# Density Gradients in Asphalt Pavements

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## Synopsis

Asphalt pavement density measurements were made using a conventional nuclear density guage and a relatively new device utilizing a dialectric physics. Five sets of density tests were made at each of nine sites during, or immediately following, paving operations between July and September, 2004. Testing at each site attempted to capture differences in density caused by segregation under five distinct sets of circumstances. These included strip segregation along the centerline created by the auger gearbox of the paver, other visible segregation caused by practices such as truck emptying practices and paver hopper wing folding, transverse segregation caused by inherent design configurations of the paver including the slat conveyor system and screed extensions and stopping of the paver. Control sections were included where segregation was not visible during construction. Tests were conducted at random for each data set and replicated so that rigorous statistical analysis could be conducted. Results indicate that for the 'strip' and 'visible' data sets, an average decrease in density apparently occurs in the location of the segregation when all nine sites are included in the analysis. However, variability of the density data for all nine sites was very high. This variability is likely related to the differences in segregation occurring at each site. Also, a significant density gradient was measured in the transverse direction to paving and in the longitudinal direction when the paver stopped. Density gradients measured in the areas of segregation seem logical, but those measured in locations where segregation was not visible during construction indicate that either segregation is occurring beneath the surface of the pavement where it is not visible or that a lack of uniform density is occuring during paving operations.

This study evaluated the ability of the nuclear density meter and a dielectric measuring gauge to measure differences in density for areas of asphalt pavements with and without segregation. Nine projects were evaluated during the construction season of 2004 in Colorado, USA. Five different sets of data where segregation is known to occur or potentially occurs and two control sections were evaluated for each project. A minimum of five and up to eleven locations within each data set were measured.

The results of this work indicate the nuclear density gauge should be helpful for identifying potential segregation in asphalt pavements and that significant density differences exist in the insitu pavement after construction in areas where segregation is not apparent.

# Density Gradients in Asphalt Pavements

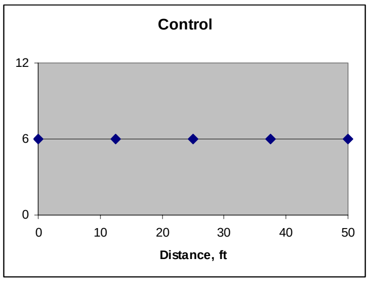
Specifications for controlling compaction of asphalt pavements often utilize random density tests to determine the level of compaction. This method of quality control and quality assurance assumes the new asphalt mixture being placed by the contractor is uniformly applied both transverse to the centerline and longitudinal to the centerline of the paving operation. Then, if random tests are made of the insitu density, and the paving process is being controlled properly, results of the tests should reflect this control. Conversely, if compaction is not being controlled properly, the random density tests should also reflect this. However, recent work by Willoughby, et al (2001) to measure temperature differentials during asphalt paving operations indicates that relatively large thermal gradients may exist behind the paver. These temperature gradients have been related to visible aggregate segregation and differences in density. The prevalence of these density gradients during paving operations was the basis of this study. If density gradients are prevalent during paving when obvious reasons such as segregation are not apparent, perhaps a change in the manner which compaction is evaluated is warranted. That is, identifying potential areas of density gradients in some non-random fashion, such as thermal imaging, so these locations are not overlooked by the owner during construction.

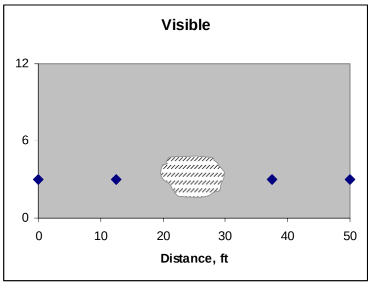
## EXPERIMENT DESIGN

Five groups of pavement density data were collected to determine if non-destructive density tests could be utilized to measure significant density differences in newly compacted asphalt pavements. Some areas evaluated had noticeable segregation, other areas did not. Two types of non-destructive tests were conducted. These included a conventional nuclear gauge and a relatively new device called the Pavement Quality Indicator (PQI) which utilizes the dielectric constant of a material to predict density. The five groups of density tests consisted of the following:

- **Strip** — density measurements conducted along a diagonal to the centerline of the paving lane where centerline segregation was observed
- **Visible** — density measurements conducted through the center of an area that was visibly segregated and not on the centerline of the pavement
- **Paver** — density measurements conducted across the width of the paving lane edge-to-edge transverse to the direction of paving where segregation was not observed
- **Stop** — density measurements taken parallel to the direction of paving before and after the paver temporarily stopped during paving
- **Control** — density measurements taken parallel to the direction of paving in an area apparently without segregation

These density groups are shown in Figure 1.



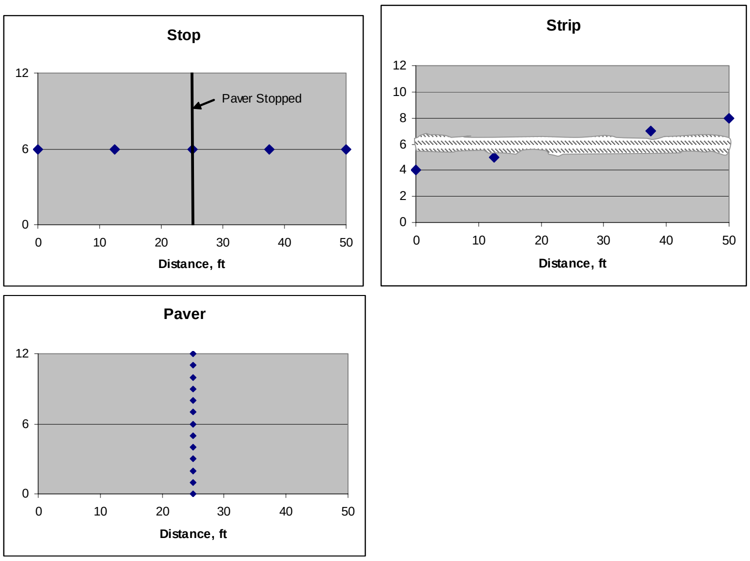



**Figure 1. Density Groups Evaluated**

Each point shown in Figure 1 was evaluated for insitu pavement density using the nuclear and PQI devices. Each device was operated by a separate technician. Testing was conducted by marking each location, then randomly evaluating density with the non-destructive devices. Two replicate density tests were conducted by each operator. Each replicate for the nuclear device consisted of taking two readings at each spot marked on the pavement. This consisted of a total of four readings to obtain an average of the two replicate density readings. Each replicate for the PQI device consisted of taking two sets of five readings at each spot marked on the pavement. This consisted of a total of twenty readings to obtain an average of the two replicate density readings. The resulting experiment can be analyzed by conventional analysis of variance (ANOVA) techniques to determine if a significant difference exists between the test locations evaluated for each density group. The model for the ANOVA is as follows:

$$y_{ij\cdot} = \mu + \tau_{i\cdot} + \varepsilon_{ij\cdot}$$

where,

| | |
|---|---|
| $y_{ij\cdot}$ | = density readings, pcf |
| $\mu$ | = the overall mean density, pcf |
| $\tau_{i\cdot}$ | = the effect of density gauge location on the pavement |
| $\varepsilon_{ij\cdot}$ | = the random error component |
| $i$ | = 1, 2, … *a* is the number of gauge locations being tested |
| $j$ | = 2, is the number of replicates |

## PROJECT LOCATIONS

Nine asphalt pavement construction sites were evaluated in this study. These sites are shown in Table 1 in the order they were constructed and tested.

**Table 1. Test Sites**

| No. | Project No. | Location | Contractor | Testing Date(s) |
|---|---|---|---|---|
| 1 | STA 0404-040 | Colfax-W Denver | PP | 7/8&9/04 |
| 2 | NH 0504-046 | US50 - Pueblo | L | 7/14/04 |
| 3 | STA 0853-051 | US85 - Greeley | L | 7/29/04 |
| 4 | NH 2873-123 | US287 - Loveland | C | 8/2/04 |
| 5 | STA 2571-008 | SH257 - Millikan | AI | 8/3/04 |
| 6 | STA 165A-010 | SH165 - Wrye | K | 9/1/04 |
| 7 | STA 009A-023 | SH9 - Kremmling | AS | 9/28 & 10/5/04 |
| 8 | STA 133A-028 | SH 133 - Paonia | E | 10/6 &10/12/04 |
| 9 | STU M055-016 | Colfax-E Aurora | B | 11/5/04 |

## MATERIALS

The grading of the asphalt concrete mixtures, Superpave gyratory compaction level, Superpave PG asphalt binder grade and percentage of asphalt by total mixture for each project are shown in Table 2.

**Table 2. Materials**

| No. | Location | Grading/ Compaction | Binder Grade | Binder, % |
|---|---|---|---|---|
| 1 | Colfax-Sheridan | S 100 | 76-28 | 5.1 |
| 2 | US50 | S 100 | 76-28 | 5.4 |
| 3 | US85 Bus | S 100 | 64-28 | 5.4 |
| 4 | US287 Loveland | S 100 | 64-28 | 5.2 |
| 5 | SH257 | S 75 | 64-28 | 5.2 |
| 6 | SH165 | S 75 | 58-28 | 5.8 |
| 7 | SH9 | SX 75 | 58-34 | 5.9 |
| 8 | SH 133 | SX 75 | 64-28 | 6.2 |
| 9 | Colfax –Peoria | S 100 | 64-22 | 5.4 |

## RESULTS

The relative density of the pavement for each of the five density data sets is presented below for the nuclear density gauge.

### Strip

The strip density data set was analyzed to determine the average difference between the density of the pavement in the center of the segregation at Test No. 3 and the density in adjacent areas of pavement where segregation should have been lower or non-existent. Analysis was conducted by evaluating the difference between the density at Test No. 3 and the average of the densities at Tests 2 and 4. The results shown in Figure 2 suggest that in the area of the centerline strip segregation the density is 1.6 pounds per cubic foot (pcf) less than the adjacent pavement. However, there is much variability in this data with a standard deviation of 1.9 pcf.

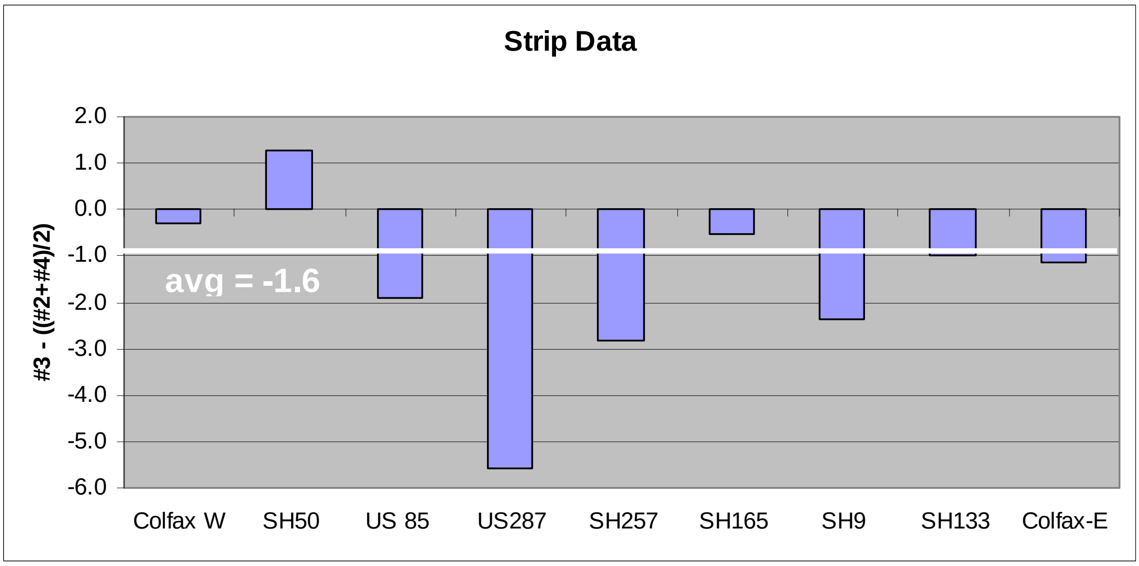



**Figure 2. Average of 'Strip' Density Data for All Sites**

## Visible

Visible density data sets were analyzed by comparing the density at Test No. 3, in the center of the visible segregation , to the highest density recorded in the data set. The average difference for all sites shown in Figure 3 is 3.4 pcf less at Test No. 3 than for the highest density recorded in the set of five tests. However, again, the variability between sites is high at 3.2 pcf.

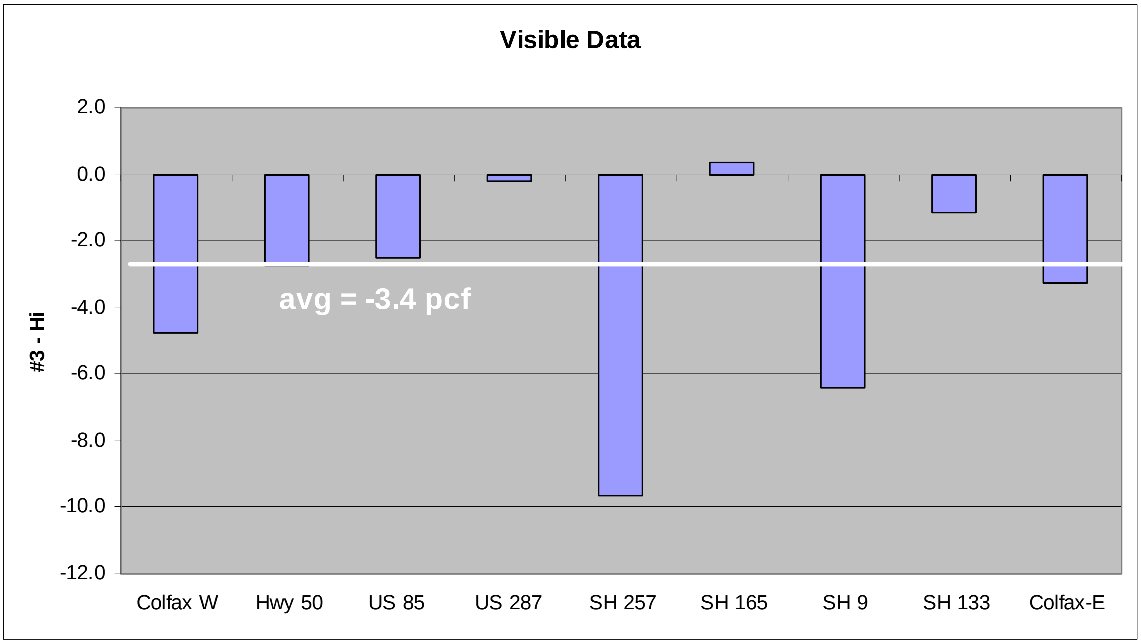



**Figure 3. Average of 'Visible' Density Data for All Sites**

## Control

The control density data sets were analyzed by comparing the difference in density of the lowest and highest density values for each site. The results shown in Figure 4 indicate the average difference for the control sections is 1.4 pcf with a standard deviation of 2.2 pcf.

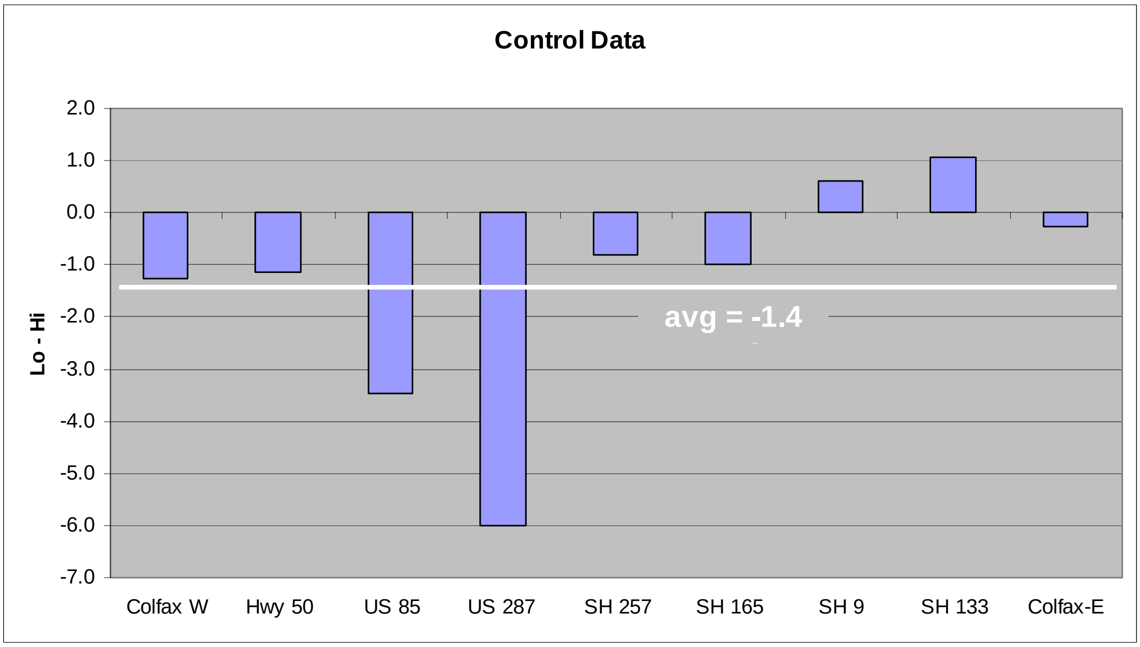



**Figure 4. Average of 'Control' Density Data for All Sites**

## Stop

The stop density data sets were evaluated by comparing the density of the pavement where the paver stopped to the highest density recorded for that set. The results shown in Figure 5 suggest that a 2.4 pcf difference exists for the average of all sites with a standard deviation of 1.8 pcf.

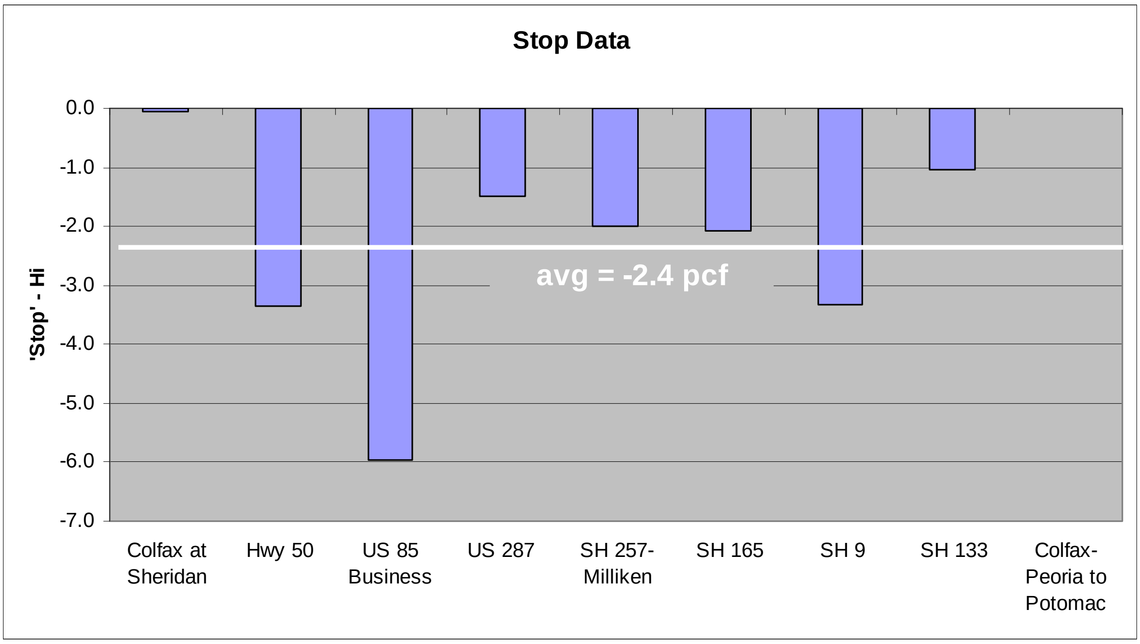



**Figure 5. Average of 'Stop' Density Data for All Sites**

## Paver

The paver density data sets were evaluated after removing a portion of the test results from the analysis. The tests removed prior to analysis were located 24 inches from the edge of the paver width. These tests were removed from the analysis because of noticeably lower densities within these zones, possibly due to an apparent difficulty in achieving compaction at the edge of the paving width. The results shown in Figure 6 indicate a differential of 5.4 pcf across the paving width with a standard deviation of 2.1 pcf.

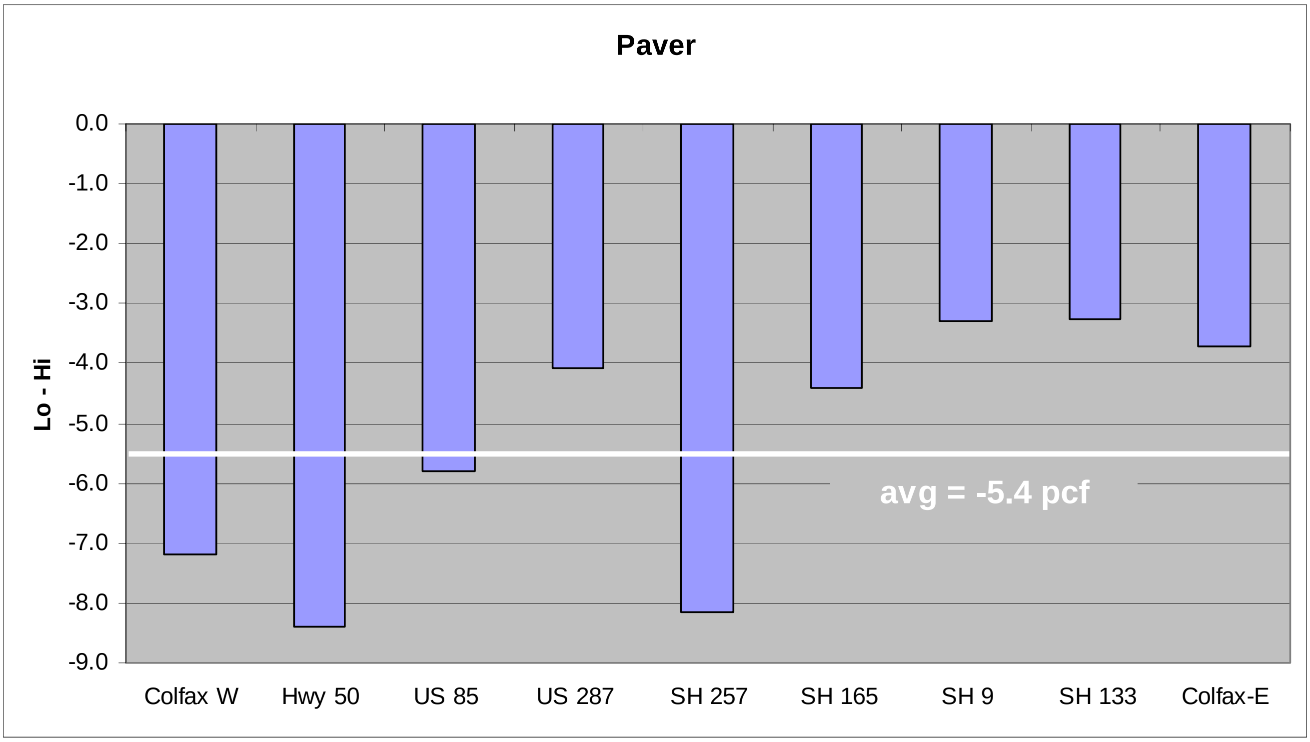



**Figure 6. Average of 'Paver' Density Data for All Sites**

The variability discussed above is likely due to variations in conditions between sites such as testing error, materials, moisture content, construction methods and segregation. Therefore, an analysis of variance (ANOVA) was conducted on each site for each density data set collected. The results are summarized in Table 4. The ANOVA was performed at an $\alpha$ level of 0.05. The results in Table 4 indicate whether a difference at the $\alpha = 0.05$ level exists for density values taken at the different gauge positions for each density data set. For example, there are five gauge positions for the 'strip' data set. If there is not a significant difference in mean density values for these five gauge positions at $\alpha = 0.05$, a notation of 'No' is shown in Table 4. This does not necessarily mean that there was no segregation, just that statistically, there is no difference between the density values recorded at the five gauge positions.

The 'paver' ANOVA was conducted without using the three gauge readings at the edges of the paver width since there tended to be a significant reduction in density in these regions.

**Table 4. Summary of ANOVA for Each Project**

| | Density Data Set | | | | |
|---|---|---|---|---|---|
| **Project** | **Strip** | **Visible** | **Stop** | **Paver** | **Control** |
| Colfax-Sheridan | Yes | Yes | Yes | Yes | Barely |
| SH 50 | Yes | Yes | Yes | Yes | No |
| US 85 Bus | Yes | Yes | Yes | Yes | Yes |
| US 287 | Yes | No | No | Yes | Yes |
| SH 257 | Yes | Yes | Yes | Yes | No |
| SH 165 | Yes | No | Yes | Yes | No |
| SH 9 | Yes | Yes | No | Yes | Yes |
| SH 133 | Yes | No | Yes | Yes | No |
| Colfax-Peoria | No | No | NA | Yes | No |

* 'Yes' = Statistically significant at $\alpha$=0.05

To determine what the difference in density would be for segregated areas compared with non-segregated areas, the density in the No. 3 position for the 'strip' and 'visible' locations was compared with the average of the 'control' density for projects where the ANOVA measured significance for the 'strip' and 'visible' tests and the 'control' measured not significant. The results of this analysis is shown in Table 5.

**Table 5. Density Differences for Statistically Significant Sites**

| **Project** | **Strip** | **Visible** | **Control** | **Strip-Control** | **Visible-Control** |
|---|---|---|---|---|---|
| SH 50 | 141.9 | 140.1 | 140.1 | +1.8 | 0 |
| SH 257 | 137.2 | 130.3 | 140.0 | -2.8 | -9.7 |
| SH 165 | 142.0 | No | 141.8 | +0.2 | na |
| SH 133 | 140.4 | No | 143.0 | -2.6 | na |

* Light shading = statistically significant at $\alpha$=0.05. Dark = no significant difference in readings

Table 5 indicates that for SH 50, the density on the centerline of the paver is 1.8 pcf higher than the control section and the area of visible segregation has equal density to the control. The density in the area of the strip segregation on SH 165 is 0.2 pcf higher than the control. However, the strip segregation density on SH 257 is 2.8 pcf lower than the control and in the area of the visible segregation the density is 9.7 pcf lower than the control. S

H 133 has 2.6 pcf lower density in the area of the strip segregation than the control.

## Comparison of Nuclear and PQI Density Tests

Each of the five density data sets evaluated with the nuclear density gauge were also evaluated using the PQI density gauge. Reading were taken at random in the same location on the pavement as the nuclear gauge. A set of five readings were taken with the PQI gauge and the average recorded. A second set of five readings was taken and averaged producing the second replicate. The results of the average of the two replicates is presented below and compared with the nuclear density data. The PQI density gauge generally was less sensitive to changes in the asphalt pavement density than the nuclear gauge. Each of the density sets is presented in the next section.

### Strip

Except for projects SH133 and Colfax E there appears to be little correlation between the nuclear density tests and the PQI tests as shown in Figure 7 for the average values of the differences in density between gauge position #3 and the average of gauge postions #2 and #4. The regression analysis shown in Figure 8 confirms this.

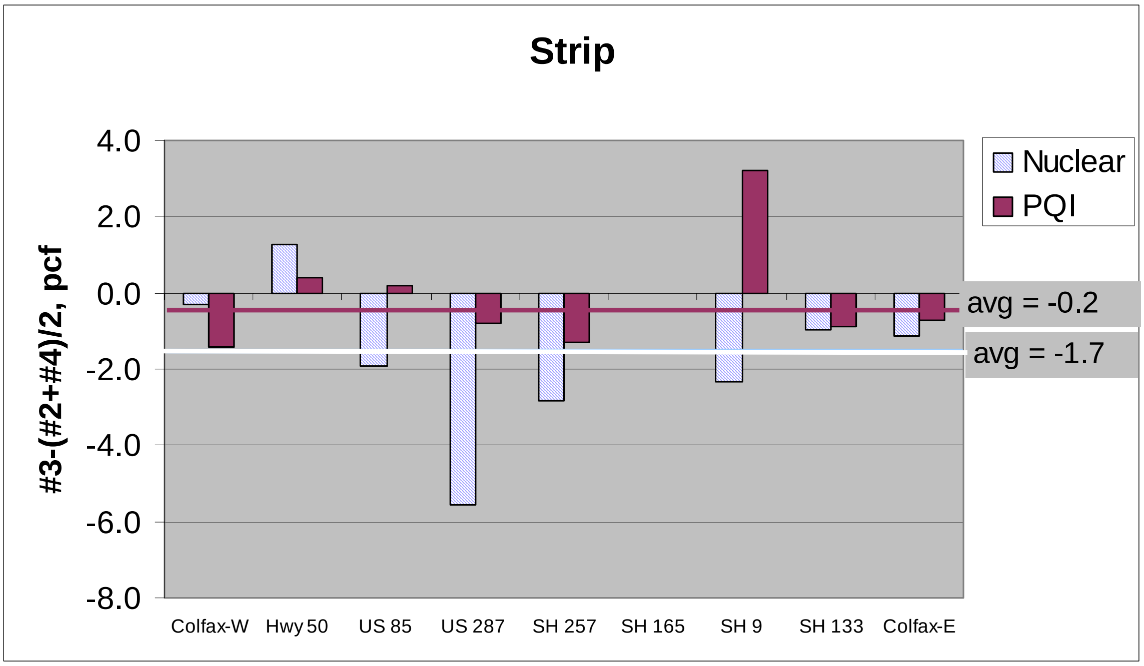



Figure 7- Nuclear and PQI Density Comparison for 'Strip' Data

### Visible

Except for US287 there appears to be little correlation between the nuclear density tests and the PQI tests as shown in Figure 9 for the average values of the differences in density between gauge position #3 and the highest average density reading. The regression analysis shown in Figure 10 also confirms this.

### Control

The control density data sets were analyzed by comparing the difference in density of the lowest and highest density values for each site. Except for SH133 there appears to be little correlation between the nuclear density tests and the PQI tests as shown in Figure 11 for the average values of the differences in density between the lowest density and the highest density readings. The regression analysis shown in Figure 12 also confirms this.

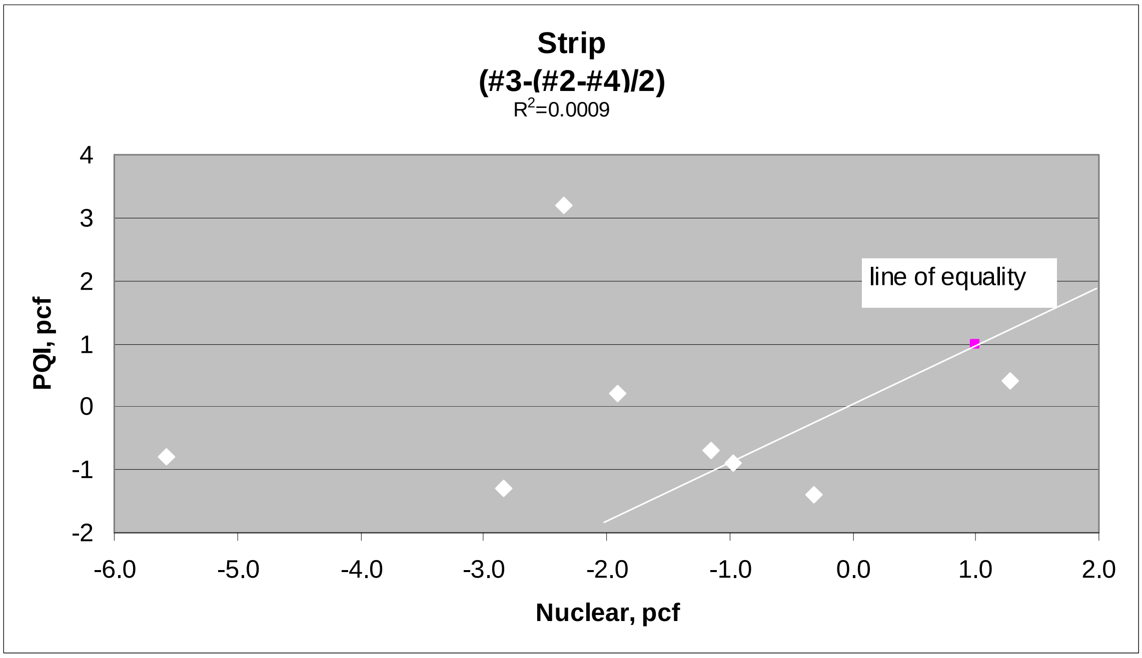



Figure 8 – Regression Analysis of Nuclear and PQI 'Strip' Data

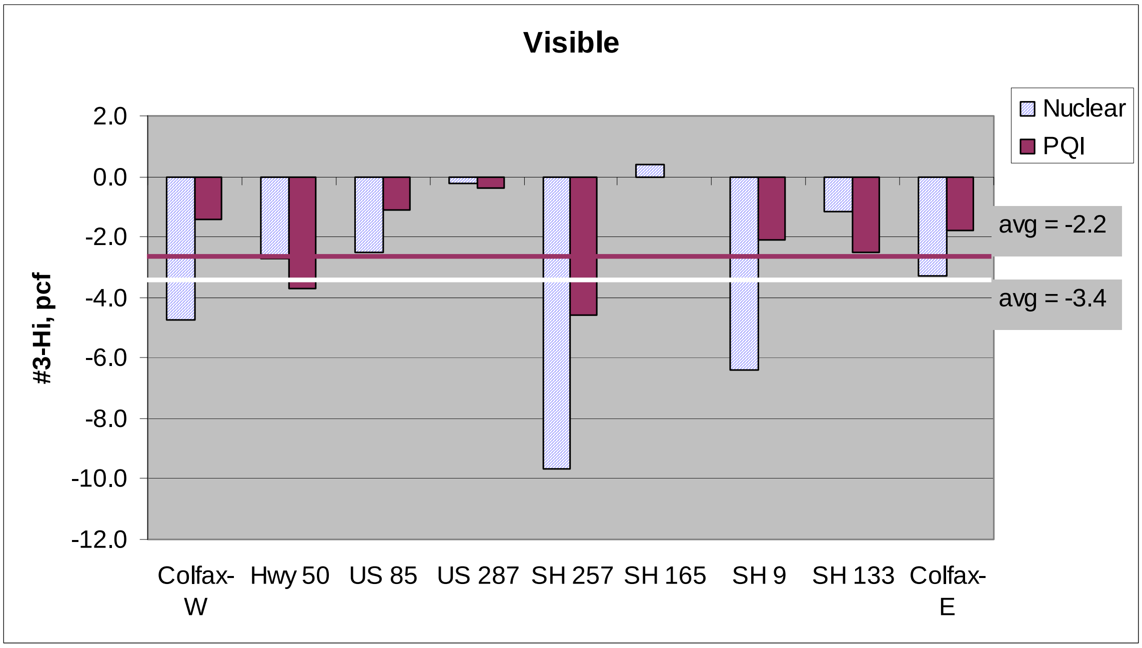



Figure 9- Nuclear and PQI Density Comparison for 'Visible' Data

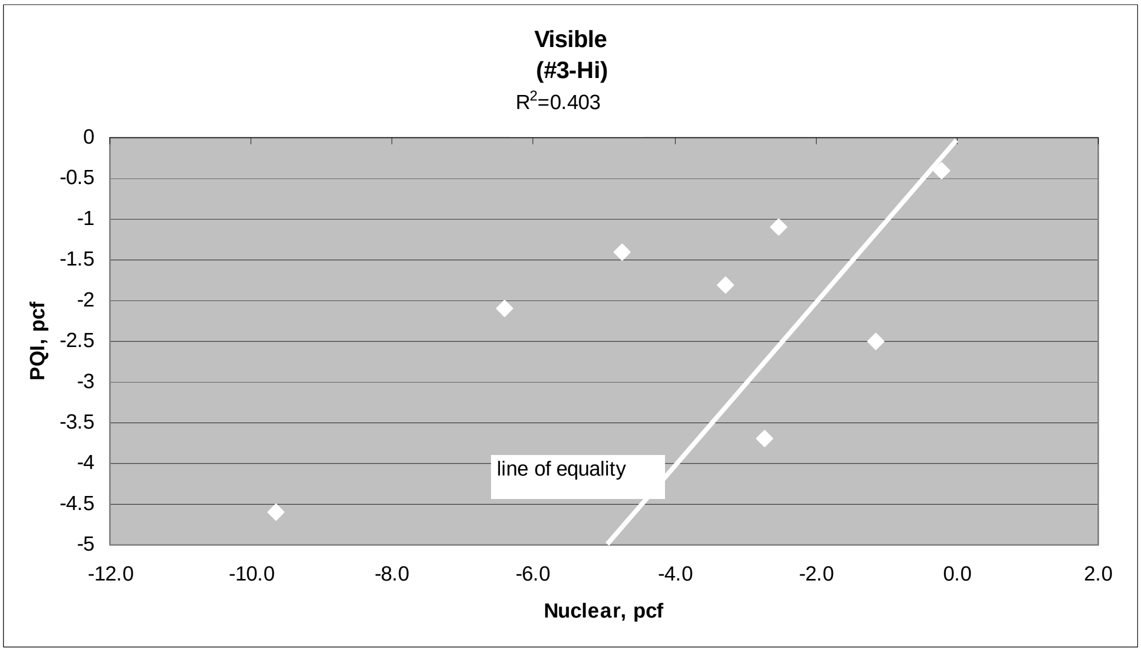



Figure 10 – Regression Analysis of Nuclear and PQI 'Visible' Data

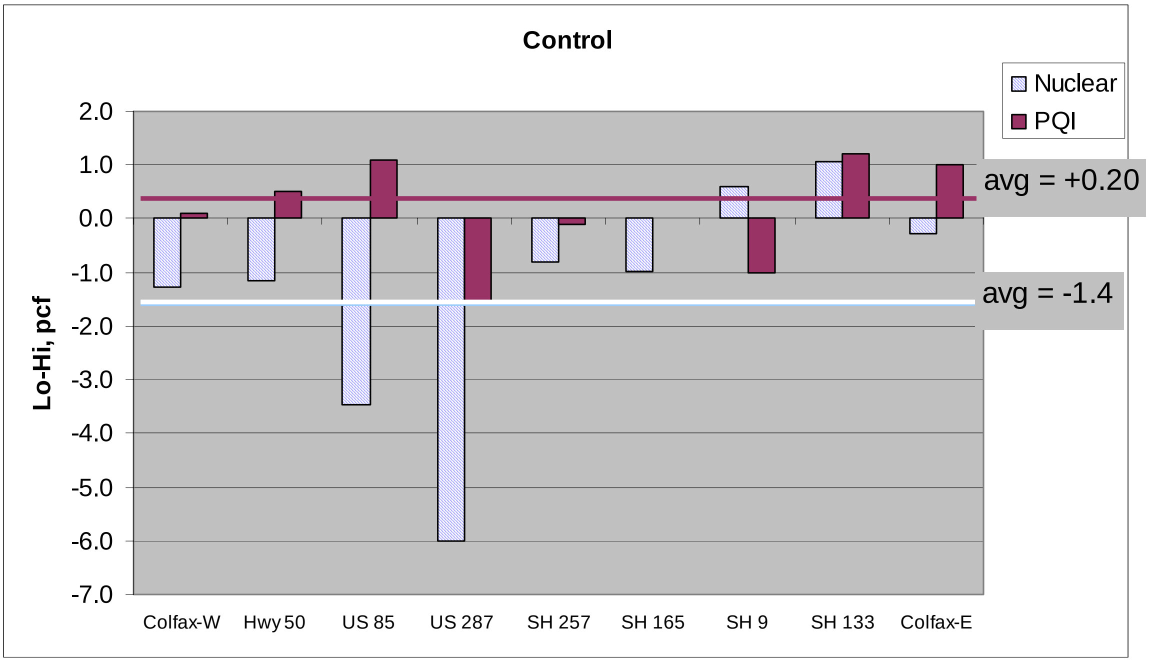



Figure 11- Nuclear and PQI Density Comparison for 'Control' Data

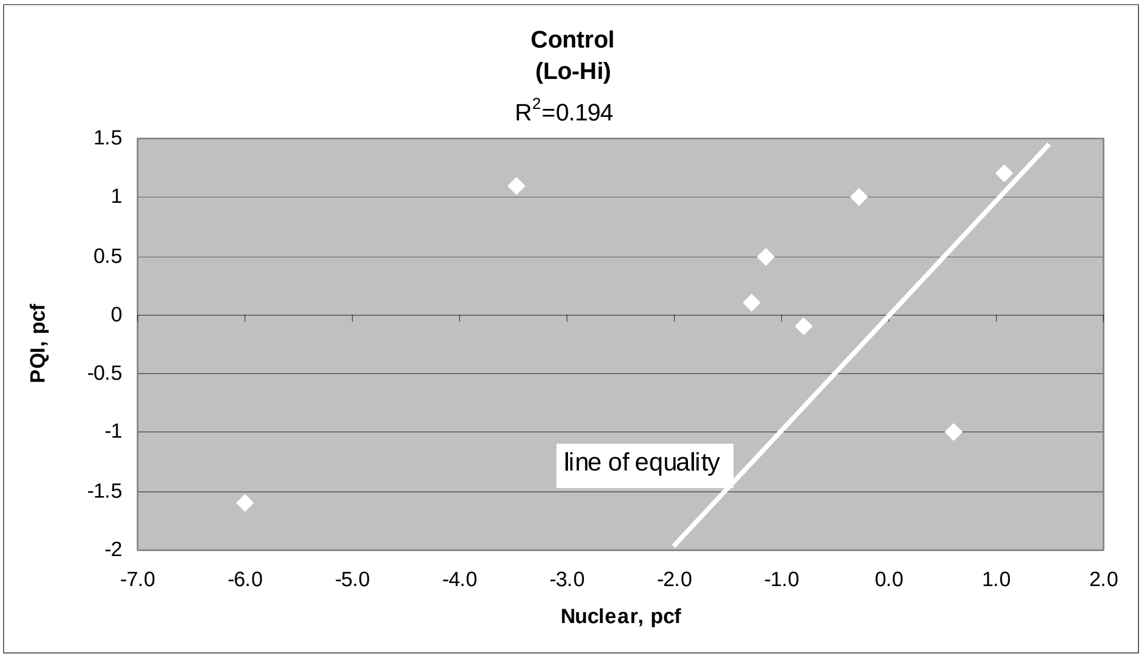



Figure 12 – Regression Analysis of Nuclear and PQI 'Control' Data

## Stop

The stop density data sets were evaluated by comparing the density of the pavement where the paver stopped to the highest density recorded for that set of density readings. In this case, there appears to be reasonably good correlation between the nuclear test results and the PQI readings as shown in Figure 13. The regression analysis shown in Figure 14 indicates a good correlation between the two sets of data.

## Paver

The paver density data sets were evaluated after removing a portion of the test results from the analysis. The tests removed prior to analysis were located 24 inches from the edge of the paver width. These tests were removed from the analysis because of noticeably lower densities within these zones, possibly due to an apparent difficulty in achieving compaction at the edge of the paving width. Results shown in Figure 15 indicate reasonable agreement between nuclear and PQI for some sites and poor agreement for other sites. The regression analysis in Figure 16 indicates a poor correlation between the two density testing devices.

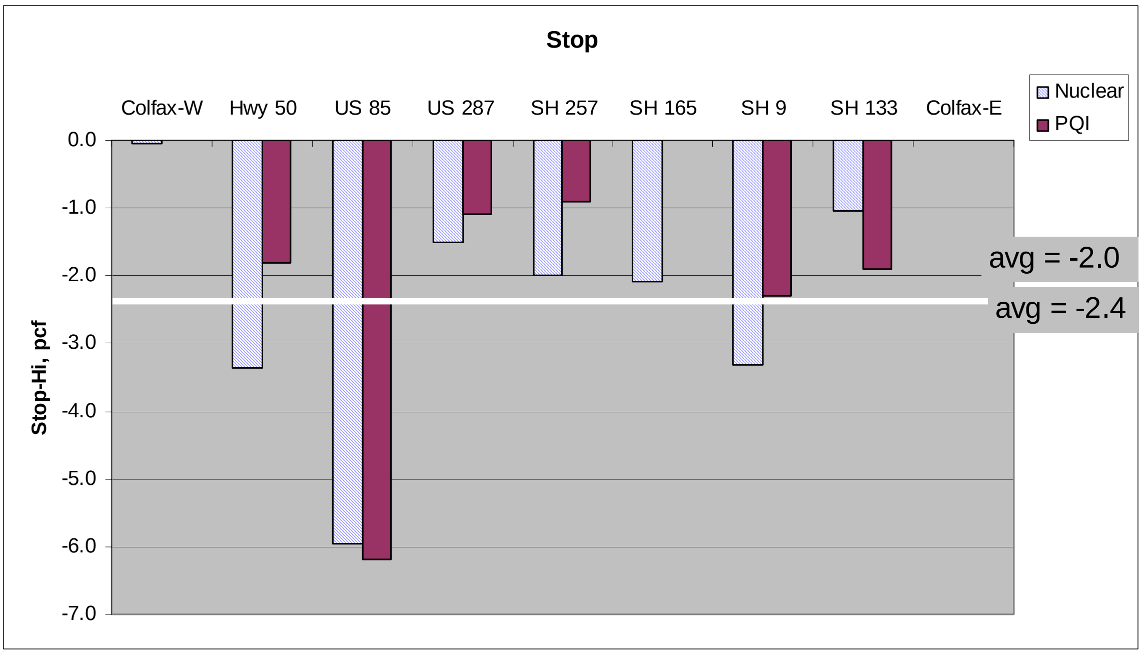


Figure 13- Nuclear and PQI Density Comparison for ‘Stop’ Data

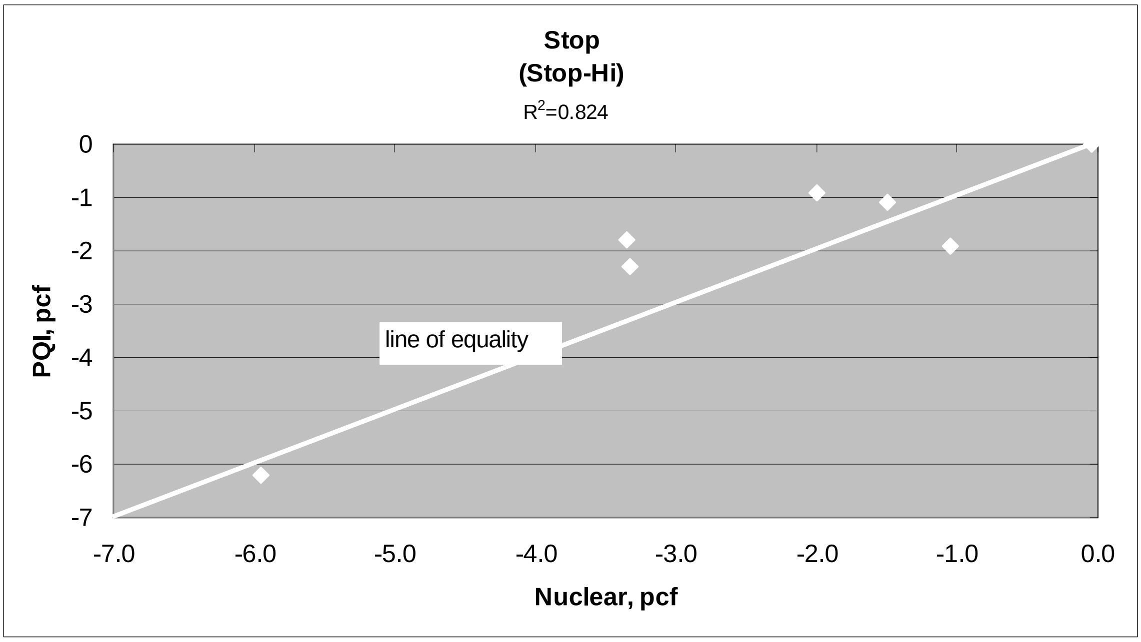



Figure 14 – Regression Analysis of Nuclear and PQI ‘Stop’ Data

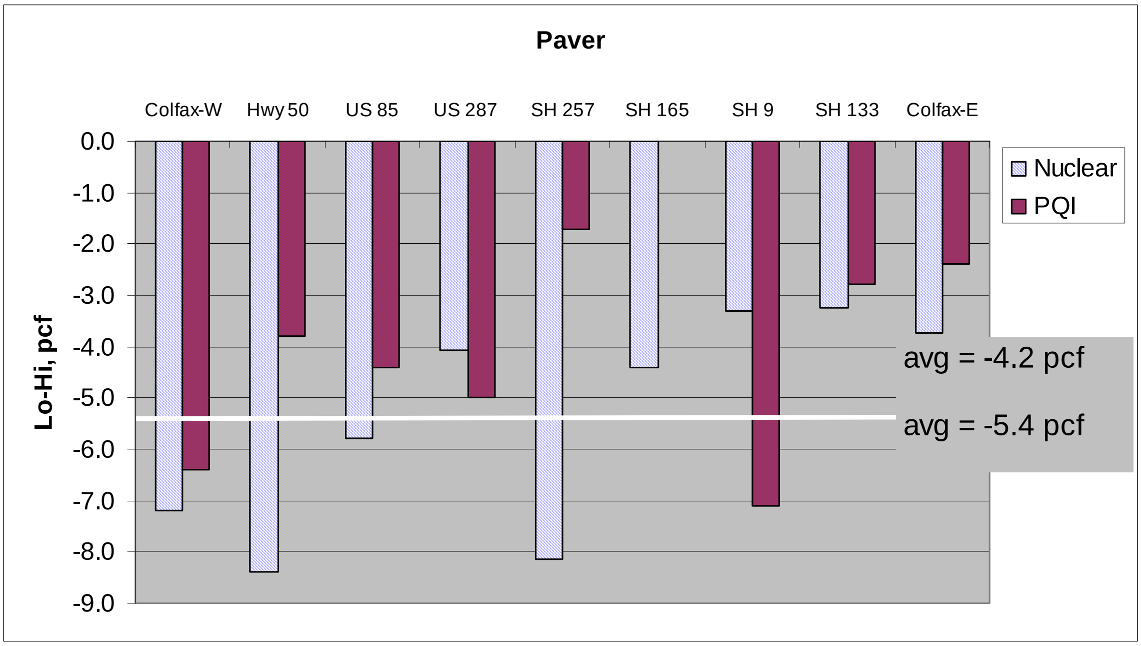



Figure 15- Nuclear and PQI Density Comparison for ‘Paver’ Data

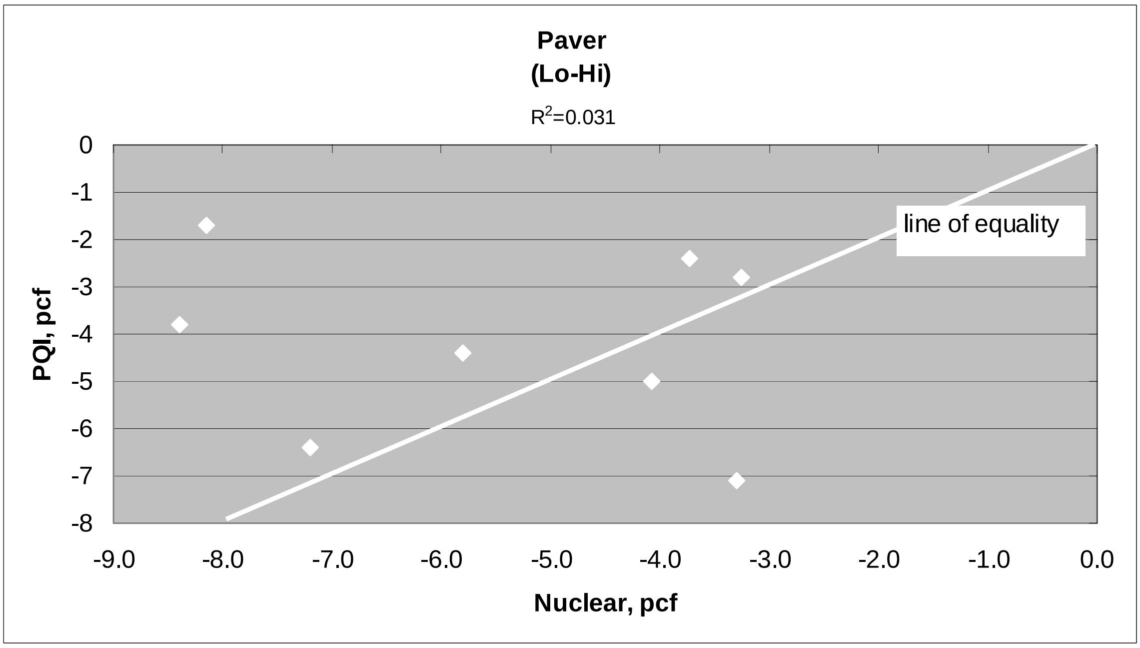



Figure 16 – Regression Analysis of Nuclear and PQI 'Paver' Data

## CONCLUSIONS

1. Significant variation in density occurs during asphalt paving which may not be detected by conventional random quality control and quality assurance techniques.

2. A statistically significant difference in density was measured at nine construction projects for the transverse 'Paver' density sets. The average difference in density was 5.4 pcf or approximately 3.8% of the pavement maximum unit weight.

3. A statistically significant difference in density was measured at eight of nine sites for the 'Strip' density sets. The average difference in density was 1.7 pcf or approximately 1.1% of the pavement maximum unit weight.

4. A statistically significant difference in density was measured at five of nine sites for the 'Visible' density sets. The average difference in density was 5.2 pcf or approximately 3.7% of the pavement maximum unit weight.

5. A correlation between the nuclear density gauge and the PQI gauge was not apparent for the 'strip', 'visible', 'control' or 'paver' data sets. A relatively good relationship ($R^2 = 0.82$) was observed for the 'stop' data set.

6. The large variability in density recorded for areas of pavement which did not have apparent segregation present ('paver' data set) suggests a more comprehensive method should be considered for measuring insitu asphalt compaction in the future since it is possible these areas of reduced density could contribute to decreased pavement performance.

## REFERENCES

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Willoughby, Kim A., Mahoney, Joe P., Pierce, Linda M., Uhlmeyer, Jeff S., Anderson, Keith W., Read, Steven A., Muench, Stephen T., Thompson, Travis R., and Moore, Robyn, “Construction-Related Asphalt Concrete Pavement Temperature Differentials and the Corresponding Density Differentials”, Washington State DOT, Report No. WA-RD 476.1, July 2001.