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

Final Report

SPR 386

RESEARCH

Oregon Department of Transportation

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

FINAL REPORT

SPR 386

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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.

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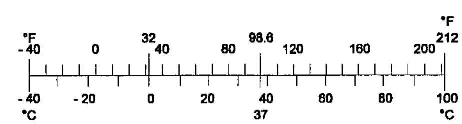
SI* (MODERN METRIC) CONVERSION FACTORS

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)

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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.

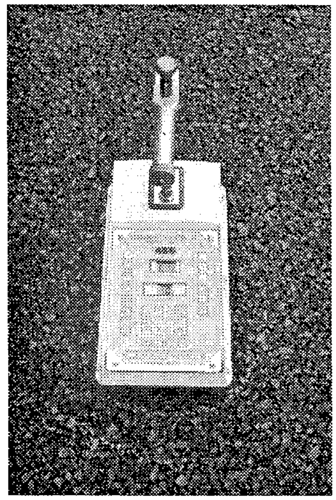

Figure 3.1: Humboldt Nuclear Gauge

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

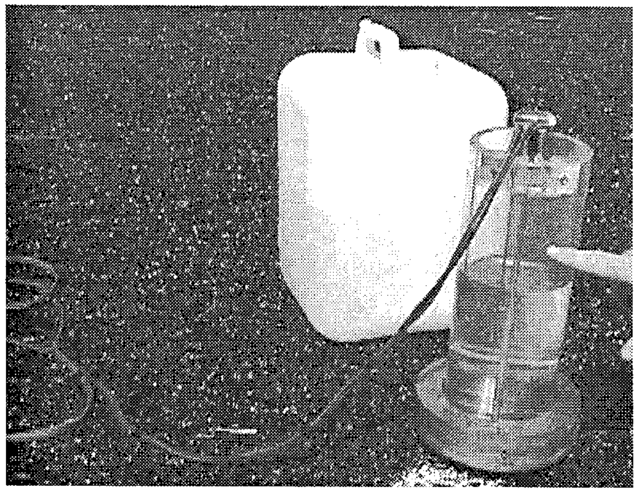

Figure 3.4: Permeameter Probes

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.

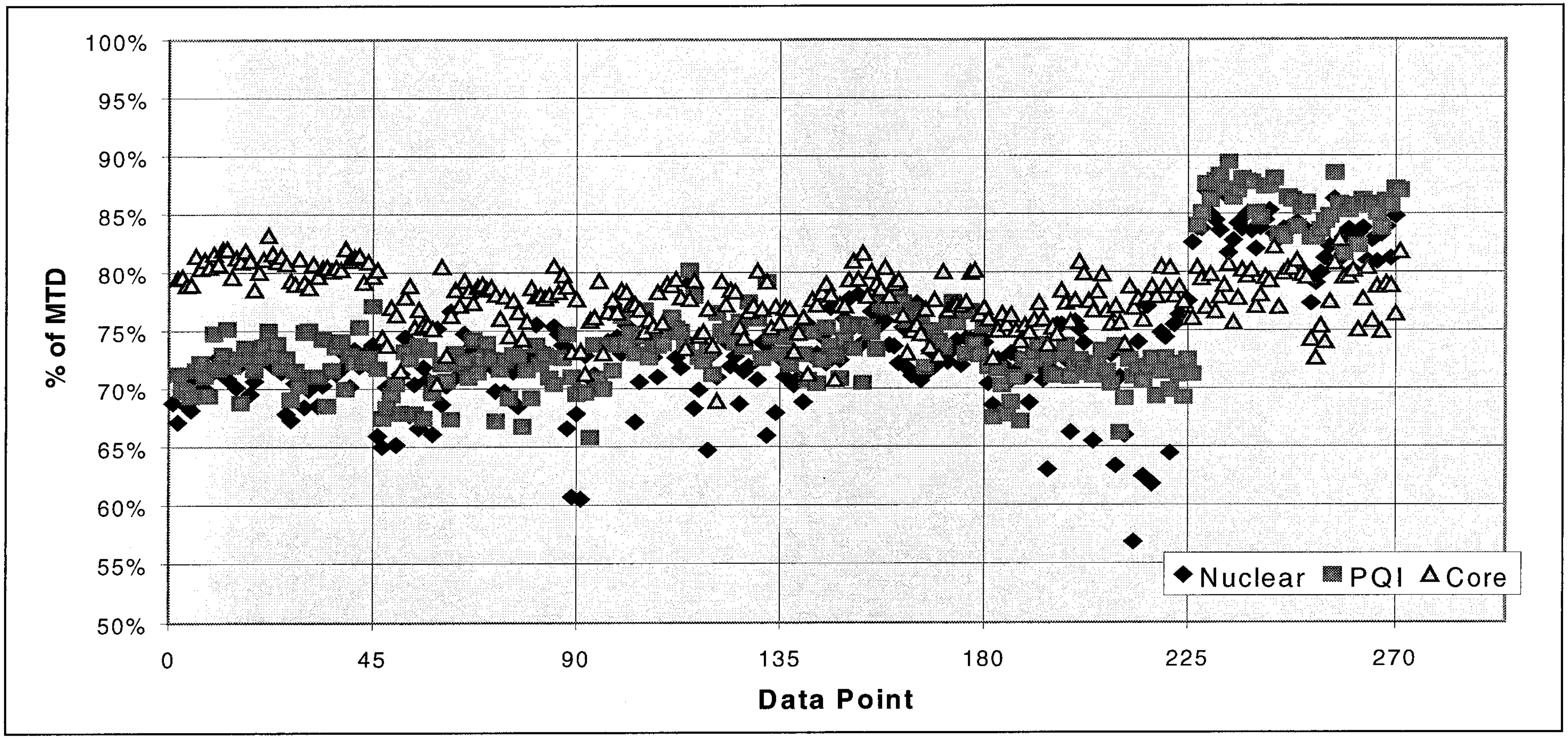

Figure 4.1: Density Measurements

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.

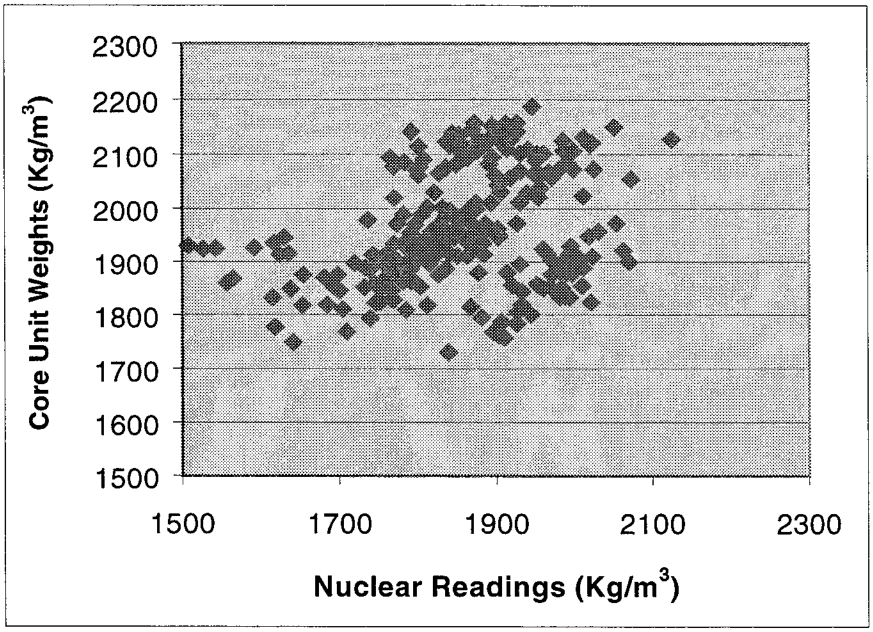

Figure 4.2: Core Unit Weights vs. Nuclear Readings

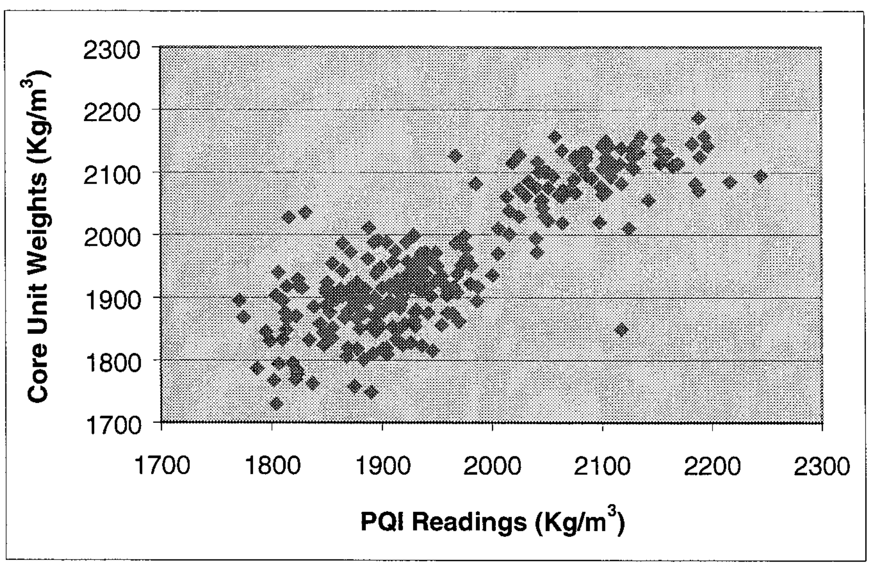

Figure 4.3: Core Unit Weights vs. PQI Readings

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/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³		kg/m³	kg/m³	kg/m³	
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/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³		kg/m³	kg/m³	kg/m³	
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/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³		kg/m³	kg/m³	kg/m³	
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/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³		kg/m³	kg/m³	kg/m³	
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/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³		kg/m³	kg/m³	kg/m³	
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/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³		kg/m³	kg/m³	kg/m³	
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

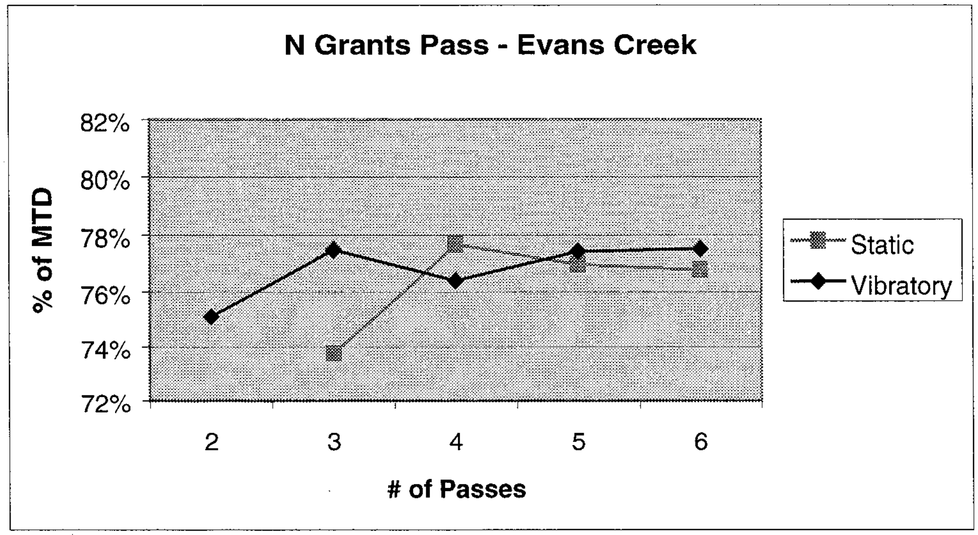

Figure 4.4: Percent of MTD, N Grants Pass – Evans Creek

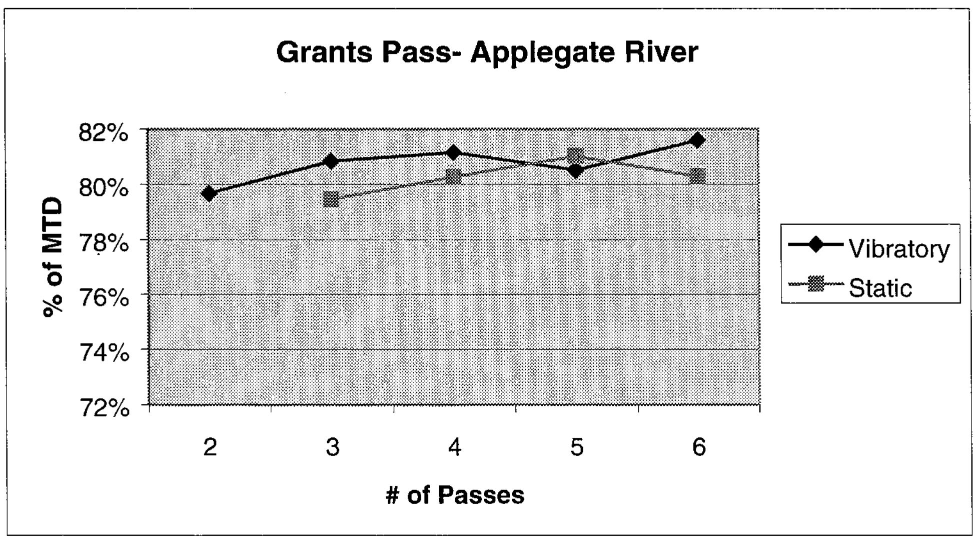

Figure 4.5: Percent of MTD, Grants Pass – Applegate River

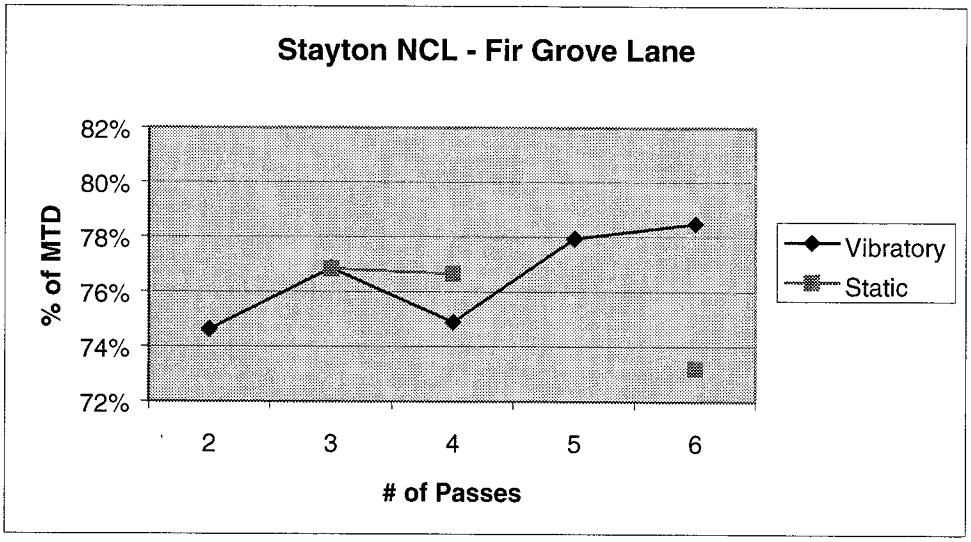

Figure 4.6: Percent of MTD, Stayton NCL – Fir Grove Lane

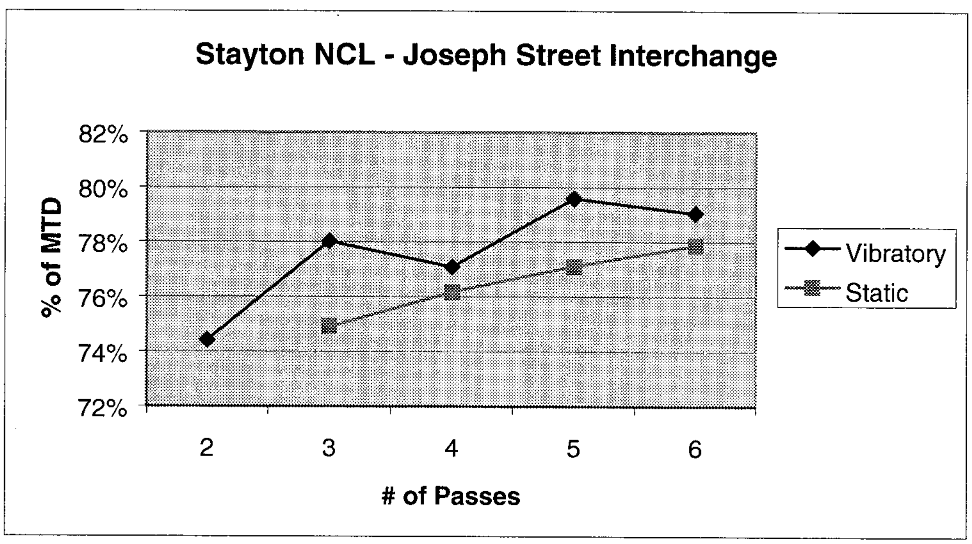

Figure 4.7: Percent of MTD, Stayton NCL – Joseph Street Interchange

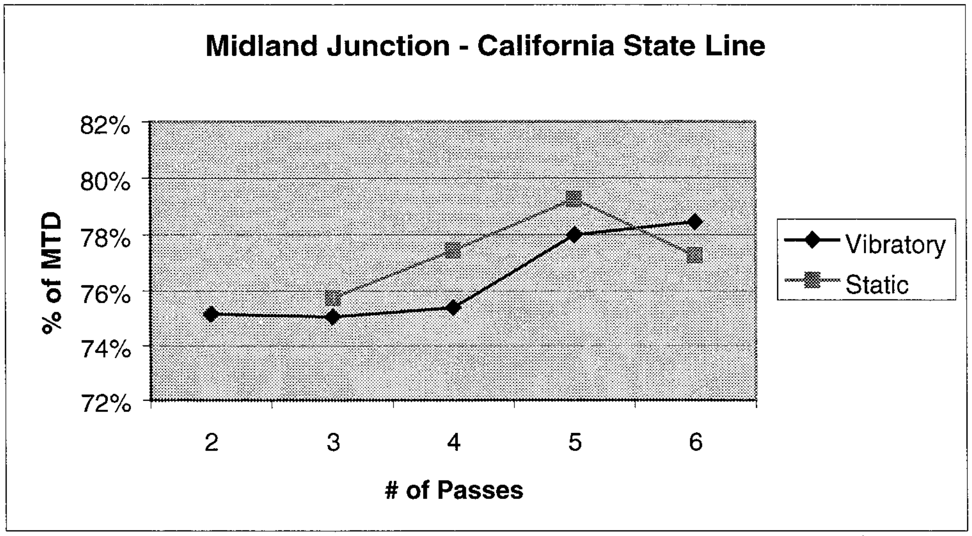

Figure 4.8: Percent of MTD, Midland Junction – California State Line

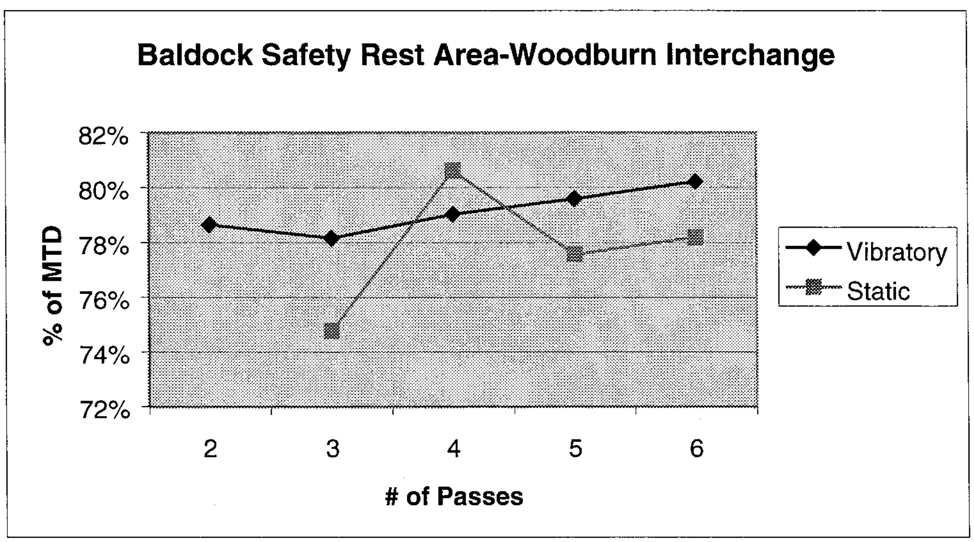

Figure 4.9: Percent of MTD, Baldock Safety Rest Area – Woodburn Interchange

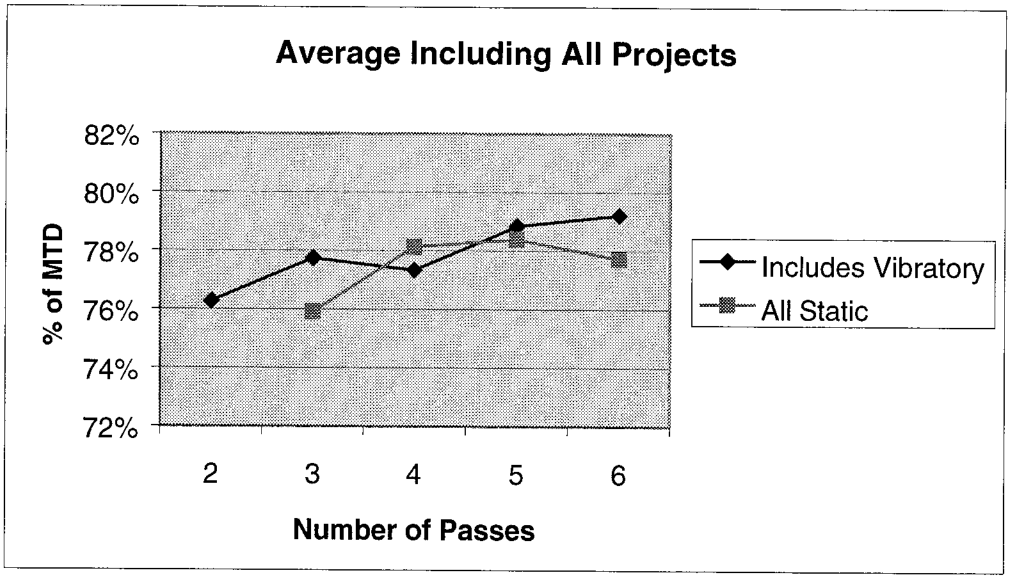

Figure 4.10: Percent of MTD vs. Number of Passes, All Projects

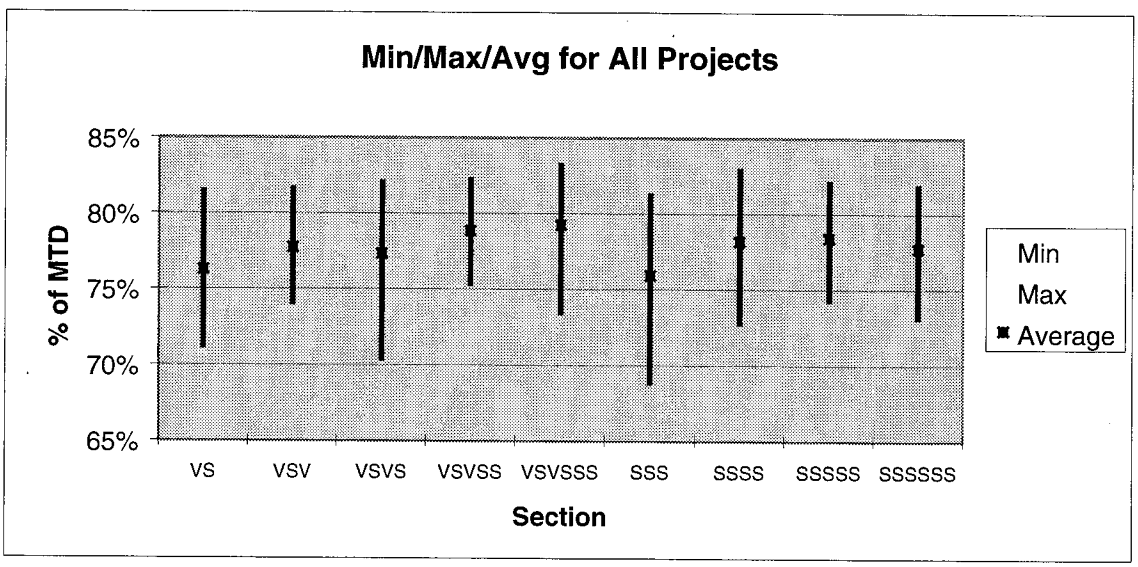

Figure 4.11: Min/Max/Average for each Test Section

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

	Pattern								
Project	**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 not 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%.

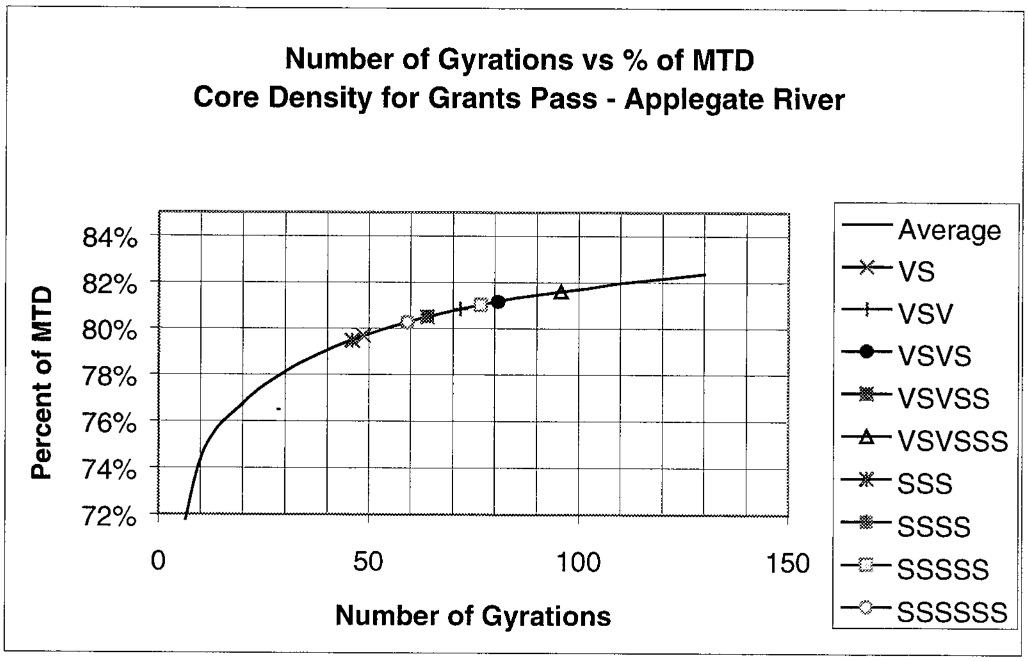

Figure 4.12: Gyratory Compaction Curve for Grants Pass – Applegate River

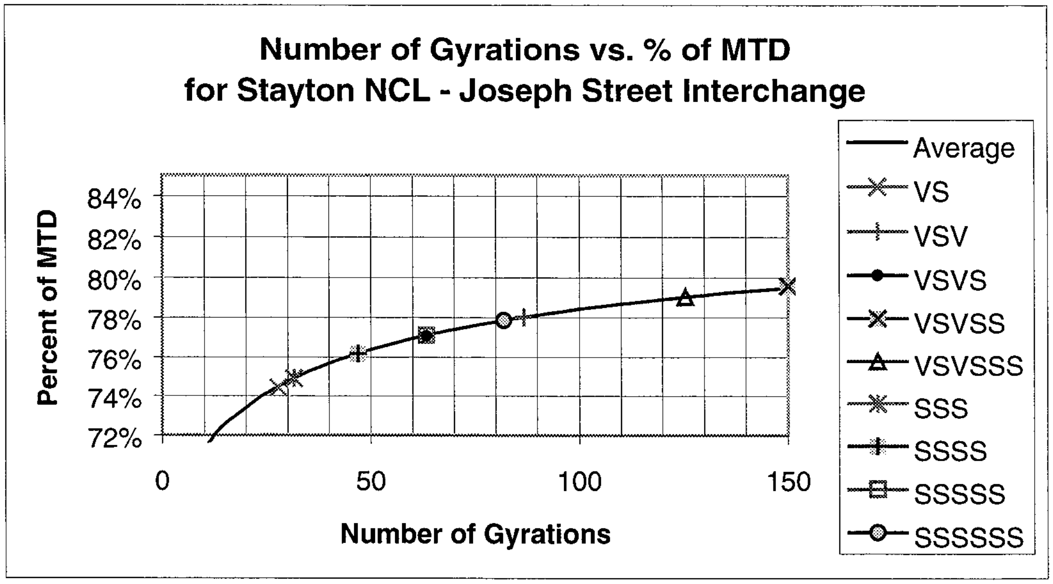

Figure 4.13: Gyratory Compaction Curve for Stayton NCL – Joseph Street Interchange

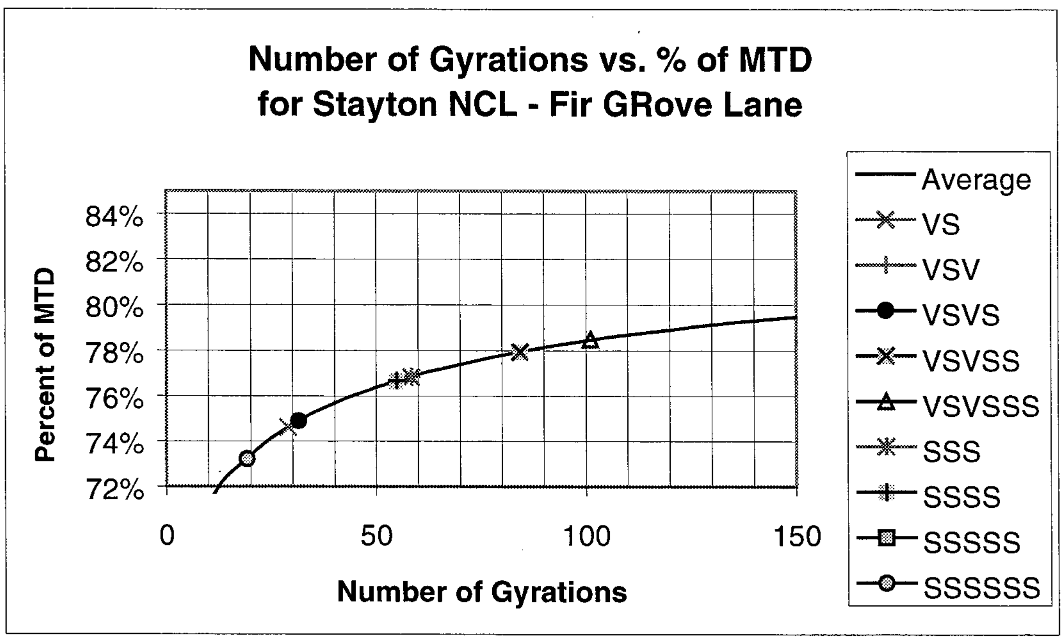

Figure 4.14: Gyratory Compaction Curve for Stayton NCL – Fir Grove Lane

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

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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

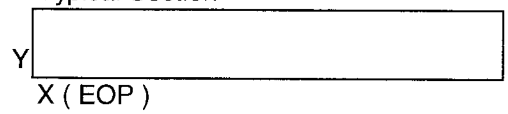
Definitions
V = Vibratory Pass
S = Static Pass

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



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

STATE OF OREGON **INTEROFFICE MEMO**

DEPARTMENT OF TRANSPORTATION - OPERATIONS SUPPORT SECTION - 986-3000

FILE

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Chuck Reeves, Region 2
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Ron Shartner, Region 4
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September 26, 1994

OPERATIONS SUPPORT SECTION
MGR BMS CAE ~~DOE~~ MSE QSE
RME SME OM COMM TSSU PTLO

REC'D SEP 26 1994

TO
FOR:
ROUGH DRAFT ACT INFO DIRECT REPLY FILE

Tony Mandich
Tony Mandich
Construction Training/RSO

r: **Density Testing of Open Graded "F" Mixtures**

Compaction specifications for open-graded mixtures specify a method only. Section 745.24 covers roller specifications and 745.49(d) specifies type of rollers for open-graded mixtures and minimum coverages (four). The last sentence in the paragraph states that the contractor shall make additional passes as directed to obtain thorough compaction.

I believe all of us can see if all the roller marks have been removed, but eyeballing specified density can be difficult.

There is some direction in Section 745.49(a)(1) General: Compaction must be completed before the temperature of the mixture drops below 180°F. The Department interprets these specifications to mean that four complete coverages using the required rollers must be accomplished prior to the mixture temperature dropping below 180°F.

I'm sure both the Department and the industry wants to build the best product possible and to this end I have developed a tool to give us some added assurance. Remember, "This is a tool, not a specification!"

The following procedure tests and calculates the in-place voids of "F" mixtures when placing 2" depths. Research shows that results from these tests will be within 4% of core "measured gravities" or "bulk gravities." Be aware that "F" mix designs are based on drain down (getting the thickest coating of asphalt on the aggregates as possible) and changes in asphalt percentage will not make major changes in voids.

A Humboldt 5001C must be used for testing.

A. Obtain the average density of the underlying mixture.

1. If a dense graded mixture was placed prior to the "F", use the average of the compaction test results.
2. If an overlay and the design for the mixture placed in this area can be found, use 96% of the maximum specific gravity.
3. If cores were taken by surface design, they may be able to provide the Maximum Specific Gravity.
4. As a last resort use 95% of the Rice shown on the "F" mixture JMF (this will not be as accurate as the previous three methods).

Input the lower density (A) into the gauge:

1. **Press shift LWRD key at the same time (a number may or may not show on the screen).**
2. **While holding down the shift key type in the lower density by pushing the appropriate numerical keys.**
3. **When the screen shows the correct lower density, take your finger of the shift key and press enter.**

> NOTE: Make sure you're in asphalt mode by pushing the S/A key while in Safe Position. When the screen reads asph push the enter key.

Set the gauge to 2.0 inch nomograph mode.

1. Set the gauge probe to backscatter position.
2. Push the S/A key. A number should show on the screen which denotes the depth of measurements.
3. Using the up-down keys in the upper left-hand corner of the gauge push one or the other until 2.0 shows on the screen.

You're now ready to take tests!

> NOTE: If, at anytime during testing, you set the probe to backscatter position and 2.0 does not show up on the screen just push the S/A key.

Testing should be done for the purpose of getting the lowest void content possible with specification mixture and consistency across the panel. Tests are taken in one direction using one-minute counts with no sanding of the site. I usually like to run a test every three feet across the panel and every station for about 500' to see if there is a problem with the pattern being used by the contractor. Contractors seem to appreciate this information and will make the appropriate adjustments in their operation.

Voids are calculated from density readings as follows:

Divide the individual density readings by the Maximum Specific Gravity (Rice) found on the JMF, subtract this from 1 and you have voids. Example:

Rice = 158.5
Density reading = 119.6

$$1 - \frac{119.6}{158.5} = 24.5\% \text{ voids}$$

Based upon core studies made by surface design and several projects tested this year the normal field void content for "F" mixes is between 17% and 26%, so don't panic if you see this.

If you have questions about any of this please call...and thanks for your support.

TM:nj
DENTEST

c: Doug Tindall
Gary Thompson

APPENDIX D - PAVEMENT QUALITY INDICATOR PROCEDURES

2.0 Controls and Components

Prior to learning how to operate the unit, we recommend you familiarize yourself with the unit's operating controls and components. Illustrations and listings of the main components and their basic functions are shown below.

2.1 External Components

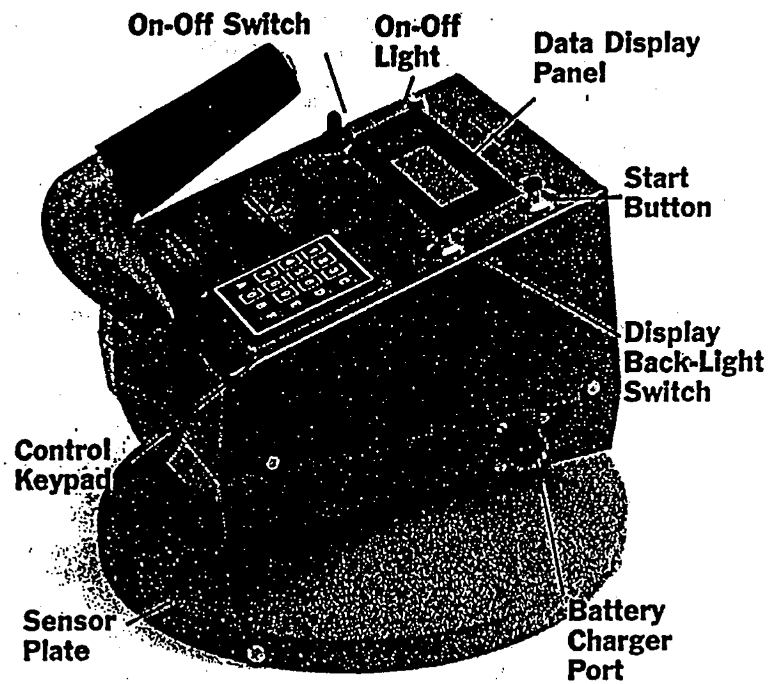

Figure 1. Major Components and Controls of the Pavement Quality Indicator

2.3 Internal Components

Components which are located inside the instrument enclosure include the sensing circuitry, signal processing microprocessor, rechargeable battery, and related electronic components.

Opening the enclosure may result in damage to the equipment, unless special precautions are taken. Under normal operating conditions and use, there is no need to disassemble the unit to access any of the internal components.

Caution

UNAUTHORIZED DISASSEMBLY OF THE UNIT WILL VOID THE WARRANTY.

3.1 General Operation Overview

The TransTech Pavement Quality Indicator is designed to be an extremely flexible unit, with several very useful modes of operation. Each mode of operation is accessed through the control keypad, shown in Figure 2.

Figure 2 Control Keypad

A summary of the keypad codes which you will use to calibrate the unit, change measurement modes, and enter data is presented in Table 1. Each mode of operation is discussed in more detail in the following sections of the manual.

Table 1. Keypad Functions

Key	Function
A	Unassigned (reserved for future expansion)
B	Switches between measurement modes
C	Enters calibration mode for offset calibration
D	Enters diagnostics mode
E	Exits and return to main menu
F	Enters the MTD setting mode
0-9	Respond to menu choices or enter numerical calibration data

3.2 Starting and Initially Setting the Unit

A. Turn the unit on by moving the On-Off switch up, into the "on" position. The power indicator light should go on, indicating that the unit is on. The PQI Display Panel should show the "Bootup" screen of Fig. 3A.

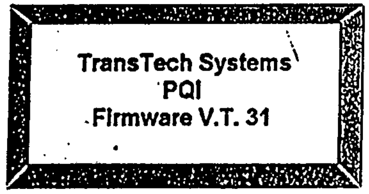

Fig. 3A. Bootup screen

B. Wait for the bootup message to change to the screen shown in Fig. 3B, which allows you to use the current instrument settings or set new values for measurement units, MTD, and reading mode). On the keypad press the 2 key to change the setting. (Pressing the 1 key to accept the current values will take you to the mode changing screen in Section 3.5).

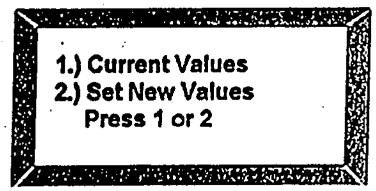

Fig. 3B. Set values screen

C. The screen shown in Fig. 3C will appear, allowing you to change any of three instrument settings.
   - Changing Measurement units
   - Changing MTD values
   - Changing Reading modes.

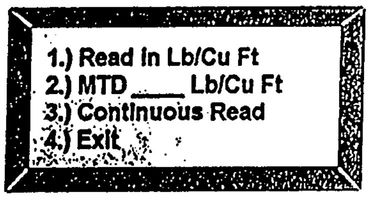

Fig. 3C. Change settings screen

Each of these choices are described in the following sections of the manual.

3.3 Changing Measurement Units

The PQI can be set to read in either English or Metric Units with the following procedure.

A. Make sure the screen shown in Fig. 3D is showing in the Display Panel. If it is not, press the E key to bring up this screen.

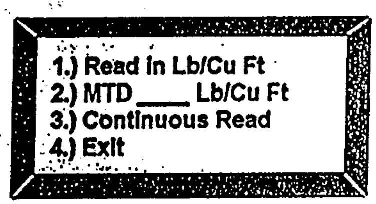

Fig. 3D. Changing Units

B. On the keypad, press the 1 key to toggle between the two measurement unit systems until you see the choice you desire (English or Metric).

C. On the keypad, press one of the following keys to proceed:
   - press the 2 key to change the MTD setting
   - press the 3 key to change measurement modes
   - press the 4 key to exit

3.4 Changing MTD Values

The PQI can be set to a user-defined value of Maximum Theoretical Density (MTD) to the asphalt mix being measured, by using the following procedure.

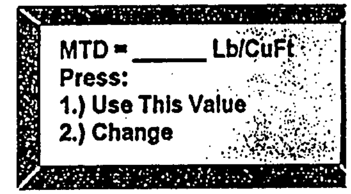

Fig. 3E. Change MTD screen

A. Make sure the screen shown in Fig. 3E is showing in the Display Panel. If it is not, press the F key to bring up this screen.

B. Press the 2 key on the Keypad to allow setting a maximum theoretical density (MTD) value for the asphalt being measured.

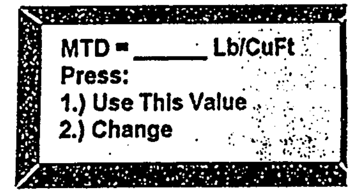

Fig. 3F. Set MTD screen

C. Wait for the Display Panel to show the "Set MTD" screen shown in Fig. 3F. Use the keypad to enter the MTD of the asphalt by entering 4 numbers equaling the MTD to one decimal point accuracy. (e.g., 1400 would equal an MTD of 140.0)

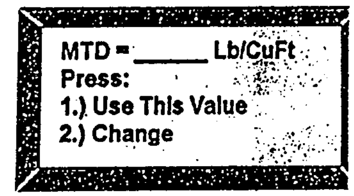

Fig. 3E. Change MTD screen

D. You will be returned to the screen shown in Fig. 3G. Press the 1 key to accept the value you have just set or the 2 key to change the MTD to a different value.

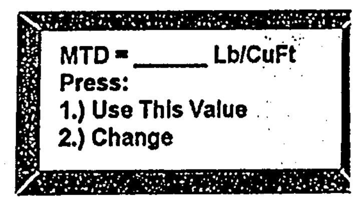

Fig. 3G. Use MTD screen

3.5 Changing the Reading Mode

The PQI can be set to read in three different modes, for maximum flexibility of use:

- Continuous reading mode
- Single point reading mode
- Average of multiple readings mode

To change the reading mode, follow the procedures listed below.

A. Make sure the screen shown in Fig. 3H is showing in the Display Panel. If it is not, press the B key to bring up this screen

B. Press the 3 key on the Control Keypad to toggle between the 3 modes of operation. The screen shown in Fig. 3H will display the current mode on the third line.

C. Press the 4 key on the keypad to exit to the chosen mode of operation, each of which is described below.

1.) Read in Lb/Cu Ft
2.) MTD ____ Lb/Cu Ft
3.) Continuous Read
4.) Exit

Fig. 3H. Toggling mode screen

3.6 Taking Data in Continuous Reading Mode of Operation

A. Make sure you are set in continuous reading mode. The Display Panel should show the continuous read mode screen shown in Fig. 3I. If you are not in this mode, follow the procedure given in Section 3.5.

B. Set the PQI on the asphalt pavement to be measured and record the density readings shown on the display screen.

C. As you move the PQI from location to location on the asphalt surface, you will note that the reading continuously changes to the density measurement at the new location. It is providing a **continuous** reading of density.

1.) Read in Lb/Cu Ft
2.) MTD ____ Lb/Cu Ft
3.) Continuous Read
4.) Exit

Fig. 3I Continuous read screen

3.7 Taking Data in Single Reading Mode of Operation

A. Make sure you are set in single reading mode. The Display Panel should show the single read mode screen shown in Fig. 3J. If you are not in this mode, follow the procedure given in Section 3.5. Once in this mode, you are ready to take a single point reading on the asphalt surface being measured.

Single Reading Mode
Press to read
MTD________Lb/CuFt

Fig. 3J. Single read scree #1

B. To take the measurement, press the "Start Button," shown earlier in Fig. 1. The Display Panel will change to screen shown in Fig. 3K. while the reading is being taken.

Single Reading Mode

Reading: Please Wait

Fig. 3K. Single read scree #2

C. In a moment or two, the Display Panel will change to the Density Output screen shown in shown in Fig. 3L. This display will show you both the density reading in % and the MTD in the units you have chosen earlier.

Single Reading Mode
Press to read again
MTD________Lb/CuFt
Density____ ____%

Fig. 3L Single read scree #3

3.8 Taking Data in Average Reading Mode of Operation

A. Make sure you are set in average reading mode. The Display Panel should show the average read mode screen shown in Fig. 3M. If you are not in this mode, follow the procedure given in Section 3.3. Once in this mode, you are ready to take an average of a number of different density readings (between 2 and 9) at different locations on the asphalt surface being measured.

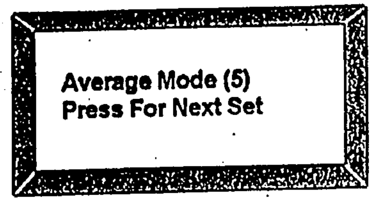

Fig. 3M Avg read screen #1

B. The "next set" message on this screen indicates you are ready to begin taking a new set of density measurements, which will be averaged by the unit. Press the number of readings (2-9) you want to take on the Control Key Pad. The example used here shows 5 readings have been chosen. press Start

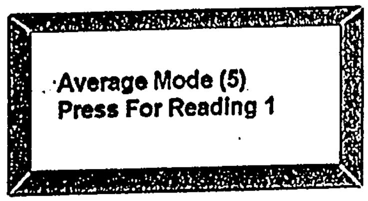

Fig. 3N. Avg read screen #2

C. Wait for the Display Panel to change to the "Press for Reading 1" message shown in Fig. 3N. To take the first measurement, place the unit on the first location to be averaged and press the "Start" Button.

D. The Display Panel will change to the "Average Mode - Please Wait" message shown in Fig. 3O. while the first reading is being taken.

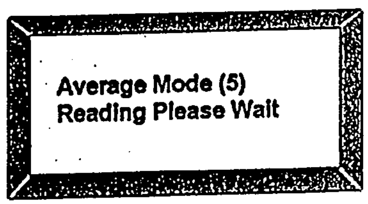

Fig.3O. Avg read screen #3

E. When the Instrument is ready for the next reading, the "Press for Reading 2 " screen shown in Fig. 3P will appear. Now move the instrument to a new location on the asphalt surface and press the "Start" Button to take the second measurement.

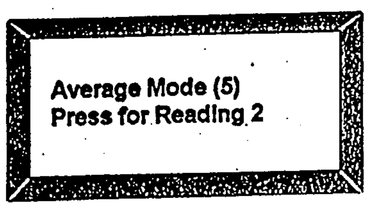

Fig.3P. Avg read screen #4

F. Repeat steps C through E for the five locations which you want to include in your average density measurements. Density results will be averaged as you go along.

G. When the final reading has been taken, the output screen shown in Fig. 3Q will appear, showing the average density of the five points taken.

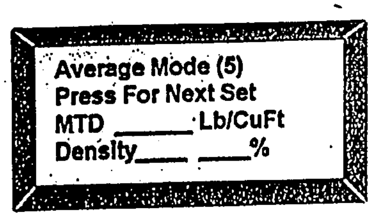

Fig. 3Q. Avg read screen #5

3.9 Calibrating the Unit

3.9.1 Fundamental Principles

A calibrated instrument will show density readings which correspond to known values of density (for instance, established by core data) over a reasonably wide operating range of the instrument. With the TransTech PQI, accuracy increases when calibrated to the specific asphalt pavements being measured.

An instrument which is "out of calibration" will show density readings which differ from the established "known" values of density. These differences may be due to either a misadjustment in the **offset** or the **slope** of the instrument circuitry, Calibrating the instrument to known values consists of adjusting either the offset, the slope (or perhaps both) to obtain readings which correspond to known values over the operating range. Calibration procedures will be described in the next section.

To illustrate the meaning of instrument offset and slope calibration errors, please refer to Figure 4. The solid line (line A) in the figure shows an instrument which needs no adjustment in offset or slope. The density values on the vertical axis, the "Instrument Reading," correspond exactly to the density values of "Known Density" shown on the horizontal axis.

On the other hand, line B shows an instrument which needs adjustment in both offset and slope to yield accurate density indications with respect to the known sample values. For instance, at the point where the known density is 100 (lowest value on the horizontal axis) the instrument shows a reading of 110, and is improperly "offset" on the high side by 10 units. Correcting this offset would, in effect, move the entire solid line down by 10 units.

This would result in Line C, which has no offset at the lowest reading point, but has substantial inaccuracies above this (compared to Line A), due to a much lower slope than required. The instrument calibration would have to be changed to increase the slope to correspond to that of the "perfectly-calibrated" curve represented by line A. Quite often, changing either the slope or offset of an instrument is an iterative process. After adjusting one calibration variable, the other should normally be checked and readjusted as needed.

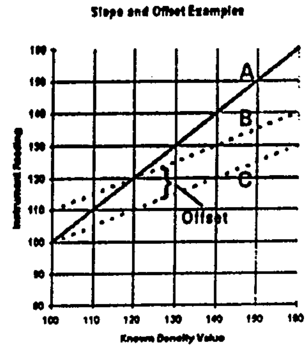

Figure 4. Instrument Offset and Slope Calibration

3.9.2 Overview of Calibrating the PQI

Since the pavement quality indicator has been designed for typical ranges of asphalt densities, typically only the offset will need to be changed to calibrate the instrument to the specific pavement you are measuring. The slope will generally not require major adjustment, if any. Usually, when applying the unit to different asphalt types or conditions, simply changing the offset to correspond to a known density value (close to the optimum density required in the job) will yield acceptable accuracy.

The following is an overview of the steps involved in calibrating the PQI. Detailed instructions are presented in Section 3.9.3.

1. Identify a section of pavement where core density data or nuclear densitometer measurements have been taken and recorded.
2. Choose what will represent your "reference" value for calibration. If a core is used, it is the density value determined by the test lab. If a nuclear densitometer is used, it is the average of at least 3 random readings.
3. Place the PQI on the pavement in close proximity to the cored-out area or on the pavement locations measured by the nuclear gauge.
4. Using the procedures given in Section 3.8, take an average of at least 5 readings at these points with the PQI.
5. Determine the difference between the average "reference" density value determined in Step 2 and the average value determined by the PQI in Step 3.
6. Using the procedures given in Section 3.9.3, increase the offset of the PQI by this difference if the PQI average is lower than the reference value. Decrease the offset if the PQI average is higher than the reference value.

3.9.3 Changing the Calibration

The PQI can be calibrated by changing either the offset or the slope of the measurement circuitry. Since it is not normally required, nor recommended to change the instrument's slope, the following procedure for adjusting the offset is given. You can adjust the PQI's offset by following the following procedure.

A. Make sure the offset calibration screen shown in Fig. 5A is showing in the Display Panel. If it is not, press the C key on the Control Keypad to enter the offset calibration mode.

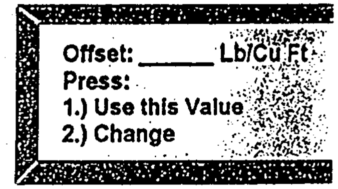

Fig.5A. Offset value scree

B. If the value of offset is acceptable, press the 1 key on the numeric keypad. If you wish to change the offset, press 2 on the keypad and follow the next step.

C. If you chose to change the value of the offset, the screen shown in Fig. 5B. will appear. . Use the keypad to enter the new offset for the instrument readings by entering 4 numbers equaling the offset to one decimal point accuracy. (e.g., 1400 would equal an offset of 140.0.

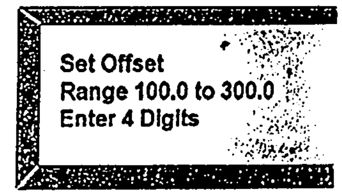

Fig. 5B. Offset change screen

D. After entering the new offset, you will be returned to the mode screen shown in Fig. 5A.

3.8 Diagnostic Procedures

The PQI has a built-in diagnostic mode, which can be accessed by using the following procedure.

A. Make sure the screen shown in Fig. 6 is showing in the Display Panel. If it is not, press the D key to bring it up.

B. The screen shows key information about the status of the PQI system, which can be used to identify problem areas when corresponding to factory personnel, in the event problems arise.

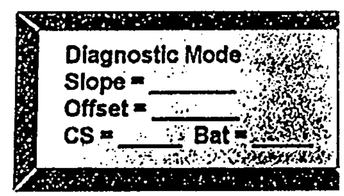

Fig. 6 Diagnostic screen

APPENDIX E - CORE DENSITIES

Core Densities (kg/m^3)

Core Location	Grants Pass-Evans	Grants Pass-Apple	Stayton-Fir Grove	Stayton-Joseph	Midland Junction	Baldock-Woodburn
1-1	1913	2091	1849	1908	1794	1915
1-2	2036	2094	1832	1818	1853	1892
1-3	2043	2075	1912	1858	1887	1833
1-4	2127	2076	1897	1890	1865	1900
1-5	1961	2142	1777	1769	1885	1824
2-1	2057	2113	1934	1929	1853	1854
2-2	2082	2132	1959	1917	1830	1878
2-3	2054	2117	1870	1943	1863	1921
2-4	2106	2146	1908	1962	1849	1801
2-5	2101	2123	1875	1938	1875	1852
3-1	2072	2157	1876	1758	1910	1910
3-2	2073	2157	1867	1918	1876	1897
3-3	2061	2094	1749	1915	1823	1909
3-4	2010	2137	1999	1971	1859	1835
3-5	2038	2128	1810	2011	1845	1858
4-1	2023	2153	1895	1972	1937	1894
4-2	2101	2110	1950	2028	1911	1888
4-3	2030	2065	1916	1935	1871	1957
4-4	2121	2105	1970	1988	1916	1833
4-5	2118	2133	1948	1962	1998	1903
5-1	2131	2187	1922	1951	1974	1913
5-2	2089	2147	1957	1998	1915	1913
5-3	1972	2129	1961	1935	1894	1929
5-4	2085	2142	1952	1963	1935	1901
5-5	2128	2125	1955	1970	1971	1895
6-1	2001	2086	1940	1894	1894	1768
6-2	2010	2077	1889	1815	1866	1730
6-3	2062	2135	1936	1862	1903	1795
6-4	1978	2081	1852	1875	1868	1763
6-5	1849	2070	1926	1856	1824	1844
7-1	2126	2123	1902	1908	1945	1924
7-2	2072	2096	1845	1828	1900	1972
7-3	2106	2114	1882	1928	1920	1895
7-4	2102	2116	1954	1809	1875	1896
7-5	2020	2107	1937	1988	1925	1909
8-1	1995	2115	1938	1905	1946	1787
8-2	2056	2110	1932	1916	1924	1850
8-3	2069	2158	1939	1917	1988	1915
8-4	2150	2132	2001	1916	1945	1806
8-5	2061	2138	1945	1923	1986	1876
9-1	2125	2142	1982	1986	1926	1784
9-2	2019	2082	1957	1991	1945	1882
9-3	2067	2128	1818	1896	1913	1877
9-4	2029	2095	1930	1911	1879	1819
9-5	2064	2109	1819	1887	1879	1947

APPENDIX F -- FIELD DENSITY MEASUREMENTS

Density Readings -- Project: N Grants Pass - Evans Creek				Date: 27-Oct-98
Correlation				
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1	1991	1999	1995	1297
2	1970	1969	1970	1409
3	2043	2033	2038	1347
4	1945	1968	1957	1333
5	2038	2013	2026	1396
Average			1997	1356
New Offset =	1997-1356+2000 =		2641	
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1-1	1618	1631	1625	1869
1-2	1946	1964	1955	1766
1-3	1904	1902	1903	1981
1-4	1912	1911	1912	1903
1-5	1890	1882	1886	1878
2-1	1977	1965	1971	1980
2-2	1980	1998	1989	1921
2-3	2074	2072	2073	1980
2-4	2001	1997	1999	2046
2-5	1961	1960	1961	1983
3-1	2027	2023	2025	2006
3-2	1988	1974	1981	1960
3-3	1800	1803	1802	1999
3-4	1887	1901	1894	2060
3-5	1950	1962	1956	1951
4-1	2015	2007	2011	1986
4-2	1952	1952	1952	1978
4-3	1912	1900	1906	1983
4-4	2019	2027	2023	2011
4-5	2016	2024	2020	2043
5-1	2008	2016	2012	2018
5-2	1953	1949	1951	2010
5-3	1938	1916	1927	1976
5-4	1989	1992	1991	2152
5-5	2131	2119	2125	2092
6-1	1832	1833	1833	1951
6-2	1868	1883	1876	1941
6-3	1963	1949	1956	1966
6-4	1744	1729	1737	1912
6-5	1964	1956	1960	2053
7-1	1892	1917	1905	2011
7-2	1997	2007	2002	2000
7-3	2004	1970	1987	2018
7-4	1927	1934	1931	1985
7-5	1954	1954	1954	2033
8-1	1835	1850	1843	1975
8-2	1915	1921	1918	2078
8-3	1937	1924	1931	2039
8-4	2051	2052	2052	2039
8-5	1899	1900	1900	1949
9-1	1987	1984	1986	2125
9-2	1768	1773	1771	1999
9-3	1970	1965	1968	2011
9-4	1817	1828	1823	1960
9-5	1948	1950	1949	1996

Density Readings --Project: Grants Pass - Applegate River				Date:13-Jul-98
Correlation				
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1	1945	1949	1947	968
2	1933	1927	1930	979
3	1943	1922	1933	1006
4	1919	1924	1921	958
5	1892	1913	1902	855
Average			1927	953
New Offset =	120.3 - 59.5 = 60.8			
MSG = 2.630 (164.11)				
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1-1	1813	1804	1808	1874
1-2	1762	1768	1765	1839
1-3	1839	1836	1837	1834
1-4	1818	1788	1803	1823
1-5	1794	1791	1792	1884
2-1	1853	1869	1861	1900
2-2	1853	1839	1846	1869
2-3	1845	1839	1842	1825
2-4	1863	1879	1871	1965
2-5	1884	1882	1883	1887
3-1	1905	1921	1913	1919
3-2	1869	1877	1873	1977
3-3	1857	1873	1865	1892
3-4	1905	1901	1903	1911
3-5	1845	1842	1844	1808
4-1	1900	1892	1896	1935
4-2	1916	1913	1914	1911
4-3	1825	1833	1829	1884
4-4	1849	1868	1858	1913
4-5	1905	1922	1913	1937
5-1	1945	1948	1946	1972
5-2	1916	1922	1919	1916
5-3	1889	1898	1893	1943
5-4	1927	1919	1923	1890
5-5	1874	1884	1879	1911
6-1	1778	1789	1784	1816
6-2	1765	1775	1770	1882
6-3	1844	1865	1854	1847
6-4	1842	1858	1850	1969
6-5	1780	1820	1800	1972
7-1	1841	1836	1838	1869
7-2	1865	1865	1865	1869
7-3	1794	1810	1802	1953
7-4	1847	1850	1849	1802
7-5	1877	1877	1877	1884
8-1	1885	1884	1885	1937
8-2	1887	1865	1876	1948
8-3	1924	1930	1927	1841
8-4	1892	1898	1895	1917
8-5	1863	1828	1845	1901
9-1	1906	1953	1929	1980
9-2	1879	1905	1892	1901
9-3	1913	1925	1919	1911
9-4	1884	1908	1896	2028
9-5	1937	1945	1941	1887

Density Readings -- Project: Stayton NLC - Fir Grove Lane			Date: 4-Jun-98	
Correlation				
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1	1725	1731	1728	
2	1687	1704	1695.5	
3	1796	1779	1787.5	
4	1743	1734	1738.5	
5	1696	1699	1697.5	
Average			1729.4	1007
New Offset =	1729-1007 = 722			
	1600 + 722 = 2322		2328	
Rice = 2484				
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1-1	1637	1639	1638	1676
1-2	1612	1618	1615	1697
1-3	1746	1739	1743	1725
1-4	1722	1717	1720	1749
1-5	1615	1622	1619	1686
2-1	1780	1761	1771	1818
2-2	1855	1842	1849	1802
2-3	1679	1684	1682	1685
2-4	1752	1743	1748	1832
2-5	1652	1657	1655	1675
3-1	1776	1794	1785	1823
3-2	1769	1748	1759	1729
3-3	1637	1646	1642	1753
3-4	1868	1867	1868	1792
3-5	1708	1701	1705	1755
4-1	1732	1757	1745	1673
4-2	1901	1906	1904	1814
4-3	1762	1763	1763	1793
4-4	1802	1793	1798	1799
4-5	1857	1856	1857	1762
5-1	1813	1817	1815	1844
5-2	1827	1837	1832	1773
5-3	1839	1832	1836	1803
5-4	1815	1833	1824	1836
5-5	1819	1817	1818	1802
6-1	1784	1789	1787	1669
6-2	1731	1735	1733	1780
6-3	1788	1798	1793	1800
6-4	1733	1731	1732	1718
6-5	1783	1793	1788	1812
7-1	1768	1781	1775	1808
7-2	1708	1693	1701	1658
7-3	1782	1785	1784	1779
7-4	1795	1788	1792	1718
7-5	1803	1807	1805	1832
8-1	1876	1875	1876	1791
8-2	1810	1827	1819	1810
8-3	1811	1822	1817	1762
8-4	1820	1806	1813	1748
8-5	1867	1876	1872	1806
9-1	1858	1854	1856	1804
9-2	1839	1825	1832	1855
9-3	1645	1662	1654	1764
9-4	1510	1506	1508	1727
9-5	1685	1684	1685	1732

Density Readings -- Project: Stayton NLC - Joseph Street Interchange			Date: 3-Sep-98	
Correlation				
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1	1827	1842	1834.5	1485
2	1902	1878	1890	1469
3	1866	1891	1878.5	1512
4	1910	1900	1905	1535
5	1825	1829	1827	1467
Average			1867	1493.6
New Offset =	1867-1493.6+2000 =		2373	
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1-1	1769	1759	1764	1790
1-2	1800	1825	1812.5	1813
1-3	1751	1740	1745.5	1856
1-4	1761	1761	1761	1812
1-5	1704	1715	1709.5	1757
2-1	1874	1876	1875	1860
2-2	1802	1815	1808.5	1749
2-3	1818	1809	1813.5	1800
2-4	1845	1855	1850	1869
2-5	1797	1788	1792.5	1830
3-1	1905	1917	1911	1810
3-2	1822	1809	1815.5	1760
3-3	1804	1797	1800.5	1843
3-4	1887	1887	1887	1876
3-5	1932	1928	1930	1824
4-1	1869	1870	1869.5	1875
4-2	1931	1948	1939.5	1751
4-3	1834	1838	1836	1871
4-4	1858	1865	1861.5	1858
4-5	1896	1908	1902	1823
5-1	1863	1902	1882.5	1917
5-2	1865	1885	1875	1911
5-3	1881	1886	1883.5	1938
5-4	1825	1839	1832	1913
5-5	1824	1834	1829	1941
6-1	1792	1794	1793	1922
6-2	1867	1870	1868.5	1882
6-3	1771	1793	1782	1906
6-4	1765	1767	1766	1900
6-5	1920	1921	1920.5	1890
7-1	1748	1762	1755	1785
7-2	1767	1772	1769.5	1862
7-3	1820	1819	1819.5	1850
7-4	1783	1788	1785.5	1840
7-5	1801	1811	1806	1828
8-1	1804	1827	1815.5	1878
8-2	1797	1794	1795.5	1923
8-3	1817	1825	1821	1879
8-4	1845	1838	1841.5	1901
8-5	1785	1792	1788.5	1813
9-1	1840	1852	1846	1903
9-2	1854	1835	1844.5	1832
9-3	1805	1826	1815.5	1810
9-4	1852	1852	1852	1873
9-5	1837	1837	1837	1785

Density Readings -- Project: Midland Junction - California State Line			Date: 31-Aug-98	
Correlation				
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1	1801	1797	1799	1069
2	1714	1708	1711	1082
3	1803	1809	1806	1103
4	1798	1796	1797	1125
5	1829	1834	1831.5	1140
Average	1789	1788.8	1788.9	1103.8
New Offset =	1788.9-1103.8+1600 =		2285.1	
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1-1	1737	1742	1740	1667
1-2	1695	1692	1694	1770
1-3	1785	1798	1792	1735
1-4	1783	1777	1780	1674
1-5	1742	1735	1739	1699
2-1	1805	1803	1804	1751
2-2	1769	1764	1767	1659
2-3	1793	1791	1792	1790
2-4	1751	1754	1753	1776
2-5	1695	1701	1698	1803
3-1	1794	1806	1800	1823
3-2	1779	1773	1776	1790
3-3	1742	1751	1747	1797
3-4	1546	1568	1557	1757
3-5	1765	1769	1767	1755
4-1	1865	1864	1865	1801
4-2	1865	1864	1865	1821
4-3	1790	1791	1791	1754
4-4	1651	1620	1636	1778
4-5	1871	1871	1871	1790
5-1	1860	1850	1855	1773
5-2	1819	1832	1826	1761
5-3	1790	1777	1784	1755
5-4	1624	1610	1617	1783
5-5	1775	1773	1774	1810
6-1	1772	1769	1771	1767
6-2	1762	1752	1757	1738
6-3	1810	1791	1801	1820
6-4	1562	1568	1565	1635
6-5	1750	1755	1753	1708
7-1	1628	1632	1630	1790
7-2	1806	1788	1797	1754
7-3	1407	1400	1404	1768
7-4	1826	1829	1828	1744
7-5	1548	1538	1543	1776
8-1	1895	1911	1903	1793
8-2	1529	1524	1527	1711
8-3	1780	1785	1783	1765
8-4	1853	1842	1848	1795
8-5	1836	1839	1838	1725
9-1	1593	1591	1592	1782
9-2	1865	1864	1865	1758
9-3	1881	1889	1885	1710
9-4	1879	1877	1878	1792
9-5	1921	1908	1915	1759

Density Readings -- Project: Baldock Safety Rest Area - Woodburn Interchange				Date: 29-Oct-98
Correlation				
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1	2014	1997	2006	1407
2	1983	2007	1995	1430
3	2026	2018	2022	1517
4	2055	2054	2055	1478
5	2025	2034	2030	1478
Average			2021	1462
New Offset =	2000+2021-1462 =		2559	
Location	Nuclear 1	Nuclear 2	Average Nuc.	PQI
1-1	1967	1963	1965	2000
1-2	1991	1999	1995	2026
1-3	2006	1981	1994	2085
1-4	2064	2076	2070	2052
1-5	2031	2012	2022	2091
2-1	2006	2014	2010	2103
2-2	1991	1988	1990	2074
2-3	2071	2055	2063	2129
2-4	1939	1949	1944	2056
2-5	1960	1979	1970	2071
3-1	2011	1996	2004	2095
3-2	1984	2001	1993	2090
3-3	2021	2025	2023	2088
3-4	1980	1996	1988	2027
3-5	1953	1951	1952	2016
4-1	1984	2005	1995	2079
4-2	2023	1999	2011	2080
4-3	2045	2017	2031	2096
4-4	1990	1973	1982	1982
4-5	1978	1965	1972	1976
5-1	1981	2005	1993	2057
5-2	1984	2004	1994	2052
5-3	1983	2007	1995	1996
5-4	1993	2020	2007	2036
5-5	2005	1989	1997	2046
6-1	1885	1908	1897	1974
6-2	1823	1857	1840	1976
6-3	1877	1887	1882	1991
6-4	1894	1913	1904	2009
6-5	1921	1945	1933	2019
7-1	1964	1951	1958	2107
7-2	2049	2059	2054	2044
7-3	1936	1924	1930	1943
7-4	1977	1974	1976	2030
7-5	1990	1994	1992	2041
8-1	1906	1908	1907	1959
8-2	1998	1969	1984	2052
8-3	1988	2002	1995	2044
8-4	1939	1917	1928	2040
8-5	1968	1973	1971	2025
9-1	1933	1919	1926	1995
9-2	1978	1985	1982	2051
9-3	1989	2005	1997	2041
9-4	1919	1947	1933	2076
9-5	2026	2011	2019	2071

APPENDIX G - ALL DENSITY RESULTS

	N Grants Pass - Evans Creek			Grants Pass – Applegate River		
Project	Grants Pass 1			Grants Pass 2		
Location	Nuclear	PQI	Core	Nuclear	PQI	Core
1-1	1625	1869	1913	1808	1874	2091
1-2	1955	1766	2036	1765	1839	2094
1-3	1903	1981	2043	1837	1834	2075
1-4	1912	1903	2127	1803	1823	2076
1-5	1886	1878	1961	1792	1884	2142
2-1	1971	1980	2057	1861	1900	2113
2-2	1989	1921	2082	1846	1869	2132
2-3	2073	1980	2054	1842	1825	2117
2-4	1999	2046	2106	1871	1965	2146
2-5	1961	1983	2101	1883	1887	2123
3-1	2025	2006	2072	1913	1919	2157
3-2	1981	1960	2073	1873	1977	2157
3-3	1802	1999	2061	1865	1892	2094
3-4	1894	2060	2010	1903	1911	2137
3-5	1956	1951	2038	1844	1808	2128
4-1	2011	1986	2023	1896	1935	2153
4-2	1952	1978	2101	1914	1911	2110
4-3	1906	1983	2030	1829	1884	2065
4-4	2023	2011	2121	1858	1913	2105
4-5	2020	2043	2118	1913	1937	2133
5-1	2012	2018	2131	1946	1972	2187
5-2	1951	2010	2089	1919	1916	2147
5-3	1927	1976	1972	1893	1943	2129
5-4	1991	2152	2085	1923	1890	2142
5-5	2125	2092	2128	1879	1911	2125
6-1	1833	1951	2001	1784	1816	2086
6-2	1876	1941	2010	1770	1882	2077
6-3	1956	1966	2062	1854	1847	2135
6-4	1737	1912	1978	1850	1969	2081
6-5	1960	2053	1849	1800	1972	2070
7-1	1905	2011	2126	1838	1869	2123
7-2	1999	2000	2072	1865	1869	2096
7-3	1987	2018	2106	1802	1953	2114
7-4	1931	1985	2102	1849	1802	2116
7-5	1954	2033	2020	1877	1884	2107
8-1	1843	1975	1995	1885	1937	2115
8-2	1918	2078	2056	1876	1948	2110
8-3	1931	2039	2069	1927	1841	2158
8-4	2052	2039	2150	1895	1917	2132
8-5	1900	1949	2061	1845	1901	2138
9-1	1986	2125	2125	1927	1980	2142
9-2	1771	1999	2019	1892	1901	2082
9-3	1968	2011	2067	1919	1911	2128
9-4	1823	1960	2029	1896	2028	2095
9-5	1949	1996	2064	1941	1887	2109

	Stayton NCL - Fir Grove Lane			Stayton - Joseph Street Int.		
Project	Stayton 1			Stayton 2		
Location	Nuclear	PQI	Core	Nuclear	PQI	Core
1-1	1638	1676	1849	1764	1790	1908
1-2	1615	1697	1832	1813	1813	1818
1-3	1743	1725	1912	1746	1856	1858
1-4	1720	1749	1897	1761	1812	1890
1-5	1619	1686	1777	1710	1757	1769
2-1	1771	1818	1934	1875	1860	1929
2-2	1849	1802	1959	1809	1749	1917
2-3	1682	1685	1870	1814	1800	1943
2-4	1748	1832	1908	1850	1869	1962
2-5	1655	1675	1875	1793	1830	1938
3-1	1785	1823	1876	1911	1810	1758
3-2	1759	1729	1867	1816	1760	1918
3-3	1642	1753	1749	1801	1843	1915
3-4	1868	1792	1999	1887	1876	1971
3-5	1705	1755	1810	1930	1824	2011
4-1	1745	1673	1895	1870	1875	1972
4-2	1904	1814	1950	1940	1751	2028
4-3	1763	1793	1916	1836	1871	1935
4-4	1798	1799	1970	1862	1858	1988
4-5	1857	1762	1948	1902	1823	1962
5-1	1815	1844	1922	1883	1917	1951
5-2	1832	1773	1957	1875	1911	1998
5-3	1836	1803	1961	1884	1936	1935
5-4	1824	1836	1952	1832	1913	1963
5-5	1818	1802	1955	1829	1941	1970
6-1	1787	1669	1940	1793	1922	1894
6-2	1733	1780	1889	1869	1882	1815
6-3	1793	1800	1936	1782	1906	1862
6-4	1732	1718	1852	1766	1900	1875
6-5	1788	1812	1926	1921	1890	1856
7-1	1775	1808	1902	1755	1785	1908
7-2	1701	1658	1845	1770	1862	1828
7-3	1784	1779	1882	1820	1850	1928
7-4	1792	1718	1954	1786	1840	1809
7-5	1805	1832	1937	1806	1828	1988
8-1	1876	1791	1938	1816	1878	1905
8-2	1819	1810	1932	1796	1923	1916
8-3	1817	1762	1939	1821	1879	1917
8-4	1813	1748	2001	1842	1901	1916
8-5	1872	1806	1945	1789	1813	1923
9-1	1856	1804	1982	1846	1903	1986
9-2	1832	1855	1957	1845	1832	1991
9-3	1654	1764	1818	1816	1810	1896
9-4	1508	1727	1930	1852	1873	1911
9-5	1685	1732	1819	1837	1785	1887

	Midland Junction - California			Baldock Safety Rest Area		
Project	Klamath Falls			Wilsonville		
Location	Nuclear	PQI	Core	Nuclear	PQI	Core
1-1	1740	1667	1794	1965	2000	1915
1-2	1694	1770	1853	1995	2026	1892
1-3	1792	1735	1887	1994	2085	1833
1-4	1780	1674	1865	2070	2052	1900
1-5	1739	1699	1885	2022	2091	1824
2-1	1804	1751	1853	2010	2103	1854
2-2	1767	1659	1830	1990	2074	1878
2-3	1792	1790	1863	2063	2129	1921
2-4	1753	1776	1849	1944	2056	1801
2-5	1698	1803	1875	1970	2070	1852
3-1	1800	1823	1910	2004	2095	1910
3-2	1776	1790	1876	1993	2090	1897
3-3	1747	1797	1823	2023	2088	1909
3-4	1557	1757	1859	1988	2027	1835
3-5	1767	1755	1845	1952	2016	1858
4-1	1865	1801	1937	1995	2079	1894
4-2	1865	1821	1911	2011	2080	1888
4-3	1791	1754	1871	2031	2096	1957
4-4	1636	1778	1916	1982	1982	1833
4-5	1871	1790	1998	1972	1976	1903
5-1	1855	1773	1974	1993	2057	1913
5-2	1826	1761	1915	1994	2052	1913
5-3	1784	1755	1894	1995	1996	1929
5-4	1617	1783	1935	2007	2036	1901
5-5	1774	1810	1971	1997	2046	1895
6-1	1771	1767	1894	1897	1974	1768
6-2	1757	1738	1866	1840	1976	1730
6-3	1801	1820	1903	1882	1991	1795
6-4	1565	1635	1868	1904	2009	1763
6-5	1753	1708	1824	1933	2019	1844
7-1	1630	1790	1945	1960	2107	1924
7-2	1797	1754	1900	2054	2044	1972
7-3	1404	1768	1920	1930	1943	1895
7-4	1828	1744	1875	1976	2030	1896
7-5	1543	1776	1925	1992	2041	1909
8-1	1903	1793	1946	1907	1959	1787
8-2	1527	1711	1924	1984	2052	1850
8-3	1783	1765	1988	1995	2044	1915
8-4	1848	1795	1945	1928	2040	1806
8-5	1838	1725	1986	1971	2025	1876
9-1	1592	1782	1926	1926	1995	1784
9-2	1865	1758	1945	1982	2051	1882
9-3	1885	1710	1913	1997	2041	1877
9-4	1878	1792	1879	1933	2076	1819
9-5	1915	1759	1879	2019	2071	1947

APPENDIX H - FIELD TEMPERATURE MEASUREMENTS

Project:	N Grants Pass - Evans Creek		
Date:	21-Apr-98		
Weather:	Sunny		
Equipment Type	Model Number	Weight	Comments
Ingersoll-Rand	DD-110		Vibrations per min: 2600
Section	Pass Type	Temp. of mix (C)	Comments
1	V	75	
1	S	72	
2	V	77	
2	S	75	
2	V	64	
3	V	66	
3	S	64	
3	V	60	
3	S	58	
4	V	63	
4	S	62	
4	V	60	
4	S	56	
4	S	55	
5	V	59	
5	S	56	
5	V	56	
5	S	55	
5	S	53	
5	S	53	
6	S	68	
6	S	70	
6	S	58	
7	S	69	
7	S	69	
7	S	62	
7	S	61	
8	S	68	
8	S	66	
8	S	62	
8	S	62	
8	S	62	
9	S	68	
9	S	68	
9	S	68	
9	S	64	
9	S	61	
9	S	61	

Project:	Grants Pass - Applegate River		
Date:	13-Jul-98		
Weather:	Sunny		
Equipment Type	Model Number	Weight	Comments
CAT	CB-634C		2500 - 2600 RPM
Section	Pass Type	Temp. of mix (C)	Comments
1	V	73	
1	S	72	
2	V	68	
2	S	66	
2	V	66	
3	V	72	
3	S	71	
3	V	68	
3	S	67	
4	V	71	
4	S	68	
4	V	66	
4	S	64	
4	S	63	
5	V	63	At the beginning of this section a
5	S	63	truck drove across so the roller had to
5	V	61	make a couple more passes in the
5	S	61	first 50 -100 feet of this section.
5	S	59	There may have been seven passes
5	S	59	on this section.
6	S	64	
6	S	64	
6	S	63	
7	S	63	
7	S	63	
7	S	62	
7	S	62	
8	S	67	There were some problems rolling a
8	S	67	joint at the intersection, therefore
8	S	67	section 8 was reduced in length.
8	S	65	
8	S	65	
9	S	61	Air temperature was 76 degrees at
9	S	59	9:15 PM
9	S	58	
9	S	58	
9	S	55	
9	S	55	

Project:	Stayton NCL - Fir Grove Lane		
Date:	4-Jun-98		
Weather:	Overcast, 60 C		
Equipment Type	Model Number	Weight	Comments
Hypac	C766B		VPM = 3000
Section	Pass Type	Temp. of mix (C)	Comments
1	V	57	3" mat
1	S	52	
2	V	59	3" mat
2	S	58	
2	V	58	
3	V	55	3" mat
3	S	54	Downhill
3	V	51	vibration
3	S	50	
4	V	52	2" mat for
4	S	20	remaining
4	V	50	sections
4	S	48	
4	S	47	
5	V	57	
5	S	55	
5	V	54	
5	S	52	
5	S	52	
5	S	51	
6	S	59	
6	S	56	
6	S	56	
7	S	62	
7	S	61	
7	S	60	
7	S	60	
8	S	55	
8	S	55	
8	S	52	
8	S	52	
8	S	56	
9	S	55	
9	S	54	
9	S	50	
9	S	50	
9	S	48	
9	S	47	

Project:	Stayton NCL - Joseph Street Interchange		
Date:	3-Sep-98		
Weather:	Sunny, 22 C		
Equipment Type	Model Number	Weight	Comments
Hypac	C766B		
Section	Pass Type	Temp. of mix (C)	Comments
1	S	69	The roller operator did a Static pass
1	V	67	and then the vibratory pass.
2	V	64	
2	S	63	
2	V	63	
3	V	68	
3	S	66	
3	V	61	
3	S	57	
4	S	62	The order of passes was a little
4	S	61	different than other projects, on this
4	V	56	section.
4	S	54	
4	V	54	
5	V	63	
5	S	58	
5	V	58	
5	S	57	
5	S	57	
5	S	56	
6	S	63	
6	S	61	
6	S	59	
7	S	55	
7	S	53	
7	S	53	
7	S	53	
8	S	63	
8	S	63	
8	S	61	
8	S	61	
8	S	61	
9	S	69	
9	S	69	
9	S	65	
9	S	65	
9	S	65	
9	S	64	

Project:	Midland Junction – California State Line		
Date:	31-Aug-98		
Weather:	Sunny		
Equipment Type	Model Number	Weight	Comments
CAT	CB - 534B		
Section	Pass Type	Temp. of mix (C)	Comments
1	V	65	The first half got 1 extra Static pass
1	S	63	
2	V	55	
2	S	53	
2	V	50	
3	V	72	
3	S	70	
3	V	65	
3	S	62	
4	V	67	
4	S	64	
4	V	60	
4	S	59	
4	S	57	
5	V	60	The finish roller did 2 static passes
5	S	59	while the breakdown roller was getting
5	V	58	water. Then the breakdown roller
5	S	58	did a V S V S pattern.
5	S	57	
5	S	55	
6	S	61	
6	S	60	
6	S	60	
7	S	63	
7	S	62	
7	S	60	
7	S	60	
8	S	64	
8	S	64	
8	S	63	
8	S	62	
8	S	62	
9	S	70	
9	S	70	
9	S	69	
9	S	68	
9	S	68	
9	S	67	

Project:	Baldock Safety Rest Area - Woodburn Interchange		
Date:	16-Aug-98		
Weather:	Partly cloudy, 19 C		
Equipment Type	Model Number	Weight	Comments
Hypac	C766B		
Section	Pass Type	Temp. of mix (C)	Comments
1	V	70	Finish roller went on the first half of
1	S	67	this section.
2	V	67	The finish roller went on the last part
2	S	65	of this section.
2	V	61	
3	V	68	
3	S	67	
3	V	66	
3	S	61	
4	V	73	
4	S	71	
4	V	70	
4	S	70	
4	S	69	
5	V	67	
5	S	63	
5	V	58	
5	S	57	
5	S	55	
5	S	54	
6	S	63	
6	S	62	
6	S	45	
7	S	62	
7	S	60	
7	S	54	
7	S	49	
8	S	62	
8	S	60	
8	S	54	
8	S	53	
8	S	50	
9	S	65	
9	S	62	
9	S	57	
9	S	55	
9	S	48	
9	S	46	