Research

Laboratory R-Value vs. In-Situ NDT Methods

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The NMDOT uses the Resistance R-Value as a quantifying parameter in subgrade and base course design. The parameter represents soil strength and stiffness and ranges from 1 to 80, 80 being typical of the highest strength for typical granular materials (theoretically R can vary between 0 and 100). Currently, a field empirical method allows estimation of this value by first determining the AASHTO Soil Classification and the Plasticity Index (PI), and then referencing the R-Value from a standard estimated table of values. This methodology often leads to overestimated R-Values and can be costly. Soil stiffness is a parameter more closely related to the R-Value than the PI and AASHTO classification of a soil. Therefore, it can be used to obtain a more accurate estimate of the R-Value. Three devices, the Clegg Impact Hammer, GeoGauge™, and a Dynamic Cone Penetrometer are possible candidates for obtaining such an in-situ soil stiffness. By obtaining mathematical relationships between the stiffness values by using the above-mentioned devices and laboratory determined R-Values, a suitable replacement for the current R-Value estimation method may be chosen.</td></tr>
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LABORATORY R-VALUE VS. IN-SITU NDT METHODS

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PREFACE

The research reported herein evaluates the possibility of replacement of the current method of R-Value estimation used in the preparation of subgrade and base course materials. This research was conducted by measuring stiffness values of said subgrade or base course using three candidate devices: the Clegg Impact Hammer, the GeoGauge, and a Dynamic Cone Penetrometer. The stiffness values were then correlated with laboratory determined R-Values of the same material to find a mathematical relationship with the candidate devices.

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ABSTRACT

The NMDOT uses the Resistance R-Value as a quantifying parameter in subgrade and base course design. The parameter represents soil strength and stiffness and ranges from 1 to 80, 80 being the highest strength for typical granular materials (theoretically *R* can vary between 0 and 100). Currently, a field empirical method allows estimation of this value by first determining the AASHTO Soil Classification and the Plasticity Index (PI), and then referencing the R-Value from a standard estimated table of values. This methodology often leads to overestimated R-Values and can be costly. Soil stiffness is a parameter more closely related to the R-Value than the PI and AASHTO classification of a soil. Therefore, it can be used to obtain a more accurate estimate of the R-Value. Three devices, the Clegg Impact Hammer, GeoGauge, and a Dynamic Cone Penetrometer are possible candidates for obtaining such an in-situ soil stiffness. By obtaining mathematical relationships between the stiffness values by using the above-mentioned devices and laboratory determined R-Values, a suitable replacement for the current R-Value estimation method may be chosen.

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INTRODUCTION

The New Mexico Department of Transportation (NMDOT) is currently using the Resistance R-Value as a necessary quantifying parameter in the evaluation of subgrade and base course for pavement design. This parameter can range from zero to 80, representing low soil strength and stiffness to high soil strength and stiffness, respectively (see Lenke et al for a discussion of the relation between strength and stiffness). The test is time consuming, requires specific equipment, and is generally performed at the NMDOT State Materials Bureau in Santa Fe or by a qualified private testing laboratory. After the preliminary determination of the R-Value in the laboratory, it is useful to determine how the R-Value changes, if at all, as subgrade preparation proceeds along a work site. Therefore, a method has been developed and implemented for field estimation of the R-Value. This estimation method is based on soil classification and plasticity index (PI). However, this method is often erroneous, in some cases overestimating the R-Value and in other cases underestimating the R-Value. More specifically, the NMDOT State Materials Engineer has documented that the DOT's reliance on Index Tests (plasticity tests and soil classification) to estimate R-Value of subgrade material in the field is highly unreliable. Currently the Department has established a chart with a 60% reliability rate index, which means that 40% of the time the R-Value could be underestimated, while 60% of the time the R-Value could be overestimated. A more accurate estimation method would save the NMDOT time and money, when actual R-Value testing is not possible, resulting in more durable and longer lasting pavements.

There are devices capable of directly testing parameters of *in-situ* soils that more directly relate to the R-Value than the PI and soil classification. Three of these devices are the Clegg Hammer, the Dynamic Cone Penetrometer (DCP) and the GeoGauge (a soil stiffness gauge).

The NMDOT is interested in one of these methods as a replacement for the current estimation method. All three devices are being quantitatively field evaluated in an effort to determine which will be the best possible estimation method for estimating the laboratory R-Value. This interim report summarizes efforts and progress for the period of October 2004 through December 2005.

BACKGROUND INFORMATION

Resistance R-Value

The Resistance R-Value test that is used by NMDOT uses a 300 psi exudation pressure and is described in AASHTO T 190 (ASTM D 2844 identical to AASHTO T 190 includes a precision and bias statement). The results of the test are indicative of the subgrade or base course performance of a roadbed when subjected to traffic loadings. The results generally range from zero to 80 for typical granular materials, high numbers signifying high performance, strength, stiffness, and stability, while low numbers signify low performance, strength, stiffness, and stability. The test is time consuming, and only specialized laboratories have the necessary equipment and expertise to perform this test method. The NMDOT State Materials Bureau in Santa Fe is capable of performing the R-Value test as well as a select few other private labs in New Mexico. However, this is costly and data may not be received for more than a week. This is impractical for use in NMDOT construction projects, as it slows work and adds additional costs.

Current Methods of R-Value Estimation

A method for estimating the R-Value using field data has been developed by the NMDOT State Materials Bureau at the direction of the State Construction Bureau. This method uses the Plasticity Index (PI) and the AASHTO Soil Classification in a tabular format as shown in Table 1. A field or laboratory technician can easily determine these parameters from field or borrow samples and look up the R-Value on the chart.

The values in Table 1 (generated by the NMDOT State Materials Engineer) were calculated using a 60% reliability index, from 2694 data points, resulting in more conservative estimates of the R-Value. In order to compare average-mean values from the field study described in this report, it is necessary to calculate the 50% reliability index data (i.e., the mean regression model) for plasticity index and AASHTO Soil Type as they relate to R-Value. This was accomplished by using the same data set used to generate Table 1. Table 2, generated by the authors, shows the 50% reliability data that will be used in subsequent comparisons with data for this study.

TABLE 1 NMDOT R-Value Estimation Chart (60% Reliability)

New Mexico Department of Transportation

Estimated R-Value Chart (60% Risk)

Effective Date: 1/1/06

NOTE: The estimated R-Values shown on this chart have a 60% chance of being equal to or greater than the indicated estimated R-Value and a 40% chance of being equal to or less than the indicated estimated R-Value. If there is reason to believe that the actual laboratory R-Value would be higher than what this chart estimates, then a representative sample of that material should be tested using AASHTO T 190 by either the Department's State Materials Bureau or at an approved laboratory that is certified by the Department's State Materials Bureau to perform AASHTO T 190.

Plasticity Index	AASHTO Soils Classification											
	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7	A-3	A-4	A-5	A-6	A-7-5	A-7-6
0	72	69	55	No Correlations Presently Exists			No Correlations Presently Exists	46	46			
1	72	67	53					43	43			
2	71	65	50					41	40			
3	71	63	48					38	36			
4	71	62	45					36	33			
5	70	60	43					33	30			
6	70	58	40					31	27			
7			38					28	24			
8			35					26	21			
9			33					23	18			
10			30					20	15			
11					31	33				11	9	7
12					30	32				11	9	7
13					29	31				11	9	7
14					28	29				10	9	6
15					27	28				10	9	6
16					26	27				10	8	6
17					25	26				9	8	6
18					24	25				9	8	6
19					23	23				9	8	6
20					22	22				8	8	6
21					21	21				8	7	6
22					20	20				7	7	6
23					19	19				7	7	6
24					18	17				7	7	6
25					17	16				6	7	6
26					16	15				6	6	6
27					15	14				6	6	6
28					14	13				5	6	6
29					13	11				5	6	6
30					12	10				< 5	6	6
31					11	9				< 5	6	5
32					10	8				< 5	5	5
33					9	7				< 5	5	5
34					8	5				< 5	5	5
35					7	< 5				< 5	5	5
36					6	< 5				< 5	5	5
37					5	< 5				< 5	< 5	5
38					< 5	< 5				< 5	< 5	5
39					< 5	< 5				< 5	< 5	5
40					< 5	< 5				< 5	< 5	5

TABLE 2 NMDOT R-Value Estimation Chart (50% Reliability)

New Mexico Department of Transportation

Estimated R-Value Chart (50% Risk)

Prepared by Lary R. Lenke and Evan M.C. Kias UNM Civil Engineering

NOTE: The estimated R-Values shown on this chart have a 50% chance of being equal to or greater than the indicated estimated R-Value and a 50% chance of being equal to or less than the indicated estimated R-Value.

Plasticity Index	AASHTO Soils Classification											
	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7	A-3	A-4	A-5	A-6	A-7-5	A-7-6
0	72	69	56	No Correlations Presently Exists			No Correlations Presently Exists	46	45			
1	71	68	53					44	42			
2	71	66	51					41	38			
3	70	64	48					39	35			
4	70	62	46					36	32			
5	70	61	43					34	29			
6	69	59	41					31	26			
7			38					28	23			
8			36					26	20			
9			33					23	17			
10			31					21	14			
11					29	33				12	9	7
12					28	32				12	9	7
13					27	31				11	9	7
14					26	30				11	9	7
15					25	28				11	8	7
16					24	27				10	8	7
17					23	26				10	8	6
18					22	25				10	8	6
19					21	24				9	8	6
20					20	22				9	7	6
21					19	21				8	7	6
22					18	20				8	7	6
23					17	19				8	7	6
24					16	18				7	7	6
25					15	16				7	6	6
26					14	15				7	6	6
27					13	14				6	6	6
28					12	13				6	6	6
29					11	11				6	6	6
30					10	10				5	5	6
31					9	9				5	5	6
32					8	8				4	5	6
33					7	7				4	5	6
34					6	5				4	5	6
35					5	4				3	4	5
36					4	3				3	4	5
37					3	2				3	4	5
38					2	1				2	4	5
39					1	N/A				2	4	5
40					N/A	N/A				2	3	5

Proposed Methods for R-Value Estimation

The R-Value is an indication of a soil's strength, stiffness and resultant elastic modulus (resilient modulus for example). A test that measures stiffness would be a much better indicator of the R-Value than the current methodology using the PI and AASHTO Soil Classification of a field sample. Several of these tests are available, and can be used on site with little to no site disturbance. Such test methods are also amenable to laboratory test methods as well. This project has identified three methods with ASTM procedures that may replace the current estimation method, viz., the Clegg Hammer, the Dynamic Cone Penetrometer, and the GeoGauge. Note that a fourth device was considered, viz., the BCD (see Briaud et al). However, it was deemed insufficiently developed at the genesis of this study for inclusion; it also lacked a standard ASTM test method at the time. The BCD is simple static plate bearing test using very low vertical loading over a small diameter plate. It is deemed to be a small strain test.

Clegg Hammer

The Clegg Hammer is basically a modified proctor hammer of a known weight that is dropped from a known height. An accelerometer is integral to the hammer. When the hammer impacts the compacted soil, the accelerometer reads the deceleration of the hammer and provides a readout in terms of the Clegg Impact Value (CIV). One CIV is equal to 10 g, where g is the acceleration due to gravity (1 g = 32.2 ft/s^2). The stiffer the soil, the higher the deceleration, and the higher the instrument reading, i.e., the CIV. The hammer is dropped four times on the surface of the soil and displays the highest CIV of the four drops. The procedures are found in ASTM Standard D 5874. The cost of this piece of equipment is approximately $2300. A single test cannot take longer than 30 seconds, as the equipment will power off at that time. Nearly immediate results can be found using this device. Its small size and weight make it easy to transport and to take several readings in a very short time period. A picture of the Clegg Hammer with its readout device attached is shown in Figure 1.

Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer (DCP) is a simple mechanical device described in ASTM Standard D 6951. A 17.64 lb hammer is dropped several times, through a distance of approximately 23 inches, and drives a small cone (60° cone, 0.79 inch diameter) through the compacted soil. The number of hammer blows needed to drive the cone 25-30 mm deep, (approximately one-inch), is recorded as the cone penetrates the soil. The cone is driven between 20 and 28 inches below the surface, and the data shows a profile of the soil stiffness versus depth. This profile can be useful for determining layer thickness and the stiffness properties of an underlying layer. It also shows the changes in stiffness throughout the layer being tested, showing voids or rocks under the surface. The apparatus costs approximately $1650 and is easy to operate. Replaceable cones tips are used, and cost about $2.00 each. The stainless steel apparatus is fairly heavy, and requires significantly more effort to transport than the Clegg Hammer. It must be reassembled and disassembled before and after each use adding to the testing time. The actual test can take anywhere from five to twenty minutes to perform depending on the soil stiffness of the site. A picture of the DCP is shown in Figure 2. The DCP data requires considerable post processing and analysis compared to the Clegg or GeoGauge, each of which provide instant field results.

FIGURE 1 Clegg Hammer with Readout Device.

GeoGauge

The GeoGauge, referred to in ASTM Standard D 6758 as a soil stiffness gauge, is an electro-mechanical method of measuring the *in-situ* soil stiffness. The apparatus performs a dynamic load test on the compacted soil. By means of a mechanical shaker, the GeoGauge imparts small displacement sinusoidal loadings at discrete frequencies between 100 and 200 Hz. Transducers measure this small displacement and imparted force to the subgrade through the annular aluminum foot of the GeoGauge. The apparatus then calculates an average stiffness based on these measured displacements and forces over the operating frequency of 100 to 200 Hz. The display provides the soil stiffness, *K*, in SI (MN/m) or English (kip/in) units, (the ASTM calls for the SI units to be standard).

FIGURE 2 DCP in Operation.

While the apparatus itself is rather complicated, performing the test is fairly simple. The GeoGauge is seated on the soil by twisting it approximately 45 degrees without applying a downward pressure. The operator then simply presses the measure button. The apparatus runs the rest of the procedure itself with few constraints. Due to the dynamic nature of the test, vibrations in the ground must be at a minimum, meaning that there must be sufficient space between the apparatus and any heavy equipment in operation. This test takes less than two minutes to complete and gives readouts immediately. After the data is recorded, the GeoGauge is removed to check the seating. At least 60% of the foot must have been in contact with the soil. This is determined by the footprint on the soil after the apparatus is removed. If the footprint does not show at least 60% contact, the use of a moist sand interface is recommended by the ASTM in order to transfer the force from the annular foot to the soil. Due to the success of using a moist sand interface, a revised ASTM may require the use of the moist sand at all times. Therefore, all tests in this study are performed with the sand and without the sand for completeness and comparison purposes. The cost of the GeoGauge is approximately $5000. Figure 3 is a picture of the GeoGauge.

METHODS AND PROCEDURES

Locating a Test Site

NMDOT has provided the research team with several project listings for past and current projects. Each list had contact information for the Project Manager/Engineer, and the construction crew working on the job. To supplement the project listings, letting schedules were also used. These schedules give a better idea of when a project will start, and what projects are coming up throughout the state. NMDOT personnel are the most valuable resource the research team could use in finding sites. Assistant District Engineers and NMDOT District Laboratory Supervisors are familiar with the projects and designs in each district. They were able to refer University of New Mexico (UNM) project personnel to Project Managers/Engineers without having to go through a long telephone chain.

FIGURE 3 The GeoGauge.

Once a job was determined as a possible test site, the team would contact the Project Engineer and research the details of the pavement design. The research requires that the testing be done on a subgrade that has been tested and has met the specific moisture and density requirements of that project. Some base course testing is acceptable, however, as it will be shown later in this report, base course accounts for only a small portion of the soil range. Due to boundary effects and the possible need to revisit a test site, testing near culverts and in embankments was deemed inappropriate. Stabilization is a common practice throughout the state for high volume roads, but projects using stabilized soil were outside of the scope of this research. As a final verification that the soil was prepared correctly, and would meet design specifications, the research demands that nuclear density tests be used, in order to verify proper density and moisture for the quality control and quality assurance (QA/QC) at a given test site.

Travel Procedures

New Mexico is the fifth largest state in the United States. The research team is based at the University of New Mexico, in Albuquerque, requiring the team to travel long distances to test sites. This dilemma is complicated further by the need to transport a relatively high volume of equipment to the test site and to retrieve samples. In order to accommodate this need, the research team rented a cargo van from a local rental company for the summer of 2005. The van was labeled as a UNM research vehicle and outfitted with a yellow light bar for safety purposes. The van allowed the team to keep a majority of the test equipment ready for transportation to a test site and reduce the team's response time to a site. This is vital, as the window of opportunity on a test site can be limited by a construction crew's need to complete a stretch of roadbed construction before a deadline. During the academic year, the research team is restricted due to student class loads. For this reason, the cargo van was returned, and vehicles are rented or borrowed as needed for site visits.

On Site Testing Procedures

Before leaving the University, the research team identifies a contact that will meet with the team on site. This meeting is usually held at the field construction offices, where a discussion on the best area for the testing to occur can be held without holding up construction in the field. At this time the team reinforces the needs of the research. If at any point the parameters of the research are not met, the issues are brought up and resolved (on occasion the test is cancelled because of constraints that cannot be met). Once the Project Manager/Engineer chooses a stretch of the project that will accommodate the research, the team makes a visual observation and either approves or disapproves the site. Upon approval, the Quality Control Technician (generally NMDOT QA/QC personnel) takes two readings of the in-place density and the in-place water content using nuclear methods. At least one of these readings must pass the specifications of the project for site approval. If the specifications are not met the contractor will return to the site and rework the stretch until it passes, or a different location is selected that meets the research criteria and that will meet moisture-density specifications.

After meeting nuclear density requirements, the research team begins outlining the test-site using white chalk. A twenty-five foot by four-foot grid is drawn on the site, identifying a total of eighteen test locations for the three different methods, numbered one through six, in the direction of traffic. The centerline of this grid identifies the six GeoGauge test locations spaced every 5 feet. To the left of the GeoGauge (facing the direction of travel) are six Clegg Hammer test locations. To the right of the centerline are the four DCP test locations, at location one, three, four, and six, with nuclear densometer testing at locations two and five. A diagram of a typical test site is shown in Figure 4. While the grid is being outlined, digital photos of the test site are being taken for archival purposes. The locations of positions one and six on the centerline are recorded via handheld global positioning (GPS) unit for future reference. Air and soil temperatures are taken to find any possible effects they may have on the equipment or resultant data.

One member of the team then begins assembling the DCP, while the other verifies the operation of the GeoGauge by the use of the verifier mass as described in the GeoGauge manual. While checking the GeoGauge operations, that team member may run the Clegg Hammer at the specified test locations in accordance with ASTM Standard D 5874. These readings are recorded on the data sheet, and GeoGauge verifier mass readings are logged for reference. At this point the DCP should be completely assembled. The DCP test is best completed using two people. One for dropping the hammer and counting the number of blows and one for reading the depth of penetration and recording the data. This method ensures the most accurate readings. Once the DCP testing over the four locations is completed, the apparatus can be disassembled while GeoGauge tests are being performed.

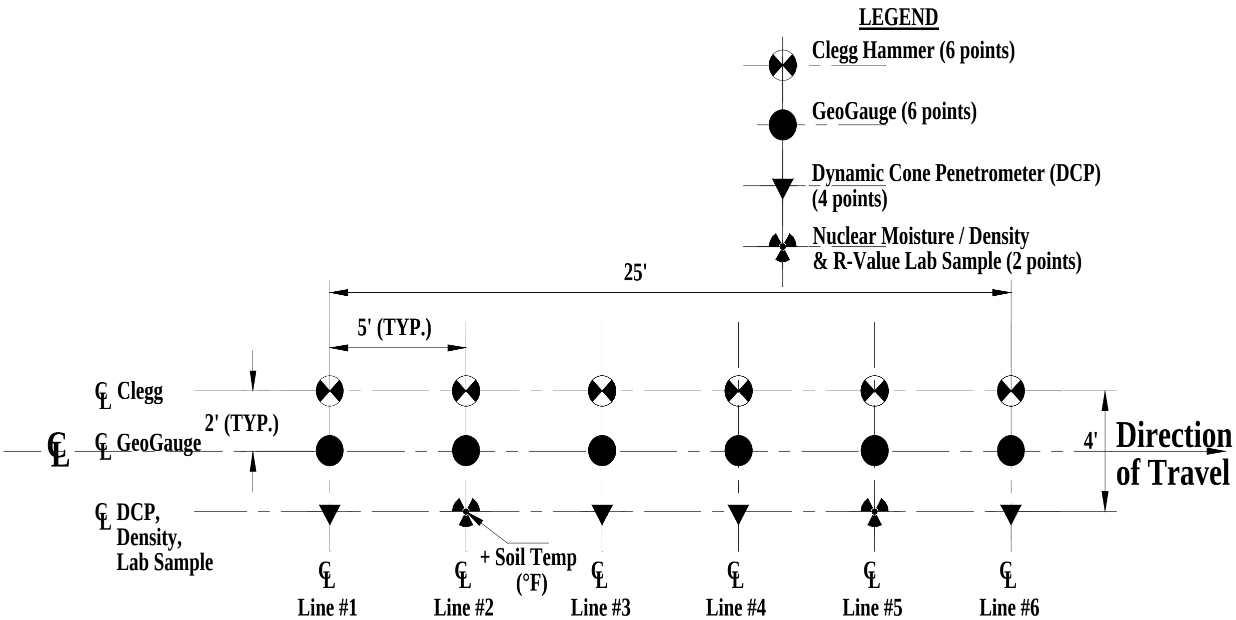

FIGURE 4 Test Grid.

This research is looking at two GeoGauge measurement protocols; one with the GeoGauge in direct contact with the compacted soil, the other with a moist masonry sand interface layer between the GeoGauge foot and the soil surface. The GeoGauge manufacturer and the ASTM procedure recommend this procedure when proper seating is not met. On each location two readings are taken, the first reading is taken without the use of the sand interface, and the second, taken approximately six inches from initial reading with the use of the moist sand interface. Both readings are recorded for analysis. This procedure is repeated on all six locations. Once the GeoGauge tests are completed, the GeoGauge must be cleaned so that no sand is lodged in the setscrews located on the bottom of the foot. This sand can cause inaccurate readings when the GeoGauge is later placed on the Verifier Mass. During the GeoGauge measurement, the other team member assembles the auger for sampling.

Sampling is completed by Auger Methods as described in ASTM Standard D 1452 and samples are reduced in accordance with AASHTO T-248. Approximately 160 pounds of material is taken from each site for testing at UNM and Western Technologies (4, each 40 pound samples). This amount varies depending on the aggregate size, as more soil is needed for soils with larger aggregates. The samples are then transported to the labs using cloth sample bags with two plastic liners, one per sample, provided by NMDOT. Once sampling is complete, the research team refills the auger holes left on the site with subgrade or base course using a heavy metal tamper. The Project Engineer/Manager is notified of the sampling, and photos of the site after testing and sampling are taken.

Laboratory Testing

Western Technologies in Albuquerque was chosen to complete most of the laboratory work required by the research. This includes three replicates of the Resistance R-Value test (AASHTO T-190 (ASTM D 2844)), field moisture content (AASHTO T-255), a standard proctor density curve analysis for maximum density and optimum moisture content (AASHTO T-99), Atterberg Limits (AASHTO T- 89, AASHTO T-90), sieve analysis (AASHTO T-27), and AASTHTO soil classification (AASHTO M-145). Samples are retained by Western Technologies until they can be returned to UNM and stored. Western Technologies has a well-equipped laboratory for performing these tests and is conveniently located to the University of New Mexico. UNM completes three additional replicates of the moisture content on each sample in their UNM laboratories.

The NMDOT has asked for the ability to test samples taken from the test sites at will. To meet this request, samples are being retained for this purpose in UNM storage. If at any point a sample is called into question, it can be retrieved from UNM storage for testing by the NMDOT State Materials Bureau in Santa Fe. Sites 1-4 have already been tested in this manner for verification of the R-Value. The stored samples are labeled by site number and can be referenced to data sheets to find GPS locations of sampling.

DATA AND ANALYSIS

As of the writing of this report, fifteen test sites have been completed. Table 3 tabulates these sites their locations, and summarizes the data taken. The first column of Table 3 presents the site number (or sample number), the second column is a brief description of the test site location, and the third column is a NMDOT control number identifier or other appropriate identifier. Columns 4 through 8 provide experimental data for each test site. Column four is the average of the GeoGauge measurements without a sand interface between the annular foot and the compacted subgrade, while column five presents similar results for the GeoGauge average with a sand interface. The sixth column presents the average of the Clegg Hammer data at a test site in terms of the Clegg Impact Value (CIV). Column seven is the inverse of the Dynamic-Cone Penetration Index (DPI) in units of blow/in. The reason for this choice of units is that the inverse of DPI will be proportional to strength or stiffness, whereas, DPI will be inversely related. Column eight presents the average value of the three laboratory R-Value tests performed by Western Technologies. The last column presents the R-Value of the soil at each test site obtained by use of the NMDOT R-Value estimation chart (Table 2, 50% Reliability) via plasticity index and

AASHTO soil classification determined by Western Technologies. Note that all data in Table 3 are mean values.

R-Value tests were unable to be completed by Western Technologies on Sample #15. They cited the coarse nature of the soil causing an inability of the sample to retain its shape after being removed from the mold because of its extreme porous nature. Since Western Technologies was unable to determine the R-Value the test site data is deemed unusable and hence the Estimated R-Value data is not applicable.

TABLE 3 Test Sites and Corresponding Data

Sample #	Location Desciption	CN or Project #	Geo-Gauge w/o Sand, k(kip/in)	Geo-gauge w/ Sand, k(kip/in)	Clegg Hammer, (CIV)	DCP DPI-1 (blow/in)	Average R-Value (W. Tech)	Estimated R-Value (by DOT Method, 50% Reliability)
1	Motel Blvd, Las Cruces, NM	CN3448	61.38	73.37	19.4	1.4539	19	NA
2	US 70, Ruidoso Downs, NM	CN3393	122.15	189.11	57.1	8.0709	38	28
3	Golf Course & Paradise, Abq, NM	CN7504	56.87	57.88	13.9	1.7035	56	56
4	NM 63, Rowe, NM	CN2075	73.42	86.34	36.2	3.8383	22	10
5	US 54, Santa Rosa, NM	CNG3B24	95.94	129.01	58.8	9.8122	31	43
6	Double Eagle Airport	DoubleEag	78.10	81.03	18.7	4.3279	20	46
7	I40 and Tramway, Albuquerque, NM	CNG1123	100.85	135.74	38.1	7.2915	28	69
8	I40 & Coors, Albuquerque, NM	CN G1013	116.76	121.81	31.3	4.6592	78	69
9	NM 300, Old Pecos, Santa Fe	CN 2968	53.31	73.37	15.7	3.5548	13	28
10	NM 128, Jal, NM	CN G2152	72.80	86.62	19.2	5.0080	73	69
11	NM 209, Tucumcair, NM	CN 3157	39.98	44.13	10.0	1.0436	57	56
12	US 54, Santa Rosa, NM	CN G3B24	92.58	102.59	33.4	9.4219	82	69
13	US 54, Santa Rosa, NM	CN G3B24	100.95	93.48	31.2	4.7918	78	72
14	I-40 MP 123	CN 1462	74.35	86.65	42.0	4.6473	67	69
15	I-40 MP 122	CN 1462	26.45	27.52	22.4	2.4766	NA	NA

Before research began, it was determined that three to four samples of each AASHTO soil classification should be tested in order to get enough data points to show a reliable correlation. As of the authoring of this report, this goal has not been reached. Most of the samples tested have fallen under the range of "*Excellent to Good*" on the R-Value Estimation Chart (Tables 1 and 2). There is a definite paucity of data on the right side of the chart, referred to as “*Fair to Poor*” soils. These soils have a low estimated R-Value according to the chart, and are therefore treated with lime or cement for added strength. It is not common for the NMDOT to complete R-Value testing on these samples. Therefore, any design that calls for treatment of these soils has been excluded from this research. In order for a reliable correlation to be formulated, testing across all soil classifications must be acquired.

The empirical data found through this research has shown two clusters of data points that are repeated by each apparatus. These clusters suggest a second parameter in action, creating more than one function. In fact, investigation of the sieve analysis data from Western Technologies suggests that this parameter is the amount of soil passing the #200 sieve. AASHTO Soil Classification procedures instruct that if more than 35% of a soil is composed of fine grains (grains that pass the #200 sieve) then the soil is classified as a fine-grained soil. However, the data from this research suggests a change in the R-Value when the percent of fines in the soil is more than 20%. To simplify this report, the soils with more than 20% fines will be referred to as fine-grained soil, and soils with less than 20% fines will be referred to as coarse-grained soils.

In the proceeding sections the analyzed data will be presented along with an estimation of the correlation’s reliability in the form of a statistical parameter called the Coefficient of Determination (R^2). The closer the Coefficient of Determination is to unity, the more reliable the correlation.

Estimated R-Value by NMDOT Method

Figure 5 presents the Estimated R-Value obtained by use of the NMDOT R-Value Estimation Chart at 50 percent reliability plotted against the R-Value obtained by the procedure described in AASHTO T190. The best-fit line produces an R^2 value of 0.5837. In addition to the low coefficient of determination, one will note that the regression line departs significantly from the one-to-one line suggesting a poor model (i.e., the current NMDOT method for estimating R-Value). It seems obvious that a more accurate method of determining the R-Value in the field is desirable.

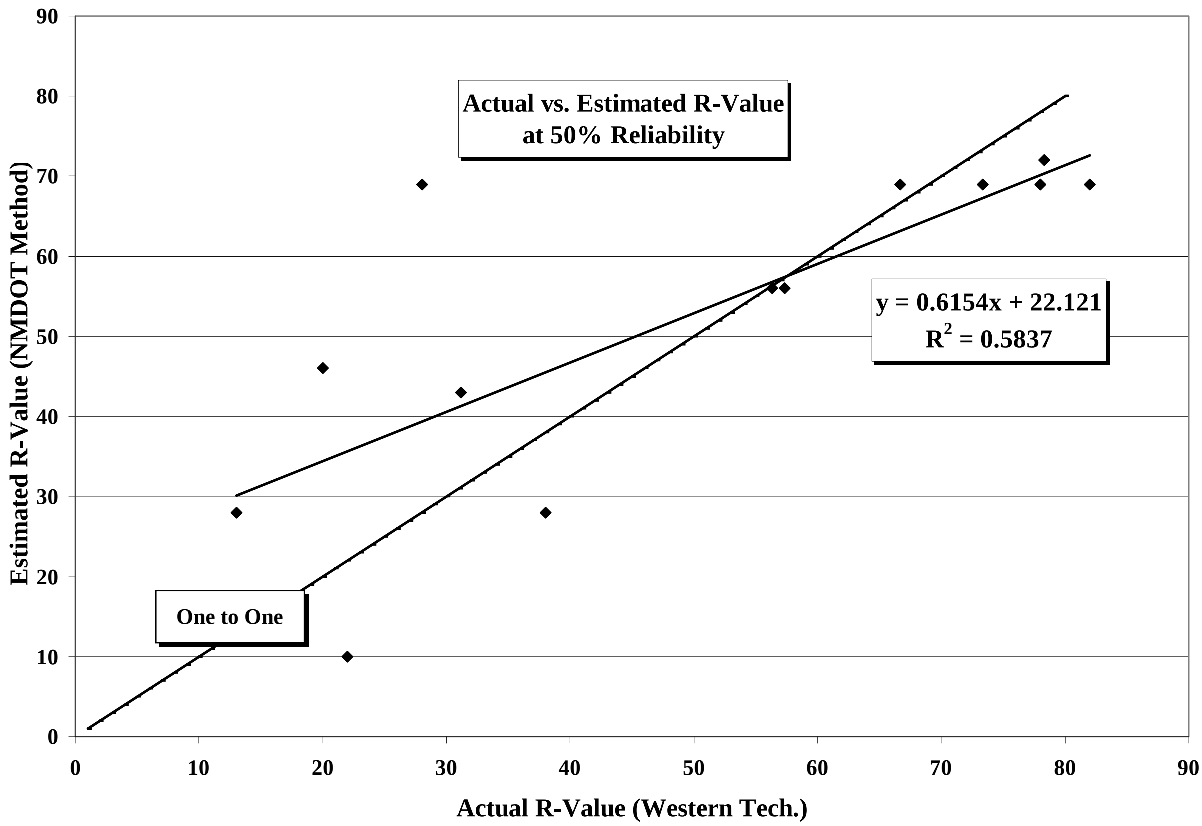

FIGURE 5 Field Estimated R-Value (by NMDOT method, 50% Reliability) vs. Actual R-Value.

Clegg Hammer

Figure 6 depicts plots of the average Clegg Impact Values on the x-axis, versus the average R-Value readings on the y-axis for all 14-test sites evaluated. The figure shows two clusters of data, with the 20% fines parameter differentiated by distinctly different functions. Notice the coefficient of determination (R^2) for the linear correlations. The value of (R^2) for the fine-grained soils is 0.8551, a decent value for soils. The value for the coarse-grained soils is considerably lower (R^2 of 0.4147). However, both of these values will likely change as more experimental data is added, as will the functional relations between CIV and R-Value.

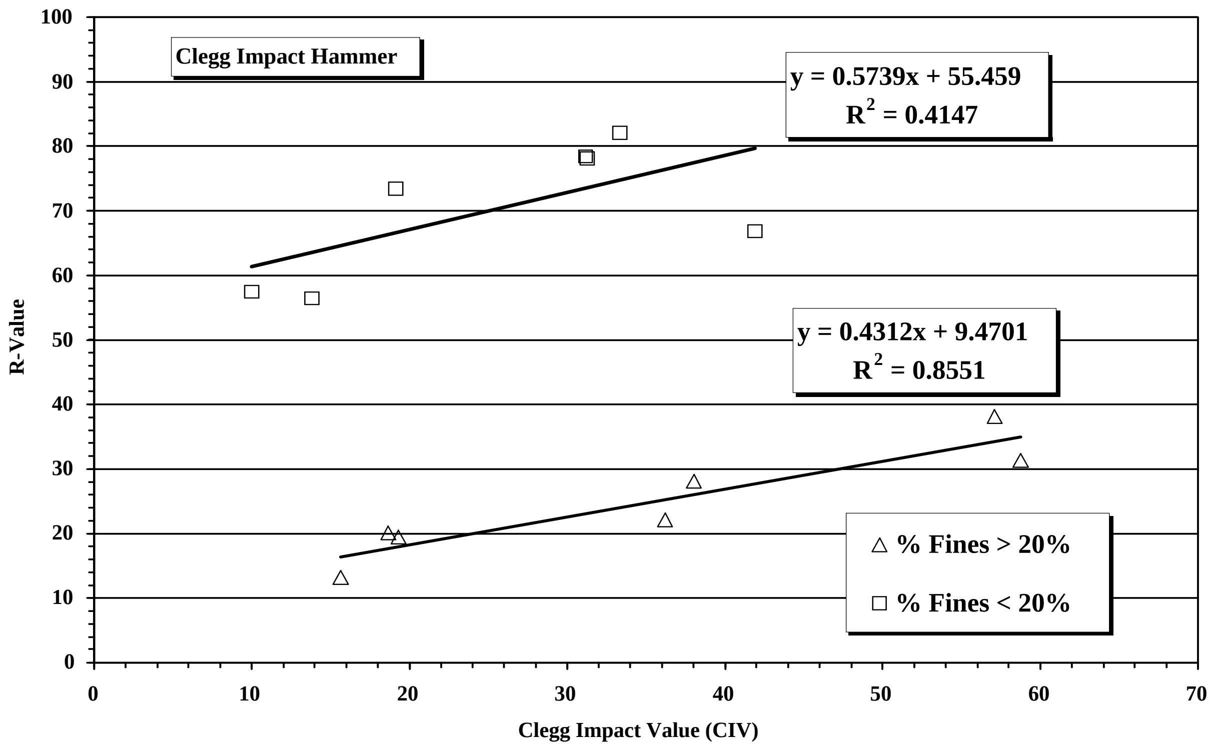

FIGURE 6 Laboratory Determined R-Value vs. CIV.

Dynamic Cone Penetrometer (DCP)

The DCP gives a reading for every inch of penetration (in terms of depth of penetration per blow, or Dynamic Penetration Index (DPI). In order to reduce these readings down to a single value for each of the locations, an average reading was obtained. In order to assure this average was an accurate representation of the data, graphs, similar to Figure 7 were created showing the DCP Index (DPI) versus the depth of penetration. These graphs are effectively a profile of the soil's stiffness. An example of the four soil profiles at a given test site are shown in Figure 7. Using these graphs, it is possible to see the depth where the DCP passed through the subgrade layer, and penetrated the underlying softer un-compacted soil. Once this was determined and checked with design parameters acquired on the site, the readings were averaged by means of trapezoidal integration across the relevant compacted soil depth. The number was then used as a single reading for that location. A mean of the four location averages at a given site was then found and used to find a correlation with the average R-Value laboratory tests.

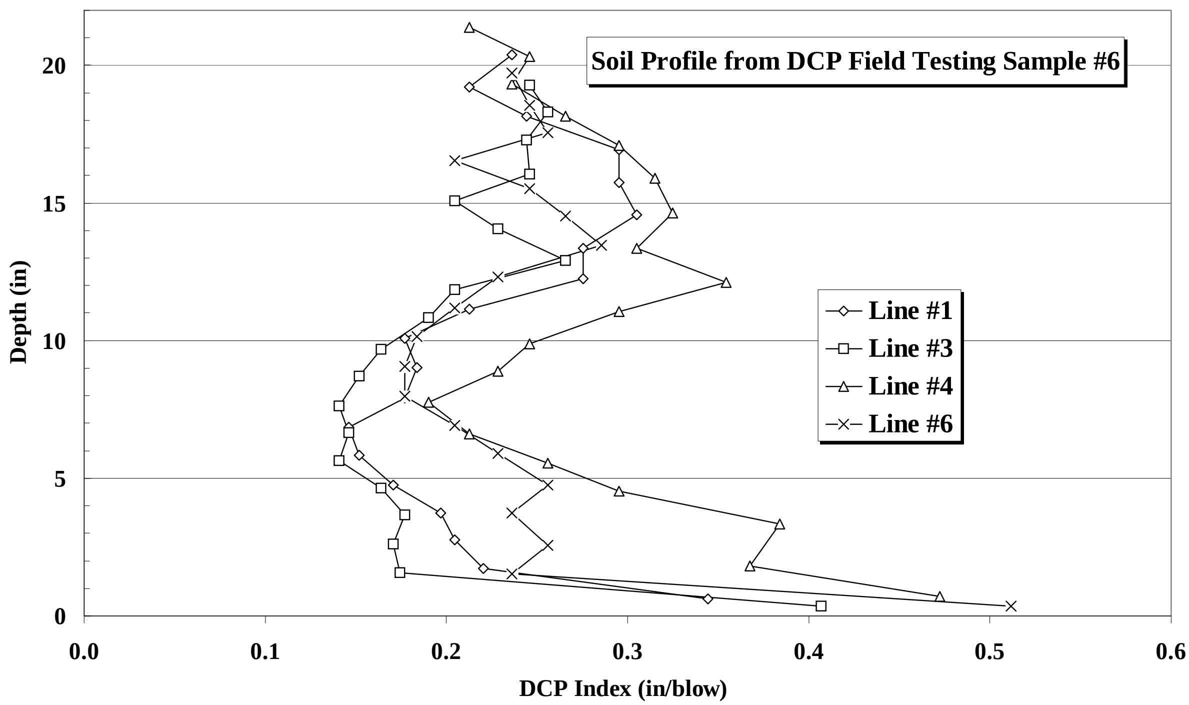

FIGURE 7 Soil Profile from DCP Field Testing.

Figure 8 shows two linear correlations between the field DCP test results and the R-Value laboratory tests dependent on percent fines. The x-axis is the inverse of the DPI, or DPI^{-1} (blow/in). These values are very small. The inverse of DPI allows a positive correlation between the DCP reading and the R-Value. The same pattern in the data clusters, with the separation parameter of 20% fines is repeated in this data. The R^2 values for both correlations are approximately 0.7. These values seem acceptable considering the mechanical operations of the DCP, the averaging procedure used, and the limited number of data points. Again, the R^2 values will change as more data is collected as will the form of DCP versus R-Value.

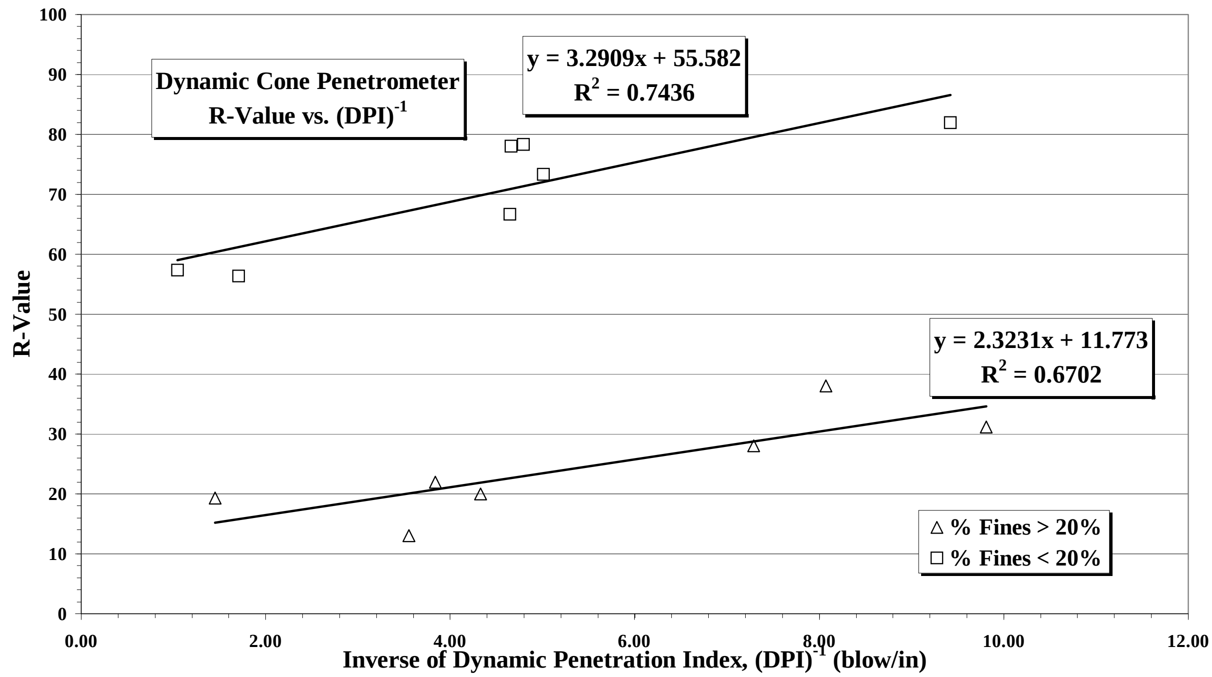

FIGURE 8 Laboratory Determined R-Value vs. $(DPI)^{-1}$.

GeoGauge Without the Use of a Moist Sand Interface

As stated in the procedures section, readings were taken with both the use of moist masonry sand, and without the use of moist masonry sand. This was to determine if there was any significant difference in the methods. First, tests are performed without the use of a moist sand interface. Figure 9 shows again that two clusters of data emerged and two linear correlations are presented for coarse and fine soils. These correlations repeat the parameter of 20% fines. The R^2 value is much higher for soils consisting of more than 20% fines (0.9368). While the R^2 value for the coarser materials is lower (0.7695), it still appears to be an acceptable value. This occurrence, perhaps, represents the procedural concern with the proper seating of the GeoGauge. On a coarser soil, there are no sand fines to fill the voids between the foot and the surface causing less contact, perhaps suggesting that this results in less accurate readings on coarse grained material.

GeoGauge With the Use of a Moist Sand Interface

These results were taken using a moist sand interface of Masonry Sand (ASTM 144) prepared to a moisture content of approximately 16%. In accordance with the ASTM standard, a layer of approximately one-quarter inch thickness smoothed out by hand or trowel was placed on the soil surface. The GeoGauge was then seated as normal, and readings were recorded.

Figure 10 shows the correlations between the averaged six GeoGauge field readings versus the three averaged R-Value laboratory tests for each test site. The R^2 value for the coarser material has increased slightly (0.8007), while the R^2 value for the finer material has decreased (0.9012). The ASTM suggests only using the moist sand interface when the GeoGauge has insufficient contact with the soil. This would occur on the coarser material; therefore the use of moist sand may be more justified for these types of material. However, on finer material there should be no need for sand. Therefore, using sand could result in a less accurate reading. It is still unclear how exactly the sand affects the readings, if at all.

DEVICE ESTIMATED R-VALUE

In order to choose the most appropriate device, it must be determined which device can most accurately predict the laboratory determined R-Value. The correlations developed from analysis of the test data collected from the fourteen accepted test sites can be used to determine the "Estimated R-Value". For example, refer to Figure 10. The correlation of GeoGauge stiffness with the use of a moist sand interface for fine-grained soils to laboratory determined R-Value is $y = 0.1835x + 4.3731$, where y is the estimated R-Value and x is GeoGauge stiffness. The estimated R-Value can be determined by plugging the GeoGauge stiffness readout for a field test into the equation and performing the appropriate arithmetic operations. This estimated R-Value predicted using the candidate field test methods can then be plotted against the actual R-Value measurements determined in the laboratory (by Western Technologies). If the model predictor (e.g., Clegg, or DCP, or GeoGauge) is a good one the plotted relation should plot close to the one-to-one line with a slope close to unity and a zero intercept. Figure 11 presents such data obtained from the GeoGauge w/o a sand interface. The coefficient of determination is 0.8864 and the slope and intercept are 0.9835 and 1.5023, respectively. This is quite an improvement in contrast to Figure 5, the current NMDOT estimation methodology. Similar operations were performed for the other devices and their correlations were plotted. Figures 12, 13, and 14 show these correlations in order of increasing accuracy (coefficient of determination).

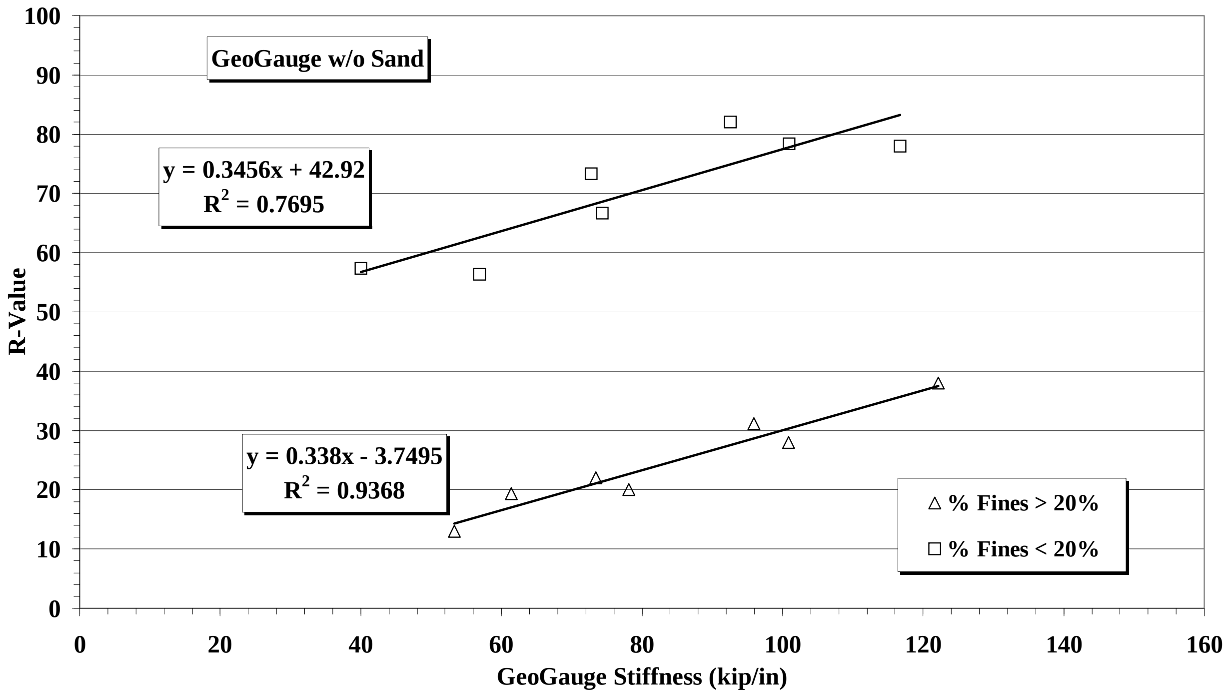

FIGURE 9 Laboratory Determined R-Value vs. GeoGauge Stiffness (k) w/o Sand.

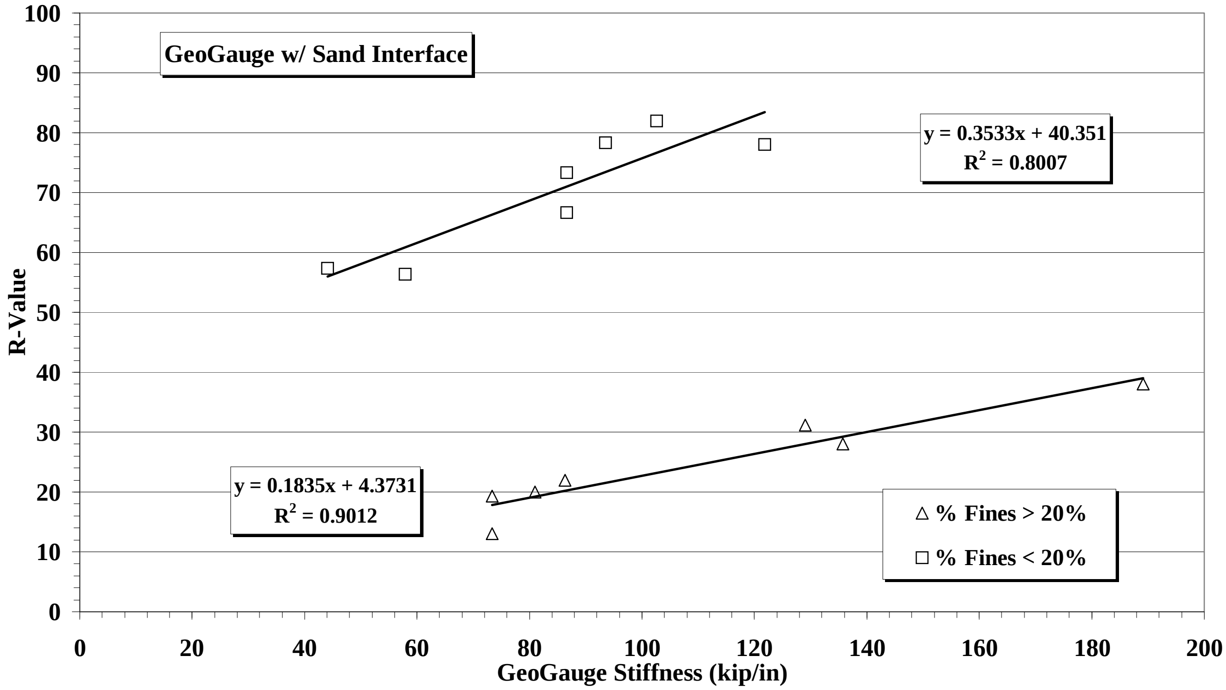

FIGURE 10 Laboratory Determined R-Value vs. GeoGauge Stiffness (k) w/ Sand.

Notice the R^2 values for Figures 11, 12, 13, and 14. Not only are the R^2 values significantly higher than the R^2 value for NMDOT Chart estimated R-Value at 50% reliability versus the actual R-Value, but they are also increasingly close to unity, and are close to the one-to-one line. Although, under further study, you will notice two clusters of data present in Figures 11, 12, 13, and 14. This clustering is a byproduct of both soil classification and incomplete data sets (i.e., soil types). Notice that the gap between the two data clusters closes in the case of the GeoGauge used with a moist sand interface. The authors believe this is directly related to the tighter correlation between GeoGauge estimated R-Value and actual R-Value. As more data is collected (i.e., soil types), the authors believe that this gap will narrow, resulting in a uniform distribution.

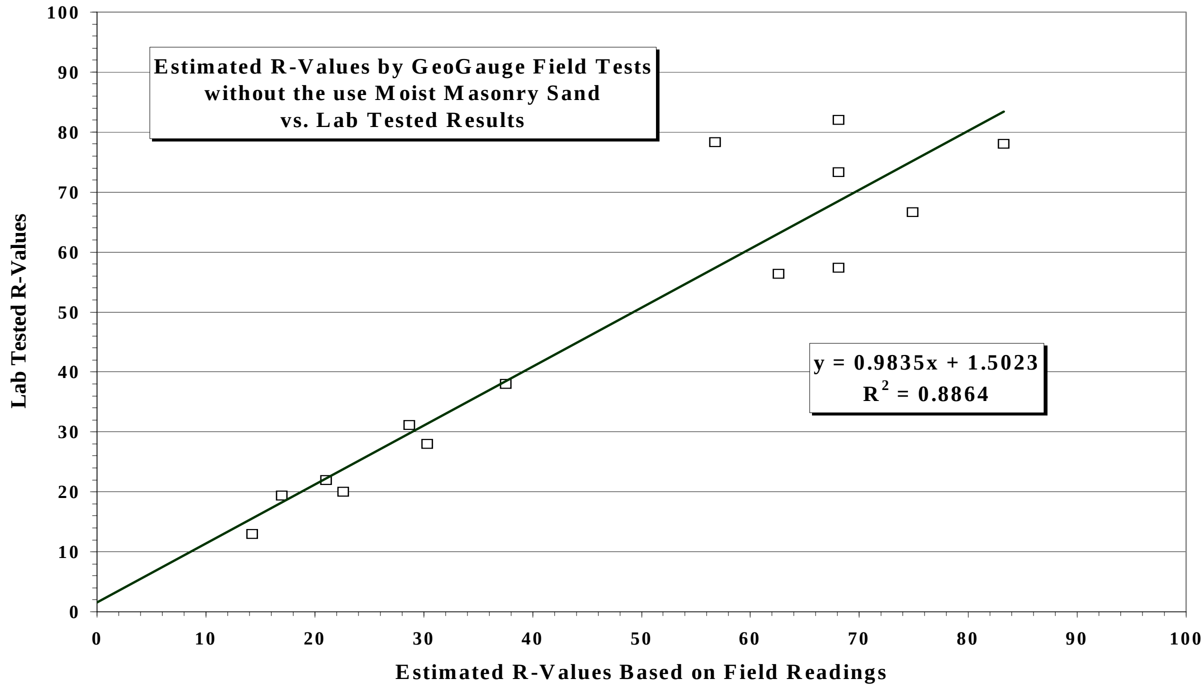

FIGURE 11 GeoGauge w/o Use of Sand Estimated R-Value vs. Actual R-Value.

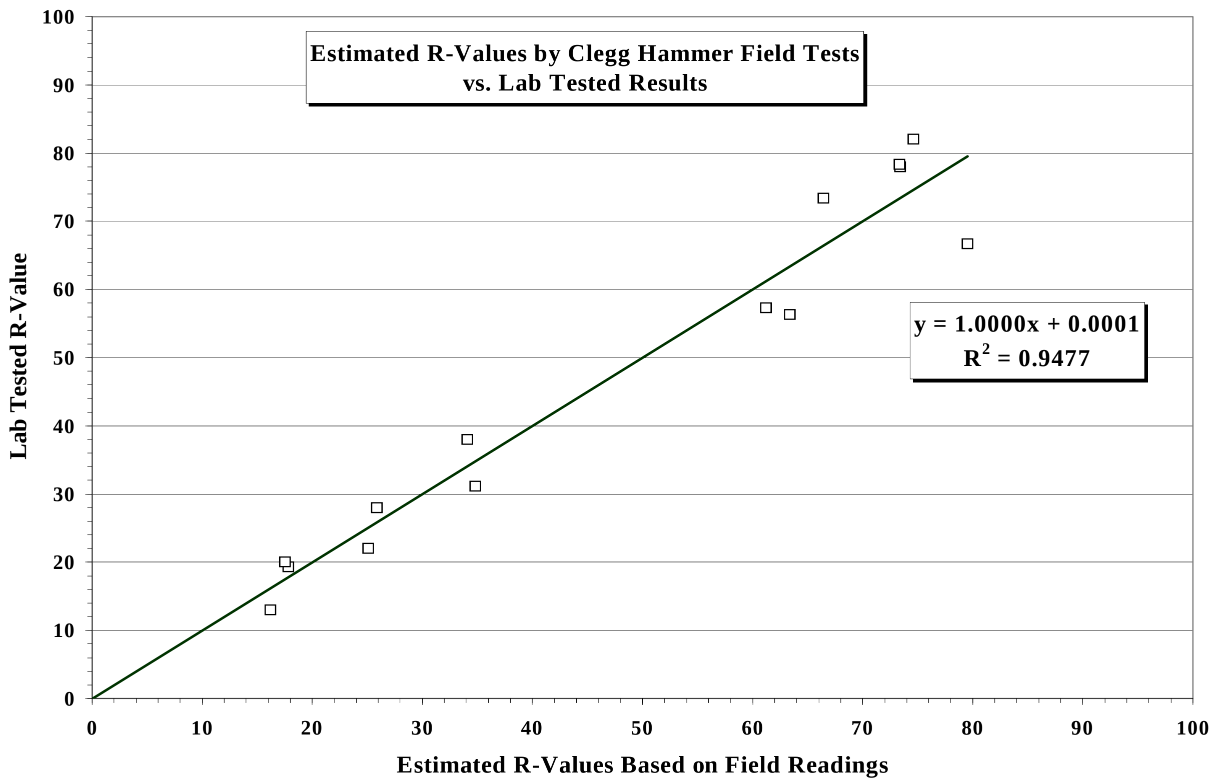

FIGURE 12 Clegg Hammer Estimated R-Value vs. Actual R-Value.

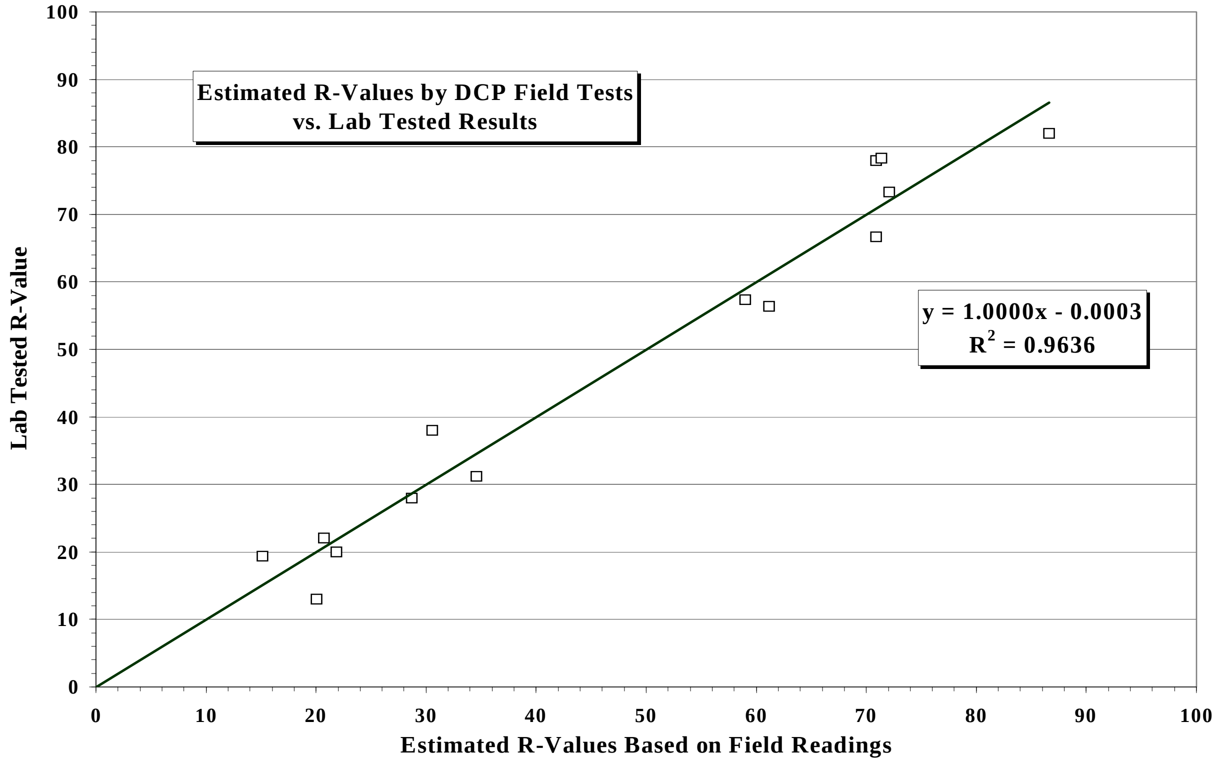

FIGURE 13 DCP Estimated R-Value vs. Actual R-Value.

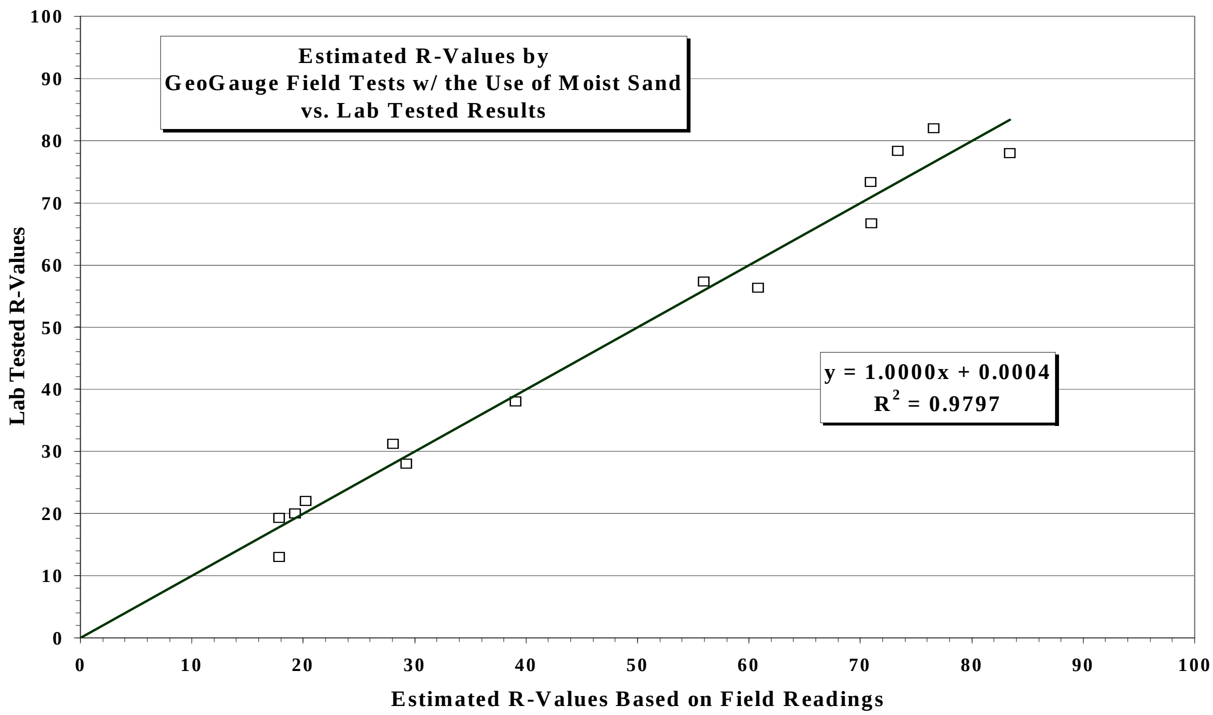

FIGURE 14 GeoGauge w/ Use of Sand Estimated R-Value vs. Actual R-Value.

SUMMARY OF CORRELATIONS

Table 4 shows a summary of the reliability of the correlations developed during this study in the form of the Coefficient of Determination, (R^2). From the table, one might conclude that the GeoGauge shows the most promising correlation. In addition, the correlations for the fine-grained materials seem to be stronger.

TABLE 4 Listing of Coefficients of Determination

	Coefficient of Determination for Device Readout vs. R-Value, (R^2)	
	Coarse Grained	Fine Grained
Clegg Hammer	0.4147	0.8551
DCP	0.7436	0.6702
GeoGuage w/ Sand	0.8007	0.9012
GeoGuage w/o Sand	0.7695	0.9368

TABLE 5 Coefficients of Determination for Actual vs. Estimated R-Value

	Coefficient of Determination for Estimated vs. Actual R-Value, (R^2)
NMDOT Chart	0.5837
GeoGauge w/o Sand	0.8864
Clegg Hammer	0.9477
DCP	0.9636
GeoGauge w/ Sand	0.9797

Overall, the correlations for estimated R-Value to actual R-Value are overwhelmingly stronger for each of the devices than the correlation for the NMDOT R-Value Estimation Chart. Table 4 depicts the R^2 values of these correlations.

CONCLUSIONS AND RECOMMENDATIONS

Despite these encouraging results it is too early to make a choice on the most appropriate device, as more data must be collected. Table 6 is exemplary of this lack of raw data. One will notice that there is a clear paucity of soils sampled and tested to date. Twelve of the fourteen soils evaluated are A-2 types or better. Only fifteen percent of the “poorer” soils

TABLE 6 Soil Type Breakdown for UNM Compiled Data

	Soil Type Breakdown for UNM Compiled Data (per R-Value study)												
Soil Type	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7	A-3	A-4	A-5	A-6	A-7-5	A-7-6	Total # Evaluated
No. Evaluated to Date	1	5	4	0	2	0	0	1	0	1	0	0	**14**
% of Total Evaluated	7.1%	35.7%	28.6%	0.0%	14.3%	0.0%	0.0%	7.1%	0.0%	7.1%	0.0%	0.0%	100.0%
Likelihood of Finding in NM	**BASE COURSE**	**BASE COURSE**	HIGH	NEARLY ZERO	HIGH	NOT LIKELY	~ ZERO	REALLY HIGH	NOT LIKELY	REALLY HIGH	NOT LIKELY	FAIRLY HIGH	
Total Required Based on **NM %** to Obtain 40 Samples	0	0	6	0	5	1	0	13	0	11	1	3	**40**
No. Evaluated to Date	1	5	4	0	2	0	0	1	0	1	0	0	14
Approx. No. NEEDED for Project Completion	-1	-5	2	0	3	1	0	12	0	10	1	3	**32**

Twelve of the fourteen soils evaluated are A-2 types or better. Only fifteen percent of the “poorer” soils have been tested to date (soils on the right side of the chart). It is worthwhile to note that Table 1 was developed based on almost 2700 R-Value tests with corresponding soil index tests and classifications. Based on this voluminous amount of data, one can infer the likelihood of finding various soil types, in New Mexico. The chances of finding field/construction work with A-2-5, A-2-7, A-3, A-5, and A-7-5 are not likely as shown in Row 4 of Table 6, which describes the likelihood of finding that soil type in New Mexico. Based on this likelihood/possibility, it is possible to compute the number of samples per soil type necessary to complete a test matrix with a total of 40 test sites (the value of 40 was selected at the genesis of this project as perhaps representative of 4 sites per soil type). Row 5 of Table 6 provides a breakdown of the desired number of sites per soil type. Hence, Row 7 provides the number required to complete a total of approximately 40 sites based on the fourteen sites tested and evaluated to date.

One caveat, many of these “poorer” soils are often treated or stabilized during NMDOT construction projects precluding their evaluation as described in this report. On such projects, the R-Values are known to be low and the decision has been made to treat and or stabilize. Hence, it has been difficult for UNM personnel to test such soils because of field treatments. For this reason, the authors suggest looking to other sources of compacted base course and subgrade to find these “poorer” soils. Possible alternatives in consideration are city and county roadwork, and other private sector construction sites.

Despite the incompleteness of the above-mentioned chart and the attractiveness of the GeoGauge correlation, the authors see definite promise in the current procedure. This suggests any one of the three proposed methods may be adopted for use by the NMDOT. It is expected that after uniform testing over the entire AASHTO scale the best instrument will reveal itself. This may be due simply to its ease of use rather than having performed better empirically.

FUTURE RESEARCH

In an effort to provide the most appropriate instrument as a replacement for the current method of field estimation of the R-Value, all possibilities should be explored. Therefore, all other stiffness/strength measuring devices should be considered. The Briaud Compaction Device or BCD is such a device. The device requires the user to impose a 50 lb vertical load on a post that contacts the soil via a flexible metal disc about six inches in diameter. Strain gauges mounted on top of the disc measure the deformation of the disc, which is then used to calculate the stiffness of the soil. The BCD is part of a trend in which soil stiffness/strength is being used to determine the stiffness and elastic modulus of a soil.

Additionally, the authors have determined that a precision analysis should be done on all data. Not only is it important that a device accurately predicts the laboratory determined R-Value, but the device should do so repeatedly.

The authors suggest that the focus on field work be revisited. Because of the difficulties encountered in acquiring data in the field with the "poorer" soil types, it may prove more plausible at this juncture to design a laboratory experiment to evaluate the poorer soil types with the candidate test devices.

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