EVALUATING THE METHODOLOGY OF LIGHT WEIGHT DEFLECTOMETER (LWD) TO BE USED FOR CONSTRUCTION QUALITY CONTROL AND ASSURANCE OF RECLAIMED ASPHALT PAVEMENT (RAP) AGGREGATES

by

Emre Akmaz

A Thesis
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Civil, Environmental, and Infrastructure Engineering

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Evaluating the Methodology of Light Weight Deflectometer (LWD) To Be Used For Construction Quality Control and Assurance of Reclaimed Asphalt Pavement (RAP) Aggregates

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Bachelor of Science
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DEDICATION

To my dear wife Irem Akmaz

and

my dear family

who supported me and made it possible for me to complete this work.

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LIST OF ABBREVIATIONS AND SYMBOLS

Light Weight Deflectometer .... LWD
Nuclear Density Gauge .... NDG
Falling Weight Deflectometer .... FWD
Large Scale Model Experiment .... LSME
Reclaimed Asphalt Pavement .... RAP
Virgin Aggregate .... VA
Department of Transportation .... DOT
American Standard and Testing Methods .... ASTM
American Association State Highway and Transportation Officials .... AASHTO
Virginia Department of Transportation .... VDOT
Elastic Modulus .... E
Stiffness .... k
Poisson's Ratio v
Stress Distribution Factor .... A
Deflection .... δ
Settlement Factor .... I_p
Multilayer System Deflection .... $\Delta_z|_2$
LWD's surface load .... $q_{surface}$
Plate Diameter .... D
Mold Height .... H

ABSTRACT

EVALUATING THE METHODOLOGY OF LIGHT WEIGHT DEFLECTOMETER (LWD) TO BE USED FOR CONSTRUCTION QUALITY CONTROL AND ASSURANCE OF RECLAIMED ASPHALT PAVEMENT (RAP) AGGREGATES

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Reclaimed Asphalt Pavement is being produced from asphalt concrete, is mostly aggregate material and is itself granular and can be used in a variety of applications for which freshly produced natural aggregates have traditionally been used and does not behave like aggregate (Hoppe, Lane, Fitch, & Shetty, 2015). According to recent VCTIR study (2015), there is approximately 4.7 million tons of excess RAP stockpiled in VA. RAP has a binder content over the top of aggregate and due to the complex nature of the RAP. The quality control of compacted unbound aggregate pavements is performed by the traditional method of the nuclear density gauge (NDG) (Smith & Diefenderfer, 2008). However, the nuclear density gauge does not provide accurate results for density and moisture content measurements on reclaimed asphalt pavement (RAP) (Viyanant et al., 2004). For this reason, the light weight deflectometer (LWD) is another preferable tool for compaction quality control of soil pavements in highway construction to determine

the elastic modulus (Fleming et al., 2000; Fleming et al., 2007; Nazzal et al. 2007; Mooney & Miller, 2009; Vennapusa & White, 2009; Ebrahimi & Edil, 2013; Khosravifar, 2015). The LWD works with dropping weight from a given height on a circular plate over the soil ground and measures applied force and deflection using geophone which is underneath center of the plate (Fleming et al. 2000; Ebrahimi & Edil, 2013). Some studies stated the depth of influence for the LWD is 0.9-1.1 times the plate diameter which means between 27 and 33 cm (Kavussi et al. 2010; Kudla et al. 1991; Mooney & Miller, 2009; Nazzal et al. 2007; Ryden & Mooney, 2009; Senseney & Mooney, 2010). Therefore, if the thickness of the layer under observation is less than the plate diameter then the determine modulus is affected by the layer underneath the test layer. In that case the determined modulus is the result of the combined response of test layer and the layer underneath it. For this situation, multilayer system method has to be used to back-calculate the tested layer's elastic modulus (Nazzal et al. 2007). There is a lack of research on the confirmation of validity of the LWD. The multilayer system and depth of influence effects has not been implemented with RAP and RAP-VA blends materials. Therefore, the purpose of this research is to focus on how to use the LWD tool to analyze the reclaimed asphalt pavement in order to develop methodology to implement quality control during construction of roadways. To achieve this scope, first phase of the research covers laboratory testing program using the Large Scale Model Experiment (LSME) and proctor mold tests to obtain the target elastic modulus values of VA, RAP, and RAP-VA blends materials with LWD. Additionally, the nuclear density gauge is not useful for bituminous materials and LWD device does not provide moisture content control therefore speedy moisture tool was calibrated and performed for each material in the laboratory. The second phase of the research validates laboratory findings in the field implementation. The study will be geared towards the evaluation of suitable quality assurance (QA) /quality control (QC) methods for RAP-Virgin Aggregate blends in the field. Also, this test method can be implemented for VA materials.

INTRODUCTION

The quality control of compacted unbound aggregate pavements is performed by the traditional method of the nuclear density gauge (NDG) (Smith & Diefenderfer, 2008). The nuclear density gauge is rapid device to evaluate the moisture content and density of the compacted soils in the field (Viyanant et al., 2004). However, the nuclear density gauge does not provide accurate results for density and moisture content measurements on reclaimed asphalt pavement (RAP) (Viyanant et al., 2004). To be specific, the NDG has a limitation with collecting data on RAP materials because the hydrocarbon compounds in the RAP material absorb the gamma rays from the radioactive source that affect in deceptive results (Smith & Diefenderfer, 2008). Additionally, moisture content and density are not engaged as input parameters in the mechanistic empirical pavement design (Alshibli et al., 2005; Hossain & Apeagyei, 2010). The resilient modulus is the material characteristic that describe the performance of pavement layer with MEPDG and the light weight deflectometer (LWD) provides the in-situ modulus determination. For this reason, the LWD is another preferable tool for compaction quality control of soil pavements in highway construction to determine the elastic modulus (Fleming et al., 2000; Fleming et al., 2007; Nazzal et al. 2007; Mooney & Miller, 2009; Vennapusa & White, 2009; Ebrahimi & Edil, 2013; Khosravifar, 2015). In addition to this, moisture content can be controlled from the speedy moisture tester that uses the calcium carbide in the pressure vessel to absorb moisture content of the tested material.

The LWD device is the portable version of the Falling Weight Deflectometer (FWD) and was developed in 1981 at Germany (Nazzal et al. 2007; Vennapusa et al., 2012). In this research, Dynatest LWD was used for testing program and developed in Denmark. Using homogeneous, isotropic, linear half-space elastic theory, the LWD determines stiffness and elastic modulus of unbound materials in pavements. The LWD works with dropping weight from a given height on a circular plate over the soil ground and measures applied force and deflection using geophone which is underneath center of the plate (Fleming et al. 2000; Ebrahimi & Edil, 2013). The software allows the users to enter poisson's ratio with the device depending on test material (Dynatest, 2010). LWD has also additional geophones to measure deeper thicknesses than conventional LWD testing and depth of thickness is 1.8 times plate diameter (Senseney & Mooney, 2010).

In the U.S., the highway construction industry annually produces 100 million tons of reclaimed asphalt pavements (RAP) (Hoppe et al. 2015). In Virginia, there is 4.7 million tons of access RAP that unless recycled is going to be sent to landfill and this is extremely costly and it takes landfill spaces that could be better utilized for waste material (Hoppe et al. 2015). Bennert et al. (2000) and Taha et al. (1999) suggest that mixing the RAP with high quality virgin aggregate (VA) gives better quality and develops the consistency of the blend. Locander (2009) concluded that RAP may be an alternative for unbound aggregate base course. Twelve DOTs and four countries specified that use of mixture RAP in the base course section is up to 60 percent (Hoppe et al. 2015). Using RAP in base course section is sustainable development and reduces the industrial waste of stockpiles (Ullah et al. 2018).

As explained in the above section that LWD works on the principle of conversion of potential energy into kinetic energy when the weight hits the rubber pads. The potential energy stored in the weight is transferred to the ground as soon it hits the rubber pad, as a reaction of this energy transfer the ground vibrates and the movement is recorded by the geophone attached on the LWD. The depth to which the energy is transmitted after the weight is dropped is referred to as the zone of influence. The depth of influence is typically dependent on the diameter of the plate, several studies suggest that the depth of influence may vary between 0.9 – 1.1 times the plate diameter (Kavussi et al. 2010; Kudla et al. 1991; Mooney & Miller, 2009; Nazzal et al. 2007; Ryden & Mooney, 2009; Senseney & Mooney, 2010). Therefore if the thickness of the layer under observation is less than the plate diameter then the determine modulus is affected by the layer underneath the test layer. In that case the determined modulus is the result of the combined response of test layer and the layer underneath it. The combined modulus can mislead the operator performing the test. This problem has been identified in the past literature. Nazzal et al. (2007) stated that the depth of influence LWD can reach under the top layer and into the subgrade. For this situation, multilayer system method has to be used to back-calculate the tested layer's elastic modulus (Nazzal et al. 2007). However, Nazzal et al. (2007) did not present the multilayer system formula and poisson's ratios of the subgrade and base course. Mazari et al. (2016) proposed the single layer system to determine target elastic modulus value for construction quality control. However, the LWD's depth of influence may reach second layer of the pavement. Based on pavement layers thickness, the LWD can be performed on multilayer system. Schwartz et al. (2017) provided a formula for unbound multilayer pavement systems. However, the formula does not include bottom layer's poisson's ratio which is necessary to measure the elastic modulus of top layer. The main purpose of the multi-layer system is to show different elastic modulus and stiffness within the LWD's depth of influence because each layer can have a different poisson's ratio, as related to each layer's thickness (Balunaini et al. 2013). In modern pavement design method, elastic modulus, poisson's ratio and thickness of the material give the prediction of deformation (Ryden & Mooney, 2009). Therefore, LWD's elastic modulus value is related to testing material's poisson's ratio. Kazmee et al. (2016) stated that 100% RAP performed higher elastic modulus than 100 % VA on subbase layer with LWD. However, the results show that subgrade layer under the 100% RAP and VA subbase might affect the LWD elastic modulus values because of the LWD depth of influence. Kazmee et al., (2017) stated that the LWD was used on the subgrade and unbound granular layers to control the quality of compacted layers however no solutions have been provided.

In the literature, Khosravifar (2015) provided a new approach using LWD testing directly on the compaction mold to come up with target elastic modulus for the field. The compaction mold test gives opportunity to obtain elastic modulus value for quality control tests instead of density based quality control method (Schwartz et al., 2017). Khosravifar (2015) found that the comparison of the large scale field and mold surface elastic modulus values on subgrade and base layers have a poor correlation. However, after excluding the virgin aggregate material's elastic modulus from the graph, correlation was stronger than before. In order to obtain better correlation, performing multiple tests on compaction mold and large scale model experiment (LSME) test pit is suggested (Khosravifar, 2015). To extend the finding of Khosravifar (2015), performing LWD with VA, RAP, and RAP-VA blends in the LSME test pit, the compaction mold and the field studies might be promising procedures to obtain better elastic modulus correlation with course materials.

There is a lack of research on the confirmation of validity of the LWD. The multilayer system and depth of influence effects has not been implemented with RAP and RAP-VA blends materials. Therefore, the purpose of this research is to focus on how to use the LWD tool to analyze the reclaimed asphalt pavement in order to develop methodology to implement quality control during construction of roadways. To achieve this scope, first phase of the research covers laboratory testing program using the Large Scale Model Experiment (LSME) and compaction mold tests to obtain the target elastic modulus values of VA, RAP, and RAP-VA blends materials with LWD. Additionally, the nuclear density gauge is not useful for bituminous materials and LWD device does not provide moisture content control therefore speedy moisture tool was calibrated and performed for each material in the laboratory. The second phase of the research validates laboratory findings in the field implementation. The study will be geared towards the evaluation of suitable quality assurance (QA) /quality control (QC) methods for RAP-VA blends in the field. Furthermore, this test method can be implemented for VA materials.

METHODOLOGY

Light Weight Deflectometer (LWD):

The LWD performs on compacted geomaterials in highway construction to determine elastic modulus and stiffness (Ebrahimi & Edil, 2013; Khosravifar, 2015). The LWD uses Bousinesq Equation with measured deflection and force to connect with static linear-elastic half space theory which calculates LWD elastic modulus (ELWD) which is shown in Equation 1

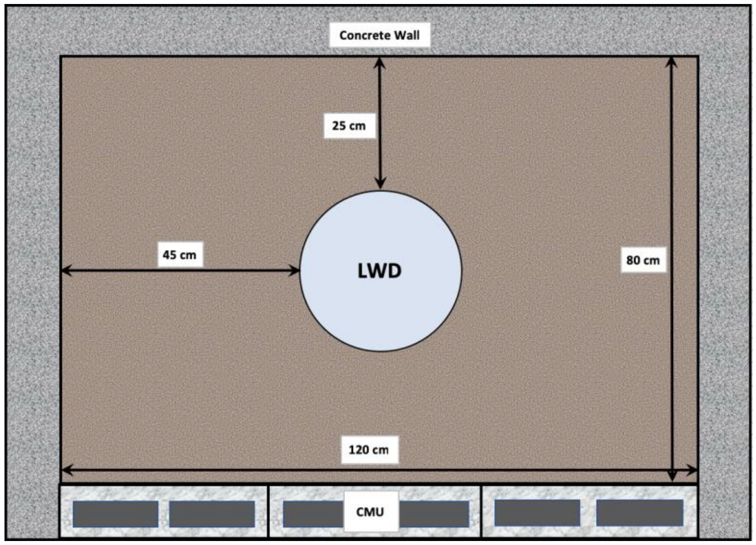
Equation 1

$$E = \frac{2k_s(1 - v^2)}{Ar_0}$$

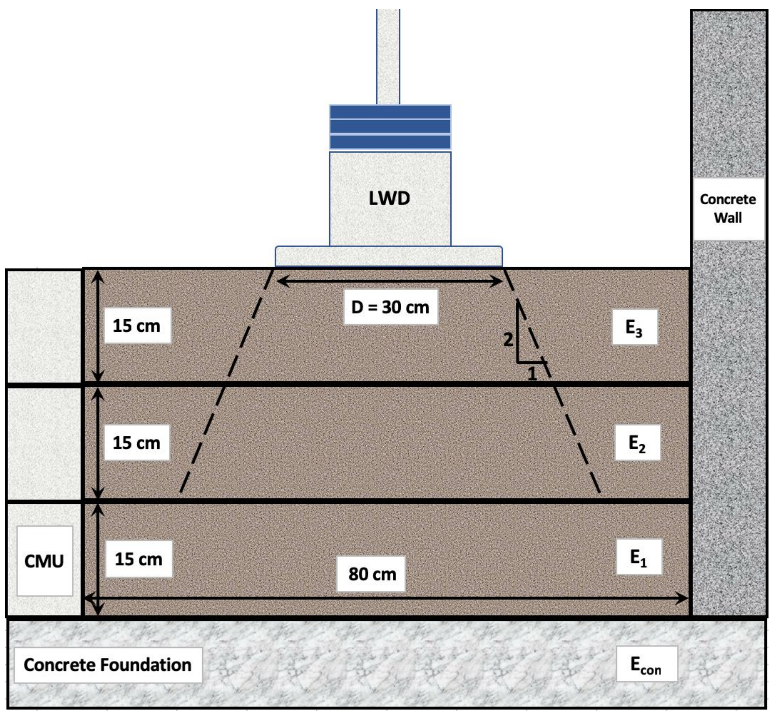
Equation 1 shows stiffness (k_s) where $k_s = F_{peak} / \delta_{peak}$, Stress distribution factor (A), Poission's ratio (v), and plate radius (r_0). Force (F) and deflection (δ) values are an input parameter of LWD. Stress distribution factor can be different for different types of soil. Schwartz et al. (2017) stated the different types of stress distribution factor for each soil type. Dynatest LWD can produce maximum 15 kN load with 10 kg standard drop weight and has the option to select poission's ratio and shape factor via application (Dynatest, 2010). Using the measured deflections are to calculate the stiffness and elastic modulus of bound and unbound pavement surfaces. The coefficient of variation of the test method was determined 15 percent for this research (ASTM E2583, 2015). The LWD measures applied force and deflection using geophone which is underneath center of the plate (Fleming et al. 2000). For the LWD drop tests, at least first two drops should not be included in calculations because these two drops do not reach the maximum deflection and impact load and the plate needs to sit on the surface (ASTM E2583, 2015). The last six drops were used in analysis for elastic modulus and stiffness values. The drop height of LWD was chosen at maximum point (85 cm) in this study considering the fact that drop height does not affect the elastic modulus of LWD (Lin et al., 2006). The LWD can measure deeper with additional sensors and the depth of influence reaches up to 1.8 times plate diameter (Senseney & Mooney, 2010). However, additional geophones were not used in this research and the depth of influence was between 0.9 and 1.1 times plate diameter, which equated to 27 cm and 33 cm.

Large Scale Model Experiment (LSME):

In the laboratory testing program, the LWD provides elastic modulus and stiffness of the materials using 100% VA and RAP-VA blends as base course materials in the LSME test pit. The Kushlan products mixer was used to mix materials at optimum moisture content. Figure 1 shows the LSME test pit had a 120 cm length, 80 cm width test area and the height of the concrete walls were 100 cm.



(a)



(b)

Figure 1 - Schematic of the large scale model experiment (LSME) test pit and stress distribution of LWD (a) plan view and (b) cross section of the LSME.

The LWD tests were not affected by the LSME test pit sizes because stress distribution of the LWD does not reach the concrete wall. The plate diameter of LWD was chosen 30 cm so that the load stress is shown in Figure 1 and reached up to 30 cm vertically and 15 cm horizontally. The effect of each LWD drop reaches up to 30 cm below the surface. Each layer was compacted with Packer Brothers electric plate compactor and it’s depth of influence was 20 cm in height. Because of the LWD’s and compactor’s depth of influence, three layers were placed on the LSME test pit in which each layer has 15 cm thickness and total height of 45 cm. The readings investigated depth beyond 15 cm of the first layer and 15 cm of concrete. After placement and compaction of the first layer, eight LWD drops were performed at the center of the LSME test pit. The second layer was placed and compacted on the first layer. Same LWD test procedures were followed. Based on LWD depth of influence, the plate diameter was used 30 cm and LWD depth of influence still may reach to concrete ground. In order to eliminate possible impacts of the concrete on the test results and to obtain elastic modulus of materials, additional layer was placed on the LSME test pit. The third layer was also tested with LWD and elastic modulus of the third layer was used a target elastic modulus for field testing program for each testing material. However, performing LWD on the LSME test pit is not applicable method in the field to provide target elastic modulus tests. Instead of using LWD on LSME test pit for target elastic modulus, the compaction mold test is faster and more practical method.

Compaction Mold Testing:

On the compaction mold tests, using LWD to obtain average elastic modulus (E_{mold}) for the quality control tests. In the laboratory tests, the elastic modulus values from the LSME and the compaction mold were used to correlate VA, RAP, and RAP-VA blends. The LSME and compaction mold methods provide correlated target elastic modulus (E_{target}) of the soil. Figure 2 shows how to place the LWD on compaction mold and compacted soil.

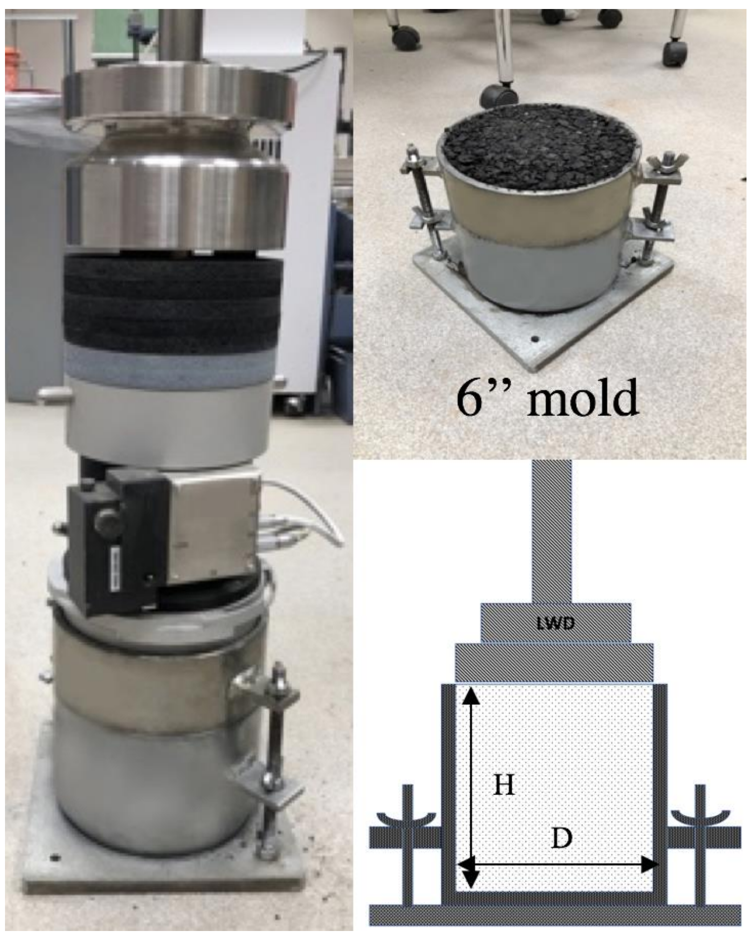


Figure 2 - Schematic of LWD on 6" compaction mold test.

In the laboratory, the LWD was performed on seven different materials. To maintain accurate results on the compacted material, the diameter of the LWD plate was 15 cm and the inner diameter of the mold is 15.24 cm is shown in Figure 2. In laboratory, three layers were placed in the compaction mold in which each layer was 5.5 cm height and total height was 16.5 cm. The soils were compacted with vibratory hammer at optimum moisture content (AASHTO T307, 2007). To estimate the elastic modulus of the soil, LWD was placed on top of the soil right above the compaction mold and the readings were obtained based on six drops. The first two of these drops were used for seating purposes and not included in the analyses. The COV (%) was calculated only using the modulus values from the six drops and by obtaining the ratio of standard deviation and average modulus values. The acceptable COV is defined in ASTM E2583 as 15% for unbound granular materials. This test was conducted based on the assumption that the drops of LWD did not plastically deformed the soil and the waves did not propagate to the concrete below where the mold sat on top of. This assumption is consistent with others who had conducted similar tests with LWD (Khosravifar, 2015).

Schwartz et al. (2017) stated the equation about compaction mold test. The equation is as follows:

Equation 2

$$E=\left(1-\frac{2v^2}{1-v}\right)\frac{4H}{\pi D^2}k$$

where, height of the mold (H), diameter of the plate or mold (D), poisson's ratio of the base course (v), soil stiffness (k) is provided by LWD drop tests and k=F/δ, where load (F) and deflection (δ).

Multilayer System Method:

The multilayer system method provides that different types of soil layer can be placed within the LWD depth of influence and the elastic modulus is affected by the layer underneath the tested layer. Balunaini et al. (2013) used a finite element method to calculate surface settlement for a multi-layer system. In our study, two layer formula was determined as a multilayer system.

For two layer system, Equation 3 is below,

Equation 3

$$\Delta_z|_2 = q_{surface} D \left[\frac{(1 - v_1^2)}{E_1} (I_{p1} - I_{p0}) + \frac{(1 - v_2^2)}{E_2} (I_{p2} - I_{p1}) \right.$$

Where, $\Delta_z|_2$ is settlement of the two layer system, E_1 is equal to E_{Top} that is top layer's elastic modulus, E_2 represents E_{Bottom} that is bottom layer's elastic modulus, $q_{surface}$ is circular load, D is the diameter of LWD, v is the poisson's ratio of top and bottom layers, Ip_0, Ip_1, and Ip_2 are symbolizing the corresponding settlement factors (I_n) representing to depth of z=0 (i.e., Ip_0), $z=H_1$ (i.e., Ip_1), $z=H_1+H_2$ (i.e., Ip_2), respectively (Balunaini et al., 2013). Using these input parameters, the multilayer system was created and base course elastic modulus (E_{Top}) were obtained in the field. The target elastic modulus (E_{target}) control the multilayer system's computed base course elastic modulus values (E_{Top}).

Vesic's graph (1963) was used to procure vertical settlement factors based on this research's two-layer system in Figure 3.

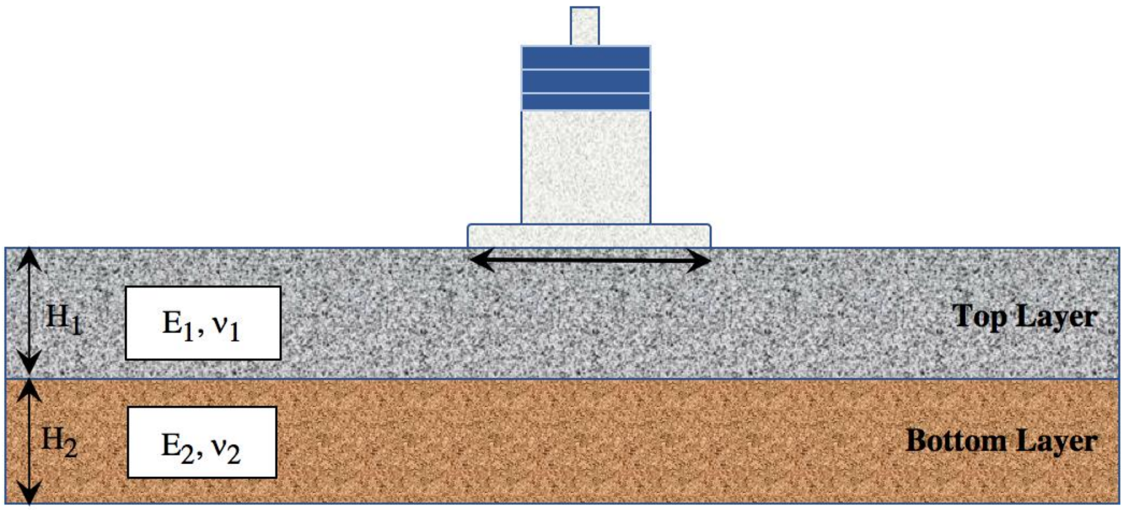
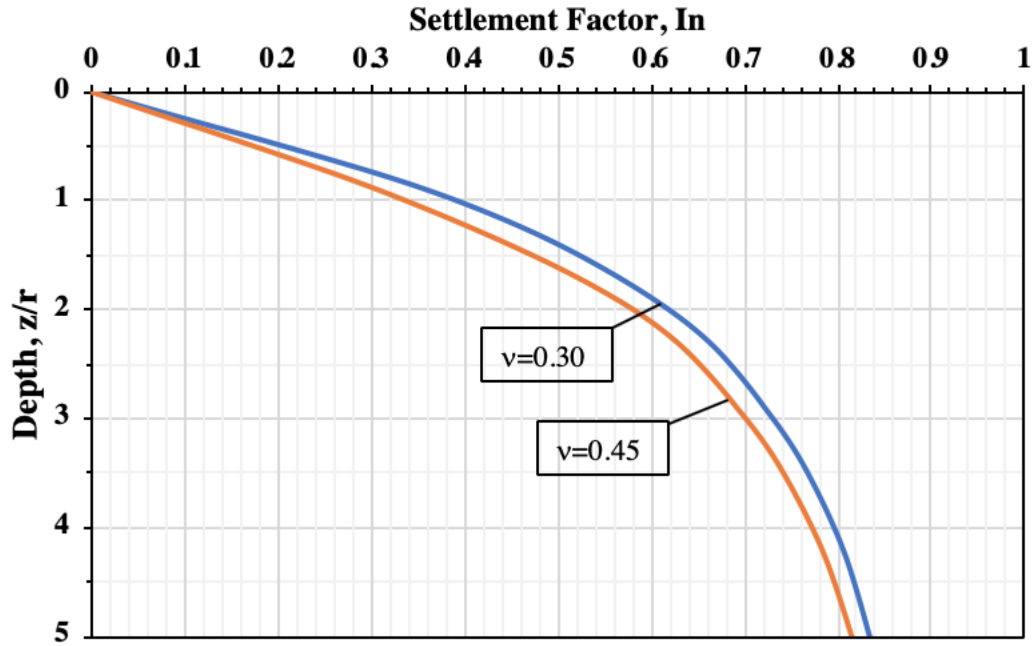


Figure 3 - Schematic of the multilayer system.

Schwartz et al. (2017) suggested the typical values of materials' poisson's ratio based on mechanistic empirical pavement design guide (MEPDG). Maher and Bennert (2008) stated that typical values of untreated granular materials and saturated soft clay poisson's ratios are 0.3 and 0.45, respectively. In this study, the base course material was assumed 0.3 poisson's ratio. In the field multilayer system, poisson's ratio of subgrade was assumed 0.45. Figure 4 was recreated based on this research and shows settlement factor values for poisson's ratios 0.3 and 0.45. Because poisson's ratios of 0.3 and 0.45 were used in this study. Settlement factors were sensitive and should be controlled by thickness of the layer. In multilayer system formula, if there are any changes on the thickness of the top layer, Ip1 value has to be calculated based on thickness of the base course layer.



Note: In corresponding to different depths are represented as Ip_0, Ip_1, etc. as defined in equation 3.

Figure 4 - Settlement factors for multilayer systems (Balunaini et al., 2013).

After completing the LWD testing program, the sand cone test method was used to determine the in-plate density and unit weight of soils (ASTM D1556, 2016). In the laboratory, seven sand cone tests were performed with 100% VA, 100% HB and LB RAP, RAP-VA mixtures on the last layer of each material in the LSME test pit.

In the laboratory testing program, the speedy moisture tests were used to measure the moisture content result of VA and RAP-VA blends. The principle of the speedy moisture content test method relies on the moisture of the soil (that is freely released by the soil) to react with calcium carbide to form a gas. This gas is referred as acetylene gas and once it is generated, it releases pressure, which is recorded by the pressure dial gauge on the speedy moisture test device. The higher the moisture the higher the measured pressure reading becomes. The standard procedure on how to conduct the speedy moisture tests is outlined in the AASHTO standard T217 (2014). Figure 5 shows the components of the speedy moisture test device.

Figure 5 - Speedy moisture test equipment.

The standard procedure to test soils include placement of 20 grams of sieved (No. 4) soil into the speedy moisture chamber, adding 3 scoops of calcium carbide, and shaking the mixture for 3 minutes followed by a one-minute resting time (AASHTO T217, 2014).

However, AASHTO T217 (2014) stated that the speedy method may not be accurate for granular materials which are larger than No. 4 (4.75mm) sieve because coarser particles may affect the accuracy of the test. In response to this limitation, the samples used for testing have not been sieved through No.4 (4.75 mm) sieve. Additionally, more than 20 g of soil was used in the tests because the coarser particles were not effectively represented when the samples were created from 20 g. As the procedure followed in these tests deviated from the standard, a correction factor had to be created to calculate the moisture content that may be evaluated as the equivalent of the moisture content if the samples were tested with 20 g of soil as suggested by AASHTO T217 (2014). This correction was achieved by dividing the pressure reading from the speedy chamber to a number that is calculated by diving the amount of soil used in the test (certain number of grams) by 20 g. In addition to the speedy moisture tests, each soil sample was also air-dried and the results were compared against the moisture content values estimated from the speedy moisture test. This comparison was used to confirm the relevancy of the measurement from the speedy moisture test to estimate air dried moisture values.

The multilayer system method was confirmed based on target elastic modulus value from laboratory characterization tests. Based on the multilayer system test method, LWD tool was performed on subgrade layer after compaction with electric plate compactor. The wooden box test pit was placed on the subgrade and the test pit is shown in Figure 6 has 120 cm length, 120 cm width and height of the wooden box 20 cm. On the subgrade, 15 cm 100% HB RAP base course was placed into wooden box and compacted with electric place compactor. Both subgrade and base course layers, eight LWD drops were applied at the center of the wooden box and first two drops were not included measurements of the multilayer system. For wooden box multilayer system, the same quality control test program was implemented for field test program.

Figure 6 - Multilayer system method control with LWD on wooden box test pit.

Field Testing Program:

The field-testing program was constructed in Minnieville, Northern Virginia. The objective of the field-testing program was to investigate suitability of variety of QC measures to better assess uniformity during construction. Six sections were constructed with 100% VA and RAP-VA mixtures as their base course. Same RAP-VA blends were created by asphalt company and the company provided also RAP materials for laboratory testing program. Each section has 46 m length and 3.7 m width. In the field-testing program, the LWD and speedy moisture tests were used to control the quality of the base course section. Laboratory tests concluded that the multilayer system affects the pavement design and has to be controlled in the field. Similar to the multi-layer system that we used in laboratory, the field multi-layer system had base course thickness of 15 cm, and it was placed on subgrade. After placement base course layer, 24 cm of hot mix asphalt was placed. Table 1 shows a summary of each tested sections and the properties of the materials used in these sections. Four LWD tests were performed on both subgrade and base layers to determine the multilayer system procedure in each section at the same point. The same dropping procedures that applied in the laboratory were followed in the field-testing program. Each LWD point's test period was between 5 to 7 minutes to analyze quality control of compacted layers.

Table 1 - The field-testing program and properties of subgrade layer.

Test Sections	Base Course Material	Base Course Layer Thickness (cm)	Subgrade Layer			
			Liquid Limit (%)	Plastic Limit (%)	USCS Soil Classification	CBR (%)
Section-1	100% VA	15	44	30	ML	29
Section-2	30% HB RAP		47	34	ML	13
Section-3	20% HB RAP		46	34	ML	17
Section-4	30% LB RAP		46	37	ML	22
Section-5	20% LB RAP		46	34	ML	19

The nuclear density gauge tool was used to measure the dry unit weight and the moisture content in field testing program. The direct transmission method was used in this program and nuclear probe was penetrated approximately 8 cm into base course layer. In each section, nuclear density gauge tests were performed in order to compare with the speedy moisture tests which were also used to determine moisture content of the VA and RAP-VA blends in the field-testing program.

MATERIAL CHARACTERIZATION

The VA was collected and used as is gradation from one field site in Virginia. Virginia Department of Transportation (VDOT) requires in Road and Bridge Standards (2016) the upper and lower limit for the base course material (21 aggregate) for the VA. Figure 7 shows as is gradation of VA with upper and lower limits for 21 VA based on VDOT requirements.

The two northern Virginia plants from which the materials were collected used two different types of gradation (Ullah et al. 2018). They produce fine and coarse processed RAP samples which are characterized by different gradations. Using a ½-inch size sieve determine the processed RAP sample. Fine processed RAP has finer particles than 1/2-inch sieve size and more binder content than the coarse RAP (Ullah et al. 2018). Figure 7 shows the grain size distribution of the as is gradation RAP materials that used in this research. High binder (HB) and low binder (LB) RAP have binder content values 5.59 and 4.89, respectively. Ullah et al. (2018) stated HB and LB RAP have similar trends but their properties affect the elastic moduli results.

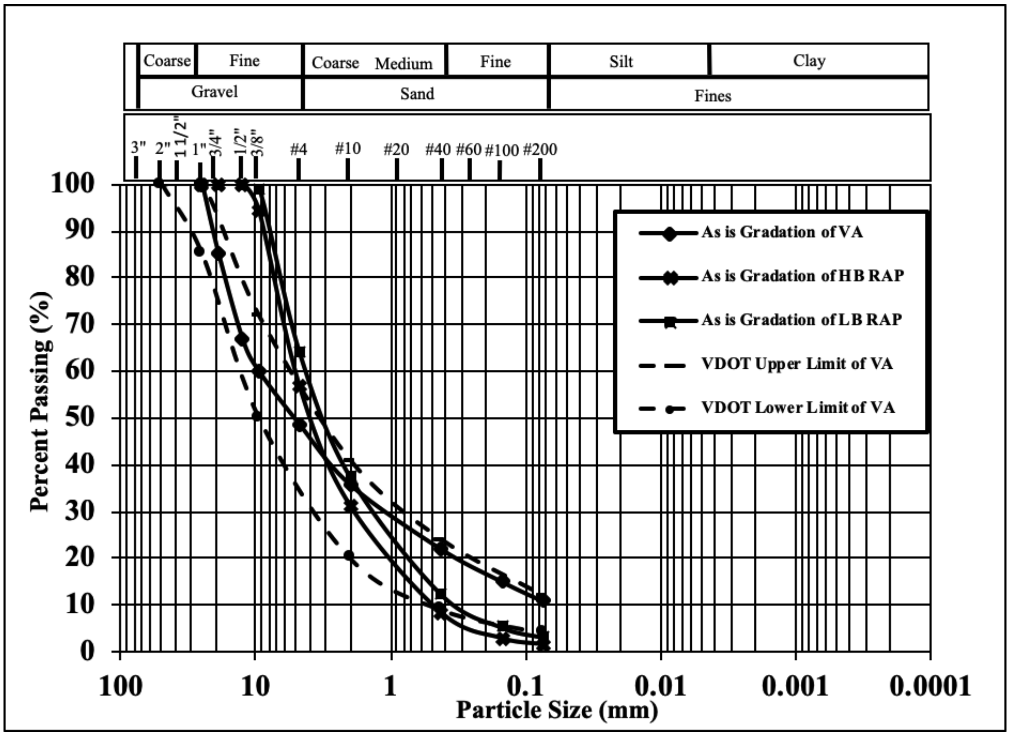


Figure 7 - Grain size distribution of As-Is VA, RAP HB, and RAP LB materials used laboratory tests.

The VA and RAP materials were mixed by weight based on their individual as-is gradation (Ullah et al. 2018). Table 2 show the laboratory ignition test results from two different binder content of RAP-VA blends. In this research, 100% VA, 100% HB RAP, 100% LB RAP, 30% HB RAP + 70% VA, 20% HB RAP + 80% VA, 30% LB RAP + 70% VA, 20% LB RAP + 80% VA were created for laboratory testing program. Ullah et al. (2018) reported the findings of permanent deformation tests results and concluded that 30% and 20% RAP-VA blends have equal or less cumulative strains than VA. Therefore, the threshold of RAP-VA blends were determined accordingly.

Table 2 - Properties of RAP-VA blends laboratory and field test samples.

Grain Size Distribution ASTM D6913	**30% HB RAP (Lab.)**	**20% HB RAP (Lab.)**	**30% LB RAP (Lab.)**	**20% LB RAP (Lab.)**	**30% HB RAP (Field)**	**20% HB RAP (Field)**	**30% LB RAP (Field)**	**20% LB RAP (Field)**
Passing 3/4” (<19 mm)	93.68	87.30	91.23	90.32	94.59	94.40	100	94.13
Passing 3/8” (<9.5 mm)	74.58	68.93	71.71	66.64	86.96	83.15	84.68	70.75
Passing #4 sieve (<4.75 mm)	56.22	52.91	55.47	52.04	59.40	63.37	59.41	53.50
Passing #40 sieve (<0.43 mm)	18.50	20.07	20.39	19.81	16.15	19.05	16.45	15.70
Passing #200 sieve (<0.075 mm)	8.94	9.74	8.57	9.41	7.42	8.39	7.37	7.04
Ignition Test ASTM D7387								
Binder Content (%)	2.01	1.46	1.71	1.32	1.90	1.60	1.80	1.30
Vibratory Compaction Method ASTM D7382								
Optimum Moisture Content (%)	6.25	6.20	6.10	6.20	6.60	6.40	6.20	6.70
Maximum Dry Density (g/cm^3)	2.31	2.35	2.21	2.37	2.34	2.40	2.34	2.39

In the index property tests program, Table 2 show washed and dry sieve analyses as tested based with ASTM D1140 and ASTM D6913 procedures, respectively. Each test sample was compacted with electric vibratory compactor based on ASTM D7382 Method A to decide maximum dry density and optimum moisture content.

In field testing program, the maximum dry density was determined by construction company 2.47 g/cm^3 and optimum moisture content was 6.2 % for VA. Binder content values for HB and LB RAP are 5.9 and 5.4, respectively. Table 2 shows RAP-VA blends washed and dry sieve analysis. Also, binder content, optimum moisture content, and maximum dry density values is shown in Table 2. Table 1 shows that atterberg limit and CBR tests were performed for field subgrade characterization based on ASTM D4318 and D1883, respectively.

RESULTS AND ANALYSES

The light weight deflectometer was performed on the LSME test pit and the average elastic modulus values are summarized in Table 3. Each LWD drop test has high repeatability and sensitivity in the LSME test pit. The repeatability and sensitivity were controlled with COV (%) that is calculated based on the ratio of standard deviation and average of modulus values obtained from LWD test drops. The COV values were between 0.76% and 1.56% which shows the acceptable results because target COV is 15% (ASTM E2583, 2014). 100% RAP HB, 100% RAP LB, 30% HB RAP + 70% VA, 30% LB RAP + 70% VA, 20% HB RAP + 80% VA, 20% LB RAP + 80% VA, and 100% VA are listed from highest to lowest elastic modulus. Table 3 shows the average elastic modulus values on layers 1 and 2. The average elastic modulus of layer 1 has been influenced by the depth of influence of the LWD because the thickness of the first layer was 15 cm and the depth of influence of LWD was between 27 and 33 cm. On the layer 2, the average elastic modulus was also influenced by the depth of influence affect, but this effect was more evident in the tests conducted with 30% HB RAP, 30% LB RAP, and 100% VA. Therefore, for the purposes of this study only the average elastic modulus values of layer 3 were used to determine the elastic modulus of the materials ($E_3 = E_{LSME}$) tested in this study. This is because the depth of influence of the LWD (i.e., up to 33 cm) was much less than the total thickness of the LSME test layer (i.e., 45 cm). The results showed that 100% HB RAP has the highest elastic modulus (176.2 MPa) and 100% VA has the lowest elastic modulus (106.2 MPa) of all the materials tested. Results show that higher binder content and higher mixture of RAP gives higher elastic modulus results. Sand cone was used to determine the relative compaction of each layer to confirm the consistency and relevancy of the compaction efforts used to prepare the samples in LSME. The results confirmed that all layers were compacted based on relative compaction between 95 and 99 percent, which satisfies the VDOT's minimum compaction criteria (VDOT Road and Bridge Specification, 2016).

In the laboratory testing program, VA, RAP and RAP-VA blends were performed on the compaction mold. The average elastic modulus (E_{mold}) was obtained from the VA, RAP, and RAP-VA blends. Table 3 shows that the average elastic modulus results are from highest to lowest, 100% HB RAP, 100% LB RAP, 30% HB RAP-VA, 30% LB RAP-VA, 20% HB RAP-VA, 20% LB RAP-VA, and 100% VA, respectively. The COV of compaction mold tests are between 0.75% and 4.39% and smaller than target COV values.

Table 3 - LWD laboratory testing program results.

Material	**LSME Test Pit**						**Mold**	
	Average Elastic Modulus, E_1 (MPa)	**E_1 COV (%)**	**Average Elastic Modulus, E_2 (MPa)**	**E_2 COV (%)**	**Average Elastic Modulus, E_3 (MPa)**	**E_3 COV (%)**	**Average Elastic Modulus, E_{Mold} (MPa)**	**E_{Mold} COV (%)**
100% HB RAP	143.5	0.85	177.5	0.59	176.2	1.45	202.7	2.18
100% LB RAP	116.2	1.58	161.0	0.68	161.5	0.76	192.5	0.78
30% HB RAP	68.3	3.42	77.5	1.08	149.7	1.09	192.2	0.75
30% LB RAP	82.8	0.91	118.3	0.75	124.2	1.56	151.6	4.39
20% HB RAP	89.8	2.58	113.0	1.77	112.8	1.04	135.6	2.36
20% LB RAP	104.8	1.64	108.7	1.02	109.7	0.90	130.5	6.82

100% VA	85.8	1.71	92.2	0.82	106.2	1.51	128.7	2.84

Note: Target COV is 15% based on ASTM E2583

Elastic modulus of the layer three ($E_3 = E_{LSME}$) from the LSME test pit and compaction mold (E_{mold}) were plotted against each other as shown in Figure 8. The relationship between these elastic modulus values were then used to create a correlation, which is used to obtain target elastic modulus (E_{Target}). The principal of this approach requires the user to obtain modulus value from the mold test (E_{mold}) and then to relate this value to E_{LSME}, which becomes the target elastic modulus (E_{Target}) for the field application (see Figure 8).

Figure 8 shows the equation below;

Equation 4

$$E_{LSME} = 0.8472\ E_{Mold} - 2.2551 \quad (R^2=0.96)$$

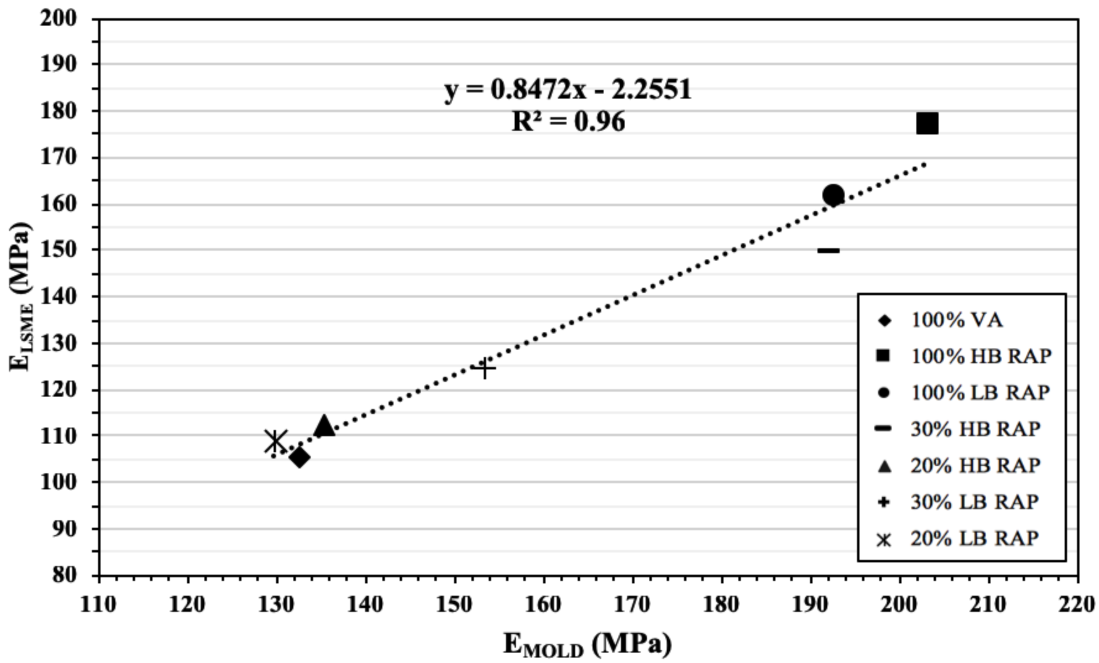


Figure 8 - LSME vs compaction mold tests elastic modulus relationship.

The wooden box testing program result is shown in Table 4. E_{Target} was determined from the laboratory and $E_{ComputedBase}$ was determined from the field test (i.e., wooden box test). The ratio of $E_{ComputedBase}$ and E_{Target} shows that the tested area passed the compaction quality control. If the ratio is equal or greater than 1, it is stated the compaction quality control is matched with passing criteria. The multilayer system is an implementable method for compacted base course layers quality control in the field. Furthermore, If the ratio of $E_{ComputedBase}$ and E_{Target} does not meet the passing criteria, the soil in the field has to be further compacted or moisturized.

Table 4 - Multilayer system method control based on wooden box testing program.

Material	$E_{Subgrade}$ (MPa)	COV (%)	$E_{Multilayer}$ (MPa)	COV (%)	$E_{ComputedBase}$ (MPa)	E_{Target} (MPa)	Average $E_{ComputedBase}/E_{Target}$
30% HB RAP	34.17	1.11	65.17	0.63	163.6	160.0	1.02

In the field-testing program, LWD was performed on subgrade layer and the average elastic modulus values are shown in Table 5 for each section. After placement and compaction of the base course layer, the base course thickness was measured for each test point. The LWD was tested on base course layer at the same test point with subgrade layer. The average elastic modulus of the multilayer system values ($E_{Multilayer}$) are shown in Table 5 for VA and RAP-VA blends. The COV values were between 2.45% and 12.61% from five sections. The COV values show that repeatability of the LWD drops are accurate and sensitive. The average elastic modulus of computed base course layer ($E_{Computed-Base}$) are determined from the multilayer formula based on field tests in Table 5. Figure 8 provided the target elastic modulus (E_{Target}) values are correlated formula from compaction mold tests that are shown in Table 5 for each tested materials. The results of the multilayer formula method showed that the base course elastic modulus ($E_{Computed-Base}$) values are greater than the target elastic modulus (E_{Target}) values for VA and RAP-VA blends base course layers.

Table 5 - Field testing program average elastic modulus results on base course layers.

Material	$E_{Subgrade}$ (MPa)	COV (%)	$E_{Multilayer}$ (MPa)	COV (%)	$E_{ComputedBase}$ (MPa)	E_{Target} (MPa)	Average $E_{ComputedBase}$ / E_{Target}	Percent Compaction (%)

								(Nuclear Density Gauge)
30% HB RAP	**40.0**	**4.47**	**83.8**	**12.61**	**173.1**	**159.8**	**1.07**	**95.9**
	40.0	**4.47**	**97.5**	**6.89**	**171.5**			
	54.2	**5.01**	**101.7**	**5.55**	**167.9**			
	43.5	**5.58**	**95.7**	**4.66**	**168.3**			
20% HB RAP	**27.8**	**1.47**	**61.5**	**3.04**	**113.7**	**112.3**	**1.04**	**96.0**
	29.9	**1.37**	**64.7**	**3.62**	**118.1**			
	29.8	**1.37**	**61.8**	**2.79**	**116.8**			
	24.2	**3.11**	**55.7**	**3.70**	**118.9**			
30% LB RAP	**27.3**	**2.99**	**48.5**	**5.01**	**139.1**	**125.1**	**1.08**	**96.5**
	29.7	**8.70**	**53.5**	**2.83**	**131.0**			
	23.3	**3.50**	**52.8**	**3.86**	**141.3**			
	23.5	**3.56**	**50.3**	**4.65**	**128.5**			
20% LB RAP	**25.3**	**7.76**	**55.5**	**2.48**	**114.4**	**107.8**	**1.07**	**97.4**
	28.0	**2.26**	**61.5**	**3.53**	**112.9**			
	36.3	**1.42**	**74.5**	**4.86**	**118.1**			
	36.9	**1.52**	**73.0**	**2.45**	**114.7**			
100% VA	**68.8**	**3.10**	**76.8**	**5.99**	**113.8**	**107.0**	**1.03**	**96.0**
	86.8	**7.65**	**76.3**	**3.94**	**108.1**			
	67.7	**3.11**	**75.6**	**4.88**	**111.9**			
	38.7	**2.11**	**72.3**	**3.23**	**108.8**			

Notes: $E_{Subgrade}$: Average subgrade layer elastic modulus, $E_{Multilayer}$: Average multilayer elastic modulus, $E_{ComputedBase}$: Average base course layer elastic modulus, E_{Target}: Target elastic modulus from Figure-7.

The base course elastic modulus ($E_{Computed\text{-}Base}$) to target elastic modulus (E_{Target}) values ratio is compared to percent compaction values from nuclear density gauge and plotted on the graph in Figure 9. The results show that field elastic modulus values are valid based on target elastic modulus value and the nuclear density gauge field test results demonstrate that percent compaction values verify the quality control of each compacted layer. Each compacted layer satisfied both the density and modulus requirements in the field. However, the LWD test results also demonstrate that 30% HB RAP-VA blend has higher elastic modulus than 30% LB RAP-VA blend in Table 5. Thus, LWD can evaluate different bituminous unbound granular materials characterization.

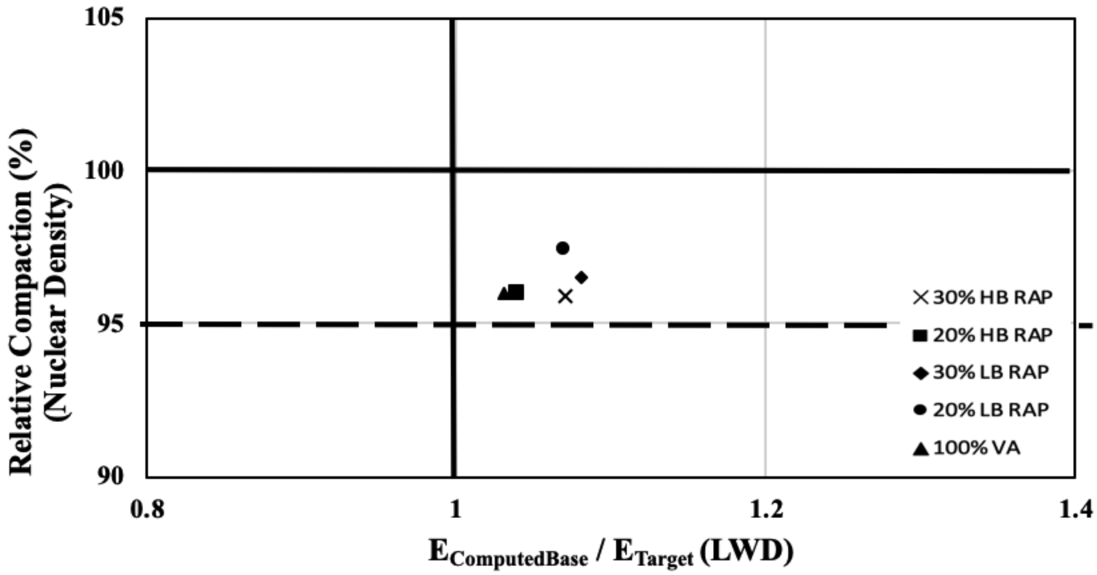


Figure 9 - Relative compaction versus $E_{ComputedBase}$ to E_{Target} ratio for field test sections.

The calibration results show that on the basis of the speedy moisture and air-dry test methods, Figure 10 shows R^2=0.98, supporting the method of using more than 20 g of RAP-VA sample in the speedy moisture test, and gives the consistent result.

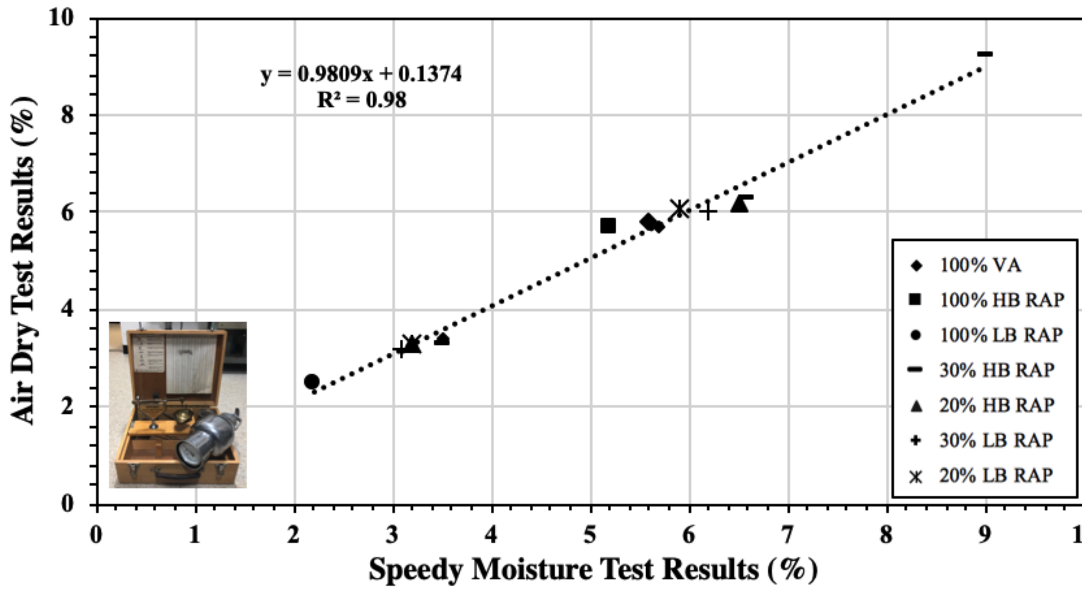


Figure 10 - Calibration tests on RAP-VA blends with speedy moisture test.

Using laboratory calibration formula provides consistent predicted air dry value from the speedy moisture test. The speedy moisture air dry test moisture results were shown in Figure 11 and R^2=0.92 for the RAP-VA blends.

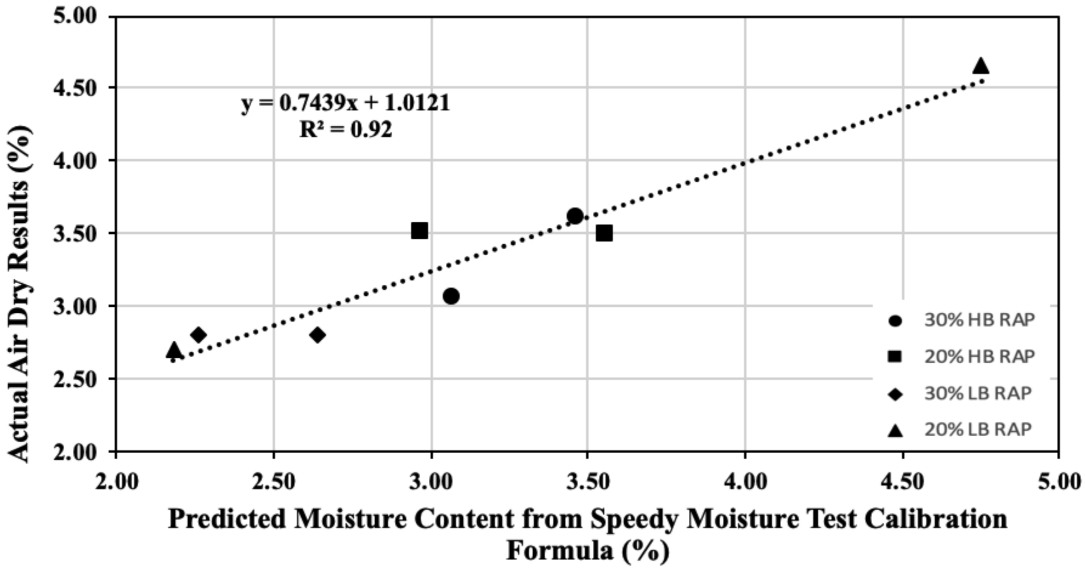


Figure 11 - Speedy moisture test vs air dry test moisture content relationship.

The field test results present that the nuclear density gauge and air dry method test moisture results were plotted and concluded R^2=0.10 for the RAP-VA blends in Figure 12. The nuclear density gauge test results show that the nuclear density gauge does not provide accurate results on RAP-VA blends in the field. Therefore, the speedy moisture test is more applicable, and the test results represent acceptable moisture values (R^2=0.92) for RAP-VA blends.

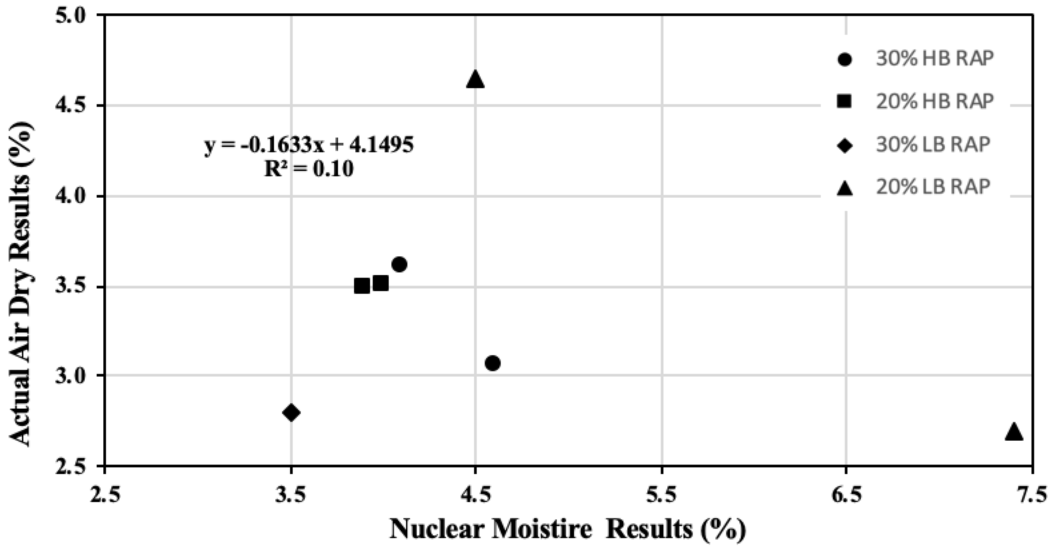


Figure 12 - Nuclear density gauge test vs air dry test moisture content relationship.

DISCUSSION AND CONCLUSION

In this study, the LWD device was used to determine elastic modulus of the base course layer on the multilayer system for the VA, RAP, and RAP-VA mixtures. Laboratory and field-testing programs were compared and related to each other to control the multilayer pavement systems quality based on the LWD working principles. Using the multilayer system method provides elastic modulus which is the input parameter of mechanistic empirical pavement design guide. Furthermore, the poisson's ratio of materials affects the target elastic modulus in the MEPDG (NCHRP, 2015). Within the range of the LWD depth of influence, the multilayer system may have different poisson's ratios for each layer.

In the laboratory testing program, the LWD tests provided the target elastic modulus (E_{target}) values for field quality control of base course layer on each compacted VA and RAP-VA blend layers. Both LSME test pit and compaction mold tests are sensitive and repeatable based on LWD drop tests. The average LWD elastic modulus COV values are clearly smaller than target COV values. The LWD requires target elastic modulus from correlated formula in Figure 8 using the compaction mold method to analyze quality control unbound reclaimed asphalt pavement because compaction mold test is faster and more applicable than LSME test pit.

The LWD test results supported that the poisson's ratio of materials significantly influence the elastic modulus values at the depth of influence in the multilayer system. For this reason, the LWD tests need to be determined right underneath where the base course LWD tests will be conducted with LWD device to obtain average elastic modulus ($E_{subgrade}$) value for multilayer system method. After elimination of the subgrade layer effect from multilayer system at the LWD depth of influence, the multilayer system formula method provided elastic modulus of the compacted base course layer ($E_{Computed-Base}$). Based on field test results, the formula shown as Equation 3, requires the control of the top layer's thickness because the thickness of the base course layer affects the settlement factor (I_n). The settlement factor is very sensitive and changes elastic modulus of top layer in the multilayer system. In this study, Figure 4 shows depth and settlement factor relationship for poisson's ratio 0.3 and 0.45. For example if the depth of the layer is 18 cm instead of 15 cm at Section 3 (20% HB RAP) , the elastic modulus value decrease from 162.30 to 113.7 MPa. Because of the sensitivity of the settlement effect, the thickness of the top layer has to be measured before performing the LWD test on the multilayer system.

In regards to unbound pavement materials, Table 5 displays that the LWD can evaluate different binder contents of the RAP and RAP-VA blends. This tool will be able to provide the elastic modulus of different various percentage RAP-VA blends. Therefore, the LWD is an advantageous device for bituminous materials that are used as an alternative unbound base course layer.

Schwartz et al. (2017) concluded that the moisture content control is extremely important for the compacted soils in the field and needs to be measured. However, the nuclear density gauge is not an achievable test method for RAP and RAP-VA blend materials. In our study, speedy moisture test tool was performed on testing materials for moisture content control in the laboratory and field tests. The results showed that the speedy moisture test device is more applicable than nuclear density gauge.

The LWD and speedy moisture test devices are going to be desirable for the evaluation of the quality assurance and control methods on compacted RAP-VA blend layers in the field. However, the LWD drops take longer time than nuclear density gauge for one test location in the field. Even though the nuclear density gauge is still applicable when using 100% VA material, the LWD methodology is also useful for this type of material.

PRACTICAL IMPLICATIONS

Future practitioners of the highway industry may follow the procedures that are shown in Figure 13 to evaluate quality control in an effective and efficient way.

As recommended for the laboratory testing program, the compaction mold tests proved a more appropriate and effortless test method than the LSME to characterize the elastic modulus of the different soil types. This finding shows not only LSME tests give valid results but also the compaction mold tests give accurate results and can be performed easily with correlated formula in Figure 8.

Based on the results, using the LWD tool provides a better quality-control system in the field. This research will be remarked towards the evaluation of suitable Quality Assurance (QA) /Quality Control (QC) methods for RAP-Virgin Aggregate blends in the field.

Notes: $h_{toplayer}$: thickness of the top layer, $E_{toplayer}$: elastic modulus of the top layer, E_{target}: target elastic modulus, $E_{bottomlayer}$: elastic modulus of the bottom layer, $E_{multilayer}$: elastic modulus of the multilayer, I_n: settlement factor

Figure 13 - Schematic of the quality control procedure steps.

APPENDIX

In this section, Geogauge and Dynamic Cone Penetrometer (DCP) tools results are shown and these tools were applied in same laboratory and field-testing program. However, the test results have not been evaluated yet. The results will be used in future researches.

LWD Number of Drops Analyses:

In this section, the effects of number of drops from LWD device has been evaluated to determine the highest repeatable elastic modulus values. ASTM E2583 (2014) stated that excluding first two LWD drops will provide more repeatable results because during the initial drops it is assumed that LWD's plate move and get a better contact with the soil surface, which allows the equipment to apply the peak load for the measurement. In this research, eight drops were performed on each test material.

Tables 1 through 8 provide the results obtained from various combinations of eliminating different number of drops to determine the best repeatable elastic modulus results. Figures 1 through 8 relate the average E_{LSME} to E_{MOLD} based on the data presented in Tables 1 through 8. The comparison of the results showed that at least 2 number of drops should be excluded to obtain the highest repeatable elastic modulus of LWD. Therefore, the analyses used in this research were based on the data generated by eliminating the results from the first two drops.

Table – 1. Two drops excluded 6 drops calculated for LWD drops measurements.

Material	Average E_{LSME} (MPa)	Standard Dev (%)	COV (%)	Average E_{Mold} (MPa)	Standard Dev (%)	COV (%)
100% #21 VA	106.2	1.60	1.51	131.0	4.05	3.09
30% HB RAP	149.7	1.63	1.09	192.2	2.24	1.17
20% HB RAP	112.8	1.17	1.04	135.6	3.48	2.57
100% HB RAP	176.2	2.56	1.45	202.7	3.85	1.90
100% LB RAP	161.5	1.22	0.76	192.5	2.02	1.05
30% LB RAP	124.2	1.94	1.56	151.7	6.41	4.23
20% LB RAP	109.2	0.98	0.90	127.1	8.39	6.60

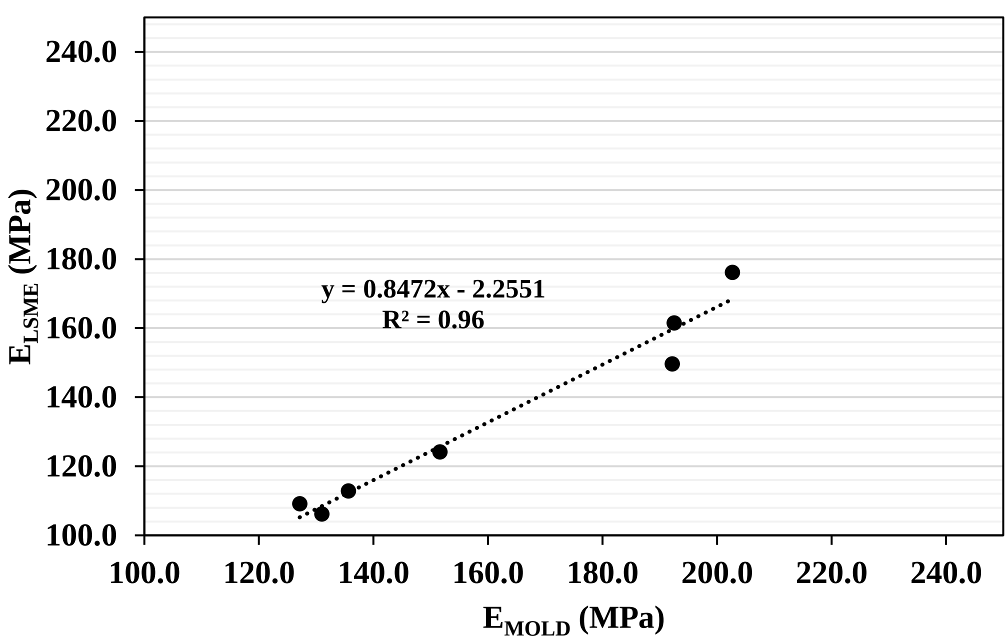


Figure – 1 LSME vs compaction mold tests elastic modulus relationship.

Table – 2. Three drops excluded 5 drops calculated for LWD drops measurements.

Material	Average E_{LSME} (MPa)	Standard Dev (%)	COV (%)	Average E_{Mold} (MPa)	Standard Dev (%)	COV (%)
100% #21 VA	105.6	0.89	0.85	132.5	1.97	1.48
30% HB RAP	149.8	1.79	1.19	192.3	2.49	1.30
20% HB RAP	112.6	1.14	1.01	135.5	3.88	2.87
100% HB RAP	176.8	2.28	1.29	203.5	3.61	1.77
100% LB RAP	161.2	1.10	0.68	192.9	2.01	1.04
30% LB RAP	124.6	1.82	1.46	153.5	5.17	3.37
20% LB RAP	109.4	0.89	0.82	129.8	5.89	4.53

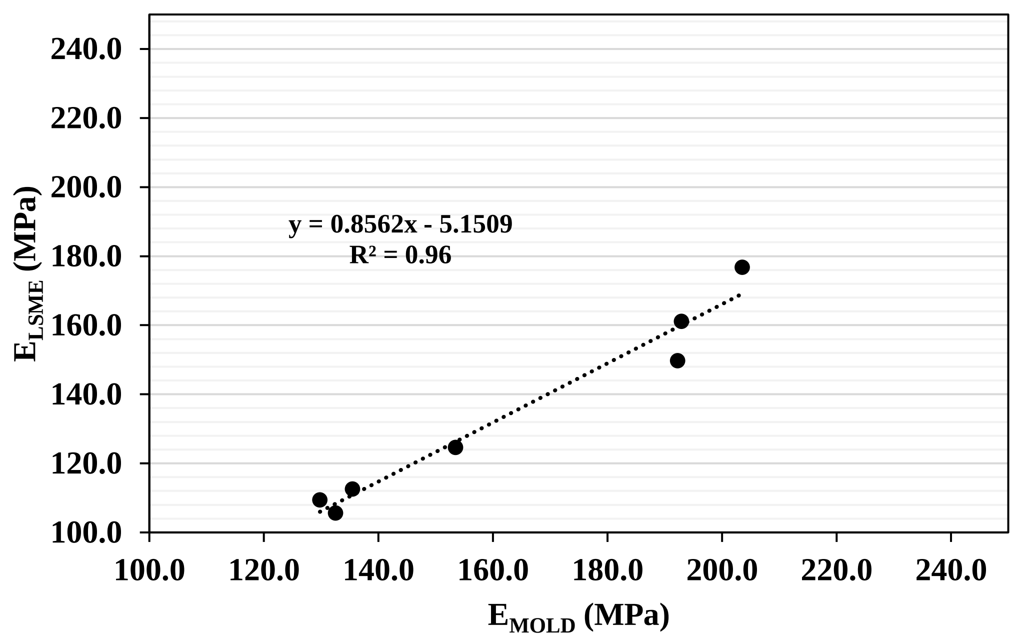


Figure – 2 LSME vs compaction mold tests elastic modulus relationship.

Table – 3 Four drops excluded 4 drops calculated for LWD drops measurements.

Material	Average E_{LSME} (MPa)	Standard Dev (%)	COV (%)	Average E_{Mold} (MPa)	Standard Dev (%)	COV (%)
100% #21 VA	105.3	0.50	0.48	132.6	2.26	1.70
30% HB RAP	150.3	1.71	1.14	192.2	2.87	1.49
20% HB RAP	112.8	1.26	1.12	135.5	4.48	3.31
100% HB RAP	177.8	0.96	0.54	203.9	4.03	1.97
100% LB RAP	160.8	0.50	0.31	193.3	2.12	1.10
30% LB RAP	125.0	1.83	1.46	152.4	5.34	3.50
20% LB RAP	109.3	0.96	0.88	129.8	6.80	5.23

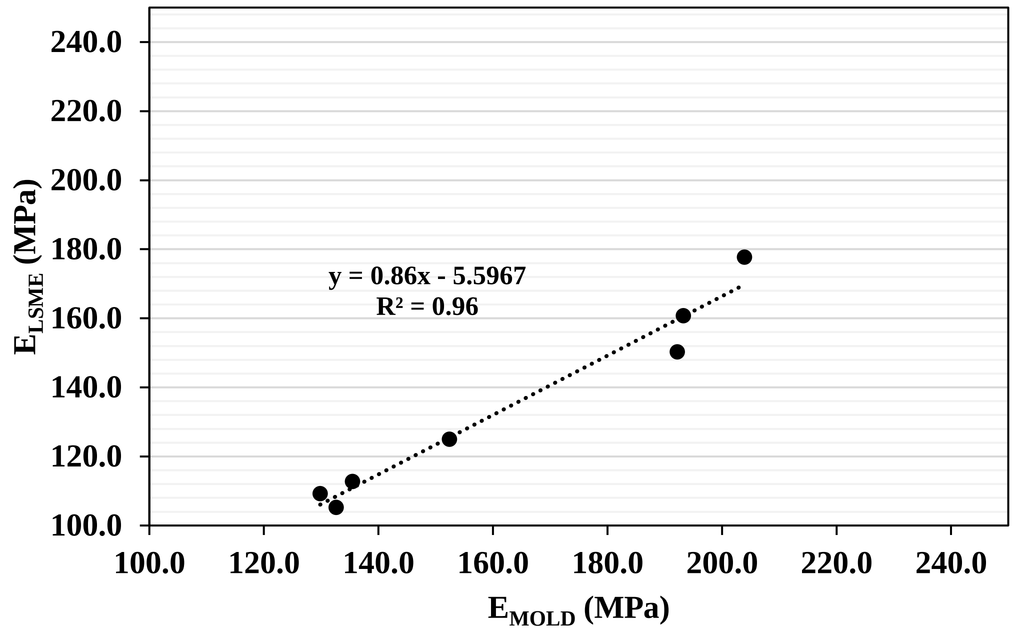


Figure – 3 LSME vs compaction mold tests elastic modulus relationship.

Table – 4 Two drops excluded 4 drops calculated for LWD drops measurements.

Material	Average E_{LSME} (MPa)	Standard Dev (%)	COV (%)	Average E_{Mold} (MPa)	Standard Dev (%)	COV (%)
100% #21 VA	106.5	1.91	1.80	130.3	4.55	3.49
30% HB RAP	149.3	1.89	1.27	190.9	1.46	0.76
20% HB RAP	113.3	0.96	0.85	135.0	3.18	2.36
100% HB RAP	175.8	3.20	1.82	200.8	2.68	1.34
100% LB RAP	162.0	1.15	0.71	192.3	2.18	1.14
30% LB RAP	123.8	2.22	1.79	149.8	6.89	4.60
20% LB RAP	108.8	0.96	0.88	127.8	9.69	7.58

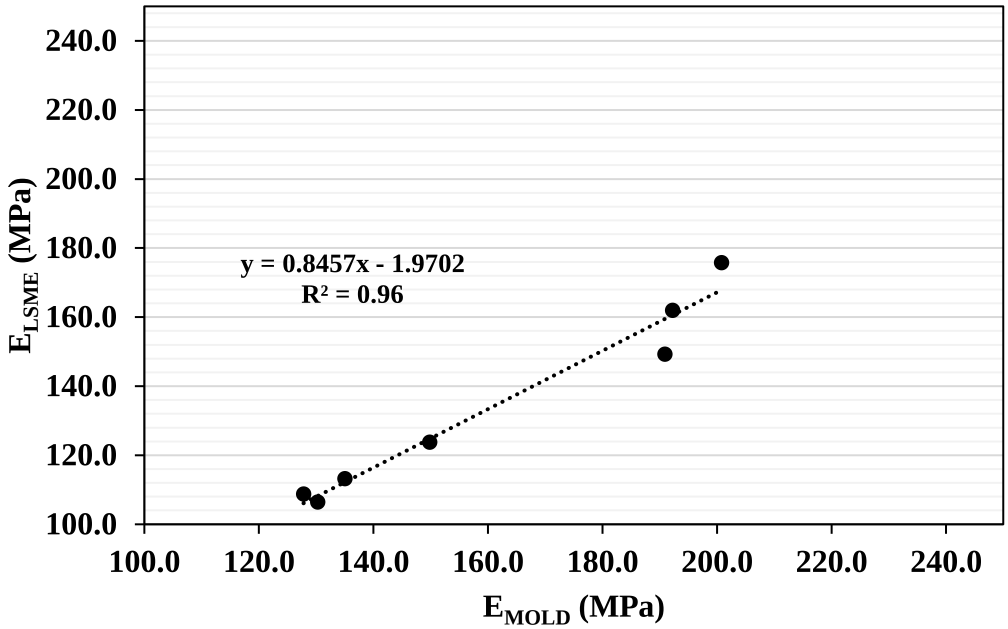


Figure-4 LSME vs compaction mold tests elastic modulus relationship.

Table – 5 Three drops excluded 3 drops calculated for LWD drops measurements.

Material	Average E_{LSME} (MPa)	Standard Dev (%)	COV (%)	Average E_{Mold} (MPa)	Standard Dev (%)	COV (%)
100% #21 VA	105.7	1.15	1.09	132.6	0.85	0.64
30% HB RAP	149.3	2.31	1.55	190.7	1.67	0.87
20% HB RAP	113.0	1.00	0.88	134.6	3.78	2.80
100% HB RAP	176.7	3.21	1.82	201.6	2.63	1.31
100% LB RAP	161.7	1.15	0.71	192.8	2.33	1.21
30% LB RAP	124.3	2.08	1.67	152.2	4.09	2.69
20% LB RAP	109.0	1.00	0.92	132.5	3.16	2.39

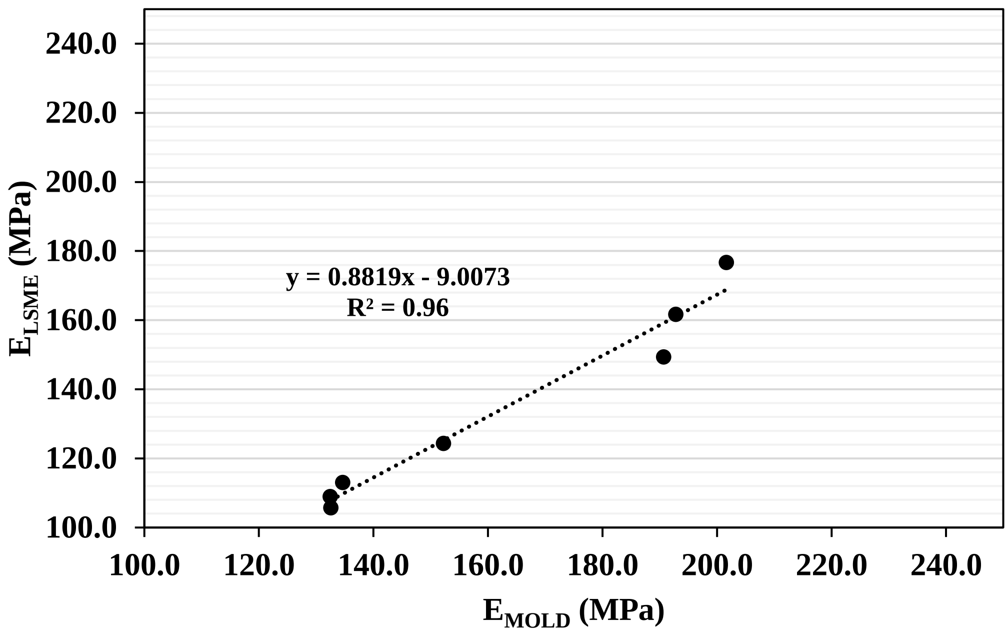


Figure - 5 LSME vs compaction mold tests elastic modulus relationship.

Table – 6 Four drops excluded 2 drops calculated for LWD drops measurements.

Material	Average E_{LSME} (MPa)	Standard Dev (%)	COV (%)	Average E_{Mold} (MPa)	Standard Dev (%)	COV (%)
100% #21 VA	105.0	0.00	0.00	132.8	1.08	0.81
30% HB RAP	150.0	2.83	1.89	189.7	0.56	0.29
20% HB RAP	113.5	0.71	0.62	134.2	5.24	3.90
100% HB RAP	178.5	0.71	0.40	201.5	3.71	1.84
100% LB RAP	161.0	0.00	0.00	193.5	2.86	1.48
30% LB RAP	125.0	2.83	2.26	149.6	5.46	3.65
20% LB RAP	108.5	0.71	0.65	133.9	2.82	2.11

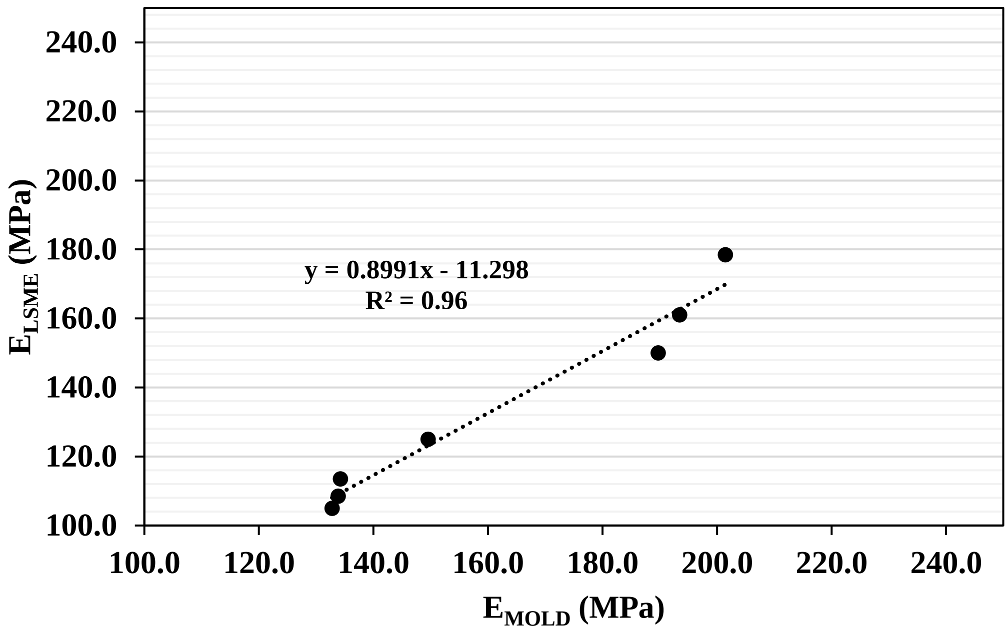


Figure - 6 LSME vs compaction mold tests elastic modulus relationship.

Table – 7 Eight drops calculated for LWD drops measurements.

Material	**Average E_{LSME} (MPa)**	**Standard Dev (%)**	**COV (%)**	**Average E_{Mold} (MPa)**	**Standard Dev (%)**	**COV (%)**
100% #21 VA	105.6	2.72	2.58	128.2	6.21	4.84
30% HB RAP	149.3	3.11	2.08	185.9	11.90	6.40
20% HB RAP	106.5	16.83	15.80	134.7	4.86	3.61
100% HB RAP	179.0	8.77	4.90	198.7	8.11	4.08
100% LB RAP	161.3	2.19	1.36	192.5	1.91	0.99
30% LB RAP	122.4	4.27	3.49	151.1	6.51	4.31

20% LB RAP	109.1	0.83	0.76	122.8	16.58	13.50

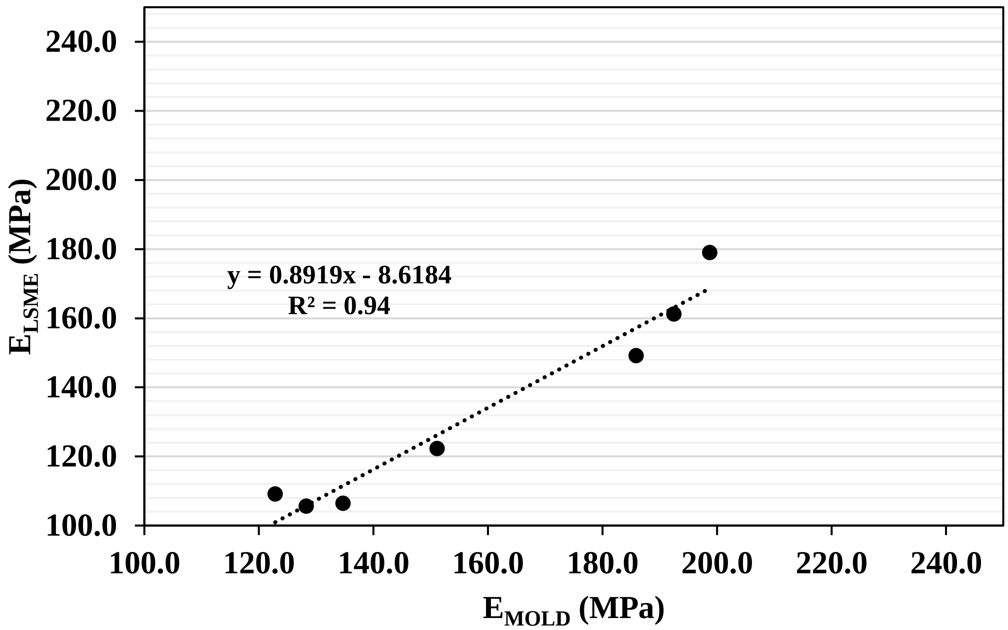


Figure - 7 LSME vs compaction mold tests elastic modulus relationship.

Table – 8 One drop excluded 7 drops calculated for LWD drops measurements.

Material	**Average E_{LSME} (MPa)**	**Standard Dev (%)**	**COV (%)**	**Average E_{Mold} (MPa)**	**Standard Dev (%)**	**COV (%)**
100% #21 VA	106.4	1.62	1.52	129.6	5.28	4.08
30% HB RAP	150.1	1.95	1.30	188.8	9.22	4.88
20% HB RAP	112.4	1.51	1.34	134.2	5.01	3.73
100% HB RAP	176.0	2.38	1.35	200.7	6.21	3.09
100% LB RAP	161.9	1.46	0.90	192.7	1.91	0.99

30% LB RAP	123.7	2.14	1.73	152.3	6.08	3.99
20% LB RAP	109.1	0.90	0.82	121.3	17.26	14.23

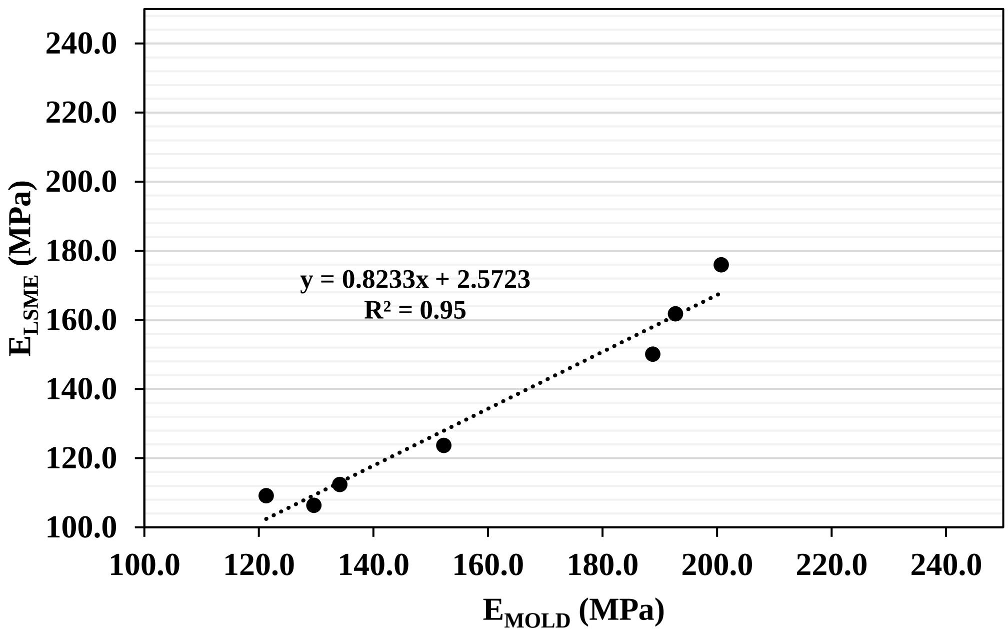


Figure - 8 LSME vs compaction mold tests elastic modulus relationship.

Earth Pressure Cells (EPC) Test Results:

Earth pressure cells (EPC) are designed to determine the stress in the soil based on the two stainless steel plates that are welded to each other. There is a gap between these two plates and this gap is filled with aired hydraulic oil that is connected to a transducer. The transducer converts the hydraulic pressure to electric signal and this electric signal sends the data from cell to datalogger to estimate the soil stress. Earth pressure cells can be designed circular or rectangular in shape. Figure 9 and Figure 10 show the earth pressure cells that were used in this study. Two different EPCs were used in this study. Circular

EPC was placed above the ground to evaluate the LWD's depth of influence based on applied load. The rectangular EPC was placed at the back end of the CMU block that is used to create a wall to determine the influence of the LWD to the boundary of test pit.

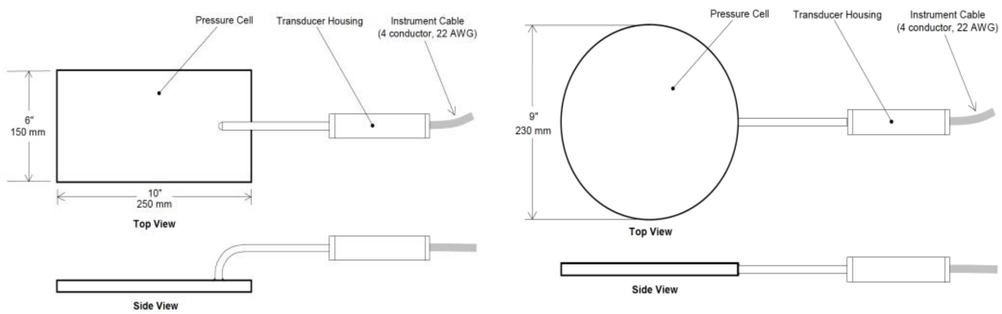


Figure – 9 Rectangular and circular earth pressure cells

Figure – 10 Placement of rectangular and circular earth pressure cells

The vertical and horizontal pressure signals on EPCs showed that using LWD on the compacted layer has depth of influence of about 30 cm layer because vertical pressure on EPC does not have increased signals after 30 cm layer thickness in Table 9. The EPC results support that LWD depth of influence is between 0.9 – 1.1 times plate diameter. In addition to this, rectangular earth pressure cell results show in Table 10 that the size test pit was adequate for performing LWD on each test material because the pressure results are not affected by LWD drops load pressure.

Table – 9 Circular Earth Pressure Cell (EPC) (Vertical) laboratory test results.

	Test Material Pressure (kPa)						
Test Layer Thickness	100% VA	100% HB RAP	100% LB RAP	30% HB RAP	20% HB RAP	30% LB RAP	20% LB RAP
15 cm	8.90	5.13	6.63	10.40	8.14	4.37	3.60
30 cm	11.16	9.65	8.14	11.92	13.72	6.64	6.64
45 cm	11.16	9.65	8.14	11.92	14.17	6.64	6.64

Table – 10 Rectangular Earth Pressure Cell (RPC) (Horizontal) laboratory test results.

	Test Material Pressure (kPa)						
Test Layer Thickness	100% VA	100% HB RAP	100% LB RAP	30% HB RAP	20% HB RAP	30% LB RAP	20% LB RAP
15 cm	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30 cm	1.18	2.95	3.08	3.60	0.30	1.84	1.18
45 cm	1.18	2.95	2.95	4.00	0.10	1.84	0.96

Geogauge:

The Humboldt Geogauge provides a stiffness and elastic modulus of soil, that is shown in Figure 11. Alshibli et al. (2005) stated that the Geogauge stiffness device can evaluate young modulus and stiffness characteristic feature of well compacted base, subgrade and soil layers. Test results shows acceptable coefficient of variations for geogauge device in the laboratory. According to the test results, the geogauge is useful device to calculate the young modulus and stiffness characterization on compacted soil layers (Alshibli et al., 2005). The results can be contributed by geogauge stiffness devices for material's void ratio and dry unit weight within the testing process (Lee et al., 2014). This part is very applicable for RAP materials because the binder content affects the RAP materials analyze. For that reason, the geogauge is one of the applicable test tools for analyzing the RAP. At the construction side, geogauge is very convenient for quality control because values of the device are ready to use within 70 seconds. Especially, asphalt materials need to be analyzed on limited time because asphalt is hot and rapidly cooling. Therefore, they have to decide the values of stiffness and elastic modulus within very limited time. In conclusion, using geogauge stiffness device can directly analyze for RAP materials as effective as in earth materials (Sawangsuriya & Edil, 2005). Table 11 shows the geogauge test results on the LSME test pit and field.

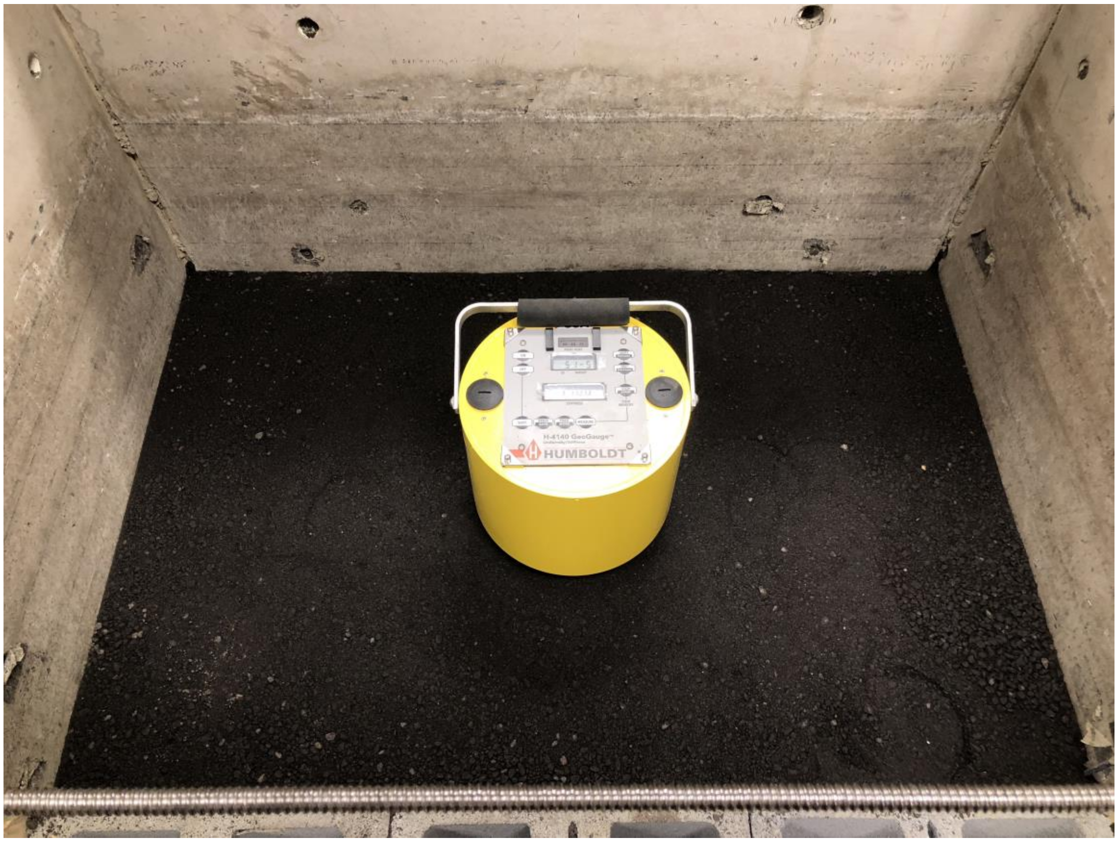


Figure – 11 Humboldt Geogauge placed in the LSME test pit

Table – 11 Geogauge laboratory and field tests results

Material	LSME Test Pit			Field	
	Average Elastic Modulus, E_3 (MPa)	E_3 COV (%)	Percent Compaction (%) Sand Cone Test	Average Elastic Modulus, E_{Field} (MPa)	E_{Field} COV (%)
100% HB RAP	162	2.57	99.0	N/A	N/A
100% LB RAP	153.7	2.96	95.0	N/A	N/A
30% HB RAP	110.99	1.02	97.1	95.54	0.75
30% LB RAP	90.72	0.45	98.7	103.08	1.16
20% HB RAP	90.45	2.09	95.6	92.78	1.18
20% LB RAP	90.65	1.71	98.4	73.01	0.96
100% VA	94.54	0.35	98.4	95.09	0.59

Dynamic Cone Penetrometer (DCP):

The Dynamic Cone Penetrometer (DCP) was used first time in South Africa for pavement evaluation tests (Nazzal et al., 2007). The DCP is solid, easy and inexpensive and there is no high expectation about training and maintenance (Nazzal, 2014). Nazzal et al. (2007) compared DCP and LWD as a standard test method and the correlation was acquired between LWD and DCP with R^2=0.87. These results will be beneficial for future researches to compare the quality control of RAP materials. Huang and Kang (2010) found reasonable results which is R^2=0.90 between LWD and DCP contingent on elastic modulus. Both researches almost have results which are good enough to use these devices together at the field. Furthermore, these comparisons demonstrate that these devices are usable for quality control testing in the laboratory. Figures 12 and 13 show the use of DCP in the test pit and the results.

Figure – 12 Dynamic Cone Penetrometer (DCP) laboratory quality control tests.

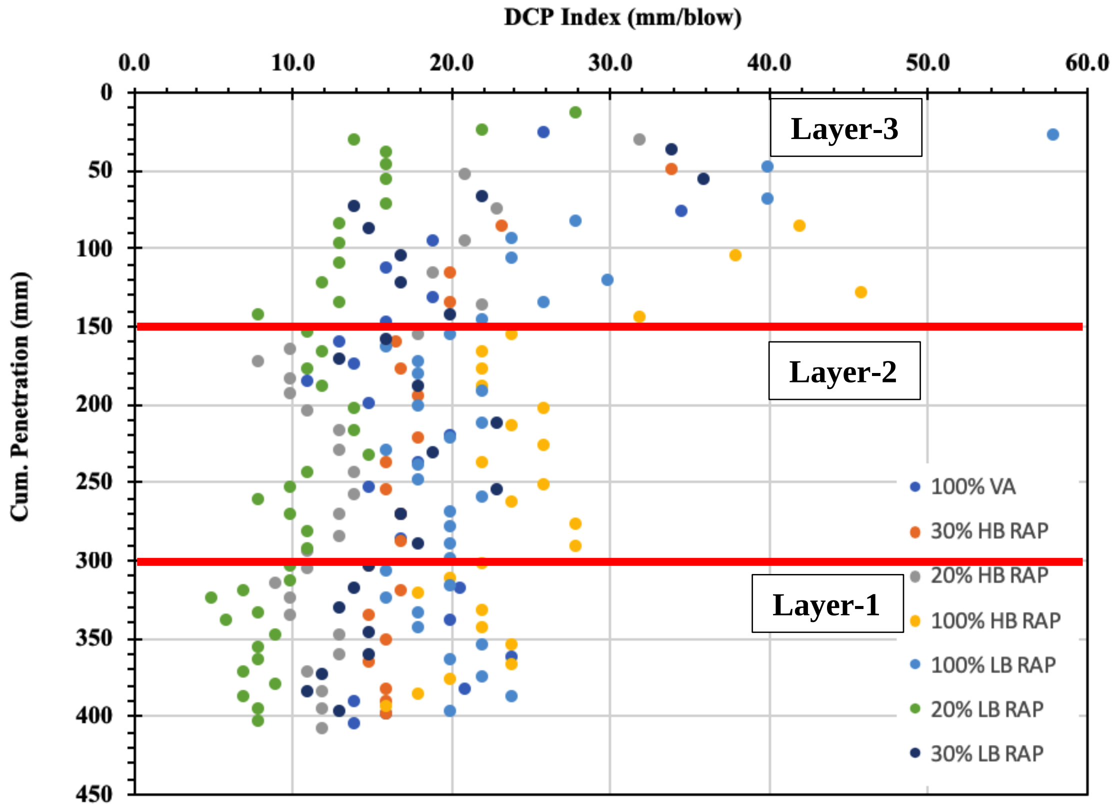


Figure - 13 DCP test results on LSME test pit

DCP device was also used in the field. Details of the field study have been explained previously in the main body of this report. In the field, six DCP tests were performed for compaction quality control on each section. Figure 14 shows the test points where the DCP tests were placed. For each section, same test process was followed in the field. The results show in Figures below that DCP index values are between 20 and 50 for each test material.

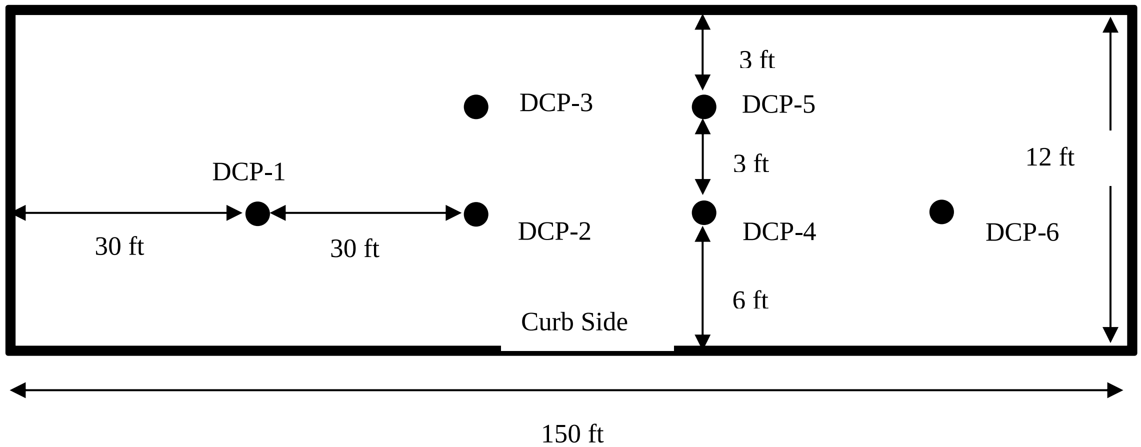


Figure -14 six DCP tests conducted in the field plan of each section (Five sections were created with same test plan)

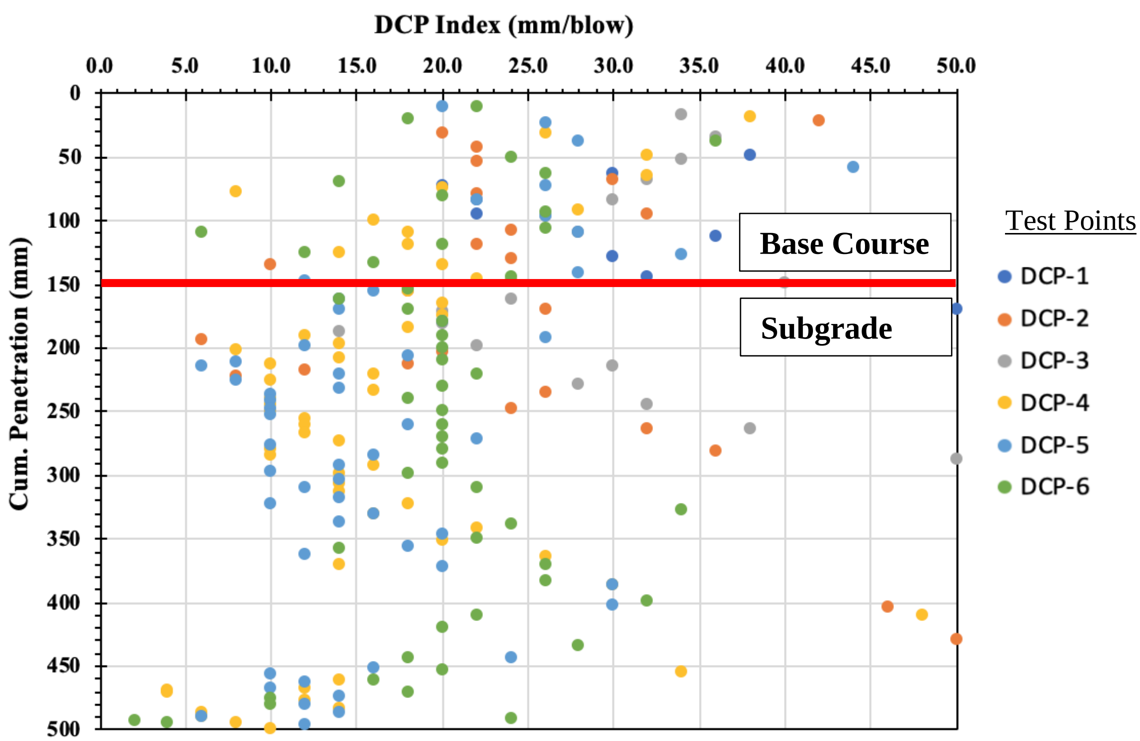


Figure - 15 DCP test results on 100% VA base course layer in the field.

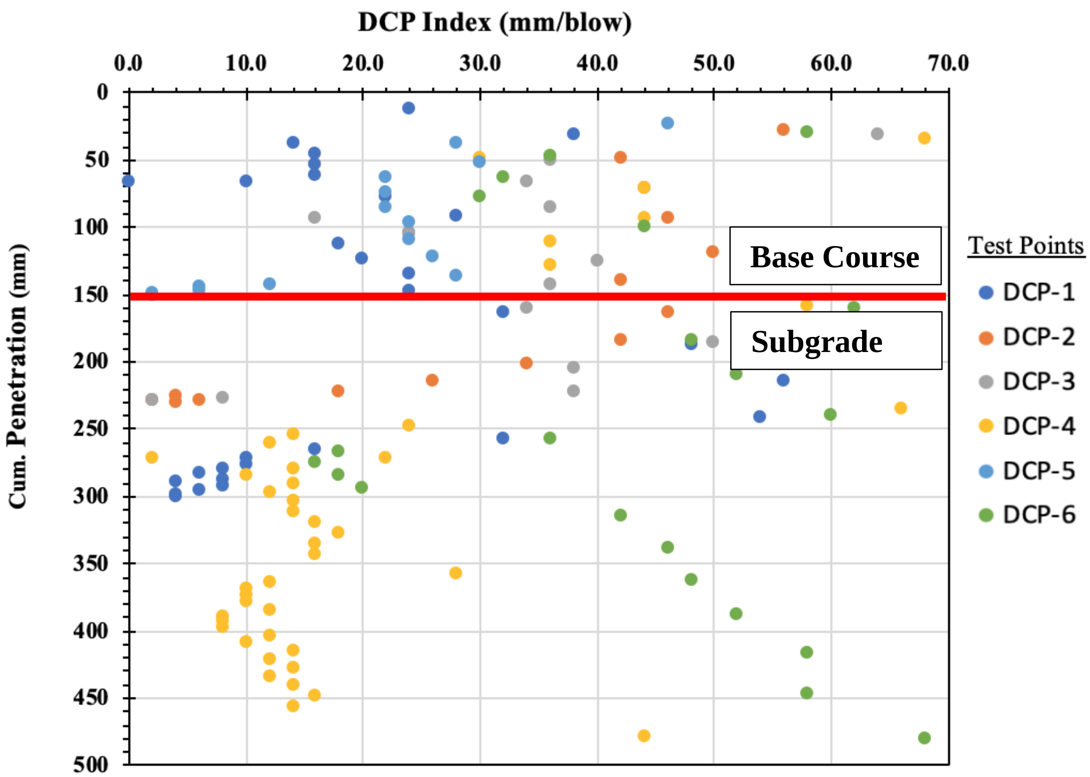


Figure - 16 DCP test results on 30% HB RAP base course layer in the field.

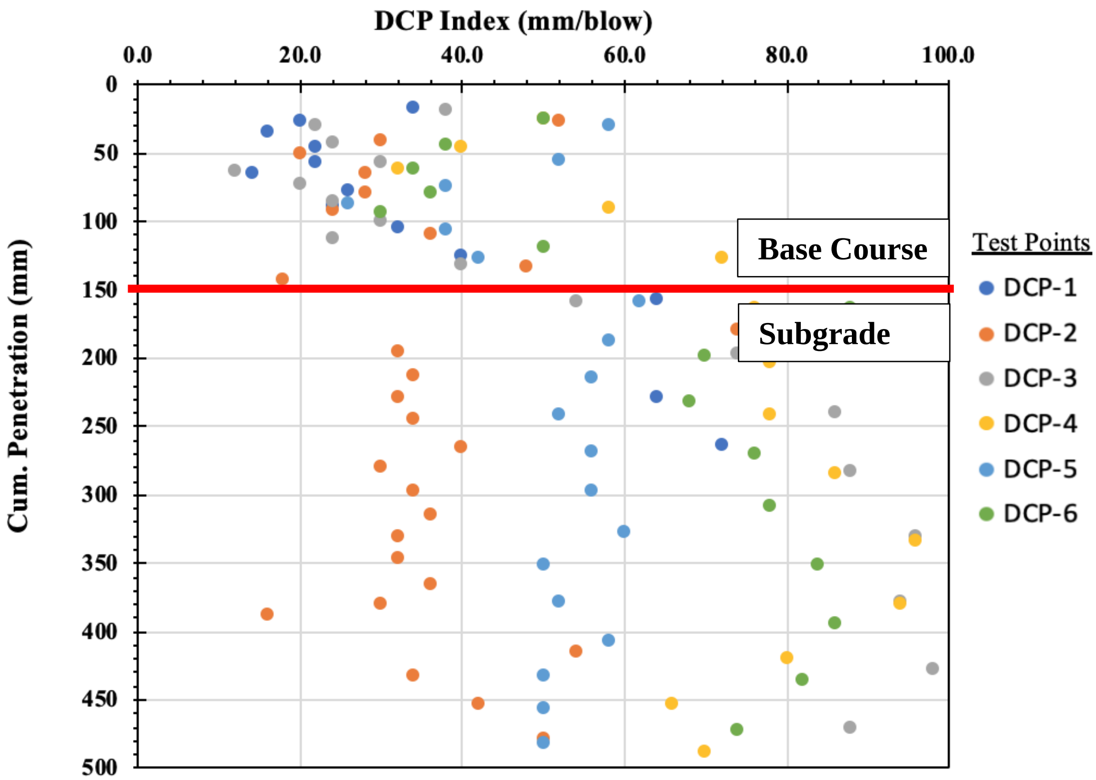


Figure - 17 DCP test results on 20% HB RAP base course layer in the field.

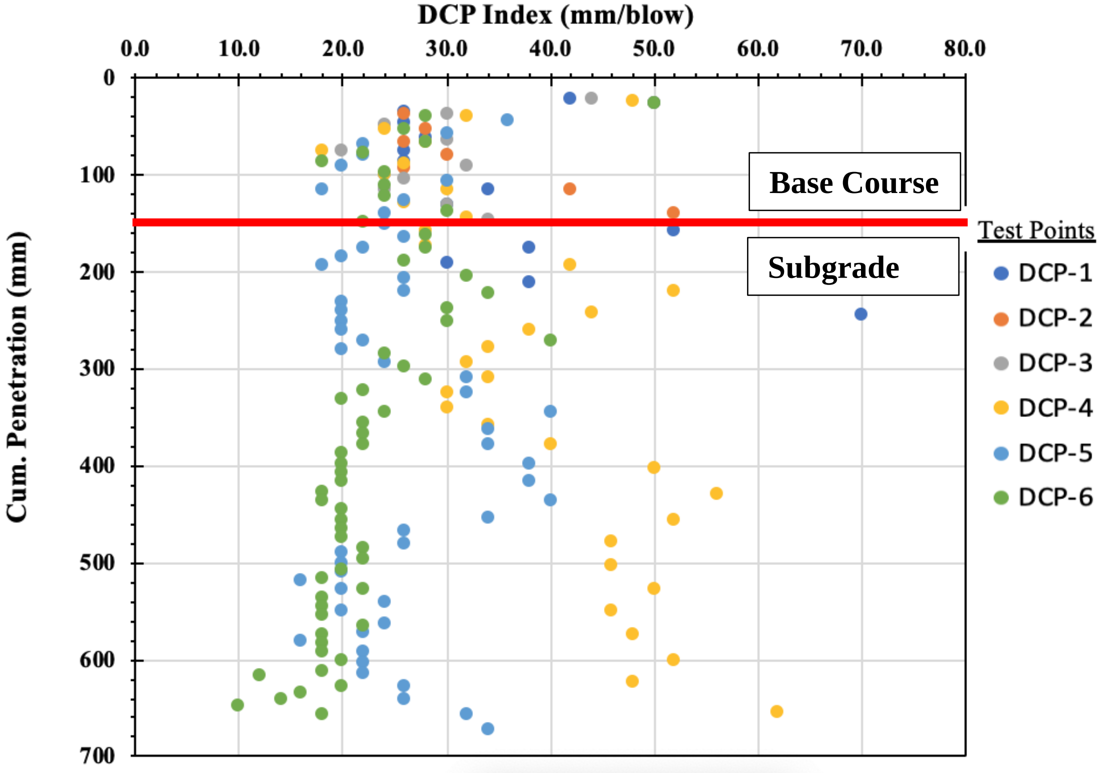


Figure - 18 DCP test results on 30% LB RAP base course layer in the field.

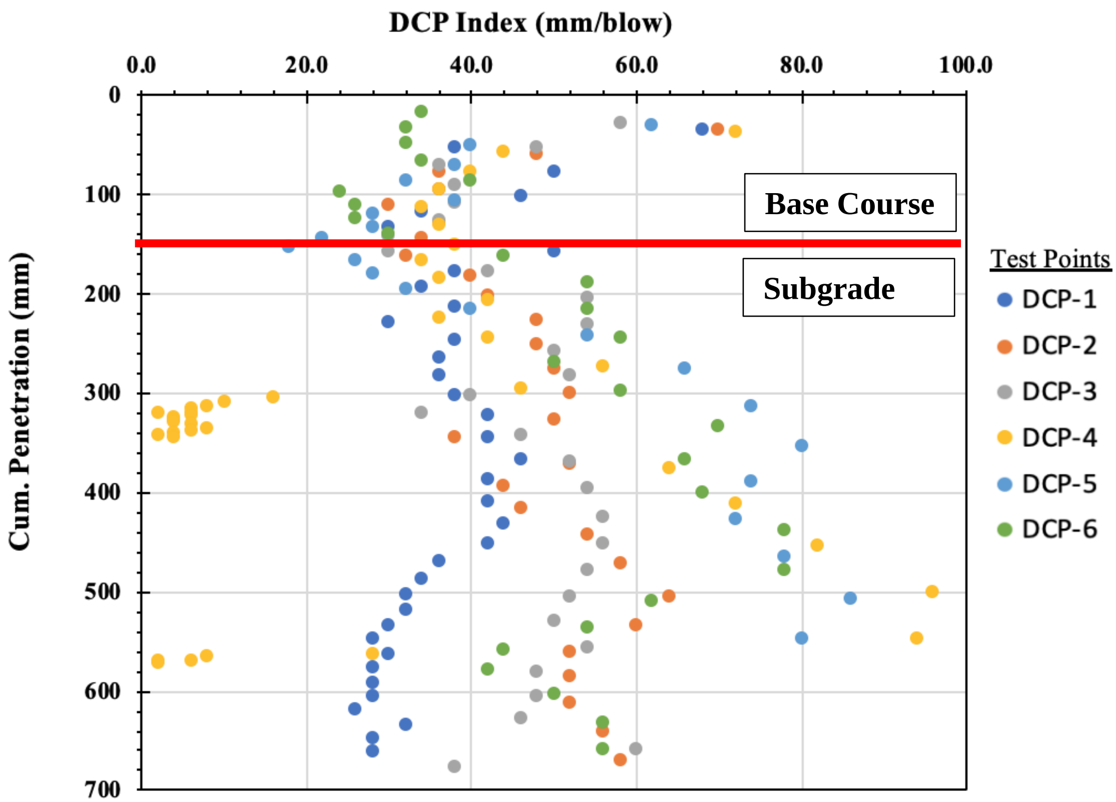


Figure - 19 DCP test results on 20% LB RAP base course layer in the field.

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