Use of Waste Quarry Fines as a Binding Material in Unpaved Roads

Final Report
June 30, 2021

Michigan State University

Department of Civil and Environmental Engineering

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16. Abstract

The goal of this project was to investigate the performance of the stabilized granular sections with quarry fines by-products and perform a benefit-cost analysis to find the most beneficial quarry fines options in stabilization.

Five quarry fines were selected among nineteen quarries across Iowa to build three sections in Jones and four sections in Boone County, Iowa. These two sites are among the most populated roads with a relatively stiff subbase and subgrade layers and suffer from heavy traffic loads and freeze-thaw effects during winter and spring seasons. Construction and maintenance procedures are detailed. The costs of aggregate, hauling, and equipment for construction and maintenance are also documented in this report.

Extensive laboratory and field tests were performed before and after construction, as well as after one seasonal freeze-thaw period from 2019 to 2020, to evaluate and monitor the performance of the constructed sections. A benefit-cost analysis was performed using the documented construction and maintenance costs for service life scenarios of 20, 30, 40, and 50 years. The benefit-cost ratio was calculated for each test section for different scenarios based on the performance measures including gravel content change, average fines content, total breakage, gravel-to-sand ratio, stiffness, shear strength, surface roughness, and dust emission. Performance measures were categorized into three overall mechanistic performance-based groups, and their benefit-cost ratios were compared.

Overall, the results of this study showed that stabilization by quarry fines improved performance by providing binding between the surface aggregates, to reduce dust emission, gravel content loss, and increasing the stiffness and strength of the surface layers. Stabilization could be cost-effective by reducing the maintenance frequency depending on the material, hauling, and labor costs. Limestone and Moscow Mine sections in Jones County, and Moscow and Ames Mine sections in Boone County had the best performances and cost-effectivity among all other stabilized sections. Although the Clay Slurry material was helpful to reduce the dust emission compared to the rest of the section, sections with the Clay Slurry were among the average-performance sections, and the increased construction costs made them not a cost-effective option for both counties.

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EXECUTIVE SUMMARY

The goal of this project was to examine the effects of mixing quarry fine by-products with the existing surface aggregates and evaluate the most cost-effective quarry fine options with the most serviceability. Quarry fine materials were collected from four different locations in Iowa and used to build test sections in Boone and Jones counties in Iowa. Several series of laboratory and field tests were conducted to characterize the materials and assess their performance in service through one seasonal freeze-thaw periods, from 2019 to 2020. Laboratory tests included sieve and hydrometer analyses, Atterberg limits, compaction tests, mini-vane shear test, pocket penetrometer test, X-ray fluorescence (XRF), and California Bearing Ratio (CBR) tests. Field performance was evaluated via density, material loss, modulus, gradation change, dust production, ride quality, and shear strength. Field tests included dynamic cone penetrometer (DCP), international roughness index (IRI), dust measurement, lightweight deflectometer (LWD), and falling weight deflectometer (FWD) tests.

Quarry fines were tested in the laboratory to evaluate the plasticity indices and shape characteristics. Quarry fines with the highest plastic behaviors were selected. Overall, five quarry fine materials (Clay Slurry, Limestone from Frenchtown, Moscow, Ames Mine, and Crescent fines) were used in this project to build four sections in Boone, and three sections in Jones counties. The results of CBR, XRF, mini-vane shear and pocket penetrometer tests were used to select the quarry fines and the optimum amount of fines for the mixture with the existing surface aggregates in both counties. Construction occurred in late October and early November 2019 first in Jones, and then in Boone counties. Sections were bladed four times in Boone and three times in Jones counties throughout the length of the project. The purpose of this study was to add the fines to the existing surface aggregates; however, it was required to add new aggregates during the construction in Boone County for Clay Slurry section, and after construction in Jones County for Clay Slurry and Moscow sections. Control sections with the surface aggregate without quarry fines were considered as a base case for both counties to compare the performance and cost benefits of the demonstration sections with the base case.

The construction and maintenance procedures were documented in detail and are presented in this report. Extensive laboratory and field tests were performed before and after the one freeze-thaw season to monitor and evaluate the performance of the different surface aggregate materials alone and when mixed with quarry fine materials.

A benefit-cost analysis (BCA) was conducted based on the construction costs to estimated cumulative costs. Maintenance scenarios were considered for renewing 2 inches of the surface materials whenever maintenance is required. Accordingly, the benefit-cost ratio, user cost savings, and maintenance cost savings values were calculated based on the BCA and with the consideration of different service lives, and maintenance frequencies compared to continuing the current maintenance practices.

Laboratory and field test results showed that stabilization of the existing surface aggregates with quarry fines could improve the performance of the section in reducing gravel loss, total breakage, dust emission, and increasing the mechanical properties of the surface layer, including stiffness and shear strength.

Moscow and Limestone in Jones County and Moscow and Ames Mine in Boone County had the highest BCR values among all sections due to their performance and lower construction costs.

Overall observations, challenges, and recommendations are summarized below based on the results of this project:

- An increase in fines content and decrease in gravel content were observed for all sections. In contrast, the stabilized sections had better performance regarding these two factors than the control sections in both counties.
- model developed in TR-704 project was used to evaluate the best cost-effective alternative among all the stabilized sections in Boone and Jones counties.
- Quarry fines selected for both counties helped to improve the performance of the sections for dust emission, surface stiffness and strength, and material deterioration.
- Sections with the lowest hauling time were the most cost-effective options for stabilization.
- Clay Slurry sections in both counties performed average among all stabilized options, but better than the control section. However, high equipment, labor, material, and hauling costs made this section having BCR values lower than 1.

CHAPTER 1. INTRODUCTION

1.1 Problem Statement

This research proposes to use quarry fines as a binding agent in unpaved roads. Granular-surfaced (unpaved) roads are large portions of road systems in United State and Iowa in particular. The sustainability of unpaved roads is critical to the rural economy since these roads provide access to rural land and enable the transportation of agricultural products. Any interruption on these roads traffic can have a significant impact on agricultural productivity and the local economy. Heavy traffic loads and freeze-thaw cycles can cause extensive damage to unpaved roads, leading to material loss, surface erosion, rutting, and potholes. The rate of deterioration (or damage) is directly correlated to the quality of the granular aggregate materials used during construction of unpaved roads. Performance and long-term sustainability of granular roadways are significantly dependent on the quality of the aggregate materials used, which varies considerably from one source to another. Sometimes the quality of coarse aggregates is low, and it crushes under traffic load, increasing the fines content in the aggregate matrix. In other cases, the quality of the aggregates is high, but the aggregates are floating on the road surface due to the lack of an adequate amount of fines within the aggregate matrix.

It is known that chemical stabilization can be applied to solve the binding issue of coarse aggregates in unpaved roads; however, these methods are usually not economical and easy to apply and are also not sustainable. Therefore, it is vital to find an alternative material to overcome this problem while making sure it is sustainable, economical, and environmentally friendly. One of the alternative materials to use is quarry fines, which are generated at an approximate rate of 159 million metric tons (175 million tons) per year. At this rate, as much as 3.6 billion metric tons (4 billion tons) of quarry fines have likely accumulated to date (Sandra et al. 1993). Quarry fines have been successfully used to replace sands in concrete and asphalt mixtures. However, they have not yet been widely used in unpaved road systems, where they have great potential to be used as a source of high quality and economic fines.

County engineers and their employees invest considerable effort in managing and maintaining granular roads. When maintenance and construction of granular roadways are costly, counties must spend a considerable portion of their budget (sometimes up to 28% of the total county budget) just to purchase granular materials (excluding placement and maintenance) to replace those lost during the service life of a granular road. The problems commonly encountered with unpaved roads are (1) improper material usage, (2) inadequate material distribution, (3) surface deterioration through aggregate loss, (4) surface abrasion, (5) ineffective drainage, (6) insufficient road maintenance. The proposed study aims to test the problems associated with reasons 1 and 4.

In this project, the research team conducted laboratory and field tests to examine the impact of the inclusion of waste quarry fines in granular aggregate materials used in unpaved road designs, using materials collected from various quarries. Based on the laboratory test results, field test sections were constructed using materials with different quarries. The field performance (abrasion resistance, freeze/thaw resistance, density, material loss, modulus, gradation change) of sections built with different quarry fines were compared. Then, a comprehensive cost-performance and benefit-cost analyses were conducted to evaluate the cost-effectiveness and sustainability of these unpaved roads to determine whether it is economically advantageous to add waste quarry fines into granular unpaved road materials.

1.2 Research Objectives

The overall goal of this project is to determine the effects of adjusting the gradation of the surface aggregates with quarry fines to provide a binding for the aggregates to increase the performance of the surface. The specific objectives of this project are listed as follows:

1. Determine the stiffness and strength of unpaved road materials blended with different quarry fines.
2. Determine the long-term performance of field test sections built with optimum quarry fines content.
3. Analyze the benefit-cost analysis and cost-effectiveness of this approach.

1.3 Site Selection

After discussions with county engineers, Boone and Jones counties were selected to construct the sections for this project (**Figure 1**). Quarry fines with plasticity indices were selected to mix with the surface aggregates. The percentage of mixtures were selected based on the California bearing ratio (CBR) values that will be discussed in the materials and laboratory results sections. Clay slurry from Frenchtown quarry (A22090), Ames Mine quarry fines (A85006), Moscow quarry fines (A70002), and Crescent quarry fines (A78002) were selected for constructing the sections in Boone County. Clay slurry and Limestone quarry fines from the Frenchtown quarry (A22090), and Moscow quarry fines (A70002) were selected for constructing the sections in Jones County.

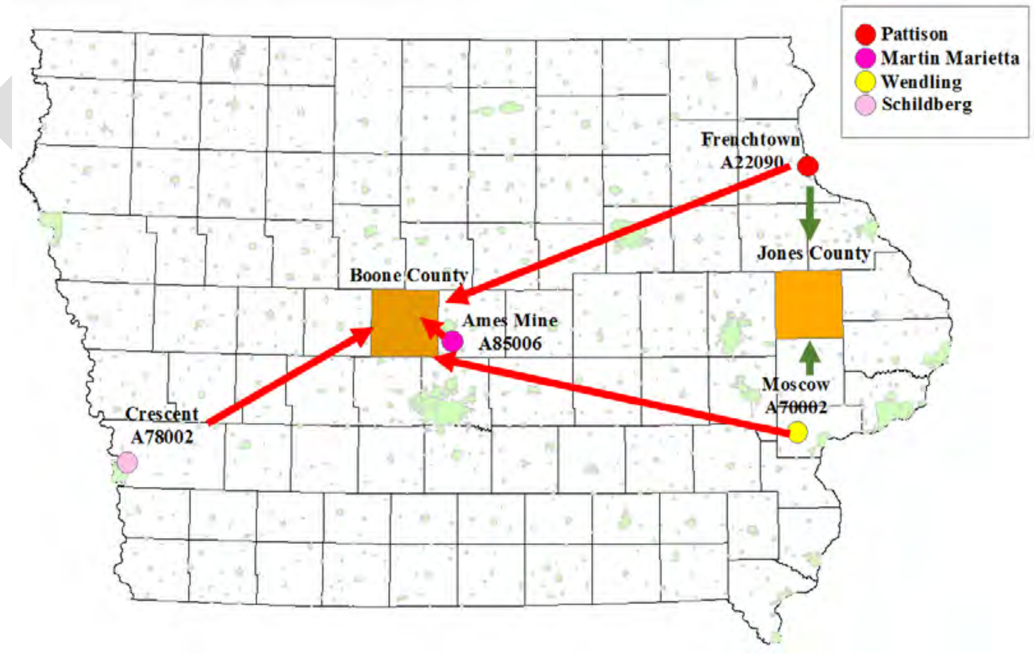


Figure 1. Location of the project

These sites were selected due to the following reasons. Annual average daily traffic for Boone County location was 100, and for Jones County was 70. Daily traffic load and the truck percentage were slightly above average than those of other granular roads in Iowa (Iowa DOT 2012). The surface level of the road was reasonably higher than the ground surface around the road. This provides better conditions for drainage. There was a 5 in subbase layer on the subgrade in both counties, which were made with the surface aggregates used in the mixtures. Furthermore, the subgrade was very strong (CBR >5) for both counties.

1.4 Significance of the Research

The purpose of this research was to investigate the effects of including various quarry fines in the gradation of surface aggregate materials in granular roadways. The performance of the sections built in two different counties was monitored after construction, and a comprehensive benefit-cost analysis was performed to find out which quarry fines would be more beneficial to use to decrease the overall costs.

1.5 Organization of the Report

This report includes eight chapters. Chapter 1 (Introduction) explains the problem statement, objectives, site selection, and the significance of the research. Chapter 2 (Background) consists of a review of the previous studies on the granular roads, previous use of quarry fines, and cost analysis. Chapter 3 (Methods) presents different methods of laboratory and field tests that were conducted in this project. Chapter 4 (Materials) provides information about the geomaterials and the preliminary results of the laboratory tests, which presents the index properties, compaction characteristics, strength, and chemical compositions of quarry fines used in this study. Chapter 5 describes the sites and sections and construction procedures. Chapter 6 (Results and discussions) provides the results of the field tests over a year period of the project after construction. Chapter 7 (Cost analysis) contains the results of the economic analysis on all different test sections. Chapter 8 (Conclusions and recommendations) presents the conclusions of this project and recommendations. Supporting materials are presented in the appendix section.

CHAPTER 2. BACKGROUND

2.1 Quarry Fines

Unbound aggregates are the main constituent of the surface of granular roadways, and large quantities of aggregates are annually required for construction and maintenance of such roads. However, due to the lack of sufficient resources, they are becoming increasingly scarce and expensive. Annual production of almost two billion tons of aggregate in the United States costs approximately $17.2 billion, which contributes an average of $40 billion to the U.S. gross domestic product (Ricci 2014). The byproducts of aggregate production are often considered as waste and the disposal and stockpiling of such byproducts is a significant problem for the aggregate quarries (Satvati et al. 2020). Blasting, crushing, drilling, excavating, and screening during the extraction process of aggregate industries are unsustainable due to the massive production of waste byproduct fine materials commonly known as quarry fines. Disposing of such fines could be hazardous for the environment and has negative impacts on the ecological cycle. Therefore, pilling these quarry fines is not favorable for aggregate industries due to land pollution and the waste of land (Gautam et al. 2017). Moreover, relatively higher interests in the use of aggregates with larger sizes in the construction industry encourage the production of aggregate gradations with lower fines (>US sieve #200) which lead to an imbalance in the aggregates production process and excessive increase in the amount of waste fines. The amount of quarry fines produced during aggregate production process can be up to 25% of the total aggregate produced depending on the type of rock quarried (Stroup-Gardiner and Wattenberg-Komas 2013). Thus, it is important to find a way to use these materials in sustainable applications. Investigating new ways for sustainable use of such materials in the construction and maintenance of roadway structures is vital. Therefore, the use of locally generated waste materials is a significant step forward in searching for resources that may provide a sustainable aspect by reducing the consumption of natural resources and landfill usage (Gautam et al. 2017, 2018). Quarry fines are typically less than ¼ in in size and consist of sands particles (<US sieve #4 and >US sieve #200), and a clay–silt fraction (> US sieve #200). Quarry fines can be recycled and used in other applications including such as reclaimed asphalt pavement, recycled asphalt shingles and recycled concrete aggregate (Jalali et al. 2019; Kapugamage et al. 2008; Kumar and Hudson 1992; McClellan et al. 2002; Rajput et al. 2014; Satvati et al. 2020; Stroup-Gardiner and Wattenberg-Komas 2013; Vargas-Nordcbeck and Jalali 2020). However, the disposal, reuse, and recycling costs of quarry fines in aggregate production sometimes exceed their potential economic and environmental benefits (Mwumvaneza et al. 2015). The use of quarry fines in roadway applications compared to other materials makes them a suitable option for departments of transportations (DOTs) and other transportation agencies due to their relatively lower costs and vast availability. Such application of quarry fines has been a focus of several studies (Kalcheff and Machemehl Jr 1980; Kumar and Hudson 1992; Puppala et al. 2008; Stroup-Gardiner and Wattenberg-Komas 2013).

Ho et al. (2001) investigated the application of mixtures of granite fines (<0.1 in) with superplasticizers to achieve control of the segregation potential and deformability of self-compacting concrete (SCC). The results of this study showed that applying granite fines to SCC effectively decreases the overall supply costs with almost similar rheological properties that a SCC with limestone powder could reach (Ho et al. 2002).

Xia et al. (2016) studied the effects of mixing quarry fines by-products with coarse crushed granite aggregates (CCGA) in different percentages for pavement foundation applications. Permeability and monotonic triaxial compression tests were performed to determine the optimum percentage that satisfies the highest stability without compromising the drainability.

Mwumvaneza et al. (2015) examined the suitability of using quarry fines in the pavement layers by investigating shape characteristics, gradation, and mineralogy of quarry fines produced in different stages of aggregate productions and evaluating the shear strength properties and unconfined compressive strength of treated quarry fines with Portland cement and Class C fly ash. 0 to 30 times increases in the strength of quarry fines were observed when they were mixed with optimum percentages of stabilizers (Mwumvaneza et al. 2015).

2.2 Aggregate Deterioration

Index properties of the aggregates, subgrade and weather-related conditions, traffic loads, and lack of drainage play an essential role in deterioration of aggregates used in granular roadways (Alzubaidi and Magnusson 2002; Farhangi and Karakouzian 2020; Melugiri-Shankaramurthy et al. 2019; Morovatdar et al. 2019; Paterson 1987; Provencher 1995; Strombom 1987). Surface aggregate materials are under effects of weather and load conditions as well as blading and compaction during construction and maintenance of these roadways during their service life. Therefore, the combination of these factors affect the aggregates shape characteristics, material loss, and performance measures such as dust emission, stiffness, and strength (Cetin et al. 2019; Fathi et al. 2019; Hardin 1985; Lade, Yamamuro, and Bopp 1996; Lees and Kennedy 1975; Marsal 1967; Nurmikolu 2005; Paterson 1991; Satvati et al. 2020; White et al. 2004; Wu et al. 2020; Zeghal 2009).

Quality of the aggregate materials, including abrasion resistance, has a significant impact on the aggregate loss and deterioration under traffic loads and freeze-thaw cycles (Alzubaidi and Magnusson 2002; Dobson and Postill 1983; Isemo and Johansson 1976). Granular roadways in cold regions such as Iowa experience a considerable number of freeze-thaw cycles. Therefore, the rate of deterioration of such roads happens faster than those in warmer regions. Deterioration of granular materials includes changes in material sizes from coarse aggregates to fine soils, and it results in reducing the surface layer thickness, development of several distresses such as potholes, rutting, and washboarding, and consequently lowering the ride quality standards. Besides, dust emission increases for the roads with higher fines content, and affects the quality of life for the residence of the rural regions (Li et al. 2016; Cho et al. 2004; Mahedi et al. 2020; Nurmikolu 2005; Satvati et al. 2020; Cetin, et al. 2019; Vallejo et al. 2006; White and Vennapusa 2014; White and Vennapusa 2013; Wu et al. 2020). Wu et al. (2020) investigated the effectivity of mixing ground tire rubber, Portland cement, and Clay Slurry materials with optimized gradation with surface aggregates, in addition to mixing proprietary chemical stabilizer with surface and subgrade course and monitored the stiffness and shear strength of the road layers. Results of this study showed that stabilization with cement and Clay Slurry increased the stiffness and shear strength of the surface and subgrade layers. Moreover, it was hypothesized that sections stabilized with Clay Slurry had lower gravel loss relative to the control section.

Li et al. (2016) evaluated the performance of the granular roads stabilized with cement, fly ash, and bentonite, macadam stone base, and geosynthetics. Stiffness and strength of the road layers were monitored over the length of the study, and it was concluded that the Macadam stone base, fly ash, and cement stabilized sections, respectively, had the highest elastic modulus values right after construction. However, implementing the Macadam stone base could be more cost-effective relative to the other stabilization methods (Li et al. 2017). Freezing and thawing along with lack of drainage caused capillary water to get trapped on top of the subgrade layer and saturated the surface aggregate materials. Thus, high traffic loads, in addition to using aggregate materials with lower abrasion resistances, deteriorate the surface aggregate materials with increasing the fines content by breaking the coarse surface aggregates. Therefore, stiffness and shear strength of the road layers get altered after each freeze-thaw period and lead to the development of various distresses such as aggregate loss, potholes, and rutting (Mahedi et al. 2020). Dumping virgin aggregates and blading the existing surface aggregates are common practices for renewing the surface layer and obviating the freeze-thaw damages, while improving the frost susceptibility of surface layers could be a better option to have lower deteriorations and reduce the maintenance costs (Ashtiani et al. 2019; Cetin et al. 2019; Farhangi et al. 2020; Morovatdar et al. 2019; Satvati et al. 2020; White 2013; White and Vennapusa 2014). Vallejo et al. (2006) reported that the use of low abrasion-resistant materials in subsurface paved roads along with the unfavorable weather condition and high traffic loads result in aggregate crushing (Vallejo et al. 2006). Nurmikolu (2005) showed that the use of aggregate materials with higher porosity and moisture content in road construction in the cold regions were disadvantageous for frost susceptible weather conditions (Nurmikolu 2005). Ashlock et al. (2018) reported that certain parts of Iowa, such as the north-east, had higher abrasion resistance aggregates than the sources in the west and south. Therefore, using half as much aggregate for the same roadway performance would perform similar to the field tests with granular materials from south-western Iowa (Ashlock 2018).

2.3 Cost Analysis

Life Cycle Cost Analysis (LCCA) includes consideration of construction and maintenance costs during the service life of a project with a defined discount rate to compare the cost-effectiveness of alternative options compared to a base option (Vosoughi et al. 2017). LCCA was initially conducted by state agencies in the 1950s to evaluate the cost-effectiveness of different pavement systems (AASHTO 1960). Several factors such as pavement types, qualities of materials in pavement layers, the motoring public, and construction and maintenance costs are the input factors for conducting LCCA for pavement structures, where it investigates the overall construction, maintenance, and salvage costs (Walls III and Smith 1998; Wilde et al. 1999). The service life considered in LCCA is the period that cost analysis will cover and evaluate. It should be long enough to reflect the long-term reasonable design strategies of the project. After first defining the actual initial costs, including the construction and initial maintenance costs, future costs, including any maintenance and rehabilitation costs, should be discounted to the current year by calculating the net present value (NPV) for alternatives.

In this study, only renewing the surface layer with virgin aggregate materials was considered as the basic maintenance procedure, while the routine blading, which happens for all sections regularly, has low costs and is the same for all sections. Thus, it has almost zero effect on the NPV compared to the other significant costs, particularly in extended periods (over 20 years) (Cetin et al. 2019). Moreover, salvage value, which represents the value of an investment alternative at the end of the project life, usually is considered to be zero for road systems. (Vosoughi et al. 2017).

Cost analyses in road construction can be useful in cases with several stabilization options when the materials for alternative sections have different hauling and material costs and construction procedures. Cetin et al. (2019) and Satvati et al. (2020) investigated the effects of assessing different possible routes and transportation modes between high-quality aggregate sources and construction sites lacking nearby high-quality sources (Cetin et al. 2019; Satvati et al. 2020).

This project utilizes a previously developed benefit-cost analysis (BCA) model for two gravel roads constructed in the rural road system. The findings of the cost analysis part of this project could be helpful to DOTs and City and County Engineers to determine the most efficient and cost-effective quarry fines as alternatives for the existing granular roads to have lower material and hauling costs associated with construction and maintenance costs. Performing BCA is essential before making any decisions to invest in transportation infrastructures to investigate the effectivity of a project in employing the resources, due to the need to facilitate social and economic activities (Carlsson et al. 2015; Dharmadhikari et al. 2016; Prest and Turvey 1965; Satvati et al. 2019a). Deterministic BCA as a traditional decision-making tool has been commonly used in pavement systems economic analysis (Cetin et al. 2019; Nahvi et al. 2018; Satvati 2020; Satvati et al. 2019; Walls III and Smith 1998). Defining the costs, evaluation of benefits, choosing the discount rate, and relevant constraints are the four major factors considered in BCA (Prest and Turvey 1965). Besides, selecting the base case and alternatives of the project, defining the benefits of each alternative, calculating the costs and benefits associated with each alternative, and calculating the present value of costs and benefits are of the four main steps in performing BCA (Dharmadhikari et al. 2016). The base case is defined as the most available choice that comes to the mind in the first place. In this study, the control section with existing aggregates and without any stabilization was considered as the base case.

Further, careful attention should be paid in defining and evaluating the benefits for the alternative options to have an accurate analysis. Projects are different in their purposes and in many details; therefore, the benefits of one project could not be considered beneficial for another project due to the different circumstances (Gibson and Wallace 2016). The annual costs and benefits values, and the NPV of the project properties considering a valid discount rate, shape the overall figure of the BCA (Layard 1994). Major challenges in conducting BCA for transportation infrastructures were reported as traffic forecast, cost estimation, discount rate, the value of life, safety, the value of time, regional impacts, local impacts, equity, environmental impacts, and residual use (Jones et al. 2014). The main factor in deterministic BCA is the benefit-cost ratio (BCR), which is the ratio of the net present value (NPV) of the benefits divided to the NPV of the costs of a project (Walls III and Smith 1998). BCR value higher than one indicates that the alternative could be beneficial relative to the base case. In comparison, BCR value lower than one demonstrates that alternative is costly, and the benefits do not make it beneficiary relative to the base case.

Cetin et al. (2019) and Satvati et al. (2020) investigated the use of different aggregate options with different hauling and material prices to construct granular sections in Decatur County, Iowa. A BCA model was developed and was used to evaluate the benefits of alternatives in case of dust emission, stiffness, shear strength, material, and thickness loss, and change in gradation of the surface aggregates. The results showed that it could be beneficial to construct granular roads using higher quality materials from farther sources that can sustain their performance for a longer extended time with less maintenance frequency, because there is a lack of high-quality aggregates in Iowa (Cetin et al. 2019; Satvati et al. 2020).

CHAPTER 3. METHODS

This chapter includes the methods for both laboratory and field tests. Laboratory tests are conducted to determine the classification and soil index properties, shear strength, penetration resistance, and compaction behavior of the surface and subgrade materials, while field tests were performed to investigate the mechanistic properties of the surface and subgrade layers such as strength, stiffness, in-situ water content and dry density, the amount of dust, and surface roughness.

3.1 Laboratory Tests

Laboratory tests such as particle-size analysis, Atterberg limits, Proctor test, California Bearing Ratio, pocket penetrometer, and mini-vane shear tests were conducted in the laboratory to acquire the particle size distribution, the plasticity of soil, maximum dry density (γ_{dmax}), optimum water content (w_{opt}), shear strength, and compaction characteristics. In addition, the X-Ray Fluorescent test was performed by Iowa DOT to find the elemental composition of quarry fines materials.

3.1.1 Particle-Size Analysis

The particle-size analysis was performed in accordance with ASTM D 422 "Standard test method for particle-size analysis of soils". Sieve sizes are at the range of 1-1/2 in (75 mm) to sieve # 200 (75 µm). Besides, to determine the size distribution of fine particles (particles go through # 200 sieve) hydrometer tests were conducted on the materials passed through sieve #10 (2 mm). To test a representative sample, a sampling method ASTM D 75-13 "Standard practice for sampling aggregates" was followed. **Figure 2** shows the picture of the sieve test set up used during sieve analysis.

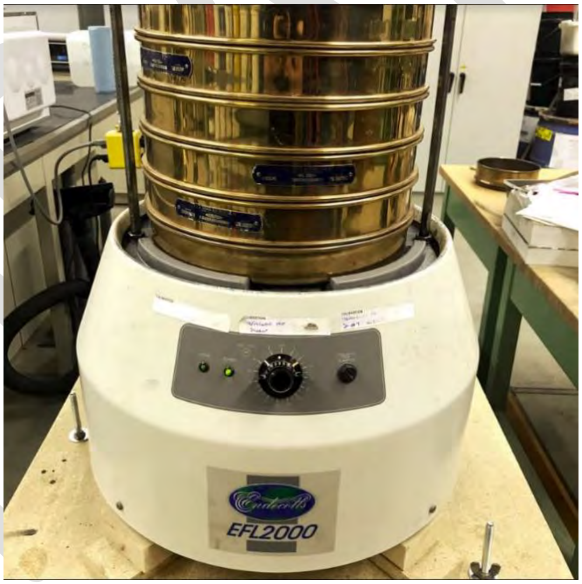


Figure 2. Shaker for sieve analysis

3.1.2 Atterberg Limits

Atterberg limit test was performed on the surface aggregate and subgrade materials to determine the liquid limit (LL), plastic limit (PL), and the plasticity index (PI) of materials. Wet preparation-multiple point test method was conducted on materials after they were sieved through #40 (425 µm) sieve. ASTM D 4318-10e1 "Standard Test Methods for Liquid Limit, Plastic Limit, and

Plasticity Index of Soils" were followed for these analyses. A standard brass cup and a glass plate were used to find the liquid and plastic limits, respectively (**Figure 3**).

Figure 3. Liquid limit test device used in this study

3.1.3 Soil Classification

The results of the sieve analyses and Atterberg limits were used to classify the materials. Materials were classified in accordance with the ASTM D 2487-11 "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System (USCS))" and the ASTM D 3282-09 "Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes (AASHTO classification system)".

3.1.4 Proctor test

Standard Proctor tests (ASTM D 698-12e1 "Standard test methods for laboratory compaction characteristics of soil using standard effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3))" were conducted on all materials (both surface aggregates and subgrade) to determine their optimum water content (w_{opt}) and the maximum dry density (γ_{dmax}). **Figure 4** shows the pictures of the equipment used for compaction tests.

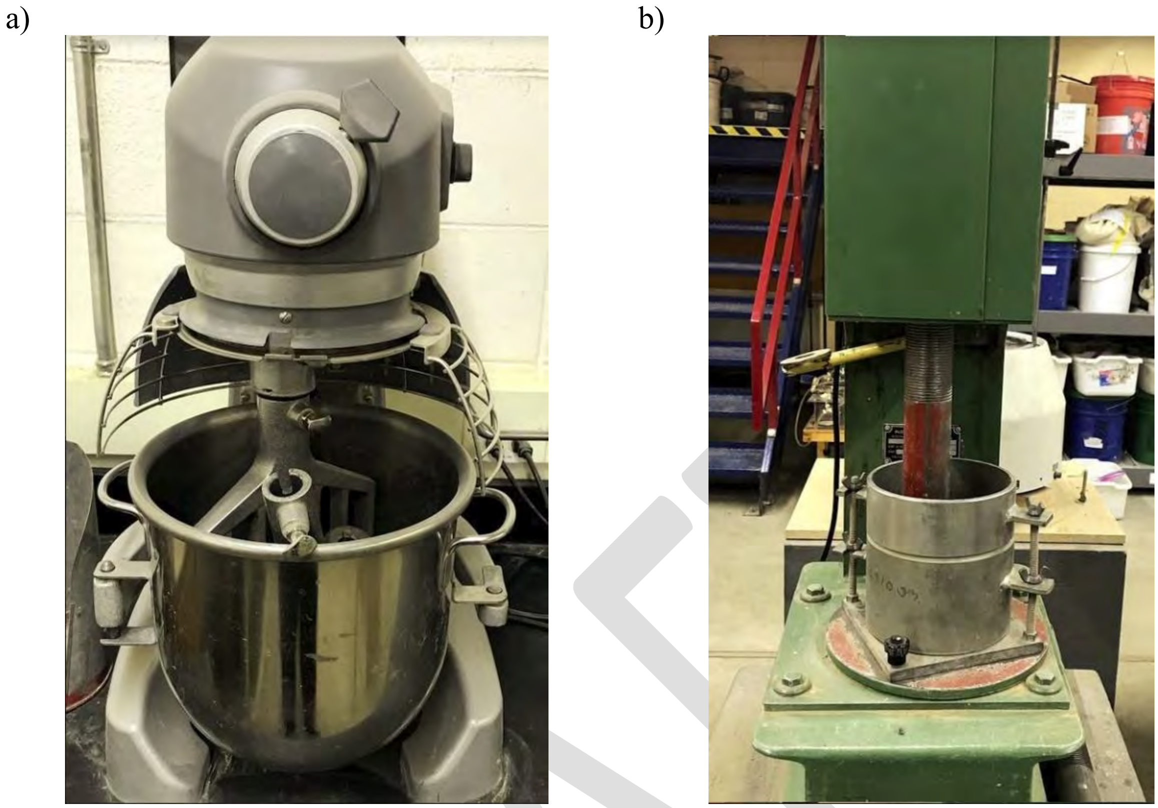


Figure 4. (a) Hobart mixer and (b) automated mechanical rammer used in this study

3.1.5 California bearing ratio (CBR)

California bearing ratio (CBR) was performed to evaluate the shear strength of the granular road surface aggregate and subgrade materials. It was conducted in accordance with ASTM D1883-16 “Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils”. Each specimen was compacted at optimum moisture content with standard Proctor energy. CBR tests were performed on both un-soaked and soaked to simulate the optimum and saturated conditions in the field, respectively. **Figure 5** shows the picture of the CBR equipment.

Figure 5. California Bearing Ratio device for this study

3.1.6 Moisture Determination

Samples were collected each time when field tests were conducted and the moisture contents of the samples from each section were measured in the laboratory in accordance with ASTM D2216—10, “Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass”.

3.1.7 Pocket Penetrometer Test

Pocket penetrometer test (**Figure 6**) was performed on the quarry fines passing US sieve #200 to find the penetration resistance of the saturated quarry fines by passing time. This test helped to determine which one of the quarry fines had higher ability to lose water in the room temperature (70°C) and reached the maximum penetration resistance (4.5 tsf) by getting dry faster than others.

Figure 6. Pocket penetrometer device for this study

3.1.8 Mini Vane Shear Test

This test measures the undrained shear strength of very soft to stiff fine-grained clayey soils (**Figure 7**). In this method, an electric device applies a torque to a four-bladed vane inserted in a remolded or undisturbed soil sample in a constant rate.A cylindrical surface is sheared by the vane in accordance with ASTM D4648/D4648M − 16, “Standard Test Methods for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil”. The laboratory vane shear device used in this study was a four-bladed, 1” by 1” square vane with a vane blade thickness of 0.03” and a rod diameter of 0.13”. The torque rotation rate was constant at 90°/min and the torque spring had a calibration factor of 13 E-3lb-in/°.

Figure 7. Mini-vane shear device for this study

3.1.9 X-Ray Fluorescent (XRF)

The chemical constituent of the quarry fine materials was determined by performing XRF test in Iowa DOT materials laboratory. In this test releasing the electrons from their atomic orbital position causes a burst of energy that helps to determine the elements in soil.

3.1.10 Slaking test

Slaking test was performed to investigate the long-term moisture susceptibility of the treated and untreated specimens and to determine the time that the specimens become disintegrated (Gopalakrishnan et al. 2015). These specimens consist of the minus No.40 fraction of the samples. Specimens 2” by 2” in size were compacted in their optimum moisture content by using the Unconfined Compressive Strength compaction device (**Figure 8**) (Edgar 1963). Then specimens were tested shortly after compaction without curing. Plastic wraps were used to seal the specimens to prevent loss of moisture immediately after compaction.


(a) (b)

Figure 8. (a) compacting slaking specimens by UCS compaction device, (b) prepared and plastic wrapped 2 by 2 specimens

To perform the slaking tests, specimens were placed on a U.S. # 4 sieve and half-way soaked in tap water at room temperature. Then the temperature and the elapsed time (slaking time) at which the specimens became disintegrated were recorded. (**Figure 9**).

Figure 9. Slaking test for 2-by-2 specimens of Jones County existing surface aggregate mixing with 2% clay slurry, 2, 6, and 10% Moscow

3.2 Field tests

Falling weight deflectometer (FWD), Light weight deflectometer (LWD), Dynamic cone penetrometer (DCP), Nuclear gauge, International Roughness Index (IRI), and Dustometer tests were conducted to determine stiffness, strength, in-situ density, moisture content, roughness, and dust emission of surface materials. All tests were performed at the same points with 100ft distance in all sections.

3.2.1 Falling weight deflectometer (FWD)

In this project a SN121 JILS model FWD was used to determine the elastic modulus of surface, subbase, and subgrade layers (**Figures 10 and 11**). The FWD device used in this study applies a pressure via a segmented loading plate. In order to achieve a good contact between the 12-in diameter plate and the surface materials, a 1200-lb static load was applied on the surface. Then, three different dynamic pressures (4,000, 4,500, and 5,000 lb) were applied on the plate to make the deflection basin on the ground. Then, nine sensors measured the deflections on the surface while applying dynamic loads. **Table 1** shows the configuration of the device used for this study. **Figure 10** shows the schematic diagram of the FWD test setup, deflection bowl and the granular road layers.

Table 1. FWD configuration

Parameter	FWD
Number of geophones	9
Geophone spacing (in)	6 to 12[a]
Total length (in)	66
Distance from the source to the first geophone (in)	0
Static load (lb)	1200

Dynamic loads (lb)	4000, 4500, 5000

a Distance between the transducers in FWD are -12, 0, 6, 12, 18, 24, 36, 48 and 54 inches

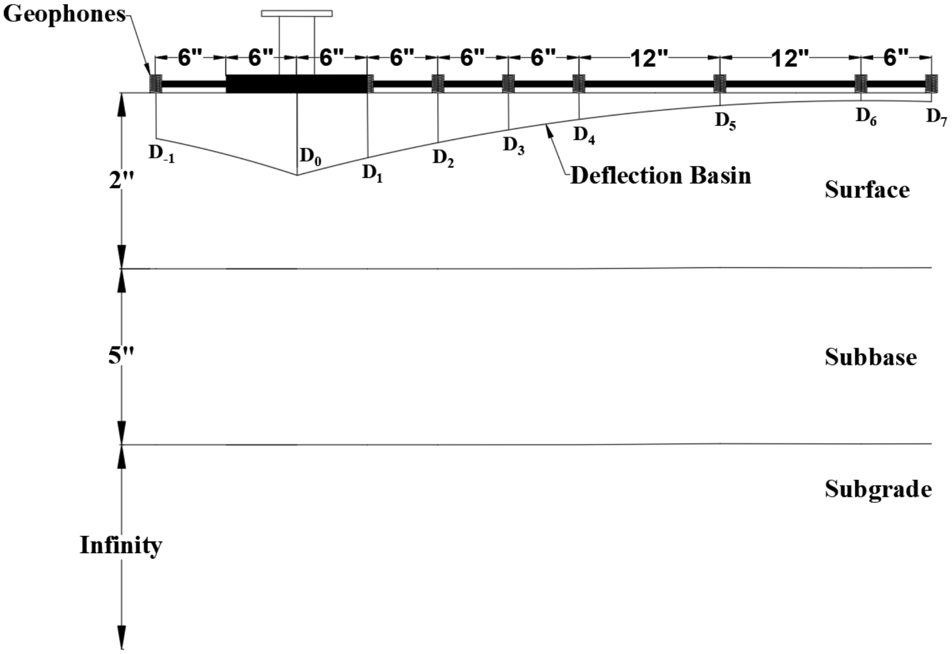


Figure 10. Falling Weight Deflectometer overview

Figure 11. FWD device for this study

For the purpose of analyzing the results of FWD test, back-calculation was done based on the dynamic loads and peak deflections that were observed under the geophones on the three-layered system (Boussinesq 1885; Grasmick et al. 2014; Li et al. 2017; Odemark 1949; Saltan et al. 2013; Stokoe et al. 1994). In this regard, BAKFAA code was used for the back-calculation analysis to determine the best match between the calculated and measured deflection basin. BAKFAA was developed by the Federal Aviation Administration (FAA) for the FWD back-calculation on airfield pavements based on the LEAF-layered elastic computation program (Gopalakrishnan and Thompson 2004) and is an iteration-based back-calculation method that uses layered elastic theory (Hayhoe 2002). BAKFAA has the ability to model up to 10 pavement layers and can be used for airfield or pavement layer systems for a measured deflection basin. BAKFAA as a Windows-based program had a simple and user-friendly graphical interface. The inputs in BAKFAA are the seed values for elastic modulus, thickness, and Poisson's ratio values for each layer, deflection basin, geophone spacing, plate radius (6 in), plate load, and evaluation depth (assumed to be 25 in for this project). Poisson's ratio values for surface, subbase, and subgrade were assumed to be 0.3, 0.35, 0.4, respectively. BAKFAA minimizes the root mean square (RMS) of error between field-measured deflections and generated-deflections and iteratively alters the user-defined seed moduli for all layers until the generated and measured deflection measurements match within some user-defined tolerance. Seed values for surface, subbase, and subgrade layers were considered to be 100 ksi, 40 ksi, and 10 ksi, respectively.

3.2.3 Light weight deflectometer

The Light weight deflectometer (LWD) equipment as a non-destructive test was specifically developed to perform rapid field-testing of pavement materials and LWD tests in this study were conducted to determine the maintenance frequency required for the test sections. The tests were performed on five points within each test section to evaluate the in-situ composite elastic modulus (E_{Comp}) (stiffness) of the granular surfaces and subgrades, as a measure of road serviceability. This stiffness is a function of several factors, including compaction quality, packing structure of the various particle sizes (Tirado et al. 2017; Xiao et al. 2012), density of the road layers, water content, and temperature (Oloo et al. 1997). Any changes in these factors can result in severe distresses (e.g. potholes, rutting, etc.), creating a need for road maintenance. Therefore, along with the E_{Comp} data for each test section, the surface layer temperature and water content are presented. The ambient temperature of the surface course was measured using a thermocouple installed in the middle of the first section and the same ambient temperature was assumed for all the sections. The water content values were measured from samples collected during field testing. The LWD device used for testing in this study features a 22 lb hammer with a drop height of 19.69 in., and a base plate diameter of 11.81 in. The in-situ elastic modulus then is calculated based on the average vertical deflection as it is shown in Equation 1. **Figure 12** shows the picture of LWD test set up used in this study.

$$E_{LWD} = \frac{(1-\nu^2)\sigma_0 A f}{d_0} \tag{1}$$

where E_{LWD} is elastic modulus, as the result of LWD test, σ_0 is vertical stress applied on top of the plate, ν is Poisson's ratio (assumed as 0.4), d_0 is applied stress, A is plate radius, and f is shape factor (assumed 2 for a uniform stress distribution (Vannapusa and White 2009).

Figure 12. Light Weight Deflectometer device for this study

3.2.4 Dynamic cone penetrometer

DCP was used to determine the shear strength and thicknesses of granular surface and subgrade layers for each test section. DCP tests were conducted in accordance with ASTM D6951 (D6951M-09 2015). A DCP cone with a 0.79 in. base diameter was used to penetrate to the soil up to 23 in. by using a 17.6 lb hammer. **Figure 13** shows the picture of the DCP set up. Using the DCP Index (in/blow) as the rate of penetration and empirical correlations based on the ASTM standard, the California Bearing Ratio (CBR) values for each layer were calculated, as noted in equations 2 and 3 (D6951M-09 2015).

$$\text{CBR}= \frac{292}{\text{DCPI}^{1.12}} \quad , \text{CBR} > 10 \qquad (2)$$

$$\text{CBR}= \frac{1}{(0.017019\times\text{DCPI})^2} \quad , \text{CBR} < 10 \qquad (3)$$

Figure 13. Dynamic Cone Penetrometer device for this study

Sudden changes in the cumulative blows versus depth is identified as the change in the layer characteristics. Therefore, the depth of the penetration to the transition zone is the thickness of the surface layer, as it is shown in **Figure 14**. The weighted average of the surface and subgrade CBR values then are calculated as it is shown in equations 4 to 5.

$$CBR_{AGG} = \frac{\sum_{i=1}^{n} CBR_i \times D_i}{Surface\ thickness} \tag{4}$$

$$CBR_{SG} = \frac{\sum_{i=n+1}^{m} CBR_i \times D_i}{Final\ depth\ measurement - Surface\ thickness} \tag{5}$$

where CBR_{AGG} and CBR_{SG} are the weighted average CBR values for the surface and subgrade, CBR_i is the CBR value calculated by (11-12) formulas for each reading in the surface or subgrade layer, D_i is the reading of the depth of penetration in each layer, n is the number of readings in the surface layer, and m is the total number of readings.

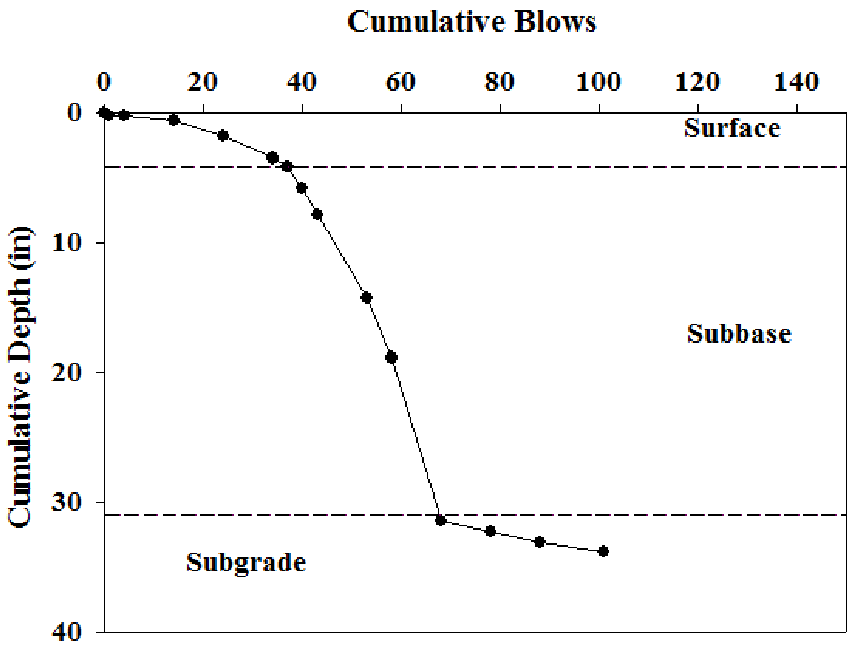


Figure 14. DCP results; cumulative blows vs. cumulative depth

3.2.6 International roughness index

Roughness of the road surface as representative of ride quality is an important factor to evaluate the granular roadway performance, and lower IRI values reflect higher ride quality, lower fuel consumption, and longer service life (Jia et al. 2018). In the current study, the collection of road roughness measurements representative of road condition was done using a smart phone application named Roadroid. This software uses a built-in smart phone accelerometer to evaluate roughness index of the different surfaces in a rapid and cost-effective manner (Akinmade et al. 2017). In this method, the smart phone is mounted on the windshield of a one-ton truck, and, after adjustments, the calculated International Roughness Index (cIRI) values are measured and stored in the phone while driving between 40 and 50 mile/hr In this regard, the driver should reach to above 30 mile/hr and then push the break until the car completely stops. The friction value (μ) and a photo of the stop point are stored to the phone. The data are uploaded and available in the Roadroid website in addition to the location of the test.

3.2.7 Dustometer

The dustometer test was another road-performance measure used in this study to estimate the appropriate granular road maintenance frequency. To evaluate the dust production of each test section in relation to the different aggregate sources utilized in the surface layers, dustometer tests were performed several times over the length of the project. **Figure 15** shows the setup of the dustometer device, attached to the bumper of a one-ton truck by a steel bracket. It has a 12in×12in steel mesh with a 0.0079 in mesh size sieve to prevent large particles from damaging the tightly-held filter paper. A 1/3-horsepower suction pump is connected to the mounted dustometer with a

2 in. diameter flexible hose to collect dust behind the rear wheel while driving at a speed of 45 mile/h). A 4,400-Watt gasoline-powered generator provides power for the suction pump. The filter paper is removed after performing the test over a section, and the mass of the dust on the paper divided by the length of the sections to determine the amount of dust per unit length.

(a) (b)

(c) (d)

Figure 15. Dustometer test set up: (a and b) dustometer setup; (c and d) dust production measurement paper

3.2.8 Nuclear gauge test

The nuclear gauge test, a fast and non-destructive test, was performed by Iowa DOT to measure the in-situ density and the moisture content of the surface material by attenuation of the gamma radiation at a known depth. It is conducted in accordance with ASTM D6938−15 “Standard Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)”. In this test, the setup should be placed in a good contact to the surface of the granular roadway. The device records the wet density and the water content. The dry density (γ_{dry}) is calculated by using the **Equation 6**. **Figure 16** shows the picture of the nuclear density gauge device.

$$\gamma_{\text{dry}} = \frac{\gamma_{wet}}{1+WC/100} \tag{6}$$

where the γ_{dry} is the dry density, γ_{wet} is the wet density, and WC is the water content.

Figure 16. Nuclear Density Gauge test device (Cetin et al. 2019)

CHAPTER 4. MATERIALS

Results of the sieve analysis, Atterberg limits, compaction, pocket penetrometer, and mini-vane shear tests for the geomaterials used for this project are summarized in this chapter.

4.1 Geomaterials

Figure 17 shows the quarries that were selected for quarry fines collection in the beginning of the project. Nineteen (19) quarries in total were investigated all over the state and their gradation and

Atterberg limits were examined. Quarry fines with high plasticity were selected and used for this project to construct the sections in Boone and Jones counties.

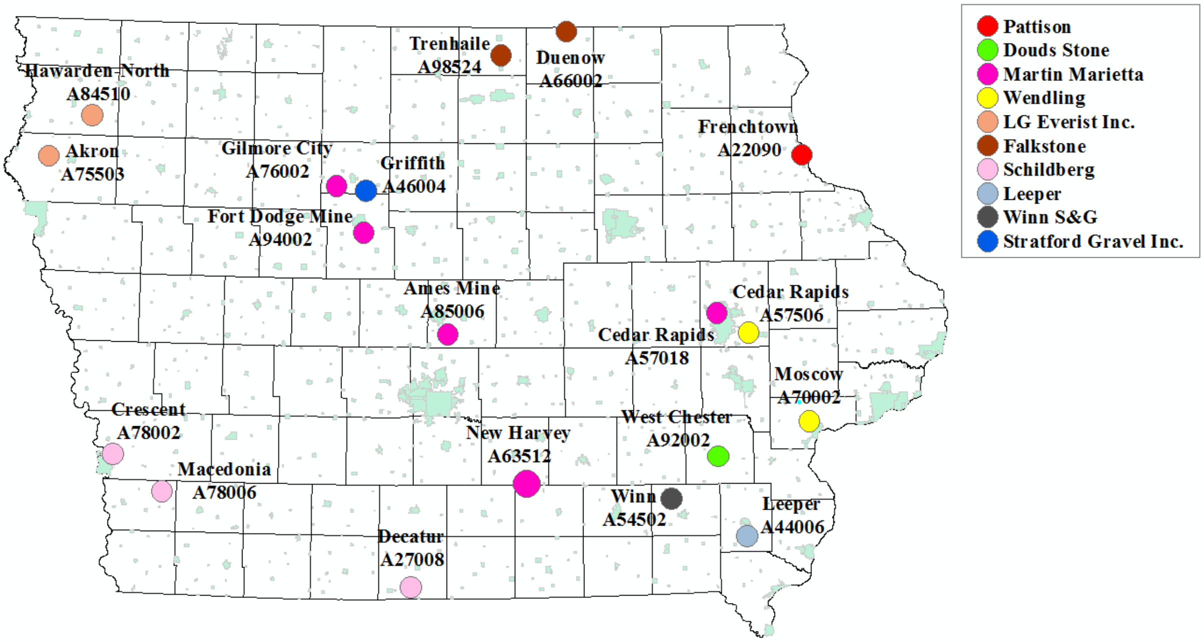


Figure 17. location of the quarries for quarry fines collection

Figure 18 shows the quarry fines materials that were used in this project. It should be mentioned that Clay Slurry fines came as slurry and the picture shows the mixture of existing aggregates with clay slurry in Jones County. Moscow, Crescent and Ames Mine fines were dried and collected from the piles. However, Limestone and Clay slurry were collected from ponds. Although Limestone materials were coming from ponds, they hauled as dried fines with around 20% moisture content to ease the construction process.

Figure 18. Quarry fines used in this study

4.2 Gradation

Boone County

Figure 19 shows the gradation of surface aggregate and subgrade materials from Boone and Jones counties. Surface aggregates for Jones County are from Stone City quarry and surface aggregates for Boone are from the local quarry in Boone County. As shown in the figure, Boone County surface aggregates are relatively finer than surface aggregates from Jones County. On the other hand, subgrade materials from Jones County were finer than subgrade materials from Boone County.

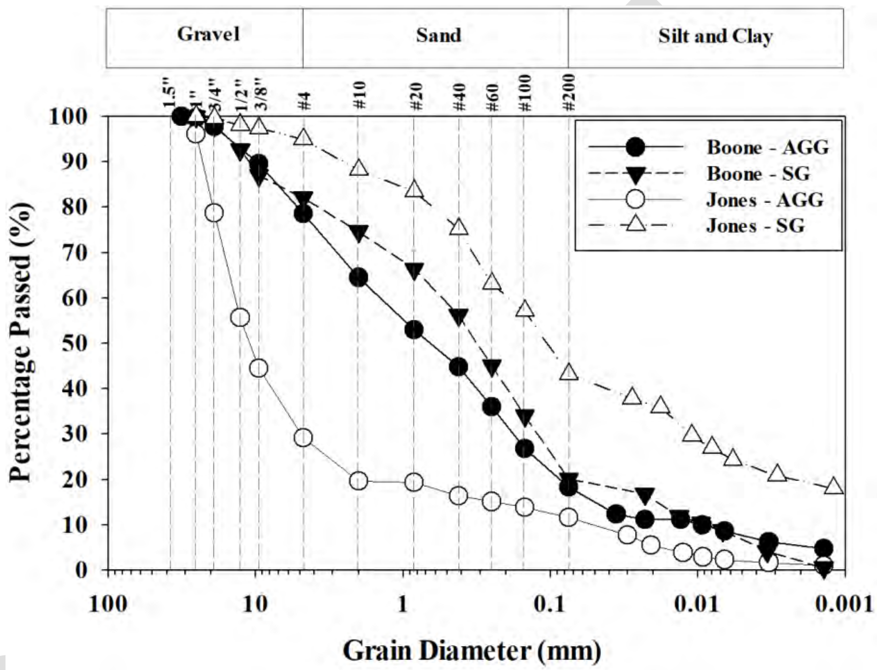


Figure 19 Particle size distribution curves for surface aggregates and subgrade materials from Boone and Jones counties

Table 2 shows the index properties of the surface aggregate materials in Boone and Jones counties. Plasticity index (PI) for surface aggregates in Boone County (10%) was higher than that of Jones County (8%). Subgrade materials from both counties had the same plasticity index values (24%). There was 42% gravel (> US sieve #4) in the surface aggregates for Jones County and 20% in Boone County. Gravel content for Boone County (13%) was a little higher than the gravel content of Jones County (5%). Sand content (<US sieve $4 and >US sieve #200) for surface aggregates was higher in Boone County (63%) than that of Jones County (36%). On the other hand, sand content for both Boone (53%) and Jones (52%) counties was almost the same. Fines content (<US sieve #200) for surface aggregates in both counties were similar (17 and 22%). Fines content of the subgrade materials in Jones County (43%) was higher than fines content of subgrade materials in Boone County (34%). Surface aggregate materials were classified as silty sand (SM) in Boone and silty gravel (GM) in Jones counties according to the Unified Soil Classification System (USCS) and surface aggregates in both counties were classified as A-1-b according to the AASHTO Classification system. On the other hand, subgrade materials of both Jones and Boone

counties were classified as silty sand (SM) and A-2-4(0) according to the USCS and AASHTO Classification systems, respectively.

Table 2. Index properties for surface aggregates and subgrade materials in Boone and Jones counties

Counties	**Boone**		**Jones**	
	AGG	**SG**	**AGG**	**SG**
LL (%)	16	29	16	39
PL (%)	5	5	8	15
PI (%)	10	24	8	24
D_{60}	0.9	0.3	6	0.12
D_{30}	0.2	0.1	0.2	0.01
D_{10}	0.05	0.01	0.03	NA
C_u	18.7	34.2	174	NA
C_c	1	1.4	0.2	NA
Gravel (%) (>4.75mm)	20	13	42	5
Sand (%) (4.75mm – 75µm)	63	53	36	52
Fines (75µm – 2µm)	17	34	22	43
AASHTO	A-1-b	A-2-4(0)	A-1-b	A-2-4(0)
USCS	SM	SM	GM	SM

Notes: LL=liquid limit, PL=plastic limit, PI=plasticity index, C_u=coefficient of uniformity, C_c=coefficient of curvature.

4.3 Compaction test

The standard Proctor test was performed on all surface aggregates and aggregate-quarry fines mixtures. The mixture of existing aggregates and quarry fines with different dry mass percentages were prepared and tested to determine the effects of adding quarry fines on the optimum moisture content (w_{opt}) and the maximum dry density (γ_{dmax}) of each material (ASTM D 698-12e1). Summary of the results are shown in **Table 3**. The γ_{dmax} of the subgrade was lower than that of all granular road surface aggregates (113 pcf) and its w_{opt} was the highest (13%). The w_{opt} of granular road surface aggregates were between 4.9% and 9.6%.

Table 3. Optimum moisture content and the maximum dry density results of the Proctor test

	Materials	Optimum Moisture Content (%)	Maximum Dry Density (pcf)
Boone County	Exist + 2% Ames Mine	7.2	143
	Exist + 6% Ames Mine	8.4	140
	Exist + 10% Ames Mine	6.5	144
	Exist + 2% Moscow	7.9	139
	Exist + 6% Moscow	8	130
	Exist + 10% Moscow	8.7	123
	Exist + 2% Clay Slurry	7.9	132
	Exist + 6% Clay Slurry	9.7	136
	Exist + 10% Clay Slurry	6.8	132
	Exist + 2% Crescent	5.8	141
	Exist + 6% Crescent	6.7	137
	Exist + 10% Crescent	6.4	136
	Exist	7.1	128
Jones County	Exist + 2% Moscow	11.2	123
	Exist + 6% Moscow	11	128
	Exist + 10% Moscow	11.4	131
	Exist + 2% Clay Slurry	4.2	125
	Exist + 6% Clay Slurry	9.7	127
	Exist + 10% Clay Slurry	9	125
	Exist + 2% Limestone	8.4	128
	Exist + 6% Limestone	5.9	126
	Exist + 10% Limestone	9.4	128
	Exist	8.2	125

4.4 CBR test

Figures 20 (a) and (b) show the results of the laboratory CBR tests under soaked condition that are performed on the untreated and treated surface aggregates from Boone and Jones counties mixed with quarry fines. The percentages of the quarry fines in the mixtures with surface aggregates in the design were decided based on the optimum mixtures obtained from the CBR tests.

The results of CBR tests in Boone County showed that mixing Clay Slurry with the surface aggregates would not increase the CBR values. However, 2% of Clay Slurry was decided to be mixed with 98% of the surface aggregates in the design to evaluate the performance of the section with Clay Slurry. 2% of Crescent, 6% of Moscow, and 10% of Ames Mine are the optimum amount to be mixed with surface aggregates in Boone County.

CBR of the untreated surface aggregates in Jones County was significantly higher than the CBR of untreated surface aggregates in Boone County. Mixing Clay Slurry with the surface aggregates of Jones County did not increase the CBR. However, 2% of Clay Slurry was decided to be mixed with 98% of the surface aggregates in the design to evaluate the performance of the section with Clay Slurry. 2% of Limestone, and 10% of Moscow are the optimum amount to be mixed with surface aggregates in Jones County.

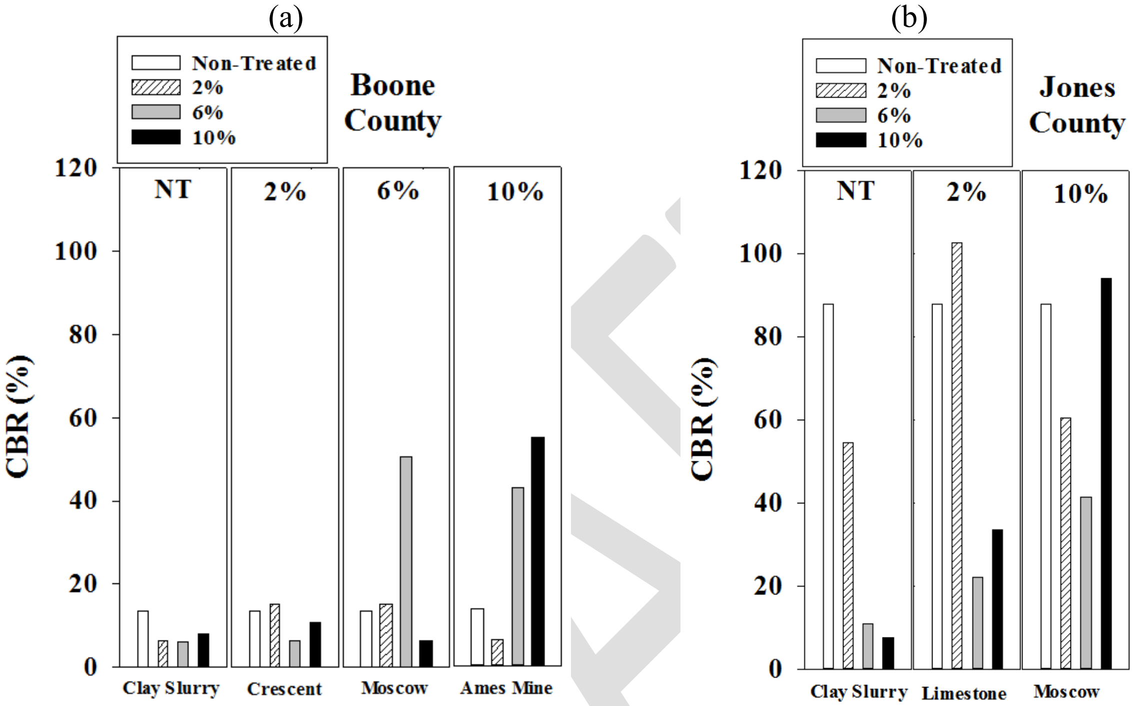


Figure 20. CBR for the untreated and treated surface aggregates with quarry fines for (a) Boone County, and (b) Jones County

4.5 Pocket penetrometer test

Triplicate pocket penetrometer tests were conducted on the specimens mixed with quarry fines passing through U.S. #200 sieve and in slurry condition (25% solid content) in shallow dishes to measure the penetration resistance over time due to combination of dehydration and setting up. The final reading was when the resistance reached 4.5 tsf, which was the maximum penetration resistance that pocket penetrometer could measure. **Figure 21** shows that Crescent and Moscow fines reach the maximum strength faster than rest of the fines (72 hours), Macedonia, Limestone, and Decatur reach their maximum strength after 120 hours, and Ames Mine and Clay Slurry reach the maximum strength after 144 hours and 192 hours, respectively.

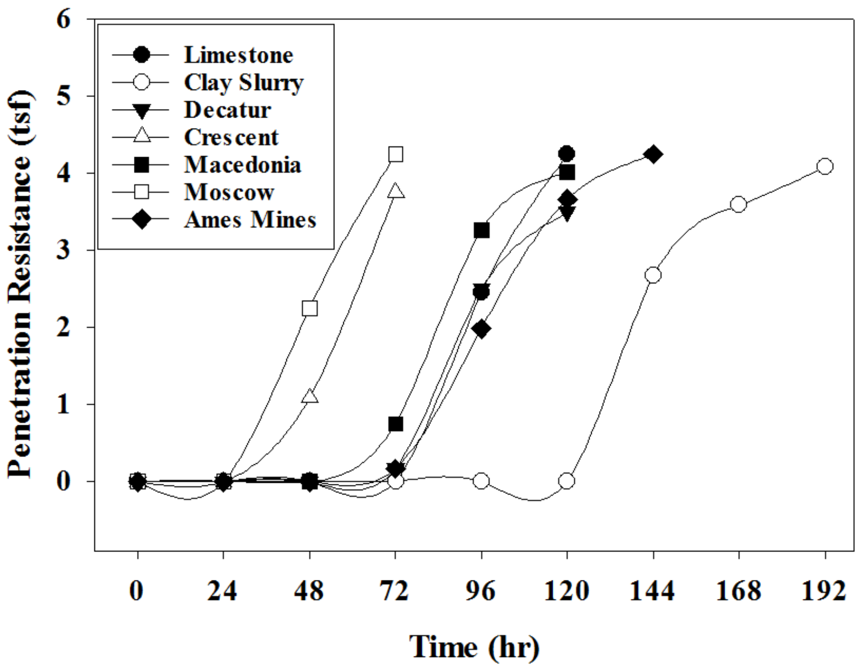


Figure 21. Penetration resistance of the saturated quarry fines samples versus time

4.5 Mini-vane shear test

Mini-vane shear tests were conducted on the quarry fines passing through the U.S sieve #200 in saturated conditionsThe saturated quarry fines specimens were prepared in plastic containers having a diameter of 4” and length of 4.7”. The blades of the laboratory vane shear tests were penetrated into each sample at the middle of the specimens, to a depth of 1.2” below the sample’s surface (ASTM D4648). **Figure 22** shows that Crescent (0.011 tsf) and Moscow (0.009 tsf) have the maximum vane shear strength and Ames Mine, Macedonia, and Decatur quarry fines have the minimum shear strengths (0.004 to 0.007 tsf) after 96 hours of gaining strength due to combination effects of drying out and setting up.

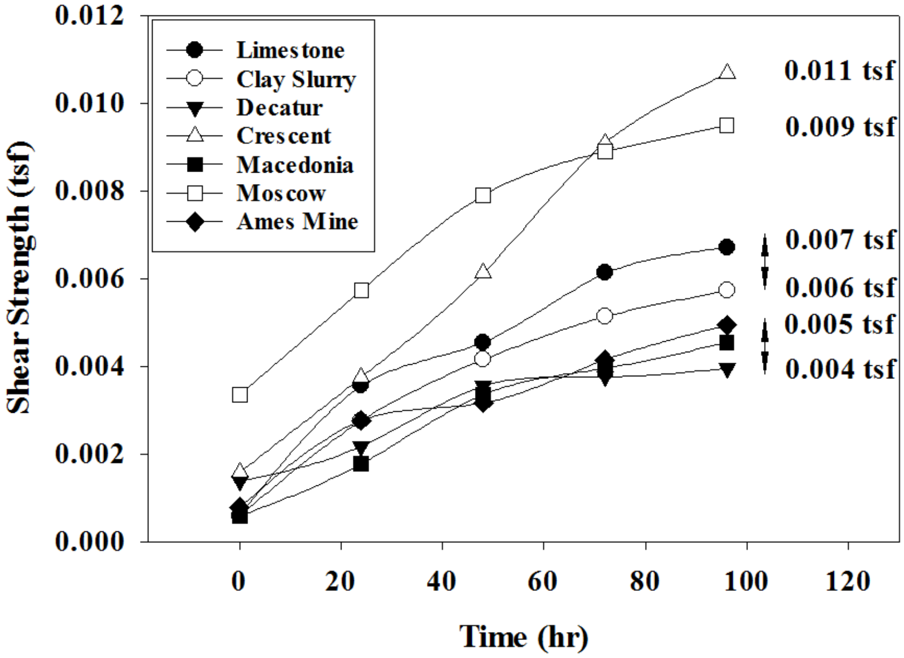


Figure 22. Change of the undrained shear strength with time for all specimens

4.7 Slaking test

Slaking tests were conducted on 2 by 2-in specimens of Boone and Jones counties existing surface aggregate. In addition, specimens were prepared for the mixtures of the quarry fines with existing aggregates. Three replicates were prepared for each material. **Table 4** shows the summary of the results. It was observed that Boone County materials has relatively lower slaking times than that of Jones County materials. Addition of Ames Mine to the existing surface aggregates from Boone County reduced the slaking time compared to the untreated surface materials from Boone County. However, mixing Moscow, Clay Slurry, and Crescent with the Boone County surface aggregates almost doubled the slaking time. For Jones County materials, mixing surface aggregates with all different fines increased the slaking time, where the increase was the greatest for Limestone and the lowest for Clay Slurry. **Figure 23** shows three existing surface aggregates that became disintegrated with water after almost 2 minutes and the mixtures of Clay Slurry and existing surface aggregates were still did not disintegrate after 3.5 minutes.

Table 4. Slaking test results for Boone and Jones counties surface aggregate and their mixtures with quarry fines

	Specimen	Slaking time (min)	Water temperature (°C)
Boone County	Existing + 10% Ames Mine	1	23.4
	Existing + 6% Moscow	3.5	23.1
	Existing + 2% Clay Slurry	4	22.8
	Existing + 2% Crescent	4.5	23.6
	Existing	2	24.1
Jones County	Existing + 10% Moscow	10	23.8
	Existing + 2% Clay Slurry	7	24.6
	Existing + 2% Limestone	12	22.9
	Existing	5	22.9

Figure 23. Slaking test for 2-by-2 specimens of Boone County existing surface aggregate, and mixing with 2% Clay Slurry

4.8 XRF

Depending on the natural properties of the parent rock, the mineralogy of the quarry fines vary from source to source (Stokowski 1992). **Table 5** shows the chemical constituents of the quarry fines samples as determined from XRF tests. The results showed that CaO, MgO, SiO_2, and Al_2O_3 were the dominant chemical constituents for all quarry fines collected in this study. However, the Alumina content is one of the most important factors, as it is an indicator of the plastic clay characteristic. The maximum and minimum Alumina contents were observed for Decatur (4.56 %) and Limestone (1.12 %) quarry fines, respectively.

Table 5. XRF results for chemical compositions of selected quarry fines materials (wt. %)

Quarry fines	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	S	Na_2O	K_2O	P_2O_5	LOI[1]
Clay Slurry	23.89	16.28	19.6	1.12	0.77	<0.1	-	<0.1	0.62	-	36.7
Limestone	22.5	13.91	23.57	2.58	1.88	0.13	<0.1	0.63	1.48	0.18	37.7
Moscow	34.77	9.96	12.28	2.12	1.09	<0.1	0.37	<0.1	0.73	<0.1	38.4
Ames Mine	53.24	0.35	0.74	0.28	0.24	<0.1	0.11	<0.1	<0.1	<0.1	44.9
Macedonia	47.03	1.03	9.97	1.7	0.76	0.1	0.2	0.16	0.42	<0.1	38.5
Crescent	43.95	2.04	10.98	2.06	1.25	0.11	0.21	0.17	0.51	<0.1	38.5
Decatur	30.78	2.91	25.02	4.56	1.98	0.23	0.26	0.38	1.17	0.13	32.4

[1]LOI = loss on ignition

CHAPTER 5. SITE DESCRIPTION, DESIGN, AND CONSTRUCTION

5.1 Site description

Boone and Jones counties were selected to construct the field test sections. This chapter explains the properties of each section in Boone and Jones counties and provide additional information about the location of the sites and dimensions of each section.

5.1.1 Boone County

Four test sections were constructed in Boone County at the end of October and the beginning November 2019. The length and width of each section was 0.25 mile (1320 ft) was 26 ft, respectively. The surface material was mixed with quarry fines down to a depth of 2 in (**Figure 24**). **Figures 25 and 26** show the location of the test section in Boone County, where it is on 210th street between U and V avenues from the west to the east. One control section with existing surface aggregates was on the far east end. All sections were constructed on a 5~7 in thick subbase layer containing surface aggregates.

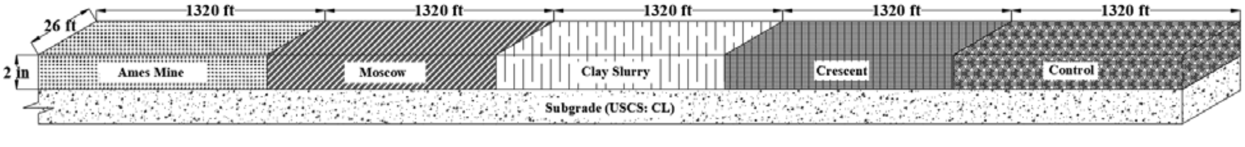


Figure 24. Layout of the sections in Boone County

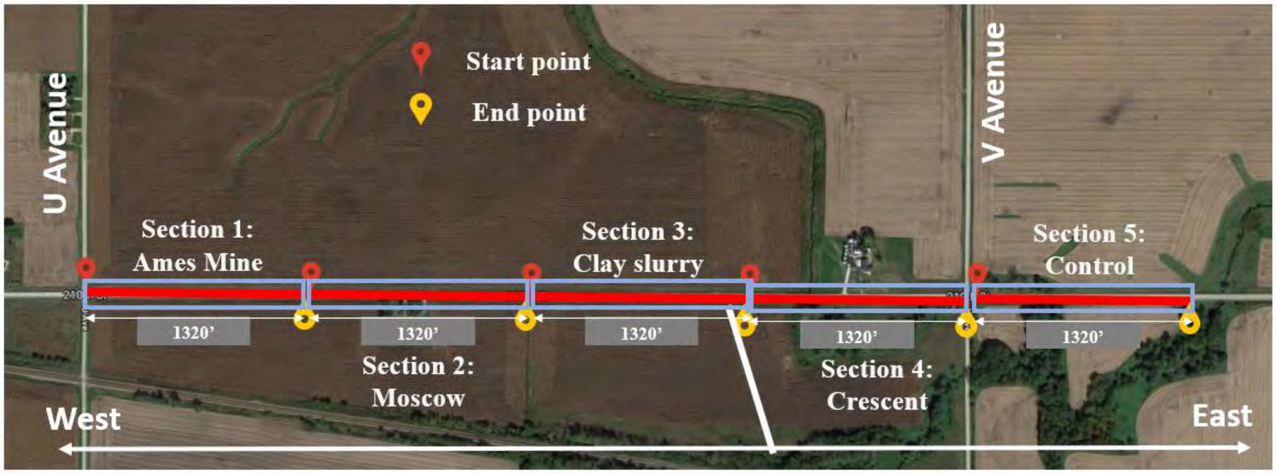


Figure 25. Boone county sections in Google map

Figure 26 Access to the site location

5.1.2 Jones County

Three sections were constructed in Jones County on October 17th, 2019. The length and width of each section was 0.25 mile (1320 ft) and 26 ft, respectively. The surface material was mixed with quarry fines down to a depth of 2 in (**Figure 27**). **Figures 28 and 29** show the location of the test section in Jones County, where it is on 15th street, Lisbon, Iowa. One control section with existing surface aggregates was on the far east end. All sections were constructed on a 5~6 in subbase layer containing surface aggregates that were used during the construction. All sections had relatively stiff subgrade layer and they were leveled up and pipes were used for providing suitable drainage.

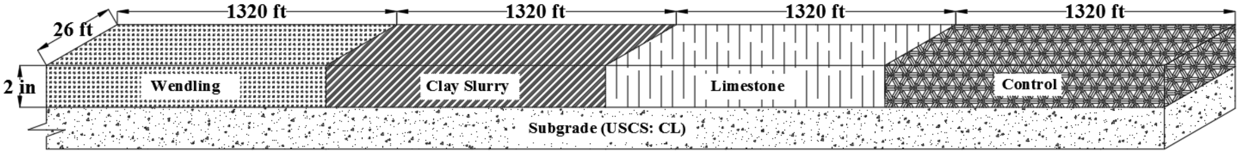


Figure 27. Layout of the sections in Jones County

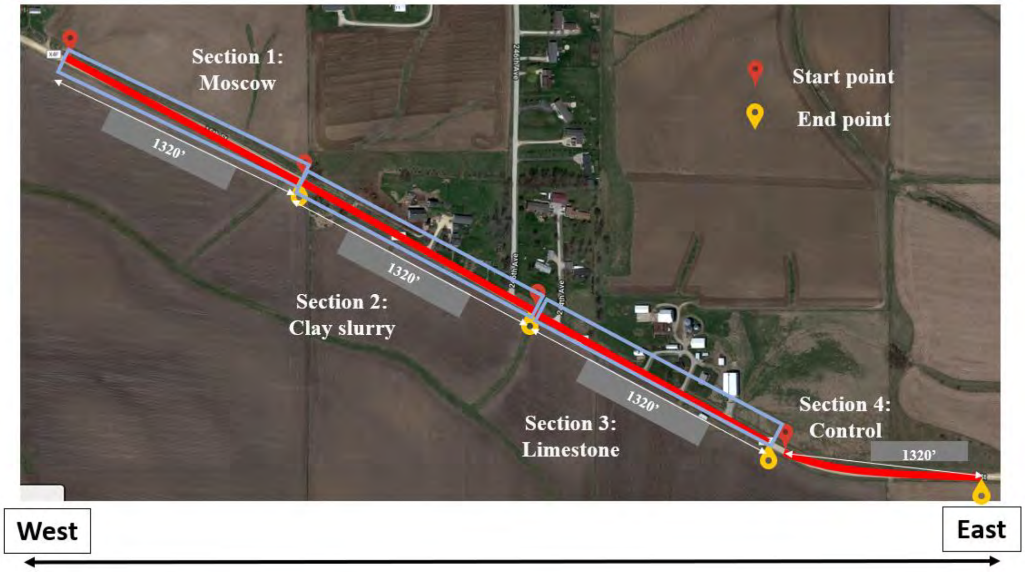


Figure 28. Jones county sections in Google map

Figure 29 Access to the site location

5.2 Construction

Clay slurry and limestone fines from Frenchtown A22090, Moscow A70002 fines, Ames mine A85006 fines, Crescent A78002 fines were the seven quarry fines with appropriate plasticity indices which were selected after performing sieve analysis and Atterberg limit tests. **Figure 30** shows the locations of the quarries and construction sites.

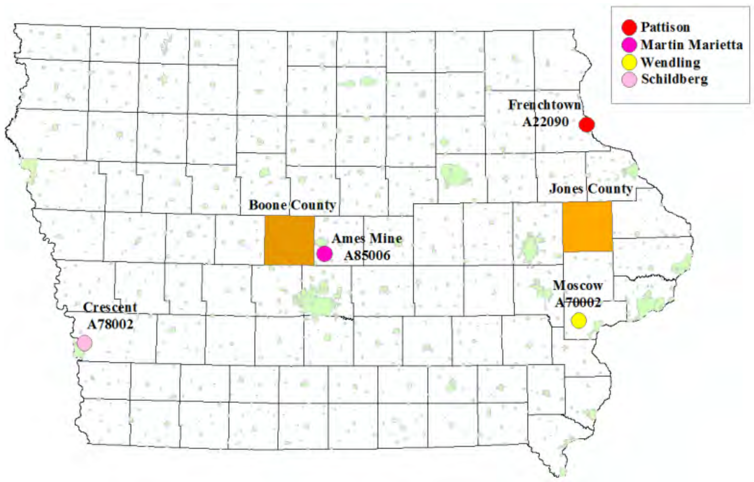


Figure 30. Locations of the quarries and construction sites

In this project, quarry fines for construction in Boone County were Ames Mine (A85006), Moscow (A70002), Clay Slurry (A22090), and Crescent (A78002). These materials were hauled by trucks to the site location. **Table 6** shows the hauling time between quarries and site location. Clay Slurry (3.5 hr) and Moscow (2.5 hr) were the farthest locations to the construction site in Boone County. However, Ames Mine fines were adjacent to the site location. Quarry fines for construction in Jones County were Moscow (A70002), Clay Slurry and Limestone (A22090). These materials were hauled by trucks to the site location. Location of the quarry fines used in Jones County were closer to the site location than those for Boone County.

Table 6. Hauling time for the quarry fines for Boone and Jones Counties

	Quarry Fines	Time (hr)
Boone	Clay Slurry - Pattison Frenchtown A22090	3.5
	Ames Mine Ames Mine A85006	0.25
	Moscow A70002	2.5
	Schildberg Crescent A78002	1.5
Jones	Clay Slurry & Limestone - Pattison Frenchtown A22090	1.5
	Moscow A70002	1

For both counties, construction started with ripping the first 1” of the existing surface aggregates to windrow to both sides to reduce runoff. Then, the quarry fines were spread on top of the surface. Windrowed materials were placed back on the road. Mixing depth of the motor grader was calibrated to 2” below the road surface and several grader passes happened to shape the surface. Moisture contents of the surface materials were checked by hand-feel, and when it was required, water was sprayed on the materials. After that, compaction with rubber tire roller was performed following the motor grader to reduce the compaction time. For the sections built with clay slurry, the fine materials were sprayed on the surfaces on several rounds. 120 ton of aggregates were then added to the surface materials of Clay Slurry section in Boone County to reduce the water content and dry the surface materials faster. **Figure 31** (a, b, and c) shows the windrow, Clay Slurry spraying, and the wetted surface after spraying the Clay Slurry in Jones County.

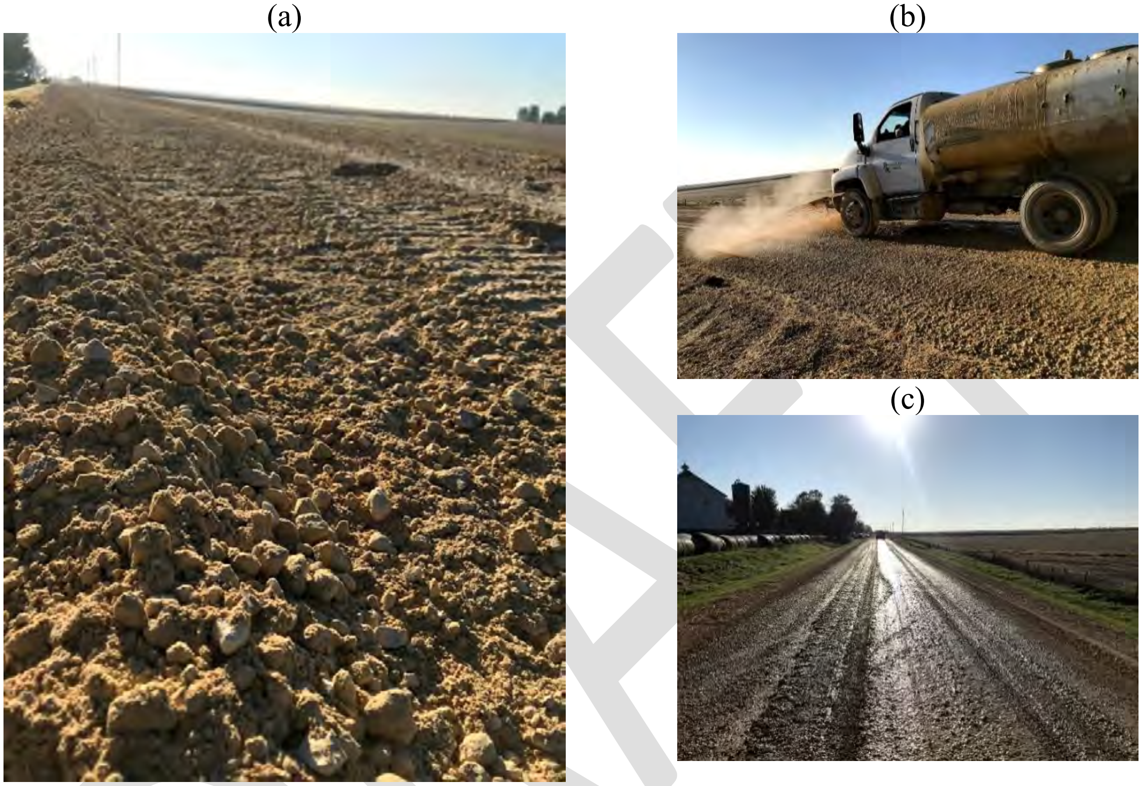


Figure 31. Construction in Jones County

5.3 Maintenance

Granular roadways in cold regions such as Iowa are prone to severe distresses such as potholes, washboarding, and rutting due to the deterioration of the surface materials during freezing and thawing. Accordingly, blading is a common procedure to recover the surfaces and improve the riding quality on a smooth surface. **Figure 32** shows the potholes and rutting that happened in the Moscow section in Jones County after the freeze-thaw period. All sections were bladed (four times in Boone County and three times in Jones County).

Figure 32. Distress types happened to the surface materials, (a) big pothole in middle of Moscow section in Jones County, (b) sever rutting in Moscow section in Jones County

Figure 33 shows the motor grader that is used for blading the sections in Jones County. Motor grader is the only equipment that is required for maintenance during this project.

Figure 33. Motor grader for blading and removing the distresses

Surface thickness was measured for all sections in both counties to evaluate aggregate deterioration. However, all the sections performed excellent, and the surface thickness remained 2” which was the initial design thickness. Therefore, maintenance including adding new aggregate materials was not required for all demonstration sections. In addition, field surveying reports were filled every time research team was present in the field or by county personnel. These survey reports are attached in the Appendix part G section.

5.4 Quality Assurance and Quality Control (QA/QC)

Amount of material, numbers of blading and compaction passes during construction were recorded and observed by the research crew and county engineers for the quality control (QC) and quality assurance (QA).

Moisture content of the mixture of the surface aggregates and quarry fines were evaluated by hand to be consistent with the design moisture content, which was measured and checked in the laboratory. Compaction of the mixture of surface aggregates and quarry fines was performed by ruler compactor~~to shape a smooth surface~~. After compaction, the thickness of the surface layer was measured to ensure that it was 2 inches.

CHAPTER 6. RESULTS AND DISCUSSIONS

In this chapter, results of field tests including gradation change, nuclear density gauge, DCP, FWD, IRI, LWD, and dustometer tests are presented and discussed. The first set of field tests were performed in November 2019, after the construction to evaluate the as-constructed performance of the sections. On March 2020, sample collection for investigating the gradation changes, photo surveying, and LWD tests were performed. These tests required only one person to do the tests during COVID-19 situation. However, rest of the tests including DCP, IRI, and Dustometer tests were performed in June 2020 with two research personnel by following the university covid safety instructions.

6.1 Gradation change

The research team performed sample collections from the sections in Jones and Boone counties in November 2019 and March 2020 to investigate the changes in gradation parameters including fines, sand, and gravel contents, gravel to sand ratio, and total breakage. Following sections presents the summary of these results for Boone and Jones counties.

6.1.1 Boone County

Figure 34 shows the fines content of the surface aggregate materials from sections in Boone County. Results showed that fines content of all sections increased from November 2019 to March 2020. This increase was the greatest for Ames Mine and the lowest for Clay Slurry and the Moscow sections. In November 2019, the Ames Mine section had the lowest and Moscow and the control sections had the highest fines contents. However, Ames Mine and the control section had the highest and Clay Slurry and Crescent sections had the lowest fines content after freeze-thaw cycle by March 2020.

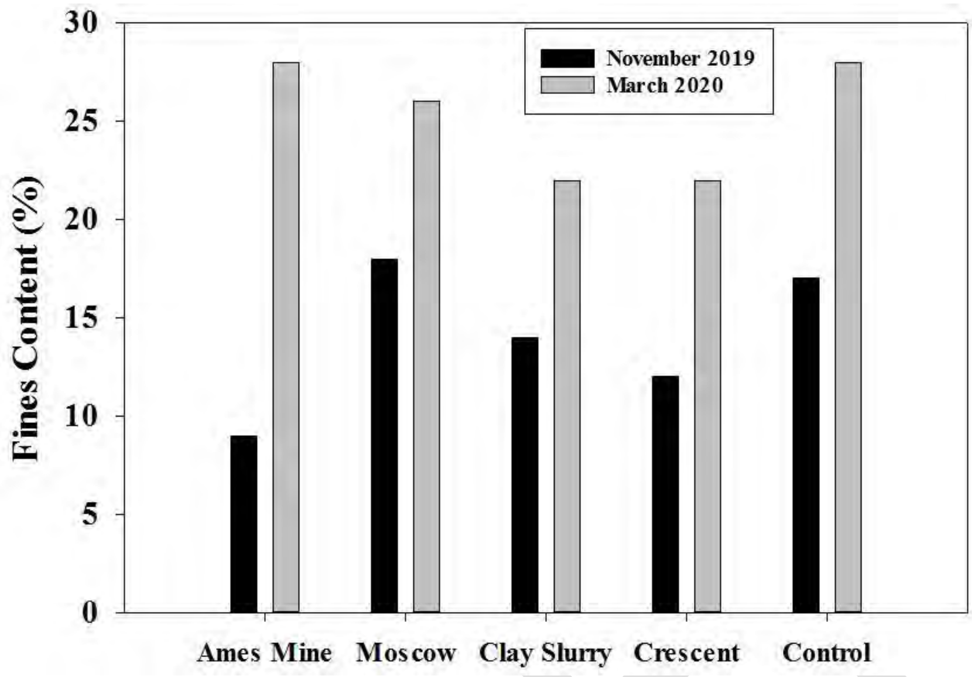


Figure 34. Fines content of the surface materials in Boone County

According to **Table 7**, average fines content of the sections was in a close range between 17% for Crescent section and 22% for Moscow and the control section. All sections had increases in their fines contents and such increase was the highest for Ames Mine section (192%) and the lowest for Moscow section (41%).

Table 7. Fines content of the surface aggregate materials in Boone County sections

	November 2019	March 2020	Average	Change (%)
Ames Mine	9	28	19	198
Moscow	18	26	22	41
Clay Slurry	14	22	18	56
Crescent	12	22	17	80
Control	17	28	22	70

Figure 35 shows that the sand content of all sections in Boone County decreased from November 2019 to March 2020. This decrease was the highest for Ames Mine and the control section and it was the lowest for the Crescent section. The amount of changes in the sand content was not significant from November 2019 to March 2020. Control and Crescent sections had, respectively, the highest and lowest sand content in November 2019. Control section remained as the section

with the highest sand content from November 2019 to March 2020, while Ames Mine section had the lowest sand content on March 2020.

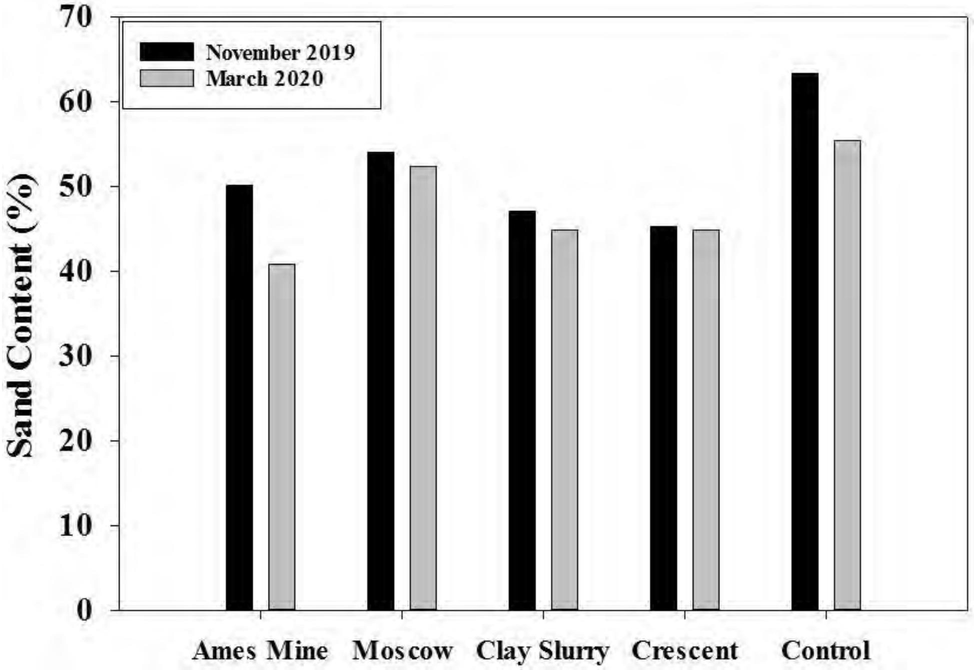


Figure 35. Sand content of the surface materials in Boone County

Table 8 shows that all sections in Boone County experienced a decrease in their sand content from November 2019 to March 2020. This decrease was the highest for Ames Mine section (-19%) and the lowest for Crescent (-1%) section. Average sand content values for all sections were at the ranges of 45% for Crescent section and 59% for the control section.

Table 8. Sand content of the surface aggregate materials in Boone County sections

	November 2019	March 2020	Average	Change (%)
Ames Mine	50.2	40.9	46	-19
Moscow	54	52.4	53	-3
Clay Slurry	47.1	44.8	46	-5
Crescent	45.3	44.8	45	-1
Control	63.3	55.4	59	-12

Figure 36 shows the results of gravel content for the sections in Boone County for November 2019 and March 2020. Due to the aggregate deterioration during freeze-thaw period, all sections had a decrease in their gravel content from November 2019 to March 2020. All demonstration sections had higher gravel contents than the control section. Ames Mine and Crescent sections had relatively the highest gravel contents change, and control section had the lowest gravel contents change from November 2019 to March 2020. Crescent, Ames Mine, and Clay Slurry sections had

the highest and the control and Moscow sections had the lowest gravel contents both on November 2019 and March 2020.

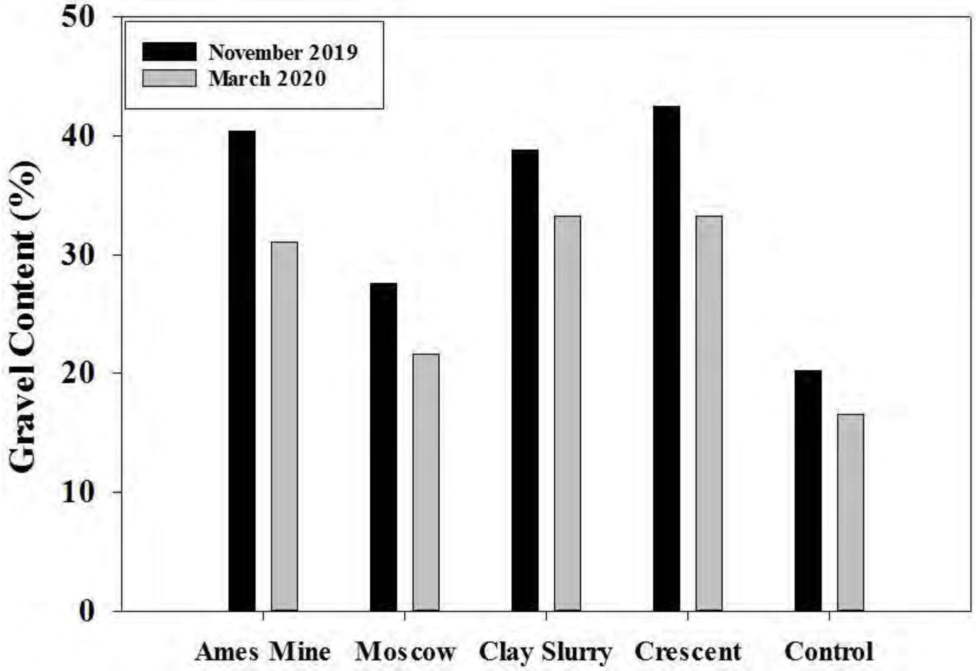


Figure 36. Gravel content of the surface materials in Boone County

Table 9 shows that all sections had a decrease in their gravel contents from November 2019 to March 2020 between -14% (Clay Slurry) and -23% (Ames Mine). Average gravel contents for all sections were between 18% for control section and 38% for Crescent section.

Table 9. Gravel content of the surface aggregate materials in Boone County sections

	November 2019	March 2020	Average	Change (%)
Ames Mine	40.4	31.1	36	-23
Moscow	27.6	21.6	25	-22
Clay Slurry	38.8	33.2	36	-14
Crescent	42.5	33.2	38	-22
Control	20.2	16.6	18	-18

Figure 37 shows the gravel to sand ratio for all sections in Boone County in November 2019 and March 2020. As shown in the figure 37, Crescent section had the highest and the control section had the lowest change in their gravel to sand ratios from November 2019 to March 2020. Crescent had the highest and the control section had the lowest gravel to sand ratios in November 2019.

However, Ames Mine, Clay Slurry, and Crescent sections had the highest and similar gravel to sand ratios in March 2020 and the control section had the lowest.

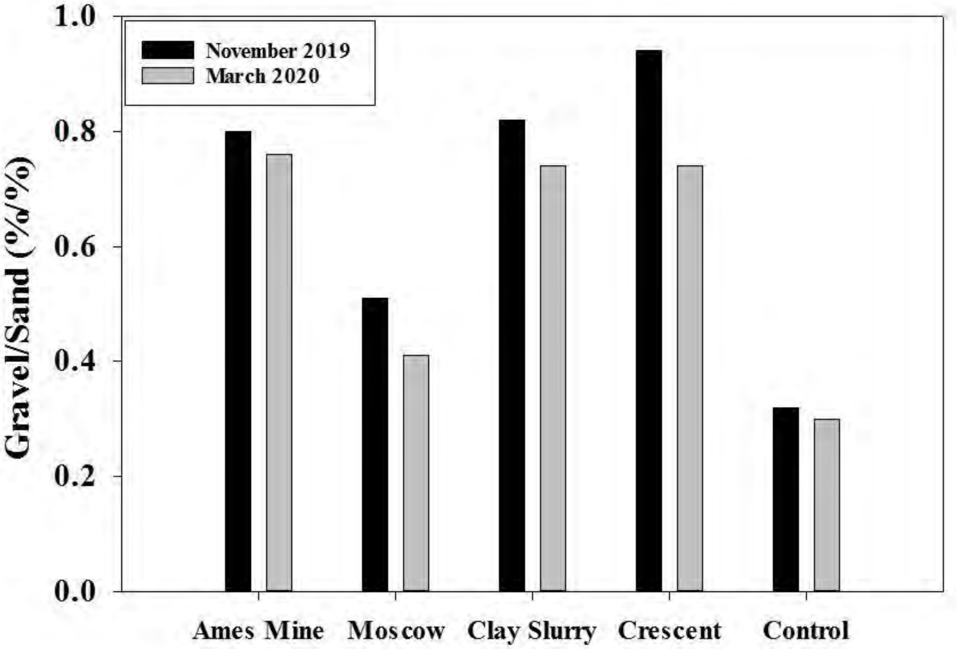


Figure 37. Gravel to sand ratio of the surface materials in Boone County

Table 10 shows the summary of the gravel to sand ratio values for all sections in Boone County in November 2019 and March 2020. The results of this table showed that Crescent, Clay Slurry, and Ames Mine sections had the same average gravel to sand ratios (0.8) and the control section (0.3), and Moscow section had lower gravel to sand ratios (0.5). Ames Mine and the control sections with -6% and Crescent section with -21% had the lowest and the highest change in their gravel to sand ratios from November 2019 to March 2020.

Table 10. Gravel to sand ratio of the surface aggregate materials in Boone County sections

	November 2019	March 2020	Average	Change (%)
Ames Mine	0.80	0.76	0.8	-6
Moscow	0.51	0.41	0.5	-19
Clay Slurry	0.82	0.74	0.8	-10
Crescent	0.94	0.74	0.8	-21
Control	0.32	0.30	0.3	-6

Figure 38 shows the results of total breakage for all sections in Boone County. Total breakage is defined as the area between the particle size distribution curves, which can be an indicator of material degradation over time (Hardin 1985). Moscow and the control sections had the lowest and Ames Mine section had the highest total breakage from November 2019 to March 2020.

Crescent and Clay Slurry sections had similar total breakage values from November 2019 to March 2020.

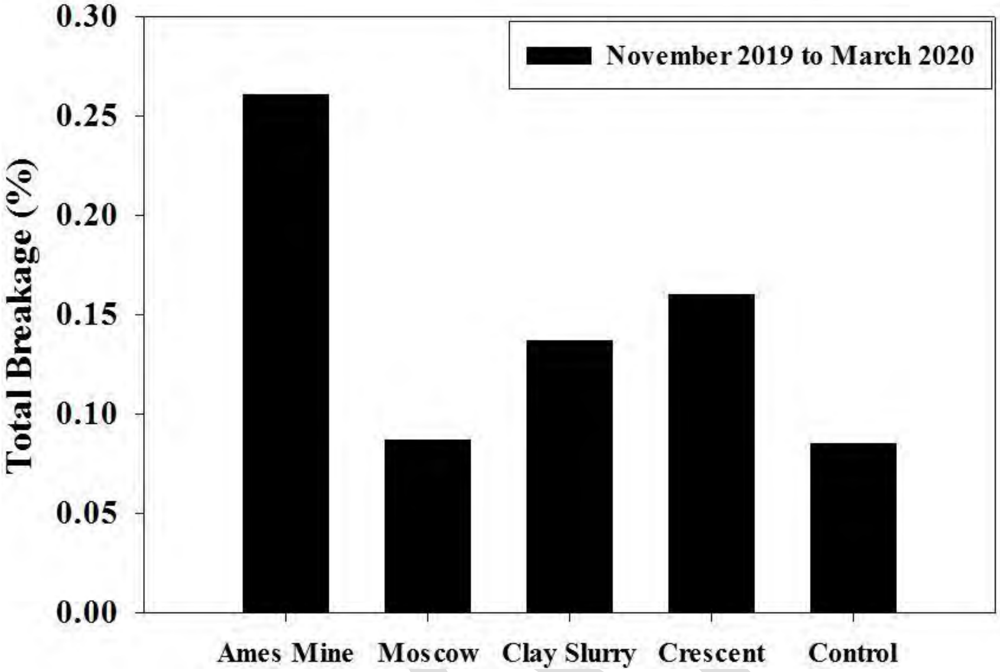


Figure 38. Total breakage of the surface materials in Boone County

6.1.2 Jones County

Figure 39 shows the fines contents of the surface aggregate materials from sections in Jones County. It was observed that fines contents of all sections increased from November 2019 to March 2020. This increase was the greatest for Moscow and the control sections and the lowest for Clay Slurry and Limestone sections. In November 2019, Moscow section had the lowest and Limestone section had the highest fines contents. However, the control section had the highest and Moscow section had the lowest fines content after freeze-thaw period in March 2020.

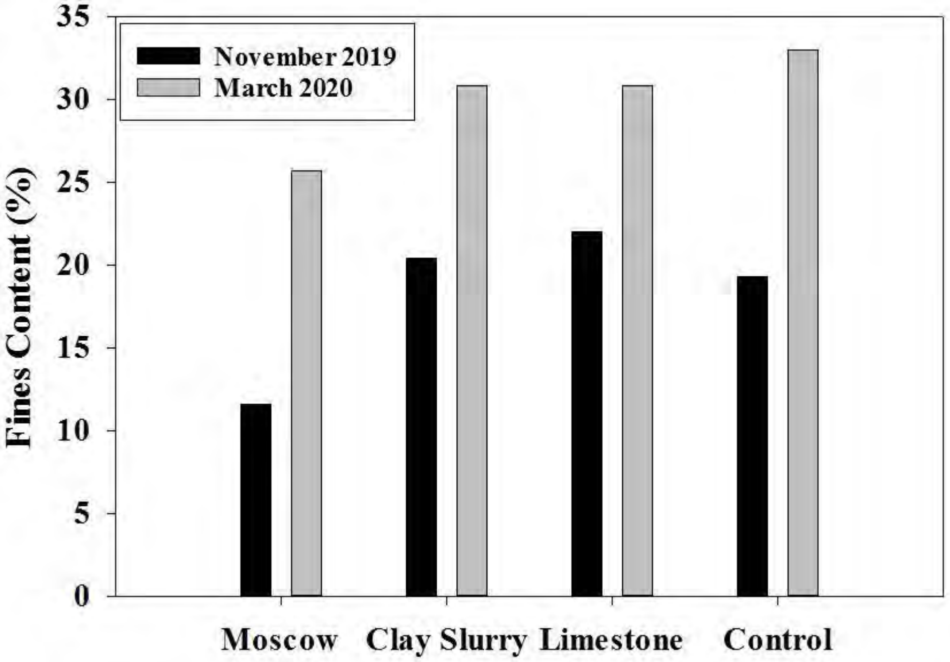


Figure 39. Fines content of the surface materials in Jones county

As shown in **Table 11**, the average fines content of the sections was in a close range between 19% for Moscow section and 26% for the rest of the sections. All sections had increase in their fines content and such increase was the highest for Moscow section (122%) and the lowest for Limestone section (40%).

Table 11. Fines content of the surface aggregate materials in Jones County sections

	November 2019	March 2020	Average	Change (%)
Moscow	11.6	25.7	19	122
Clay Slurry	20.4	30.8	26	51
Limestone	22	30.8	26	40
Control	19.3	33	26	71

Figure 40 shows that the sand content of all sections in Jones County decreased from November 2019 to March 2020. This decrease was the highest for Limestone section and it was the lowest for Clay Slurry section. The amount of changes in the sand content for all sections was not significant from November 2019 to March 2020. Control and Moscow sections had, respectively, the highest and lowest sand contents in November 2019. Control section along with Clay Slurry

section remained as the section with the highest sand content from November 2019 to March 2020, while Moscow section had the lowest sand content on March 2020.

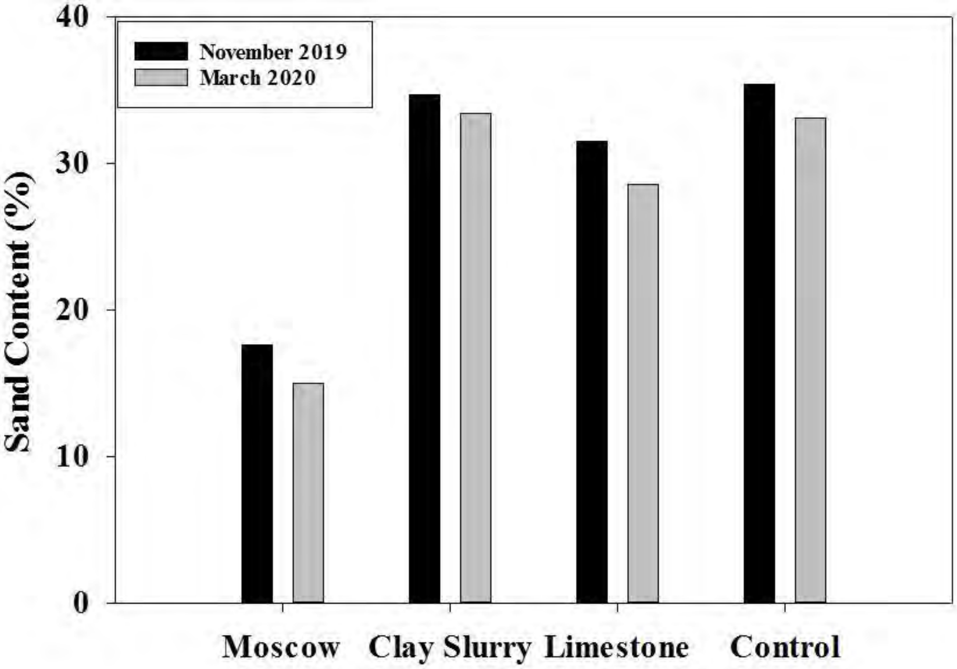


Figure 40. Sand content of the surface materials in Jones County

Table 12 shows that all sections in Boone County experienced a decrease in their sand content values from November 2019 to March 2020. This decrease was the highest for Moscow section (-15%) and the lowest for Clay Slurry section (-4%) section. Average sand content values for all sections were at the ranges of 16% for Moscow section to 34% for the Clay Slurry and the control sections.

Table 12. Sand content of the surface aggregate materials in Jones County sections

	November 2019	March 2020	Average	Change (%)
Moscow	18	15	16	-15
Clay Slurry	35	33	34	-4
Limestone	32	29	30	-9
Control	35	33	34	-6

Figure 41 shows the results of gravel content for the sections in Jones County for November 2019 and March 2020. Due to the aggregate deterioration during freeze-thaw period, all sections had a decrease in their gravel contents from November 2019 to March 2020. All demonstration sections had higher gravel contents than the control section. Moscow and the control sections had relatively the highest gravel content changes and Limestone section had lowest gravel content change from

November 2019 to March 2020. Moscow section had the highest and the control and Clay Slurry sections had the lowest gravel contents both on November 2019 and March 2020.

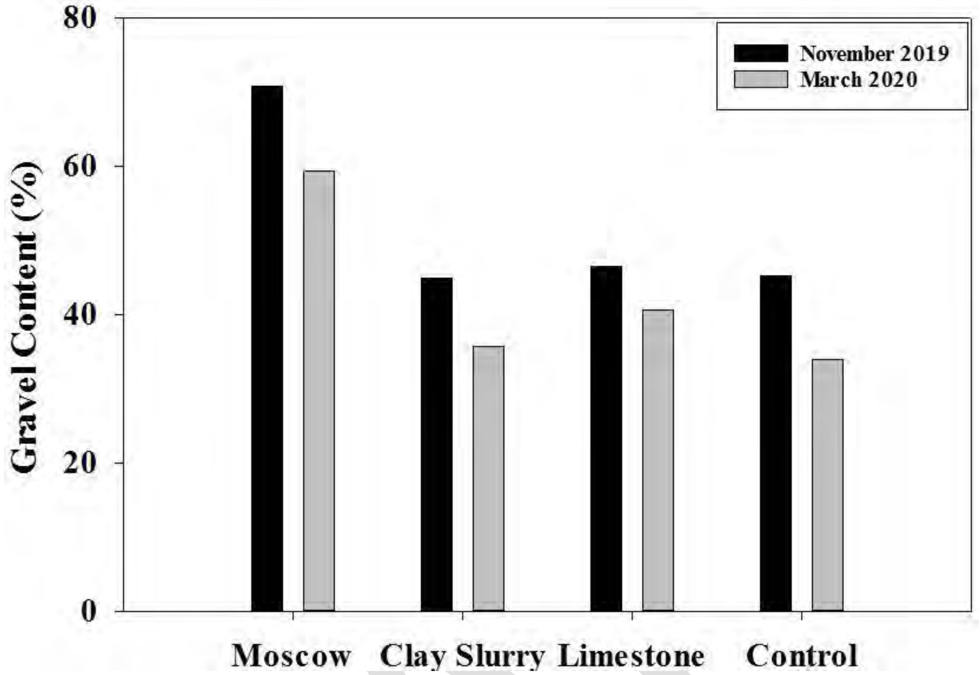


Figure 41. Gravel content of the surface materials in Jones County

Table 13 shows that all sections had a decrease in their gravel contents from November 2019 to March 2020 between -14% (Clay Slurry) and -23% (Ames Mine). Average gravel contents of all sections were between 18% for control section and 38% for Crescent section.

Table 13. Gravel content of the surface aggregate materials in Jones County sections

	November 2019	March 2020	Average	Change (%)
Moscow	71	59	65	-16
Clay Slurry	45	36	40	-20
Limestone	47	41	44	-13
Control	45	34	40	-25

Figure 42 shows the gravel to sand ratio for all sections in Jones County in November 2019 and March 2020. According to **Figure 42**, the control section had the highest and Limestone and Moscow sections had the lowest changes in their gravel to sand ratios from November 2019 to

March 2020. Moscow had the highest and Clay Slurry section had the lowest gravel to sand ratios on both November 2019 and March 2020.

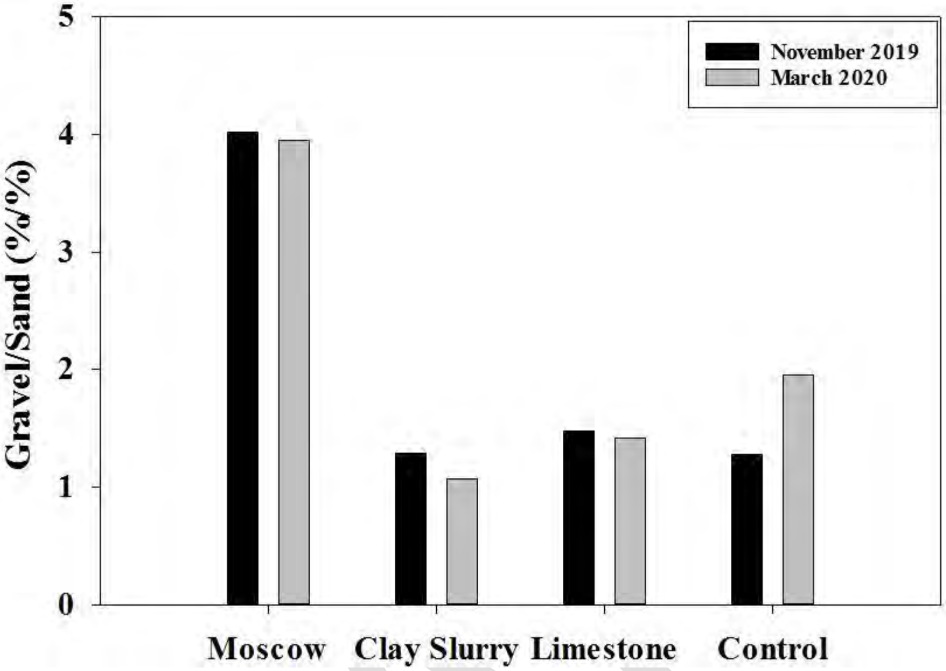


Figure 42. Gravel to sand ratio of the surface materials in Jones County

Table 14 shows the summary of the gravel to sand ratio values for all sections in Jones County in November 2019 and March 2020. The results showed that the control and Clay Slurry sections had the same and lowest average gravel to sand ratios (1.2) and Moscow section had the highest gravel to sand ratios (4). Gravel to sand ratios of all sections decreased from November 2019 to March 2020 and this rate of change was the lowest for Moscow section (-2%) and the highest for the control section (-20%).

Table 14. Gravel to sand ratio of the surface aggregate materials in Jones County sections

	November 2019	March 2020	Average	Change (%)
Moscow	4.0	4.0	4.0	-2
Clay Slurry	1.3	1.1	1.2	-17
Limestone	1.5	1.4	1.4	-4
Control	1.3	1.0	1.2	-20

Figure 43 shows the results of total breakage for all sections in Jones County from November 2019 to March 2020. Limestone section had the lowest and the control section had the highest total breakage from November 2019 to March 2020.

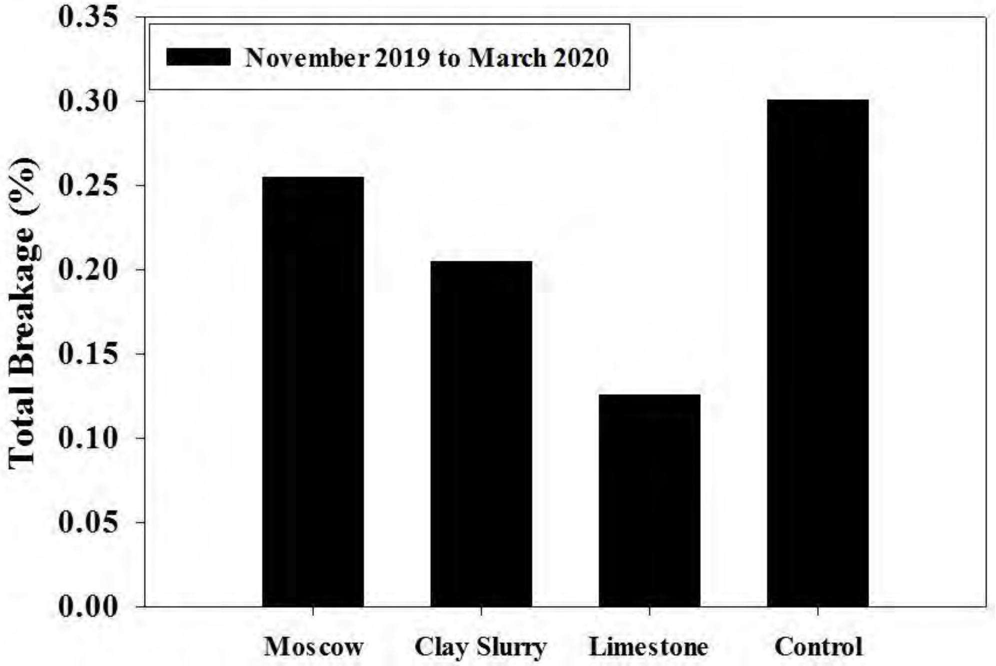


Figure 43. Total breakage of the surface materials in Jones County

6.2 Nuclear Density Gauge Tests

The nuclear gauge test was performed by Iowa DOT at 10 points for each section both in Boone and Jones counties. This test shows the results of wet and dry densities and the moisture content of the surface materials.

6.2.1 Boone County

Table 15 shows the average values of the dry and wet densities and the water content of each section in Boone County on March 2020. The maximum dry density (142 pcf) and wet density (134 pcf) were observed on the Clay Slurry section. On the other hand, the minimum dry density (137 pcf) and wet density (128 pcf) were measured for the control section. The water content values ranged between 5% (Ames Mine) and 7% (control section).

Table 15. Nuclear gauge results for dry density, wet density, and water content in Boone County

Section	March 2020		
	γ_w (pcf)	γ_d (pcf)	ω (%)
Ames Mine	138	131	5
Moscow	139	131	6
Clay Slurry	142	134	6
Crescent	140	133	5
Control Section	137	128	7

6.2.1 Jones County

Table 16 shows the average values of the dry and wet densities and the water content of each section in Jones County. The maximum dry density (141 pcf) and wet density (130 pcf) were observed for the Limestone section. On the other hand, the minimum dry density (136 pcf) and wet density (124 pcf) were measured for the Clay Slurry section. The water content values ranged between 8% (Moscow and the control) and 10% (Clay Slurry).

Table 16. Nuclear gauge results for dry density, wet density, and water content in Boone County

Section	March 2020		
	γ_w (pcf)	γ_d (pcf)	ω (%)
Moscow	139	129	8
Clay Slurry	136	124	10
Limestone	141	130	9
Control Section	138	128	8

6.3 DCP test

In order to determine the shear strength of the surface, subbase, and subgrade layers, DCP tests were performed in November 2019 and June 2020 in Boone and Jones counties. DCP results were used to determine the thickness of the surface and subbase layers, where a sudden change was observed in the cumulative blows versus cumulative depth. Subgrade layer was assumed to have infinite thickness. The cumulative blows versus cumulative depth, DCPI versus cumulative depth, and correlated CBR values versus the cumulative depth for all the testing points of Boone and Jones counties are presented in Appendix C figures. **Figure 44** shows the cumulative blows, DCPI, and correlated CBR values versus the cumulative depth for the first point of Ames Mine section in Boone County to show an example. Rating of the performance of the sections was followed in accordance with the "Statewide Urban Design and Specification Design Manual"(SUDAS 2015) (**Table 17**).

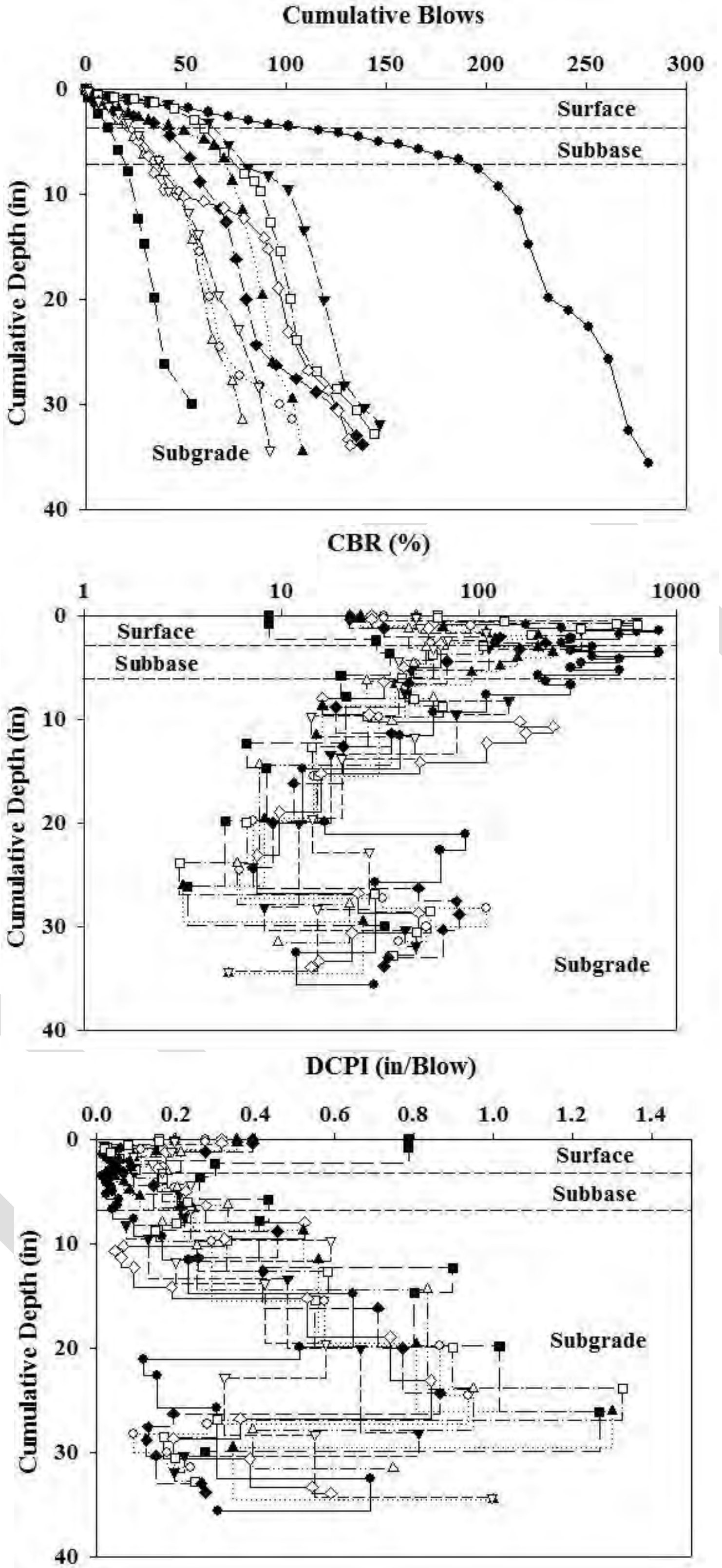


Figure 44. Cumulative blows, DCPI, and correlated CBR versus cumulative depth for the first section

Table 17. Relative ratings of subbase and subgrade layers based on CBR values (SUDAS 2015)

CBR (%)	Material	Rating
> 80	Subbase	Excellent
50 to 80	Subbase	Very Good
30 to 50	Subbase	Good
20 to 30	Subgrade	Very Good
10 to 20	Subgrade	Fair to Good
5 to 10	Subgrade	Poor to Fair
<5	Subgrade	Very Poor

Boones County

DCP tests were performed in November 2019 and June 2020 in Boone County. The distance between the points were 100 ft and 10 locations per section were chosen every time DCP test was conducted. Three-layered system including surface, subbase, and subgrade layers were considered for all demonstration sections. However, control section only had surface and subgrade layers.

6.3.1 November 2019

The DCP test was performed in November 2019 to investigate the shear strength and thickness of the surface, subbase, and subgrade layers right after the construction. The detailed results for the average values of shear strength and thickness are shown in **Table 18**. Moreover, **Figure 45** shows the CBR values of surface, subbase, and subgrade layers. In addition, the highest, median, lowest, and the ranges of the data for 10 testing locations are shown in Figure 45. Figure 45 shows that CBR value of the surface layer of Ames Mine section is rated as **Excellent**, where this section had highest median surface CBR value than others. Moscow, Clay Slurry, and Crescent sections had almost same surface CBR values, and they all were rated as **Very Good**. Control section had the lowest range and median of surface CBR values, and its rate was below good which is not available in the SUDAS rating system.

The behavior of the subbase layer was almost the same for all the sections. They all had **Good** and **Very Good** conditions per their CBR values. This behavior was expected for subbase layer of the sections because they all had same thicknesses (5”) and their subbase layer was constructed at the same time. However, the range of subbase-CBR for Moscow and Clay Slurry sections were greatest and lowest than others, respectively.

The results of CBR values for subgrade layers are **Fair-Good** for all the sections, except for the Clay Slurry section, which was **Very Good**.

The average surface thickness values for all demonstration sections were between 2.7” and 3.3”. However, the average surface thickness for control section was 12”. The thickness value of the subbase layer ranged between 4.6 “(Moscow) and 12.2” (Clay Slurry).

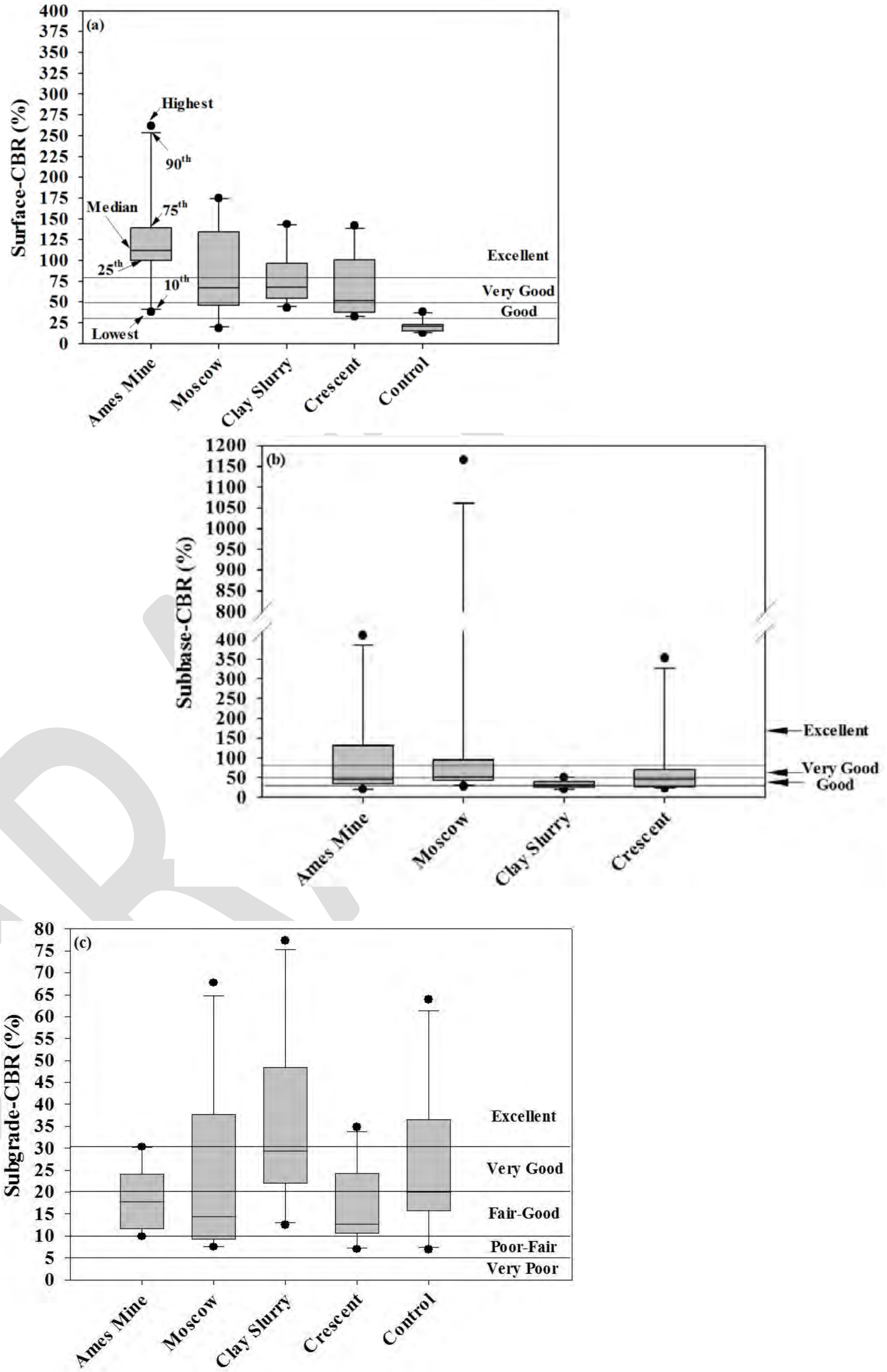


Figure 45. DCP results of thickness for (a) surface, (b) subbase, and (c) subgrade CBR and rating in Boone County in November 2019

Table 18. DCP results for thickness of the surface, subbase, and subgrade CBR and rating in Boone County in November 2019

November 2019	Thickness (in)			CBR (%)			Rating		
	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade
Ames Mine	3.2	6.4	Inf.	112	101	19	Excellent	Excellent	Poor-Fair
Moscow	2.7	4.6	Inf.	84	171	23	Excellent	Excellent	Very Good
Clay Slurry	3.3	12.2	Inf.	78	34	35	Very Good	Good	Excellent
Crescent	3.3	8.3	Inf.	68	77	17	Very Good	Very Good	Fair -Good
Control	12.0	NA	Inf.	21	NA	25	Good	NA	Very Good

6.3.2 June 2020

Another set of DCP tests were performed in June 2020, after the first freeze-thaw period. CBR values of the surface layer for all the sections were rated as **Excellent**, except for the control section, which was rated as **Good**. Clay Slurry section had the highest range of surface CBR data, among others. The results show that all the sections experience improvement in their surface CBR values than that of measured in November 2019. The reason for this trend could be the occurrence of continuing cementation reactions between quarry fines and surface aggregate materials. Surface CBR values ranged between 20% for Control section and 152% for Ames Mine (**Figure 46**).

The median CBR values for the subbase layers for all sections were rated as below **Good** based on SUDAS system, except for Ames Mine section, which was rated **Good**. The results showed that all sections faced a decrease in their subbase shear strength due to freeze-thaw cycles, which could force the water from subgrade layer to the other layers. However, binding between surface aggregates prevented the penetration of water from the surface layer and water got trapped in the subbase and caused subbase materials to become weaker. Subbase CBR values ranged between 9% for Clay Slurry section and 29% for Crescent section.

Ames Mine, Moscow, and Clay Slurry sections had relatively **Excellent** rating regarding the subgrade CBR values. Crescent had **Fair-Good** condition and Control had **Very Good** condition. Ames Mine had the highest range of CBR subgrade data among all of sections.

Surface thickness of all sections got decreased since November 2019 and ranged between 0.6" for Ames Mine and 4.7" for Control section. On the other hand, subbase layer thickness for all sections got increased except for Crescent section which was decreased from 12" in November 2019 to 5.9" in June 2020 (**Table 19**).

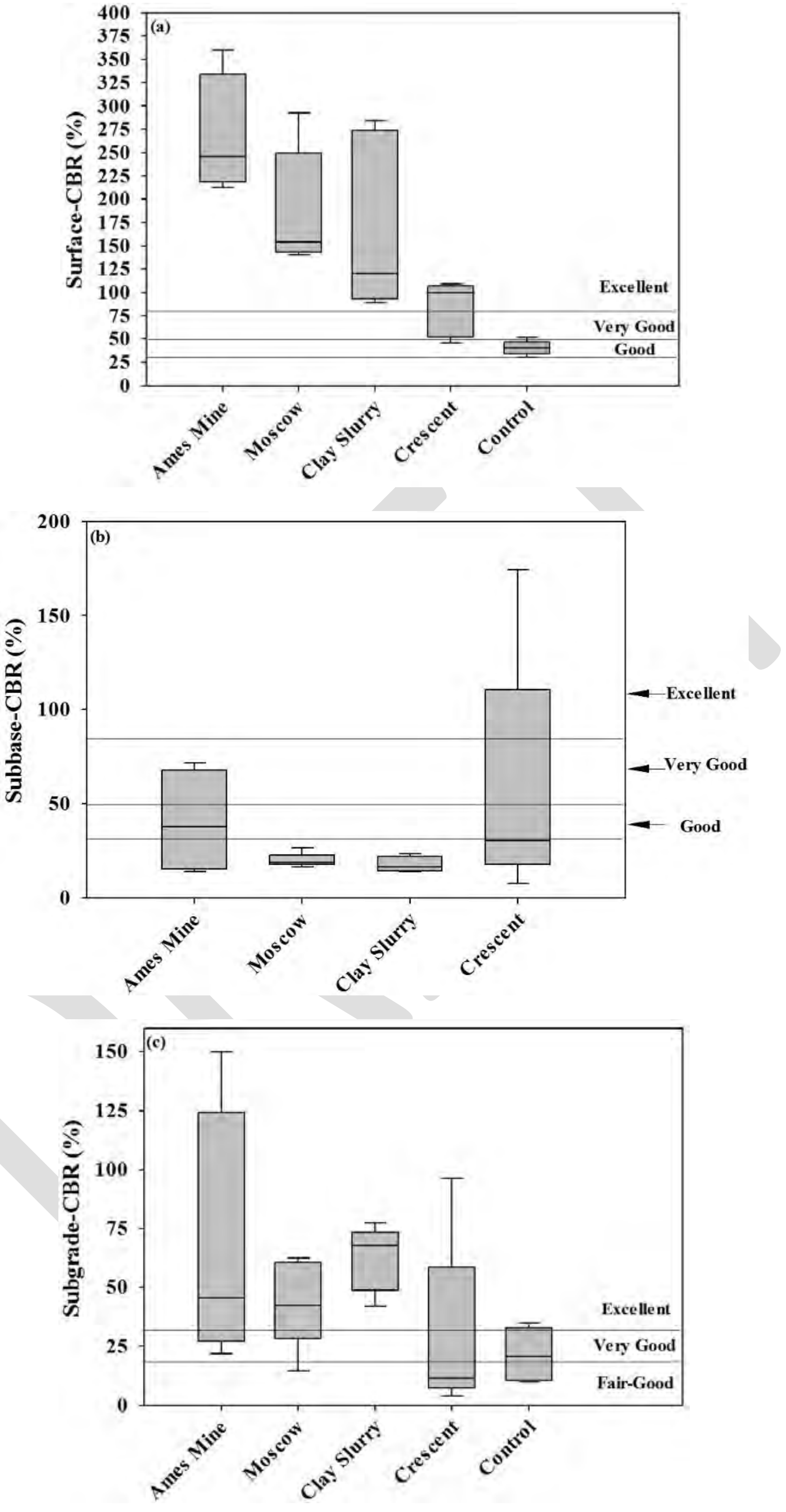


Figure 46. DCP results of thickness for (a) surface, (b) subbase, and (c) subgrade CBR and rating in Boone County in June 2020

Table 19. DCP results of thickness for the surface, subbase, and subgrade CBR and rating in Boone County in Boone County in June 2020

June 2020	Thickness (in)			CBR (%)			Rating		
	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade
Ames Mine	0.6	9.0	Inf	152	16	26	Excellent	<Good	Fair-Good
Moscow	1.0	12.0	Inf	94	10	22	Excellent	<Good	Fair-Good
Clay Slurry	1.2	13.8	Inf	85	9	31	Excellent	<Good	Very Good
Crescent	1.1	5.9	Inf	42	29	14	Good	<Good	Fair-Good
Control	4.7	NA	Inf	20	NA	11	<Good	NA	Fair-Good

Jones County

DCP tests were performed in November 2019 and June 2020 in Jones County. Distance between the test locations were 100 ft and 10 locations per section were chosen every time DCP test was conducted. Three-layered system including surface, subbase, and subgrade layers were considered for all demonstration sections. However, control section only had surface and subgrade layers.

6.3.1 November 2019

The DCP test was performed in November 2019 to investigate the shear strength and thickness of the surface, subbase, and subgrade layers right after the construction. The detailed results for the average values of shear strength and thickness are shown in **Table 20**. Moreover, **Figure 47** shows the CBR values surface, subbase, and subgrade layers. In addition, the highest, median, lowest, and the ranges of the data for 10 testing locations are shown in Figure **47**.

Figure 47 shows that the median value of the surface CBR for Moscow section was rated as **Excellent**, for Clay Slurry and Limestone sections was rated as **Good**, and for the control section it was rated as **Very Good**. Clay Slurry section had the highest range of surface CBR data compared than others, while Moscow and the control sections had relatively close ranges of surface CBR data. Limestone section had the most consistent range of data for surface CBR.

Limestone, Clay Slurry, and Moscow sections had **Very Good**, **Good**, and **below good** ratings, respectively, based on SUDAS system for median subbase CBR values. More consistent range of data was also observed for the Limestone section than the other two sections. However, Clay Slurry section had the highest range of subbase CBR data.

The median values for subgrade CBR for the control section, Limestone, Clay Slurry, and Moscow sections were rated as **Poor-Fair**, **Fair-Good**, **Good**, and **Very Good**, respectively. Control section had the lowest range of subgrade CBR data, while the other sections had same range of subgrade CBR.

The average surface thickness of the sections ranged between 2.9” for Limestone and 7.9” for Clay Slurry sections. However, subbase thicknesses for all three-demonstration section were between 10.3” for Limestone and 12.9” for Clay Slurry.

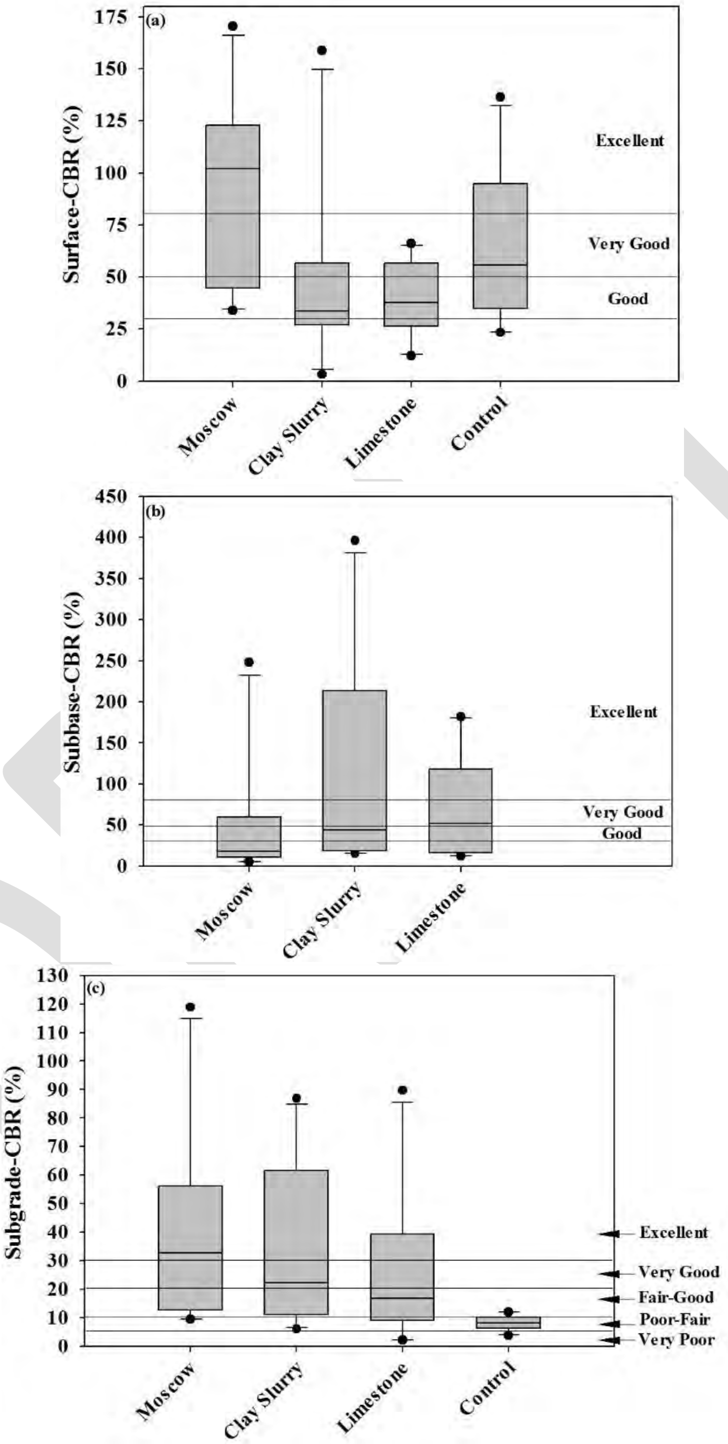


Figure 47. DCP results of thickness for (a) surface, (b) subbase and (c) subgrade CBR and rating in Jones County in November 2019

Table 20. DCP results of thickness for the surface, subbase, and subgrade CBR and rating in Jones County in November 2019

June 2020	Thickness (in)			CBR (%)			Rating		
	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade
Moscow	5.7	12.9	Inf	93	49	41	Excellent	Good	Excellent
Clay Slurry	7.9	11.7	Inf	47	117	35	Good	Excellent	Excellent
Limestone	2.9	10.3	Inf	39	71	26	Good	Very Good	Very Good
Control	7	NA	Inf	67	NA	8	Very Good	NA	Very Poor

6.3.2 June 2020

Another set of DCP tests were performed in June 2020, after the first freeze-thaw cycling period. CBR values of the surface layer of all sections were rated as **Good**, except for the **Moscow** section which was rated **Excellent**. Moscow section had the highest range of surface CBR data and all the surface CBR values for 10 locations of this section were in the **Excellent** performance category. Clay Slurry, on the other hand, had the minimum range of surface CBR values rated between **below Good and Good**. However, surface CBR values for Limestone and the control sections were rated between **below Good and Very Good** (**Figure 48**).

The subbase CBR values of Moscow section was higher than other sections, where the median CBR values was **Very Good.** Limestone section also had the same trend as Moscow section regarding the subbase CBR values, but the only difference was the range of data, which was rated between **below Good to Excellent**. Clay Slurry section on the other hand had the minimum median for subbase CBR, where it was rated as **below Good** (**Figure 48**).

Control section and Clay slurry had the lowest median value for subgrade CBR values (**Poor-Fair**), Limestone was rated as Fair-Good, and Moscow section was rated as Very Good. Range of data for subgrade CBR value was the highest and most of data for this section were rated as Excellent (**Figure 48**).

Thickness of the surface layer for Clay slurry was the lowest 1", and it was the highest for the control section (3.9"). Subbase thickness for Limestone section was the lowest 6.5" and it was the highest for the Moscow section (10.8"). These results showed that both surface and subbase layers of all sections experienced a decrease in their thicknesses after freeze-thaw period. This thickness reduction for Limestone section was the lowest (2.9" to 1.3"), and the highest for Moscow (5.7" to 1.2") and Clay Slurry (7.9" to 1") (**Table 21**).

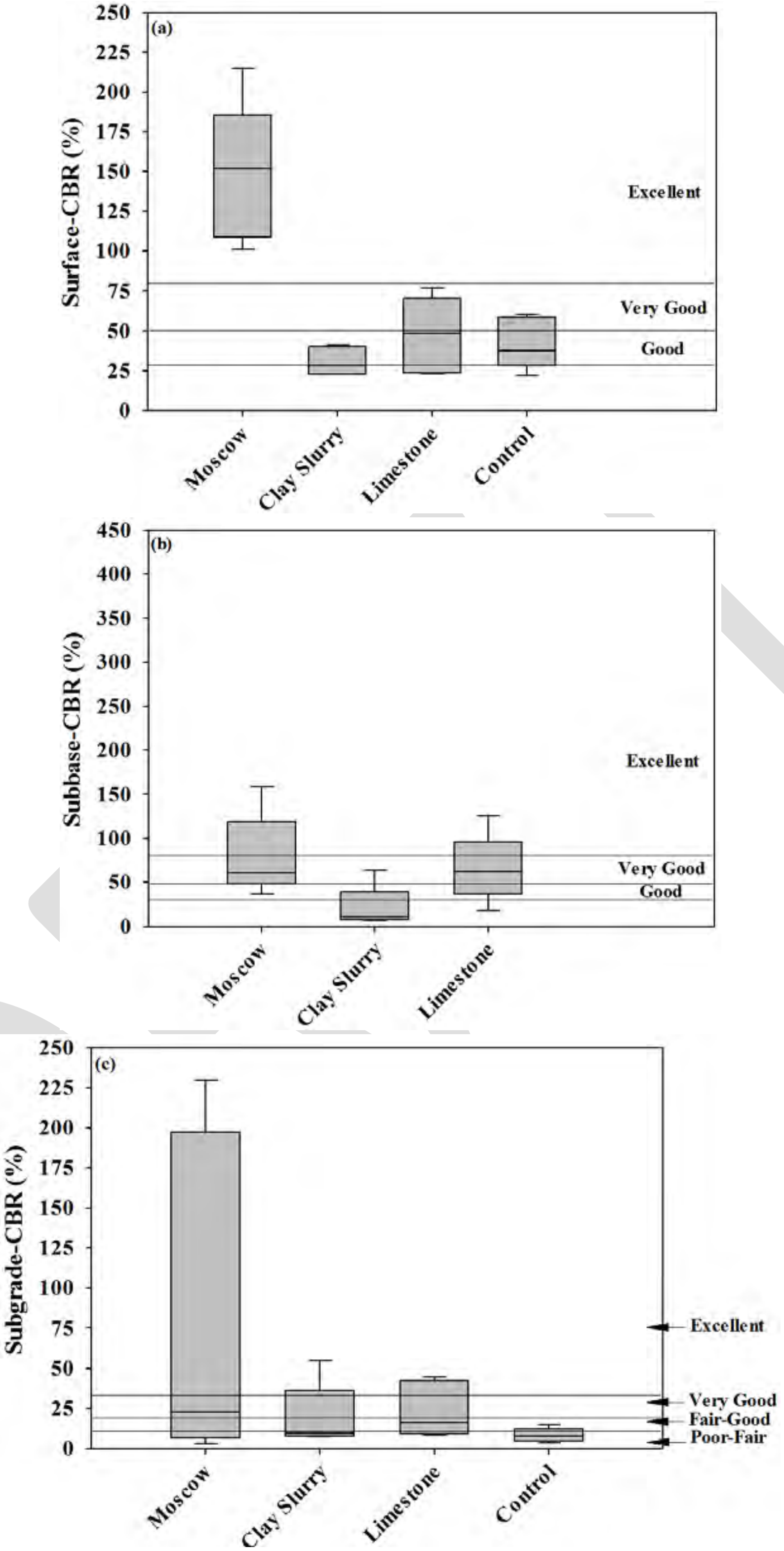


Figure 48. DCP results of thickness for (a) surface, (b) subbase, and (c) subgrade CBR and rating in Jones County in June 2020

Table 21. DCP results of thickness for the surface, subbase, and subgrade CBR and rating in Jones County in June 2020

June 2020	Thickness (in)			CBR (%)			Rating		
	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade
Moscow	1.2	10.8	Inf	106	40	43	Excellent	Good	Excellent
Clay Slurry	1.0	8.8	Inf	15	10	10	<Good	<Good	Fair-Good
Limestone	1.3	6.5	Inf	24	33	12	<Good	Good	Fair-Good
Control	3.9	NA	Inf	21	NA	4	<Good	NA	Very Poor

6.5 Falling Weight Deflectometer (FWD) Test

Falling weight deflectometer (FWD) tests were conducted in this project at 10 locations in each test section in March 2020 (after the first freeze-thaw period) in both counties. FWD is the most common test that is used to simulate the traffic load and evaluate the elastic modulus of the roadway layers. The three-layered system assumption (surface, subbase, and subgrade) was considered for the back-calculation of FWD by using BAKFAA software. Poisson's ratios of surface, subbase, and subgrade layers were assumed to be 0.4, 0.35, and 0.3, respectively. Test results are summarized for each county and the modulus values of each section are compared.

Boone County

6.5.1 March 2020

FWD moduli results of surface, subbase, and subgrade layers are shown in **Figures 49** to **51**. **Table 22** shows the average, maximum, minimum, standard deviation, and range of FWD back-calculation results in Boone County. Ames Mine (69 ksi) and Moscow (63 ksi) sections had relatively higher average surface elastic modulus values than others and control section had the lowest average surface elastic modulus value (20 ksi) (**Table 22**). Ames Mine and the control sections also had the highest and the lowest range of surface elastic moduli, respectively.

Table 22. Surface elastic modulus of FWD test in Boone County in March 2020

Surface Elastic Modulus (ksi)					
Sections	E_{Mean}	E_{Max}	E_{Min}	STD	Range
Ames Mine	69	89	10	24	80
Moscow	63	95	38	20	57
Clay Slurry	47	74	28	14	46
Crescent	50	88	32	20	56
Control Section	20	28	11	6	18

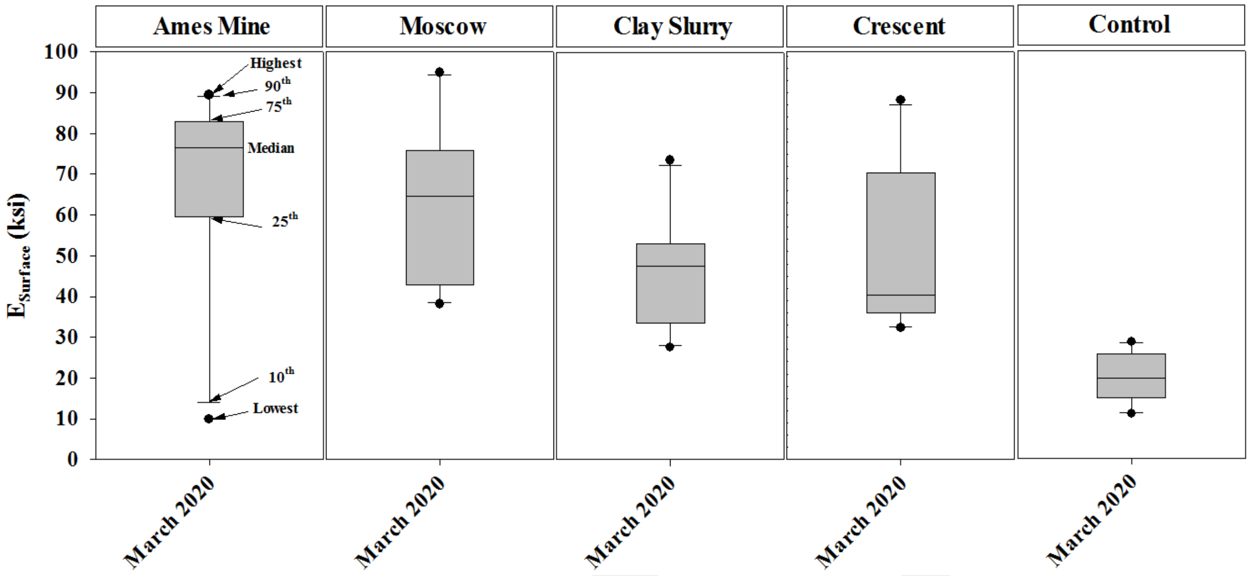


Figure 49. Surface elastic modulus of FWD in Boone County in March 2020

Table 23 and **Figure 50** show the mean, maximum, minimum, standard deviation, range, and median values of subbase elastic modulus for Boone County in March 2020. All the sections showed very close average subbase elastic modulus ranged between 20 and 26 ksi. This behavior was expected due to the use of same material and construction method for subbase layer in all sections.

Table 23. Subbase elastic modulus of FWD test in Boone County in March 2020

Subbase Elastic Modulus (ksi)					
Sections	E_{Mean}	E_{Max}	E_{Min}	STD	Range
Ames Mine	26	40	14	8	26
Moscow	21	32	12	7	19
Clay Slurry	21	37	10	9	27
Crescent	20	43	12	10	31

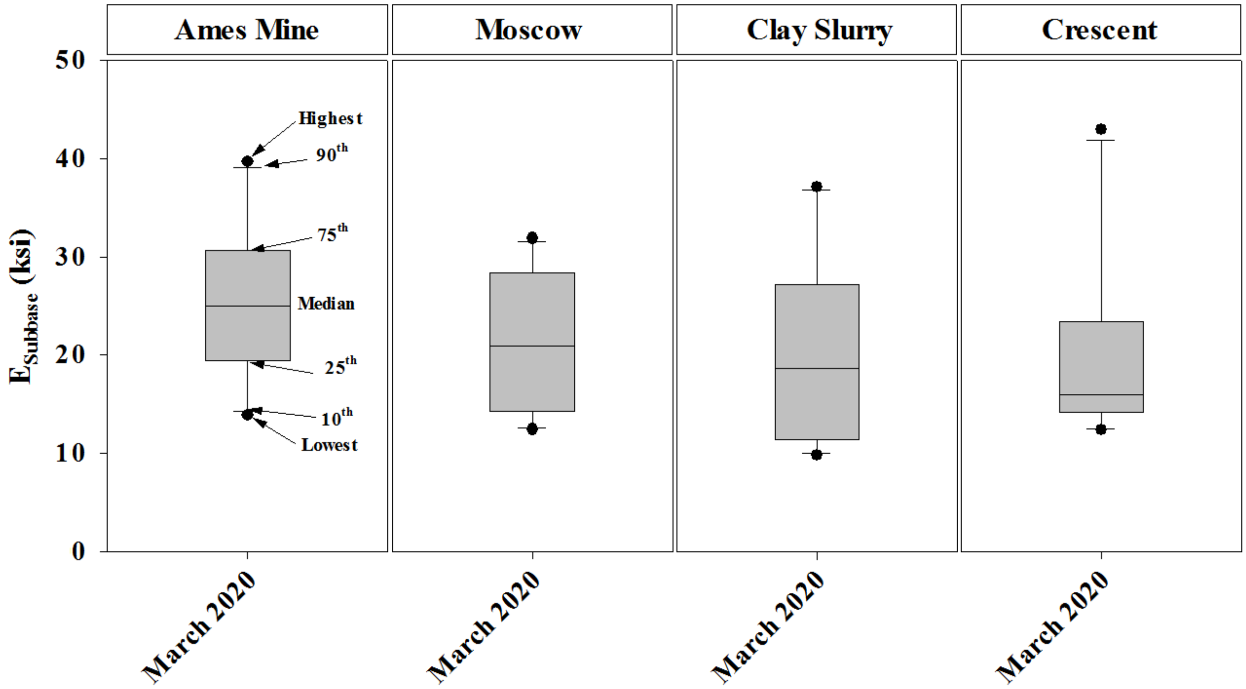


Figure 50. Subbase elastic modulus of FWD in Boone County in March 2020

Average values of back-calculated subgrade elastic moduli for all sections were in a close range between 12 ksi for Ames Mine and 16 ksi for the control section. Standard deviations for all of them were 2 ksi and the range of elastic modulus of all locations of each section was between 5 ksi and 8 ksi (**Table 24**). This close range of subgrade elastic moduli was expected as all sections were built on the subgrade layer (**Figure 51**).

Table 24. Subgrade elastic modulus of FWD test in Boone County on March 2020

	Subgrade Elastic Modulus (ksi)				
Sections	E_{Mean}	E_{Max}	E_{Min}	STD	Range
Ames Mine	12	16	10	2	6
Moscow	14	17	12	2	5
Clay Slurry	13	17	12	2	5
Crescent	14	19	12	2	8
Control Section	16	20	14	2	6

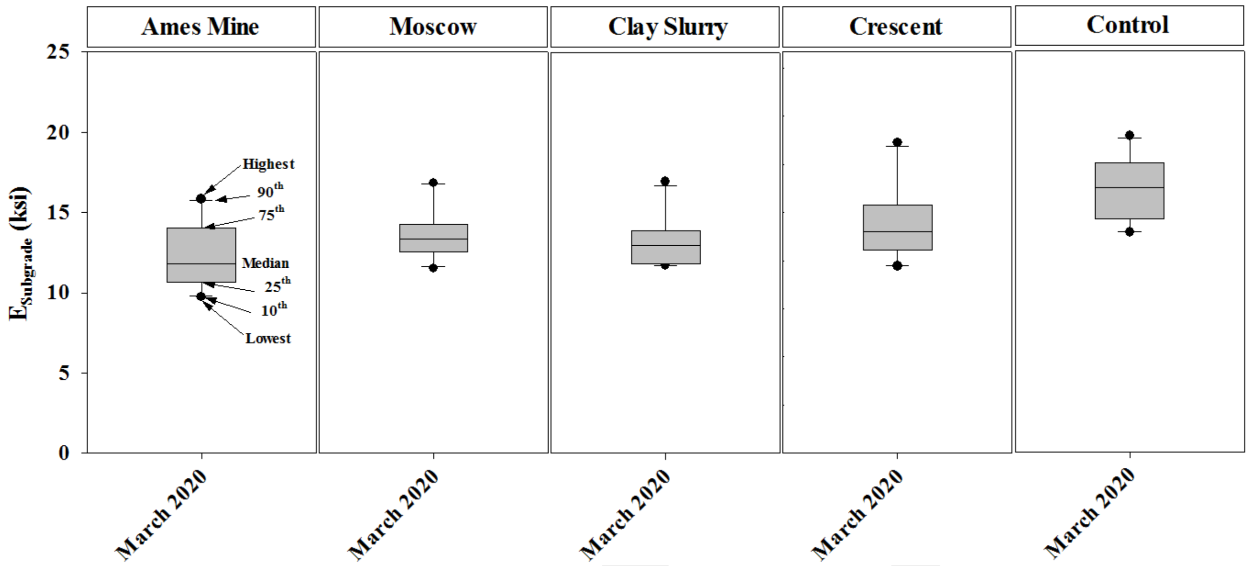


Figure 51. Subgrade elastic modulus of FWD in Boone County in March 2020

Jones County

6.5.1 March 2020

Table 25 and **Figure 52** show the average, median, range, and standard deviation of the back-calculated surface elastic moduli of sections built in Jones County in March 2020. The results show that Limestone (97 ksi) and Moscow (88 ksi) sections had the highest surface elastic moduli among all. The standard deviation and range of the surface moduli for Moscow and Limestone sections were the highest among all sections. On the other hand, Clay Slurry (44 ksi) and the control section (42 ksi) had similar surface elastic moduli. The highest surface elastic moduli were observed for the Limestone section (206 ksi).

Table 25. Surface elastic modulus of FWD test in Jones County on March 2020

	Surface Elastic Modulus (ksi)				
Sections	E_{Mean}	E_{Max}	E_{Min}	STD	Range
Moscow	88	175	39	45	135
Clay Slurry	44	83	24	17	59
Limestone	97	206	23	67	183
Control Section	42	106	14	29	91

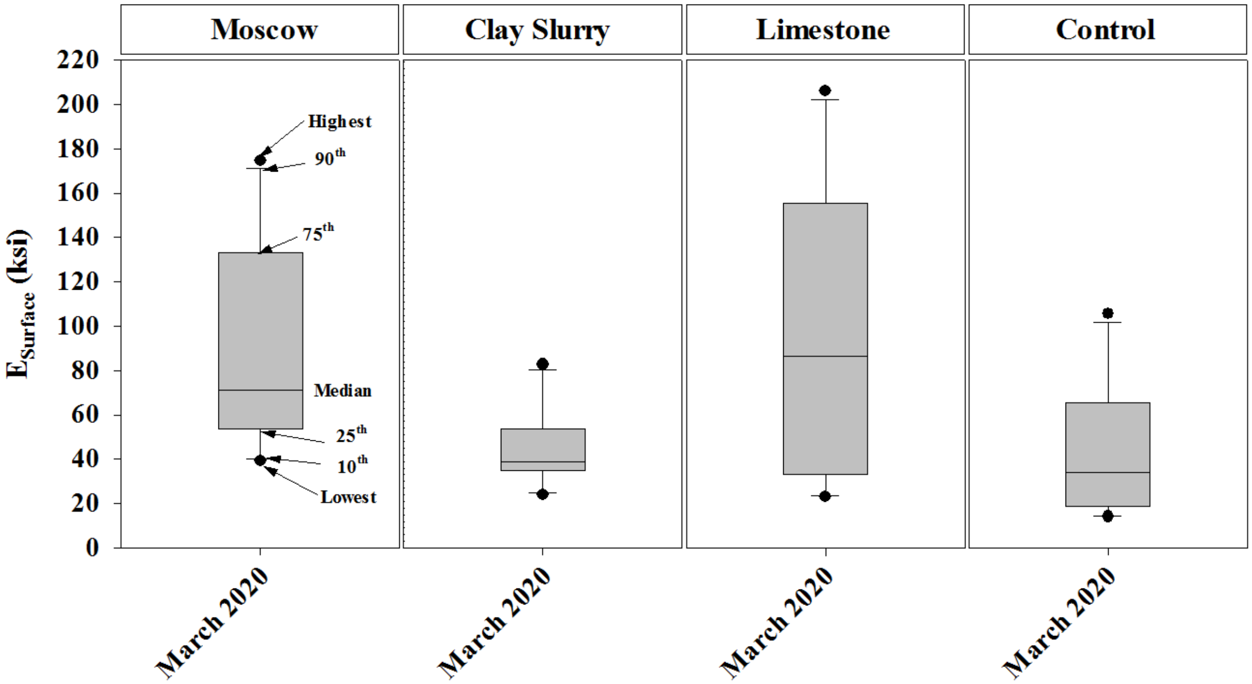


Figure 52. Surface elastic modulus of FWD in Jones County in March 2020

Table 26 and **Figure 53** show the summary of the results of back-calculated subbase elastic moduli for all sections in Jones County, in March 2020. All sections had similar subbase elastic moduli between 17 and 37 ksi. This observation was expected due to the use of same materials with the same thickness value (5”) for building subbases for all sections. Limestone and Clay Slurry sections had the highest and lowest mean, maximum, standard deviation, and range of subbase elastic modulus, respectively.

Table 26. Subbase elastic modulus of FWD test in Jones County on March 2020

	Subbase Elastic Modulus (ksi)				
Sections	E_{Mean}	E_{Max}	E_{Min}	STD	Range
Moscow	28	58	16	13	42
Clay Slurry	17	31	9	6	22
Limestone	37	85	10	26	75

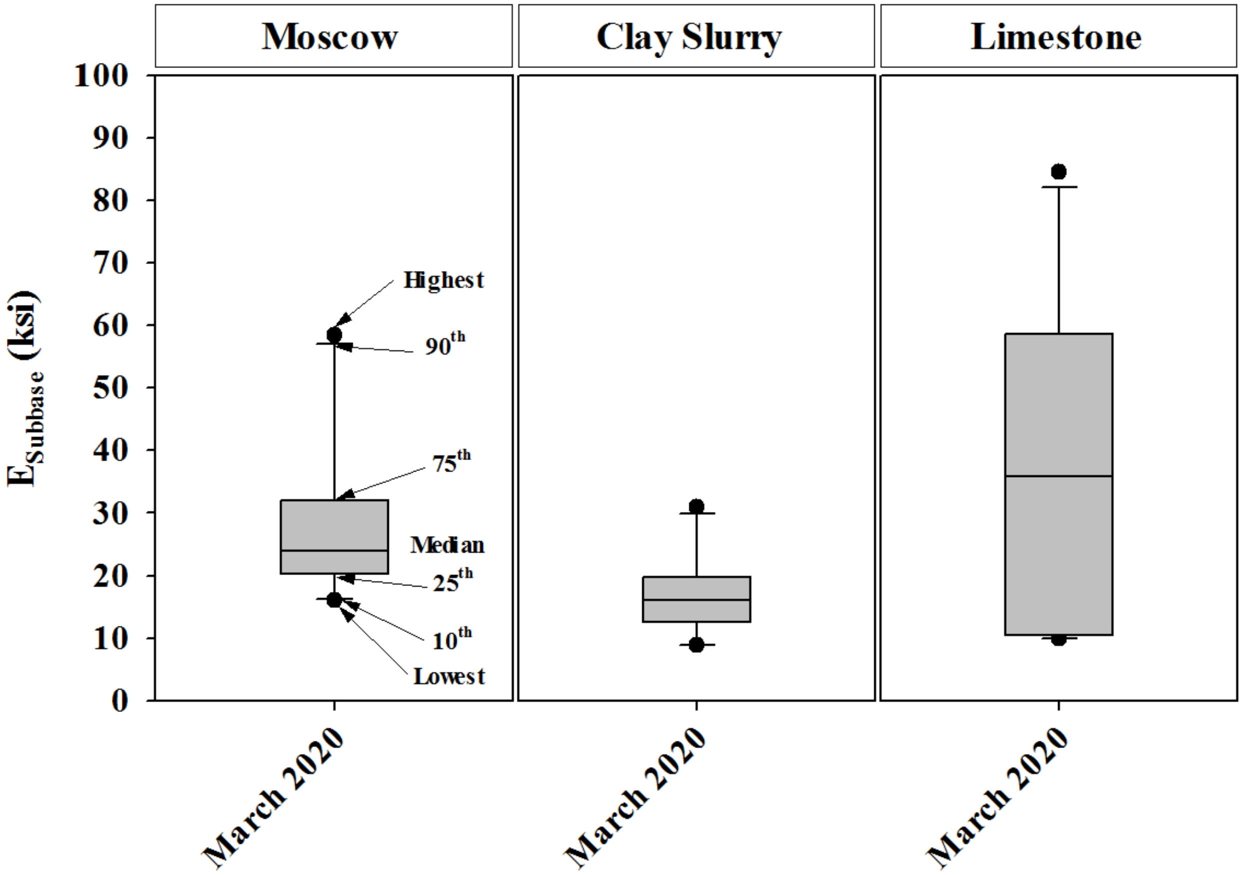


Figure 53. Subbase elastic modulus of FWD in Jones County in March 2020

The range of the subgrade elastic moduli for Jones County was in a close range, between 11 ksi for control section and 20 ksi for Clay Slurry section. Clay slurry and the control sections also had, the maximum and minimum range of subbase elastic moduli among all sections, respectively. Standard deviation for subbase elastic moduli was very low for all sections (between 1 and 7 ksi) (**Table 27**). This behavior seemed to be reasonable since all sections were built on the same subgrade (**Figure 54**).

Table 27. Subgrade elastic modulus of FWD test in Jones County on March 2020

	Subgrade Elastic Modulus (ksi)				
Sections	E_{Mean}	E_{Max}	E_{Min}	STD	Range
Moscow	16	24	11	4	13
Clay Slurry	20	38	14	7	24
Limestone	15	25	9	5	16
Control Section	11	13	9	1	4

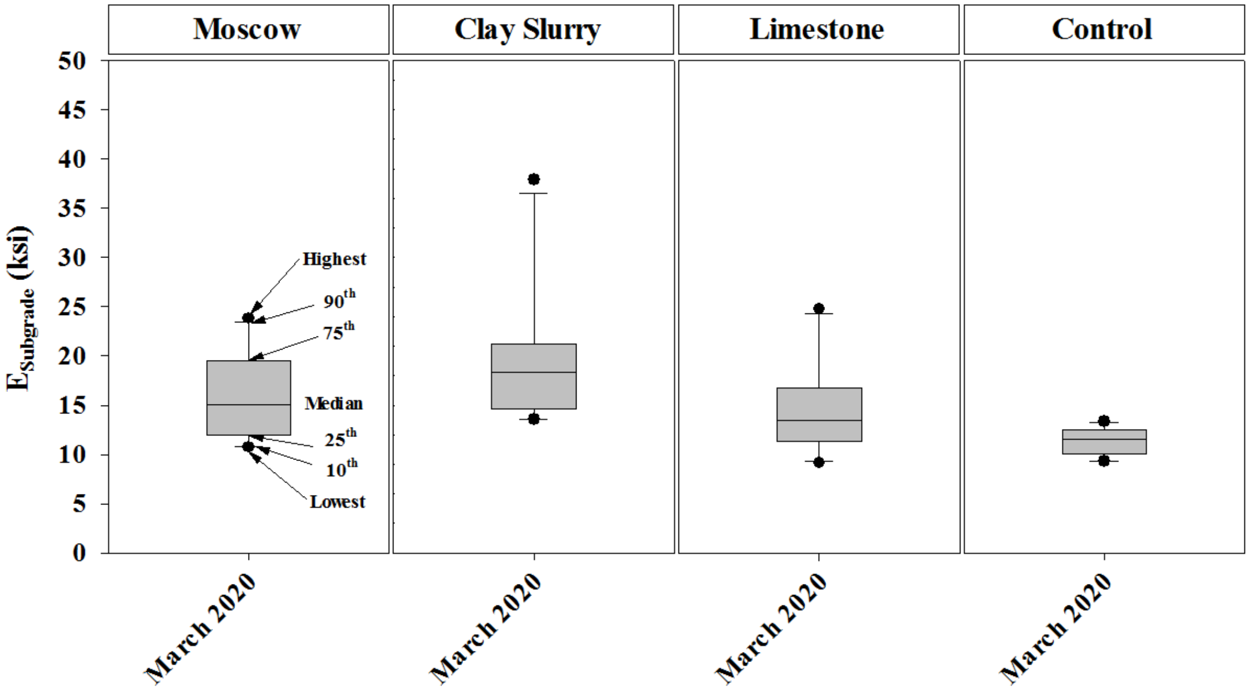


Figure 54. Subgrade elastic modulus of FWD in Jones County on March 2020

6.7 International Roughness Index (IRI)

Surface roughness is an important parameter to evaluate the performance of granular roadways. International Roughness Index (IRI) is a representative of surface roughness and it is evaluated by using "Roadroid" software in this project (Gopisetti 2017). Roadroid is a phone-based android software that measures the vertical and horizontal movement of the vehicle, while a phone is fixed on the windshield of the truck by a firm mount. A similar vehicle was used to measure IRI every time when it was performed. Roadroid gives estimated IRI (eIRI) and calculated IRI (cIRI) results. The difference between these two measures is the range of speed in a way the software measures the IRI value. This range for eIRI is broader (between 12mph and 62 mph) and it is narrower for cIRI (between 37 mph and 50 mph). Therefore, cIRI provides better accuracy than eIRI. Thus, it was used in this study to show the surface roughness. The calculated IRI (cIRI) with a narrower range of speed between 37 mph and 50 mph was used, rather than of the estimated IRI (eIRI) which had a broader range of speed between 12 mph and 62 mph (Forslöf and Jones 2015). Therefore, cIRI values provided higher accuracy than eIRI values. **Table 28** shows four different categories of specifications for IRI measures. The cIRI values used in this study are all reported as inch per mile. The results of IRI for both counties are explained afterwards.

Table 28. IRI classification (Forslöf and Jones 2015).

IRI Specification	IRI Values
Good	<253
Fair	253-380
Poor	380-507
Bad	>507

Boone County

Figure 55 and **Table 29** show the summary of the IRI results for November 2019 and March 2020 in Boone County. According to **Figure 55**, surface roughness increased in Ames Mine, Moscow, and Control sections from November to March. Clay slurry section did not have any changes in the cIRI value, which was the indicator of reliability of this section and sufficient binding between aggregates. Surface roughness for Crescent section decreased from November to March and it showed that ride quality in this section became better overtime. Higher compaction due to the traffic load and lower deterioration could be the reasons for this behavior. Ames Mine, Moscow, and the control sections had Excellent surface roughness in November, and their surface roughness condition decreased to Good and Fair conditions in March. However, Crescent and Clay Slurry sections were both in Good and Excellent surface roughness conditions in both November and March.

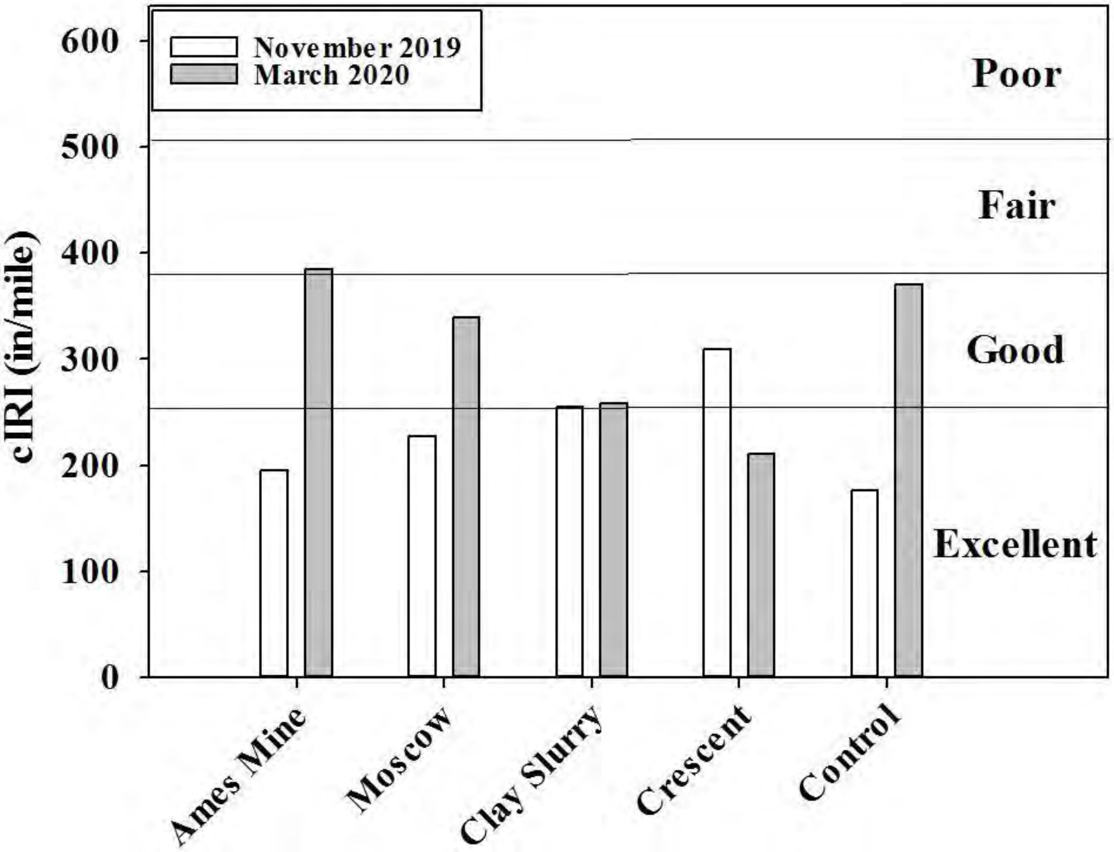


Figure 55. Average values of cIRI for each section over time

Table 29 shows the average cIRI results for all sections in Boone County in November 2019 and March 2020. Average cIRI values for all sections had Good rating surface roughness conditions. Table 29 shows that all sections experienced an increase in their average cIRI values from November to March between 1% for Clay Slurry and 110% for the control section, except for Crescent section of which surface roughness condition improved 32% from November to March.

Table 29. Average cIRI values (in/mile) for each section over time in Boone County

Section	November 2019	March 2020	Average (in/mile)	Change (%)	Condition
Ames Mine	195	385	290	97	Good
Moscow	227	339	283	49	Good
Clay Slurry	255	258	257	1	Good
Crescent	309	210	260	-32	Good
Control Section	176	370	273	110	Good

Jones County

Figure 56 and **Table 30** show the summary of the IRI results for November 2019 and March 2020 in Jones County. According to **Figure 56**, surface roughness of all sections decreased from November 2019 to March 2020. This decrease was more significant for Moscow and Clay Slurry sections as they had Fair conditions in November and Good conditions in March. This can be due to the blading of these sections to repair the distresses such as rutting and potholes. Limestone section had the lowest surface roughness both in November 2019 and March 2020 and its rating from Good in November 2019turned to Excellent in March 2020. Control section had the Good surface roughness condition both in November 2019 and March 2020.

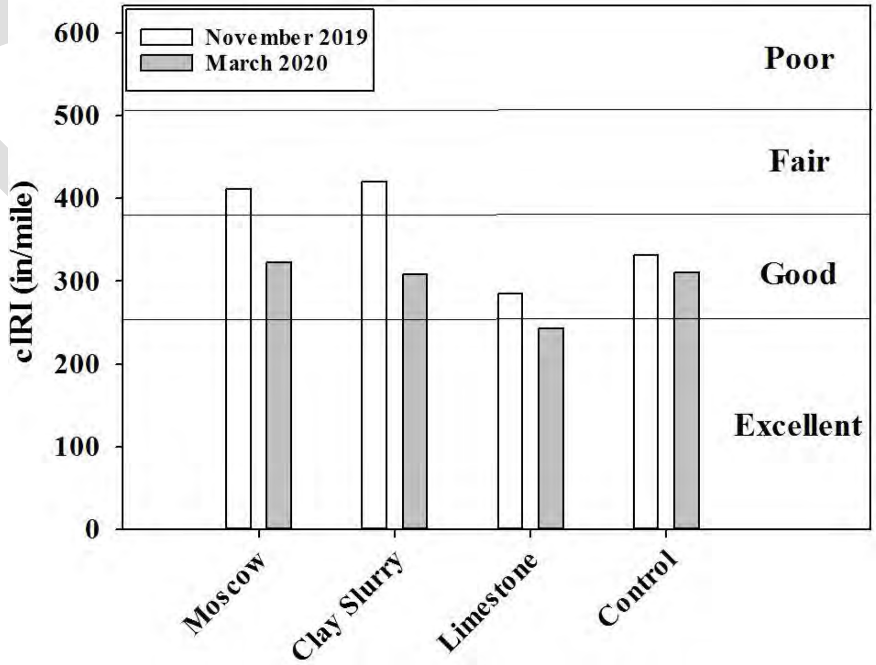


Figure 56. Average values of cIRI for each section over time

Table 30 shows the average cIRI results for all sections in Jones County in November 2019 and March 2020. Average cIRI values for all sections were in Good rating surface roughness condition. **Table 30** shows that all sections experienced a decrease in their average cIRI values from November 2019 to March 2020 between -6% for the control section and -27% for Limestone section.

Table 30. Average cIRI values (in/mile) for each section over time in Jones County

Section	November 2019	March 2020	Average (in/mile)	Change (%)	Condition
Moscow	412	323	367	-22	Good
Clay Slurry	420	308	364	-27	Good
Limestone	285	243	264	-15	Good
Control Section	332	311	321	-6	Good

6.8 Light Weight Deflectometer (LWD)

LWD tests were performed in November 2019 and March 2020 in Boone and Jones County test sections to evaluate the composite elastic modulus ($E_{Comp.}$) of each section. **Figure 57** and **Table 31** illustrate the E_{Comp} values of 10 locations in each section. Following sections will describe the summary of E_{Comp} values measured in test sections in both counties.

6.8.1 Boone

LWD tests were performed twice in Boone County once in November 2019 right after the construction and another time in March 2020 after the first freeze-thaw cycling period. **Figure 57** shows that all sections experienced a decrease in their $E_{Comp.}$ values, except for the control section which had a little bit of increase both in the median and range of $E_{Comp.}$ Data. Ames Mine and control sections had the maximum and minimum median $E_{Comp.}$ Values in November 2019, respectively. On the other hand, Crescent and control sections had the maximum and Moscow section had the minimum $E_{Comp.}$ Values in March 2020.

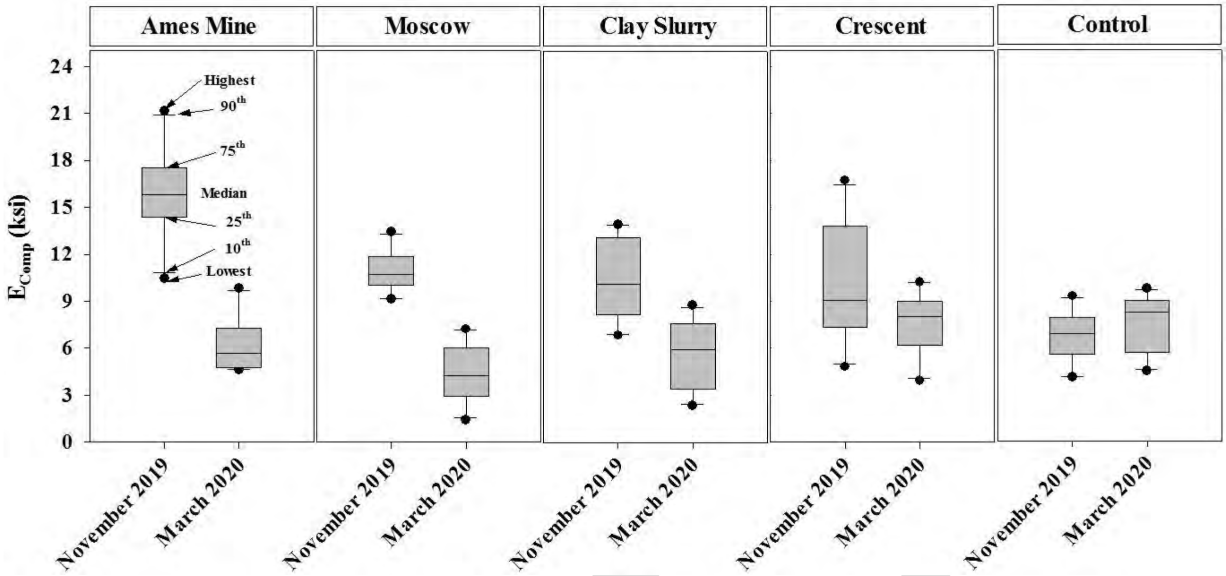


Figure 57. Composite elastic modulus values for Boone County

Table 31 shows that range of $E_{Comp.}$ of all sections in November 2019 which is between 7 ksi for control section and 16 ksi for Ames Mine. All sections had relatively similar behaviors regarding composite elastic modulus and their average stiffness values decreased from November 2019 to March 2020 except for the control section, which remained the same.

Ames Mine and Crescent sections had the highest range of $E_{Comp.}$ (11 and 12 ksi) in November 2019, while Moscow and the control sections had lower ranges of $E_{Comp.}$ values (4 and 5 ksi). Range of $E_{Comp.}$ values of each section were between 5 ksi and 6 ksi for all sections in March 2020.

Table 31. Surface elastic modulus of FWD test

	Sections	Ames Mine	Moscow	Clay Slurry	Crescent	Control Section
Nov-19	E_{Mean}	16	11	10	10	7
	E_{Min}	10	9	7	5	4
	E_{Max}	21	13	14	17	9
	Range	11	4	7	12	5
	STD[1]	3	1	2	4	2
Mar-20	E_{Mean}	6	4	6	8	7
	E_{Min}	5	1	2	4	4
	E_{Max}	10	7	9	10	10
	Range	5	6	6	6	5
	STD[1]	2	2	2	2	2

[1] Standard deviation

6.8.2 Jones

Figure 58 and **Table 32** both show the summary of the LWD results in Jones County for November 2019 and March 2020. All sections experienced an increase in the mean $E_{Comp.}$ values from November 2019 to March 2020, except for the control section. Range of $E_{Comp.}$ data for all sections in November 2019 also was greater than that of March 2020, except the control section. Overall, it was observed that stiffness of all sections increased over time, except the control section. Mean values of all sections were relatively close to each other.

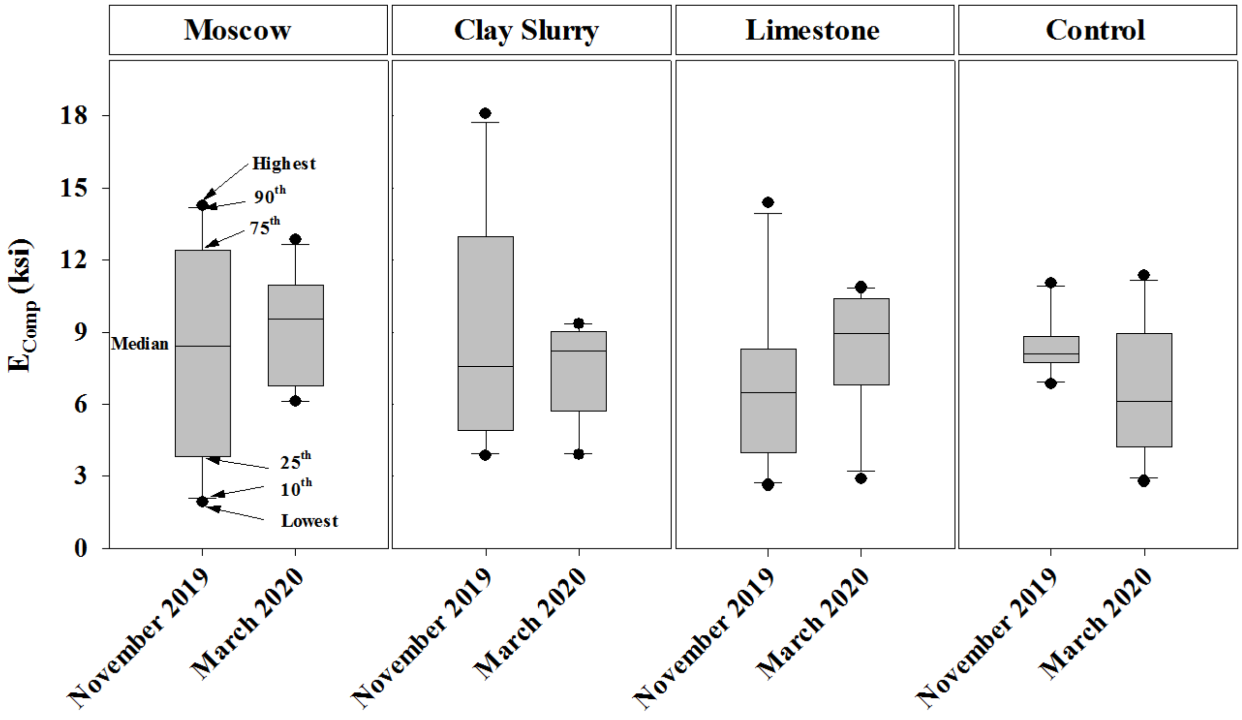


Figure 58. Composite elastic modulus values for Jones County

Table 32 shows that average $E_{Comp.}$ values of all sections in November 2019 and March 2020 were between 7 ksi and 9 ksi.

Table 32. LWD composite elastic modulus mean values and the standard deviations for each section

	Sections	Moscow	Clay Slurry	Limestone	Control Section
19-Nov	E_{Mean}	8	9	7	8
	E_{Min}	2	4	3	7
	E_{Max}	14	18	14	11
	Range	12	14	12	4
	STD[1]	4	5	3	1
20-Mar	E_{Mean}	9	7	8	7
	E_{Min}	6	4	3	3
	E_{Max}	13	9	11	11
	Range	7	5	8	9
	STD[1]	2	2	2	3

[1] Standard deviation

6.9 Dustometer Tests

Dustometer test is a well-known indicator of dust emission and can provide a way to compare performances of different test sections based on their dust productions. Dustometer test was conducted in Boone and Jones counties twice in November 2019 immediately after construction of the sections and in June 2020 after the freeze-thaw period.

Boone County

Figure 59 shows the values for dust emission of all sections in Boone County. The results showed that all sections in Boone County experienced an increase in dust emission after freeze-thaw cycle. This increase in dust emission was attributed to the aggregate deteriorations happening during freeze-thaw period. Dust emission was the highest in control section and the smallest in Clay Slurry section. Clay slurry was the least dusty section both in November 2019 and March 2020 than the others. Crescent and control sections were the highest dust emission in November 2019 and June 2020, respectively.

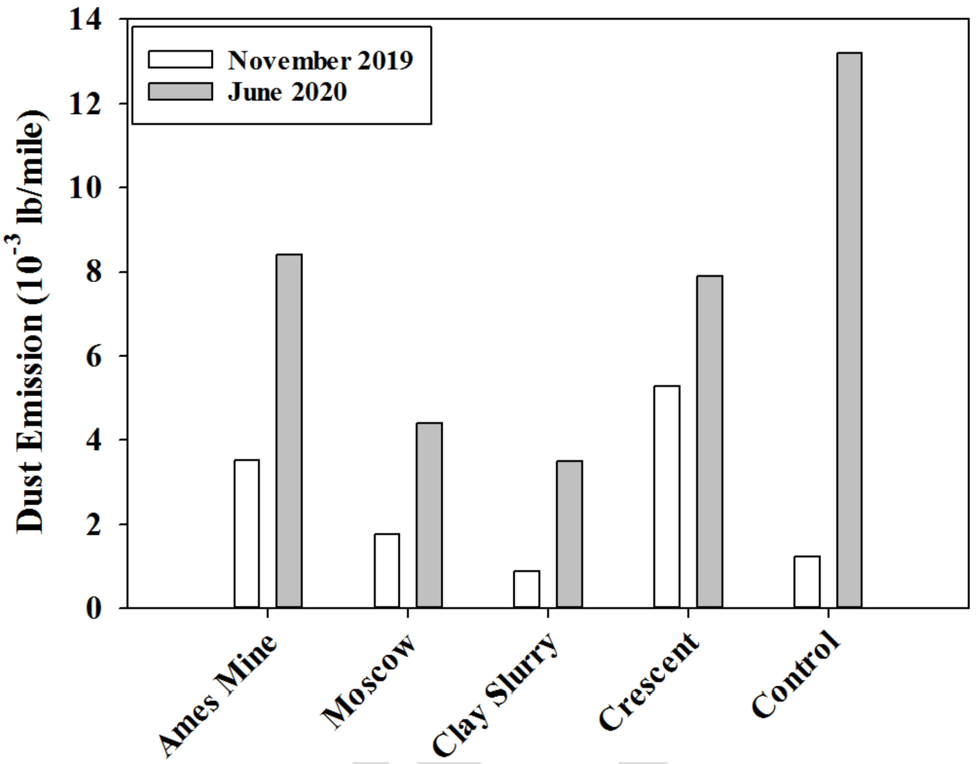


Figure 59. Dust production (E-03 lb/mile) for all sections over time in Boone County

Table 33 shows the summary of the results of dustometer tests in Boone County. It shows that Crescent and Clay Slurry sections have the maximum and minimum average dust emissions, respectively. On the other hand, the control section with 525% increase, and Crescent section with 42% increase in dust emission values had the maximum and minimum change in their dust emission over time.

Table 33. Dust production (E-03 lb/mile) for all sections over time in Boone County

Section	November 2019	June 2020	Average	Change (%)
Ames Mine	3.5	8.4	6	140
Moscow	1.8	4.4	3.1	144
Clay Slurry	0.9	3.5	2.2	289
Crescent	5.3	7.5	6.4	42
Control	1.2	7.5	4.4	525

Jones County

Figure 60 shows the results of dustometer tests in Jones county in November 2019 and June 2020. **Figure 60** shows that Clay Slurry and Limestone sections had the lowest dust emission values among all sections both in November 2019 and June 2020. Moscow and control sections had the highest dust emission in November 2019 and June 2020, respectively.

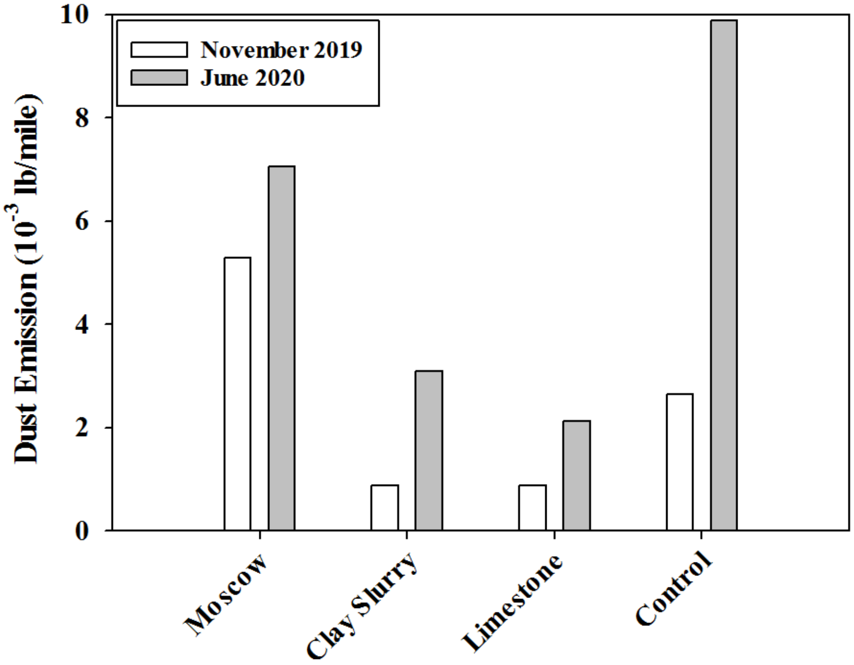


Figure 60. Dust production (E-03 lb/mile) for all sections over time in Jones County

Table 34 shows the summary of the dustometer results in Jones County. Moscow and control sections were the sections with the highest dust emission, while Limestone and Clay slurry sections had the lowest dust emission values. All sections experienced an increase in their dust emissions from November 2019 to June 2020.

Table 34. Dust production (E-03 lb/mile) for all sections over time in Jones County

Section	November 2019	June 2020	Average	Change (%)
Moscow	5.3	7.1	6.2	34
Clay Slurry	0.9	3.1	2	244
Limestone	0.9	2.1	1.5	133
Control	2.6	9.9	6.25	281

CHAPTER 7. COST ANALYSIS

Quarry fine materials were hauled from different quarries to Boone and Jones County as shown in **Figure 61**. In general, Jones County was relatively closer to the quarry locations compared to Boone County. This chapter first shows the labor, equipment, hauling, and materials costs for each section in Boone and Jones counties, then explains the method used in this study to determine the benefits and cost-effectivity of choosing each quarry fines for mixing with surface aggregates.

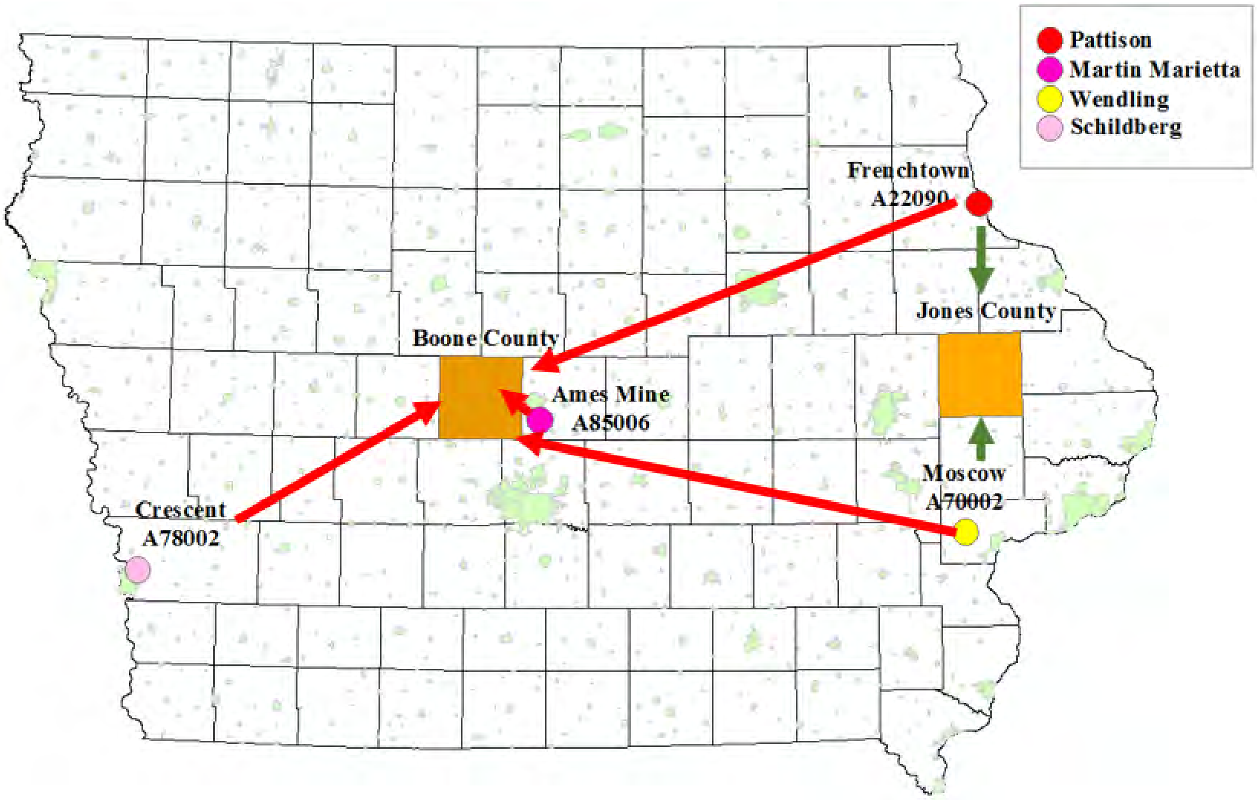


Figure 61. Locations of the aggregate resources and field sites in Iowa

Notes: Pattison provided the limestone and clay slurry and Wendling provided Moscow quarry fines.

Table 35 shows the approximate distances between the quarries and field site locations in Boone and Jones counties. Time distances of Clay Slurry, Moscow and Crescent fines with Boone County test sites were between 2 and 3 hours, while Ames Mine fines were only 15 minutes away from this location. Therefore, Ames Mine had relatively lower hauling cost than others. Clay Slurry and Limestone quarry fines were from one quarry and had the same hauling time (between 1 and 2 hours) for test sites in Jones County, while Moscow fines were in close proximity to the sites in Jones County (1 hour). Therefore, Moscow fines was an inexpensive option for building test sites in Jones County than Clay Slurry and Limestone fines.

Table 35. Time distances between the quarry fines sources

	Quarry Fines	Time
Boone	Pattison Frenchtown A22090	3 - 4 hr
	Ames Mine Ames Mine A85006	15 min
	Moscow A70002	2 – 3 hr
	Schildberg Crescent A78002	2 - 3 hr
J	Pattison Frenchtown A22090	1 to 2 hr

	Moscow A70002	1 hr

7.1 Construction costs: Boone County

Construction procedure required utilizing road construction equipment such as motor grader, tandem truck, tractor/roller, and water truck. The labor cost and the costs of the equipment per hour are presented in **Table 36**.

Table 36. Labor and equipment unit costs

Category	Unit Cost
On-Site Labor	$43.15/hr
Grader	$76.15/hr
Tandem Dump Truck	$59.55/hr
Water Truck	$49.85/hr
Tractor & Roller	$35.04/hr

Table 37 shows the labor, and equipment times and costs for the construction of the demonstration sections in Boone County. It shows that Clay Slurry section requires more labor and equipment time during the construction due to the high moisture in the clay slurry. This section required more time for the grader, and tractor/roller for mixing and compacting the slurry with existing aggregates. In addition, 120 ton of surface aggregates were added to the mixture of existing aggregates and slurry to decrease the moisture content, which resulted in higher time. Ames Mine and Moscow sections had the same labor and equipment costs, while Crescent section required more time due to the use of water tank for this section.

Table 37. labor and equipment time and costs for construction in Boone County

	Unit	Labor	Motor grader	Tandem truck	Tractor/Roller	Water truck
Ames Mine	(hr)	4	2	2	1	-
	($)	173	152	119	35	-
Moscow	(hr)	4	2	2	1	-
	($)	173	152	119	35	-
Clay Slurry	(hr)	28	12	12	4	-
	($)	1208	914	715	140	-
Crescent	(hr)	10	2	4	2	2
	($)	431.5	152	238	70	100

Table 38 shows the unit costs and hauling time for the quarry fines and existing aggregates used in Boone County. Unit cost for aggregates was higher than quarry fines as it was expected. Moreover, Crescent fines were relatively less expensive than Moscow and Ames Mine fines. Clay Slurry fines came as slurry in two loads, $100 each. Proximity of the Ames Mine quarry fines resulted in lower hauling time for these materials. Surface aggregates were from Boone County and there was no hauling time considered for them due to the proximity of the quarry fines piles to the site location.

Table 38. Unit cost and time for the fines and surface aggregates

Materials	Unit Cost ($/ton)	Time (hr)
Aggregates	10.5	-
Moscow	8.3	2.6
Ames Mine	7.95	0.25
Crescent	3	2.5

Table 39 shows the amount and costs of the surface aggregates and quarry fines, and hauling costs including labor and trucking for construction in Boone County. Clay Slurry (120 ton) and Crescent (24ton) sections required surface aggregates to be added to the mixture of existing aggregates and quarry fines during the construction to decrease the moisture content of the sections. Moscow and Ames Mine sections needed 40 and 39 ton of quarry fines based on the design sheets, respectively. However, Crescent and Clay Slurry sections needed only 7 ton of fines. Clay Slurry materials were hauled as slurry in two loads. Among all sections, Clay Slurry had the maximum hauling (labor and trucking) costs and Crescent and Moscow sections had relatively similar hauling costs. Clay Slurry is delivered as slurry and a tanker, and a spray truck were delivered to spray the slurry through the section. However, the hauling costs for Ames Mine section was the lowest due to the proximity of Ames Mine quarry to Boone County. Quarry fines were mixed with existing aggregates during construction.

Table 39. Material weight and costs for the construction in Boone County

Sections	Extra Aggregates		Quarry Fines		Hauling ($)		Existing Surface Aggregates	
	ton	$	ton	$	Labor	Truck	ton	$
Ames Mine	0	-	39	310	17	30	352	3694
Moscow	0	-	40	332	175	310	362	3805
Clay Slurry	120	1,260	7 (2 loads[1])	200	1,550	1,125	343	3604
Crescent	24	252	7	21	169	298	343	3604
Control	-	-	-	-	-	-	363	3814

[1] Clay Slurry materials came in tanks as slurry.

7.2 Construction costs: Jones County

Construction procedure required utilizing road construction equipment such as motor grader, skid loader, water truck, and tractor/roller. The labor cost and the costs of the equipment per hour are presented in **Table 40**.

Table 40. Labor and equipment unit costs

Category	Unit Cost
On-Site Labor	\$43.15/hr
Grader	\$76.15/hr
Skid Loader	\$32.85/hr
Water Truck	\$72.62/hr
Tractor & Roller	\$30.53/hr

Table 41 shows the labor, and equipment times and costs for the construction of the demonstration sections in Jones County. It shows that Clay Slurry section requires more labor and equipment time during the construction and due to the high moisture in the clay slurry. It requires more time for the grader, and tractor/roller for mixing and compacting the slurry with existing aggregates. Limestone and Moscow sections had the same labor and equipment costs, and water truck was used for both sections to achieve the optimum moisture content for the surface materials.

Table 41. Labor and equipment time and costs for construction in Jones County

	Unit	Labor	Motor grader	Skid Loader	Tractor/Roller	Water Truck
Moscow	(hr)	3	2	1	0.25	1
	(\$)	107	152	33	8	73
Clay Slurry	(hr)	22	7	-	0.5	-
	(\$)	781	533	-	15	-
Limestone	(hr)	3	2	1	0.25	1
	(\$)	107	152	33	8	73

Table 42 shows the unit costs and hauling time for the Moscow fines and existing aggregates used in Jones County. The unit cost for aggregates was a bit more expensive than Moscow fines. Clay Slurry and Limestone fines were delivered in loads and their costs per load will be in the upcoming section (**Table 43**). Quarries selected for this project were relatively closer to the Jones County site compared to Boone County site. Surface aggregates were from Stone city, which is close to the test site location and no hauling time was considered for surface aggregates due to the proximity of the quarry fines piles to the location.

Table 42. Unit cost and time for the fines and surface aggregates

Materials	Unit Cost (\$/ton)	Time (hr)
Aggregates	8.4	-
Moscow	8.3	1

Table 43 shows the amount and costs of the surface aggregates and quarry fines, and hauling costs including labor and trucking for construction in Jones County. Clay Slurry (61 ton) and Moscow (91.5 ton) sections required surface aggregates to be added to the mixture of existing aggregates and quarry fines after the construction to decrease the moisture content of the sections and provide

smoother surfaces. Moscow section needed 55 ton of quarry fines based on the design sheets. However, Limestone and Clay Slurry sections needed only 7 ton and 8 ton of fines, respectively. Clay Slurry materials were hauled as slurry in two loads. Limestone fines were dewatered on site and had around 20% moisture content. Limestone fines came out of truck as a large mass and needed to be picked up and spread on the section by skid loader and bladed with motor grader.

Among all sections, Clay Slurry had the maximum hauling (labor and trucking combined) costs and Limestone and Moscow fines had relatively similar hauling costs. Clay Slurry delivered as slurry and a tanker, and a spray truck were delivered to spray the sly through the section. Quarry fines were mixed with existing aggregates during construction.

Table 43. Material weight and costs for the construction in Jones County

Sections	Extra Aggregates		Quarry Fines		Hauling ($)		Existing Surface Aggregates	
	ton	$	ton	$	Labor	Truck	ton	$
Moscow	91.5	769	55	453	453	30	370	3,111
Clay Slurry	61	512	7 (2 Loads[1])	200	2,050		358	3,010
Limestone	-	-	8 (1 Load[2])	250	550		368	3,94
Control	-	-	-	-	-	-	358	3,003

[1] Clay Slurry materials came in tanks as slurry.

[2] Limestone materials were delivered in a load.

7.3 Benefit-cost analysis

This project collected quarry fines from two quarries for Jones County and from 4 quarries for Boone County. Three sections were constructed in Jones and four sections in Boone, where each section had different properties, conditions, and costs. Construction costs, durability (gradation change, total breakage), dust production, and engineering properties (stiffness and strength) were the important factors that were considered in the benefit-cost analysis (BCA) model to determine the cost efficiency of mixing each quarry fines with surface aggregates. BCA starts with defining the base case, which in this study was the control section in Boone and Jones counties. Determining the benefits of using different quarry fines was the second step, where the environmental and serviceability factors (dust emission, ride quality), mechanical properties of the surface layers (strength and stiffness), and size characteristics (total breakage, fines content, gravel to sand ratio, and gravel loss) of the sections were compared to determine the best option in each county. Calculating the current values of costs and benefits was the third step for building the BCA model. These steps for BCA analyses are discussed next.

7.4 Defining the benefits

7.4.1 User Cost Saving

Granular roadways in cold regions undergo freezing and thawing and suffer from traffic loading, which result in deterioration of their surface aggregates. Therefore, it was assumed that maintenance including renewing at least 2” surface layer was necessary every year by blading new aggregates for an untreated granular section. Thus, it was decided to consider an annual maintenance for the control sections both in Boone and Jones counties. Maintenance procedure causes a usual double travel time. Travel time for a section with quarter of miles was assumed 3 minutes and travel time during the maintenance with considering delay was assumed to be 6 minutes. Therefore, user time will be saved for the passengers by performing maintenance less frequently for the sections. Travel time saving outcome is user cost saving, and this value differs based on the type of the vehicles. U.S Bureau of Labor Statistic suggested the value of user cost saving \$54/hr for trucks and \$25/hr for passenger cars (BLS 2018). Subject matter experts (County Engineers at Boone and Jones Counties’ Engineering Office) suggested truck traffic to be 25% of the AADT in both roads. Moreover, the total AADT of the road in Boone and Jones counties was 70 and 80, respectively, based on the Iowa Traffic Map (IDOT 2007).

Maintenance Cost Saving: Performing the regular maintenance including adding new aggregates result an additional cost saving. Renewing the surface layer of the gravel roads in the cold region areas is almost necessary at least for the first top 2” of the surface aggregates due to the aggregate loss, and distresses such as rutting, potholes and washboarding (Cetin et al. 2019; Mahedi et al. 2020; Satvati, Cetin, et al. 2019). However, providing binding between the aggregates by utilizing the quarry fines in the surface aggregates helps to prevent such issues. Therefore, it was reasonable to reduce the maintenance costs by delaying the regular maintenance procedure, when mixing aggregates with quarry fines (Satvati et al. 2020; Wu et al. 2020). The maintenance frequency was decided based on the performance and serviceability of each section, where it was once a year for low-performance sections, twice a year for medium-performance sections, and every three years for high-performance sections. Moreover, three different scenarios including worst case, most-likely case, and best case were considered of which these scenarios added one year delay to the maintenance intervals.

7.4.2 Net Present Value (NPV) calculation for benefit-cost calculation

After defining the base case and benefits, the next step would be calculating the annual values of the costs and benefits. Equation 7 shows how to calculate net present value (NPV). The service life and the discount rate are the two main factors in NPV calculations.

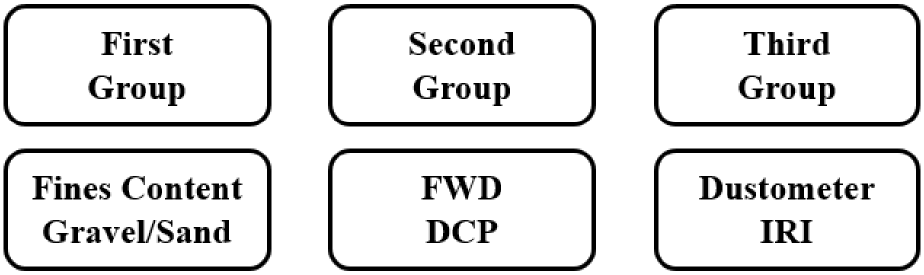
$$NPV = \text{Construction Costs} + \sum_{k=1}^{n} Maintenance\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ Value[\frac{1}{(1+i)^{n_k}}] \tag{7}$$

, where “i” is the discount rate and “n” are the service life of the project. The salvage value of the road, which represents the value of an investment alternative at the end of the analysis period, was assumed to be zero because it was thought that there was no remaining life for the surface materials after the service life of the road.

Benefit cost ratio (BCR) was defined as the ratio between NPV of the benefits divided by the NPV of the total costs. User cost and maintenance cost savings were two benefits, which were defined and used in BCR calculations. An excel sheet framework developed and was used to calculate the BCR values for each alternative section. Several assumptions were considered for the service life of this project (20, 30, 40, and 50 years). Moreover, discount rate of 3% and maintenance intervals between 1, 2, 3, 4, and 5 years were the other inputs of the BCA Model.

7.4.3 Performance-based benefit cost analysis

Laboratory and field test results including surface stiffness (FWD), surface shear strength (DCP), dust emission (Dustometer), ride quality (IRI), and grain shape characteristics (fines content and gravel to sand ratio) were divided into three different categories based on their degree of importance for maintenance procedure. In order to combine all the BCA results and finally select the most beneficial alternative, a weight was given to each performance measure (**Figure 62**). Total breakage and gravel content change were considered the most important considerations for performing maintenance and the weight of "1" was given to these materials. Other performance measures including average fines content, gravel to sand ratio, FWD and DCP results, ride quality and dust emission were placed into three groups based on their importance level for maintenance consideration. The average results of fines content and gravel to sand ratio were considered as the first group due their importance by being representative of the grain shape characteristics of the surface aggregates and the weight of "0.75" was selected for this group. FWD (surface elastic modulus) and DCP (average surface shear strength) results were placed as the second group since they are representative of structural properties of surface layer, with the weight of "0.5". Finally, average results of dustometer and IRI tests (dust emission and surface roughness/ride quality) were assigned to the third group with the degree of importance of "0.25". Following sections explain the results of BCA for each section in both counties.



First Group	Second Group	Third Group
Fines Content Gravel/Sand	FWD DCP	Dustometer IRI

Figure 62. Classification of the laboratory and field results for BCA

7.5 Results and discussions: Boone County

Figure 63 shows the costs per quarter of mile for equipment, aggregates, and quarry fine materials, and hauling for all alternative sections in Boone County. The construction costs for Clay Slurry were the highest among all sections due to the higher hauling, equipment, and materials costs

(~$7,000). On the other hand, Ames Mine section had the lowest total costs ($836) most specifically because of lower hauling costs. Material costs for Clay Slurry, Ames Mine, and Crescent sections were almost the same, while Ames Mine and Moscow had the lowest equipment costs compared to others.

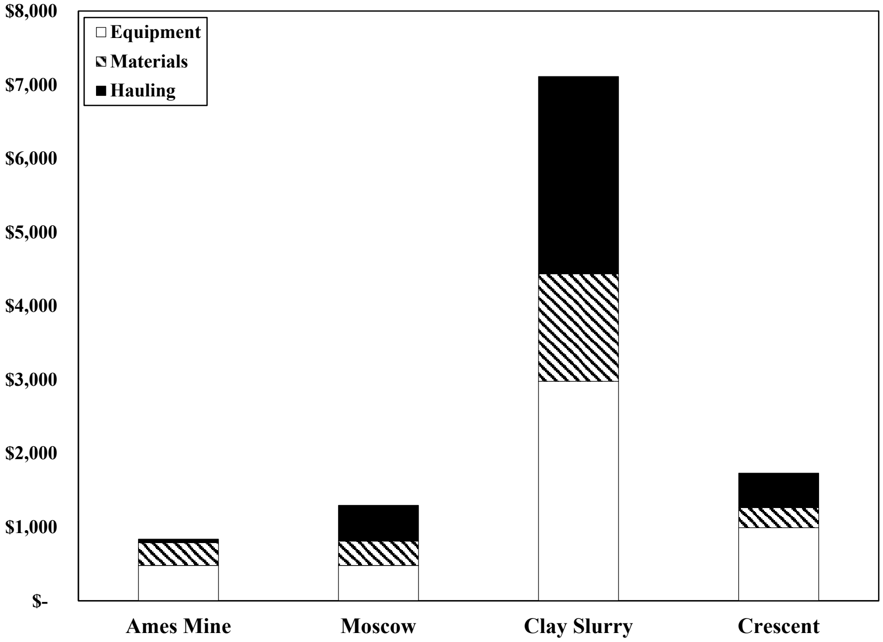


Figure 63. Construction costs for equipment, materials, and hauling in Boone County

In the following sections, different performance measures are considered in evaluating the serviceability of the sections and considering different maintenance scenarios, and finally the BCR values based on each performance measure. An overall BCR is calculated to select the most beneficial option for Boone County.

7.5.1 Gravel content change

Gravel (aggregate size> U.S#4 (0.19) in.) content change, or gravel loss was considered as one of the main indicators of deterioration of granular roadways in Boone County sections. **Figure 64** shows the gravel content change from November 2019 to March 2020. Demonstration sections then were categorized into three categories based on their gravel changes, where Ames Mine, Moscow, and Crescent sections had "High" (>20%), and Clay Slurry had "Medium" (20%< and >10%), and none low (<10%) gravel loss.

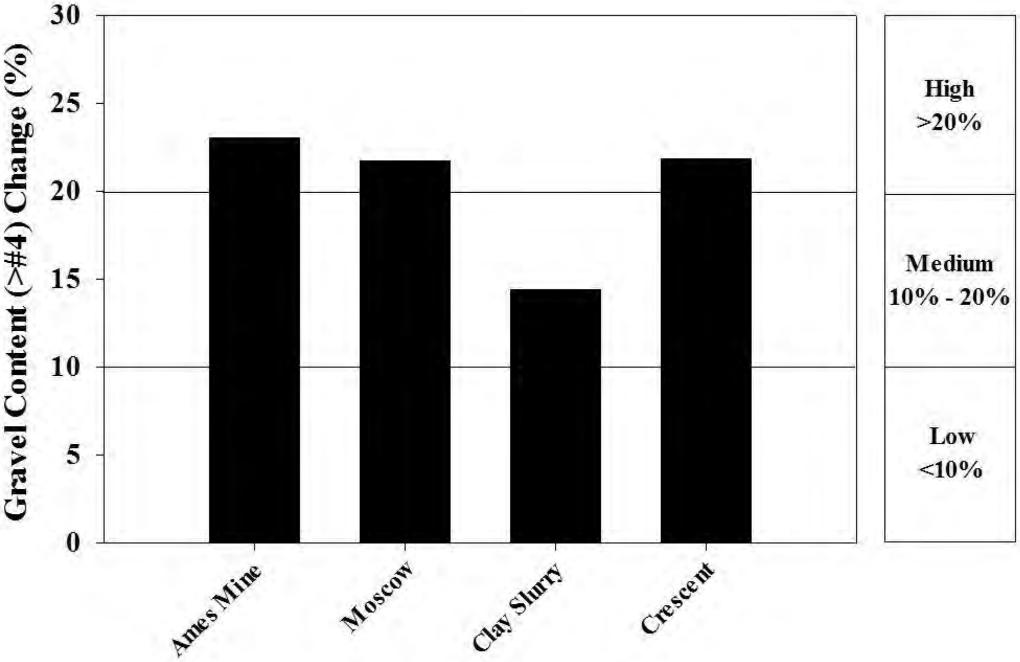


Figure 64. Gravel percentage change from November 2019 to March 2020

Table 44 shows the different scenarios based on the results of gravel content change for each section. For the sections with the "High" gravel loss (Ames Mine, Moscow, and Crescent), maintenance could be performed for every 1, 2, or 3 years. However, Clay Slurry with "Medium" gravel content change could have maintenance every 2, 3, or 4 years.

Table 44. Scenarios for maintenance frequency based on the gravel loss of each section

Sections	Worst Case	Most Likely	Best Case
Ames Mine	1	2	3
Moscow	1	2	3
Clay Slurry	2	3	4
Crescent	1	2	3

Figure 65 shows BCA results based on the scenarios of gravel content change. Ames Mine, Moscow, and Crescent sections could be beneficial as alternatives for the "Base Case – control section" by having BCR higher than 1 for the best case scenario and all considerations of service life values. BCR for Clay Slurry section, on the other hand, was lower than 1 for all scenarios. The highest BCR was observed for Ames Mine (2.02), and Moscow (1.7) for their best case scenario at 20 years of service life.

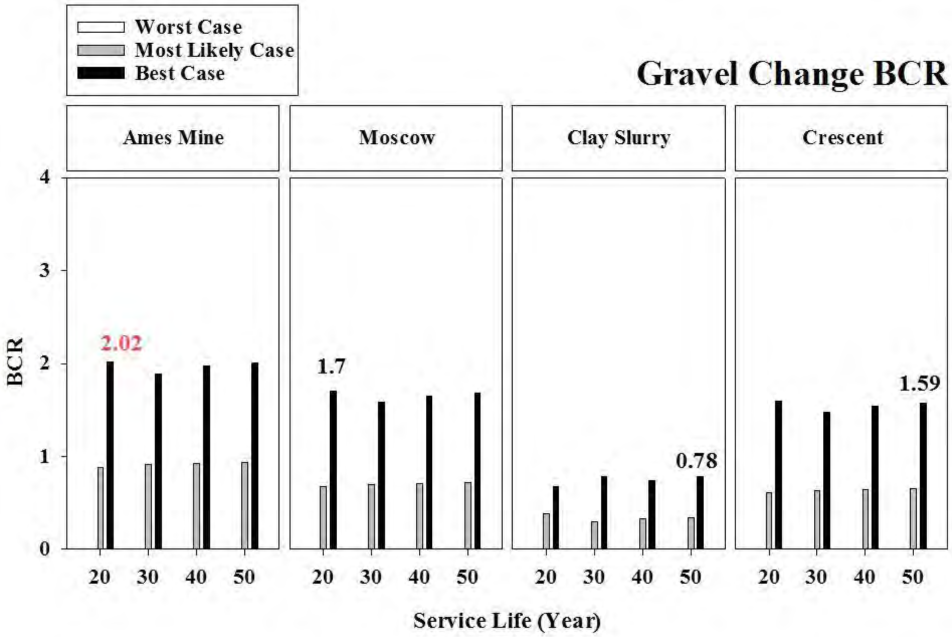


Figure 65. BCR for gravel content change

7.5.2 Total Breakage

Figure 66 shows the total breakage of all test sections since November 2019 until March 2020. Test sections were categorized into three groups where Ames Mine and Crescent had "High" (>0.15); Clay Slurry had "Medium" (0.1 to 0.15); and Moscow section had "Low" (<0.1) total breakage values.

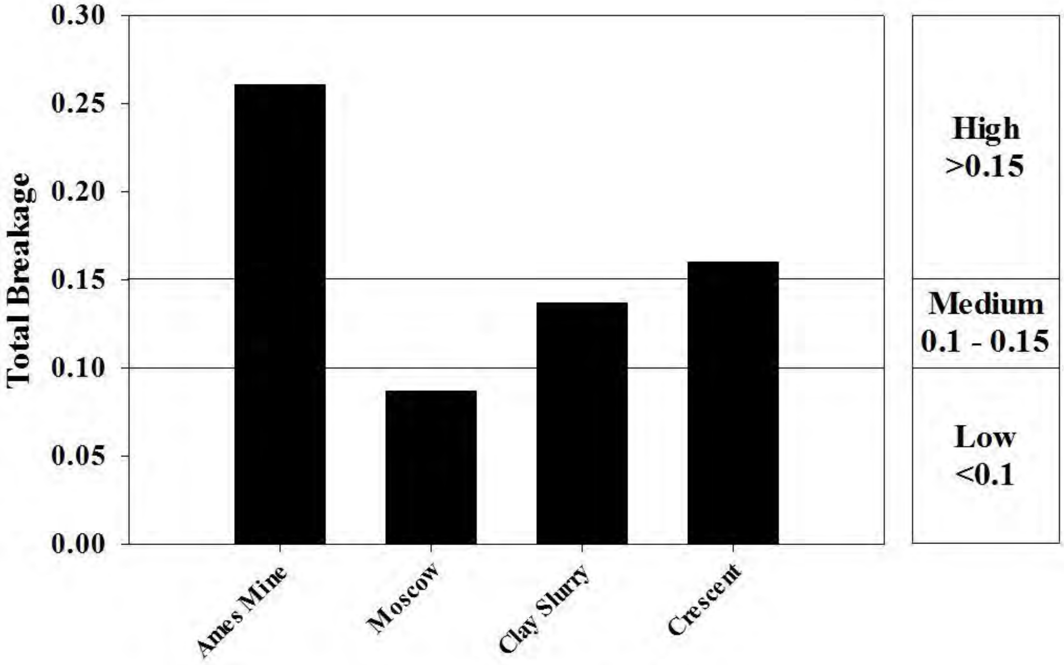


Figure 66. Total breakage average values over the length of project

Table 45 shows the different scenarios based on the results of average total breakage over the maintenance period. For the sections with the "High" average total breakage (Ames Mine and Crescent), maintenance could be performed for every 1, 2, or 3 years. Clay Slurry with "Medium" average total breakage could have maintenance for every 2, 3, or 4 years, and the sections with "Low" aggregate loss (Moscow), require maintenance less often (3,4, or 5 years).

Table 45. Scenarios for maintenance frequency based on the average total breakage

Sections	Worst Case	Most Likely	Best Case
Ames Mine	1	2	3
Moscow	3	4	5
Clay Slurry	2	3	4
Crescent	1	2	3

Figure 67 shows BCA results based on the scenarios of average total breakage. Moscow section showed to be always beneficial to use compared to the "Base Case – control section" with BCR greater than 1 for different scenarios and service life values. Clay Slurry had the lowest BCR values for all scenarios and service life values compared to the rest of the sections, with BCR value lower than 1. Ames Mine could be the second beneficial option after Moscow with BCR values higher than 1 for all service life values and for the best case scenario. The third beneficial option would be Crescent section which again had BCR greater than 1 for all service life values and in the best case scenario. Both Ames Mine and Crescent would not be beneficial options for all service life values and at worst and most-likely scenarios.

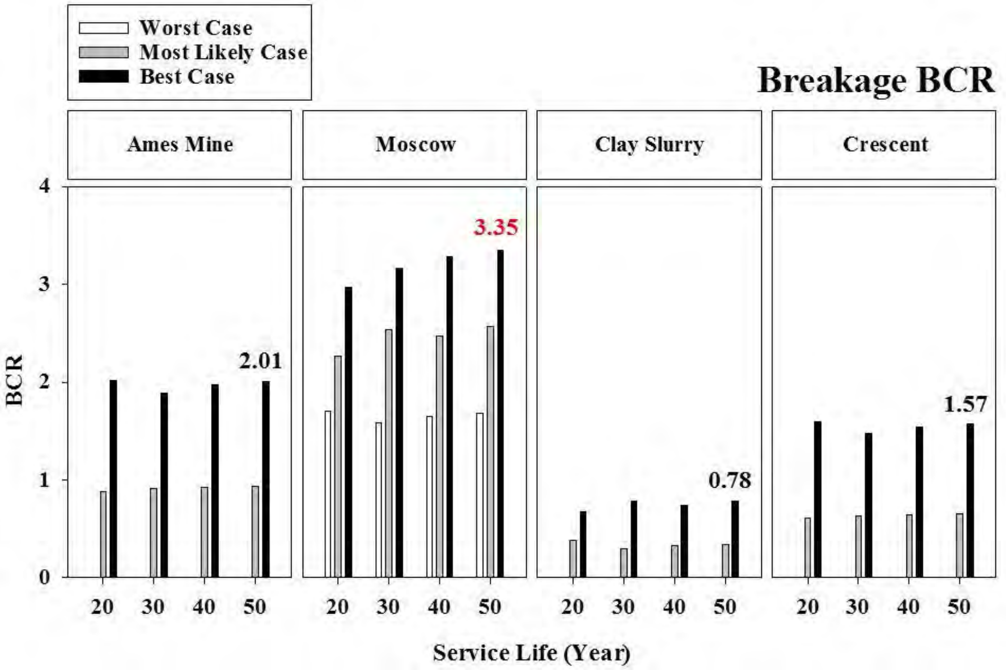


Figure 67. BCR for average total breakage

7.5.3 Fines content

Fines content of the surface aggregate materials has a relatively strong connection to the dust emission and occurrence of severe distresses. Therefore, average fines content of the sections over

November 2019 to March 2020 was selected as one of the important factors to compare BCR results of the alternative sections with the “base case-the control section”. **Figure 68** shows the average fines content values of the alternative test sections. Three groups were considered to categorize the results of fines content. Moscow had “High” (>20%), while Ames Mine, Clay Slurry, and Crescent had “Medium” (15% to 30%) average fines content values.

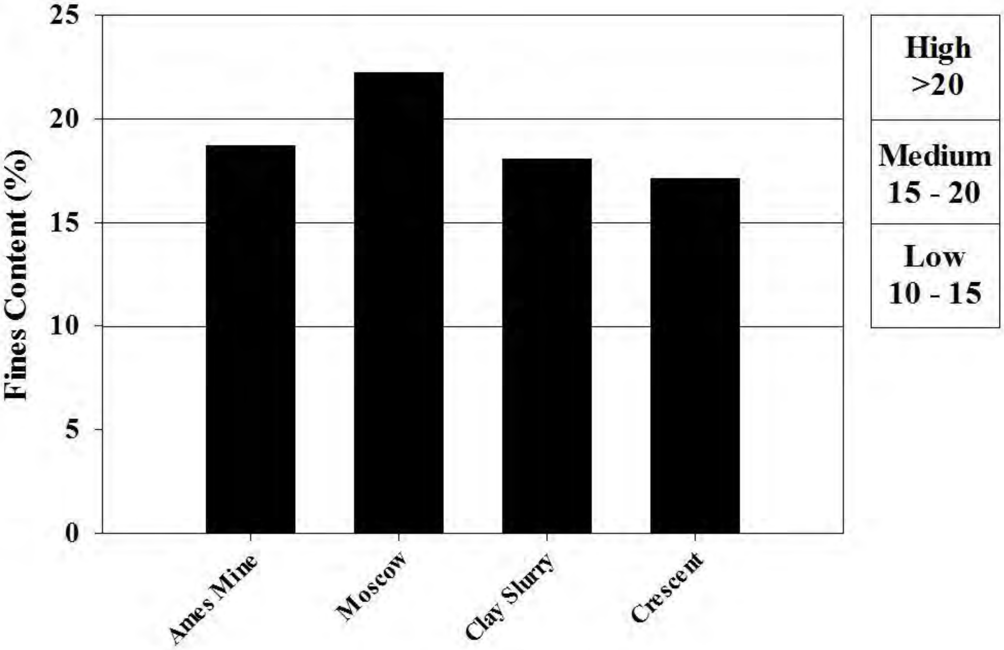


Figure 68. Average fines content values over the length of project

Table 46 shows the different scenarios based on the results of average fines content. Moscow with “High” average fines content, could have maintenance performed for every 1, 2, or 3 years. For the sections with “Medium” fines content (Ames Mine, Clay Slurry, and Crescent) maintenance procedure could occur every for 2, 3, or 4 years.

Table 46. Scenarios for maintenance frequency based on the average fines content

Sections	Worst Case	Most Likely	Best Case
Ames Mine	2	3	4
Moscow	1	2	3
Clay Slurry	2	3	4
Crescent	2	3	4

BCA results for average fines content scenarios are shown in **Figure 69**. Ames Mine and Crescent sections showed to be always beneficial to use compared to the “Base Case – control section” by having BCR higher than 1 for most-likely and the best case scenarios and all service life values. However, Ames Mine had the highest BCR for all scenarios and service life values. . Clay Slurry section could not be a cost-effective option due to having BCR below 1 for all scenarios and service life values. Moscow section only had BCR greater than 1 for the best-case scenario.

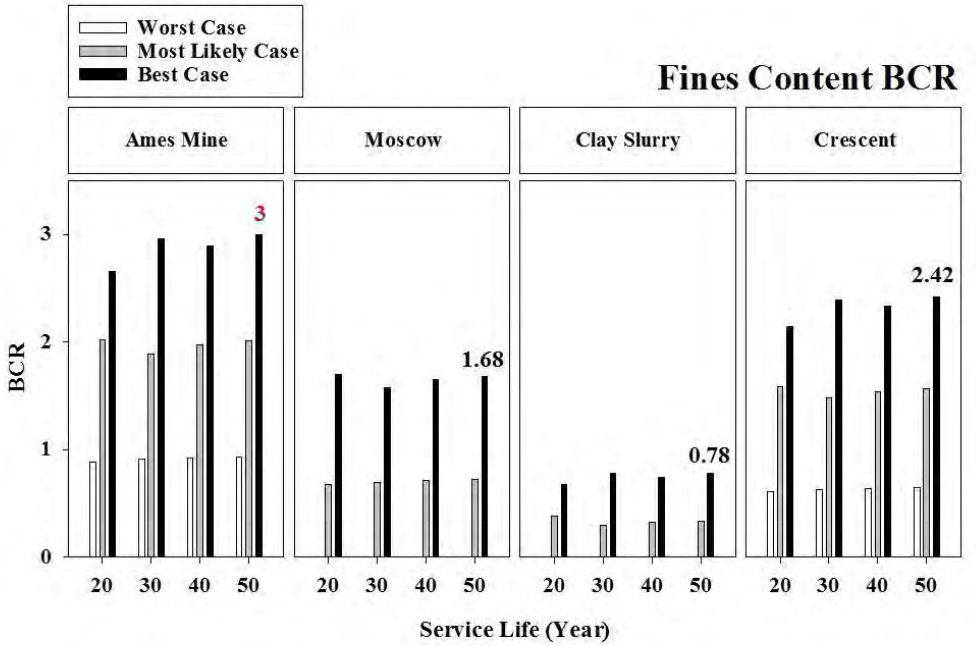


Figure 69. BCR for average fines content

7.5.4 Gravel to sand ratio

Change in the gravel to sand ratio is an indicator of breakage of the gravels to the sand particles over time and is considered to evaluate which alternative sections could have lower change than the "Base Case – control section". **Figure 70** shows the average gravel to sand ratio values based on the sieve analysis results on the samples collected from November 2019 and March 2020. Demonstration sections were categorized into three groups where Ames Mine, Clay Slurry, and Crescent sections had "High" (>0.75), and Moscow section had "Low" (<0.5) average gravel to sand ratio values.

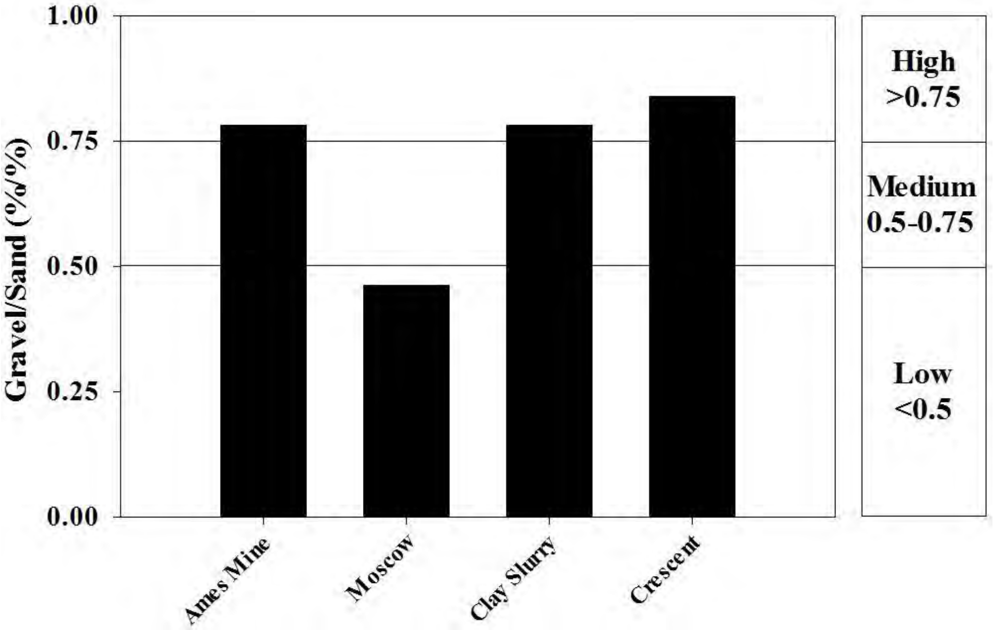


Figure 70. Average gravel to sand ratio values

Table 47 shows the different scenarios based on the results of average gravel to sand ratio. Moscow section with "Low" average gravel to sand ratio, could have maintenance performed for every 1, 2, or 3 years, and Ames Mine, Clay Slurry, and Crescent sections with "High" average gravel to sand ratio require maintenance less often (3,4, or 5 years).

Table 47. Scenarios for maintenance frequency based on the average gravel to sand ratio

Sections	Worst Case	Most Likely	Best Case
Ames Mine	3	4	5
Moscow	1	2	3
Clay Slurry	3	4	5
Crescent	3	4	5

Figure 71 demonstrates all the BCA results for the average gravel to sand ratios. All sections had BCR values greater than 1 for their best-case scenario. However, Ames Mine (3.87) and Crescent (3.16) had the highest BCR and Clay Slurry (1.16), and Moscow (1.68) had the lowest. Crescent and Ames Mine sections had BCR greater than one for all scenarios and service life values. However, Clay Slurry and Moscow sections were beneficial only for their best-case scenarios.

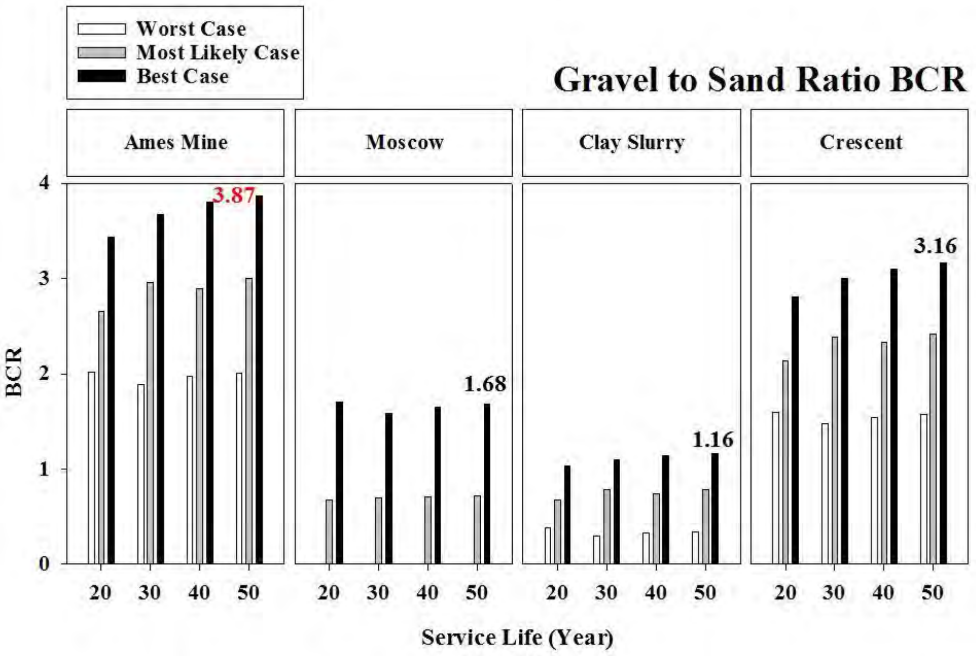


Figure 71. BCR for average gravel to sand ratio

7.5.5 Surface elastic modulus - FWD

Surface elastic modulus is an indicator of the stiffness of materials. In this section, the effects of back-calculated surface elastic modulus on having less-frequently maintenance procedure for the alternative sections have been investigated. **Figure 72** demonstrates three groups of sections based on their surface elastic modulus, where Ames Mine, Moscow, and Crescent had "High" (>50 ksi); while Clay Slurry section had "Medium" (25 ksi to 50 ksi) average back-calculated surface elastic modulus values.

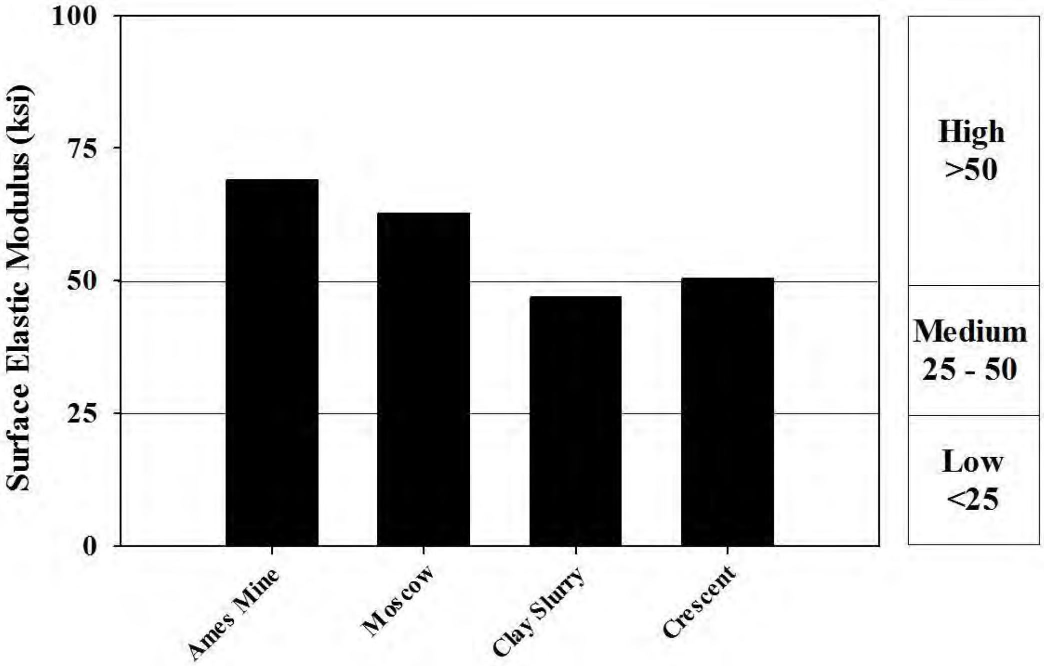


Figure 72. Average back-calculated surface elastic moduli during the project

Table 48 shows the different scenarios based on the results of average back-calculated surface elastic modulus. For Clay Slurry with “Medium” average surface elastic modulus, maintenance could be applied for every 2, 3, or 4 years, and for Ames Mine, Moscow, and Crescent sections with “High” average surface elastic modulus maintenance could be performed less often (3,4, or 5 years).

Table 48. Scenarios for maintenance frequency based on the average surface elastic modulus

Sections	Worst Case	Most Likely	Best Case
Ames Mine	3	4	5
Moscow	3	4	5
Clay Slurry	2	3	4
Crescent	3	4	5

Figure 73 shows the results of BCA based on the back-calculated surface elastic modulus. Ames Mine, Moscow, and Crescent sections were always beneficial to use compared to the “Base Case – control section” with BCR greater than 1 for all scenarios and service life values. Ames Mine had the highest BCR among all these sections. On the other hand, Clay Slurry section always had BCR lower than 1 for all maintenance scenarios and service life values due to its relatively higher hauling and material costs.

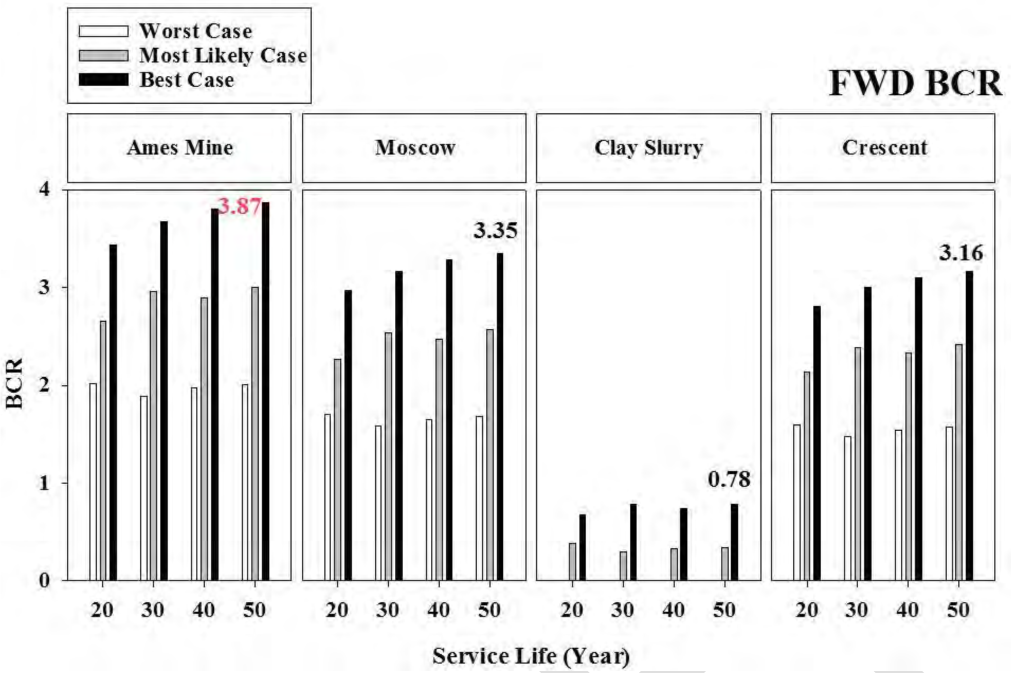


Figure 73. BCR for average back-calculated surface elastic modulus

7.5.6 Surface shear strength - DCP

Surface shear strength could be used to evaluate the advantages of using alternative sections than “Base Case – control section”. **Figure 74** shows the surface shear strength of all sections as a result of DCP test. Test sections then were categorized into three groups where Ames Mine, Moscow, and Clay Slurry sections had “High” (>80%); and Crescent had “Medium” (50% to 80%) average surface shear strength.

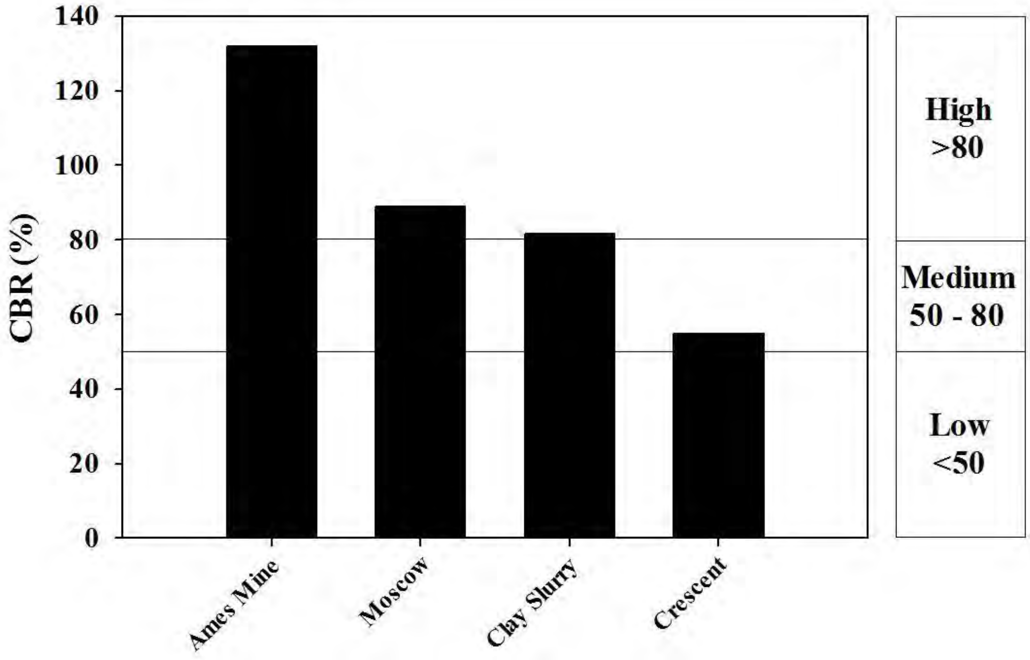


Figure 74. Average surface shear strength values over the length of project

Table 49 summarizes different maintenance scenarios based on the results of average surface shear strength. The first three sections, including Ames Mine, Moscow, and Clay Slurry with “High” average surface shear strength, could have maintenance procedure for every 3, 4, or 5 years. Crescent section with “Medium” average surface shear strength could have maintenance for every 2, 3, or 4 years.

Table 49. Scenarios for maintenance frequency based on the average surface shear strength

Sections	Worst Case	Most Likely	Best Case
Ames Mine	3	4	5
Moscow	3	4	5
Clay Slurry	3	4	5
Crescent	2	3	4

Figure 75 summarizes the BCA results for all the maintenance scenarios based on average surface shear strength. BCR for Ames Mine and Moscow sections were always greater than 1 for all maintenance scenarios and all service life values. However, Ames Mine had the highest BCR v compared to all other sections. Crescent section was the other section that could be beneficial to be considered rather than the control section with BCR greater than 1 for most-likely and the best case scenarios and for all service life considerations. Clay Slurry section also could be beneficial as an alternative section with greater than 1 BCR only for the best case scenarios and all service life considerations.

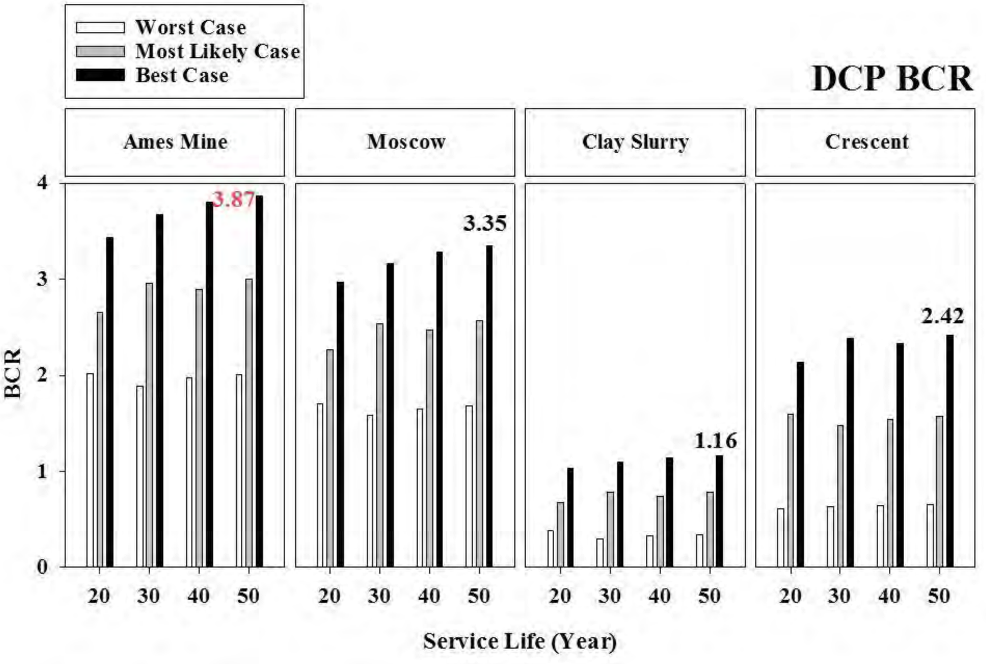


Figure 75. BCR for average surface shear strength

7.5.7 Dust production – dustometer

Dust emission is of the most associated problems with granular roadways, and it is always preferable to use surface aggregate materials with the lowest dust emissions. **Figure 76** compares dust emission values for all alternative sections. Three different groups were selected for the alternative sections, where Crescent and Ames Mine had “High” (>4.5 E-3lb/mile); Moscow had

"Medium" (3 to 4.5 E-3lb/mile); and Clay Slurry had "Low" (<3 E-3lb/mile) average dust emission.

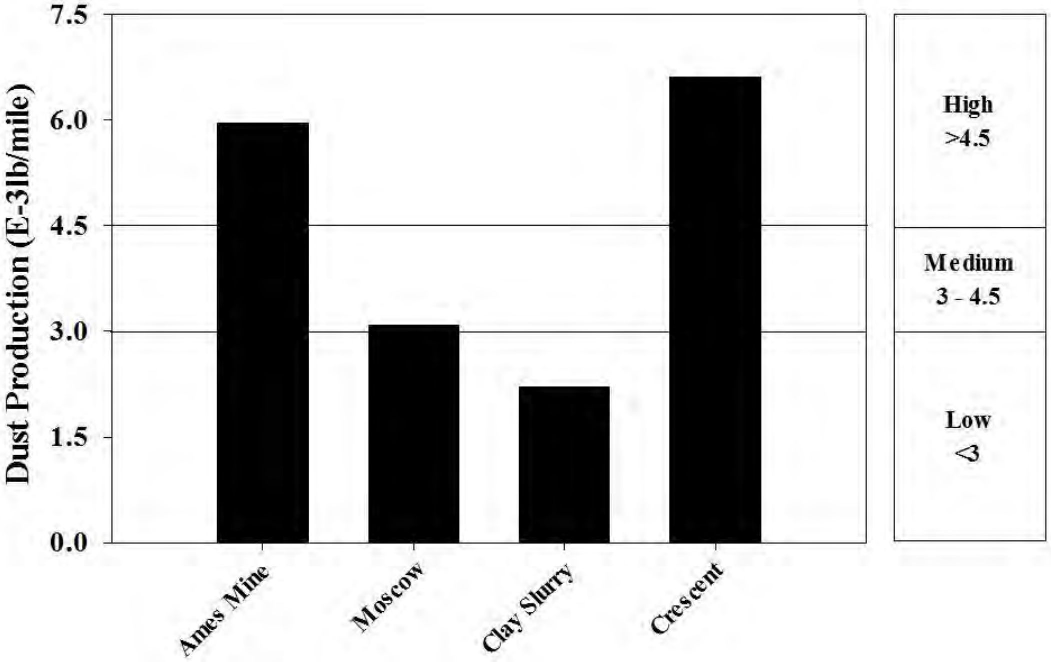


Figure 76. Average dust emission over the length of project

Table 50 shows the different maintenance scenarios for the results of average dust emission. Clay Slurry with "Low" average dust emission, could have maintenance for every 3, 4, or 5 years. Moscow with "Medium" average dust emission could have maintenance for every 2, 3, or 4 years, and Ames Mine and Crescent with "High" average dust emission could have higher maintenance frequency (1, 2, or 3 years) than the others.

Table 50. Scenarios for maintenance frequency based on the average dust production

Sections	Worst Case	Most Likely	Best Case
Ames Mine	1	2	3
Moscow	2	3	4
Clay Slurry	3	4	5
Crescent	1	2	3

Figure 77 summarizes the results of BCA for all scenarios of average dust emission. All sections could be beneficial as an alternative for their best case scenarios and for all their service life values. However, Moscow had the highest BCR values compared to the rest of the sections. Clay Slurry section again had the lowest BCR value among all sections. All sections were not beneficial for their worst case and most-likely case scenarios and their different service life values.

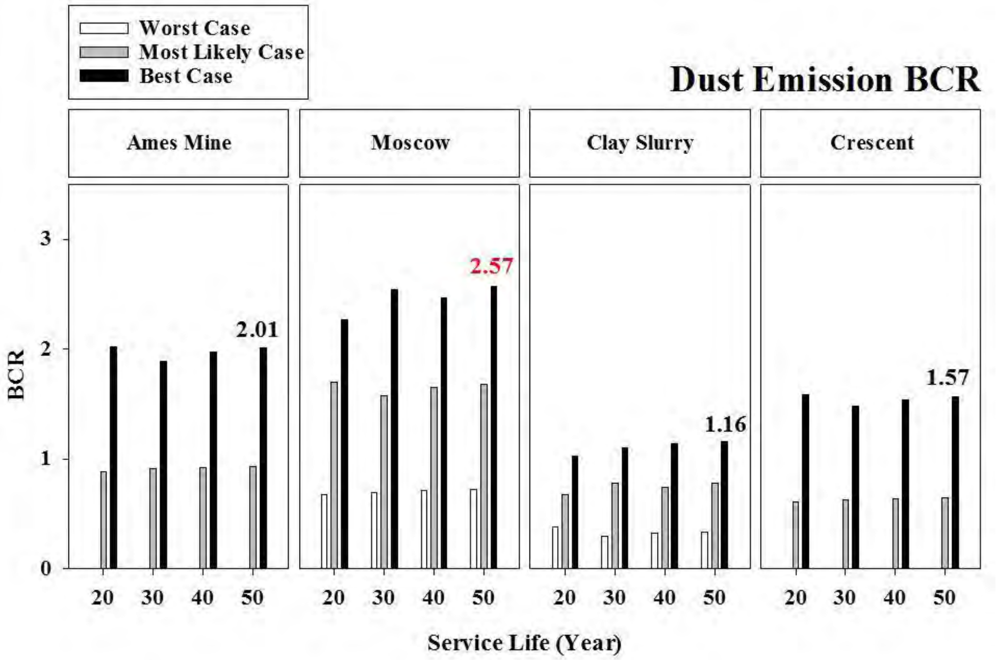


Figure 77. BCR values for average dust production

7.5.8 Surface roughness – IRI

Surface roughness or ride quality as a result of IRI test is an indicator of serviceability of the roads. In this study all sections had Fair conditions for their ride qualities (**Figure 78**). However, they have different construction costs and the BCR values for the same maintenance scenarios will be evaluated to investigate their benefits as an alternative to the control section.

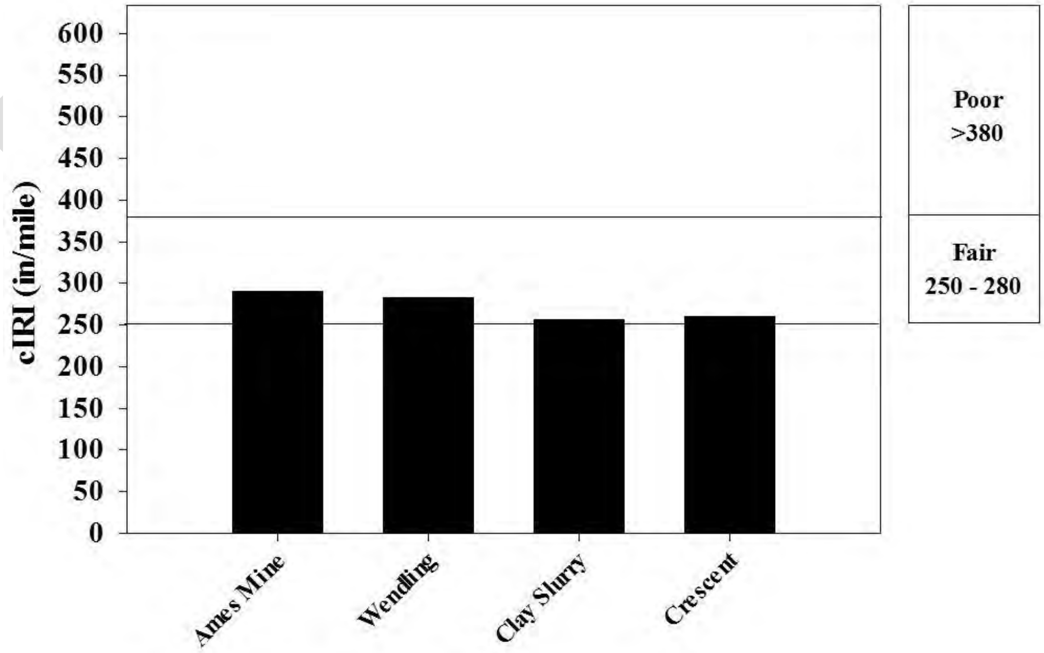


Figure 78. Average surface roughness (cIRI) over the length of project

Table 51 shows the different scenarios based on the results of average dust production. All sections had Fair conditions and their maintenance frequency values for different scenarios are between 2 (worst case), 3 (most likely case), and 4 (best case) years.

Table 51. Scenarios for maintenance frequency based on the average cIRI

Sections	Worst Case	Most Likely	Best Case
Ames Mine	2	3	4
Moscow	2	3	4
Clay Slurry	2	3	4
Crescent	2	3	4

Figure 79 shows the summary of the results of BCA for different maintenance scenarios and service life values based on their average surface roughness conditions. Ames Mine, Moscow, and Crescent were, respectively, the most beneficial sections for their best and most likely cases. However, Clay Slurry section had the lowest BCR values and could not be beneficial for all the scenarios and service life values due to its BCR always being lower than 1.

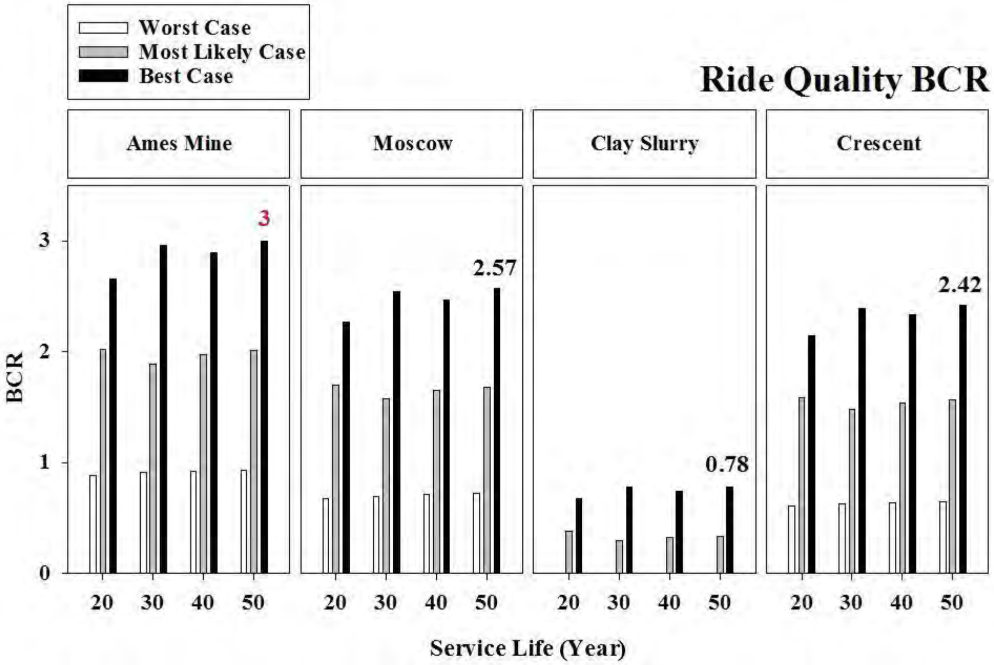


Figure 79. BCR values for average surface roughness conditions

7.5.9 Overall performance-based BCR values

For this analysis, the gravel content change and total breakage measures were weighted as 1, the first group (fines content, and gravel to sand ratio) was weighted as 0.75, the second group (FWD and DCP) was weighted as 0.5, and the third group (dustometer and IRI) was weighted as 0.25 (**Figure 80**).

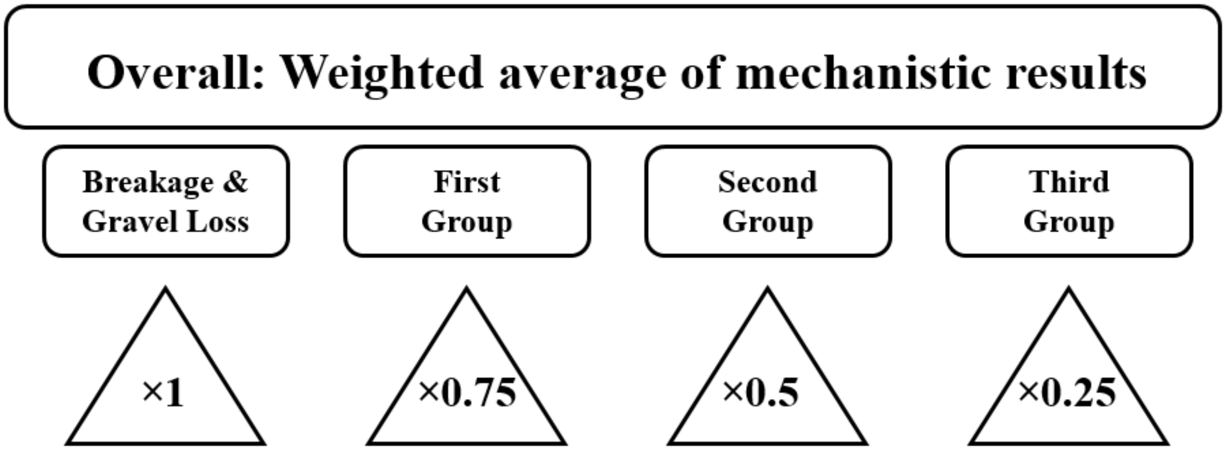


Figure 80. Weighted average of the BCR values based on the mechanical properties, total breakage and gravel loss

Figure 81 shows the BCR for average weighted values based on the performance measures for different maintenance scenarios and service life values for Boone County. Results showed that Ames Mine, Moscow, and Crescent sections, respectively, had the highest BCR values and could be considered beneficial compared to the control section for their most likely, and the best-case scenarios for all different service life values. On the other hand, Clay Slurry was the only section that would not be beneficial due to its high hauling and materials costs.

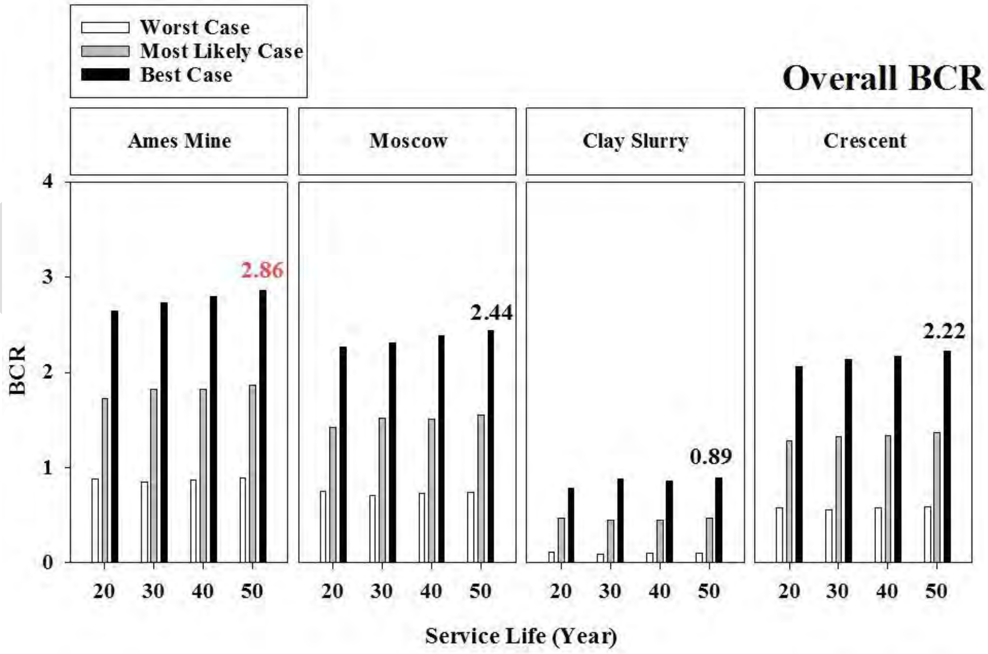


Figure 81. BCR for weighted performance measures, total breakage, and gravel content change for Boone County

7.6 Results and discussions: Jones County

Figure 82 shows the costs per quarter of mile for equipment, aggregates, and quarry fine materials, and hauling for all alternative sections in Jones County. The construction costs for Clay Slurry were the highest among all sections due to the higher hauling, equipment, and materials costs (~$4,000). On the other hand, Limestone section had the lowest total costs (~$1,000) most specifically because of lower amount of materials required to construct this section. Material costs for Moscow and Limestone sections were the highest and the lowest, respectively, while hauling costs for Clay Slurry section was the highest.

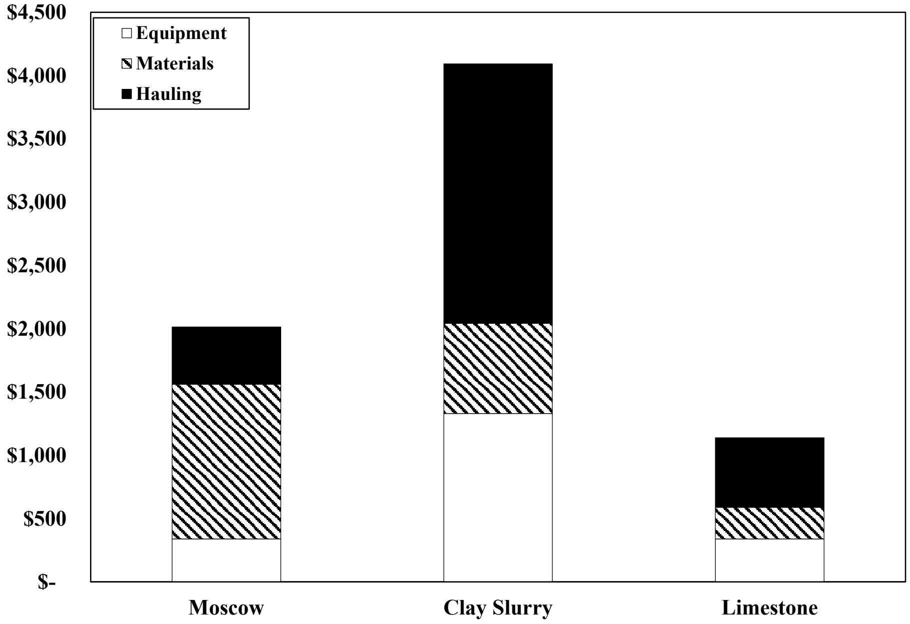


Figure 82. Construction costs for equipment, materials, and hauling in Jones County

In the following sections, different performance measures are considered in evaluating the serviceability of the sections and different maintenance scenarios, and finally the BCR values based on each performance measure. Then, an overall BCR will be calculated to select the most beneficial option for Jones County.

7.6.1 Gravel content loss

Figure 83 shows the gravel content change from November 2019 to March 2020 for Jones County sections. Demonstration sections then were categorized into three categories based on their gravel changes, where Clay Slurry section had “High” (>20%), and Moscow and Limestone sections had “Medium” (<20% and >10%) gravel loss.

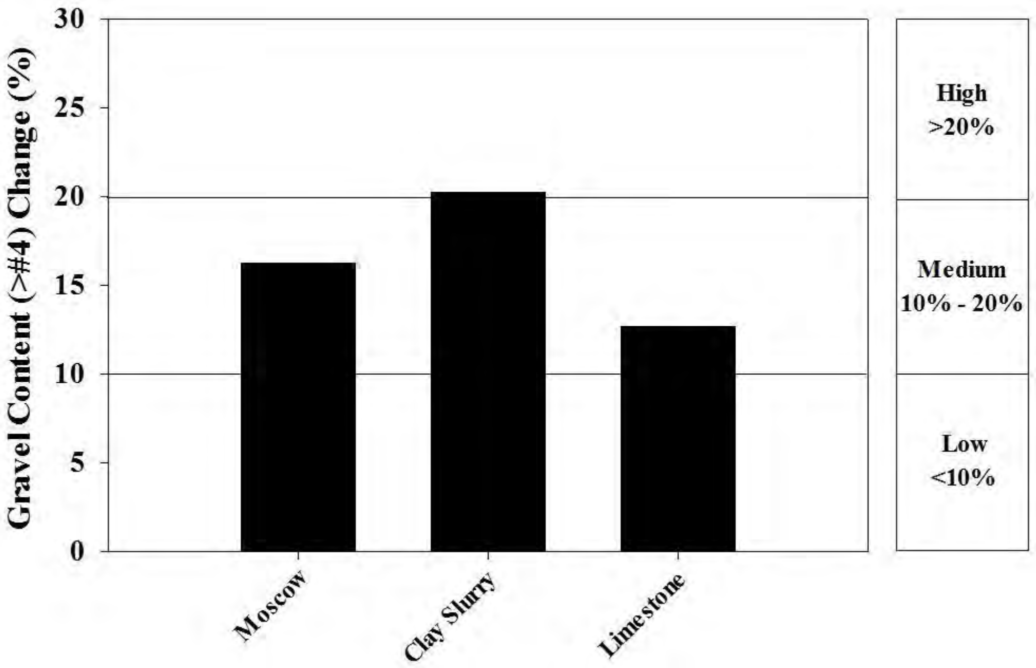


Figure 83. Gravel percentage change from November 2019 to March 2020

Table 52 shows the different scenarios based on the results of gravel content change for each section. For the sections with the "High" gravel loss (Clay Slurry), maintenance could be performed for every 1, 2, or 3 years. However, Moscow and Limestone sections with "Medium" gravel content change could have maintenance for every 2, 3, or 4 years.

Table 52. Scenarios for maintenance frequency based on the gravel content change

Sections	Worst Case	Most Likely	Best Case
Moscow	2	3	4
Clay Slurry	1	2	3
Limestone	2	3	4

Figure 84 shows BCA results based on the scenarios from gravel content change. Limestone and Moscow could be beneficial as alternatives for the "Base Case – control section" by having BCR higher than 1 for the best case and most likely case scenarios and all considerations of service life values. BCR values for Clay Slurry section, on the other hand, were lower than 1 for all scenarios except for the best case scenario. The highest BCR value was observed for Limestone (2.41), and Moscow (2.35) for their best case scenario at 50 years of service life.

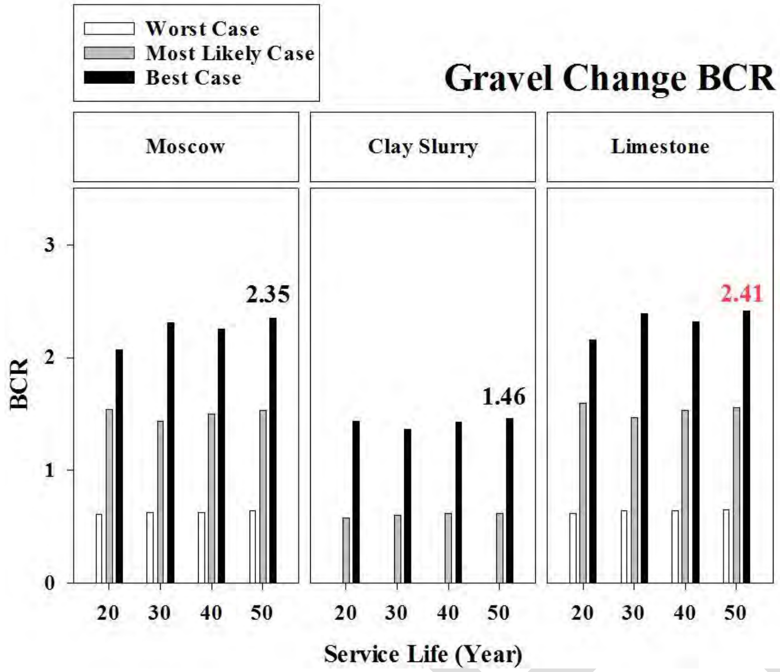


Figure 84. BCR values for gravel content change

7.6.2 Total Breakage

Figure 85 shows the total breakage of all test sections since November 2019 until March 2020 in Jones County. Test sections were categorized into three groups where Moscow and Clay slurry sections had "High" (>0.15); and Limestone section had "Low" (<0.1) total breakage values.

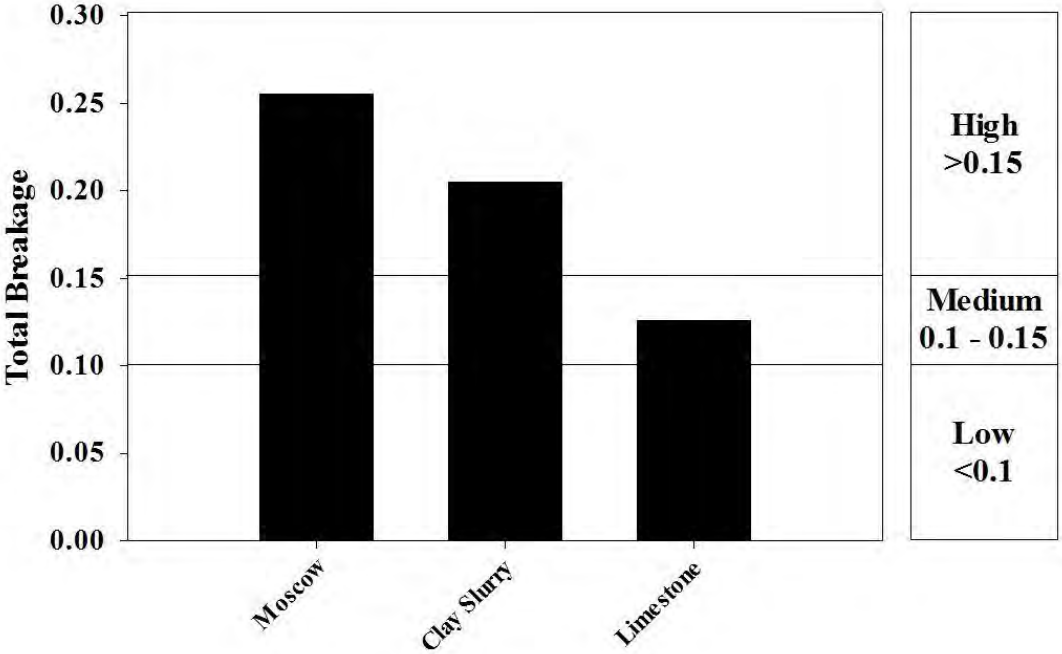


Figure 85. Total breakage average values over the length of project

Table 53 shows the different scenarios based on the results of average total breakage over the maintenance period. For the sections with the "High" average total breakage (Moscow and Clay Slurry), maintenance could be performed for every 1, 2, or 3 years. Limestone with "Medium" average total breakage could have maintenance for every 2, 3, or 4 years.

Table 53. Scenarios for maintenance frequency based on the average total breakage

Sections	Worst Case	Most Likely	Best Case
Moscow	1	2	3
Clay Slurry	1	2	3
Limestone	2	3	4

Figure 86 shows BCA results based on the scenarios from average total breakage. Limestone section would be beneficial for the most likely and the best-case scenarios for all service life values. In addition, limestone had the highest BCR value among all alternatives. On the other hand, Moscow and Clay Slurry sections were beneficial only for their best case scenarios and for all their service life values. BCR values for Clay Slurry and Moscow were similar.

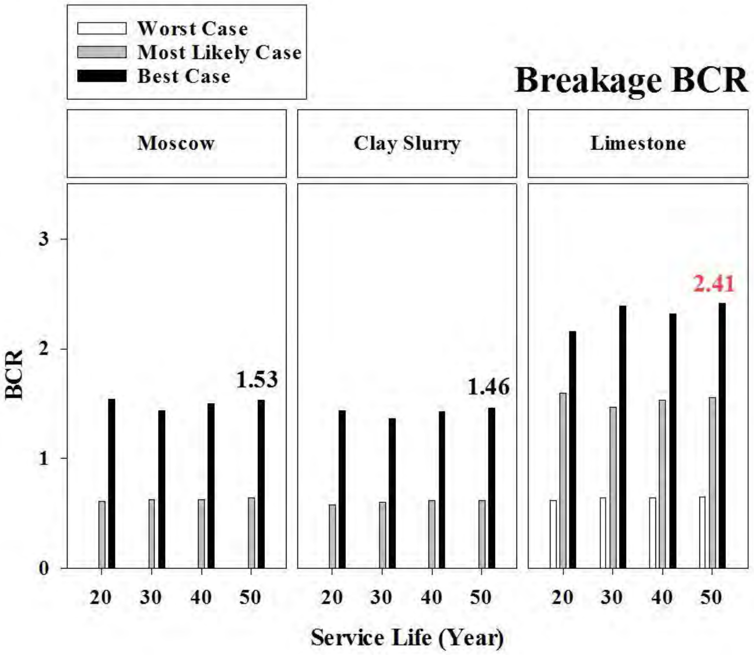


Figure 86. BCR values for average total breakage

7.6.3 Fines content

Figure 87 shows the average fines content values of the alternative test sections in Jones County. Three groups were considered to categorize the results of fines content. Clay Slurry and Limestone sections had "High" (>20%), while Moscow had "Medium" (15% to 30%) average fines content values.

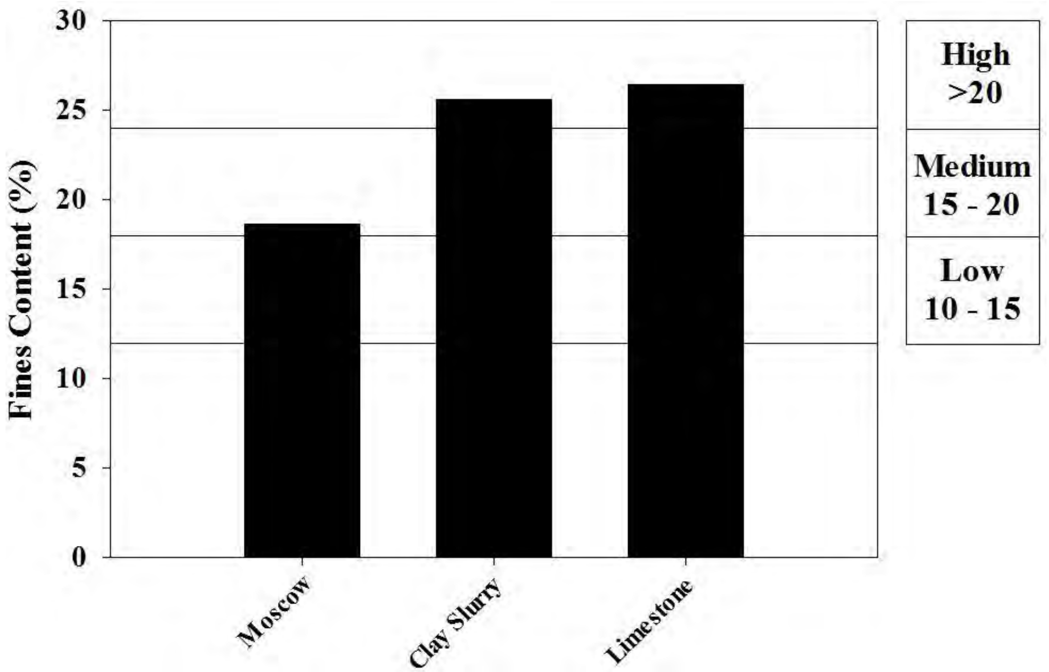


Figure 87. Average fines content values over the length of project

Table 54 shows the different scenarios based on the results of average fines content. Clay Slurry and Limestone sections with "High" average fines content, could have maintenance performed for every 1, 2, or 3 years. For Moscow section with "Medium" average fines content maintenance procedure could occur for every 2, 3, or 4 years.

Table 54. Scenarios for maintenance frequency based on the average fines content

Sections	Worst Case	Most Likely	Best Case
Moscow	2	3	4
Clay Slurry	1	2	3
Limestone	1	2	3

BCA results for average fines content scenarios are shown in **Figure 88**. Moscow section had the highest BCR values compared to the rest of the sections, where the BCR values for this section were always greater than 1 for most likely and the best case scenarios. On the other hand, Clay Slurry and Limestone sections had relatively close BCR values, where these two sections had greater BCR values than 1 for their best case scenarios and all their service life considerations. Moreover, these two sections could not be beneficial for the worst and most likely cases.

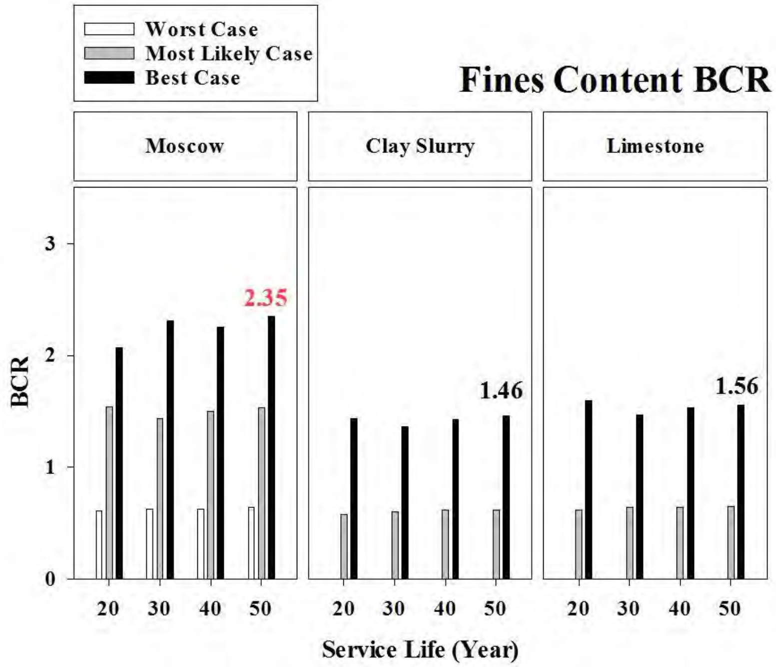


Figure 88. BCR values for average fines content

7.6.4 Gravel to sand ratio

Figure 89 shows the average gravel to sand ratio values based on the sieve analysis results on the samples collected from November 2019 and March 2020. Demonstration sections were categorized into three groups, where Moscow section had "High" (>2), and Clay Slurry and Limestone sections had "Medium" (<2 and >1) average gravel to sand ratio values.

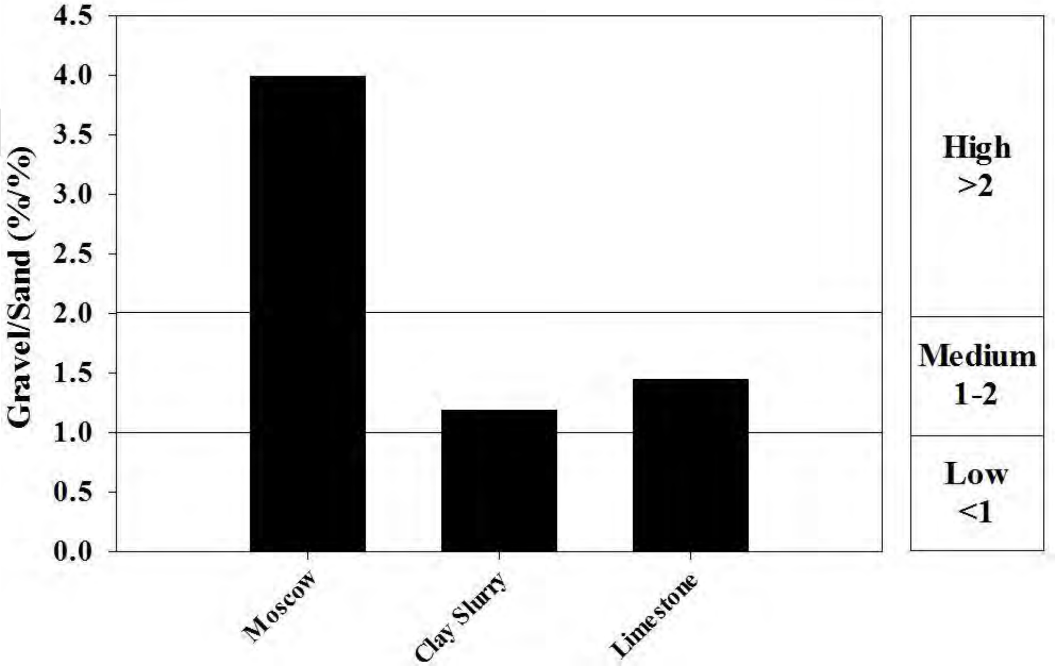


Figure 89. Average gravel to sand ratio values over the length of project

Table 55 shows the different scenarios based on the results of average gravel to sand ratio. Clay Slurry and Limestone sections with “Medium” average gravel to sand ratio, could have maintenance performed for every 2, 3, or 4 years, and Moscow section with “High” average gravel to sand ratio require maintenance less often (3,4, or 5 years).

Table 55. Scenarios for maintenance frequency based on the average gravel to sand ratio

Sections	Worst Case	Most Likely	Best Case
Moscow	3	4	5
Clay Slurry	2	3	4
Limestone	2	3	4

Figure 90 demonstrates all the BCA results for the average gravel to sand ratios. Moscow section always had BCR values greater than 1 for all maintenance scenarios and service life values. Clay Slurry and Limestone sections had almost the same BCR values, where for their most likely and the best case scenarios they had BCR values greater than 1.

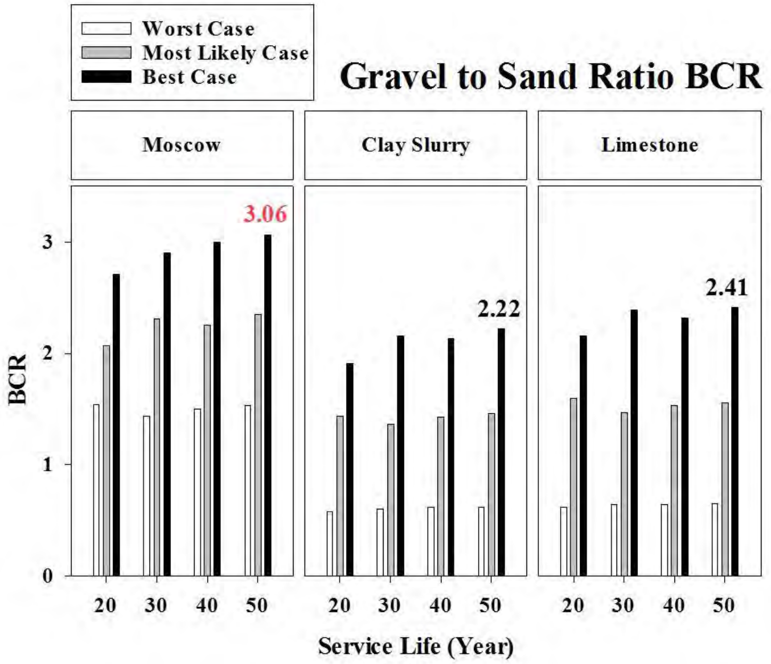


Figure 90. BCR values for average gravel to sand ratio

7.6.5 Surface elastic modulus - FWD

Figure 91 demonstrates three groups of sections based on their surface elastic modulus, where Moscow and Limestone sections had “High” (>50 ksi); while Clay Slurry section had “Medium” (25 ksi to 50 ksi) average back-calculated surface elastic modulus values.

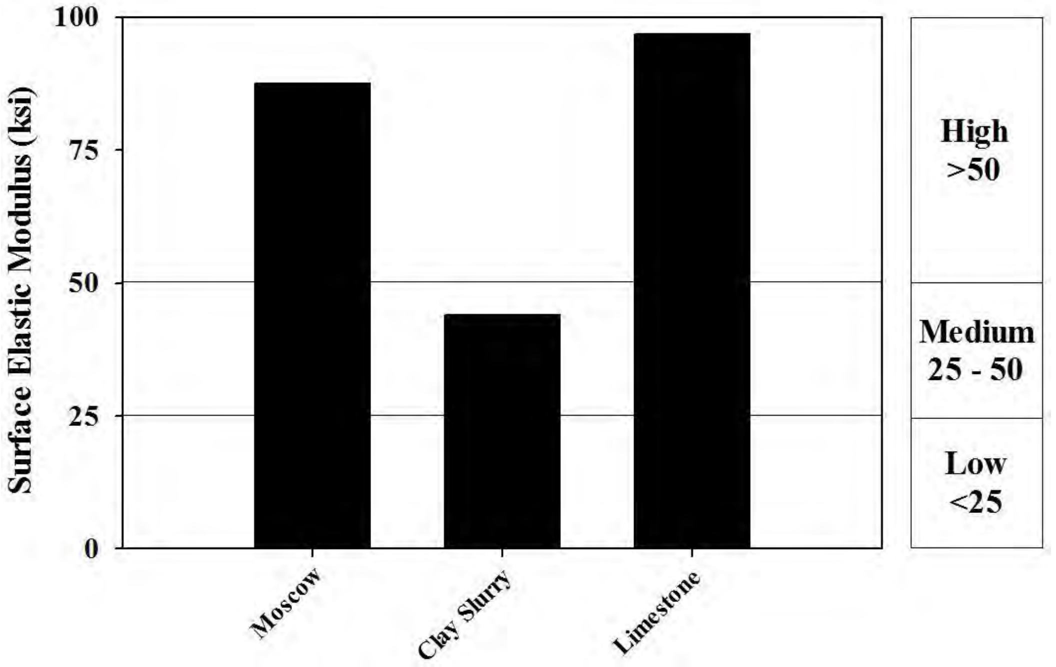


Figure 91. Average back-calculated surface elastic moduli during the project

Table 56 shows the different scenarios based on the results of average back-calculated surface elastic modulus. For Clay Slurry with "Medium" average surface elastic modulus, maintenance could be applied for every 2, 3, or 4 years, and for Moscow and Limestone sections with "High" average surface elastic modulus maintenance could be performed less often (3,4, or 5 years).

Table 56. Scenarios for maintenance frequency based on the average surface elastic modulus

Sections	Worst Case	Most Likely	Best Case
Moscow	3	4	5
Clay Slurry	2	3	4
Limestone	3	4	5

Figure 92 shows the results of BCA based on the back-calculated surface elastic modulus. Moscow and Limestone sections were always beneficial to use compared to the "Base Case – control section" with BCR greater than 1 for all scenarios and service life values. Limestone had the highest BCR (3.16) among all these sections. On the other hand, Clay Slurry section had always BCR values greater than 1 for most likely and the best case maintenance scenarios and all service life values.

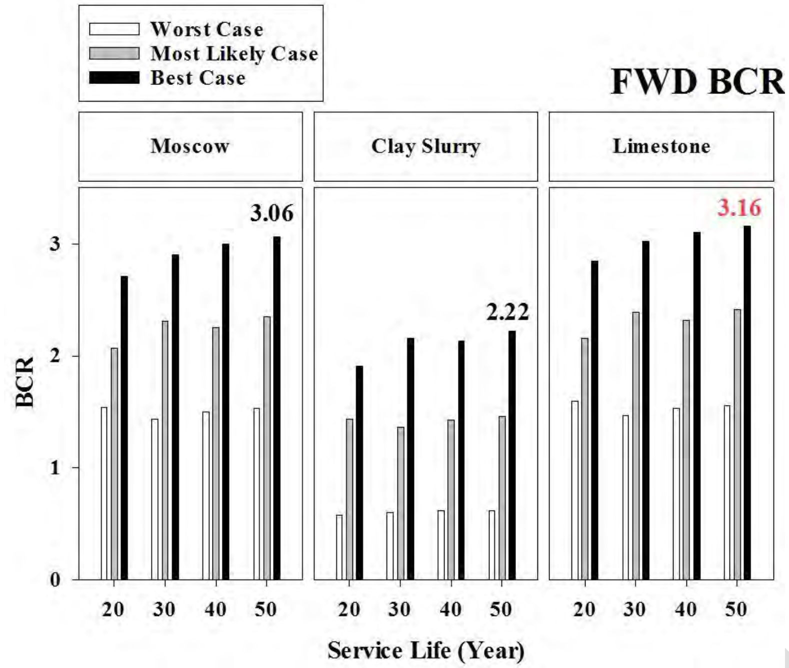


Figure 92. BCR values for average back-calculated surface elastic modulus

7.6.6 Surface shear strength - DCP

Figure 93 shows the surface shear strength of all sections as a result of DCP test. Test sections then were categorized into three groups where Moscow had "High" (>80%); and Clay Slurry and Limestone had "Low" (below 40%) average surface shear strength.

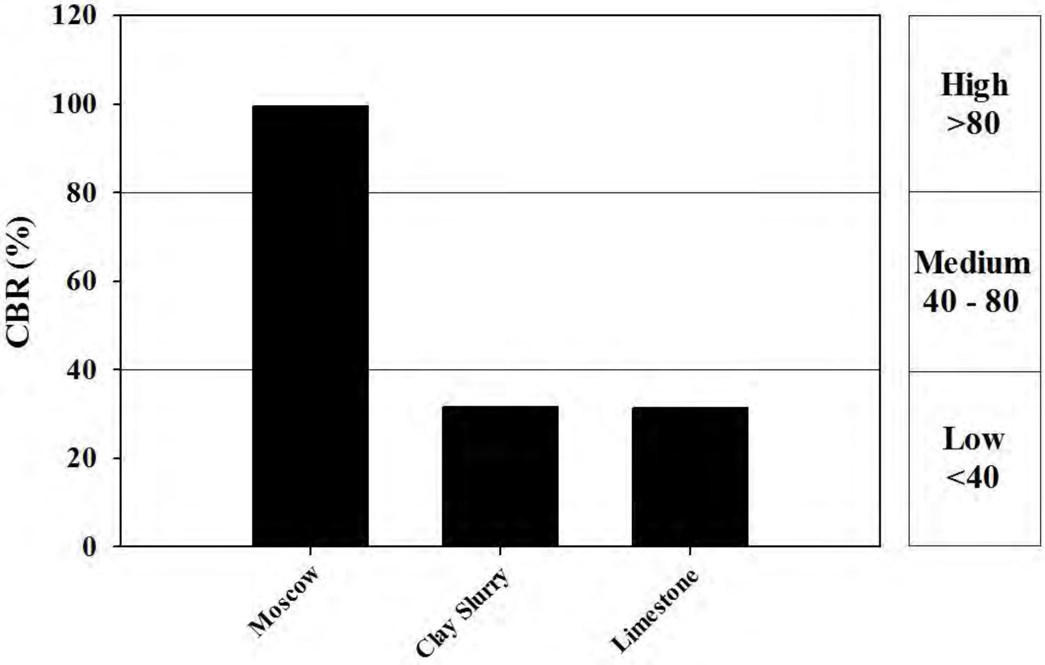


Figure 93. Average surface shear strength values over the length of project

Table 57 summarizes different maintenance scenarios based on the results of average surface shear strength. Moscow with "High" average surface shear strength, could have maintenance procedure for every 3, 4, or 5 years, while Clay Slurry and Limestone sections with “Low” average surface shear strength could have maintenance for every 1, 2, or 3 years.

Table 57. Scenarios for maintenance frequency based on the average surface shear strength

Sections	Worst Case	Most Likely	Best Case
Moscow	3	4	5
Clay Slurry	1	2	3
Limestone	1	2	3

Figure 94 summarizes the BCA results for all the maintenance scenarios based on average surface shear strength. BCR values for Moscow section were always greater than 1 for all maintenance scenarios and all service life values. Clay Slurry and Limestone sections were the other sections that could be beneficial to be considered rather than the control section with BCR values greater than 1 for the best case scenarios and for all service life considerations.

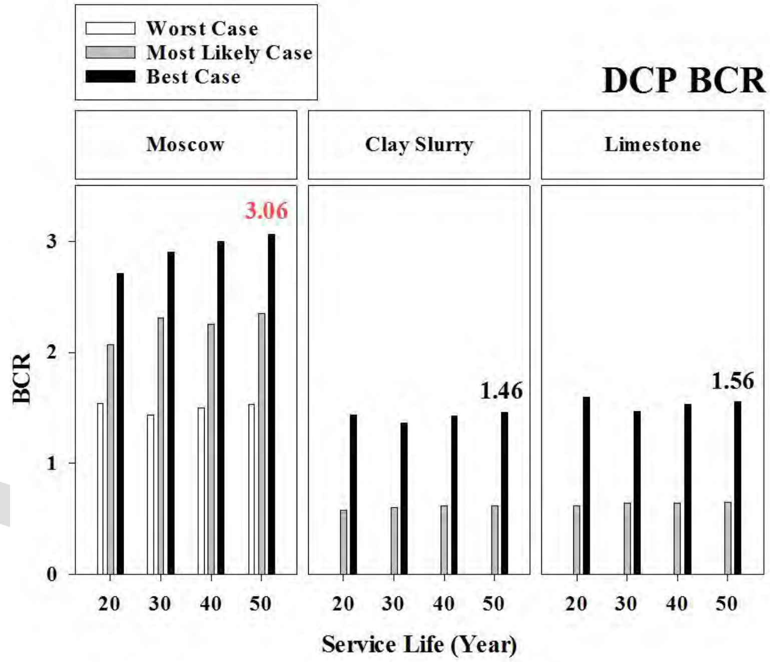


Figure 94. BCR values for average surface shear strength

7.6.7 Dust production – dustometer

Figure 95 compares dust emission values for all alternative sections. Three different groups were selected for the alternative sections, where Moscow section had “High” (>4.5 E-3lb/mile); and Clay Slurry and Limestone sections had “Low” (<3 E-3lb/mile) average dust emission.

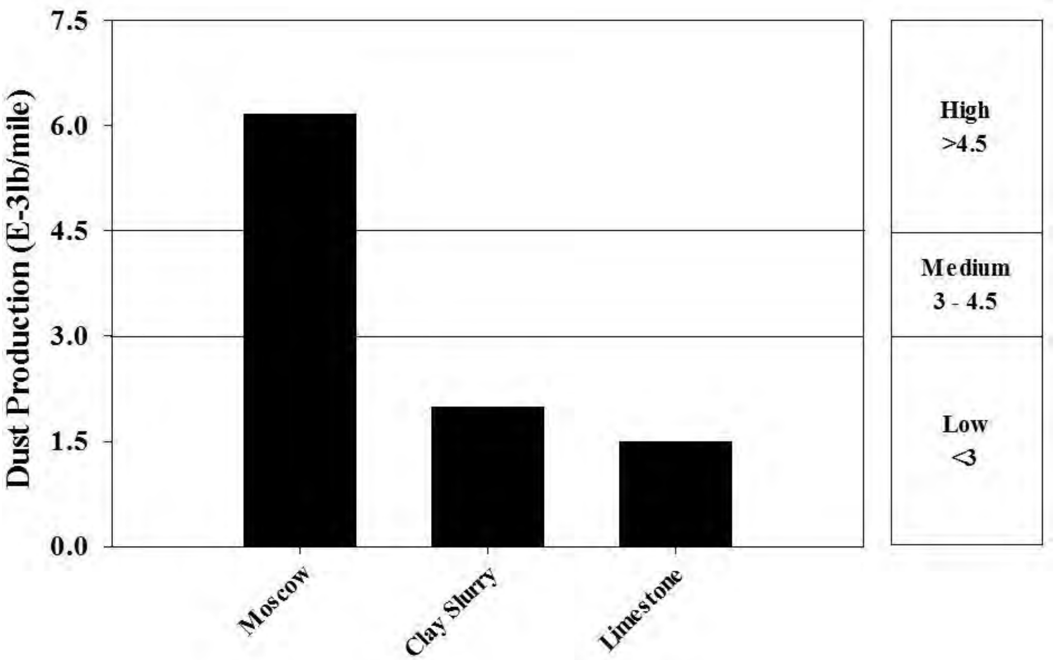


Figure 95. Average dust production over the length of project

Table 58 shows the different maintenance scenarios for the results of average dust emission. Clay Slurry and Limestone with "Low" average dust emission, could have maintenance for every 3, 4, or 5 years, and Moscow sections with "High" average dust emission could have higher maintenance frequency (1, 2, or 3 years) than the others.

Table 58. Scenarios for maintenance frequency based on the average dust production

Sections	Worst Case	Most Likely	Best Case
Moscow	1	2	3
Clay Slurry	3	4	5
Limestone	3	4	5

Figure 96 summarizes the results of BCA for all scenarios of average dust emission. Clay Slurry and Limestone sections could be beneficial as an alternative for their best-case scenarios and for all their service life values. However, Limestone had the highest BCR compared to the rest of the sections. Moscow section had the lowest BCR among all sections, where this section was only beneficial for its best case maintenance scenario.

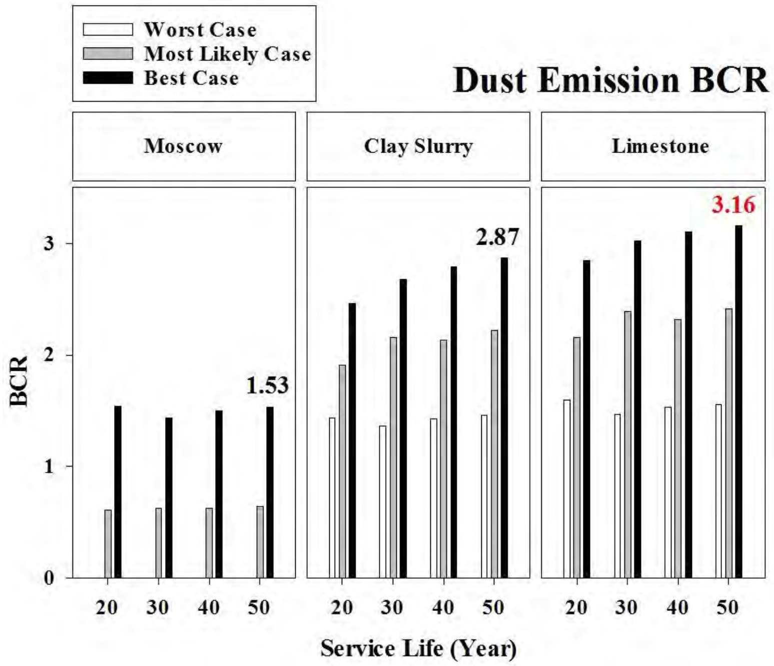


Figure 96. BCR values for average dust emission

7.6.8 Surface roughness – IRI

Surface roughness or ride quality as a result of IRI test is an indicator of serviceability of the roads. In this study all sections had Fair conditions for their ride qualities (**Figure 97**). However, they had different construction costs and the BCR for the same maintenance scenarios were evaluated to investigate their benefits as an alternative to the control section.

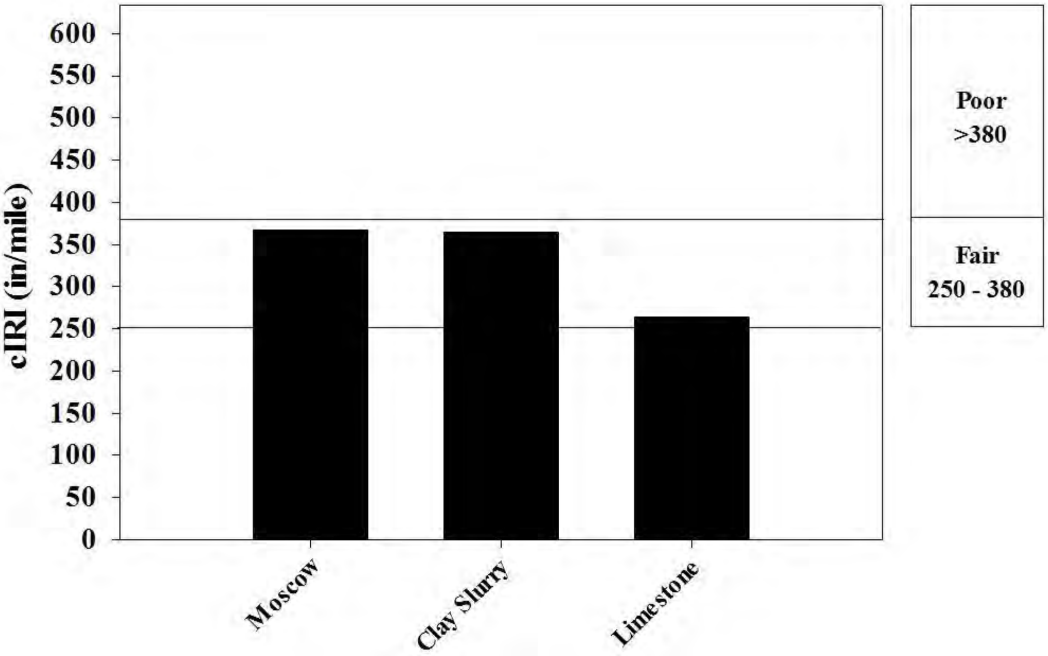


Figure 97. Average surface roughness (cIRI) over the length of project

Table 59 shows the different scenarios based on the results of average dust production. All sections had Fair conditions and their maintenance frequency values for different scenarios were between 2 (worst case), 3 (most likely case), and 4 (best case) years.

Table 59. Scenarios for maintenance frequency based on the average ride quality

Sections	Worst Case	Most Likely	Best Case
Moscow	2	3	4
Clay Slurry	2	3	4
Limestone	2	3	4

Figure 98 shows the summary of the results of BCA for different maintenance scenarios and service life values based on their average surface roughness conditions. Limestone, Moscow, and Clay Slurry were, respectively, the most beneficial sections for their best and most likely cases.

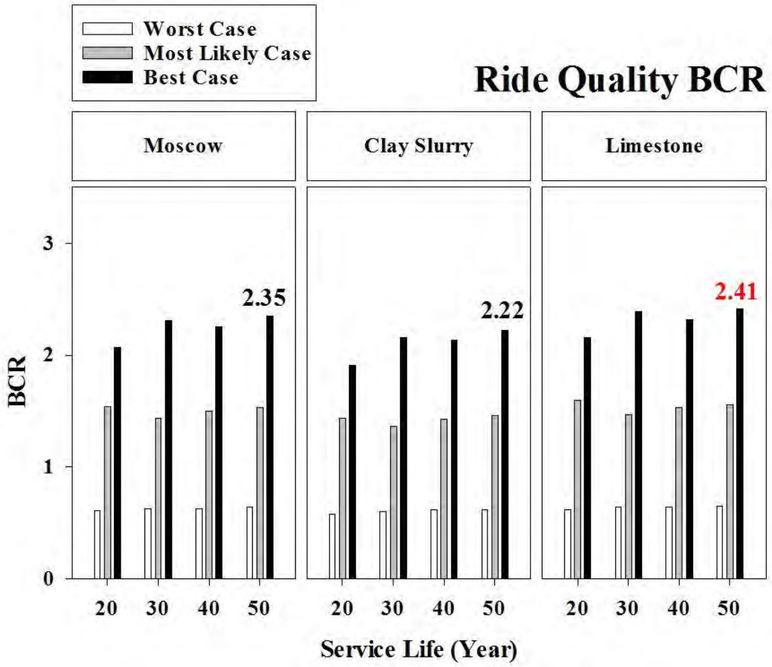


Figure 98. BCR for average ride quality conditions

7.6.9 Overall performance-based BCR values

For this analysis, the gravel content change and total breakage measures were weighted as 1, the first group (fines content, and gravel to sand ratio) was weighted as 0.75, the second group (FWD and DCP) was weighted as 0.5, and the third group (dustometer and IRI) was weighted as 0.25 (**Figure 99**).

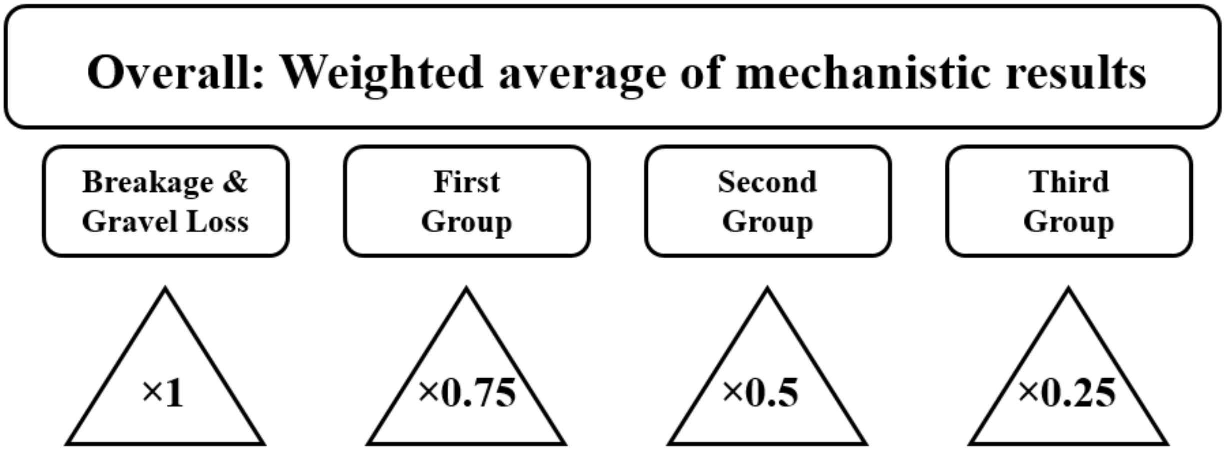


Figure 99. Weighted average of the BCR values based on the mechanical properties, total breakage and gravel loss

Figure 100 shows the BCR for average weighted values based on the performance measures for different maintenance scenarios and service life values for Jones County. Results showed that Moscow and Limestone sections, respectively, had the best BCR values and could be considered beneficial compared to the control section for their most likely, and the best-case scenarios for all different service life values. Clay Slurry section also could be beneficial only for the best-case maintenance scenario.

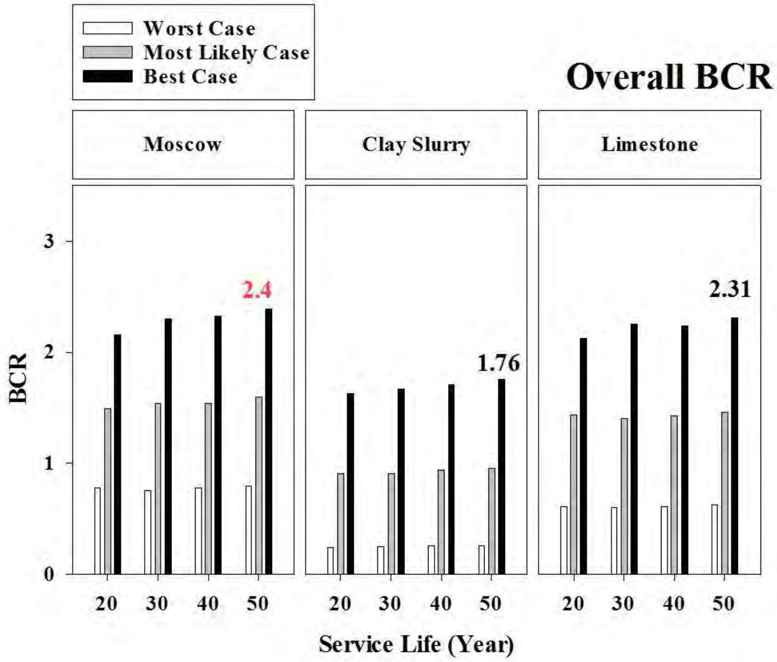


Figure 100. BCR for weighted performance measures, total breakage, and gravel content change for Jones County

CHAPTER 8. CONCLUSIONS

This chapter briefly summarizes the results of the laboratory and field tests and cost analysis for the test sections. In addition, recommendations for future studies are provided.

8.1 Field observations

Based on the observations throughout construction and field surveying over a year, it was concluded that the Ames Mine and Moscow section in Boone County and Moscow and Limestone section in Jones County had the best performances and cost-efficiency. The Clay Slurry section had the highest construction costs, and its performance, with the exception of dust emission, was average compared to the other sections in both counties.

8.2 Laboratory test results

Extensive laboratory testing, including sieve & hydrometer analysis, Atterberg limits, compaction, mini-vane shear, pocket penetrometer, slaking, and CBR tests were conducted on surface materials collected from each section.

- According to the USCS and AASHTO classification systems, all the surface aggregate materials were classified as Silty Gravel (GM) or A-1-b in Boone County and Silty Sand SM or A-1-b in Jones County, while the subgrade was classified as Sandy Silt (SM) or A-2-4 in both counties. The plasticity index (PI) values of the surface aggregates were 10 for surface materials in Boone County and 8 for Jones County. These results showed that the surface aggregates were all plastic. The plasticity index of the subgrade material was 24 for both counties.
- The results of the CBR tests showed that mixing Clay Slurry with the surface aggregates would not increase the shear strength of the mixture. However, mixing 2% of Crescent, 6% of Moscow, and 10% of Ames Mine with the Boone County surface aggregates, and mixing 2% of Limestone and 10% of Moscow with Jones County surface aggregates would increase the shear strength. These values, besides 2% of Clay Slurry, were selected as the optimum mixture in the field test section design.
- Pocket penetrometer results showed that Crescent and Moscow fines would reach the maximum penetration resistance faster than the rest of the quarry fines. Clay Slurry had the slowest rate to reach the penetration resistance.
- The results of the mini-vane shear test also showed that Crescent and Moscow's fines had the highest, and Ames Mine and Clay Slurry had the lowest shear strength values among the fines selected for this project.
- Slaking times for the surface aggregate materials from Boone County were lower than that of in Jones County. Mixing Limestone with the surface aggregates in Boone County and Crescent with the surface aggregates in Jones County significantly increased their slaking times, while mixing Clay Slurry with surface aggregates in both counties did not affect their slaking times.

8.3 Field test results

Field testing includes sample collection, LWD, dustometer, IRI, and DCP tests, which were performed once after construction and once after the first freeze-thaw period on the sections in

Boone and Jones counties. Samples collected from the sections were used for the sieve analysis and hydrometer tests to evaluate the changes in fines content, gravel to sand ratio, and breakage of the surface materials over time.

- Crescent had the lowest while Moscow and the control sections had the highest average fines contents in Boone County. Ames Mine had the highest, and Moscow had the lowest increase in the fines content in Boone County. Moscow had the lowest average fines content in Jones County, while the rest of the sections had the same average fines content in this county. The Moscow and Limestone sections had, respectively, the highest and the lowest increase in their fines content over time in Jones County.
- The Control and Moscow section had the lowest average gravel to sand ratio, while Ames Mine, Clay Slurry, and Crescent had the same average gravel-to-sand ratios in Boone County. The Control and Ames Mine had the lowest, and Crescent had the highest decrease in the gravel to the sand ratio in Boone County. Moscow had the highest gravel to sand ratio, while the rest of the sections had similar values for gravel to sand ratio in Jones County. The Control section and Moscow section, respectively, had the highest and the lowest gravel to sand ratio changes in Jones County.
- Moscow had the lowest total breakage while Ames Mine and Crescent had the highest total breakage values in Boone County. The Control section and Limestone section in Jones County had the highest and the lowest total breakage values, respectively.
- The Ames Mine, Moscow, and Clay Slurry sections had the highest while the Crescent section had the lowest average CBR values in Boone County. In Jones County, Moscow had the highest while the Limestone and Clay Slurry sections had the lowest CBR values.
- LWD test results showed that all sections in Boone and Jones counties had similar results for the composite elastic moduli. However, FWD results showed that Ames Mine had the highest while the control section had the lowest surface elastic modulus values in Boone County. The Limestone and Moscow sections had the highest while the control section and Clay Slurry had the lowest surface elastic moduli in Jones County. Subbase and subgrade elastic moduli were nearly the same for all sections in both Boone and Jones counties.
- Dustometer test results showed that Clay Slurry had the lowest while the control section had the highest dust emission in both counties.

8.4 Cost analysis results

A benefit cost analysis (BCA) was conducted based on performance measures including gravel (>U.S. #4 sieve, 0.19 in.) content change, total breakage, fines content, gravel-to-sand ratio, surface stiffness, surface shear strength, dust emission, and surface roughness, to determine the most cost-effective quarry fines options. Different maintenance scenarios were considered based on the performance of the sections for 20, 30, 40, and 50 years of service life. Finally, overall benfit cost ratio (BCR) values were calculated by assigning weighting factors to the BCR values based on the relative importance of each of the performance measure.

- Clay Slurry had the highest construction costs in both Jones and Boone counties due to the highest hauling time and material and equipment costs, while Limestone in Jones and Ames Mine in Boone counties had the lowest construction costs.

- All quarry fines in Jones County had a similar hauling time while the hauling of Clay Slurry was most costly.
- In Boone County, the Moscow section had the highest BCR for total breakage and dust emission consideration. In contrast, Ames Mine had the highest BCR for Ride quality, DCP, FWD, gravel to sand ratio, gravel content change, and fines content change. Overall, Ames Mine was the most cost-effective option in Boone County due to its lower hauling costs and performance.
- In Jones County, the Limestone section had the highest BCR for gravel content change, dust emission, total breakage, FWD, and ride quality. The Moscow section had the highest BCR values for gravel-to-sand ratio, fines content, DCP, and in overall performance measures.
- The Clay Slurry section, due to its high material, equipment, and hauling costs, could not be a cost-effective option for both counties.

RECOMMENDATIONS

Based on the observations and results of this research, the following future research activities and developments are recommended:

- Building new test sections in different regions to examine a broader range of local quarry materials, traffic loads, and subgrade conditions.
- Finding quarry fines with higher plasticity and cementitious behaviors among other quarries, and around new site locations to reduce the hauling costs.
- Mixing quarry fines with recycled materials instead of only aggregates to reduce construction costs.
- Investigating the binding effect of subgrade and subbase materials stabilized by quarry fines could help reduce the freeze-thaw effects on the sub-ground layers.
- Performing BCA on construction and maintenance of low-volume roads with different materials, stabilization methods, or other conditions.
- Investigating the effects of maintenance costs for projects related to stabilization with quarry fines, and over longer periods (five years).
- Developing statistical models to predict the performance of road layers based on the available data from granular road projects.

The results of this study showed that mixing quarry fines with surface aggregate materials could be an efficient way to reduce costs due to the binding provided with such materials, which could help gravel and thickness loss. Therefore, the required amount of materials for maintenance procedures for stabilized sections will be lower than sections with only existing surface aggregates. Moreover, hauling quarry fines from adjacent sources would decrease construction costs by reducing hauling costs. In this study, five different quarry fines were mixed with surface aggregate in two counties, and the performance of the sections was monitored. However, it would also be useful to investigate the effectiveness of mixing more quarry fines with surface aggregates in more locations, over more extended periods, and with different subgrade and subbase, weather, and traffic conditions. In this case, stabilization with quarry fines from adjacent quarries and in more counties could capture a more precise view of the efficiency of implementing quarry fines as stabilizers.

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APPENDIX A: PHOTO LOG OF GRAVEL ROAD IN BOONE AND JONES COUNTIES, IA – CONSTRUCTION AND FIELD SURVEYING

Equipment

Appendix A – Figure 1. Spray tank for Clay Slurry section, Jones County, November 2019

Appendix A – Figure 2. Water tank in Jones County

Appendix A – Figure 3. Motor grader used in Boone County

Appendix A – Figure 4. Roller used to compact the shaped surfaces in Boone County

Appendix A – Figure 5. Loader that was used for Limestone section in Jones County

Boone County, Section 1: Existing Aggregates and Ames Mine

Appendix A – Figure 6. Ames Mine section after construction in Boone County

Appendix A – Figure 7. Ames Mine section in Boone County, March 2020

Appendix A – Figure 8. Ames Mine section in Boone County, May 2020

Appendix A – Figure 9. Ames Mine section in Boone County, June 2020

Boone County, Section 2: Existing Aggregates and Moscow

Appendix A – Figure 10. Moscow section in Boone County after construction, November 2019

Appendix A – Figure 11. Moscow section in Boone County, March 2020

Appendix A – Figure 12. Moscow section in Boone County, May 2020

Appendix A – Figure 13. Moscow section in Boone County, June 2020

Boone County, Section 3: Existing Aggregates and Clay Slurry

Appendix A – Figure 14. Clay Slurry section in Boone County, one day after construction, November 2019

Appendix A – Figure 15. Clay Slurry section in Boone County, March 2020

Appendix A – Figure 16. Clay Slurry section in Boone County, May 2020

Appendix A – Figure 17. Clay Slurry section in Boone County, June 2020

Boone County, Section 4: Existing Aggregates and Crescent

Appendix A – Figure 18. Crescent section in Boone County after construction, November 2019

Appendix A – Figure 19. Crescent section in Boone County, March 2020

Appendix A – Figure 20. Crescent section in Boone County, May 2020

Appendix A – Figure 21. Crescent section in Boone County, June 2020

Boone County, Section 5: Existing Aggregates (Control Section)

Appendix A – Figure 22. Control section in Boone County, March 2020

Appendix A – Figure 23. Control section in Boone County, May 2020

Appendix A – Figure 24. Control section in Boone County, June 2020

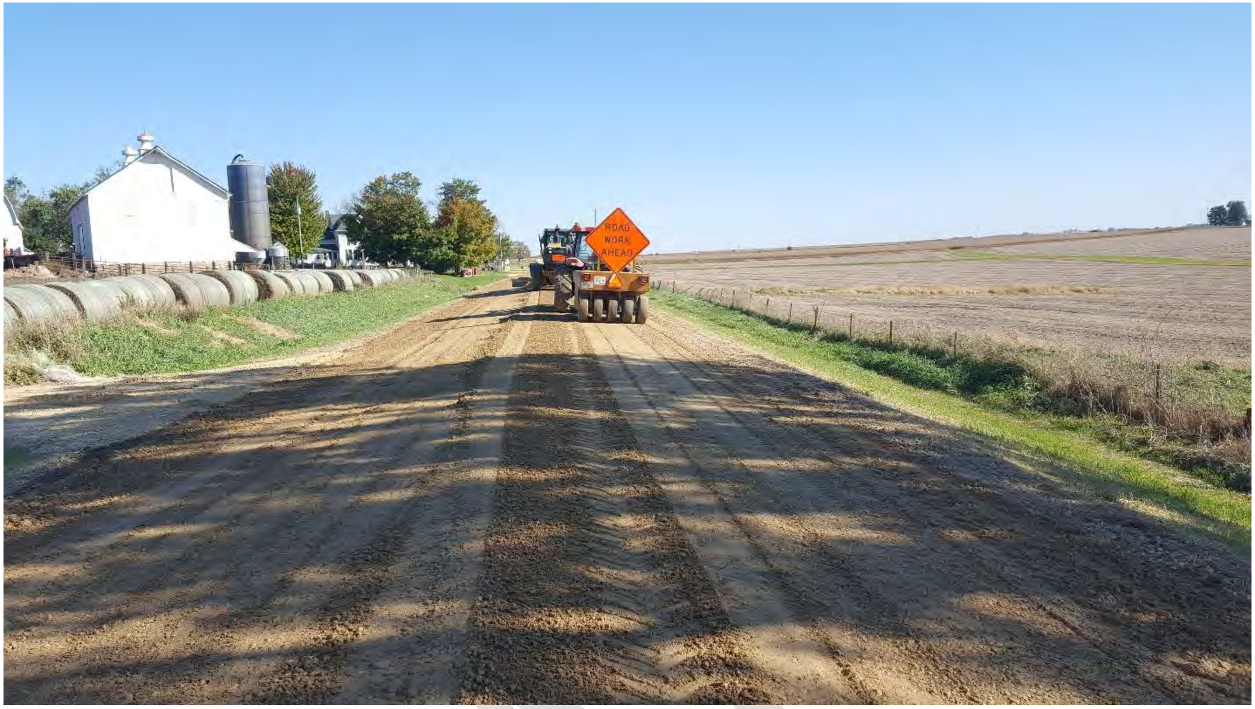
Jones County, Section 1: Existing Aggregates and Moscow

Appendix A – Figure 25. Moscow section in Jones County after construction, November 2019

Appendix A – Figure 26. Moscow section in Jones County, March 2020

Appendix A – Figure 27. Moscow section in Jones County, June 2020

Jones County, Section 2: Existing Aggregates and Clay Slurry



Appendix A – Figure 28. Clay Slurry section ion Jones County, during the construction, November 2019

Appendix A – Figure 29. Clay Slurry section in Jones County, March 2020

Appendix A – Figure 30. Clay Slurry section in Jones County, June 2020

Jones County, Section 3: Existing Aggregates and Limestone

Appendix A – Figure 31. Limestone section in Jones County after construction, November 2019


Appendix A – Figure 32. Limestone section in Jones County, March 2020

Appendix A – Figure 33. Limestone section in Jones County, June 2020

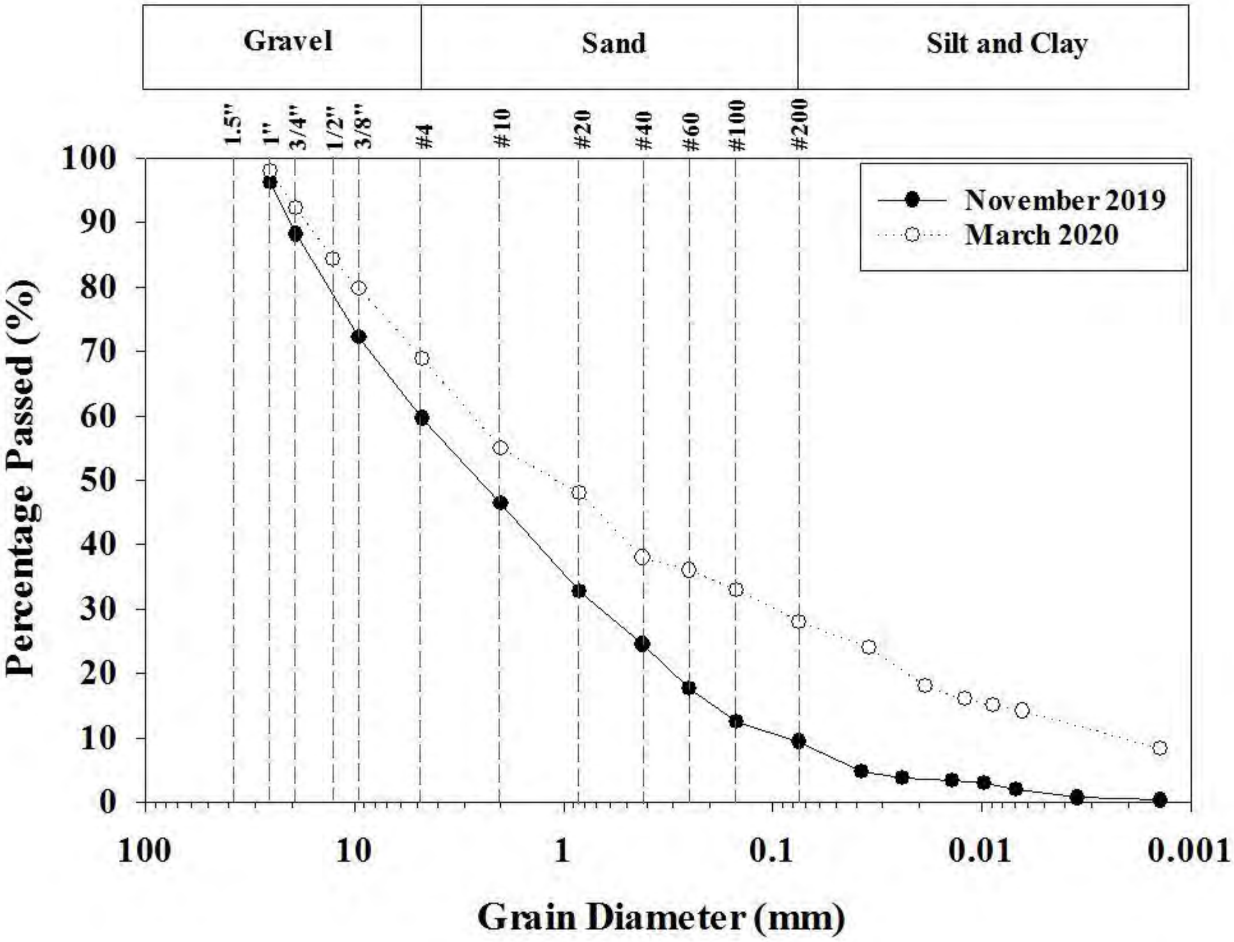
Jones County, Section 4: Existing Aggregates (Control Section)

Appendix A – Figure 34. Control section in Jones County, November 2019

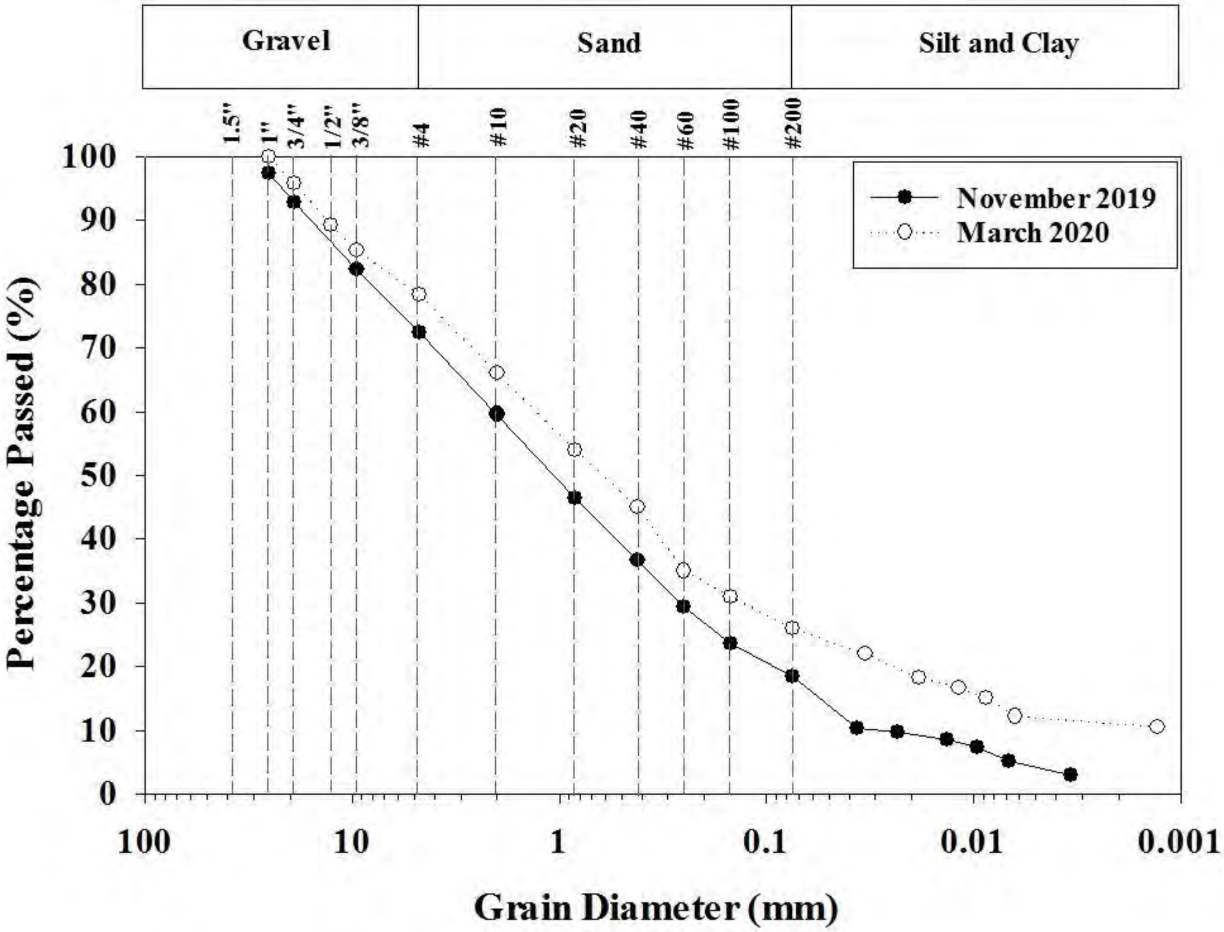
Appendix A – Figure 35. Control section in Jones County, March 2020

Appendix A – Figure 36. Control section in Jones County, June 2020

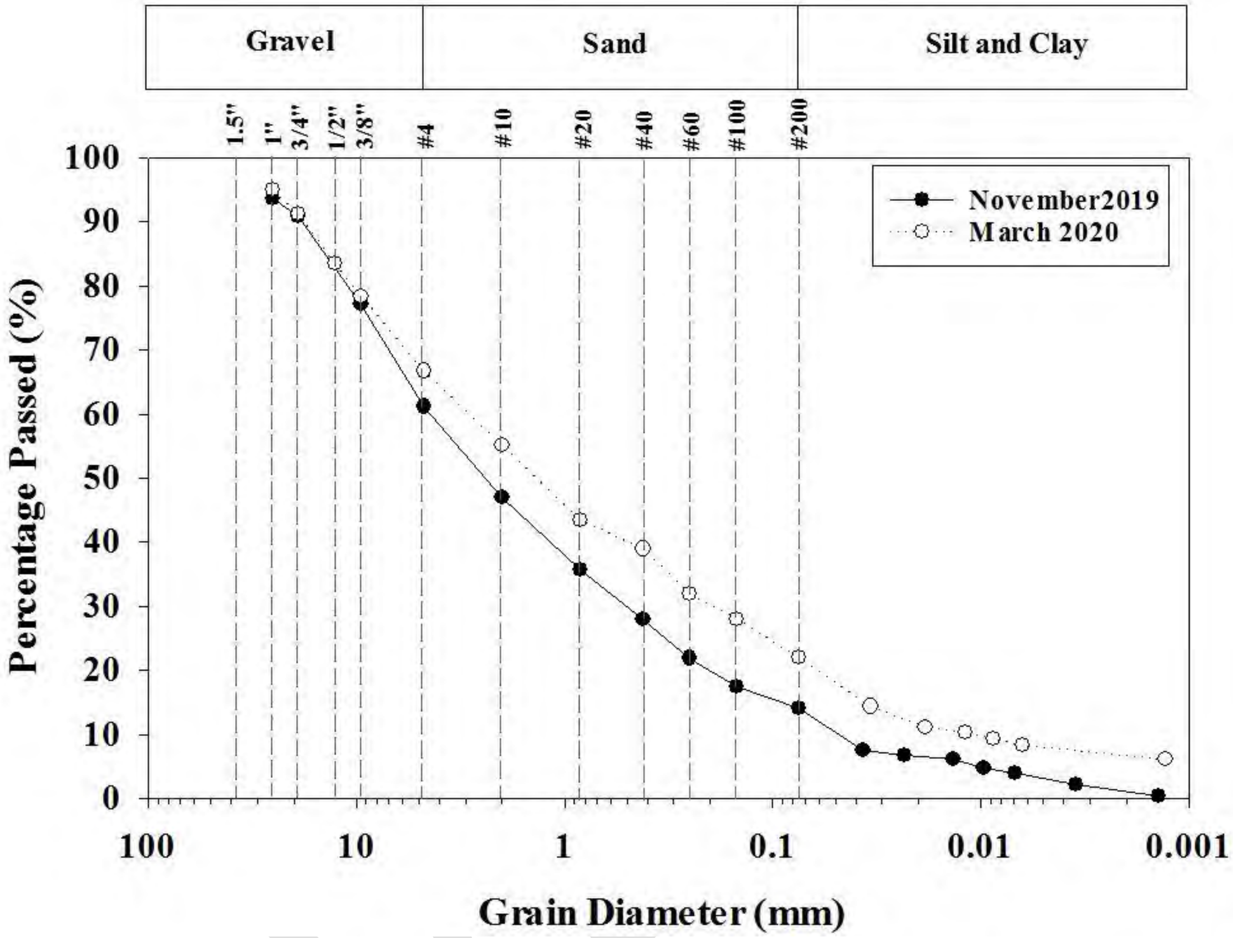
APPENDIX B: PARTICLE SIZE ANALYSIS RESULTS



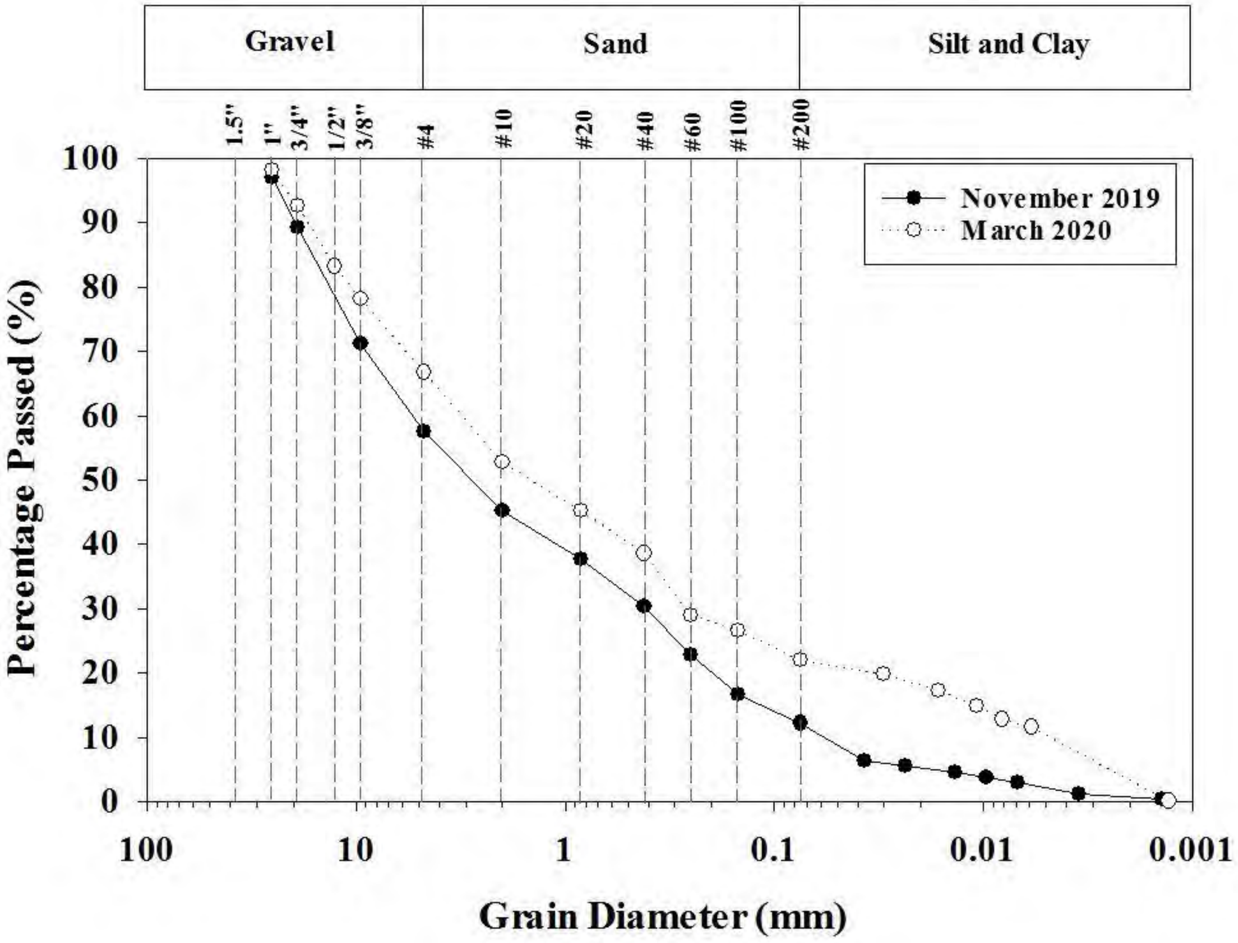
Appendix B – Figure 1. Particle size distributions of Boone county - Ames Mine section over time



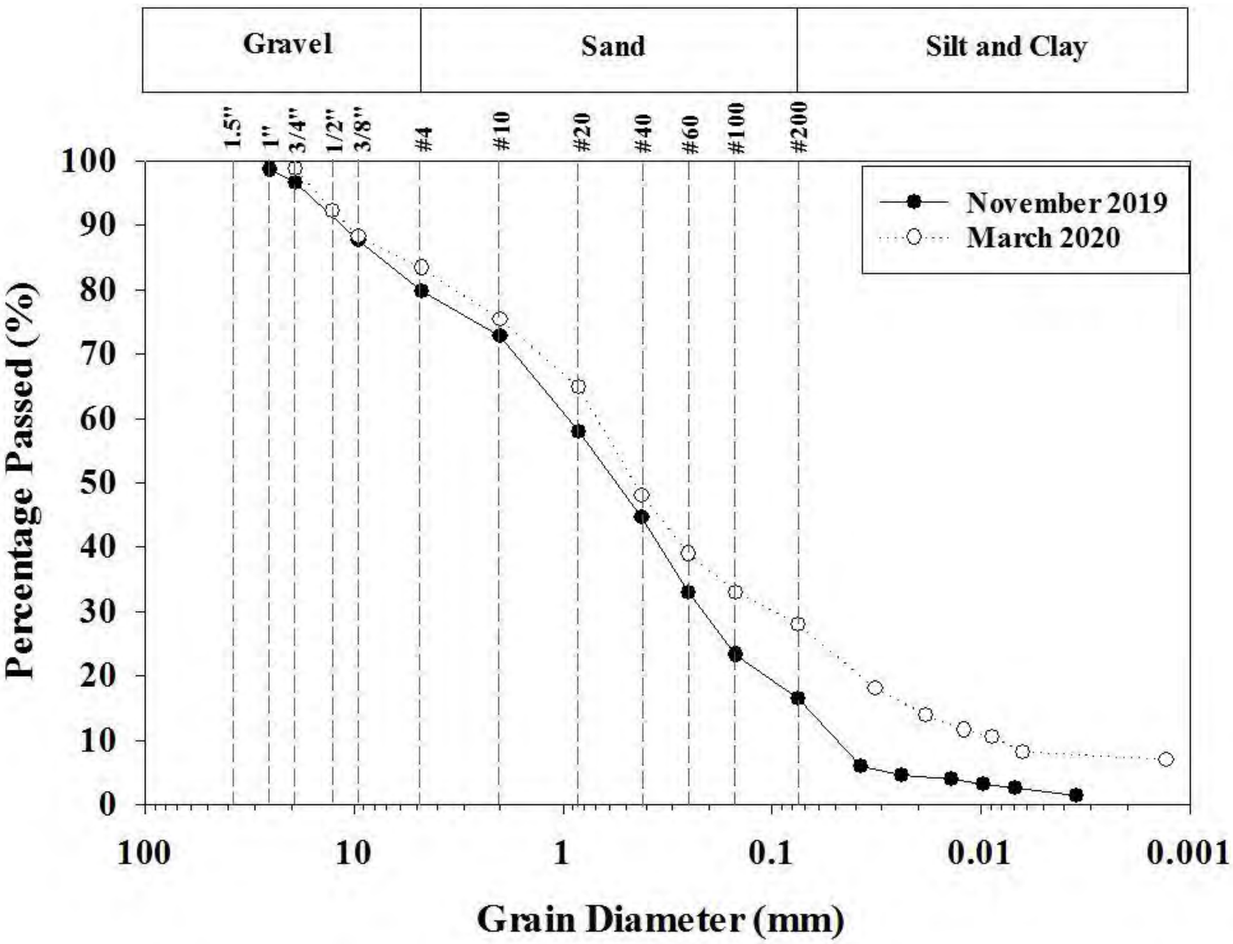
Appendix B – Figure 2. Particle size distributions of Boone county - Moscow section over time



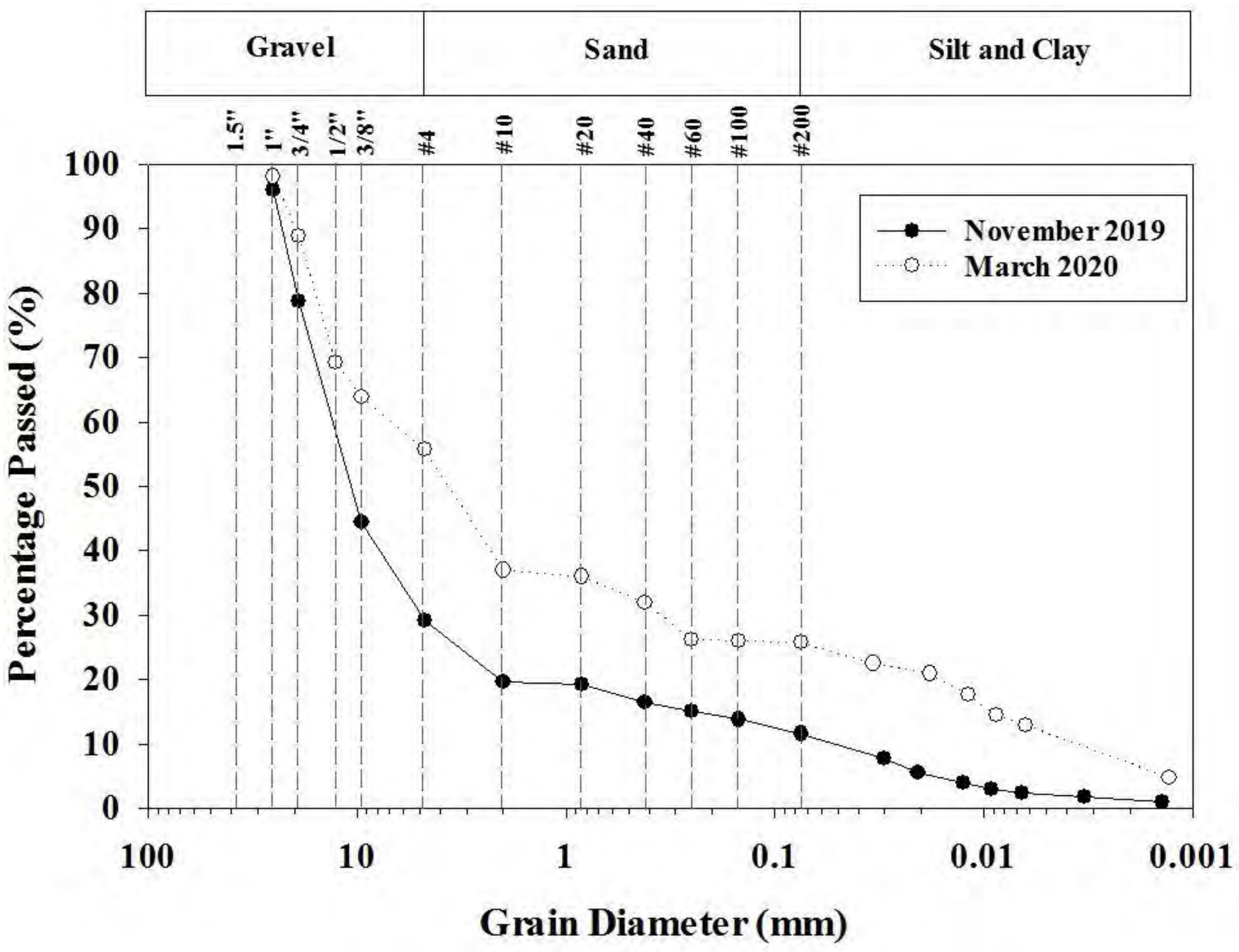
Appendix B – Figure 3. Particle size distributions of Boone County – Clay Slurry section over time



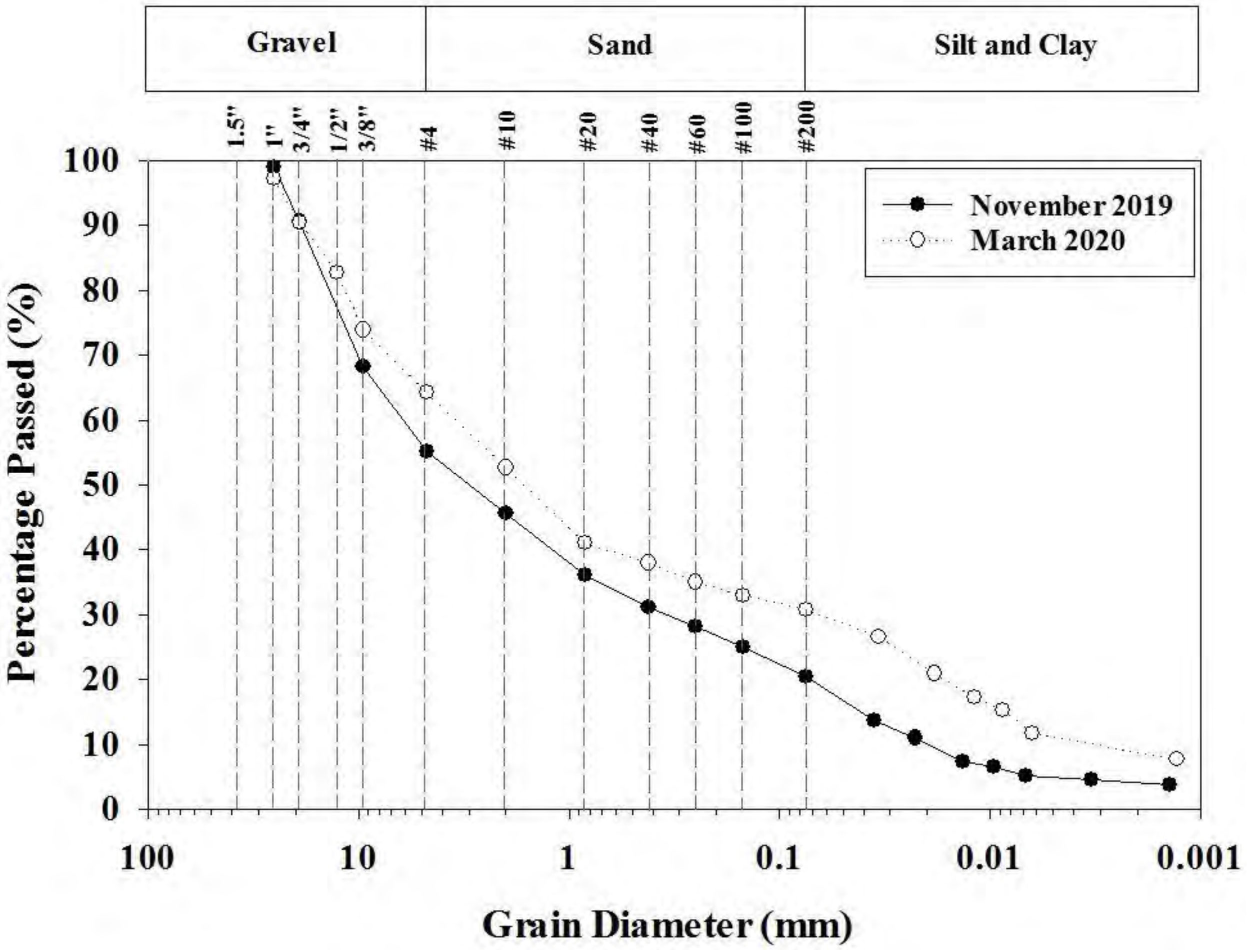
Appendix B – Figure 4. Particle size distributions of Boone County – Crescent section over time



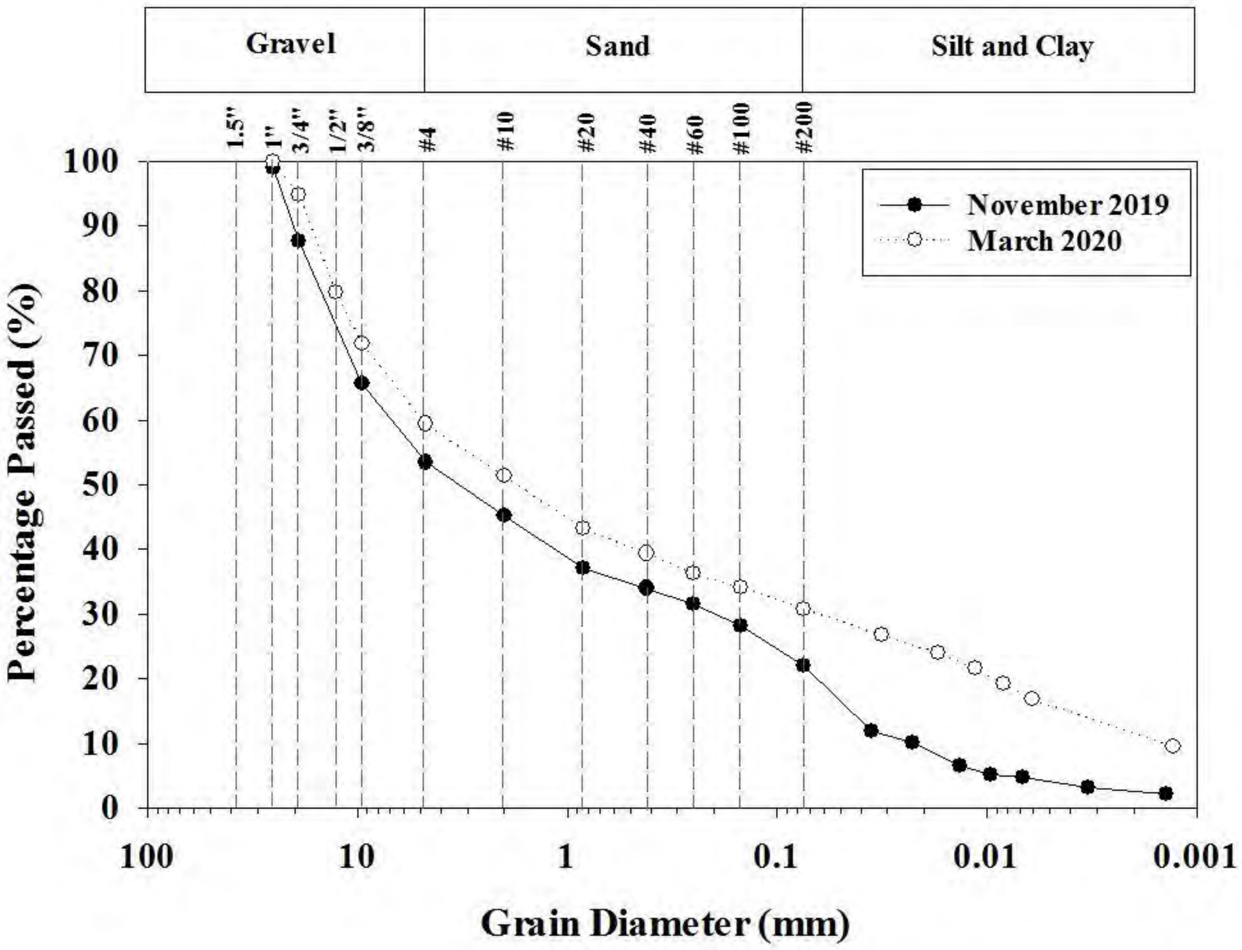
Appendix B – Figure 5. Particle size distributions of Boone County – Control section over time



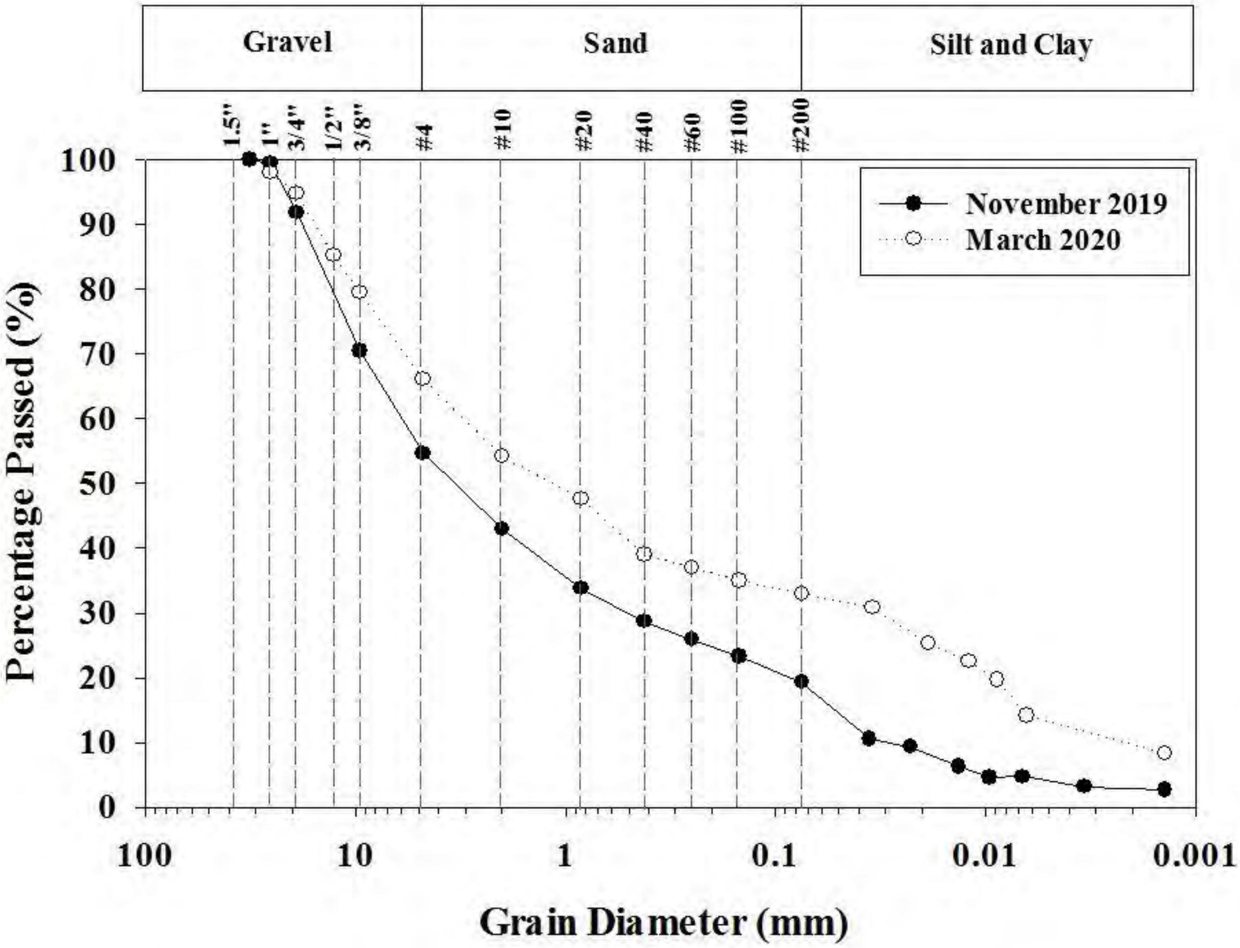
Appendix B – Figure 6. Particle size distributions of Jones County – Moscow section over time



Appendix B – Figure 7. Particle size distributions of Jones County – Clay Slurry section over time

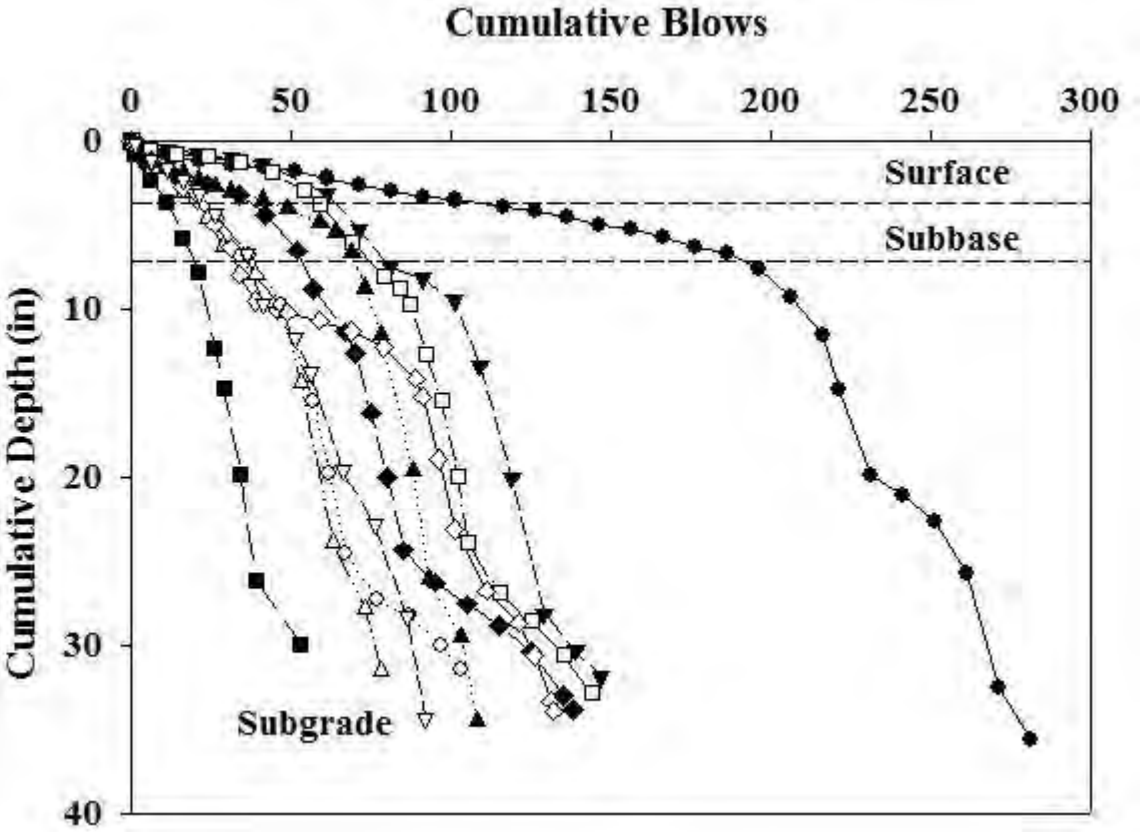


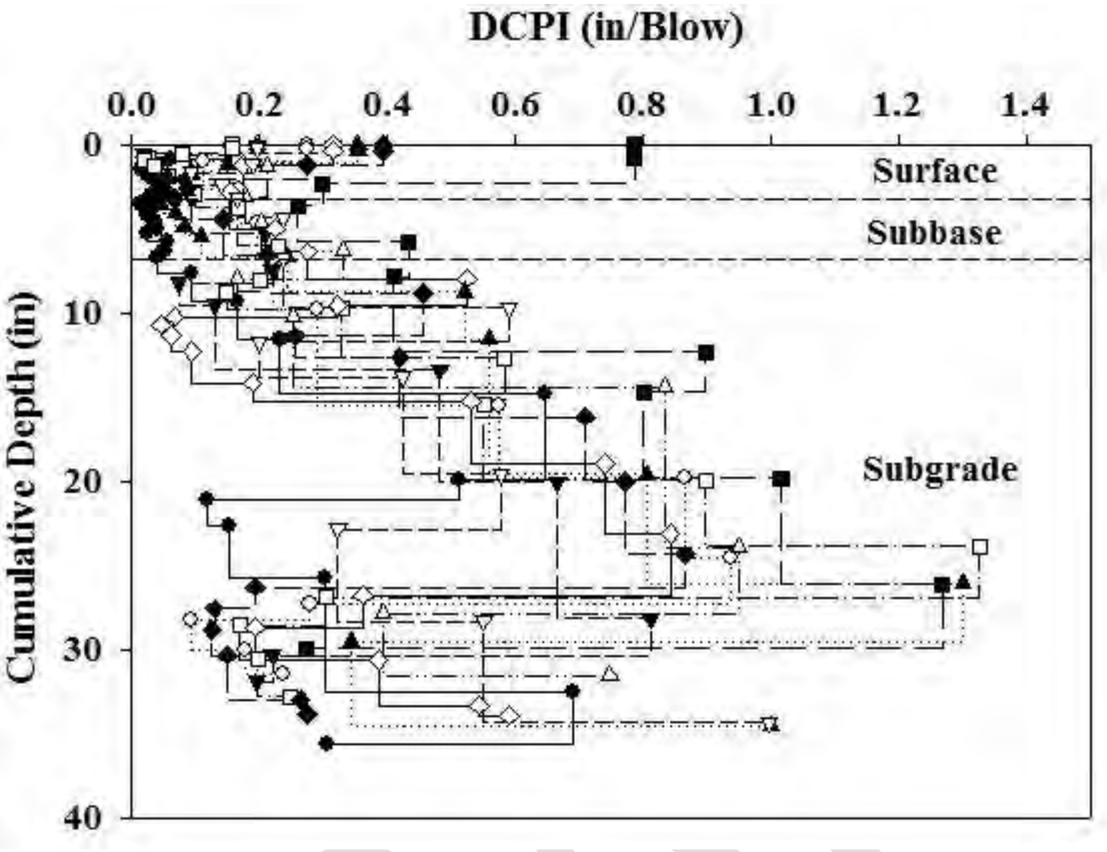
Appendix B – Figure 8. Particle size distributions of Jones County – Limestone section over time

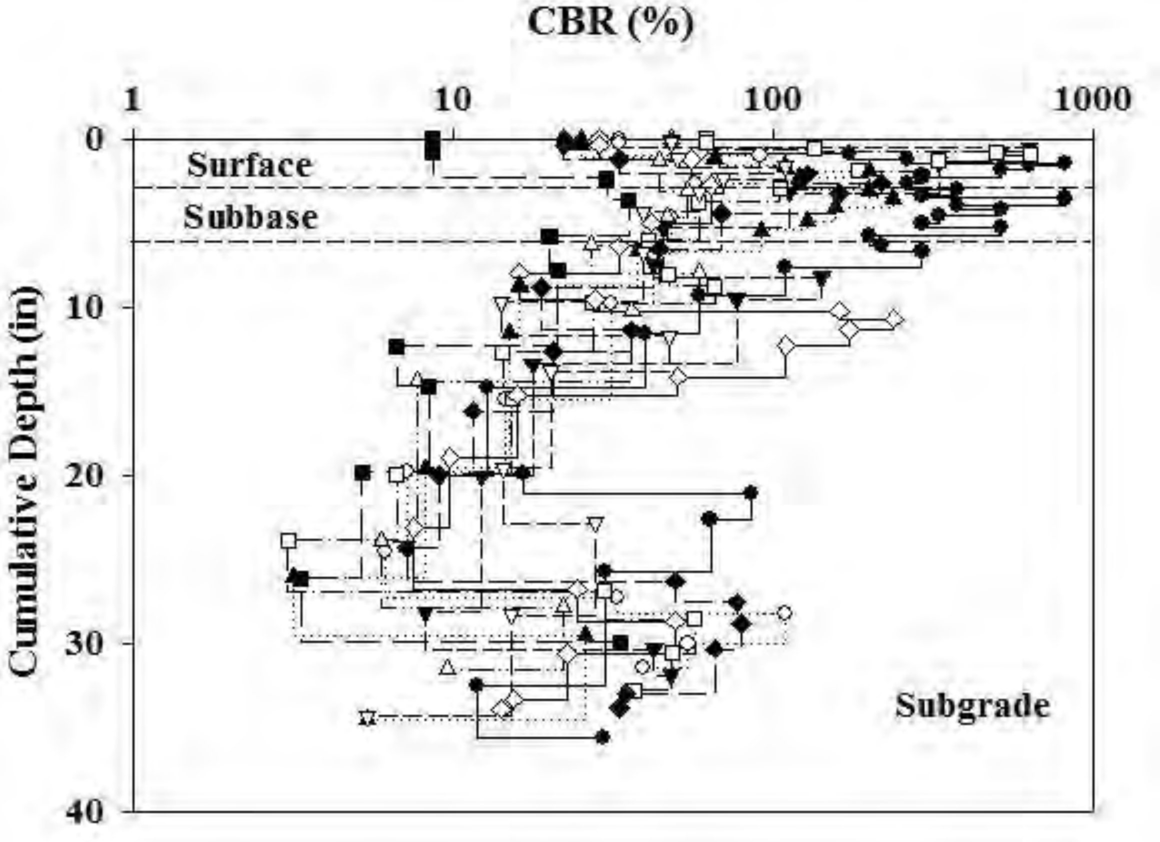


Appendix B – Figure 8. Particle size distributions of Jones County – Control section over time

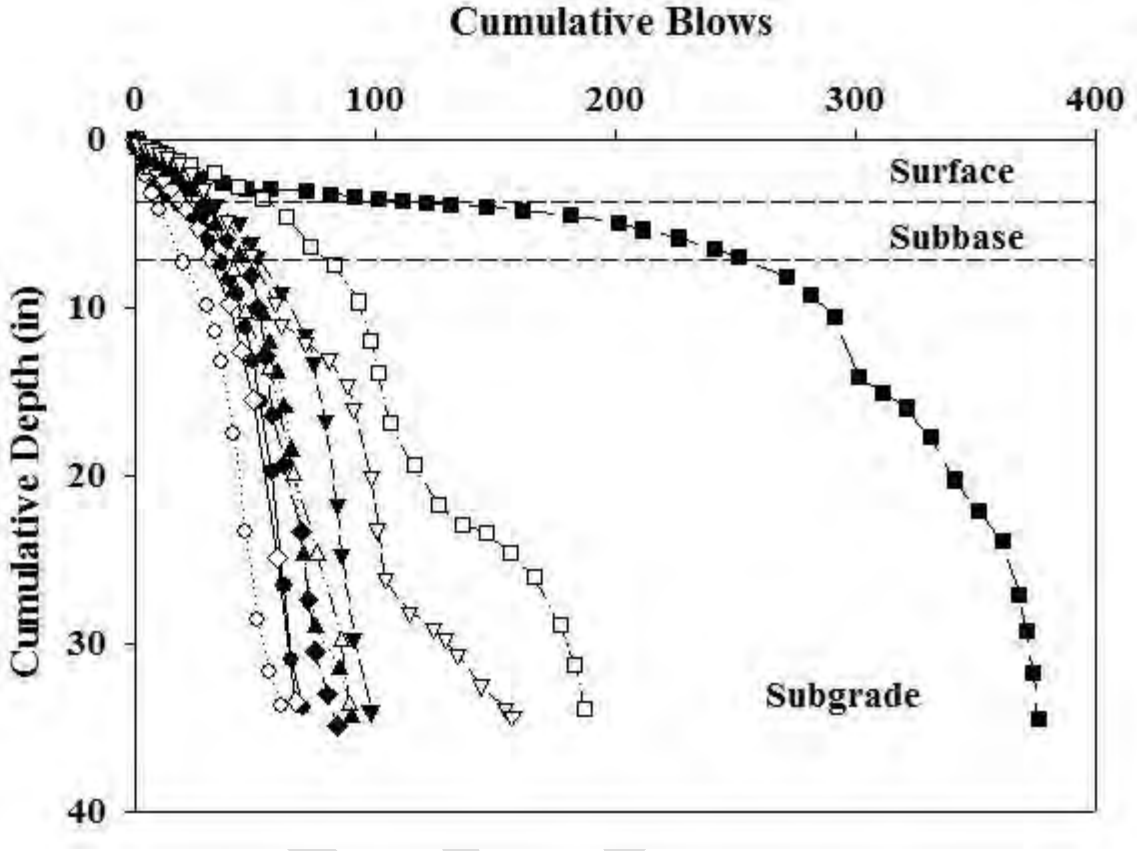
APPENDIX C: DCP TEST RESULTS

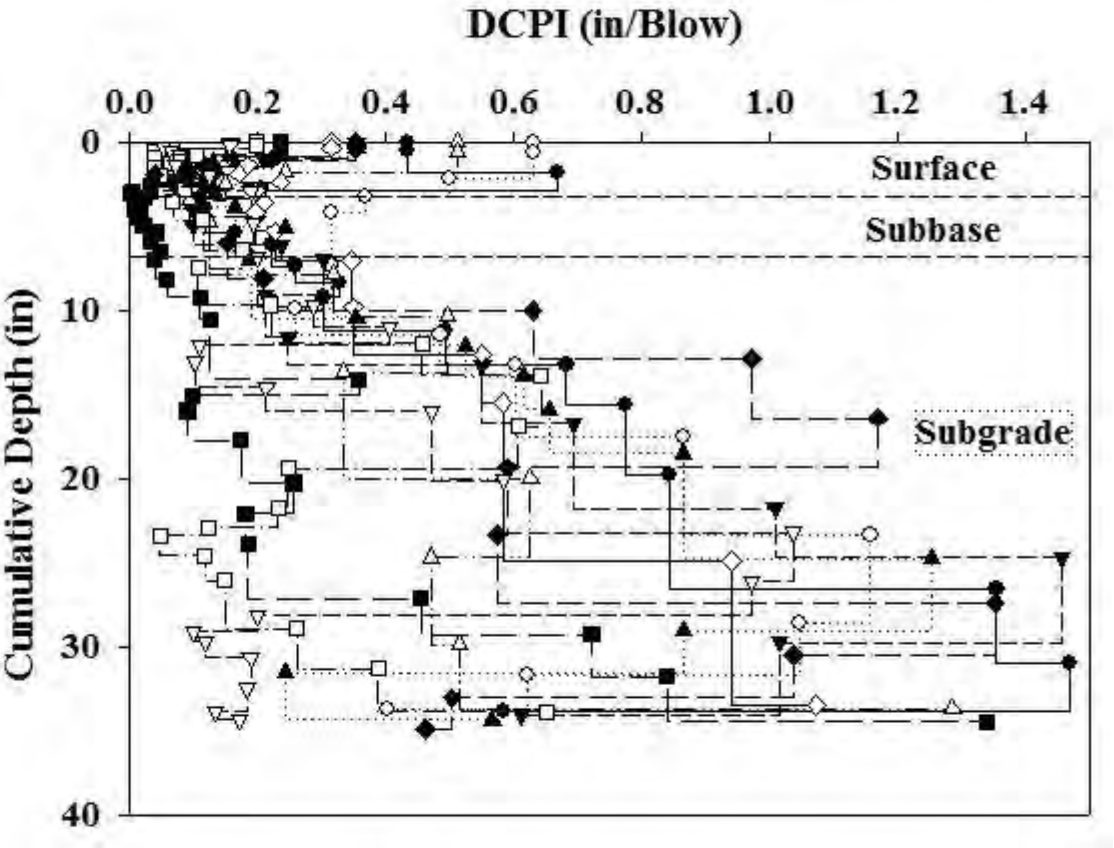


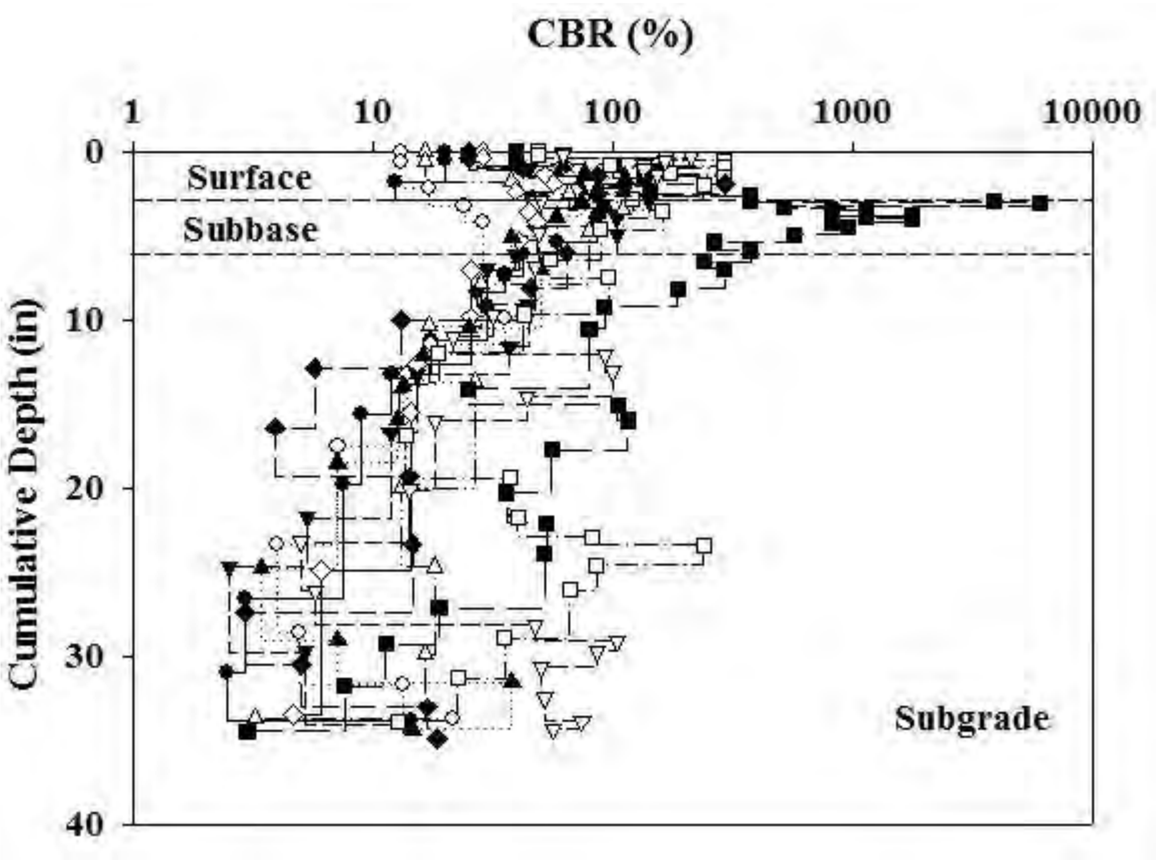

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
10
20
30
40
Cumulative Depth (in)
Surface
Subbase
Subgrade


CBR (%)
1
10
100
1000
0
10
20
30
40
Cumulative Depth (in)
Surface
Subbase
Subgrade

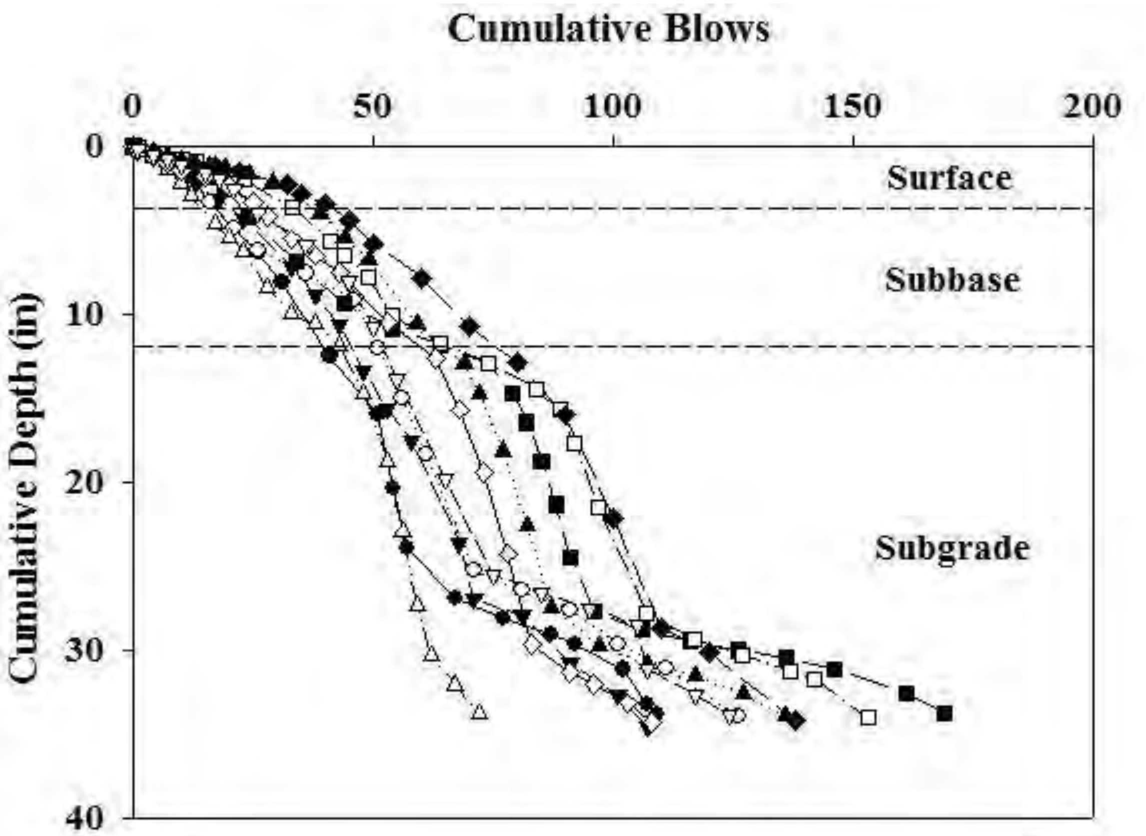
Appendix C – Figure 1. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Boone County – Section 1 (Ames Mine)

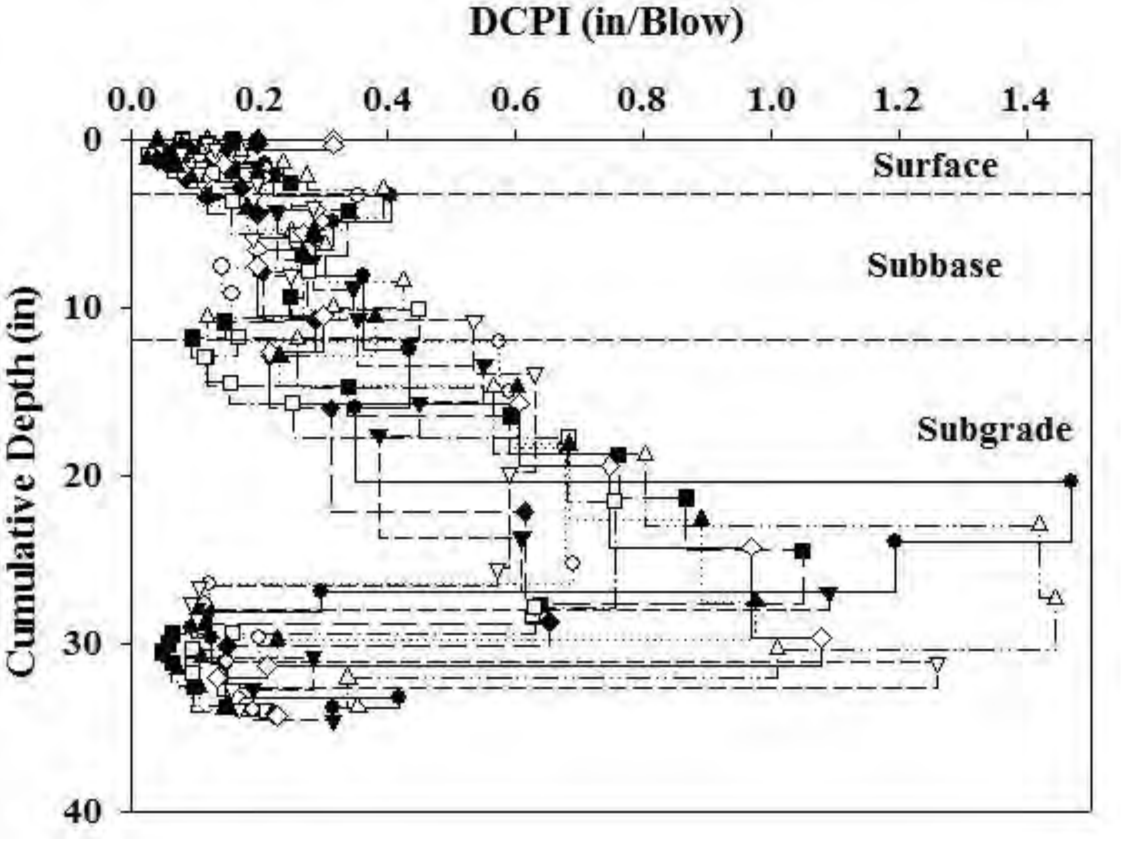


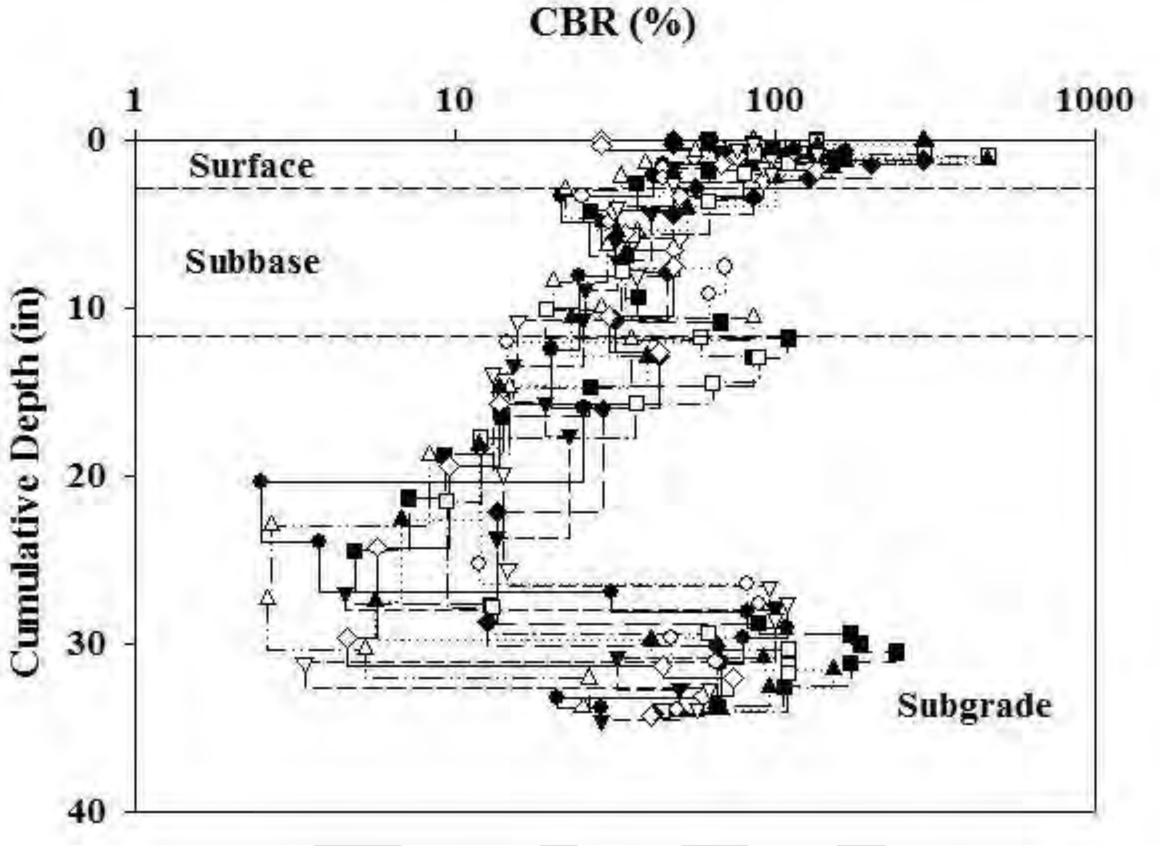

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade



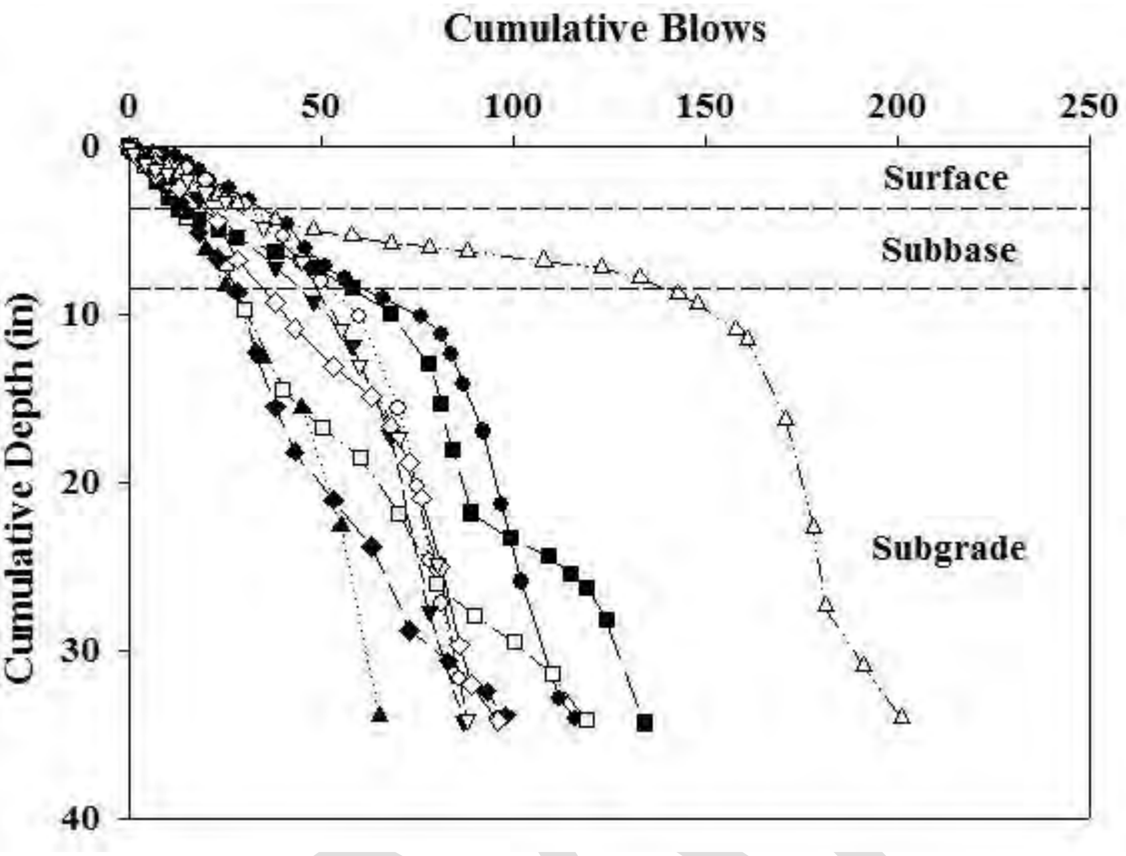
Appendix C – Figure 2. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Boone County – Section 2 (Moscow)

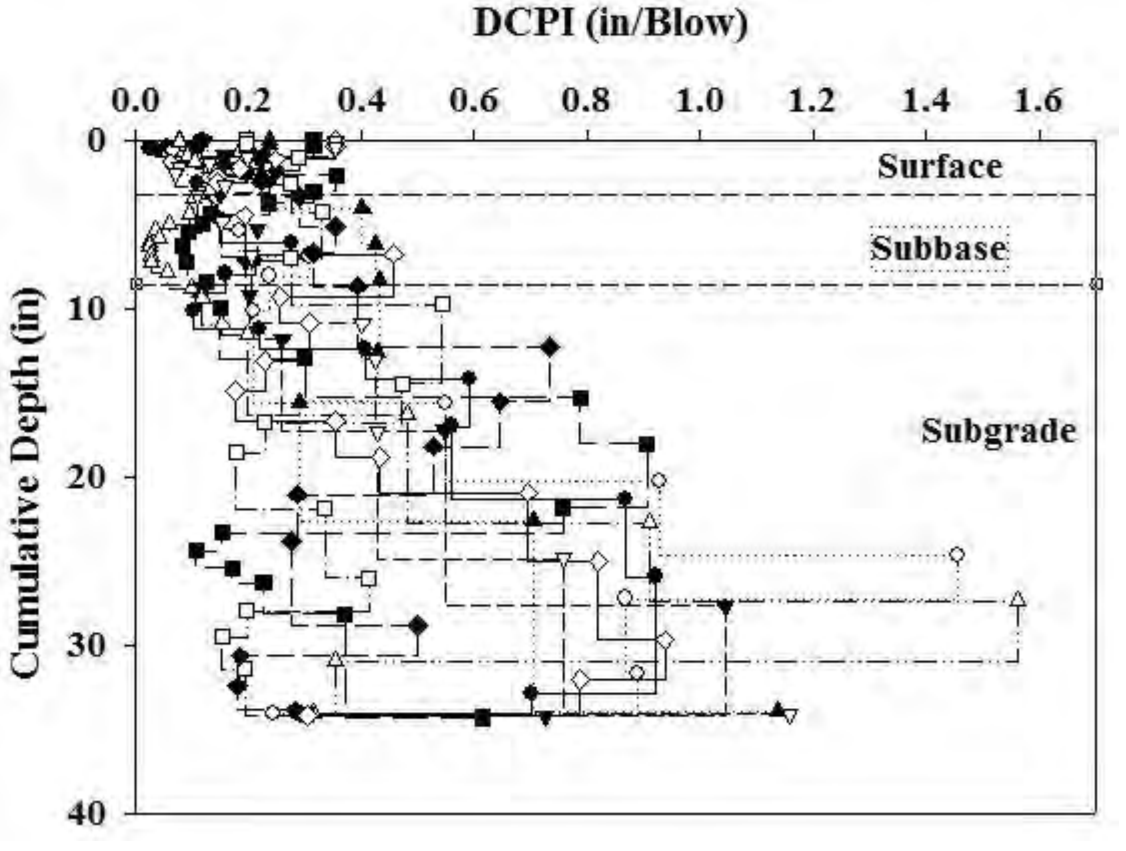

Cumulative Blows
0
50
100
150
200
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade

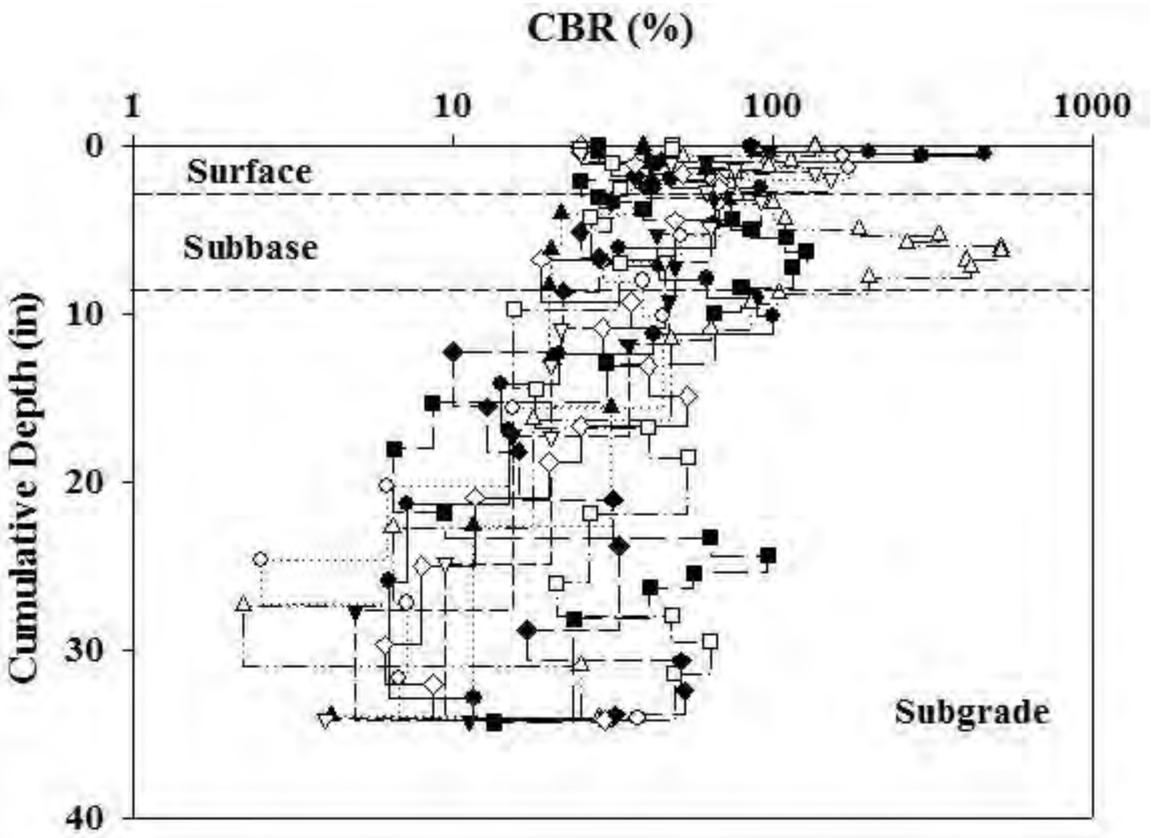

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade



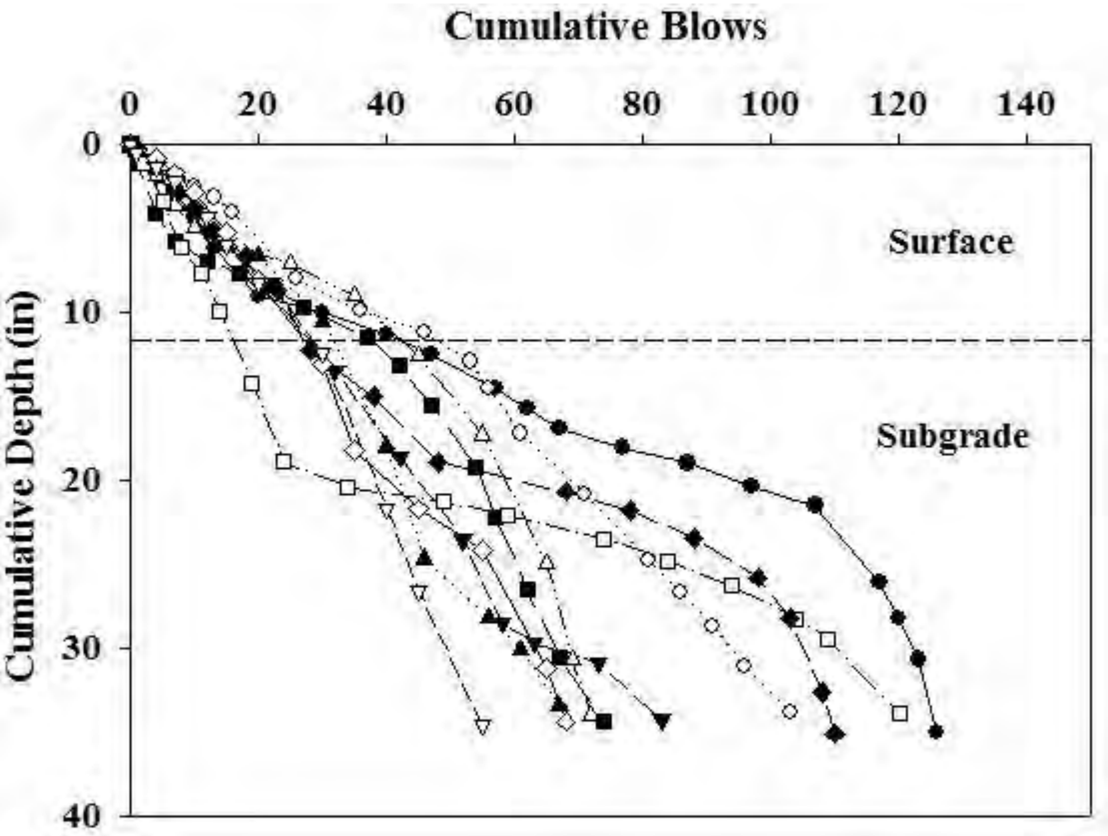
Appendix C – Figure 3. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Boone County – Section 3 (Clay Slurry)

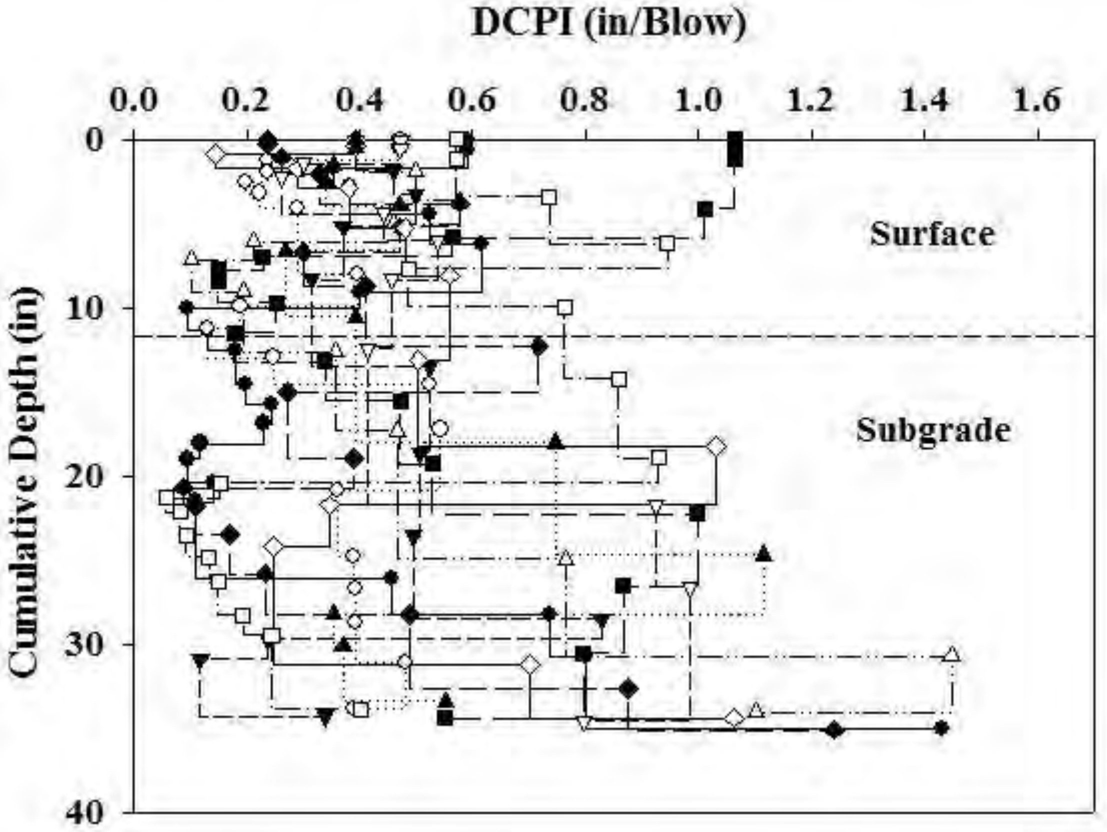

Cumulative Blows
0
50
100
150
200
250
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade

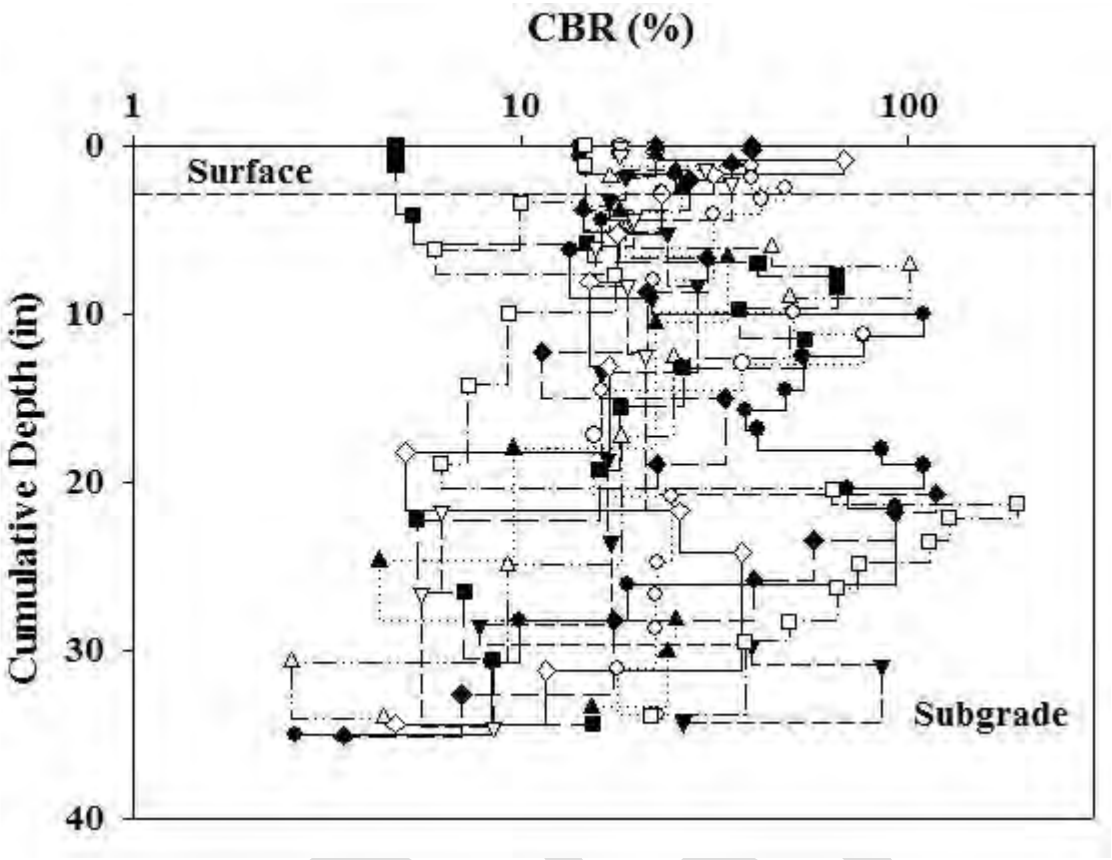

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade



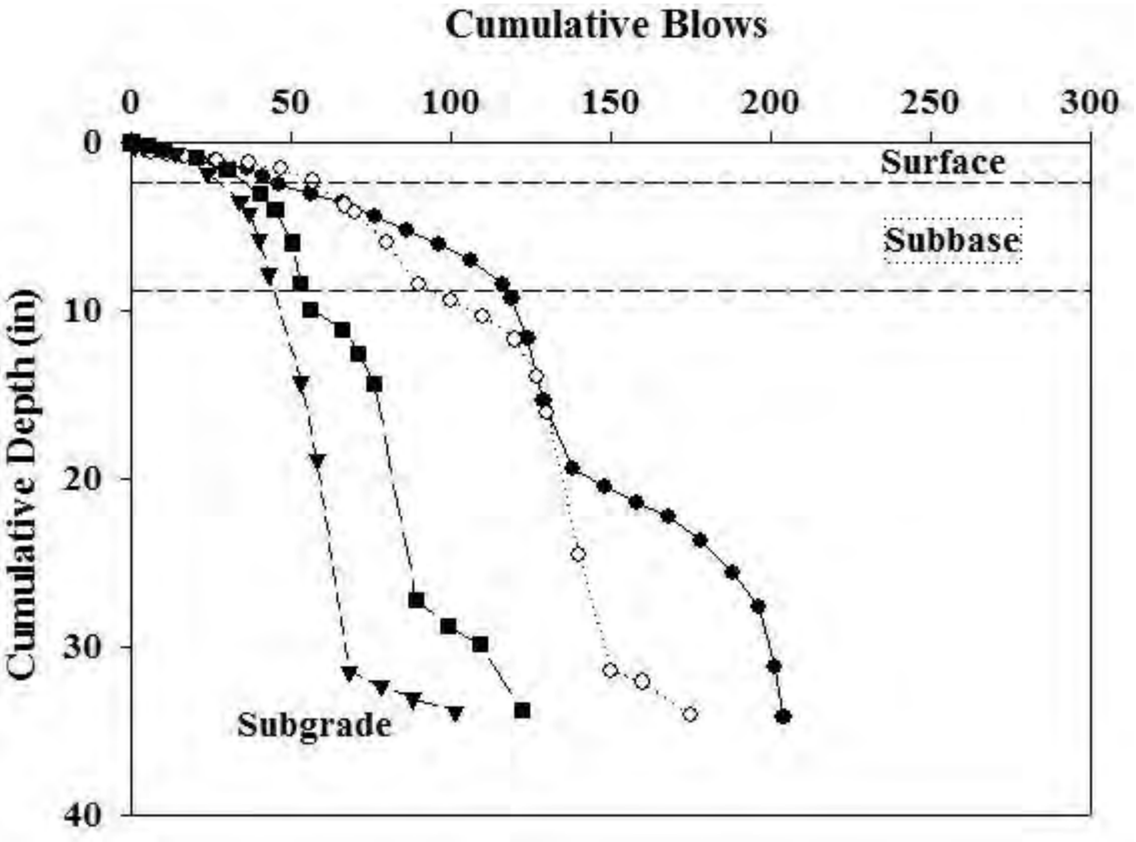
Appendix C – Figure 4. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Boone County – Section 4 (Crescent)

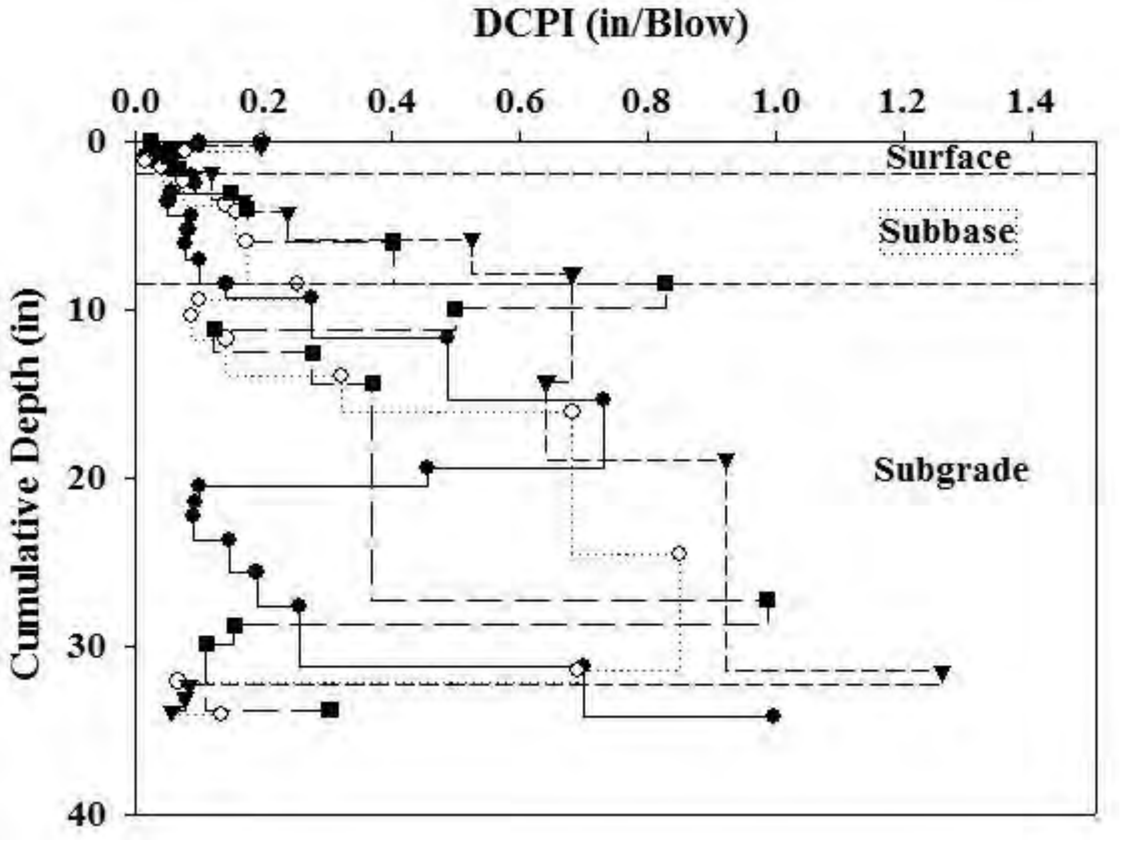

Cumulative Blows
0
20
40
60
80
100
120
140
0
10
20
30
40
Cumulative Depth (in)
Surface
Subgrade

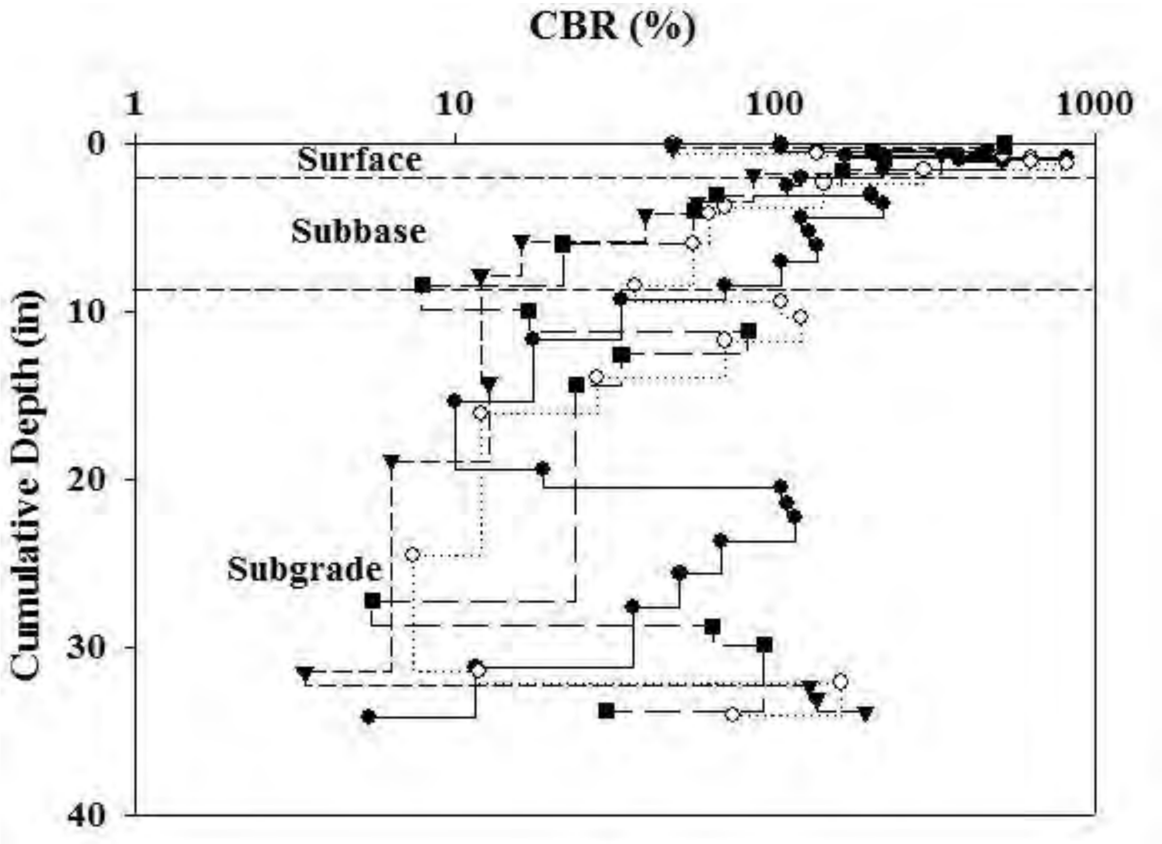

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
10
20
30
40
Cumulative Depth (in)
Surface
Subgrade



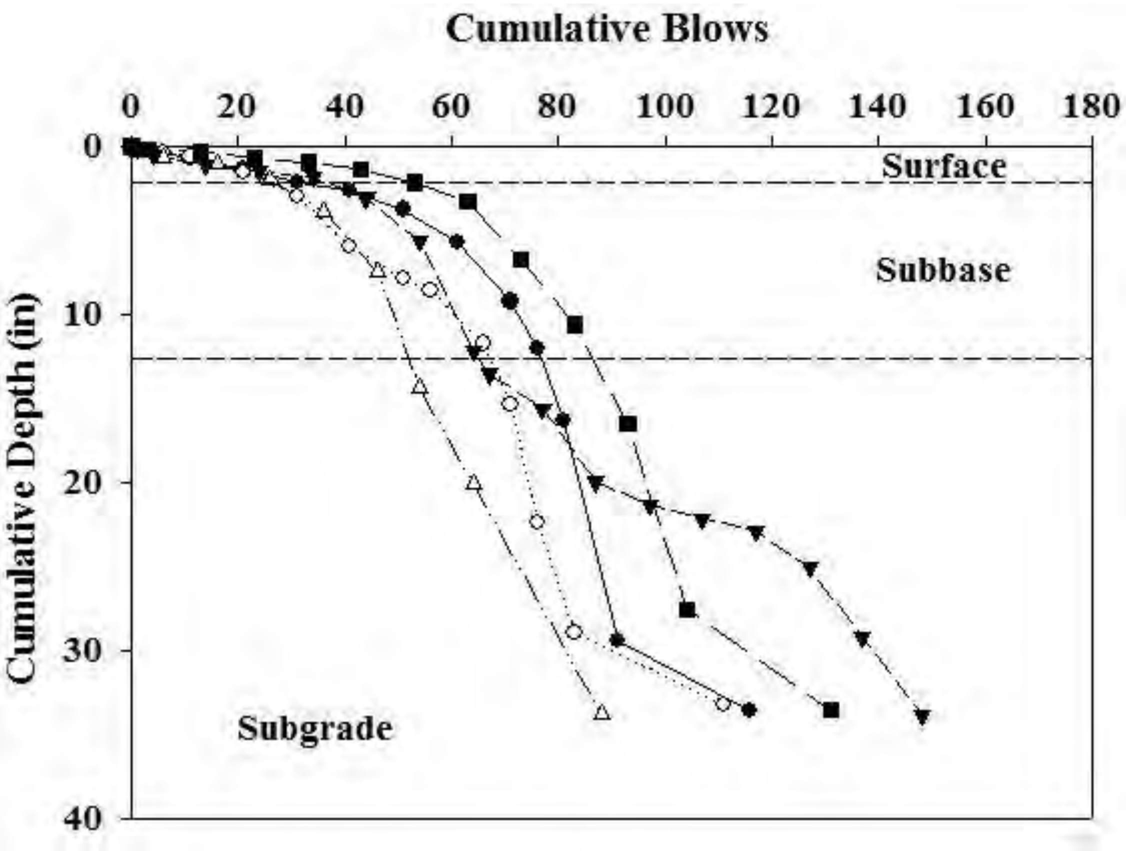
Appendix C – Figure 5. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Boone County – Section 5 (Control)

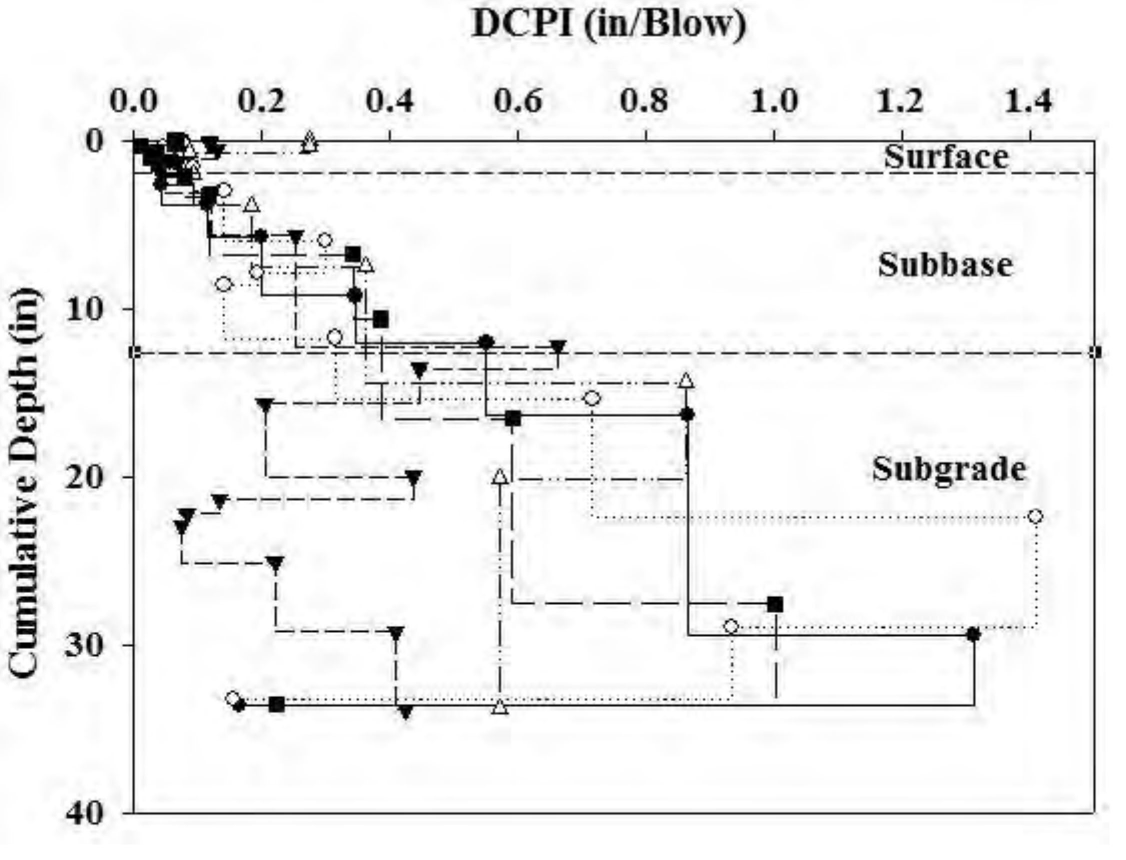

Cumulative Blows
0
50
100
150
200
250
300
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade

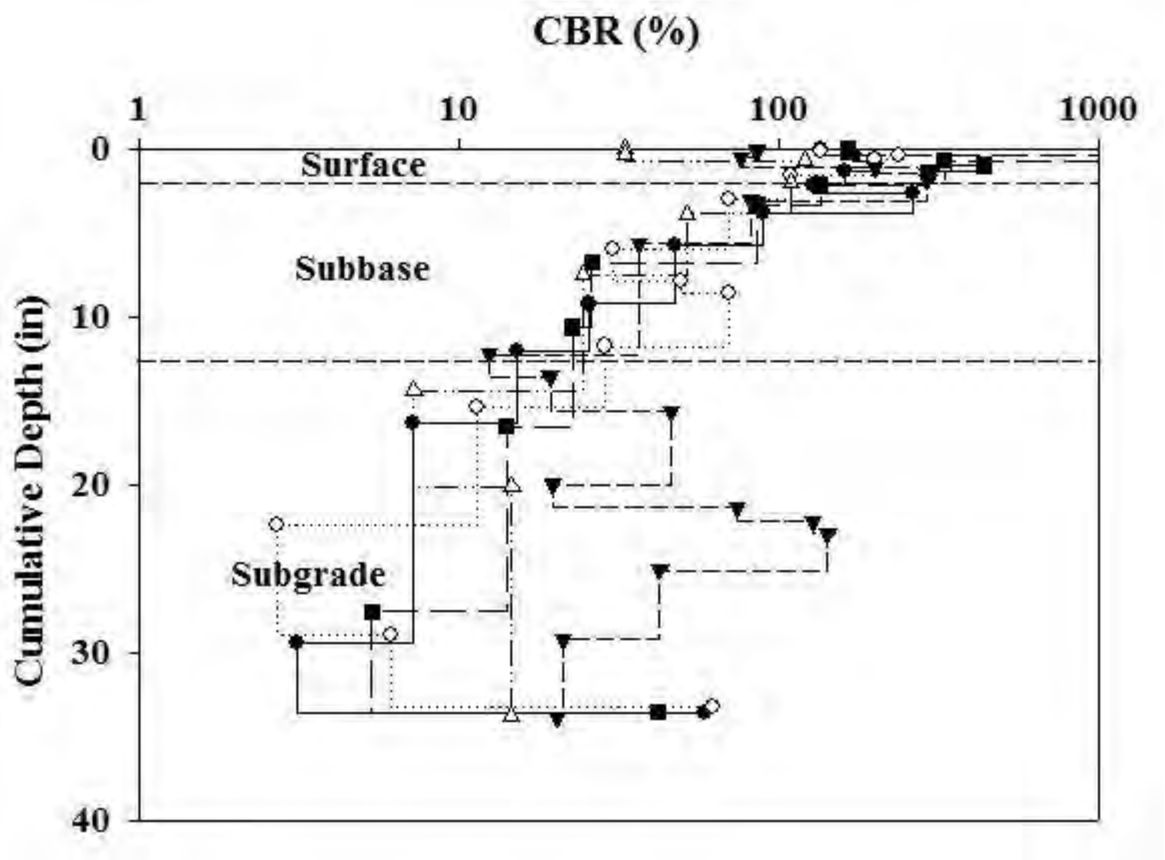

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade



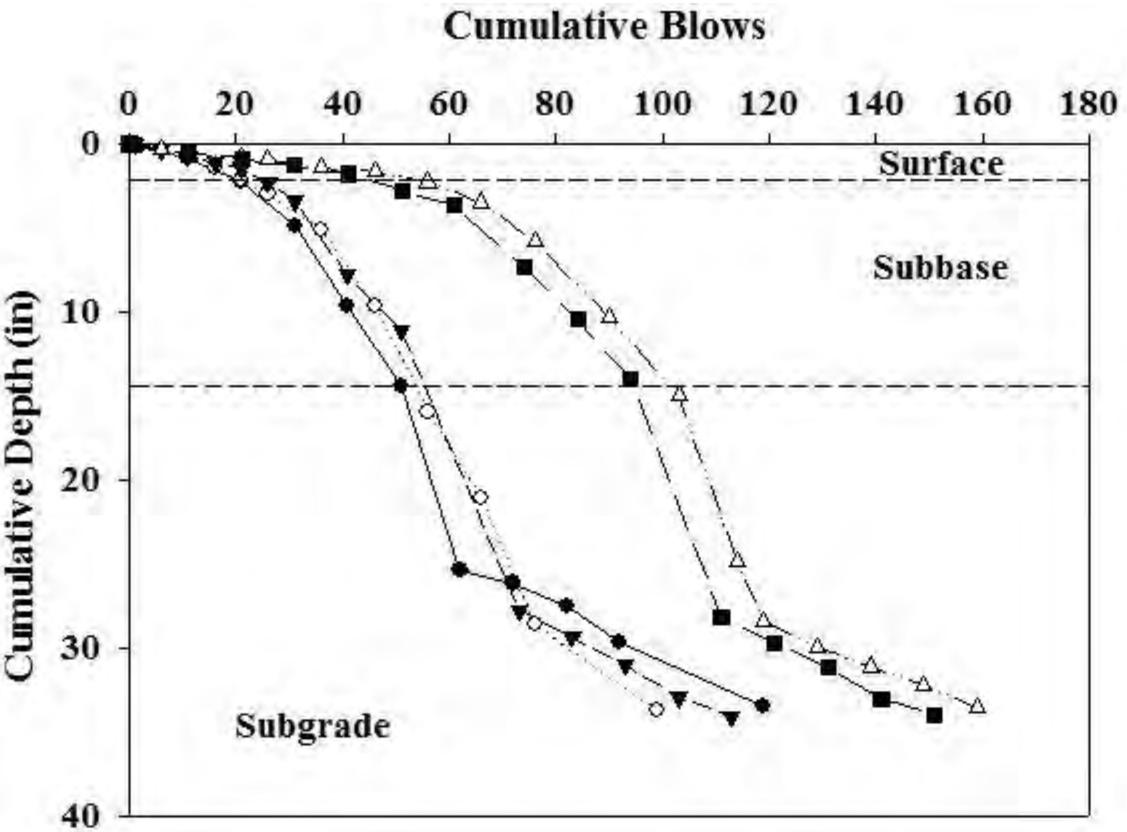
Appendix C – Figure 6. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Boone County – Section 1 (Ames Mine)

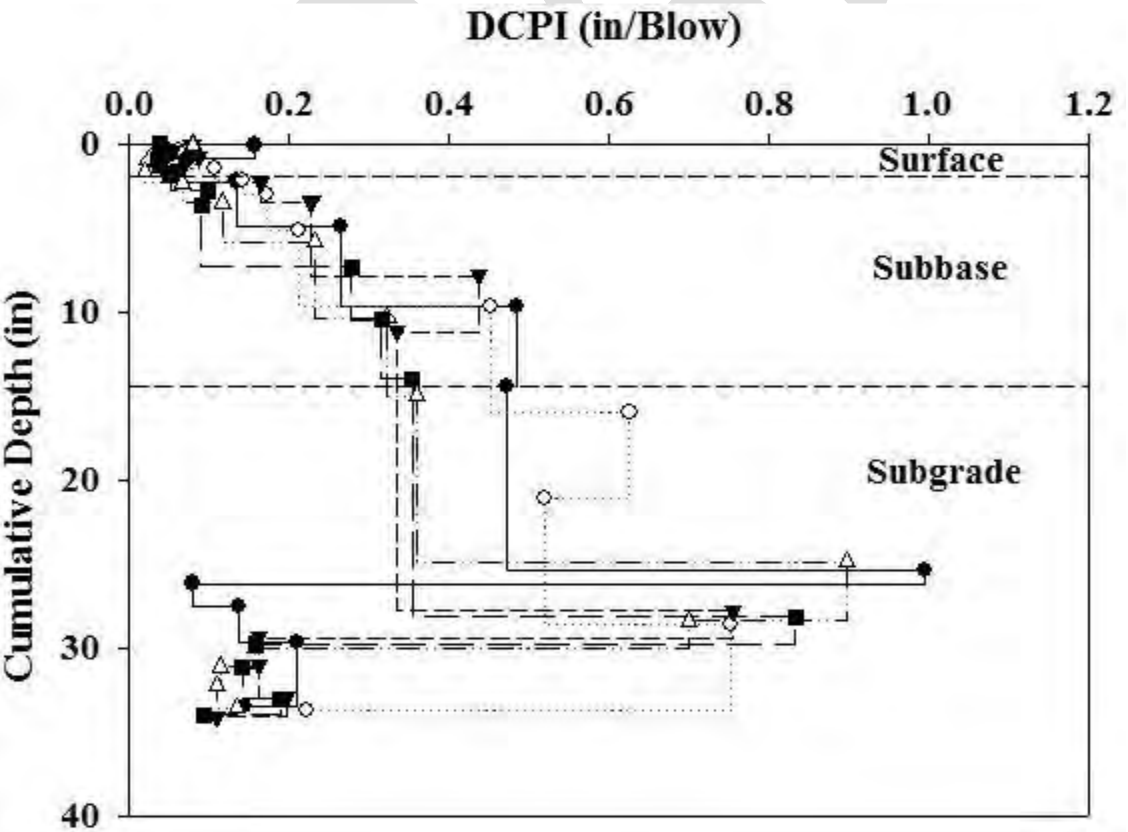

Cumulative Blows
0
20
40
60
80
100
120
140
160
180
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade

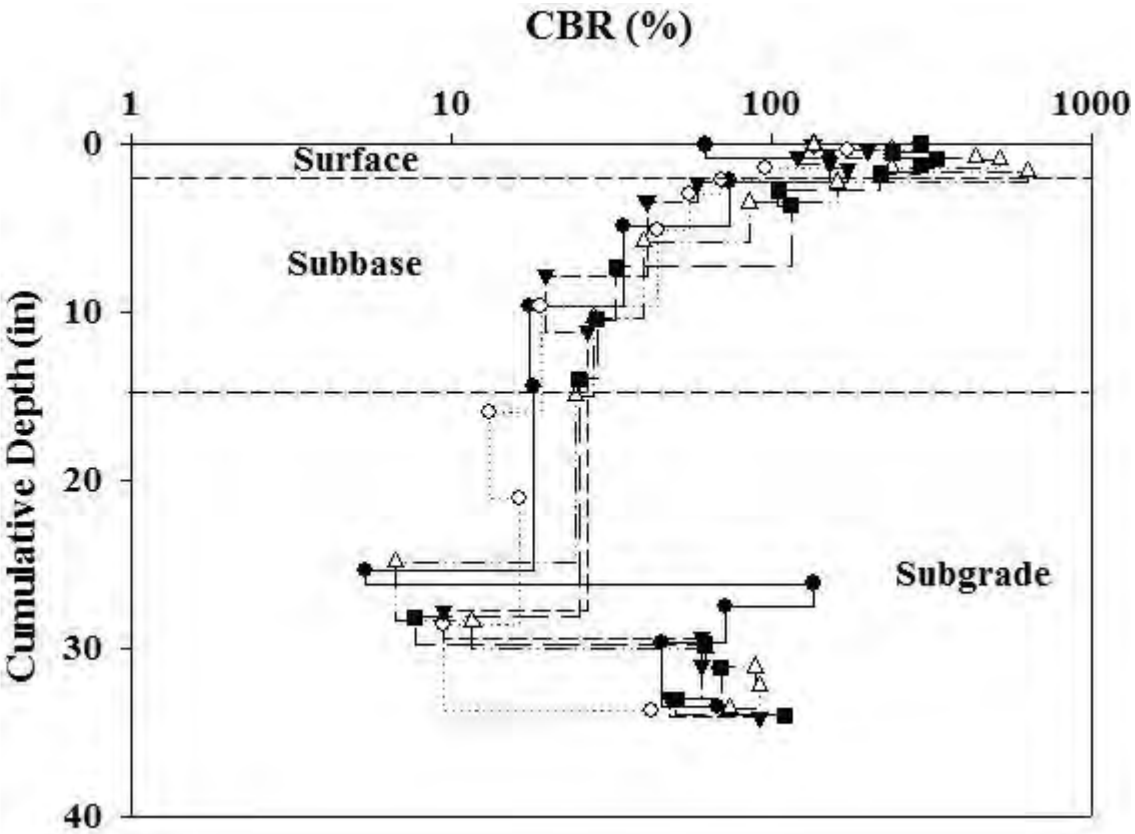

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade



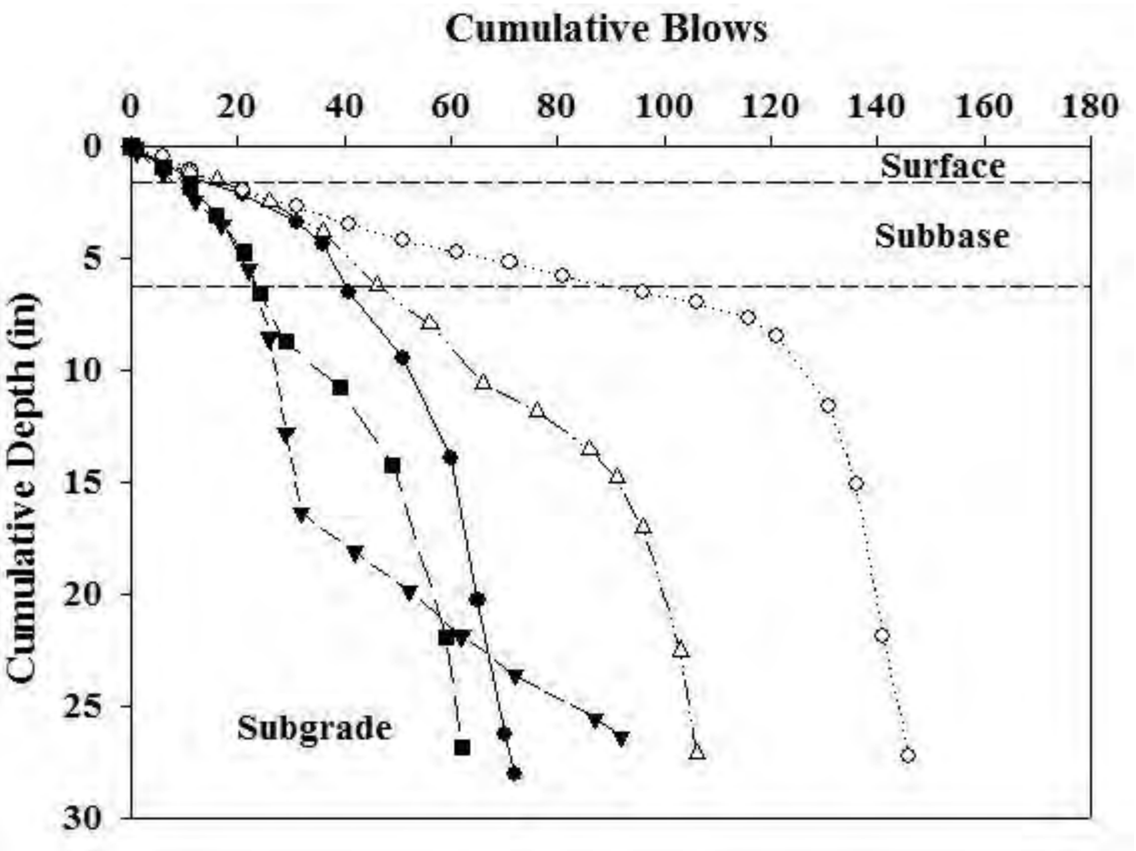
Appendix C – Figure 7. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Boone County – Section 2 (Moscow)

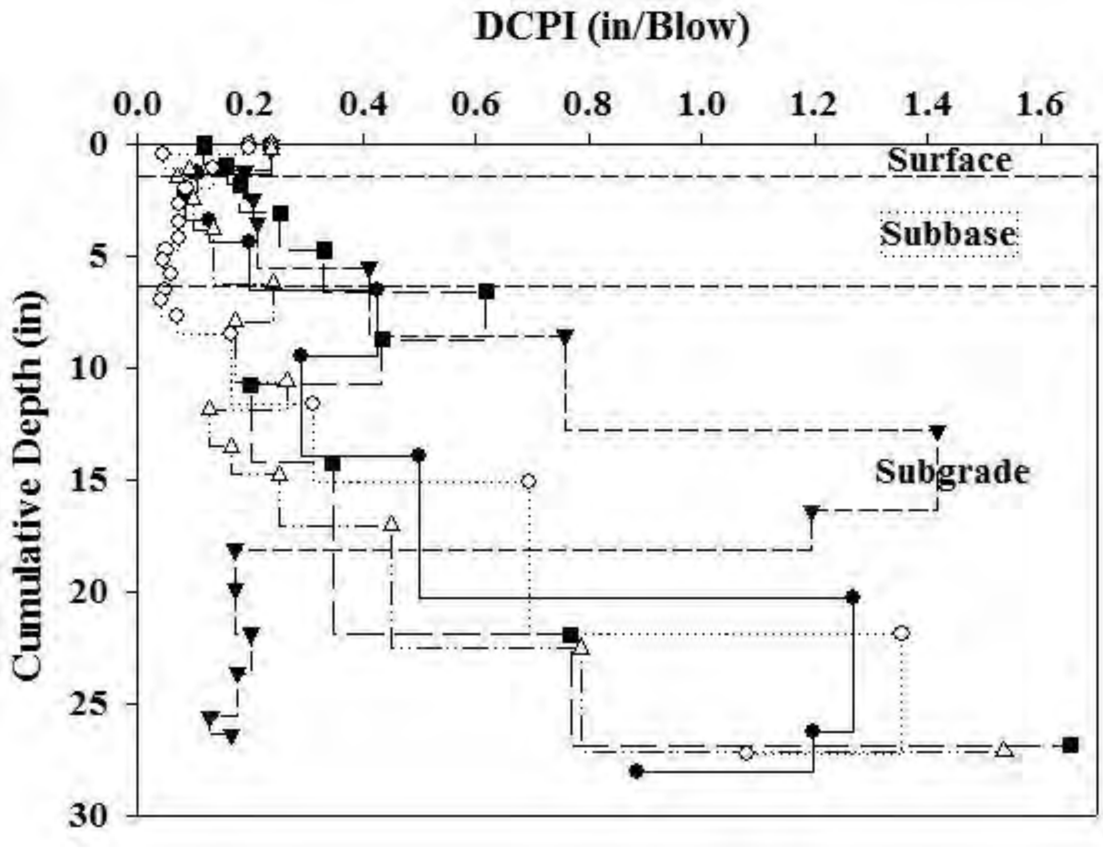

Cumulative Blows
0
20
40
60
80
100
120
140
160
180
0
10
20
30
40
Cumulative Depth (in)
Surface
Subbase
Subgrade

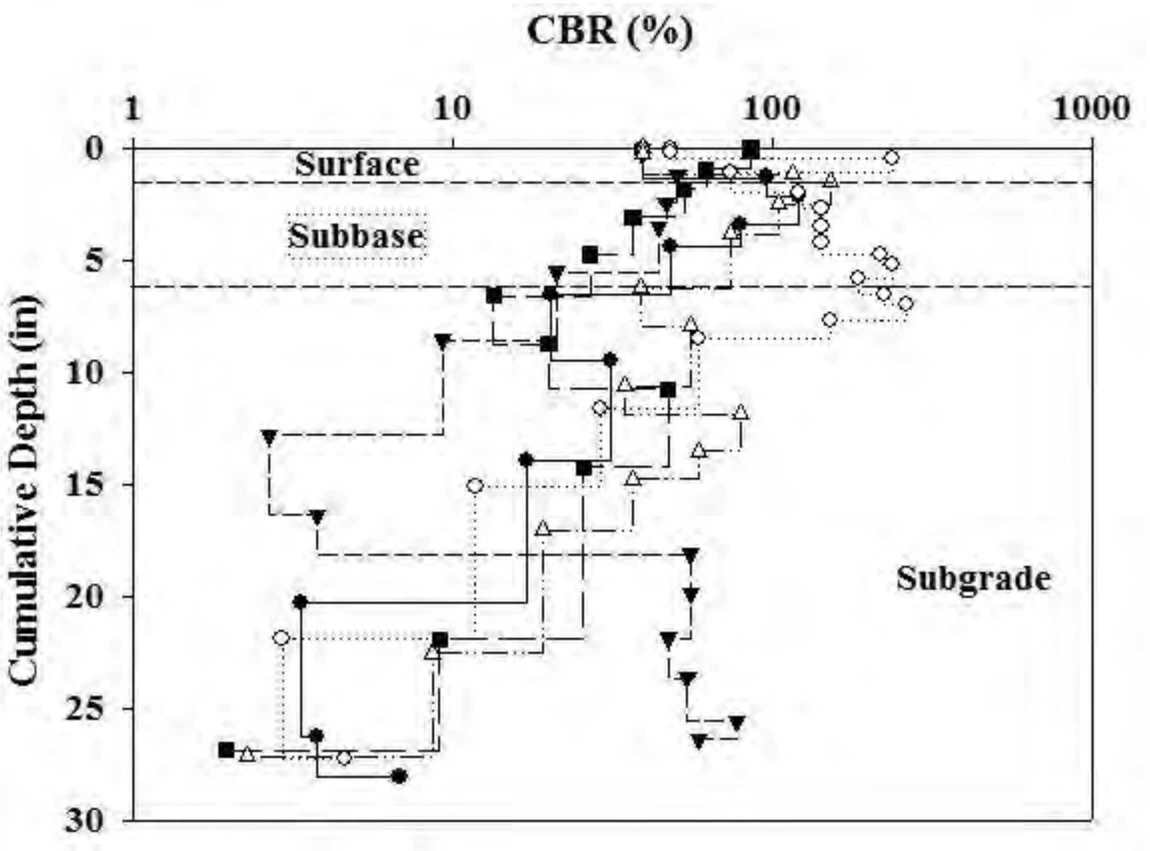

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
10
20
30
40
Cumulative Depth (in)
Surface
Subbase
Subgrade



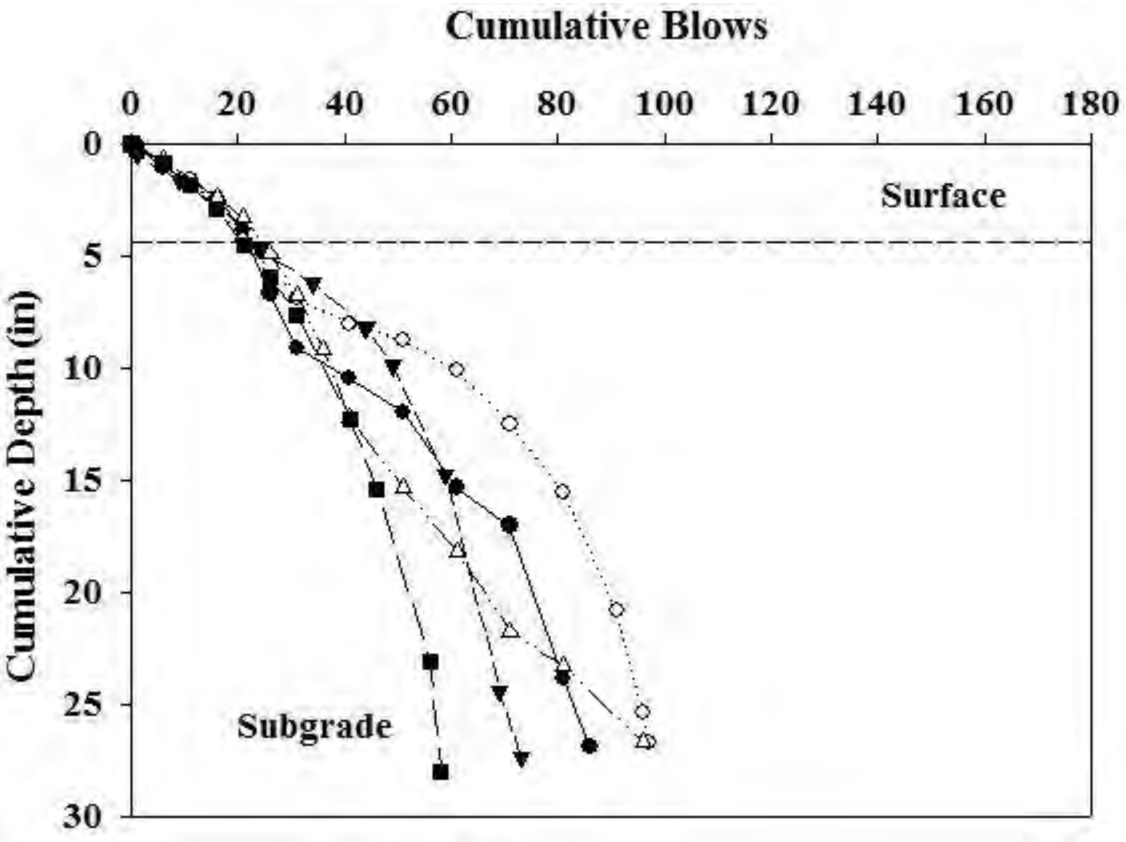
Appendix C – Figure 8. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Boone County – Section 3 (Clay Slurry)

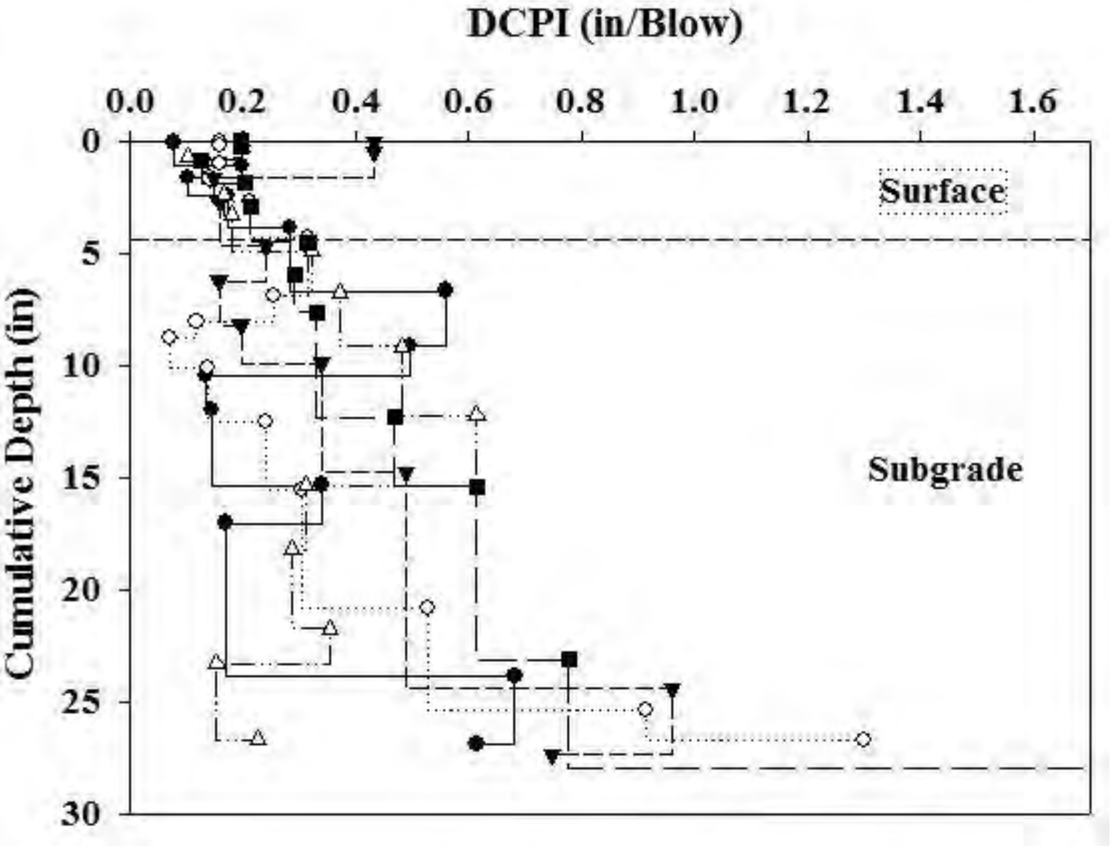

Cumulative Blows
0
20
40
60
80
100
120
140
160
180
Cumulative Depth (in)
0
5
10
15
20
25
30
Surface
Subbase
Subgrade

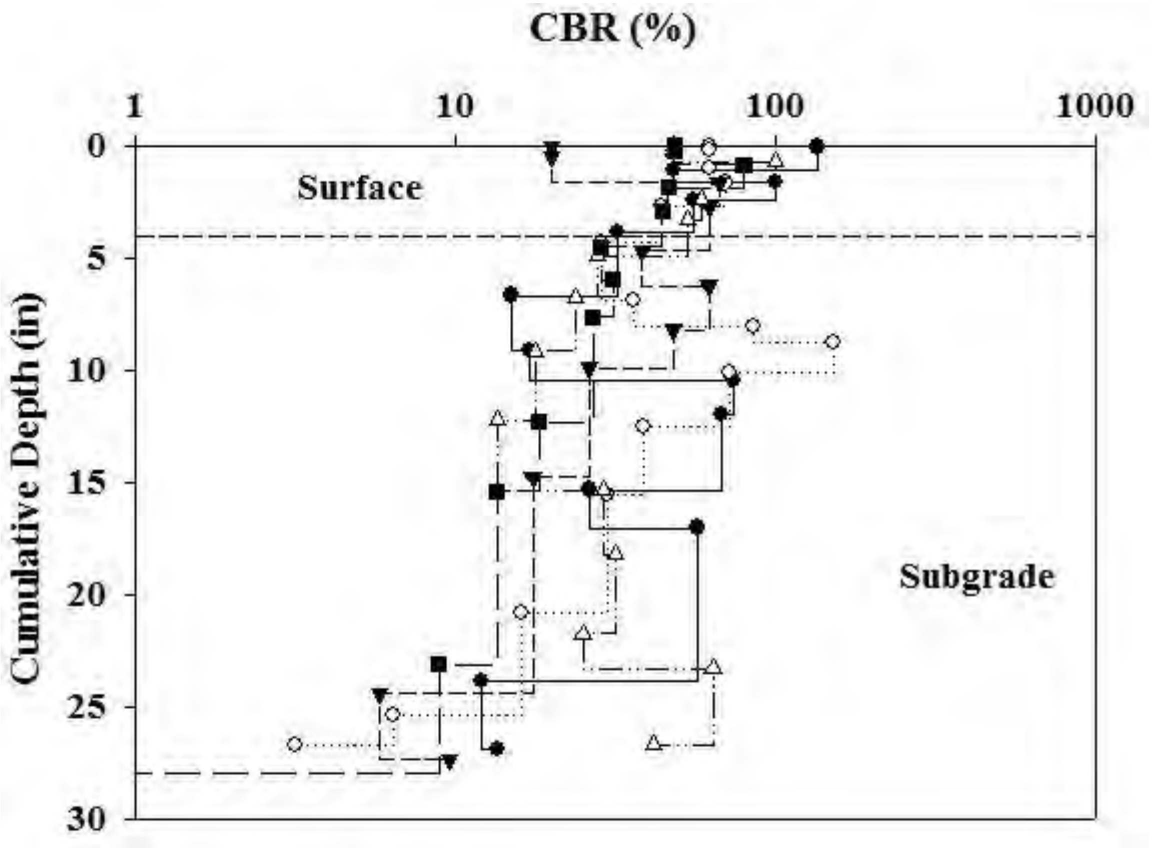

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Cumulative Depth (in)
0
5
10
15
20
25
30
Surface
Subbase
Subgrade



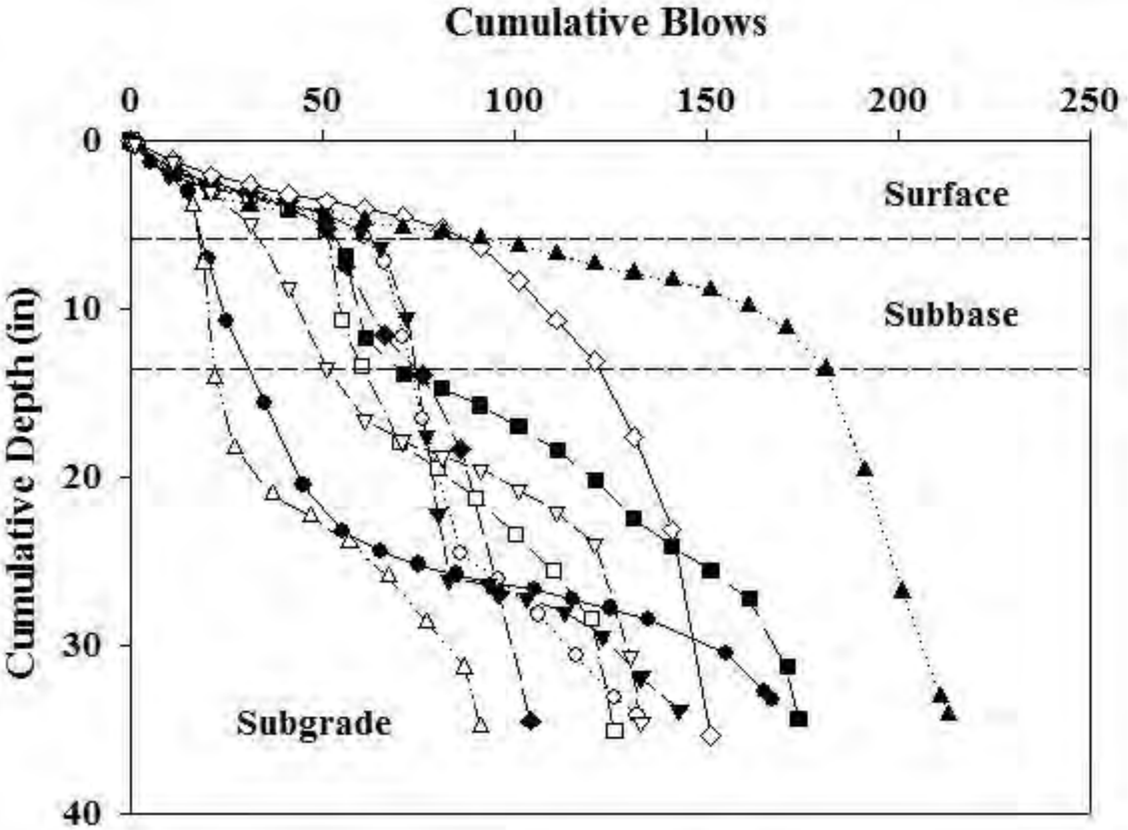
Appendix C – Figure 9. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Boone County – Section 4 (Crescent)


Cumulative Blows
0
20
40
60
80
100
120
140
160
180
Cumulative Depth (in)
0
5
10
15
20
25
30
Surface
Subgrade

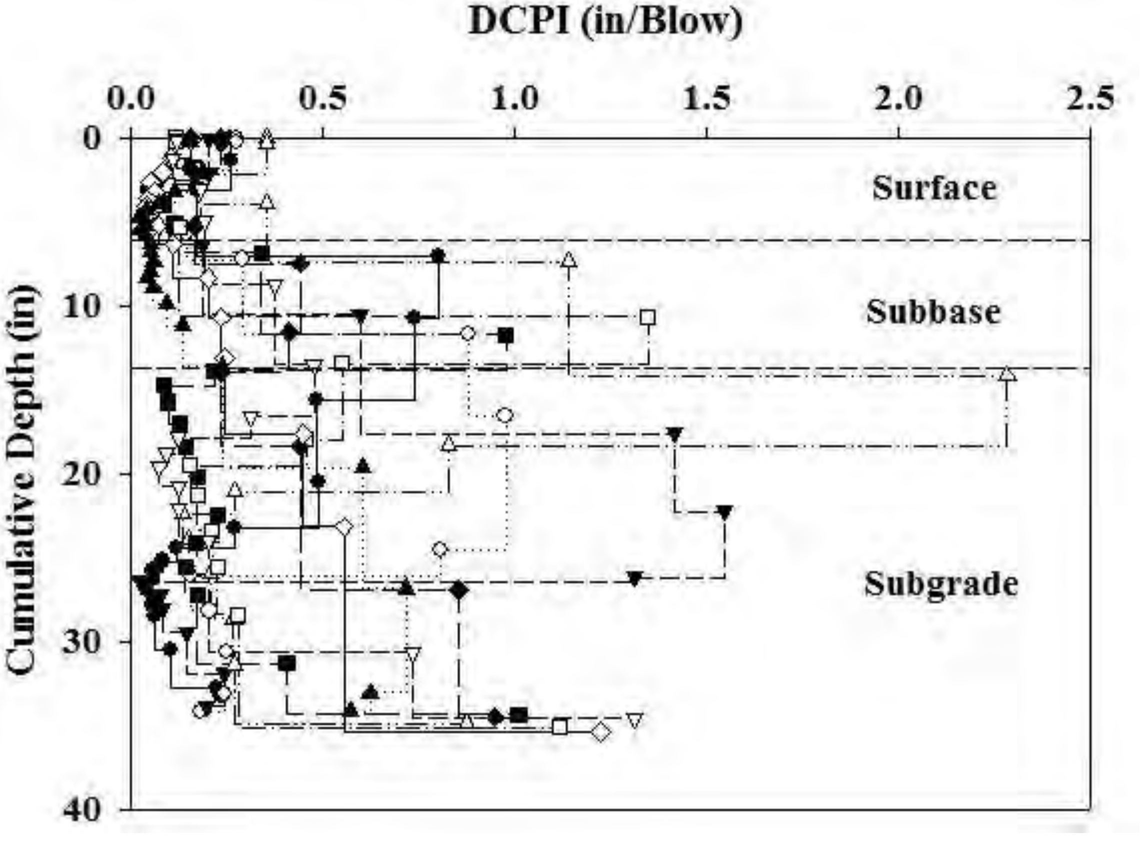

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Cumulative Depth (in)
0
5
10
15
20
25
30
Surface
Subgrade



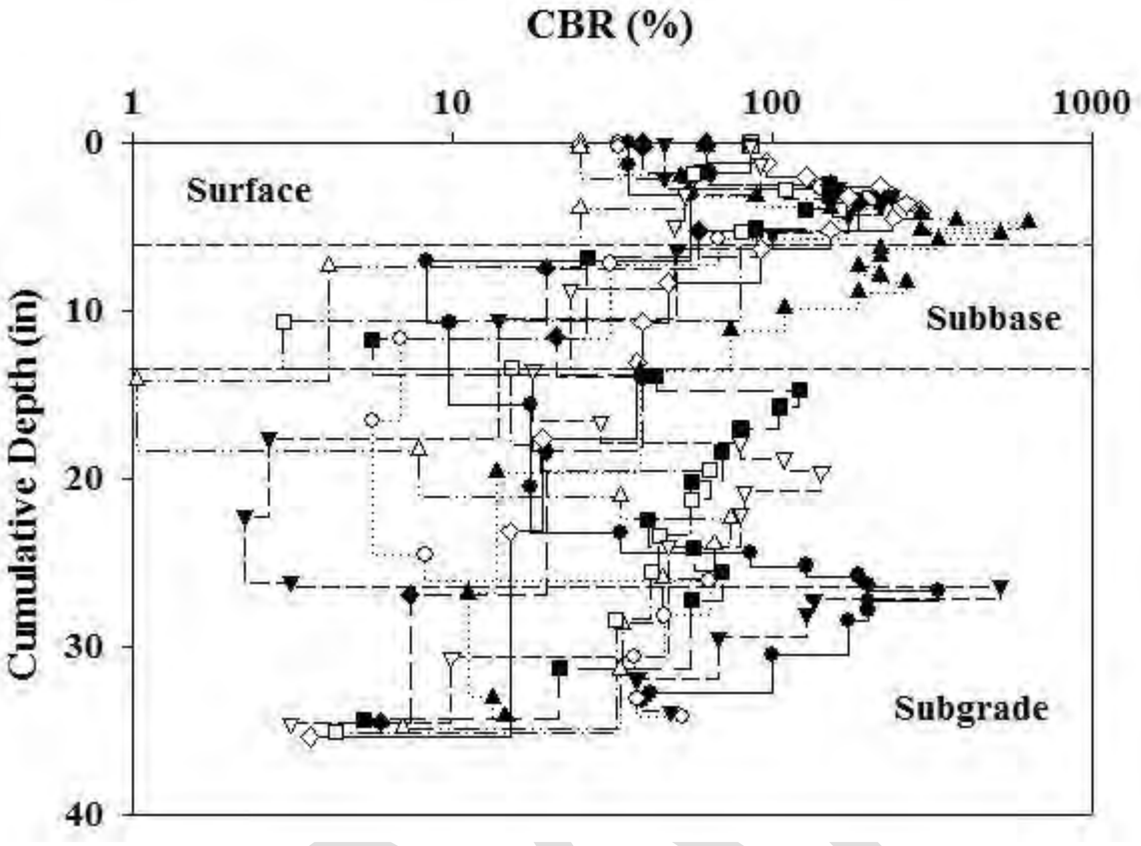
Appendix C – Figure 10. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Boone County – Section 5 (Control)



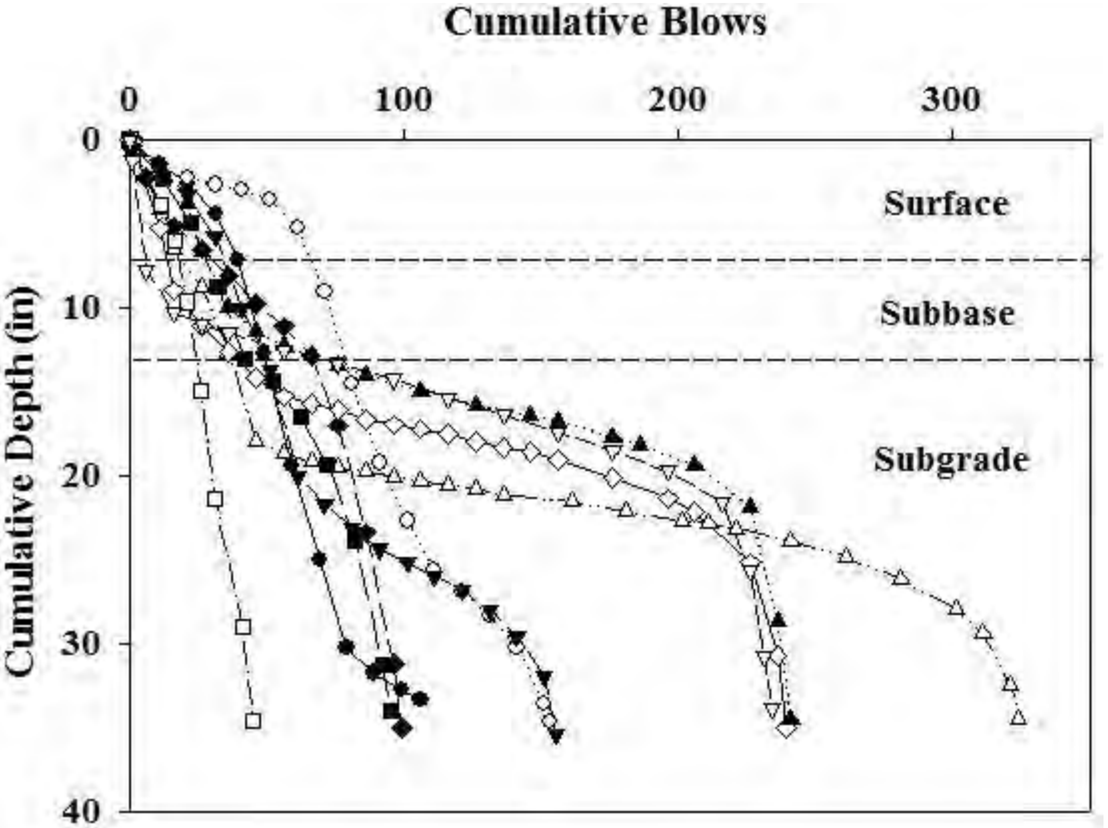
Cumulative Blows
0
50
100
150
200
250
0
10
20
30
40
Cumulative Depth (in)
Surface
Subbase
Subgrade

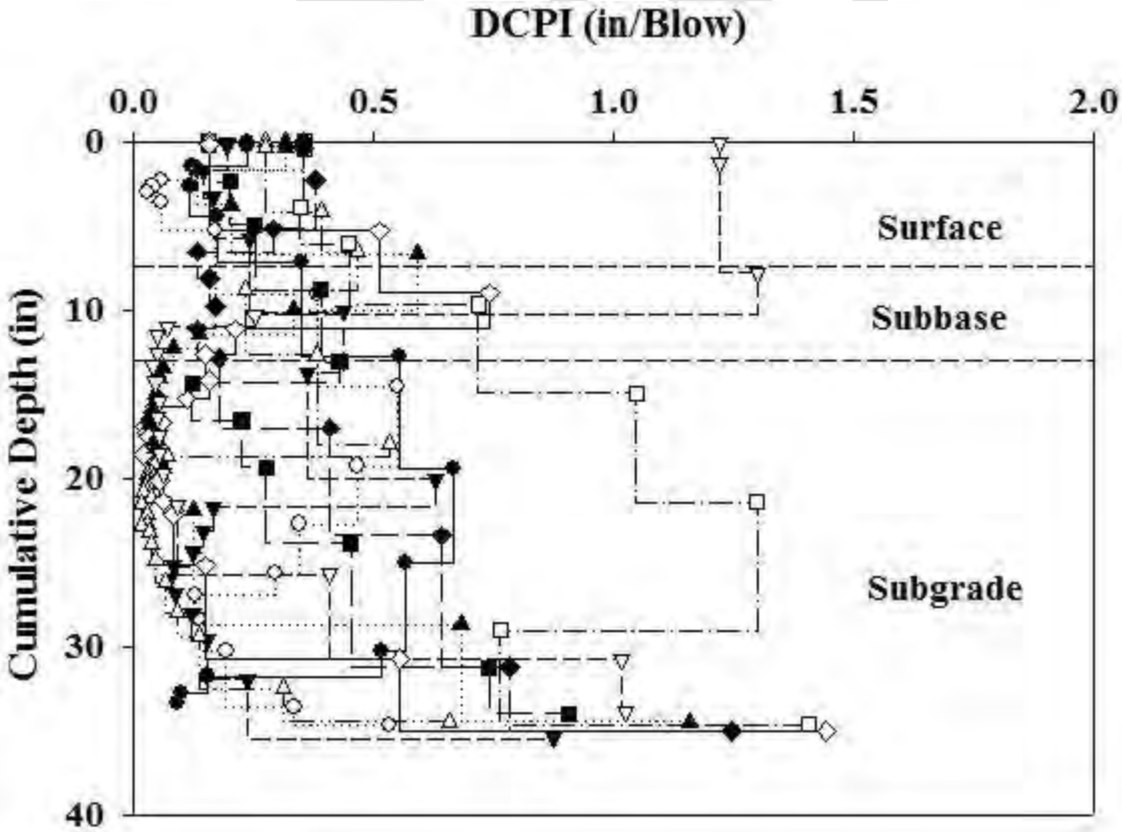


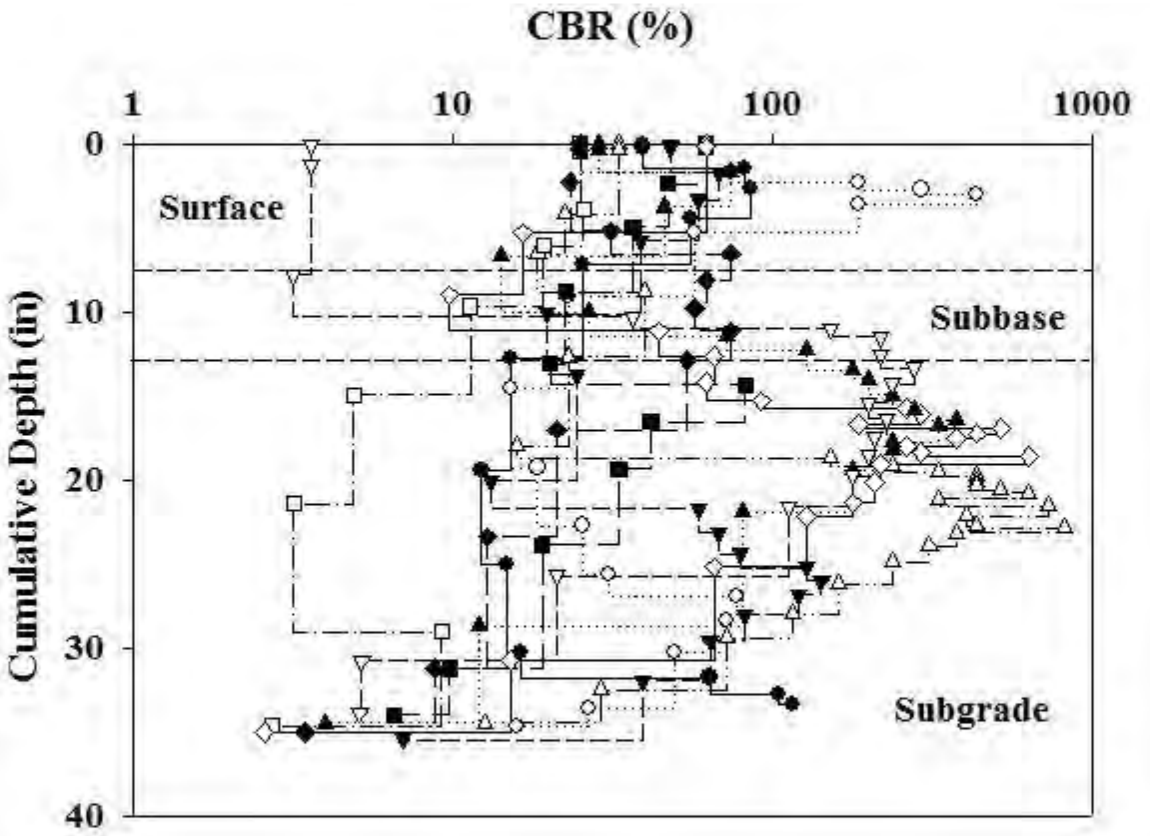
DCPI (in/Blow)
0.0
0.5
1.0
1.5
2.0
2.5
0
10
20
30
40
Cumulative Depth (in)
Surface
Subbase
Subgrade



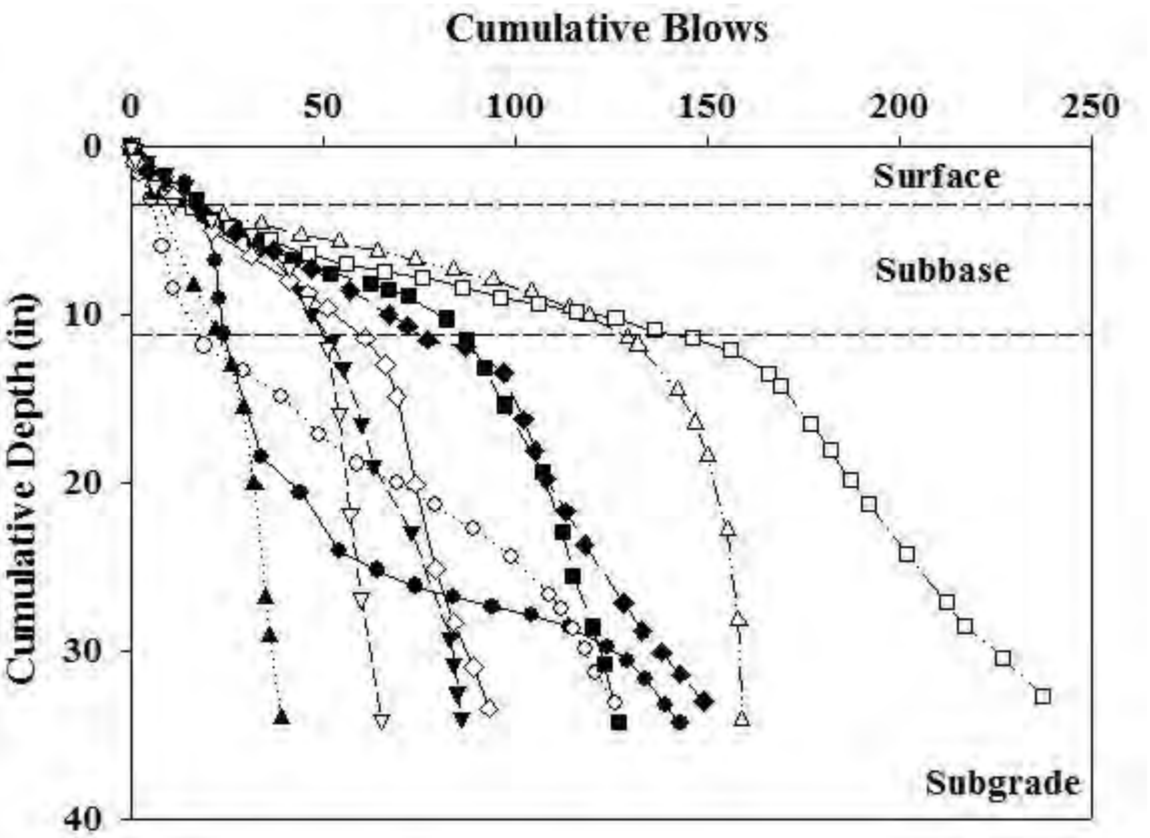
Appendix C – Figure 11. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Jones County – Section 1 (Moscow)


Cumulative Blows
0
100
200
300
0
10
20
30
40
Cumulative Depth (in)
Surface
Subbase
Subgrade

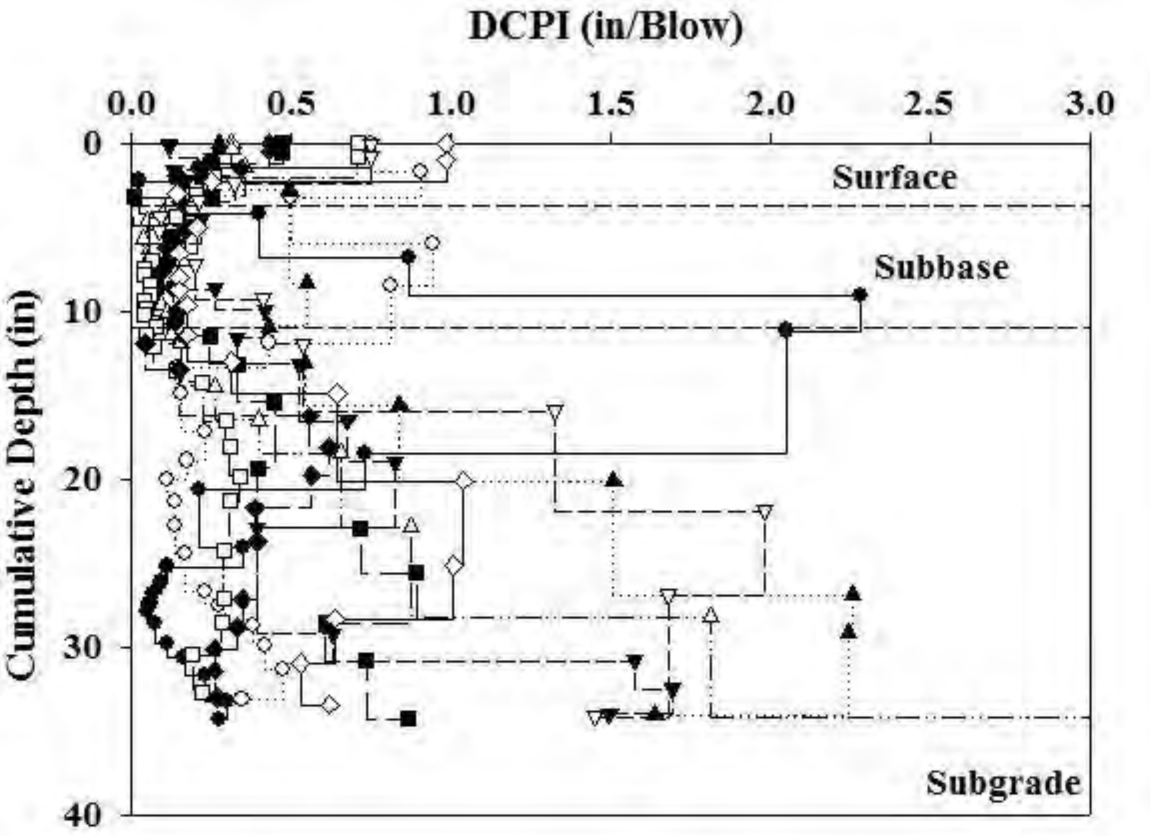

DCPI (in/Blow)
0.0
0.5
1.0
1.5
2.0
0
10
20
30
40
Cumulative Depth (in)
Surface
Subbase
Subgrade



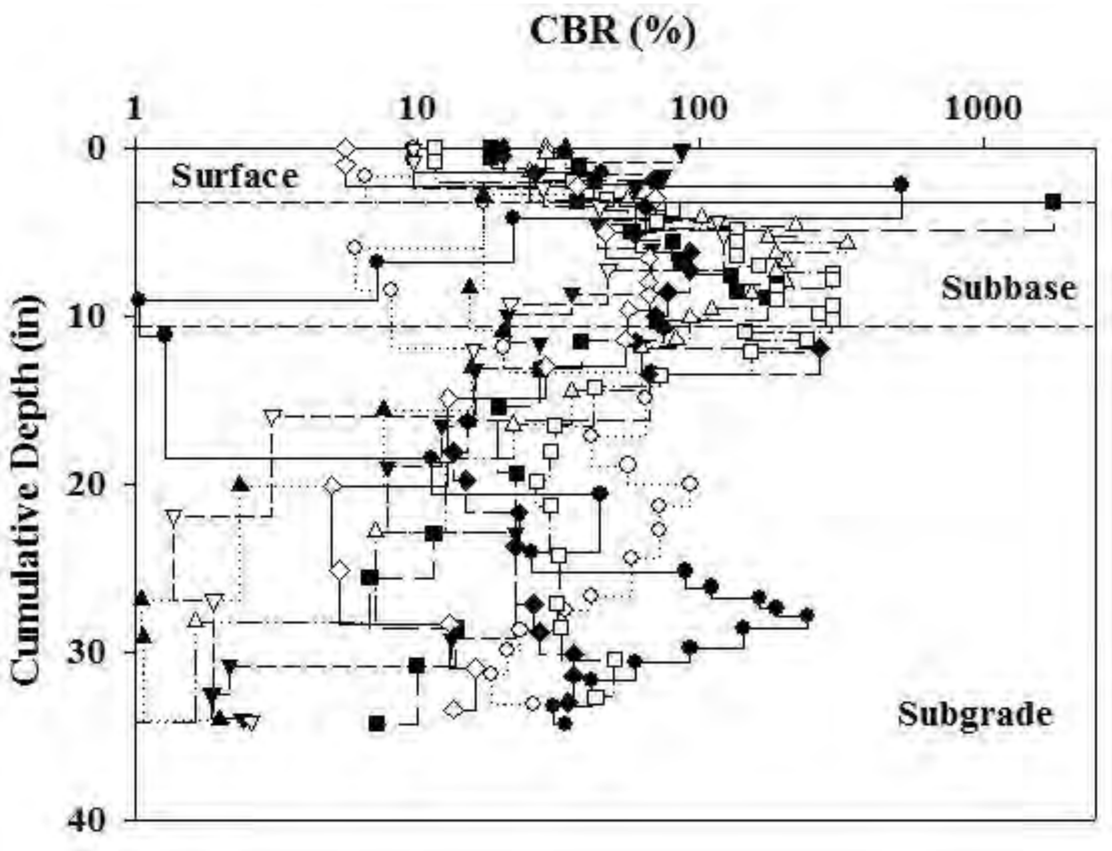
Appendix C – Figure 12. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Jones County – Section 2 (Clay Slurry)



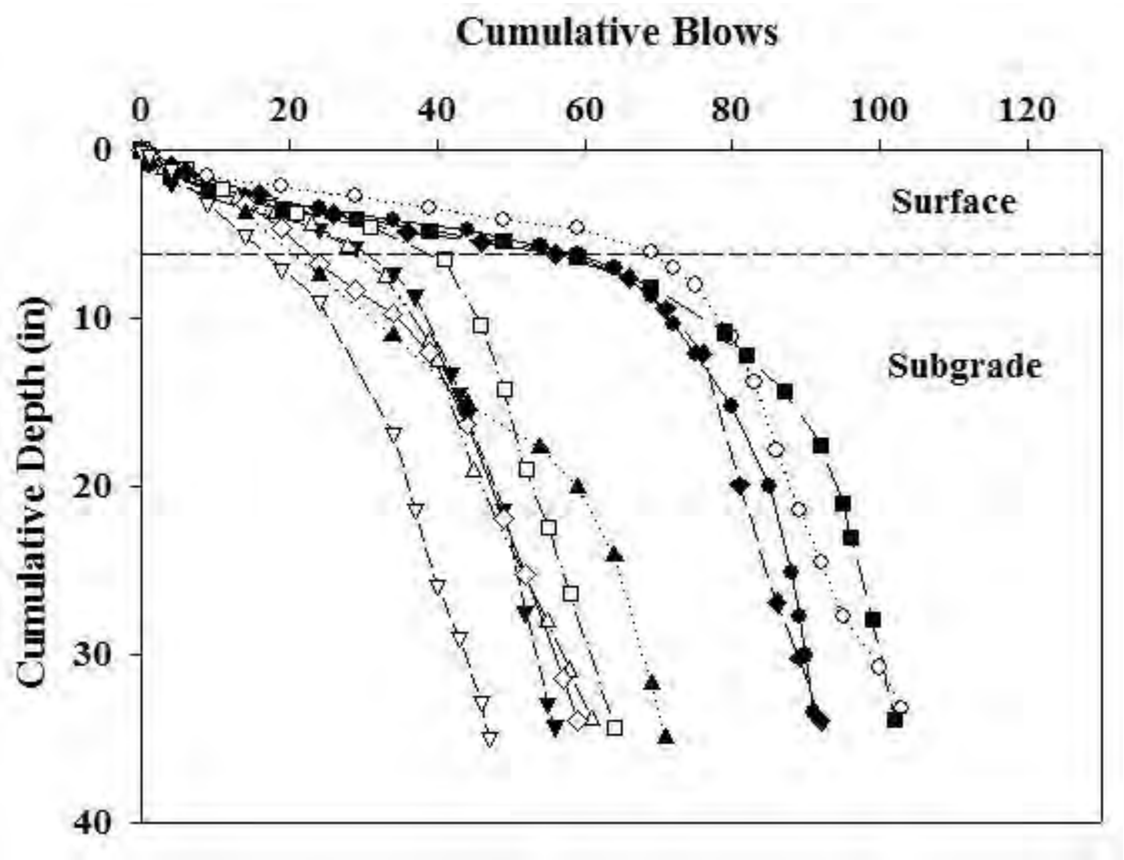
Cumulative Blows
0
50
100
150
200
250
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade

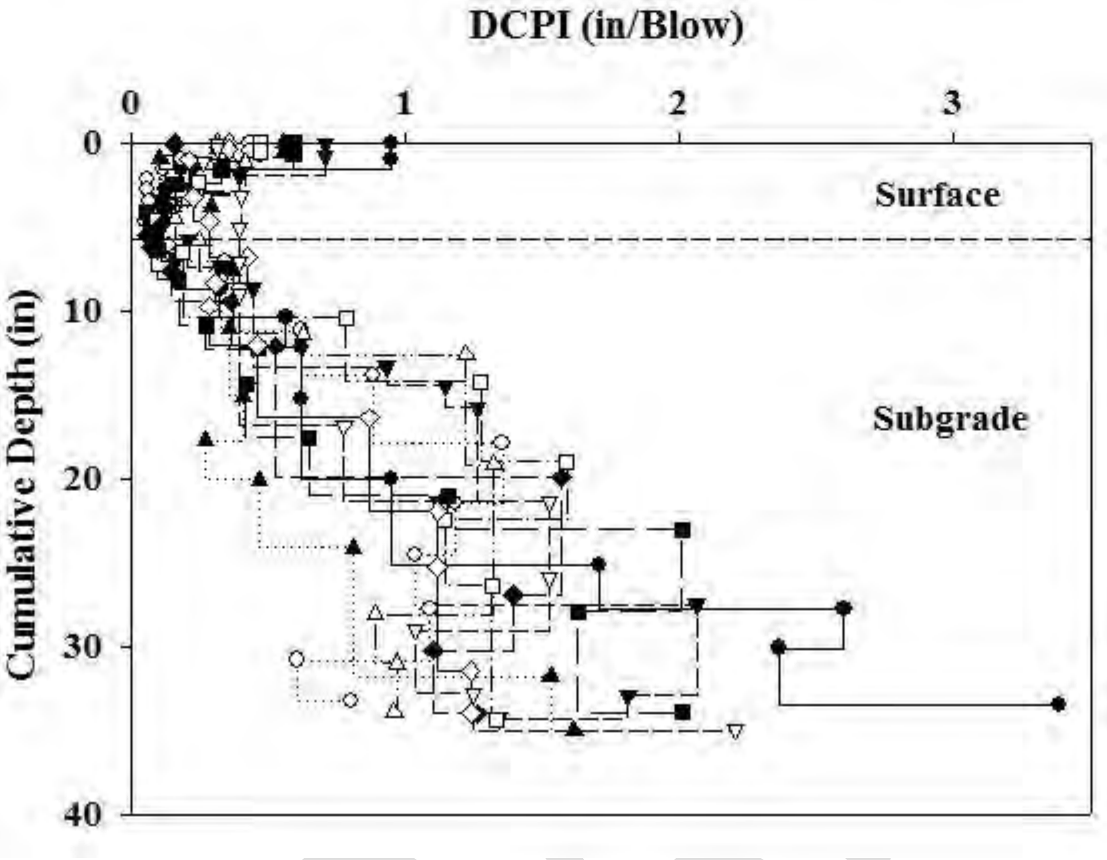


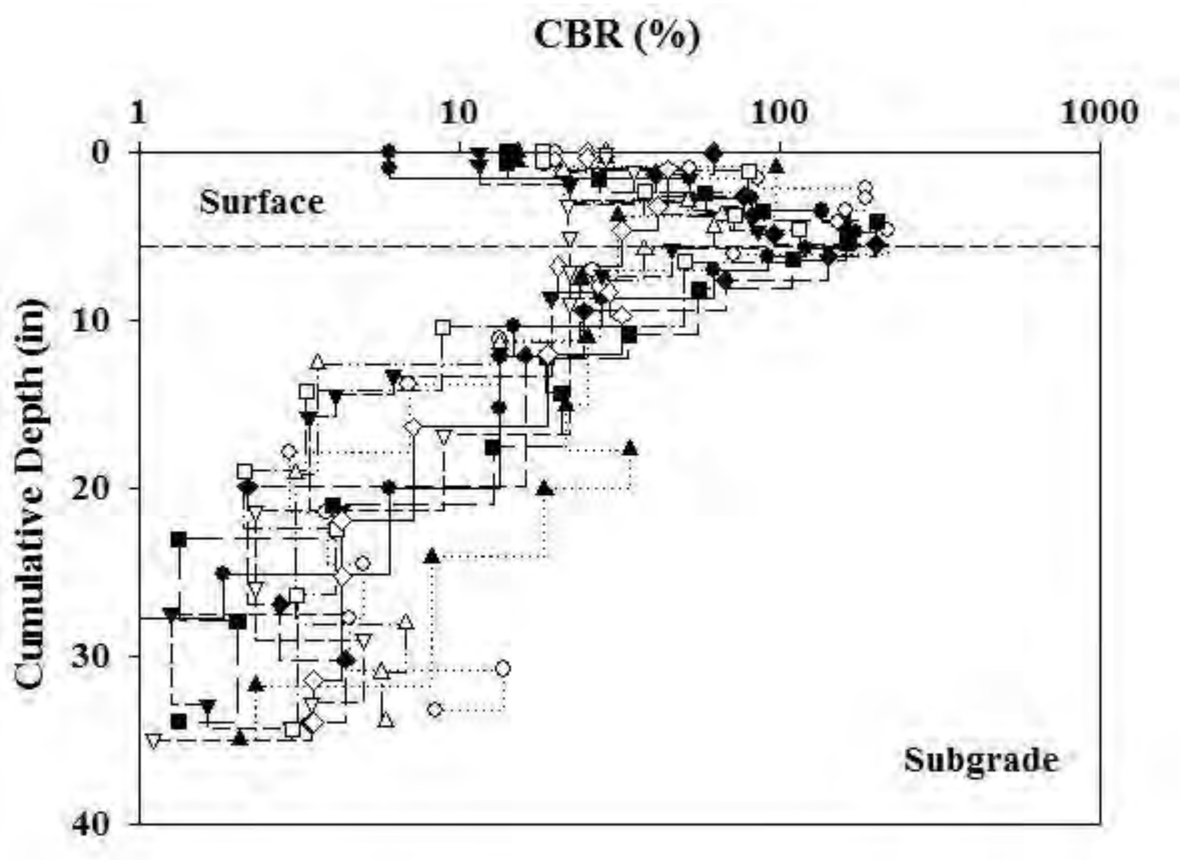
DCPI (in/Blow)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade



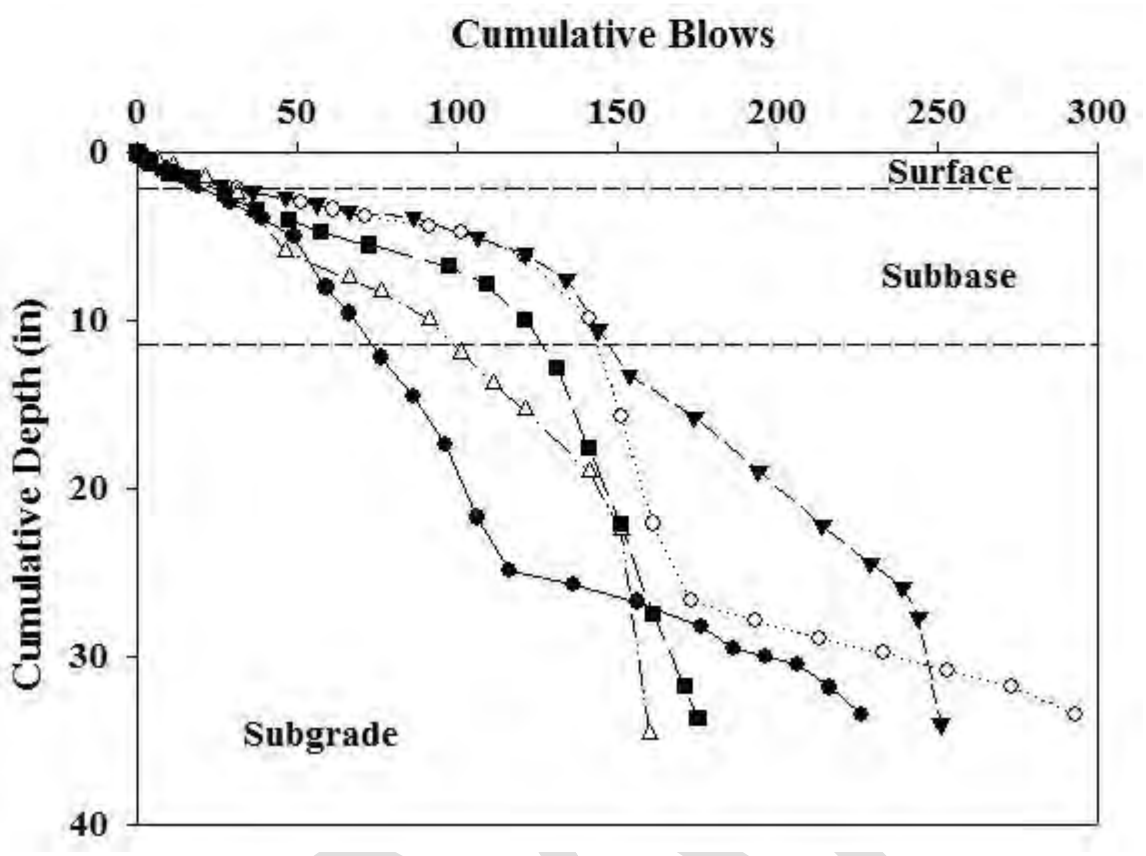
Appendix C – Figure 13. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Jones County – Section 3 (Limestone)


Cumulative Blows
0
20
40
60
80
100
120
0
10
20
30
40
Cumulative Depth (in)
Surface
Subgrade

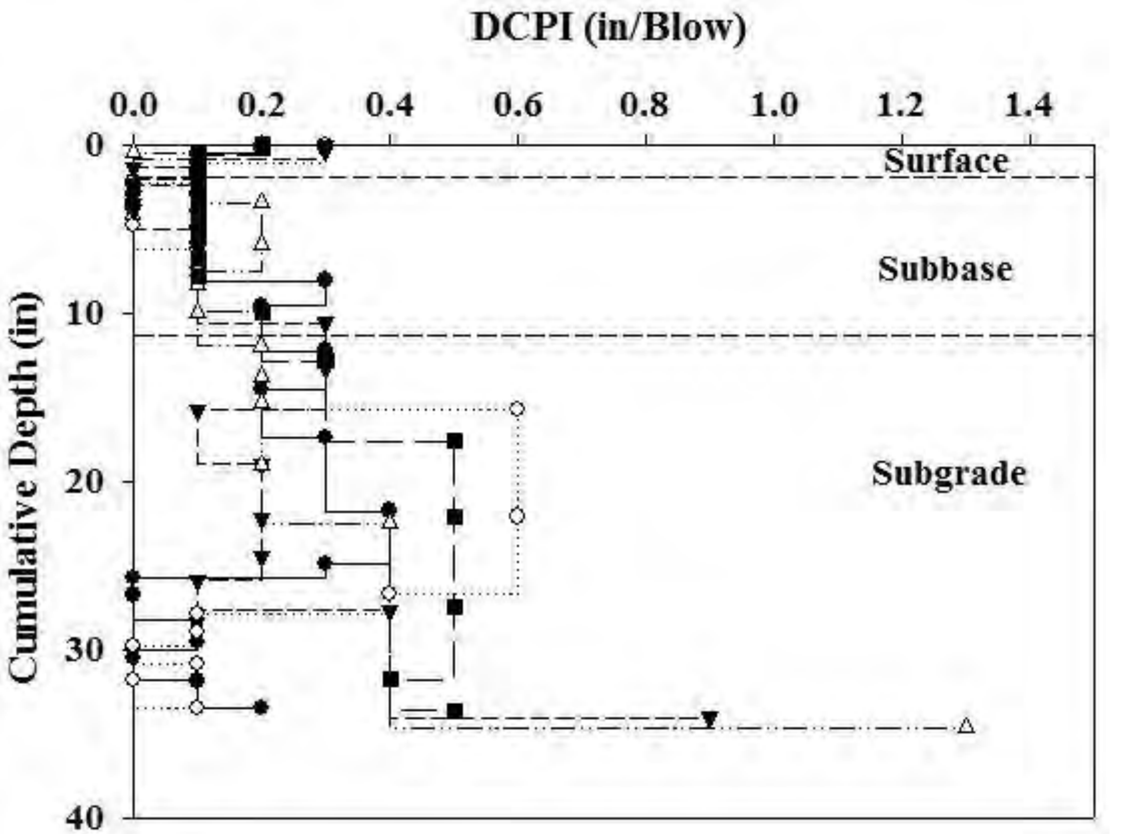

DCPI (in/Blow)
0
1
2
3
0
10
20
30
40
Cumulative Depth (in)
Surface
Subgrade

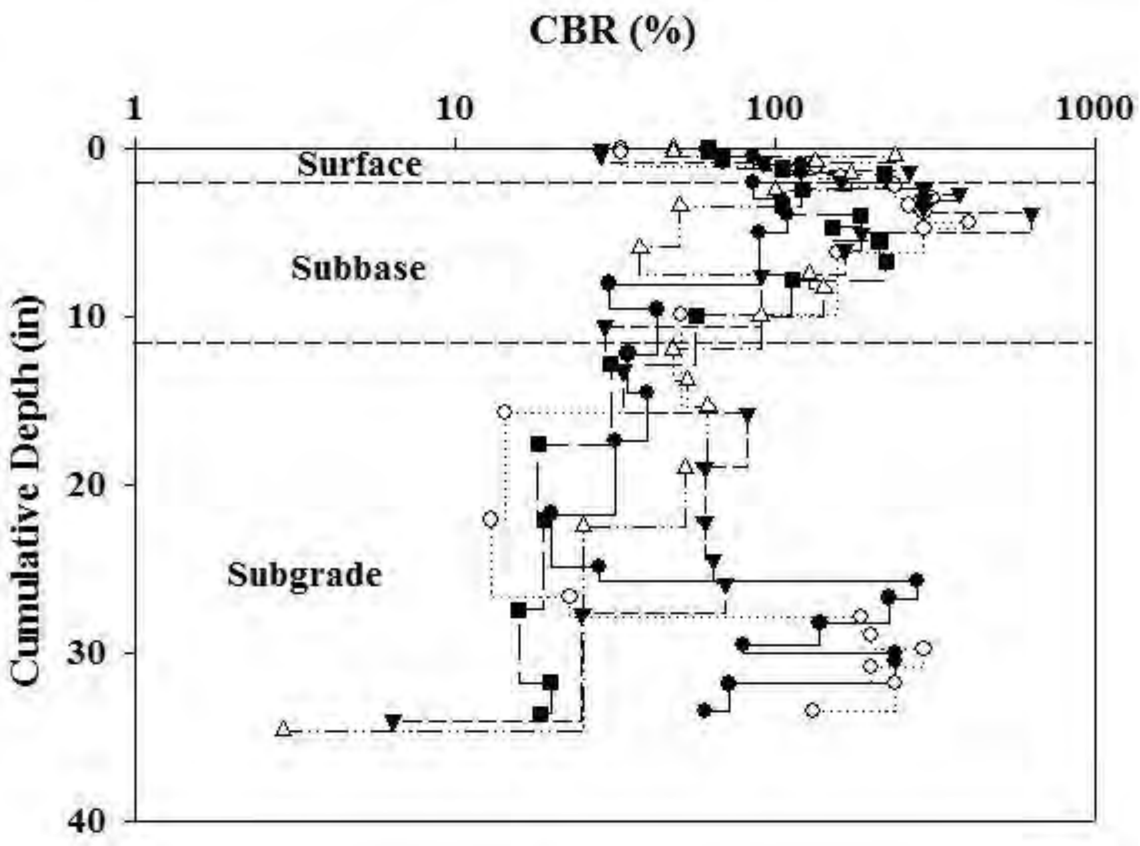


Appendix C – Figure 14. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for November 2019 – Jones County – Section 4 (Control)

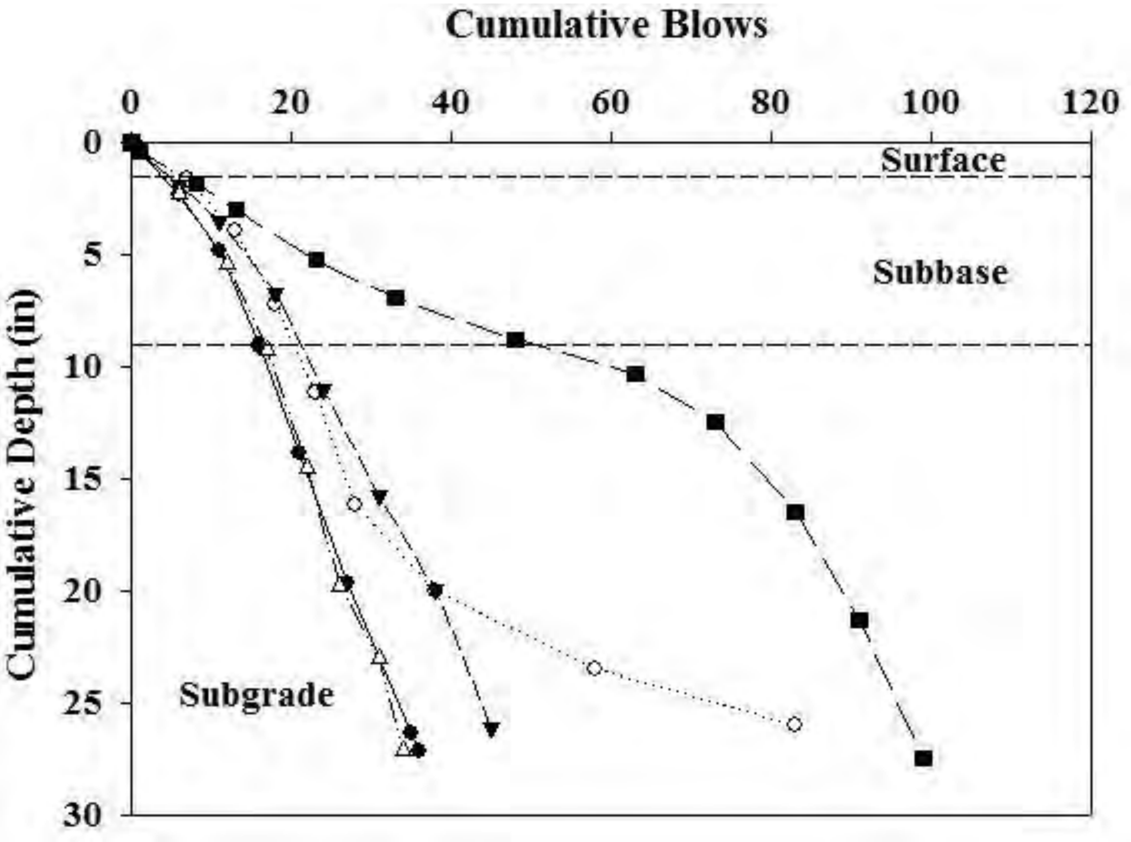


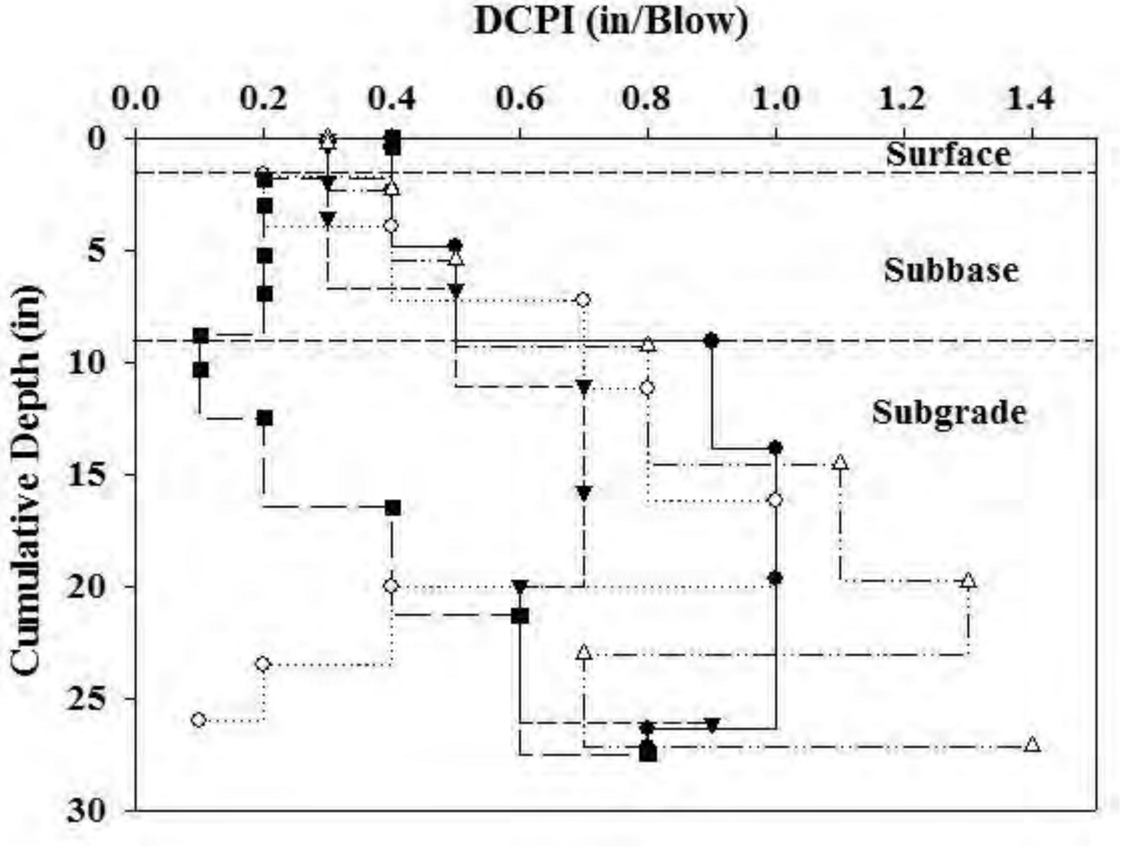
Cumulative Blows
0
50
100
150
200
250
300
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade

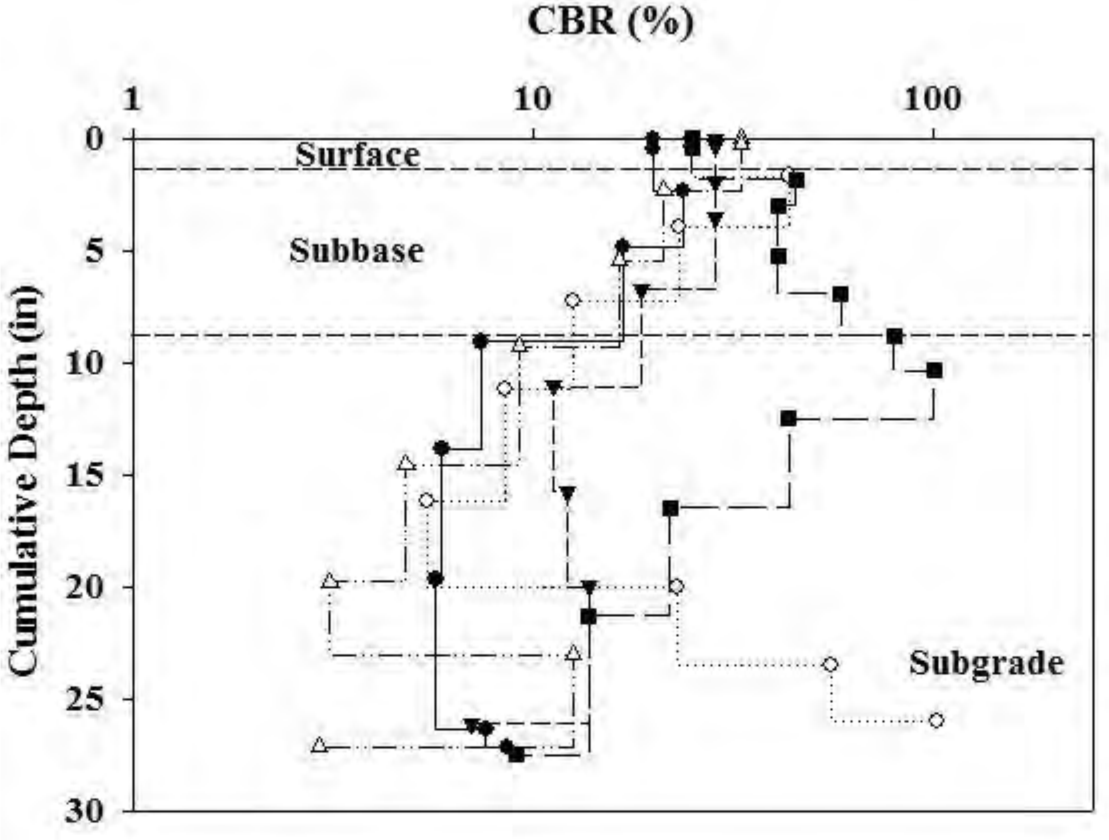

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade


CBR (%)
1
10
100
1000
Cumulative Depth (in)
0
10
20
30
40
Surface
Subbase
Subgrade

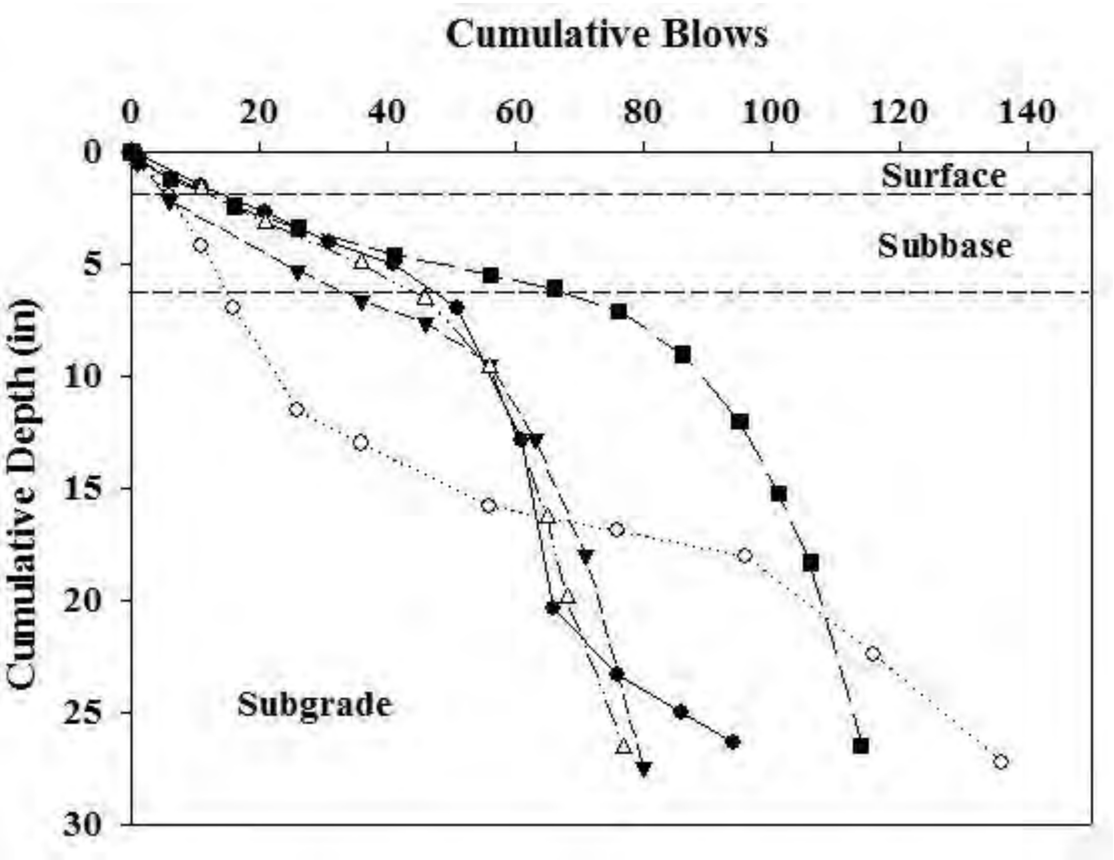
Appendix C – Figure 15. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Jones County – Section 1 (Moscow)

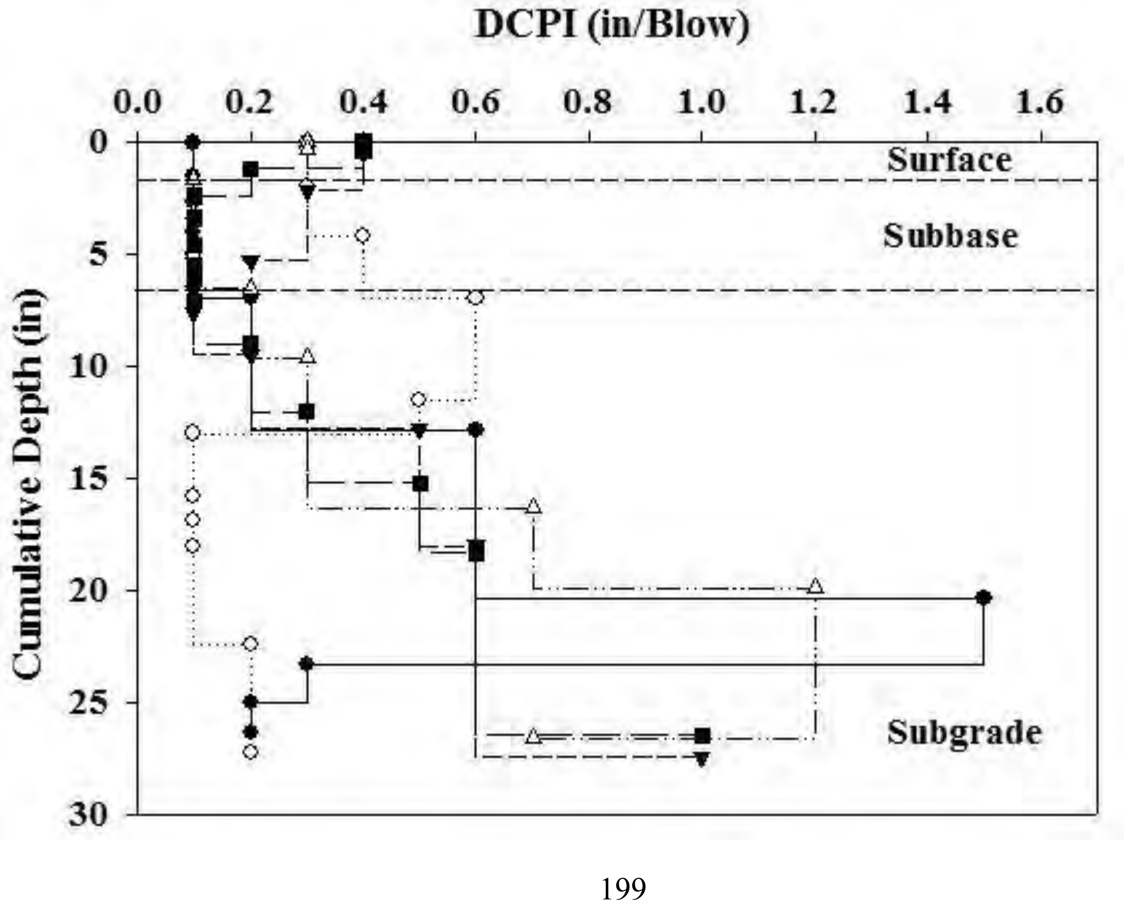

Cumulative Blows
0
20
40
60
80
100
120
Cumulative Depth (in)
0
5
10
15
20
25
30
Surface
Subbase
Subgrade

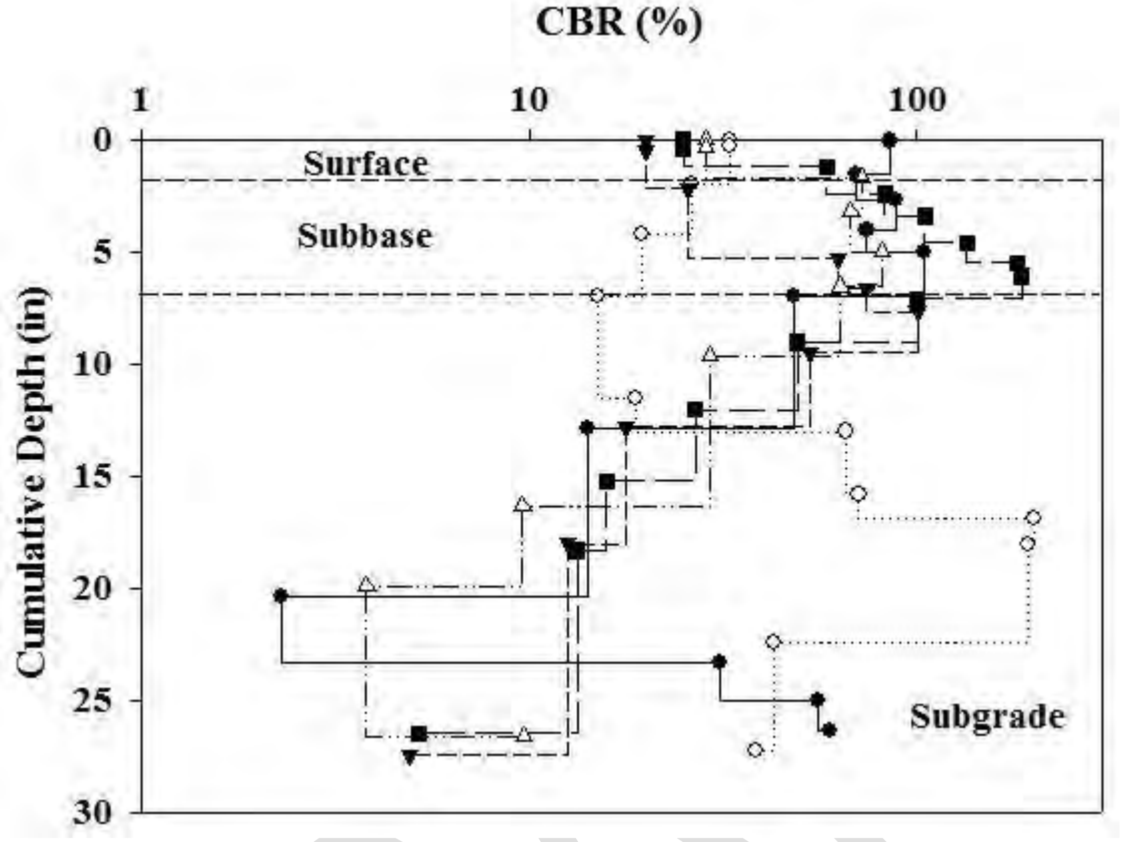

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cumulative Depth (in)
0
5
10
15
20
25
30
Surface
Subbase
Subgrade



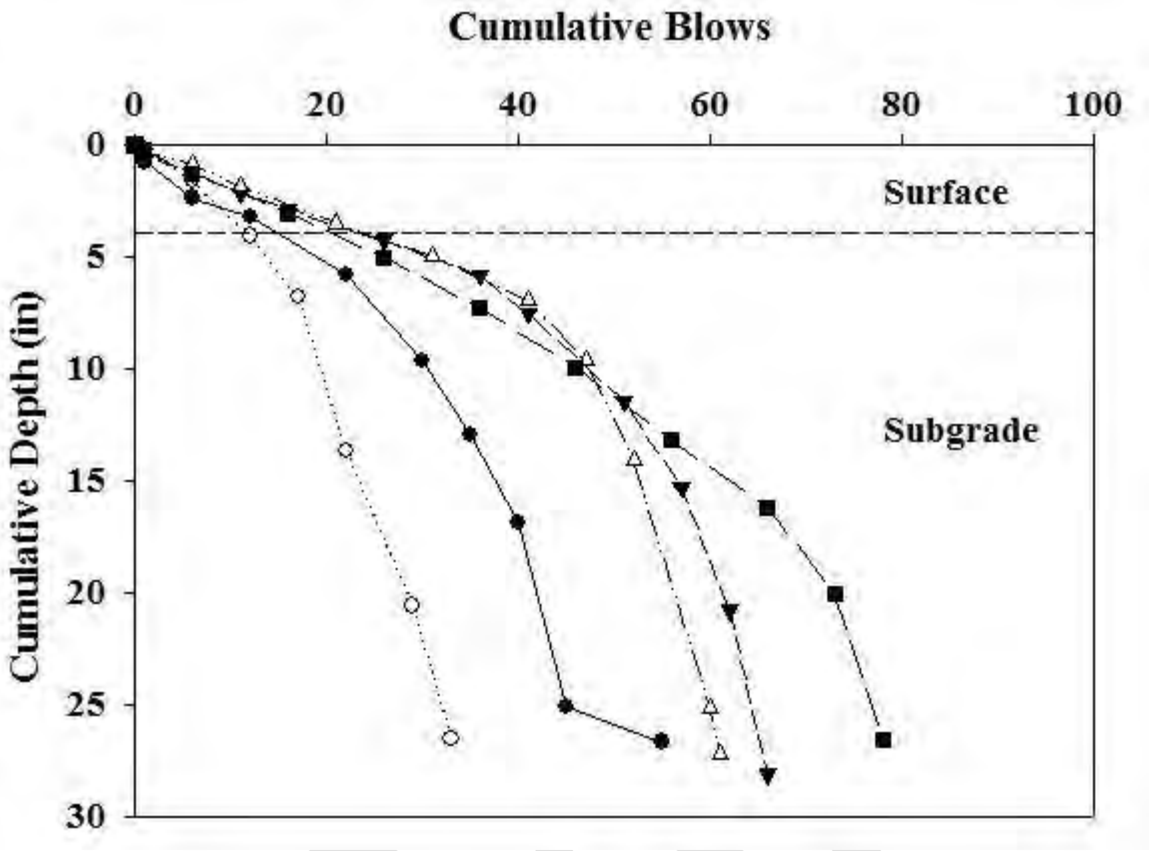
Appendix C – Figure 16. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Jones County – Section 2 (Clay Slurry)

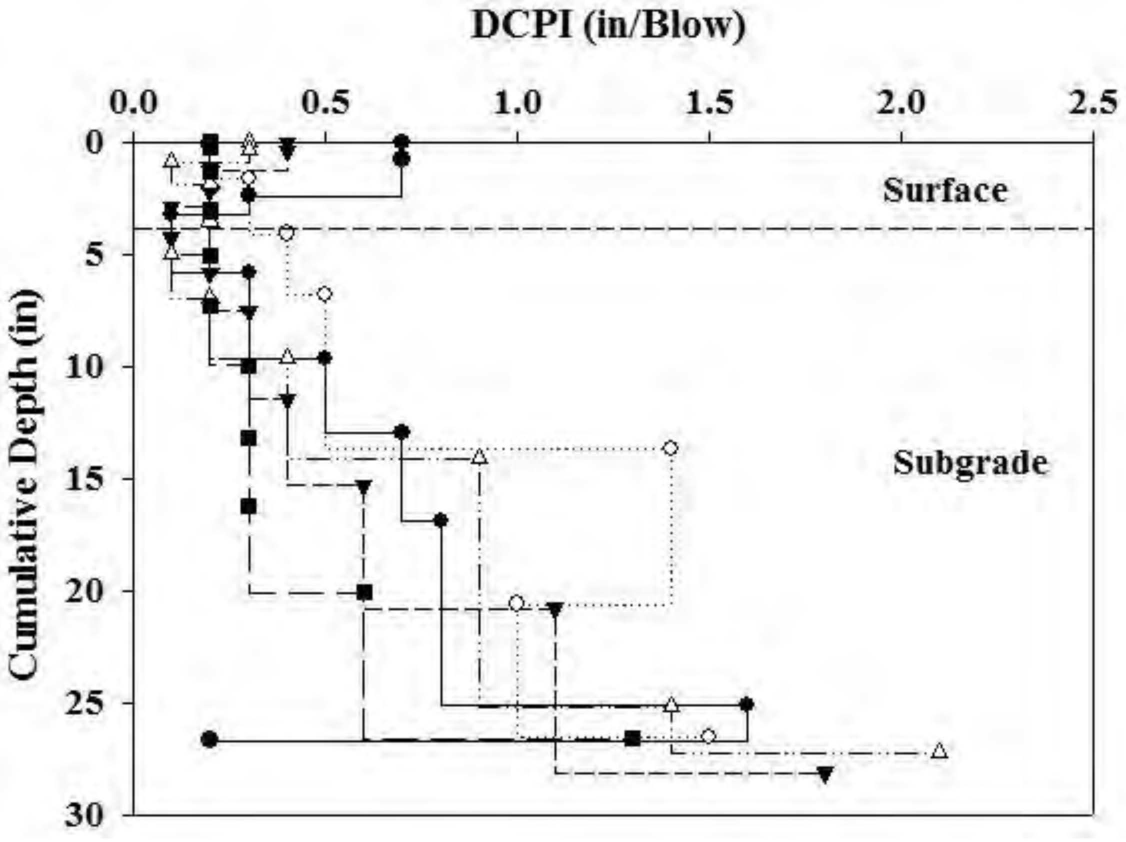

Cumulative Blows
0
20
40
60
80
100
120
140
Cumulative Depth (in)
0
5
10
15
20
25
30
Surface
Subbase
Subgrade

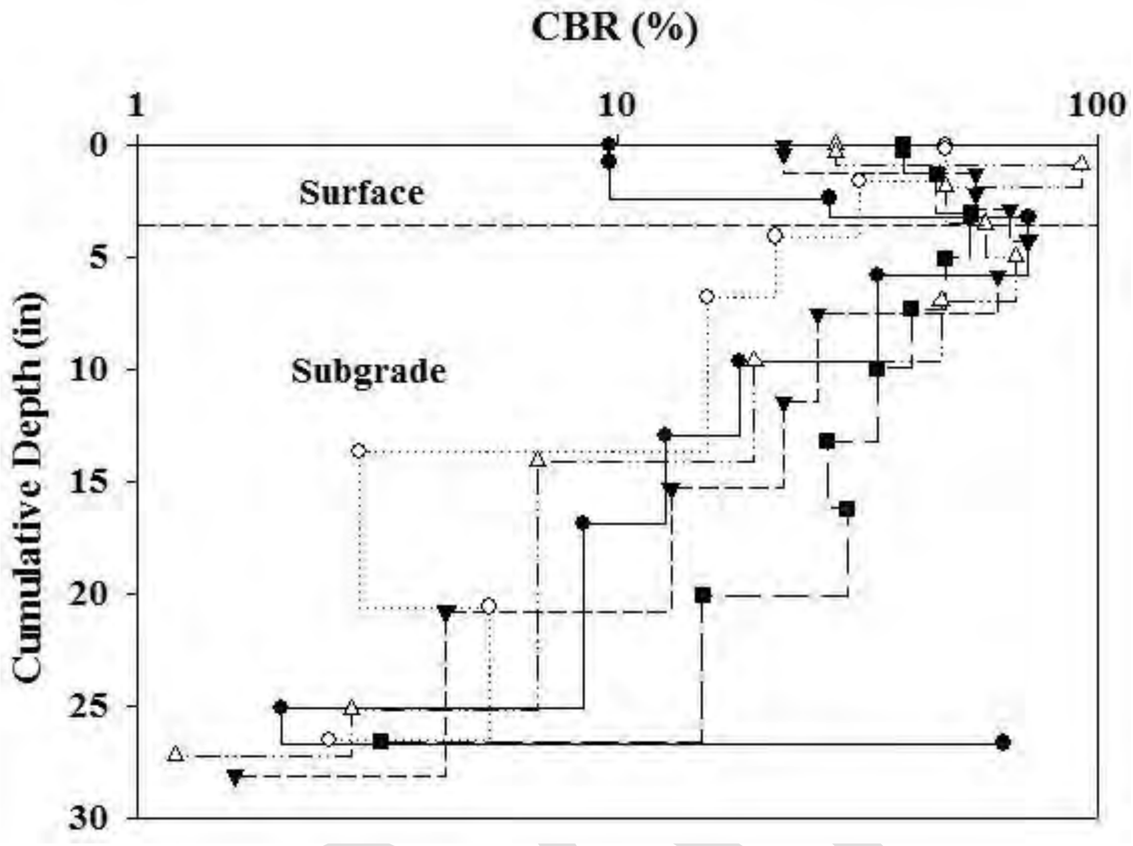

DCPI (in/Blow)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Cumulative Depth (in)
0
5
10
15
20
25
30
Surface
Subbase
Subgrade



Appendix C – Figure 17. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Jones County – Section 3 (Limestone)

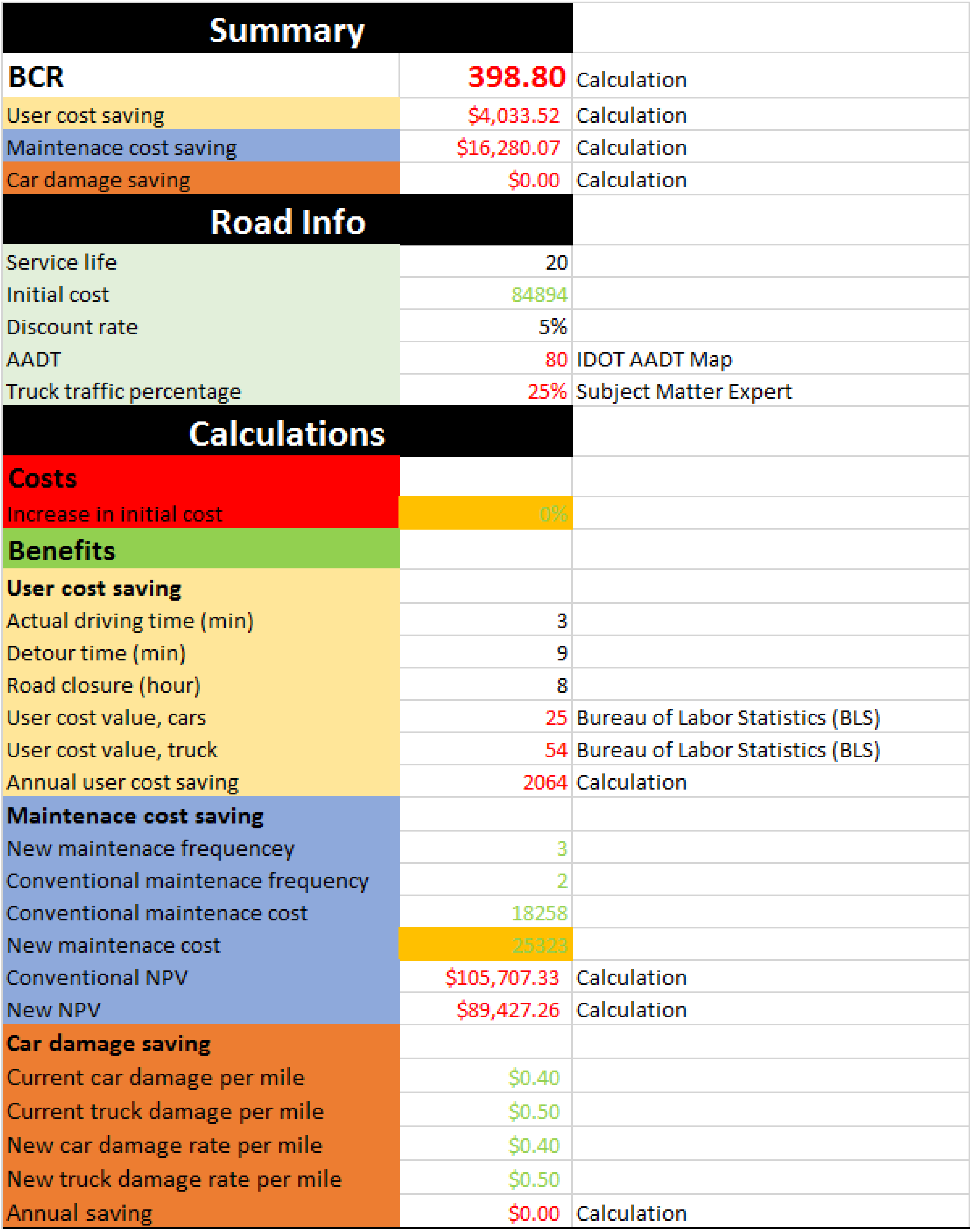

Cumulative Blows
0
20
40
60
80
100
0
5
10
15
20
25
30
Cumulative Depth (in)
Surface
Subgrade


DCPI (in/Blow)
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
25
30
Cumulative Depth (in)
Surface
Subgrade



Appendix C – Figure 18. DCP results for changes in the blows, DCPI, and DCP-CBR with cumulative depth for June 2020 – Jones County – Section 4 (Control)

APPENDIX F: BENEFIT-COST ANALYSIS SPREADSHEET



Summary		
BCR	**398.80**	Calculation
User cost saving	$4,033.52	Calculation
Maintenace cost saving	$16,280.07	Calculation
Car damage saving	$0.00	Calculation
Road Info		
Service life	20	
Initial cost	84894	
Discount rate	5%	
AADT	80	IDOT AADT Map
Truck traffic percentage	25%	Subject Matter Expert
Calculations		
Costs		
Increase in initial cost	0%	
Benefits		
User cost saving		
Actual driving time (min)	3	
Detour time (min)	9	
Road closure (hour)	8	
User cost value, cars	25	Bureau of Labor Statistics (BLS)
User cost value, truck	54	Bureau of Labor Statistics (BLS)
Annual user cost saving	2064	Calculation
Maintenace cost saving		
New maintenace frequencey	3	
Conventional maintenace frequency	2	
Conventional maintenace cost	18258	
New maintenace cost	25323	
Conventional NPV	$105,707.33	Calculation
New NPV	$89,427.26	Calculation
Car damage saving		
Current car damage per mile	$0.40	
Current truck damage per mile	$0.50	
New car damage rate per mile	$0.40	
New truck damage rate per mile	$0.50	
Annual saving	$0.00	Calculation

Appendix F – Figure 1. BCR calculator excel sheet