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Framework of Non-Nuclear Methods Evaluation for Soil QC and QA in Highway Pavement Construction

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Abstract: This study introduces a methodology to evaluate different types of non-nuclear technologies to see how they are competitive to the nuclear technology for quality control (QC) and quality assurance (QA) in soil condition measurement for highway pavement construction. The non-nuclear methods including the Electrical Density Gauge (EDG) and the Light Weight Deflectometer (LWD) were tested for their performance against a nuclear gauge, and traditional methods were used as baselines. An innovative way of comparing a deflection gauge to a density gauge was introduced. Results showed that the nuclear gauge generally outperformed the non-nuclear gauge in accuracies of soil density and moisture content measurements. Finally, a framework was developed as a guideline for evaluating various types of non-nuclear soil gauges. From other perspectives rather than accuracy, it was concluded that the non-nuclear gauges would be better alternative to the nuclear gauge when the followings are considered: (1) greater life-cycle cost savings; (2) elimination of intense federal regulations and safety/security concerns; and (3) elimination of licensing and intense training.

Keywords: Soil compaction, highway construction, nuclear gauge, non-nuclear gauge, density test, moisture content test, quality control, quality assurance

I. INTRODUCTION

The quality of pavement foundation is affected by the properties of its sub-grade and compaction conditions [1, 2]. To ensure appropriate backfill, soil is compacted to achieve its minimum required physical properties. The foundation materials are therefore usually compacted at different moisture conditions to identify moisture and density maximum values [3, 4] that will be used later for quality assurance (QA). For those reasons, density and moisture content are the common factors used to evaluate soil compaction. The density in-place or in-situ density is the general and traditional method used for QA. A portable nuclear gauge can also measure in-place soil density and moisture content [3] which can be compared to the soil's maximum dry density and optimum moisture content for quality control (QC) and QA purposes.

With nuclear gauges, come many advantages and disadvantages. The nuclear gauge technology has been used successfully to replace and/or complement traditional methods in many U.S. states due to its portability, simplicity of operation, and fairly high accuracy. However, the nuclear gauge operates with the use of radioactive materials that may be hazardous to the health and well-being of the operators. Therefore, proper precautions and care need to be taken during operation. All users must have received radiation safety training and be aware of the applicable safety procedures and regulations. The use of dosimeters or film badges is also required for personal monitoring during use. Along with operation guidelines, routine procedures such as source leak tests and annual calibration are either required or recommended to properly maintain the gauges. Strict licensing and re-licensing, record-keeping, and storage of the gauges are all added to the complications of nuclear gauge technology. Finally, transporting radioactive materials also requires complicated safety rules and regulations. Consequently, there is a high demand for a device that is accurate, easy to use, quick, non-destructive, and nonradioactive. It seems that non-nuclear gauges can overcome all the problems caused by the nuclear gauge if they produce the acceptable level of accuracy.

Other traditional means of obtaining in situ density are the Standard Test Method for Density and Unit Weight of Soil In-Place by the Sand-Cone Method [3], the Standard Test Method for Density and Unit Weight of Soil In-Place by the Rubber Balloon Method [3], or Standard Test Method for Density of Soil In-Place by the Drive-Cylinder Method [3]. When these lengthy and destructive traditional methods are combined with the high costs, intense regulations, and safety concerns (to just name few problems with nuclear gauges), non-nuclear technology standardization for QA and QC seems logical.

Thus, it is a timely topic to study the efficiency of these non-nuclear devices whether they can resolve the aforementioned issues of nuclear and traditional methods. However, no study has tested the various non-nuclear technologies compared to the nuclear technology in soil density and moisture measurements yet although there has been very active research among several researchers testing the non-nuclear methods compared to the nuclear method for QC and QA of hot mix asphalt (HMA) during paving construction[14,15,16,17,18].

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II. Research Objectives

The main goal of this study was to test a hypothesis that the non-nuclear method can be used as a test modality to assess in-place soil compaction QC and QA for highway pavement construction. As a step towards this goal, the objectives of this research were:

(1) To find the most effective method among available technologies to assess soil compaction through intensive and extensive field and lab tests,
(2) To identify a method to accurately compare soil density to soil stiffness,
(3) To compare costs associated with ownership and operation between the nuclear method and the non-nuclear methods, and
(4) To develop a framework as a guideline for testing performance of various non-nuclear technologies.

This study attempts to evaluate the effectiveness of non-nuclear gauges in terms of accuracy in density and moisture measurements, user-friendliness, licensing and regulations requirements, ownership and operation cost associated with their use. Concurrently, a nuclear gauge test and a series of standard traditional tests were all performed for comparison.

III. Methodology for Gauge Performance Tests

To accomplish the objective of assessing soil compaction, a comparison study of usability and performance was conducted between a nuclear gauge (Troxler 3440) and two non-nuclear gauge alternatives [5], including the Electrical Density Gauge (EDG) and the Light Weight Deflectometer (LWD). The EDG was tested for in-place moisture and density. The LWD, a stiffness-strength based criterion for evaluating QA and QC of a material, was also tested. The nuclear gauge was utilized to measure the in-situ dry density and moisture content. Finally, the previously mentioned measurements were all compared to a standard, the field dry unit weight measurement, as a baseline. It was determined by taking a sample representative of each measurement area either with a Shelby tube or other method for lab testing [6, 7]. More details of each testing method used in this study are as follows:

A. Drive-Cylinder Method

The Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method [3] involves obtaining a relatively undisturbed soil sample by driving a cylinder open at both ends in the ground (Figure 1). Once flush, the material around the cylinder is then excavated. With the empty volume of the cylinder already known, the unit weight of the soil in the cylinder can then be calculated in the lab. While in the lab, the sample of the soil can be dried to provide a dry density of the material. This method was preferred over the sand cone test [3] which consists of determining the in-place density and unit weight of soils using a sand cone apparatus. However, the sand cone test yielded inconsistency of density results (poor repeatability). Similar to the sand cone method, the rubber balloon method [3] consists of excavating a sample of soil and measuring the volume of the hole dug out with a rubber-balloon apparatus. This method also provided inconsistent results depending on operators and pressure applied to the apparatuses while filling the holes. A higher force applied on apparatuses showed a greater displacement. Based on the tested poor repeatability in data readings by the sand cone method and the rubber balloon method, the research team adopted the density-drive cylinder as a standard to measure in-place density in this study.

FIGURE I
SHELBY TUBE DRIVEN IN THE GROUND

B. Water Content of Soil by Oven Dry method

While the previously mentioned methods only determine in-place density, soil bulk density is determined by weight of the soil per unit volume that is found by using an oven maintained at a temperature between 105°C and 115°C. This method [3] consists of drying a wet sample of soil in the oven for about 24 hours, and determining the weight of moisture. This method was used as the standard and baseline of comparison for moisture content measurement.

C. Nuclear Method

The nuclear gauges emit gamma rays to measure density and moisture content. Measurements were done according to ASTM D6938-10 [3], Standard Test Method for In-Place Density and Water Content of Soil and Soil Aggregate in Place by Nuclear Methods. Unlike the HMA pavement measurement, the gauge probe needs to be driven into the ground to take measurements at 4, 6, and 8 inches. Thus, it is required to carefully clean gauge's internal parts after using on soil. Figure 2 shows a nuclear gauge taking soil density and moisture content measurements.

FIGURE II
NUCLEAR GAUGE TAKING SOIL MEASUREMENTS

D. The Electric Density Gauge (EDG)

The EDG measures the electrical dielectric properties, along with moisture levels of the material's compacted soil to determine its density and moisture content. The EDG does so by measuring the radio-frequency current between four darts driven in the ground, as shown in Figure 3. In order to measure the in-place physical properties of the soil, a soil model or calibration process needs to have taken place in the lab. A sample representative of the soil to be tested needs to be excavated and tested in the lab with the EDG at different moisture and compaction levels. ASTM D7698-11 [3] was applied for the EDG testing. A minimum of three lab tests are recommended by EDG's manufacturer to have a good soil fit. A total of nine lab tests to develop soil models were conducted.

FIGURE III
DARTS DRIVEN INTO GROUND FOR EDG TEST

E. The Light Weight Deflectometer (LWD)

The LWD shown in Figure 4 measures a surface deflection as a result of applying an impulse load to it by using ASTM E2583-07, the Standard Test Method for Measuring Deflections with an LWD [3]. The LWD consists of a light mass, an accelerometer and a data collection unit [8, 9]. Starting in 2005, the LWD has been used by the Minnesota DOT as an acceptance method for the compaction of roadbed and miscellaneous embankment.

FIGURE IV
MEASURING STIFFNESS OF THE SOIL WITH THE LWD

Because the LWD measures the deflection and modulus of elasticity of the soil, there was no direct relationship or method to compare its measurements with the other gauges being tested in this study (i.e, strain vs. density). The research team therefore adapted the QA procedure developed by the Minnesota DOT [8] along with their specifications for excavation and embankment [10] to determine whether a soil area has been properly compacted. Based on the developed pass/fail criterion, comparisons could then be made with other gauges. More details about this new proposed methodology are discussed in the analysis section.

F. Test Procedures

Two sites composed of brown dirt and peorian loess soils were tested for this research. The team first collected representative samples from each site to develop soil curves by the EDG and the Standard Proctor Method. The results were then used to calibrate the nuclear gauge, and determine in-place measurements for the EDG. Once a spot was selected, all gauges were operated and their variables recorded at the site. The different densities and moisture contents of the EDG and nuclear gauge were then compared against the standard baselines of measurement methods mentioned above. Next, a pass/fail analysis of all the methods was developed referencing the Standard Specifications for Construction in Nebraska Department of Roads (NDOR) [11]. This analysis would give a better idea of what method correlates most closely with the LWD. For better accuracy, other important analyses were conducted to compare the gauges' performance, which will be discussed in the following section.

IV. Data Analysis

A. Outliers

An outlier is an observation that lies outside the overall pattern of a data distribution [19]. In this study, data was considered an outlier when the difference between the standard density and moisture was considerably greater or lower than the gauges' data - that is, a standard deviation plus or minus 3. Due to external variables inherent to the field data collection, erroneous data could be obtained caused by poor soil samples, human's measurement reading error, equipment calibration error, etc. Total four outliers were identified and removed from the data pool in order to better analyze soil measurements; one from the density measurements and three from the moisture content measurements.

B. Regression analysis

To observe a linear relationship between the gauges and the standard measure, the whole pool of data were analyzed after removing the outliers. The nuclear gauge correlated better with the standard measurement than the EDG in both the density and moisture readings as shown in Figures 5 and 6. This could be due to the fact that the initial nuclear gauge data had been corrected using the density and moisture corrections factors, as required by the state DOT's new Standard Test Method for Nuclear Density Testing for Soils [12]. Currently there is no method available that allows for ways to improve and correct the EDG's initial data.

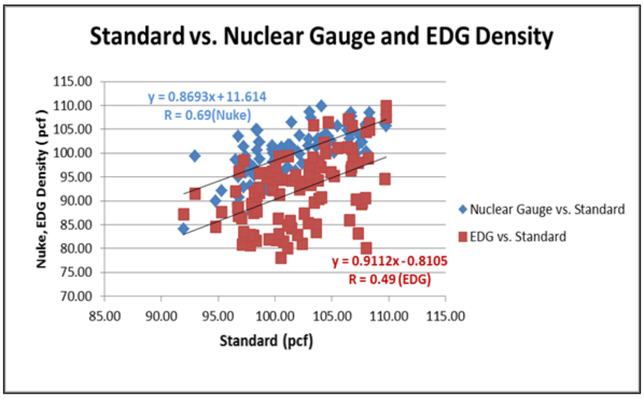

FIGURE V
STANDARD VS. NUCLEAR GAUGE AND EDG DENSITY (PCF)

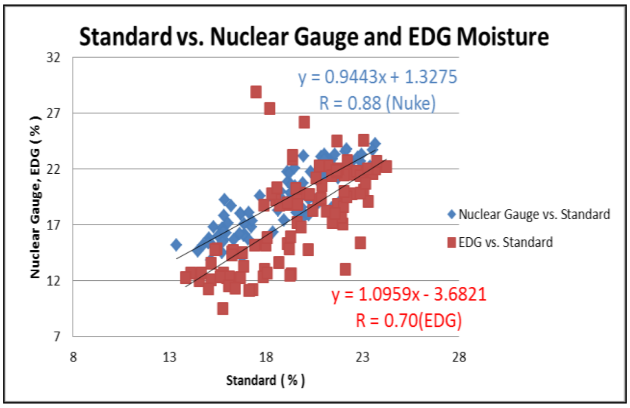

FIGURE VI
STANDARD VS. NUCLEAR GAUGE AND EDG MOISTURES (%)

C. Average Difference and Error of Standard Deviation

To determine how both gauges vary within the lab data, standard deviations (STDV) of measurement errors were analyzed for density (Figure 7) and moisture contents (Figure 8). Also, the average differences of data readings between the standard and the two gauges were measured (Table 1). The average measurement differences were 1.71 pcf (=27.36 kg/m3) for the nuclear gauge's density data and 0.22% for moisture content compared to 9.86 pcf (=157.76 kg/m3) and 1.66% for the EDG's density and moisture content respectively. There were high variations among the EDG data. This could be due to the fact that the soil model range built based on the soil properties at the two test sites might be too wide for the EDG.

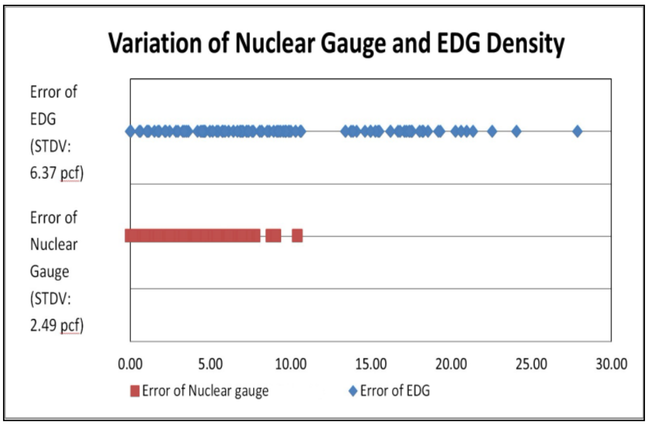

FIGURE VII
VARIATION OF NUCLEAR GAUGE AND EDG DENSITY (PCF)

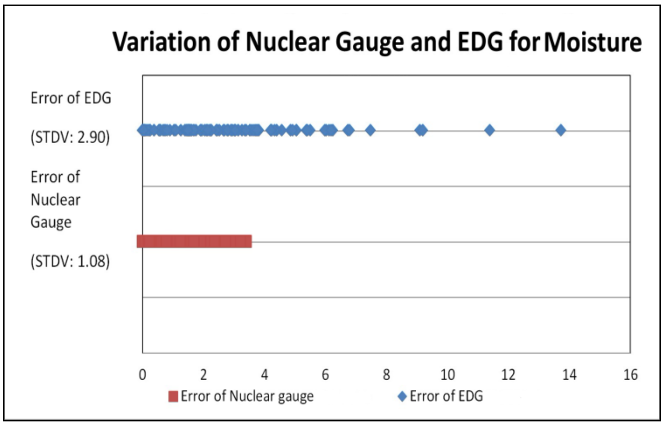

FIGURE VIII
VARIATION OF NUCLEAR GAUGE AND EDG MOISTURE CONTENT (%)

D. Site by Site Analysis

Coefficient of correlations and standard deviation of errors were analyzed with the data derived from each site. As shown in Tables 2 and 3, the analysis results showed that the nuclear gauge had a higher correlation and less variation in both the density and moisture than the EDG regardless of the site. However, it should be noted that the correlation of the nuclear gauge in density measurement was not consistent between the sites.

TABLE I
AVERAGE DIFFERENCES OF MEASUREMENTS BETWEEN THE STANDARD AND THE GAUGES (1lb/ft3 (pcf) = 16 kg/m3)

	Density (pcf)		Moisture Contents (%)	
	Nuclear Gauge	EDG	Nuclear Gauge	EDG
Average Difference	1.71	9.86	0.22	1.66

E. 95% Interval Analysis

To meet the compaction requirements, a test is deemed passed or failed when the measured density is within 95% of the maximum density determined by the soil curve, and also within the moisture content requirements [11]. Different scenarios were analyzed to view the trends among the methods of measurements (standard, EDG, and nuclear gauge).

The first scenario was how the nuclear gauge and the EDG performed when the standard passed the 95% density requirement. The second and third scenarios looked at how the other gauges would perform when the nuclear gauge or the EDG each passed the 95% requirement. It can be observed that when the standard passed the 95% test, the nuclear gauge had a higher correlation with the standard, thus very likely to pass the test as well (Figure 9). When the nuclear gauge passed the requirement, the correlations of the other methods of measurement were lower (Figure 10). Especially, both the standard and the EDG did not follow the "pass" test of the nuclear gauge. Figure 11 shows the similar results for both the standard and the nuclear gauge when the EDG passed the 95% interval. This analysis confirmed that the standard method identified as a baseline was the best to see the trends when using the 95% test. The nuclear gauge also showed a better correlation with the standard using the 95% compaction requirement.

F. Test Status Analysis

Random measurements were taken at various spots to compare all gauges, including the LWD. In this study, some measurements were deliberately taken at the areas that were not previously compacted; therefore, some measurement spots would fail the quality assurance test. As briefly mentioned earlier, there was a difficulty to compare the LWD with the other density methods because the LWD, which measures soil deflection and elastic modulus, could not be directly compared to the density of the nuclear gauge and the EDG. For this reason, the research team adapted the excavation and embankment specification method [13] to know when the LWD passed or failed the test. A pass or fail test status comparison was uniquely developed in this study to view the relationship of each gauge with the standard. In this analysis, the previously mentioned 95% of the maximum density determined by the soil was used again to compare between density (nuclear and non-nuclear gauges) and strain (LWD) based on the proposed pass and fail status. The hypothesis of this test was that a successful relationship would be one in which a gauge would pass when the standard passes, and would fail when the standard fails.

Table 4 summarizes the test status comparison. Here, the percentage indicates how well other gauge's fail and pass status is matched to the standard's pass and fail status for each measurement. As results, the nuclear gauge at Site 1 and the LWD at Site 2 had better agreement with the standard method using the proposed pass or fail method. It should be noted that when the nuclear gauge's initial data was not adjusted by the correction factor, its test status relationship was only 63%, which is closer to the LWD.

V. ECONOMIC ANALYSIS

A. Life Cycle Costs

Various techniques can be used to predict and analyze how much equipment would cost over time. A lifecycle cost analysis considers all the costs associated with owning, operating, and maintaining equipment for the duration of its useful life.

TABLE II
NUCLEAR GAUGE AND EDG VS. STANDARD FOR SITE 1 (1lb/ft3(pcf)= 16 kg/m3)

	Density		Moisture Contents	
	Nuclear Gauge	Nuclear Gauge	EDG	EDG
R	0.87	0.64	0.01	0.63
STDV	2.47pcf	0.84%	2.12%	6.95 pcf

TABLE III
NUCLEAR GAUGE AND EDG VS. STANDARD FOR SITE 2 (1lb/ft3 (pcf) = 16 kg/m3)

	Density		Moisture Contents	
	Nuclear Gauge	EDG	Nuclear Gauge	EDG
R	0.29	0.06	0.68	0.49
STDV	2.50 pcf	5.41 pcf	0.8%	1.72%

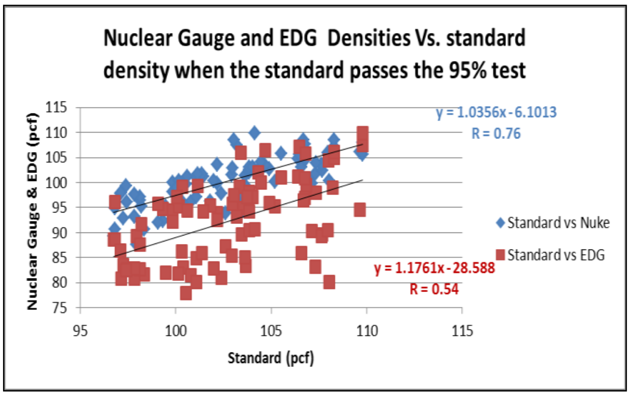

Figure IX
SCENARIO WHEN THE STANDARD METHOD PASSES 95% DENSITY TEST

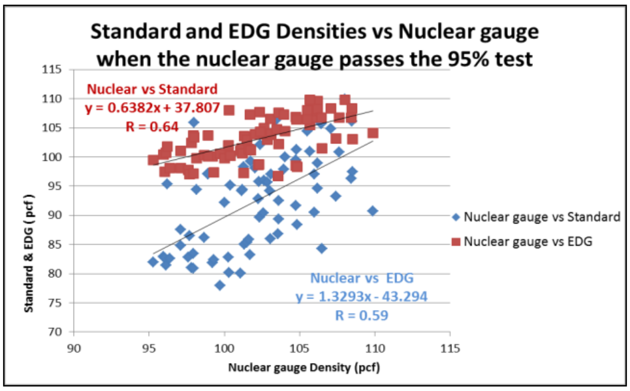

Figure X
SCENARIO WHEN THE NUCLEAR GAUGE PASSES 95% DENSITY TEST

Costs such as maintenance and other non-directly measurable expenses were estimated using previous data, quotes, and manufacturers' recommendations. Initial costs were those received from retailers when purchasing the gauges. Tables 5 and 6 summarize the costs associated with possessing the nuclear and non-nuclear gauges.

B. Analysis

A basic analysis done by adding costs incurred over the gauges' life expectancies showed that a nuclear gauge cost much more than any non-nuclear soil gauge as shown in Figure 12. The analysis was done using the lesser of the gauges' life expectancies, which is equivalent to 15 years. In order to view the current benefit of using non-nuclear gauges, a net present worth cost of all gauges was computed based on 10% minimum attracted rate of return as explained below:

- Net Present Worth of Costs (NPW) = Initial Costs + Yearly Operation & Maintenance Costs (P/A, 15 yrs, 10%)
- NPW of Nuclear Gauge = $10,873 + $2,155 (P/A, 15yrs, 10%)=$27,264
- NPW of EDG = $9,000
- NPW of LWD = $8,675

The EDG and the LWD cost about the same over their lifecycles. High annual cost of the nuclear gauge related to maintenance and operation made both non-nuclear gauges three times greater investments. In addition, the state DOT's construction and QA teams reported that there were other factors related to the nuclear gauge usage which cannot be directly measured in dollar values including:

- Transportation is allowed only with authorized vehicles,
- On-site penalty or fine is possible when inadequate control and security violation of gauge is spotted by an inspector,
- A special caution is required when cleaning a nuclear gauge parts after each time of use for soil, and
- A stolen gauge can be used as a nuclear weapon by terrorists.

TABLE IV
TEST STATUS ANALYSIS OF ALL GAUGES

Test Status Agreement with the Standard Method (%)	Site 1	Site 2	Average
Nuclear Gauge	80.62%	65.00%	72.81%
LWD	41.24%	67.50%	54.37%
EDG	41.00%	37.50%	39.80%

TABLE V
COSTS ASSOCIATED WITH OWNING AND OPERATING A NUCLEAR GAUGE

Cost of nuclear gauge	$6,950	Maintenance & Recalibration	$500/year
Radiation safety & Certification Class	$750	Leak test	$15
Safety training	$179	Shipping	$120
HAZMAT certification	$99	Radioactive Materials License	$1,600
RSO training	$395	License Renewal	$1500/ year
TLD Badge monitoring	$140/yr	Reciprocity	$750
Life of source capsule integrity	15 yr		

TABLE VI
COSTS OF OWNING AND OPERATING THE NON-NUCLEAR GAUGES

	Initial Costs	Annual Maintenance
EDG	$9,000	$0
LWD	$8,675	$0

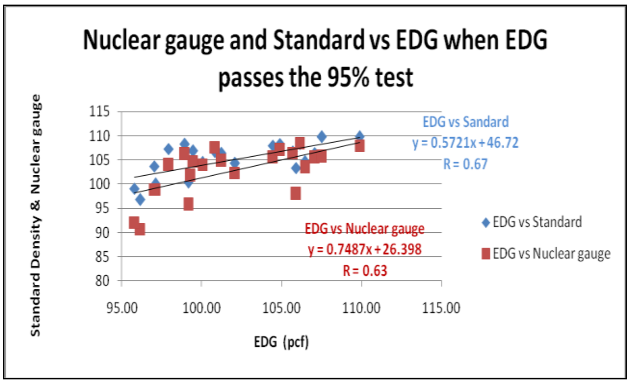

Figure XI
SCENARIO WHEN THE EDG PASSES 95% DENSITY TEST

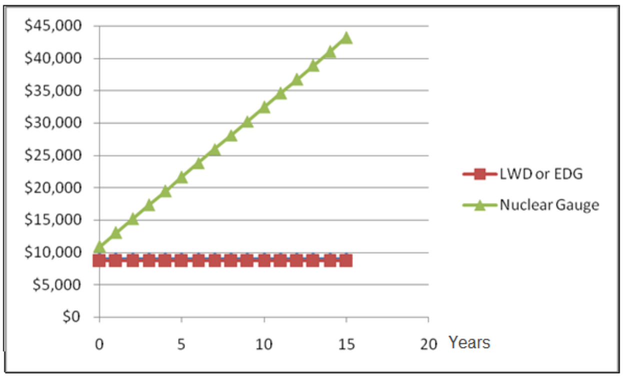

Figure XII
LIFE-CYCLE COST COMPARISON FOR GAUGES

VI. FRAMEWORK FOR NON-NUCLEAR GAUGE ANALYSIS

In this study, several performance comparison methods were suggested to fairly evaluate different types of gauges including the nuclear gauge, the EDG, and the LWD. Although it was not successfully employed in this study because of the hardware defects, the Moisture + Density Indicator (M+DI) was one of non-nuclear technologies that the research team initially attempted to test. In addition to these gauges, there are new products which continuously are being introduced in the market. The TrensTech's newly released Soil Density Gauge (SDG 200) is a good example. Thus, it is important to establish a framework which can be used as a guideline for evaluating performance of different types of non-nuclear soil technologies.

As found in this study, there are generally two types of non-nuclear gauges: 1) density and/or moisture content measurement and 2) deflection or stiffness measurement. Based on these two types, a framework was developed as shown in Figure 13. The framework shows three different groups of paths based on gauge types and each group measures a different soil property for comparison: (1) Deflection vs. Density; (2) Density; and (3) Moisture.

VII. CONCLUSION AND RECOMMENDATION

Intense regulation and destruction of materials all call for a new method for soil QA and QC to improve pavement subgrade soil condition. Unlike HMA, few studies have been conducted to compare the performance of non-destructive soil testing methods. Two different types of non-nuclear gauges, the EDG and the LWD, were introduced in this paper to evaluate their performance compared to the nuclear gauge. Traditional standard measurement methods were used as baselines to evaluate these three gauges. A modified density and stiffness comparison method was introduced to compare the LWD to the other density-based methods.

Overall, the test results showed that the nuclear gauge had higher correlation to the standard method than the EDG and the LWD in both the density and moisture measurements. Although the evaluated non-nuclear methods in this study were not technically as accurate as the nuclear gauge, both the non-nuclear gauges were positively acceptable for QC, thus the gauges can be frequently used during the soil compacting process at sites. One of the interesting findings was that the LWD showed higher accuracy at one of test sites than the nuclear gauge, which implied the LWD can be employed for the QA process. The EDG showed reliable accuracy in soil's moisture content measurement (70%) as well. To improve EDG's density reading accuracy, the soil modeling process has been being redesigned by the manufacturer.

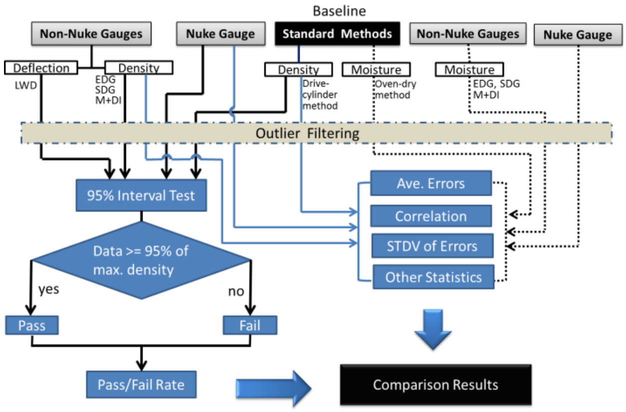

Figure XIII
FRAMEWORK FOR NON-NUCLEAR GAUGE PERFORMANCE TESTS

The users may consider the other benefits of non-nuclear gauges for their adoption such as 1) much lower life cycle costs thus a greater return on investments; and 2) no regulations and safety concerns, which cannot be measured in dollar values. These benefits are the main reason why some state DOTs (e.g., Nebraska, Minnesota) are replacing the nuclear gauges with the non-nuclear gauges for HMA and soil QC and QA.

For the future study, different mold shapes and compaction methods will be tested for the EDG to improve the current soil model. Also, several new non-nuclear technologies recently released from other manufacturers will be tested based on the evaluation framework developed in this study.

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