COMPACTION AND MEASUREMENT OF FIELD DENSITY FOR OREGON OPEN-GRADED (F-MIX) ASPHALT PAVEMENT

FINAL REPORT

SPR 386

by

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June 1999

<table>
<tr><td>1. Report No.

FHWA-OR-RD-99-26</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle

Compaction and Measurement of Field Density For Oregon Open-Graded (F-Mix) Asphalt Pavement</td><td>5. Report Date

June 1999</td></tr>
<tr><td>6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)

David F. Rogge and Michael Adam Jackson</td><td>8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address

Oregon Department of Transportation
Research Group
200 Hawthorne Avenue SE -- Suite B-240
Salem, Oregon 97301-5192</td><td>10. Work Unit No. (TRAIS)</td></tr>
<tr><td>11. Contract or Grant No.</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address

Oregon Department of Transportation
Research Group
200 Hawthorne SE -- Suite B-240
Salem, Oregon 97301-5192

and

Federal Highway Administration
400 Seventh Street NW
Washington, D.C. 20560</td><td>13. Type of Report and Period Covered

Final Report</td></tr>
<tr><td>14. Sponsoring Agency Code</td></tr>
<tr><td colspan="3">15. Supplementary Notes</td></tr>
</table>

16. Abstract:

A research project conducted by Oregon State University (OSU) and the Oregon Department of Transportation (ODOT) investigated compaction of Oregon F-mix asphalt pavement, an open-graded mix with 25-mm maximum size aggregate and air voids typically in the 17-26% range.

The research sought to determine

- variations in compaction resulting from different compaction patterns, and
- accuracy of measurement of field densities to determine the feasibility of a density specification for F-mix.

Nine different compaction patterns varying from 2 to 6 passes with minimum 7 Mg rollers and utilizing combinations of static and vibratory compaction were employed on six different overlay paving projects. Core densities were determined at five random locations on each control strip, resulting in 270 (5x6x9) core densities. Densities between compaction patterns were compared. Although the data indicate that introducing vibration and increasing the required number of passes from 4 to 6 would increase densities from those achieved with the current specification, the increase is relatively small and the effect on open-graded pavement performance is unknown.

Prior to coring, field densities were determined by nuclear density measurement and through measurements with the Pavement Quality Indicator (PQI), a measuring device being developed by Trans Tech Systems Inc. and the FHWA. Data obtained in this study did not show good correlations between measurements with either device and core densities.

<table>
<tr><td colspan="2">17. Key Words

porous pavement; open-graded asphalt pavement; compaction; field density</td><td colspan="2">18. Distribution Statement

No Restrictions</td></tr>
<tr><td>19. Security Classification (of this report)
Unclassified</td><td>20. Security Classification (of this page)
Unclassified</td><td>21. No. of Pages
42 plus Appendices</td><td>22. Price</td></tr>
</table>

Technical Report Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

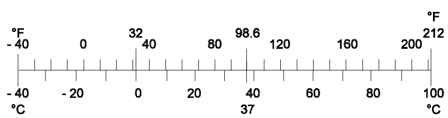
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



***** SI is the symbol for the International System of Measurement

(4-7-94 jbp)

ACKNOWLEDGEMENTS

The authors are grateful for the assistance of the staff of the Oregon Department of Transportation. Particularly noteworthy were the contributions of Elizabeth A. Hunt, Michael D. Remily, Barnie P. Jones, Tony Mandich, and the ODOT laboratory personnel. Gratitude is also expressed to the pavement contractors, and particularly their equipment operators for changing their job routines to advance the body of knowledge regarding compaction of Oregon F-mix.

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COMPACTION AND MEASUREMENT OF FIELD DENSITY FOR OREGON F-MIX ASPHALT PAVEMENT

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1.0 INTRODUCTION

Since the late 1980's, the Oregon Department of Transportation (ODOT) has used open-graded F-Mix (25-mm max. size aggregate hot mix) for widespread use as a wearing course. F-Mix pavements have demonstrated superior rut-resistance and road spray reduction characteristics. Because it is an open-graded mix, designed and constructed to have high void content, specifications and field control for compaction are different than for traditional dense-graded asphalt pavements.

ODOT's current specification is a "methods specifications". Wording of the specification as well as variable enforcement of the specification means that total compactive effort applied varies from job to job. The extent of this variation and the effect on pavement performance is not known. Because F-mix is such an important part of ODOT's asphalt paving operations, a study was initiated to evaluate compaction of open graded mixtures. In September 1997, Oregon DOT contracted with Oregon State University (OSU) to perform the study.

1.1 OBJECTIVES

The research project had four primary objectives as follows.

1) Evaluate the relationship, if any, between compactive effort and/or in-place density.

2) Determine if there is an accurate, non-destructive, practical, and rapid means of measuring the in-place density of open-graded asphalt mixtures. This should include a formal evaluation of the applicability of nuclear density gauges to F-mix.

3) Investigate equipment requirements for most effective compaction of F-mix.

4) Develop density or compaction specifications for F-mix.

This report presents a discussion of the methodology employed, data collected, and analysis performed to accomplish these research objectives.

1.2 CURRENT F-MIX COMPACTION PROCEDURES

The current specification for compaction of Oregon F-mix (ODOT Operations Support 00745.49 (d)) is included in Appendix A, and briefly summarized here. The current specification calls for steel-wheeled rollers, compacting until the entire surface has been compacted with at least four static passes or until the inspector directs compaction otherwise. Compaction must be complete before the mat temperature falls below 80° C.

1.3 SELECTION OF PROJECTS FOR FIELD STUDY

This research project collected data from six ODOT F-mix projects constructed during the summer of 1998. The six projects, selected by the ODOT Pavement Quality Engineer, are listed in Table 1.1. Attempts were made to utilize projects with climatic region and aggregate source diversity. Three projects were located in the Willamette Valley, two in the Rogue Valley, and one in the high desert environment of the Klamath Basin.

Five different aggregate sources and mix designs were used. The two Stayton projects utilized the same aggregate source and mix design. All aggregates were river run material except the aggregate for the Midland Junction – California State Line project, which was quarried rock.

Table 1.1: Test Section Project Names and Locations

Project Name	Highway	Nearest City	Approximate Milepost	Date Constructed
Stayton NCL – Fir Grove Lane	Hwy 22	Stayton	MP 15	4 Jun 1998
Joseph Street Interchange – Stayton NCL	Hwy 22	Stayton	MP 9	3 Sep 1998
Midland Junction – California State Line	Hwy 97	Klamath Falls	MP 292	31 Aug 1998
N Grants Pass – Evans Creek	Interstate 5	Grants Pass	MP 49	21 Apr 1998
Grants Pass – Applegate River	Hwy 199	Grants Pass	MP 3	13 Jul 1998
Baldock Rest Area – Woodburn Int'g.	Interstate 5	Wilsonville	MP 81	16 Aug 1998

1.4 F-MIX COMPACTION TEST SECTIONS

One of the objectives of the research project was identification of optimum levels of compaction. To evaluate the results of compaction for the projects listed in Table 1-1, test sections with varying compactive effort were constructed on a section of shoulder paving utilizing the contractor's compaction equipment.

ODOT's Technical Advisory Committee (TAC) for the research determined that nine test sections utilizing a mixture of vibratory and static compaction should be used for each project. The nine test sections on each project were approximately 150 m long. All of the test sections were on the shoulders of these projects, and each test section had a different compaction pattern. Some test sections utilized a mix of "vibratory" and "static" mode and some were only "static" mode. The test sections with their compaction patterns are listed in Table 1.2.

Table 1.2: Compaction Test Patterns

Section	Description*
1	V-S
2	V-S-V
3	V-S-V-S
4	V-S-V-S-S
5	V-S-V-S-S-S
6	S-S-S
7	S-S-S-S
8	S-S-S-S-S
9	S-S-S-S-S-S

*V = Vibratory Pass
*S = Static Pass

1.5 MEASURING FIELD DENSITY OF OPEN-GRADED F-MIX

Investigation of a rapid, accurate method for determination of field densities was another objective of the research project. A promising new measurement device was identified: the Pavement Quality Indicator (PQI), being jointly developed by TransTech, Inc. and the Federal Highway Administration (FHWA). To determine its usefulness for determining field densities of F-mix, a PQI was purchased by the Oregon DOT and readings were taken at 45 locations on each of the six projects presented in Table 1.1. These readings were taken subsequent to Humboldt nuclear gage readings and prior to coring and determination of unit densities. On the Grants Pass – Applegate River project field permeameter measurements were also taken and compared to the density values.

1.6 COMPARISON OF LABORATORY COMPACTION CURVES AND FIELD DENSITIES

To determine the relationship between field compaction and laboratory compaction, box samples of field mix were collected from the Grants Pass – Applegate River project and the Stayton NCL – Joseph Street Interchange project. Curves showing percent of maximum theoretical density (MTD) versus number of gyrations using the gyratory compactor were generated in the laboratory for both projects and compared to densities produced by the various compaction patterns used in the field with the mixes.

1.7 REPORT ORGANIZATION

The report includes five chapters. Chapter 2 presents the results of a literature review conducted to determine methods for measuring asphalt pavement field densities and open-graded mix desirable compaction levels. Chapter 3 describes the data collection process. Chapter 4 summarizes and discusses the data collected. Chapter 5 presents conclusions resulting from the research project and makes recommendations for further research and implementation.

2.0 LITERATURE REVIEW

The purpose of the literature review was to identify and investigate potential methods of non-destructively measuring in-place density of open-graded mixtures, and to determine specifications and field control procedures for open-graded asphalt pavements. Searches of databases of the Transportation Research Board (TRB) and the World Road Association (PIARC) identified several promising references, but information with application to field density measurements of Oregon F-mix was limited. The terminology, "porous pavements," is used in international literature to describe pavements similar to Oregon F-mix.

2.1 MEASURING FIELD DENSITIES

The most widely accepted equipment for measuring asphalt pavement field densities is the nuclear density gauge. It is routinely used for quality control of ODOT's dense-graded mixes. A recommended procedure for its use with F-mix has been developed (Mandich, 1994), but its use with F-mix has not been viewed as favorably.

One field measurement device with potential for simulating density measurement is the field permeameter (Isenring, 1990). Permeability of open-graded pavement should be related to its density. Although permeability measurements are inconvenient and were not developed for density measurement, the Principal Investigator decided to explore their use for field density measurements. Procedures are presented in Chapter 3 and results are presented in Chapter 4.

A recent development that shows promise is the Pavement Quality Indicator (PQI) being developed by TransTech Systems, Inc. (1998). This hand-held non-nuclear testing device is in the final phase of testing. It is being developed specifically to measure field densities of asphalt pavements. There is no licensing process and it weighs less than 4.5 kg. The PQI uses a capacitance (complex-impedance) measurement technique. The technology behind this device is the use of constant current, low frequency, and complex impedance. The measurements are taken by creating an electrical sensing field that is established in the material by a flat sensing plate. This approach allows the depth of measurement to be controlled precisely.

2.2 FIELD COMPACTION OF OPEN-GRADED ASPHALT PAVEMENTS

Watson (1998) reports that with open-graded mixes there is a much greater need for the rollers to follow the paving machine very closely because the temperature drops faster with these mixes than with dense-graded mixes. This is consistent with ODOT's experience.

Additional information regarding field compaction of porous pavements was found in a report from the European Pavement Committee. *Porous Asphalt* (PIARC, 1993) states that during placement of porous asphalt, vibrating rollers should be avoided because they lead to excessive surface compacting. The aggregates will be pressed too tightly against one another, resulting in reduced void space. There is also a risk of breaking down the aggregates with vibrating rollers. This publication recommends that a smooth-rimmed static compactor weighing a maximum of 10-12 Mg making 2-3 passes be used. Oregon currently requires a minimum of seven Mg with four passes. Oregon F-mix is generally coarser than European porous pavements and less susceptible to over-compaction.

3.0 DATA COLLECTION

The data collection for this project involved several steps. The test sections on each of the six projects of Table 1.1 were measured and marked so that the test sections could be monitored during construction. After all of the test sections were constructed the density readings were taken using two field test methods, the Humboldt nuclear gauge and the PQI. In addition, field permeameter tests were conducted on the Grants Pass – Applegate River project. After these tests were completed core samples were taken at all 45 test locations (five cores per nine roller patterns per project) , for a total of 270 cores.

3.1 TEST SECTION LAYOUT

Each paving project utilized nine test sections as previously described in Section 1.4. The nine test sections were measured and stakes were placed to mark the beginning and end of each section. Five locations were marked as the test locations in each section. These locations were determined by using the random number function in Microsoft's Excel program. The test locations are identified in Appendix B. .

3.2 FIELD CONSTRUCTION MONITORING

During construction of the test sections, the following information was recorded:

- The temperature of the mat after each roller pass.. Temperature was determined through use of a thermocouple.
- Any variation of the test patterns; and
- The type of compaction equipment used.

The breakdown roller was used for the test sections. The finish roller was directed to leave the test sections unfinished.

3.3 TEST METHODS

The three field tests performed for this research project were the Humboldt nuclear gauge, the Pavement Quality Indicator (PQI), and the field permeameter. Of these three the field permeameter was only used on one project while the other two test methods were used on all six projects. Each test is discussed below.

3.3.1 Humboldt Nuclear Gauge

The most widely accepted method of measurement of field densities of asphalt pavement is the nuclear gauge [ASTM Standard: D 2950 - 97 (Reapproved 1997)]. Procedures for its use are presented in Appendix C and briefly summarized here. It is pictured in Figure 3.1.

Figure 3.1: Humboldt Nuclear Gauge

The gauge must be in asphalt mode, set to 50-mm nomograph mode, and the gauge probe must be set to the backscatter position. The average density of the underlying mixture is determined and entered into the gauge. Unless better information is available, a density value typical of the underlying pavement (B-mix, C-mix, etc.) is used. One-minute tests are taken with no sanding of the site. The nuclear gauge reading used for analysis consisted of two readings that were averaged.

3.3.2 Pavement Quality Indicator (PQI)

The Pavement Quality Indicator is pictured in Figure 3.2. During the winter of 1998 ODOT agreed to purchase a PQI to determine its potential for measuring compaction of F-mix. TransTech, Inc. with the Federal Highway Administration (FHWA) and the United States Department of Energy (USDOE) is developing the PQI.

Figure 3.2: Pavement Quality Indicator

Procedures for using the PQI are presented in Appendix D and briefly summarized here. The PQI does not require a lot of training to use. The maximum theoretical density (MTD) must be entered if a valid percent of MTD reading is desired. An "offset" must be entered. The "offset" is a number input into the PQI for calibration purposes. The offset is obtained by using a known density from either cores or a nuclear gauge reading. For metric units the offset must be between 1,600 and 2,800 kg/m^3. This research project used the nuclear gauge readings for calibration purposes.

The PQI can be set to measure in one of three modes. The single test mode, the average mode, or the continuous mode. The single mode takes one test and gives the answer. The average mode takes a user defined number of tests and gives the average. The continuous mode simply reads the density on an ongoing basis and the user must determine the most accurate reading. All of these tests read the density and give as a reading the maximum density detected.

The PQI was calibrated using readings from the nuclear gauge readings, as recommended in the user manual. Five locations were chosen and readings were taken with both gauges. The difference of means plus the original "offset" was entered into the PQI as an "offset". The PQI readings used for analysis were obtained with the PQI gauge set for five averaged readings. The PQI gives only the averaged result, not the five individual test results.

3.3.3 Permeameter

A falling head permeameter was used to measure permeability of the newly compacted pavement layer. It is pictured in Figure 3.3 and Figure 3.4. The test measures the time required for a fixed volume of water to flow out of the bottom of the permeameter through the pavement. It is called a falling head permeameter because the head decreases continuously as the water flows out of the permeameter into the pavement.

Figure 3.3: Permeameter

Figure 3.4: Permeameter Probes

The test consists of setting the permeameter on the pavement and connecting the probes to the timer. The permeameter is filled with water. The timer is set to 0.00. The rubber stopper in the bottom is raised and the water is allowed to flow out through the opening in the bottom and into the pavement. The timer measures the time taken to drain a known quantity of water. The test is done three times and the average is calculated.

3.4 FIELD CORES

The field cores for the Stayton NCL – Fir Grove Lane and Grants Pass – Applegate River projects were taken by PSI Testing of Eugene, OR. They were delivered to the laboratory at OSU in Apperson Hall. The cores ranged from 152.4 to 381.0 mm in length with diameters of 152.4 mm. All cores were trimmed to 51 mm in length to represent the 51-mm overlay constructed. For all but eight of the cores, the trimming resulted in specimens of F-mix representative of the F-mix in the field. The top 51 mm of the other eight cores had 6 to 13 mm of dense graded mix remaining. An attempt was made to trim the excess dense-graded mix, but the cores broke apart. In the end, these eight cores could not be used since they were not representative of the F-mix overlay.

Unit weights of the specimens were determined geometrically, as is standard ODOT practice. The samples were measured using a micrometer. Three heights and three diameters were measured and the average of each was used to determine the volume of the sample. The samples were allowed to air dry for 24 to 48 hours. Each sample was weighed and placed in an oven for 45 minutes at 60° C. They were removed and cooled for 30 minutes, and weighed again. This procedure was used until the weight changed less than one gram.

Century West Engineering Corporation of Bend, OR took the field cores for the other four projects. Their process was to drill down and snap the core off at the contact between the F-Mix and the underlying dense graded mix. There was not a problem with this technique as all of the samples delivered to the ODOT Materials Laboratory were acceptable. ODOT personnel determined unit weights for these four projects. The core densities for all projects are listed in Appendix E.

3.5 DATA COLLECTED

All density measurements taken in the field are tabulated in Appendix F. Appendix G compares the nuclear density readings, PQI readings, and core densities for all locations on all projects. Mean values of these densities for each test pattern are summarized in Table 3.1.

Table 3.1: Average Results for All Projects

Section	Pattern	Kg/m^3 Nuclear	Kg/m^3 PQI	Kg/m^3 Core
1	VS	1807	1834	1924
2	VSV	1864	1883	1961
3	VSVS	1859	1890	1951
4	VSVSS	1894	1892	1988
5	VSVSSS	1894	1921	1998
6	SSS	1816	1874	1915
7	SSSS	1830	1879	1971
8	SSSSS	1867	1895	1978
9	SSSSSS	1860	1897	1963
	Average	1855	1885	1961

4.0 DATA ANALYSIS

The objectives of the research project required that two fundamental questions be addressed. These questions were:

1) Is there a rapid accurate method to measure in-place density of open-graded F-mix?

2) Is there an optimum level of compaction for Oregon F-mix?

Analysis begins with the first question.

4.1 COMPARISON OF NUCLEAR GAUGE AND PQI DATA TO DATA FROM FIELD CORES

To evaluate the ability of the Humboldt nuclear gauge and the PQI to accurately measure field densities of F-mix, nuclear gauge and PQI readings were taken at precisely the same locations on each project. These precise locations were cored and actual densities of the top 51 mm were determined in the laboratory, as discussed in Section 3.4.

Cores were obtained from five locations on the nine test sections for all six projects. Nuclear gauge and PQI readings had already been obtained at each of the core sites. Thus, measurements using the nuclear gauge and the PQI could be directly compared to corresponding core values and regression analysis performed.

The core densities were all determined and recorded. All of the data from the field and the lab were compiled onto a single spreadsheet to facilitate the analysis. All measurements are in metric units. The results are in Appendix G. A plot of the field density measurements and the core densities at each test location is presented in Figure 4.1.

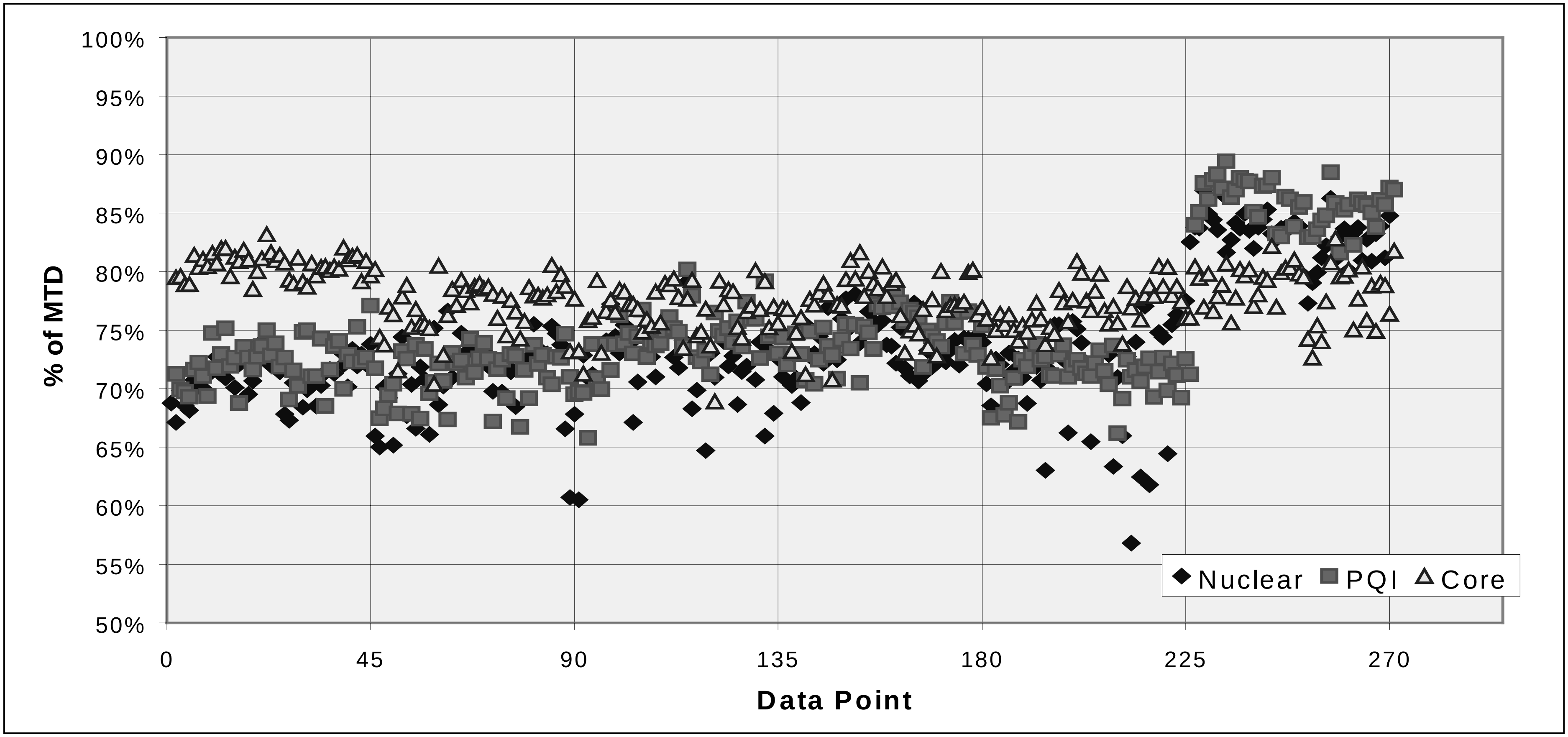

Figure 4.1: Density Measurements

Each consecutive set of 45 points of Figure 4.1 represents a different project. The order starting at zero is: N Grants Pass – Evans Creek, Stayton NCL – Fir Grove Lane, Grants Pass – Applegate River, Stayton NCL – Joseph Street Interchange, Midland Junction – California State Line, and Baldock Safety Rest Area – Woodburn Interchange.

Note that the shift between nuclear and PQI values and core values is not consistent between projects. For example, for the first project (points 1 - 45) nuclear and PQI readings are consistently lower than the core values. For the last project (points 236 - 270) the nuclear and PQI readings are higher than the core values. Mean values of nuclear gage readings, PQI readings, and core densities for each project are presented in Table 4.1. Clearly, calibration between projects was not consistent. As discussed in Section 3.3.2, the PQI was calibrated to the nuclear gauge readings in the field.

Table 4.1: Mean Unit Weights by Project

Project	Kg/m^3 Nuclear	Kg/m^3 PQI	Kg/m^3 Core	Kg/m^3 Core minus Nuclear	Kg/m^3 Core minus PQI	Kg/m^3 PQI minus Nuclear
N Grants Pass – Evans Creek	1936	1991	2055	119	65	54
Grants Pass – Applegate River	1866	1901	2118	252	217	35
Stayton NCL - Fir Grove Lane	1764	1766	1908	144	142	2
Stayton NCL – Joseph Street Interchange	1829	1851	1916	87	65	22
Midland Junction – California State Line	1755	1759	1899	144	140	4
Baldock Safety Rest Area – Woodburn Interchange	1977	2042	1870	-107	-172	65

Five of six projects had mean core densities greater than mean nuclear gage and PQI readings. Mean field density measurements were generally within about 10% of mean core densities. PQI and nuclear gauge readings were generally within 3% of each other. Mean values for PQI readings were always slightly greater than mean values for nuclear gauge readings.

Figures 4.2 and 4.3 show scattergrams comparing core densities to nuclear gage readings and to PQI readings. A summary of the regression analysis with nuclear gage and PQI readings as independent variables and core densities as dependent variables is presented in Table 4.2. The plot and the regression analysis include 270 points for the nuclear gauge - core comparison and 262 points for the PQI - core comparisons. The reasons for the different numbers of cores used in the comparisons are now presented.

The nuclear gauge measures the top 51 mm of the pavement. The PQI measures the top 38 mm of the pavement. Several of the cores removed from the pavement showed portions of the underlying dense-graded asphalt pavement encroaching into the top 51 mm of the core, reducing the F-mix section to between 38 and 44 mm. For these locations, the nuclear gauge readings (reading the top 51 mm) should be compared to the density of the full 51 mm of each core. Consequently, all 270 cores may be compared to the nuclear gauge readings.

For PQI comparisons, which measures only the top 38 mm, cores of only F-mix are required. Consequently, for the regression analysis between PQI and core unit weights, cores that showed dense-graded material in the top 51 mm are not used. As a result, the regression analysis for the PQI only includes 262 data points.

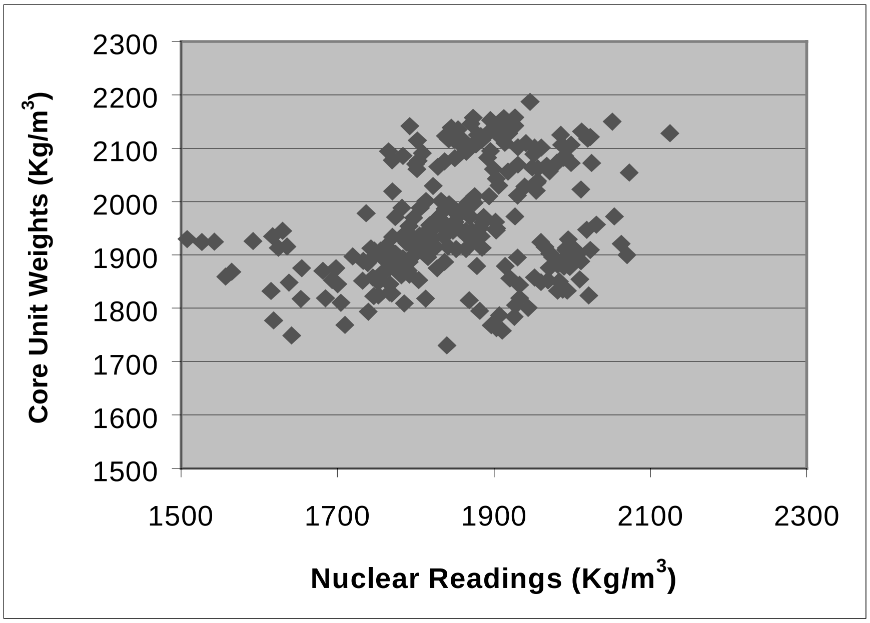

Figure 4.2: Core Unit Weights vs. Nuclear Readings

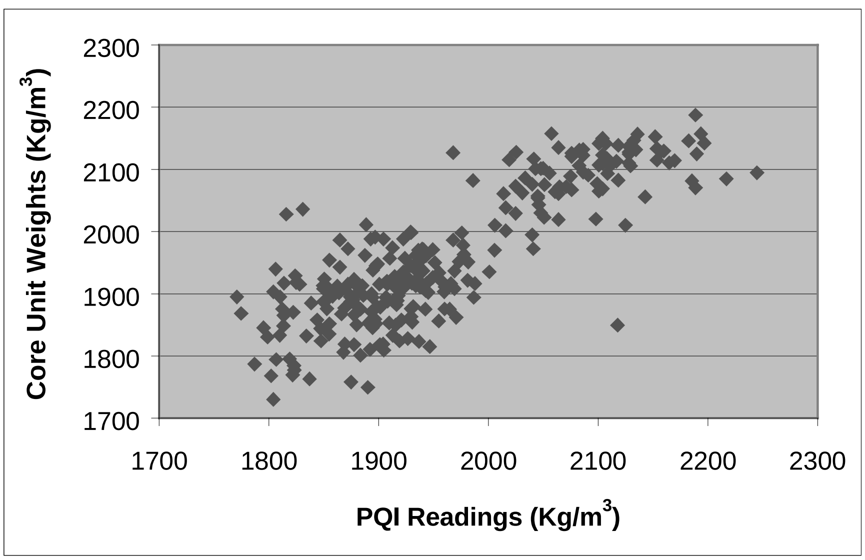

Figure 4.3: Core Unit Weights vs. PQI Readings

Table 4.2: Results of Regression Analysis for Data from All Projects

	R Value	Coefficient	Intercept
Core Density vs. Nuclear Gage	0.306	0.290	1423.964
Core Density vs. PQI	0.258	0.234	1519.772

The R-values obtained by regression analysis are low. They indicate that for the projects included in this research project, neither the nuclear gauge nor the PQI did a good job of predicting field densities determined from cores.

The low R-values may be partially explained by errors in calibration. Because calibration error varied from project to project, and in fact was not even always in the same direction, the likelihood of a high R-value was reduced.

Because of the errors in calibration, regression analysis of the data points within each project's data set (45 points) may be more meaningful. The results of regression analysis on a project by project basis are presented in Table 4.3.

Table 4.3: Regression Results by Project

Raw Data:	Nuclear vs. Core			PQI vs. Core			
Project	R-value	Coefficient	Intercept	R-value	Coefficient	Intercept	PQI Offset Used
N Grants Pass – Evans Creek	0.58	0.385	1310	0.34	0.306	1447	2641
Grants Pass – Applegate River	0.59	0.351	1463	0.23	0.126	1879	59
Stayton NCL – Fir Grove Lane	0.74	0.507	1014	0.49	0.511	998	2328
Stayton NCL – Joseph Street Interchange	0.43	0.518	969	0.15	0.174	1593	2373
Midland Junction – California State Line	0.11	0.045	1820	0.40	0.431	1140	2285
Baldock Safety Rest Area – Woodburn Interchange	0.78	0.918	56	0.42	0.527	794	2559

Regression analysis on a project by project basis also yielded low R-values. Only one of six projects showed the PQI to be a better density predictor. Only the nuclear gauge readings for the Stayton NCL – Fir Grove Lane and Baldock Safety Rest Area – Woodburn Interchange projects approached acceptable values for predicting core densities. A regression line with coefficient of 1.0, an intercept of 0.0, and R of 1.0 would mean that the nuclear gauge would perfectly predict the core density. The values of 0.918, 56, and 0.78 for coefficient, intercept, and R-value with the nuclear gage for the Baldock Safety Rest Area – Woodburn Interchange project are the best results obtained.

Further examination of the nuclear density readings casts doubt on the Baldock Safety Rest Area – Woodburn Interchange results as well. The ASTM standard for precision with the nuclear gauge states that an instrument count precision of 10 kg/m^3 for the Backscatter Method is typical on material of approximately 2.25 Mg/m^3 density (ASTM Standard Specification). This applies for repetitive measurements at the same location. The average density of the 270 cores of this project was 1.96 Mg/m^3. Examination of the individual nuclear readings in Appendix F shows that only 14 of 45 measurement locations fell within this 10 kg/m^3 range for the Baldock project. This was the worst of the six projects. Values for other projects were 26 of 45, 32 or 45, 28 of 45, 28 of 45, and 33 of 45.

Previous ODOT experience (Mandich, 1994) suggests that nuclear density readings for F-mix can be "within 4% of core 'measured gravities' or 'bulk gravities.'" (See Appendix C.) Examination of measurements summarized in Appendix G shows that only 63 of 270 core locations meet this criteria. Of the six projects, Baldock Safety Rest Area – Woodburn Interchange was only in the midrange for meeting this criteria, with 13 of 45 nuclear readings within 4% of the corresponding core density values. The six projects ranged from 0 of 45 for Grants Pass – Applegate River to 18 of 45 for Stayton NCL – Joseph Street Interchange.

The nuclear gauge readings obtained for this study show the ability of the nuclear gauge to accurately measure density of F-mix to be questionable. Correlation with core densities and ability to meet ASTM and ODOT targets for precision and agreement with core densities are not good. One explanation for this disappointing performance is the variation in nuclear gauge operator. Because nuclear density readings were not needed to support the construction paving contracts, nuclear gauge readings were not a routine, well-practiced part of quality control. Nuclear readings were obtained by a qualified nuclear gauge operator who happened to be available from the ODOT Region at the time that readings needed to be taken for the research. Other research has indicated that nuclear density readings of asphalt pavement may be highly operator-dependent (Choubane, et. al., 1999).

Although the correlations with core densities were better for five of six projects for the nuclear gauge, examination of mean densities for projects favors the PQI. Table 4.1 shows that for all projects except the Baldock Safety Rest Area – Woodburn Interchange project, the difference between mean gauge readings and mean core densities was less for the PQI than for the nuclear gauge.

The fact that the PQI had to be calibrated to the nuclear gauge readings adds to the difficulty of evaluating the accuracy of the PQI. Correlation of 262 comparable readings by nuclear gauge and PQI produces an R-value of 0.77. One thing is clear: the PQI is much easier to use and much less dependant on operator skills than the nuclear gauge.

One final note about comparisons between core densities, nuclear readings, and PQI readings should be made. The volumes being measured by the three methods are different. Cores were a nominal 150 mm in diameter and 50 mm thick. The nuclear gauge measures a larger volume. Based on findings reported by Choubane (1999), corrections for underlying layers improve the accuracy of even thin-lift gauges, so apparently the nuclear gauge reading extends below the 50 mm overlay depth. The PQI measures a cylindrical volume 38 mm high and 38 mm in diameter. It seems logical that the combination of pavement variability, high voids content, and maximum aggregate size of 25 mm would provide opportunity for variations in density for the three different volumes being measured.

Field permeameter measurements were taken approximately three months after construction on the Grants Pass – Applegate River project. Three of the data points were deleted because they were clogged with dry dirt and debris, making an accurate reading impossible. Correlation of the remaining data points yields an R-value of 0.346. This R-value compares to 0.23 for correlation of core densities and PQI measurements for this project and 0.59 for correlation of nuclear density readings and core densities. Because the field permeameter was not developed for field density control, and because of the results at Grants Pass – Applegate River, field permeameter readings were not taken on the remaining projects.

4.2 OPTIMUM LEVEL OF COMPACTION

A second objective of the research project was determination of the most effective F-mix compaction procedure. Relevant data for this determination are now presented.

The compaction equipment used on each project is summarized in Table 4.4. Each project utilized the same nine test compaction patterns, previously listed in Table 1.2. Unit weights from field cores for each project are presented in Tables 4.4 - 4.10.

Curves showing compaction as a percent of maximum theoretical density (MTD) are plotted from these tables and are shown in Figures 4.4 - 4.9. The MTD was obtained from the mix design. The percent of MTD was used as a means to normalize the data. Separate curves for patterns including vibratory passes and for patterns with all static passes are shown. Similar curves with average values from all projects are shown in Figure 4.10. Finally, the minimum, maximum, and average for each test pattern are represented in Figure 4.11. For the 262 valid cores, values for individual cores from 69% to 83% of MTD were recorded.

Table 4.4: Compaction Equipment

Project Name	Brand	Model Number	Operating Weight (Mg)
N Grants Pass – Evans Creek	Ingersoll-Rand	DD-110	11.4
Grants Pass – Applegate River	CAT	CB - 634C	11.7
Stayton NCL – Fir Grove Lane	Hypac	C766B	9.8
Stayton NCL – Joseph Street Interchange	Hypac	C766B	9.8
Midland Junction – California State Line	CAT	CB - 534B	10.2
Baldock Safety Rest Area – Woodburn Interchange	Hypac	C766B	9.8

Table 4.5: N. Grants Pass – Evans Creek

Project: N Grants Pass - Evans Creek												
MTD:	2684 kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3		kg/m^3	kg/m^3	kg/m^3	
Section	**Pattern**	**1**	**2**	**3**	**4**	**5**	**Mean**	**% of MTD**	**Min**	**Max**	**Standard Deviation**	**Coefficient of Variation**
1	VS	1913	2036	2043	2127	1961	2016	75.1%	1913	2127	82.29	0.0408
2	VSV	2057	2082	2054	2106	2101	2080	77.5%	2054	2106	24.11	0.0116
3	VSVS	2072	2073	2061	2010	2038	2051	76.4%	2010	2073	26.81	0.0131
4	VSVSS	2023	2101	2030	2121	2118	2079	77.4%	2023	2121	48.23	0.0232
5	VSVSSS	2131	2089	1972	2085	2128	2081	77.5%	1972	2131	64.56	0.0310
6	SSS	2001	2010	2062	1978	1849	1980	73.8%	1849	2062	79.42	0.0401
7	SSSS	2126	2072	2106	2102	2020	2085	77.7%	2020	2126	41.25	0.0198
8	SSSSS	1995	2056	2069	2150	2061	2066	77.0%	1995	2150	55.30	0.0268
9	SSSSSS	2125	2019	2067	2029	2064	2061	76.8%	2019	2125	41.62	0.0202

Table 4.6: Grants Pass – Applegate River

Project: Grants Pass - Applegate River												
MTD:	2630 kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3		kg/m^3	kg/m^3	kg/m^3	
Section	**Pattern**	**1**	**2**	**3**	**4**	**5**	**Mean**	**% of MTD**	**Min**	**Max**	**Standard Deviation**	**Coefficient of Variation**
1	VS	2091	2094	2075	2076	2142	2095	79.7%	2075	2142	27.09	0.0129
2	VSV	2113	2132	2117	2146	2123	2126	80.9%	2113	2146	13.12	0.0062
3	VSVS	2157	2157	2094	2137	2128	2135	81.2%	2094	2157	26.15	0.0123
4	VSVSS	2153	2110	2065	2105	2133	2113	80.4%	2065	2153	33.06	0.0156
5	VSVSSS	2187	2147	2129	2142	2125	2146	81.6%	2125	2187	24.77	0.0115
6	SSS	2086	2077	2135	2081	2070	2090	79.5%	2070	2135	25.89	0.0124
7	SSSS	2123	2096	2114	2116	2107	2111	80.3%	2096	2123	10.35	0.0049
8	SSSSS	2115	2110	2158	2132	2138	2131	81.0%	2110	2158	18.94	0.0089
9	SSSSSS	2142	2082	2128	2095	2109	2111	80.3%	2082	2142	24.20	0.0115

Table 4.7: Stayton NCL – Fir Grove Lane

Project: Stayton NCL - Fir Grove Lane												
MTD:	2484 kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3		kg/m^3	kg/m^3	kg/m^3	
Section	**Pattern**	**1**	**2**	**3**	**4**	**5**	**Mean**	**% of MTD**	**Min**	**Max**	**Standard Deviation**	**Coefficient of Variation**
1	VS	1849	1832	1912	1897	1777	1853	74.6%	1777	1912	53.96	0.0291
2	VSV	1934	1959	1870	1908	1875	1909	76.9%	1870	1959	37.78	0.0198
3	VSVS	1876	1867	1749	1999	1810	1860	74.9%	1749	1999	92.81	0.0499
4	VSVSS	1895	1950	1916	1970	1948	1936	77.9%	1895	1970	29.81	0.0154
5	VSVSSS	1922	1957	1961	1952	1955	1949	78.5%	1922	1961	15.90	0.0082
6	SSS	1940	1889	1936	1852	1926	1909	76.8%	1852	1940	37.66	0.0197
7	SSSS	1902	1845	1882	1954	1937	1904	76.7%	1845	1954	43.27	0.0227
8	SSSSS	1938	1932	1939	2001	1945	1951	78.5%	1932	2001	28.34	0.0145
9	SSSSSS	1982	1957	1818	1930	1819	1901	76.5%	1818	1982	77.62	0.0408

Table 4.8: Stayton NCL – Joseph Street Interchange

Project: Stayton NCL - Joseph Street Interchange												
MTD:	2484 kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3		kg/m^3	kg/m^3	kg/m^3	
Section	**Pattern**	**1**	**2**	**3**	**4**	**5**	**Mean**	**% of MTD**	**Min**	**Max**	**Standard Deviation**	**Coefficient of Variation**
1	VS	1908	1818	1858	1890	1769	1849	74.4%	1769	1908	56.13	0.0304
2	VSV	1929	1917	1943	1962	1938	1938	78.0%	1917	1962	16.75	0.0086
3	VSVS	1758	1918	1915	1971	2011	1915	77.1%	1758	2011	96.19	0.0502
4	VSVSS	1972	2028	1935	1988	1962	1977	79.6%	1935	2028	34.41	0.0174
5	VSVSSS	1951	1998	1935	1963	1970	1963	79.0%	1935	1998	23.46	0.0119
6	SSS	1894	1815	1862	1875	1856	1860	74.9%	1815	1894	29.26	0.0157
7	SSSS	1908	1828	1928	1809	1988	1892	76.2%	1809	1988	73.74	0.0390
8	SSSSS	1905	1916	1917	1916	1923	1915	77.1%	1905	1923	6.50	0.0034
9	SSSSSS	1986	1991	1896	1911	1887	1934	77.9%	1887	1991	50.34	0.0260

Table 4.9: Midland Junction – California State Line

Project: Midland Junction - California State Line												
MTD:	2470 kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3		kg/m^3	kg/m^3	kg/m^3	
Section	**Pattern**	**1**	**2**	**3**	**4**	**5**	**Mean**	**% of MTD**	**Min**	**Max**	**Standard Deviation**	**Coefficient of Variation**
1	VS	1794	1853	1887	1865	1885	1857	75.2%	1794	1887	37.86	0.0204
2	VSV	1853	1830	1863	1849	1875	1854	75.1%	1830	1875	16.76	0.0090
3	VSVS	1910	1876	1823	1859	1845	1863	75.4%	1823	1910	32.85	0.0176
4	VSVSS	1937	1911	1871	1916	1998	1927	78.0%	1871	1998	46.51	0.0241
5	VSVSSS	1974	1915	1894	1935	1971	1938	78.5%	1894	1974	34.85	0.0180
6	SSS	1894	1866	1903	1868	1824	1871	75.8%	1824	1903	30.81	0.0165
7	SSSS	1945	1900	1920	1875	1925	1913	77.5%	1875	1945	26.60	0.0139
8	SSSSS	1946	1924	1988	1945	1986	1958	79.3%	1924	1988	28.07	0.0143
9	SSSSSS	1926	1945	1913	1879	1879	1908	77.3%	1879	1945	29.15	0.0153

Table 4.10: Baldock Safety Rest Area – Woodburn Interchange

Project: Baldock Safety Rest Area - Woodburn Interchange												
MTD:	2381 kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3		kg/m^3	kg/m^3	kg/m^3	
Section	**Pattern**	**1**	**2**	**3**	**4**	**5**	**Mean**	**% of MTD**	**Min**	**Max**	**Standard Deviation**	**Coefficient of Variation**
1	VS	1915	1892	1833	1900	1824	1873	78.7%	1824	1915	41.40	0.0221
2	VSV	1854	1878	1921	1801	1852	1861	78.2%	1801	1921	43.64	0.0234
3	VSVS	1910	1897	1909	1835	1858	1882	79.0%	1835	1910	33.63	0.0179
4	VSVSS	1894	1888	1957	1833	1903	1895	79.6%	1833	1957	44.16	0.0233
5	VSVSSS	1913	1913	1929	1901	1895	1910	80.2%	1895	1929	13.08	0.0068
6	SSS	1768	1730	1795	1763	1844	1780	74.8%	1730	1844	42.59	0.0239
7	SSSS	1924	1972	1895	1896	1909	1919	80.6%	1895	1972	31.78	0.0166
8	SSSSS	1787	1850	1915	1806	1876	1847	77.6%	1787	1915	51.85	0.0281
9	SSSSSS	1784	1882	1877	1819	1947	1862	78.2%	1784	1947	62.81	0.0337

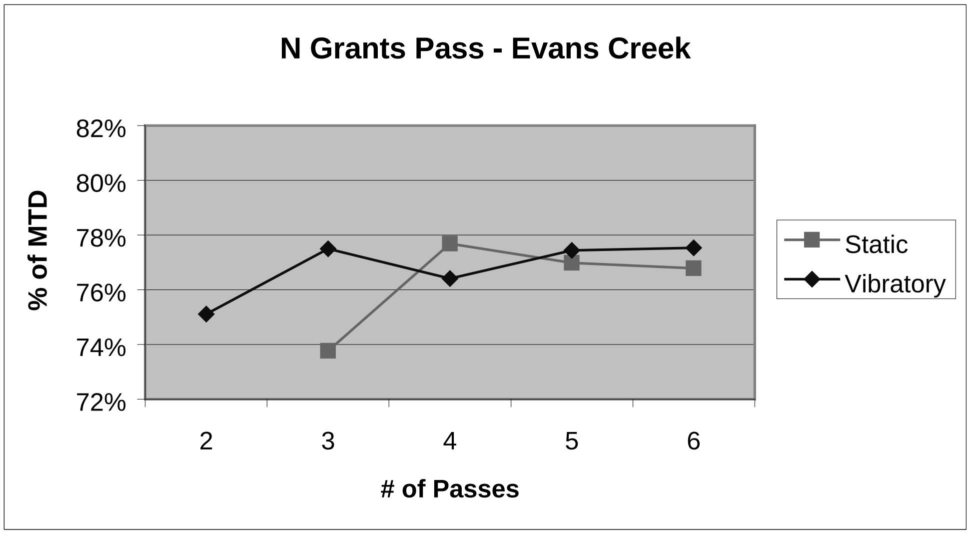

Figure 4.4: Percent of MTD, N Grants Pass – Evans Creek

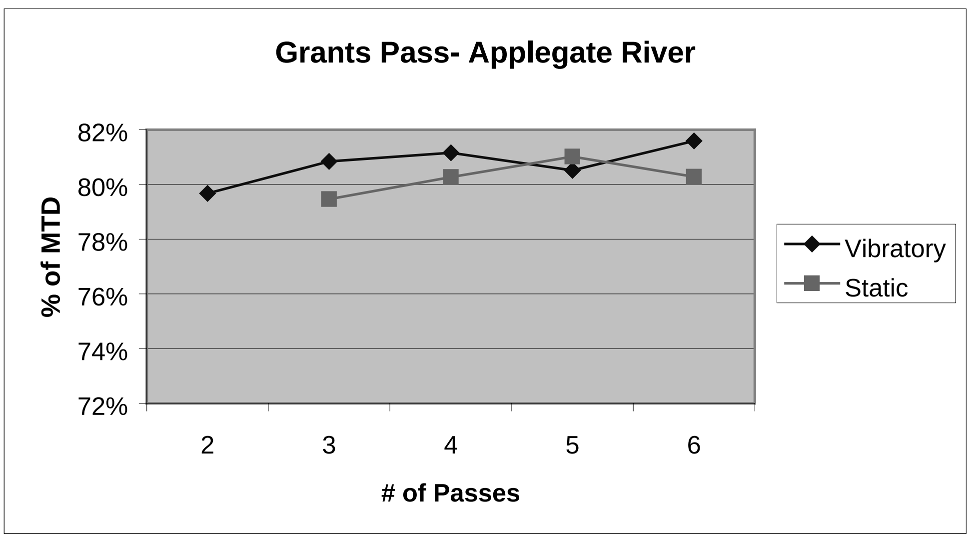

Figure 4.5: Percent of MTD, Grants Pass – Applegate River

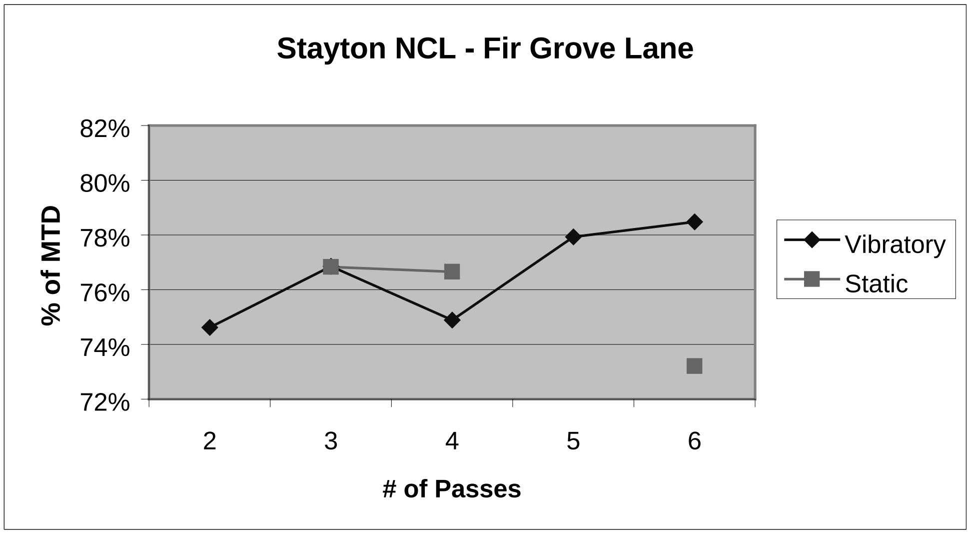

Figure 4.6: Percent of MTD, Stayton NCL – Fir Grove Lane

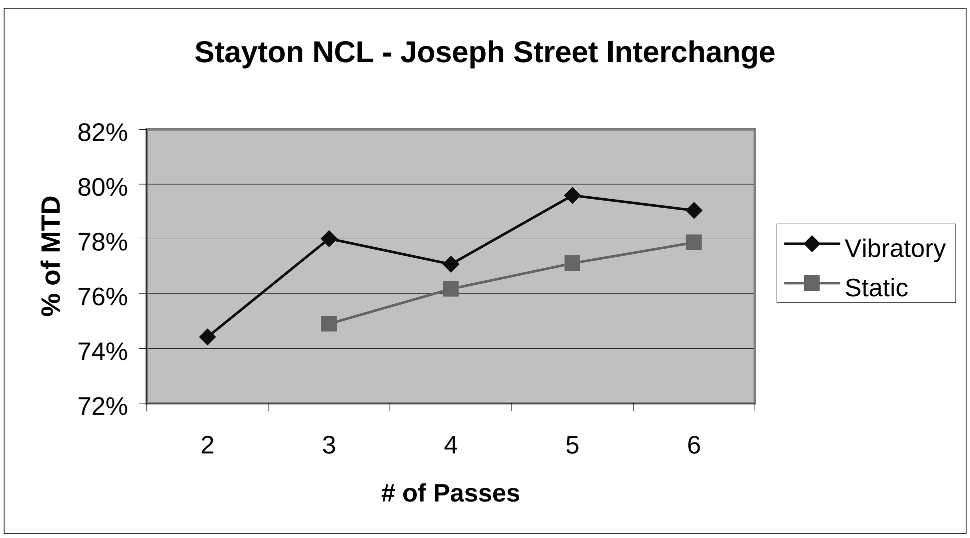

Figure 4.7: Percent of MTD, Stayton NCL – Joseph Street Interchange

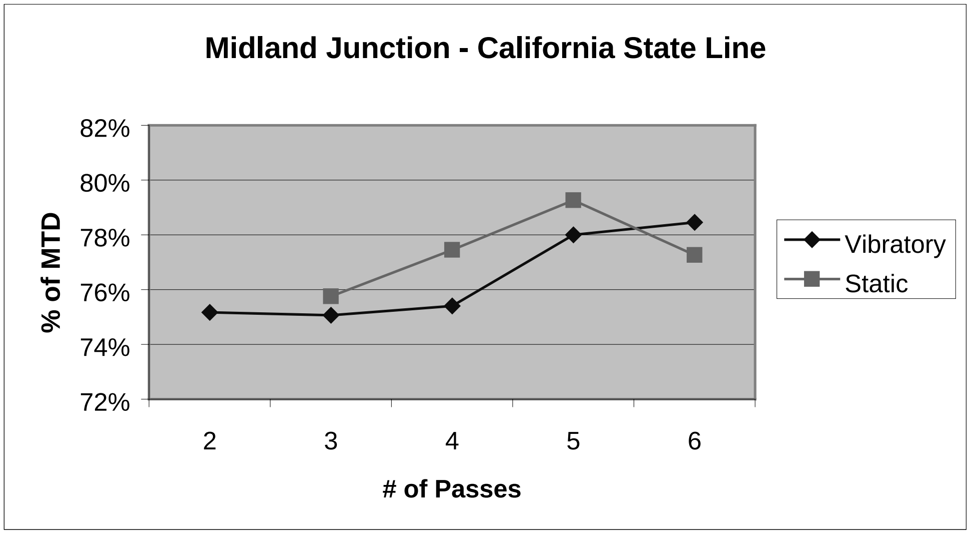

Figure 4.8: Percent of MTD, Midland Junction – California State Line

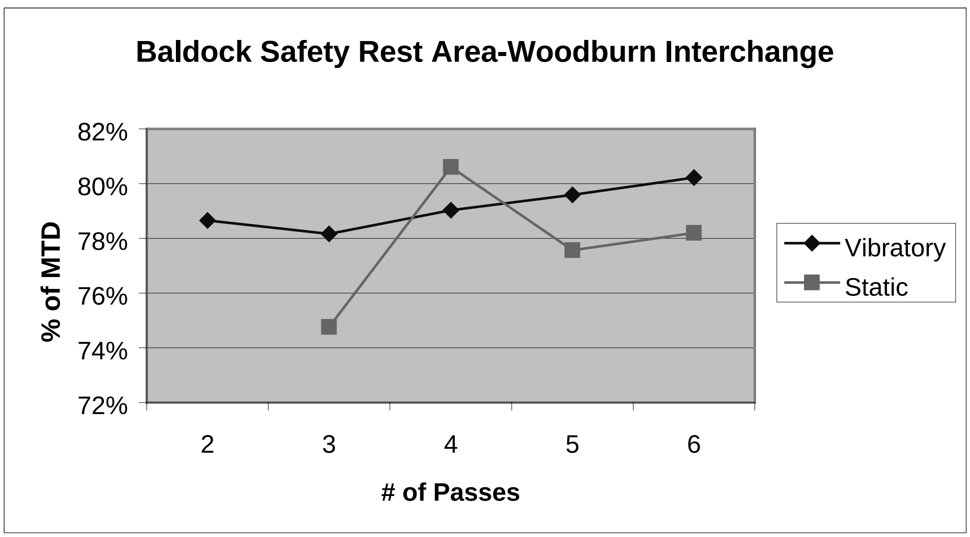

Figure 4.9: Percent of MTD, Baldock Safety Rest Area – Woodburn Interchange

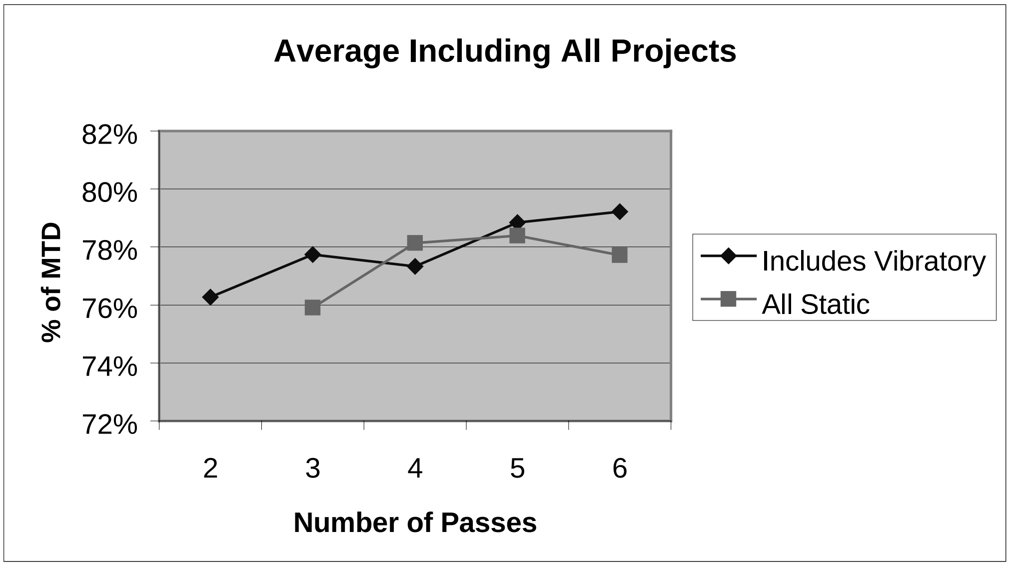

Figure 4.10: Percent of MTD vs. Number of Passes, All Projects

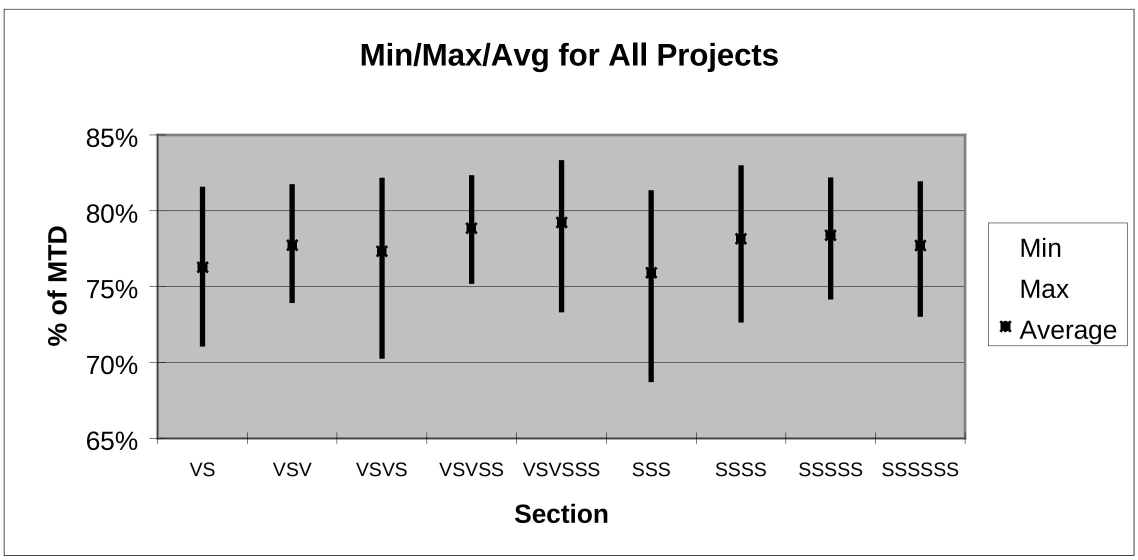

Figure 4.11: Min/Max/Average for each Test Section

Perhaps the most striking conclusion from examination of the curves of average compaction for all projects is that the range from least average compaction to greatest average compaction is from 76% to 79%, a range of only 3%.

Although the plot of compaction for all projects (see Figure 4.10) indicates highest compaction for five and six passes including vibratory (VSVSS and VSVSSS), examination of each project's curves shows that this trend is not uniform across all projects.

Although patterns of five and six passes including vibratory generally produce the highest compaction, there are cases where four or five static passes produce higher compaction. Table 4.11 shows that for three, five, and six total passes, inclusion of vibratory passes produced higher compaction on more projects than did all static passes.

Table 4.11: Compaction with Vibratory Mode versus All Static

Number of projects that yield higher density from:	3 Passes	4 Passes	5 Passes	6 Passes
Compaction Including Vibratory	4.5	2	3	6
All Static Compaction	1.5	4	2	0

4.3 TEMPERATURE EFFECT

It is known that open-graded mixes lose heat faster than dense-graded mixes. To determine if anomalies in compaction versus compactive effort curves could be attributed to temperature differences, temperature of mix was examined.

The mat temperature during construction was monitored after each roller pass . The temperature was measured in degrees Celsius using a thermocouple. The thermocouple could only measure a finite area, so temperature measurements were taken on the surface of a large piece of aggregate. An attempt was made to locate the highest temperature in the vicinity, and after each pass, measure the same aggregate each time a reading was taken.

The temperatures are recorded in Appendix H. Note that all of the projects' temperatures are lower than the specification requirement that all passes be completed before the mat temperature falls to 80° C. It was not possible to relate temperature measured by thermocouple to mat temperature. Temperature measurements by thermocouple do provide temperatures that are comparable across the range of nine compaction patterns and six projects however.

Table 4.12 shows average temperature for each project's test pattern and the test pattern average for all projects. The compaction pattern that averaged the highest compaction (VSVSSS) actually had the lowest average temperature. The three patterns producing second, third, and fourth lowest average compactions overall (VS, VSV, VSVS) had the highest average temperature. Average temperature does not appear to relate consistently to compaction.

Table 4.12: Mean Temperature (degrees Celsius as measured by Thermocouple) for each Test Pattern

Project	Pattern								
	VS	**VSV**	**VSVS**	**VSVSS**	**VSVSSS**	**SSS**	**SSSS**	**SSSSS**	**SSSSSS**
N Grants Pass – Evans Creek	74	72	62	59	55	65	65	64	65
Grants Pass – Applegate River	73	67	70	69	61	64	63	66	58
Stayton NCL - Fir Grove Lane	55	58	53	43	54	57	61	54	51
Stayton NCL – Joseph Street Interchange	68	63	63	57	58	61	54	62	66
Midland Junction – California State Line	64	53	67	61	58	60	61	63	69
Baldock Safety Rest Area – Woodburn Interchange	69	64	66	71	59	57	56	56	56
Average	67.2	62.8	63.5	60.0	57.5	60.7	60.0	60.8	60.8

Correlations of temperatures and core densities were determined. Correlations were determined using the values of the temperature after the first, second, third, fourth, fifth, and sixth passes, as well as the average temperature for each section. The R-values obtained are presented in Table 4.13. The strongest relationship between temperature and core density occurs after three passes. The weakest relationships are after five and six passes.

Table 4.13: Temperature - Density Correlations

Using temperature after the ________ pass	R-value
First	0.28
Second	0.32
Third	0.42
Fourth	0.31
Fifth	0.23
Sixth	0.22
Average Temperature	0.32

4.4 MULTIPLE REGRESSION ANALYSIS USING DUMMY VARIABLES

Thus far, the discussion of results has focused on the variables of compaction pattern and temperature. An ideal research study would have been able to isolate only the experimental variable, compaction pattern, and maintain all other variables such as temperature, asphalt mix, and compaction equipment constant. Working under the practical constraints of contract administration, this was not possible. The best that can be accomplished is the determination of the effects of other variables in the data collected. This was done through the use of multiple regression analysis with dummy variables [Hardy, 1993].

The variables, other than compaction pattern, that would be expected to affect field compaction would be mix design, asphalt binder type, aggregate type and source, temperature during compaction, and roller weight. The regression model was established to determine the relative effects of these variables, compare them to the effect of number of compaction passes, and contrast static to vibratory compaction. The variable of mix design is accounted for by identifying the dependent variable as compaction expressed as per cent of MTD rather than as unit weight in kg/m^3. Aggregate and binder variables for the projects are summarized in Table 4.14. Roller weights and average temperatures for the projects were previously presented in Tables 4.4 and 4.12 respectively. The effects of making more passes and of addition of vibratory compaction are to be determined through the dummy variables coded as shown in Table 4.15. The theoretical reference case becomes compaction at zero degrees Celsius, with one vibratory and one static pass of a weightless compactor.

The 262 points with valid core densities were included in the regression model. Analysis was performed by ODOT Research using the Statistical Package for the Social Sciences (SPSS). The results are presented in Table 4.16.

Table 4.14: Aggregate and Binder Variables

Project	Agg Type	Binder Type
N Grants Pass-Evans Creek	Gravel	PBA-6
Grants Pass-Applegate River	Gravel	PBA-5
Stayton NCL-Fir Grove Lane	Gravel	PBA-5
Stayton NCL-Joseph Street Interchange	Gravel	PBA-5
Midland Junction-California State Line	Quarry	PBA-6
Baldock Safety Rest Area-Woodburn Interchange	Gravel	PBA-6

Table 4.15: Dummy Variables Coded

VARIABLE	VS	SSS	SSSS	SSSSS	SSSSSS	VSV	VSVS	VSVSS	VSVSSS
3 Passes	0	**1**	0	0	0	**1**	0	0	0
4 Passes	0	0	**1**	0	0	0	**1**	0	0
5 Passes	0	0	0	**1**	0	0	0	**1**	0
6 Passes	0	0	0	0	**1**	0	0	0	**1**
3 Pass increment with Vibratory	0	0	0	0	0	**1**	0	0	0
4 Pass increment with Vibratory	0	0	0	0	0	0	**1**	0	0
5 Pass increment with Vibratory	0	0	0	0	0	0	0	**1**	0
6 Pass increment with Vibratory	0	0	0	0	0	0	0	0	**1**

Table 4.16: SPSS Regression Results

	Model	R	R Squared	Adjusted R Squared	Std. Err.	
		0.549	0.302	0.271	2.172	

Variable	Label	B	Std. Error	Beta	t	Sig.
	(Constant)	64.91	1.992		32.59	0.000
Ave. temp	Average Temperature (° Celsius)	0.09	0.026	0.233	3.52	0.001
Binder	Binder (1=PBA-5, 2=PBA-6)	-0.79	0.269	-0.155	-2.92	0.004
Weight	Roller Weight (Mg)	0.55	0.188	0.173	2.92	0.004
x1s	3 Passes	0.43	0.605	0.072	0.72	**0.474**
x2s	4 Passes	2.60	0.598	0.430	4.35	0.000
x3s	5 Passes	2.62	0.609	0.421	4.31	0.000
x4s	6 Passes	2.16	0.613	0.351	3.52	0.001
x1sx1v	3 Pass increment with Vibratory	1.51	0.568	0.189	2.65	0.009
x2sx1v	4 Pass increment with Vibratory	-0.96	0.562	-0.121	-1.71	**0.088**
x3sx1v	5 Pass increment with Vibratory	0.68	0.592	0.085	1.15	**0.252**
x4sx1v	6 Pass increment with Vibratory	1.78	0.581	0.224	3.07	0.002
	Dependent Variable: PCTMAX (Percent of Maximum Theoretical Density)					

The regression model produces an overall R-value of 0.549, thus explaining about 30% of the variance ($R^2 = 0.302$). However, variations within each compacted area account for 37% of total variance. Since all the independent variables in the regression are constant within test sections, they cannot possibly differentiate within-section differences. The upper practical limit for R^2 is only about 0.63, rather than 1. There are important variables not specified in the regression model. What these variables are is not known. Possibilities include aggregate type – composition, angularity, etc., or deviations from average temperature measured by thermocouple, or density of underlying layer.

The actual regression coefficients are displayed in the column designated B in Table 4.16. The Beta coefficients displayed in the table are the normalized regression coefficients. They are measures of the relative amount of variance explained by the variable. The "Sig." column indicates the level at which the coefficients are statistically significant. If a cut-off is set of only accepting results significant at the 0.05 level, the values shown in bold are not significant. The changes from the VS compaction pattern to the SSS compaction pattern, the changes from SSSS to VSVS, and from SSSSS to VSVSS were <u>not</u> statistically significant.

The actual regression coefficients (B) indicate that for the reference case of one vibratory and one static pass of a weightless compactor at 0° C, compaction of 65% of maximum theoretical density would be predicted. For any data point, the predicted value of per cent of maximum theoretical density achieved would be equal to the sum of 65% (constant) plus the sum of the applicable products of the independent variables and their respective regression coefficients. For example, for a point with average compaction temperature of 60° C, and PBA-6 binder compacted with six passes including vibratory compaction (VSVSSS), the predicted per cent of maximum theoretical density achieved would be 64.9 plus 0.09 * 60 - 0.79*2 + 0.55*10 +2.16*1 + 1.78*1 = 78.1.

The actual regression coefficients show the increase in per cent of MTD to be expected from a change of one unit in their respective independent variable. For the data collected, an increase in average temperature of one degree Celsius produced a 0.09% increase in compaction. An increase of one Mg in roller weight raised compaction 0.55%.

The normalized regression coefficients (Beta) indicate that the independent variable that best predicts the per cent of MTD achieved is changing the compaction pattern from VS to SSSS (0.43). Changing from VS to SSSSS and to SSSSSS are next best at explaining variance (0.42 and 0.35), but are not worth the extra compactive effort compared to SSSS. The next most useful independent variables for explaining variance are average temperature, incrementing from SSSSSS to VSVSSS, incrementing from SSS to VSV, and roller weight.

4.5 IMPLICATIONS FOR CURRENT SPECIFICATION

What do the regression results mean with respect to changing the current specification for compaction of Oregon F-mix? The regression model predicts the achievement of 76.1% of MTD for the current specification of four static passes with a minimum 7 Mg roller, PBA-5 binder, and a temperature measured with thermocouple of 61° C (median for SSSS compaction). For a given roller weight and compaction temperature, the highest level of compaction would be achieved with a six-pass pattern including vibratory compaction (VSVSSS). The level of compaction versus the current SSSS pattern would be expected to increase 1.3% (2.16+1.78-2.60). Current understanding of F-mix performance does not allow determination of the benefit of an increase from 76.1% to 77.4% of MTD. Increasing from four to six passes is likely to decrease production rate and thus increase ODOT's cost.

The regression model suggests that moving from minimum 7-Mg roller to minimum 11-Mg roller would increase percent of MTD from 76.1% to 78.3%. Again, there is likely a cost associated with such a specification change, and the benefit is unknown.

Increasing the temperature of the mix and changing asphalt binder specification are related issues. Changing binder specification introduces many considerations that are outside of the scope of this research project and therefore will not be considered.

What is the value of increasing percent of compaction when values are already in the 75% to 80% range? Perhaps comparison of field compaction results to results from laboratory compaction testing will provide useful information.

4.6 COMPARING FIELD AND LABORATORY COMPACTION

Box specimens of F-mix were obtained from the Grant's Pass – Applegate River project and from the Stayton – Joseph Street project. Laboratory specimens using the gyratory compactor were prepared with both mixes by OSU. The plots of percent of MTD versus compactive effort measured in gyrations are displayed in Figures 4.12 - 4.14. Also included in these plots are the points indicated by the nine test compaction patterns utilized in the field. Since the Stayton –

Joseph Street mix design was also used on the Stayton NCL – Fir Grove Lane project, points from field compaction on this project are displayed in Figure 4.14. The density was known and the position on the graph was estimated by interpolation.

The Grants Pass – Applegate River mix is more easily compacted than the mix used for the Stayton projects, both in the lab and in the field. It took 120 lab gyrations with the Stayton mix to produce 79% compaction, while only 40 lab gyrations produced 79% compaction for the Grants Pass – Applegate River mix. In the field the Grants Pass project produced compaction in excess of 81%, while the Stayton projects' best field compaction was less than 80%.

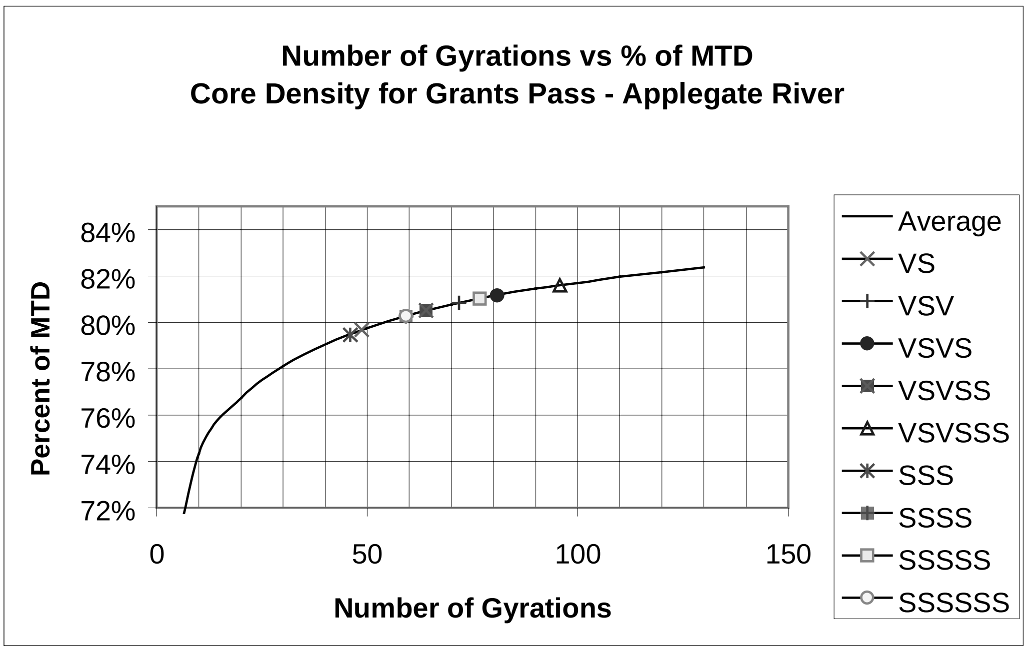

Figure 4.12: Gyratory Compaction Curve for Grants Pass – Applegate River

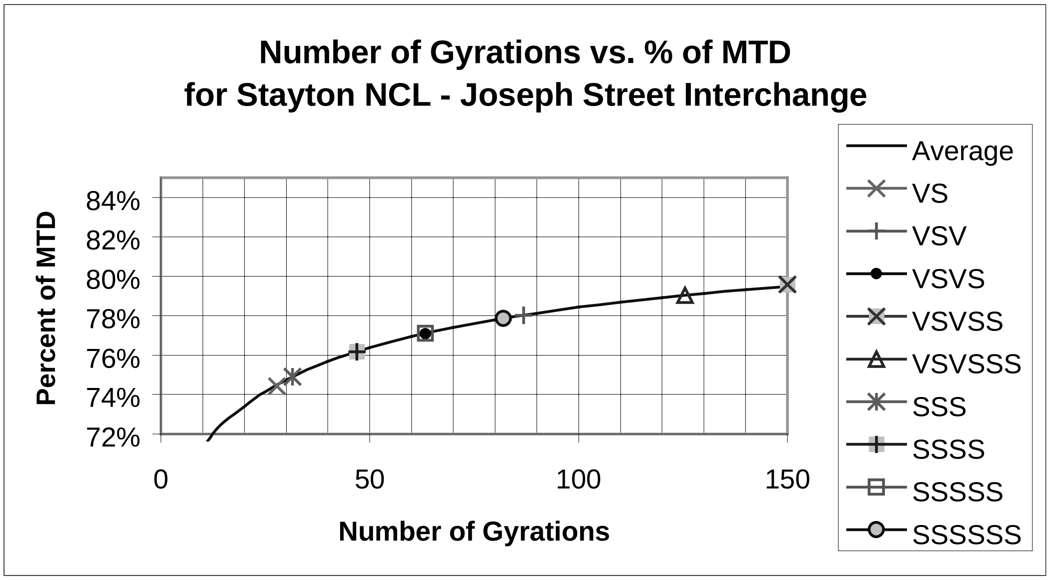

Figure 4.13: Gyratory Compaction Curve for Stayton NCL – Joseph Street Interchange

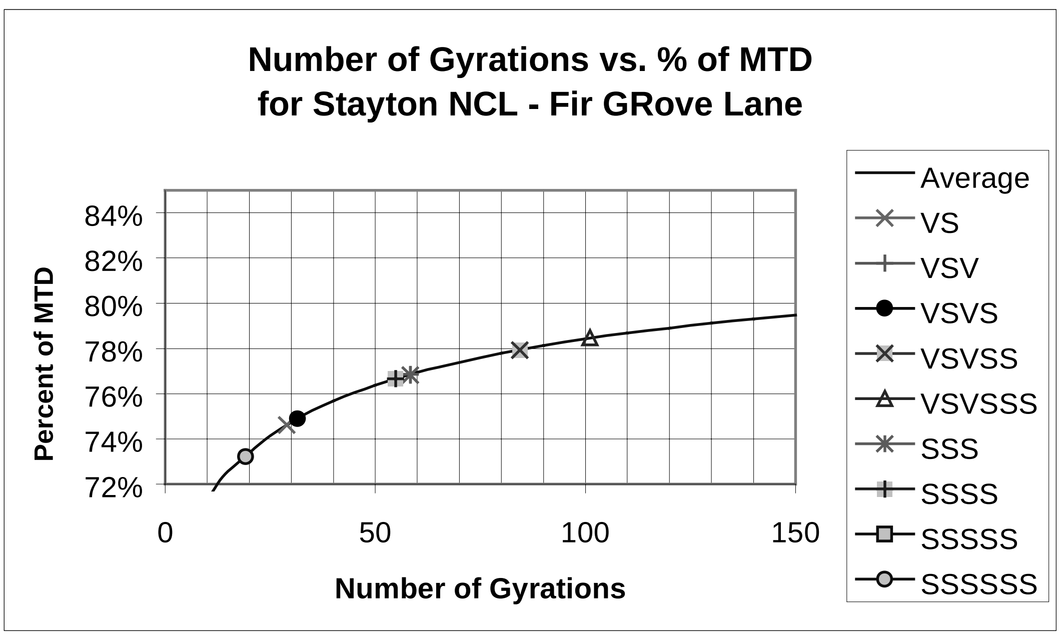

Figure 4.14: Gyratory Compaction Curve for Stayton NCL – Fir Grove Lane

Although the two Stayton projects used the same mix design and the same compaction equipment (see Table 4.4), the densities achieved in the field for the Stayton NCL – Fir Grove Lane project were about 1.5% lower than for the Stayton Joseph Street project. A look at average temperatures for these two projects shows that for all compaction patterns except SSSS, the Fir Grove project temperatures were 6% to 25% lower. The compaction for SSSS was slightly higher for Fir Grove than for Joseph Street. Of the variables measured, temperature appears to be the most likely explanation for the differences in field compaction for the two Stayton projects using the same mix design and equipment.

It should also be noted that the core density data that had to be rejected came from the Stayton Fir Grove project, and primarily from the SSSSSS pattern. Because of the rejections, only two cores for this pattern remained and their average was the lowest density in the entire study.

For all three projects shown in Figures 4.12 - 4.14, the lab compaction efforts comparable to the field SSSS pattern of the current specification are 59, 48, and 55 gyrations. For the Grants Pass – Applegate River mix, lab values of 45 - 95 gyrations covered the complete range of field compaction tested. For the mix of the Stayton projects, comparable lab compaction efforts ranged from 20 - 150 gyrations.

How many gyrations in the laboratory are comparable to compaction in the field to the current specification? The regression model predicts 76.1% of MTD with the current specification. Figure 4.9 shows that for Grants Pass-Applegate River only 15 gyrations are required to reach 76% of MTD. Figure 4.10 shows that for the mix design used on the Stayton projects, 45 gyrations are required to reach 76% of MTD.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Analysis of the field and lab data obtained in this study leads to the following conclusions:

1. Neither the nuclear density gage nor the PQI produced results adequate to control field compaction on the six projects tested. Calibration of the nuclear gauge was not good, and the calibration for the PQI was based on the nuclear gauge readings.

2. Prior to this study, ODOT expected that nuclear density readings within 4% of core densities could be consistently achieved (Mandich, 1994). This level of accuracy was not achieved in the study. Since nuclear readings were needed only for the research project, they were not taken as a routine daily activity by a project-based inspector. Rather readings were taken by a qualified technician who could be conveniently brought to the job site at the time needed.

3. The PQI is much faster and easier to operate than the nuclear gauge. Although correlations of PQI readings with core densities were weaker than correlations between nuclear gauge readings and core densities, the device has great potential if improvements in the technology continue, and if methods of calibration are improved.

4. Analysis of the relationship between permeability as measured by the field permeameter and density of field cores produces Pearson's Correlation Coefficient (R-value) of 0.35, thus explaining 12 % of the variance.

5. The regression equation resulting from the analysis of 262 data points resulting from nine compaction patterns on six projects indicates that the current F-mix compaction specification should be expected to produce an average compaction of 76.1% of MTD.

6. The regression model predicts that the average compaction could be increased from 76.1% of MTD to 78.3% by changing the minimum roller weight requirement in the specification from 7 Mg to 11Mg.

7. The regression model predicts that the average compaction could be increased from 76.1% of MTD to 77.4% by changing the requirement for compaction from a minimum of four static passes to a minimum of six passes with a VSVSSS sequence.

8. Benefits of raising compaction of F-mix to levels higher than 76.1 % of MTD are unknown.

5.2 RECOMMENDATIONS

Based on analysis of the data obtained in this research project, the following recommendations are made.

1. The benefits of higher compaction for F-mix are unknown. It may be that improvements in compaction of F-mix lead to improved quality and performance. If this is the case, higher costs for improved compaction may be justified. An accurate determination of whether additional money should be spent to improve compaction is not possible until the relationship between compaction and performance for F-mix is known. Such knowledge can only be obtained through additional research.

2. ODOT should continue exploration of the potential use of the PQI concentrating on its use with dense-graded mix. Construction of dense-graded mixes is already controlled with a density specification, so nuclear gauge readings are routinely taken by well-trained technicians using well-maintained equipment. Data for comparing nuclear gauge results with PQI results will be readily available. As reliability of the PQI improves, ODOT should consider the use of the PQI with a control strip to control compaction . It may also be possible to calibrate the PQI from lab specimens compared with the job mix formula using the gyratory compactor.

3. With the current level of knowledge of the benefits of improved compaction for F-mix, there is no justification for changing the specification in any way that would increase cost. Comparison of the field density readings with the laboratory compaction curves indicates that all compaction patterns tested are on the near-horizontal part of the compaction curve. Any compaction increases will be relatively minor.

6.0 REFERENCES

American Society for Testing and Materials (ASTM), D2950-91 (Re-approved 1997): Standard Test Method for Density of Bituminous Concrete in Place by Nuclear Methods.

Choubane, Bouzid, Upshaw, Patrick B., Sholar, Gregory A., Page, Gale C., and Musselman, James A., "Nuclear Density Readings and Core Densities: A Comparative Study," Preprint -- Transportation Research Board 78th Annual Meeting, January 10-14, 1999.

Hardy, Melissa A., *Regression with Dummy Variables,* Sage Publications, 1993.

Hedderson, *SPSS Made Simple,* page 105, 1987.

Isenring, T., Koster, H., and Scazziga, I., "Experiences with Porous Asphalt in Switzerland," TRR 1265, Transportation Reassert Board, 1990, pages 41 - 43.

Mandich, Tony, "Memo to ODOT Region Inspectors," entitled, "Density Testing of Open Graded 'F' Mixtures," September 26, 1994.

Norusis, Marija J., *SPSS Introductory Guide: Basic Statistics and Operations,* McGraw – Hill Book Company, 1982.

PIARC Technical Committee On Surface Characteristics, *Porous Asphalt*, 1993, page 61.

Transportation Research Board, *Determining Asphaltic Concrete Pavement Structural Properties By Non-Destructive Testing*, NCHRP Report #327, June 1990.

TransTech Systems, Inc., *Pavement Quality Indicator Operating Manual*, 968 Albany Shaker Rd., Latham New York 12110, 1-800-724-6306, April, 1998.

Watson, Johnson, and Jared, *Georgia DOT's Progress In Open-Graded Friction Course Development*, 1998 Annual Meeting of the Transportation Research Board.

APPENDIX A - CURRENT OREGON DOT SPECIFICATION

OREGON DEPARTMENT OF TRANSPORTATION
SUPPLEMENTAL STANDARD SPECIFICATIONS

APRIL 1999

SECTION 00745 QA - HOT MIXED ASPHALT CONCRETE (HMAC)

This information comprises a 33-page document, which can be found at the following ODOT internet address: http://www.odot.state.or.us/techserv/roadway/specs/supplement/0745supl.pdf

The document is in **Adobe Acrobat Portable Document Format (pdf)**. To view it online, you will need Adobe Acrobat Reader.

The Supplemental Standard Specifications are also available by ordering from:

Oregon Department of Transportation
355 Capitol Street N.E., Room 1
Salem, OR 97301-3871

Telephone (503) 986-3718

APPENDIX B - TEST LOCATIONS

Project: N Grants Pass - Evans Creek
Date: 21-Apr-98
Location: Northbound, 100 m from city
Mileage sign north of the Rogue
River on ramp, approx. MP 49
In the slow lane shoulder

Typical Section

Y

X (EOP)

Section	Location
1	100 - 250 m north of the sign
2	250 - 400 m north of the sign
3	400 - 550 m north of the sign
4	550 - 700 m north of the sign
5	700 - 850 m north of the sign
6	850 - 1000 m north of the sign
7	1000 - 1150 m north of the sign
8	1150 - 1300 m north of the sign
9	1300 - 1450 m north of the sign

Definitions
V = Vibratory Pass
S = Static Pass

Section	Description
1	V-S
2	V-S-V
3	V-S-V-S
4	V-S-V-S-S
5	V-S-V-S-S-S
6	S-S-S
7	S-S-S-S
8	S-S-S-S-S
9	S-S-S-S-S-S

Core	X(m)	Y(m)
1-1	58.4	1.9
1-2	141.1	0.1
1-3	61.9	0.2
1-4	144.5	1.0
1-5	124.5	1.4
2-1	71.8	0.2
2-2	97.4	1.4
2-3	93.3	1.3
2-4	63.5	1.0
2-5	88.7	0.5
3-1	143.7	0.9
3-2	141.6	0.5
3-3	53.8	0.3
3-4	114.8	1.3
3-5	9.6	0.6
4-1	61.1	1.4
4-2	70.7	1.1
4-3	54.6	1.5
4-4	76.6	0.4
4-5	124.3	0.3
5-1	12.9	0.4
5-2	130.7	2.0
5-3	90.4	1.7
5-4	67.2	1.1
5-5	90.8	0.6
6-1	23.4	0.6
6-2	68.4	1.9
6-3	45.7	0.5
6-4	92.1	1.7
6-5	120.9	1.1
7-1	127.9	1.1
7-2	77.5	0.5
7-3	121.6	0.5
7-4	141.4	1.8
7-5	54.5	0.9
8-1	23.0	0.4
8-2	92.6	0.6
8-3	66.4	1.2
8-4	99.4	0.5
8-5	141.3	0.7
9-1	132.7	1.1
9-2	61.3	1.7
9-3	34.7	0.6
9-4	102.7	1.9
9-5	77.8	1.9

Project:	Grants Pass - Applegate River
Date:	13-Jul-98
Location:	East bound shoulder of Hwy. 199
	Near the intersection of Hwy. 199 and Dowell St.

Typical Section

Y

X (EOP)

Section	Location
1	91.4m west of Dowell St intersection
2	150.9m after beginning of section 1
3	150.9m after beginning of section 2
4	150.9m after beginning of section 3
5	150.9m after beginning of section 4
6	150.9m after beginning of section 5
7	150.9m after beginning of section 6
8	150.9m after beginning of section 7
9	150.9m after beginning of section 8

Definitions
V = Vibratory Pass
S = Static Pass

Section	Description
1	V-S
2	V-S-V
3	V-S-V-S
4	V-S-V-S-S
5	V-S-V-S-S-S
6	S-S-S
7	S-S-S-S
8	S-S-S-S-S
9	S-S-S-S-S-S

Core	X(m)	Y(m)
1-1	74.9	0.8
1-2	130.8	1.0
1-3	90.9	1.1
1-4	49.6	0.7
1-5	135.8	0.8
2-1	114.8	0.6
2-2	98.2	1.2
2-3	60.3	0.6
2-4	84.2	1.2
2-5	73.0	1.0
3-1	131.4	0.7
3-2	113.9	1.2
3-3	137.0	0.8
3-4	23.2	0.8
3-5	95.6	1.3
4-1	132.6	1.2
4-2	81.7	0.6
4-3	99.0	1.4
4-4	26.5	0.6
4-5	113.1	0.8
5-1	127.4	1.1
5-2	101.6	1.5
5-3	48.3	1.4
5-4	31.8	1.0
5-5	133.2	0.9
6-1	16.9	1.0
6-2	26.0	1.2
6-3	68.1	0.7
6-4	99.1	0.8
6-5	131.3	1.3
7-1	125.8	1.2
7-2	18.2	0.6
7-3	132.6	1.4
7-4	83.6	1.0
7-5	45.5	0.7
8-1	19.5	0.7
8-2	42.0	1.3
8-3	47.9	0.7
8-4	35.9	0.8
8-5	29.6	0.9
9-1	121.0	0.7
9-2	34.3	0.7
9-3	126.4	0.7
9-4	101.8	0.9
9-5	23.7	0.6

Project: Stayton NCL - Fir Grove Lane
Date: 4-Jun-98
Location: Old Mehama Rd., E. Santiam St.,
Jct. 1/2 mile sign
on Hwy 22, app. MP 15
East Bound Shoulder

Typical Section

Y

X (EOP)

Section	Location
1	Jct. 1/2 mile sign, Hwy 22, MP 15
2	150 m from beginning section 1
3	300 m from beginning section 1
4	51.5m past stop sign of E. Santiam St.
5	150 m from beginning section 4
6	300 m from beginning section 4
7	450 m from beginning section 4
8	600 m from beginning section 4
9	750 m from beginning section 4

Definitions
V = Vibratory Pass
S = Static Pass

Section	Description
1	V-S
2	V-S-V
3	V-S-V-S
4	V-S-V-S-S
5	V-S-V-S-S-S
6	S-S-S
7	S-S-S-S
8	S-S-S-S-S
9	S-S-S-S-S-S

Core	X(m)	Y(m)
1-1	90.2	1.1
1-2	131.2	0.6
1-3	54.4	0.6
1-4	70.3	0.5
1-5	133.8	0.2
2-1	85.4	0.7
2-2	150.0	1.1
2-3	125.9	1.1
2-4	41.7	0.6
2-5	116.9	0.2
3-1	126.9	0.3
3-2	71.0	1.0
3-3	24.9	0.2
3-4	3.5	1.1
3-5	20.5	1.1
4-1	101.1	0.6
4-2	146.3	1.4
4-3	14.2	0.6
4-4	83.5	0.9
4-5	6.9	0.8
5-1	19.4	0.9
5-2	77.4	0.8
5-3	74.7	0.9
5-4	68.3	1.0
5-5	28.8	1.0
6-1	3.6	0.7
6-2	10.4	0.6
6-3	22.4	0.7
6-4	59.9	0.6
6-5	36.3	0.8
7-1	94.7	0.7
7-2	135.3	0.7
7-3	62.1	0.8
7-4	106.4	0.6
7-5	44.5	1.1
8-1	50.9	1.0
8-2	86.6	0.4
8-3	88.2	0.8
8-4	23.7	1.6
8-5	117.3	0.8
9-1	23.5	0.5
9-2	13.0	0.6
9-3	86.9	0.6
9-4	82.5	0.2
9-5	89.1	0.8

Project:	Stayton NCL - Joseph Street Interchange
Date:	3-Sep-98
Location:	

Typical Section

Y

X (EOP)

Section	Location
1	
2	
3	
4	
5	
6	
7	
8	
9	

Definitions
V = Vibratory Pass
S = Static Pass

Section	Description
1	V-S
2	V-S-V
3	V-S-V-S
4	V-S-V-S-S
5	V-S-V-S-S-S
6	S-S-S
7	S-S-S-S
8	S-S-S-S-S
9	S-S-S-S-S-S

Core	X(m)	Y(m)
1-1	44.5	0.4
1-2	106.8	0.6
1-3	56.4	0.5
1-4	72.9	1.1
1-5	63.5	0.7
2-1	59.9	0.6
2-2	76.9	1.2
2-3	86.3	1.1
2-4	71.2	1.1
2-5	92.7	0.5
3-1	116.7	0.5
3-2	46.9	1.0
3-3	89.2	1.1
3-4	32.9	0.5
3-5	71.5	1.0
4-1	33.6	0.8
4-2	65.0	1.1
4-3	109.1	0.6
4-4	102.0	0.8
4-5	46.0	1.0
5-1	43.1	0.6
5-2	114.9	0.5
5-3	31.8	0.9
5-4	89.2	1.1
5-5	67.5	0.5
6-1	32.5	0.5
6-2	46.5	1.2
6-3	116.2	0.9
6-4	108.7	0.5
6-5	67.0	0.5
7-1	32.8	1.0
7-2	79.1	1.2
7-3	53.1	0.5
7-4	109.1	0.8
7-5	116.3	0.6
8-1	71.9	0.8
8-2	36.8	0.5
8-3	75.3	1.0
8-4	101.7	0.5
8-5	56.4	1.0
9-1	41.4	0.4
9-2	59.3	0.8
9-3	71.6	1.0
9-4	108.9	0.9
9-5	93.3	0.5

Project: Midland Junction - California State Line
Date: 31-Aug-98
Location: Hwy. 97 Southbound shoulder.
Directly across from the farm scale door
The test sections go in ascending order
going north on the Southbound shoulder.

Typical Section
X (EOP)
Y

Section	Location
1	
2	
3	
4	
5	
6	
7	
8	
9	

Definitions
V = Vibratory Pass
S = Static Pass

Section	Description
1	V-S
2	V-S-V
3	V-S-V-S
4	V-S-V-S-S
5	V-S-V-S-S-S
6	S-S-S
7	S-S-S-S
8	S-S-S-S-S
9	S-S-S-S-S-S

Core	X(m)	Y(m)
1-1	121.4	0.7
1-2	42.6	0.8
1-3	35.4	1.2
1-4	69.1	0.6
1-5	73.0	1.0
2-1	36.4	0.8
2-2	131.6	0.9
2-3	42.4	1.0
2-4	60.8	0.8
2-5	102.7	1.0
3-1	120.6	1.2
3-2	88.5	1.2
3-3	67.4	0.9
3-4	55.7	0.6
3-5	32.6	0.8
4-1	105.9	0.5
4-2	66.0	0.5
4-3	81.8	1.1
4-4	101.4	1.1
4-5	52.0	0.5
5-1	47.7	0.5
5-2	63.1	1.1
5-3	132.5	0.7
5-4	83.9	1.1
5-5	103.8	0.9
6-1	124.1	0.9
6-2	104.6	1.0
6-3	89.9	0.5
6-4	64.3	0.5
6-5	40.1	1.2
7-1	120.4	1.0
7-2	55.5	1.0
7-3	98.7	1.2
7-4	34.1	1.1
7-5	79.1	1.0
8-1	103.0	0.5
8-2	61.4	1.0
8-3	37.6	1.1
8-4	131.6	1.0
8-5	89.9	1.1
9-1	82.9	1.0
9-2	57.4	1.0
9-3	129.1	0.6
9-4	113.6	0.6
9-5	37.4	0.6

Project: Baldock Safety Rest Area - Woodburn Interchange
Date: 16-Aug-98
Location: I-5 SB just past Rest Area, approx. MP 281
805 feet south of Trucks-Trailers-Campers-
Buses- Unlawful to use left lanes
Except to Pass sign.

Typical Section

Y

X (EOP)

Section	Location
1	805 feet south of sign listed above
2	492.1 feet after beginning of section 1
3	492.1 feet after beginning of section 2
4	492.1 feet after beginning of section 3
5	492.1 feet after beginning of section 4
6	492.1 feet after beginning of section 5
7	492.1 feet after beginning of section 6
8	492.1 feet after beginning of section 7
9	492.1 feet after beginning of section 8

Definitions
V = Vibratory Pass
S = Static Pass

Section	Description
1	V-S
2	V-S-V
3	V-S-V-S
4	V-S-V-S-S
5	V-S-V-S-S-S
6	S-S-S
7	S-S-S-S
8	S-S-S-S-S
9	S-S-S-S-S-S

Core	X(m)	Y(m)
1-1	48.9	0.9
1-2	63.9	1.1
1-3	108.7	1.2
1-4	120.4	0.8
1-5	123.6	0.6
2-1	32.2	0.4
2-2	40.9	0.9
2-3	60.5	0.9
2-4	111.0	0.4
2-5	131.9	0.4
3-1	36.3	0.5
3-2	51.2	1.0
3-3	77.4	0.7
3-4	121.1	0.5
3-5	131.0	0.9
4-1	45.3	0.5
4-2	60.7	0.3
4-3	71.7	0.6
4-4	97.2	1.0
4-5	133.8	0.5
5-1	37.8	0.7
5-2	50.7	0.4
5-3	61.1	1.1
5-4	117.8	0.5
5-5	119.9	0.9
6-1	35.9	0.9
6-2	43.7	0.5
6-3	74.4	0.5
6-4	90.6	1.1
6-5	114.2	0.4
7-1	32.8	1.0
7-2	49.6	1.2
7-3	126.8	0.5
7-4	130.6	0.6
7-5	135.8	1.0
8-1	56.1	0.9
8-2	77.6	0.3
8-3	103.1	0.9
8-4	110.5	0.4
8-5	132.2	0.6
9-1	38.0	0.5
9-2	46.6	1.2
9-3	56.0	1.1
9-4	73.8	0.8
9-5	106.1	0.9

APPENDIX C - NUCLEAR GAUGE PROCEDURES