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ASSESSMENT OF DESIGN PARAMETERS AND CONSTRUCTION REQUIREMENTS FOR FULL DEPTH RECLAMATION PROJECTS WITH CEMENT

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February 2015

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Reporting on Work Plan SPR-718

STATE OF VERMONT
AGENCY OF TRANSPORTATION

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16. Abstract

The ability to efficiently rehabilitate and maintain the State of Vermont's Highway infrastructure in a cost-effective manner is a daunting task. Historically, pavement overlay treatments were specified because it was a rapid low cost solution to poor ride conditions. While effective at correcting surface defects, thin overlays are unable to address inadequate road base strength and thicker overlays are cost prohibitive. The Agency of Transportation (VTrans) has employed a reclaimed stabilized base method to add strength to the highway base as a cost effective approach to highway rehabilitation. The Agency has a growing interest in using non-destructive evaluation (NDE) methods as a means to evaluate the quality of the reclaiming process. NDE can also provide a more rapid test result depending on the technology applied.

The results of this research have shown that the Clegg Impact Soil Tester (CIST) proved to be a reliable means to test the quality of the reclaimed stabilized base quickly without causing damage. The other non-destructive testing methods utilized also proved to have value in certain circumstances. Where the Agency has used cores to test for the compressive strength of the subbase material, the quality of the coring can be poor, providing a wide variation with the testing results. The testing results obtained from the non-destructive methods used in this research proved to have less variation than that of the cores.

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ABSTRACT

The ability to efficiently rehabilitate and maintain the State of Vermont's Highway infrastructure in a cost-effective manner is a daunting task. Historically, pavement overlay treatments were specified because it was a rapid low cost solution to poor ride conditions. While effective at correcting surface defects, thin overlays are unable to address inadequate road base strength and thicker overlays are cost prohibitive. The Agency of Transportation (VTrans) has employed a reclaimed stabilized base method to add strength to the highway base as a cost effective approach to highway rehabilitation. The Agency has a growing interest in using non-destructive evaluation (NDE) methods as a means to evaluate the quality of the reclaiming process. NDE can also provide a more rapid test result depending on the technology applied.

The results of this research have shown that the Clegg Impact Soil Tester (CIST) proved to be a reliable means to test the quality of the reclaimed stabilized base quickly without causing damage. The other non-destructive testing methods utilized also proved to have value in certain circumstances. Where the Agency has used cores to test for the compressive strength of the subbase material, the quality of the cores can be poor, providing a wide variation with the testing results. The testing results obtained from the non-destructive methods used in this research proved to have less variation than that of the cores.

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Without the assistance of those listed below, greater understanding of non-destructive evaluation of Reclaimed Stabilized Base would not have been possible.

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- The Soils and Foundations Drill Crew

Contractors:

- Pike Industries
- Kubricky Construction
- Gorman Brothers Inc.

EXECUTIVE SUMMARY

The Vermont Agency of Transportation (VTrans) assessed nondestructive techniques for evaluation of the predicted performance of Full Depth Reclamation with cement or FDR-C. Many highways in Vermont were located by historic trade routes along valley floors at river confluences. As a result, highways that have been reconstructed to current geometric standards experience shorter service life and lower service capacity.

FDR-C has been found to be a promising technique for improving the pavement section's capacity and durability in many locations, including Vermont. VTrans has found the technique to present mixed results in our project delivery. The climatic conditions of Vermont have caused cracking and deterioration of ride especially during the winter months. Freeze thaw activity is a principal contributor. The ability to provide meaningful quality assurance and construction quality control feedback is expected to address the less successful placements of this treatment technique.

The results of this report confirmed that Clegg Impact Soil Tester (CIST) testing provided a highly reliable predictor of minimum FDR-C strengths. The methods are listed in descending order of value as applied in the research project. Other techniques available and meaningful were Falling Weight Deflectometer testing (FWD), Lightweight Falling Weight Deflectometer (LFWD), Nuclear Density Gauge (NDG) testing and Dynamic Cone Penetrometer (DCP) testing. All methods are nondestructive to the final product of the construction efforts.

Secondary findings of the research effort concluded that stronger specification of quality control and quality assurances practices including the timing of those quantitative tests are necessary to address freeze thaw susceptibility. Three critical components of control are amount of cement addition, moisture control of the mixture and compaction effort applied to the FDR-C. This control effort must be addressed at the design stage and construction completion for a project to be fully successful. Field observations during the research efforts highlighted opportunities in both areas to be become more quantitative and responsive to field conditions.

It is recommended that Clegg Impact testing be added as a Quality Assurance measure at a specified point in time after final mixing and compaction of the FDR-C. It is recommended that a measured compaction index be achieved before advancing the project to further stages such as microcracking. Specification and design changes to assure that these critical elements receive greater importance in project delivery should be pursued immediately.

INTRODUCTION

The Vermont Agency of Transportation's (VTrans) mission is to provide for the movement of people and commerce in a safe, reliable, cost-effective and environmentally responsible manner. One of the most crucial aspects in achieving this mission is to maintain acceptable conditions for one of the State's most valuable assets: namely, the 3,200 miles of highway (*1*). In recent years, fiscal constraints have dictated that transportation agencies, like VTrans, use more cost-effective and efficient means that provide long-term benefits, when they rehabilitate and maintain their respective highway inventory. Short-term solutions such as applying an overlay treatment at regular intervals have become increasingly expensive. Since then, other more cost effective methods have become available.

A technology known as Full Depth Reclamation (FDR), or Reclaimed Bases (RB), has gained popularity in North America as an effective means of correcting structural deficiencies without the substantial costs of rehabilitation. Different types of additives may be incorporated to stabilize or improve base conditions. Chemical additives, such as Portland cement, increase the resilient modulus, or stiffness, of the reclaimed layer. The use of cement in the FDR layer is referred to as FDR with cement or FDR-C. This increases structural support and resistance to pavement fatigue. The strength gain is governed by the type of reclaimed layer being stabilized along with type and amount of stabilizer used. If the percentage is too low, a low modulus will cause the pavement structure may crack or rut prematurely. Too high a percentage of a stabilizer may result in a stiffened layer that adversely affects the flexibility of the treated material. Higher stiffness may also introduce undesired characteristics such as shrinkage. Obtaining the optimum amount of cement is often challenging especially along Vermont routes due to the changing topography, geology and non-engineered pavement structures (*1*).

The objectives of this research initiative include examining alternative means and methods for assessing performance characteristics of the reclaimed stabilized base material; this data would then be used to develop acceptance criteria and to validate design assumptions with an overall objective of optimizing VTrans' FDR-C pavement design model (*1*).

MATERIAL DESCRIPTION

FDR-C is a highway rehabilitation process that reuses some portion of the existing asphalt bound pavement section and a predetermined portion of the base material, uniformly pulverizing and blending them together to produce a base course. The base course can be bound further with stabilizing agents such as Portland Cement. This allows for the correction of deficiencies in the bound and unbound layers. Specifically, discontinuities in the bound layer are removed, while stiffness is increased with lower variability in the base course. A surface consisting of a thin bituminous chip seal, hot-mix asphalt, or concrete completes the road. The FDR-C will be stronger and have greater uniformity than the original base, resulting in a long, low-maintenance life. Advantages include the in-place reuse of existing materials, a reduction of 25 to 50 percent of applied asphalt pavement and a reduction in the time needed for construction activities as compared to a standard reconstruction and associated costs (*1*).

The general sequence of construction is begun by the removal of surface by cold planing, followed by pulverizing the remaining base by an initial pass by a reclaimer. A second pass mixes the stabilizing agent within the base course. Paving occurs in two courses, either a hot or cold mix binder course, finished with a hot-mix wearing course.

PROJECT LOCATION AND SUMMARY

Projects were selected for testing based on recommendations from the Research Technical Advisory Committee (TAC) for the project. Table 1 and Table 2 summarize pavement and base profiles and the construction operation dates related to the reclaim process. Specific project details are located in the following paragraphs.

Table 1 Pavement and Subbase Profiles.

PROJECT	DETAILS
Thetford-Fairlee	2" Cold Plane, 8" Reclaim, 8" Portland Cement Stabilized Base, 3" Type II Superpave Bituminous Concrete Pavement, 1 1/2" Type IV Superpave Bituminous Concrete Pavement
Addison-New Haven	3" Cold Plane, 8" Reclaim, 8" Portland Cement Stabilized Base, 3" Cold Mix with Reclaimed Bituminous Concrete Pavement and Stabilized with Portland Cement, 2 1/2" Cold Mix with Reclaimed Bituminous Concrete Pavement and Stabilized with Portland Cement, 1 3/4" Type III Superpave Bituminous Concrete Pavement, 1.5" Type IV Superpave Bituminous Concrete Pavement
Warren-Waitsfield	3" Cold Plane, 8" Reclaim, 8" Portland Cement Stabilized Base, Fog Seal, 2 1/2" Cold Mix with Reclaimed Bituminous Concrete Pavement and Stabilized with Portland Cement, 1 3/4" Type III Superpave Bituminous Concrete Pavement, 1 1/2" Type IV Superpave Bituminous Pavement
Vershire-Thetford	4" Cold Plane, 8" Reclaim, 8" Portland Cement Stabilized Base, 3" Cold Mix with Reclaimed Bituminous Concrete Pavement and Stabilized with Portland Cement, 1/2" Level Type IV Superpave Bituminous Concrete Pavement, 1 1/2" Type IV Superpave Bituminous Concrete Pavement

Table 2 Construction Dates.

Project	Project Begin Date	Cold Planing	First Reclaim Pass	Fine Grading Elevation Correction	Second Reclaim Pass with Portland Cement	Cold Mix	First Paving Lift	Top Paving Lift
Thetford-Fairlee (5.620 mi)	8/16/2011	8/16/2011 to 8/25/2011	8/23/2011 to 9/6/2011	8/26/2011 to 9/17/2011	9/14/2011 to 9/23/2011	N/A	9/28/2011 to 10/6/2011	10/11/2011 to 10/21/2011
Addison-New Haven (7.330 mi)	6/11/2012	6/12/12 to 6/22/12	6/27/12 to 8/23/12	8/14/2012 to 9/13/2012	8/29/2012 to 9/20/2012	9/20/2012 to 10/7/2012	10/8/2012 to 10/22/2012	*MM 8.393 in Addison to MM .215 in Weybridge (total distance of 2.957 miles) = Paved 10/24/2012 to 11/1/2012 *Remainder of project = Paved 10/7/2013 to 10/12/2013
Warren-Waitsfield (7.878 mi)	4/15/2013	5/1/2013 to 5/16/2013	5/9/2013 to 6/6/2013	5/31/2013 to 7/29/2013	6/5/2013 to 7/16/2013	7/1/2013 to 8/2/2013	7/22/2013 to 8/24/2013	9/6/2013 to 9/24/2013
Vershire-Thetford (7.860 mi)	5/6/2013	5/6/2013 to 5/15/2013	5/15/2013 to 6/5/2013	5/29/2013 to 6/17/2013	6/17/2013 to 7/5/2013	7/8/2013 to 7/26/2013	7/27/2013, 7/29/2013, and 8/6/2013	8/28/2013 to 9/6/2013

Thetford-Fairlee - STP 2710(1)

The Thetford-Fairlee reclaimed stabilized base project began on Tuesday, August 16, 2011, by the prime contractor Pike Industries, Inc. The prime contractor was the sole contractor for all reclaiming and paving operations. According to contract plans, "*work to be performed under this project includes cold planing, reclaiming and paving of the existing highway, new pavement markings, guardrail, signs and incidental items as shown in the project quantities.*" The project began at the intersection of VT 113 and VT 244 in Thetford at mile marker (MM) 0.008 and extended easterly along VT 244 a distance of 5.620 miles to MM 2.639, ending at the intersection of VT 244 and US 5 in Fairlee. Table 3 summarizes the annual average daily traffic (AADT) data collected by the VTrans' Traffic Research Section within the project limits. The overall AADT is 1,300 (*2*).

Table 3 Thetford-Fairlee AADT.

Location	AADT		DHV		ESALs	
	2011	**2021**	**2011**	**2021**	**2011-2021**	**2011-2031**
Begin project to Middlebrook Road	1200	1200	160	160	88,000	202,000
Middlebrook Road to End of project	1400	1400	190	190	323,000	785,000

Addison-New Haven - STP 9632(1)

The Addison-New Haven reclaimed stabilized base project began on Monday, June 11, 2012, by the prime contractor Pike Industries, Inc. The prime contractor was the sole contractor for all reclaiming and paving operations. According to contract plans, "*work to be performed under this project includes cold planing, reclaiming, correcting superelevation deficiencies, resurfacing with base, intermediate, and wearing courses, new pavement markings, guardrail improvements, drainage improvements and other related highway items.*" The project began at a point in the town of Addison at MM 8.393 and extended easterly along VT 17 for a distance of 7.330 miles to MM 3.449 in the town of New Haven. Table 4 summarizes the AADT within each VTrans' Traffic Research collection section within the project limits. The overall AADT is 1,300 (*3*).

Table 4 Addison-New Haven AADT.

Location	AADT		DHV		ESALs	
	2011	2021	2011	2021	2011-2021	2011-2031
Begin project to VT Route 23	1500	1600	170	180	612,000	1,416,000
VT Route 23 to Green Street (Waltham)	1100	1200	120	140	486,000	1,223,000
Green Street to End of project	1300	1400	170	180	547,000	1,278,000

Warren-Waitsfield - STP 2506(1)

The Warren-Waitsfield reclaimed stabilized base project began on Monday, April 15, 2013 by the prime contractor Kubricky Construction Corporation. The prime contractor subcontracted the reclaiming operations to The Gorman Group. According to project plans, "*work to be performed under this project included reclaiming, and/or cold planing segments of the existing highway and overlaying with an intermediate course and a wearing course, with pavement markings, guardrail, drainage improvements and other highway related items.*" Work began at a point in the town of Warren, on VT 100 at approximately MM 0.850 and extending approximately 4.967 miles northerly and stopping in Warren, at MM 5.817. Then it resumed at MM 5.979 and continued approximately 2.749 miles to an ending at approximately MM 2.380 in the town of Waitsfield. Table 5 summarizes the AADT within each VTrans' Traffic Research collection section within the project limits in Warren and Waitsfield. The overall AADT is 3,025 (*4*).

Table 5 Warren-Waitsfield AADT.

Location	AADT		DHV		ESALs	
	2011	2021	2011	2021	2011-2021	2011-2031
Begin Project to Lincoln Gap Rd (TH #3)	1600	1600	200	200	350,000	782,000
Lincoln Gap Rd (TH #3) to Main St (TH #4)	2100	2100	260	260	320,000	779,000
Main St. (TH #4) to Sugarbush Access Rd (TH #5)	3300	3400	410	420	494,000	1,226,000
Sugarbush Access Rd (TH #5) to End project	5100	5300	630	660	615,000	1,432,000

Vershire-Thetford STP 2911(1)

The Vershire-Thetford reclaimed stabilized base construction project began on Monday, May 6, 2013, by awarded contractor Pike Industries, Inc. According to project plans, "*work to be performed under this project includes cold planing, reclaiming and paving the existing highway, new pavement markings, guardrail, signs and other related highway items.*" The project began in the town of Vershire on VT 113 at MM 3.505 and extended easterly along VT 113 a distance of approximately 7.860 miles to MM 0.813 in the town of Thetford. Table 6 summarizes the AADT within each VTrans' Traffic Research collection section within the project limits in Vershire and Thetford. The overall AADT is 1300 (*5*).

Table 6 Vershire-Thetford Traffic Data

Location	AADT		DHV		ESALs	
	2012	2022	2012	2022	2012-2022	2012-2032
Begin Project to Beanville RD/Mill St	980	980	110	110	93,000	212,000
Beanville Rd/Mill St to West Fairlee Rd	1900	1900	210	230	212,000	473,000
West Fairlee Rd. to End of project	1300	1300	150	160	91,000	233,000

TEST EQUIPMENT DESCRIPTION

Alternative means and methods for assessing performance characteristics of the reclaimed stabilized base material were studied. Upon completion of the state of the technology assessment, five methods were selected for the comparison. First, the Nuclear Density Gauge (NDG) is a device the Agency has historically used to get compaction density and moisture data. The next device was the Dynamic Cone Penetrometer (DCP), which is also a device that the Agency has used historically to measure the strengths of pavement layers and subgrades. The study also included three new non-destructive evaluation methods: the Clegg Impact Soil Tester (CIST), the Light Weight Deflectometer (LWD) and the Falling Weight Deflectometer. Equipment was chosen based on factors that included ease of use, cost and ability to correlate testing results.

Equipment considered, but not chosen for the study, included:

1. Dynamic Deflection Determination System (Dynaflect) which is a trailer mounted device, which induces a dynamic load of 1,000 lbs. on a pavement surface and measures the resulting slab deflections by use of geophones spaced under the trailer at

approximately 1-foot intervals. The load is applied at a frequency of 8 cycles per second, which is produced by a counter rotation of two unbalanced flywheels. The cyclic force is transmitted vertically through two steel wheels spaced 20 inches apart. The dynamic force during each rotation of the flywheels varies from 1,100 to 2,100 lbs. The structural number (SN) is determined through a series of equations and graphs. The layer coefficient (SN divided by the thickness of the base layer) is used for soil/cement base courses in flexible pavement design. (*6*)

2. Accelerated Loading Facility (ALF) device is a transportable, linear, full-scale accelerated loading facility, which imposes a rolling wheel load on a 39-foot by 4-foot area test pavement. The loading is one direction at a constant speed of 10.4 miles per hour. Each 8-second cycle is applied through a standard dual truck tire capable of loads between 9,750 lbs. and 18,950 lbs. Each pass is equal to 1.38 to 19.7 ESALs. The ALF is capable of simulating 8,100 wheel passes per day. (*6*)
3. Humboldt GeoGauge is a hand portable device capable of performing simple and robust measurements of the in-situ stiffness of soils. On the bottom of the device lies a ring shaped foot, which rests on the soil surface. Attached to the foot, is a vibratory mechanism, which shakes the GeoGauge from 100 to 196 Hz in 4 Hz increments, equaling 25 frequencies. Sensors within the device measure the force and deflection-time history of the foot. The GeoGauge can be used to perform construction process control to measure real-time performance of compacted layers in order to comply with specified performance and warranties. It can be used to monitor the stiffness gain with each pass or sets of passes of rollers. The compaction of a layer will be optimized when the stiffness no longer increases in a pass. (*7*)

Nuclear Density Gauge (NDG)

The NDG is a lightweight portable device in which a radioactive isotope is used to determine the density of the subbase materials (see Figure 1). It is commonly used for determining the density and moisture content of various roadway base materials such as granular fill, bituminous or concrete pavement and other earthworks. The NDG directs a minimal amount of radioactivity through the different layers to be tested, to get a reading of the level of radioactivity returning to the sensor.

A material's density will determine how easily radioactive waves will propagate through it. As the density decreases, the radioactivity will pass through more readily. The NDG requires calibration against materials obtained from cores when applied to hot mix asphalt. Granular materials can be directly testing by placing a probe into the layer to be tested. Materials with similar gradation and mineralogy may be tested within a single calibration of the NDG. Materials that vary significantly in gradation and mineralogy will require the NDG be recalibrated for each material group. (8*)*

Figure 1 Nuclear Density Gauge (NDG) being used to collect data on a project.

Testing for this project was performed in accordance with AASHTO T-310-10 *In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)* (*9*).

Optional Benefits

According Troxler, the manufacturer, "*the nuclear moisture / density gauge, Model 3430, can quickly and precisely determine the moisture and density of soils, soil bases, aggregate, concrete, and asphalt without the use of core samples or other destructive methods*." Examples include pavement-resurfacing projects for all pavement types; reclaim projects with varying stabilizers and concrete bridge decks (*22*).

Dynamic Cone Penetrometer (DCP)

A hand held instrument (see Figure 2) introduced by Scala in 1956, the DCP was developed to determine the California Bearing Ratio (CBR) of cohesive soils. Through extensive research of its uses, the DCP has proven to be an effective tool to assess the strength of pavement layers and subgrades. The device consists of a 17.6 lb. (*8kg*) sliding hammer, which falls a distance of 22.6 inches (*575 mm*) onto an anvil attached to a penetrometer rod, which drives a 0.787 inch (*22mm*) diameter 60º steel cone located at the end of the rod. Data collection consists of recording the number of hammer drops versus cone Penetration Rate (PR). The average PR of a layer can be used to estimate the CBR and the Elastic Modulus (E) using available correlations (*7*).

Research has shown that uses for the DCP are (*7*):

- Identifying weak spots in compacted layers
- Locating layers in pavement structures
- Monitoring the effectiveness of stabilization
- Quality acceptance testing for performance based specifications

Testing within this research project was carried out in accordance with ASTM D 6051-03, "*Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications*," (*10*).

Figure 2 Dynamic Cone Penetrometer (DCP) being used to collect data on a project.

Optional Benefits

According to ASTM D6951/D6851M-09, the Standard Test Method for "*Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications*," the DCP is typically used in horizontal construction applications to assess in-situ strength of undisturbed soil and compacted materials of fine and coarse-grained soils, granular construction materials and weak stabilized or modified materials. The test method states that the DCP cannot be used in highly stabilized or cemented materials or for granular materials containing a large percentage of aggregates greater than 2 inches. Examples include reclaim projects without cement stabilization, bridge approaches and airport construction (*10*).

Clegg Impact Soil Tester (CIST)

The Clegg Impact Soil Tester (CIST) was developed by the late Dr. Baden Clegg (University of Western Australia in Nedlands) in the late 1960's. Dr. Clegg theorized that he could obtain data that could be used to determine soil stiffness if he instrumented a laboratory compaction hammer with an accelerometer. In 1978, the University marketed and sold the new device through a newly created marketing venture called Univentions Ltd. (*11*) Currently, the CIST is available in different weight configurations from several manufacturers. The 22 lbs. (*10 kg*) and 44 lbs. (*20 kg*) models are ideal for testing flexible pavement, aggregate roadbeds, repairs stemming from highway or pipeline trench work, and foundations.

The basic principle behind the CIST (see Figure 3) is to obtain a measurement of the deceleration of a free falling mass (hammer) from a set height onto a surface under the device. The impact of the hammer produces an electrical pulse, which is converted into a Clegg Impact Value (CIV). Four successive blows of the hammer on the same spot constitute one test. The peak CIV is shown on the digital display. The first two blows essentially set the surface to conform to the head of the hammer. The subsequent blows routinely produce the peak CIV value. In most cases, the readings increase over the four blows. The largest CIV reading is what remains on the display. According to product literature, "*the CIV is displayed in units of tens of gravities. This value correlates to the California Bearing Ratio (CBR), Texas Class Number, Elastic Modulus and PSI*" (*12*). "Tens of gravities" is a measure that represents the deceleration in gravitational terms, experienced by the hammer as it comes to a stop. A CIV value of 1 represents 10 times g, or 322 ft/s^2. All testing was conducted in accordance with ASTM test methods D5874-02(2007), "*Standard test Method for Determination of the Impact value (IV) of a Soil*," (*13*) and F1702-10, "*Standard Test Method for Measuring Impact-Attenuation Characteristics of Natural Playing Surface Systems Using a Lightweight Portable Apparatus,*" (*14*). In one research study, 250 tests were performed with the CIST in half a day (*12*).

Figure 3 Clegg Impact Soil Tester (CIST) being used to collect data on a project.

CIST Features include (*12*):

- The CIST is extremely mobile and easy to operate. The hammer has a hardened strike face, and comes in weights of 1.10 lbs. (*0.5 kg*,) 4.96 lbs. (*2.25 kg*,) 9.92 lbs. (*4.5 kg*,) 22.05 lbs. (*10 kg*) and 44.09 lbs. (*20 kg*.)
- The guide tube is metal and will provide years of reliable, accurate service.
- The control box features a digital display, which is powered by a standard 9-volt battery. During operation, the control box may be hand held or mounted to the guide tube or carrying cart.
- The test procedure is very rapid and can easily be performed by site personnel with minimal training. Each test can be completed in less than 30 seconds. The results are immediate.
- It may be transported and operated by one person, allowing for low cost, rapid field and laboratory testing, as well as direct readout of the test results.
- The CIST can test a full range of soils and stone as encountered in the construction of flexible pavement and earthworks.

- It is useful for quickly checking variations during construction and monitoring changes over time due to seasonal environmental changes or road traffic as well as testing natural and "as constructed" conditions.

CIST tests were performed at each test location within the research study. A test consists of placing the device on a flat, level surface and standing on the lower ring to provide stability as shown in Figure 3. The hammer is raised to its full extension and dropped four times to obtain a set of readings for the test location. When the hammer hits a rock at or near the surface, the resulting reading would be uncharacteristically high, or the CIST would assume a problem and return a reading of zero. In these cases, the CIST was moved 12-inches to the side and the test was restarted.

To obtain the best results with the CIST, the tests are conducted on relatively flat surfaces. On a significant incline, the hammer will experience friction as it slides on the interior guide bars, thereby affecting the readings. For this study, all readings were taken on relatively flat ground, thereby allowing for a complete free fall of the hammer.

Optional Benefits

Lafayette Instruments, the manufacturer states "*the device can test a range of soils and stone during the construction of flexible pavement and earthworks to check for variations during construction and monitoring changes over time due to seasonal environmental changes or road traffic as well as testing natural and* 'as constructed' *conditions*". Examples include testing on various horizontal soil projects including reclaim projects with and without stabilizing agents, bridge approaches, etc. (*12*).

Light Weight Deflectometer (LWD)

The Light Weight Deflectometer (LWD) is a lightweight, portable device used to obtain the dynamic deformation modulus (Evd) in pavement and soil layers. In this study, the LWD was used (see Figure 4) with additional geophones sensors. According to ASTM International, ASTM E2583-07 (2011) *"this test method is a type of plate bearing test. The load is a force generated by a falling mass dropped onto a spring assembly that transmits the load pulse to a plate resting on the material under test."* (*15*)

Figure 4 Light Weight Deflectometer (LWD) being used to collect data on a project.

The LWD used in this study is manufactured in Denmark and is marketed and sold by Dynatest Consulting, LLC in the US. The precision-engineered equipment is manufactured out of stainless or anodized material for all metal parts, and is highly portable, weighing approximately 48 lbs., with the acquired 33 lb. drop weight. A pack of four AA alkaline or rechargeable batteries powers the data collection system, providing approximately 2,000 measurements or the equivalent to more than 12 hours of continuous operation. The LWD is an effective testing device for Quality Assurance/Quality Control on subgrade, subbase and thin flexible pavement constructions to verify that specifications are met. It can also be used to identify weaknesses, leading to further tests using a FWD and other material analysis techniques (*16*).

LWD features include (*16)*:

- Electronics are interfaced to a handheld PDA via a wireless Bluetooth connection.
- Electronics are dust and splash proof (IP56) for safe outdoor use.
- The drop height is adjusted easily and quickly by a movable release handle.

- A laser engraved scale on the weight guide shaft allows for easy setting of the desired drop height.
- The magnitude of the impact force is determined from actual measurements by a precision load cell, measuring the time history and peak value of the impact force from the standard 22.05lbs (*10 kg,*) the optional 33.07lbs (*15 kg*) or the 44.09lbs (*20 kg*) drop weight setups. To obtain 33lbs, an optional 11.02lb (*5kg*) weight is attached to the 22.05lb weight. The optional 11.02lb weight cannot be used separately.
- The loading plate diameter can be switched between 11.81-inch (*300 mm*) and 5.91-inch (*150 mm*) quickly. A 3.94-inch (*100 mm*) plate diameter is included, and an optional 7.87-in. (*200 mm*) plate is available.
- The center deflection time history and peak value is measured through a hole in the loading plate by a highly accurate, seismic transducer (geophone).
- An integrated lever to ensure the center geophone is correctly centered and seated.
- The field program can be linked to a GPS.
- Optionally, two more geophones can be added.

Using the guidance from the manufacturer for roughened ground, the 11.81-inch (*300 mm*) plate on a level sand surface was used for data collection. For the research project, weights were dropped from three heights, which mimic various traffic loading levels. Each height consisted of three drops for better data relevance, with two additional preliminary drops being used as seating drops. This testing pattern was run at each testing location. Data was later analyzed using Dynatest's LWDmod software. All testing was conducted in accordance with ASTM E 2583-07, "*Standard Test Method for Measuring Deflections with a Light Weight Deflectometer,*" (*17*).

Optional Benefits

According to the manufacturer, Dynatest Consulting, Inc., "*the LWD can be used to test thin asphaltic pavements; recycled materials bound with foamed bitumen and directly test the unbound subbase and subgrade*" (*16*). Examples include reclaim projects with or without stabilizing agents, thin pavement overlays, and preventative maintenance projects such as paver placed, microsurfacing, chip seal, etc.

Falling Weight Deflectometer (FWD)

The FWD (see Figure 5) is a trailer mounted towed device that is capable of applying a various loads through a circular plate causing the pavement to deflect. A 9,000 lb load closely approximates the effect of a moving wheel load, both in magnitude and duration. The applied load is measured by a heavy-duty precise load cell, located above the loading plate. The deflection data is acquired through a high-speed transducer. The Transducer signal is sent to a hand held data collection device. Later, the data is transferred to a computer where back-calculation processes are used to determine moduli for each layer (*6*).

The subbase material stiffness as determined by the calculated moduli can provide an indication of its condition and its uniformity. The moduli are compared to typical values found in stabilized soil cement or cement treated soil. In general, results from FWD testing should indicate that the cement treated design bases met the established criteria and were statistically the same as the target stabilized cement design (*6*).

Figure 5 Falling Weight Deflectometer (FWD) being used to collect data on a project.

For this research project, a preset program was used which automated the testing. Weights were dropped from various heights, which mimic various traffic loading levels. Each height consisted of three drops for better data relevance. The program was run at each testing location. Data was later analyzed using Dynatest's Elmod 6 software. FWD testing was completed in accordance with ASTM D 4694-09, "*Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device*," (*18*).

Optional Benefits

According to the manufacturer, Dynatest states that, "*a Dynatest FWD enables the engineer to determine a deflection basin caused by a controlled load with accuracy and resolution superior to other existing test methods. The FWD produces a dynamic impulse load that simulates a moving wheel load, rather than a static, semi-static or vibratory load.*" (*23*) Examples include all roadway projects including all pavement and subbase rehabilitation, with and without stabilization and all pavement types, airports, etc.

Coring and Compression Testing

The coring and compression testing of a material is a repeatable method of determining the strength of an in place material. While reliable, it is also destructive to the material as well as expensive and time consuming.

Research personnel initially performed core extraction for this project using a portable core rig (see Figure 6) or a trailer mounted core rig. Water or air was used to cool the core bit. Later, it was determined that extracting cores using the Agency's drilling crew or the contractor; both who had access to heavier machinery, would result with better cores for testing. Cores were extracted utilizing 4, 5 or 6-inch diameter core barrels through the entire depth of the FDR-C layers. Though 4-inch diameter cores were specified for the study, in certain places, they were difficult to extract. Factors such as aggregate size, equipment used and personnel extracting the cores proved to be significant differences in the ability to extract adequate cores for testing. The choice to increase the diameter to 5 or 6 inches provided better results in obtaining cores. The larger diameter cores required heavier equipment for extraction, which may have contributed to the higher quality cores. In certain circumstances, the extraction resulted in a lack of recovery or the core had aggregate sizes of 3-inches or larger, that rendered the core meaningless for the study. In these cases, an alternate core location was selected for extraction within the proximity of the point defined by the study.

Figure 6 A typical 4" core being drilled and extracted on a project.

Typically, contractors are required to extract cores at random locations throughout these types of projects, after which they deliver the cores to the Agency's Central Materials Laboratory for compression testing (see Figure 7.) These contractor cores were still tested for the projects related to this research effort, however additional cores were extracted by the Agency's Drill Crew (except where noted) within test sites for the research. In the study, core extraction was scheduled on Day 5 following stabilization. In several incidents, the extraction occurred on Day 4 due to weather conditions, construction limitations and personnel availability.

In the instances where a core could not be tested that data point was eliminated. These incidents occurred when there was a lack of recovery or the core cylinder was either too short or lacked the proper geometry to be tested adequately. In certain test sites, this skewed the data towards a higher strength bias. In some cases, when the cores were not supplied to Research and Development, there were no accompanying reports on the condition of the extraction.

Once at the laboratory, Research and Materials testing personnel prepared the cores for testing two days later on day seven. Cores were cut with a concrete saw to create level surfaces for compression testing. To ensure a flat and continuous surface, cores were capped on both ends with a sulfur compound. Cores are then tested in a compression-testing machine to determine their compressive strength in psi. Core breaks were conducted under AASHTO T-22-06, "*Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens,*" (*19*).

Figure 7 Compression test on a core.

Optional Benefits

Coring can be used to test the compressive strength of various projects including: all pavement types, bridge decks, and reclaim projects with and without stabilizing agents. The Tinius Olsen equipment used to test the specimens is used for many other Agency testing procedures, some including concrete cylinder testing and cement cube testing.

TESTING SUMMARY

Four research test locations were established over the 2011, 2012 and 2013 construction seasons. A combination of testing equipment was used in an effort to assess the capability of each in relation to core strengths and possible future acceptance testing. All test sites were either 420-foot or 600-foot in length. One 20-foot testing segment is represented in Figure 8. This 20-foot segment was repeated throughout each test site.

Each site was comprised of either 21 or 30 testing segments, 420 or 600 feet in length respectively. The research plan required a test site to include 30 test segments. It was determined that soil conditions were significantly varied on either side of the Otter Creek in the Addison-New Haven project site. A supplemental test site was added to the research to accommodate the testing of this soil condition. The available length with the same site characteristics of VT Route 17 did not provide for 30 segments. Instead, Research and Development chose to test 21 segments. The results of testing 21 segments proved to be sufficient for the analysis; therefore, all subsequent test sites included the fewer number of segments. Within each segment, all testing devices were evenly spaced in 5-foot intervals to eliminate the possibility of interference with accuracy during testing. Because the NDG, DCP, and coring were completed on different days or had little impact on one another, the devices were grouped together, 1-foot apart. Figure 9 illustrates a typical test site in the field.

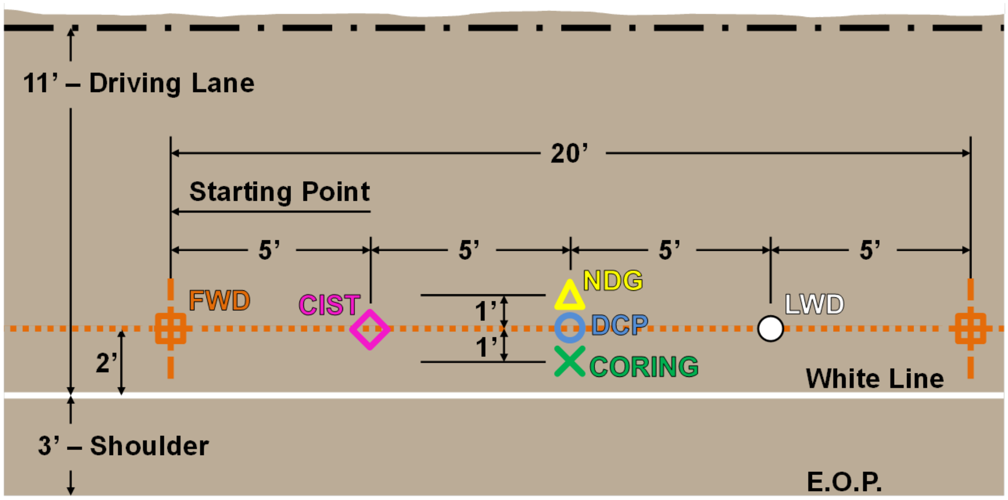

Figure 8 One 20-Foot Test Section

Figure 9 Example Test Site in the Field

The testing plan, including number of test sites, test spots, equipment used, and days of testing varied depending on the project and observations made in previous testing years. The FWD was used to test prior to construction, during construction and after construction due to its' intrinsic ability to obtain data through multiple pavement structure layers. Based on the literature search and manufacturer recommendations, all other devices could only be used during construction because they cannot accurately depict site conditions through an asphalt pavement layer. Each project site has a summary table describing the tests and intervals. Numbers under the Day column heading indicate the number of days following reclamation with Day 0 referring to the day of final grading and compaction of the FDR-C. Testing during these days was completed at the convenience of the Contractor and VTrans staff. All individual project-testing details are summarized in the following paragraphs.

Thetford-Fairlee STP 2710(1)

A preconstruction site visit was conducted to establish two 600-foot research test sites (RS1 and RS2) prior to construction in July 2011. RS1 was located between MM 0.858 and MM 0.972 in the town of West Fairlee, and RS2 was located between MM 1.286 and MM 1.400 in the town of Fairlee. During the site visit, preconstruction readings were collected in both RS1 and RS2 using the FWD. The intent of testing was to test RS1 and reserve testing in RS2 in the event of errors in testing or construction. Table 7 denotes what dates and days each testing device was used and each is summarized in the following paragraphs.

Table 7 Thetford-Fairlee Testing Dates.

Test Site	Day	Date	Equipment Used
RS1	Preconstruction	7/28/2011	FWD
	0	9/17/2011	NDG, DCP, CIST, LWD, & FWD
	4, 5	9/21/2011 – 9/22/2011	Coring
	7	9/24/2011	CIST, LWD & FWD
	32 – Wearing Course	10/19/2011	FWD
	416 -Wearing Course	11/6/2012	FWD
RS2	Preconstruction	7/28/2011	FWD
	0	9/21/2011	NDG, DCP, CIST, LWD, & FWD
	4, 5	9/25/2011 – 9/26/2011	Coring
	7	9/28/2011	CIST, LWD, FWD
	30 - Wearing Course	10/21/2011	FWD
	412 -Wearing Course	11/6/2012	FWD

The FDR-C in RS1 was completed September 17, 2011, initiating Day 0 testing. The apparatus used on Day 0 testing were NDG, DCP, CIST, LWD, and FWD. Data acquisition functioned as planned, with no substantial limitations or complications, however following compaction a considerable amount of surface water was observed as a result of the reclaim process. Due to the wet surface, some of the equipment during testing produced error messages or invalid readings, most notably the FWD and CIST.

Following the initial data collection, cores were extracted by Research staff and the Contractor on Day 4 and 5. The portable core rig was equipped with both air and water to cool the core bit during drilling operations. After Research tried both methods of cooling the bit, the device was found to be inadequate, providing insufficient stability to extract intact cores. While drilling, the chatter of the machine broke the cores in place. The Contractor agreed to conduct the coring activities for the remainder of the test site and the entire RS2.

On Day 7, the following testing methods were performed: CIST, LWD and FWD. Testing did not include the NDG and DCP on this day because in order to conduct the test, the device must penetrate the surface. The hardness of the cured subbase prevented any penetration into the FDR-C layer. FWD testing was not completed on Day 28 because the top course of bituminous concrete pavement had not been placed. The testing was completed on Day 32. FWD data was collected within RS1 approximately one year later on November 6, 2012.

For the study, the Technical Advisory Committee (TAC) chose to proceed with testing in RS2 due to errors in testing caused by excessive surface water in RS1. Day 0 in RS2 was on September 21, 2011. All scheduled tests were performed with no major complications. Minimal or no surface water was noted during testing. No errors were noted with any of the testing equipment. The DCP test results showed that during the two hour and 40 minute testing period the material had begun the curing process. All testing began between 30 minutes to an hour after compaction, once the test site was prepared. The DCP testing occurred between 30 minutes to 3.5 hours after compaction. This indicates that results, as obtained by the requirements of the study, are not reliable because the structure conditions were changing during the test. What was observed; however, was that the CBR values obtained between test locations 0 to 18 or between 30 minutes to 2 hours after compaction were relatively consistent. This is evident in Figure 10 where the locations towards the end of the test site had been curing for about 3.5 hours and the CBR values are much higher.

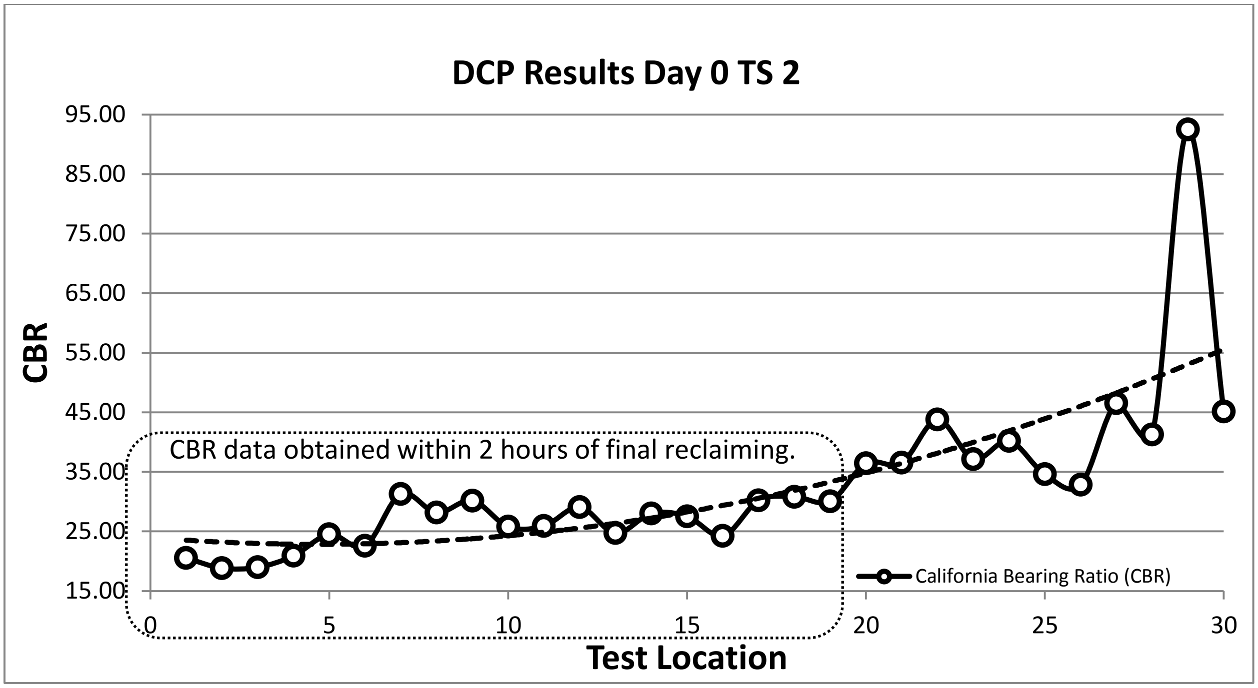

Figure 10 Thetford-Fairlee DCP Test Results – RS2 – Day 0.

Addison-New Haven STP 9632(1)

Since there was variability in results in Thetford-Fairlee, two research test sites (RS1 and RS2), both 600 feet in length were selected for testing in Addison-New Haven. Preconstruction site selection and FWD testing was conducted on May 18, 2012 and May 21, 2012. During the reclaim process, large boulders were uncovered in the shoulders and partially in the travel lanes. This increased reclaim time was due to excessive damage to the reclaimer, causing repeated repairs. Shortly after the first reclaim commenced and problems persisted, it was determined a different method should be used where the shoulders were excavated and filled with a fine graded coarse aggregate before the shoulder pass was reclaimed. This method was used throughout the project across the roadway width. As mentioned previously, the in situ base material west of the Otter Creek was found to be different from that of the east. Where large boulders were encountered east of the creek, they were largely absent west of the creek. Due to the in place material change, a third research test site was selected (RS3). Preconstruction data was collected for this site on August 15, 2012. Cold planing activities had already taken place; however, there was some pavement still in place and data was collected before the site was reclaimed. RS3 was 420 feet in length and comprised of 21 test spots per testing device. Table 8 denotes what dates and days each testing device was used and each is summarized in the following paragraphs.

Table 8 Addison-New Haven Testing Dates.

Test Site	Day	Date	Equipment Used
RS1	Preconstruction	5/18/2012	FWD
	First Reclaim Pass	8/15/2012	FWD
	0	9/12/2012	NDG & CIST
	1	9/13/2012	NDG, CIST, LWD, FWD
	3	9/15/2012	CIST, LWD, FWD
	5&6	9/17/2012 & 9/18/2012	Coring
	7	9/19/2012	CIST, LWD, FWD
	30	10/12/2012	FWD
	Top Course	12/3/2013	FWD
RS2	Preconstruction	5/21/2012	FWD
	First Reclaim Pass	8/20/2012	FWD
	0	9/19/2012	NDG & CIST
	1	9/20/2012	NDG, CIST, LWD, FWD
	3	9/22/2012	CIST, LWD, FWD
	5	9/24/2012	Coring
	7	9/26/2012	CIST, LWD, FWD
	28	10/17/2012	FWD
	Top Course	12/3/2013	FWD
RS3	Preconstruction	8/15/2012	FWD
	First Reclaim Pass	8/24/2012	FWD
	0	9/11/2012	NDG & CIST
	1	9/12/2012	NDG, CIST, LWD, FWD
	3	9/14/2012	CIST, LWD, FWD
	5	9/16/2012	Coring
	6	9/17/2012	CIST, LWD, FWD
	36	10/17/2012	FWD
	First Year	12/3/2013	FWD

Testing was conducted on the following days in RS1, RS2 and RS3: first reclaim pass and Days 0, 1, 3, 4-5, 7, and 28+ after reclaiming. The additional testing days provided a larger data pool to contribute to the analysis of testing results. Testing completed on the first reclaim pass was to quantify the strength increase as a result of the second reclaim pass including the addition of the Portland Cement. Results showed that the structure with the stabilizing agent was indeed much stronger, exhibiting a stiffer modulus value.

The surface of the reclaimed material in Thetford-Fairlee showed excessive variability after compaction. The compacted base material was sufficient; however, water puddles and thin layers of mud over the top of the FDR-C resulted in data irregularities with some of the testing equipment. FWD results indicated that the reclaim base was excessively soft. Research chose to limit the equipment used for Day 0 testing to the NDG and CIST devices due to these factors. To obtain compaction data, for each of the three FDR-C operations (Day 0), the NDG tests had to commence immediately following final reclamation, compaction, and grading, prior to the subbase curing (shown in Table 8.) The CIST data was collected to provide a correlation with the data gained from the NDG and to obtain more CIV data to contribute to acceptance range research. There were no issues reported during testing.

Days 1 and 3 testing included FWD, LWD, and CIST devices with no issues reported during testing. Day 5-6 was reserved for coring activities. VTrans Soils and Foundations Drilling Unit extracted all research cores required for comparison in the Addison-New Haven Research study. There were several locations where cores could not be extracted. In an area adjacent to an underdrain installation, there was great difficulty in obtaining cores that were intact. Several attempts were required to extract cores from the planned sample points. The matrix of the FDR-C comprised of a loose stone and cement mix that failed to remain intact upon extraction. This made it challenging to achieve enough cores from adjacent testing areas for data analysis.

Testing is highly dependent upon weather and the construction schedule. Day 7 testing was conducted in RS1 and RS2 as planned. In RS3, similar testing occurred a day earlier on Day 6 because the weather forecast on Day 7 had a high probability of rain. Data collected on Day 6 and 7 showed to be representative of each other. There were no reported issues during testing.

The boulders uncovered during construction prolonged the project schedule and forced it into late fall. Therefore, the placement of the wearing course was limited to the roadway west of the Otter Creek Bridge, which included RS3 test site. East of the bridge at MM 0.00 in New Haven, the binder/base course of pavement could be placed, which includes RS1 and RS2. Day 30 FWD testing was conducted in RS1 and Day 28 in RS2. Day 36 testing was completed in RS3. Placement of the top wearing course was scheduled for early 2013; however, due to longitudinal cracking along the centerline in several locations that were not paved with the wearing course, final paving was delayed until corrective action could be determined. This delayed FWD testing on the wearing course in RS1 and RS2 until December 3, 2013, when the project was completed. Year 1 testing in RS3 was also conducted that day.

Warren-Waitsfield STP 2506(1)

RS1 and RS2 in Warren-Waitsfield were established prior to the collection of preconstruction FWD data on April 18, 2013. Each test site was 420 feet in length, providing 21 test spots for each testing method. Table 9 denotes what dates and days each testing device was used and each is summarized in the following paragraphs.

Table 9 Warren-Waitsfield Testing Dates.

Test Site	Day	Date	Equipment Used
RS1	Preconstruction	4/18/2013	FWD
	0	6/25/2013	NDG
	1	6/26/2013	CIST, LWD, FWD
	4	6/29/2013	Coring
	7	7/2/2013	LWD & FWD
	24 - Cold Mix	7/19/2013	FWD
	122 -Wearing Course	10/25/2013	FWD
RS2	Preconstruction	4/18/2013	FWD
	0	6/19/2013	NDG & CIST
	1	6/20/2013	CIST, LWD, FWD
	5	6/24/2013	Coring
	7	6/26/2013	CIST, LWD, FWD
	28 - Cold Mix	7/17/2013	FWD
	128 -Wearing Course	10/25/2013	FWD

Day 0 testing was performed in RS1 and RS2 on June 25 and June 19 respectively. While reclaiming RS1, an unexpected thunderstorm severely affected construction and produced significant downpours while the Contractor was completing final compaction and grading of the site. This left the surface extremely wet and soft, prohibiting CIST testing. NDG readings were collected despite the inclement conditions. Weather did not significantly influence construction activities in RS2, however during the Portland Cement spreading process, the cement spreader truck ran out of material to spread and had to stop and restart within the test site instead of spreading a continuous path throughout. It was noted that there was an excess of Portland Cement at Test Points 9 and 10. All associated results are discussed later in this report.

Day 1 testing proceeded as planned in both test sites. The CIST, LWD and FWD were used for collecting data with no problems noted during testing. Initial analysis of the Day 3 data collected from the Addison-New Haven project did not result in valuable correlations; therefore, Day 3 testing was not included in the testing plan for Warren-Waitsfield.

VTrans Soils and Foundations Drilling Unit collected all cores for data analysis relative to the Warren-Waitsfield research project. Cores were extracted on Days 4 and 5 in RS1 and RS2, respectively. Dissimilar to previous attempts in other projects, cores were extracted from every planned sample point without significant complications. The compacted base material was observed to be visually consistent throughout the project in comparison to previous projects.

Day 7 testing was completed in RS1 and RS2. It was planned that the CIST, LWD, and FWD were to be used for testing as in all previous projects, however the CIST testing could not be performed in RS1 on Day 7 because the data-acquisition control box was producing errors. It is suspected that the errors were caused from testing in heavy rain conditions in Vershire-Thetford the day before. There were no other issues to report.

FWD testing was conducted on the cold mix layer at Days 24 and 28 in RS1 and RS2, respectively, because placing the top wearing pavement course was not scheduled until a later date. Once the project was complete, FWD testing was conducted again on October 25 in both sites.

Vershire-Thetford STP 2911(1)

RS1 and RS 2 were established in the same manner as Warren-Waitsfield on May 8, 2013 and May 1, 2013 as shown in Table 10. All testing days with associated testing devices used are also in the table.

Table 10 Vershire-Thetford Testing Dates.

Test Site	Day	Date	Equipment Used
RS1	Preconstruction	5/8/2013	FWD
	0	6/27/2013	NDG & CIST
	1	6/28/2013	CIST, LWD, FWD
	4	7/1/2013	Coring
	6	7/3/2013	LWD & FWD
	28 - Cold Mix	7/25/2013	FWD
	97 - Wearing Course	10/2/2013	FWD
RS2	Preconstruction	5/1/2013	FWD
	0	6/20/2013	NDG & CIST
	1	6/21/2013	CIST, LWD, FWD
	5	6/25/2013	Coring
	7	6/27/2013	CIST, LWD, FWD
	28 - Cold Mix	7/18/2013	FWD
	104 - Wearing Course	10/2/2013	FWD

Day 0 testing on June 27, 2013 in RS1 and June 20, 2013 in RS2 presented no problems. Similar to Day 0, Day 1 testing in RS 2, had no documented issues. Day 1 testing RS1 was completed. The day was met with heavy rain however due to scheduling complications, testing on Day 2 instead of Day 1 was not feasible. Because of the weather event, the site was noted as extremely wet and the data-acquisition control box for the CIST stopped working correctly. The data collected during this visit is believed to be accurate; however, the equipment could not be used for further testing for Day 6 in RS1 on this project and Day 7 testing in RS1 in Warren-Waitsfield. The problem has since been confirmed by the manufacturer and has been repaired.

Cores were extracted by VTrans Soils and Foundations Drilling Unit for data analysis in conjunction with the Vershire-Thetford research project. Cores were extracted on Days 4 and 5 in RS1 and RS2. Although the core extraction was noted to be more successful in this project than in previous years, due to factors previously mentioned, some sample points required 2 or 3 attempts to extract a successful core from the sample point area.

As with Warren-Waitsfield, FWD Day 28 testing was conducted on the cold mix layer in RS1 and RS2. The wearing course was tested on October 2, 2013 after the project was completed.

TEST RESULTS

The Agency has required the Contractor to extract cores from the FDR-C layer at random locations chosen by the Engineer. Once extracted the cores undergo compression testing at the Agency's Concrete Laboratory. All strength results are measured in pounds per square inch (psi). Since the method is destructive to the FDR-C layer and cores have reportedly been difficult to obtain, the primary objective of this research project was to find an alternative method of testing the strength of the base. All testing results are summarized in relation to core compressive strengths as extracted from the research test sites. Please note that all data is available upon request.

Variability

One theme that is consistent throughout data acquisition and analysis within this project is that of variability. All data sets, associated with all testing equipment, display a considerable amount of variance. To quantify this, coefficients of variance were computed for each type of test, for each day, on each test site. The coefficient of variance (CoV) is computed by dividing the standard deviation of a data set by its mean, typically multiplied by 100 to convert it to a percentage. Through this computation, data sets can be more easily compared as it normalizes sets that may have large differences in means, as they do in this project. A CoV near zero would represent a low variability (standard deviation very small compared to the mean), a value near or over 100 a large variability. For the purpose of this study, the degree of variance would indicate the reliability of any particular piece of equipment used in data collection.

Table 11 shows the minimum, average and maximum CoV values for the different days and tests as a summarized way to display the variability throughout the data analysis; complete values available upon request. The field data exhibiting the lowest CoV's (or the least variability) were derived from the NDG compaction values, which were closely followed by the moisture determination derived from the same piece of equipment. These tests intrinsically have lower variability as the outcome values are typically limited to a small range of possibilities. Clegg impact values showed relatively low variability, at a level around 20%, which seems adequate when compared to other tests in this study.

Table 11 Coefficient of Variation of the Testing Equipment

Test	Day	Min	Avg	Max
NDG, Moisture	Day 0	7.3	10.8	15.1
NDG, Compaction	Day 0	1.5	3.6	13.5
Clegg Impact Values	Day 1	19.3	22.8	26.7
	Day 7	13.4	18.1	23.4
LWD, Moduli	Day 1	42.0	64.8	88.7
	Day 7	43.2	59.5	97.7
FWD, Moduli	Day 1	40.4	62.7	87.7
	Day 7	30.7	52.6	81.2
Core Strengths	Day 7	21.8	53.5	154.6

The LWD and FWD determination of moduli have a large amount of variability, with values ranging from 30 to near 100%. These tests intrinsically could be expected to have somewhat higher CoV values as they utilize a back calculation methodology and numerous sensors' data to develop moduli. Even with these inherent issues, the calculated CoVs are much larger than anticipated. Compression strengths of cores provided the largest range of CoV values, from 20 to 155% (155% indicating a higher standard deviation than the actual mean of the data set). Large CoV ranges would imply that it is very difficult to determine whether or not a reliable set of data is obtained from the field test, as actual conditions being tested could fall anywhere within the range.

This research project revealed a tremendous amount of variability in the data, resulting from many sources including the testing methods, the in-place material, inherent construction issues and the cement/moisture design itself. The FDR-C design is developed based on only a few material samples throughout the project. This may not be enough data points to depict accurately all the possible different materials types that may be present throughout a several mile project. In addition, all testing and variability presented in the project are longitudinal, i.e. all testing was performed at the same offset. The same level of variability can be expected transversely across the roadway as well.

Nuclear Density Gauge (NDG)

The Nuclear Density Gauge (NDG) was useful in testing, depicting the moisture and compaction within each test site. Most importantly, the NDG cannot detect any change in base strength that is a function of the cement stabilization. Like the DCP, however, the curing of the FDR-C layer affects the usability of the device; therefore, it can only be used on Day 0. As mentioned previously, unexpected rain during the final grading and compaction of RS1 in Warren-Waitsfield resulted in wet material. Compaction was not reached except in one test spot. One may presume that because compaction did not meet project specifications (98%), core results would show poor strengths, however core strengths were in the acceptable 200-800 psi range. A comparison between compaction and core strengths is shown in Figure 11.

Similar NDG results were evident in Addison-New Haven with regard to scatter. However, compaction in RS1 was reportedly well over the required minimum of 98% with an average of 105.3%. Coring proved to be difficult in this test site. Many cores were unable to be extracted, falling on the x-axis in Figure 12. While it might be assumed that if compaction meets the required minimum then core strengths should be within the acceptable range (200-800 psi), it is not always the case. Extraordinary results for compaction suggest an inaccurate system of measurement for compaction was evidenced in this study. Compaction values do not incorporate the effects of the cement activity in the matrix. Different aggregate matrices will not respond in the same way to the cement activity.

The quantification of compaction has the potential for large variability. The underlying premise is a target value for a measured compaction is established from an optimum density derived from a moisture density curve. The three or four points used to define this curve require good technique or results derived from the curve will be inaccurate. To compound the vulnerability in obtaining inaccurate results is the variability of the base course over the length of the project. The selection of target values without consideration of these factors will render the value of using field density measurement uncertain.

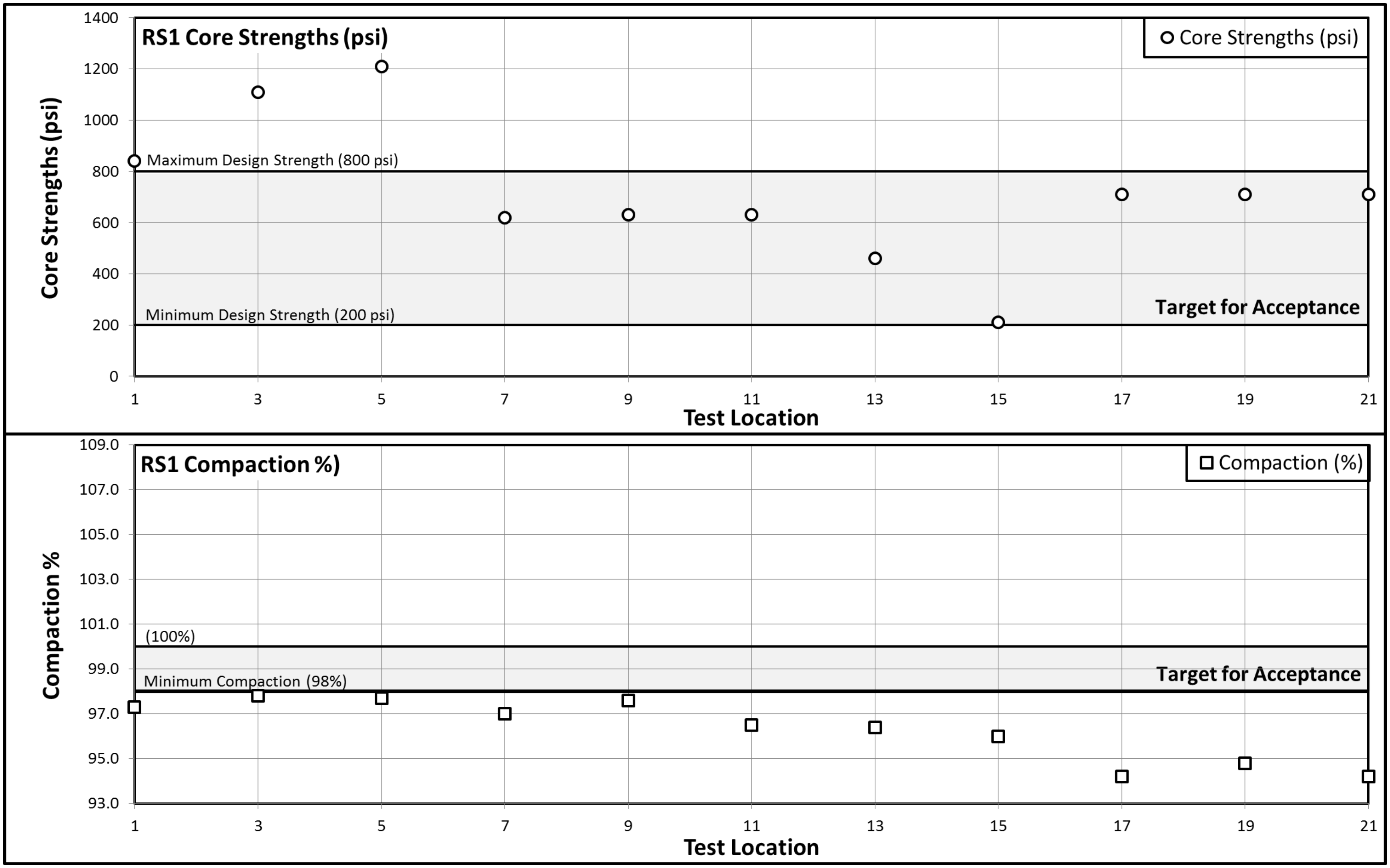

Figure 11 Warren-Waitsfield RS1 Compaction percentage and Core Strength Results Comparison (psi).

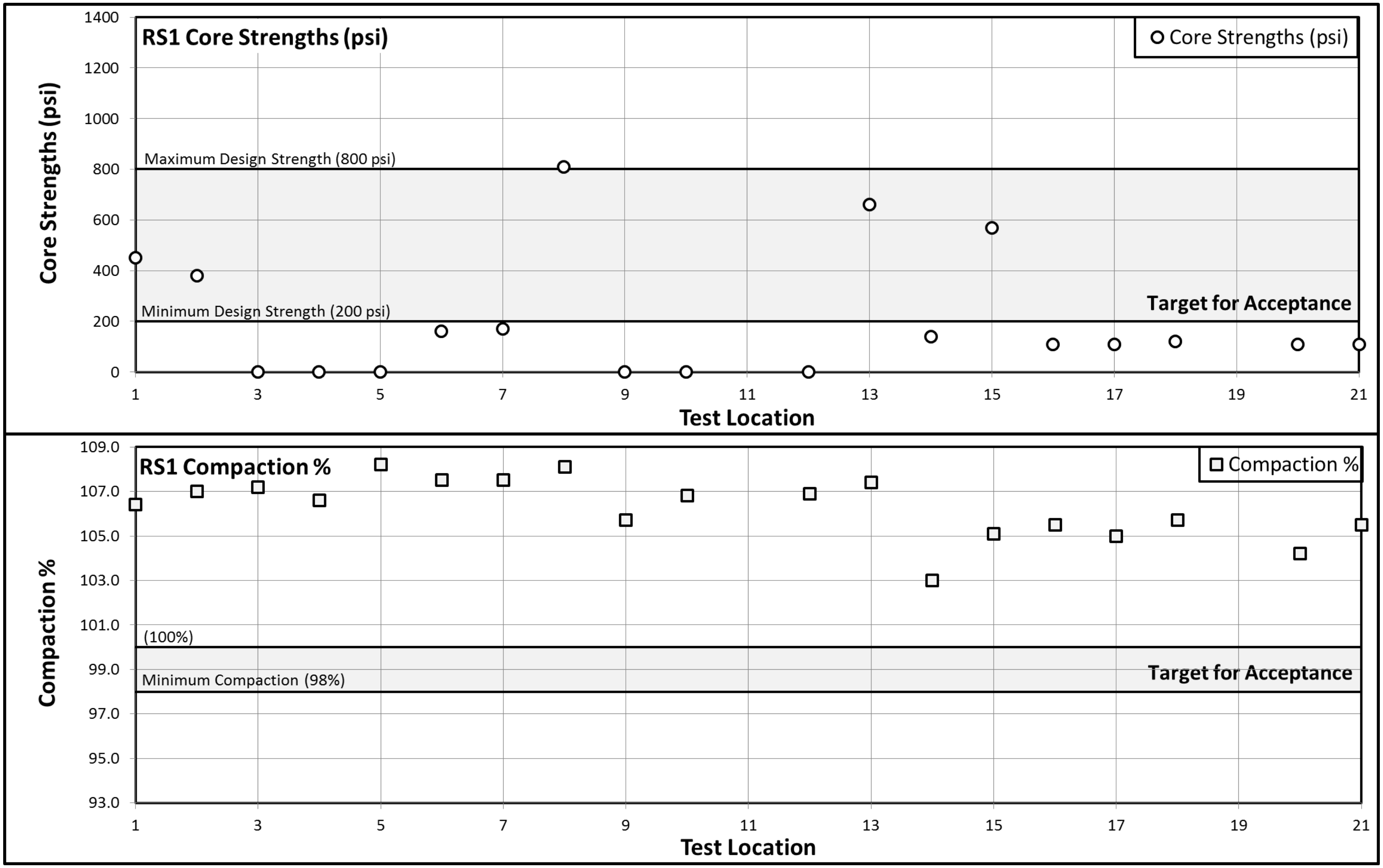

Figure 12 Addison-New Haven RS1 Compaction percentage and Core Strength Results Comparison (psi)

Dynamic Cone Penetrometer (DCP)

As noted in the Testing Summary section, the curing of the FDR-C resulted in difficult testing conditions due to the hardness of the FDR-C. Figure 13 illustrates no correlation of Dynamic Cone Penetrometer (DCP) results and core strengths in Thetford-Fairlee RS2. As can be seen in the figure, California bearing ratios (CBR) increase as the testing progressed from the beginning to the end, indicating that the FDR-C layer was setting within the three-hour testing period. This occurred in RS1 as well.

Clegg Impact Soil Tester (CIST)

The Clegg Impact Soil Tester (CIST) provided reasonable correlations in most test sites throughout the research project. Figure 14 illustrates all Day 1 CIST values (CIV) versus core strength results (psi). Thetford-Fairlee data is not displayed on the graph because Day 1 CIST data was not collected. The data shows that a majority of the time when a test point has a minimum CIV value of 30; the core strength is within the acceptable range at Day 7 compression testing. It should be noted that cores given a strength value of 1 psi were cores that were unable to be recovered.

Light Weight Deflectometer (LWD)

The Agency's Pavement Management Unit contracted with Dynatest Consulting to conduct Light Weight Deflectometer (LWD) data analysis in several lengths of roadway rehabilitated with FDR-C and FDR without Portland Cement. The analysis included Thetford-Fairlee and Addison-New Haven. Because Warren-Waitsfield and Vershire-Thetford were not part of the original contract, these projects were analyzed in-house.

The overall average deflection reported in mils for Thetford-Fairlee is shown in Table 12. The recorded deflections for RS1 and RS2 were 22.9 mils and 10.01 mils on Day 0 and 1.93 mils and 3.25 mils on Day 7 respectively. RS1 on Day 7 exhibited a 91.44% decrease in deflection where RS2 showed a smaller decrease of 67.53% from Day 0 to Day 7 (*20*). The difference in deflection was predominately due to the excessive moisture problems as mentioned in this report.

Table 12 Thetford-Fairlee LWD Results – Average Deflection Reduction (mils).

Test Site	Day 0	Day 7	% Decrease
RS1	22.9	1.96	91.44
RS2	10.01	3.25	67.53

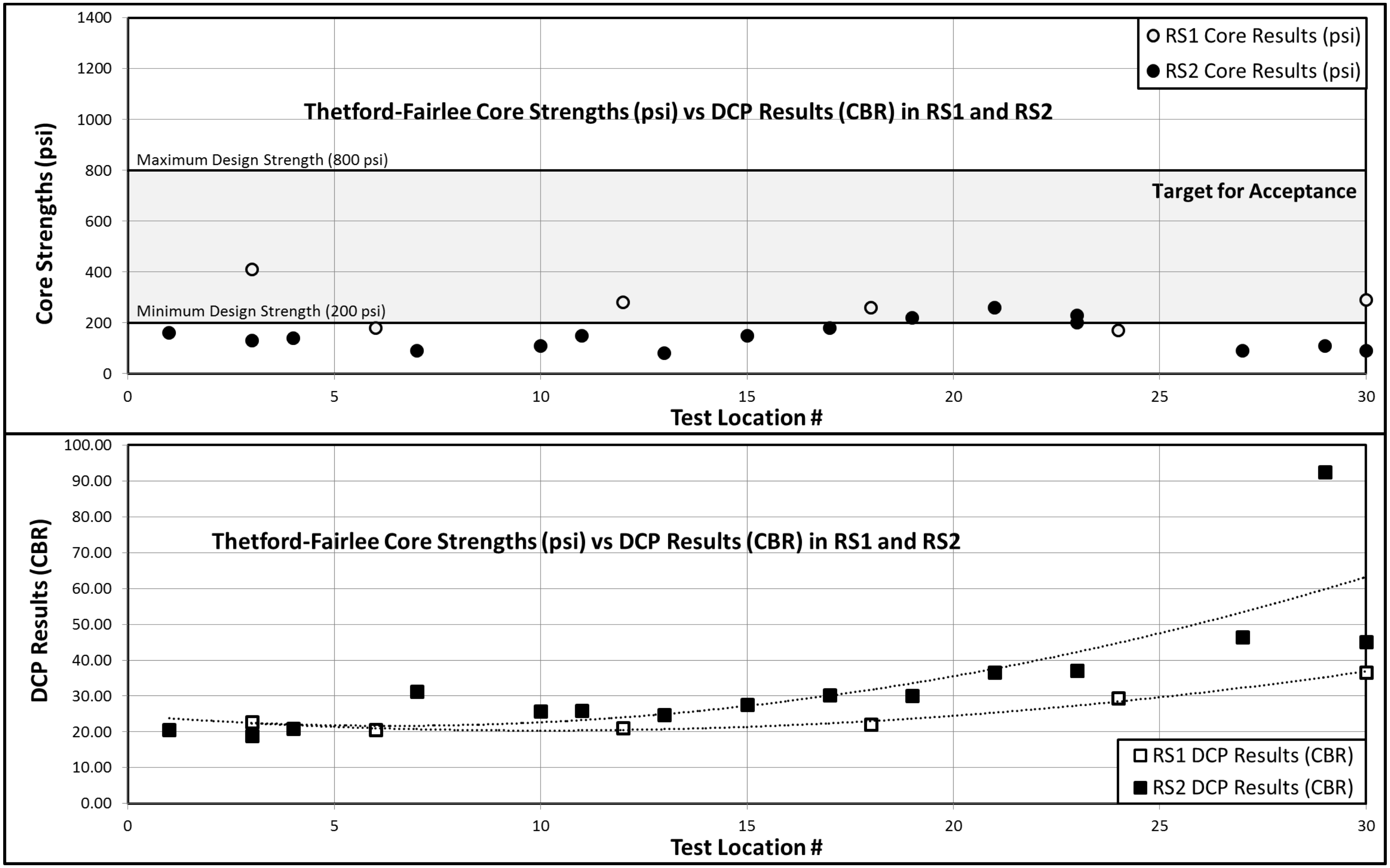

Figure 13 Thetford-Fairlee RS2 DCP (CBR) and Core Strengths (PSI) Comparison

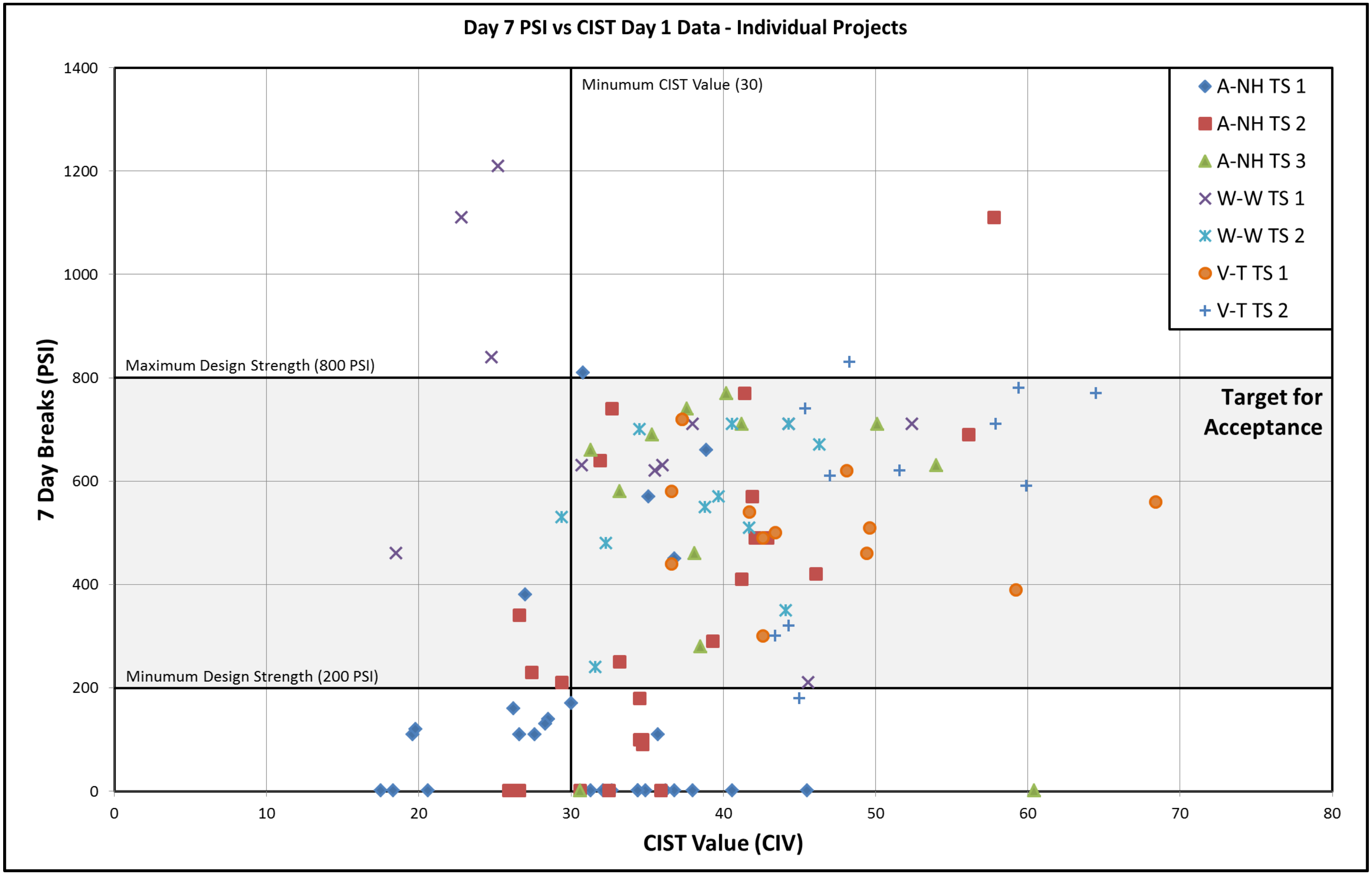

Figure 14: CIV vs. Core Strengths (psi).

Addison-New Haven deflection changes, shown in Table 13 exhibited similar characteristics. The deflection values from the LWD shown are the average deflections in RS1, RS2 and RS3 on the first reclaim, Day 1, Day 3 and Day 7. The deflections measured for the first reclaim were taken between final compaction and the starting of the second reclaim with cement. Comparing the values provided for Day 1, Day 3 and Day 7 to the first reclaim show the contribution of the cement to the stiffening of the. (*21*)

Table 13 Addison-New Haven LWD Results – Average Deflections (mils).

RS 1		RS 2		RS 3	
Day	**Def Mils**	**Day**	**Def Mils**	**Day**	**Def Mils**
First Reclaim	8.7	First Reclaim	9.46	First Reclaim	9.48
Day 1	4.18	Day 1	2.97	Day 1	2.07
Day 3	3.18	Day 3	2.16	Day 3	1.94
Day 7	3.07	Day 7	2.07	Day 7	2.67

The results demonstrate that with the quick decrease of deflections, the FDR-C is gaining strength at a rapid rate. Individual test locations were not provided to the Agency in tabular form therefore a direct analysis of core strengths versus LWD moduli could not be compared.

The VTrans' analysis for the 2013 projects is shown in Figure 15 and Figure 16, comparing test location versus both elastic modulus (as determined by LWD results) and core strength. All test points are shown in the graphs for Day 1 and 7. Although many of the core strengths are within the acceptable range, no trend was identified with the LWD results for either project.

The overall moduli values are summarized for all projects in Table 14. The average moduli values between projects and individual test sites vary greatly. For example, Warren-Waitsfield RS2, averaging 2244 ksi was triple the amount of RS1, averaging 745 ksi.

Table 14 Overall LWD Elastic Modulus (ksi).

Project	**Day 7**		
	RS1	**RS 2**	**RS 3**
Thetford-Fairlee	545	200	N/A†
Addison-New Haven	206	657	396
Warren-Waitsfield	745	2244	N/A†
Vershire-Thetford	1350	1024	N/A†

†These projects did not include a third test site.

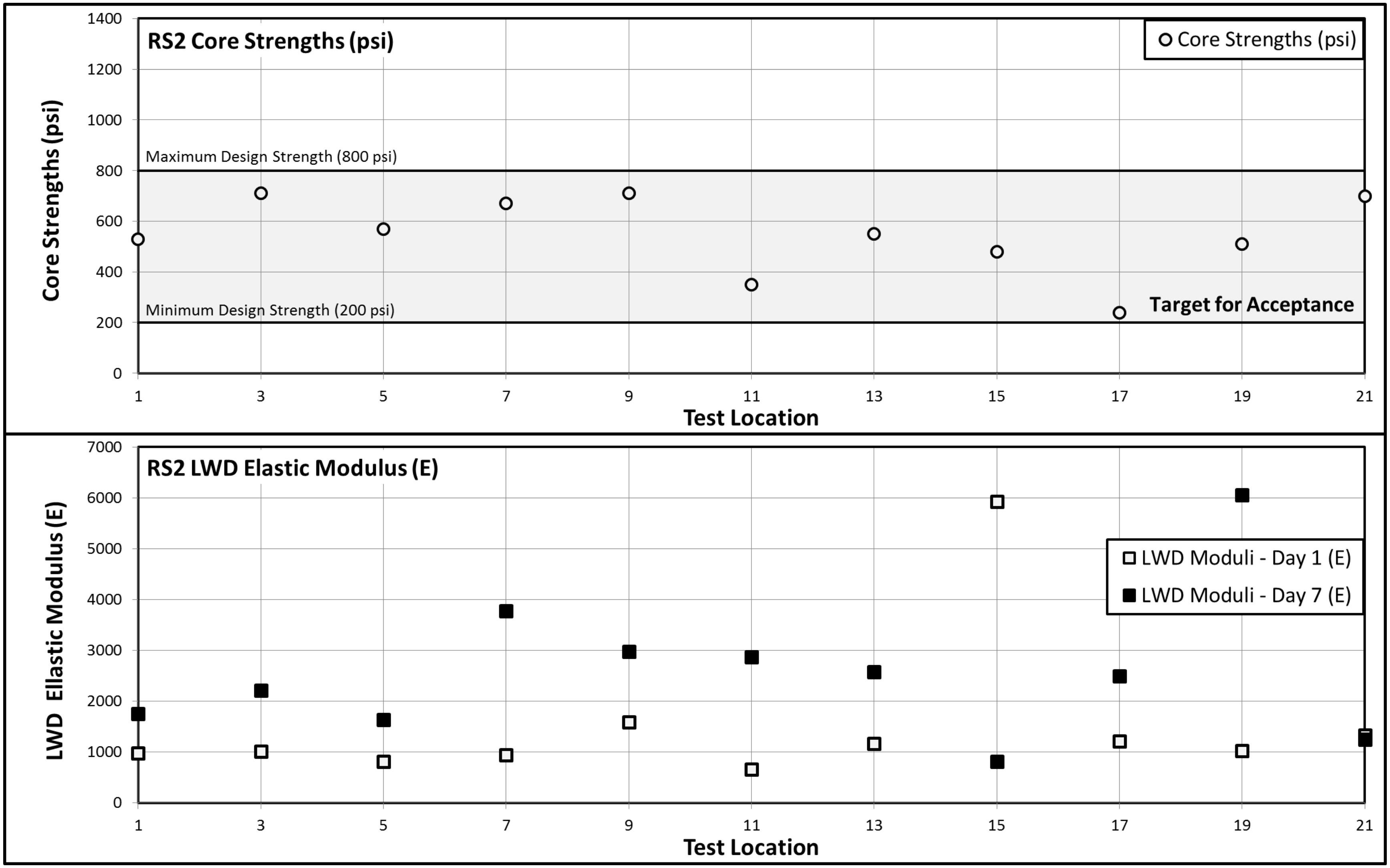

Figure 15 Warren-Waitsfield RS2 LWD Moduli and Core Strength (psi) Comparison.

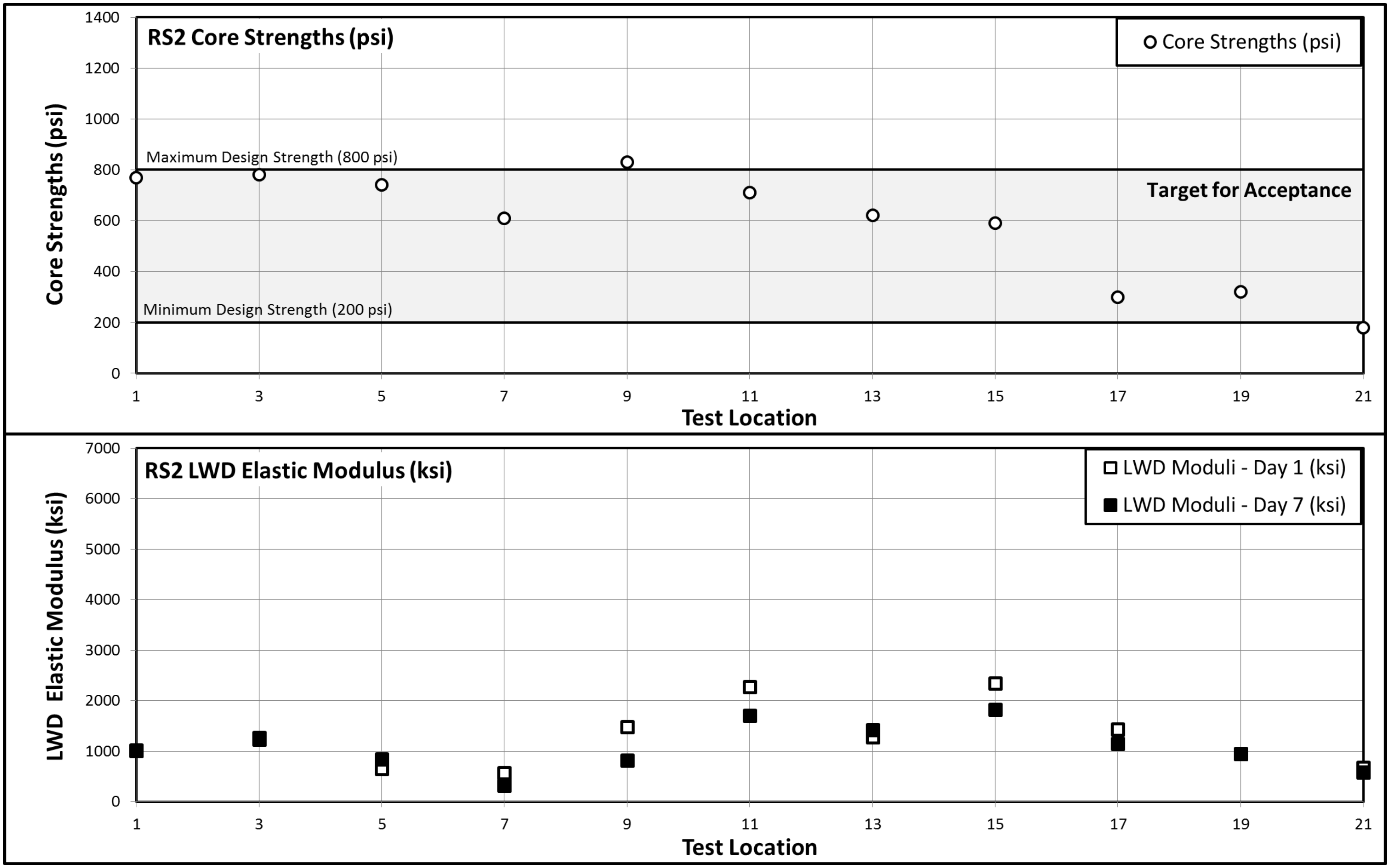

Figure 16 Vershire-Thetford RS2 LWD Moduli and Core Strength (psi) Comparison.

Falling Weight Deflectometer (FWD)

As with the LWD, the Falling Weight Deflectometer (FWD) data was analyzed by Dynatest Consultants for the first two projects. The 2013 projects were analyzed in-house. Preconstruction data was obtained by testing the existing pavement section including hot mix asphalt surface layers. All post-construction data was obtained by directly testing the base course. Pavement can add stiffness to the roadbed matrix thereby influencing the overall stiffness and the back-calculated modulus for the FDR-C layer.

Table 15 shows the average deflections from the FWD reported in mils in Thetford-Fairlee. Both test sites saw a large increase from preconstruction data to Day 0 data. This confirms that immediately after final grading and compaction on Day 0, the FDR-C had not cured enough to exhibit an increase in strength and reduction in average deflections. Days 7 and 28 however show a decrease in deflection from preconstruction conditions. Like the LWD, the FWD results show that with the addition of Portland Cement, there is a rapid strength gain of the FDR-C (*20*, *21*).

Table 15 Thetford-Fairlee FWD Results – Average Deflection Reduction.

RS 1		RS 2	
Day	**Def Mils**	**Day**	**Def Mils**
Preconstruction	21.13	Preconstruction	27.49
Day 0	50.79	Day 0	50.62
Day 7	13.12	Day 7	24.26
Day 28	7.02	Day 28	11.77

Addison-New Haven showed similar FWD results; however, the FDR-C appears to have gained strength at a slower rate as shown in Table 16. After the first reclaim pass, all test sites showed an increase of deflections (*21*).

Once the FDR-C was completed, all test sites exhibited lower deflections, resulting in increased strength from preconstruction conditions. RS1 did not exhibit a reduction of deflection from preconstruction conditions until Day 7. RS2 and RS3 exhibited deflection reduction from preconstruction on Day 1 (*20*).

Table 16 Addison-New Haven FWD Results – Average Deflection Reduction.

RS 1		RS 2		RS 3	
Day	**Def Mils**	**Day**	**Def Mils**	**Day**	**Def Mils**
Preconst.	25.08	Preconst.	26.75	Preconst.	52.78
First Reclaim	44.08	First Reclaim	42.15	First Reclaim	77.22
Day 1	29.16	Day 1	25.35	Day 1	29.88
Day 3	25.64	Day 3	18.23	Day 3	19.33
Day 7	22.14	Day 7	15.4	Day 7	23.19
Day 30	15.3	Day 28	12.25	Day 36	15.67

The VTrans' moduli analysis for Vershire-Thetford is shown in Figure 17. Higher moduli values in test points 17 and 19 resulted in lower core strength results. Theoretically, if core strengths were lower, then moduli values should also be lower, exhibiting a lower stiffness of the FDR-C.

The overall moduli values are summarized for all projects in Table 17. Like the LWD results showed, the FWD values were inconsistent, not only between projects but within the project itself. Addison-New Haven for example in RS1 and RS2 where 4% Cement was used in the FDR-C had a variance of more than double, averaging 520 ksi over RS2 where RS1 averaged only 191 ksi.

Table 17 Overall FWD Elastic Modulus (E).

Project	Day 7		
	RS1	**RS 2**	**RS 3**
Thetford-Fairlee	388	257	N/A
Addison-New Haven	191	520	361
Warren-Waitsfield	1103	1228	N/A
Vershire-Thetford	770	885	N/A

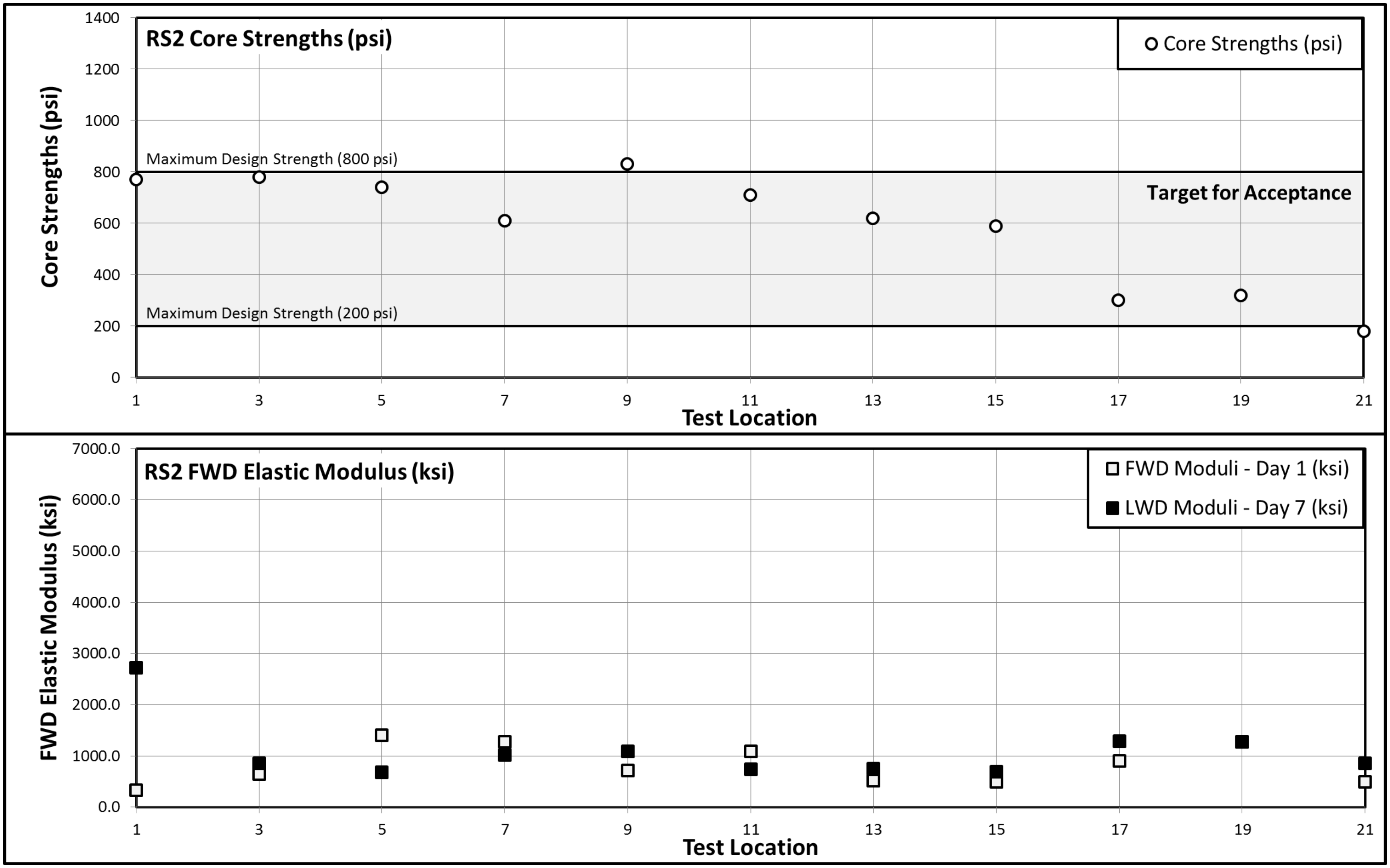

Figure 17: Vershire-Thetford RS2 FWD Moduli and Core Strength (psi) Comparison.

RECOMMENDATIONS

Based on the testing results the following are recommendations regarding future equipment use for each device.

Nuclear Density Gauge (NDG)

Moisture content and compaction results of the FDR-C are useful in gathering information about the construction process and reclaimed area. The testing can be conducted quickly and anywhere in the roadway, as the device is extremely mobile. No analysis is required to determine useful results therefore allowing, quick decisions in the field. Although test results can be produced quickly, application of the method as an acceptance criterion is limited by a potential inaccurate moisture-density curves and inability to identify strength gain from cement activity.

Dynamic Cone Penetrometer (DCP)

Although traffic control requirements are minimal, testing itself proved to be lengthy. Test results were directly affected by the wetness of the FDR-C material. Improper wetting caused no correlation from testing. Delayed testing as conducted in the study is not recommended for FDR-C, as the subbase will stiffen over time. From field observations, the DCP may be considered as a sufficient testing method if it was used prior to the cement setting up in the base material. DCP testing should be completed within 45 minutes of final compaction. Results after 2 hours were not accurate.

Clegg Impact Soil Tester (CIST)

Data correlated well to the core strength data. Roadway weaknesses at the surface are easily identifiable. Like the NDG testing, it can be conducted quickly and anywhere in the roadway as the device is extremely mobile and no data analysis is required to determine a useful result. Again, quick field decision making could allow time for corrective action such as reclaiming the base material an additional time with minimal disruption to the construction schedule. The equipment is inexpensive in comparison with the other devices. Calibration is required annually however the cost is minimal, $150 plus shipping. The CIST is recommended as a primary acceptance test mechanism.

Based on correlations with core strengths, it is recommended to conduct further testing to identify CIST values on Day 1 where the FDR-C layer will be in an acceptable strength range. Currently it appears that a minimum reading between 25-30 CIV will coincide with obtainable core strengths exceeding 200psi. Future testing should be done to better define an upper limit for CIST value so that excessive strength gain can be corrected in the field. CIST readings should be taken in the exact same spot and in multiple areas across the roadway as the core locations for direct comparison in test points.

Light Weight Deflectometer (LWD)

Notable advantages are that the results to date are promising and show roadway weaknesses or deformations with consistent trends to the FWD, but on a smaller scale. Equipment and calibration costs are greater than the other methods evaluated with the exception of the Falling Weight Deflectometer. Testing requires more time than previously discussed methods. Analysis of the data requires additional time and data processing capacity. Trained staff is required to run the software that converts field data to modulus. Factors other than the quality of the base affect the test results making interpretation of construction quality more subjective. Additional traffic control may be required depending on the sequencing of operations and timing of the LWD usage.

Although the testing process requires traffic control during testing, the mobility, cost, and usage training of the LWD is far less than the FWD. LWD provides a more precise estimate of the stabilized base performance than the strength and hardness index provided by the CIST. Further assessment of the selective use of LWD to define areas of concern and corrective action is appropriate.

Falling Weight Deflectometer (FWD)

Like the LWD, results to date are promising with respect to defining the performance of the reclaimed base. The FWD has the highest equipment and calibration costs. It has the highest personnel costs because of the duration and complexity of test and data processing. The equipment is trailer mounted and towed by truck placing physical limitations on the test locations. Test results must be evaluated once accompanying software is used to convert raw data into modulus. Staff training for equipment operation and post processing are essential to good results. FWD results are affected by site conditions beyond the reclaimed base. Application of the test results to the construction work includes subjectivity in addition to delay. FWD does not lend itself to an initial acceptance practice because of intrinsic characteristics of the test method and equipment. FWD does present an opportunity to define appropriate corrective actions in reclaimed areas that do not meet specification.

Coring

Coring results show that there is an inconsistency of FDR-C across the roadway. Core recovery has been inconsistent as a function of variable core strength and coring equipment that was not suitable for use. Extracted cores vary in length (depth of recovery) as well as cross section. Further testing should be conducted as previously mentioned in conjunction with the CIST testing. Consideration of eliminating field cores with a conversion to field casting should improve the reliability of the test method. The use of compression strength testing produces irrefutable evidence of the amount of binding in the FDR-C and aggregate condition in the FDR-C. Because of breakage and poor recovery, coring does not account for compressive strength in the matrix of an unbound granular material. That omission reduces the accuracy of coring in assessing in-place performance of the reclaimed base.

SUMMARY RECOMMENDATION

The three most effective techniques for defining the uniformity, strength and compaction levels of a FDR-C are:

1. Nuclear Density Gauge testing immediately after compaction provides an accurate description of unbound base strength. Care must be taken to develop accurate and appropriate Moisture Density Curves for the in-place materials.

2. Compression testing at early age provides direct assessment of the strength and binding potential for the FDR-C. Poor core condition after recovery warrants use of field sample molds to improve test accuracy.

3. Clegg Impact Strength Tester shows good correlation to minimum strengths when completed at one day after FDR-C compaction. The test assesses a combined strength for the unbound and strength gain from cement activity as it is applied at the surface. Additional work to develop an upper bound for CIV is needed to limit strength and reduce cracking of the FDR-C.

The use of both compression testing and density are excellent surrogates for in-place strength of FDR-C because it accounts for unbound strength and strength gain from cement activity. Deployment of Nuclear density gauge testing (#1 above) necessitates compression testing (#2 above).

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