2019

Construction and performance of chemically and mechanically stabilized granular road test sections

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Recommended Citation
Wu, Yijun, "Construction and performance of chemically and mechanically stabilized granular road test sections" (2019). *Graduate Theses and Dissertations*. 17127.
https://lib.dr.iastate.edu/etd/17127

Construction and performance of chemically and mechanically stabilized granular road test sections

by

Yijun Wu

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Geotechnical Engineering)

Program of Study Committee:
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Iowa State University

Ames, Iowa

2019

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ACKNOWLEDGMENTS

I would like to thank my advisors Dr. Jeramy C. Ashlock and Dr. Bora Cetin for their guidance and support throughout the course of this research. Their vast knowledge, abundant experience, great patience and encouragement helps me during my graduate study at Iowa State University. I really appreciated that my advisors assisted me to improve this thesis report and gave me comments to advance it. I am also very thankful to Dr. Kristen S. Cetin be my committee member. Thanks also to Dr. Cheng Li trained me and teach me a lot.

In addition, I would also like to thank my family, all my friends and the Younkins making my time at Iowa State University a wonder experience, I would like to thank my parents and my sister for being my strong supporter in my life.

ABSTRACT

Granular-surfaced roadways in Iowa rural area frequently experience damage and degradation from the effect of rainfall, flooding, seasonal freeze-thaw cycles, heavy agricultural machinery and steadily increasing traffic loads. Rutting, potholes and frost boil problems appeared usually and leading these granular roads to unpassable. As a result, many counties have to close damaged roads for repairs and spend significant portions of their budgets on maintenance and rehabilitation of granular roads. Several stabilization methods for granular roads were examined for improving the performance and minimizing damages in Iowa by the previous completed Phase II Iowa Highway Research Board Project TR-664 “Low-Cost Rural Surface Alternatives: Demonstration Project”. To investigate additional stabilization methods suitable for use in Iowa, six mechanical and five chemical stabilization methods employing different types of virgin and recycled materials were examined and used to build test sections in this study. Comprehensive construction procedures were developed and 31 test sections were built in four counties distributed geographically around the state of Iowa in August through October 2018. Extensive laboratory, field tests, and photographic surveys were performed prior to construction, as well as after construction to monitor the performance of the demonstration sections. The shear strength and elastic modulus of granular roads surface course were obviously improved by one of the chemical methods, cement treated surface, and three of the mechanical methods, optimized gradation with clay slurry and two slag stabilization methods. The composite elastic modulus was improved by two cement treated methods and two mechanically methods, optimize gradation with clay slurry and aggregate columns. Several equipment was also found that can shorten the construction time and stabilize the soil more efficiently.

CHAPTER 1. INTRODUCTION

Granular-surfaced roads in seasonally cold regions frequently experience damage and degradation from the effect of rainfall, flooding, seasonal freeze thaw cycles, heavy agricultural machinery and steadily increasing traffic loads, which leads to extensive damage such as frost heave, frost boils, thaw weakening, rutting and potholes. As a result, many counties spend significant portions of their budget on repair and maintenance of granular roads. Some county engineers have to post load restrictions or frost embargos to reduce heavy agricultural traffic loads in spring, since the saturated unbound granular materials loose strength when liquid water cannot drain efficiently and becomes trapped above the zone of frozen soils in the crucial spring thawing period. In some regions, low-strength of locally available aggregates further compound the problems.

In the previous Phase I Iowa Highway Research Board (IHRB) Project TR-632 “Low-Cost Rural Surface Alternatives” (White et al. 2013), an extensive analysis of existing literature on the topic of the construction and performance of granular-surfaced roads with respect to freeze-thaw damage and resistance were conducted. Several of the stabilization methods and technologies identified in the study were implemented for improving the performance and minimizing freeze-thaw damage of granular roads in the subsequent Phase II IHRB Project TR-664 “Low-Cost Rural Surface Alternatives: Demonstration Project” (Li et al. 2015). Seventeen test sections and five control sections were constructed in Hamilton County on a heavily traveled two-mile section of granular-surfaced road that required frequent maintenance during previous thawing periods. Construction procedures and costs for the demonstration sections were documented and the maintenance requirements were tabulated through two seasonal freeze-thaw periods. The most effective and economical methods suitable for the soil and climate conditions in the Iowa region were identified.

For the currently ongoing IHRB Project TR-721 “Low-Cost Rural Surface Alternative Phase III: Demonstration Project” detailed in this thesis, 31 addition demonstration sections were built in four counties distributed geographically around the state of Iowa utilizing 6 mechanical and 5 chemical stabilization methods and employing different types of virgin and recycled materials.

The mechanically stabilized demonstration sections were constructed in Howard County (9 sections total) and Cherokee County (8 sections total), including one control section in each county. The following 8 types of mechanically stabilized sections were constructed in these two counties:

1. aggregate columns
2. optimized gradation with clay slurry
3. ground tire rubber mixed at 20% by volume in a 2 in. base layer of aggregate and covered by a 2 in. surface layer of aggregate (in Howard county only)
4. recycled asphalt pavement (RAP) mixed at 50% by volume with aggregates
5. 2-in. thick slag surface overlying 2-in. existing aggregate base (Source #1)
6. 2-in. thick slag surface overlying 2-in. existing aggregate base (Source #2)
7. 4-in. thick slag surface (Source #1)
8. 4-in. thick slag surface (Source #2)

The feasibility of the aggregate column method was verified in the previous IHRB project TR-664, and it had the lowest initial cost of all methods examined, while improving the freeze-thaw performance of the roadway by reducing the occurrence of frost-boils. A new pattern with a denser grid of columns was applied in this study, to help minimize rutting which was observed near the shoulder in the previous study (Li et al. 2015).

In the previous IHRB Project TR-685 “Feasibility of Granular Road and Shoulder Recycling” (Li et al. 2018), the in-situ granular surface materials were recycled by blending them with virgin materials in optimum proportions, and recommended construction procedures were developed. According to the study, a proper gradation of surface materials along with plastic fines for binding can greatly improve the strength and longevity of roadway surfaces, while helping to minimize freeze-thaw damage. The Microsoft Excel-based program developed by Li and Ashlock (2018) in the TR-685 project was utilized in the present study to calculate the quantity of fresh quarry materials needed for mixing with existing surface materials to approach the optimum design gradations. To help bind the coarse aggregates and reduce material loss, the previous study also recommended mixing plastic fines into the top 50.8 mm to 76.2 mm (2 to 3 in.) of the roadway. The goal was to form a surface crust underlain by a cleaner, load-bearing aggregate layer, because the fines can greatly reduce shear strength of granular materials under prolonged wet conditions (Li et al. 2018). The theory is that when the top few inches of the surface course is mixed with clay, the fines perform the desired function of binding the larger aggregates to reduce material loss while preserving the shear strength of the deeper aggregates in the lower part of the surface course. However, the previous study employed bags of powdered bentonite to achieve the desired plasticity, which was labor intensive to incorporate and the bentonite content was significantly reduced after one freeze-thaw season. In this study, a newly available clay slurry from Pattison Sand Company was applied to the optimized gradation mixture instead of using bentonite or local clays.

Due to the economy and past successful performance of the aggregate columns and optimized gradation with clay slurry, test sections using these two methods were constructed in all four counties, including Washington and Hamilton, which otherwise featured chemical stabilization methods.

Ramaji (2012) performed a review of prior literature and concluded that use of different sizes of waste rubber in soil reinforcement could be a low-cost and effective method for soil stabilization. In a previous study, mixing shredded tires with sand showed the greatest improvement in shear strength using a rubber content of 6% by weight (20% by volume) and shredded tire size of 5x5 mm for triaxial tests, while CBR tests indicated the highest penetration resistance at a rubber content of 3% by weight (10% by volume) for the same shred size (Hassona et al. 2003). In this study, ground tire rubber with a top size of 9.5 mm (3/8 in.) was mixed with aggregate at 20% by volume in the bottom 50.8 mm (2 in.) of the granular surface course in Howard County.

Recycled Asphalt Pavement has been used in granular roads for many years. The design function of RAP is binding fines and course aggregates in the surface layer. However, Koch et al. (2011) investigated the use of RAP in gravel roads in two Wyoming counties and showed that RAP was helpful for reducing dust but gave no improvement in road condition. The study also mentioned that compacting a RAP blend with gravel will help in maintaining long-term road serviceability. The two RAP demonstration sections in the present study were constructed by mixing 50% locally available RAP with the existing granular surface material which was then blended and roller compacted.

Mathur et al. (1999) investigated utilization of industrial wastes in low-volume roads and indicated that steel slag, which is a very dense hard material that can be readily crushed to a suitable particle shape and size, produces an excellent aggregate with high crushing strength, low abrasion value, and excellent skid resistance. They also concluded that the slag mixture initially behaves like unbound material, but it generally turns into a bound material because of the self-stabilization characteristics of slags. In the present study, four steel slag sections using two different slag sources were constructed in both Howard and Cherokee counties. Considering that steel slag is harder than natural aggregates and could therefore possibly accelerate aggregate deterioration, the slag was placed in separate layers above the existing aggregate base and was not blended with the natural aggregates.

Chemical stabilization methods were implemented in Washington County and Hamilton County, and included the following:

1. cement treated subgrade (in Washington County only)
2. cement treated aggregate surface course (not yet constructed in Hamilton County)
3. TeamLab T15 Base One (a silicic acid, sodium salt concentrated liquid stabilizer which will be denoted SA-CLS)
4. SSPCo EMC Squared (a neutral pH, non-ionic concentrated liquid stabilizer which will be denoted NI-CLS)
5. Claycrete (an ionic concentrated liquid stabilizer, which will be denoted I-CLS)

In Henry et al. (2005), 6%-8% Portland cement by weight was mixed into native road surface materials to create a stabilized surface course that had significantly improved weighted CBR values in the top 76.2 mm (3 in.) of cement treated soil during spring thawing. In the present study, two types of cement treated test sections were constructed; 7% Portland cement by weight in the 101.6 mm (4 in.) thick surface aggregate course with an untreated subgrade, and a 304.8 mm (12 in.) thick subgrade layer treated at 5% by weight with an untreated surface course.

A study by Jahren et al. (2011) showed that Base One can mechanically bind fine particles. Although it did not provide noticeable improvements on US 20 shoulders in that particular study, it can be easily applied with typical DOT maintenance equipment. In the present study, a representative from the manufacturer was present to oversee construction to achieve the best possible performance. Based on their recommendations, 0.5 in. of subgrade was incorporated with existing and virgin aggregate materials to construct the test sections.

In projects funded by the Bureau of Affairs (2014) on the Mescalero Apache Reservation in New Mexico, EMC Squared was used for base course stabilization. Stabilized base layers treated by EMC squared can exhibit superior resistance to freeze-thaw, and environmental impacts were examined in previous project. According to the manufacturer, the expected performance can be achieved by carefully following the recommended construction procedures and incorporating subgrade soils within the surface course to a total depth of 10 in. during treatment. In the present study, test sections were therefore constructed by incorporating a target depth of 6 in. of subgrade material with the surface course.

Huang et al. (2003) evaluated the characteristics of Claycrete stabilizer for improving clay soils, and determined that the stabilizer could improve the performance of the soil in freeze-thaw conditions. In the present study, a representative from the manufacturer was present and instructed the county’s crews in construction of the Claycrete test sections. Approximately 0.5 in. of subgrade was incorporated with the surface curse materials.

In the remainder of this thesis, Chapter 2 summarizes the laboratory and field test methods used to evaluate and compare the various stabilization methods. Chapter 3 provides details on the sources and properties of the geomaterials and various stabilizers used in this study. Chapter 4 introduces the test site selections and Chapter 5 describes the procedures and equipment used for constructions of the various test sections. Chapter 6 presents the results and discussion of laboratory and field tests conducted on the test sections before and after construction. Chapter 7 includes the conclusions and outcomes derived from this study, as well as recommendations for further research. Supporting materials are included in the appendices.

CHAPTER 2. METHODS

This chapter includes two parts: (1) laboratory testing methods used to determine soil index properties, compaction behavior, and shear strength of the geomaterials used, and (2) field testing methods used to determine in-situ shear strength, stiffness, surface material dry unit weight, and moisture content for the granular-surfaced test sections.

2.1 Laboratory Tests

Laboratory tests conducted to determine soil index properties, compaction behavior, shear strength and durability are described below. They were used to help develop the recommended construction procedures and associated calculations for the test sections.

2.1.1 Soil Index Properties

To determine soil index properties and classification of the geomaterials, particle-size distributions (gradations) were determined by sieve and hydrometer tests, liquid limit tests, and plastic limit tests. The soils were then classified according to American Society for Testing and Materials (ASTM) standard practice for the Unified Soil Classification System (USCS).

2.1.1.1 Particle-Size Distribution

Particle-Size distribution determination for geomaterials was performed according to ASTM D6913/D6913M – 17 "*Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*" and ASTM C136/C136M – 14 "*Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.*" The latter Standard was only used for determining the gradation of soil between 3-in. (75-mm) and No. 200 (75-µm) sieves when hydrometer analysis was not required. The equipment used for this part of sieve analysis is shown in Figure 1.

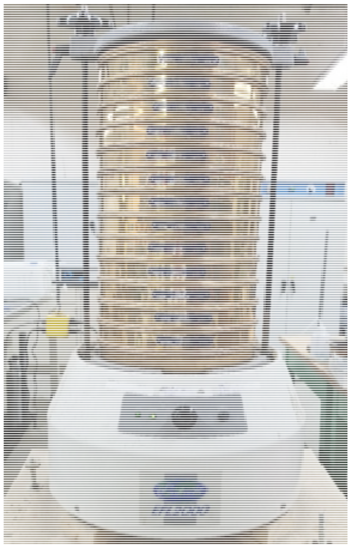


Figure 1 Sieve analysis device

The gradations of particles smaller than the No. 200 (75-µm) sieve were determined by using ASTM D7928 – 17 “Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis”. This test was performed on soil passing the No. 10 (2.0-mm) and the results are presented as the mass percent finer versus the log of the particle diameter. The equipment used for this test is shown in Figure 2.

Figure 2 Hydrometer test equipment

2.1.1.2 Atterberg Limits (Liquid Limit, Plastic Limit, and Plasticity Index)

The liquid limit (LL) of geomaterials passing the No. 40 (425-µm) sieve was determined using the fall cone test in accordance with Wasti (1987), and at least three data points were plotted to determine the LL for each sample. The plastic limit (PL) and plasticity index (PI) were determined in accordance with ASTM D4318 – 17e1 "*Standard Test Methods for Liquid, Plastic Limits, and Plasticity Index of Soils*" using the plastic limit rolling device. The devices used for the fall cone and plastic limit tests are shown in Figure 3. To determine the PI, both LL and PL were first rounded to the nearest integer values. The geomaterials were reported as non-plastic (NP) if either the LL or PL could not be determined, or the PL was equal to or greater than the LL, in accordance with ASTM D4318.

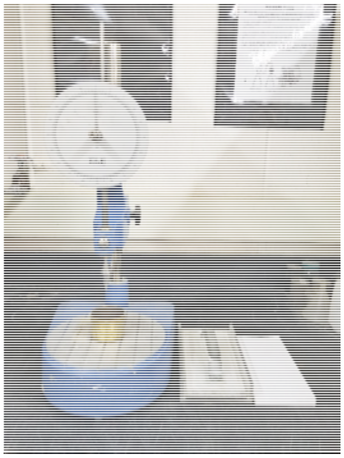


Figure 3 Fall cone test device and plastic limit rolling device

2.1.1.3 Soil Classification

The results of the particle-size distribution and Atterberg limits tests were used for classification of soils by the USCS and AASHTO systems in accordance with ASTM D2487 – 17 "*Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*" and ASTM D3282 – 15 "*Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes.*"

2.1.2 Compaction Behavior

The relationships between moisture content and dry unit weight of geomaterials were determined by conducting Standard Proctor compaction test in accordance with ASTM D698 – 12e2 "*Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN-m/m3))*." To prepare fine-grained geomaterials to predetermined moisture contents, the Hobart mixer shown in Figure 4 was used. According to the material gradation, the mold size was selected following the specifications of ASTM D698. For soils containing oversize particles ASTM D4718/D4718M – 15 "*Standard Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles*" was used.

Figure 4 Hobart mixer

2.1.3 Shear Strength Tests

To evaluate and compare the effects of the clay fraction on the undrained shear strength properties of compacted geomaterials, unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were performed. These tests are detailed in the following sections.

2.1.3.1 Unconfined Compressive Strength Tests

To evaluate the strength of compacted untreated and chemically stabilized soil specimens, the UCS tests were generally performed in accordance with ASTM D2166/D2166M

– 16 “*Standard Test Methods for Unconfined Compressive of Cohesive Soil*”, except cylindrical specimens with 2 in. height and 2 in. diameter were prepared by using the 2-by-2 compaction apparatus developed at Iowa State University (ISU). According to a study by Oflaherty et al. (1963), the 2-by-2 compaction device can be used to prepare specimens having moisture-density conditions similar to those obtained by standard Proctor compaction tests. UCS tests were performed on specimens consisting of the minus No.40 fraction of the samples. The 2-by-2 compaction device and a sample during a UCS test are shown in Figure 5.

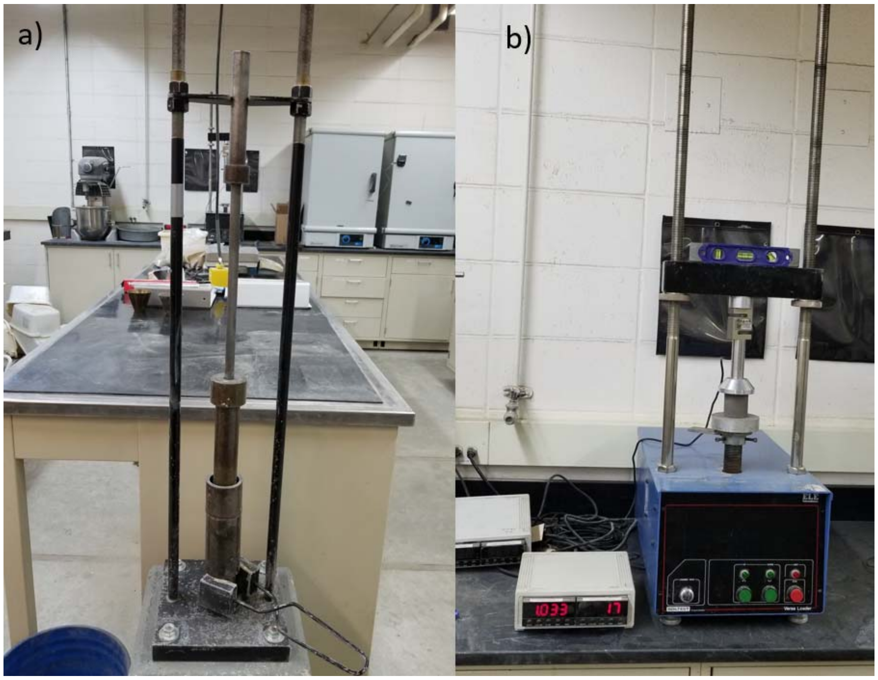


Figure 5 Photographs of a) 2-by-2 compaction device b) UCS test device

2.1.3.2 California Bearing Ratio Tests

Soaked CBR tests were performed to evaluate the effect of the clay fraction on shear strength of granular surface materials under saturated conditions. The testing procedures followed ASTM D1883 – 16 “*Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils.*” All of the specimens were compacted to standard Proctor maximum dry unit weight and soaked for at least 24 hours before testing. The CBR test device is shown in Figure 6. Surcharge weight was applied on the specimen at uniform rate of 1.3 mm/min. The load applied to the specimen and corresponding penetration depth were recorded and the load-penetration curve was plotted for CBR determination.

Figure 6 CBR test device

2.1.4 Durability

The slaking test is not a standard geotechnical experimental test, but rather a test for soil quality to indicate the stability of soil aggregates and resistance to erosion. Slaking is the breakdown of a lump of soil into smaller fragments upon wetting (McMullen 2000). Slaking tests were also conducted in IHRB Project TR-582 to evaluate long-term moisture susceptibility (Gopalakrishnan et al. 2010). In the present study, the 2-by-2 samples were also used for slaking tests, as shown in Figure 7. To perform the slaking tests, specimens of compacted minus No. 40 material were placed on a No. 4 sieve and soaked in tap water at room temperature. The specimens were then observed over a period of several minutes to hours, and the elapsed time at which the structure of a specimen can no longer be observed was recorded as its slaking time. For example, the samples shown in Figure 7 completely lost stability after 30 minutes of soaking.

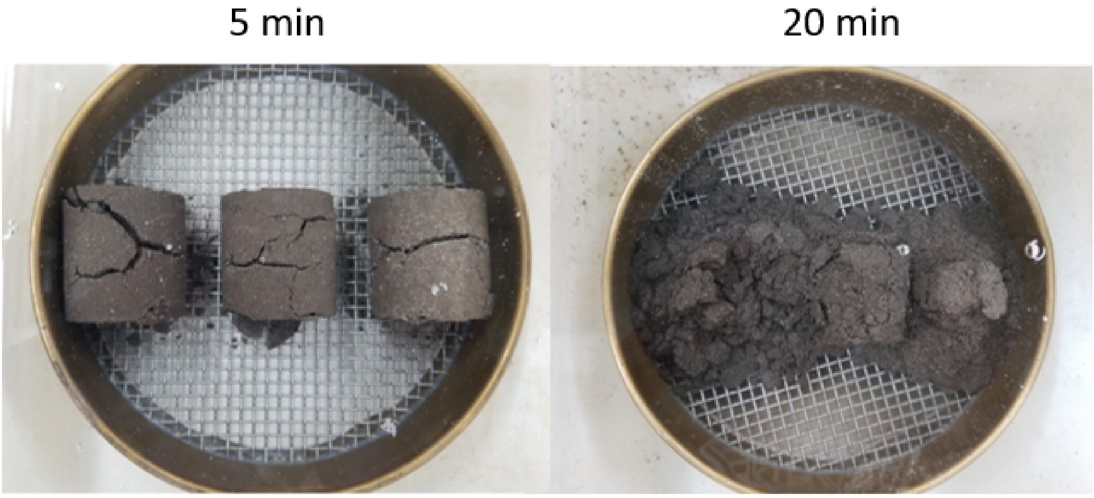


Figure 7 Slaking test for 2-by-2 specimens of Washington existing surface aggregate mixing 7% clay slurry

2.2 Field Tests

The field tests performed to determine the in-situ moisture content, surface course density, surface quality, elastic modulus and the shear strength of the surface and subgrade layers are presented in the following sections. Light Weight Deflectometer (LWD), Falling Weight Deflectometer (FWD), and Dynamic Cone Penetrometer (DCP) tests were conducted for investigation of the existing roadway materials prior to stabilization. Falling Weight Deflectometer (FWD), LWD, DCP, Dustometer, Nuclear Gauge and visual/photo surveys were conducted for the demonstration sections after construction.

2.2.1 Dynamic Cone Penetrometer (DCP) Tests

The dynamic cone penetrometer (DCP) test was conducted in accordance with ASTM D6951/D6951M – 18 “*Standard Test Method for Use of the Dynamic Cone Penetrometer in*

Shallow Pavement Applications" to determine the relative strength profiles via CBR correlations for the surface course and subgrade material of all demonstration sections. The DCP equipment used in this study follows the ASTM standard and was made by Kessler Soils Engineering Products (Figure 8). In the DCP test, the operator drives the DCP tip into the soil with an 8-kg [17.6-lb] sliding hammer and 20 mm [0.79 in] diameter disposable cones. The penetration distance measured per blow is referred to as the dynamic cone penetrometer index (DCPI).

Figure 8 Kessler K-1000 dynamic cone penetrometer

The DCPI values with units of millimeters per blow were measured for all demonstration sections and used in the empirical correlations of Equation 1 through 3 to estimate the in-situ CBR (referred to as DCP-CBR) values:

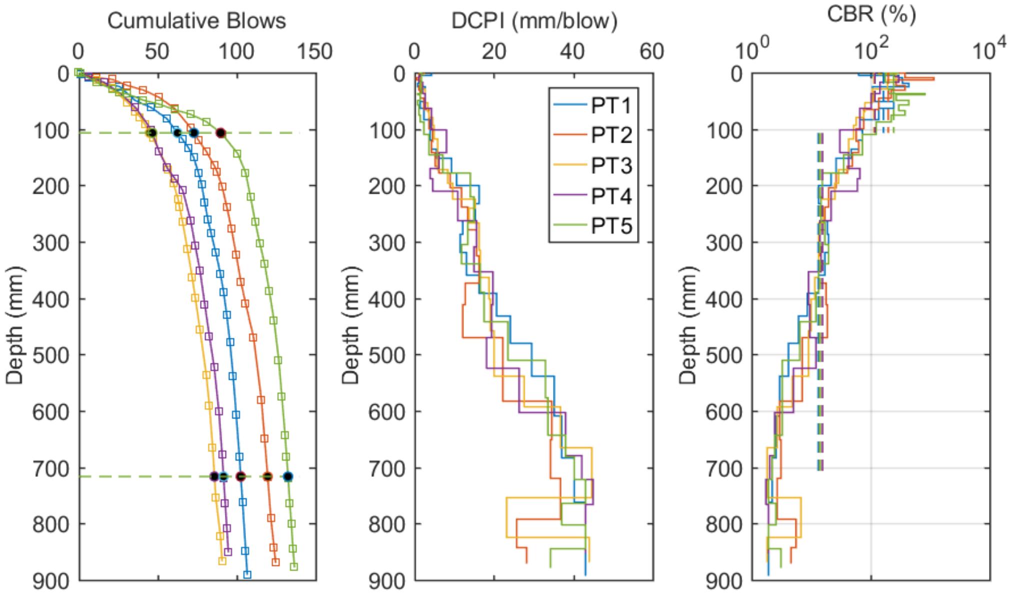
$for\ all\ soils\ except\ CL\ soils\ with\ CBR < 10\ and\ CH\ soils,$

$$DCP - CBR = 292/(DCPI)^{1.12} \tag{1}$$

$$for\ CL\ soils\ with\ CBR < 10, \quad DCP - CBR = 1/(0.017019 * DCPI)^2 \tag{2}$$

$$for\ CH\ soils, \quad DCP - CBR = 1/(0.002871 * DCPI) \tag{3}$$

All the demonstration sections built in this project were analyzed as two-layered systems, consisting of an aggregate surface layer and a subgrade layer. To determine the average DCP–CBR value for each layer, the boundary between the two layers was identified by a sharp change in the slope of the cumulative blows versus depth plot. An example of using the first criterion is shown in Figure 9.



(a) (b) (c)

Figure 9 Example of DCP depth profiles: a) cumulative blows b) DCPI and c) DCP–CBR

The weighted average DCP–CBR of the surface aggregate layer will be denoted as DCP–CBR$_{AGG}$, and the weighted DCP–CBR of the subgrade up to the maximum depth of interest (609.6 mm or 24 in.) will be denoted as DCP–CBR$_{AGG}$. The weighted average DCP–CBR for either layer can be calculated using Equation 4:

$$Weighted\ Average\ DCP - CBR\,\frac{(CBR_i * H_i)+(CBR_{i+1} * H_{i+1})+\cdots(CBR_n * H_n)}{\sum_i^n H_i} \qquad (4)$$

where H_i is the thickness of the i^{th} layer.

2.2.2 Falling Weight Deflectometer (FWD) Tests

The falling weight deflectometer (FWD) tests were performed by the Iowa DOT using a SN121 JILS FWD device shown in Figure 10. After a static load was applied, three dynamic loads 1,814 kg (4,000 lb), 2,268 kg (5,000 lb), and 2,721 kg (6,000 lb), were applied. The actual applied forces were recorded by a load cell, and geophones recorded the deflections of the roadway surface. A segmented loading plate was used to ensure a uniform stress distribution over the plate (Crovetti et al. 1989).

Figure 10 SN121 JILS falling weight deflectometer used in this study

According to the AASHTO Guide for Design of Pavement Structures (AASHTO 1993), the elastic moduli of the surface course and subgrade layer can be calculated using FWD test data. The AASHTO approach combines the Boussinesq theory (Boussinesq 1885) and Odemark’s method of equivalent layer thickness (MET) assumption (Odemark 1949) for calculating moduli of a two-layered system, and is based on the equivalent layer theory. The Boussinesq theory in the form of Equation 5 can be used to calculate stresses, strains, and deformations at a given radius and depth in a homogeneous linear elastic half-space, caused by a point load applied on the surface. The vertical surface deflection of a homogeneous layer material underneath the loading plate is calculated by integrating Boussinesq's solution over a circular area, giving Equation 6 since the FWD dynamic load was applied to a circular plate.

$$d_{r,z} = \frac{(1+v)F_{max}}{2\pi E\sqrt{z^2+r^2}}[2(1-v)+\frac{z^2}{z^2+r^2}] \tag{5}$$

$$d_{0,z} = \frac{(1+v^2)F_{max}f}{\pi aE}\frac{1}{\sqrt{1+(\frac{z}{R})^2}} \tag{6}$$

where the r is the radius from the point load; z is vertical depth from the point load; $d_{r,z}$ is the vertical deflection at radius r and depth z; E is elastic modulus; and F_{max} is maximum vertical force.

According to AASHTO (1993), for pavement systems, deflections measured at a sufficiently large distance from the load are considered to be independent of the size of the loading plate and caused only by subgrade deformation. Therefore, the elastic modulus of the subgrade (E_{FWD-SG}) can be calculated using a single deflection measurement as shown in Equation 7:

$$E_{FWD-SG} = \frac{(1-v^2)F_{max}}{\pi r d_{r,0}} \tag{7}$$

By converting the thickness of the top layer into an equivalent thickness (h_e) of additional subgrade material by Equation 8 below, the elastic modulus of the surface aggregate layer ($E_{FWD-AGG}$) can be determined according to that Odemark's assumption which is used to determine the deflection of a two-layer system under an applied load, where h_e is the equivalent single thickness of the two-layer system and h is the thickness of surface layer:

$$h_e = h^3\sqrt{\frac{E_{FWD-AGG}}{E_{FWD-SG}}} \tag{8}$$

The surface deflection should be measured at a distance greater than the effective radius (a_e) of the stress bulb at the interface of the top and bottom layers (AASHTO 1993):

$$a_e = \sqrt{[a^2 + (h^3 \sqrt{\frac{E_{FWD-AGG}}{E_{FWD-SG}}})^2]} \quad (9)$$

As the measurement distance increases, the magnitude of the deflection decreases, which increases the effects of measurement error in the calculated subgrade modulus. Based on a series of numerical analyses, AASHTO (1993) recommended that the deflection ($d_{r,0}$) used for calculating the subgrade modulus in Equation 9 be greater than or equal to $0.7a_e$.

Combining the Boussinesq theory and Odemark's assumption, the total surface deflection directly under the loading plate resulting from the deformation of both the top and bottom layers can be calculated using Equation 10.

$$d_{0,0} = \frac{(1-v^2)F_{max}f}{\pi a}\left\{\frac{1}{E_{FWD-SG}\sqrt{1+(\frac{h^3}{a}\sqrt{\frac{E_{FWD-GR}}{E_{FWD-SG}}})^2}} + \frac{[1-\frac{1}{\sqrt{1+(\frac{h}{a})^2}}]}{E_{FWD-GR}}\right\} \quad (10)$$

After matching the calculated deflection to the measured deflection under the loading plate, the surface layer elastic modulus ($E_{FWD-AGG}$) can be determined by using Equation 10.

2.2.3 Nuclear Density Gauge

To measure the in-situ density and moisture of the test section soil, the MC3 Elite nuclear density gage was used in accordance with ASTM D6938-17a "*Standard Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)*". These tests were performed by the Iowa DOT Office of Construction and Materials.

Figure 11 MC3 Elite nuclear density gauge

2.2.4 Light Weight Deflectometer (LWD) Tests

The light weight deflectometer (LWD) test was conducted in accordance with ASTM E2583-07 (Reapproved 2015) “*Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)*” to rapidly evaluate the composite elastic modulus of the test sections. The test involves dropping a falling weight on a buffer system that transmits the load pulse onto a circular loading plate on the road surface. The peak deflection of the ground surface is measured by an embedded accelerometer. The Zorn Model ZFG 3000 LWD device was used in this study (Figure 12). The manufacturer states that this device suitable for stiff cohesive soils, mixed soils, and coarse-grained soil with maximum particle size less than 63.5 mm (2.5 in.).

Figure 12 Zorn Model ZFG 3000 LWD device

Table 1 Dimensions of Zorn ZFG 3000 LWD device

Categories	Parameter	
Falling Weight	10 kg	22.05 lb
Drop Height	710 mm	27.95 in.
Maximum Applied Force	7.07 kN	1,589.4 lb
Total Load Pulse	18 ± 2 ms	
Measuring Range	0.2 to 30 (± 0.02) mm	0.0079 to 1.18 (± 0.00079) in.
Plate Diameter	300 mm	11.81 in.
Plate Thickness	20 mm	0.79 in.
Type of Buffer	Steel spring	
Deflection Transducer	Accelerometer in plate	

For each LWD test point, three seating drops were applied to improve contact between the loading plate and roadway surface, then three subsequent drops were applied for measuring the deflections. The applied force, F can be calculated by Equation 11, where m is the mass of the falling weight, g is the acceleration due to gravity (9.81 m/s^2), h is the drop height, and C is the spring material stiffness constant, equal to 362,396 N/m for this device:

$$F = \sqrt{2mghC} \tag{11}$$

Based on Boussinesq's solution (elasticity theory), the elastic modulus (E_{LWD}) can be calculated from the average peak deflection for the three pulses of subsequent drop loads using Equation 12.

$$E_{LWD} = \frac{(1-v^2)\sigma_0 a}{d_0} f \tag{12}$$

Where d_0 (mm) is the measured average peak deflection at the center of the loading plate; v is the Poisson's ratio (assumed to be 0.4); σ_0 (MPa) is the normalized applied peak stress; a (mm) is the radius of the plate; and f is a shape factor that depends on the assumed contact stress distribution (Table 2). The shape factor of 2 was assumed for the LWD tests, which corresponds to an inverse parabolic to uniform stress distribution and material with intermediate characteristics. The influence depth of an LWD test measurement is approximately equal to one or two times the diameter of its loading plate (Stamp et al. 2023).

Table 2 Summary of shape factors in elastic modulus estimation

(Terzaghi and Peck 1967; Fang 1991)

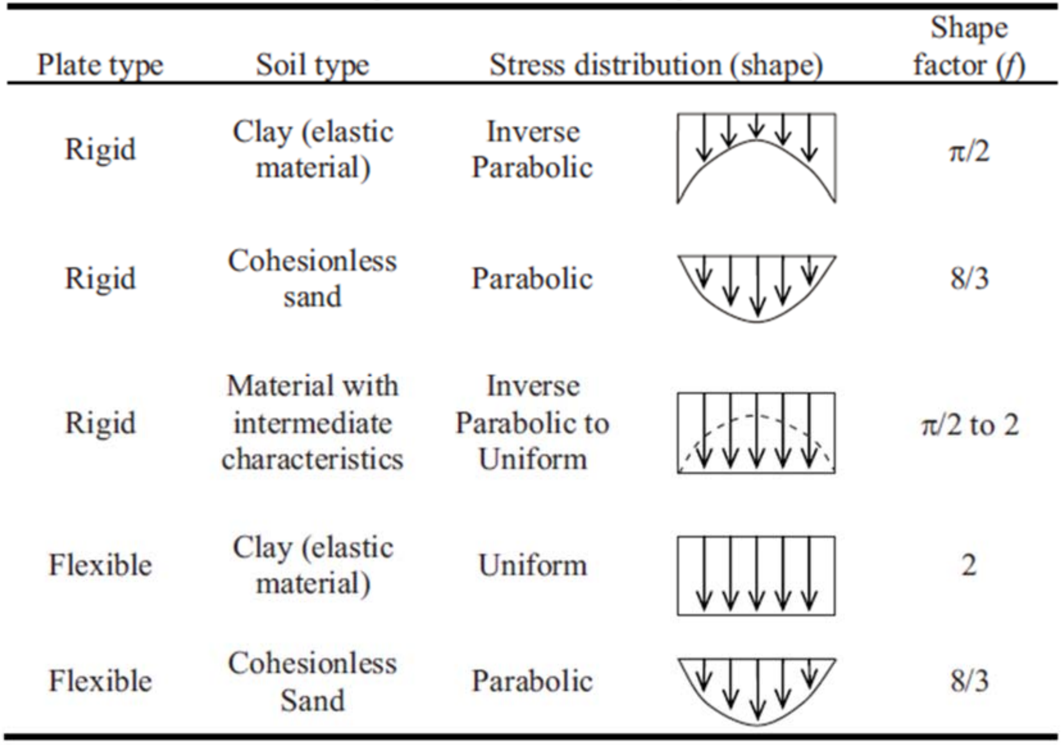


Plate type	Soil type	Stress distribution (shape)	Shape factor (*f*)
Rigid	Clay (elastic material)	Inverse Parabolic	π/2
Rigid	Cohesionless sand	Parabolic	8/3
Rigid	Material with intermediate characteristics	Inverse Parabolic to Uniform	π/2 to 2
Flexible	Clay (elastic material)	Uniform	2
Flexible	Cohesionless Sand	Parabolic	8/3

2.2.5 Dustometer

The dustometer device used to evaluate the fugitive dust emissions of the test sections was developed by Colorado State University (Sanders and Addo 2000). The dustometer device is a metal box attached to a pickup truck's rear bumper behind the rear-wheel as shown in Figure 13b. A 1/3-horsepower high-volume suction pump is attached to the metal box by 2 in. hose. The suction pump is powered by an electric generator. An 8 in. x 10 in. EMP 2000 glass microfiber filter paper was placed in the metal box for each test to catch the dust generated by the truck tires, and sucked up by the vacuum pump (Figure 13e and Figure 13f). The mass of the filter paper and dust was measured before and after each test to determine the mass of dust collected. The results were then converted to grams of dust per mile.

Figure 13 (a, b, and c): Dustometer test setup, (d): a test conducted on the granular-surfaced road test sections, (e): EMP 2000 glass microfiber filters, and (f): filter paper before and after test.

2.2.6 Visual Surveys with Photographs

Photographs of each test section's surface conditions were taken on the day of the DCP and LWD tests, and any surface distress such as rutting or potholes were noted. These visual surveys were conducted after test section construction and after periods of thawing and precipitation to assess the performance of the various control and stabilized sections. Condition rating reports for each test section were also distributed to the motor grader operators, and they were asked to complete the forms and rate the surface conditions of the test sections when performing maintenance.

CHAPTER 3. MATERIALS

This chapter presents the sources, descriptions, and soil index properties of the various geomaterials used in this study. The types and sources of chemical stabilizers used are also discussed.

3.1 Geomaterials

The soil index properties and classifications of a total of 8 types of materials existing at the test sites prior to construction are summarized in Table 3, including surface and subgrade materials collected from the test sites located in Cherokee, Howard, Hamilton and Washington counties. A total of 14 additional types of construction geomaterials from different quarries including road stone, clean aggregates, river rock, concrete stone, rubber tire chips, steel slag, and clay slurry were used in this study. The experimentally determined soil index properties and classifications of these geomaterials are summarized in Table 4.

Table 3 Soil index properties of the existing materials of test sections

Parameter	Cherokee Surface	Cherokee Subgrade	Howard Surface	Howard Subgrade	Hamilton Surface	Hamilton Subgrade	Washington Surface	Washington Subgrade
Particle-size Distribution Results (ASTM D6913)								
Gravel Content (%)	25.9	5.7	43.3	2.8	20.4	3.3	32.9	0.2
Sand Content (%)	58.4	36.8	37.6	34.9	56.3	33.0	29.4	5.4
Silt Content (%)	9.9	34.2	12.7	26.3	12.7	31.3	23.0	47.9
Clay Content (%)	5.8	23.3	6.2	36.0	10.6	21.4	14.7	46.5
D10 (mm)	0.0192	-	0.0123	-	0.0044	-	0.0022	-
D30 (mm)	0.3148	0.0114	0.3117	0.0024	0.1700	0.0038	0.0315	-
D60 (mm)	2.3251	0.1203	5.5170	0.0385	1.3814	0.0495	2.3741	0.0100
Coefficient of Uniformity, c_u	121.12	-	449.19	-	312.73	-	1064.27	-
Coefficient of Curvature, c_c	2.22	-	1.43	-	4.74	-	0.19	-
Atterberg Limits Test Results (Wasti 1987 & ASTM D4318-17)								
Liquid Limit (%)	NP	38	18	41	19	40	26	44
Plastic Limit (%)		18	13	19	14	18	16	20
AASHTO and USCS soil classification (ASTM D3282-17 & ASTM D2487-17)								
AASHTO Classification	A-1-b	A-6(9)	A-1-b	A-7-6(11)	A-1-b	A-6(12)	A-4(0)	A-7-6(24)
USCS Classification	SM	CL	GC-GM	CL	SC-SM	CL	GC	CL
Group Name	Silty sand with gravel	Sandy lean clay	Silty clayey gravel with sand	Sandy lean clay	Silty clayey sand with gravel	Sandy lean clay	Clayey gravel with sand	Lean clay

Table 4 Soil index properties of the quarry and byproducts used in this study

Parameter	Hamilton Grandgeorge Quarry, Road Stone	Hamilton Alden Quarry, 1" Road Stone	Hamilton Grandgeorge Quarry, 1" Clean	Cherokee DOT Quarry, River Rock	Cherokee Moore Quarry, Class A Road Stone	Cherokee Moore Quarry, D57 Concrete Stone	Howard County Dotzler Quarry, Class A
Particle-size Distribution Results (ASTM D6913)							
Gravel Content (%)	67.9	69.6	98.7	26.4	52.8	99.3	60.0
Sand Content (%)	25.2	24.4	1.3	70.6	34.6	0.3	25.0
Silt Content (%) Clay Content (%)	6.9	6.0	0.0	3.0	12.6	0.4	15.0
D10 (mm)	0.2823	0.2301	6.9029	0.4747	-	8.7655	-
D30 (mm)	4.2377	4.6672	10.1876	1.0562	1.8671	11.9182	2.7484
D60 (mm)	12.5800	11.9082	14.7346	2.6470	7.1321	15.7751	9.0070
Coefficient of Uniformity, c_u	44.56	51.74	2.13	5.58	-	1.80	-
Coefficient of Curvature, c_c	5.06	7.95	1.02	0.89	-	1.03	-
Atterberg Limits Test Results (Wasti 1987 & ASTM D4318-17)							
Liquid Limit (%) Plastic Limit (%)	NA	NA	NA	NA	NA	NA	NA
AASHTO and USCS soil classification (ASTM D3282-17 & ASTM D2487-17)							
AASHTO Classification	A-1-a	A-1-a	GP	A-1-b	A-1-a	A-1-a	A-1-a
USCS Classification	GP-GM	GP-GM	A-1-a	SP	GM	GP	GM
Group Name	Poorly graded gravel with silt and sand	Poorly graded gravel with silt and sand	Poorly graded gravel	Poorly graded sand with gravel	Silty gravel with sand	Poorly graded gravel	Silty gravel with sand

Table 4. (continued)

	Washington Conklin Quarry, 3/4" Class A Crushed Stone	Washington Conklin Quarry, 1" Road Stone	Liberty Tire Recycling, 7/8" Rubber Tire Chips	Liberty Tire Recycling, 3/8" Rubber Tire Chips	Phoenix 1" Steel Slag	Harsco ¾" Steel Slag	Pattison Clay Slurry
Particle-size Distribution Results (ASTM D6913)							
Gravel Content (%)	58.0	69.5	100.0	66.1	51.5	40.1	0.0
Sand Content (%)	31.6	19.4	0.0	33.9	44.9	54.7	0.0
Silt Content (%)	10.4	11.1	0.0	0.0	3.6	5.2[a]	55.2
Clay Content (%)							38.5
D10 (mm)	-	-	7.9857	3.1182	0.4928	0.2288	-
D30 (mm)	2.5144	4.5323	11.0930	4.5196	2.3204	1.3870	0.0021
D60 (mm)	8.8969	11.8516	14.2226	6.2466	6.8854	4.7628	0.0164
Coefficient of Uniformity, cu	-	-	1.78	2.00	13.97	20.81	-
Coefficient of Curvature, cc	-	-	1.08	1.05	1.59	1.76	-
Atterberg Limits Test Results (Wasti 1987 & ASTM D4318-17)							
Liquid Limit (%)	NA	NA	NA	NA	NA	NA	53
Plastic Limit (%)							22
AASHTO and USCS soil classification (ASTM D3282-17 & ASTM D2487-17)							
AASHTO Classification	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-7-6(32)
USCS Classification	GP-GM	GP-GM	GP	GP	GW	SW-SM	CH
Group Name	Poorly graded gravel with silt and sand	Poorly graded gravel with silt and sand	Poorly graded gravel	Poorly graded gravel with sand	Well-graded gravel with sand	Well-graded sand with silt and gravel	Fat clay

[a] Percentage shown includes both silt and clay content.

3.1.1 Existing Materials Collected from Test Sites

Representative samples of the existing surface aggregate and subgrade materials were collected from Vail Avenue between 300th Street and 310th Street in Hamilton County, Old 21 Road between 480th Street and 490th Street in Cherokee County, 100th Street between Pine Avenue and Quail Avenue in Howard County, and 260th Street between Palm Avenue and Quince Avenue in Washington County. The surface aggregate samples were collected in July 2018, and the subgrade material samples were collected in August 2017. Particle-size distribution and Atterberg limits tests were conducted on these eight types of materials to determine the soil index properties, which are shown in Table 3. The particle-size distribution curves of these materials are shown in Figure 14 and Figure 15. Because they had been deteriorated by traffic for some time, all of the existing surface materials fell outside the Iowa DOT granular surfacing materials specifications. The shaded area indicates the Iowa DOT specification for granular surfacing material Class A&B (4120) (Iowa DOT 2012).

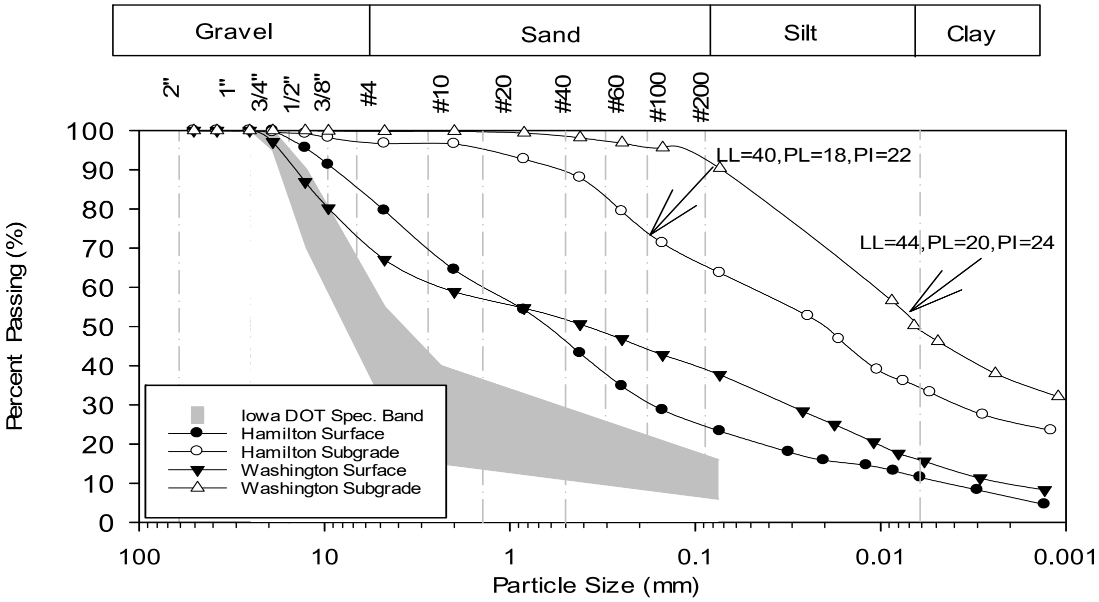


Figure 14 Particle size distribution curves of samples from Hamilton County and Washington County

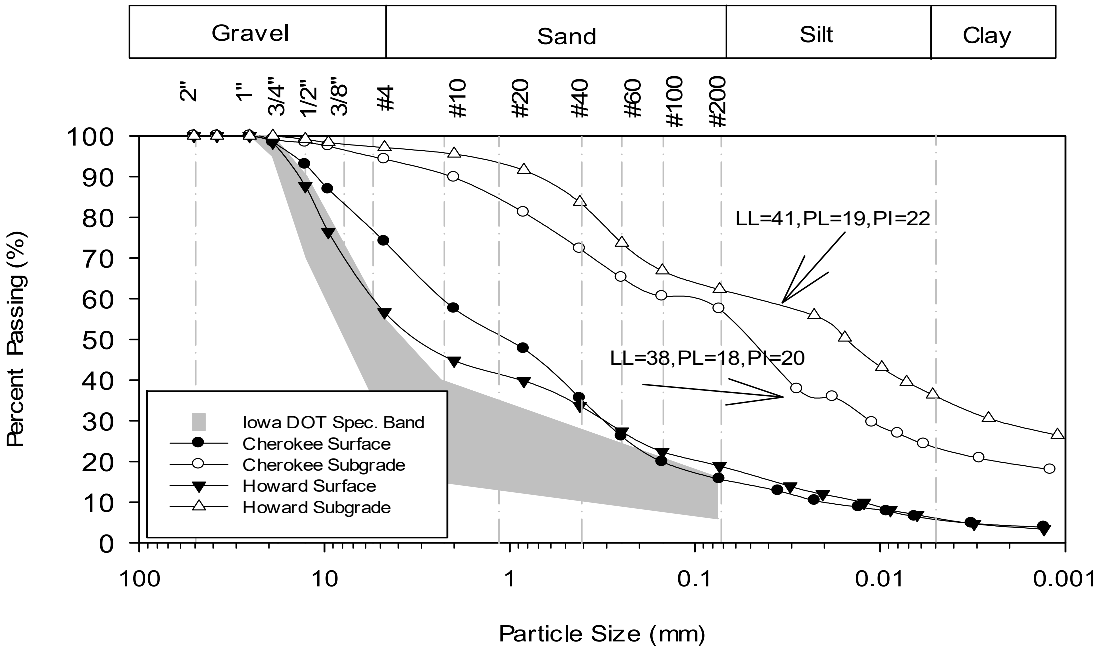


Figure 15 Particles size distribution curves of samples from Cherokee County and Howard County

3.1.2 Rubber Tire Chips, Steel Slag and Clay Slurry

The rubber tire chips used in this study were obtained from Liberty Tire Recycling LLC in Des Moines, IA. The Phoenix 1” steel slag was obtained from Phoenix Service LLC in Wilton, IA. The Harsco ¾” steel slag was obtained from Harsco Metals & Minerals. The Pattison clay slurry was obtained from Pattison Sand Company in Clayton, IA. Figure 16 shows 1 in. grid scaled photographs of samples of rubber tire chips and steel slag. The Pattison clay slurry is shown in Figure 17.

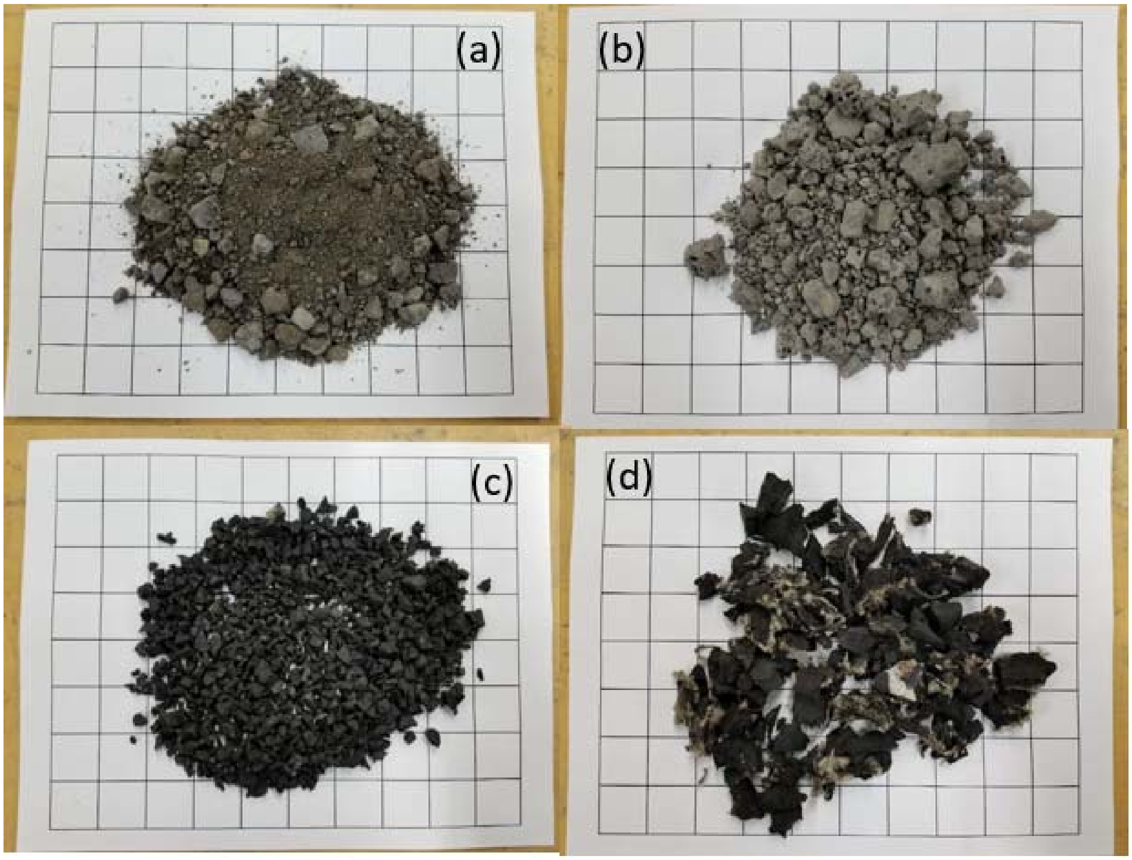


Figure 16 Sample of (a) Harsco3/4" steel slag, (b) Phoenix 1" steel slag, (c) 3/8" rubber tire chips, and (d) 7/8" rubber tire chips. Grid size = 1 in.

Figure 17 Pattison clay slurry

Table 5 shows the experimentally determined dry unit weight of the rubber tire chips and steel slag, optimum moisture content of the steel slag, and solids content of the clay slurry. The dry unit weights of the rubber tire chips and steel slag were determined using the standard proctor compaction test (ASTM D689-12e2). The solids content of the clay slurry was calculated as the mass of dry clay solids after completely oven drying at 50°C divided by the total slurry mass. The particle-size distribution curves for these materials are also shown in Figure 18. Both the Phoenix 1” steel slag and Harsco ¾” steel slag come close to meeting the Iowa DOT specifications (4120) (Iowa DOT 2012) for Class A&B granular surfacing material.

Table 5 Parameters of rubber tire chips, steel slag, and clay slurry

Parameter	7/8" Rubber Tire Chips	3/8" Rubber Tire Chips	Phoenix Steel Slag	Harsco Steel Slag	Pattison Clay Slurry
Dry Unit Weight (lb/ft^3)	46.6	46.6	144.5	153.0	-
Dry Unit Weight (kN/m^3)	7.3	7.3	22.7	24.0	-
O.M.C. [a] (%)	-	-	4%	9%	
Solids Content (%)	-	-	-	-	21%-29%

[a] Optimum Moisture Content

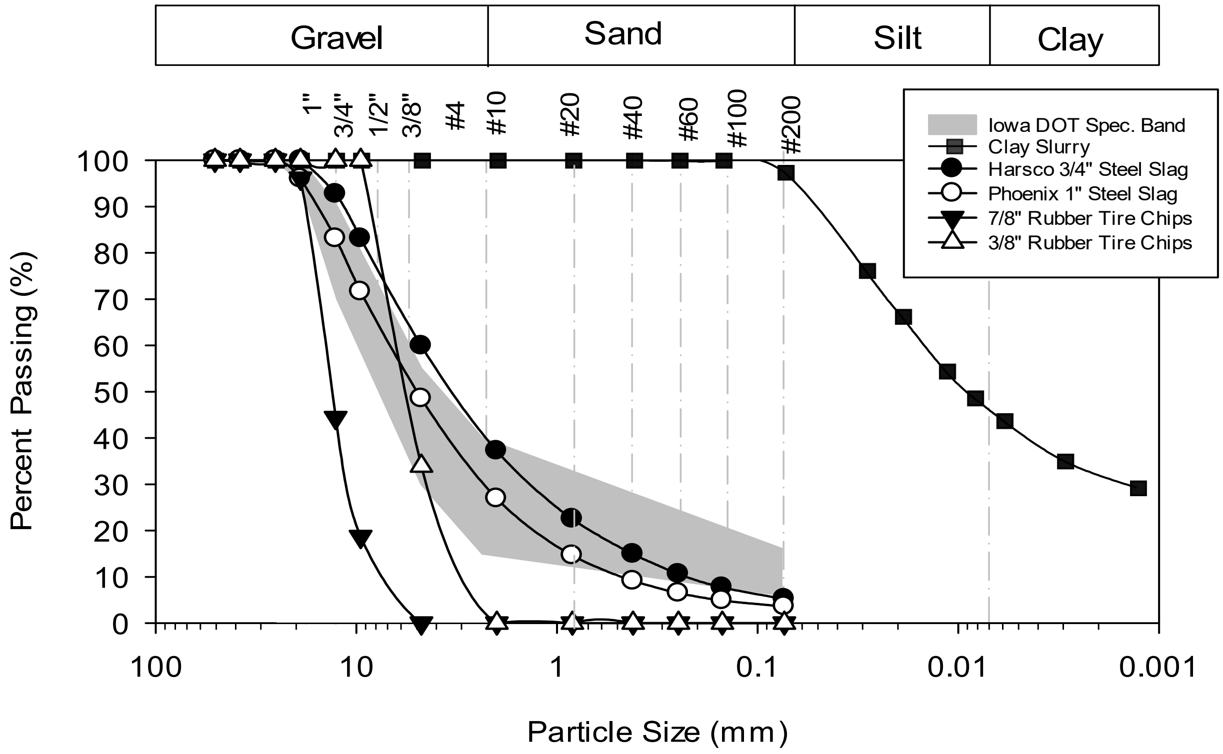


Figure 18 Particle-Size distribution curves of rubber tire chips, steel slag and clay slurry

3.1.3 Quarry Products and Recycled Asphalt Pavement

The quarry products used for the demonstration sections were purchased from the following sources: the Martin Marietta Grandgeorge and Alden quarries for the materials in Hamilton County, the River Products Conklin quarry for Washington County, the Dotzler quarry for Howard County, and the Martin Marietta Moore quarry and Cherokee County DOT quarry for Cherokee County. The recycled asphalt pavement (RAP) used for demonstration sections in Howard County and Cherokee County were obtained from the nearest sources to the test sites.

3.2 Chemical Stabilizers

Type I/II Portland cement, TeamLab T15 Base One, SSPCo EMC Squared (1000), and Claycrete were used to improve performance and durability of the granular surface materials in 5 test sections in Washington County and 3 test sections in Hamilton County. The proposed cement treated section in Hamilton County will be constructed in summer or fall of 2019. The details of these four chemical stabilizers are shown in Table 6.

Table 6 Sources of chemical stabilizers used in this study

Chemical Stabilizer Type	**Manufacturer**	**Source**
Type I/II cement	Ash Grove Cement Co	Des Moines, IA
TeamLab T15 Base One	Team Laboratory Chemical Corp.	Detroit Lakes, MN
SSPCo EMC Squared (1000)	Soil Stabilization Products Company, Inc.	Merced, CA
Claycrete	Claycrete North America	Sioux City, IA

The application rate of TeamLab T15 Base One was 0.005 gallons per square yard per inch of stabilized reclamation depth (see MNDOT specification of Figure 66 in Appendix). According to Jahren et al. (2011), the material to be stabilized with T15 Base One should have a binder (clay) content of 8 to 15%. The application rate of SSPCo EMC Squared (1000) was 0.067 gallons per cubic yard (SSPCo 2017). For Claycrete, the suggested application rate of 0.0404 gallons per cubic yard (Road Pavement Products PTY LTD 2017) was increased to 0.0505 gallons per cubic yard, since the additional 0.5 in. of subgrade blended in for adjusting the cation exchange capacity (CEC), was silty. A measure of the CEC can be estimated by multiplying the fraction of clay in the material by the PI, with both values given in percent. Claycrete is suitable for material having a clay fraction greater than 10% and PI greater than 7%, but is less predictable for soils having a CEC greater than 400. For the cement treated aggregate surface course in Washington County, an application rate of 7% Type I/II Portland cement by dry weight was used in the 4 in. granular surface layer, based on results of Henry et al. (2005). For the cement treated subgrade, an application rate of 5% Type I/II Portland cement by dry weight was used in the top 12 in. of subgrade.

CHAPTER 4. CONSTRUCTION SITE SELECTION

Four test locations were selected and built in Iowa to cover a range of different aggregate sources, subgrade soil types, and the weather conditions. These tests sites are built on (1) Vail Avenue between 300th Street and 310th Street in Hamilton County, (2) Old 21 Road between 480th Street and 490th Street in Cherokee County, (3) 100th Street between Pine Avenue and Quail Avenue in Howard County, and (4) 260th Street between Palm Avenue and Quince Avenue in Washington County. Sites in four different regions were selected to have similar annual average daily traffic (AADT), so each test section was subjected to same traffic load. The layout of test sections in maps along with the traffic flow maps (AADT maps per county) are provided in Appendix. Table 7 summarizes the location, AADT, length, and truck percentages of each test region.

Table 7 Test sites selection details

County	Road Section	Length (ft)	AADT	AADT Year	Trucks
Hamilton	Vail Avenue between 300th Street and 310th Street	2,733	100	2011	High
Cherokee	Old 21 Road between 480th Street and 490th Street	5,210	70	2011	-
Howard	100th Street between Pine Avenue and Quail Avenue	5,333	110	2013	High
Washington	260th Street between Palm Avenue and Quince Avenue	3,936	90	2011	High

CHAPTER 5. CONSTRUCTION METHODS

This chapter presents the details of construction procedures and dates for each demonstration test section. A total of 31 demonstration test sections were constructed and in four different regions of Iowa in this study. Test sections were built with 11 different stabilization methods. These include six mechanical stabilization (aggregate columns, optimized gradation with clay slurry, ground tire rubber, recycled asphalt pavement mixed 50/50 with aggregate, 2-in. slag surface above 2-in. existing aggregate base, 4-in. slag surface) and five chemical stabilization (12 in. Type I/II cement treated subgrade, 4 in. Type I/II cement treated aggregate surface course, TeamLab T15 Base One, SSPCo EMC Squared, Claycrete) methods. Mechanically stabilized test sections were built in Howard and Cherokee counties, while chemically stabilized test sections were built in Washington and Hamilton counties. Cement treated sections were only constructed in Washington County since the difficulty of construction, lack of necessary equipment and schedules conflicts in 2018. Additionally, two of the mechanical methods (optimized gradation with clay slurry and aggregate columns) were also used in Washington and Hamilton counties to assess the performance of these two economical methods in all regions. The pictures of each test section at the end of construction are attached in appendix.

Table 8 Types and locations of the 31 filed test sections used in this study

		Counties			
	Stabilization Method	Howard	Cherokee	Washington	Hamilton
	None (control section)	X	X	X	X
Mechanical	Aggregate columns	X	X	X	X
	Optimized gradation with clay slurry	X	X	X	X
	Ground tire rubber (eliminated)	X			
	Recycled Asphalt Pavement mixed 50/50 with aggregate	X	X		
	2-in. slag surface above 2-in. existing aggregate base (Harsco ¾” Steel Slag)	X	X		
	2-in. slag surface above 2-in. existing aggregate base (Phoenix 1” Steel Slag)	X	X		
	4-in. slag surface (Harsco ¾” Steel Slag)	X	X		
	4-in. slag surface (Phoenix 1” Steel Slag)	X	X		
Chemical	12-in. Type I/II cement treated subgrade			X	
	4-in. Type I/II cement treated aggregate surface course			X	X*
	TeamLab T15 Base One			X	X
	SSPCo EMC Squared			X	X
	Claycrete			X	X

X = Section constructed in this county. X* = Section will be constructed in this county.

5.1 Mechanically Stabilized Sections

The construction procedures of mechanically stabilized demonstration sections including optimized gradation with clay slurry, recycled asphalted pavement (RAP), two steel slag, and aggregate columns sections are explained in this chapter. The ground tire rubber section was eliminated from the list due to its lack of performance in Howard County after construction. It did not provide a stable roadway condition. The rubber tire chips could not bind with the traditional granular roadway aggregates yielding a very soft road. Figure 19 shows the schematic diagram of test sections built with mechanical stabilization methods in Howard and Cherokee counties. The 2” Phoenix steel slag section (Cherokee 5b) in Cherokee was shortened by 50 ft due to lack of steel slag material.

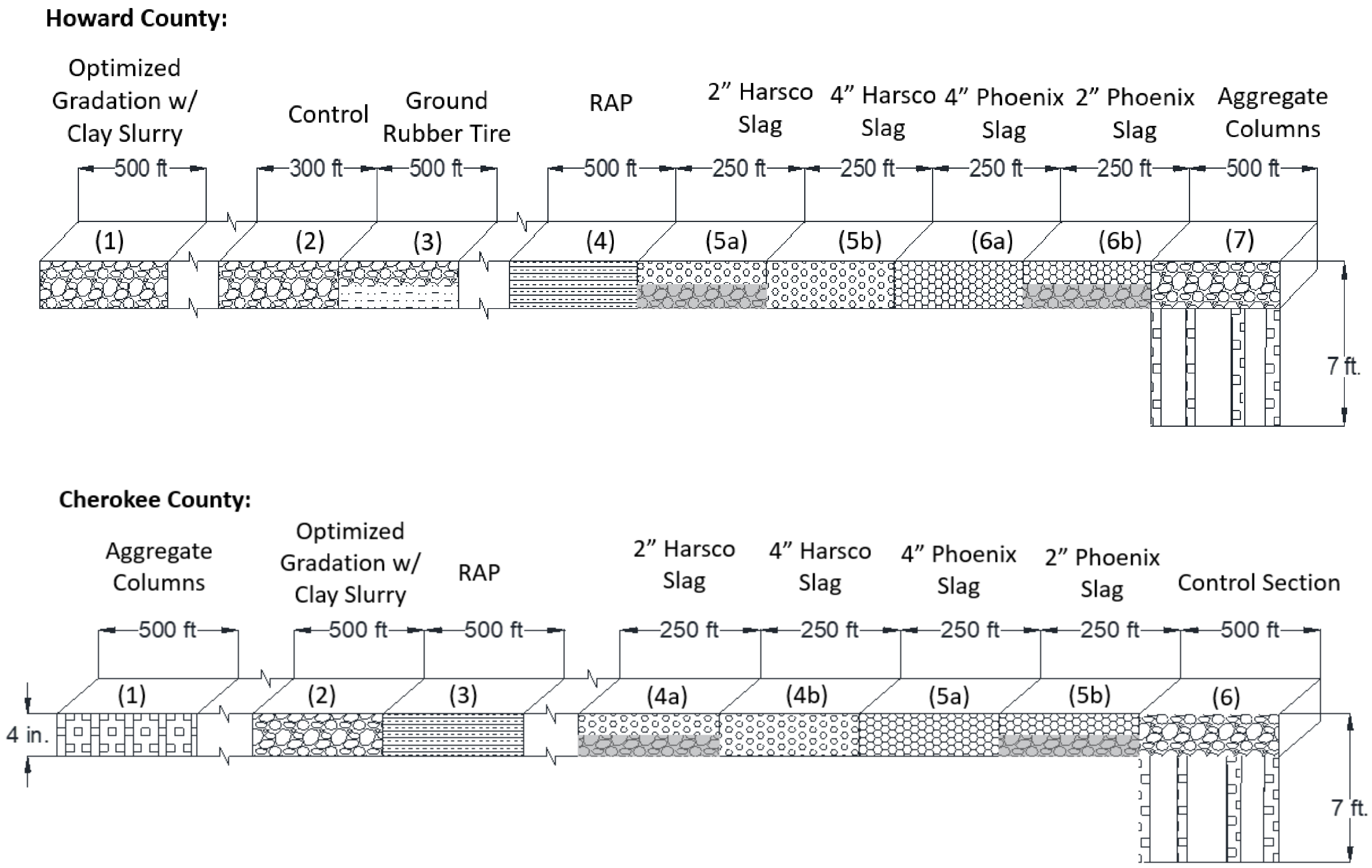


Figure 19 Mechanical stabilized demonstration sections in Howard and Cherokee Counties

5.1.1 Optimized Gradation with Clay Slurry

The optimized gradation with clay slurry sections were built via guidance provided in the final report of the IHRB project TR-685 and the related journal paper (Li et al. 2018). Accordingly, gradations of existing roadway surface materials and the potential quarry material were used to determine the optimum mixture proportions to calculate the tightest particle packing which supposedly provided the greatest strength. Based on the required quantities of each material were determined, a motor grader (Figure 20b) was used to rip the certain depth of existing material and mixed with the calculated amount virgin aggregates which was loaded on the roadway surface. Then the clay slurry was spread over the test section to increase its plasticity and aggregate binding capacity to reduce material loss. It was sprayed by a self-unloading tanker trailer with a custom-fabricated deflector plate (Figure 20g), (the tanker used in Cherokee county was different shown in Figure 21). After clay slurry application, the test section was bladed/mixed edge to edge with 10 to 15 grader passes. The top 2 inches of the surface aggregates were mainly blade-mixed with 0.155 gallons per square foot apply rate of clay slurry. The solid content of clay slurry was at the range of 25% to 35%. The water content was increased due to addition of clay slurry and it was adjusted where/when necessary. After blade mixing of the slurry and aggregates, a light cover of fresh dry aggregate (two truckloads spread over a 500 ft section) were applied to minimize the sticking of the wet mixture to the compaction equipment. Then, the clay slurry test section was compacted using the rubber tire roller (Figure 20f) (6 passes) and the smooth-drum vibratory roller (Figure 20d) (1 pass) for smoothening. The optimization spreadsheet used for calculations can be downloaded from the Project TR-685 final report webpage given in the references.

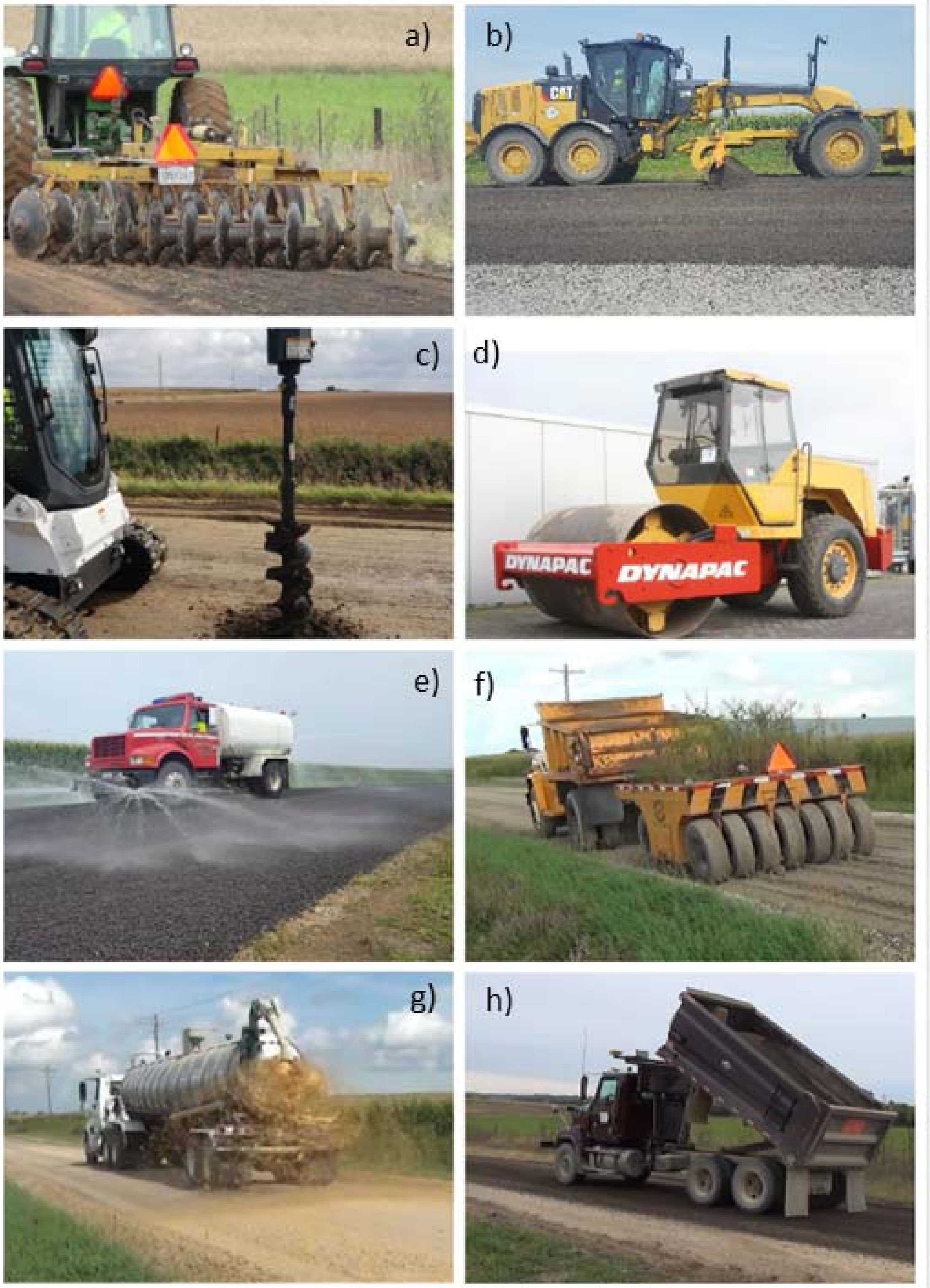


Figure 20 Equipment used for mechanically stabilized sections a) disk plow harrow b) motor grader c) power auger d) vibratory compactor e) water truck f) rubber tire roller g) self-unloading tanker trailer spraying clay slurry h) dump truck

Figure 21 Tanker used for spraying clay slurry in Cherokee County

The demonstration sections of optimized gradation with clay slurry method were constructed on August 16, 2018 in Howard County, September 27, 2018 in Cherokee County, August 23, 2018 in Washington County, and September 04, 2018 in Hamilton County.

5.1.2 Ground Tire Rubber Section

The rubber was placed in the bottom half of the layer to minimize its effect on reducing binding by fines in the surface layer. First used motor grader to rip and windrow existing surface aggregate to sides. Then dumped the ground tire rubber onto the subgrade surface and bring the windrowed surface aggregate back. Since there was only about 1 in. existing material can be used, another 75 tons fresh aggregate was added to ensure 2 in. base course. The aggregates and ground tire rubber were mixed by using motor grader (Figure 20b) and followed by 4 passes rubber tire roller (Figure 20f) and 2 passes drum roller (Figure 20d). The cover with 2 in. fresh aggregate and compacted using 4 passes of rubber tire roller and 4 passes of drum roller. Water was sprayed as needed to adjust the compaction water content to 8.5%. The ground tire rubber section in Howard county was finished on August 15, 2018.

5.1.3 RAP Sections

RAP sections were built using conventional granular roadway construction methods and blade-mixed using motor graders. First, top 2 inches of the locally existing material was ripped and windrowed via motor grader. It should be noted that some additional materials added to the RAP test section in Howard County since the thickness of the existing material in Howard County was less than 2 inches. Then, the RAP materials were spread onto the roadway surface and mixed with 2 inches existing aggregate by the motor grader. In Cherokee county, a disc plow harrow (Figure 20a) was also found effective for mixing the RAP and aggregate together. After mixing the RAP and aggregates uniformly, test sections were compacted using rubber tire roller first (6 passes) and the smooth-drum vibratory roller (1 pass) for smoothening. The water content was adjusted based on the laboratory compaction test results. The RAP section in Howard county was constructed on August 15, 2018 while it was built on September 27, 2018 in Cherokee County.

5.1.4 Steel Slag Sections

Steel slag sections were also built using conventional methods to the procedure used to build RAP sections. Steel slag was spread onto the road surface first and water was sprayed as needed. After steel slags were spread, the road surface was shaped via motor graders as needed. Then, test sections were compacted using rubber tire roller (6 passes) and at least four passes of the smooth-drum vibratory roller for finishing. For 2 in. Harsco steel slag section and 2 in. Phoenix slag section, at least 2 in. thick conventional aggregate layers was put under the steel slag layer to avoid having high amount of steel slag. In Cherokee County, the interface between roadway surface and subgrade was not clear, so the conventional aggregate layer under slag was thicker than 2 inches. Two Phoenix steel slag sections in Howard county were constructed on August 14, 2018, and two Harsco steel slag sections were constructed on August 15, 2018. Both

Phoenix steel slags and Harsco steel slag sections in Cherokee county were constructed on October 25, 2018.

5.1.5 Aggregate Columns sections

The aggregate column section in Howard County were built by following the pattern 1 (Figure 22) (each 100 square feet approximately have 1 column), since the roadway width was 40 ft, which was much wider than other three test locations (Washington County, Hamilton County, and Cherokee County). All other 3 aggregate columns sections followed the pattern 2 (Figure 22) (each 100 square feet approximately have 1 column). It was assumed that the void ratios of 0.56 and 0.25 for aggregate columns and roadway surface material, respectively (17.3 kN/m^3 [110 lb/c.f.] dry unit weight for the aggregate column material and 21.5kN/m^3 [136.8 lb/c.f.] dry unit weight for the roadway surface material). By using this assumption, 29.2% more voids of surface course can be provided for each 100 square feet roadway. The first step to build aggregate columns was to mark out the locations of the columns on a 10 ft grid as shown in Figure 22. Then, the columns were drilled to 7ft below the roadway surface via use of 12 inch diameter power auger as shown in Figure 20c. After drilling holes, columns were filled with clean aggregates which was poured via truck with conveyor or chute (Figure 23a). Since the subgrade soil was fully saturated and the groundwater table level was high (4ft below of ground surface) in Hamilton County, the hole collapse soon after the drilling and it was filled by clean aggregate right after the drilling. Spoil was removed with small skid-steer or other loader. After columns installed, the maintenance aggregate was spread when needed. The position of columns could be adjusted slightly if necessary when encountering utility lines. The demonstration sections of aggregate columns were constructed on August 15-16, 2018 in Howard county, September 27-28, 2018 in Cherokee county, August 21-23, 2018 in Washington county, and September 04-06, 2018 in Hamilton county.

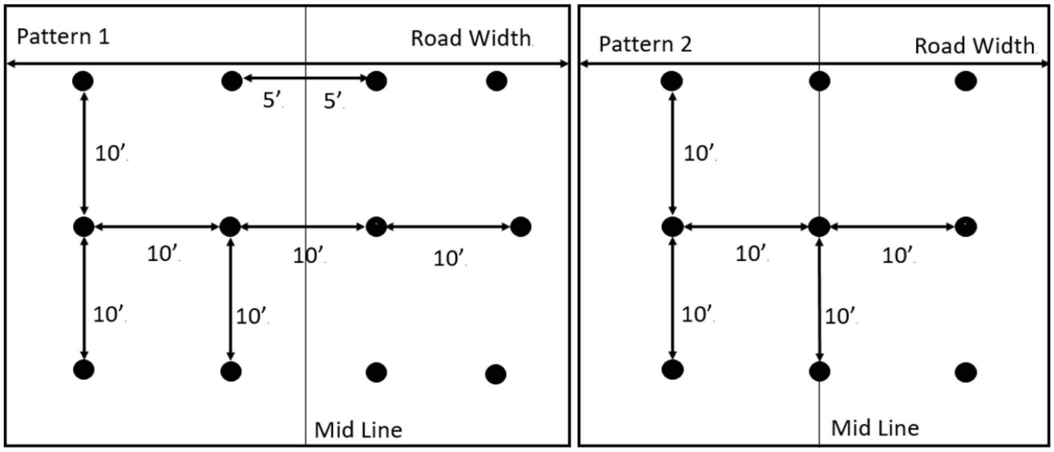


Figure 22 Aggregate columns layout pattern

Figure 23 (a) Fill column with clean aggregate by using dump truck with chute and (b) hole made by power auger

5.2 Chemically Stabilized Sections

The construction procedures of chemically stabilized test sections are described in this chapter. These sections include cement treated surface-subgrade, cement treated surface course, and three liquid stabilizers (TeamLab T15 Base One, SSPCo EMC Squared, Claycrete). The schematic diagram of the chemically stabilized demonstration sections in Washington and Hamilton counties are shown in Figure 24.

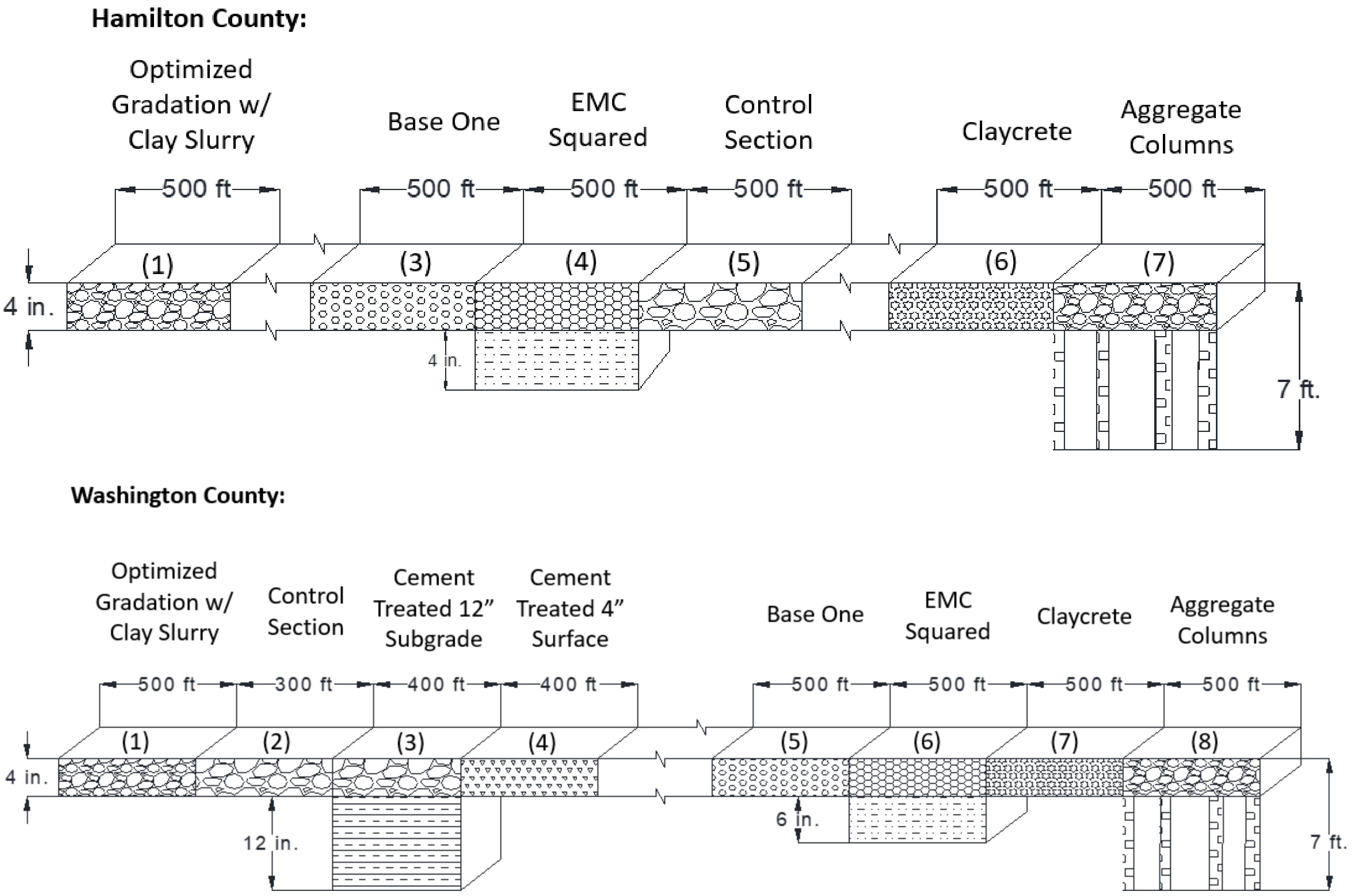


Figure 24 Chemically stabilized demonstration sections in Hamilton and Washington counties

5.2.1 12 inches Type I/II Cement Treated Subgrade Test Section

The cement treated 12 in. subgrade section was constructed by GeoMax, Inc. Before the cement application, the existing surface material was ripped and windrowed or stockpiled to stabilize the 304.8 mm (12 in.) subgrade. Then, the Portland cement (Type I/II) was spread on the road using a spreader truck (Figure 25e) and the subgrade soil was dry tilled with a reclaimer (Figure 25c) up to 304.8 mm (12 in.) deep. After tilling, the cement-subgrade soil mixture was compacted with padfoot drum roller with vibration and revised roller compactor without vibration (Figure 25d) (1 pass for each). Then all area was tilled again with spraying water at same time, and re-compacted immediately with vibratory padfoot roller compaction and reverse roller compactor without vibration. At least 12 passes were done during compaction process. Afterwards the cement-subgrade soil mixture surface was smoothened with drum roller (Figure 20d) the windrowed existing material was brought back to the roadway with motor grader. Finished with rubber tire roller (6 passes) and smooth roller compaction (1 pass with vibration and 1 pass without vibration). The demonstration section in Washington County was constructed on August 30, 2018, and the road was closed overnight.

5.2.2 4 inches Type I/II Cement Treated Aggregate Surface Course Test Section

The new aggregate was spread previously to ensure the thickness of surface course is 101.6 mm (4 in.). The GeoMax spreader truck was used to spread the cement uniformly on top of the aggregate road surface. Then, the cement and granular aggregate were mixed with the RoadHog which was calibrated to mix 101.6 mm (4 in.) below the roadway surface. The water truck accompanied with RoadHog to adjust the needed water content (7.5% optimal). After proper mixing, test sections were compacted with at least 4 passes using rubber tire roller followed by the vibratory roller for surface smoothening. The motor grader was also used during this period to shape the roadway surface. Finished by 1 pass drum roller without vibration. The demonstration section in Washington County was constructed on August 30, 2018, and the road was closed over a night.

5.2.3 SSPCo EMC Squared Stabilized Test Section

All of the liquid chemical stabilizers were mixed using a 60-in. wide RoadHog (Figure 25a) mounted on a Caterpillar 938M Wheel Loader and attached to a water truck (Figure 25b) by a hose system. For the EMC Squared test section, 152.4 mm (6 in.) subgrade was also treated. The existing surface course in Washington and Hamilton counties were slightly greater than 101.6 mm (4 in.), which was the targeted treatment thickness of surface course. The motor grader was used to windrow the surface course material to sides and RoadHog was used to till 152.4 mm (6 in.) subgrade afterwards (the treated subgrade depth in Hamilton county is 101.6 mm since boulder existing damages RoadHog and slows work). The 60% of EMC Squared liquid stabilizer was diluted in water truck to stabilize the subgrade. Then, the diluted EMC Squared solution was injected into the tilled subgrade soil (tilling achieved with RoadHog). The water content was adjusted as needed during construction (22% optimal). After uniform mixing of EMC Squared solution with subgrade soil, it was compacted using rubber tire roller (6 passes) followed by at least 4 passes of vibratory roller. Then, the windrowed surface material was moved back on the treated subgrade soil surface which was tilled again via RoadHog to 101.6 mm (4 in.) depth and mixed with the remaining (40%) EMC Squared solution. After uniform mixing process, the test section was compacted using rubber tire roller (6 passes) and vibratory roller (1 pass with vibration and 6 passes without vibration), and the roadway surface was shaped via motor grader. Since the three liquid stabilizers could have low viscosity in cold weather, it is important to get a smooth finished surface by using the smooth drum roller and tight blading.

Figure 25 Equipment used for chemically stabilized sections a) RoadHog reclaimer b) water truck with chemical stabilizer added to tank connected to RoadHog c) road reclaimer d) sheepsfoot vibratory compactor e) powder spreader truck

5.2.4 TeamLab T15 Base One (Base One) and Claycrete Test Sections

Both Base One and Claycrete need specific amount if fines content (particles <0.074 mm) to be effective stabilizers for granular roadway applications, they were mixed with 12.7 mm (0.5 in.) top subgrade soil. The RoadHog was calibrated down to 12.7 (0.5 in.) deeper than subgrade surface to achieve the most efficient treatment method for these stabilizers. During tilling, the RoadHog also incorporated these stabilizers into the subgrade and surface aggregate mixture. Then, test sections were compacted using rubber tire roller and vibratory roller, and shaped via motor grader. There is a little difference of construction procedures of Base One section and Claycrete section. For Base One, construction finished by rubber tire roller and then final motor grader blade. For Claycrete, finished by motor grader trim cut and then final roll with drum roller but no vibration. All three liquid chemical stabilizer sections were constructed on the same day on September 06, 2018 on Hamilton county and on August 30, 2018 on Washington county.

5.3 Control Sections

For all control sections in four counties, the existing road surfaces without any treatment were used as control sections. The maintenance rock was spread during the days of test sections construction to ensure 4 inches surface course thickness.

CHAPTER 6. RESULTS AND DISCUSSION

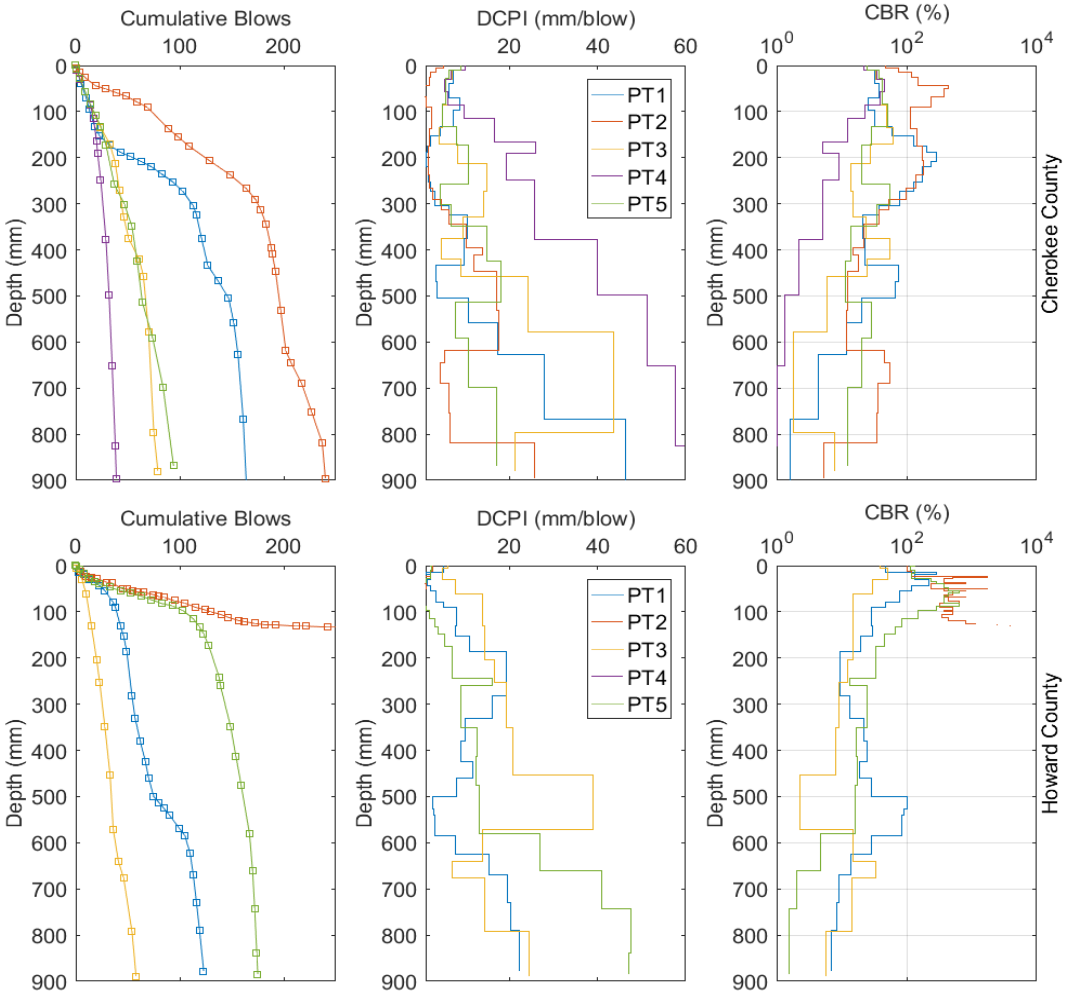
This chapter presents the results of field and laboratory tests conducted on existing roadway materials prior to stabilization and demonstration sections after they were built along with control sections.

6.1 In-situ Tests and Laboratory Tests Conducted Prior to Construction

Prior field and laboratory tests were conducted to evaluate the in-situ soil and existing granular aggregate materials conditions at construction sites. Dynamic cone penetrometer (DCP) and light weight deflectometer (LWD) tests were performed to determine the penetration resistance profiles and composite elastic modulus of the existing roadways. Unconfined compressive strength (UCS), California bearing ratio (CBR), and slaking tests were performed to evaluate the impact of mixing locally available granular aggregate materials with clay slurry.

6.1.1 Results of DCP and LWD Tests

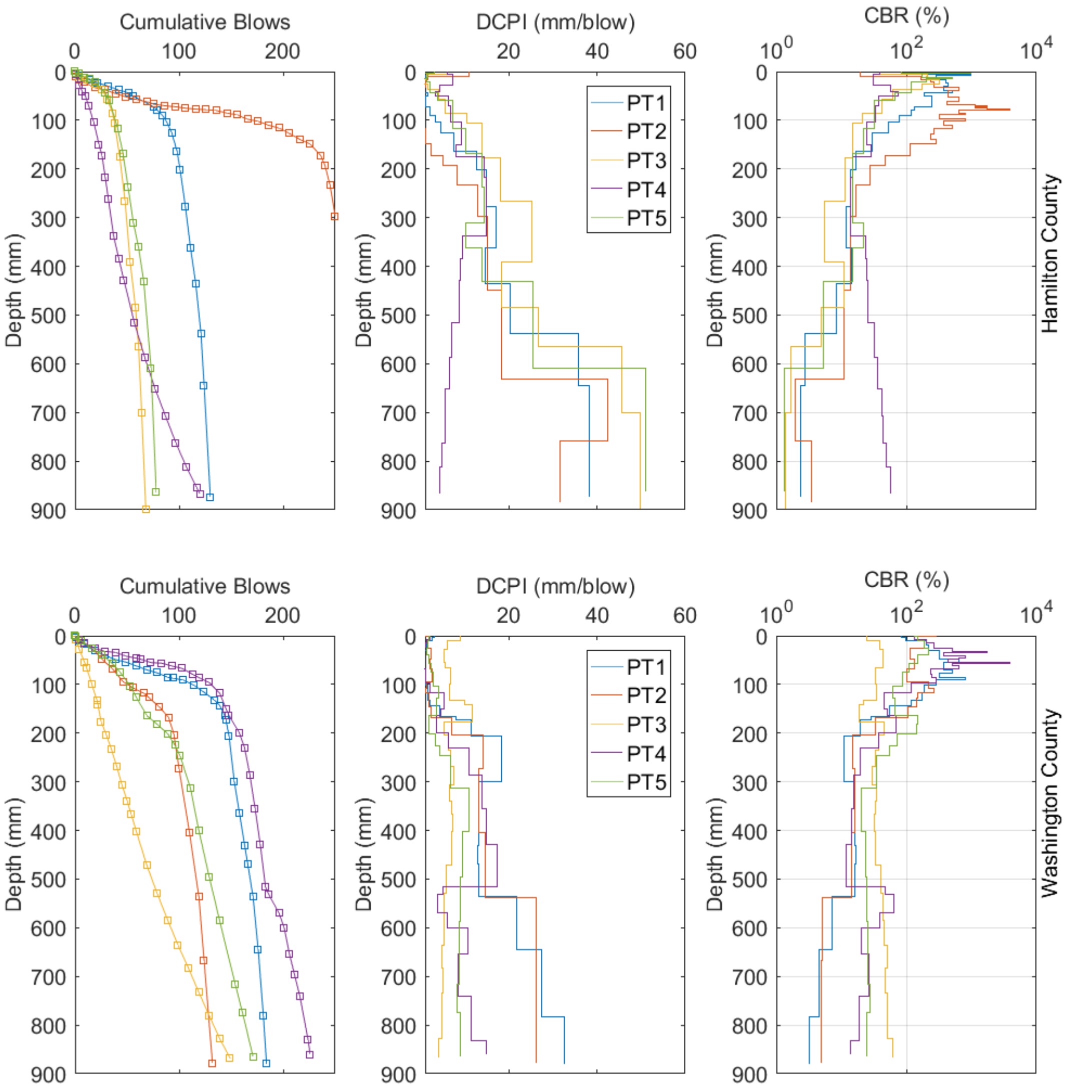
The DCP and LWD tests were performed on all four sites on August, 2017. For each site, five DCP tests were conducted to evaluate the in-situ DCP related CBR of surface course and the underlying subgrade to a depth of about 900 mm (36 in.). The nominal thickness of the surface course in four sites was also estimated based on the DCP data. The pre-construction DCP results for Cherokee County and Howard County are shown in Figure 26, which only include mechanical stabilization methods. The pre-construction DCP results of chemically stabilized counties, Washington County and Hamilton County are shown in Figure 27. In Cherokee county, there was no obvious interface between surface course and subgrade since the soil was gradually changing to subgrade form course aggregate. In Howard County, the surface course thickness was calculated to be in the range of 50.8 mm to 101.6 mm (2.0 to 4.0 in) (Figure 26).



(a) (b) (c)

Figure 26 Pre-construction DCP-CBR Results of Cherokee County and Howard County: a) cumulative blows b) DCPI and c) DCP-CBR

The thickness of surface course in Hamilton County was calculated to be in the range of 58.4 mm to 88.9 mm (2.3 to 3.5 in.). In Washington County, the surface course thickness was calculated to be around 101.6 mm (4.0 in). The detailed calculated surface course thickness and DCP-CBR values for the both surface aggregate layer (DCP-$\mathrm{CBR_{AGG}}$) and subgrade (DCP-$\mathrm{CBR_{SG}}$) are summarized in Table 9. The surface course in Cherokee was assumed as 101.6 mm (4.0 in.), which is the design thickness used for demonstration sections construction. The DCP-$\mathrm{CBR_{AGG}}$ in Howard, Hamilton, Washington counties are rated as excellent according to the relative CBR rating from Iowa SUDAS (2015). The SUDAS relative rating of Cherokee county course surface is good to very good since the result of test point 3 has large variation. The SUDAS relative rating of subgrade in Cherokee and Washington counties are very good. The SUDAS relative rating of subgrade in Howard and Hamilton counties are fair to good. The pre-construction field condition during the in-situ testing for all sites were relatively dry and stable with no significant rutting. Figure 28 shows the DCP related CBR of surface course and subgrade of four main test sections.



(a) (b) (c)

Figure 27 Pre-construction DCP-CBR results of Hamilton County and Washington County: a) cumulative blows b) DCPI and c) DCP-CBR

Table 9 Summary of pre-construction DCP-CBR results of four main test sections

County Name	Test Point	Thickness of Surface Course (mm)	Thickness of Surface Course (in.)	DCP-CBR_{AGG} (%) / Rating[a]	Ave. DCP-CBR_{SG} (%) / Rating[b]
Cherokee	1	101.6	4.0	31.2 / G	61.5 / >VG
	2	101.6	4.0	204.8/ E	59.7 / >VG
	3	101.6	4.0	40.2 / G	20.3 / VG
	4	101.6	4.0	35.7 / G	5.2 / P-F
	5	101.6	4.0	41.4 / G	29.1 / VG
Average		101.6	4.0	70.7 / VG	35.2 / VG
Coefficient of Variation		0.0 %	0.0 %	106.3 %	70.4 %
Howard	1	78.0	3.1	122.5 / E	29.2 / VG
	2	Refusal	-	-	-
	3	58.9	2.3	39.0 / G	11.1 / F-G
	4	114.3	4.5	290.7 / E	17.1 / F-G
	5	Refusal	-	-	-
Average		83.7	3.3	150.7 / E	19.1 / F-G
Coefficient of Variation		33.6 %	33.6 %	85.1 %	48.2 %
Hamilton	1	86.89	3.4	279.9 / E	14.4 / F-G
	2	148.8	5.9	456.9 / E	19.8 / F-G
	3	56.9	2.2	151.1 / E	10.1 / F-G
	4	69.1	2.7	44.7 / G	28.0 / VG
	5	56.9	2.24	159.8 / E	15.4 / F-G
Average		83.7	3.3	218.5 / E	17.5 / F-G
Coefficient of Variation		45.9 %	45.9 %	71.9 %	38.7 %
Washington	1	140.0	5.5	290.9 / E	14.2 / F-G
	2	9450	3.7	132.5 / E	34.1 / >VG
	3	98.8	3.9	38.0 / G	40.1 / >VG
	4	95.0	3.7	420.1 / E	32.4 / >VG
	5	101.1	4.0	140.5 / E	40.2 / >VG
Average		106.0	4.2	204.4 / E	32.2 / > VG
Coefficient of Variation		18.1 %	18.1 %	73.8 %	33.2 %

[a] SUDAS relative rating of supporting strengths as function of CBR for subbase: E=Excellent, VG=Very Good, G=Good, <G=below Good; [b] SUDAS relative rating of supporting strengths as function of CBR for subgrade: >VG=greater than Very Good, VG=Very Good, F-G=Fair-good, P-F=Poor-fair, VP=Very Poor.

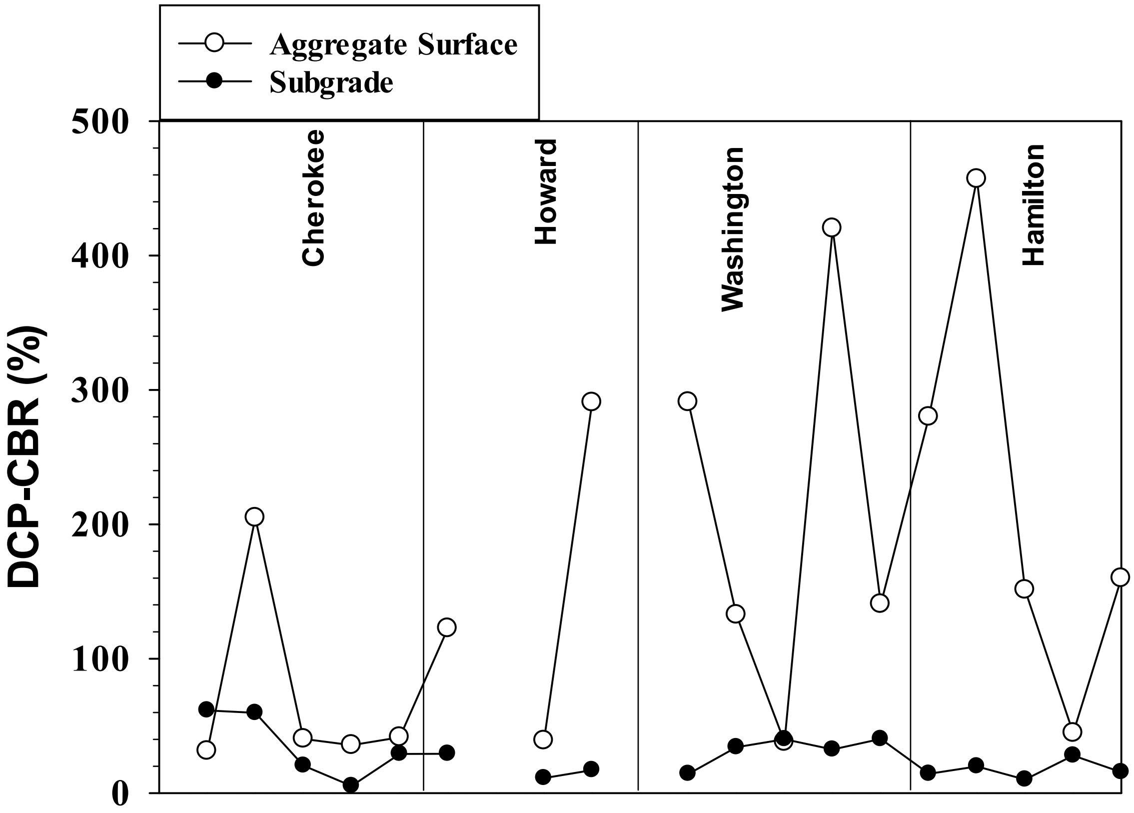


Figure 28 Pre-construction DCP-CBR results

LWD tests were also conducted on all four main test sections to determine their in-situ composite elastic modulus (E_{LWD}) as described in Section 3.2.4 above. The LWD test results are shown in Figure 29 and the average values of E_{LWD} are shown in Table 10.

Table 10 Summary of pre-construction LWD test results

	Cherokee	Howard	Washington	Hamilton
Average E_{LWD} (MPa)	75.1	84.7	68.3	76.1
Coefficient of Variation	20.2	21.3	24.5	15.2

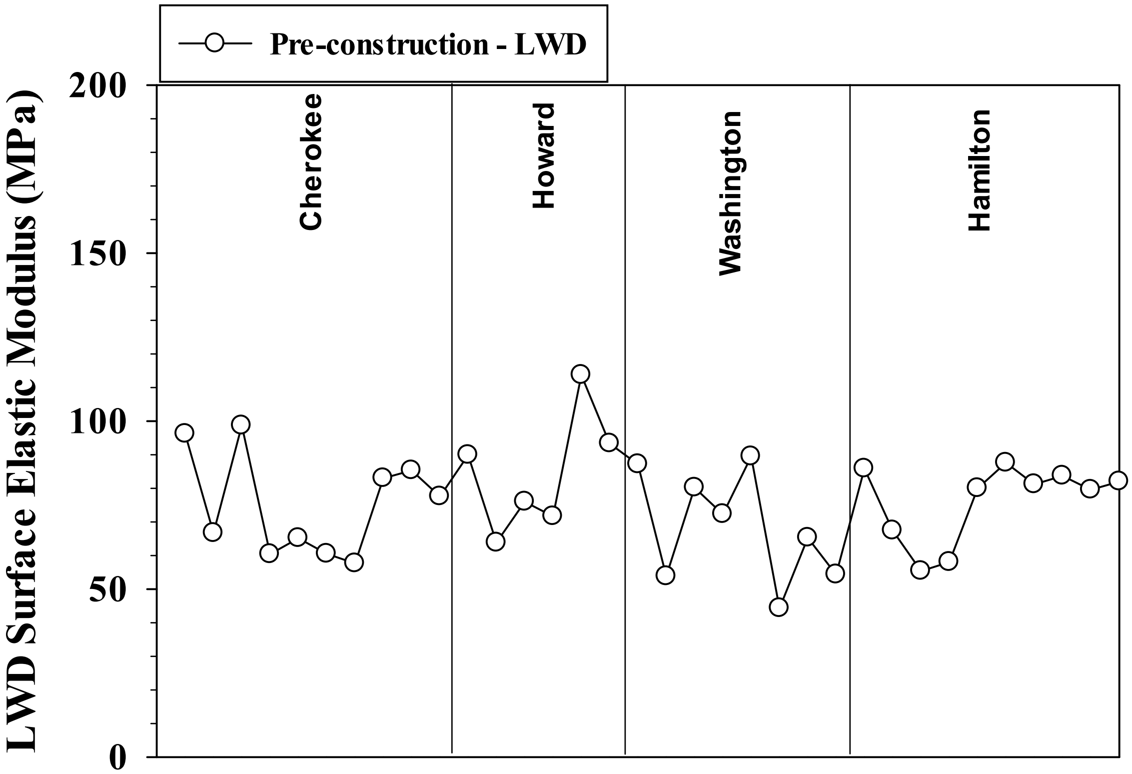


Figure 29 Pre-construction LWD results

6.1.2 Laboratory CBR and UCS Tests for the Clay Slurry Mixtures

To evaluate the impact of mixing clay slurry, CBR tests were conducted on the granular surface materials collected from the site in the Washington County that was mixed with 7% clay slurry solid by dry weight. 7% was selected for testing since it was expected that clay slurry was going to behave similar to standard Portland cement. It is very well known that recommended cement content for soil stabilization ranges from 2% to 10% by weight (Mahedi et al. 2018). CBR specimens were prepared at their corresponding optimum moisture content (OMC) per the laboratory standard Proctor tests results and soaked for more than 24 hours for saturation. The shear stress versus penetration depth for the CBR tests on the surface aggregate-7% clay slurry mixture is shown in Figure 30. Under 2 mm penetration, the penetration resistance of granular aggregate-clay slurry mixture was slightly lower, while at high penetration, the penetration resistance of non-treated surface aggregate material was 3 times higher than that of the surface aggregate-7% clay slurry mixture.

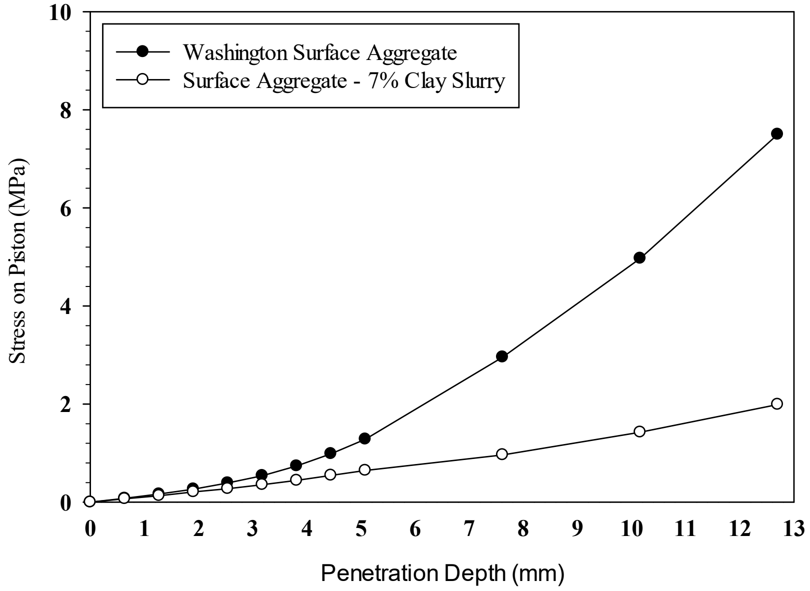


Figure 30 Uncorrected stress on piston versus penetration depth from CBR tests Washington surface aggregate only and 7% clay slurry mixing

For each specimen, the laboratory CBR value, dry unit weight, and moisture content before and after CBR testing are summarized in Table 11. With mixing the clay slurry, the CBR value of granular surface aggregates decreased considerably.

Table 11 Laboratory CBR test results for soaked specimens

Specimen	Dry Unit Weight (lb/ft^3)	Dry Unit Weight (KN/m^3)	As Compaction w (%)	Lab CBR (%)/Rating[a]
Washington Surface Aggregate	141.6	22.2	7.1	28.0/ <G
7% Clay Slurry Mixing	134.8	21.2	7.7	11.0/ <G

[a] SUDAS relative rating of supporting strengths as function of CBR for subbase: E=Excellent, VG=Very Good, G=Good, <G=below Good;

UCS tests were performed to 2 by 2 specimens of Washington surface aggregate only and surface aggregate-7% clay slurry mixtures to evaluate the impact of clay slurry on the shear strength. These specimens consist minus U.S. sieve No. 40 fractions of the materials and compacted at optimum moisture content determined by standard laboratory Proctor test (Section 3.1.3.1). Specimens were tested in both wet condition (as-compacted) and dry condition (oven dried). The UCS of Washington surface aggregate had the average value of 0.10 MPa in wet condition and 2.24 MPa in dry condition, while the average UCS of the surface aggregate-7% clay slurry mixture was 0.23 MPa in wet condition and 5.86 MPa in dry condition (Figure 31). Results showed that the unconfined compressive strength of surface aggregate-7% clay slurry mixtures specimens increased 130% in wet condition and 160% in dry condition. Slaking tests were also conducted to 2 by 2 specimens of Washington surface aggregate only and 7 surface aggregate-7% clay slurry mixtures, and the results are summarized in Table 12. It was observed that surface aggregate-7% clay slurry mixtures had slower dissolution rate indicating that adding clay slurry increased the resistance of the local aggregate materials against dissolution.

Table 12 Slaking test results for Washington surface aggregate and 7% clay slurry mixture

Water Temperature (°C)	23.5	23.1	23.1	22.6
Specimen	Slaking Time (min)			
Washington Surface Aggregate	11.0	12.0	11.0	10.0
7% Clay Slurry Mixing	21.0	20.0	24.0	20.0

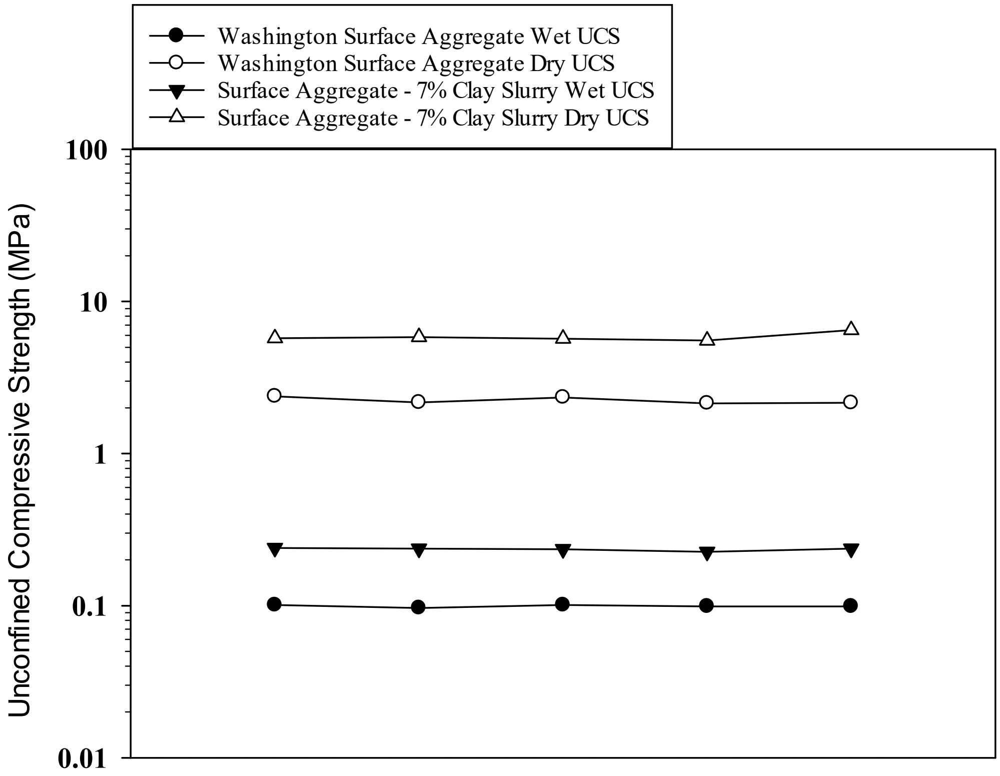


Figure 31 UCS test results for Washington surface aggregate and 7% clay slurry mixing

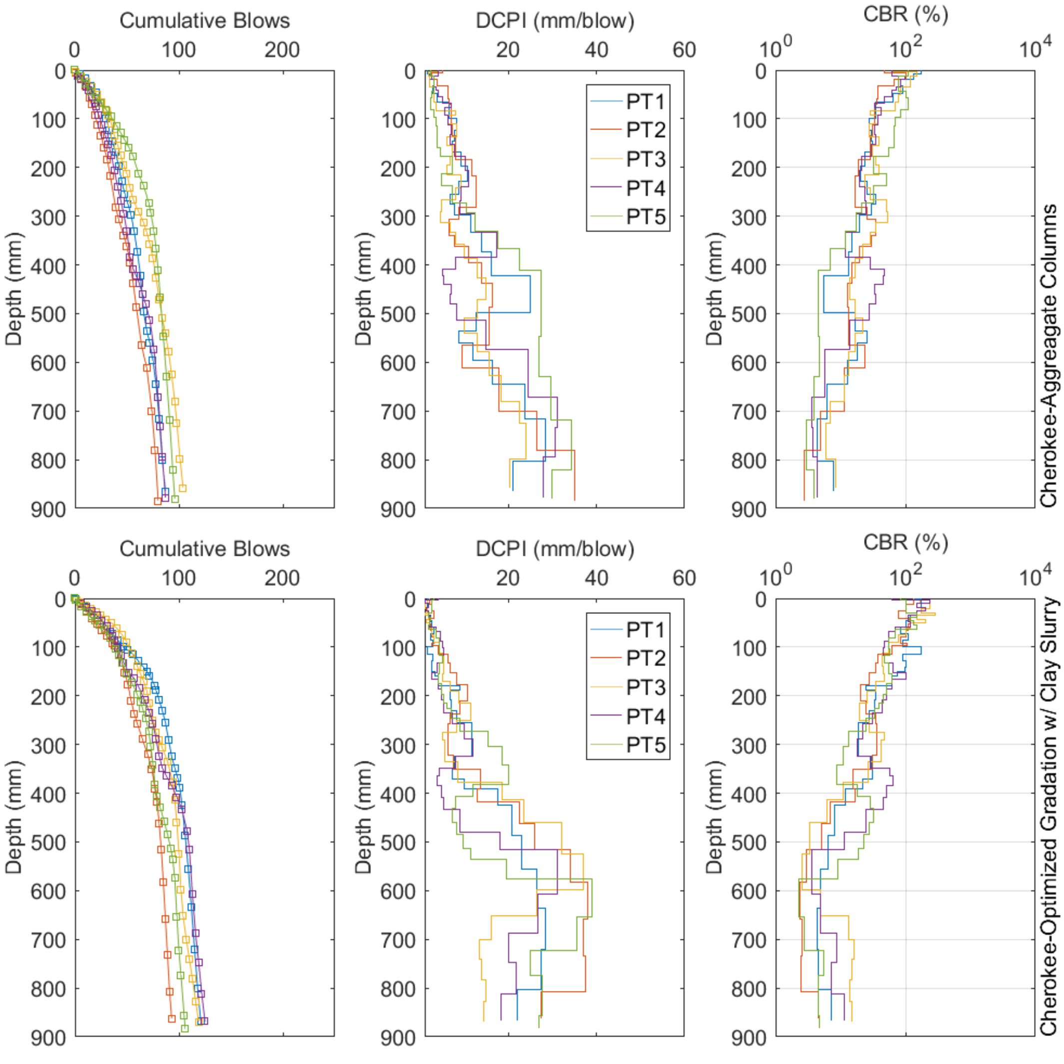
6.2 In-situ Tests and Laboratory Tests Conducted after Construction

Field and laboratory tests were conducted to evaluate the in-situ performance of test sections after construction. Dynamic cone penetrometer (DCP), light weight deflectometer (LWD), and falling weight deflectometer (FWD) tests were conducted on each test section to determine their strength and elastic modulus. Nuclear density gauge tests were performed to determine the in-situ density and moisture content of each section. The dustometer tests were also conducted to measure the fugitive dust emissions of the test sections. In addition, visual surveys were performed to determine and observe the failure on each test section. In terms of laboratory tests, sieve analysis, hydrometer tests, and Atterberg limits test were performed on both granular surface aggregate and subgrade soils collected from test sections during construction to monitor the particle size distribution and soil index properties.

6.2.1 DCP Test Results

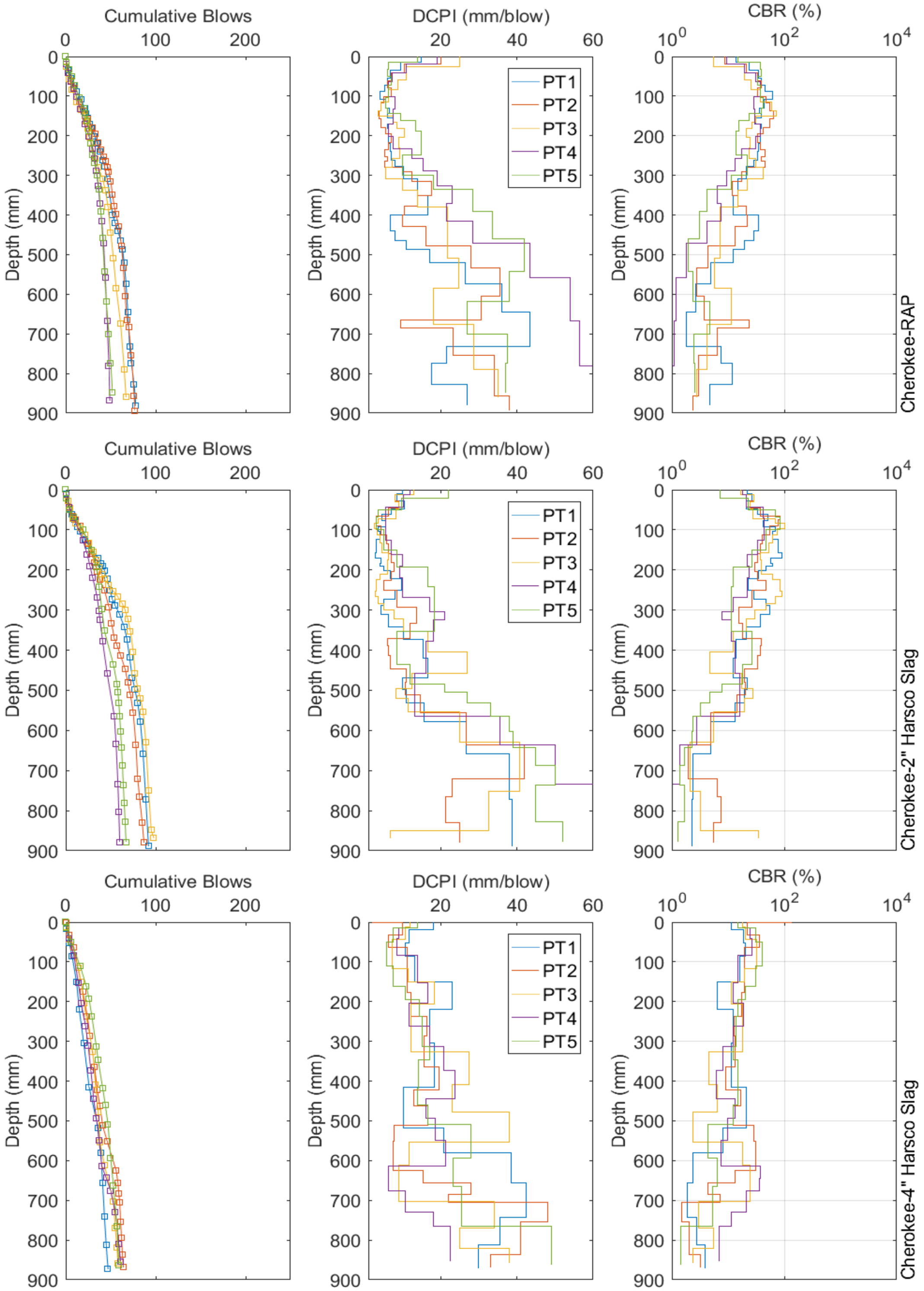
6.2.1.1 DCP Test Results for the Cherokee County Test Sections

The DCP tests in Cherokee County were conducted on November 08, 2018. Test sections included RAP, optimized gradation with clay slurry, and aggregate columns and all of which were constructed on September 27, 2018. On the other hand, the four steel slag sections were constructed on October 25, 2018 and they were set for 14 days before DCP tests were performed. The cumulative blows, DCPI, and DCP-CBR values versus depth for all sections of Cherokee County are shown in Figures 32-34. The DCP results could not identify clear interface between treated surface layer and subgrade layer. The surface thickness was set as 101 mm (4 in.) for average DCP-CBR analysis since there was no clear trend showed a clear difference between surface and subgrade layers as indicated previously. The trend of DCP-CBR of the RAP section and the four steel slag sections indicated that the 0 mm depth to 50 mm (2 in.) depth of surface layer were loose and had relatively low CBR value. The surface layer in the control section and the aggregate column section had relatively high uniformly DCP-CBR since the existing surface were not disturbed during the construction. The optimized gradation with clay slurry surface layer also had high DCP-CBR values throughout the section. The DCP-CBR with SUDAS rating of analyzed surface layer and subgrade layer, in-situ surface dry density, and in-situ moisture content are summarized in Table 13.



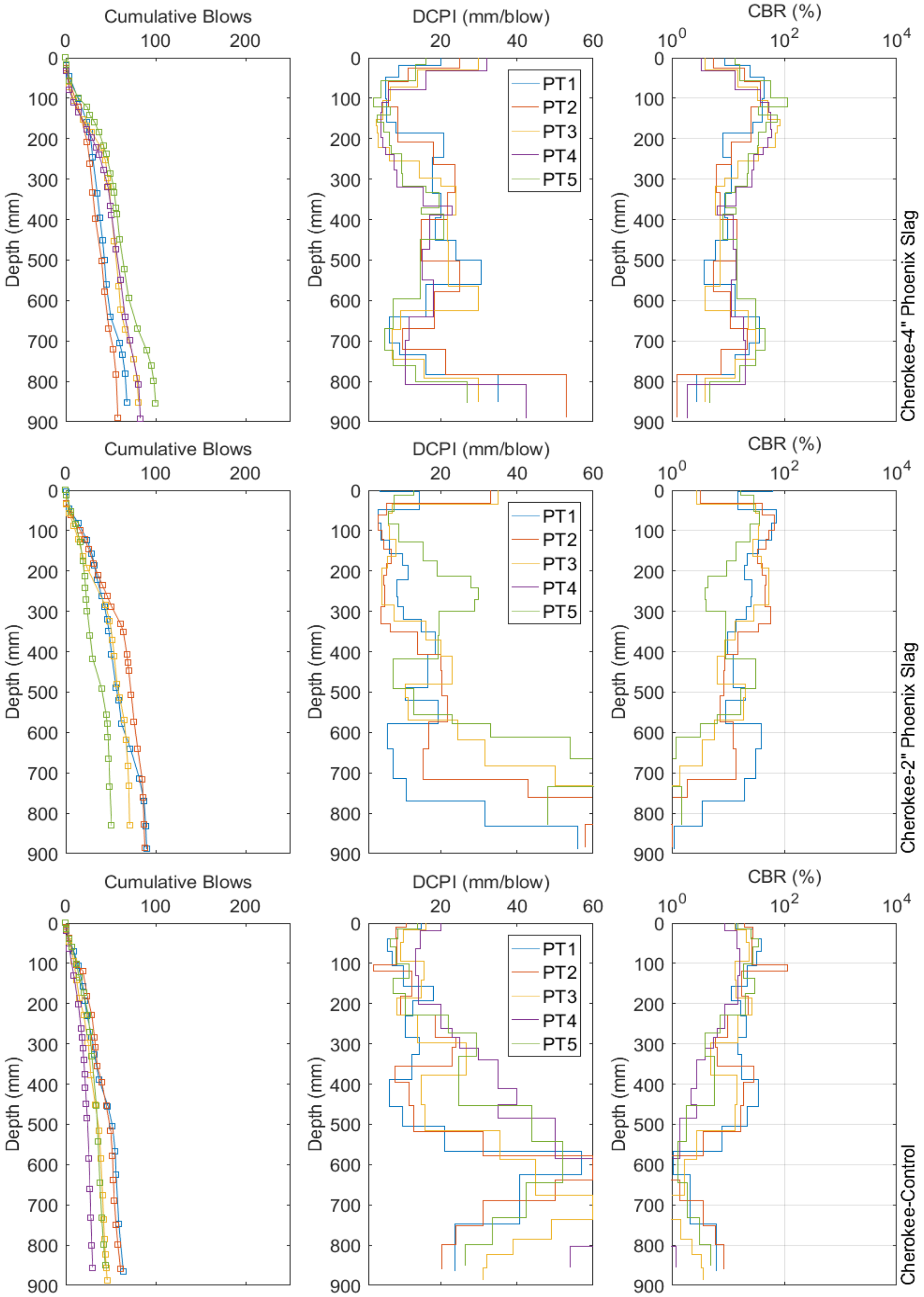
(a) (b) (c)

Figure 32 DCP test results for aggregate columns and optimized gradation w/ clay slurry sections in Cherokee County: a) cumulative blows b) DCPI and c) DCP-CBR



(a) (b) (c)

Figure 33 DCP test results for RAP, 4" Harsco slag, and 4" Harsco slag section in Cherokee county: a) cumulative blows b) DCPI and c) DCP-CBR



(a) (b) (c)

Figure 34 DCP test results for 4" Phoenix slag, 2" Phoenix slag, and control sections in Cherokee County: a) cumulative blows b) DCPI and c) DCP-CBR

Table 13 Summary of Cherokee demonstration sections: (1) DCP-CBR, (2) in-situ dry unit weight, and (3) in-situ moisture content

Section Name	Thickness of Surface Course		AVG Thickness		DCP CBR_{AGG}	AVG DCP-CBR_{AGG}/ Rating[a]	DCP-CBR_{SG}	AVG DCP-CBR_{SG}/ Rating[b]	In-situ Dry Unit Weight		In-situ Moisture Content	
	(mm)	(in.)	(mm)	(in.)	(%)	(%)	(%)	(%)	(lb/ft^3)	(KN/m^3)	(%)	AVG
(1) Aggregate Columns	101.0	4.0	101.0	4.0	76.3	72.4/ VG	17.6	19.9/ F-G	131.9	20.7	9.6	9.6
	101.0	4.0			48.7		20.6		140.2	22.0	9.6	
	101.0	4.0			84.9		23.1		128.5	20.2	9.8	
	101.0	4.0			59.2		20.1		130.6	20.5	10.1	
	101.0	4.0			93.0		18.0		132.0	20.7	8.9	
(2) Optimized Gradation w/ Pattison Clay Slurry	101.0	4.0	101.0	4.0	125.7	114.4/ E	24.8	22.5/ VG	128.6	20.2	8.9	7.1
	101.0	4.0			99.7		17.1		137.5	21.6	5.7	
	101.0	4.0			141.1		20.3		135.0	21.2	7.1	
	101.0	4.0			106.8		28.2		137.5	21.6	7.0	
	101.0	4.0			98.8		22.2		132.6	20.8	6.7	
(3) RAP	101.0	4.0	101.0	4.0	35.7	28.9/ <G	19.5	16.4/ F-G	116.7	18.3	9.8	9.8
	101.0	4.0			27.0		20.9		113.4	17.8	9.1	
	101.0	4.0			21.1		19.5		113.8	17.9	9.9	
	101.0	4.0			26.9		11.1		109.0	17.1	10.8	
	101.0	4.0			33.8		10.8		115.8	18.2	9.3	
(4a) 2" Harsco Slag	101.0	4.0	101.0	4.0	35.6	40.5/ G	27.0	21.1/ VG	135.7	21.3	6.9	6.8
	101.0	4.0			44.4		22.1		144.7	22.7	7.0	
	101.0	4.0			42.1		26.8		140.0	22.0	6.9	
	101.0	4.0			33.4		14.7		142.5	22.4	6.2	
	101.0	4.0			46.8		15.1		146.0	22.9	7.0	

Table 13. (continued)

	Thickness of Surface Course		AVG Thickness		DCP CBR$_{AGG}$	AVG DCP-CBR$_{AGG}$/ Rating[a]	DCP-CBR$_{SG}$	AVG DCP-CBR$_{SG}$/ Rating[b]	In-situ Dry Unit Weight		In-situ Moisture Content	
Section Name	(mm)	(in.)	(mm)	(in.)	(%)	(%)	(%)	(%)	(lb/ft^3)	(KN/m^3)	(%)	AVG
(4b) 4" Harsco Slag	101.0	4.0	101.0	4.0	17.6	25.6/ <G	10.7	13.7/ F-G	140.6	22.1	6.5	6.1
	101.0	4.0			27.9		16.7		137.5	21.6	6.1	
	101.0	4.0			26.8		13.7		141.9	22.3	6.1	
	101.0	4.0			22.6		14.4		144.9	22.8	6.1	
	101.0	4.0			33.3		12.9		141.0	22.1	5.7	
(5a) 4" Phoenix Slag	101.0	4.0	101.0	4.0	31.6	24.7/ <G	15.9	19.8/ F-G	164.7	25.9	3.6	3.6
	101.0	4.0			23.4		14.1		165.0	25.9	3.6	
	101.0	4.0			17.4		20.6		156.4	24.6	3.5	
	101.0	4.0			15.4		24.0		154.0	24.2	3.5	
	101.0	4.0			35.8		24.3		156.4	24.6	3.8	
(5b) 2" Phoenix Slag	101.0	4.0	101.0	4.0	44.8	34.1/ G	23.0	19.7/ F-G	157.8	24.8	4.5	5.7
	101.0	4.0			38.6		23.8		159.0	25.0	4.8	
	101.0	4.0			23.7		21.0		154.6	24.3	4.6	
	101.0	4.0			29.1		11.2		144.4	22.7	5.4	
(6) Control	101.0	4.0	101.0	4.0	30.3	23.6/ <G	15.2	10.6/ F-G	127.1	20.0	9.4	10.2
	101.0	4.0			26.3		15.0		130.3	20.5	9.9	
	101.0	4.0			20.5		10.0		129.3	20.3	10.2	
	101.0	4.0			13.9		5.1		131.4	20.6	10.4	
	101.0	4.0			26.9		7.6		133.2	20.9	10.1	

[a] SUDAS relative rating of supporting strengths as function of CBR for subbase: E=Excellent, VG=Very Good, G=Good, <G=below Good; [b] SUDAS relative rating of supporting strengths as function of CBR for subgrade: >VG=greater than Very Good, VG=Very Good, F-G=Fair-good, P-F=Poor-fair, VP=Very Poor.

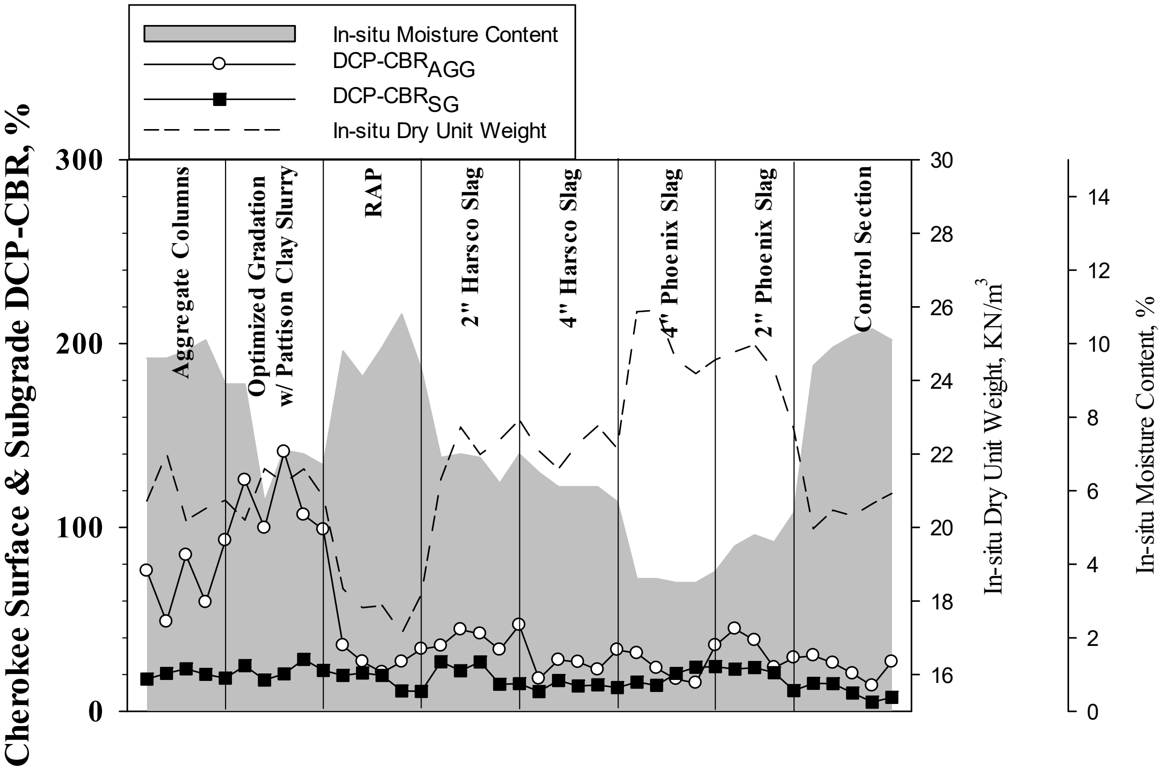


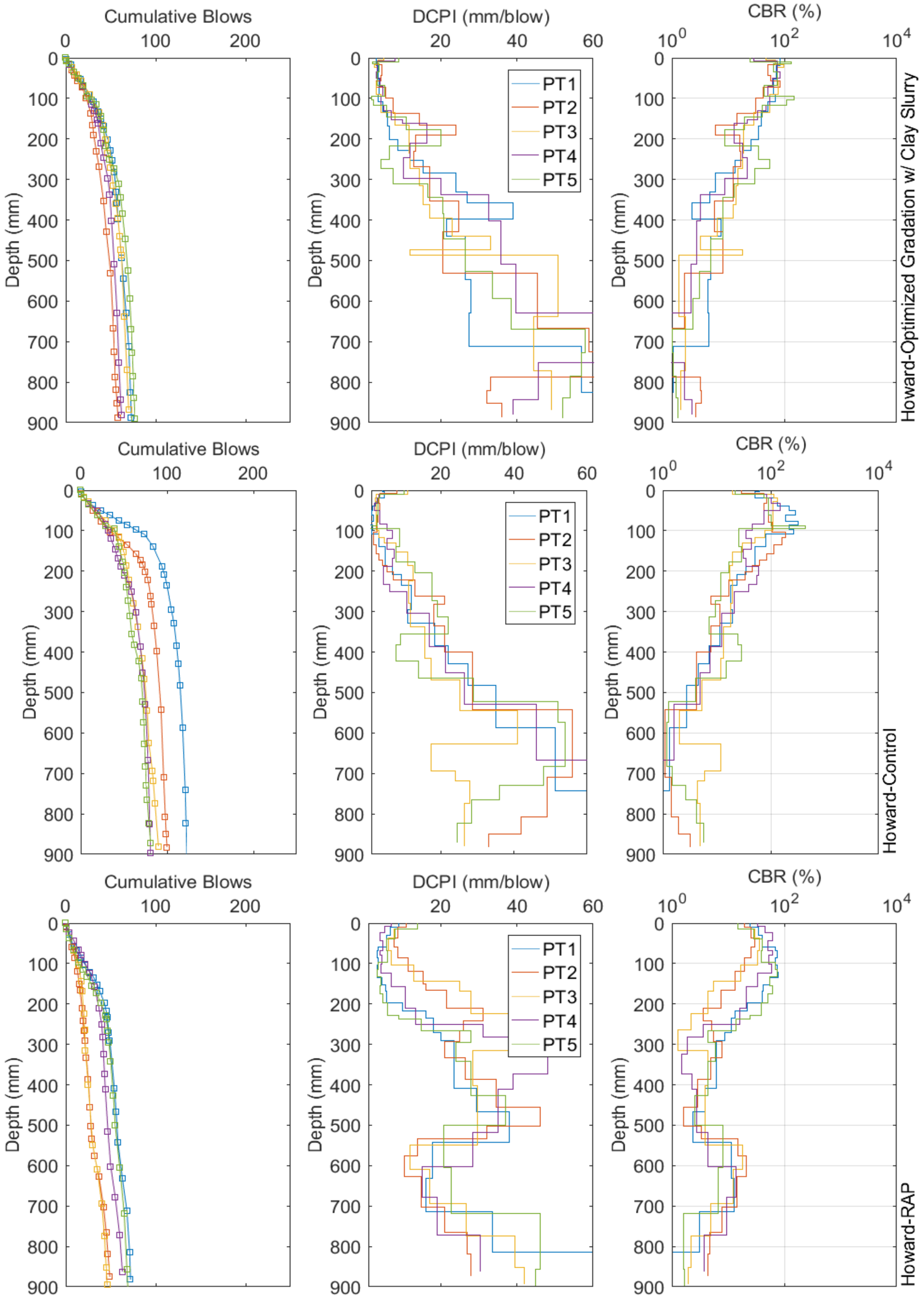
Figure 35 Cherokee demonstration sections: (1) DCP-CBR, (2) in-situ dry unit weight, and (3) in-situ moisture content

The optimized gradation with clay slurry section had the highest average DCP-CBR$_{AGG}$ value with the excellent SUDAS relative rating (SUDAS 2015). The DCP-CBR$_{AGG}$ of this section ranged from 98.8% to 141.1% with the 101 mm (4 in.) average thickness of surface course. The in-situ dry unit weight of the optimized gradation with clay slurry section was similar to the control section. The aggregate columns section had the similar value of in-situ dry unit weight and moisture content to control section, but the DCP-CBR$_{AGG}$ was higher than control section with the values in the range 48.7% to 93.0. The steel slag sections had higher in-situ dry unit weight since the steel slag materials had higher specific gravities than other geomaterials used in this study, and lower in-situ moisture content due to lower amount of fines content. The DCP-CBR$_{AGG}$ of 2” Harsco steel slag section and 2” Phoenix steel slag section have the SUDAS rating of good. But the SUDAS relative rating of average CBR-DCP$_{AGG}$ of other two

4” steel slag sections and RAP section were below good. The possible explanation for the status for these steel slag sections and the RAP section was that the surface layer was loose and the materials had not been bonded well yet. The CBR-DCP$_{SG}$ for all demonstration sections were higher than the subgrade of the control section. The average CBR-DCP$_{SG}$ for optimized gradation with clay slurry section, 2” Harsco steel slag section, aggregate columns section and Phoenix steel slag sections had relative higher values than those of others.

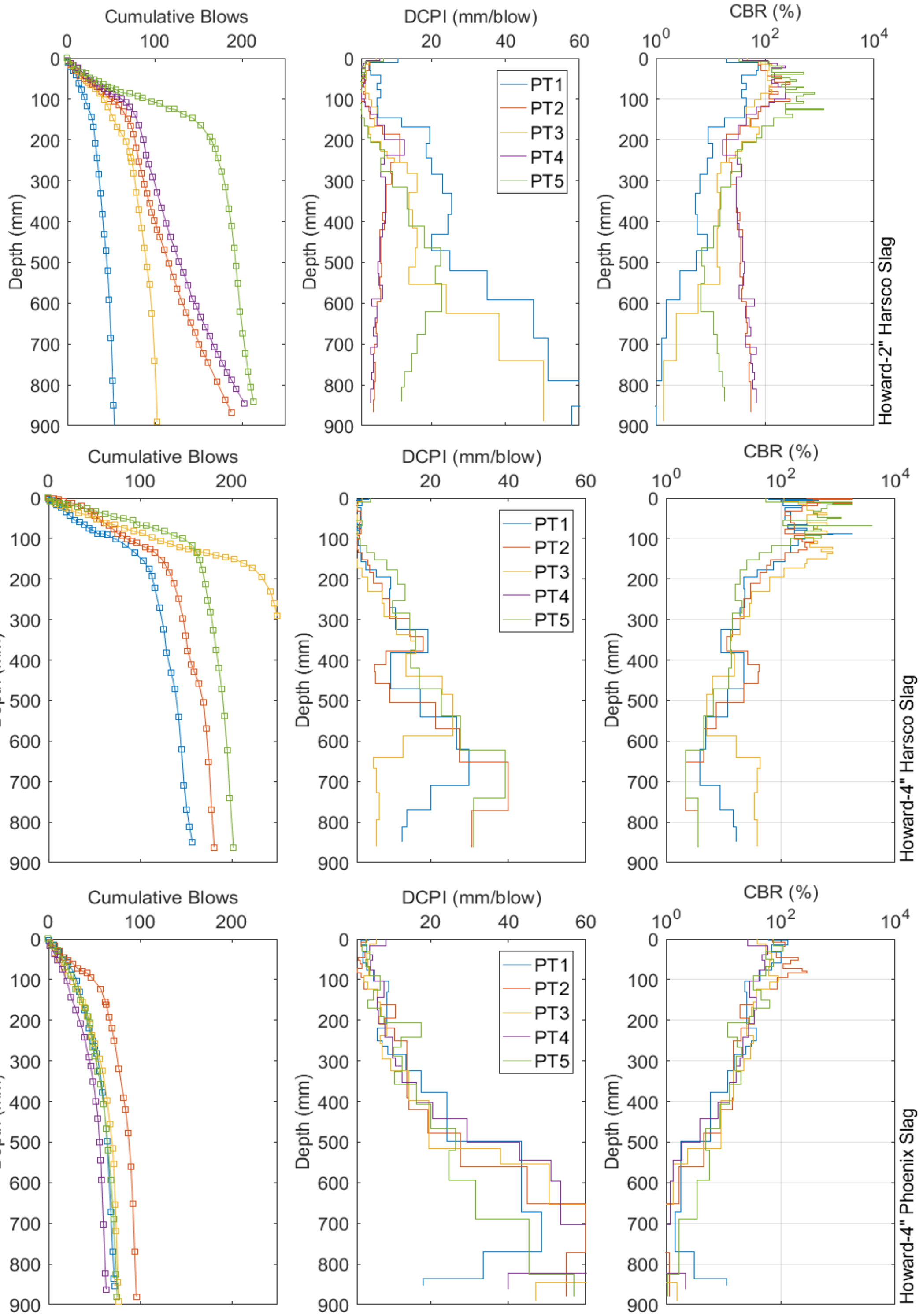
6.2.1.2 DCP Test Results of Howard Demonstration Sections

The DCP tests in Howard County were conducted on October 23, 2018. The construction of test section in Howard County was completed on August 16, 2018. The cumulative blows, DCPI, and DCP-CBR values versus depth for all sections of Howard County are shown in Figures 36-38. The DCP results of Howard test sections could identify clear interface between treated surface and subgrade around 101mm (4 in.). The surface course thickness of 101 mm (4 in.) was used to calculate the weight average DCP-CBR. The surface course thickness of several DCP tests were adjusted according to a clear interface shown in different depth. The DCP-CBR plot of control section shows that the surface in depth between 0 mm to 50 mm (2 in.) has relatively low CBR value. The possible reason is that the top loose part of surface layer is the newly spread maintenance aggregate, which is not compacted. The bottom part of surface layer close to 101 mm (4 in.) depth is denser and stiffer because it was not disturbed for construction and it was compacted by passing traffic. The DCP-CBR with SUDAS relative rating of analyzed surface layer as well as subgrade layer, in-situ surface dry density, and in-situ moisture content are summarized in Table 14.



(a) (b) (c)

Figure 36 DCP test results for optimized gradation with clay slurry section, control section, and RAP section in Howard County: a) cumulative blows b) DCPI and c) DCP-CBR



(a) (b) (c)

Figure 37 DCP test results for 2" Harsco slag section, 4" Harsco steel slag section, and 4" Phoenix steel slag section in Howard County: a) cumulative blows b) DCPI and c) DCP-CBR

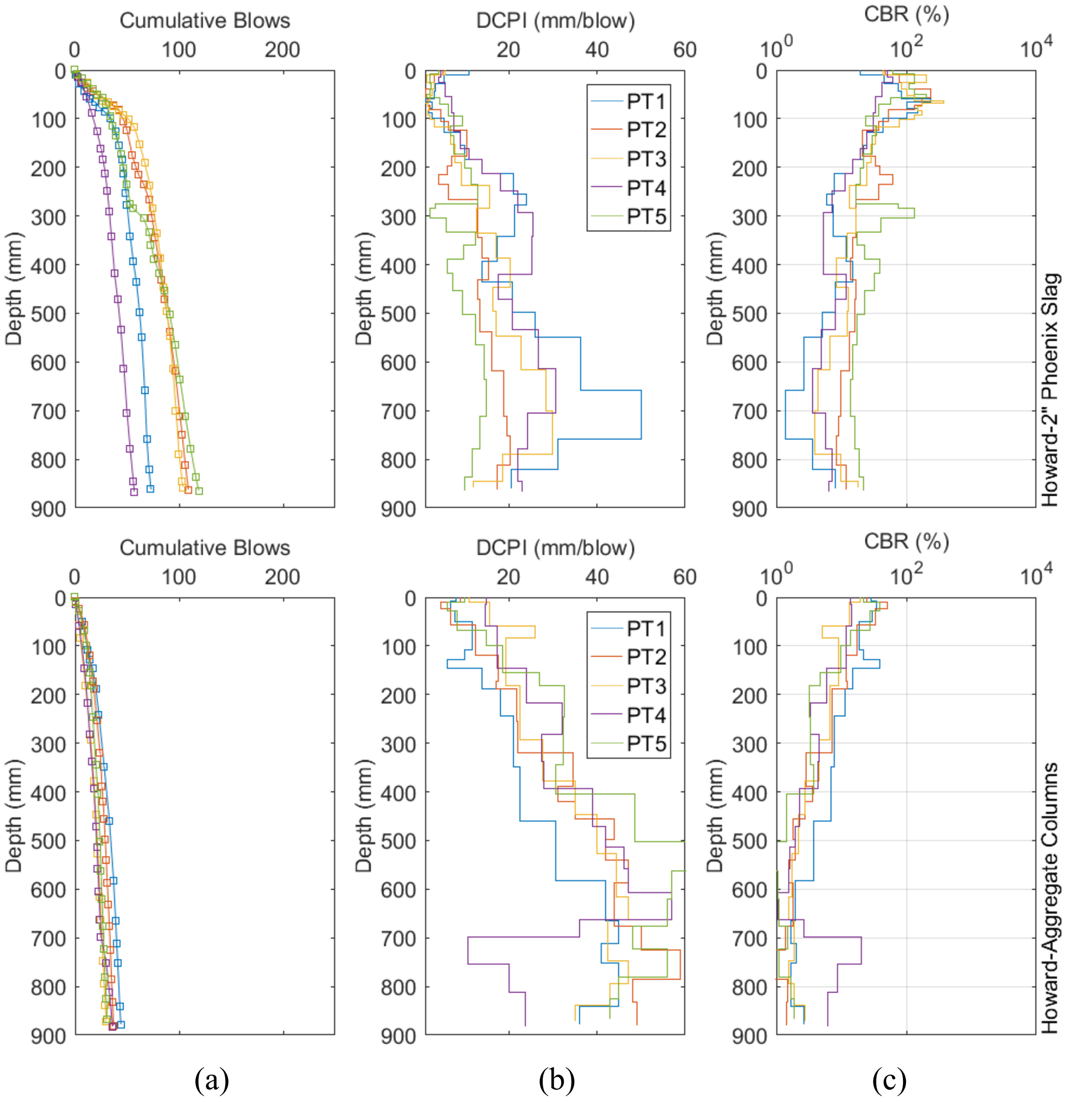


Figure 38 DCP test results for 2" Phoenix steel slag section and aggregate columns section in Howard County: a) cumulative blows b) DCPI and c) DCP-CBR

Table 14 Summary of Howard demonstration sections: (1) DCP-CBR, (2) in-situ dry unit weight, and (3) in-situ moisture content

Section Name	Thickness of Surface Course		AVG Thickness		DCP CBR_{AGG}	AVG DCP-CBR_{AGG}/ Rating[a]	DCP-CBR_{SG}	AVG DCP-CBR_{SG}/ Rating[b]	In-situ Dry Unit Weight		In-situ Moisture Content	
	(mm)	(in.)	(mm)	(in.)	(%)	(%)	(%)	(%)	(lb/ft^3)	(KN/m^3)	(%)	AVG
(1) Optimized Gradation w/ Pattison Clay Slurry	101.0	4.0	101.0	4.0	56.0	66.6/ VG	9.1	12.0/ F-G	127.7	20.1	9.0	7.4
	101.0	4.0			73.5		12.4		125.5	19.7	7.7	
	101.0	4.0			62.9		10.0		124.8	19.6	6.8	
	101.0	4.0			69.1		15.4		124.7	19.6	6.7	
	101.0	4.0			71.6		13.0		126.5	19.9	6.6	
(2) Control	107.0	4.2	108.8	4.3	190.1	116.7/ E	15.8	14.8/ F-G	133.8	21.0	7.7	7.8
	134.0	5.3			105.1		15.6		135.4	21.3	7.2	
	101.0	4.0			102.0		15.0		137.3	21.6	7.1	
	101.0	4.0			81.6		16.2		136.4	21.4	7.3	
	101.0	4.0			104.7		11.4		119.1	18.7	9.6	
(4) RAP	101.0	4.0	101.0	4.0	51.3	39.0/ G	16.0	12.7/ F-G	116.8	18.3	10.5	9.2
	101.0	4.0			25.2		10.2		121.6	19.1	9.6	
	101.0	4.0			31.0		8.3		125.1	19.7	8.0	
	101.0	4.0			52.5		12.1		122.7	19.3	9.5	
	101.0	4.0			35.3		16.8		125.1	19.7	8.3	
(5a) 2" Harsco Slag	101.0	4.0	113.2	4.5	47.8	143.4/ E	8.6	27.6/ VG	146.4	23.0	6.9	6.3
	101.0	4.0			131.4		39.4		139.6	21.9	6.5	
	101.0	4.0			108.3		19.2		148.6	23.3	6.3	
	119.0	4.7			154.5		42.4		149.0	23.4	5.9	
	144.0	5.7			275.2		28.3		138.6	21.8	5.7	

Table 14. (continued)

	Thickness of Surface Course		AVG Thickness		DCP CBR AGG	AVG DCP-CBR AGG/ Rating[a]	DCP-CBR SG	AVG DCP-CBR SG/ Rating[b]	In-situ Dry Unit Weight		In-situ Moisture Content	
Section Name	(mm)	(in.)	(mm)	(in.)	(%)	(%)	(%)	(%)	(lb/ft^3)	(KN/m^3)	(%)	AVG
(5b) 4" Harsco Slag	101.0	4.0	101.0	4.9	209.0	330.1/ E	28.5	25.1/ VG	156.5	24.6	5.5	5.3
	101.0	5.3			254.7		21.3		151.0	23.7	5.7	
	101.0	6.3			387.3		33.0		148.8	23.4	4.6	
	101.0	3.9			469.4		17.6		156.4	24.6	5.3	
(6a) 4" Phoenix Slag	101.0	4.0	101.0	4.0	76.9	77.1/ VG	12.1	14.3/ F-G	169.4	26.6	4.5	4.3
	101.0	4.0			131.8		13.8		168.1	26.4	4.4	
	101.0	4.0			63.1		16.2		163.5	25.7	4.0	
	101.0	4.0			48.3		14.1		168.2	26.4	4.4	
	101.0	4.0			65.5		15.2		170.4	26.8	4.2	
(6b) 2" Phoenix Slag	101.0	4.0	101.0	4.0	87.8	95.9/ E	10.2	16.3/ F-G	165.2	26.0	6.3	6.9
	101.0	4.0			122.7		17.5		170.1	26.7	5.4	
	101.0	4.0			138.9		15.3		161.2	25.3	4.5	
	101.0	4.0			41.3		10.8		172.5	27.1	6.0	
	101.0	4.0			89.0		28.0		167.0	26.2	7.0	
(7) Aggregate Columns	101.0	4.0	101.0	4.0	25.0	20.3/ <G	7.8	5.1/ P-F	121.1	19.0	12.2	12.2
	101.0	4.0			28.1		4.8		126.9	19.9	11.0	
	101.0	4.0			11.2		4.4		110.0	17.3	15.1	
	101.0	4.0			13.3		5.7		114.6	18.0	15.2	
	101.0	4.0			24.2		2.9		125.0	19.6	7.3	

[a] SUDAS relative rating of supporting strengths as function of CBR for subbase: E=Excellent, VG=Very Good, G=Good, <G=below Good; [b] SUDAS relative rating of supporting strengths as function of CBR for subgrade: >VG=greater than Very Good, VG=Very Good, F-G=Fair-good, P-F=Poor-fair, VP=Very Poor.

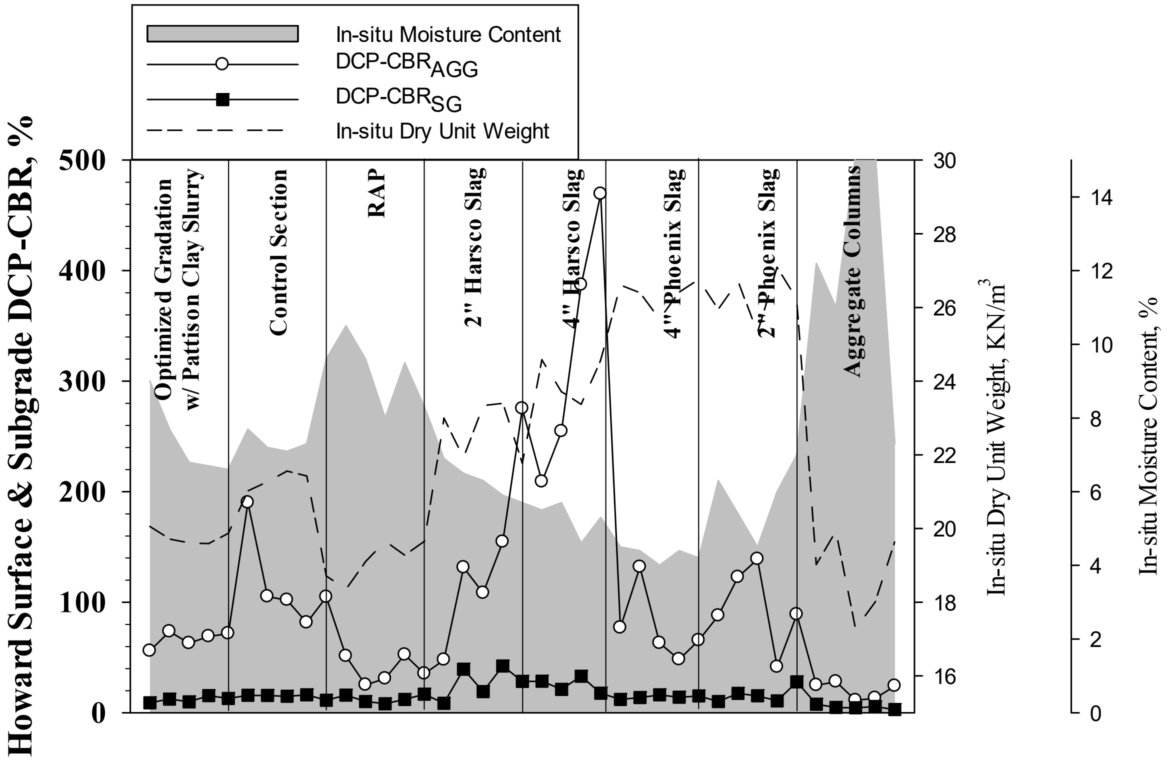


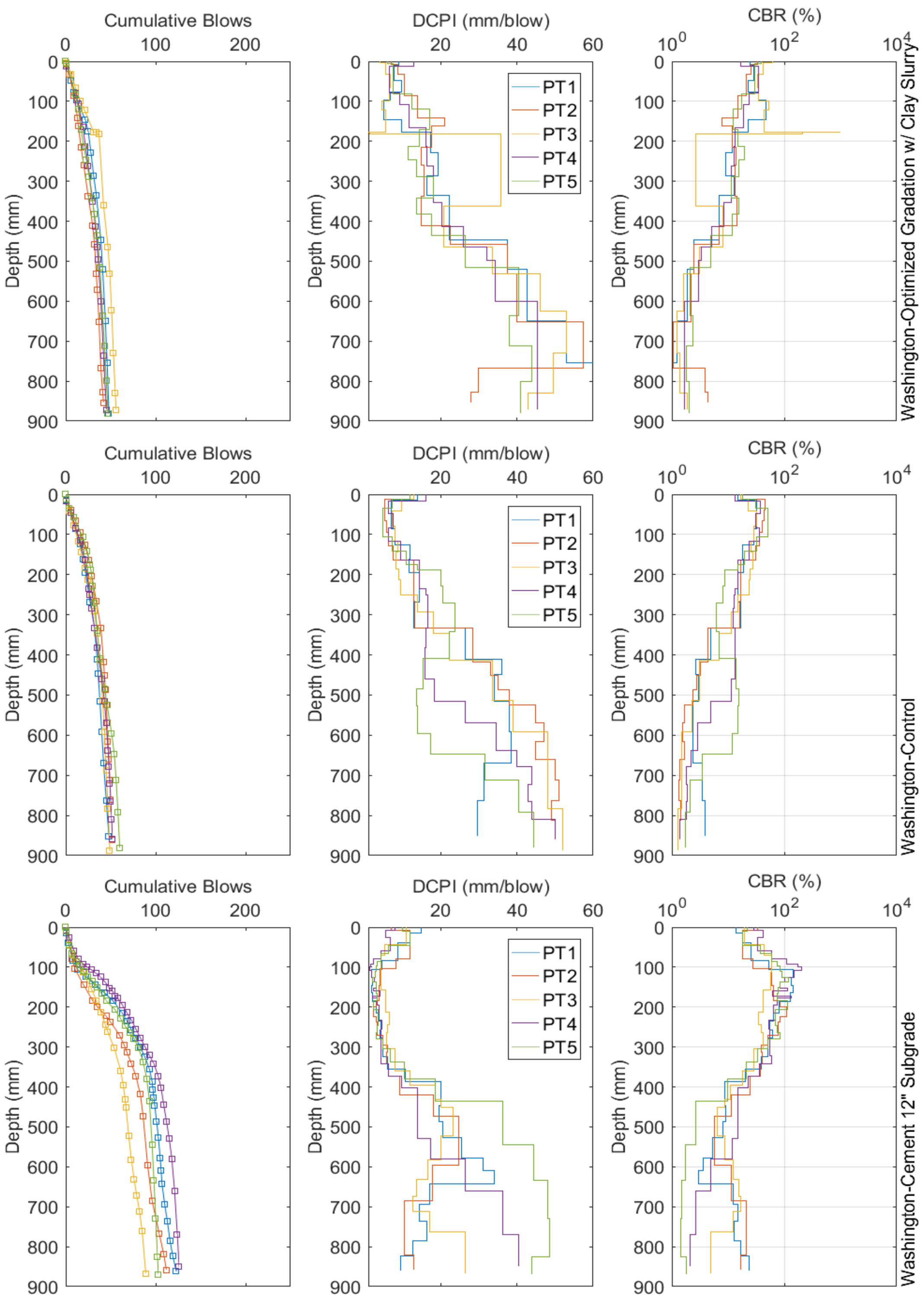
Figure 39 Howard demonstration sections: (1) DCP-CBR, (2) in-situ dry unit weight, and (3) in-situ moisture content

Similar to the Cherokee county, the in-situ dry unit weight of slag sections is higher than other sections and the in-situ moisture content is lower than other sections. The average DCP-CBR$_{AGG}$ of 4” Harsco slag section is the highest (330.1%/E), which is 1.8 times higher than control section (116.7%/E). The 2” Harsco slag section average DCP-CBR$_{AGG}$ (143.3/E) is slightly higher than control section. The average DCP-CBR$_{AGG}$ of Phoenix slag sections (2”- 95.9%/E; 4”- 77.1%/VG) and optimized gradation with clay slurry (66.6%/VG) section are lower than control section, but they can still have excellent or very good SUDAS relative rating. The RAP section has good DCP-CBR$_{AGG}$ (39.0%/G) and the aggregate columns section has SUDAS relative rating below good (20.3%/G). Although the DCP-CBR plot indicates the top of control section surface layer is loose, the control section can still have excellent average DCP-CBR$_{AGG}$.

Since top part of the surface layer in control section is unstable, the aggregates could lose faster than other sections.

6.2.1.3 DCP Test Results of Washington Demonstration Sections

The DCP tests in Washington County were conducted on November 06, 2018. The construction of test sections in Washington County was completed on August 30, 2018. The cumulative blows, DCPI, and DCP-CBR values versus depth for these sections are shown in Figures 40-42. The designed treatment surface thickness of test sections in Washington County is 101 mm (4 in.), which is also the surface layer thickness used for analysis. For the cement 12" treated subgrade section, there is no treatment to the surface course. The EMC Squared section has 101 mm (4 in.) surface course treated and 152 mm (6 in.) subgrade treated under the surface. Obvious trend changes at 101 mm (4 in.) depth can be easily found in the DCP-CBR plot of cement treated 12" subgrade section and cement treated 4" surface section. For all the other sections, the trend changes are not clear as cement sections. There is a suddenly increase in the DCP-CBR plot of EMC Squared section. The possible reason is that a dense, stiff but thin layer exists in subgrade at 500 mm (20 in.) depth. This also happened in DCP-CBR plot of Base One section, which is connected with ECM Squared section. The DCP-CBR with SUDAS relative rating of analyzed surface layer as well as subgrade layer, in-situ surface dry density, and in-situ moisture content are summarized in Table 15.



(a) (b) (c)

Figure 40 DCP test results for optimized gradation with clay slurry section, control section, and cement 12" subgrade section in Washington County: a) cumulative blows b) DCPI and c) DCP-CBR

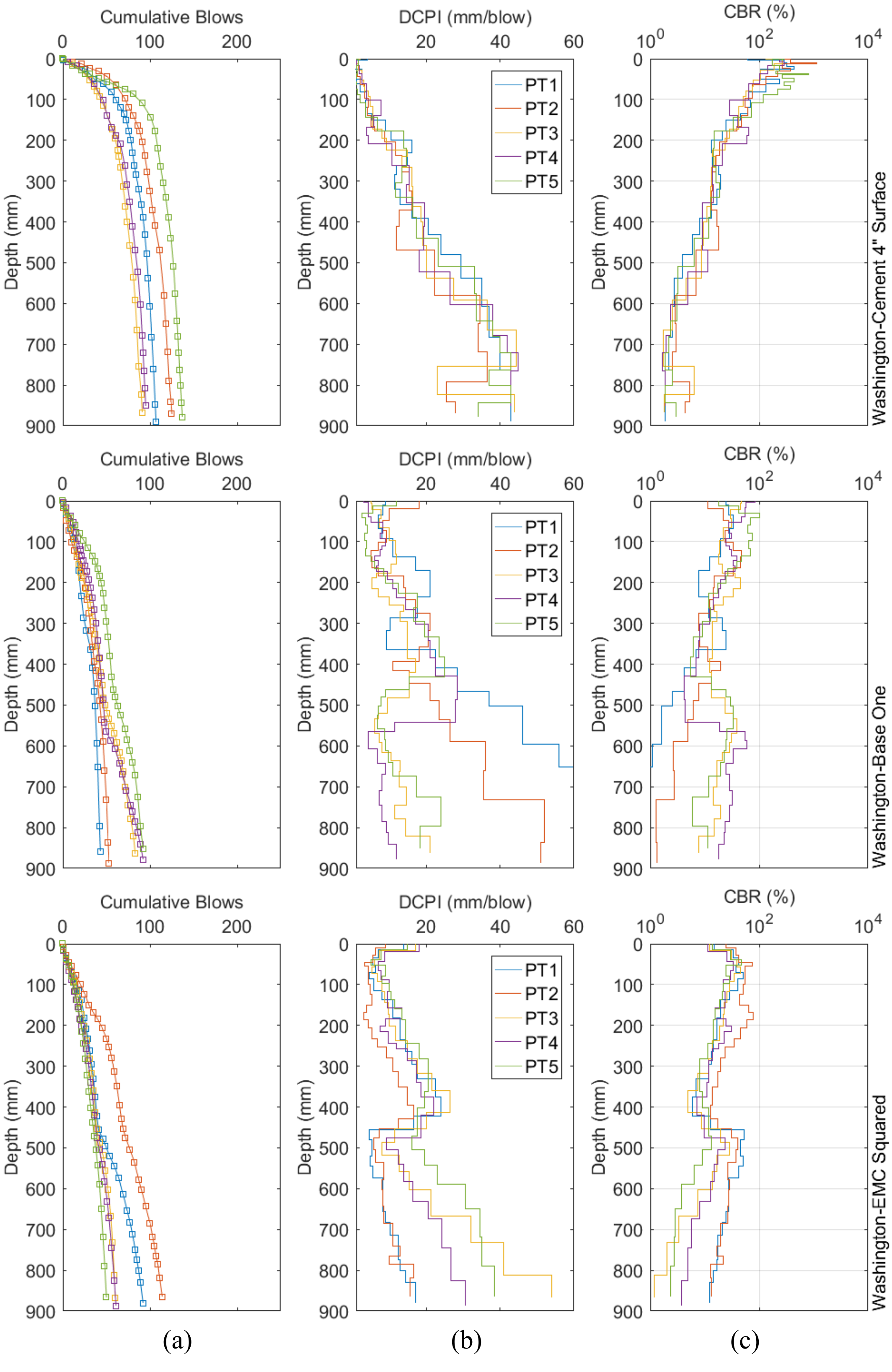
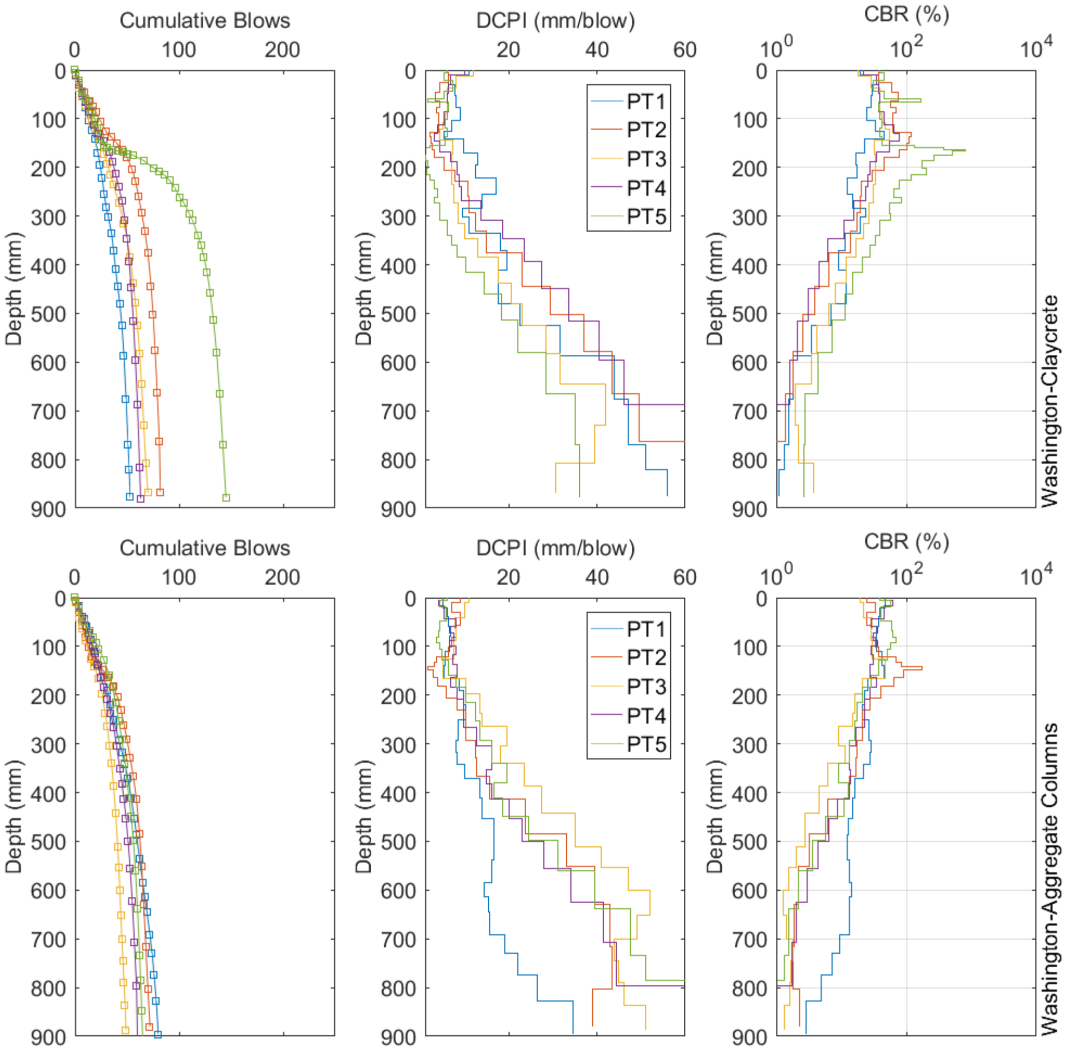


Figure 41 DCP test results for cement 4" surface section, Base One section, and EMC Squared section in Washington County: a) cumulative blows b) DCPI and c) DCP-CBR



(a) (b) (c)

Figure 42 DCP test results for Claycrete section, and aggregate columns section in Washington County: a) cumulative blows b) DCPI and c) DCP-CBR

Table 15 Summary of Washington demonstration sections: (1) DCP-CBR, (2) in-situ dry unit weight, and (3) in-situ moisture content

Section Name	Thickness of Surface Course		AVG Thickness		DCP CBR$_{AGG}$	AVG DCP-CBR$_{AGG}$/ Rating[a]	DCP-CBR$_{SG}$	AVG DCP-CBR$_{SG}$/ Rating[b]	In-situ Dry Unit Weight		In-situ Moisture Content, %	
	(mm)	(in.)	(mm)	(in.)	(%)	(%)	(%)	(%)	(lb/ft^3)	(KN/m^3)	(%)	AVG
(1) Optimized Gradation w/ Pattison Clay Slurry	101.0	4.0	101.0	4.0	29.1	29.7/ <G	9.7	9.2/ P-F	136.1	21.4	3.7	6.0
	101.0	4.0			22.2		8.4		135.8	21.3	7.5	
	101.0	4.0			38.4		10.8		139.4	21.9	5.6	
	101.0	4.0			30.3		8.1		137.1	21.5	6.9	
	101.0	4.0			28.2		9.1		138.1	21.7	6.4	
(2) Control	101.0	4.0	101.0	4.0	29.5	33.9/ G	8.7	10.5/ F-G	130.0	20.4	9.8	7.9
	101.0	4.0			39.6		9.8		132.3	20.8	8.4	
	101.0	4.0			26.6		10.5		128.9	20.2	5.4	
	101.0	4.0			31.3		11.2		120.5	18.9	8.3	
	101.0	4.0			42.5		12.3		130.5	20.5	7.7	
(3) Cement Treated 12" Subgrade	101.0	4.0	101.0	4.0	27.2	37.9/ G	39.5	34.4/ >VG	124.7	19.6	9.2	8.3
	101.0	4.0			21.1		36.9		126.7	19.9	7.2	
	101.0	4.0			38.1		25.9		125.9	19.8	9.6	
	101.0	4.0			63.0		37.9		130.8	20.5	8.3	
	101.0	4.0			39.9		32.1		125.4	19.7	7.2	
(4) Cement Treated 4" Surface	101.0	4.0	101.0	4.0	166.6	169.9/ E	13.4	14.6/ F-G	129.1	20.3	9.3	9.2
	101.0	4.0			201.2		15.7		134.3	21.1	8.7	
	101.0	4.0			114.6		14.1		131.9	20.7	8.9	
	101.0	4.0			120.3		15.5		132.5	20.8	8.9	
	101.0	4.0			246.9		14.6		117.7	18.5	10.4	

Table 15. (continued)

	Thickness of Surface Course		AVG Thickness		DCP CBRAGG	AVG DCP-CBRAGG/ Rating[a]	DCP-CBRSG	AVG DCP-CBRSG/ Rating[b]	In-situ Dry Unit Weight		In-situ Moisture Content, %	
Section Name	(mm)	(in.)	(mm)	(in.)	(%)	(%)	(%)	(%)	(lb/ft^3)	(KN/m^3)	(%)	AVG
(5) Base One	101.0	4.0	101.0	4.0	28.6	37.0/ G	8.0	16.4/ F-G	122.5	19.2	8.7	8.4
	101.0	4.0			22.1		12.1		124.8	19.6	8.8	
	101.0	4.0			30.5		21.4		120.5	18.9	8.3	
	101.0	4.0			42.1		19.9		127.6	20.0	7.5	
	101.0	4.0			61.8		20.8		132.6	20.8	8.8	
(6) EMC Squared	101.0	4.0	101.0	4.0	36.7	34.2/ G	23.4	18.7/ F-G	121.4	19.1	10.4	10.5
	101.0	4.0			48.9		30.2		129.0	20.3	8.6	
	101.0	4.0			32.1		14.3		120.4	18.9	10.6	
	101.0	4.0			25.2		15.3		128.4	20.2	11.3	
	101.0	4.0			28.2		10.3		121.9	19.1	11.5	
(7) Claycrete	101.0	4.0	101.0	4.0	28.5	40.5/ G	11.8	22.7/ VG	125.7	19.7	9.3	9.0
	101.0	4.0			57.4		19.6		121.5	19.1	8.6	
	101.0	4.0			34.7		16.6		131.3	20.6	9.0	
	101.0	4.0			37.2		14.7		129.5	20.3	9.2	
	101.0	4.0			44.9		50.6		128.8	20.2	8.9	
(8) Aggregate Columns	101.0	4.0	101.0	4.0	38.3	37.4/ G	20.4	15.3/ F-G	122.8	19.3	9.2	9.0
	101.0	4.0			29.2		19.6		130.5	20.5	8.5	
	101.0	4.0			26.3		10.4		126.7	19.9	10.0	
	101.0	4.0			39.8		13.6		136.2	21.4	8.8	
	101.0	4.0			53.4		12.7		132.5	20.8	8.5	

[a] SUDAS relative rating of supporting strengths as function of CBR for subbase: E=Excellent, VG=Very Good, G=Good, <G=below Good; [b] SUDAS relative rating of supporting strengths as function of CBR for subgrade: >VG=greater than Very Good, VG=Very Good, F-G=Fair-good, P-F=Poor-fair, VP=Very Poor

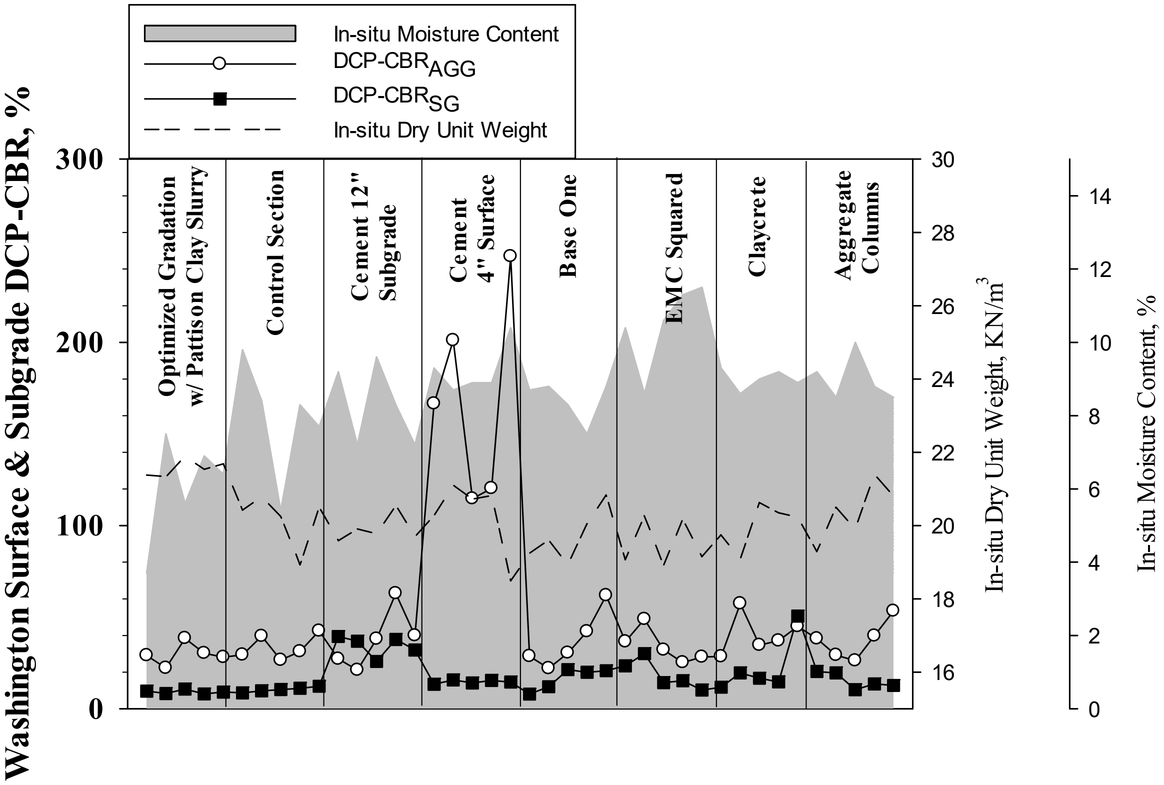


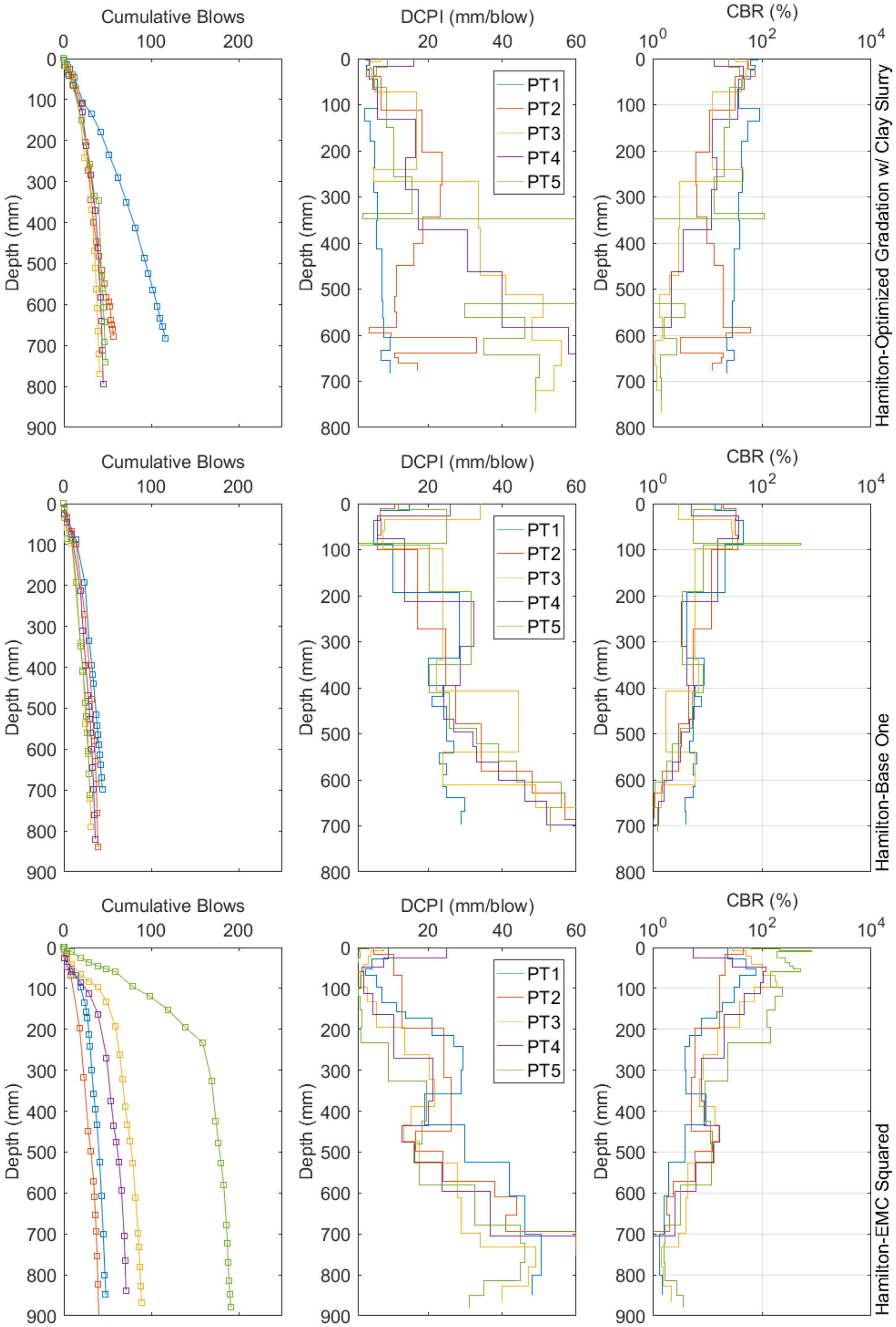
Figure 43 Washington demonstration sections' (1) DCP-CBR, (2) in-situ dry unit weight, and (3) in-situ moisture content

The average DCP-CBR$_{AGG}$ of cement treated 4” surface is greatly higher than other sections, which is 169.9% with excellent SUDAS relative rating. The DCP-CBR$_{AGG}$ of all the other test sections are in a same range 30-40%. The average DCP-CBR$_{SG}$ of cement treated 12” subgrade section is 34.4% with the SUDAS relative rating of greater than very good, which is higher than all the other sections. The optimized gradation with clay slurry section’s average DCP-CBR$_{SG}$ (9.2%) only has poor fair SUDAS relative rating, which is lower than other sections. Adding cement into the soils can greatly increase the shear strength for both surface course (130% DCP-CBR$_{AGG}$) and subgrade (15% DCP-CBR$_{SG}$).

6.2.1.4 DCP Test Results of Hamilton Demonstration Sections

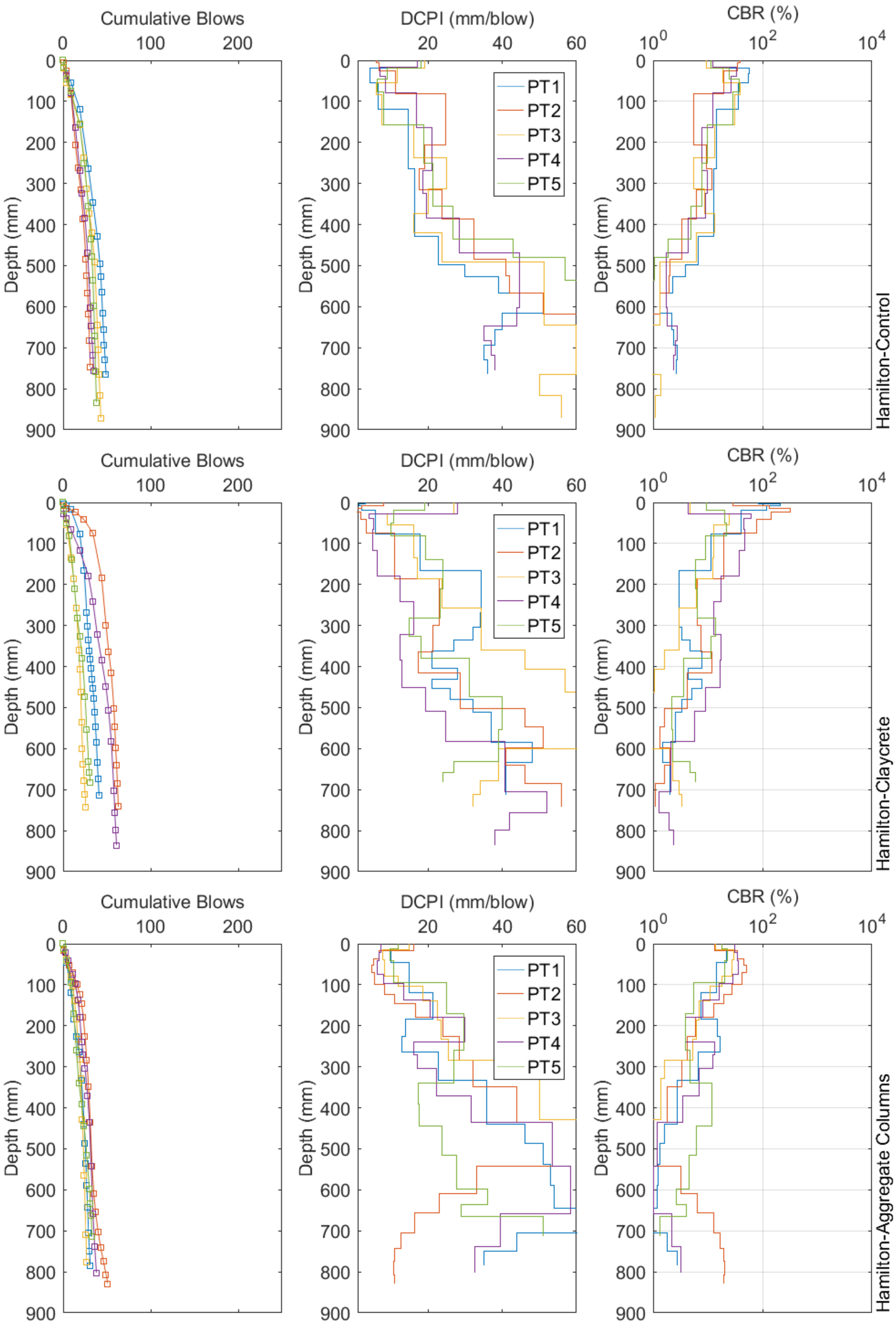
The DCP tests in Hamilton County were conducted on November 15, 2018. The construction of test sections in Hamilton County was completed on September 06, 2018. The cumulative blows, DCPI, and DCP-CBR values versus depth for these sections are shown in Figures 44-45. The proposed cement treated sections in Hamilton County were not completed in 2018. A hammer drill was used to penetrate the frozen depth since the test sections roadway surface were frozen during the day DCP test performed, Figure 44 and Figure 45 cannot show the entire profile of surface aggregate layer properties. The thickness of surface course shown in Table 16 was after corrected. Because the DCP tests performed in the test sections in Hamilton county skipped frozen depth which is the most part of surface course, the values of DCP-CBR_{AGG} are not accurate as other three counties. The DCP-CBR with SUDAS relative rating of analyzed surface layer and subgrade layer, in-situ surface dry density, and in-situ moisture content are summarized in Table 16.

The in-situ moisture content for demonstration sections in Hamilton County varies a lot. The optimized gradation with clay slurry section and Claycrete section have the similar and lower moisture content. The in-situ dry unit weight for all section are similar and around 20 KN/m^3 (128.5 lb/c.f.). The possible reason of the low point of in-situ dry unit weight in aggregate columns section is that the test point is above the column position. Since the fill of columns are clean aggregates, the density of columns is lower than soils around. Because of the surface frozen, the values of DPC-CBR_{AGG} have large variation especially and not trustable in EMC Squared section and Claycrete section. The DCP-CBR_{SG} of optimized gradation section (18.1%/ F-G) and EMC Squared section (15.0%/ F-G) are slightly higher than others sections (7.0%-9.4% P-F).



(a) (b) (c)

Figure 44 DCP test results for optimized gradation with clay slurry section, Base One section, and EMC Squared section in Hamilton County: a) cumulative blows b) DCPI and c) DCP-CBR



(a) (b) (c)

Figure 45 DCP test results for control section, Claycrete section, and aggregate columns section in Hamilton County: a) cumulative blows b) DCPI and c) DCP-CBR

Table 16 Summary of Hamilton Demonstration Sections: (1) DCP-CBR, (2) in-situ dry unit weight, and (3) in-situ moisture

Section Name	Corrected Thickness of Surface Course[a]		AVG Thickness		DCP CBR_{AGG}	AVG DCP-CBR_{AGG}/ Rating[b]	DCP-CBR_{SG}	AVG DCP-CBR_{SG}/ Rating[c]	In-situ Dry Unit Weight		In-situ Moisture Content, %	
	(mm)	(in.)	(mm)	(in.)	(%)	(%)	(%)	(%)	(lb/ft^3)	(KN/m^3)	(%)	AVG
(1) Optimized Gradation w/ Pattison Clay Slurry	204.1	8.0	168.3	6.6	66.95	48.9/ G	39.4	18.1/ F-G	134.3	21.1	5.6	5.7
	219.1	8.6			62.12		15.6		126.4	19.9	5.1	
	140.1	5.5			49.34		9.2		129.0	20.3	5.2	
	117.1	4.6			32.87		12.6		131.9	20.7	6.2	
	161.1	6.3			33.29		14.0		138.3	21.7	6.6	
(5) EMC Squared	241.1	9.5	188.3	7.4	43.4	91.3/ E	9.0	15.0/ F-G	119.7	18.8	13.3	10.5
	142.1	5.6			23.1		7.9		115.0	18.1	15.3	
	172.1	6.8			103.6		15.6		130.1	20.4	10.7	
	155.1	6.1			63.4		13.2		134.4	21.1	6.4	
	231.1	9.1			222.8		29.4		136.9	21.5	6.7	
(6) Control	102.0	4.0	102.0	4.0	39.5	26.0/ <G	12.0	9.1/ P-F	132.9	20.9	6.6	9.5
	102.0	4.0			27.3		5.7		133.7	21.0	7.9	
	102.0	4.0			15.9		11.3		115.8	18.2	12.6	
	102.0	4.0			24.7		7.4		130.7	20.5	10.1	
	102.0	4.0			22.9		8.9		129.6	20.4	10.1	
(4) Base One	147.9	5.8	127.9	5.0	35.1	23.1/ <G	9.3	7.3/ P-F	138.0	21.7	5.1	7.8
	203.9	8.0			30.7		7.6		127.7	20.1	9.0	
	71.9	2.8			16.1		5.8		133.5	21.0	8.9	
	137.9	5.4			25.8		6.6		130.7	20.5	10.4	
	77.9	3.1			7.6		7.3		140.5	22.1	5.5	

Table 16. (continued)

	Corrected Thickness of Surface Course		AVG Thickness		DCP CBRAGG	AVG DCP-CBRAGG/ Rating[a]	DCP-CBRSG	AVG DCP-CBRSG/ Rating[b]	In-situ Dry Unit Weight		In-situ Moisture Content, %	
Section Name	(mm)	(in.)	(mm)	(in.)	(%)	(%)	(%)	(%)	(lb/ft^3)	(KN/m^3)	(%)	AVG
(7) Claycrete	204.8	8.1	178.4	7.0	75.6	56.0/ VG	6.6	9.4/ P-F	140.0	22.0	5.0	6.2
	197.8	7.8			149.0		11.0		140.3	22.0	4.9	
	183.8	7.2			13.6		5.0		141.0	22.1	5.0	
	77.8	3.1			25.7		17.3		139.9	22.0	5.8	
	227.8	9.0			16.2		6.9		135.8	21.3	5.1	
(8) Aggregate Columns	137.0	5.4	124.0	4.9	18.9	25.6/ <G	6.3	7.0/ P-F	128.0	20.1	11.5	10.4
	78.0	3.1			29.8		9.5		124.0	19.5	12.6	
	110.0	4.3			24.4		5.0		106.4	16.7	15.7	
	107.0	4.2			33.4		7.2		134.1	21.1	7.5	
	188.0	7.4			21.4		7.1		135.9	21.3	5.9	

[a] The values in this columns are corrected, see section 7.2.1.4; [b] SUDAS relative rating of supporting strengths as function of CBR for subbase: E=Excellent, VG=Very Good, G=Good, <G=below Good; [c] SUDAS relative rating of supporting strengths as function of CBR for subgrade: >VG=greater than Very Good, VG=Very Good, F-G=Fair-good, P-F=Poor-fair, VP=Very Poor

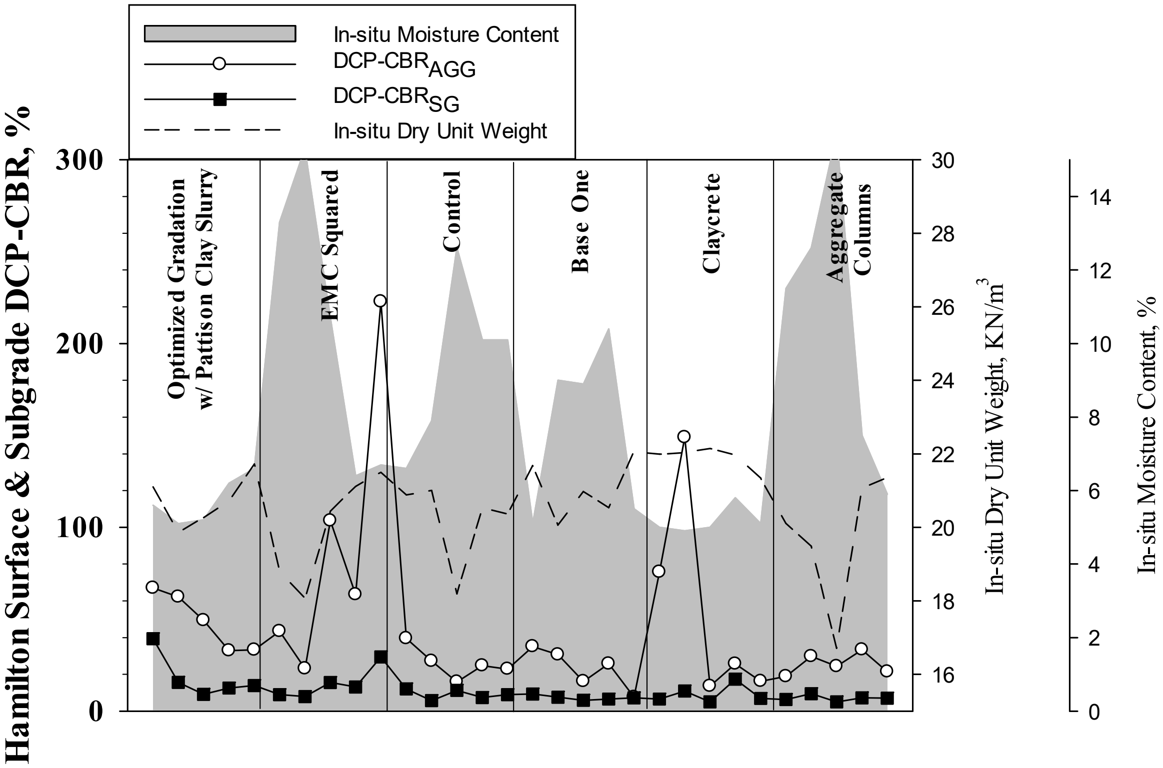


Figure 46 Hamilton demonstration sections: (1) DCP-CBR, (2) in-situ dry unit weight, and (3) in-situ moisture content

According to the results above, cement treatment can greatly improve the strength of surface course material and subgrade. Optimized gradation with clay slurry can improve strength for surface course as well. Optimized gradation with clay slurry section has higher DCP-CBR comparing to control section in Cherokee County. In Howard County, control section has higher strength because of surface course was not disturbed during construction. Optimized gradation with clay slurry stabilization method can improve strength comparing to RAP and aggregate columns sections.

Steel slag section in Cherokee county have no strength improvement. But in Howard County, Harsco steel slag method greatly improved strength of surface course and Phoenix steel slag sections shown strength improvement as well. The possible reason of this difference is because steel slag materials self-stabilization conducted slowly. Mathur et al. (1999) concluded that the slag mixture initially behaves like unbound material, but it generally turns into a bound material because of the self-stabilization characteristics of slags. The time between the day of steel slag sections constructed and the day of DCP tests performed is 69 days in Howard County and days.

In Washington County, cement treatment can greatly improve the strength of both surface course material and subgrade material. Optimized gradation with clay slurry method and other chemical stabilization methods can only create surface course have same strength as control section. The optimized gradation with clay slurry section does not have improvement may because of compaction and low aggregate quality. The DCP results of Hamilton County test sections of surface course are not reliable because of surface frozen.

6.2.2 LWD Test Results

The LWD tests were conducted at the same day as DCP tests performed. The optimized gradation with clay slurry section in both Cherokee County and Howard County had higher composite elastic modulus than those of other sections. In the Cherokee county, the composite elastic modulus measured in aggregate columns section was similar to the modulus of the optimized gradation section. In the Howard County, the control section had almost the same composite elastic modulus as the optimized gradation section. The composite elastic modulus of RAP and steel slag sections in both Howard County and Cherokee County were majorly than all other test sections. Figures 47-48 show the LWD results of the Cherokee County and the Howard County, respectively.

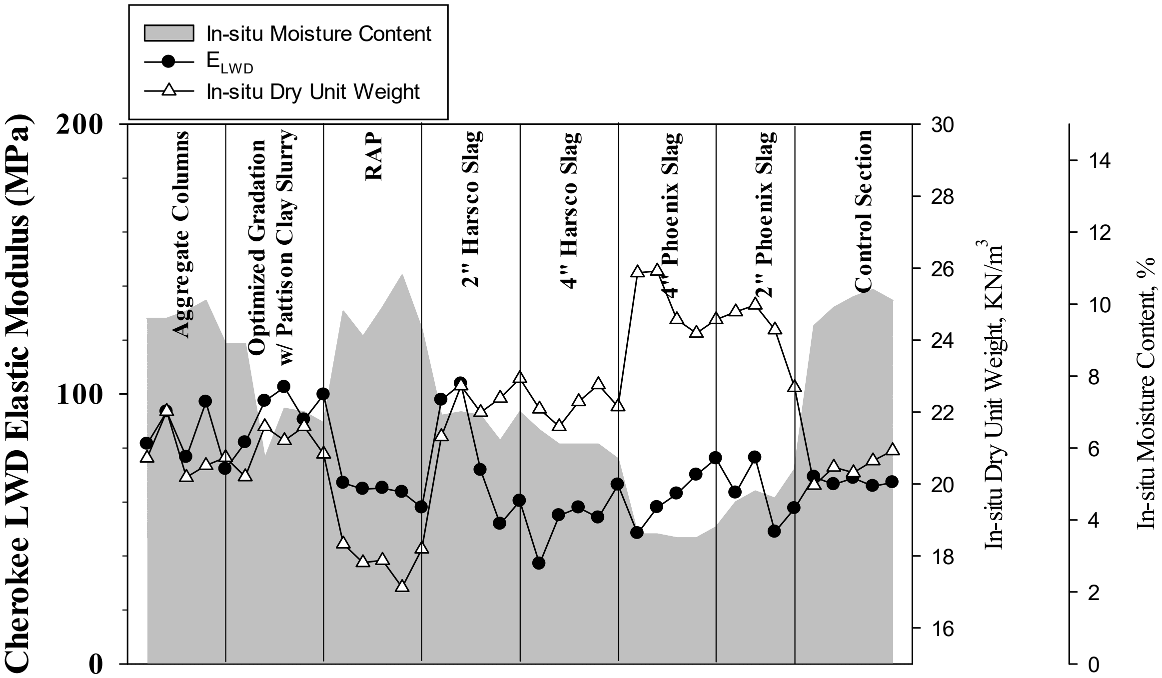


Figure 47 LWD test results of test sections in the Cherokee County

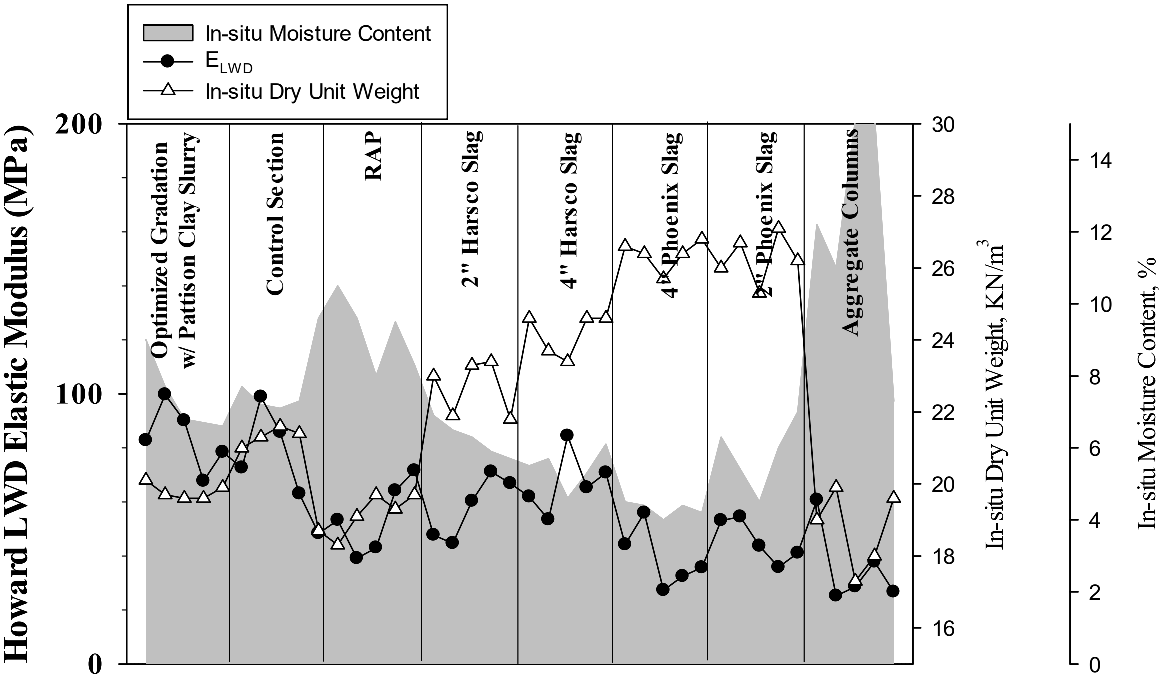


Figure 48 LWD test results of test sections in Howard County

The composite elastic modulus of the optimized gradation section and aggregate columns sections in the Cherokee County had the average 94.4 MPa (13.6 ksi) and 84.1 MPa (12.2 ksi). Other sections in Cherokee county had the average composite elastic modulus ranged from 63.7 MPa (9.1 ksi) to 77.1 MPa (11.2 ksi). The composite elastic modulus of the optimized gradation section and control sections in the Howard County had the average of 83.8 MPa (12.2 ksi) and 73.8 MPa (10.7 ksi). Other sections in the Cherokee county had the average of composite elastic modulus ranged from 31.5 MPa (4.6 ksi) to 67.2 MPa (9.7 ksi).

In the Washington county, two cement treated sections had the higher composite elastic modulus than those of other test sections (average 98.9 MPa (14.3 ksi) for the cement treated 12" subgrade section and average 109.32 MPa (15.86 ksi) for the cement treated 4" surface section). The average composite elastic modulus of the gradation optimized with clay slurry sections was slightly higher than control section, 63.5 MPa (9.2 ksi). Other sections had average composite elastic modulus ranged from 33.3 MPa (4.83 ksi) to 50.37 MPa (7.3 ksi).

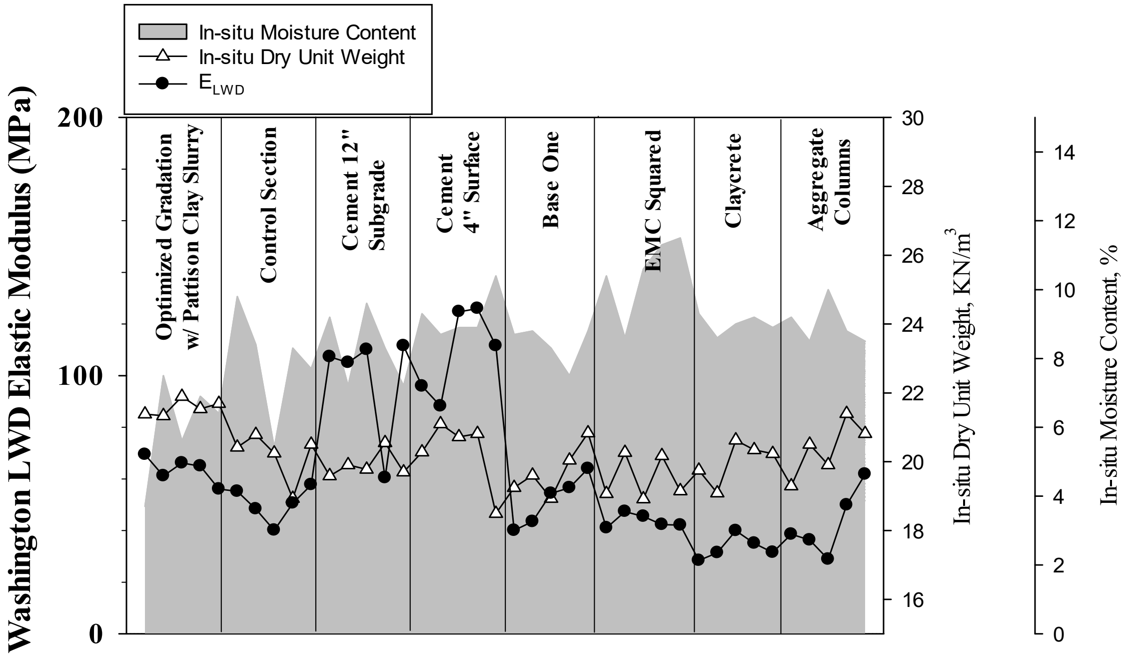


Figure 49 LWD Test results of test sections in Washington County

It should be noted that since the surface layer was frozen during testing in Hamilton County, the composite elastic modulus measured by LWD tests could higher than the values that would be measured under non-freezing conditions. The composite elastic modulus of the optimized gradation section and aggregate columns sections in the Hamilton County had the average of 89.5 MPa (13.0 ksi) and 79.4 MPa (11.5 ksi). Other sections in the Hamilton County had the average composite elastic modulus ranged from 100.1 MPa (14.5 ksi) to 123.7 MPa (17.9 ksi).

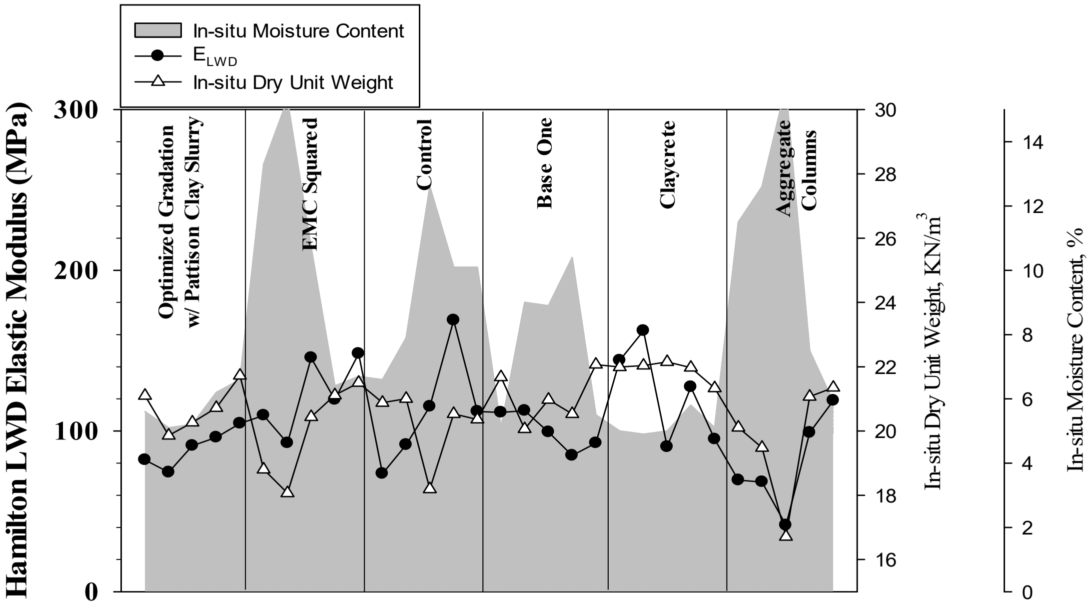


Figure 50 LWD test results of test sections in Hamilton County

6.2.3 FWD Test Results

The FWD test results of the surface course in Cherokee and Howard counties showed that the optimized gradation with clay slurry section had relative higher elastic modulus than all other test sections. Phoenix steel slag sections had the highest elastic modulus in the Cherokee County. However, the Harsco steel slag sections had the highest elastic modulus in the Howard County. Two cement sections had the highest elastic moduli in the Washington County. In the Hamilton County, the optimized gradation with clay slurry section and Claycrete section had the highest elastic modulus. The FWD tests results for the surface layers are shown in Figures 51-54, and the FWD results for subgrade layers are shown in Figures 55-58. The cement treated 12” subgrade section had higher elastic modulus for the subgrade layer since the subgrade layer in that section was treated with Portland cement. The existing of a thin stiff layer in the subgrade could be used to explain why the elastic modulus of subgrade layer under Base One and EMC Squared sections were relatively higher than those of other subgrade moduli of test sections in Washington County.

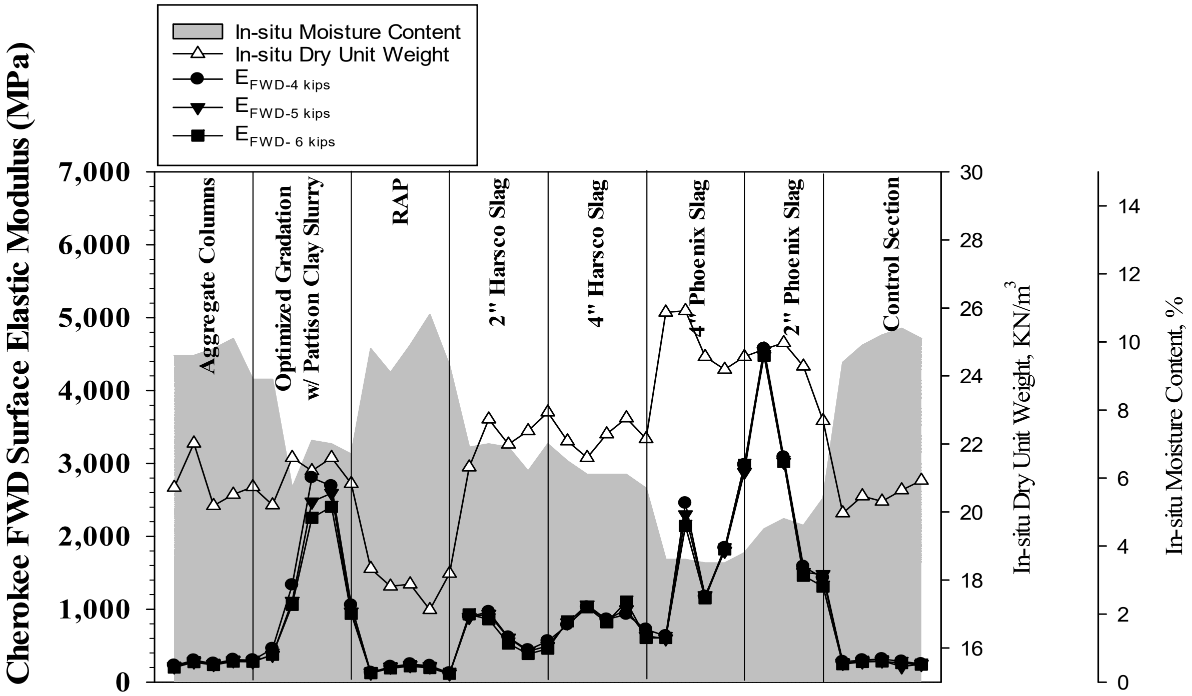


Figure 51 FWD test results for surface course in Cherokee County

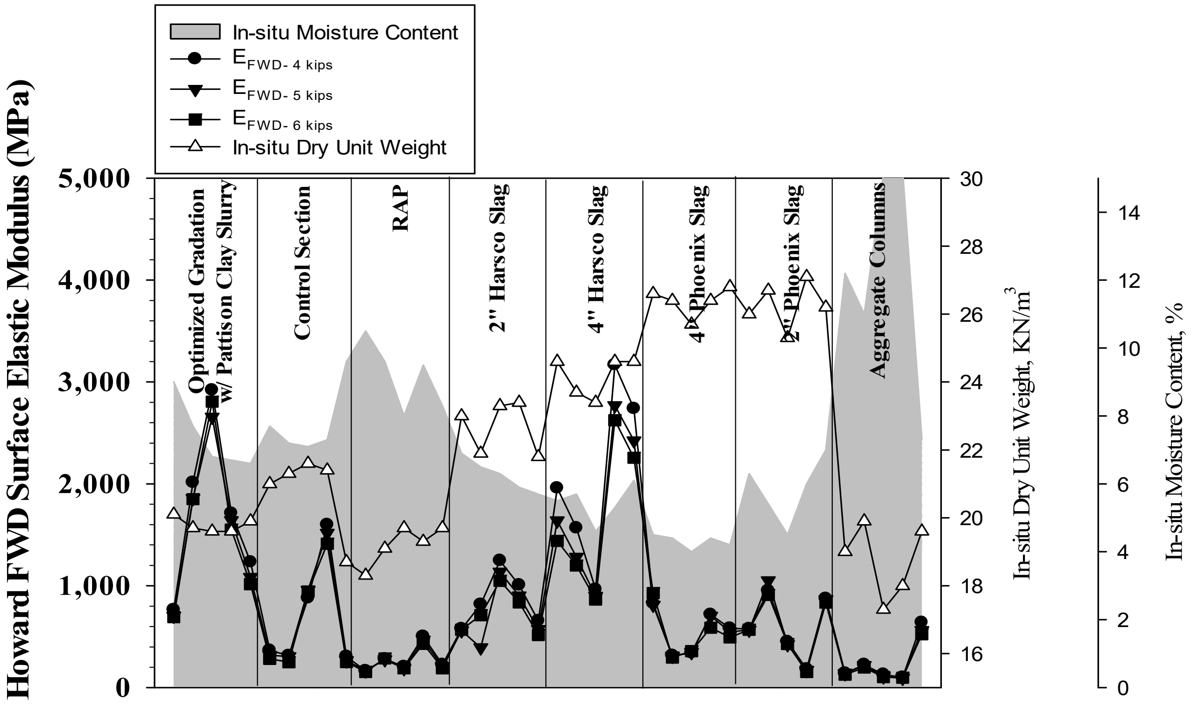


Figure 52 FWD test results for surface course in Howard County

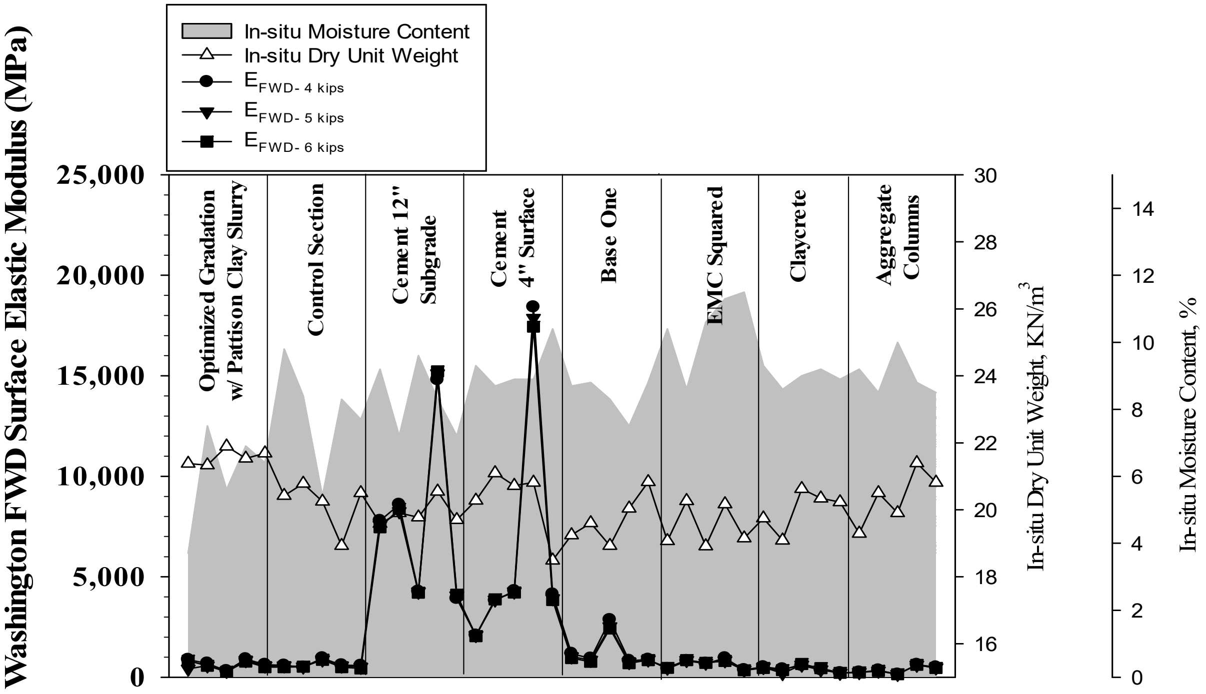


Figure 53 FWD test results for surface course in Washington County

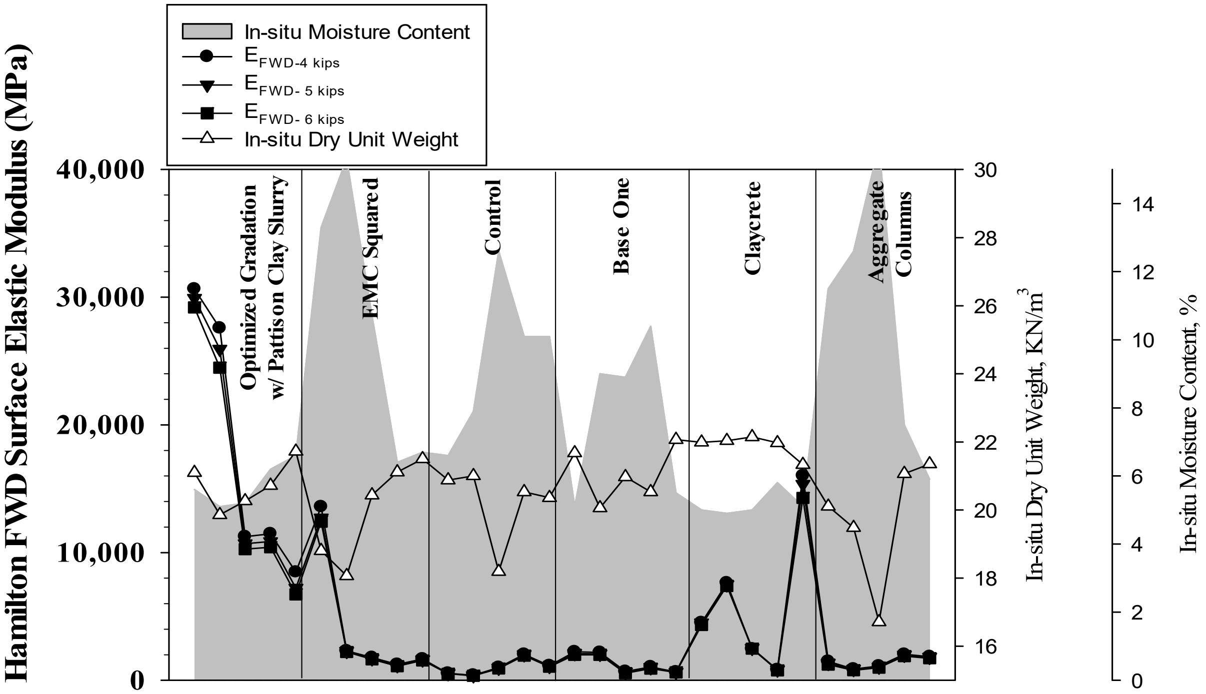


Figure 54 FWD Test results for surface course in Hamilton County

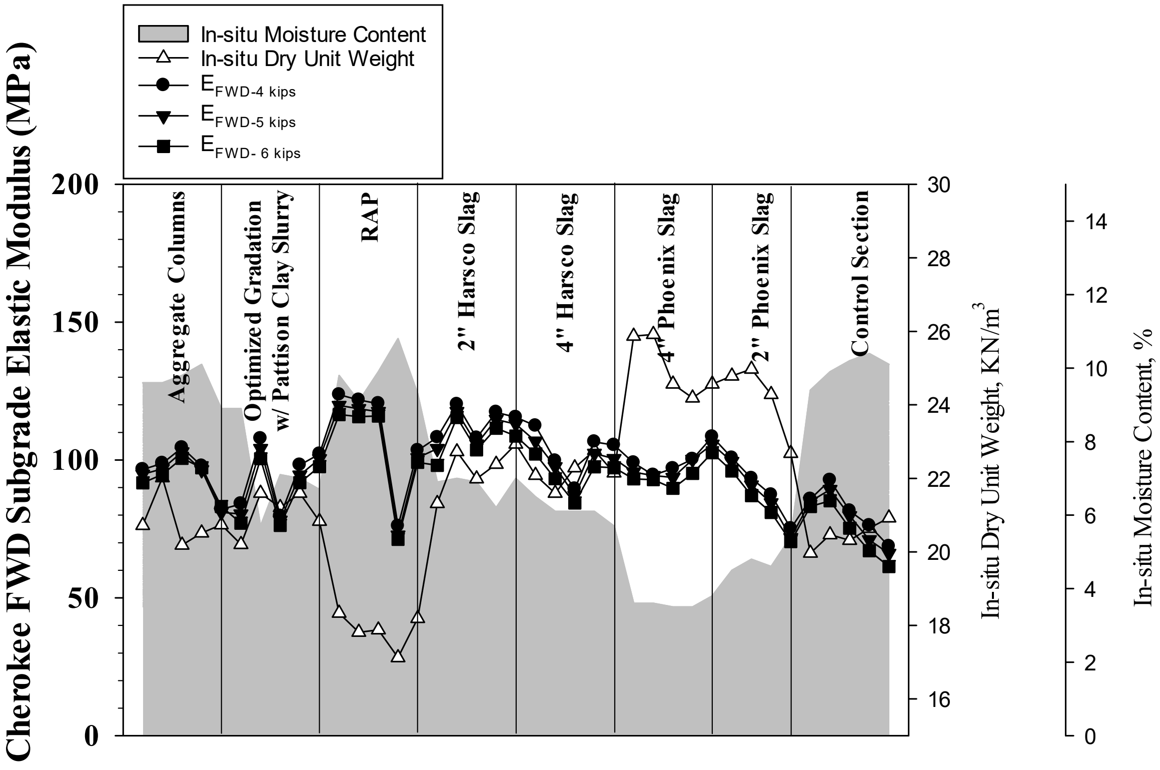


Figure 55 FWD test results for subgrade layer in Cherokee County

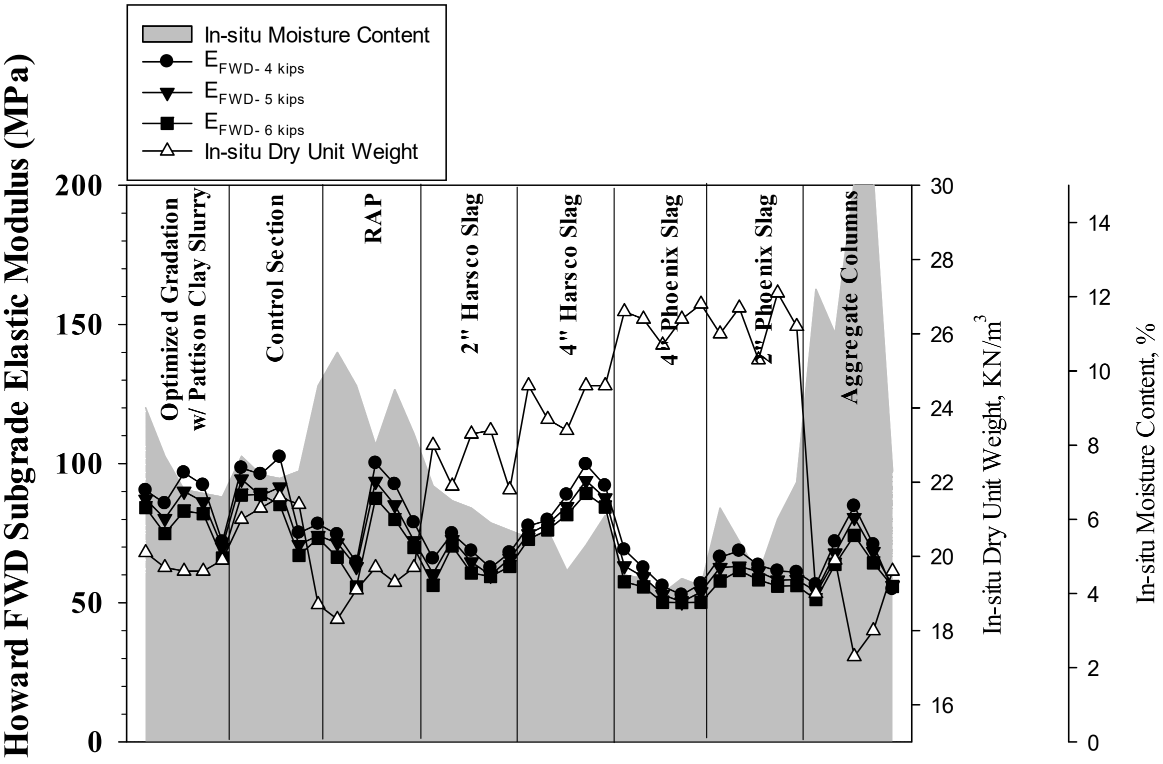


Figure 56 FWD test results for subgrade layer in Howard County

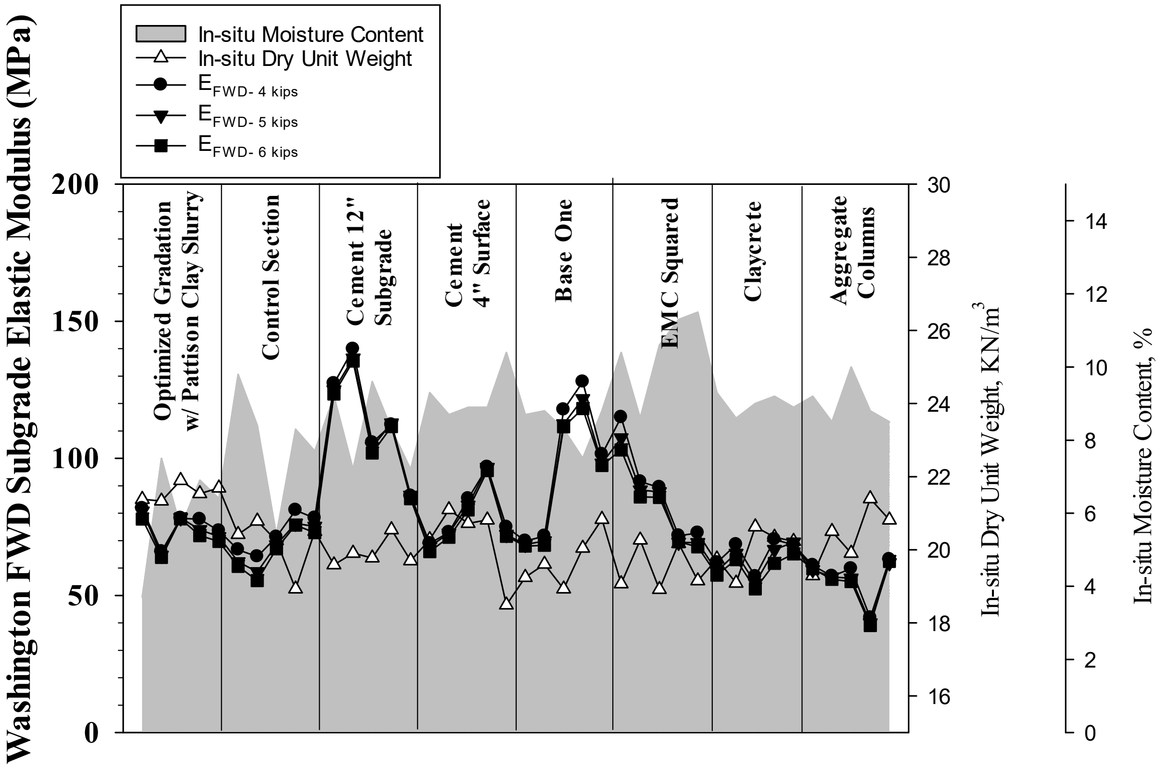


Figure 57 FWD test results for subgrade layer in Washington County

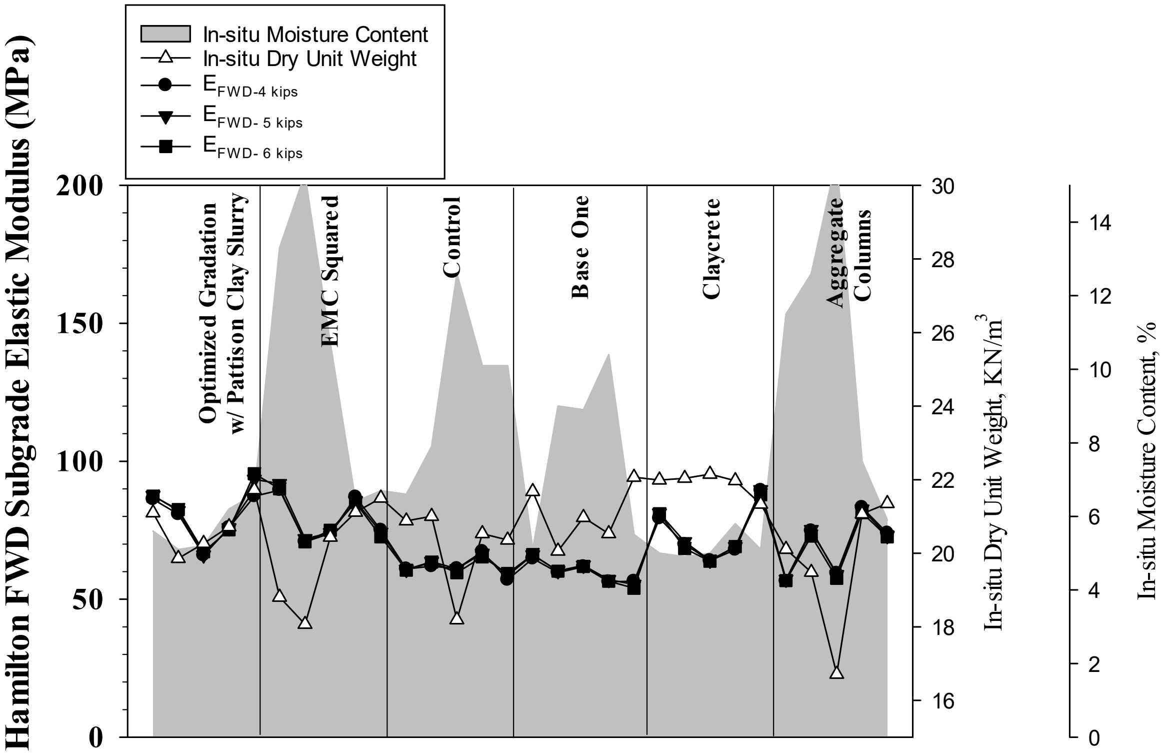


Figure 58 FWD test results for subgrade layer in Hamilton County

For mechanically stabilization methods, optimized gradation with clay slurry and steel slag can improve the surface course stiffness. After construction, Phoenix steel slag section has higher elastic modulus than Harsco steel slag section. The surface course stiffness of Harsco steel slag section increased and Phoenix steel slag section decreased with time. The possible reason is that more large particles of Phoenix steel slag were moved to sides by passing traffics since it contains less fines and cannot bind together.

The chemically stabilization methods only have cement treatment can increase stiffness for surface course and subgrade. The elastic modulus of cement treated subgrade section is also higher for surface course is because stronger subgrade can lead efficient compaction by construction and passing traffic for surface course.

6.2.4 Particle Size Distribution

Representative samples of the surface material during construction were collected to monitor surface course gradation. The soil index properties are summarized in Tables 17-20 for all test sections. Soil index properties indicated that all the chemical sections met their requirements for the concentrated liquid stabilizer applications (section 3.2).

The particles size distribution curves are shown in Figures 59-62. The surface materials' gradation of mechanically stabilized test section in Cherokee County meet the Iowa DOT granular surface aggregate Class A&B specification (4120) (Iowa DOT 2012). The clean aggregate for aggregate columns section fill contains less than 1% fines (passing # 200 sieve). In Howard County, the gradation of surface materials from mechanically stabilized sections meet the Iowa DOT specification except Phoenix slag which is close to the specification and contains less fines. The fill clean aggregate for columns contains less than 1% fines. The surface material of optimized gradation with clay slurry section (mechanically stabilization method) in Washington and Hamilton counties meet the Iowa DOT specification. The fill aggregate for columns in Washington County contains less than 1% fines and the fill aggregate in Hamilton County contains 2.2% fines.

The gradation of surface material in optimized gradation with clay slurry sections in all four counties are close to and slightly lower than the target optimized gradation curves. After compaction during construction and passing traffics, the large particles could break down and get closer to target gradation. The n value of target optimized gradation curve is 0.35 for Cherokee County and 0.4 for other three counties.

Table 17 Soil index properties of the surface materials collected at construction in Cherokee County

	Cherokee County				
Section Name	Aggregate Columns[a]	Optimized Gradation w/ Clay Slurry	RAP	Harsco Slag sections	Phoenix Slag section
Particle-size Distribution Results (ASTM D6913)					
Gravel Content (%)	99.8	54.9	42.1	49.0	52.5
Sand Content (%)	0.2	31.8	53.4	43.1	44.6
Silt Content (%)	0.0	6.3	3.0	6.4	1.7
Clay Content (%)	0.0	7.0	1.5	1.5	1.2
D10 (mm)	10.1620	0.0164	0.4525	0.1614	0.6104
D30 (mm)	12.4736	1.0117	1.5152	1.8705	2.5075
D60 (mm)	15.5550	9.2258	5.1752	6.3757	6.9667
Coefficient of Uniformity, c_u	1.53	563.39	11.43	39.50	11.41
Coefficient of Curvature, c_c	0.98	6.78	0.98	3.40	1.48
Atterberg Limits Test Results (Wasti 1987 & ASTM D4318-17)					
Liquid Limit (%)	NP	28	NP	NP	NP
Plastic Limit (%)		14			
AASHTO and USCS soil classification (ASTM D3282-17 & ASTM D2487-17)					
AASHTO Classification	A-1-a	A-2-6(0)	A-1-a	A-1-a	A-1-a
USCS Classification	GP	GC	GP	GP-GM	GW
Group Name	Poorly graded gravel	Clayey gravel with sand	Poorly graded sand with gravel	Poorly graded gravel with silt and sand	Well-graded gravel with sand

[a]The numbers for aggregate columns section is the information of filled clean aggregates.

Table 18 Soil index properties of the surface materials collected at construction in Howard County

	Howard County				
Section Name	Optimized Gradation w/ Clay Slurry	RAP	Harsco Slag sections	Phoenix Slag section	Aggregate Columns[a]
Particle-size Distribution Results (ASTM D6913)					
Gravel Content (%)	71.6	52.6	56.3	77.6	97.8
Sand Content (%)	14.6	42.4	33.0	22.2	2.2
Silt Content (%)	10.6	4.6	9.4	0.0	0.0
Clay Content (%)	3.2	0.4	1.3	0.2	0.0
D10 (mm)	0.0259	0.5080	0.0690	2.1668	8.4193
D30 (mm)	5.1281	2.6032	0.3381	6.3134	11.6160
D60 (mm)	11.0046	6.6296	7.7217	11.7520	14.8601
Coefficient of Uniformity, c_u	425.45	13.05	111.93	5.42	1.76
Coefficient of Curvature, c_c	92.39	2.01	12.89	1.57	1.08
Atterberg Limits Test Results (Wasti 1987 & ASTM D4318-17)					
Liquid Limit (%)	26	NP	NP	NP	NA
Plastic Limit (%)	17				
AASHTO and USCS soil classification (ASTM D3282-17 & ASTM D2487-17)					
AASHTO Classification	A-2-4(0)	A-1-a	A-1-a	A-1-a	A-1-a
USCS Classification	GC	GW-GM	GP-GM	GW	GP
Group Name	Clayey gravel	Well-graded gravel with silt and sand	Poorly graded gravel with silt and sand	Well-graded gravel with sand	Poorly graded gravel

Table 19 Soil index properties of the surface materials collected at construction in Washington County

	Washington County						
Section Name	Optimized Gradation w/ Clay Slurry	Cement Treated 12" Subgrade	Cement Treated 4" Surface	Base One	EMC Squared	Claycrete	Aggregate Columns[a]
Particle-size Distribution Results (ASTM D6913)							
Gravel Content (%)	55.4	47.7	69.5	33.3	26.9	31.3	96.8
Sand Content (%)	24.5	34.1	27.3	25.3	25.7	31.0	3.2
Silt Content (%)	10.7	13.0	2.7	27.4	30.6	19.7	0.0
Clay Content (%)	9.4	5.2	0.5	14.0	16.8	18.0	0.0
D10 (mm)	0.0056	0.0379	2.3072	0.0018	-	-	9.2516
D30 (mm)	1.3730	1.0582	4.6909	0.0249	0.0202	0.0217	13.1780
D60 (mm)	8.5988	6.1738	9.3598	2.4059	0.3744	1.1821	17.9144
Coefficient of Uniformity, c_u	1535.78	163.09	4.06	1318.91	-	-	1.94
Coefficient of Curvature, c_c	39.16	4.79	1.02	0.14	-	-	1.05
Atterberg Limits Test Results (Wasti 1987 & ASTM D4318-17)							
Liquid Limit (%)	27	NP	NP	27	31	28	NP
Plastic Limit (%)	14			11	15	14	
AASHTO and USCS soil classification (ASTM D3282-17 & ASTM D2487-17)							
AASHTO Classification	A-2-6(0)	A-1-b	A-1-a	A-6(2)	A-6(4)	A-4(0)	A-a-a
USCS Classification	GC	GM	GP	GC	GC	GM	GP
Group Name	Clayey gravel with sand	Silty gravel with sand	Well-graded gravel with sand	Clayey gravel with sand	Clayey gravel with sand	Silty gravel with sand	Poorly graded gravel

Table 20 Soil index properties of the surface materials collected at construction in Hamilton County

	Hamilton County				
Section Name	Optimized Gradation w/ Clay Slurry	Base One	EMC Squared	Claycrete	Aggregate Columns[a]
Particle-size Distribution Results (ASTM D6913)					
Gravel Content (%)	48.2	35.4	43.1	30.6	94.4
Sand Content (%)	23.6	41.7	38.6	52.8	3.4
Silt Content (%)	9.2	11.8	10.0	5.8	2.2
Clay Content (%)	6.7	11.1	8.3	10.8	
D10 (mm)	0.0150	0.0040	0.0090	0.0040	5.9507
D30 (mm)	1.6554	0.2399	0.5618	0.3376	10.0812
D60 (mm)	10.2715	3.5016	5.4767	2.4241	15.8303
Coefficient of Uniformity, c_u	685.23	880.73	608.52	609.39	2.66
Coefficient of Curvature, c_c	17.80	4.14	6.40	11.82	1.08
Atterberg Limits Test Results (Wasti 1987 & ASTM D4318-17)					
Liquid Limit (%)	23	20	26	17	NP
Plastic Limit (%)	13	11	17	9	
AASHTO and USCS soil classification (ASTM D3282-17 & ASTM D2487-17)					
AASHTO Classification	A-2-4(0)	A-2-4(0)	A-2-4(0)	A-2-4(0)	A-1-a
USCS Classification	GC-GM	SC	GC	SC	GP
Group Name	Clayey gravel with sand	Clayey gravel with sand	Clayey gravel with sand	Clayey sand with gravel	Poorly graded gravel

Most of the test sections’ surface material met the Iowa DOT specification for granular surfacing material (4120) (Iowa DOT 2012). The gradation of surface materials collected from Base One and Claycrete sections were out of the range since subgrade was mixed in for the concentrated liquid stabilizers requirements.

The clay content of Base One section surface material is 14.0% in Washington County and 11.1% in Hamilton County (Base One requirement is 8-15%). The clay fraction of Claycrete section surface material is 18.0% in Washington County and 10.8% in Hamilton County (Claycrete requirement is above 10%). The PI of Claycrete section surface material is 14 in Washington County and 8 in Hamilton County (Claycrete requirement is above 7). The CEC values of Claycrete sections in both Washington and Hamilton counties are blow than 400 (252 in Washington, 86.4 in Hamilton).

The gradation of EMC Squared surface material in Washington County suppose similar to below Base and Claycrete sections, contains less fines, since surface should not incorporate subgrade. During the construction, EMC Squared section incorporated some subgrade results the surface material contains more fines, gradation curve above Base One and Claycrete sections.

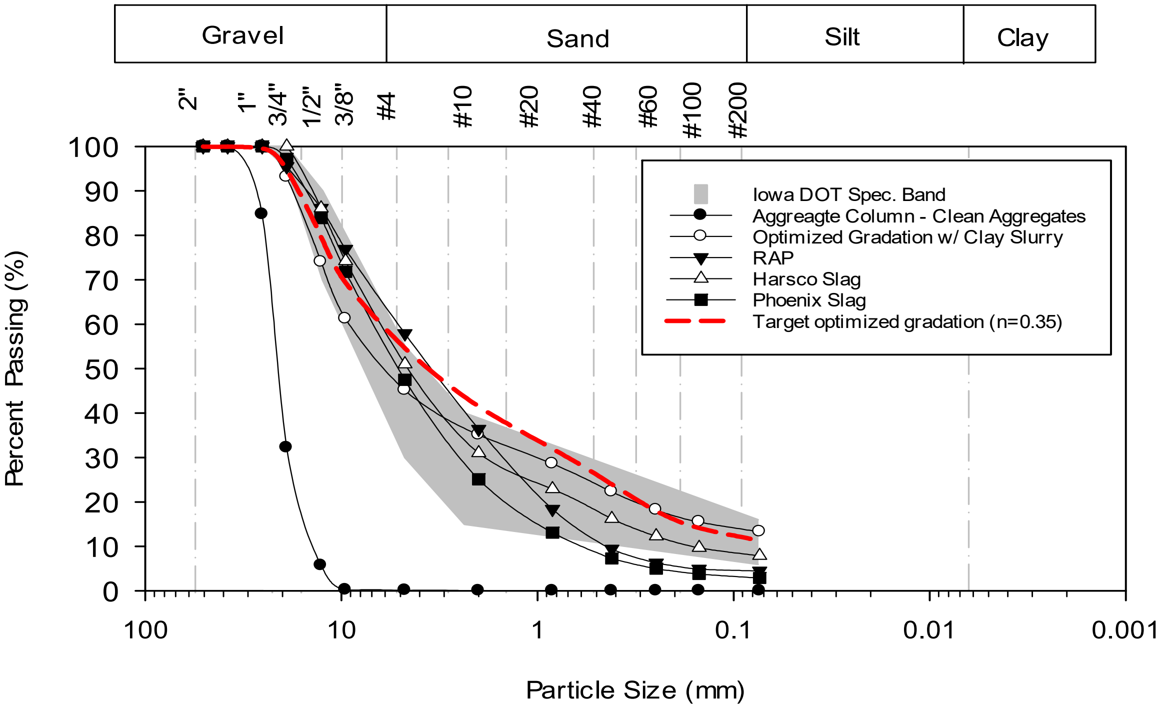


Figure 59 Particle-size distribution curves of materials collected in Cherokee county at construction

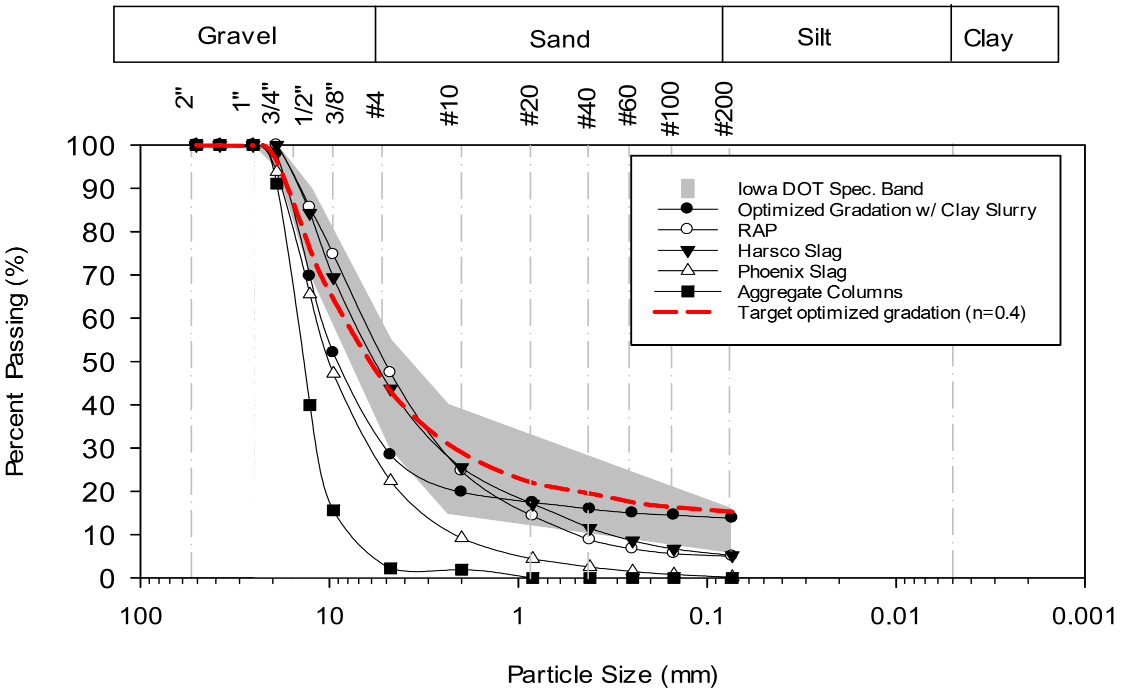


Figure 60 Particle-size distribution curves of materials collected in Howard County at construction

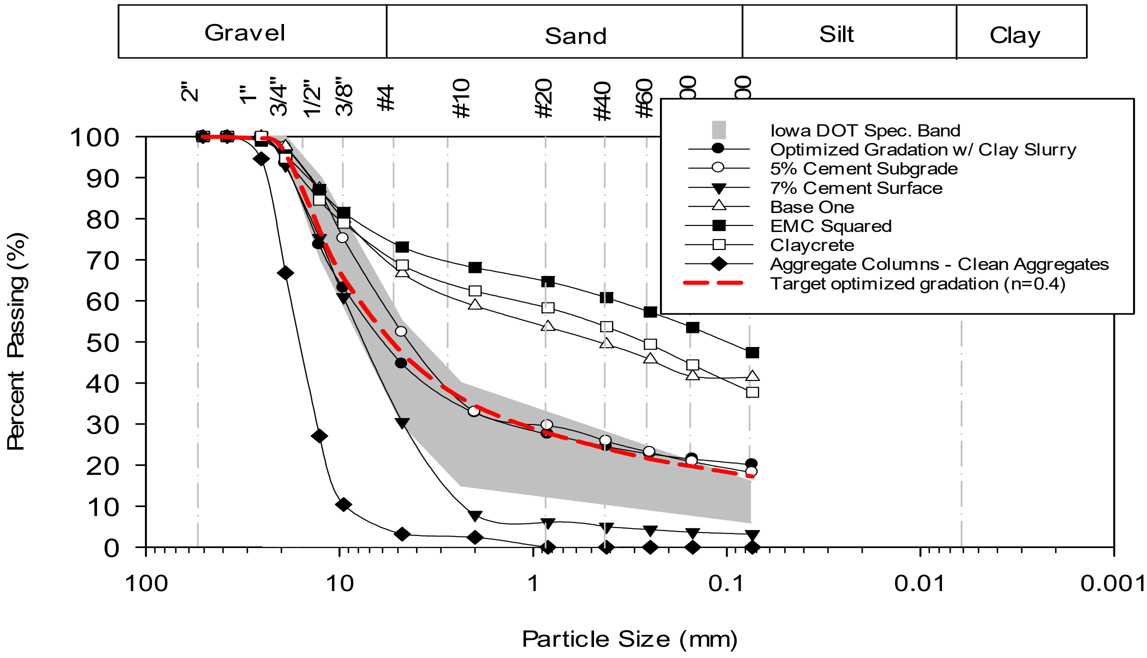


Figure 61 Particle-Size distribution curves of materials collected in Washington County at construction

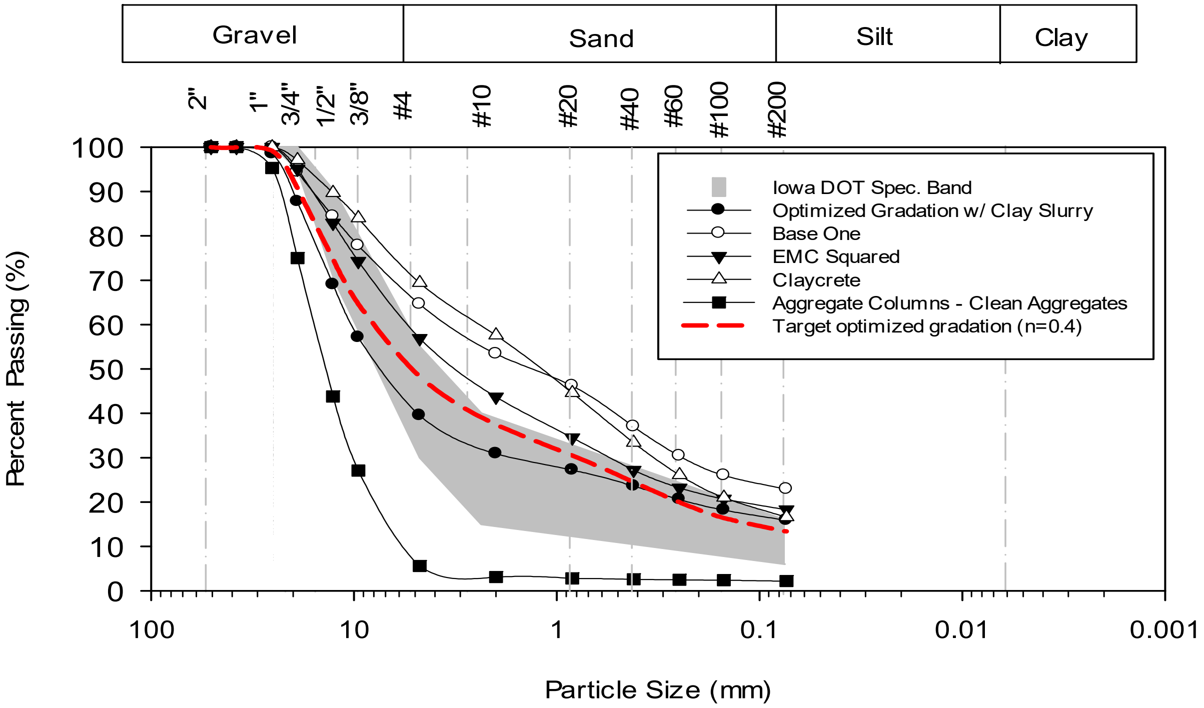


Figure 62 Particle-size distribution curves of materials collected in Hamilton County at construction

6.2.5 Dustometer Results

The dustometer tests were performed on October 30, 2018 on the Howard County, November 13, 2018 on the Cherokee County and the Hamilton County, and November 14, 2018 on the Washington County. The results are shown in Figure 63. The parameter used for comparisons between each test section was equivalent to gram dust generated per mile. Since the road moisture condition varied for different sites, the fugitive dust generated varied a lot between counties. In Howard County, the aggregate columns section creates the most dust and optimized gradation with clay slurry section creates the least dust. In Cherokee County, the control section creates the most dust and the Harsco steel sections creates the least dust. In Hamilton County, the aggregate columns section creates the most dust and EMC Squared section creates the least dust. In Washington County, EMC Squared section creates the least dust and other sections creates same level dust. The weather information was recorded when the dustometer performed (Table 21).

Table 21 Weather information for dustometer

Location	Test Date	Temperature (°C)	Humidity (%)	Wind Speed, (km/h)	Precipitation. in Past 3 days
Cherokee County	11/23/2018	-3	68%	8	1 in. snow (11/11/2018)
Howard County	10/30/2018	7	70%	16	No
Washington County	11/14/2018	-5	93%	8	No
Hamilton County	11/13/2018	-7	80%	16	No

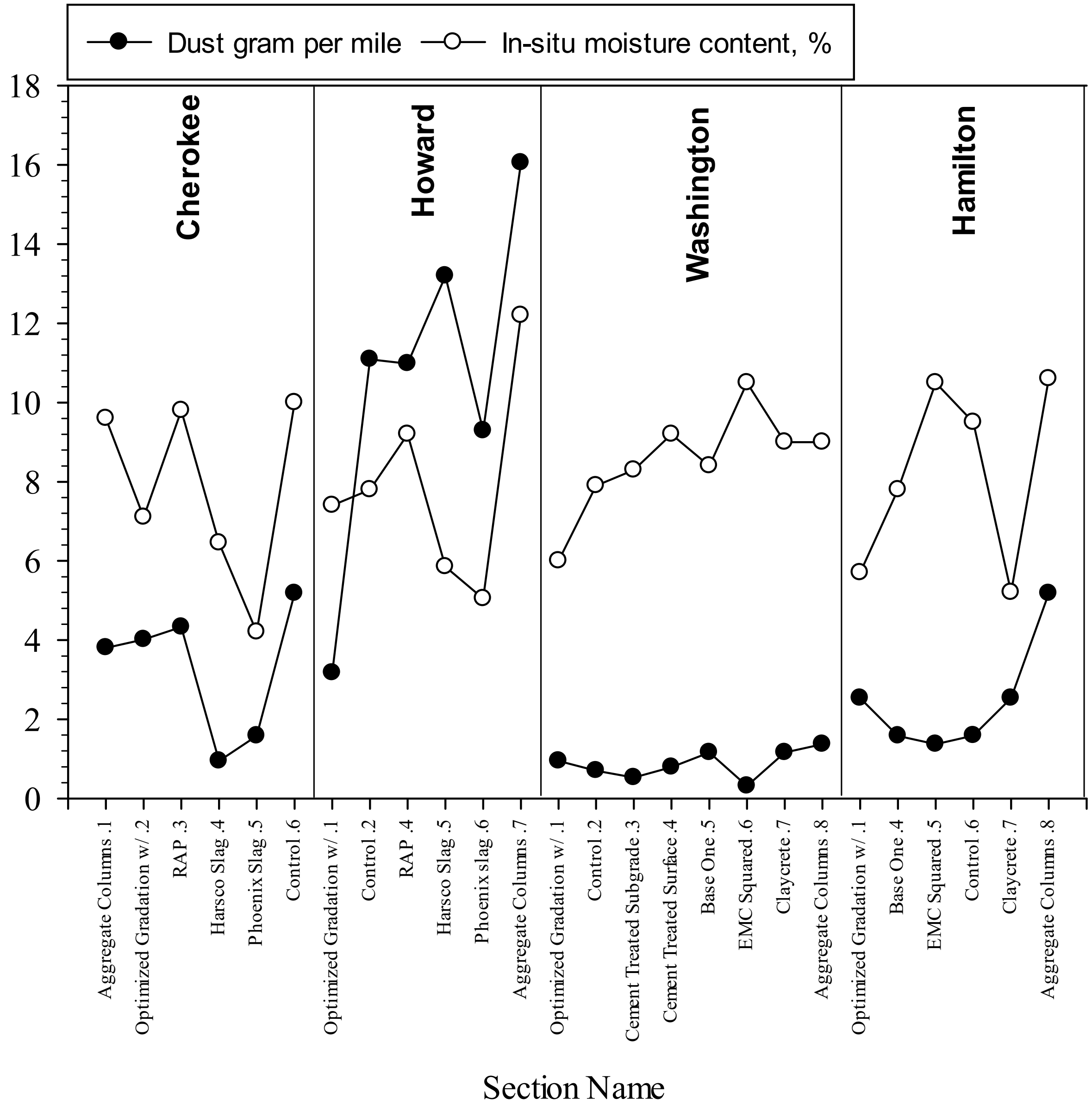


Figure 63 Dustometer results

6.2.6 Visual Surveys with Photographs

The photographs were taken during DCP and LWD testing to evaluate the roadway surface conditions. Figure 64 includes the pictures taken in Cherokee County and Howard County, which consist of mechanically stabilized test sections (aggregate columns, optimized gradation with clay slurry, ground tire rubber, RAP, 2-in. slag surface, and 4-in. slag surface). Figure 65 includes the pictures taken in Washington County and Hamilton County, which has all the chemical stabilized test sections and the two mechanically stabilized test sections (Base One, EMC Squared, Claycrete, aggregate columns, and optimized gradation with clay slurry). Pictures showed that there was no obvious rutting or other major performance failures on test sections few weeks/months after their constructions were completed. Only few potholes appeared in the optimized gradation with clay slurry section in the Cherokee county and 4” Harsco steel slag section in the Howard County. Phoenix steel slag sections have more loose aggregates on sides comparing to Harsco steel slag sections.

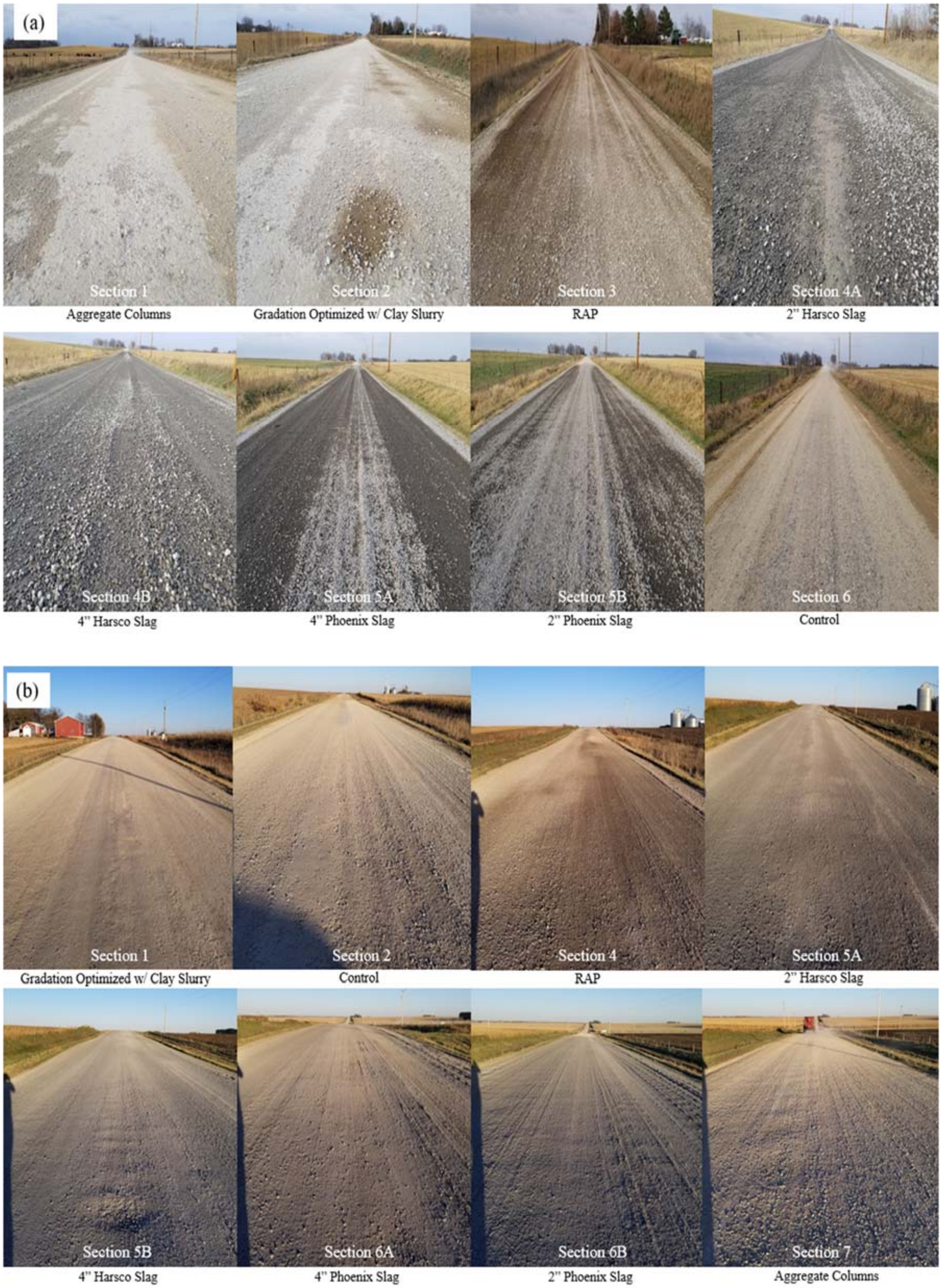


Figure 64 Survey photos of test sections in (a) Cherokee county and (b) Howard County

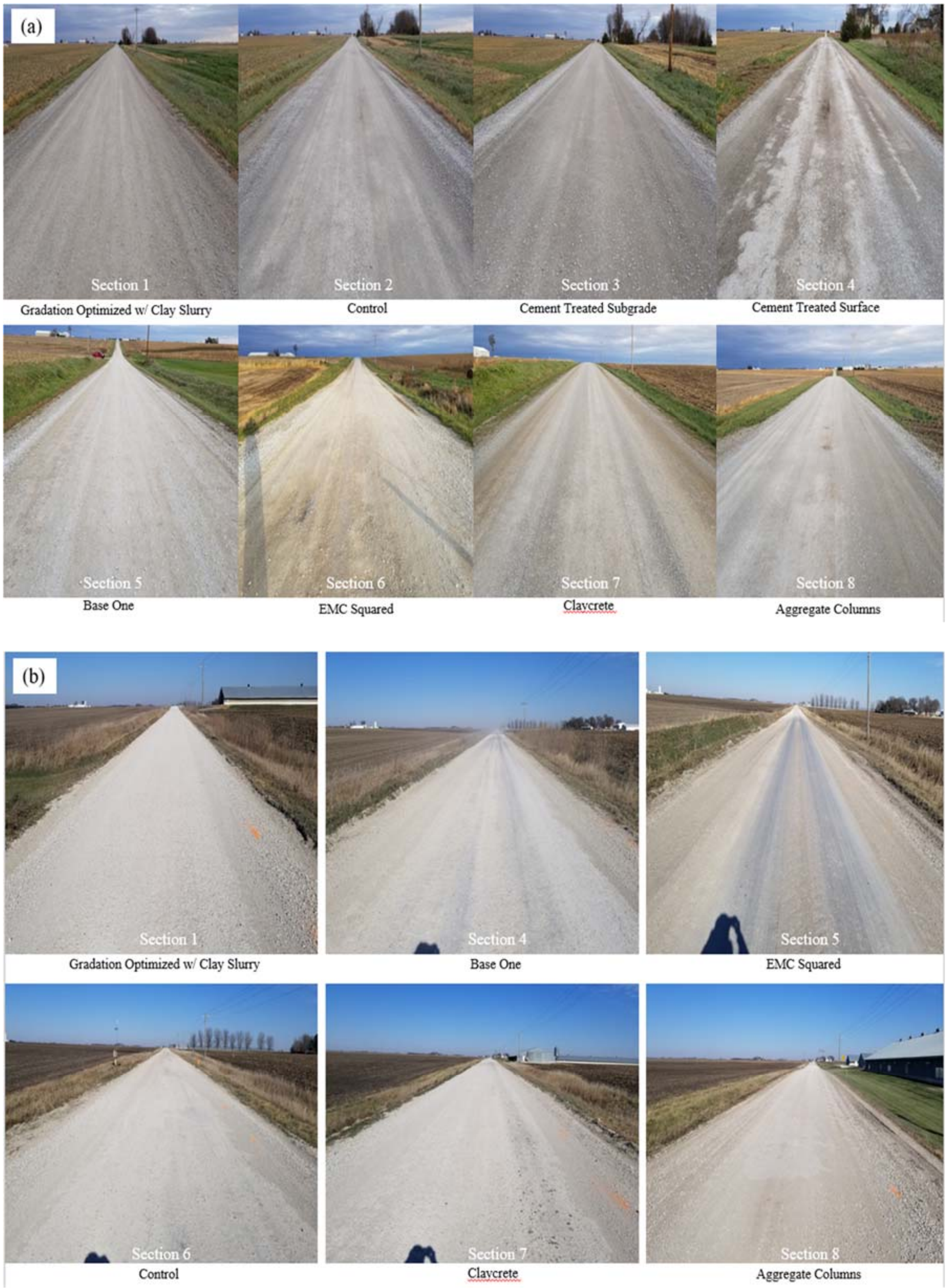


Figure 65 Survey photos of test sections in (a) Washington county and (b) Hamilton County

CHAPTER 7. CONCLUSIONS AND RECOMMEDATIONS

7.1 Conclusions

All of the demonstration sections can be stabilized well and have good quality surfaces immediately after construction except the section utilized ground tire rubber method. Only 20 % ground tire rubber by volume was incorporated in the bottom 50.8 mm (2 in.) of a 101.6 mm (4 in.) thick surface course, but the ground tire rubber cannot stay in the bottom part results a soft, unstable surface that had to be removed. Applying clay slurry to ground tire rubber section was tried to bind particles, but it did not farm up after couple days.

The mechanical stabilization methods can be easily implemented by county secondary roads departments with available equipment and crews. The clay slurry results in a rather wet construction procedure, but the surface is passable by the end of construction. Disk plow harrow was used in Cherokee County for RAP section, it could allow county engineers efficiently mix surface course materials to uniform.

The auger used for aggregate columns installation was always pasted on sticky clay after every drill. Manually cleaning the auger was time consuming but necessary after each drilling in some counties, and resulted installation process slowly. The clean aggregate fill has to be done immediately after the hole was drilled in case collapse, because to the fully saturated subgrade was soft.

Chemical stabilization methods require using RoadHog reclaimer to mix the cement treated surface course and liquid stabilizers effectively and uniformly. The existing of boulders and cobbles in top 152.4 mm (6 in.) could slow the work and cause damage to the bay door hinges.

For liquid stabilizer sections, to adjust the surface course material incorporated existing subgrade until workable and meet the optimal moisture content, water was added during the construction. But the surface was soft at the end of construction and easily has rutting problem, following shaping and compaction were needed in the few days after construction.

For cement stabilization methods, a power spreader truck was necessary to apply cement power and a sheepsfoot vibratory compactor was needed to compact the cement treated subgrade. The roadway has to be closed at least a night for stabilizing.

Both Harsco slag and Phoenix slag sections’ surface course performed like unbound material at the end of construction. Fourteen days were consumed for self-stabilization before DCP test conducted for slag sections in Cherokee County, 68 days were consumed for slag sections in Howard County. Both Harsco slag sections and Phoenix slag section performed higher DCP-CBR$_{AGG}$ values in Howard County which has longer time to self-stabilize. Phoenix slag sections exhibited more loose aggregate than Harsco slag section.

Cement mixing can greatly improve the DCP-CBR and elastic modulus for both surface course aggregates and subgrade. Cement treated 304.8 mm (12 in.) subgrade 4% by weight and cemented treated 101.6 mm (4 in.) surface 7 % by weight performed same improvement for composite elastic modulus.

The surface course materials for most of mechanically stabilized sections as well as cement treated sections are fitted or close to the Iowa DOT specification (4120) (Iowa DOT 2012).

Incorporating clay could increase materials' shear strength in unconfined condition but decrease it in confined condition. The incorporated existing subgrade for chemical stabilizations methods to meet the required binder content was also increasing the silt content which result that surface course materials out of Iowa DOT specification for granular surfacing material and low in-situ strength.

Optimized gradation with clay slurry comparing with control section shows improvement of DCP-CBR$_{AGG}$ in Cherokee and Hamilton counties, no improvement in Washington and Howard counties. But the optimized gradation with clay slurry section in Howard County still performed better than RAP and aggregate columns, as good as Phoenix slag. It also shows increasing of surface course elastic modulus or composite elastic modulus for all counties.

All concentrated liquid stabilizers don't show any obvious improvement at the end of construction with current gradations.

All of the demonstration sections performed stiff, smooth and good quality surfaces with few potholes after a period of construction except the section utilized ground tire rubber method.

7.2 Recommendations

Steel slag material performed unbound at early time, adding clayey fines could reduce loose aggregate and protect surface course during self-stabilization period. Mixing clay products for liquid stabilizer sections instead of nature subgrade could reduce none cohesive fine incorporated into surface layer, and it will result surface materials' gradation fitting Iowa DOT specification (2012) and closing to the optimal gradation. This may lead more obvious improvement to shear strength and elastic modulus.

Disc plow harrow could also use for optimized gradation with clay slurry, it is fast and effective for mixing surface course materials.

The best proportion of clay content could be determined for optimized gradation sections according to the particle distribution. Put several loads of dry aggregate materials would be an efficient way to solve the wet roadway surface at the end of construction.

REFFERENCES

AASHTO (1993). *AASHTO guide for design of pavement structures 1993*, American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO M 145-91 (2004). *Classification of soils and soil-aggregate mixtures for highway construction purposes*, American Association of State Highway and Transportation Officials, Washington, D.C.

Ashmawy, A., McDonald, R., Carreon, D., & Atalay, F. (2006). *Stabilization of marginal soils using recycled materials* (No. BD-544-4).

ASTM C136/C136M – 14 (2014). *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*, ASTM International, West Conshohocken, PA.

ASTM D1883 – 16 (2016). *Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils*, ASTM International, West Conshohocken, PA.

ASTM D2166/D2166M – 16 (2016). *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil1*, ASTM International, West Conshohocken, PA.

ASTM D2487 – 17 (2017). *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, ASTM International, West Conshohocken, PA.

ASTM D3282 – 15 (2015). *Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes*, ASTM International, West Conshohocken, PA.

ASTM D4318 – 17e1 (2017). *Standard Test Methods for Liquid, Plastic Limits, and Plasticity Index of Soils*, ASTM International, West Conshohocken, PA.

ASTM D4718 – 15 (2015). *Standard Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles*, ASTM International, West Conshohocken, PA.

ASTM D6913/D6913M -17 (2017). *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*, ASTM International, West Conshohocken, PA.

ASTM D6938 - 17a (2017). *Standard Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)*, ASTM International, West Conshohocken, PA.

ASTM D6951/D6951M – 18 (2018). *Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications*, ASTM International, West Conshohocken, PA.

ASTM D698 – 12e2 (2012). *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN-m/m3))*, ASTM International, West Conshohocken, PA.

ASTM D7928 – 17 (2017). *Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis*, ASTM International, West Conshohocken, PA.

ASTM E2583 - 07 (2015). *Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)*, ASTM International, West Conshohocken, PA.

Bosscher, P. J., Edil, T. B., & Kuraoka, S. (1997). Design of highway embankments using tire chips. *Journal of geotechnical and geoenvironmental engineering*, *123*(4), 295-304.

Boussinesq, J. (1885). *Application des potentiels à l'étude de l'équilibre et du mouvement des solides élastiques: principalement au calcul des déformations et des pressions que produisent, dans ces solides, des efforts quelconques exercés sur une petite partie de leur surface ou de leur intérieur: mémoire suivi de notes étendues sur divers points de physique, mathematique et d'analyse* (Vol. 4). Gauthier-Villars.

Crovetti, J. A., Shahin, M. Y., & Touma, B. E. (1989). Comparison of two falling weight deflectometer devices, Dynatest 8000 and KUAB 2M-FWD. In *Nondestructive Testing of Pavements and Backcalculation of Moduli*. ASTM International.

Fang, H. (1991), *Foundation Engineering Handbook*, 2nd ed., Van Nostrand Reinhold, New York, pp. 170–171.

Hassona, F. A., & Marei, N. A. (2003) Shredded Waste Tires as a Stabilizing Material for Unpaved Roads. *Mansoura Engineering Journal* (MEJ), Vol.31, No.1, March 2003. 11 pp.

Iowa DOT (2012). "Standard Specifications for Highway and Bridge Construction." Iowa Department of Transportation, Ames, IA.

Jahren, C. T., White, D. J., Phan, T. H., Westercamp, C., & Becker, P. (2011). *Stabilization Procedures to Mitigate Edge Rutting for Granular Shoulders–Phase II* (No. IHRB Project TR-591). Iowa. Dept. of Transportation. Highway Division.

Henry, K. S., Olson, J. P., Farrington, S. P., & Lens, J. (2005). *Improved performance of unpaved roads during spring thaw* (No. ERDC/CRREL-TR-05-1). ENGINEER RESEARCH AND DEVELOPMENT CENTER HANOVER NH COLD REGIONS RESEARCH AND ENGINEERING LAB.

Koch, S., Ksaibati, K., & Huntington, G. (2011). Performance of recycled asphalt pavement in gravel roads. *Transportation Research Record: Journal of the Transportation Research Board*, (2204), 221-229.

Li, C., Ashlock, J. C., Cetin, B., Jahren, C. T., & Goetz, V. (2018). Performance-based design method for gradation and plasticity of granular road surface materials. *Transportation Research Record*, 0361198118787372.

Li, C., Ashlock, J. C., Cetin, B., & Jahren, C. (2018) "Feasibility of Granular Road and Shoulder Recycling", Final Report, IHRB Project TR-685, 182 pp., April 2018. https://intrans.iastate.edu/research/completed/feasibility-of-gravel-road-and-shoulder-recycling/

Li, C., Ashlock, J. C., White, D. J., & Vennapusa, P. (2015) "Low-Cost Rural Surface Alternatives: Demonstration Project." IHRB Project TR-664, InTrans Project 13-479, Ames, Iowa, 242 pgs., 2018, https://intrans.iastate.edu/research/completed/low-cost-rural-surface-alternatives-demonstration-project-2/

Mathur, S., Soni, S. K., & Murty, A. V. S. R. (1999). Utilization of industrial wastes in low-volume roads. *Transportation research record*, *1652*(1), 246-256.

McMullen, B. (2000) SOILpak for vegetable growers [M]. NSW Agriculture, Orange. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/167533/soipak-vegetable-prelim.pdf

Odemark, N. (1949). *Investigations as to the Elastic Properties of Soils and Design of Pavements According to the Theory of Elasticity* (No. Meddelande 77).

Oflaherty, C. A., Edgar, C. E., & Davidson, D. T. (1963). Iowa State Compaction Apparatus for Measurement of Small Soil Samples. *Highway Research Record*, (22).

Ramaji, A. E. (2012). A review on the soil stabilization using low-cost methods. *Journal of Applied Sciences Research*, *8*(4), 2193-2196.

Road Pavement Products PTY LTD, (2017). *Claycrete Application and Road Construction Manual*.

Sanders, T. G., & Addo, J. Q. (2000). Experimental road dust measurement device. *Journal of transportation engineering*, *126*(6), 530-535.

SSPCo, (2017) *EMC SQUARED Construction Handbook & General Information*, Soil Stabilization Products Co., Inc., Technical Bulletin No. 857 5. EMC^2/EMS 3/17, 2017.

SSPCo, (2014) *Comparison of FDR road projects using EMC Squared Stabilizer with a mill and overlay project*, Soil Stabilization Products Co., Inc., http://www.sspco.com/docs/EMC/Mescalero8763.pdf.

Stamp, D. H., & Mooney, M. A. (2013). Influence of lightweight deflectometer characteristics on deflection measurement. *Geotechnical Testing Journal*, *36*(2), 216-226.

SUDAS (2015). *Design Manual Chapter 6 – Geotechnical, 6E-1 – Subgrade Design and Construction*, 2013 Edition, Statewide Urban Design and Specifications (SUDAS), Institute of Transportation, Iowa State University, Ames, IA.

TEAMLAB (2015) *T15 Base One Safety Data Sheet (SDS)*, Team Laboratory Chemical Corp, http://www.teamlab.net/product?id=base-one

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). *Soil mechanics in engineering practice*. John Wiley & Sons.

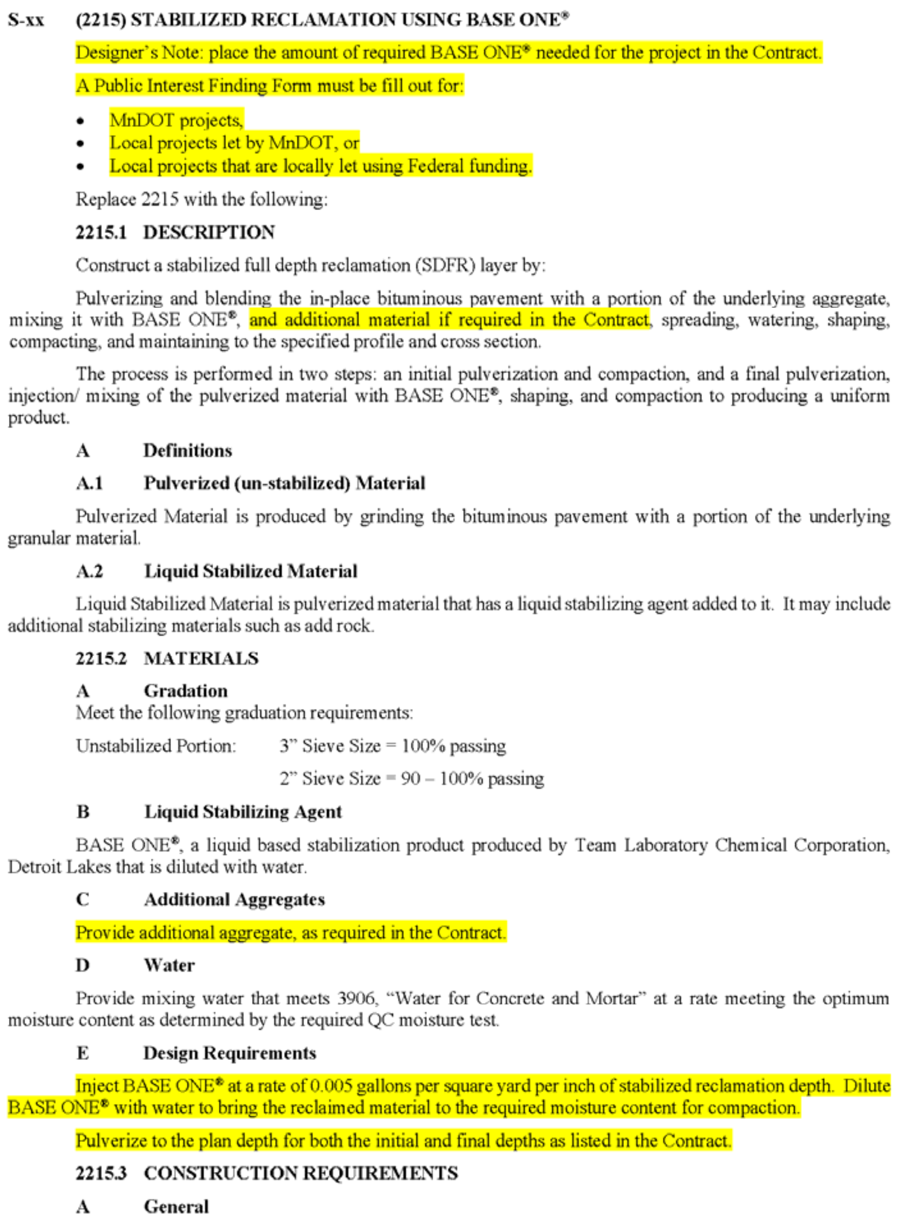
Vennapusa, P. K., & White, D. J. (2009). Comparison of light weight deflectometer measurements for pavement foundation materials. *Geotechnical Testing Journal*, *32*(3), 1-13.

Wasti, Y. (1987) Liquid and Plastic Limits as Determined from the Fall Cone and the Casagrande Methods. *Geotechnical Testing Journal*, Vol. 10, No. 1, 1987, pp. 26 30, https://doi.org/10.1520/GTJ10135J. ISSN 0149-6115

White, D. & Vennapusa, P., (2013). *Low-cost rural surface alternatives: literature review and recommendations*. Ames, IA: Iowa Department of Transportation, Project TR-632. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1027&context=intrans_reports

Zhijun, H., Bo, L., & Changxin, S. (2003). Study of Characteristic of Claycrete Clay Soil Stabiliser Improved Soil Under Thawing Condition.

APPENDIX A. BASE ONE APPLICATION INSTRUCTION



S-xx (2215) STABILIZED RECLAMATION USING BASE ONE®

Designer's Note: place the amount of required BASE ONE® needed for the project in the Contract.

A Public Interest Finding Form must be fill out for:

- MnDOT projects,
- Local projects let by MnDOT, or
- Local projects that are locally let using Federal funding.

Replace 2215 with the following:

2215.1 DESCRIPTION

Construct a stabilized full depth reclamation (SDFR) layer by:

Pulverizing and blending the in-place bituminous pavement with a portion of the underlying aggregate, mixing it with BASE ONE®, and additional material if required in the Contract, spreading, watering, shaping, compacting, and maintaining to the specified profile and cross section.

The process is performed in two steps: an initial pulverization and compaction, and a final pulverization, injection/ mixing of the pulverized material with BASE ONE®, shaping, and compaction to producing a uniform product.

A Definitions

A.1 Pulverized (un-stabilized) Material

Pulverized Material is produced by grinding the bituminous pavement with a portion of the underlying granular material.

A.2 Liquid Stabilized Material

Liquid Stabilized Material is pulverized material that has a liquid stabilizing agent added to it. It may include additional stabilizing materials such as add rock.

2215.2 MATERIALS

A Gradation

Meet the following graduation requirements:

Unstabilized Portion: 3" Sieve Size = 100% passing

2" Sieve Size = 90 – 100% passing

B Liquid Stabilizing Agent

BASE ONE®, a liquid based stabilization product produced by Team Laboratory Chemical Corporation, Detroit Lakes that is diluted with water.

C Additional Aggregates

Provide additional aggregate, as required in the Contract.

D Water

Provide mixing water that meets 3906, "Water for Concrete and Mortar" at a rate meeting the optimum moisture content as determined by the required QC moisture test.

E Design Requirements

Inject BASE ONE® at a rate of 0.005 gallons per square yard per inch of stabilized reclamation depth. Dilute BASE ONE® with water to bring the reclaimed material to the required moisture content for compaction.

Pulverize to the plan depth for both the initial and final depths as listed in the Contract.

2215.3 CONSTRUCTION REQUIREMENTS

A General

Figure 66 MnDOT stabilized full depth reclamation Base One specification

APPENDIX B. IOWA COUNTY TRAFFIC MAP

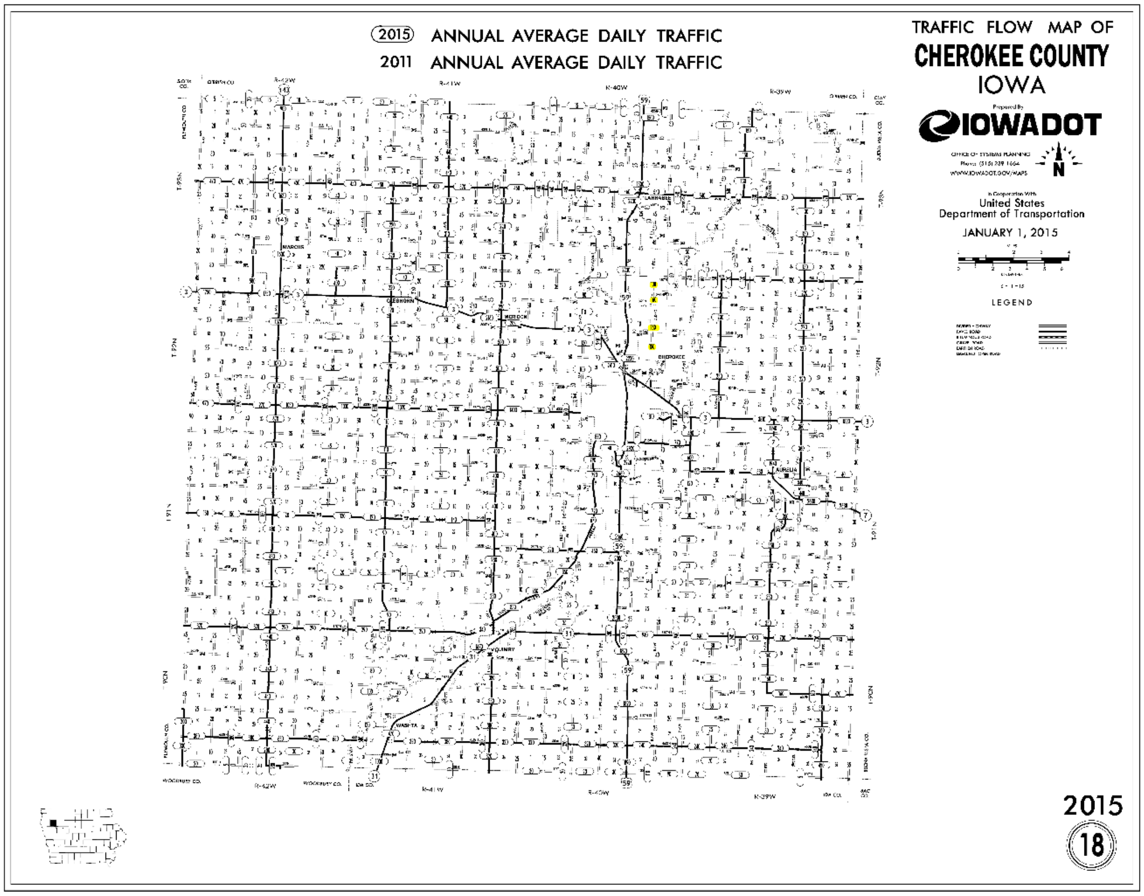


Figure 67 Cherokee County traffic map

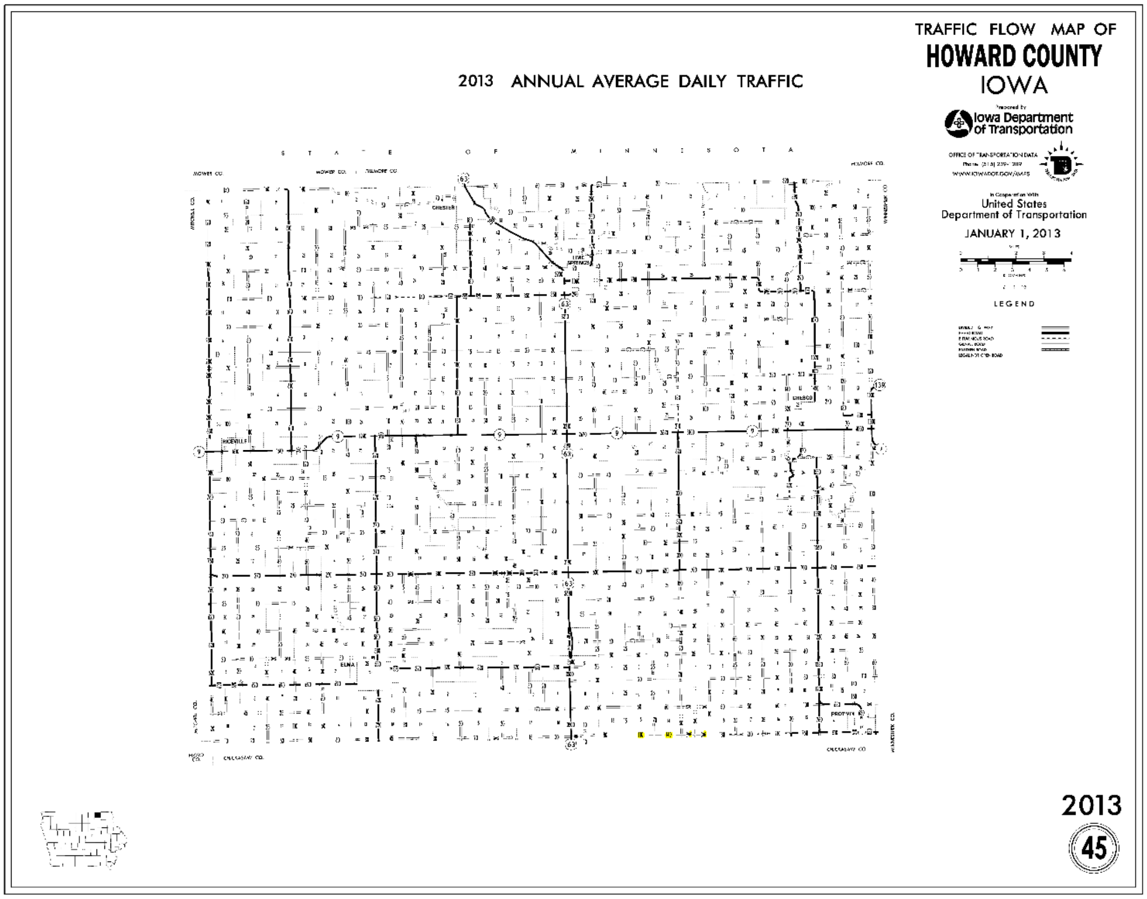


Figure 68 Howard County traffic map

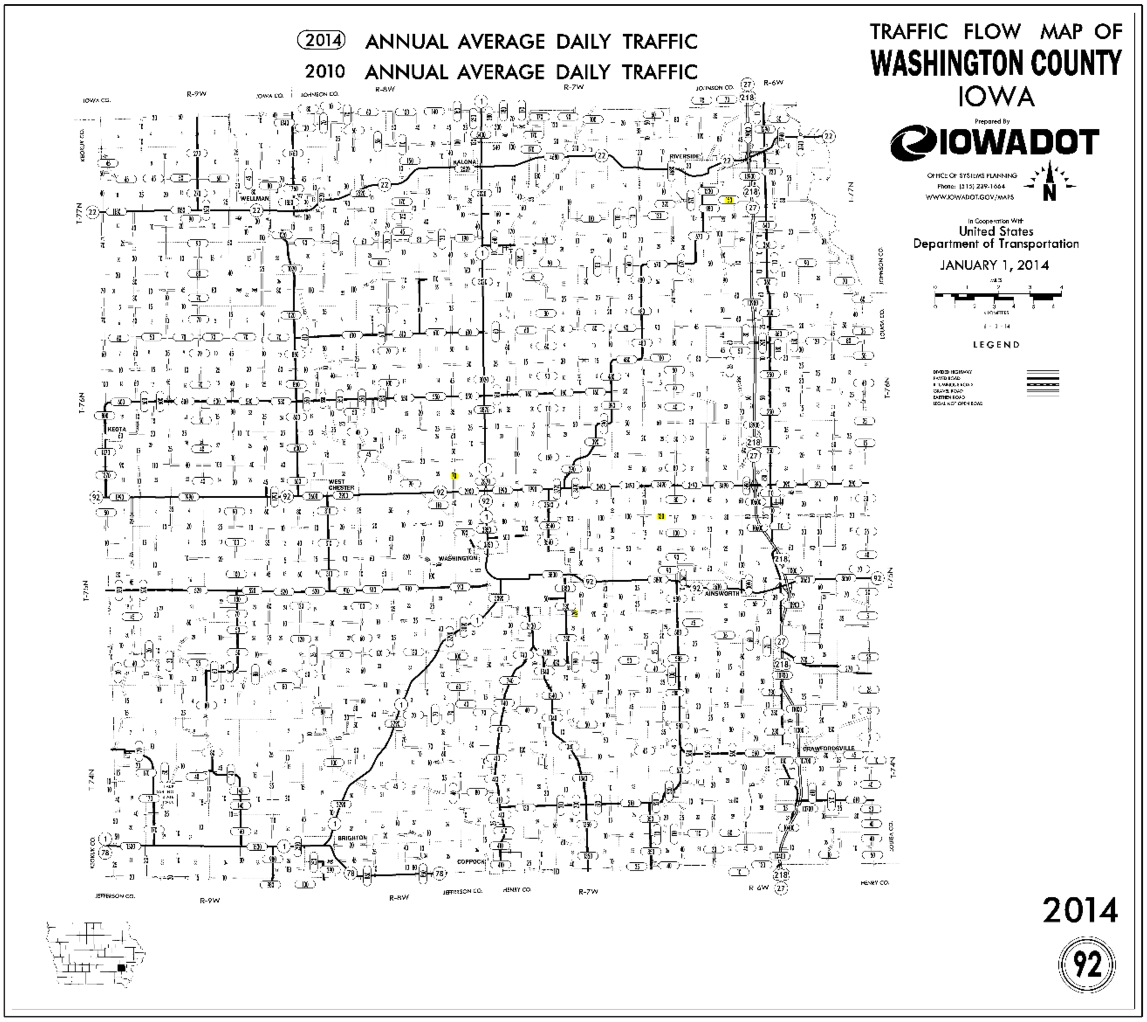


Figure 69 Washington County traffic map

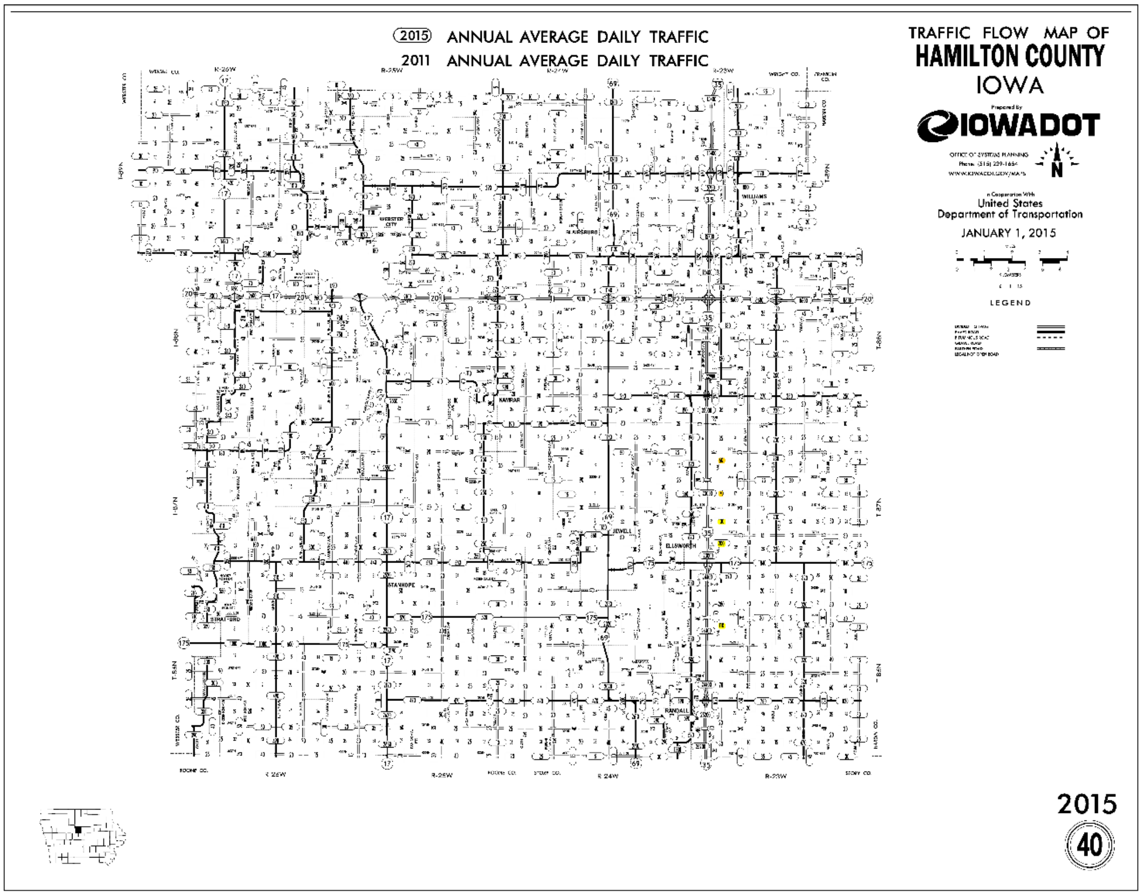
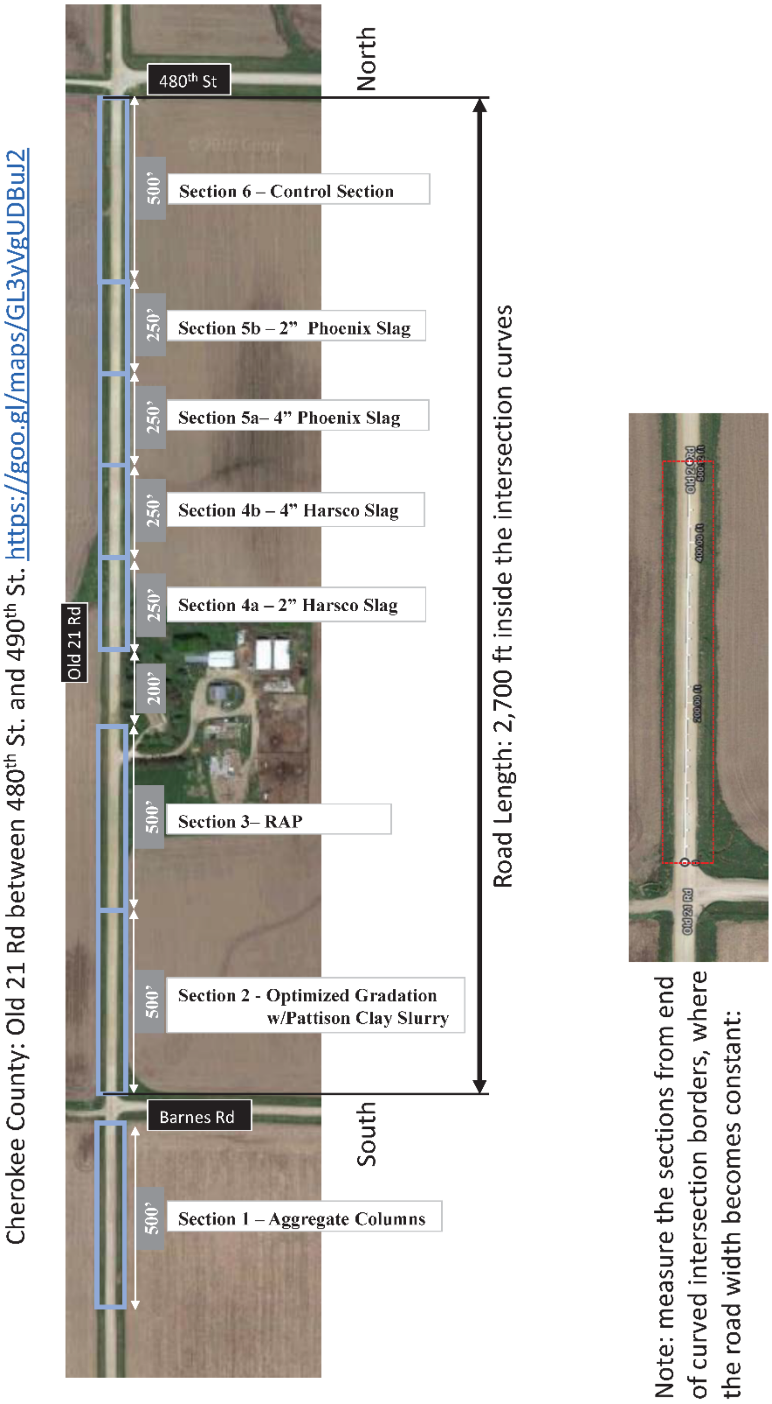


Figure 70 Hamilton County traffic map

APPENDIX C. TEST SECTIONS LAYOUT

Cherokee County Test Sections for TR-721 Phase III Project



Note: measure the sections from end of curved intersection borders, where the road width becomes constant:

Figure 71 Cherokee County test sections layout

Howard County Test Sections for TR-721 Phase III Project

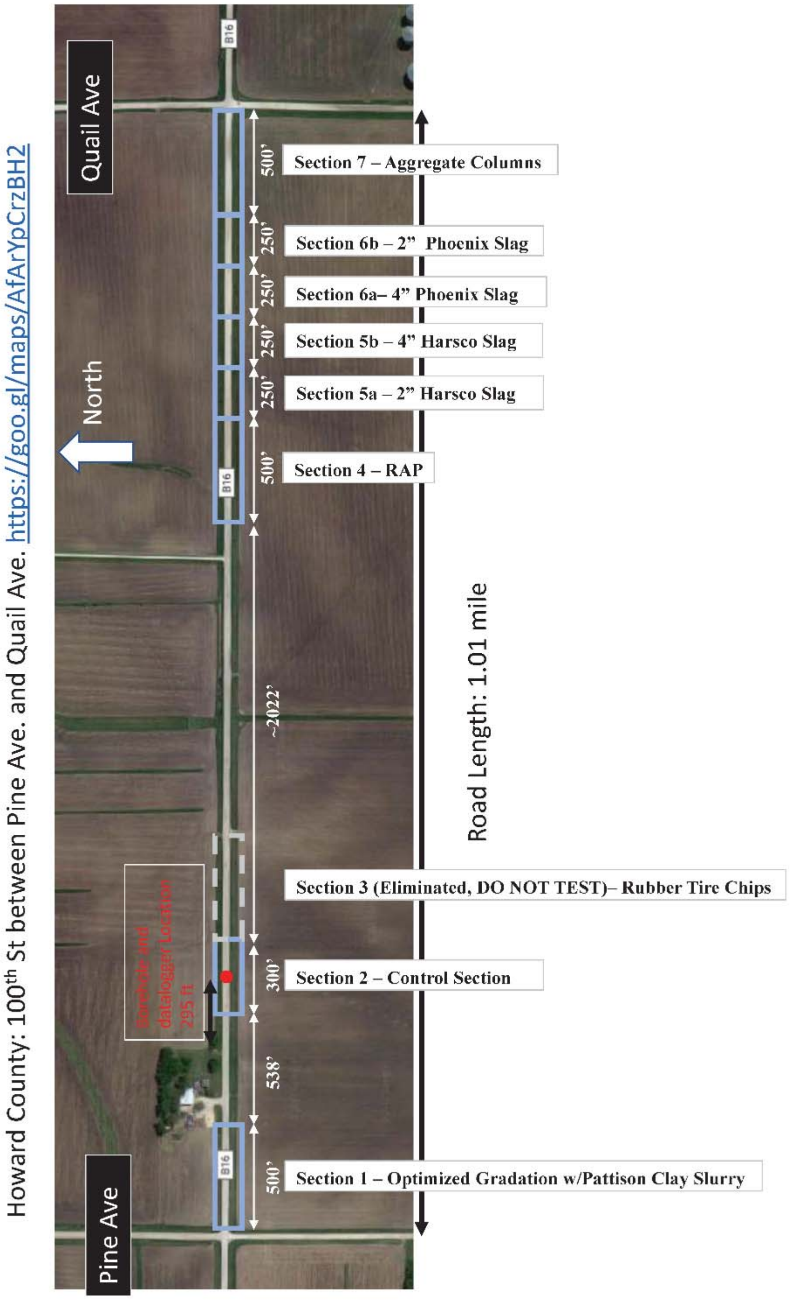


Figure 72 Howard County test sections layout

Washington County Test Sections for TR-721 Phase III Project

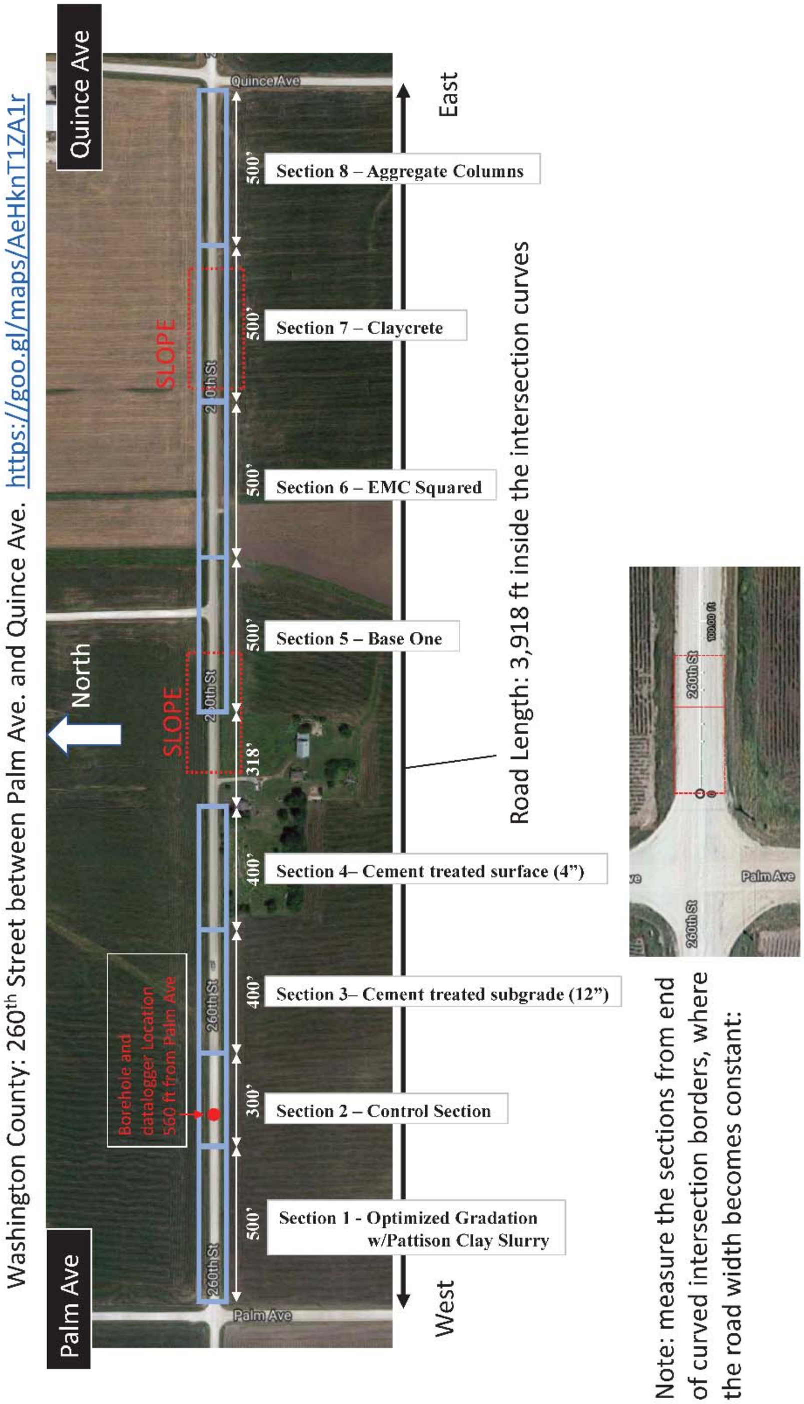
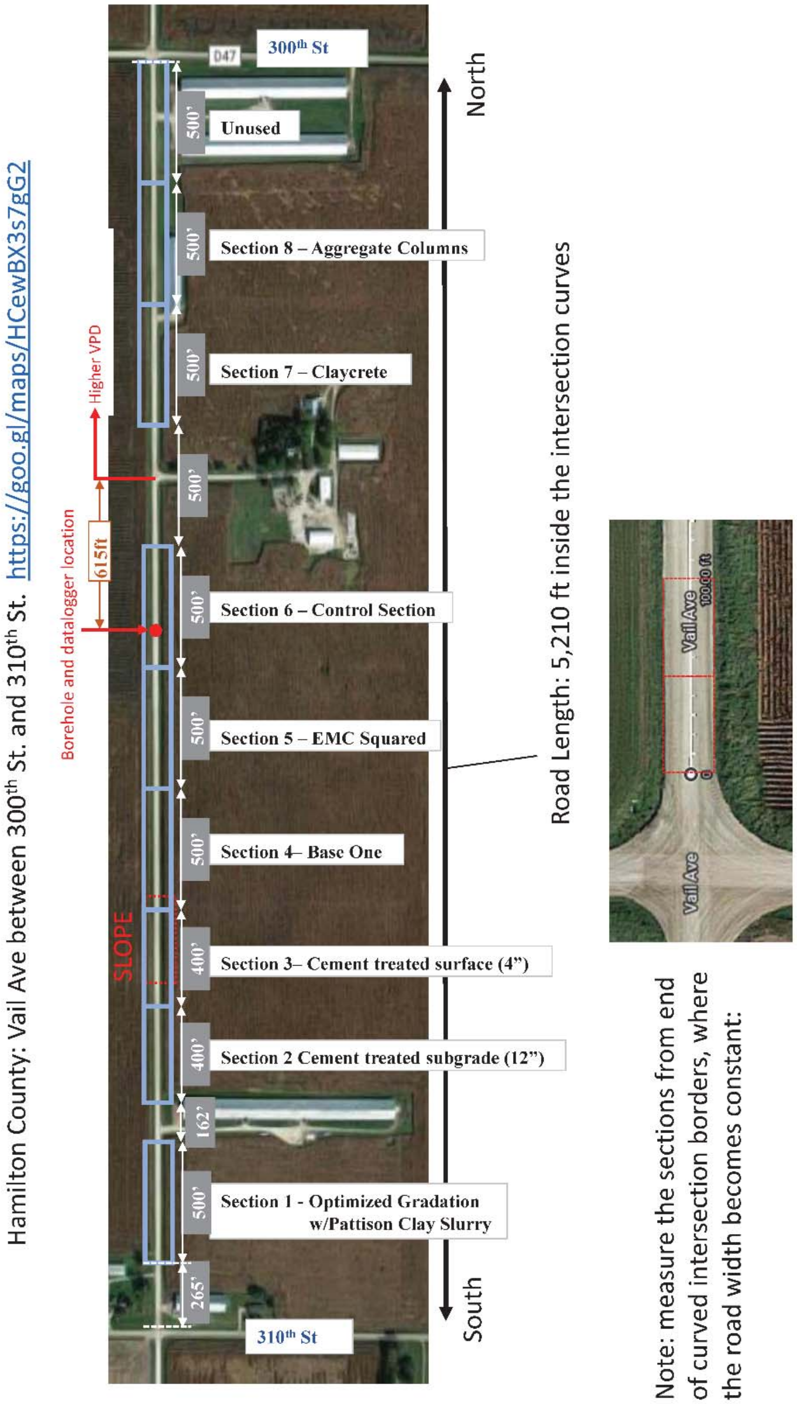


Figure 73 Washington County test sections layout

Hamilton County Test Sections for TR-721 Phase III Project



Hamilton County: Vail Ave between 300th St. and 310th St. https://goo.gl/maps/HCewBX3s7gG2

Note: measure the sections from end of curved intersection borders, where the road width becomes constant:

Figure 74 Hamilton County test sections layout

APPENDIX D. TEST SECTIONS LOCATION

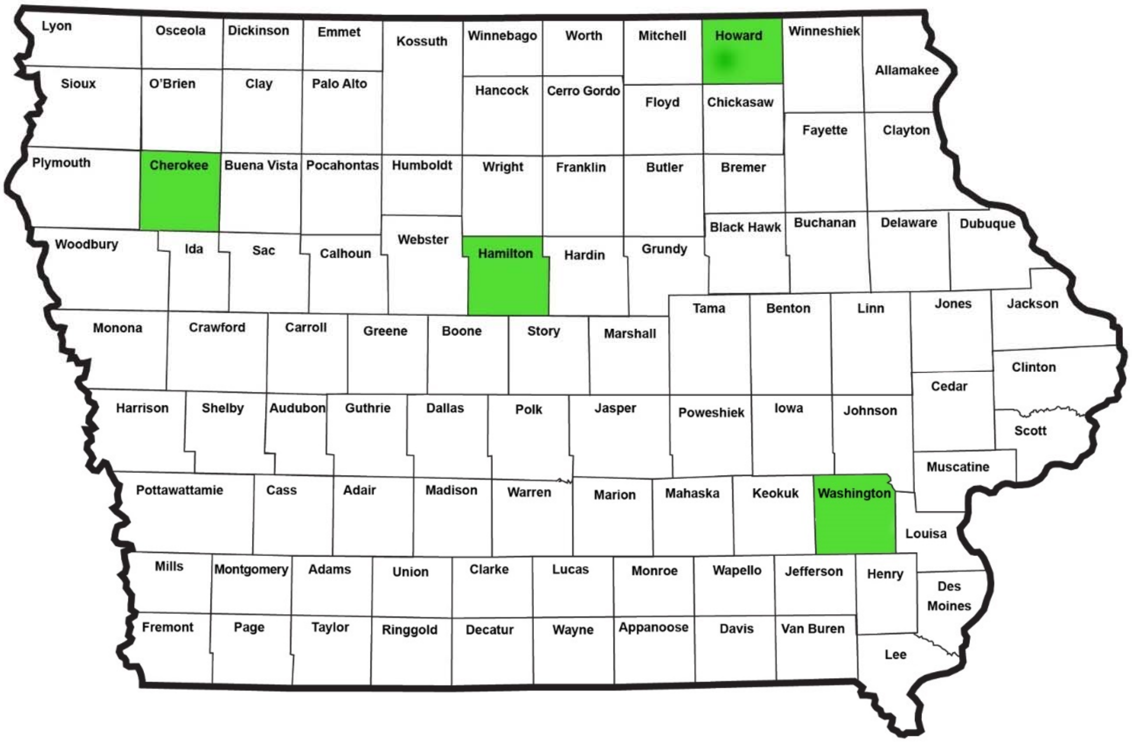


Figure 75 County locations of test sections

APPENDIX E. PHOTOS OF TEST SECTIONS AT END OF CONSTRUCTION

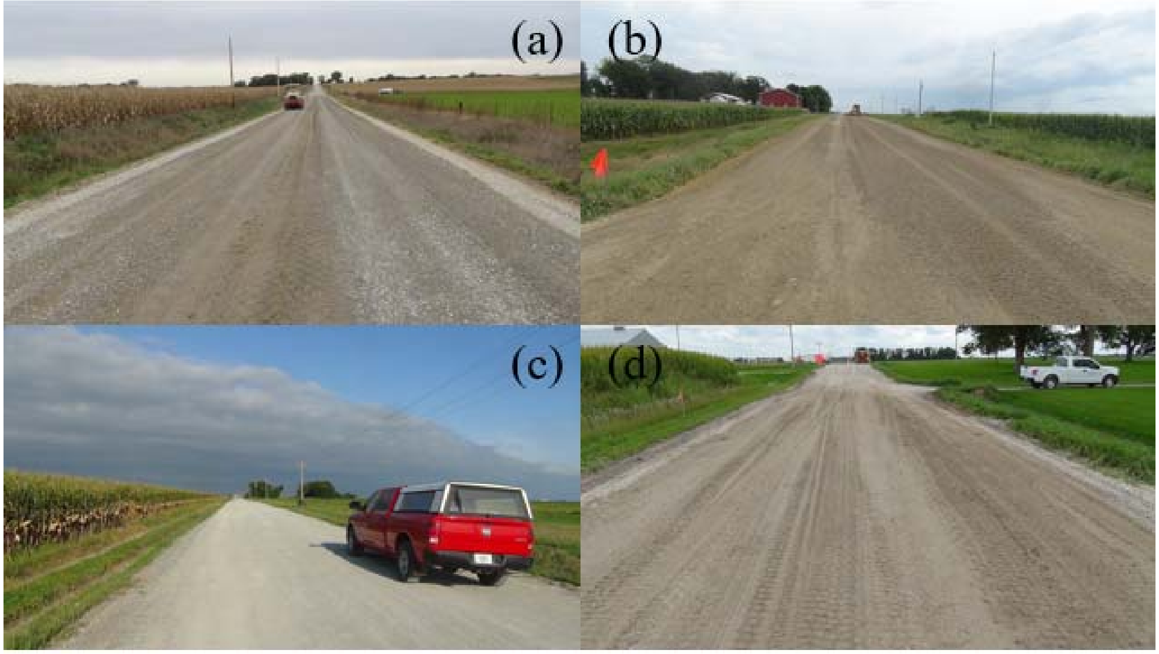


Figure 76 Optimized gradation sections at end of construction (a) Cherokee (b) Howard (c) Washington (d) Hamilton

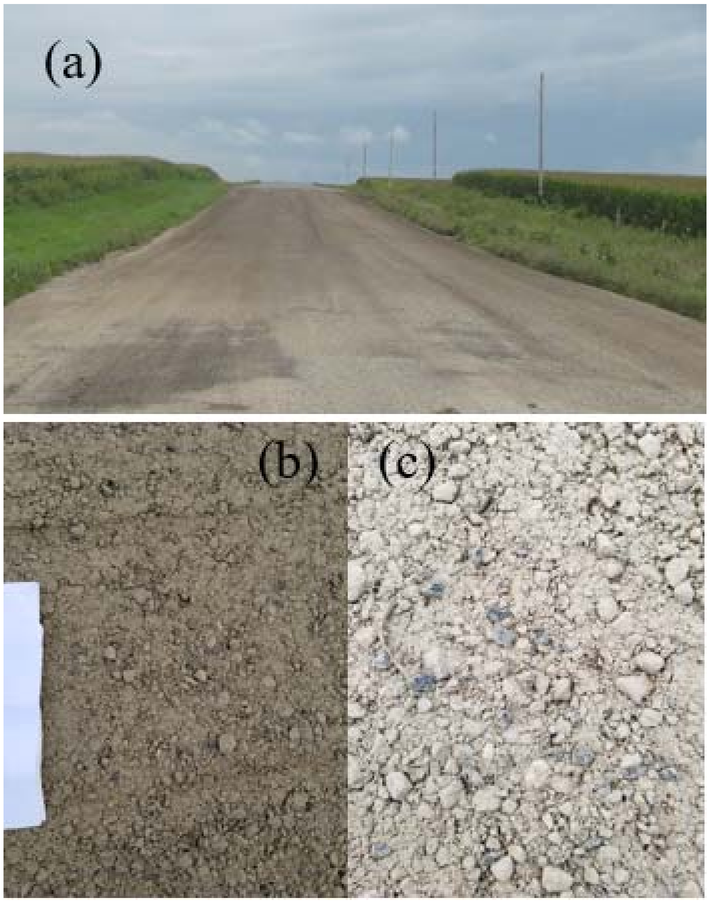


Figure 77 Ground tire rubber section (a) test section in Howard County (b and c) Howard test section surface

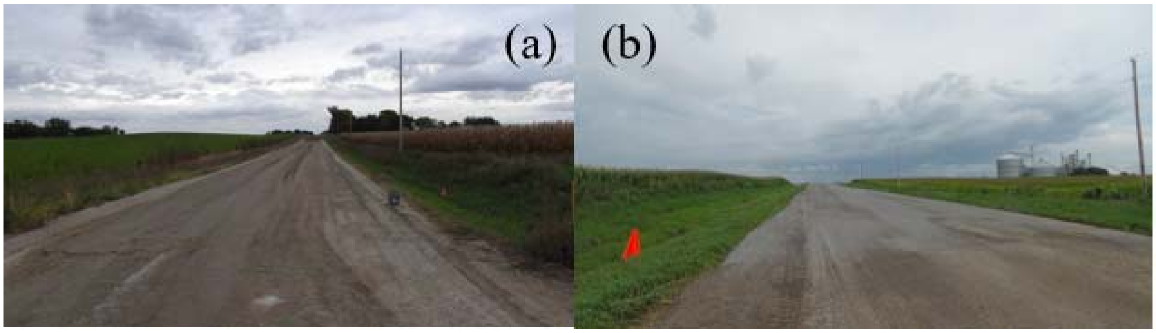


Figure 78 RAP sections at end of construction (a) Cherokee (b) Howard

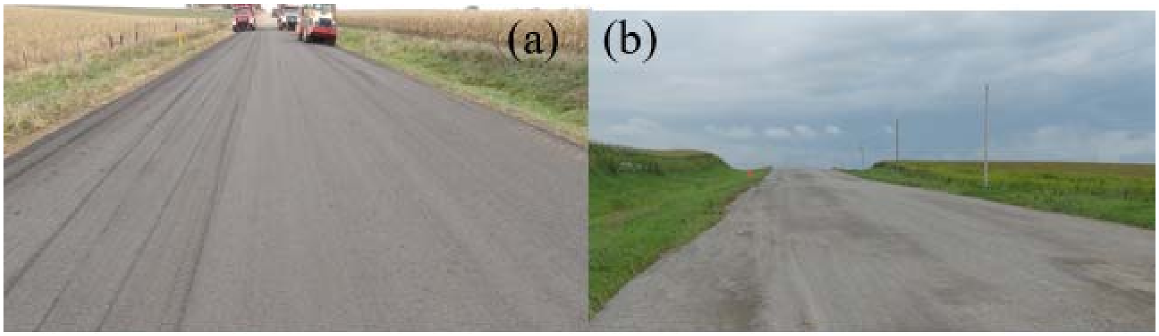


Figure 79 Harsco steel slag sections at end of construction (a) Cherokee (b) Howard

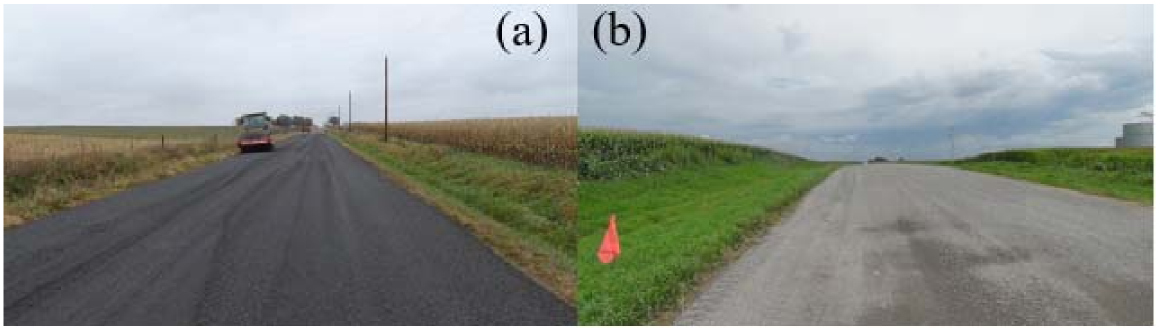


Figure 80 Phoenix steel slag sections at end of construction (a) Cherokee (b) Howard

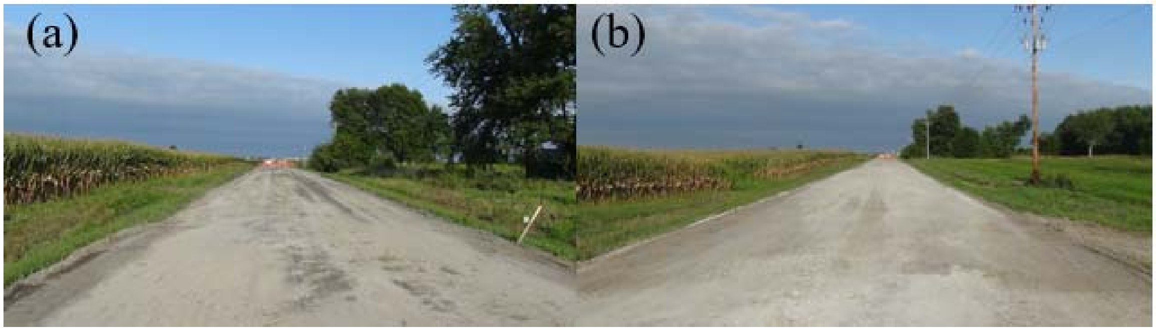


Figure 81 (a) Cement treated surface section (b) Cement treated subgrade section in Washington County at end of construction

Figure 82 EMC Squared sections at end of construction (a) Washington (b) Hamilton

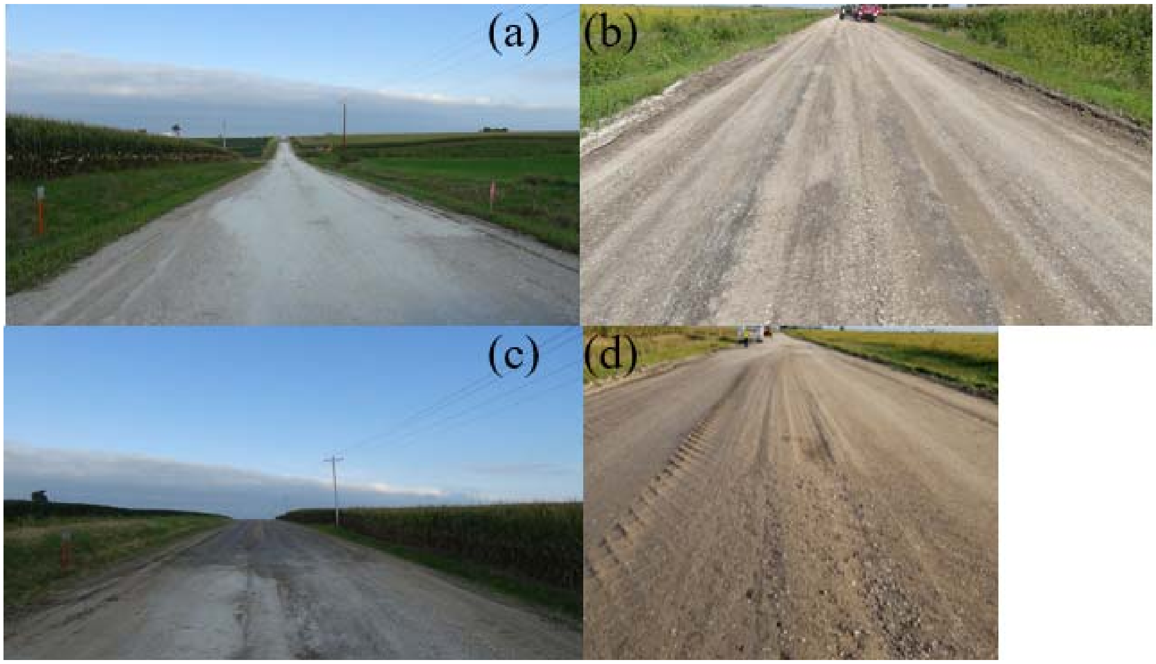


Figure 83 Base One sections at end of construction (a) Washington (b) Hamilton, and Claycrete sections at end of construction (c) Washington (d) Hamilton