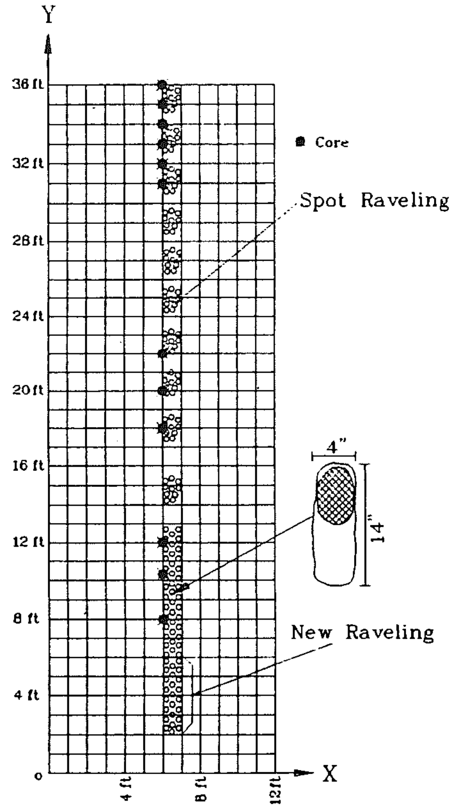

Y
24 ft
20 ft
16 ft
12 ft
8 ft
4 ft
0
Sample
7 8 9 10 11 12
1 2 3 4 5 6
Sample
4 ft
8 ft
12ft
X
() Nuclear
▨ Core

Appendix B

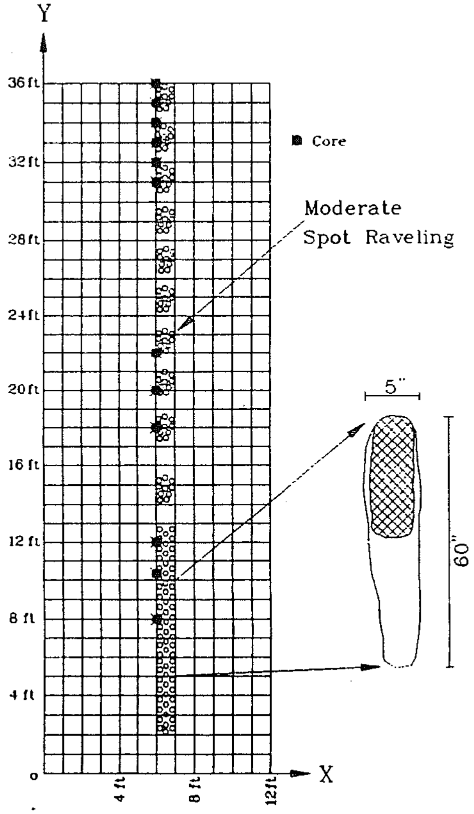
Pavement Distress at Site 1
(Parking Lot, Jackson)



Survey Date: Feb.2, 98

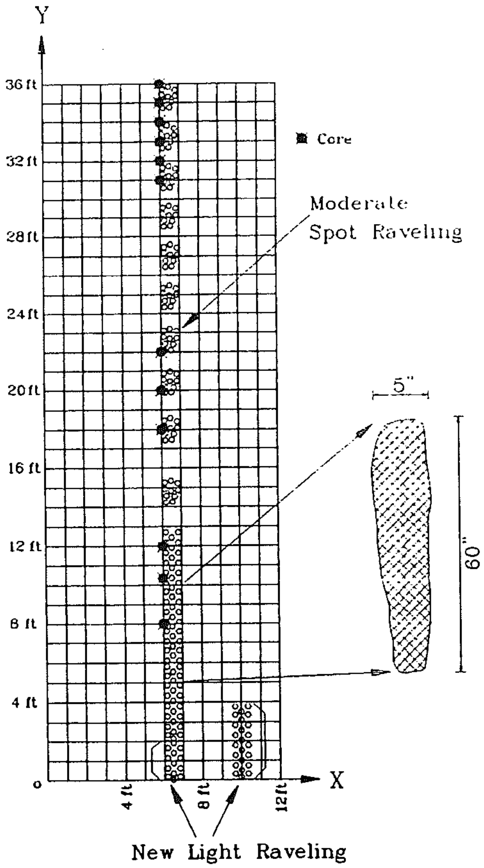


Survey Date: May 27, 98

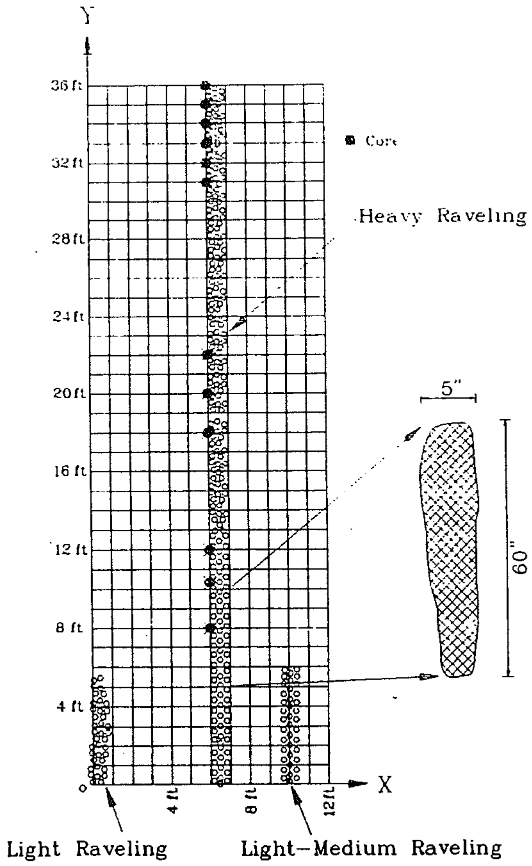


Survey Date: October 2, 98

Pavement Distress at Site 1
(Parking Lot, Jackson)

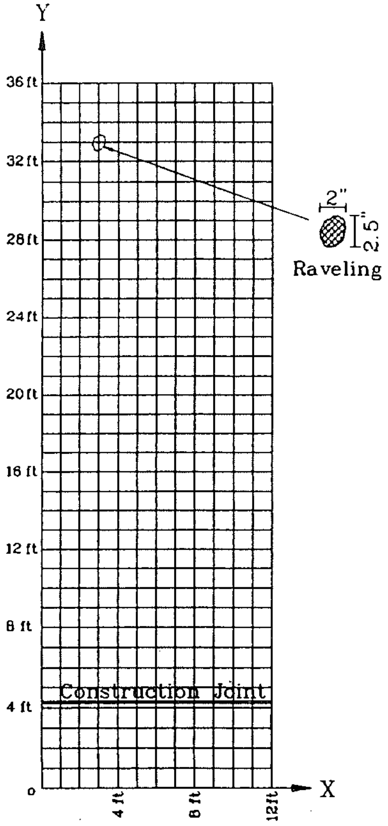


Survey Date: April 5, 99

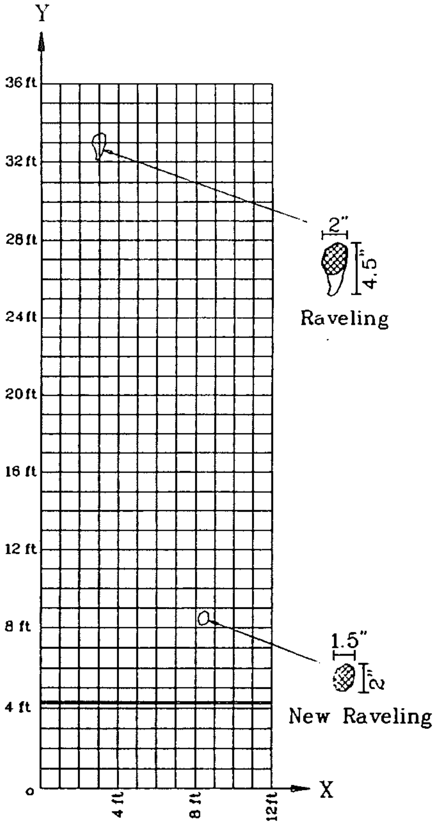


Survey Date: June 21, 99

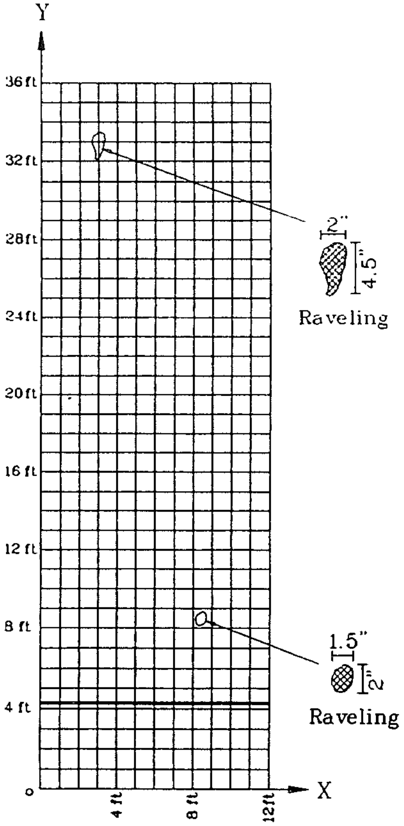
Pavement Distress at Site 2
(Michigan Ave. Jackson)



Survey Date: Feb.2, 98



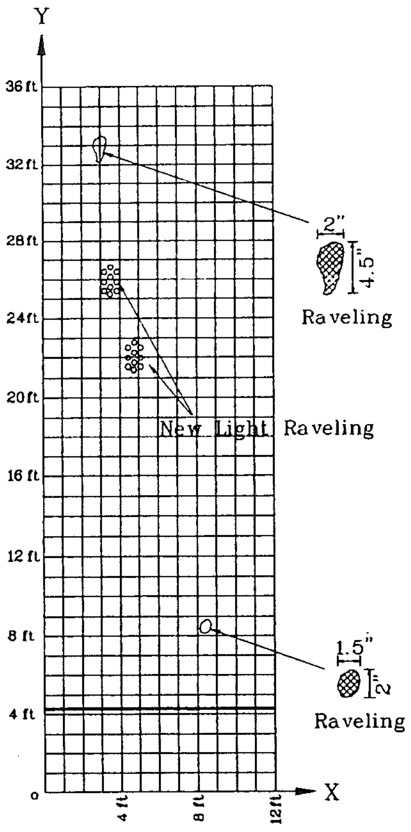
Survey Date: May 27, 98



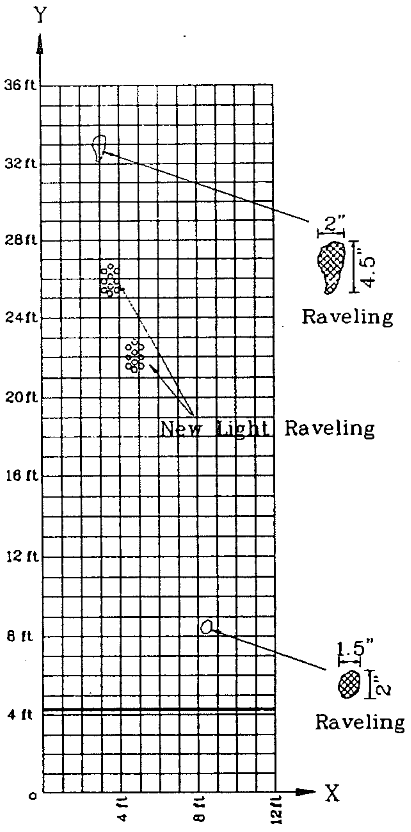
No Change

Survey Date: October 2, 98

Pavement Distress at Site 2
(Michigan Ave. Jackson)

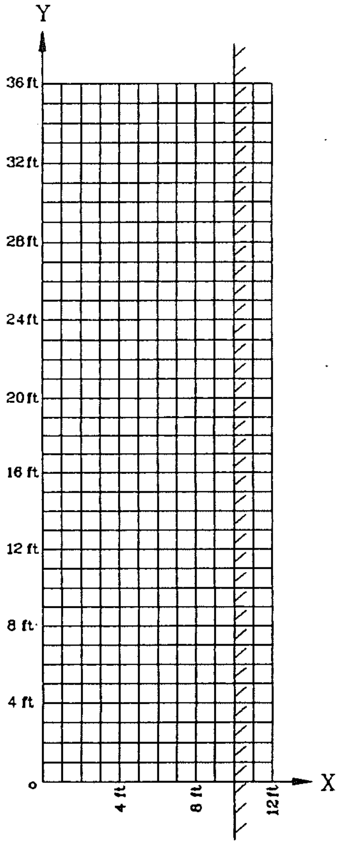


Survey Date: April 5, 99



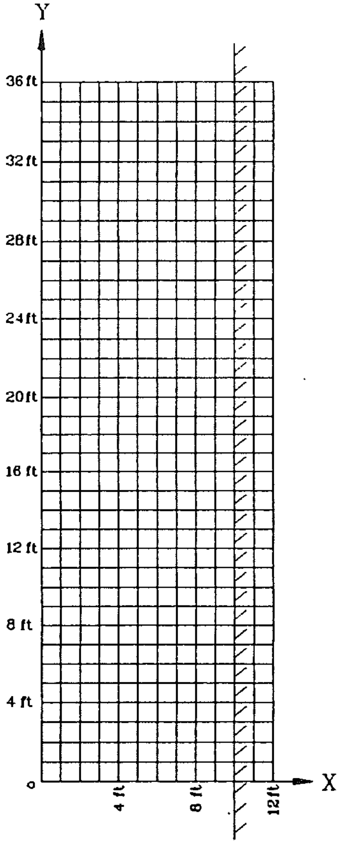
No Change
Survey Date: June 21, 99

Pavement Distress at Site 3
(Michigan Ave. Jackson)



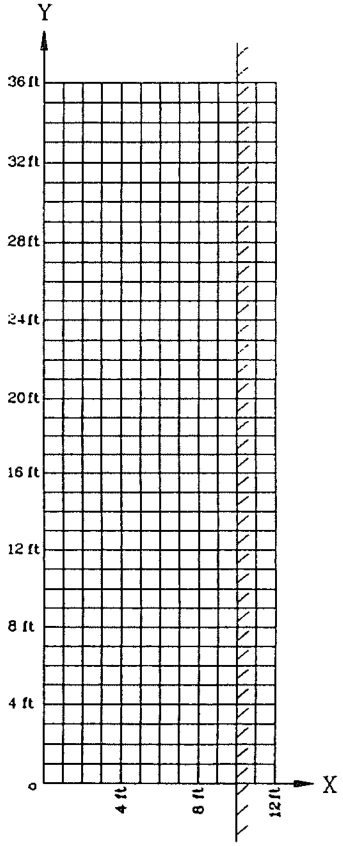
No Distress

Survey Date: Feb. 2, 98



No Distress

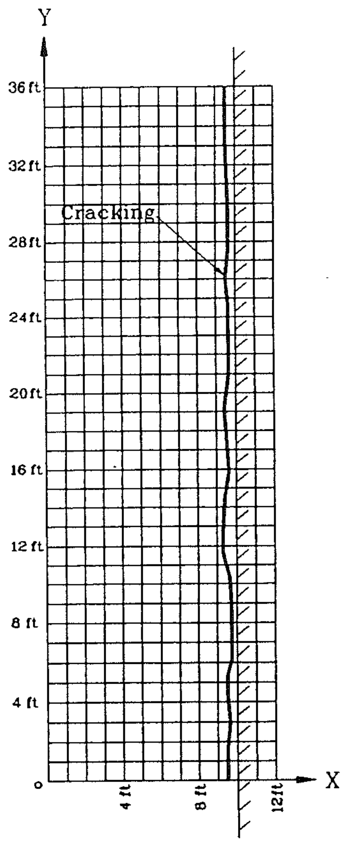
Survey Date: May 27, 98



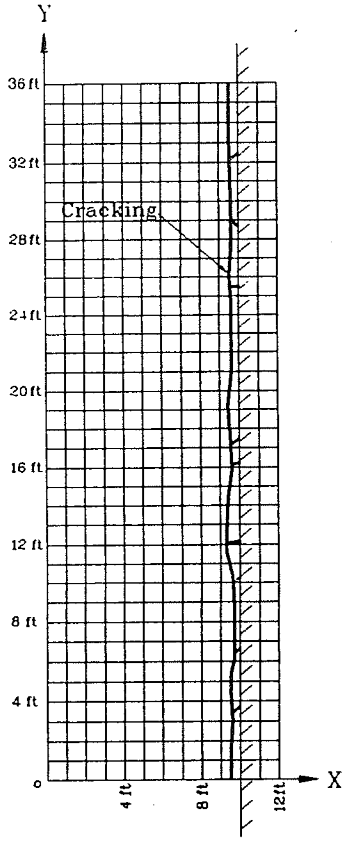
No Distress

Survey Date: October 2, 98

Pavement Distress at Site 3
(Michigan Ave. Jackson)

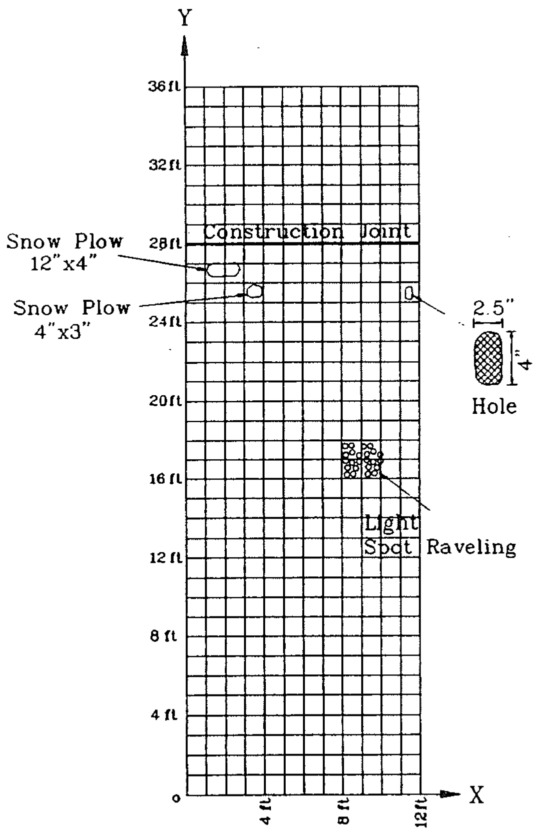


Survey Date: April 5, 99

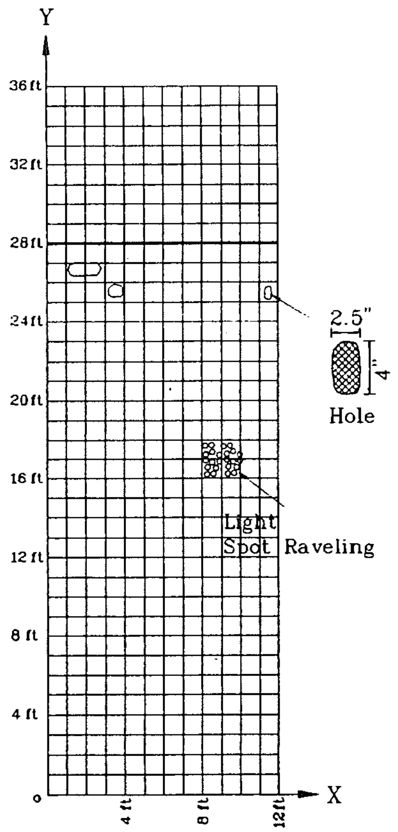


Survey Date: June 21, 99

Pavement Distress at Site 5
(US-12, Moscow)

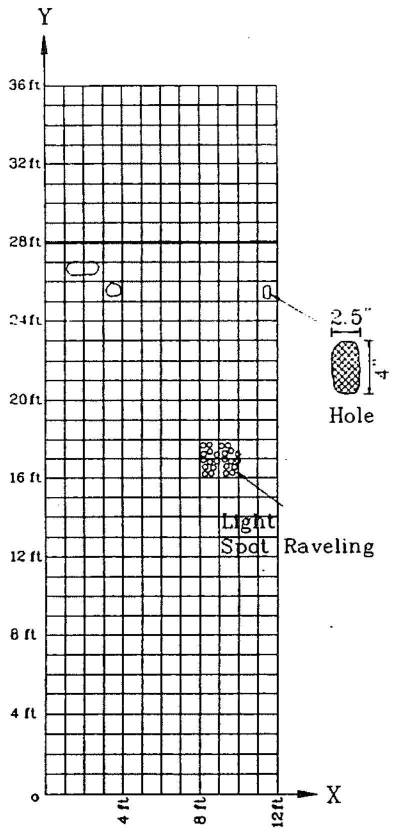


Survey Date: Feb.2, 98



No Change

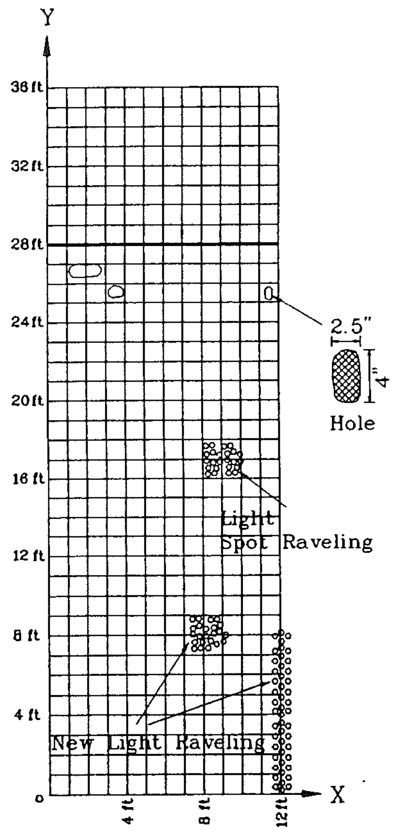
Survey Date: May 27, 98



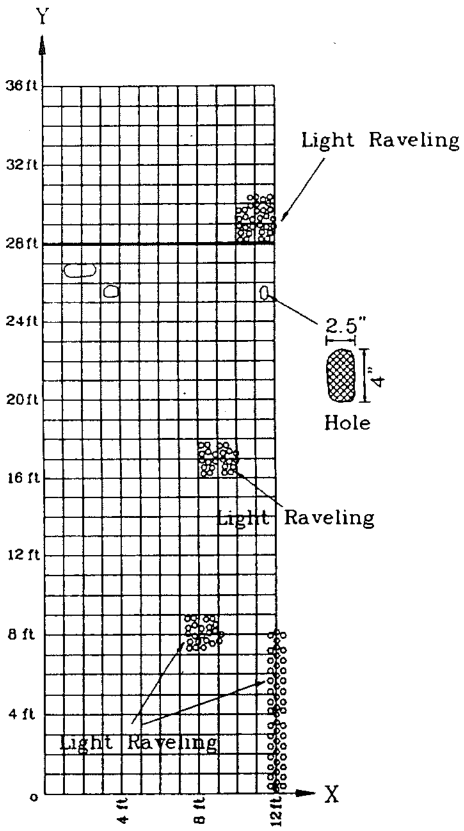
No Change

Survey Date: October 2, 98

Pavement Distress at Site 5
(US-12, Moscow)

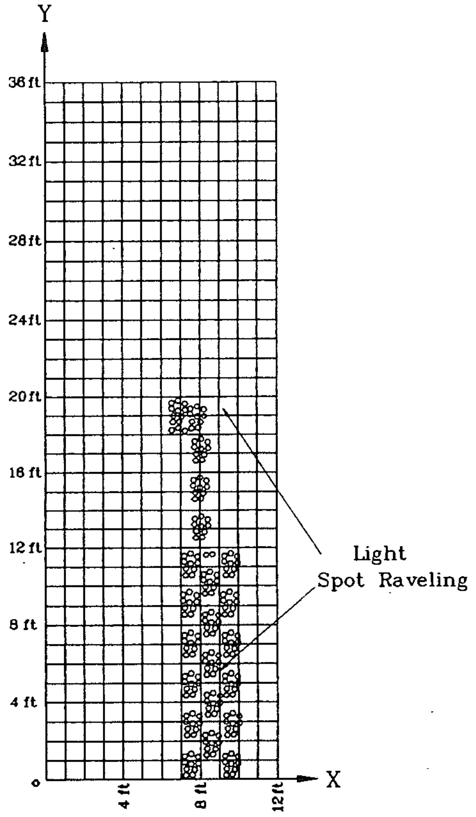


Survey Date: April 5, 99

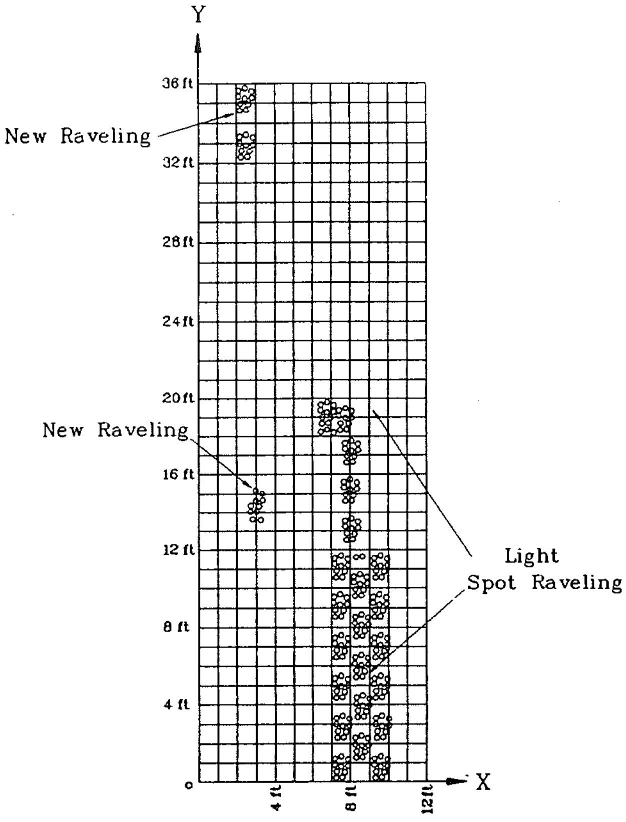


Survey Date: June 21, 99

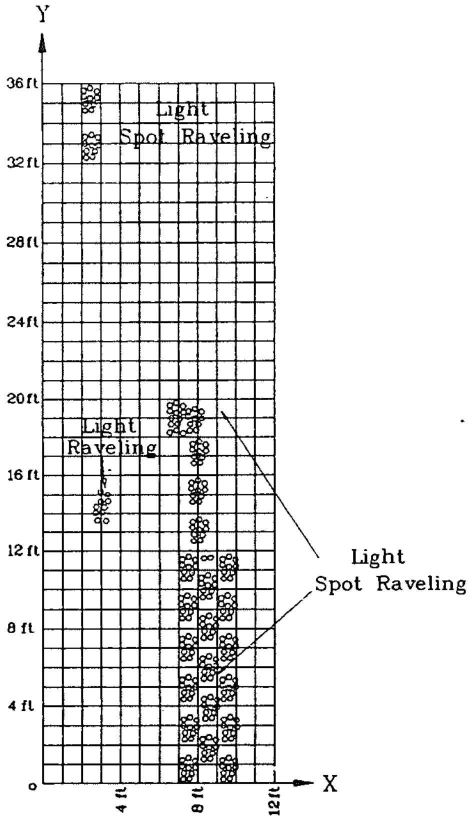
Pavement Distress at Site 6
(Sterling Road)



Survey Date: Feb.2, 98



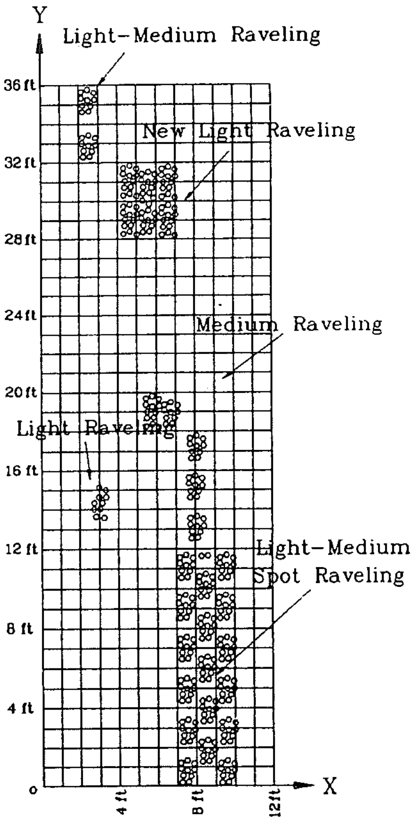
Survey Date: May 27, 98



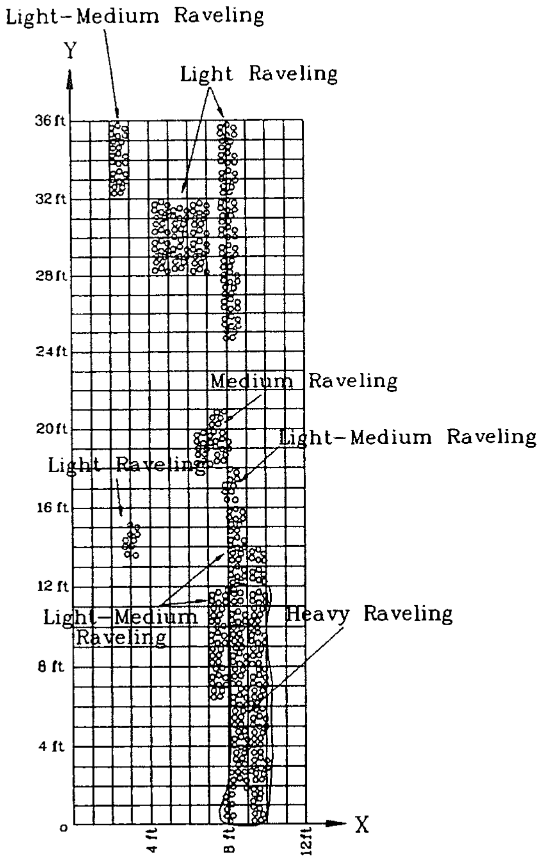
No Change

Survey Date: October 2, 98

Pavement Distress at Site 6
(Sterling Road)

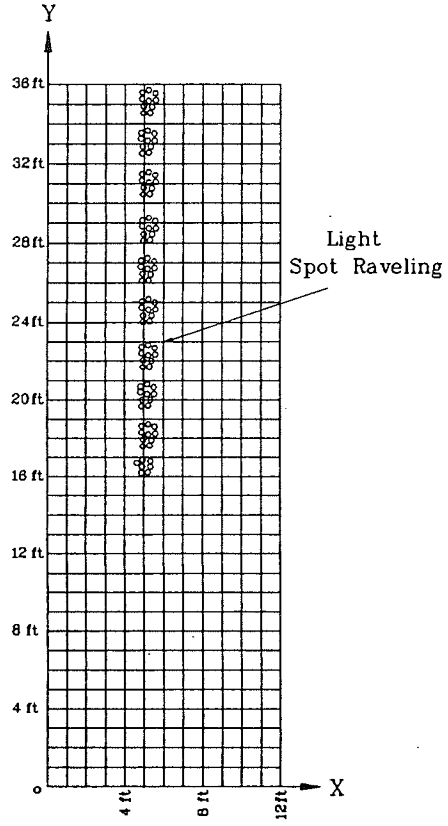


Survey Date: April 5, 99

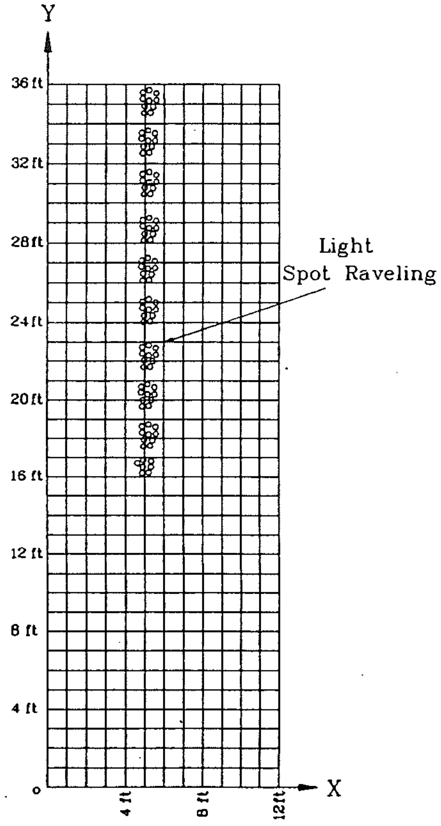


Survey Date: June 21, 99

Pavement Distress at Site 7
(Sterling Road)

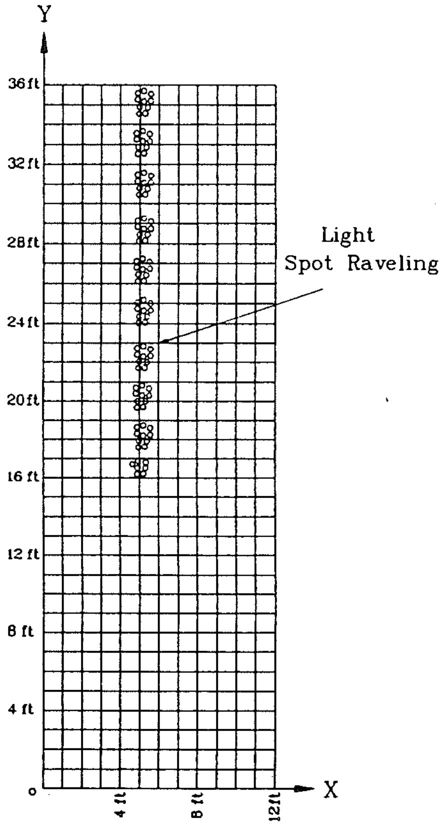


Survey Date: Feb.2, 98



No Change

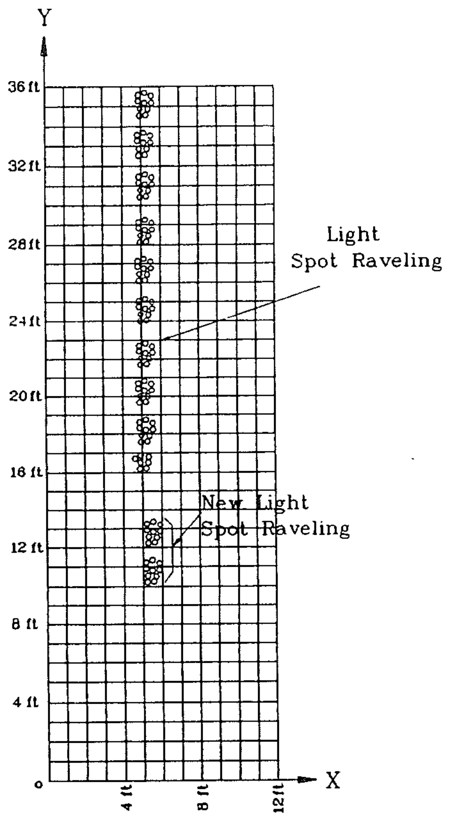
Survey Date: May 27, 98



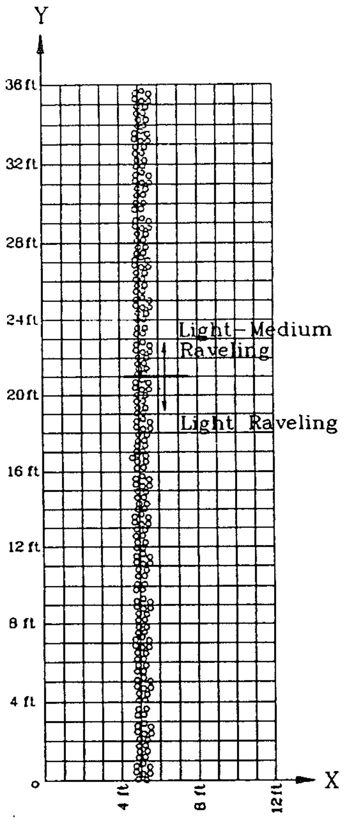
No Change

Survey Date: October 2, 98

Pavement Distress at Site 7
(Sterling Road)

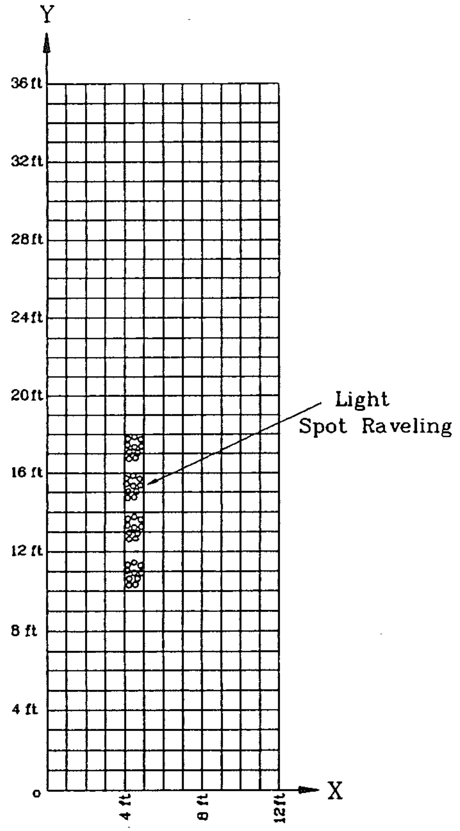


Survey Date: April 5, 99

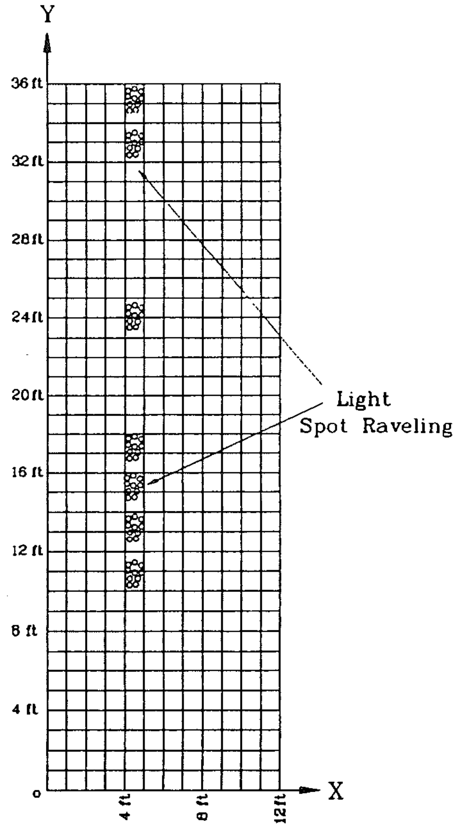


Survey Date: June 21, 99

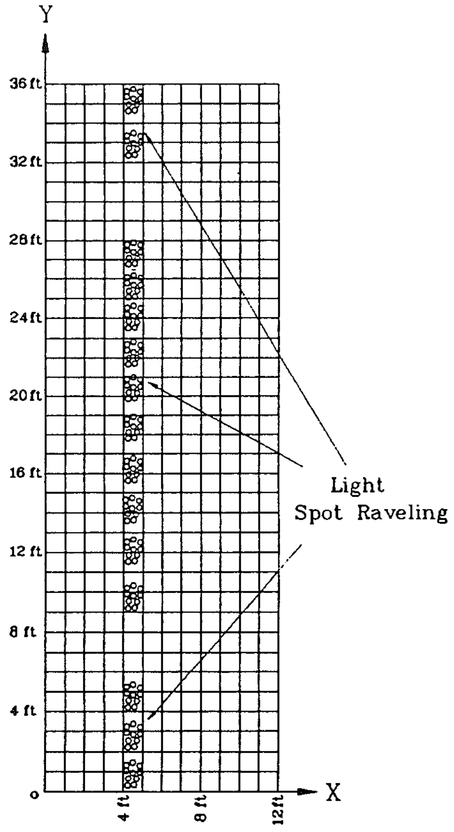
Pavement Distress at Site 8
(Sterling Road)



Survey Date: Feb.2, 98

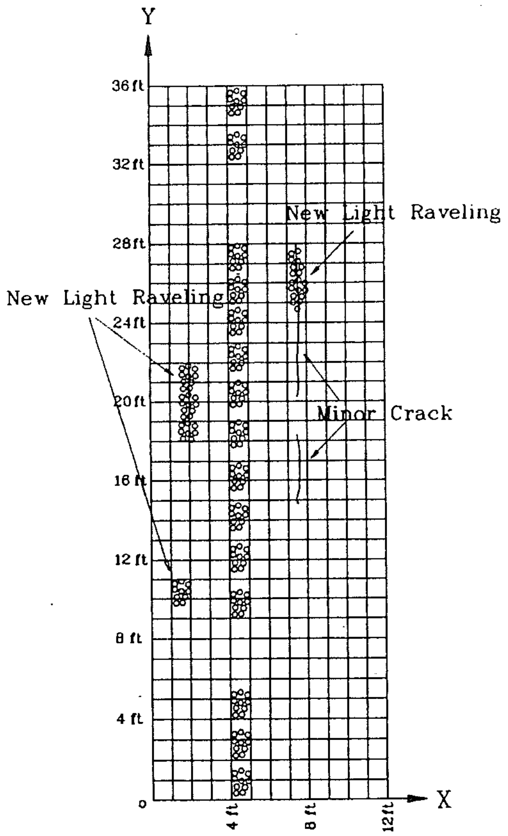


Survey Date: May 27, 98

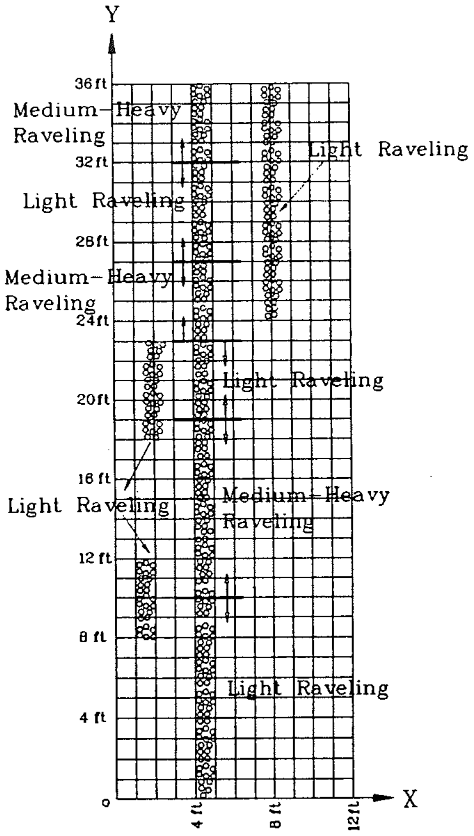


Survey Date: October 2, 98

Pavement Distress at Site 8
(Sterling Road)

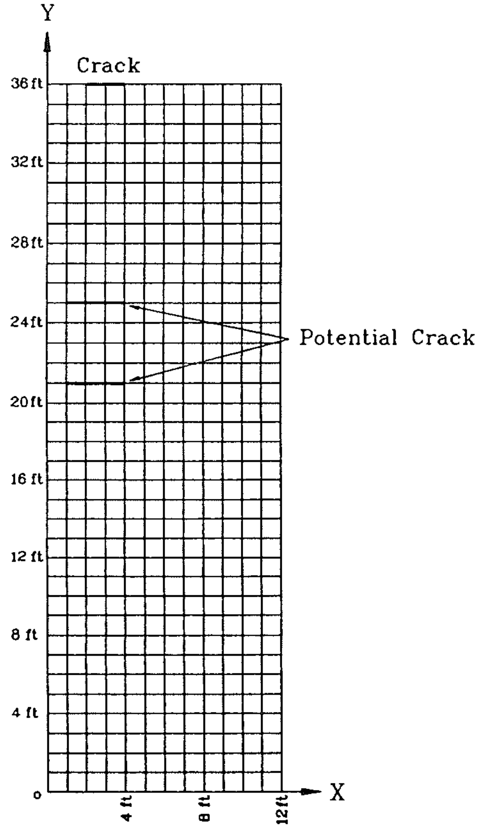


Survey Date: April 5, 99

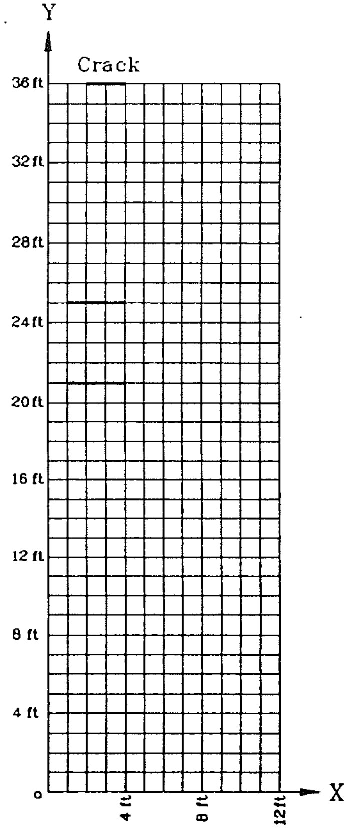


Survey Date: June 21, 99

Pavement Distress at Site 11
(M–100, Grand Ledge)

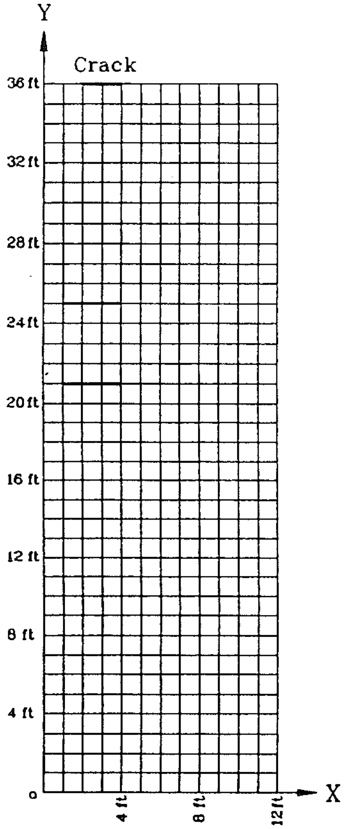


Survey Date: Feb.25, 98



No Change

Survey Date: May 28, 99

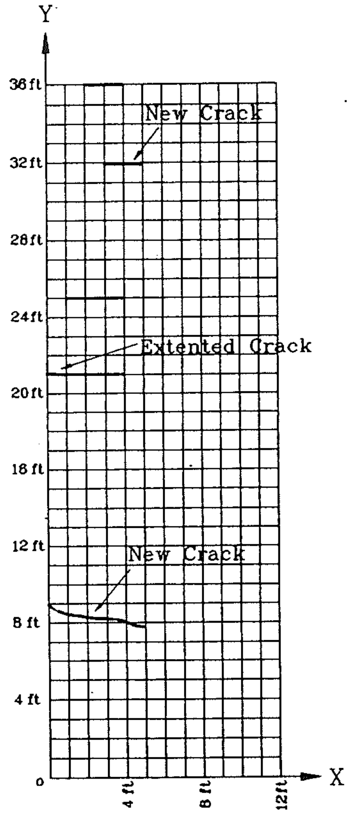


No Change

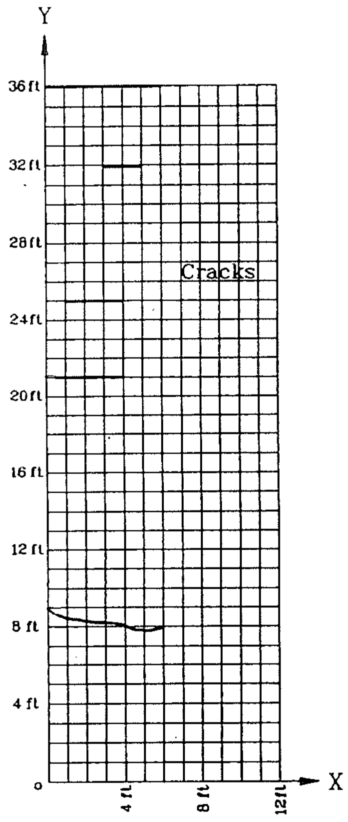
Survey Date: October 2, 98

Pavement Distress at Site 11

(M-100, Grand Ledge)

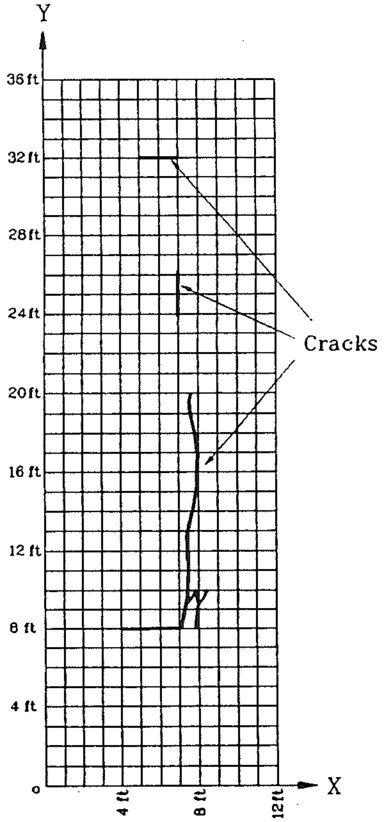


Survey Date: April 5, 99

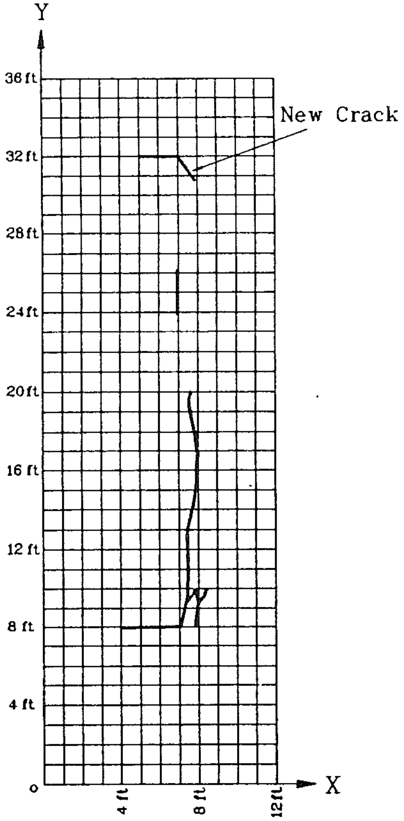


Survey Date: June 21, 99

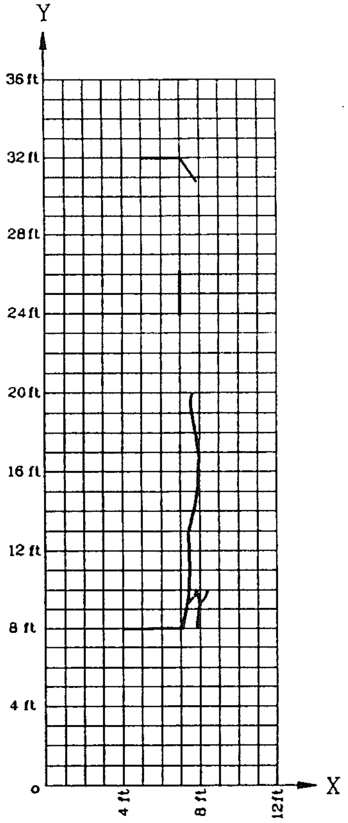
Pavement Distress at Site 13
(M–50)



Survey Date: Feb.25, 98

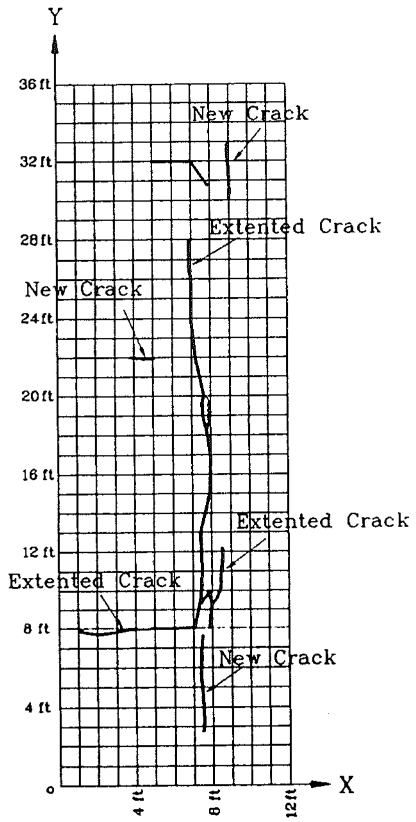


Survey Date: May 27, 98

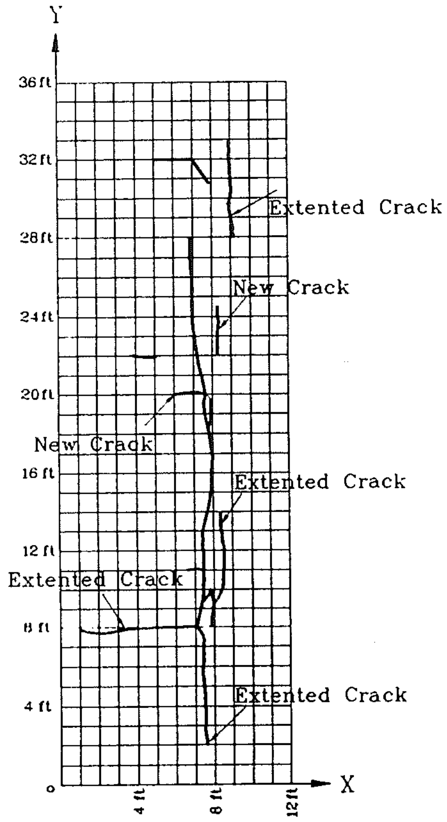


No Change
Survey Date: October 2, 98

Pavement Distress at Site 13
(M-50)

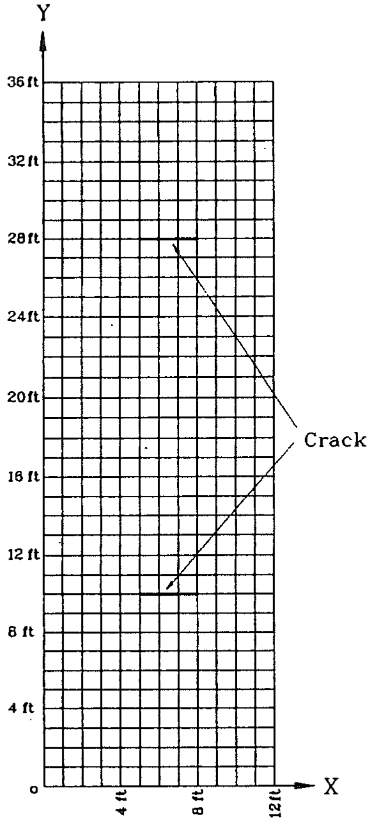


Survey Date: April 5, 99

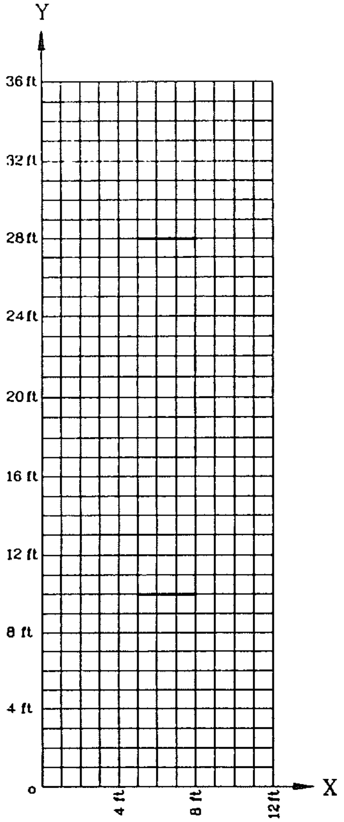


Survey Date: June 21, 99

Pavement Distress at Site 14
(M–50)

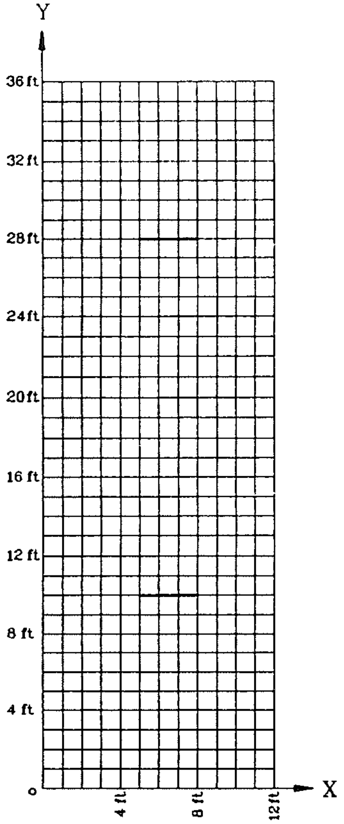


Survey Date: Feb.25, 98



No Change

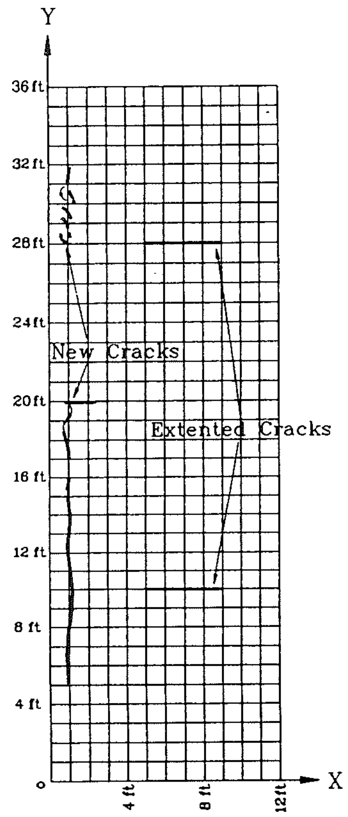
Survey Date: May 27, 98



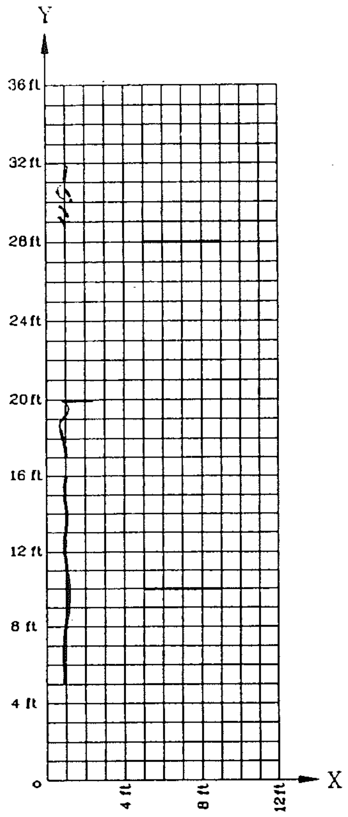
No Change

Survey Date: October 2, 98

Pavement Distress at Site 14
(M–50)



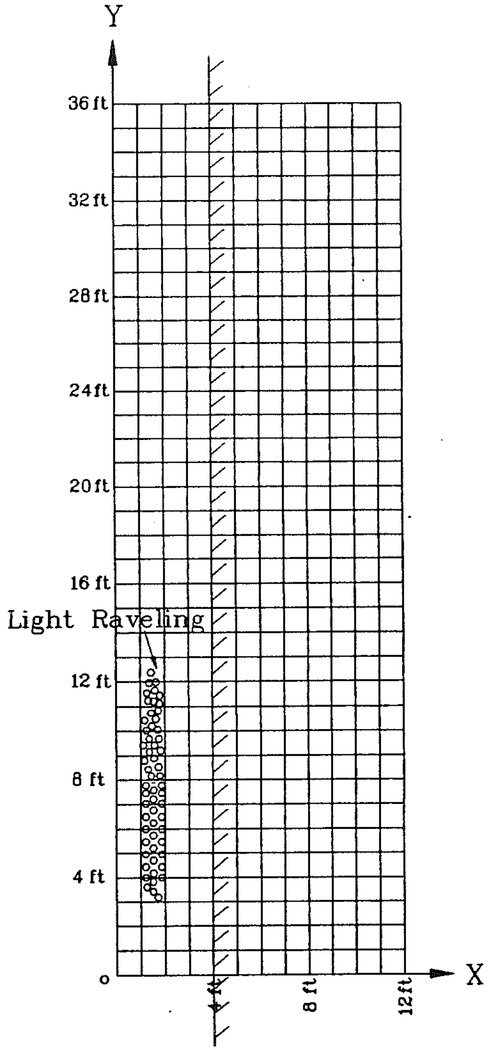
Survey Date: April 5, 99



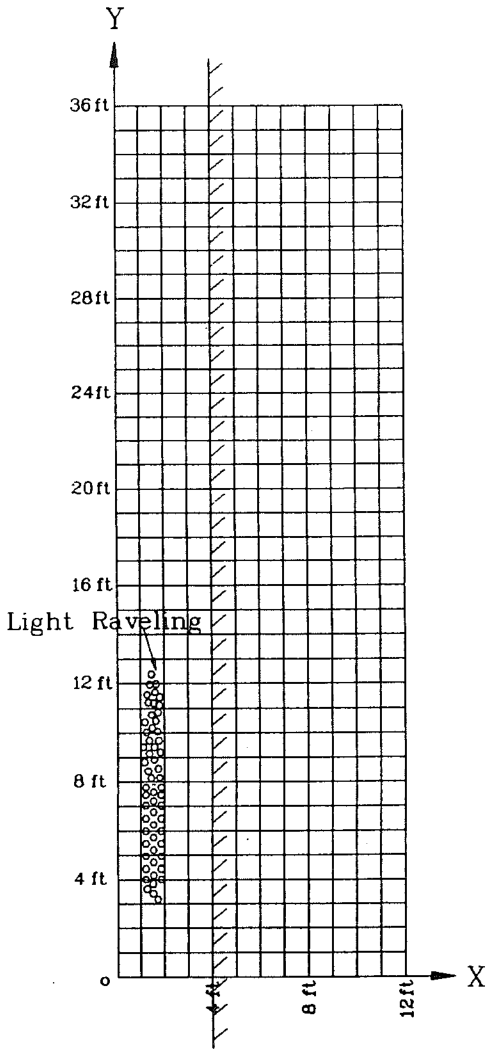
No Change

Survey Date: June 21, 99

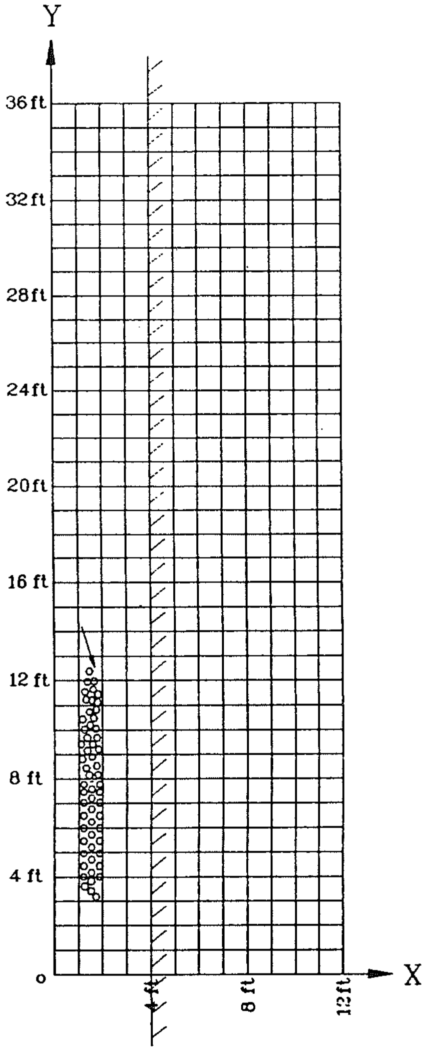
Pavement Distress at Site 15
(US-23, Shoulder)



Survey Date: July 31, 98



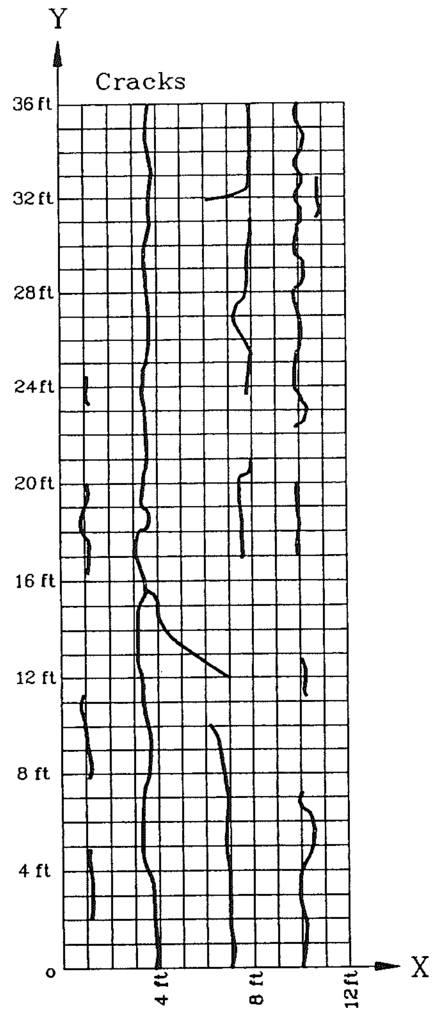
No Change
Survey Date: April 20, 99



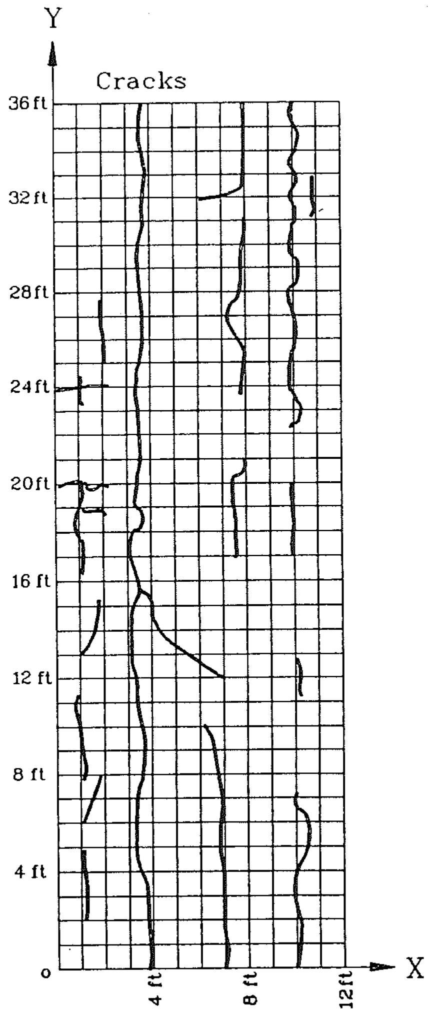
No Change
Survey Date: June 21, 99

Pavement Distress at Site 16

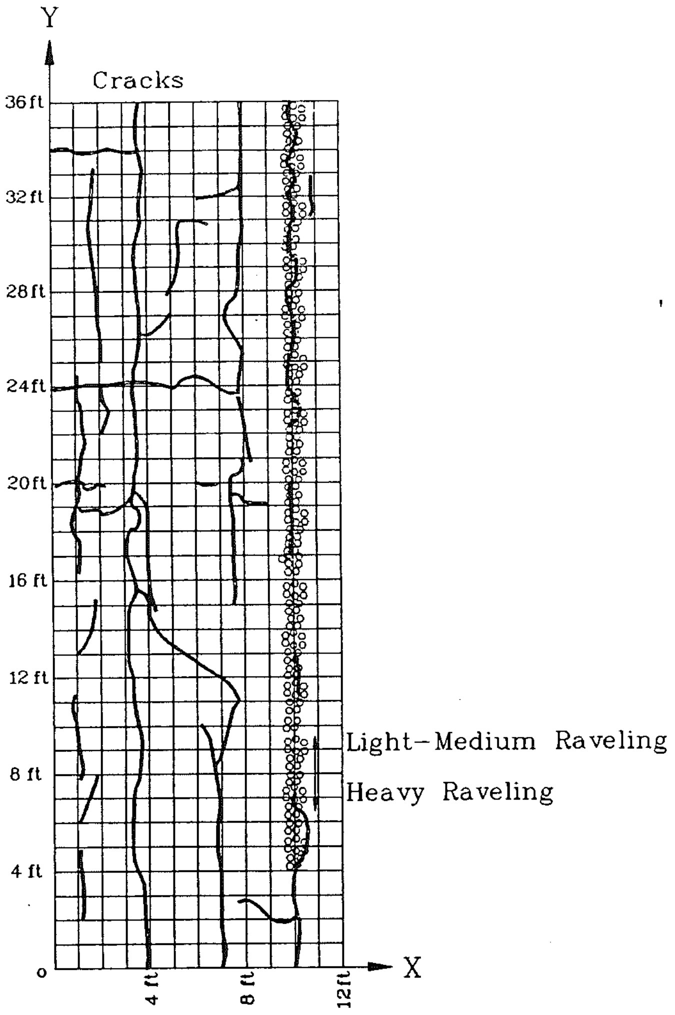
(US-23, Ramp Exit)



Survey Date: July 31, 98

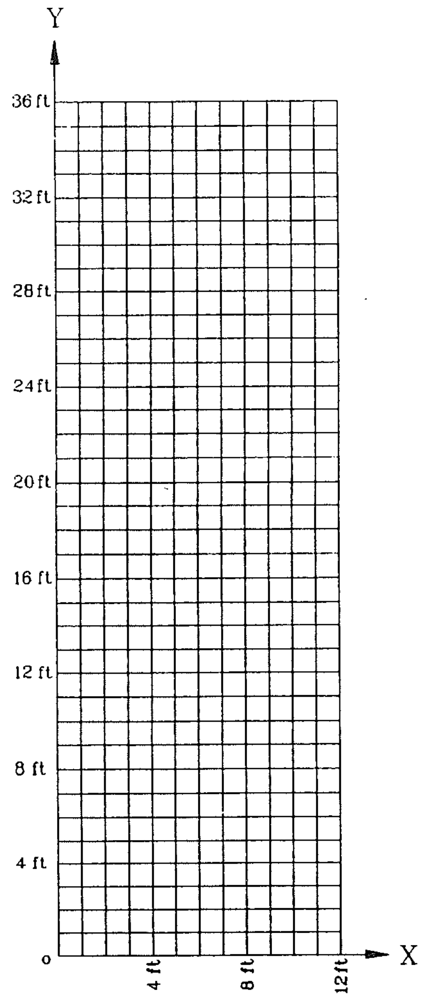


Survey Date: April 20, 99

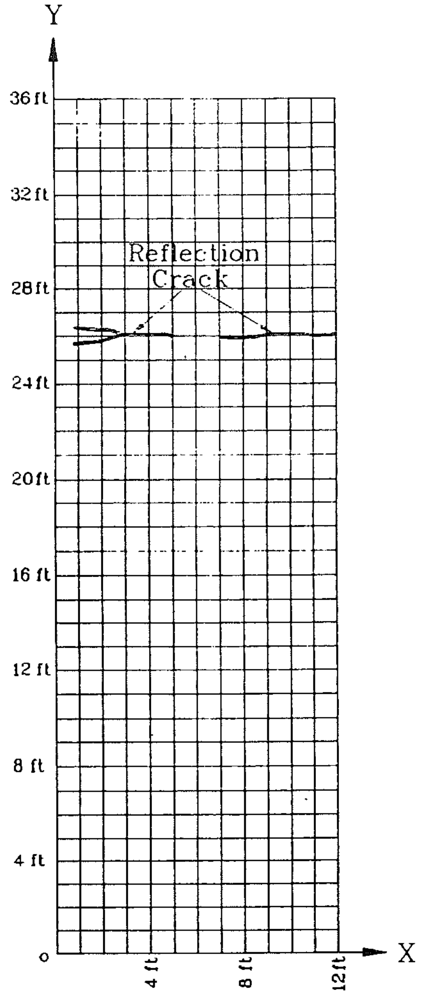


Survey Date: June 21, 99

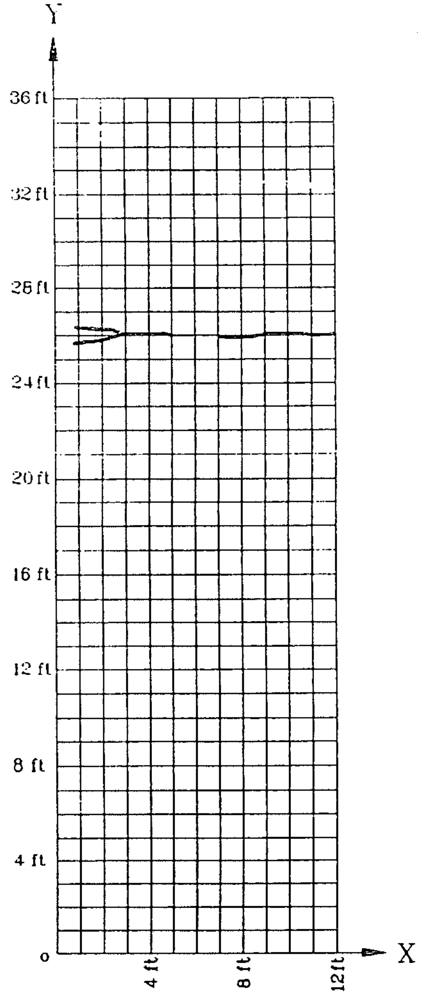
Pavement Distress at Site 17 (Composite)
(69 Bus East Lansing)



No Distress
Survey Date: August 12, 98

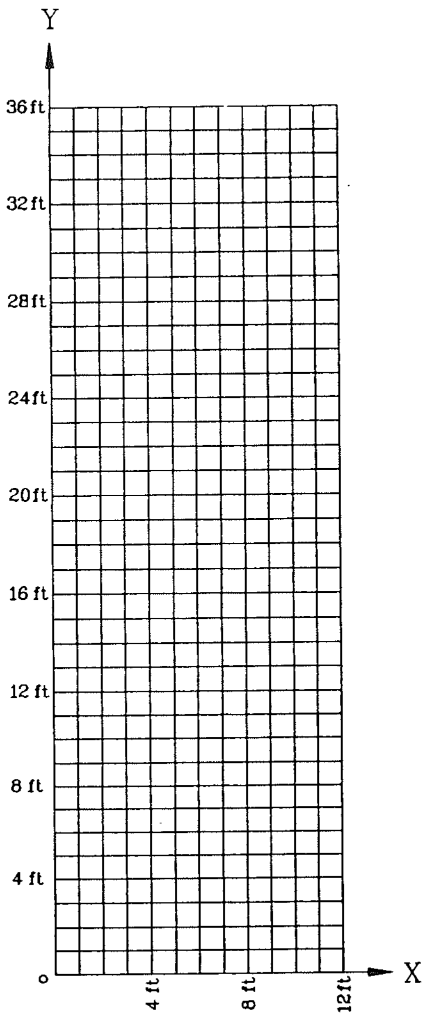


Survey Date: April 28, 99



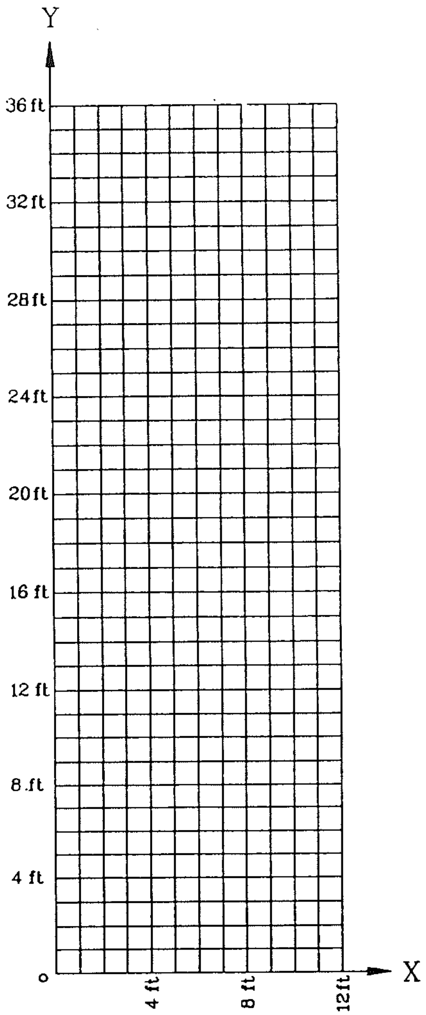
No Change
Survey Date: August 20, 99

Pavement Distress at Site 18
(M–99, Lansing)



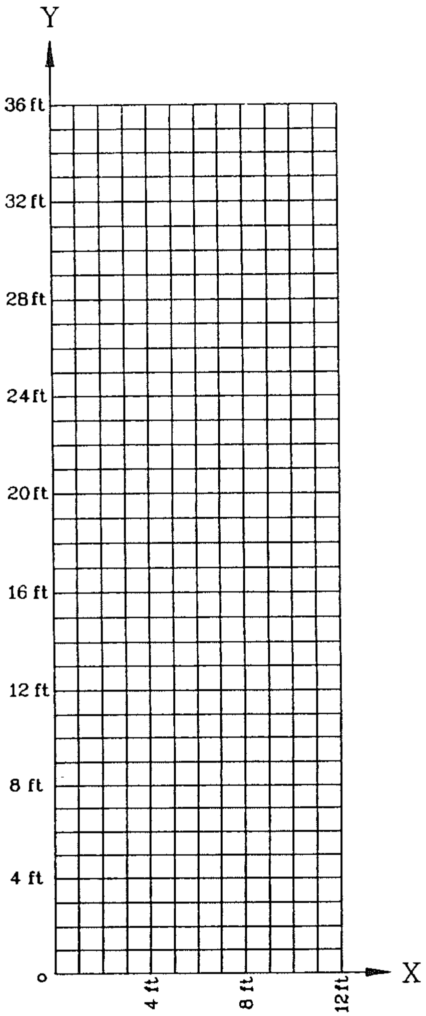
No Distress

Survey Date: August 12, 98



No Distress

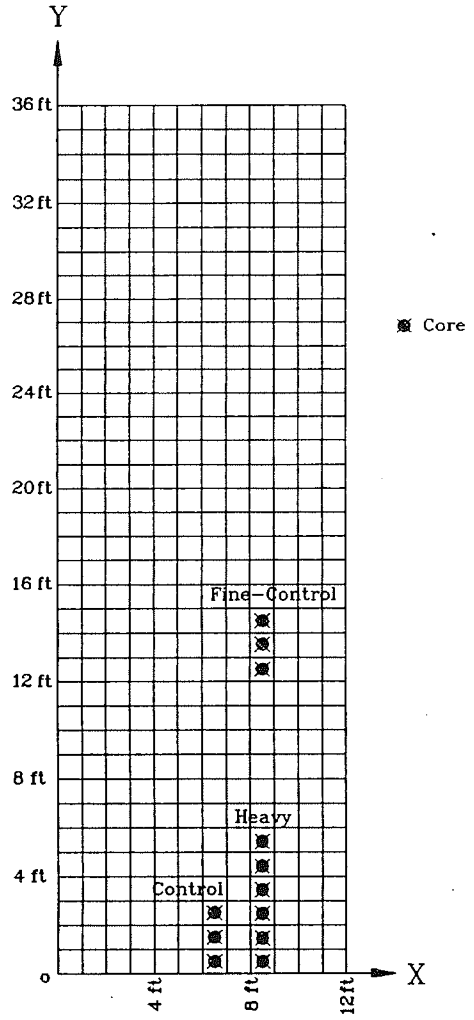
Survey Date: April 28, 99



No Distress

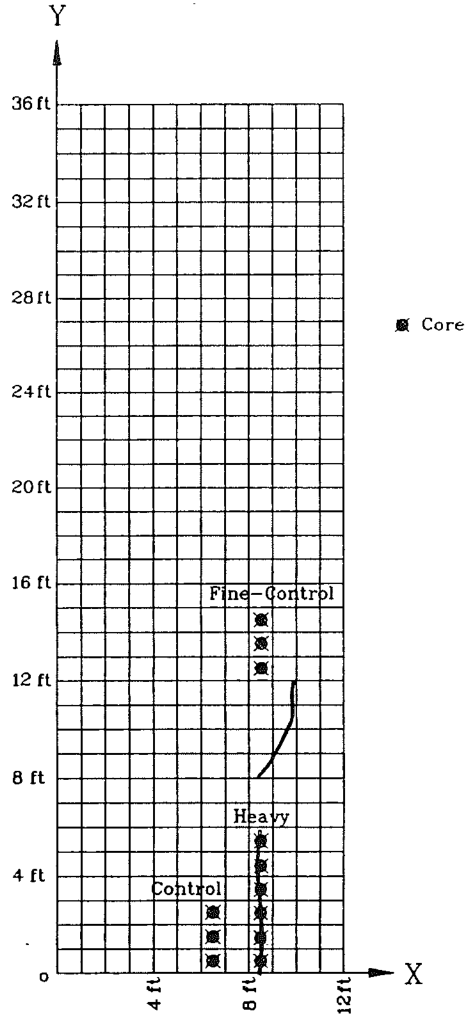
Survey Date: June 21, 99

Pavement Distress at Site 20 Section 4
(I-75, near Rondo overpass)

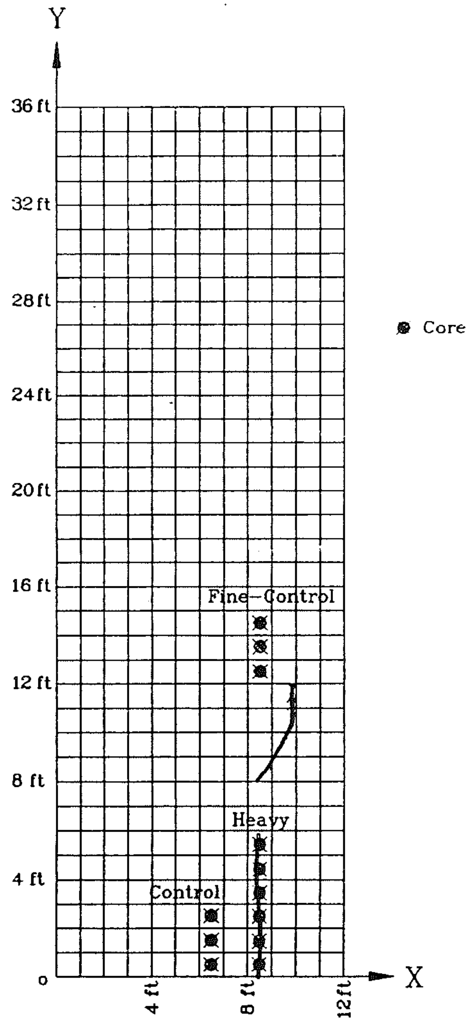


No Distress

Survey Date: October 21, 98



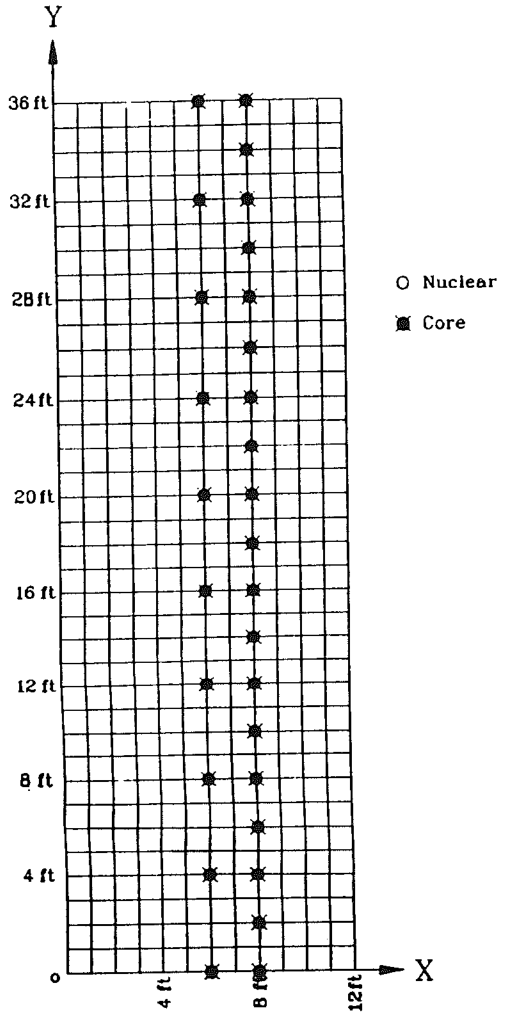
Survey Date: April 20, 99



No Change

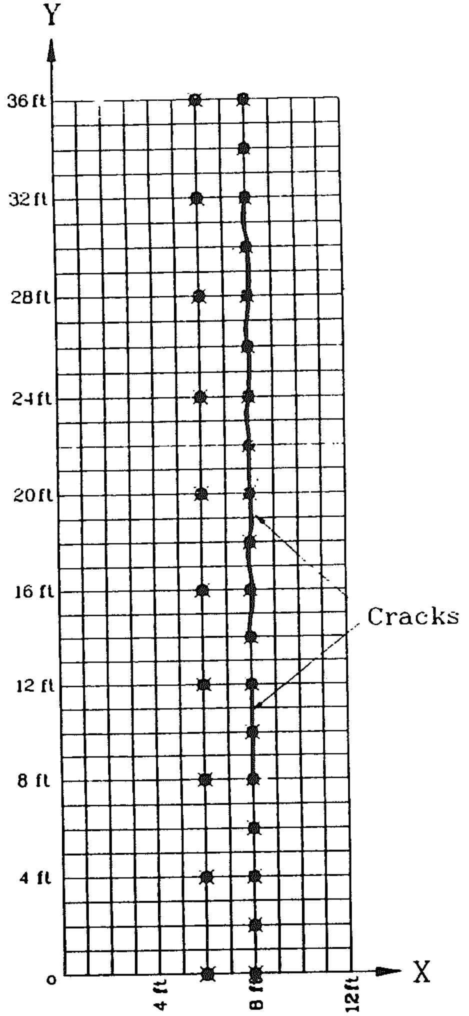
Survey Date: June 22, 99

Pavement Distress at Site 20 Section 6
(I–75, near Rondo overpass)

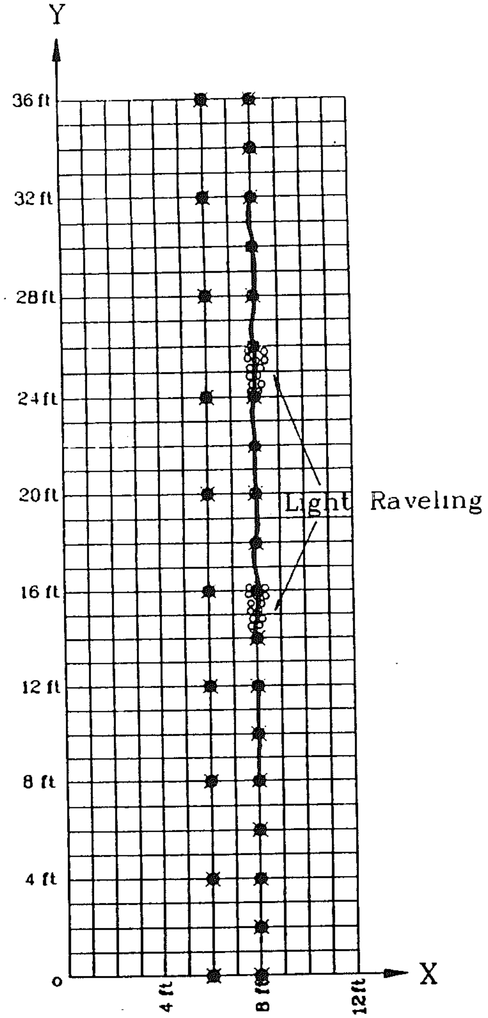


No Distress

Survey Date: October 21, 98



Survey Date: April 20, 99



Survey Date: June 22, 99

Appendix C

Gradation Comparisons at Sites 1, 3, 5, 10, 13, 15, 16, 17, 18, 19 ,20 and 21

Site 1

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	C-C	Sample 2 - Sample 5	5.6E-02	1.62	9.4E-02	1.59	3.2E-01	0.77
0	C-C	Sample 2 - Outside	5.9E-01	0.70	4.5E-01	0.89	8.2E-01	0.18
0	C-C	Sample 5 - Outside	3.1E-01	0.91	4.7E-01	0.70	4.8E-01	0.59
1	C-L	Sample 2 - Sample 1	4.9E-04	6.27	1.1E-03	9.44	1.2E-03	8.06
1	C-L	Sample 5 - Sample 1	7.7E-07	7.89	5.8E-06	11.02	1.5E-05	8.83
1	C-L	Outside - Sample 1	4.4E-04	6.98	7.3E-04	10.33	1.2E-03	8.24
1	L-M	Sample 1 - Sample 4	4.7E-06	10.20	1.1E-06	14.23	1.5E-06	12.22
1	M-H	Sample 4 - Sample 3	1.5E-01	2.29	3.2E-01	1.21	6.5E-01	0.47
2	C-M	Sample 4 - Sample 2	1.0E-05	16.48	1.3E-07	23.66	1.3E-07	20.28
2	C-M	Sample 4 - Sample 5	7.6E-09	18.10	5.1E-11	25.25	1.1E-10	21.05
2	C-M	Sample 4 - Control	1.1E-05	17.18	1.5E-07	24.55	1.8E-07	20.46
2	L-H	Sample 1 - Sample 3	2.4E-06	12.49	3.6E-06	15.44	5.8E-06	12.69
3	C-H	Sample 2 - Sample 3	1.7E-05	18.76	1.4E-06	24.87	1.3E-06	20.75
3	C-H	Sample 5 - Sample 3	1.2E-08	20.38	7.6E-10	26.46	1.3E-09	21.52
3	C-H	Outside - Sample 3	1.9E-05	19.47	1.6E-06	25.77	1.6E-06	20.93

Site 3

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	C-C	Sample 1 - Sample 5	1.0E-02	3.65	3.3E-04	6.08	5.5E-04	3.73
1	C-L	Sample 1 - Sample 2	1.5E-03	4.87	1.8E-03	5.06	1.9E-02	2.43
1	C-L	Sample 5 - Sample 2	3.1E-01	1.22	2.8E-01	1.03	6.5E-02	1.29
1	L-M	Sample 2 - Sample 4	1.5E-01	1.75	5.6E-05	6.27	9.9E-05	4.16
2	C-M	Sample 1 - Sample 4	2.0E-04	6.62	2.1E-06	11.33	7.7E-06	6.59
2	C-M	Sample 5 - Sample 4	2.9E-02	2.96	1.2E-04	5.25	1.7E-04	2.87

Site 5

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	M-M	Sample 4 - Sample 5	4.5E-01	1.51	1.0E+00	0.01	9.4E-01	0.10
1	C-L	Outside - Sample 3	8.9E-01	0.09	4.4E-02	2.14	9.2E-03	1.98
1	L-M	Smaple 3 - Sample 4	7.7E-03	3.82	1.6E-02	4.78	1.1E-03	3.30
1	L-M	Sample 3 - Sample 5	1.8E-01	2.31	2.7E-02	4.76	1.5E-02	3.20
1	M-H	Sample 4 - Sample 1	3.8E-02	3.57	2.8E-02	4.93	3.5E-03	3.38
1	M-H	Sample 5 - Sample 1	2.9E-01	2.06	4.0E-02	4.91	2.2E-02	3.28
2	C-M	Outside - Sample 4	1.8E-02	3.91	1.7E-01	2.63	1.4E-01	1.32
2	C-M	Outside - Sample 5	2.2E-01	2.41	2.2E-01	2.62	3.4E-01	1.22
2	L-H	Sample 3 - Sample 1	8.1E-01	0.25	9.1E-01	0.15	9.2E-01	0.08
3	C-H	Outside - Sample 1	7.9E-01	0.34	1.4E-01	2.29	3.4E-02	2.06

Site 10

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	L-L	Sample 2 - Sample 5	2.9E-01	1.57	2.3E-01	2.47	2.5E-01	1.41
0	ML-ML	Sample 1 - Sample 3	9.6E-01	0.05	8.1E-01	0.27	2.7E-01	0.96
0	C-C	Control C - Control D	9.5E-02	2.34	9.0E-01	0.08	7.3E-01	0.18
0.5	L-ML	Sample 2 - Sample 1	6.8E-03	6.16	1.3E-02	6.35	3.1E-03	4.35
0.5	L-ML	Sample 2 - Sample 3	2.5E-03	6.21	2.7E-02	6.08	2.0E-02	3.39
0.5	L-ML	Sample 5 - Sample 1	3.1E-03	7.73	7.1E-04	8.82	3.4E-03	5.76
0.5	L-ML	Sample 5 - Sample 3	1.1E-03	7.78	3.3E-03	8.55	1.2E-02	4.80
0.5	ML-M	Sample 1 - Sample 4	6.2E-01	0.54	8.8E-03	2.37	4.2E-02	1.44
0.5	ML-M	Sample 3 - Sample 4	4.0E-01	0.59	1.3E-01	2.11	5.7E-01	0.48
1	L-M	Sample 2 - Sample 4	6.7E-03	5.62	6.0E-02	3.98	1.4E-02	2.91
1	L-M	Sample 5 - Sample 4	2.9E-03	7.19	3.3E-03	6.45	9.8E-03	4.32
1	C-L	Control C - Sample 2	1.5E-02	5.55	3.1E-02	4.96	2.1E-03	4.59
1	C-L	Control C - Sample 5	6.7E-03	7.12	1.8E-03	7.43	2.6E-03	6.01
1	C-L	Control D - Sample 2	1.2E-03	7.89	3.0E-02	5.04	2.8E-03	4.78
1	C-L	Control D - Sample 5	6.4E-04	9.45	1.8E-03	7.51	3.0E-03	6.19
1.5	C-ML	Control C - Sample 1	6.6E-01	0.61	3.3E-02	1.39	5.9E-01	0.25
1.5	C-ML	Control D - Sample 3	9.4E-03	1.68	3.9E-01	1.05	1.6E-01	1.39
1.5	C-ML	Control C - Sample 1	6.6E-01	0.61	3.3E-02	1.39	5.9E-01	0.25
1.5	C-ML	Control D - Sample 3	9.4E-03	1.68	3.9E-01	1.05	1.6E-01	1.39
2	C-M	Control C - Sample 4	9.5E-01	0.07	1.8E-01	0.98	1.8E-02	1.68
2	C-M	Control D - Sample 4	3.1E-02	2.27	1.7E-01	1.06	2.8E-02	1.87

Site 13

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	ML-ML	Sample 1 - Sample 4	2.1E-02	2.87	2.2E-02	3.02	3.3E-02	2.19
0	C-C	Sample 8 - Sample 3	1.4E-01	2.16	2.3E-01	1.73	1.6E-01	2.15
0.5	L-ML	Sample 2 - Sample 4	3.5E-01	1.64	7.4E-01	0.81	4.7E-01	1.59
0.5	L-ML	Sample 2 - Sample 1	2.4E-02	4.51	1.4E-01	3.83	1.1E-01	3.78
1	C-L	Sample 3 - Sample 2	1.3E-01	2.99	2.5E-01	2.99	1.2E-01	3.92
1	C-L	Sample 8 - Sample 2	6.1E-01	0.84	6.0E-01	1.26	4.2E-01	1.77
1.5	ML-H	Sample 4 - Sample 6	2.9E-01	2.97	2.5E-01	3.63	4.4E-01	2.15
1.5	C-ML	Sample 3 - Sample 1	2.8E-01	1.52	5.1E-01	0.84	9.2E-01	0.14
1.5	ML-H	Sample 1 - Sample 6	9.7E-01	0.10	8.4E-01	0.61	9.9E-01	0.04
1.5	C-ML	Sample 3 - Sample 4	3.7E-01	1.36	1.6E-01	2.18	1.4E-01	2.33
1.5	C-LM	Sample 8 - Sample 1	6.1E-04	3.67	3.1E-02	2.57	3.2E-02	2.01
1.5	C-LM	Sample 8 - Sample 4	3.2E-01	0.80	6.4E-01	0.46	7.8E-01	0.18
2	L-H	Sample 2 - Sample 6	4.7E-02	4.61	1.1E-01	4.44	1.3E-01	3.74
3	C-H	Sample 3 - Sample 6	5.6E-01	1.62	6.4E-01	1.45	9.5E-01	0.18
3	C-H	Sample 8 - Sample 6	1.8E-01	3.77	3.1E-01	3.18	4.8E-01	1.97

Site 15

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	L-L	Sample 1 -Sample 3	3.86E-01	1.05	8.81E-02	2.42	1.57E-02	2.42
0	L-L	Sample 1 -Sample 5	1.17E-03	6.14	4.75E-03	7.21	1.17E-03	6.71
0	C-C	Sample 2 -Sample 4	5.79E-01	0.17	7.55E-01	0.52	9.80E-01	0.03
0	C-C	Sample 2 -Sample 7	6.25E-03	2.90	1.84E-03	6.98	2.28E-03	5.74
0	C-C	Sample 2 -Sample 8	4.17E-01	1.42	3.20E-02	4.33	9.35E-03	4.10
0	C-C	Sample 2 -Sample 9	8.18E-01	0.42	6.89E-01	1.21	7.62E-01	0.74
0	L-L	Sample 3 -Sample 5	7.40E-03	5.09	2.67E-02	4.79	1.21E-02	4.29
0	C-C	Sample 4 -Sample 7	4.40E-03	3.07	5.91E-03	6.47	6.95E-03	5.70
0	C-C	Sample 4 -Sample 8	4.69E-01	1.25	4.21E-02	4.85	3.44E-02	4.13
0	C-C	Sample 4 -Sample 9	7.45E-01	0.59	8.28E-01	0.69	7.90E-01	0.71
0	C-C	Sample 7 -Sample 8	2.99E-02	4.32	2.76E-04	11.31	2.85E-04	9.84
0	C-C	Sample 7 -Sample 9	1.68E-01	2.48	6.19E-02	5.78	6.13E-02	5.00
0	C-C	Sample 8 -Sample 9	4.68E-01	1.84	1.25E-01	5.54	1.08E-01	4.84
1	C-L	Sample 1 -Sample 2	4.32E-01	0.55	5.85E-01	0.64	1.28E-01	0.99
1	C-L	Sample 1 -Sample 4	5.66E-01	0.38	4.67E-01	1.15	4.08E-01	1.02
1	C-L	Sample 1 -Sample 7	6.96E-03	3.45	7.96E-04	7.62	7.59E-04	6.72
1	C-L	Sample 1 -Sample 8	6.29E-01	0.87	3.77E-02	3.69	1.35E-02	3.11
1	C-L	Sample 1 -Sample 9	6.16E-01	0.97	5.39E-01	1.84	4.83E-01	1.73
1	C-L	Sample 2 -Sample 3	6.24E-01	0.50	2.19E-01	1.78	1.34E-01	1.43
1	C-L	Sample 2 -Sample 5	4.08E-04	5.59	9.27E-03	6.57	3.64E-03	5.72
1	C-L	Sample 3 -Sample 4	5.08E-01	0.67	4.61E-01	1.26	3.22E-01	1.40
1	C-L	Sample 3 -Sample 7	5.67E-02	2.40	6.60E-03	5.20	8.79E-03	4.31
1	C-L	Sample 3 -Sample 8	3.47E-01	1.92	1.04E-02	6.11	3.94E-03	5.53
1	C-L	Sample 3 -Sample 9	9.69E-01	0.08	8.47E-01	0.58	7.80E-01	0.69
1	C-L	Sample 4 -Sample 5	2.88E-04	5.76	2.31E-02	6.06	1.37E-02	5.69
1	C-L	Sample 5 -Sample 7	1.34E-02	2.69	7.65E-01	0.41	9.91E-01	0.01
1	C-L	Sample 5 -Sample 8	1.24E-02	7.01	1.91E-03	10.91	7.96E-04	9.82
1	C-L	Sample 5 -Sample 9	4.15E-02	5.17	1.36E-01	5.37	1.03E-01	4.98
1.5	L-HM	Sample 1 -Sample 6	1.94E-03	7.06	1.62E-04	13.25	1.12E-04	11.20
1.5	L-HM	Sample 3 -Sample 6	7.36E-03	6.01	6.60E-04	10.83	6.97E-04	8.78
1.5	L-HM	Sample 5 -Sample 6	3.68E-01	0.92	1.01E-02	6.04	1.41E-02	4.49
2.5	C-HM	Sample 2 -Sample 6	1.34E-03	6.51	3.62E-04	12.61	3.11E-04	10.21
2.5	C-HM	Sample 4 -Sample 6	1.11E-03	6.68	1.21E-03	12.09	1.49E-03	10.18
2.5	C-HM	Sample 6 -Sample 7	9.88E-03	3.61	3.61E-03	5.63	9.51E-03	4.48
2.5	C-HM	Sample 6 -Sample 8	1.04E-02	7.93	1.74E-04	16.94	1.52E-04	14.31
2.5	C-HM	Sample 6 -Sample 9	3.06E-02	6.09	1.45E-02	11.40	1.56E-02	9.47

Site 16

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	C-C	Sample 1 -Sample 2	5.23E-01	2.36	2.19E-01	3.96	2.50E-01	2.40
0	C-C	Sample 1 -Sample 5	3.28E-01	3.45	2.00E-01	3.61	1.48E-01	2.42
0	C-C	Sample 1 -Sample 8	7.33E-01	0.91	3.83E-01	1.67	4.30E-01	0.98
0	C-C	Sample 1 -Sample 9	3.17E-01	2.41	2.49E-01	2.03	3.10E-01	1.17
0	C-C	Sample 1 -Sample 11	5.43E-01	1.13	2.18E-01	1.60	4.00E-01	0.85
0	C-C	Sample 1 -Sample 12	2.01E-01	3.55	9.65E-03	4.73	1.92E-02	3.02
0	C-C	Sample 2 -Sample 5	6.45E-01	1.08	9.07E-01	0.35	9.92E-01	0.02
0	C-C	Sample 2 -Sample 8	4.90E-01	1.45	3.11E-01	2.29	3.06E-01	1.42
0	C-C	Sample 2 -Sample 9	9.79E-01	0.04	3.52E-01	1.93	3.32E-01	1.23
0	C-C	Sample 2 -Sample 11	4.16E-01	1.23	1.26E-01	2.35	1.60E-01	1.55
0	C-C	Sample 2 -Sample 12	5.51E-01	1.19	6.57E-01	0.78	5.89E-01	0.61
0	C-C	Sample 5 -Sample 8	1.90E-01	2.54	3.26E-01	1.94	1.76E-01	1.44
0	C-C	Sample 5 -Sample 9	4.00E-01	1.04	3.72E-01	1.59	1.69E-01	1.25
0	C-C	Sample 5 -Sample 11	1.03E-01	2.31	1.40E-01	2.01	9.45E-02	1.57
0	C-C	Sample 5 -Sample 12	9.50E-01	0.11	4.32E-01	1.12	3.97E-01	0.60
0	LM-LM	Sample 6 -Sample 10	2.94E-01	1.61	1.59E-01	2.38	9.46E-02	1.82
0	C-C	Sample 8 -Sample 9	2.59E-01	1.49	7.85E-01	0.36	8.12E-01	0.19
0	C-C	Sample 8 -Sample 11	8.51E-01	0.22	9.50E-01	0.06	8.58E-01	0.13
0	C-C	Sample 8 -Sample 12	1.14E-01	2.64	1.91E-02	3.07	1.67E-02	2.03
0	C-C	Sample 9 -Sample 11	2.09E-01	1.27	6.49E-01	0.42	6.49E-01	0.32
0	C-C	Sample 9 -Sample 12	3.46E-01	1.15	1.43E-02	2.71	1.14E-02	1.85
0	C-C	Sample 11 -Sample 12	5.00E-02	2.42	1.22E-03	3.13	5.01E-03	2.17
0.5	L-LM	Sample 4 -Sample 6	1.15E-01	2.28	8.10E-02	2.41	2.98E-02	1.71
0.5	L-LM	Sample 4 -Sample 10	6.29E-01	0.67	9.81E-01	0.03	9.06E-01	0.11
0.5	LM-M	Sample 6 -Sample 13	1.05E-01	1.87	7.69E-01	0.47	3.54E-01	0.97
0.5	M-HM	Sample 7 -Sample 13	8.33E-03	6.51	3.54E-02	6.12	2.60E-02	3.99
0.5	LM-M	Sample 10 -Sample 13	1.66E-02	3.48	9.50E-02	2.85	2.71E-02	2.80
1	C-L	Sample 1 -Sample 4	9.25E-01	0.29	6.16E-01	0.91	7.65E-01	0.39
1	C-L	Sample 2 -Sample 4	3.42E-01	2.07	2.43E-01	3.05	2.25E-01	2.01
1	C-L	Sample 4 -Sample 5	8.30E-02	3.16	2.01E-01	2.70	5.91E-02	2.03
1	C-L	Sample 4 -Sample 8	7.01E-01	0.62	5.96E-01	0.76	5.06E-01	0.59
1	C-L	Sample 4 -Sample 9	5.07E-02	2.11	3.53E-01	1.12	2.95E-01	0.78
1	C-L	Sample 4 -Sample 11	4.97E-01	0.84	4.87E-01	0.70	5.82E-01	0.46
1	C-L	Sample 4 -Sample 12	6.13E-02	3.26	4.78E-04	3.83	1.93E-03	2.62
1	L-M	Sample 4 -Sample 13	2.66E-03	4.14	8.77E-02	2.88	3.72E-02	2.68
1	LM-HM	Sample 6 -Sample 7	7.81E-02	4.64	8.20E-01	0.44	5.70E-02	3.02
1	LM-HM	Sample 7 -Sample 10	1.36E-01	3.03	1.48E-01	3.27	3.51E-01	1.20

Site 16 (continued)

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
1.5	C-LM	Sample 1 -Sample 6	4.40E-01	2.57	1.51E-01	3.32	1.60E-01	2.10
1.5	C-ML	Sample 1 -Sample 10	7.05E-01	0.96	6.12E-01	0.94	8.28E-01	0.28
1.5	C-LM	Sample 2 -Sample 6	9.25E-01	0.20	8.01E-01	0.64	8.41E-01	0.30
1.5	C-LM	Sample 2 -Sample 10	4.65E-01	1.41	1.94E-01	3.02	1.60E-01	2.12
1.5	L-HM	Sample 4 -Sample 7	2.69E-01	2.36	1.92E-01	3.23	3.15E-01	1.31
1.5	C-LM	Sample 5 -Sample 6	5.97E-01	0.88	8.88E-01	0.29	7.03E-01	0.32
1.5	C-LM	Sample 5 -Sample 10	1.50E-01	2.49	1.90E-01	2.67	7.87E-02	2.14
1.5	C-LM	Sample 6 -Sample 8	3.46E-01	1.66	3.10E-01	1.65	2.29E-01	1.12
1.5	C-LM	Sample 6 -Sample 9	8.77E-01	0.16	3.48E-01	1.29	2.18E-01	0.93
1.5	C-LM	Sample 6 -Sample 11	2.74E-01	1.43	1.31E-01	1.71	1.51E-01	1.25
1.5	C-LM	Sample 6 -Sample 12	5.37E-01	0.99	1.38E-01	1.42	1.17E-01	0.91
1.5	C-LM	Sample 8 -Sample 10	9.75E-01	0.05	6.16E-01	0.73	4.50E-01	0.71
1.5	C-LM	Sample 9 -Sample 10	2.12E-01	1.45	4.16E-01	1.08	3.03E-01	0.89
1.5	C-LM	Sample 10 -Sample 11	8.73E-01	0.18	5.12E-01	0.66	4.61E-01	0.57
1.5	C-LM	Sample 10 -Sample 12	9.30E-02	2.60	6.48E-03	3.79	5.72E-03	2.74
2	C-M	Sample 1 -Sample 13	1.29E-01	4.43	1.00E-01	3.79	6.84E-02	3.07
2	C-M	Sample 2 -Sample 13	2.54E-01	2.07	9.44E-01	0.17	6.63E-01	0.67
2	C-M	Sample 5 -Sample 13	4.29E-01	0.99	9.30E-01	0.18	5.67E-01	0.65
2	C-M	Sample 8 -Sample 13	3.10E-02	3.52	1.96E-01	2.12	6.37E-02	2.09
2	C-M	Sample 9 -Sample 13	2.82E-02	2.03	2.26E-01	1.77	6.09E-02	1.90
2	C-M	Sample 11 -Sample 13	7.64E-03	3.30	5.83E-02	2.19	1.85E-02	2.22
2	C-M	Sample 12 -Sample 13	4.88E-01	0.88	3.99E-01	0.94	9.42E-01	0.06
2.5	C-HM	Sample 1 -Sample 7	5.68E-01	2.07	4.19E-01	2.33	5.95E-01	0.92
2.5	C-HM	Sample 2 -Sample 7	1.52E-01	4.44	1.02E-01	6.28	1.28E-01	3.32
2.5	C-HM	Sample 5 -Sample 7	5.95E-02	5.52	8.85E-02	5.94	5.93E-02	3.34
2.5	C-HM	Sample 7 -Sample 8	1.74E-01	2.98	9.01E-02	3.99	1.40E-01	1.90
2.5	C-HM	Sample 7 -Sample 9	2.21E-02	4.48	5.37E-02	4.35	8.32E-02	2.09
2.5	C-MH	Sample 7 -Sample 11	4.69E-02	3.21	1.49E-02	3.93	8.94E-02	1.77
2.5	C-HM	Sample 7 -Sample 12	2.25E-02	5.63	3.81E-03	7.06	4.58E-03	3.93

Site 17

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	C-C	Sample 3 - Sample 5	9.31E-01	0.02	5.59E-01	1.40	5.96E-01	0.39
0	C-C	Sample 3 - Sample 9	8.25E-01	0.05	9.65E-01	0.05	9.77E-02	1.01
0	C-C	Sample 3 - Sample 11	7.38E-01	0.74	2.67E-01	2.15	8.99E-01	0.13
0	C-C	Sample 5 - Sample 9	7.84E-01	0.78	5.37E-01	1.45	1.32E-01	1.40
0	C-C	Sample 5 - Sample 11	7.04E-01	0.70	7.86E-01	0.75	6.75E-01	0.52
0	C-C	Sample 9 -Sample 11	9.22E-01	0.03	2.40E-01	2.19	4.49E-01	0.88

Site 18

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	C-C	Sample 2 - Sample 4	8.13E-02	2.19	5.81E-01	0.72	5.95E-02	1.16
0	C-C	Sample 2 - Sample 8	1.91E-01	1.85	8.39E-01	0.32	5.13E-01	0.50
0	C-C	Sample 2 - Sample 10	3.53E-02	3.53	4.32E-01	1.35	7.70E-01	0.32
0	C-C	Sample 4 - Sample 8	6.82E-01	0.34	5.34E-01	1.04	3.46E-02	1.66
0	C-C	Sample 4 - Sample 10	1.73E-01	1.35	2.63E-01	2.07	1.74E-01	1.47
0	C-C	Sample 8 - Sample 10	1.80E-01	1.69	6.02E-01	1.04	8.69E-01	0.19

Site 19

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	C-C	sample 2 - sample 7	7.89E-02	6.18	3.17E-02	4.46	6.20E-02	2.39
0	H-H	sample 4 - sample 8	4.30E-01	2.71	7.88E-01	0.60	9.96E-01	0.01
1	M-H	sample 3 - sample 4	4.94E-03	18.81	3.62E-03	11.92	3.42E-03	6.88
1	M-H	sample 3 - sample 8	1.89E-03	16.10	5.20E-03	11.32	4.82E-03	6.88
2	C-M	sample 2 - sample 3	1.62E-01	4.44	8.45E-02	4.44	1.59E-01	2.11
2	C-M	sample 3 - sample 7	1.91E-02	10.62	4.18E-03	8.90	7.33E-03	4.50
3	C-H	sample 2 - sample 4	7.48E-04	23.26	2.33E-04	16.36	5.48E-04	8.98
3	C-H	sample 2 - sample 8	2.22E-04	20.54	2.82E-04	15.76	5.28E-04	8.99
3	C-H	sample 4 - sample 7	4.05E-04	29.44	4.05E-04	29.44	4.82E-05	11.37
3	C-H	sample 7 - sample 8	9.44E-05	26.72	4.02E-05	20.21	7.15E-05	11.38

Site 20

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	H-H	sample 1 - sample 2	3.28E-01	4.69	3.57E-01	2.61	6.97E-01	0.64
0	H-H	sample 1 - sample 4	5.67E-01	2.02	4.04E-01	1.73	5.17E-01	0.78
0	H-H	sample 1 - sample 9	5.90E-01	1.44	3.07E-01	2.03	4.37E-01	0.88
0	H-H	sample 1 - sample 14A	6.34E-01	1.85	1.82E-01	2.42	1.73E-01	1.44
0	H-H	sample 2 - sample 4	5.55E-01	2.68	7.27E-01	0.88	9.26E-01	0.13
0	H-H	sample 2 - sample 9	4.17E-01	3.25	8.06E-01	0.59	8.64E-01	0.23
0	H-H	sample 2 - sample 14A	5.35E-01	2.84	9.28E-01	0.19	5.09E-01	0.80
0	C-C(F)	sample 3 - sample 5	9.61E-02	4.23	5.79E-03	6.64	8.90E-03	3.84
0	C-C(F)	sample 3 - sample 10	2.85E-02	9.84	4.93E-02	9.92	5.01E-02	4.73
0	C-C	sample 3 - sample 11	5.79E-02	4.71	1.61E-01	4.50	9.59E-02	2.77
0	C-C	sample 3 - sample 15	5.52E-04	4.60	1.19E-03	5.06	4.19E-03	2.73
0	H-H	sample 4 - sample 9	8.21E-01	0.57	8.53E-01	0.29	8.90E-01	0.10
0	H-H	sample 4 - sample 14A	9.66E-01	0.16	6.34E-01	0.69	3.60E-01	0.66
0	H-H	sample 9 - sample 14A	9.02E-01	0.41	7.60E-01	0.40	3.69E-01	0.56
0	C(F)-C	sample 10 - sample 11	1.10E-01	5.12	2.60E-01	5.42	3.55E-01	1.97
0	C(F)-C	sample 10 - sample 15	1.78E-03	5.24	2.97E-02	4.86	7.36E-02	2.01

Site 20 (continued)

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0.5	H-MH	sample 1 - sample 14B	9.42E-01	0.23	9.15E-01	0.28	9.02E-01	0.17
0.5	H-MH	sample 2 - sample 14B	1.99E-01	4.92	4.15E-01	2.33	7.56E-01	0.47
0.5	MH-H	sample 4 - sample 14B	4.76E-01	2.24	5.72E-01	1.46	6.50E-01	0.60
0.5	MH-H	sample 9 - sample 14B	5.48E-01	1.67	4.93E-01	1.75	5.89E-01	0.71
0.5	H-MH	sample 14A - sample 14B	5.12E-01	2.08	3.36E-01	2.15	2.77E-01	1.27
0.5	MH-M	sample 14B - sample 14C	2.17E-01	4.03	1.81E-01	3.32	1.72E-01	1.85
0.5	M-LM	sample 14C - sample 14D	8.47E-01	0.60	9.77E-01	0.06	8.63E-01	0.21
1	H-M	sample 1 - sample 14C	3.09E-01	4.26	2.53E-01	3.04	2.83E-01	1.68
1	M-H	sample 2 - sample 14C	1.67E-01	7.16	7.42E-02	5.65	1.81E-01	2.32
1	M-H	sample 4 - sample 14C	1.50E-01	6.28	8.43E-02	4.77	1.11E-01	2.46
1	M-H	sample 9 - sample 14C	1.52E-01	5.71	6.60E-02	5.06	9.33E-02	2.56
1	H-M	sample 14A - sample 14C	1.43E-01	6.11	2.75E-02	5.46	2.66E-02	3.12
1	MH-LM	sample 14B - sample 14D	1.77E-01	3.43	1.55E-01	3.38	1.81E-01	1.65
1.5	H-LM	sample 1 - sample 14D	1.58E-01	3.66	1.29E-01	3.10	2.03E-01	1.47
1.5	LM-H	sample 2 - sample 14D	4.33E-02	8.35	4.03E-02	5.71	1.38E-01	2.12
1.5	C-LM	sample 3 - sample 14D	9.35E-05	19.59	7.27E-05	17.82	9.07E-05	9.86
1.5	LM-H	sample 4 - sample 14D	4.47E-02	5.68	2.48E-02	4.83	3.60E-02	2.25
1.5	LM-H	sample 9 - sample 14D	8.40E-03	5.10	1.52E-02	5.12	2.20E-02	2.35
1.5	C(F)-LM	sample 10 - sample 14D	7.60E-03	9.76	4.99E-02	7.90	1.65E-02	5.12
1.5	H-LM	sample 14A - sample 14D	9.20E-02	5.51	5.29E-03	5.52	4.49E-03	2.91
1.5	C-LM	sample 14D - sample 15	3.88E-11	14.99	5.41E-08	12.76	1.62E-07	7.13
2	C-M	sample 3 - sample 14C	1.98E-03	18.99	2.35E-04	17.88	3.80E-04	9.65
2	C(F)-M	sample 10 - sample 14C	5.51E-02	9.16	5.14E-02	7.96	2.69E-02	4.92
2	C-M	sample 14C - sample 15	2.12E-06	14.39	3.44E-07	12.82	1.25E-06	6.92
2.5	C-MH	sample 3 - sample 14B	7.95E-05	23.03	5.42E-05	21.19	4.83E-05	11.50
2.5	C(F)-MH	sample 10 - sample 14B	3.40E-03	13.19	1.00E-02	11.27	3.73E-03	6.77
2.5	C-MH	sample 14B - sample 15	2.51E-09	18.43	1.68E-08	16.13	2.34E-08	8.78
3	C-H	sample 1 - sample 3	1.27E-03	23.25	3.29E-04	20.91	6.37E-04	11.33
3	C(F)-H	sample 1 - sample 5	1.73E-03	19.02	8.31E-04	14.27	1.79E-03	7.49
3	C(F)-H	sample 1 - sample 10	1.62E-02	13.42	4.07E-02	10.99	2.20E-02	6.60
3	C-H	sample 1 - sample 11	1.10E-01	5.12	4.19E-03	16.42	3.78E-03	8.56
3	C-H	sample 1 - sample 15	1.17E-08	18.65	7.19E-08	15.86	4.32E-07	8.60
3	C-H	sample 2 - sample 3	1.98E-03	27.95	5.22E-04	23.52	1.05E-03	11.97
3	C(F)-H	sample 2 - sample 5	2.90E-03	23.71	1.35E-03	16.88	3.17E-03	8.14
3	C(F)-H	sample 2 - sample 10	1.31E-02	18.11	2.62E-02	13.61	2.15E-02	7.24
3	C-H	sample 2 - sample 11	2.86E-03	23.23	3.71E-03	19.03	4.73E-03	9.21
3	C-H	sample 2 - sample 15	4.62E-08	23.35	5.74E-08	18.47	5.66E-07	9.25
3	C-H	sample 3 - sample 4	8.25E-04	25.27	1.37E-04	22.65	1.79E-04	12.11
3	C-H	sample 3 - sample 9	1.80E-04	24.70	8.69E-05	22.94	1.14E-04	12.21
3	C-H	sample 3 - sample 14A	7.09E-04	25.11	1.10E-05	23.34	1.24E-05	12.77
3	C(F)-H	sample 4 - sample 5	1.02E-03	21.04	2.42E-04	16.00	2.77E-04	8.27
3	C(F)-H	sample 4 - sample 10	9.37E-03	15.43	2.36E-02	12.73	1.12E-02	7.37
3	C-H	sample 4 - sample 11	9.07E-04	20.56	2.35E-03	18.15	1.49E-03	9.34
3	C-H	sample 4 - sample 15	2.66E-09	20.67	1.23E-08	17.59	5.80E-08	9.38
3	C(F)-H	sample 9 - sample 10	4.24E-03	14.86	2.07E-02	13.02	9.63E-03	7.48
3	C-H	sample 9 - sample 11	3.90E-05	19.98	1.94E-03	18.44	1.15E-03	9.44
3	C-H	sample 9 - sample 15	3.79E-12	20.10	6.71E-09	17.88	3.55E-08	9.48
3	C(F)-H	sample 10 - sample 14A	9.03E-03	15.27	6.51E-03	13.42	2.10E-03	8.04
3	C-H	sample 14A - sample 15	2.43E-08	20.51	4.95E-10	18.28	1.78E-09	10.04

Site 21

Diff in Segregation		Sample comparison	p-value (3/8")	Diff in 3/8" (%)	p-value (No.4)	Diff in No.4 (%)	p-value (No.8)	Diff in No.8 (%)
0	LM-LM	sample 1 - sample 3	1.01E-05	9.31	9.52E-04	5.85	8.98E-05	3.50
0	LM-LM	sample 1 - sample 5	6.35E-04	7.67	9.78E-03	4.65	4.67E-03	2.39
0	LM-LM	sample 1 - sample 6	3.63E-01	1.66	5.14E-01	1.16	4.79E-01	0.55
0	C-C	sample 2 - sample 4	9.35E-02	2.85	9.60E-01	0.05	9.65E-01	0.02
0	C-C	sample 2 - sample 7	7.60E-01	0.34	5.45E-01	0.65	3.08E-01	0.46
0	C-C	sample 2 - sample 8	2.47E-03	5.00	1.79E-01	2.14	2.38E-01	0.89
0	LM-LM	sample 3 - sample 5	3.72E-01	1.64	3.58E-01	1.20	1.10E-01	1.11
0	LM-LM	sample 3 - sample 6	1.29E-03	7.64	1.57E-04	7.01	5.76E-05	4.05
0	C-C	sample 4 - sample 7	1.03E-01	2.51	3.68E-01	0.71	1.11E-01	0.43
0	C-C	sample 4 - sample 8	1.70E-01	2.15	1.36E-01	2.09	1.73E-01	0.91
0	LM-LM	sample 5 - sample 6	4.68E-02	6.00	9.21E-03	5.81	6.84E-03	2.94
0	C-C	sample 7 - sample 8	1.33E-03	4.66	6.18E-02	2.79	5.24E-02	1.35
1.5	C-LM	sample 1 - sample 2	9.12E-01	0.15	2.67E-02	3.62	2.80E-02	1.59
1.5	C-LM	sample 1 - sample 4	6.60E-02	3.01	1.76E-02	3.67	2.03E-02	1.57
1.5	C-LM	sample 1 - sample 7	7.06E-01	0.50	4.84E-02	2.96	7.29E-02	1.13
1.5	C-LM	sample 1 - sample 8	2.06E-03	5.15	2.77E-03	5.76	4.19E-03	2.48
1.5	C-LM	sample 2 - sample 3	2.21E-05	9.46	1.54E-05	9.47	6.78E-06	5.09
1.5	C-LM	sample 2 - sample 5	2.81E-03	7.82	3.78E-04	8.27	3.50E-04	3.98
1.5	C-LM	sample 2 - sample 6	2.95E-01	1.82	9.44E-02	2.46	1.00E-01	1.04
1.5	C-LM	sample 3 - sample 4	1.81E-05	12.32	1.09E-06	9.52	5.92E-07	5.07
1.5	C-LM	sample 3 - sample 7	3.68E-06	9.80	3.26E-06	8.81	5.71E-07	4.64
1.5	C-LM	sample 3 - sample 8	3.96E-07	14.46	1.75E-05	11.61	1.53E-05	5.98
1.5	C-LM	sample 4 - sample 5	7.50E-04	10.68	1.27E-04	8.32	1.31E-04	3.96
1.5	C-LM	sample 4 - sample 6	5.25E-02	4.67	1.77E-02	2.51	1.14E-02	1.02
1.5	C-LM	sample 5 - sample 7	1.52E-03	8.16	2.78E-04	7.61	2.31E-04	3.53
1.5	C-LM	sample 5 - sample 8	9.23E-05	12.82	1.91E-04	10.40	2.71E-04	4.87
1.5	C-LM	sample 6 - sample 7	1.60E-01	2.16	7.99E-02	1.81	2.83E-02	0.58
1.5	C-LM	sample 6 - sample 8	3.35E-03	6.82	2.86E-02	4.60	4.67E-02	1.93

Appendix D

Cell Formulas in MBITSEG2.wb3 (Calculations Sheet)

B1: MBITSEG2.wb3
B2: Segregation detection using nuclear density comparison
B3: T.F. Wolff, G.Y. Baladi and C.-M. Chang, January 2000
B5: Enter two to fifteen nuclear density values for each sample;
B6: Sample 1 apparently segregated, sample 2 non-segregated

B8: Sample 1
B9-B23: Input values
B25: @PURECOUNT(B9..B23)
B26: @PUREAVG(B9..B23)
B27: @PURESTDS(B9..B23)
B28: +B27/B26
B29: @PUREVARS(B9..B23)

D8: Sample 2
D9-D23: Input values
D25: @PURECOUNT(D9..D23)
D26: @PUREAVG(D9..D23)
D27: @PURESTDS(D9..D23)
D28: +D27/B26
D29: @PUREVARS(D9..D23)

F25: count
F26: mean
F27: std dev
F28: coeff of var.
F29: variance

F31: pooled variance
F32: pooled std dev
F33: diff in means
F34: std err of diff
F35: t-value

D31: ((B25-1)*B29+(D25-1)*D29)/(B25+D25-2)
D32: @SQRT(D31)
D33: @SQRT(D31)
D34: @SQRT(D31*((1/B25)+(1/D25)))
D35: +D33/D34

F9: TMD
F10: avg % TMD (1)
F11: avg % TMD (2)
G9: Input TMD

```
G10: +B26/G9
G11: +D26/G9

I5: Site Description
I6-I8: Input description
I9: Date
I10: Input date
I11: Tested by
I12: Input name

I14: p-value
I15: @TDIST($D$35,$B$25+$D$25-2,2)

I17: Segregation
I18: @ARRAY(@VLOOKUP(I15,Lookup table:A5..B7,1))

G20: Estimated probability of gradation difference, given that sample 2 is non-segregated
G21: @IF(@OR($I$15>0.01,$I$15=0.01),"inconclusive",@IF((+0.7096-0.0055262*
@LOG($I$15))<1,(+0.7096-0.0055262*@LOG($I$15)),1))
G22: @IF(@OR($I$15>0.01,$I$15=0.01),"inconclusive",@MIN(@IF((+0.32896-0.0723*
@LOG($I$15))<1,(+0.32896-0.0723*@LOG($I$15)),1),G21))
G23: @IF(@OR($I$15>0.01,$I$15=0.01),"inconclusive",@IF((+0.31105-0.0015658*
@LOG($I$15))<1,(+0.31105-0.0015658*@LOG($I$15)),1))

I21: Probability(at least light segregation)
I22: Probability(at least medium segregation)
I23: Probability(heavy segregation)

G25: Est. prob.of gradation difference if sample 1 appears medium through heavy
G26: @IF(@OR($I$15>0.01,$I$15=0.01),"inconclusive ",@IF($I$15<0.001,0.88,0.79))
I26: Probability(at least medium segregation)

G28: Est. prob. of gradation difference if sample 1 appears light through medium
G29: @IF(@OR($I$15>0.01,$I$15=0.01),"inconclusive",@IF($I$15<0.001,0.64,0.57))
I29: Probability(light through medium segregation)
```