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Use of Nuclear Gauge for Construction Quality Control of Unbound Base Course Containing Reclaimed Asphalt

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Abstract:

A recent study determined that the Virginia Department of Transportation (VDOT) can use up to 30% reclaimed asphalt pavement (RAP) in a pavement base aggregate layer without adverse effects on pavement performance. However, an effective quality-control protocol to monitor construction is needed to implement the use of RAP in the base course. The study recommended using a lightweight deflectometer device to perform quality-control and quality-assurance monitoring of RAP-aggregate base construction. VDOT does not currently use a lightweight deflectometer device for any of the unbound layer construction, rather a nuclear density gauge is commonly used for compaction control. Major modification of existing VDOT practices and significant resource allocations would be required to implement the use of lightweight deflectometer devices for compaction control. As an alternative, this study evaluated the use of a nuclear gauge to monitor the construction quality of a base course containing RAP. Although several state departments of transportation currently use nuclear density gauges for such construction monitoring, accurate moisture measurement using a nuclear device is challenging because of the presence of hydrogen atoms in RAP that comes from both asphalt and compaction water.

The study's research team conducted a laboratory trial using wooden boxes filled with RAP aggregate blends at different proportions and a field test section. The team measured densities using a nuclear density gauge and verified them by the sand cone method. Nuclear moisture content measurements were compared with the oven-dry test method and a Speedy® moisture tester. The team determined that the nuclear gauge measured the wet densities accurately irrespective of RAP content in the base aggregate. On the other hand, the presence of RAP affected moisture measurements, which is directly proportional to the increasing content of RAP. The team concluded that a nuclear gauge can be used to monitor RAP aggregate compaction but an offset value (or correction) for moisture measurement needs to be incorporated. Although the presence of asphalt did not affect the Speedy moisture tester's moisture measurements, a relatively small sample size affected the measurement accuracy, especially at higher RAP contents because more hydrophobic particles contributed to nonuniform moisture distribution.

FINAL REPORT

USE OF NUCLEAR GAUGE FOR CONSTRUCTION QUALITY CONTROL OF UNBOUND BASE COURSE CONTAINING RECLAIMED ASPHALT PAVEMENT

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ABSTRACT

A recent study determined that the Virginia Department of Transportation (VDOT) can use up to 30% reclaimed asphalt pavement (RAP) in a pavement base aggregate layer without adverse effects on pavement performance. However, an effective quality-control protocol to monitor construction is needed to implement the use of RAP in the base course. The study recommended using a lightweight deflectometer device to perform quality-control and quality-assurance monitoring of RAP-aggregate base construction. VDOT does not currently use a lightweight deflectometer device for any of the unbound layer construction, rather a nuclear density gauge is commonly used for compaction control. Major modification of existing VDOT practices and significant resource allocations would be required to implement the use of lightweight deflectometer devices for compaction control. As an alternative, this study evaluated the use of a nuclear gauge to monitor the construction quality of a base course containing RAP. Although several state departments of transportation currently use nuclear density gauges for such construction monitoring, accurate moisture measurement using a nuclear device is challenging because of the presence of hydrogen atoms in RAP that comes from both asphalt and compaction water.

The study's research team conducted a laboratory trial using wooden boxes filled with RAP-aggregate blends at different proportions and a field test section. The team measured densities using a nuclear density gauge and verified them by the sand cone method. Nuclear moisture content measurements were compared with the oven-dry test method and a Speedy® moisture tester. The team determined that the nuclear gauge measured the wet densities accurately irrespective of RAP content in the base aggregate. On the other hand, the presence of RAP affected moisture measurements, which is directly proportional to the increasing content of RAP. The team concluded that a nuclear gauge can be used to monitor RAP-aggregate compaction but an offset value (or correction) for moisture measurement needs to be incorporated. Although the presence of asphalt did not affect the Speedy moisture tester's moisture measurements, a relatively small sample size affected the measurement accuracy, especially at higher RAP contents because more hydrophobic particles contributed to nonuniform moisture distribution.

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INTRODUCTION

Many aged and deteriorated asphalt pavements are usually reclaimed back into the pavement construction. A portion of the reclaimed pavement is recycled back into the new hot mix asphalt, but a significant amount is available for use in other applications, such as a high-quality base or subbase in flexible pavement. A recent study sponsored by the Virginia Department of Transportation (VDOT) recommended that reclaimed asphalt pavement (RAP) can be blended in the base aggregate layer at a maximum of 30% replacement rate, with no apparent loss in performance (Tanyu et al., 2021). The study also recommended using a lightweight deflectometer (LWD) device as an effective means of quality control and quality assurance for base course construction. It is important to note that LWD directly measures stiffness, which is an input for mechanistic pavement design rather than compaction property.

Successful implementation of RAP-aggregate blends on VDOT construction projects would require using a competent field-testing technique to ensure compliance with the requisite specifications. VDOT, like many other transportation agencies, currently uses a nuclear density gauge as the primary tool for quality-control assurance of field compaction. Implementing LWD for compaction control would require a major modification of VDOT practices and a significant resource allocation. To determine if adopting the LWD testing protocol is necessary for RAP-aggregate blends, VDOT decided to explore the feasibility of using the current methodology based on the nuclear gauge. Consequently, a study was proposed to examine the applicability and possible limitations of using the existing practice of compaction testing by nuclear gauge when RAP is blended with base aggregate at 30% replacement rate.

Previous literature indicates a problem with nuclear gauge in determining accurate moisture content in the presence of RAP in the base course. Despite this shortcoming, many state highway agencies use nuclear density gauges as part of their quality-control testing during base layer construction where a certain percentage of RAP is mixed with virgin aggregate.

PURPOSE AND SCOPE

The main purpose of this study is to evaluate the suitability of nuclear gauge testing for quality-control assurance of base layer construction when a conventional aggregate is

blended with RAP material. Therefore, a nuclear density gauge was evaluated to measure both the density and moisture of a compacted base layer containing RAP blended with VDOT 21 A and B aggregate. A Speedy® moisture tester, often used in the field, was also assessed to measure the moisture content during compaction. Accuracy of the compaction and moisture measurement was verified using more conventional methods such as sand cone and oven drying, respectively. The scope of this study focuses on extensive laboratory testing and a limited number of field tests. The study was limited to evaluating a particular nuclear gauge with a single source of aggregate and one source of RAP for the field and another source for the laboratory.

METHODS

Overview

The research team performed the following tasks to achieve the study's objectives:

1. A literature review to document the challenges associated with using nuclear gauge testing to measure density and moisture when a base layer contains reclaimed asphalt materials.
2. Field and laboratory test setup construction. The team prepared a test strip in the field and five 2-feet-by-2-feet boxes in the laboratory to evaluate compaction with a range of RAP replacement for the base aggregate.
3. Construction quality testing and monitoring. The team determined construction quality by evaluating the compaction of the base layer consisting of RAP at different proportions. Both wet density and moisture content were measured using several devices: nuclear gauge, Speedy moisture tester, oven-dry method, and sand cone method.
4. Comparison of density and moisture measurements. The team analyzed all data to evaluate the suitability of nuclear density gauge testing to measure constructed base layer density as a quality-control and quality-assurance tool. The nuclear wet density measurements were compared with the sand cone method, and moisture was compared with the oven-dry method. A Speedy moisture tester was also compared with oven-dry method.
5. Development of guidance for nuclear gauge use. The team developed guidelines in collaboration with the VDOT's Materials Division to use nuclear density gauges to control the quality of unbound RAP-aggregate base layer construction.

Literature Review

An extensive review of RAP use in the base course was compiled in previous VDOT-sponsored studies. Additional research sources were reviewed for verification of the current study results. The VDOT research library and the Transportation Research and Information Database, an integrated database of the Transportation Research Board, were used to identify the relevant articles.

Field and Laboratory Test Setup Construction

The initial research concept was to build experimental test strips at a field location such as a VDOT residency. A local RAP manufacturer in Northern Virginia volunteered to construct an approximately 90-feet-long test strip in their yard to evaluate the compaction of a pavement base layer containing processed RAP. Materials were blended in the plant at a ratio of 25% RAP to 75% base aggregate with moisture and spread over a width of approximately one lane. RAP was finely processed (passing through a ½-inch sieve opening) and base aggregate was a diabase (traprock) meeting VDOT 21B gradation.

The blend was compacted in the field using a vibratory steel wheel drum roller (Figure 1). The test strip was subdivided into three distinct 30-feet long sections. Each section was compacted with 2, 4, and 6 roller passes to simulate low, medium, and high degree of compaction. Although layer thickness of the material was not uniform across the length, it was compacted in one lift.

Figure 1. Field Section Compacted with Vibratory Roller

The research team conducted the study in a controlled laboratory environment to reduce the effects of variability associated with the materials and methods employed in the field. To accomplish this task, five wooden boxes, each measuring 2 feet by 2 feet and 18 inches high, were built in the Virginia Transportation Research Council (VTRC) geotechnical laboratory (Figure 2).

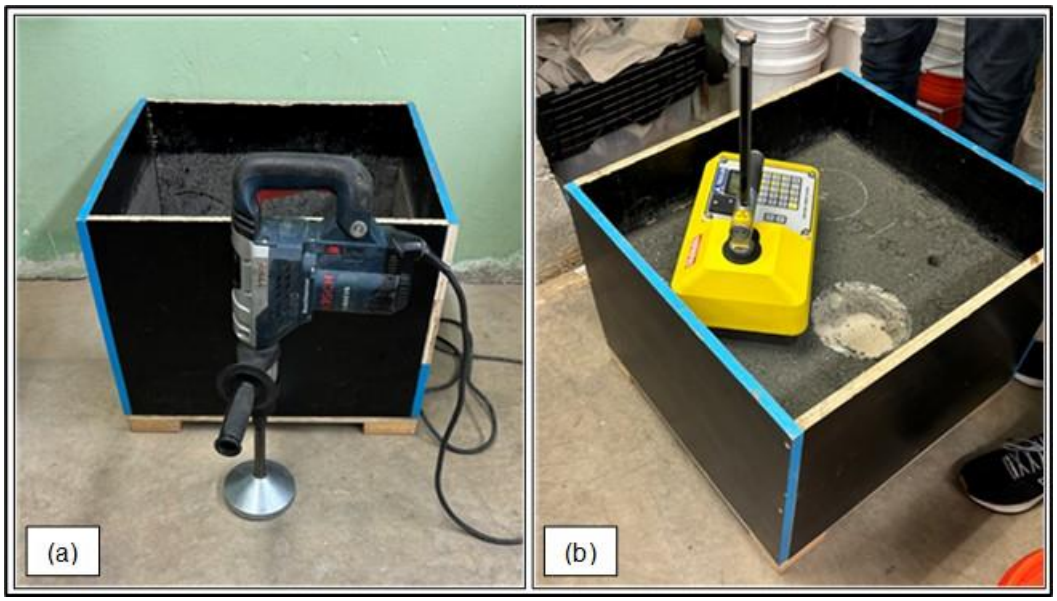

Figure 2. Laboratory Box Experimental Setup: (a) Wooden Box and Vibratory Hammer; (b) Nuclear Gauge and Sand Cone Test

The interior wood surfaces were covered with phenolic coating to minimize moisture loss. RAP-aggregate blends of different proportions were compacted in the box with a handheld vibratory hammer, up to approximately 12 inches. The aggregate originated from the same plant that supplied material for the field test section. However, the finely processed RAP was collected from a nearby asphalt plant. RAP and aggregate materials were mixed at different proportions in the laboratory using a small capacity pugmill. The experiment included the following five blends:

1. 100% aggregate.
2. 25% RAP + 75% aggregate.
3. 30% RAP + 70% aggregate.
4. 50% RAP + 50% aggregate.
5. 75% RAP + 25% aggregate.

A handheld vibratory hammer weighing around 15 kilograms was used to compact until no change in height was observed. The blended aggregate materials were compacted in four layers into the box. The weight of the materials inside the box and the compacted height were recorded for each layer. Compacted wet densities were calculated from the box dimension, compacted height, and the weight of the materials.

Moisture-density relationships were developed with standard proctors following Virginia Test Method (VTM)-1 (VDOT, 2025) for both field and laboratory experiments. The field sample was already preblended. However, RAP and aggregate were collected separately and blended in the laboratory using a pugmill before running the proctor for the laboratory experiment.

Construction Quality Testing and Monitoring

The construction quality of the field site and laboratory boxes were monitored by measuring the wet density and moisture to ensure proper compaction. The field test strip was divided into three 30-feet sections with different compaction efforts and tested separately. Each laboratory box was tested by placing the nuclear gauge at four to five different areas of the compacted surface within the box. The appendix includes an example schematic diagram of the gauge placement. The following standard tests were conducted:

1. VTM-1: Laboratory Determination of Theoretical Maximum Density and Optimum Moisture Content of Soils, Granular Subbase, and Base Materials (VDOT, 2025).
2. VTM-10: Determining Percent of Moisture and Density of Soils, Aggregate, and Full-Depth Reclamation Courses, and Density of Cold In-Place Recycling and Cold Plant Recycling (Nuclear Method) (VDOT, 2025).
3. ASTM D1556: Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method. (ASTM, 2023b)
4. ASTM D2216: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. (ASTM, 2023b)
5. ASTM D4944: Standard Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester (Speedy Moisture Tester; manufacturer's calibration was used). (ASTM, 2023b)
6. ASTM D6307: Standard Test Method for Asphalt Content of Asphalt Mixture by Ignition Method. (ASTM, 2023a)

VDOT's Materials Division helped with the nuclear gauge and sand cone measurements of density and moisture. One specific nuclear gauge, operated by VDOT's Materials Division personnel, was used throughout the study. This nuclear gauge was used to measure the wet density and moisture content of the compacted RAP-aggregate base. The sand cone method was used to verify the field and laboratory measurements. In addition, wet densities for boxed samples in the laboratory were calculated from the weight and dimensions. Moisture content was also determined by using a Speedy moisture tester. Actual moisture content was determined by oven drying the sand cone samples. A previous VDOT study (Tanyu et al., 2021) recommended air drying for materials containing RAP because the volatile fractions in asphalt can influence the moisture reading when oven dried at 110° C. Because the air-drying method requires substantial time to complete, this study did not use that method. Instead, samples containing RAP were oven dried at 60° C to minimize the volatile losses. A forced draft oven was used in this study. Some samples were dried first at 60° C to simulate air dry conditions and again dried at 110° C for comparison. In the case of the field section, an ignition oven test was performed on RAP and the blend to determine the asphalt content to verify the percentage of RAP in the mixture.

Comparison of Density and Moisture Measurements

The research team analyzed all data to evaluate the suitability of the nuclear gauge to measure the density of the constructed base layer when RAP is present. The nuclear wet density measurements were compared with the sand cone results, and the nuclear moisture contents

were compared with the oven-dry method. For each compacted laboratory box, wet density was also estimated from the actual box dimension and the material weight. A Speedy moisture tester and oven-dry method were used to measure the moisture of the sand cone samples.

In addition to the laboratory box experiment, a series of separate laboratory experiments evaluated the Speedy moisture tester against the oven-drying method. Samples of RAP and aggregate were mixed at different proportions and different moisture levels for testing. The following RAP portions (in percentage) were used in the laboratory experiments: (1) 0, 20, 40, 60, 80, and 100% and (2) 0, 30, 50, 80, and 100%.

The initial moisture content for sample preparation was targeted at 3, 5.5, and 7% by weight. In one setup, the moisture content varied randomly between 1 and 7%. A blended sample of around 2,000 grams was prepared and mixed with water. Each sample was split to produce two replicate samples of 1,000 grams each. All samples were tested with a Speedy moisture tester. This test is conducted by taking 20 grams of sample materials consisting of particles less than a number 4 sieve and mixing them with calcium carbide in a closed container. The water in the sample reacts with calcium carbide and produces acetylene gas. The pressure exerted by the gas to the container is calibrated to provide the amount of water in the sample. The rest of the 1,000-gram sample was dried at 60° C using a forced draft oven to determine moisture content. All samples were further dried at 110° C, the standard temperature for moisture determination. The samples were initially dried at 60° C to simulate air dry conditions, which prevents volatile loss from the asphalt.

Development of Guidance for Nuclear Gauge Use

Testing protocol for using the nuclear density gauge for compaction quality control of RAP-aggregate base course was drafted. This proposed plan is based on the accuracy of wet density and moisture content measurements by nuclear gauge compared with the sand cone and the oven-dry method, respectively. Using a Speedy moisture tester was also considered for field measurements.

RESULTS AND DISCUSSION

Literature Review

Two VDOT-sponsored studies addressed various issues related to the use of RAP in pavement base courses (Hoppe et al., 2015; Tanyu et al., 2021). One of the main challenges to successful implementation of RAP use is the construction quality control.

Most state departments of transportation (DOTs) use nuclear gauge to control the construction of a base layer by measuring density and moisture to achieve the prescribed level of compaction. Although the presence of an asphalt binder affects the results obtained with a nuclear gauge, the resulting consequences on the overall measurement accuracy have not been widely quantified. Although no commonly agreed-on method exists for controlling the quality

of base construction with RAP, many state DOTs use traditional nuclear density gauges for this purpose. Table 1 summarizes current state DOT practices across the United States.

Table 1. Summary of State DOT Practices for Using RAP in the Base Course[a] (Tanyu et al., 2021)

State	Maximum RAP Allowed, %	Maximum Binder Content in RAP, %	Maximum Particle Size, inches	QC/QA Testing
Alaska	–	–	1.5	Nuclear gauge
Arkansas	–	2.5 ≤ % ≤ 3.0	1.0	Nuclear gauge
California	50	–	0.75	Nuclear gauge
Colorado	100	–	2.0	Nuclear gauge
Connecticut	–	2.0	3.5	Nuclear gauge
Florida	–	≥ 4.0	3.5	Nuclear gauge
Minnesota	–	3.5	1.5	DCP and LWD
Montana	40	–	2.0	Nuclear gauge
New Hampshire	–	1.5	0.75	Nuclear gauge or sand cone
New Jersey	50	–	1.5	Nuclear gauge
New Mexico	50	–	1.0	Nuclear gauge
New York	95	–	2.0	Visual inspection
North Dakota	100	3.5	1.5	Sand cone or rubber balloon
Texas	20	–	2.0	Nuclear gauge

– = information not available; DCP = dynamic cone penetrometer; DOT = department of transportation; LWD = lightweight deflectometer; QC/QA = quality control and quality assurance; RAP = reclaimed asphalt pavement.
[a] All information gathered from the respective department of transportation specifications.

The research team reviewed the principle of operation of a nuclear gauge commonly used at a construction site to monitor earthworks to understand the challenges of using such a device in the presence of RAP materials. A typical nuclear gauge uses two separate radioactive isotopes to measure density and moisture. For a soil and aggregate nuclear gauge, a radioactive source material is lowered into a hole at a specified depth. A detector at the other end of the device detects and measures the amount of gamma radiation that passes through the material for a specified duration, such as 4 minutes (Figure 3). The amount of radiation that reaches the detector in this direct transmission mode is directly proportional to the material's density. This radiation count gets converted into the wet density by the gauge based on the calibration (APNGA, 2024).

Although both density and moisture are measured at the same time, the moisture is measured by a different source of radioactive material that acts in the backscatter mode as Figure 3 shows. This radioactive source releases "fast" neutrons, and they slow down or thermalize as they interact with the nuclei of hydrogen atoms in the material (water). The detector at the middle of the gauge can only detect these "slow" neutrons. This count directly relates to the amount of water present in the material. Any other source of hydrogen present will be falsely counted as water. The penetration depth for this backscatter depends on the level of moisture, which is usually 4 to 8 inches. The higher the moisture, the shallower the depth of measurements (APNGA, 2024).

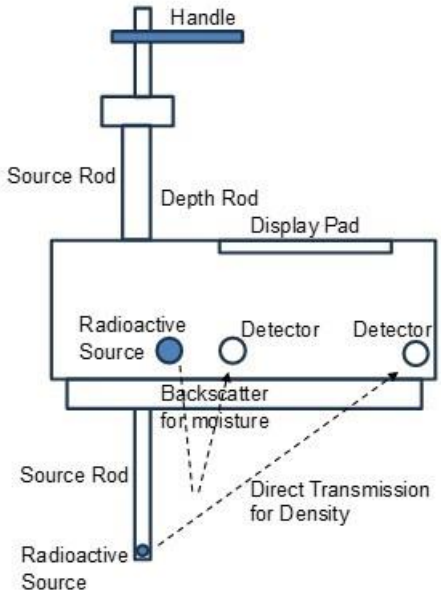

Figure 3. Operational Schematic of a Nuclear Gauge

The presence of hydrogen in the soil and aggregate unrelated to the actual moisture could affect moisture reading by the nuclear gauge. Many state DOTs apply moisture correction when a nuclear gauge is used to measure the in-situ density and moisture content of soil or aggregate layer during construction. In their respective test methods, both the Kansas and Arizona DOTs have outlined steps to determine moisture offset when nuclear gauge is used (AZDOT, 1992; KSDOT, 2016). According to their standard, an offset value of less than 1% could be ignored.

Because the presence of asphalt affects nuclear gauge readings, adjustments may be needed to obtain accurate moisture measurements to calculate dry densities. VTRC report 15-R6 lists potential corrective approaches using the following (Hoppe et al., 2015):

- Nuclear gauge moisture correction adjusted for the presence of binder in calculating dry density value.
- Nuclear gauge to measure only wet densities.
- Nuclear gauge to measure wet density and a Speedy moisture tester for moisture measurements for dry density determination.
- Nuclear gauge on a control strip and specify certain number of passes of compaction equipment over a specified layer thickness.

The U.S. Army Corps of Engineers investigated the accuracy of nuclear gauge measurement for in situ soil density and moisture in a laboratory experiment in which different natural soils were compacted in 2-feet-by-2-feet boxes (Rosser and Webster, 1969). Wet density measurements with nuclear gauge using factory calibration curve were found to be as accurate as other conventional methods, such as sand cone and water ballon. The moisture measurements by nuclear gauge were compared with the oven dried moistures. It was determined that the factory supplied calibration curve did not produce accurate results. The calibration curve developed by the Waterways Experiment Station provided sufficiently accurate water content

measurements by the nuclear gauge, with 95% of the measurements within ±2.46% of the actual water content.

The Texas DOT investigated using crushed concrete and RAP as the backfill materials in a mechanically stabilized earth retaining wall. As a part of this study, an experiment was conducted to determine the accuracy of nuclear gauge to measure density and moisture for such materials (Viyanant et al., 2004). Wet densities measured with a nuclear device corresponded closely to the density measured by the pit method in which weight and pit geometry were used for density calculation. The Texas study found that the moisture measurements by nuclear gauge were consistently higher than the oven-dried method for both crushed concrete and RAP. This differential was attributed to the presence of hydrogen atoms in both crushed concrete and RAP.

Field and Laboratory Test Setup Construction

Table 2 shows the proctor results and compacted densities. During the compaction, the moisture was kept at optimum level according to the standard proctor. The achieved compaction in the laboratory boxes was a little above 80% of maximum wet density.

Table 2. Moisture-Density Relationship with Standard Proctor According to VTM-1 (VDOT, 2025).

Blend	Maximum Dry Density, pcf	Optimum Moisture Content, %	Wet Density, pcf	Calculated Density,[a] pcf	Achieved Compaction, %
Field 25% RAP	146.0	6.0	154.8	–	–
100% Aggregate	147.5	5.5	155.6	145.1	93
75% Aggregate + 25% RAP	145.0	5.0	152.0	131.5	87
70% Aggregate + 30% RAP	145.9	5.0	153.2	132.4	86
50% Aggregate + 50% RAP	144.3	5.2	151.8	132.2	87
25% Aggregate + 75% RAP	134.8	3.5	139.5	120.8	87

– = information not available or not measured; RAP = reclaimed asphalt pavement.
[a] Densities were calculated using weight, height, and box dimensions.

Construction Quality Testing and Monitoring

Wet Density Measurements

Table 3 summarizes the field wet density test results, with the section averages highlighted in yellow. In the field, nuclear densities were measured at 6-inch depth with a 4-minute test duration. Although more compaction efforts (four passes) were used, the wet density for section 2 was less than section 1. The field section was compacted in one lift, but the layer thickness was not uniform, which resulted in nonuniform compaction.

Table 3. Measured Densities for Field Test Section

Section	Nuclear Wet Density, pcf (SD)	Sand Cone Wet Density, pcf (SD)	Difference between Nuclear Density and Sand Cone,[a] pcf
Section 1 30 ft x 12 ft (2 passes)	142.60	148.08	
	141.40	–	
	141.90	136.65	
	135.80	–	
	141.50	–	
	138.80	145.71	
	139.30	–	
	141.40	–	
Average Section 1	140.19 (2.38)	143.48 (6.03)	– 3.29
Section 2 30 ft x 12 ft (4 passes)	140.70	–	
	138.10	–	
	137.20	–	
	141.50	128.28	
	140.20	134.42	
	138.40	–	
	142.30	137.78	
Average Section 2	139.77 (1.90)	133.49 (4.82)	+6.28
Section 3 30 ft x 12 ft (6 passes)	144.50	–	
	142.90	–	
	145.30	146.89	
	143.10	–	
	147.90	140.77	
	145.10	–	
	146.20	142.58	
Average Section 3	145.00 (1.74)	143.41 (3.14)	+1.59

– = information not available or not measured; SD = standard deviation.

[a] Difference = (Nuclear density – Sand Cone).

Table 4 presents the laboratory wet densities. Laboratory nuclear gauge measurements were conducted at depths of 8, 6, 4, and 2 inches and at backscatter mode, with either 4- or 1-minute test durations. Detailed results are available in the appendix.

Table 4. Measured Wet Densities (in pcf) for Laboratory Boxes

RAP-Aggregate Blend in 2ft-x-2ft Box	Calculated Density,[a] pcf	Test Location	Nuclear Density,[b] pcf	Sand Cone Density,[c] pcf	Difference between Nuclear Density and Sand Cone Density,[d] pcf
100 % Aggregate	145.1[e]	1	139.46	–	
		2	135.95	140.58	
		3	138.88	–	
		4	138.90	139.90	
		Average	138.24	140.24	– 2.0
25% RAP +75% Aggregate	131.5[f]	1	125.88	127.57	
		2	127.42	129.65	
		3	125.94	123.94	
		4	124.58	127.15	
		Average	125.96	127.08	– 1.12
30% RAP+70% Aggregate	132.4	1	133.93	133.73	
		2	134.50	132.16	
		3	134.20	131.39	

RAP-Aggregate Blend in 2ft-x-2ft Box	Calculated Density,[a] pcf	Test Location	Nuclear Density,[b] pcf	Sand Cone Density,[c] pcf	Difference between Nuclear Density and Sand Cone Density,[d] pcf
		4	134.23	–	
		5	135.60	131.25	
		Average	134.56	132.43	+2.13
50% RAP+50% Aggregate	132.2	1	129.48	134.58	
		2	129.78	–	
		3	129.60	135.42	
		4	128.00	131.90	
		Average	129.27	133.96	– 4.69
75% RAP+25% Aggregate	120.8	1	120.90	119.02	
		2	121.58	124.40	
		3	121.76	123.51	
		4	121.66	123.50	
		Average	121.48	122.61	– 1.13

– = information not available or not measured; RAP = reclaimed asphalt pavement.
[a] Density was calculated from weight and dimension. [b] Nuclear density at each location is the average of four or five measurements at different depths. [c] Sand cone measurements are a single measurement at each location within the box. [d] Difference = (Nuclear density – Sand Cone). [e] Bottom sag was observed, so the height measurements could have been affected. [f] Weight of the top layer (≈ 3 inches) was missing.

Moisture Measurements

Table 5 summarizes the moisture values measured in the field section. Table 6 shows the moisture measurements for the laboratory box experiment. Nuclear gauge moisture measurements usually represent the top few inches of the layer on which the gauge is seated. On the other hand, oven-dry samples are the sand cone materials dug from the top 6 inches or so. Speedy moisture was measured by taking only 20 grams of materials from the sand cone samples in the laboratory box experiment.

Table 5. Moisture Measurements for Field Test Section

Section	Nuclear Moisture, % (SD)	Oven Dry Moisture, % (SD)	Difference between Nuclear Gauge and Oven Dry,[a] %
Section 1 30 ft x 12 ft (2 passes)	5.00	4.38	
	4.60	4.47	
	3.90	4.75	
	5.60	5.11	
	5.10	5.32	
	4.20	4.58	
	4.00	–	
Average Section 1	4.63 (0.63)	4.77 (0.37)	– 0.14
Section 2 30 ft x 12 ft (4 passes)	4.60	4.15	
	4.10	4.67	
	4.30	4.40	
	4.70	5.49	
	4.80	4.57	
	4.30	4.96	
	4.10	3.80	
Average Section 2	4.41 (0.29)	4.58 (0.55)	– 0.17
Section 3 30 ft x 12 ft	4.60	5.16	
	4.90	4.68	

Section	Nuclear Moisture, % (SD)	Oven Dry Moisture, % (SD)	Difference between Nuclear Gauge and Oven Dry,[a] %
(6 passes)	5.60	5.00	
	4.30	5.22	
	5.80	4.38	
	4.80	5.00	
	5.00	4.64	
Average Section 3	5.00 (0.53)	4.87 (0.31)	+0.13

– = information not available or not measured; SD = standard deviation.
[a] Difference = (Nuclear gauge – Oven dry).

Table 6. Measured Moistures (in percentage) for Laboratory Boxes

RAP-Aggregate Blend in 2ft-x-2ft Box	Test Location	Nuclear Moisture, %	Oven-Dry[a] Moisture, %	Speedy Moisture Tester Results, %	Difference between Nuclear Gauge and Oven Dry,[b] %
100% Aggregate	1	4.04	4.90	5.2	
	2	4.00	4.87	5.0	
	3	4.07	–	–	
	4	3.82	4.86	4.8	
	Average	3.99	4.88	5.0	– 0.89
25% RAP+75% Aggregate	1	4.48	4.93	4.9	
	2	4.40	4.79	5.2	
	3	4.48	4.92	5.0	
	4	4.58	4.90	5.2	
	Average	4.49	4.89	5.1	– 0.4
30% RAP+70% Aggregate	1	4.1	4.41	3.8	
	2	3.8	4.44	3.7	
	3	4.17	4.29	4.5	
	4	4.13	–	–	
	5	4.15	4.31	4.5	
	Average	4.08	4.36	4.1	– 0.28
50% RAP+50% Aggregate	1	5.4	4.39	4.4	
	2	5.3	–	–	
	3	5.27	4.69	4.6	
	4	5.33	5.24	–	
	Average	5.33	4.78	4.5	0.55
75% RAP+25% Aggregate	1	5.48	4.15	4.2	
	2	5.62	4.30	4.7	
	3	5.50	4.10	4.2	
	4	5.40	4.06	4.0	
	Average	5.50	4.15	4.3	1.35

– = information not available or not measured; RAP = reclaimed asphalt pavement.
[a] Oven dried at both 60° C and 110° C. Reported values are for 60° C when RAPs were present.
[b] Difference = (Nuclear gauge – Oven dry).

The research team conducted a separate series of laboratory experiments to evaluate the Speedy moisture test results compared with the conventional oven-dry tests. Table 7 shows the results, indicating blend ratios (% RAP), target moisture contents (sample preparation), and measured moisture contents. A moisture difference of about 0.1% between 60° C and 110° C was observed.

Table 7. Measured Moistures (in percentage) for Speedy Moisture Tester Experiment

Target Moisture, %	Reclaimed Asphalt Pavement, %	Split Sample	Speedy Moisture Tester Results, %	Oven Dry at 60° C, Moisture (%)	Oven Dry at 110° C, Moisture (%)
3.0	0	1	4.2	3.32	3.48
		2	3.9	3.32	3.48
	30	1	4.4	3.23	3.35
		2	4.5	3.23	3.35
	50	1	3.8	3.18	3.27
		2	4.5	3.18	3.27
	80	1	5.0	3.03	3.09
		2	4.5	3.03	3.09
	100	1	4.8	2.95	2.99
		2	4.7	2.95	2.99
5.5	0	1	5.2	4.48	4.67
		2	5.5	4.53	4.72
	20	1	5.5	4.55	4.72
		2	5.3	4.96	5.12
	40	1	5.8	4.73	4.84
		2	5.5	5.03	5.17
	60	1	5.6	5.94	6.04
		2	4.0	4.31	4.39
	80	1	4.6	4.95	5.03
		2	5.4	4.45	4.55
	100	1	7.5	6.22	6.23
		2	5.8	5.48	5.53
7.0	0	1	7.9	7.28	7.44
		2	7.6	7.28	7.44
	30	1	8.4	7.17	7.28
		2	8.0	7.17	7.28
	50	1	7.7	7.14	7.25
		2	7.2	7.14	7.25
	80	1	7.9	6.98	7.09
		2	7.5	6.98	7.09
	100	1	11.2	6.90	6.91
		2	8.1	6.90	6.91
Random	0	1	1.6	1.54	1.65
		2	1.7	1.82	1.82
	20	1	1.8	1.41	1.41
		2	2.0	1.64	1.64
	40	1	2.3	1.61	1.61
		2	2.1	1.48	1.48
	60	1	2.6	2.02	2.02
		2	2.8	1.94	1.94
	80	1	3.0	2.15	2.15
		2	3.2	2.29	2.29
	100	1	3.4	2.38	2.38
		2	5.4	3.68	3.68

Comparison of Wet Density and Moisture Content Measurements

Wet Density

Wet densities were measured in three different ways: nuclear, sand cone, and weight and dimension. These methods have their inherent limitations and advantages. Although the nuclear method is quick and repeatable, its accuracy depends on proper calibration. Sand cone test results are usually considered a measurement benchmark, although operator skill and material gradation can affect accuracy. The weight and dimension method should provide the most direct and accurate results. The main challenge involves integrating accurate height measurements across the entire 2-feet-by-2-feet test surface. The wood board at the bottom of the box with 100% aggregate showed some sagging. The vibratory hammer broke halfway through the compaction, and a tamper was used to finish the compaction. Figures 4 through 9 show all wet density measurements (field and laboratory) for a visual comparison. In some cases, the nuclear measurements were higher than the measurements from other devices, and they were lower in other instances. Figure 10 explores such trends further.

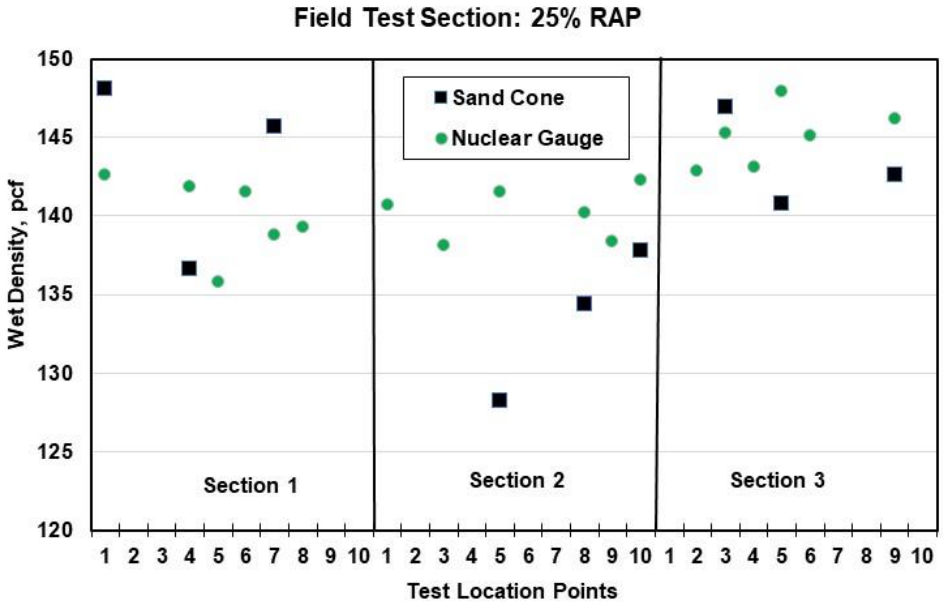

Figure 4. Field Section Densities Measured with a Nuclear Gauge and Sand Cone Method. RAP = reclaimed asphalt pavement.

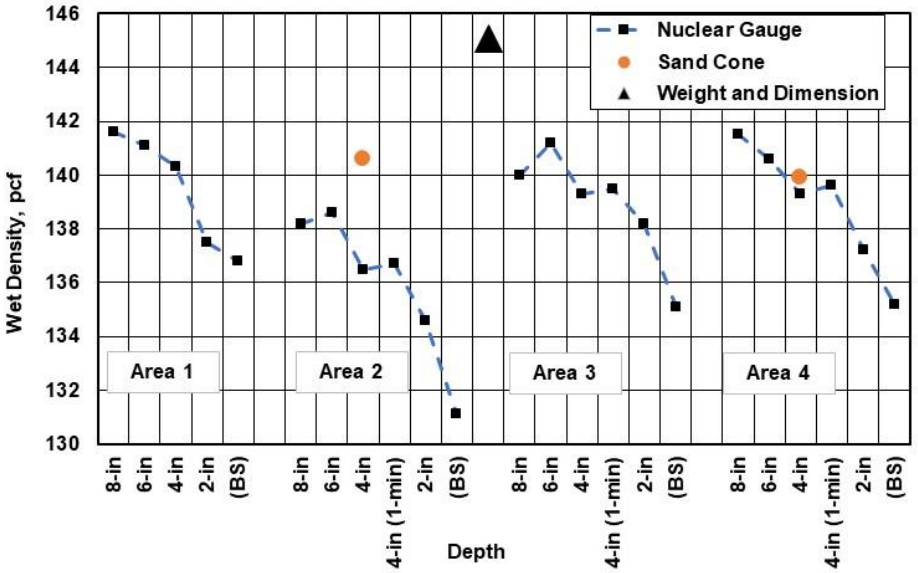

Figure 5. Measured Densities for Laboratory Box with 100% Aggregate. BS = back scatter.

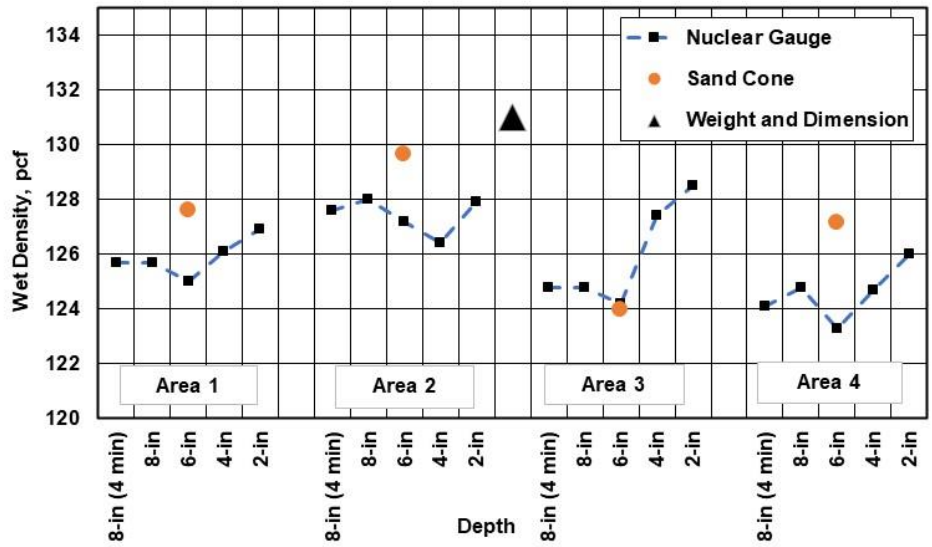

Figure 6. Measured Densities for Laboratory Box with 25% Reclaimed Asphalt Pavement

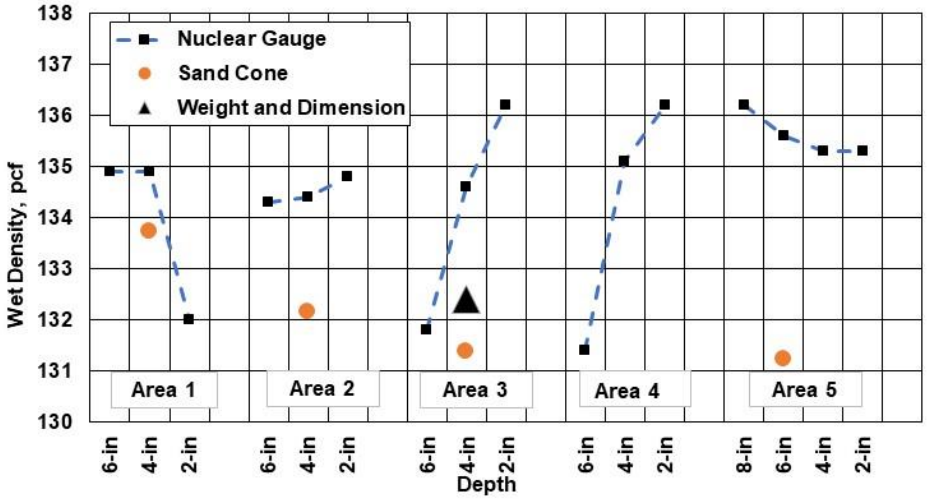

Figure 7. Measured Densities for Laboratory Box with 30% Reclaimed Asphalt Pavement

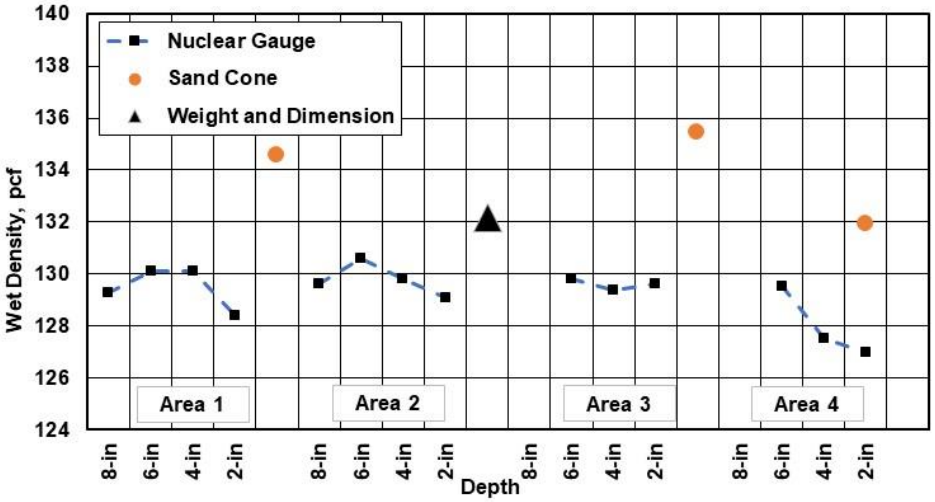

Figure 8. Measured Densities for Laboratory Box with 50% Reclaimed Asphalt Pavement

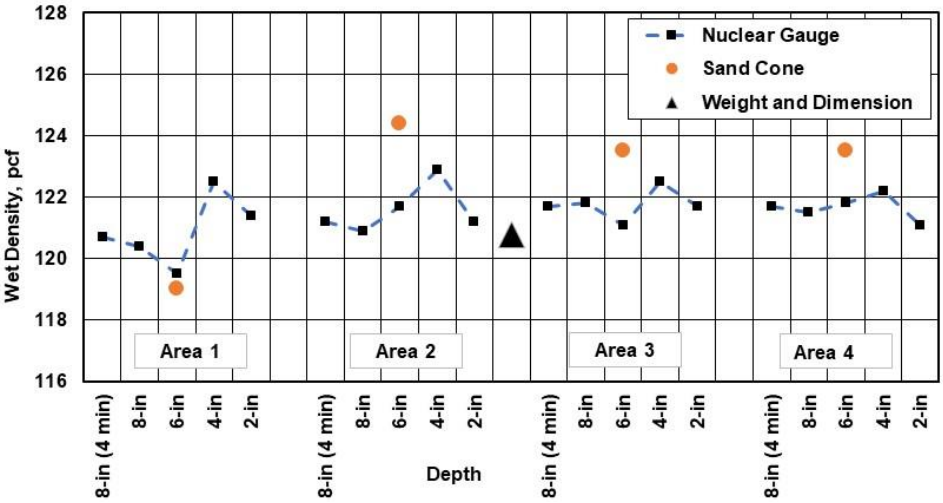

Figure 9. Measured Densities for Laboratory Box with 75% Reclaimed Asphalt Pavement

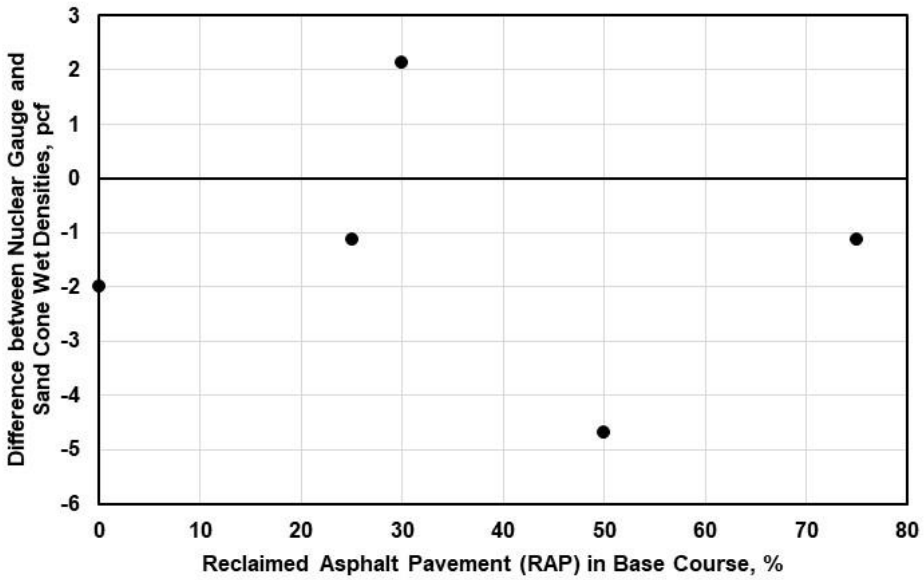

Figure 10. Difference between Nuclear Gauge and Sand Cone Densities for Laboratory Boxes

Figure 10 shows the average differences in wet density measurements between the nuclear and sand cone test methods for various RAP contents. The average test results from each laboratory box are compared. Nuclear measurements tended to be slightly less than those obtained from the sand cone tests. The results typically varied within approximately 2 pcf, except for one case of 5 pcf differential. No distinct trend was observed in these differences.

Moisture Content

Figures 11 through 16 show the moisture content measurements for the field sections and laboratory boxes. The field moisture content measurements for 25% RAP blend by nuclear gauge and oven-dry method were within 0.2%, as Figure 11 and Table 5 show. In the laboratory box experiment, nuclear gauge moisture measurements were less than the oven-dry method for RAP content up to 50% and higher for more than 50% RAP, but a linear trend was observed. The next section discusses the trend for moisture measurements in the laboratory boxes.

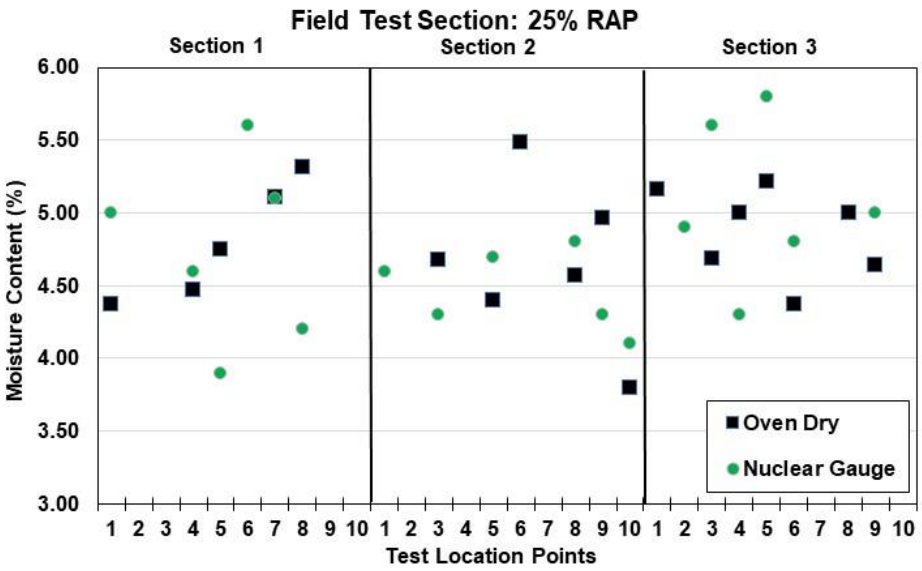

Figure 11. Field Section Moisture Measurements Using Nuclear Gauge and Oven-Dry Method. RAP = reclaimed asphalt pavement.

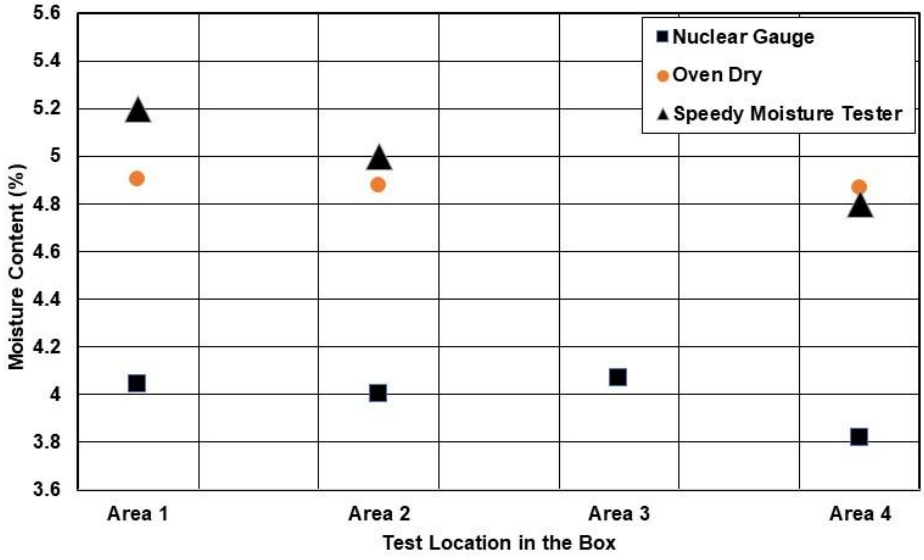

Figure 12. Moisture Measurements for Laboratory Box with 100% Aggregate

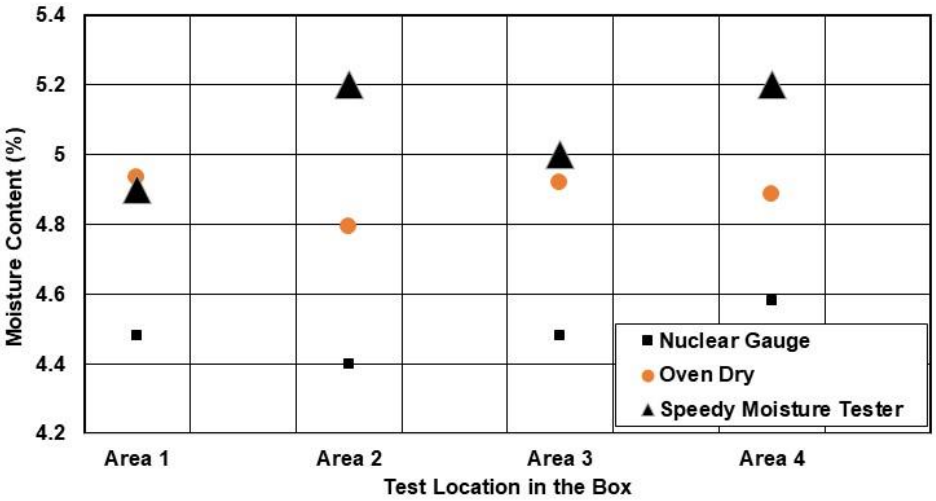

Figure 13. Moisture Measurements for Laboratory Box with 25% Reclaimed Asphalt Pavement

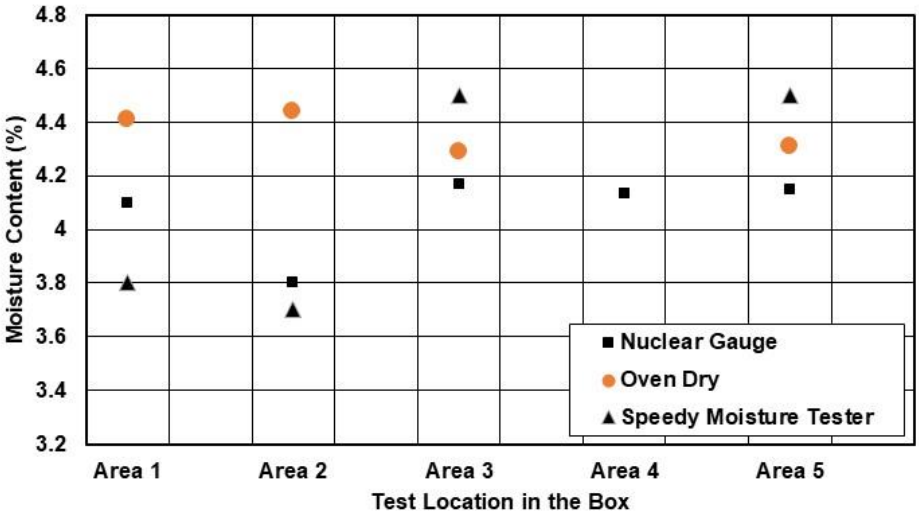

Figure 14. Moisture Measurements for Laboratory Box with 30% Reclaimed Asphalt Pavement

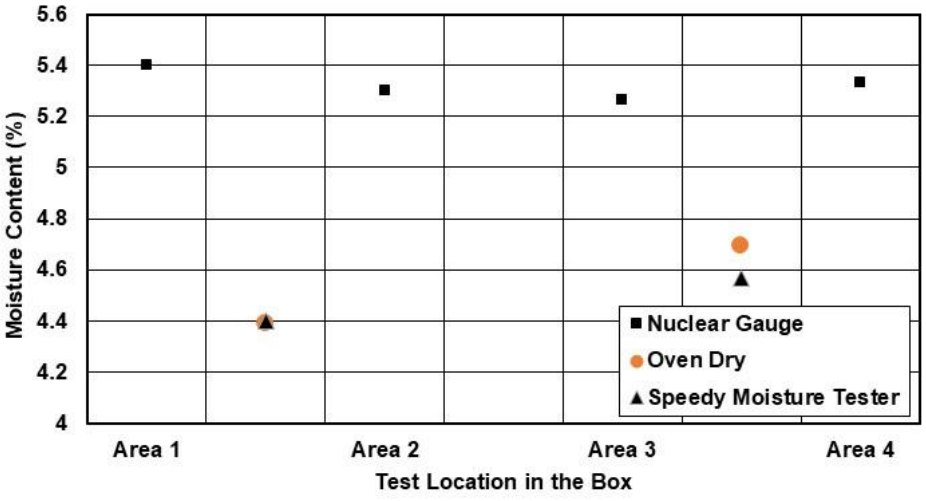

Figure 15. Moisture Measurements for Laboratory Box with 50% Reclaimed Asphalt Pavement

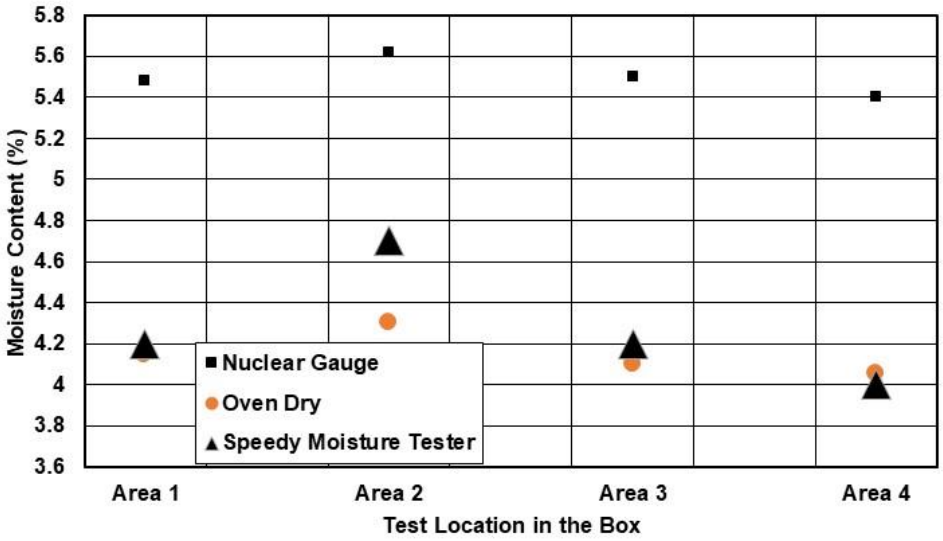

Figure 16. Moisture Measurements for Laboratory Box with 75% Reclaimed Asphalt Pavement

Comparison Between Speedy Moisture Tester and Oven-Dry Method

The Speedy moisture tester was used to measure moisture in the laboratory box experiment. Figure 17 shows the differences in moisture content measurements between the Speedy moisture tester and the oven-dried method at 60° C. Data includes all one-to-one measurements in the laboratory boxes, with the differences within 1%. All Speedy moisture tester readings are based on the wet weight of the sample (20 grams). When converted or corrected to dry weight, these readings will be about 0.1 to 0.2% higher than the actual Speedy moisture tester readings.

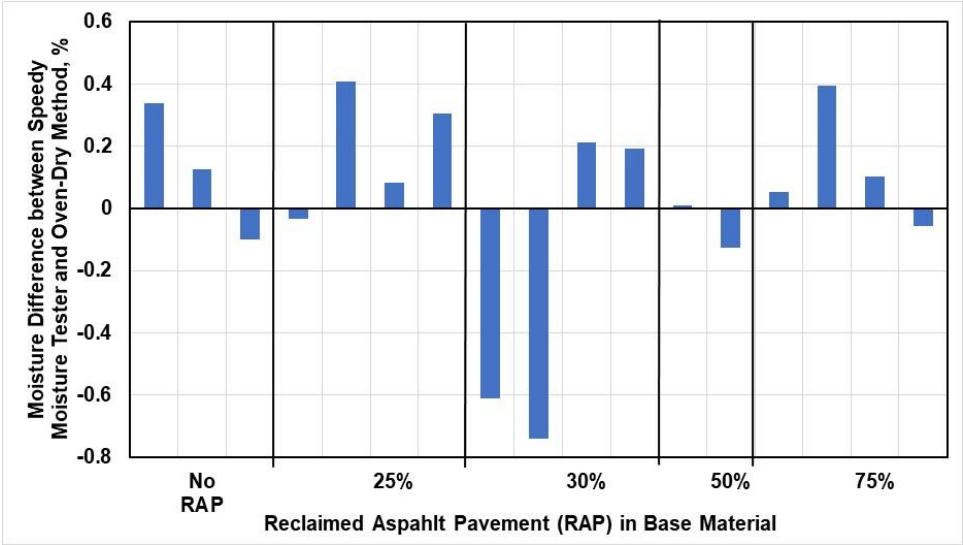

Figure 17. Difference between Speedy Moisture Tester and Oven-Dry (at 60° C) Moisture Measurements for Laboratory Box Experiment. RAP = reclaimed asphalt pavement. (Difference = Speedy Moisture Tester – Over-Dry).

Figures 18 through 20 show the results from the experiment to specifically evaluate the Speedy moisture tester on loose mix for the following cases:

- Speedy moisture tester and oven-dried method at 60° C.
- Split samples.
- Between two oven temperatures: 60° C versus 110° C.

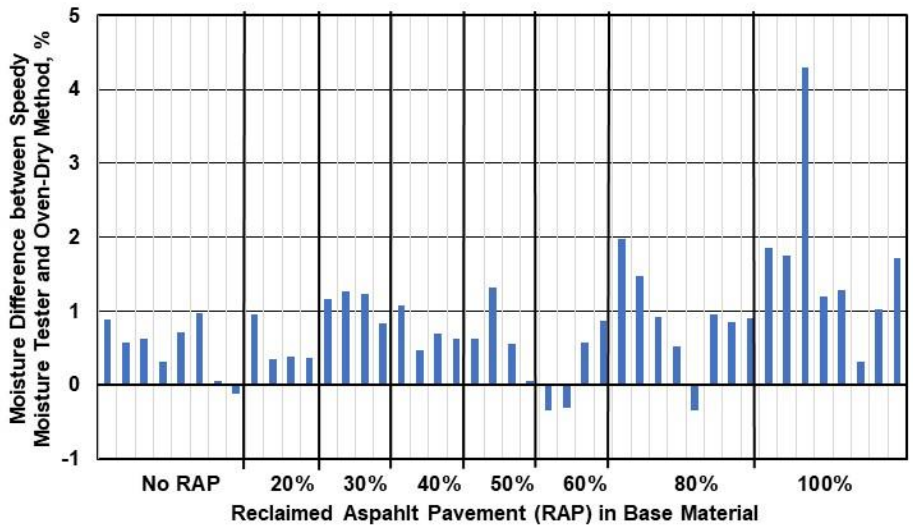

Figure 18. Moisture Difference between Speedy Moisture Tester and Oven-Dry Method (at 60° C) for Loose Mix. (Difference = Speedy Moisture Tester – Over Dry).

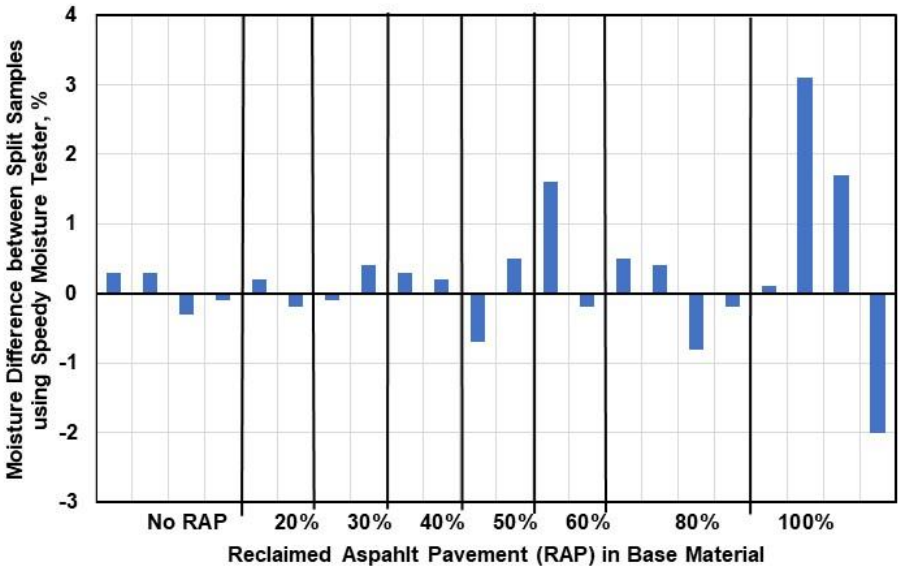

Figure 19. Moisture Difference between Two Split Samples of Loose Mix as Measured by Speedy Moisture Tester

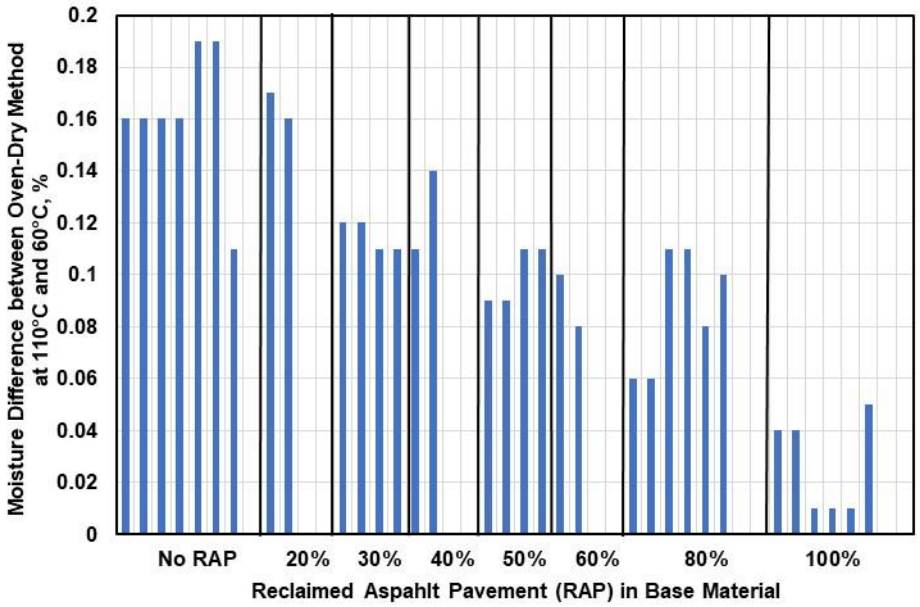

Figure 20. Difference in Oven-Dry Moisture Measurements between 110° C versus 60° C. (Difference = Oven-Dry at 110°C- Over-Dry at 60°C).

As observed in Figure 18, the Speedy moisture tester tended to measure a little higher moisture compared with the oven dried method. The difference is less than 1% for most part, except for a few cases in which the RAP content is more than 50%. The difference is attributable to a small sample size (20 grams) and exothermic reaction in the Speedy moisture tester method. The chemical reaction between calcium carbide and water produces a significant amount of heat that could drive out some of the volatiles from the asphalt in RAP, resulting in measurement error. Sotelo et al. (2014) also found the Speedy moisture tester to be a valuable measurement tool for soil but sometimes prone to error. Because the sample size is relatively small, large particles typically cannot be included in the composite measurement, which could be a source of error (Berney et al., 2011).

When the moisture contents between two identical split samples were compared for measurement consistency in Figure 19, the differences in Speedy moisture tester measurements were relatively small at low RAP content, but some large differences were observed when RAP content was high. RAP is hydrophobic and more likely to have water segregation with higher RAP content such that more water would be available near the fine particles and at the bottom of the container.

When the samples were dried at 60° C and 110° C, the resulting difference in the moisture content determination was within 0.2% for aggregate without RAP and within 0.05% for 100% RAP materials, as Figure 20 shows. The most likely explanation for this result is the relative difference in water absorption at the particle surface. RAP particles are coated with asphalt, resulting in negligible water absorption. In contrast, aggregate particles may need to be heated to 110° C to drive out the absorbed moisture. Therefore, the higher the amount of aggregate, the higher the difference.

Comparison Between Nuclear and Oven-Dry Method for Moisture

A nuclear gauge determines moisture by detecting hydrogen atoms. If the material being tested contains sources of hydrogen other than water, they will also be integrated in the overall measurement. Because the asphalt binder in RAP includes hydrogen atoms, they are counted as additional water, resulting in the apparent moisture content being more than the actual value. RAP material used in this study contained 5.74% asphalt, as determined by using the ignition oven.

Nuclear gauge moisture measurements were compared with the oven-dry moisture contents (Figure 21). A linear trend in the difference between oven-dry and nuclear gauge water contents is evident with the increasing RAP content in the aggregate blend. This trend can be quantified using a linear equation for each specific project for a particular gauge and material.

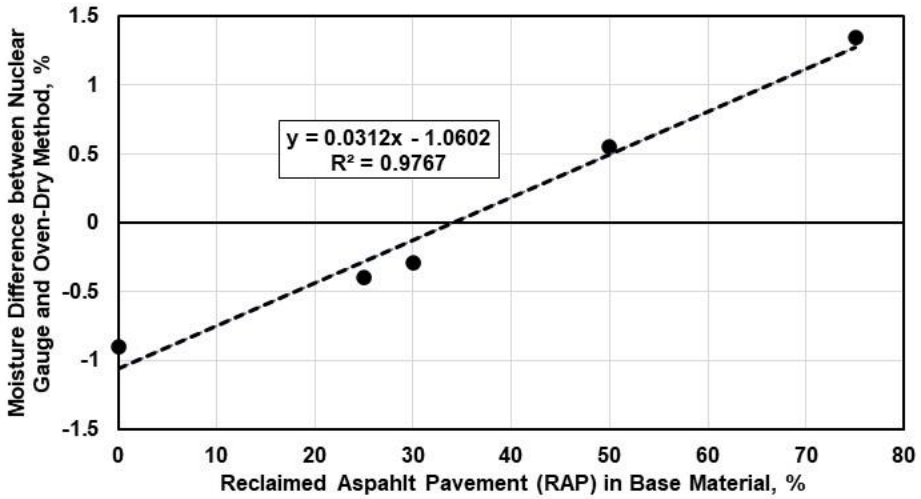

Figure 21. Difference between Nuclear Gauge and Oven-Dry Test Methods for Moisture Measurement in the Laboratory Boxes. (Difference = Nuclear Gauge - Oven-Dry).

Figure 21 shows a moisture offset at 0% RAP and a slope value of the linear fit. The intercept and the slope reflect two unrelated factors, aggregate and RAP, respectively. Theoretically, no measurable difference should be notable when a test is performed on aggregate without RAP. In practice, nuclear gauge is measuring less moisture than the over-dry method for our experiment, discrepancy sometimes arises because of the nature of the aggregate. This commonly recognized discrepancy can be easily adjusted by entering a correction value in the nuclear gauge. Many state DOTs use a correction value for moisture measurements with nuclear gauge in the base aggregate. The slope component in Figure 21 is purely indicative of the RAP content in the aggregate blend, the higher the RAP content larger the difference in the moisture measurement in linear proportion. The asphalt content in the RAP is directly contributing to the moisture measurement.

Development of Guidance for Nuclear Gauge Use

Currently, VDOT's quality-control practice for aggregate base layer construction involves monitoring compaction density and the moisture content using a nuclear gauge. The

acceptance criterion is based on achieving the required percentage of compaction as expressed by the ratio of dry densities obtained from laboratory and field testing. Dry density is calculated from the wet density and respective moisture content. Its accuracy depends on the separate measurements of wet density and moisture content.

During this study, the nuclear gauge measured wet densities of base aggregate containing RAP comparable with the sand cone method. The wet densities measured by nuclear gauge in the laboratory box experiment were within plus or minus 2 pcf of sand cone except one with close to 5 pcf, as Table 4 and Figure 10 show. On the other hand, the presence of asphalt in RAP influenced the measurement of moisture using nuclear gauge. This deviation in the measured moisture by nuclear gauge from the actual (oven dried) moisture varied linearly with the amount of RAP, as Figure 21 shows. As a result, offset values were needed for the moisture measurement.

The research team proposed using a nuclear gauge with a moisture correction applied for construction quality control when RAP is present in the unbound aggregate layer. A moisture offset correction should be determined on a project-by-project basis. For example, a correction can be established from at least five separate moisture content measurements using nuclear gauge on the test site and the corresponding oven-dry moisture contents. The difference between these two average measurements will result in a composite moisture correction value that addresses both the initial (relates only to aggregate) and RAP-dependent discrepancies. This value is then entered into the nuclear gauge for quality-control measurements. Most nuclear gauges have an option of using a preset offset value, so no additional calculation is needed during construction monitoring.

CONCLUSIONS

- *In a laboratory environment, nuclear gauge wet density measurements produced results within 2 pcf of the sand cone results, with one measurement falling within 5 pcf.* These results indicate acceptable measurement accuracy irrespective of the RAP content in a blended aggregate. Up to 75% of RAP was used in this experiment. The results were obtained using processed RAP with approximately 5.7% asphalt.

- *The presence of RAP influences the moisture content measurement in the RAP-aggregate base layer by nuclear gauge.* The moisture content is directly proportional to the RAP content in the base layer, which is attributed to the asphalt presence in RAP. An appropriate moisture offset for a nuclear gauge can easily be determined on a project-by-project basis for a particular aggregate and RAP blend.

- *Laboratory test results indicate a relatively close, within 1%, relationship between the oven-dry and Speedy moisture tester measurements up to approximately 50% RAP content in a RAP-aggregate blend, demonstrating sufficient accuracy.*

RECOMMENDATIONS

1. *VDOT's Materials Division and districts should use nuclear gauge for construction quality control of unbound aggregate base layer blended with RAP.*

2. *VDOT's Materials Division should incorporate changes in the respective Virginia Test Method to facilitate developing a moisture correction factor, or offset value, when nuclear gauge is used to measure moisture content in a base layer containing RAP.*

3. *VDOT's Materials Division should allow for the use of a Speedy moisture tester (or an equivalent where calcium carbide is used) as an alternative to the oven-dry method for determining the moisture offset when up to 50% RAP is present in the base layer. Other quick methods for moisture determination, such as using a hot plate or burner, should also be permitted.*

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

With regard to Recommendation 1, VDOT's Materials Division and districts will permit the use of nuclear gauge for construction monitoring of an unbound base layer construction when RAP is present with the requirement of a moisture-offset correction. VDOT's Materials Division will develop a special provision within two years of the publication of this report for using RAP in the base course, incorporating nuclear gauge for construction quality control.

With regard to Recommendation 2, VDOT's Materials Division will add language in the current VTM-10 to determine a moisture offset value for nuclear gauge when RAP is present. The offset value will be calculated on a project-by-project basis by comparing the moisture content measurements obtained from nuclear gauge with oven-dry measurements. The required modifications to the current VTM will be completed within two years of the publication of this report, the same time when the special provision in the implementation plan for Recommendation 1 is developed.

With regard to Recommendation 3, VDOT's Materials Division will allow for the use of a Speedy moisture tester (up to 50% RAP) or another quick method, such as hot plate or stove burner, for RAP-aggregate base on construction projects where time constraints preclude using a conventional oven-dry method for moisture offset determination. This approach will be incorporated into VTM-10 in the implementation plan for Recommendation 2 within two years of the publication of this report.

Benefits

In a recent VDOT study, Tanyu et al. (2021) found that up to 30% RAP could be used in an unbound base course without any adverse effect in the pavement performance. The study recommended using a LWD device for construction monitoring instead of VDOT's current practice of using nuclear gauge for compaction control. In practice, a significant resource allocation would be needed to implement a LWD-based quality-assurance program, including purchasing new LWD equipment and providing extensive training and skilled interpretation of the results. The necessary equipment would cost more than $100,000.

The current market price for LWD devices is around $7,000 to $10,000 for each unit. At least 13 devices would be needed for the following:

- nine districts with at least one for each district,
- three district laboratories with one for each laboratory, and
- one for the Materials Division.

In addition, expenses for training, skilled professional, and management and maintenance will be incurred. By implementing the use of nuclear gauge in RAP-aggregate base construction, VDOT will realize the following benefits:

- Not having to devote significant resources to implement an LWD program.
- Implementing RAP use in the base course immediately because all the resources are already in place for nuclear gauge testing.
- Gaining experience using RAP material in pavement base construction.

ACKNOWLEDGMENTS

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APPENDIX: NUCLEAR GAUGE RESULTS FOR LABORATORY BOXES

Table A1. Nuclear Gauge Wet Density Readings (pcf) for Laboratory Boxes

Location (reading time)	Depth, inches	100% Aggregate (4 minutes)	25% RAP (1 minute)	30% RAP (4 minutes)	50% RAP (4 minutes)	75% RAP (1 minute)
Area 1	8	141.6	125.7 (4 min)	–	129.3	120.7 (4 min)
	8	–	125.7	–	–	120.4
	6	141.1	125.0	134.9	130.1	119.5
	4	140.3	126.1	134.9	130.1	122.5
	2	137.5	126.9	132	128.4	121.4
	Backscatter	136.8	–	–	–	–
Area 2	8	138.2	127.6 (4 min)	–	129.6	121.2 (4 min)
	8	–	128.0	–	–	120.9
	6	138.6	127.2	134.3	130.6	121.7
	4	136.5	126.4	134.4	129.8	122.9
	4	136.7 (1 min)	–	–	–	–
	2	134.6	127.9	134.8	129.1	121.2
	Backscatter	131.1	–	–	–	–
Area 3	8	140	124.8 (4 min)	–	–	121.7 (4 min)
	8	–	124.8	–	–	121.8
	6	141.2	124.2	131.8	129.8	121.1
	4	139.3	127.4	134.6	129.4	122.5
	4	139.5 (1 min)	–	–	–	–
	2	138.2	128.5	136.2	129.6	121.7
	Backscatter	135.1	–	–	–	–
Area 4	8	141.5	124.1 (4 min)	–	–	121.7 (4 min)
	8	–	124.8	–	–	121.5
	6	140.6	123.3	131.4	129.5	121.8
	4	139.3	124.7	135.1	127.5	122.2
	4	139.6 (1 min)	–	–	–	–
	2	137.2	126.0	136.2	127.0	121.1
	Backscatter	135.2	–	–	–	–
Area 5	8	–	–	136.2	–	–
	6	–	–	135.6	–	–
	4	–	–	135.3	–	–
	2	–	–	135.3	–	–
Average		138.25	125.96	134.56	129.27	121.48
Standard Deviation		2.61	1.49	1.53	1.00	0.78

– = data not available; RAP = reclaimed asphalt pavement. The values within brackets indicate the time for a nuclear gauge to obtain reading.

Table A2. Nuclear Gauge Moisture Readings (%) for Laboratory Boxes

Location (reading time)	Depth, inches	100% Aggregate (4 minutes)	25% RAP (1 minute)	30% RAP (4 minutes)	50% RAP (4 minutes)	75% RAP (1 minute)
Area 1	8	3.9	4.6 (4 min)	–	5.4	5.5 (4 min)
	8	–	4.5	–	–	5.5
	6	4.1	4.3	4.0	5.4	5.6
	4	4.1	4.5	4.1	5.3	5.5
	2	4.0	4.5	4.2	5.5	5.3
	Backscatter	4.1	–	–	–	–
Area 2	8	3.9	4.3 (4 min)	–	5.2	5.6 (4 min)
	8	–	4.5	–	–	5.6
	6	3.8	4.6	3.8	5.3	5.9
	4	4.2	4.4	3.9	5.4	5.6
	4	4.0 (1 min)	–	–	–	–
	2	3.9	4.2	3.7	5.3	5.4
	Backscatter	4.2	–	–	–	–
Area 3	8	4.1	4.6 (4 min)	–	–	5.6 (4 min)
	8	–	4.5	–	–	5.3
	6	4.0	4.3	4.1	5.3	5.6
	4	4.1	4.5	4.3	5.5	5.7
	4	4.0 (1 min)	–	–	–	–
	2	4.0	4.5	4.1	5.0	5.3
	Backscatter	4.2	–	–	–	–
Area 4	8	3.7	4.6 (4 min)	–	–	5.4 (4 min)
	8	–	4.4	–	–	5.3
	6	3.8	4.5	4.3	5.2	5.5
	4	3.8	4.7	4.1	5.4	5.1
	4	3.8 (1 min)	–	–	–	–
	2	3.9	4.7	4.0	5.4	5.7
	Backscatter	3.9	–	–	–	–
Area 5	8	–	–	4	–	–
	6	–	–	4.1	–	–
	4	–	–	4.3	–	–
	2	–	–	4.2	–	–
Average		3.98	4.5	4.1	5.3	5.5
Standard Deviation		0.14	0.13	0.17	0.13	0.18

– = data not available; RAP = reclaimed asphalt pavement. The values within brackets indicate the time for a nuclear gauge to obtain reading.

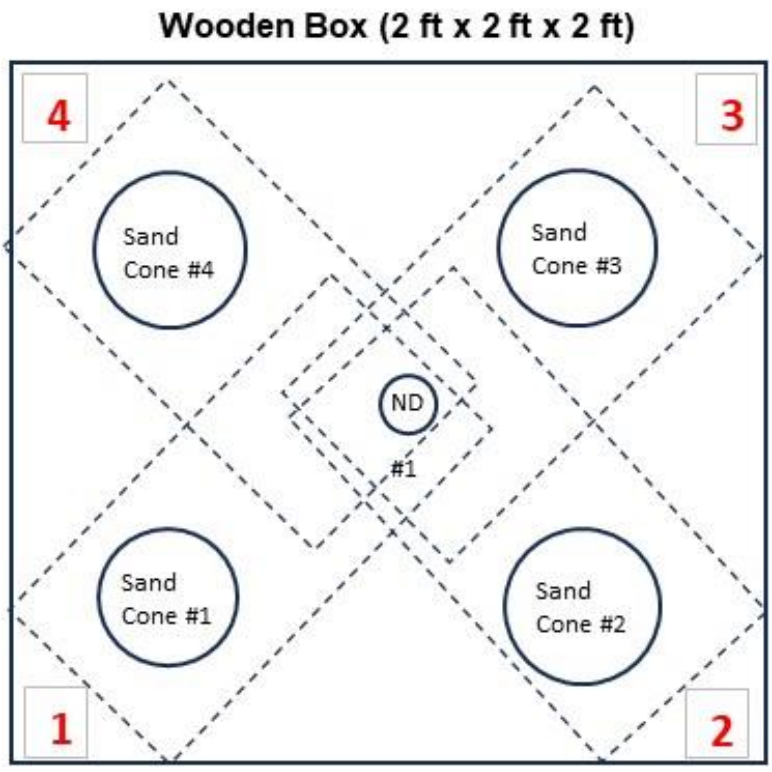

Figure A1. Schematic Diagram of Nuclear Gauge Placement inside the Laboratory Box (Example: 25% Reclaimed Asphalt Pavement). Dotted line represents nuclear gauge footprint. ND = nuclear density measurement hole.