THIN LAYER ASPHALTIC CONCRETE DENSITY MEASURING USING NUCLEAR GAGES

by

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16. Abstract

A Troxler 4640 thin layer nuclear gage was evaluated under field conditions to determine if it would provide improved accuracy of density measurements on asphalt overlays of 1-3/4 and 2 inches in thickness. Statistical analysis shows slightly improved accuracy resulting from the use of the Troxler 4640 gage compared to conventional gages. Other apparent benefits of this gage (data storage capabilities and digital readout of actual densities) are not true advantages because they are now available in gages which operate like the conventional gage tested here. One major disadvantage is that the gage lacks the versatility of conventional gages. The Troxler 4640 or similar gages are not recommended for widespread use.

Further statistical analysis shows that density as measured in the laboratory using cores is significantly higher than density measured by either of the two types of nuclear gages. The difference can be removed by developing an adjustment factor from core densities on every project. The amount of this difference varies from project to project (varying form 1.7 to 3.2 pcf for the conventional gage in backscatter mode).

The three different operating modes of the conventional gage were also evaluated and compared. As a result of this comparison, continued use of the backscatter mode with sand for seating is recommended.

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DISCLAIMER

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1.0 INTRODUCTION

The Oregon State Highway Division currently uses conventional nuclear density gages in the backscatter mode to measure compaction on all large asphaltic concrete projects. When used on thin overlays (1-1/2" to 2"), this method has been criticized because the results are believed to be affected by the density of the underlying material. This study was initiated to determine if recently developed thin layer nuclear gages could overcome this problem. This evaluation was accomplished by directly comparing the two types of gages under field conditions using core densities as the standard.

A Troxler Model 4640 thin layer gage was obtained on loan from the Manufacturer and evaluated along side conventional CPN MC-3 Portaprobe gages. During the 1988 construction season the evaluation was done on four construction projects, using a different CPN gage on each project. The density, as measured by nuclear gages, was compared to the Laboratory determined density of cores from each test site.

2.0 METHODS AND EQUIPMENT

2.1 PROJECTS TESTED

Fifteen test sites were selected for each of the four projects where the gage was evaluated. Each test site was located outside of the wheel tracks to minimize compaction by traffic between testing and coring. A four inch diameter core was taken at each test site, except on project 3, where eight of the 15 cores were six inches in diameter.

The mix design for each of the four projects is in Appendix 1 and other pertinent data is listed below:

PROJECT 1:
Detroit - Idanha (Oregon Route 22). MP 51.00 to MP 55.00
Contract Number: C10592
Project Type: preservation overlay
Nominal Thickness: 1 3/4 inch
Mix Class: class "C" wearing surface
Base: existing a/c
Compaction requirements: visual - 4 passes

PROJECT 2: Noti - Veneta (Oregon Route 126). MP 40.00 to MP 50.00
Contract Number: C10339
Project Type: new construction
Nominal Thickness: 2 inch
Mix Class: class "C" wearing surface
Base: 2" "C" a/c
6" lime treated sub grade
10" cement treated base
Compaction requirements: 91% minimum allowable density

PROJECT 3: Wapato Road - Yamhill NCL (Oregon route 47) MP 30.85 to MP 34.05
Contract Number: C10605
Project Type: preservation overlay
Nominal Thickness: 2 inch
Mix Class: class "C" wearing surface
(with rubberized asphalt - AC 20R)
Base: existing a/c
Compaction requirements: visual - 4 passes

PROJECT 4: Clackamette Road - Hedges Street (Oregon Route 99E) MP 11.50 to MP 13.44
Contract Number: C10594
Project Type: preservation overlay
Nominal Thickness: 2 inch
Mix Class: class "B" wearing surface
Base: existing PCC
Compaction requirements: visual - 4 passes

2.2 THE TROXLER 4640 NUCLEAR GAGE

This gage is designed to test thin asphalt overlays. It is not capable of allowing the radiation source to penetrate into the surface being tested. Thus, it cannot be used to test a soil, cement treated base, or aggregate base, as is possible with conventional gages in the "direct" mode.

The unique feature of the 4640 is that it has two detectors. One detector is close to the radiation source and reacts more strongly to upper layer material than does the more remote detector. This provides enough data for the gage to internally remove lower layer effects by solving two simultaneous equations.

Before the equations can be solved the operator must supply a value for the thickness of the overlay. As part of this study, densities were determined using both the measured thickness and nominal thickness. It was found that there was no significant difference between these two practices. Thus, it is generally adequate to enter the nominal thickness value for the project.

An additional feature of the Troxler 4640 gage is the "Surface Voids Mode" (SV mode). The manual recommends using this mode on open-graded or coarse mixes. These are defined as mixes having less than 40% passing the #8 sieve. None of the jobs in this study satisfied this criterion. For this reason the SV mode was not used in the main part of this study. Some SV mode data was taken to test the inherent error in the gage itself. This is discussed in Section 3.2.1 under "gage error".

2.3 FIELD PROCEDURES

Field test procedures were designed to provide data for comparing the two types of gages. The tests also evaluated the various operational modes for each gage and the effect of using sand as seating material. The Laboratory determined core density data was the standard to which all gage readings were compared. To obtain the desired field data, the gages were used at each test site as follows:

Conventional Gage - CPN MC-3:

With Sand:

- Back-scatter mode
- Direct mode
- AC mode

Troxler 4640 Thin Layer Gage:

With Sand:

- Nominal Layer Thickness
- Actual Layer Thickness

Without Sand

- Nominal Layer Thickness

On each one of the 4 projects a different CPN conventional gage was used. However, the same Troxler 4640 Thin Layer Gage was used each time.

2.3.1 Regular Test Sites

On 13 of the 15 test sites for each project, the testing was done by Oregon's established field procedure. This consists of taking two readings at right angles to each other. The corresponding core sample was taken between these two positions. The distance from the core to the hole made for testing in the direct mode was six inches. The data from these two positions is denoted by "A" and "B" in Appendix 2. The data for each project in Appendix 3 is the average of these two values.

2.3.2 Intensive Test Sites

The remaining 2 sites per job are referred to as "intensive test sites". Their purpose was to determine the best way to position the gage over the core site. The intensive testing also made it possible to evaluate the relative effect of two possible sources of error in testing: gage error and material variability. On each of these sites, nuclear gage testing was performed using eight different gage positions. Each of the test modes (as listed in Section 2.3 above) was performed in all eight positions. Four holes were made in the asphalt surface for the purpose of testing with the conventional gage in "direct mode". These holes were placed at 90 degree points relative to each other and were approximately 8" away from the center of the point marked for coring. The eight gage positions are described as follows:

A, B, C, D Test Positions (see data in Appendix 2)

These four tests were conducted with the gage positioned directly over the core location. Thus, the material tested was as nearly as possible the same as the material to be cored. The radiation source and the sensor were located on opposite sides of the core. The four gage positions were all at right angles to each other.

a, b, c, d Test Positions (see data in Appendix 2)

The other four tests were conducted with the gage source over the same point as before (8" away from the core center) but with the sensor end of the gage rotated 180 degrees away from the core location. Thus, any significant variations in the overlay density occurring within 8 to 12 inches of the core would be detected and the effect of these variations could be evaluated.

2.3.3 Other Testing Considerations

The actual overlay thickness was measured by probing the asphalt mat with a sharp implement. Whenever the measured thickness differed from the nominal thickness by more than 1/4" (except on project 2 where the tolerance was 1/8 inch) the site was retested using the measured thickness. When the thickness was in tolerance the same density was recorded for both methods (nominal and actual thickness).

All readings were from 1 minute tests.

As indicated by the data in Appendix 2, only project #1 was tested while the asphalt was still hot.

3.0 RESULTS AND DISCUSSION

3.1 THIN LAYER GAGE EVALUATION

The overall results of this study indicate that the Troxler 4640 may produce slightly more accurate density measurements than the CPN gage in backscatter mode. This result, however, is not a recommendation for widespread use of this gage, as the slight improvement in accuracy is offset by its lack of versatility.

Two different methods of analysis were used to compare accuracy. The first method, linear regression analysis, suggests that the two methods are equivalent in accuracy. This is further discussed in Section 3.1.2. The alternate method, which analyzes gage errors with respect cores, provides a more positive indication that the thin layer gage is more accurate. This is further discussed in Section 3.1.3.

The term "accuracy" as used in this discussion refers to how well the gage densities can be corrected and/or correlated to core densities. Thus, core densities are used as the standard for all comparisons. Although there is certainly some inaccuracy in the testing of the cores, this is the only standard available. Alexander and Doty (1984) have found that core densities and nuclear gage results inherently disagree because core densities are based on a water displacement volume which eliminates the effects of surface voids. Nuclear gage readings, however, are affected by any slight irregularities in the surface that prevent the gage from contacting all surface particles.

One significant result of this study is that gage densities are found to be consistently lower than core densities. This is confirmed by Alexander and Doty (1984) and by Burati and Elzoghbi (1987). This can be partially explained by the effects of surface voids. The gages are calibrated on smooth metal blocks. When used in practice, however, the gage lies on a somewhat irregular surface allowing void spaces to be incorporated into the density measurement. When the same material is tested using cores, the effect of the larger surface voids is eliminated. Therefore nuclear gages read lower because they "see" more void space than is "seen" by the core method.

Alexander and Doty also provided information that can explain why the improvement in accuracy (thin layer gage compared to backscatter) was not more significant. They found that conventional gages in the backscatter mode read primarily the top 2 inches of pavement density. More specifically, they found that the top two inches accounts for 95% of the total measured density. Since 3 of the 4 jobs studied here were 2-inch overlays, very little improvement would be expected. The fourth job was a 1-3/4 inch overlay. This thickness would still account for a high percentage of the total density measured.

It should also be noted that the underlying material in all but one job was asphaltic concrete. Although the density of the underlying material was not measured by itself, in most cases it would not vary greatly from that of the overlay. The one job that was built over PCC was a 2" overlay. Although, in this case, the difference in densities was greater, the data does not indicate that the PCC influenced the gage densities. This tends to confirm that backscatter gages measure primarily the top two inches.

3.1.1 Gage Operation

The Troxler 4640, a computerized gage, is in many ways easier to operate than the old style conventional gages. The densities are read out directly in pounds per cubic foot and stored for future retrieval if needed. The older gages read out in count per unit time and required hand calculation to obtain the actual density. The computer feature provides more rapid results which may enable the contractor to improve the quality control of the rolling operation.

While these are significant advantages over the old style gages, the newer conventional type gages (those gages that are computer based and can operate in the direct, backscatter and AC modes) have the same operational advantages as the 4640.

One operational problem with the 4640 was the difficulty in obtaining a valid daily count during calibration check. The proper count could only be obtained on a very smooth, dense surface.

3.1.2 Regression Analysis of Thin Layer & Other Gages

Figures 1 through 3, are scatter plots of density for a particular test mode versus cores. Figures 1 and 2 include combined data from all four projects. Figure 3 includes data from only projects 1, 2, and 3* . Only the relationships that are most pertinent to this study are presented.

Linear regression methods were used to derive the equations of the regression line presented in the figures. The coefficient of determination, R^2, is a measure of how well the each method correlates with core densities. An R^2 of 1.00 would indicate a perfect correlation and all of the data points would fall in a straight line.

The regression equations could be used to estimate core densities from gage data. The values obtained in this manner are estimates, however, and not a calibration. To calibrate a gage by this method would require using the particular mix in question.

Thin Layer Gage vs Conventional Gage in the Backscatter Mode

Figure 1 shows the data for the thin layer gage with sand plotted against the core data. The coefficient of determination, $R^2 = 0.85$, for this plot indicates a reasonably good correlation. Figure 2 shows conventional gage data taken in the backscatter mode vs. the core data. The coefficient of determination is $R^2 = 0.84$. The close agreement between these two R^2 values suggests that, under actual field conditions, neither gage would be more accurate than the other.

Conventional Gage in Direct Mode vs cores

Figure 3 is a plot of the conventional gage (direct mode) densities vs. core densities. This plot shows somewhat greater scatter about the regression line (as indicated by the value, $R^2 = 0.67$) than was found for the other two gage methods discussed above. This would suggest that using the conventional gage in direct mode is not as accurate as the other two alternatives discussed above.

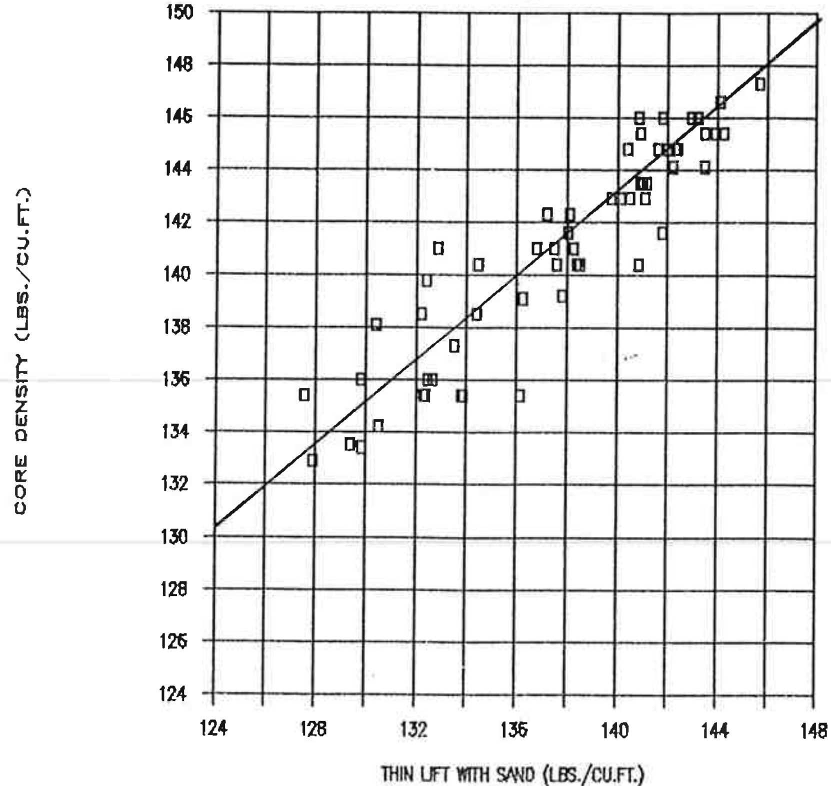
3.1.3 Alternate Method of Analysis

The data presented in Figures 1 through 3 combines all data from the 4 paving projects where the gages were evaluated. It is based on establishing a regression equation to correct to core densities. Since, in practice, such corrections are not made, it is useful to also look at the actual errors (core density minus gage density) and their standard deviations. Presented in Table 1, below, are the statistics of these errors for individual projects and for the entire study. This table allows the reader to compare for himself among all of the various methods of density measurement for each project.

* Note that the exact agreement between equations in Figures 1 and 3 is correct but highly coincidental.

THIN LIFT GAUGE VS CORE DENSITY

$R^2 = .85$



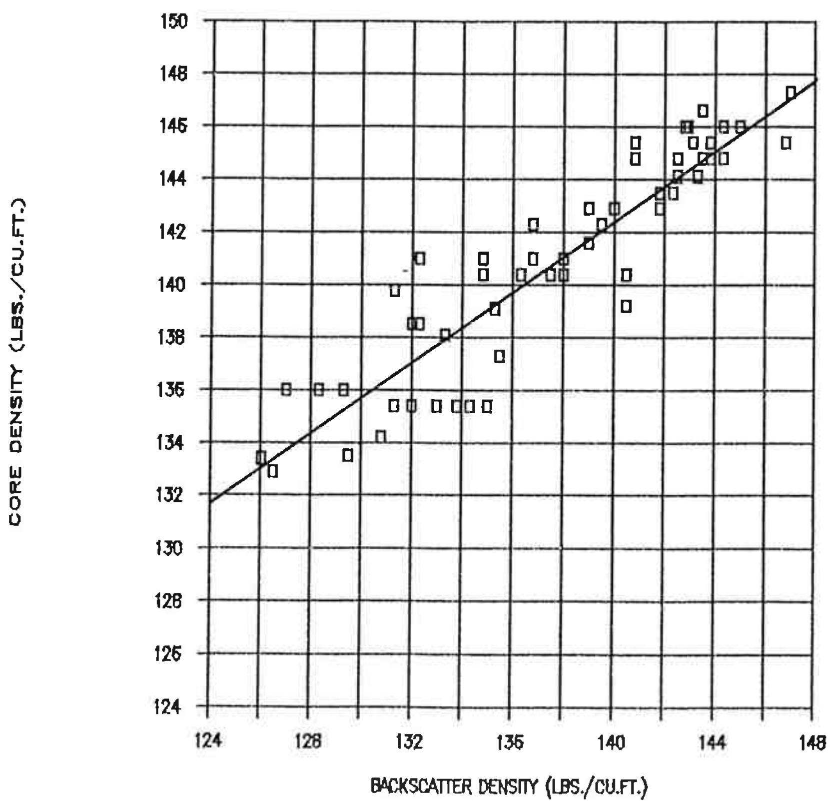
(Nominal Thickness)

$Y = 0.769 x + 35.1$

(Figure 1)

BACKSCATTER VS CORE DENSITY

$R^2 = .84$

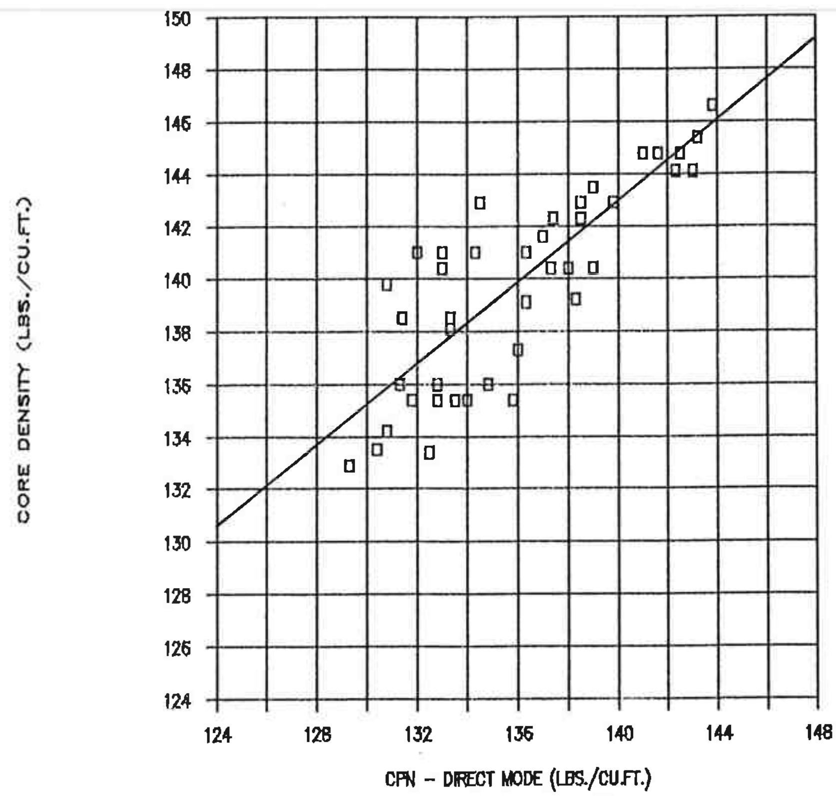


$Y = 0.668 x + 49.0$

(Figure 2)

CPN – DIRECT MODE VS CORE DENSITY

$R^2 = .68$



$Y = 0.769\,x + 35.1$

(Figure 3)

The mean can be thought of as "correctable error" because it can be removed by calibration or be corrected by adding a constant to the gage density. The "non-correctable error", or test variability, is represented by the standard deviation (STD DEV or S). The variance (S^2) is the standard deviation squared and is used in determining statically significant differences in "non-correctable errors".

Review the "means" in Table 1. Of significance is the lack of negative values. This implies that the averaged value of core densities is greater than the averaged gage determined densities. As discussed earlier this result is supported by others (Alexander and Doty, 1984; and Burati, 1987).

Table 1 data can be used to compare gages and test modes. The most pertinent comparison for this study is between the Troxler 4640 gage and the CPN model MC-3 gage. "Correctable errors" can be compared by looking at the mean error for "all projects." The two lowest values are for the CPN gage (3.22) and the Troxler (3.18). Although statistical analysis was not performed to evaluate any differences between these values, the Troxler 4640 clearly does not provide significant improvement in the "correctable error".

Now examine the "non-correctable errors" for each project. If the mean error were to be added as a correction to the gage readings and the results in table 1 were recalculated, then the means would be zero and the standard deviation would be unchanged. Specifically, after correcting for the mean error, 67% of all gage values would lie within one standard deviation of the core densities.

The "F" test can be used to determine the significance of differences between two variances (S^2) provided the means associated with the variances measure the same quantity. In the following discussion the "F" values that are most pertinent to this study are calculated and discussed. The table does not contain calculated "F" values because many comparisons are possible, and "F" can be easily calculated by the reader as follows:

$$F = S_1^2/S_2^2,$$

$$\text{where} \quad S_1^2 > S_2^2$$

In this study the "F" test was used at the 95% level of confidence. If the calculated "F" value is greater than the value given by table 1 in the "F critical" column, then there is statistical significance to the differences of the variances. For example, project 3 appears to have a large difference between the variance for the conventional gage in the backscatter mode (6.07) and the variance for the Troxler 4640 in the nominal thickness mode (2.84). Applying the "F" test it is found that (F = 6.07/2.84 = 2.14). "F" critical from Table 1 is 2.72. Since 2.14 is less than "F critical" there is no significant difference at the 95% confidence level.

TABLE 1

MEANS AND VARIANCES OF ERRORS FOR GAGE TESTING RELATIVE TO CORES
(core value minus gage value)
(Pounds per Cubic Foot)

	CPN MC-3 PORTAPROBE			TROXLER MODEL 4640			
MODE ==>				NOMINAL THICKNESS		ACTUAL	"F"
PROJECT	BACK-SCATTER SAND	DIRECT SAND	AC SAND	WITHOUT SAND	SAND	THICKNESS SAND	CRITICAL @ 95%
1 MEAN	4.94	6.0	4.57	5.51	4.12	3.33	
STD DEV	2.29	2.49	7.47	3.00	2.33	2.66	
VARIANCE	5.25	6.21	6.10	9.03	5.44	7.08	2.82
2 MEAN	1.76	2.28	3.89	3.26	1.96	1.76	
STD DEV	1.47	1.22	1.83	1.71	1.23	1.22	
VARIANCE	2.16	1.48	3.36	2.94	1.52	1.51	2.70
3 MEAN	4.78	2.58	10.52	5.62	3.85	3.87	
STD DEV	2.46	1.52	4.7	2.08	1.68	1.79	
VARIANCE	6.07	2.32	22.54	4.32	2.84	3.22	2.72
4 MEAN	1.74		11.11	4.45	3.33	3.85	
STD DEV	1.39		7.07	2.87	1.72	2.18	
VARIANCE	1.93		49.97	8.25	2.95	4.76	2.70
ALL PROJECTS							
MEAN	3.22	3.78	7.47	4.66	3.28	3.18	
STD DEV	2.43	2.31	5.50	2.58	1.91	2.14	
VARIANCE	5.90	5.31	30.28	6.64	3.65	4.59	1.53

When the "F" test was applied, only one test mode, the conventional gage in AC mode, had significantly greater error variance than the others. The error variances of 22.54 on projects 3 and 49.97 on project 4 are both significantly greater than all other test modes. This would suggest that AC mode testing has excessive variability. However the possibility must be considered that there may be an error in the test data, as projects 1 and 2 did not show this trend.

Analysis of the composite data for all projects indicates that the Troxler 4640 may have significantly lower error variance, thus improved accuracy over the conventional gage. At the 95 % level of significance, ($F = 5.90/3.65 = 1.61$), slightly greater than the "F critical" value (1.53). This is not conclusive, since there is no consistent trend for all projects studied. Also, no project, taken by itself, shows any significant difference in the two gages.

Note the difference between the results of this analysis method and the regression analysis. Although they both show the same trend for the overall data, the regression method is much less conclusive. The difference can be explained by noting that the regression method assumed that corrections were made with an equation, while in the error variance method corrections were a constant value.

3.2 OTHER RESULTS

3.2.1 Gage Error

The discussion in Section 3.1 deals with the total error. This is based on observed differences between gage readings and core densities. It is a composite of errors from all of the following sources: material variability, surface effects, core density error, underlying layer effects, and gage error. This section discusses the role of gage error and surface effects as separate phenomena.

The following simple experiment was performed to allow gage error and surface effects to be studied separately:

> A location was clearly marked on the surface of an asphalt parking lot to allow the same material to be tested in different modes. Twenty tests, using one minute readings, were then taken with the Troxler 4640 in "standard mode" and twenty more tests taken using the "SV mode." Then, to evaluate the effect of surface irregularities, the gage was raised using 0.058-inch shims. Then the same tests as above were performed again.

The results of this testing, expressed as mean and standard deviation of the 20 readings, are as follows:

	STANDARD MODE	SV MODE
Flat on surface		
MEAN	134.26	146.92
STD DEV	0.749	2.05
Raised 0.058"		
MEAN	127.93	146.37
STD DEV	0.75	1.60

The values for standard deviation correspond reasonably well with gage specifications as provided by the manufacturer (0.8 for standard mode and 2.26 for the SV mode). The manufacturer did not, however, supply information on the means or the effect that switching to SV mode would have on the magnitude of the readings.

Clearly, from the above statistics, the two test modes give significantly different results. Although calibration could remove most of the error in the mean value, the standard deviation cannot be adjusted. For the SV mode the standard deviation is significantly higher. In most cases, therefore, it would not be desirable to use SV mode unless a large number of tests were being averaged.

It is also clear from the above statistics that surface voids (as simulated by raising the gage) affect each test mode differently. The standard mode is affected significantly (6.3 pcf) by the change, while the SV mode is affected only slightly (0.5 pcf).

The above values for the standard deviation of the Troxler 4646 can be compared directly to accuracy data supplied by manufacturers of other gages. Standard gages in the backscatter mode generally have an accuracy of +/- 0.5 pcf. Therefore, except in the case of thin layer testing, the standard backscatter gages would be preferred.

It should also be noted that the gage error (standard deviation as listed above) is only a small portion of the "total error" (standard deviation as listed in Table 1). This is mentioned to show that it is not possible to greatly increase the accuracy of the overall reading by using a longer testing time. This is true for both gages tested.

3.2.2 Comparison of the Means

The paired difference "t" test was used to determine if the difference between core densities and gage densities is statistically significant. The "t" score is given by:

$$t = \sqrt{n}\,(\bar{x})/s$$

where:
- n = the number of tests
- $\bar{x}$ = the mean of the differences between the core density and the gage determined density
- s = the standard deviation associated with $\bar{x}$

The "t" score was calculated for each project and mode. The results, presented in Appendix 2, compare the "t" scores to 't critical' values that were obtained from statistical tables for the "t" distribution at the 99.9% level of confidence. As indicated in Appendix 3, the computed "t" scores are greater than "t" critical for all projects and modes. Therefore, at the 99.9% level of confidence, there is a significant difference between the core densities and the gage determined densities.

3.2.3 Effect of Gage Position

The intensive sites specifically examined the effect of two different gage positions relative to the core as indicated above. This allowed the instrument to measure a different, but repeatable, portion of the pavement. The purpose of this additional testing was to determine if some of the variability in test results was due to actual changes in material density and to also determine the importance of gage position relative to the core site.

The data for the intensive sites, which is designated by the UPPER CASE letters (A, B, C, D) in Appendix 2, was taken with the gage directly over the site to be cored. The data designated by the lower case letters (a, b, c, d) was taken with the gage rotated away from the exact core site. The averages of the four values for each position and for each site are in Appendix 4 as "A" and "a" respectively. The resulting eight pairs of values were analyzed by the paired difference "t" test in Appendix 4.

The difference in densities at the two positions were not statistically different at the 95% level of confidence. Therefore, when obtaining gage densities for correlating with core densities, it is not essential to position the gage directly over the core site.

3.3 ASSUMPTIONS AND SOURCES OF ERROR

It was necessary to make the assumption that the true density is represented by the core density, as no other known standard exists. The validity of this assumption is, to a limited degree, a function of the procedure used for the density determination. Since there is more than one method for Laboratory determination of density, the specific procedure used should be considered an approximation of the true density.

The method of probing the lift to estimate of the actual layer thickness was not verified against the actual core thickness. At times the asphalt had cooled before a measurement could be attempted.

Four different CPN MC-3 Portaprobes were used and one Troxler Model 4640. Differences in the four gages could have effected the variability between projects.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The accuracy of the Troxler 4640 Thin Layer Nuclear Gage compares favorably with the accuracy of conventional CPN nuclear gages. Although one method of analysis indicates that the thin layer gage is <u>more</u> accurate than the CPN gage, this is not consistent for all projects studied.

The conventional gage, when used in "AC mode" gives results which are significantly more variable than in the other two modes.

Densities, as measured by both nuclear gages in all modes, are significantly lower than the densities obtained from laboratory testing of cores. Accurate estimation of the core densities from nuclear gage results would require a calibration procedure to be performed for each mix design. A somewhat less accurate estimate could be obtained from the regression equations in Figures 1 through 3.

The effect of gage position, as evaluated on the intensive sites, was not significant when the readings obtained by placing the gage <u>directly over</u> the core site were compared to readings taken <u>a few inches away</u> from the core site.

With the Troxler 4640, entering the actual pavement thickness at each site as measured by probing the new AC, generally does not increase the overall accuracy of density measurement.

Recommendations

The Troxler 4640 should not be adopted for widespread use at the present time. The slight increase in accuracy that may be possible is offset by the lack of versatility of this gage as compared to conventional gages.

Continue using the conventional gage in backscatter mode with sand for seating.

If thinner overlays (1 to 1-1/2 inches) should come into common use then the gage should be evaluated again for these thicknesses.

Consider establishing a new policy of calibrating nuclear gage densities to cores on every project.

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APPENDIX 1

MIX DESIGN

PROJECT	1	2	3	4
Mix Class	"C"	"C"	"C"	"B"
Aggregate Gradation				
1"	-	-	-	100
3/4	100	-	100	99
1/2	98	100	98	88
3/8	85	86	84	72
1/4	62	63	64	57
10	32	33	29	29
40	14	16	11	9
200	5.5	6.0	5.0	3.5
Asphalt Content	5.9	5.7	6.6	6.0
Design Voids 100 % Compaction	2.2	1.2	2.6	1.3
Specific Gravity	2.46	2.46	2.39	2.48
Density	153.5	153.8	149.1	154.6
Asphalt Brand	Chevron AR 4000W 0.4% PaveBond	McCall AR 4000	Asphalt Supply A.C. 20 R	McCall AR 4000

APPENDIX 2

COMPLETE TEST DATA

PROJECT 1

*** DENSITY - POUNDS PER CUBIC FOOT ***

					* CPN MC-3 PORTAPROBE *		* TROXLER MODEL 4640 - THIN LIFT *					
CORE NO.	CORE NO.	GAGE POS.	STATION	TEMP	BACK-SCATTER SAND	DIRECT SAND	AC SAND	NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS	CORE THICKNESS
1	1	A	109.00	155	130.0	129.0	132.0	127.0	131.7	131.7	139.8	1.75
		B			131.5	130.0	130.0	126.2	131.1	131.1		
		C			128.0	129.5	131.5	129.6	133.1	133.1		
		D			129.5	131.5	131.5	129.6	133.5	133.5		
				MEAN	129.8	130.0	131.3	128.1	132.4	132.4		
		a	109.00	155	136.0	133.5	134.5	132.5	133.5	133.5		
		b			131.5	130.5	132.0	127.9	132.2	132.2		
		c			132.5	131.5	131.0	129.5	134.0	134.0		
		d			131.0	131.0	131.0	126.5	130.1	130.1		
				MEAN	132.8	131.6	132.1	129.1	132.5	132.5		
14	14	A	44.00	115	136.5	136.5	138.0	137.5	139.0	139.0	142.3	1.75
		B			138.0	137.5	137.0	136.9	138.0	138.0		
		C			140.0	138.5	140.0	137.3	137.5	137.5		
		D			135.5	138.0	139.0	139.5	138.3	138.3		
				MEAN	137.5	137.6	138.5	137.8	138.2	138.2		
		a	44.00	115	135.0	136.5	135.0	134.3	132.7	132.7		
		b			140.0	139.0	140.0	140.4	140.0	140.0		
		c			131.5	135.0	135.0	134.7	133.6	133.6		
		d			137.5	138.0	138.5	138.8	138.3	138.3		
				MEAN	136.0	137.1	137.1	137.1	136.2	136.2		
2	2	A	107.00	155	132.5	132.4	130.0	130.3	133.7	133.7	138.5	1.75
3	3	A	105.00	155	131.5	133.5	134.0	134.8	136.0	136.0	138.5	1.75
4	4	A	94.00	155	137.0	135.0	139.5	135.4	137.2	137.2	141.0	1.75
5	5	A	90.00	155	141.0	137.0	140.0	139.0	140.7	140.7	142.9	1.75
6	6	A	78.90	160	132.5	131.0	133.5	132.3	132.9	132.9	135.4	1.75
7	7	A	74.00	160	136.5		136.5	135.1	138.2	137.6	140.4	2.00
8	8	A	57.00	160	135.0	134.5	135.5	134.3	135.6	135.6	135.4	1.75
9	9	A	56.00	160	133.5	134.5	134.0	137.9	138.3	138.3	141.0	1.75
10	10	A	54.80	160	133.5	134.5	134.5	127.0	133.6	133.6	140.4	1.75
11	11	A	54.00	160	132.0	131.5	133.5	132.4	132.4	132.2	141.0	2.00
13	13	A	45.00	160	139.0	138.0	139.0	134.6	137.0	137.0	140.4	1.75
15	15	A	43.00	155	137.5	138.0	136.0	138.5	137.1	138.1	141.0	2.00
				MEAN	135.1	134.5	135.5	134.3	136.1	136.1	139.7	
2	2	B	107.00	155	131.5	130.4	133.0	129.6	130.7	138.1		
3	3	B	105.00	155	133.0	133.0	134.5	132.9	132.8	138.1		
4	4	B	94.00	155	139.0	133.5	137.0	136.8	137.8	138.1		
5	5	B	90.00	155	139.0	132.0	141.0	138.6	138.8	138.1		
6	6	B	78.90	160	130.0	132.5	130.0	131.0	131.8	138.1		
7	7	B	74.00	160	136.0		138.0	137.3	138.8	140.3		
8	8	B	57.00	160	135.0	133.5	135.0	135.2	136.7	138.1		
9	9	B	56.00	160	136.0	131.5	135.0	137.0	138.2	138.1		
10	10	B	54.80	160	136.0	131.5	135.0	133.2	135.3	138.1		
11	11	B	54.00	160	132.5	132.5	130.5	131.9	133.3	132.9		
13	13	B	45.00	160	136.0	138.0	137.5	138.1	138.1	138.1		
15	15	B	43.00	155	136.0	134.5	136.5	136.4	136.4	134.5		
				MEAN	135.0	133.0	135.3	134.8	135.7	137.6		

APPENDIX 2

PROJECT 2

*** DENSITY - POUNDS PER CUBIC FOOT ***

* CPN MC-3 PORTAPROBE * * TROXLER MODEL 4640 - *

* THIN LIFT *

CORE NO.	GAGE POS.	STATION	TEMP	BACK-SCATTER SAND	DIRECT SAND	AC SAND	NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS	CORE THICKNESS
3	A	313.15	80	143.0	141.0	136.5	139.6	141.9	142.2	144.8	2.50
	B			147.5	143.0	141.5	141.5	142.8	144.3		
	C			143.5	142.0	140.0	140.7	142.9	144.8		
	D			145.5	140.0	139.5	142.1	141.9	142.2		
			MEAN	144.9	141.5	139.4	141.0	142.4	143.4		
	a	313.15	80	143.5	140.0	137.5	140.4	140.4	142.4		
	b			142.0	142.0	140.0	142.0	142.1	142.8		
	c			144.5	143.0	140.5	141.4	143.8	143.1		
	d			144.5	142.0	139.5	140.5	142.8	144.3		
			MEAN	143.6	141.8	139.4	141.1	142.3	143.2		
11	A	253.50	80	144.5	144.0	140.0	142.7	144.2	144.2	145.4	2.00
	B			143.5	144.5	141.0	143.9	143.0	143.0		
	C			142.0	141.5	138.5	141.4	142.4	142.4		
	D			143.5	142.5	139.5	142.2	142.9	142.9		
			MEAN	143.4	143.1	139.8	142.6	143.1	143.1		
	a	253.50	80	141.5	143.0	137.0	142.1	143.0	143.0		
	b			144.5	144.0	140.0	142.9	146.1	146.1		
	c			141.0	142.0	137.5	142.2	142.6	142.6		
	d			144.0	144.5	139.0	141.7	143.8	143.8		
			MEAN	142.8	143.4	138.4	142.2	143.9	143.9		
1	A	344.07	70	141.0	139.0	141.0	140.0	140.8	138.5	140.4	1.50
2	A	329.18	75	137.5	138.0	139.0	134.3	137.7	138.0	140.4	2.10
4	A	306.49	75	141.0	139.0	136.0	136.7	137.2	139.0	139.2	2.40
5	A	305.47	75	143.5	142.5	141.0	141.4	141.8	144.0	144.8	2.50
6	A	301.07	75	140.0	140.0	137.5	137.3	138.3	139.3	142.3	1.80
7	A	300.68	75	142.0	138.0	136.5	137.3	139.3	139.2	142.9	2.50
8	A	296.59	75	142.0	138.5	139.5	141.6	140.5	140.8	143.5	1.90
9	A	287.00	65	139.5	140.0	137.0	139.1	140.9	141.3	142.9	2.13
10	A	286.00	70	138.5	137.0	138.0	140.4	141.7	140.6	141.6	2.13
12	A	254.50	75	141.5	142.0	142.0	138.3	141.7	142.8	144.8	2.50
13	A	255.00	80	143.5	143.0	142.0	142.5	142.0	145.1	144.1	2.25
14	A	256.97	80	143.5	142.0	141.0	139.6	140.3	141.6	144.1	2.38
15	A	258.32	80	144.0	143.5	142.0	141.5	143.3	143.3	146.6	2.00
			MEAN	141.3	140.2	139.4	139.2	140.4	141.0	142.9	
1	B	344.07	70	140.0	139.0	140.0	140.1	140.9	137.9		
2	B	329.18	75	138.5	136.5	139.0	137.7	139.1	138.4		
4	B	306.49	75	140.0	137.5	135.0	136.9	138.4	138.9		
5	B	305.47	75	143.5	142.5	141.5	142.4	142.1	142.6		
6	B	301.07	75	139.0	137.0	136.0	134.7	137.8	137.7		
7	B	300.68	75	141.5	139.0	137.5	140.5	141.7	140.8		
8	B	296.59	75	142.5	139.5	139.0	139.4	141.2	140.7		
9	B	287.00	65	138.5	139.5	137.0	140.1	141.3	141.0		
10	B	286.00	70	139.5	137.0	138.0	142.3	141.9	143.3		
12	B	254.50	75	140.0	140.0	140.5	140.1	141.5	141.6		
13	B	255.00	80	143.0	143.0	141.5	142.7	144.9	144.5		
14	B	256.97	80	141.5	142.5	143.0	142.3	144.0	143.4		
15	B	258.32	80	143.0	144.0	140.5	141.9	144.8	144.8		
			MEAN	140.8	139.8	139.1	140.1	141.5	141.2		

APPENDIX 2

PROJECT 3

*** DENSITY - POUNDS PER CUBIC FOOT ***
* CPN MC-3 PORTAPROBE * * TROXLER MODEL 4640 - *
* THIN LIFT GAGE *

CORE NO.	GAGE POS.	STATION	TEMP	BACK-SCATTER SAND	DIRECT SAND	AC SAND	NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS	CORE THICKNESS
	A	184.50	60	131.0	133.0	116.0	132.9	133.0	133.4	DAMAGED CORE	
	B			131.5	135.0	122.5	131.0	134.5	133.9	NO RESULT	
	C			135.0	134.5	124.0	130.7	132.0	132.7		
	D			131.0	134.0	123.0	131.6	132.0	133.3		
			MEAN	132.1	134.1	121.4	131.6	132.9	133.3		
	a	184.50	60	135.5	132.5	123.5	129.9	131.5	131.5		
	b			133.5	136.5	124.0	131.1	133.1	134.4		
	c			127.5	135.5	119.5	131.1	132.1	133.8		
	d			131.0	136.0	121.5	130.9	133.2	133.3		
			MEAN	131.9	135.1	122.1	130.8	132.5	133.3		
15	A	169.50	60	130.5	130.0	131.5	126.6	129.3	129.0	133.5	2.50
	B			129.5	130.5	130.5	126.8	129.4	129.3		
	C			128.5	129.0	128.0	125.6	127.5	129.2		
	D			130.0	129.5	130.0	126.3	129.7	130.1		
			MEAN	129.6	129.8	130.0	126.3	129.0	129.4		
	a	169.50	60	130.0	129.5	132.0	128.0	129.7	130.2		
	b			129.0	131.0	131.5	130.5	130.6	130.7		
	c			128.0	130.5	129.5	128.4	128.4	130.0		
	d			131.0	132.5	131.0	127.8	130.6	131.3		
			MEAN	129.5	130.9	131.0	128.7	129.8	130.6		
1	A	185.50	60	131.5	133.0	124.0	131.7	133.6	133.6	135.4	2.50
2	A	185.00	60	134.0	133.5	133.5	127.8	131.3	131.3	138.1	2.25
4	A	175.00	60	135.0	136.0	123.0	134.2	136.2	134.8	139.1	1.75
5	A	174.50	60	130.0	133.0	130.5	126.8	130.3	128.8	133.4	1.75
6	A	174.00	60	131.0	134.5	122.5	130.3	132.8	132.5		DAMAGED
7	A	173.50	60	134.5	135.5	124.0	132.9	131.6	133.8	135.4	2.25
8	A	173.00	60	126.5	129.5	114.5	126.8	129.1	129.1	132.9	2.00
9	A	172.50	60	125.5	134.5	117.5	132.5	132.2	132.2	136.0	2.00
10	A	172.00	60	125.5	133.5	128.5	129.8	130.7	128.8	136.0	1.50
11	A	171.50	60	131.5	130.0	120.0	129.5	130.5	127.5	134.2	1.75
12	A	171.00	60	132.5	130.5	132.0	129.9	132.8	132.4	136.0	2.10
13	A	170.50	60	133.0	132.5	124.5	130.7	134.3	134.3	135.4	2.00
14	A	170.00	60	135.0	136.5	123.0	130.4	133.1	133.1	137.3	2.00
			MEAN	131.2	133.3	124.4	130.3	132.2	131.7	135.8	
1	B	185.50	60	132.5	134.0	124.5	132.9	134.1	134.5		
2	B	185.00	60	132.5	133.0	132.0	127.3	129.5	130.7		
4	B	175.00	60	135.5	136.5	127.0	133.9	136.3	135.7		
5	B	174.50	60	122.0	132.0	120.5	127.7	129.4	129.4		
6	B	174.00	60	136.0	135.5	124.0	132.1	132.2	134.0		
7	B	173.50	60	134.0	136.0	122.5	132.4	132.9	134.7		
8	B	173.00	60	126.5	129.0	116.0	125.0	126.7	126.7		
9	B	172.50	60	133.0	135.0	123.5	131.5	133.1	133.1		
10	B	172.00	60	131.0	132.0	131.5	127.5	128.9	130.7		
11	B	171.50	60	130.0	131.5	119.5	128.0	130.5	130.5		
12	B	171.00	60	121.5	132.0	132.0	129.9	132.1	132.0		
13	B	170.50	60	133.0	133.0	122.0	133.0	133.3	133.3		
14	B	170.00	60	136.0	135.5	125.0	132.2	133.9	133.9		
			MEAN	131.0	133.5	124.6	130.3	131.8	132.2	135.8	

APPENDIX 2

PROJECT 4

*** DENSITY - POUNDS PER CUBIC FOOT ***

* CPN MC-3 PORTAPROBE *   * TROXLER MODEL 4640 - THIN LIFT GAGE *

CORE NO.	GAGE POS.	STATION	TEMP	BACK-SCATTER SAND	DIRECT SAND	AC SAND	NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS	CORE THICKNESS
5	A	500.00	50	141.0		129.0	138.5	140.8	140.7	146.0	1.75
	B			142.0		127.5	140.8	141.2	139.1		
	C			144.0		143.0	140.6	141.3	143.1		
	D			143.0		142.5	140.7	141.7	139.5		
			MEAN	142.5		135.5	140.2	141.3	140.6		
	a	500.00	50	143.0		130.0	139.6	143.6	140.3		
	b			144.0		143.5	140.8	141.5	141.1		
	c			142.0		132.0	141.3	141.8	142.2		
	d			144.0		130.5	140.3	141.7	141.0		
			MEAN	143.3		134.0	140.5	142.2	141.2		
12	A	700.50	50	144.5		143.0	143.4	143.1	143.6	144.8	2.5
	B			145.0		131.0	143.9	143.5	142.9		
	C			143.5		143.0	143.5	143.6	145.4		
	D			141.5		139.0	136.8	133.9	139.4		
			MEAN	143.6		139.0	141.9	141.0	142.8		
	a	700.50	50	144.0		143.5	140.9	144.4	140.3		
	b			144.0		144.0	141.1	142.5	140.3		
	c			143.0		145.0	145.1	144.4	143.6		
	d			145.0		130.0	143.7	142.6	142.3		
			MEAN	144.0		140.6	142.7	143.5	141.6		
1	A	100.00	60	141.0		125.0	138.8	139.2	138.9	144.8	2.25
2	A	200.00	60	141.5		138.5	139.7	141.2	139.9	143.5	2.50
3	A	300.00	60	134.5		112.0	120.8	125.2	123.2	135.4	1.75
4	A	400.00	60	140.0		122.0	138.4	140.6	139.1	145.4	1.50
6	A	500.25	50	142.0		129.5	136.5	139.6	142.6	142.9	2.25
7	A	500.50	50	141.0		128.5	136.7	140.0	139.4	143.5	1.50
8	A	600.00	50	138.0		136.5	132.7	134.9	133.0	141.6	1.50
9	A	600.25	50	146.5		132.0	146.0	144.9	143.1	145.4	1.50
10	A	600.50	50	139.0		143.0	139.4	139.5	141.5	146.0	1.75
11	A	600.75	50	144.0		131.5	144.3	144.2	145.6	145.4	2.50
13	A	800.25	50	144.5		142.5	141.5	142.1	143.0	146.0	2.50
14	A	800.50	50	144.0		144.0	144.6	143.5	142.3	146.0	2.25
15	A	900.00	50	147.5		132.0	145.0	145.1	145.1	147.3	2.00
			MEAN	141.8		132.1	138.8	140.0	139.7	144.1	
1	B	100.00	60	144.0		126.0	140.4	141.5	141.4		
2	B	200.00	60	142.0		139.0	139.4	140.8	138.8		
3	B	300.00	60	133.0		112.5	126.4	129.9	128.6		
4	B	400.00	60	141.5		124.5	139.7	141.2	140.6		
6	B	500.25	50	141.5		130.5	136.2	140.7	139.6		
7	B	500.50	50	143.5		141.0	140.2	142.3	140.4		
8	B	600.00	50	140.0		138.5	137.9	141.2	138.6		
9	B	600.25	50	147.0		131.0	145.1	142.9	142.7		
10	B	600.50	50	146.5		139.0	143.0	142.2	142.0		
11	B	600.75	50	143.5		127.5	143.8	144.3	144.1		
13	B	800.25	50	145.5		143.5	143.6	144.3	144.0		
14	B	800.50	50	144.5		143.5	143.6	142.4	142.6		
15	B	900.00	50	146.5		132.0	145.3	146.3	146.3		
			MEAN	143.0		133.0	140.4	141.5	140.7		

APPENDIX 3

DATA AVERAGED BY CORE SITE

PROJECT 1

*** DENSITY - POUNDS PER CUBIC FOOT ***

	* CPN MC-3 PORTAPROBE *			* TROXLER MODEL 4640 - THIN LIFT GAGE *			
CORE NO.	BACK-SCATTER SAND	DIRECT SAND	AC SAND	NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS
1	131.3	130.8	131.7	128.6	132.4	132.4	139.8
2	132.0	131.4	131.5	130.0	132.2	135.9	138.5
3	132.3	133.3	134.3	133.9	134.4	137.1	138.5
4	138.0	134.3	138.3	136.1	137.5	137.7	141.0
5	140.0	134.5	140.5	138.8	139.8	139.4	142.9
6	131.3	131.8	131.8	131.7	132.4	135.5	135.4
7	136.3		137.3	136.2	138.5	139.0	140.4
8	135.0	134.0	135.3	134.8	136.2	136.9	135.4
9	134.8	133.0	134.5	137.5	138.3	138.2	141.0
10	134.8	133.0	134.8	130.1	134.5	135.9	140.4
11	132.3	132.0	132.0	132.2	132.9	132.6	141.0
13	137.5	138.0	138.3	136.4	137.6	137.6	140.4
14	136.8	137.4	137.8	137.4	137.2	137.2	142.3
15	136.8	136.3	136.3	137.5	136.8	136.3	141.0
N =	14	13	14	14	14	14	14
VARIANCE	7.14	4.70	7.74	10.13	6.19	3.92	4.63
MEAN	134.9	133.8	135.3	134.3	135.7	136.5	139.9

CORE NO.	DIFFERENCES (LAB RESULTS - TEST MODE RESULTS)					
1	8.5	9.0	8.1	11.2	7.4	7.4
2	6.5	7.1	7.0	8.5	6.3	2.6
3	6.3	5.3	4.3	4.6	4.1	1.4
4	3.0	6.8	2.8	4.9	3.5	3.3
5	2.9	8.4	2.4	4.1	3.2	3.5
6	4.2	3.7	3.7	3.8	3.0	-0.1
7	4.2		3.2	4.2	1.9	1.4
8	0.4	1.4	0.2	0.7	-0.8	-1.4
9	6.3	8.0	6.5	3.5	2.8	2.8
10	5.7	7.4	5.7	10.3	5.9	4.6
11	8.8	9.0	9.0	8.8	8.1	8.4
13	2.9	2.4	2.2	4.1	2.8	2.8
14	5.5	4.9	4.5	4.9	5.1	5.1
15	4.3	4.8	4.8	3.5	4.3	4.7
COUNT	14	13	14	14	14	14
MEAN	4.94	6.00	4.57	5.51	4.12	3.33
VARIANCE	5.25	6.21	6.10	9.03	5.44	7.08

CALCULATE THE t VALUES TO TEST THE HYPOTHESIS THAT THE MEAN = 0
THE ALTERNATIVE HYPOTHESIS IS THAT THE MEAN DOES NOT = 0

t VALUE	8.06	8.68	6.93	6.86	6.61	4.69
tCRIT 99.9	3.85	3.93	3.85	3.85	3.85	3.85
HYPOTHESIS	REJECT	REJECT	REJECT	REJECT	REJECT	REJECT

APPENDIX 3

PROJECT 2

*** DENSITY - POUNDS PER CUBIC FOOT ***

CORE NO.	* CPN MC-3 PORTAPROBE * BACK-SCATTER SAND	DIRECT SAND	AC SAND	* TROXLER MODEL 4640 - * THIN LIFT GAGE * NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS
1	140.5	139.0	140.5	140.1	140.9	138.2	140.4
2	138.0	137.3	139.0	136.0	138.4	138.2	140.4
3	144.3	141.6	139.4	141.0	142.4	143.3	144.8
4	140.5	138.3	135.5	136.8	137.8	139.0	139.2
5	143.5	142.5	141.3	141.9	142.0	143.3	144.8
6	139.5	138.5	136.8	136.0	138.1	138.5	142.3
7	141.8	138.5	137.0	138.9	140.5	140.0	142.9
8	142.3	139.0	139.3	140.5	140.9	140.8	143.5
9	139.0	139.8	137.0	139.6	141.1	141.2	142.9
10	139.0	137.0	138.0	141.4	141.8	142.0	141.6
11	143.1	143.2	139.6	142.4	143.5	143.5	145.4
12	140.8	141.0	141.3	139.2	141.6	142.2	144.8
13	143.3	143.0	141.8	142.6	143.5	144.8	144.1
14	142.5	142.3	142.0	141.0	142.2	142.5	144.1
15	143.5	143.8	141.3	141.7	144.1	144.1	146.6
N =	15	15	15	15	15	15	15
VARIANCE	3.62	4.87	3.97	4.48	3.46	4.65	4.07
MEAN	141.4	140.3	139.3	139.9	141.2	141.4	143.2

DIFFERENCES (LAB RESULTS - TEST MODE RESULTS)

CORE NO.						
1	-0.1	1.4	-0.1	0.35	-0.45	2.2
2	2.4	3.15	1.4	4.4	2	2.2
3	0.5	3.2	5.4	3.8	2.4	1.5
4	-1.3	0.95	3.7	2.4	1.4	0.25
5	1.3	2.3	3.55	2.9	2.85	1.5
6	2.8	3.8	5.55	6.3	4.25	3.8
7	1.15	4.4	5.9	4	2.4	2.9
8	1.25	4.5	4.25	3	2.65	2.75
9	3.9	3.15	5.9	3.3	1.8	1.75
10	2.6	4.6	3.6	0.25	-0.2	-0.35
11	2.3	2.2	5.8	3	1.9	1.9
12	4.05	3.8	3.55	5.6	3.2	2.6
13	0.85	1.1	2.35	1.5	0.65	-0.7
14	1.6	1.85	2.1	3.15	1.95	1.6
15	3.1	2.85	5.35	4.9	2.55	2.55
COUNT	15	15	15	15	15	15
MEAN	1.76	2.88	3.89	3.26	1.96	1.76
VARIANCE	2.16	1.48	3.36	2.94	1.52	1.51

CALCULATE THE t VALUES TO TEST THE HYPOTHESIS THAT THE MEAN = 0
THE ALTERNATIVE HYPOTHESIS IS THAT THE MEAN DOES NOT = 0

t VALUE	4.64	9.17	8.21	7.35	6.14	5.56
tCRIT 99.9	3.79	3.79	3.79	3.79	3.79	3.79
HYPOTHESIS	REJECT	REJECT	REJECT	REJECT	REJECT	REJECT

PROJECT 3

*** DENSITY - POUNDS PER CUBIC FOOT ***

CORE NO.	* CPN MC-3 PORTAPROBE * BACK-SCATTER SAND	DIRECT SAND	AC SAND	* TROXLER MODEL 4640 - THIN LIFT GAGE * NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS
1	132.0	133.5	124.3	132.3	133.9	134.1	135.4
2	133.3	133.3	132.8	127.6	130.4	131.0	138.1
DAMAGED 3							
4	135.3	136.3	125.0	134.1	136.3	135.3	139.1
5	126.0	132.5	125.5	127.3	129.9	129.1	133.4
DAMAGED 6							
7	134.3	135.8	123.3	132.7	132.3	134.3	135.4
8	126.5	129.3	115.3	125.9	127.9	127.9	132.9
9	129.3	134.8	120.5	132.0	132.7	132.7	136.0
10	128.3	132.8	130.0	128.7	129.8	129.8	136.0
11	130.8	130.8	119.8	128.8	130.5	129.0	134.2
12	127.0	131.3	132.0	129.9	132.5	132.2	136.0
13	133.0	132.8	123.3	131.9	133.8	133.8	135.4
14	135.5	136.0	124.0	131.3	133.5	133.5	137.3
15	129.5	130.4	130.5	127.5	129.4	130.0	133.5
N =	13	13	13	13	13	13	13
VARIANCE	10.20	4.60	24.23	5.99	4.97	5.31	3.11
MEAN	130.8	133.0	125.1	130.0	131.7	131.7	135.6

CORE NO.	DIFFERENCES	(LAB RESULTS - TEST MODE RESULTS)				
1	3.4	1.9	11.15	3.1	1.55	1.35
2	4.85	4.85	5.35	10.55	7.7	7.1
3						
4	3.85	2.85	14.1	5.05	2.85	3.85
5	7.4	0.9	7.9	6.15	3.55	4.3
6						
7	1.15	-0.35	12.15	2.75	3.15	1.15
8	6.4	3.65	17.65	7	5	5
9	6.75	1.25	15.5	4	3.35	3.35
10	7.75	3.25	6	7.35	6.2	6.25
11	3.45	3.45	14.45	5.45	3.7	5.2
12	9	4.75	4	6.1	3.55	3.8
13	2.4	2.65	12.15	3.55	1.6	1.6
14	1.8	1.3	13.3	6	3.8	3.8
15	4	3.1	3	6	4.1	3.5
COUNT	13	13	13	13	13	13
MEAN	4.78	2.58	10.52	5.62	3.85	3.87
VARIANCE	6.07	2.32	22.54	4.32	2.84	3.22

CALCULATE THE t VALUES TO TEST THE HYPOTHESIS THAT THE MEAN = 0
THE ALTERNATIVE HYPOTHESIS IS THAT THE MEAN DOES NOT = 0

t VALUE	7.00	6.11	7.99	9.75	8.25	7.77
tCRIT 99.9	3.93	3.93	3.93	3.93	3.93	3.93
HYPOTHESIS	REJECT	REJECT	REJECT	REJECT	REJECT	REJECT

APPENDIX 3

PROJECT 4

*** DENSITY - POUNDS PER CUBIC FOOT ***

	* CPN MC-3 PORTAPROBE *		* TROXLER MODEL 4640 - * THIN LIFT GAGE *				
CORE NO.	BACK-SCATTER SAND	DIRECT SAND	AC SAND	NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS
1	142.5		125.5	139.6	140.4	140.2	144.8
2	141.8		138.8	139.6	141.0	139.4	143.5
3	133.8		112.3	123.6	127.6	125.9	135.4
4	140.8		123.3	139.1	140.9	139.9	145.4
5	142.9		134.8	140.4	141.8	140.9	146.0
6	141.8		130.0	136.4	140.2	141.1	142.9
7	142.3		134.8	138.5	141.2	139.9	143.5
8	139.0		137.5	135.3	138.1	135.8	141.6
9	146.8		131.5	145.6	143.9	142.9	145.4
10	142.8		141.0	141.2	140.9	141.8	146.0
11	143.8		129.5	144.1	144.3	144.9	145.4
12	143.8		139.8	142.3	142.3	142.2	144.8
13	145.0		143.0	142.6	143.2	143.5	146.0
14	144.3		143.8	144.1	143.0	142.5	146.0
15	147.0		132.0	145.2	145.7	145.7	147.3
N =	15		15	15	15	15	15
VARIANCE	9.61		66.09	27.43	16.19	20.46	7.63
MEAN	142.5		133.2	139.8	140.9	140.4	144.3

CORE NO.	DIFFERENCES	(LAB RESULT - TEST MODE RESULTS)				
1	2.3		19.3	5.2	4.45	4.65
2	1.75		4.75	3.95	2.5	4.15
3	1.65		23.15	11.8	7.85	9.5
4	4.65		22.15	6.35	4.5	5.55
5	3.1		11.2	5.6	4.2	5.1
6	1.15		12.9	6.55	2.75	1.8
7	1.25		8.75	5.05	2.35	3.6
8	2.6		4.1	6.3	3.55	5.8
9	-1.35		13.9	-0.15	1.5	2.5
10	3.25		5	4.8	5.15	4.25
11	1.65		15.9	1.35	1.15	0.55
12	1		5	2.5	2.5	2.6
13	1		3	3.45	2.8	2.5
14	1.75		2.25	1.9	3.05	3.55
15	0.3		15.3	2.15	1.6	1.6
COUNT	15		15	15	15	15
MEAN	1.74		11.11	4.45	3.33	3.85
VARIANCE	1.93		49.97	8.25	2.95	4.76

CALCULATE THE t VALUES TO TEST THE HYPOTHESIS THAT THE MEAN = 0
THE ALTERNATIVE HYPOTHESIS IS THAT THE MEAN DOES NOT = 0

t VALUE	4.85		6.09	6.01	7.50	6.83
tCRIT 99.9	3.79	3.79	3.79	3.79	3.79	3.79
HYPOTHESIS	REJECT	REJECT	REJECT	REJECT	REJECT	REJECT

APPENDIX 4

GAGE POSITIONING TEST

TESTING OF HYPOTHESIS - INTENSIVE SITES

*** DENSITY - POUNDS PER CUBIC FOOT ***

* CPN MC-3 PORTAPROBE * * TROXLER MODEL 4640 - * * THIN LIFT GAGE *

CORE NO.	PROJECT-POSITION	BACK-SCATTER SAND	DIRECT SAND	AC SAND	NO SAND	SAND	ACTUAL THICKNESS	LAB RESULTS
1	1A	129.8	130.0	131.3	128.1	132.4	132.4	139.8
14	1A	137.5	137.6	138.5	137.8	138.2	138.2	142.3
3	2A	144.9	141.5	139.4	141.0	142.4	143.4	144.8
11	2A	143.4	143.1	139.8	142.6	143.1	143.1	145.4
5	4A	142.5		135.5	140.2	141.3	140.6	146.0
12	4A	143.6		139.0	141.9	141.0	142.8	144.8
	3A	132.1	134.1	121.4	131.6	132.9	133.3	
15	3A	129.6	129.8	130.0	126.3	129.0	129.4	133.5
1	1a	132.8	131.6	132.1	129.1	132.5	132.5	
14	1a	136.0	137.1	137.1	137.1	136.2	136.2	
3	2a	143.6	141.8	139.4	141.1	142.3	143.2	
11	2a	142.8	143.4	138.4	142.2	143.9	143.9	
5	4a	143.3		134.0	140.5	142.2	141.2	
12	4a	144.0		140.6	142.7	143.5	141.6	
	3a	131.9	135.1	122.1	130.8	132.5	133.3	
15	3a	129.5	130.9	131.0	128.7	129.8	130.6	

CALCULATE THE DIFFERENCES BETWEEN THE "A" AND "a" SAMPLES

	-3.00	-1.63	-0.88	-1.00	-0.10	-0.10
	1.50	0.50	1.38	0.75	2.05	2.05
	1.25	-0.25	0.00	-0.10	0.10	0.22
	0.63	-0.25	1.38	0.33	-0.75	-0.75
	-0.75		1.50	-0.35	-0.90	-0.55
	-0.38		-1.63	-0.80	-2.45	1.20
	0.25	-1.00	-0.75	0.80	0.40	0.08
	0.13	-1.13	-1.00	-2.35	-0.85	-1.15
SAMPLE MEAN	-0.047	-0.625	0.000	-0.341	-0.312	0.125
SAMPLE VARIANCE	2.00	0.59	1.57	1.10	1.67	1.11
NUMBER IN TEST	8	6	8	8	8	8

CALCULATE THE t VALUES TO TEST THE HYPOTHESIS THAT THE MEAN = 0
THE ALTERNATIVE HYPOTHESES IS THAT THE MEAN DOES NOT = 0

CALCULATED t VALUE	-0.094	-1.997	0.000	-0.920	-0.684	0.336

FROM P(T<=C1) = 97.5%, P(T>=C2) = 97.5% WITH (N - 1) DEGREES OF FREEDOM
WHERE "P" IS THE PROBABILITY

C1 =	-2.37	-2.57	-2.37	-2.37	-2.37	-2.37
C2 =	2.37	2.57	2.37	2.37	2.37	2.37

SINCE t IS NOT LESS THAN C1 OR GREATER THAN C2 THE HYPOTHESIS THAT THE MEAN = 0 CANNOT BE REJECTED AT THE 95% CONFIDENCE LIMIT

STATE OF OREGON **INTEROFFICE MEMO**

Highway Construction 378-6318

TO: Jerry Wimer
Construction Operations Engineer

DATE: April 10, 1989

FROM: Tony Mandich
Construction Training Coordinator

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APR 10 1989
RESEARCH UNIT

SUBJECT: Draft Research Paper on Thin Layer Nuclear Density Gauge

The data in this report confirms the theory that we have been teaching in our compaction training classes. Although the gauge in the back scatter mode does read to a depth of about four inches, the underlying layer normally will have little or no affect on the density reading.

The reason for this is based on how the gauge itself operates. With most brands of gauges, approximately 67 percent of the reading is in the first 1. inches and approximately 85 percent is in the first two inches.

We can assume that the material (overlays) that we pave over came from the same general area as the new material, so specific gravities should be comparable. We can also assume, unless the old pavement is cracked or alligatored, that it will be a higher density from traffic - loading.

From this we deduced that if we have a good bond between pavement lifts our density readings should be reliable. If we pave over base aggregates or cement treated base the same should apply. Although there may be up to 10 pounds difference in densities, this would equate to only about 1. pounds in the density reading. Most gauges are rated at ± 1 pound accuracy.

The subject of core correlations has again come up, partly based on research on these four projects, and a paper written by Burati, Clemson University, and Elzoghbi, Stanford University.

Both these papers show the nuclear gauge to read lower than core densities. This we have found to be true. We also find the CPN gauge to read approximately one percent lower than the Troxler in back scatter. Since all our jobs are control strip method and we base all tests on one gauge used on the job, the problem of correlation of gauges does not exist.

The acceptance limits used with nuclear gauges were developed in the Construction Office using past core history and core correlation. As noted on the attached summary "Transportation Research Recording 1126" we have followed their recommendations. There is one very important item that both reports failed to investigate, delamination. Note paragraph two.

If the overlay is not bonded to the underlying layer, the nuclear gauge will read the void and compaction will fail. When a core is taken it might show a much higher density since the material is consolidated within its own mass.

Jim Huddleston has made a study of tensile strains for pavements with and without good bonding, see attached. In this study he has calculated the estimated life with good bonding at 2,000,000 loadings, without good bonding it drops to 6,000. Based on this report the gauge seems to be giving us a more accurate report of pavement quality.

In summary, the nuclear gauge as we use it is a more effective way of controlling compaction, and the speed in obtaining results gives us and the contractors time to make corrections before highway are built and the only correction that can be made is penalize the contractor.

TM:kjm

cc: Ken Husby

04072k