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

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16. Abstract

The goal of this project was to investigate the performance of granular road sections stabilized with quarry fines byproducts and perform a benefit-cost analysis (BCA) to find the most beneficial quarry fines options for stabilization.

Five sources of quarry fines were selected among 19 quarries across Iowa to build 3 test sections in Jones County, Iowa, and 4 sections in Boone County, Iowa. These two sites are among the most populated roads with relatively stiff subbase and subgrade layers, and they suffer from heavy traffic loads and freeze-thaw effects during winter and spring seasons. Construction and maintenance procedures for the test sections are detailed, and the associated costs of aggregate, hauling, and equipment 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 BCA was performed using the documented construction and maintenance costs for service life scenarios of 20, 30, 40, and 50 years. A benefit-cost ratio (BCR) was calculated for each test section for different scenarios based on various 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 BCRs were compared.

Overall, the results of this study showed that stabilization by quarry fines improved performance by providing binding between the surface aggregates, reducing dust emission and gravel 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. The Limestone and Moscow Mine sections in Jones County, and Moscow and Ames Mine sections in Boone County had the best performance and cost-effectiveness among all stabilized sections. Although the Clay Slurry material was helpful to reduce dust emission compared to the rest of the sections, sections with the Clay Slurry were among the average-performance sections, and the increased construction costs made them a less cost-effective option for both counties.

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USE OF WASTE QUARRY FINES AS A BINDING MATERIAL ON UNPAVED ROADS

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EXECUTIVE SUMMARY

The goal of this project was to examine the effects of using quarry fines byproducts to stabilize granular roadway surfaces and to determine the most cost-effective quarry fines options providing the best serviceability. Quarry fines 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 the 2019–2020 freeze-thaw season. Laboratory tests included sieve and hydrometer analyses, Atterberg limits, compaction tests, miniature vane (mini-vane) shear tests, pocket penetrometer tests, 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 their plasticity indices and shape characteristics. Quarry fines with the highest plasticity were selected for construction of the test sections. Overall, five quarry fines materials (Clay Slurry and Limestone fines from Frenchtown, and Moscow, Ames Mine, and Crescent fines) were used in this project to build four test sections in Boone County and three sections in Jones County. The results of CBR, XRF, mini-vane shear, and pocket penetrometer tests were used to select the quarry fines and determine the optimum amount of fines for mixing with the existing surface aggregates in both counties.

Construction was performed in late October and early November 2019 first in Jones County and then in Boone County. Over the project duration, the test sections were bladed four times in Boone and three times in Jones counties. Although the purpose of this study was to add the fines to the existing surface aggregates, additional new aggregates were required during construction in Boone County for the Clay Slurry section and after construction in Jones County for the Clay Slurry and Moscow sections. Control sections consisting of existing surface aggregates without quarry fines were considered as the base cases for both counties, against which the performance and cost benefits of the demonstration sections were compared.

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 one seasonal freeze-thaw period from 2019 to 2020, to monitor and evaluate the performance of the different surface aggregate materials alone and when mixed with the quarry fines materials.

A benefit-cost analysis (BCA) was conducted based on the construction costs and estimated cumulative costs. Maintenance scenarios were considered for renewing 2 in. of the surface materials whenever maintenance is required. Accordingly, the benefit-cost ratio (BCR), 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.

The laboratory and field test results showed that stabilization of the existing surface aggregates with quarry fines could improve the performance of the sections by reducing gravel loss, total breakage, and dust emission, and improving the mechanical properties of the surface layer, including stiffness and shear strength.

The Moscow and Limestone sections in Jones County and the Moscow and Ames Mine sections 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 based on the results of this project as follows:

- Over time, an increase in fines content and decrease in gravel content were observed for all sections. However, the stabilized sections had better performance regarding these two factors than the control sections in both counties.
- The BCA model developed in Iowa Highway Research Board (IHRB) Project TR-704 was used to evaluate the best cost-effective alternative among all the stabilized sections in Boone and Jones counties (Cetin et al. 2019).
- The quarry fines selected for both counties helped to improve the performance of the stabilized sections in terms of dust emission, surface stiffness and strength, and material deterioration.
- Sections with the lowest hauling time produced the most cost-effective stabilization options.
- The Clay Slurry sections in both counties exhibited average performance compared to the other stabilization options but performed better than the control sections. However, the higher equipment, labor, material, and hauling costs resulted in BCR values lower than 1 for these test sections.

CHAPTER 1. INTRODUCTION

1.1. Problem Statement

Granular-surfaced (unpaved) roads are large portions of road systems in the US, and particularly in Iowa. The sustainability of unpaved roads is critical to the rural economy, given these roads provide access to rural areas and enable the transportation of agricultural products. Any interruption of traffic on these roads 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 the construction of an unpaved road. 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. If the quality of coarse aggregates is low, the aggregates can crush under traffic loads, increasing the fines content in the aggregate matrix. In other cases, the quality of the aggregates may be high, but the aggregates float on the road surface due to a lack of adequate fines to bind the particles of the aggregate matrix together.

Chemical stabilization can be applied to help improve the binding of coarse aggregates in unpaved roads; however, this method is not usually the most economical or easy to apply. Therefore, it is vital to find alternative materials and methods to overcome this problem in a sustainable, economical, and environmentally friendly way. One of the potentially effective alternatives to help meet these criteria while improving binding is the use of quarry fines, which are generated at an approximate rate of 175 million tons (159 million metric tons) per year. At this rate, as much as 4 billion tons (3.6 billion metric tons) of quarry fines have likely accumulated to date (Wood and Marek 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 economical fines.

County engineers and their employees invest considerable effort in managing and maintaining granular roads. When maintenance and construction of granular roadways become costly, counties may spend a considerable portion of their budgets (sometimes up to 28% of the total county budget) to purchase granular materials (excluding placement and maintenance) just to replace the materials 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, and (6) insufficient road maintenance. This study aims to study the first, third, and fourth problems listed.

In this project, the research team conducted laboratory and field tests to examine the impact of incorporating waste quarry fines into granular aggregates used in unpaved road construction, using materials collected from various quarries. Based on the laboratory test results, field test sections were constructed using materials from selected quarries. The field performance of test sections built with different quarry fines were compared in terms of their abrasion resistance,

freeze-thaw resistance, density, material loss, modulus, and gradation change. Comprehensive cost-performance and benefit-cost analyses (BCAs) 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 was to determine the effects of adjusting the gradation and plasticity of surface aggregates by using quarry fines to provide binding and thereby increase the performance of the surface. The specific objectives of this project were as follows:

1. Determine the stiffness and strength of unpaved road materials blended with different sources and types of quarry fines
2. Determine the performance of field test sections built with optimum quarry fines content
3. Analyze the benefit-cost ratio (BCR) and cost-effectiveness of these options

1.3. Site Selection

After discussions with county engineers, Boone and Jones counties were selected as the locations to construct the test sections for this project (Figure 1).
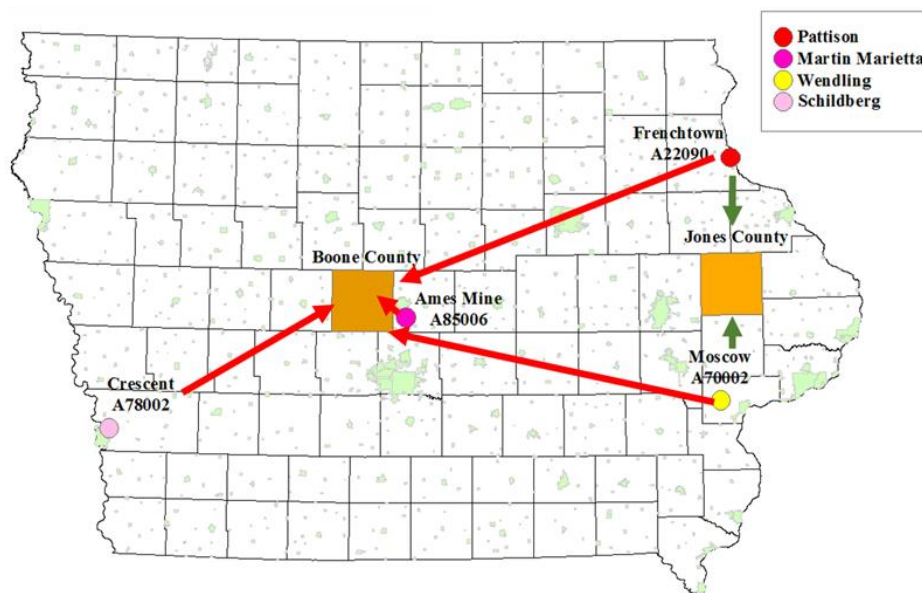
Figure 1. Locations of the quarries and test sections in this project

Quarry fines having some degree of plasticity were selected for mixing with the surface aggregates. The ratios of fines and aggregates to be used in the mixtures were selected based on the results of California bearing ratio (CBR) tests, which are discussed in Chapters 3 and 4. Clay Slurry from the Frenchtown quarry (A22090), Ames Mine quarry fines (A85006), Moscow quarry fines (A70002), and Crescent quarry fines (A78002) were selected for constructing the

test 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 test sections in Jones County.

These sites were selected based on their annual average daily traffic (AADT) counts, which were 100 vehicles per day (VPD) for Boone County and for 70 VPD for Jones County. These values as well as the truck percentages were slightly above average compared to other granular-surfaced roads in Iowa (Iowa DOT 2012). The surface elevations of the road sections were also reasonably higher than the surrounding terrain, ensuring good conditions for drainage. There was a 5 in. thick subbase layer above the subgrade in both counties, which were constructed with the same surface aggregates used in the test section mixtures. Furthermore, the subgrade was very strong (CBR >5) in 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 gradations of surface aggregate materials in granular roadways. The performance of the sections built in two different counties was monitored after construction, and a comprehensive BCA was performed to determine which types and sources of quarry fines would be most beneficial to minimize overall construction and maintenance costs.

1.5. Organization of the Report

This report includes eight chapters as follows:

- Chapter 1 explains the problem statement, objectives, site selection, and the significance of the research
- Chapter 2 consists of a review of previous studies on granular roads, previous use of quarry fines, and cost analysis
- Chapter 3 presents the different methods of laboratory and field tests that were conducted in this project
- Chapter 4 provides information about the geomaterials and the results of the laboratory tests including index properties, compaction characteristics, strength, and chemical compositions of quarry fines used in this study
- Chapter 5 describes the sites, test sections, and construction procedures used
- Chapter 6 provides the results of the field tests over a period of one year of service after construction
- Chapter 7 presents the economic analysis on all of the different control and test sections
- Chapter 8 presents the conclusions of this project and provides recommendations for further research
- Supporting materials are presented in the appendices

CHAPTER 2. BACKGROUND

2.1. Quarry Fines

Unbound aggregates are the primary constituents of the surface courses of granular roadways, and large quantities of aggregates are required annually for construction and maintenance of such roads. However, due to a lack of sufficient natural resources, such aggregates are becoming increasingly scarce and expensive. The annual production of nearly two billion tons of aggregate in the US costs approximately $17.2 billion, which contributes to an average of $40 billion to the US gross domestic product (Ricci 2014). The byproducts of aggregate production are often considered as waste, and the disposal and stockpiling of such byproducts poses a significant problem for the aggregate quarry industry (Satvati et al. 2020a). Blasting, crushing, drilling, excavating, and screening operations performed during the extraction process in the aggregate industry 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, piling of such quarry fines is not favorable for aggregate industries due to the pollution and loss of usable land that it creates (Gautam et al. 2017).

Moreover, recent increased interest in the use of larger aggregate sizes in the construction industry encourages the production of aggregate gradations with lower fines content (<US Sieve #200), which leads to an imbalance in the aggregate production process and excessive increases in the amount of waste fines generated. The amount of quarry fines produced during aggregate production processes 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 sand particles (between 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 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. 2020a, 2020b; 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 economical and environmental benefits (Mwumvaneza et al. 2015).

The use of quarry fines in roadway applications compared to other stabilization materials makes them a suitable option for departments of transportation (DOTs) and local roads agencies due to their relatively lower costs and wide availability. Such application of quarry fines has been a focus of several previous studies (e.g., Kalcheff and Machemehl Jr 1980, Kumar and Hudson 1992, Puppala et al. 2008, Stroup-Gardiner and Wattenberg-Komas 2013).

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

Xiao et al. (2016) studied the effects of mixing quarry fines byproducts with coarse crushed granite aggregates (CCGA) in different percentages for pavement foundation applications. Permeability and monotonic triaxial compression tests were performed and the optimum percentages that gave the highest stability without compromising drainability were determined.

Mwumvaneza et al. (2015) examined the suitability of using quarry fines in pavement layers by investigating shape characteristics, gradation, and mineralogy of quarry fines produced in different stages of aggregate production and evaluating the shear strength properties and unconfined compressive strength of quarry fines treated with portland cement and Class C fly ash. Increases of up to 30 times 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 and subgrade as well as weather-related conditions, traffic loads, and lack of drainage all 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 subjected to the damaging effects of weather and load conditions as well as blading and compaction during construction and maintenance over their service lives. The combination of these factors alters the aggregate shape characteristics and leads to material loss and performance measures such as increased dust emission and reduced stiffness and strength (Cetin et al. 2019, Fathi et al. 2019, Hardin 1985, Lade et al. 1996, Lees and Kennedy 1975, Marsal 1967, Nurmikolu 2005, Paterson 1991, Satvati et al. 2020a, White et al. 2004, Wu et al. 2020, Zeghal 2009).

The quality of the aggregate materials, including abrasion resistance, has a significant impact on 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 is greater than those in warmer regions. Deterioration of granular materials includes material sizes being reduced from coarse aggregates down to fine particles, resulting in reduced surface layer thickness and leading to the development of several types of distress such as potholes, rutting, and washboarding, consequently lowering the ride quality. Furthermore, dust emissions are greater for roads with higher fines contents, which affects the quality of life for residents of rural regions (Li et al. 2015; Cho et al. 2006; Mahedi et al. 2020; Nurmikolu 2005; Satvati et al. 2020a; Cetin et al. 2019; Vallejo et al. 2006; White and Vennapusa 2013, 2014; Wu et al. 2020).

To help improve freeze-thaw durability and slow the deterioration and loss of granular surface materials, Wu et al. (2020) compared the effectiveness of several stabilization methods including mixing ground tire rubber or portland cement with surface aggregates, replacing aggregates with steel slag, installing aggregate columns, adding clay slurry to an optimized aggregate gradation, and mixing proprietary chemical stabilizers with surface and subgrade materials. The study also included laboratory tests and field tests to monitor the stiffness and shear strength of the road layers through freeze-thaw seasons. Results of the study showed that stabilization with cement and clay slurry increased the stiffness and shear strength of the surface and subgrade layers. Moreover, it was found by measuring gradations over time that sections stabilized with clay slurry had lower gravel loss relative to the control sections.

Li et al. (2015) evaluated the performance of granular roads stabilized with cement, fly ash, bentonite, macadam stone base, aggregate columns, and geosynthetics. The 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 in the long term relative to the other stabilization methods (Li et al. 2017).

Freezing and thawing along with lack of drainage can cause capillary water to become trapped on top of the frozen subgrade layer and saturate the overlying surface aggregate materials. Subsequent high traffic loads, in some cases coupled with aggregate materials of low abrasion resistance then cause deterioration of the coarse surface aggregates, which increases the fines content. The result is that the stiffness and shear strength of the road layers are affected after each freeze-thaw period, often leading to the development of various distresses such as aggregate loss, potholes, and rutting (Mahedi et al. 2020). For example, Vallejo et al. (2006) reported that the use of low abrasion-resistance materials in the subsurface of paved roads along with unfavorable weather conditions and high traffic loads resulted in aggregate crushing. Similarly, Nurmikolu (2005) showed that the use of aggregate materials with higher porosity and moisture content for road construction in cold regions were disadvantageous for frost susceptible weather conditions. Li et al. (2018) reported that certain parts of Iowa, such as the northeast, produced aggregates with higher abrasion resistance than the sources in the west and south, and reasoned that the stronger materials should last longer than granular materials from southwestern Iowa.

Spreading additional virgin aggregates and blading the existing surface aggregates are two common practices to renew the surface course by repairing the freeze-thaw damage. However, rather than simply repairing damage after it occurs, reducing the frost susceptibility of surface layers by stabilization could be a better option to minimize deterioration and reduce maintenance costs (Ashtiani et al. 2019; Cetin et al. 2019; Farhangi et al. 2020; Morovatdar et al. 2019; Satvati et al. 2020a, 2021; White and Vennapusa 2013, 2014).

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-effectivity of alternative options as well as a base option (Vosoughi et al. 2017). An LCCA was initially

conducted by state agencies in the 1950s to evaluate the cost-effectivity 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, which 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 the 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, the future costs, including any maintenance and rehabilitation costs, should be discounted to the current year by calculating the net present value (NPV) for the alternatives.

In this current study, the only maintenance procedure considered was renewing the surface layer with virgin aggregate materials, while routine blading that happens regularly for all sections and has a low cost was considered to be the same for all sections. Thus, blading has almost zero effect on the NPV compared to the other significant costs, particularly in extended periods longer than 20 years (Cetin et al. 2019). Moreover, the salvage value, which represents the value of an investment alternative at the end of the project life, is usually 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. (2019, 2021) 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. 2020a).

The present project utilizes a previously developed BCA model for two gravel roads constructed in the rural road system. The findings of the cost analysis part of this current project may be helpful to DOTs and city and county engineers to determine the most efficient and cost-effective quarry fines stabilization alternatives for existing granular roads, thereby minimizing the material and hauling costs associated with construction and maintenance operations. Performing a BCA is essential prior to making any decisions to invest in transportation infrastructures in order to investigate the effectivity of a project in employing the resources, due to the need to facilitate social and economical activities (Carlsson et al. 2015, Dharmadhikari et al. 2016, Prest and Turvey 1965, Satvati et al. 2019). 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. 2021, Walls III and Smith 1998).

Defining the costs, evaluation of benefits, choosing the discount rate, and relevant constraints are the four major approaches considered in BCA (Prest and Turvey 1965). The four main steps in performing BCA are 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 (Dharmadhikari et al. 2016). The base case is defined as the most readily available choice that comes to mind. In this current study, the control section with existing aggregates and without any stabilization was considered as the base case.

Further, careful attention should be paid to defining and evaluating the benefits for the alternative options to obtain an accurate analysis. Projects can vary widely in their purposes and specific details; therefore, the benefits of one project should not be considered beneficial for another project due to the different circumstances (Gibson and Wallace 2016). The annual costs and benefit values, and the NPV of the project properties with consideration of a valid discount rate, shape the overall figure of the BCA (Layard 1994). Major challenges in conducting BCAs for transportation infrastructures are associated with traffic forecasting, cost estimations, discount rates, 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 BCR, which is the ratio of the NPV of the benefits divided by the NPV of the costs of a project (Walls III and Smith 1998). A BCR value greater than 1 indicates that the alternative could be beneficial relative to the base case. Alternatively, a BCR value lower than 1 indicates that the alternative is costlier, and the benefits are not sufficient to make it beneficial relative to the base case.

Cetin et al. (2019) and Satvati et al. (2020a) investigated the use of different aggregate options with different hauling and material costs to construct granular road sections in Decatur County, Iowa. A BCA model was developed and was used to evaluate the benefits of alternatives in terms of dust emission, stiffness, shear strength, material loss, 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 hauled from farther sources for regions where there is a lack of high-quality aggregates, as the higher quality materials can sustain their performance for a longer period of time and require less frequent maintenance (Cetin et al. 2019, Satvati et al. 2020a).

CHAPTER 3. METHODS

This chapter describes the methods for both laboratory and field tests. Laboratory tests were conducted to determine the classification and 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, dust emission, and surface roughness.

3.1. Laboratory Tests

Laboratory tests including particle-size analysis, Atterberg limits, Proctor compaction, CBR, pocket penetrometer, and miniature vane (mini-vane) shear tests were conducted in the laboratory to determine the particle size distribution (PSD), plasticity characteristics, maximum dry density (γ_{dmax}), optimum water content (w_{opt}), shear strength, and compaction characteristics of the surface and subgrade materials. In addition, X-ray fluorescence (XRF) tests were performed by the Iowa DOT to determine the elemental compositions of quarry fines materials.

3.1.1. Particle-Size Analysis

A particle-size analysis was performed in accordance with ASTM D422, Standard Test Method for Particle-Size Analysis of Soils. Sieve sizes used ranged from 1.5 in. (75 mm) to US Sieve #200 (75 μm). Additionally, to determine the size distribution of fine particles (particles passing the #200 sieve), hydrometer tests were conducted on the materials passing the US Sieve #10 (2 mm). To produce a representative sample for testing, ASTM D75-13, Standard Practice for Sampling Aggregates, was followed. Figure 2 shows the sieve test setup used during sieve analysis.
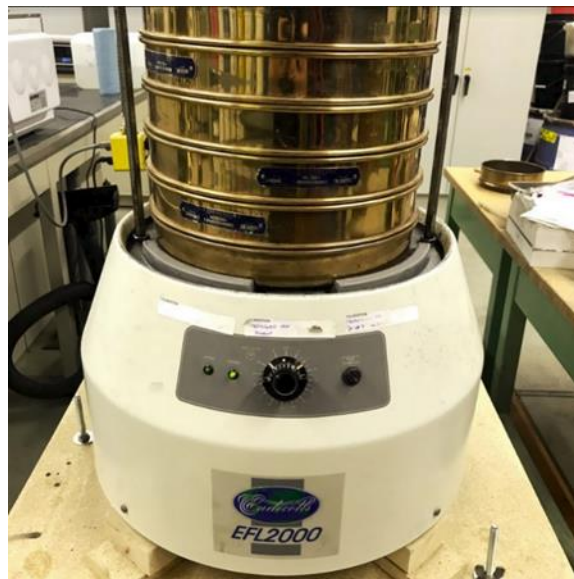
Figure 2. Shaker and sieves used for sieve analysis

3.1.2. Atterberg Limits

Atterberg limits tests were performed on the surface aggregates and subgrade materials to determine their liquid limit (LL), plastic limit (PL), and plasticity index (PI). The wet preparation-multiple point test method was conducted on materials sieved through the US Sieve #40 (425 μm). ASTM D4318-10e1, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, were followed for these analyses. A standard brass cup (Figure 3) and a glass plate were used to determine the LL and PL, respectively.

Figure 3. LL 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 in accordance with ASTM D2487-11, Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System [USCS]), and ASTM D 3282-09, Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes (American Association of State Highway and Transportation Officials [AASHTO] Soil Classification System).

3.1.4. Proctor Compaction Test

Standard Proctor compaction tests, in accordance with ASTM D698-12e1, 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 both surface aggregates and subgrade materials to determine their optimum water content (w_{opt}) and maximum dry density (γ_{dmax}). Figure 4 shows the equipment used for compaction tests.

<div align="center">(a)   (b)</div>

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

3.1.5. CBR Tests

CBR tests were performed to evaluate the shear strength of the surface aggregate and subgrade materials, in accordance with ASTM D1883-16, Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. Each test specimen was compacted at its optimum moisture content with standard Proctor energy. CBR tests were performed on both un-soaked and soaked specimens to simulate the optimum and saturated conditions in the field, respectively. Figure 5 shows the equipment used for CBR tests in this study.

Figure 5. CBR device used in this study

3.1.6. Moisture Determination

Field samples were collected from each section each time that field tests were conducted, and their moisture contents 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 Setting Time Tests

Pocket penetrometer tests (Figure 6) were performed on mixtures of water and the quarry fines passing US Sieve #200 to assess the penetration resistance of saturated quarry fines over time.

Figure 6. Pocket penetrometer device used in this study

This test helped to determine which of the quarry fines materials had a greater ability to lose water at room temperature (70°C) and which materials reached the device's maximum measurable penetration resistance of 4.5 tsf most quickly while drying at room temperature.

3.1.8. Mini-Vane Shear Tests

Mini-vane shear tests are typically performed to measure the undrained shear strength of very soft to stiff fine-grained clayey soils (Figure 7).
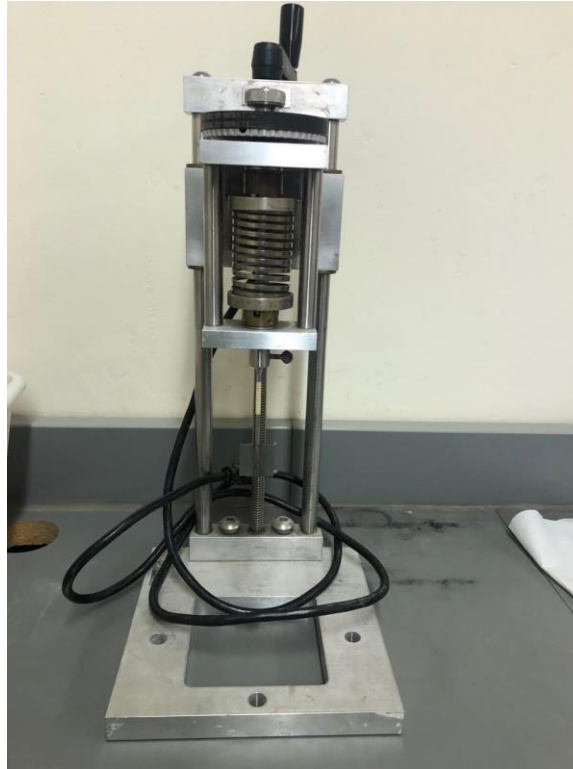
Figure 7. Mini-vane shear device used in this study

In this method, an electric motor applies a torque at a constant rate to remolded or undisturbed soil specimens, creating a cylindrical shear surface around the vane. Mini-vane shear tests in this study were performed in accordance with ASTM D4648/D4648M-16, Standard Test Methods for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil.

3.1.9. XRF Spectroscopy

The chemical constituents of the quarry fine materials were determined by XRF tests performed by the Iowa DOT Materials Laboratory. In this test, electrons are released from their atomic orbital position when excited by an X-ray that causes a burst of energy in the form of a fluorescent (secondary) X-ray to be emitted, which is analyzed by spectroscopy to determine the elemental compositions of a sample.

3.1.10. Slaking Tests

Slaking tests were performed to investigate the long-term moisture susceptibility of the treated and untreated materials and to determine the time required for a saturated specimen to disintegrate (Gopalakrishnan et al. 2010). The test specimens were first sieved through the US Sieve #40 and then compacted using the Iowa 2 in. by 2 in. compaction device at optimum moisture content (Figure 8) (Edgar 1963).

(a)   (b)
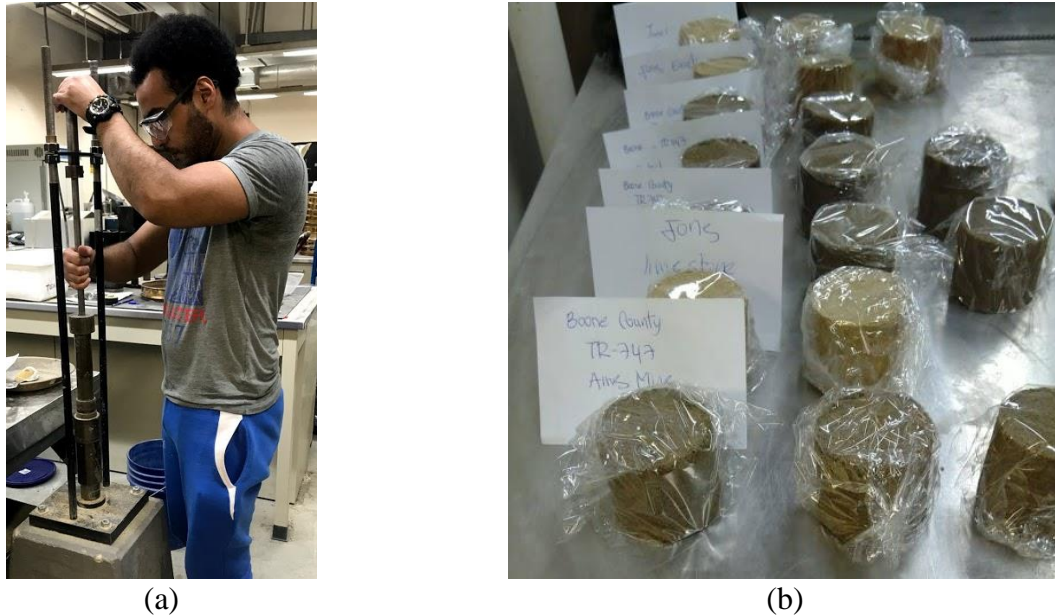
Figure 8. (a) Compact slaking specimens using Iowa 2 in. by 2 in. compaction device and (b) prepared specimens

The specimens were tested shortly after compaction without curing. Plastic wrap was used to seal the specimens immediately after compaction to prevent moisture loss.

To perform the slaking tests, specimens were placed on a US Sieve #4, submerged halfway in tap water at room temperature, and left to soak. The temperature and elapsed time (slaking time) at which the specimens fully disintegrated were then recorded (Figure 9).
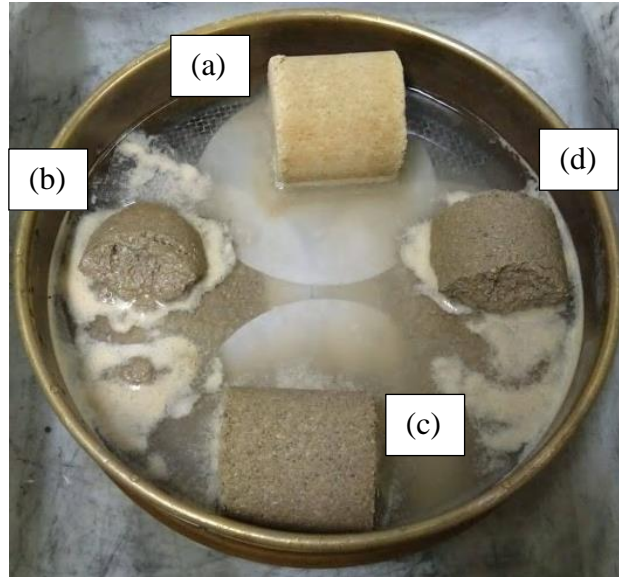
Figure 9. Slaking test for 2 in. by 2 in. specimens of Jones County existing surface aggregate mixed with (a) 2% Clay Slurry, and (b) 2%, (c) 6%, and (d) 10% Moscow fines

3.2. Field Tests

Field tests consisting of falling weight deflectometer (FWD), lightweight deflectometer (LWD), dynamic cone penetrometer (DCP), nuclear gauge density/moisture, international roughness index (IRI), and dustometer tests were conducted on the test sections to determine the stiffness, strength, in-situ density, moisture content, roughness, and dust emission, respectively, of the surface materials. All tests were performed at five points starting 50 ft into the section and spaced at 100 ft intervals for all sections.

3.2.1. FWD Tests

In this project an SN121 JILS model FWD was used to determine the elastic modulus of the surface, subbase, and subgrade layers. The FWD device used in this study applies a uniform pressure via a segmented loading plate. In order to achieve a good contact between the 12 in. diameter plate and the surface materials, a 1,200 lb static load was applied on the surface. Then, three different dynamic loads of 4,000; 4,500; and 5,000 lb were applied on the plate to create the deflection basin while nine geophones (velocity sensors) measured the deflections on the surface. Table 1 shows the configuration of the FWD device used for this study.

Table 1. FWD configuration

Parameter	Value
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)	1,200
Dynamic loads (lb)	4,000; 4,500; 5,000

[a] Horizontal coordinates of sensors relative to loading plate are -12, 0, 6, 12, 18, 24, 36, 48, and 54 in.

Figure 10 shows a schematic diagram of the FWD test setup, deflection basin, and layers of the granular-surfaced road.
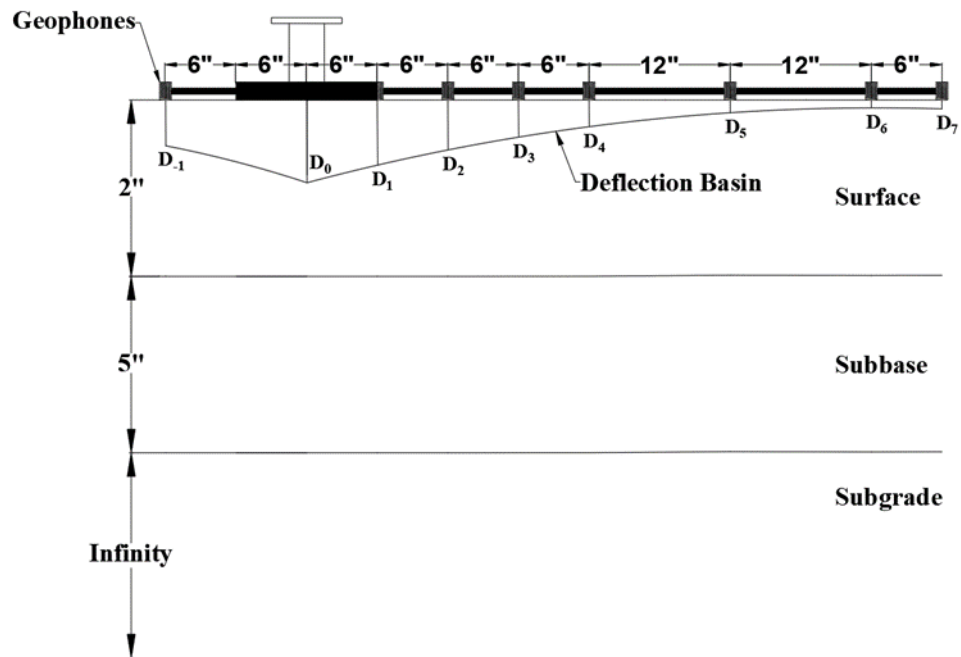
Figure 10. Schematic of FWD test configuration

Figure 11 shows the FWD device used in the study.

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Figure 11. FWD device used in this study

For the purpose of analyzing the results of FWD tests, back-calculation was performed based on the dynamic loads and peak deflections that were observed under the geophones, using a three-layered system model (Boussinesq 1885, Grasmick et al. 2014, Li et al. 2017, Odemark 1949, Saltan et al. 2013, Stokoe et al. 1994). In this regard, BAKFAA 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 Layered Elastic Analysis (LEAF) 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. The inputs in BAKFAA are the seed values for elastic modulus, thickness, and Poisson's ratio values for each layer, the 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 the surface, subbase, and subgrade layers were assumed to be 0.3, 0.35, and 0.4, respectively. BAKFAA minimizes the root mean square error (RMSE) between field-measured deflections and calculated deflections and iteratively alters the user-defined seed moduli for all layers until the generated and measured deflection measurements match within a user-defined tolerance. Seed modulus values for the surface, subbase, and subgrade layers were considered to be 100 ksi, 40 ksi, and 10 ksi, respectively.

3.2.2. LWD Tests

The LWD is a nondestructive test specifically developed to perform rapid field-testing of pavement materials. LWD tests in this study were conducted to determine the maintenance frequency required for the test sections. The tests were performed at five points within each test

section to evaluate the in-situ composite elastic modulus (E$_{Comp}$) (or 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), creating a need for road maintenance. Therefore, the surface layer temperature and water content are presented along with the E$_{Comp.}$ data for each test section. The ambient temperature of the surface course was measured using a thermocouple inserted 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 nuclear gauge field tests. Figure 12 shows a photo of LWD test device used in this study, which features a 22 lb hammer with a drop height of 19.69 in., and a base plate diameter of 11.81 in.

Figure 12. LWD device used in this study

The in-situ elastic modulus is calculated based on the average vertical deflection as shown in equation 1.

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

where E_{LWD} is elastic modulus, σ_0 is the average vertical contact stress applied underneath the plate, v is Poisson's ratio (assumed to be 0.4), d_0 is the measured deflection, A is plate radius,

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and f is a shape factor, which is assumed to be two, corresponding to a uniform stress distribution (Vennapusa and White 2009).

3.2.3. DCP Tests

DCP tests were used to determine the shear strength and thicknesses of the granular surface and subgrade layers for each test section. DCP tests were conducted in accordance with ASTM 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 slide hammer. Figure 13 shows the DCP test setup.

Figure 13. DCP device used in this study

Using the DCP Index (in./blow) as the rate of penetration and empirical correlations based on the ASTM standard, the CBR values for each layer were estimated using equations 2 and 3.

$$CBR= \frac{292}{DCPI^{1.12}}$$
(2)

$$CBR= \frac{1}{(0.017019 \times DCPI)^2}$$
(3)

Sudden changes in the slope of the cumulative blows versus depth plot indicate a change in the

layer characteristics. Such changes in slope were used to estimate the thickness of the surface layer, as shown in Figure 14.
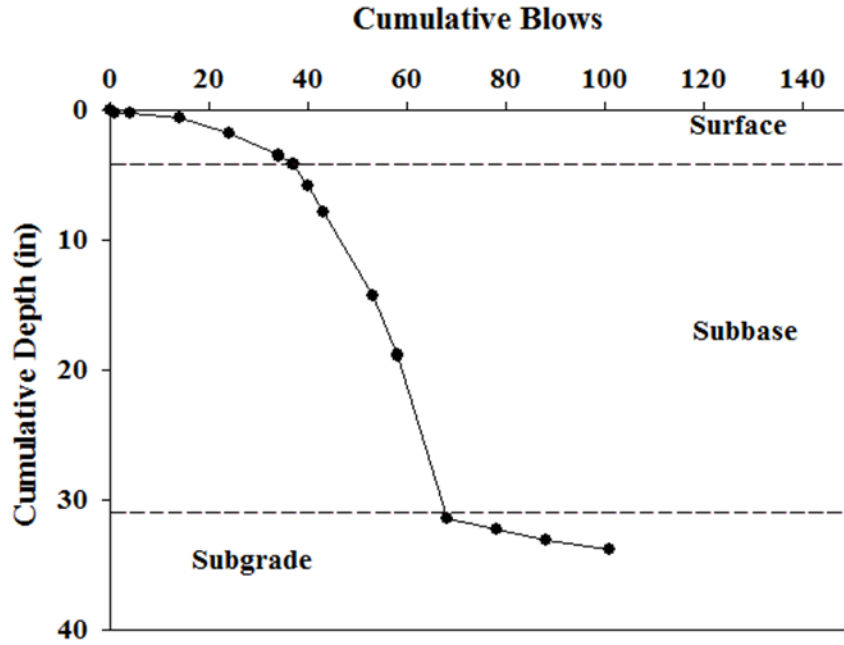
Figure 14. DCP results: cumulative blows vs. cumulative depth

The weighted averages of the CBR values within the surface aggregate layer (CBR_{AGG}) and subgrade layer (CBR_{SG}) are then calculated as shown in equations 4 and 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, respectively, CBR_i is the CBR value calculated by equation 2 or 3 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.

3.2.4. IRI Measurements

The roughness of the road surface is representative of ride quality and is an important factor to evaluate the granular roadway performance. Lower roughness values produce 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 smartphone application named Roadroid. This software uses a built-in smartphone accelerometer

to evaluate the roughness index of the different surfaces in a rapid and cost-effective manner (Akinmade et al. 2017). In this method, a smartphone was mounted on the windshield of a one-ton truck and the calculated IRI (cIRI) values were measured and stored in the phone while driving between 40 and 50 mph. Photographs are also taken by the application during the survey. Friction values were also measured by the application, which requires the driver to reach a speed of more than 30 mph and then apply the brakes until the vehicle comes to a complete stop. The friction value (μ) and a photograph of the stop point are stored in the phone. The data are then uploaded and made available on the Roadroid website along with a Global Positioning System (GPS) location of the test.

3.2.5. Dustometer Tests

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 project duration. Figure 15 shows the setup of the dustometer device, which is attached to the bumper of a one-ton truck by a steel bracket.

(a)   (b)

(c)	(d)

Figure 15. Dustometer test setup: (a) dustometer device, (b) suction pump, (c) filter paper before test, and (d) filter paper after test

It has a 12 in. × 12 in. steel mesh with a 0.0079 in. mesh sieve to prevent large particles from damaging the tightly held filter paper. A 1/3 horsepower suction pump was 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 mph. A 4,400 Watt gasoline-powered generator provided power for the suction pump. The filter paper was removed after performing the test over a section, and the mass of the dust on the paper was divided by the length of the section to determine the amount of dust generated per unit length.

3.2.6. Nuclear Gauge Test

The nuclear gauge test, a fast and nondestructive test, was performed by the Iowa DOT to measure the in-situ density and moisture content of the surface material by attenuation of the gamma radiation at a known depth. The tests were 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 nuclear gauge device should be placed in good contact with the surface of the granular roadway. The device recorded the wet density and the water content (w), from which the dry density (γ_{dry}) was calculated using equation 6.

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

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

Figure 16 shows a nuclear density gauge device similar to the one used in this study.

Cetin et al. 2019

Figure 16. Nuclear density gauge test device

CHAPTER 4. MATERIALS

The results from 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 collection of quarry fines in the beginning of the project.
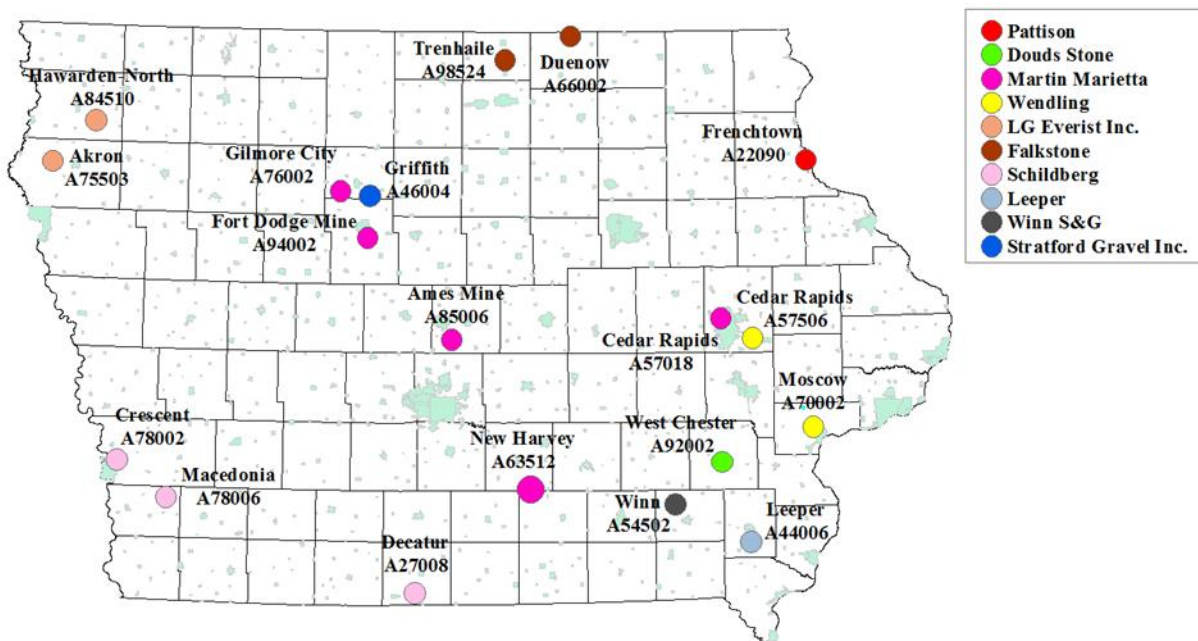
Figure 17. Location of the quarries investigated for collection of quarry fines

Nineteen quarries in total were investigated from across Iowa and their gradations and Atterberg limits were examined. Quarry fines with high plasticity were selected and used for this project to construct the test sections in Boone and Jones counties.

Figure 18 shows the quarry fines materials that were selected for test section construction in this project.

Figure 18. Quarry fines used in test section construction

It should be mentioned that the fines labeled Clay Slurry were sprayed on the road surface in the form of a liquid slurry, and the photograph shows a mixture of existing aggregates with clay slurry after its application in Jones County.

The Moscow, Crescent, and Ames Mine fines were dried by the quarries and collected from piles, whereas the Limestone and Clay Slurry were collected from ponds. However, the Limestone fines were first dried to around 20% moisture content before hauling to ease the construction process.

4.2. Gradation

Figure 19 shows the gradations of the surface aggregate (AGG) and subgrade (SG) materials from Boone and Jones counties before construction of the test sections.
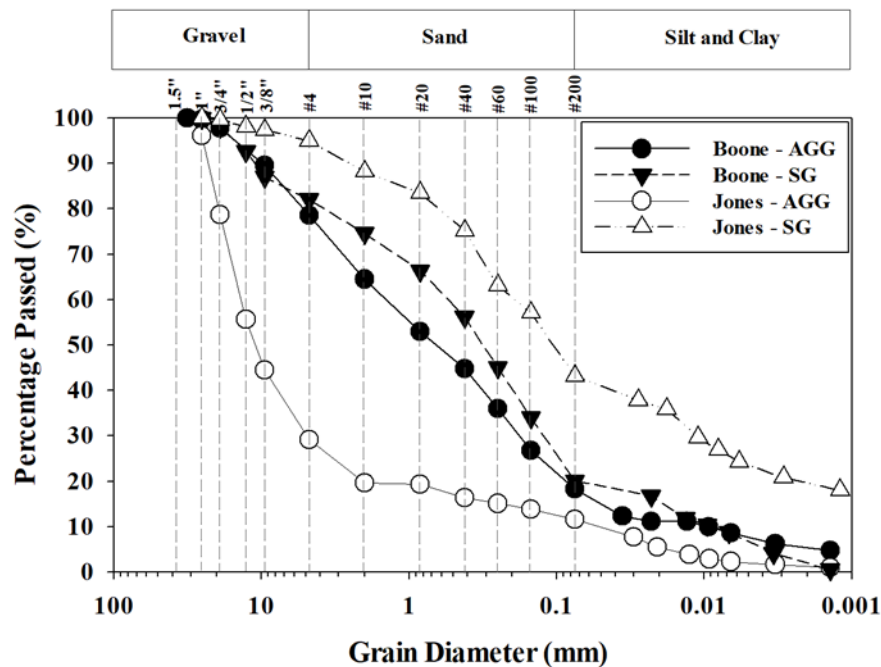
Figure 19. PSD curves for surface aggregates and subgrade materials from Boone and Jones counties

The surface aggregates for Jones County are from the Stone City quarry, and surface aggregates for Boone County are from the local quarry in Boone County. As shown in the figure, the 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 the subgrade materials from Boone County.

Table 2 shows the index properties of the surface aggregates and subgrade materials in Boone and Jones counties.

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 (%) (>4.75 mm)	20	13	42	5
Sand (%) (4.75 mm – 75 µm)	63	53	36	52
Fines (75 µm – 2 µm)	17	34	22	43
AASHTO	A-1-b	A-2-4(0)	A-1-b	A-2-4(0)
USCS	SM	SM	GM	SM

C_u=coefficient of uniformity, C_c=coefficient of curvature.

The PI of the surface aggregates in Boone County (10%) was higher than that of Jones County (8%). The subgrade materials from both counties had the same PI value of 24%. The gravel content (>US Sieve #4) of the surface aggregates was 42% in Jones County and 20% in Boone County. The gravel content of the subgrade for Boone County (13%) was a little higher than that of Jones County (5%). The sand content (between US Sieve #4 and US Sieve #200) of the surface aggregates was higher in Boone County (63%) than in Jones County (36%). On the other hand, sand content values for the subgrades of both Boone (53%) and Jones (52%) counties were almost the same. Fines content (<US Sieve #200) for surface aggregates in both counties were similar (17% and 22%), whereas the fines content of the subgrade in Jones County (43%) was higher than that of Boone County (34%).

The surface aggregate materials were classified as silty sand (SM) in Boone and silty gravel (GM) in Jones counties according to the USCS, but both 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 systems, respectively.

4.3. Compaction Tests

Standard Proctor compaction tests were performed on all surface aggregates and aggregate-quarry fines mixtures. The mixtures of existing aggregates with different percentages of quarry fines were prepared and tested to determine the effects of adding quarry fines on the optimum moisture content (w_{opt}) and maximum dry density (γ_{dmax}) of each material (ASTM D698-12e1). A summary of the results is shown in Table 3.

Table 3. Proctor compaction test results for mixtures

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

The γ_{dmax} of the subgrade was 113 pcf, lower than that of all granular road surface aggregates, and its w_{opt} was the highest at 13%. The w_{opt} of the existing surface aggregates alone ranged between 4.9% and 9.6%.

4.4. CBR Tests

Figure 20a and Figure 20b show the results of the laboratory CBR tests under soaked conditions, performed on the surface aggregates from Boone and Jones counties both untreated and treated with quarry fines.
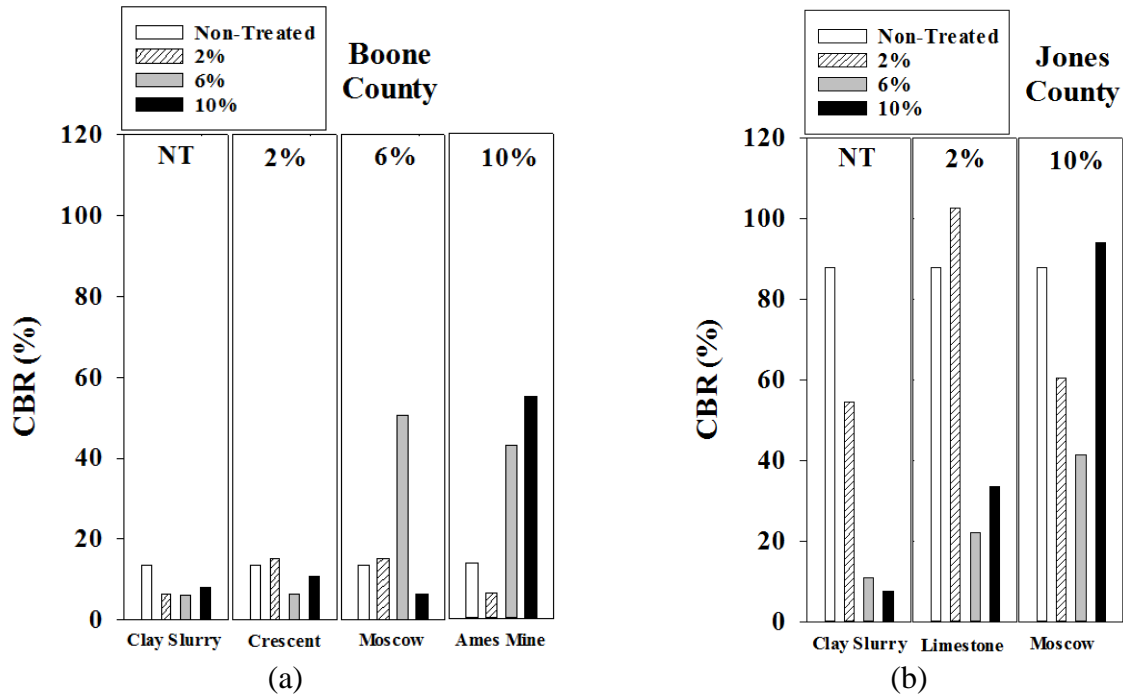
Figure 20. CBR values for surface aggregates for (a) Boone County and (b) Jones County

Note that in Figure 20 the value at the top of each subplot indicates the treatment concentration yielding the maximum CBR value. The percentages of quarry fines used in the design of the test sections were determined based on the optimum percentages obtained from CBR tests, which are shown at the top of each subplot in the figure.

The results of CBR tests in Boone County showed that mixing Clay Slurry with the surface aggregates decreases the CBR values. However, 2% Clay Slurry was mixed with 98% surface aggregates by dry weight in the Boone County Clay Slurry test section. For the other sources, 2% of Crescent, 6% of Moscow, and 10% of Ames Mine fines by dry weight were the optimum amounts to be mixed with surface aggregates in Boone County.

The CBR value of the untreated surface aggregates in Jones County was significantly higher than the corresponding value for Boone County, and mixing Clay Slurry with the surface aggregates of Jones County again decreased the CBR values. Similar to Boone County, 2% Clay Slurry was mixed with 98% surface aggregates by dry weight in the Jones County Clay Slurry test section. For the other sources, 2% of Limestone and 10% of Moscow fines were the optimum amounts and were therefore mixed with surface aggregates in Jones County.

4.5. Pocket Penetrometer Tests

Triplicate pocket penetrometer tests were conducted on the specimens mixed with quarry fines passing through US Sieve #200, prepared as slurries (25% solids content) in shallow dishes to measure the penetration resistance over time. The maximum penetration resistance that the pocket penetrometer could measure was 4.5 tsf.

Figure 21 shows that the Crescent and Moscow fines reach the maximum strength the fastest in 72 hours, while 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.
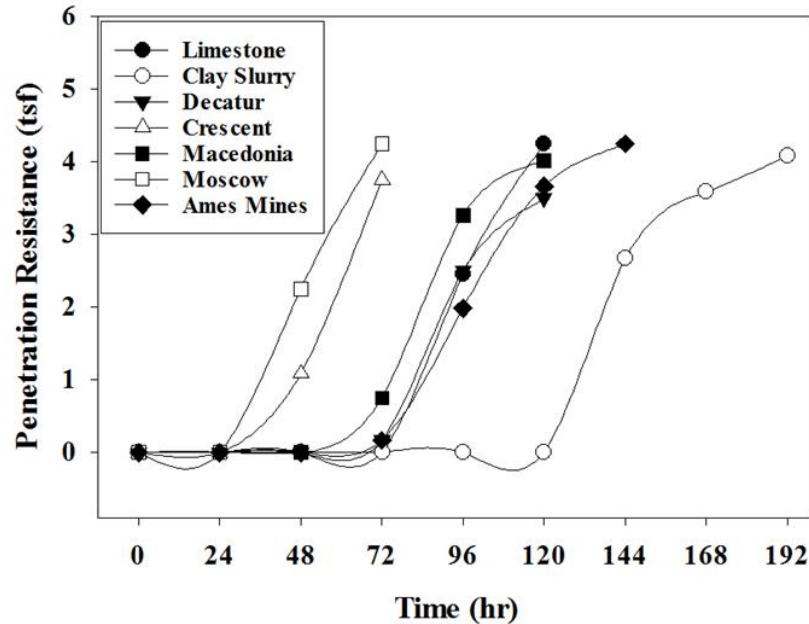
Figure 21. Penetration resistance of the saturated quarry fines samples vs. time

4.6. Mini-Vane Shear Tests

Mini-vane shear tests were conducted on the quarry fines passing through a US Sieve #200 under saturated conditions. The laboratory vane shear device used in this study was a four-bladed, 1 in. by 1 in. square vane with a vane blade thickness of 0.03 in. and a rod diameter of 0.13 in. The torque rotation rate was constant at 90°/min, and the torque spring had a calibration factor of 13×10^{-3} lb in./°. The saturated quarry fines specimens were prepared in plastic containers having a diameter of 4 in. and length of 4.7 in. 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 in. below the sample's surface (ASTM D4648). Figure 22 shows that after 96 hours, the Crescent (0.011 tsf) and Moscow (0.009 tsf) fines have the greatest maximum shear strength values, whereas the Ames Mine, Macedonia, and Decatur fines have the lowest shear strengths (0.004 to 0.005 tsf), and the Clay Slurry and Limestone fines have intermediate strengths of 0.006 and 0.007 tsf, respectively.
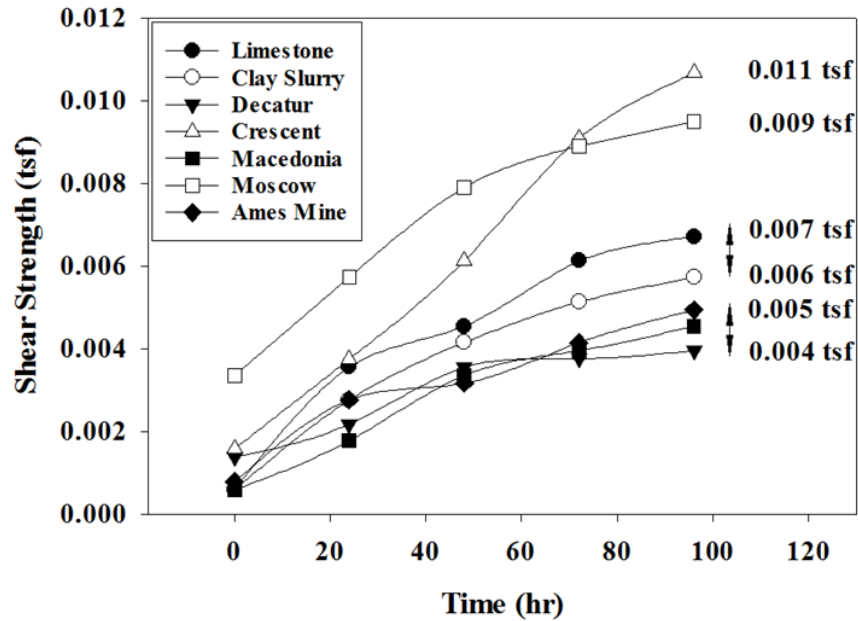
Figure 22. Undrained shear strength vs. time for all specimens

4.7. Slaking Tests

Slaking tests were conducted on 2 in. by 2 in. specimens of existing surface aggregates from Boone and Jones counties. In addition, 2 in. by 2 in. specimens were prepared for the mixtures of quarry fines and existing aggregates. Three replicate specimens were prepared for each material type. Table 4 shows the summary of the average slaking times.

Table 4. Slaking test results for mixtures

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

It was observed that the Boone County materials had relatively lower slaking times than the Jones County materials. The addition of Ames Mine fines to the existing surface aggregates from Boone County reduced the slaking time compared to the untreated materials, but the Moscow, Clay Slurry, and Crescent fines almost doubled the slaking times. For the Jones County

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materials, mixing surface aggregates with any of the fines types increased the slaking time beneficially, where the increase was the greatest for the Limestone and the lowest for Clay Slurry. Figure 23 shows an example of three samples of existing surface aggregates that disintegrated after almost 2 minutes in water, and a fourth sample of Clay Slurry and existing surface aggregates that was still intact after 3.5 minutes.

Figure 23. Slaking test for 2 in. by 2 in. specimen samples

4.8. XRF Spectroscopy

Depending on the natural properties of the parent rock, the mineralogy of quarry fines varies from source to source (Stokowski 1992). Table 5 shows the chemical constituents of the quarry fines samples determined from XRF tests.

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
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

LOI = loss on ignition

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 characteristics. The maximum and minimum Alumina contents were observed for Decatur (4.56%) and Ames Mine (0.28%) quarry fines, respectively.

CHAPTER 5. DESIGN AND CONSTRUCTION OF TEST SECTIONS

5.1. Site Descriptions

This section explains the properties of each section in Boone and Jones counties and provides additional information about the locations, design, and construction of each section.

5.1.1. Boone County Test Sections

Four test sections were constructed in Boone County in late October and early November 2019. The length and width of each section was 0.25 mi (1,320 ft) and 26 ft, respectively. To construct the test sections, the top 2 in. of the existing surface material was mixed with the quarry fines (Figure 24).
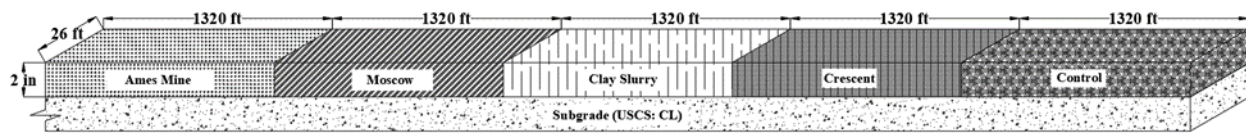
Figure 24. Schematic of Boone County test sections

Figure 25 and Figure 26 show the location of the test sections in Boone County on 210th Street between U and V avenues.

Figure 25. Locations and layout of Boone County test sections

Figure 26. Access to Boone County site location

One control section consisting of the existing surface aggregates was designated on the far east side. All test sections were constructed over a previously constructed 5 to 7 in. thick subbase layer of surfacing aggregates.

5.1.2. Jones County Test Sections

Three test sections were constructed in Jones County on October 17, 2019. The length and width of each section was 0.25 mi (1,320 ft) and 26 ft, respectively. To construct the sections, the top 2 in. of the existing surface materials were mixed with the quarry fines (Figure 27).
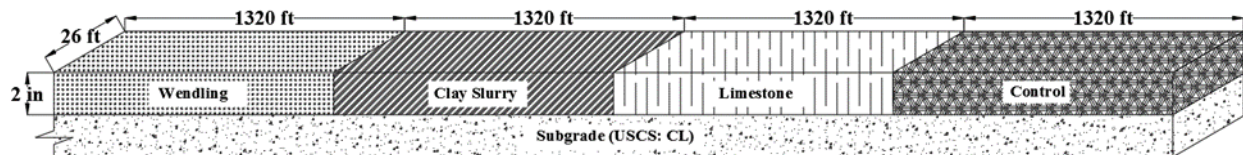
Figure 27. Schematic of Jones County test sections

Figure 28 and Figure 29 show the location of the test sections in Jones County on 15th Street in Lisbon, Iowa.
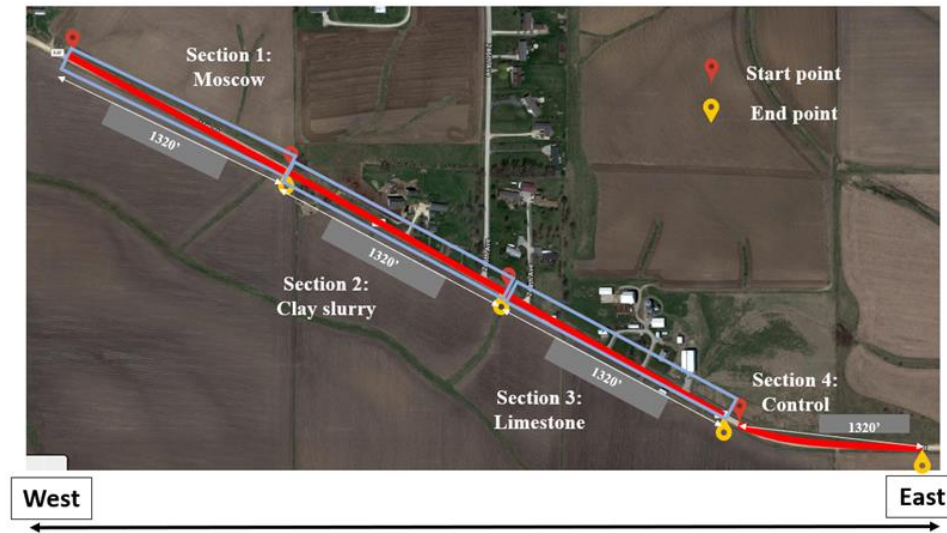
Figure 28. Locations and layout of Jones County test sections

Figure 29. Access to Jones County site location

One control section with existing surface aggregates was designated on the far east side as the control section. All test sections were constructed on a previously constructed 5 to 6 in. thick subbase layer of surface aggregates, the top 2 in. of which were mixed with the quarry fines. All sections had a relatively stiff subgrade layer that had recently been leveled up, with pipes installed to provide suitable drainage.

5.2. Construction of Test Sections

Five different types of quarry fines were found to exhibit appropriate PIs according to Atterberg limits tests and were selected for construction of the test sections. The selected fines include both Clay Slurry and Limestone fines from Frenchtown A22090, Moscow A70002 fines, Ames Mine A85006 fines, and Crescent A78002 fines. The previously given Figure 1 shows the locations of the quarries and construction sites.

The Boone County test sections were constructed using the Ames Mine (A85006), Moscow (A70002), Frenchtown Clay Slurry (A22090), and Crescent (A78002) fines. These materials were hauled by truck to the site locations. Table 6 shows the hauling times between quarries and site locations in both counties.

Table 6. Hauling times from the quarries to project sites

County	Quarry fines and sources	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

The Frenchtown and Moscow quarries were several hours away from the construction site in Boone County, while the Ames Mine quarry was only 15 minutes away. The Jones County test sections were constructed using the Moscow (A70002) fines and the Frenchtown Clay Slurry and Limestone (A22090) fines. These two quarries were 60 and 90 minutes, respectively, from the project site.

For both counties, construction started with ripping the top 1 in. of the existing surface aggregates and windrowing them to both edges to minimize runoff of the Clay Slurry or loss of the bulk fines. The quarry fines were then spread on top of the surface using dump trucks and a skid-steer loader for the bulk fines and a self-unloading tanker truck for the Clay Slurry. The windrowed materials were then bladed back onto the road and several grader passes were applied to mix the top 2 in. of materials and shape the road surface. The moisture content of the surface materials was checked by hand-feel, and water was sprayed on the surface when needed.

Compaction was performed using a rubber tire roller following a motor grader to reduce the compaction delay time. For the sections built with clay slurry, the fines materials were sprayed over the surface using several passes of the tanker truck. Due to logistical delays, the Clay Slurry section in Boone County was constructed on a relatively cold day having a high temperature of only 40°F (October 29, 2019), which prolonged the process of drying the slurry-treated surface materials out by blade mixing. To reduce the water content and help dry the surface materials faster, an additional 120 tons of fresh aggregates were added to the surface materials of this section. The Clay Slurry test section in Jones County as well as several others used in Iowa Highway Research Board (IHRB) Project TR-721 were constructed in warmer months and dried out within a day or two. However, the section in Boone County took several days to dry completely because temperatures dipped below freezing each night. Therefore, stabilization with clay slurry should be performed when overnight temperatures remain well above freezing.

Figure 30 shows the windrow used to minimize runoff, spraying of clay slurry, and the resulting wet mixture in Jones County. Additional photographs of the equipment used to construct the test sections in the two counties and the constructed test sections over time are provided in Appendix A.

Figure 30. Construction of Clay Slurry test section in Jones County: (a) windrow to minimize runoff, (b) spray clay slurry, and (c) surface after spraying clay slurry, (d) blade-mixing surface materials, (e) finished surface

5.3. Maintenance Performed on Test and Control Sections

Granular roadways in cold regions such as Iowa are prone to severe distresses such as potholes, washboarding, and rutting due to deterioration of the surface materials, especially during freezing and thawing cycles. Accordingly, blading is a common maintenance procedure to repair damage and improve ride quality by restoring surfaces to smoother conditions. Figure 31 shows examples of potholes and rutting that occurred in the Moscow section in Jones County in November 2019, two weeks after construction.

(a)   (b)

Figure 31. Distresses observed in Jones County Moscow fines test section: (a) large pothole and (b) severe rutting

Over the course of this project, the test sections were bladed as one unit on four different dates in Boone County and three different dates in Jones County. Motor graders were the only equipment needed to perform maintenance on the test sections during this project. Figure 32 shows the motor grader that was used for blading the sections in Jones County, and the motor grader used in Boone County is shown, along with other equipment, in Appendix A.

Figure 32. Motor grader used for blading Jones County test sections

The aggregate surface thickness was measured in fall 2019 and spring 2020 for all sections in both counties to evaluate the rates of aggregate deterioration and material loss over time. However, all the sections performed excellently, and the surface thickness remained close to the initial design thickness of 2 in. Therefore, neither maintenance nor spreading of new aggregate materials was required for the demonstration sections. To track the condition of the surfaces, field surveying reports were completed each time the research team was present in the field, and additional reports were completed by county personnel.

The amount of material and the number of blading and compaction passes during construction were recorded by the research crew and county engineers during construction of the test sections. The moisture content of the surface aggregate and quarry fines mixtures were evaluated by hand-feel to be consistent with the design moisture content determined in the laboratory tests. After compaction, the thickness of the surface layer was measured using a ruler to ensure that it was 2 in.

CHAPTER 6. RESULTS AND DISCUSSION

In this chapter, the results of field tests including nuclear density gauge, DCP, FWD, IRI, LWD, and dustometer tests are presented and discussed along with changes in gradations of field samples measured in the laboratory. The first set of field tests were performed in November 2019 soon after construction to evaluate the as-constructed performance of the sections. In March 2020, samples were collected for investigating the gradation changes, and field photographic surveys and LWD tests were also performed. Due to Iowa State University COVID-19 regulations at the time, these tests were required to be performed by a single researcher. However, the rest of the tests including DCP, IRI, and dustometer tests were performed in June 2020 with two research personnel following university safety requirements.

6.1. Gradation Change

Samples of the surface aggregate materials were collected from all test sections in Jones and Boone counties in November 2019 and March 2020 to investigate the changes in gradation parameters including the fines, sand, and gravel content, as well as the gravel-to-sand (G/S) ratio and total breakage. The results are discussed in the following sections, and a particle size analysis for all sections is given in Appendix B.

6.1.1. Boone County

Figure 33 shows the fines content of the surface aggregate materials from the test sections in Boone County.
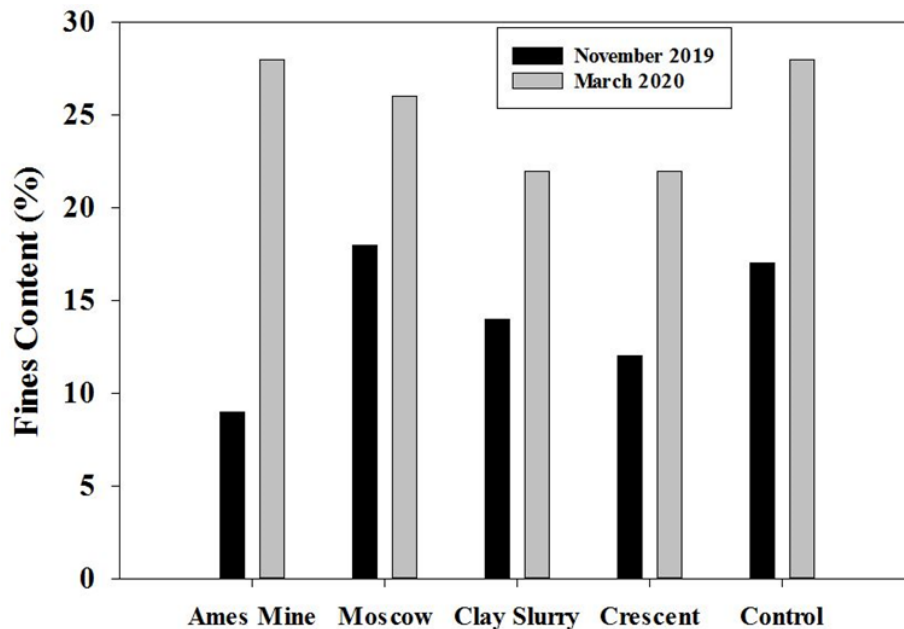
Figure 33. Fines content of surface materials in Boone County test sections

The fines content of all sections increased from November 2019 to March 2020. The increase was greatest for the Ames Mine section and lowest for the Clay Slurry and Moscow sections. After construction in November 2019, the Ames Mine section started out with the lowest fines content, while the Moscow and control sections had the highest fines content. However, after the freeze-thaw cycles in early 2020, the Ames Mine and control sections had the highest fines content, while the Clay Slurry and Crescent sections had the lowest fines content.

As summarized in Table 7, the relative change in fines content after the spring thaw was greatest for the Ames Mine section (211%) and lowest for the Moscow section (44%).

Table 7. Changes in fines content of the surface materials in Boone County test sections

Section	November 2019	March 2020	Change (%)
Ames Mine	9	28	211
Moscow	18	26	44
Clay Slurry	14	22	57
Crescent	12	22	83
Control	17	28	65

Figure 34 shows that the control and Crescent sections had the highest and lowest initial sand content, respectively, and the sand content of all sections decreased from November 2019 to March 2020.
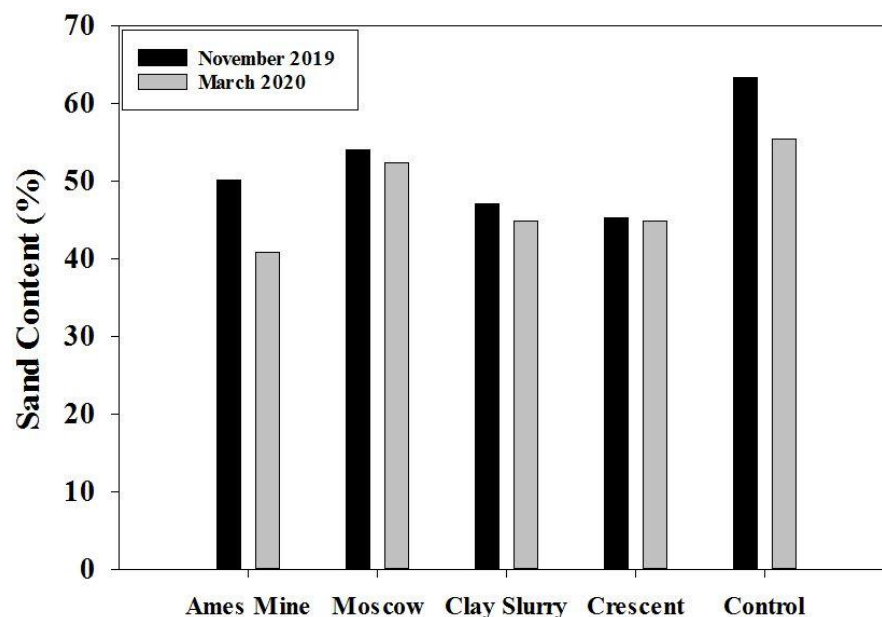
Figure 34. Sand content of surface materials in Boone County test sections

The decrease was greatest for the Ames Mine and control sections and lowest for the Crescent

section. By March 2020, the control section still had the highest sand content, while the Ames Mine section had the lowest sand content.

All sections in Boone County experienced a decrease in sand content from November 2019 to March 2020, as shown in Table 8.

Table 8. Changes in sand content of the surface materials in Boone County test sections

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

The relative decrease was greatest for the Ames Mine section at 19% and lowest for the Crescent section at 1%. Additionally, the relative decreases in sand content in Table 8 were much lower than the corresponding increases in fines content reported previously in Table 7.

The gravel content of the surface materials in the Boone County test sections are shown in Figure 35 for November 2019 and March 2020.
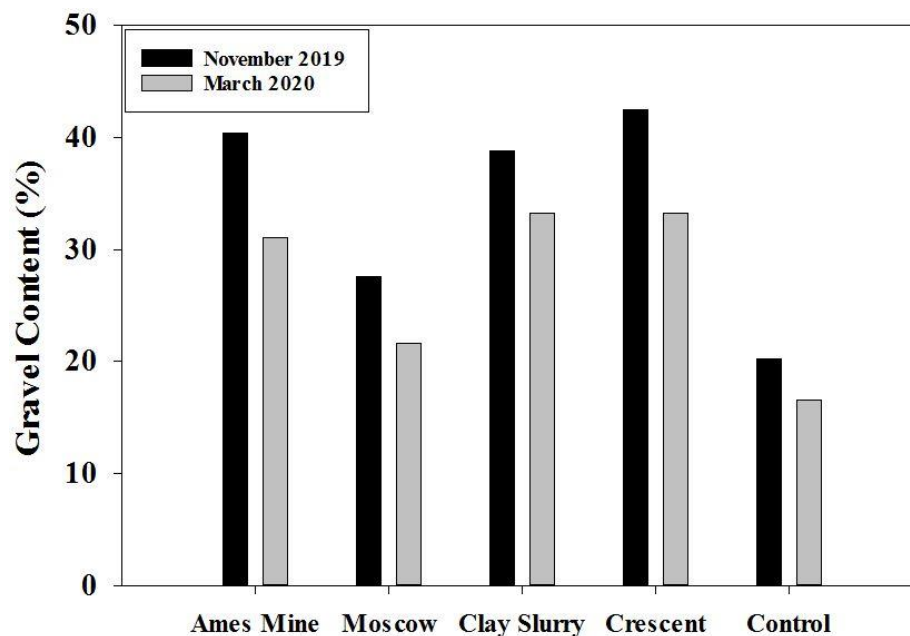
Figure 35. Gravel content of surface materials in Boone County test sections

All sections showed a decrease in gravel content from November 2019 to March 2020 due to

aggregate deterioration during the freeze-thaw period, abrasion by traffic loads, and gravel loss accelerated by segregation.

Throughout the project, all demonstration sections maintained higher gravel content than the control section but also experienced greater decreases in gravel content than the control section. In both November 2019 and March 2020, the Crescent, Ames Mine, and Clay Slurry sections had the highest gravel content, while the control and Moscow sections had the lowest gravel content. The Ames Mine and Crescent sections experienced the greatest decreases in gravel content over time.

The relative percent decreases in gravel content from November 2019 to March 2020 in the Boone County sections are reported in Table 9.

Table 9. Changes in gravel content of the surface materials in Boone County test sections

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

The relative decreases ranged from 14% for the Clay Slurry section to 23% for the Ames Mine section.

The G/S ratio is shown in Figure 36 for all Boone County sections in November 2019 and March 2020.
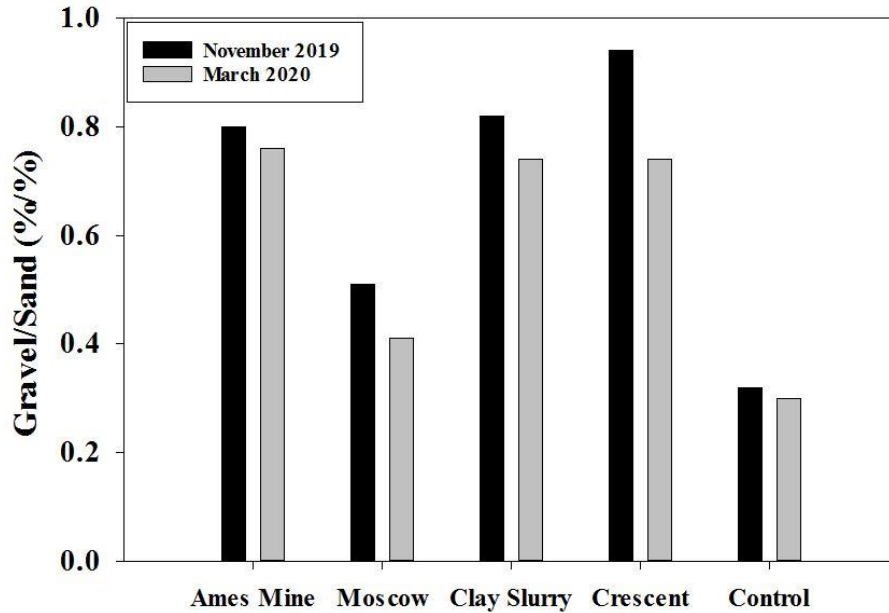
Figure 36. G/S ratio of surface materials in Boone County test sections

As shown in the figure, in both November 2019 and March 2020, the Ames Mine, Clay Slurry, and Crescent sections had the highest G/S ratios, all above 0.7. The control section had the lowest ratio of around 0.3, and the Moscow section was slightly higher at around 0.4. Through winter and spring, the Crescent and Moscow sections exhibited the greatest decreases in G/S ratio, while the Ames Mine and control sections had the smallest decreases.

The relative percent changes in G/S ratios for all sections in Boone County are shown in Table 10.

Table 10. Changes in G/S ratio of the surface materials in Boone County test sections

Section	November 2019	March 2020	Change (%)
Ames Mine	0.80	0.76	-5
Moscow	0.51	0.41	-20
Clay Slurry	0.82	0.74	-10
Crescent	0.94	0.74	-21
Control	0.32	0.30	-6

The results in this table show that the Moscow and Crescent sections had the greatest percent decreases in G/S ratio of around 20%, while the Clay Slurry had a smaller decrease of 10%, and the Ames Mine and control sections had the smallest relative changes of around 5%.

The total breakage is shown in Figure 37 for all sections in Boone County over the November 2019 to March 2020 time frame.
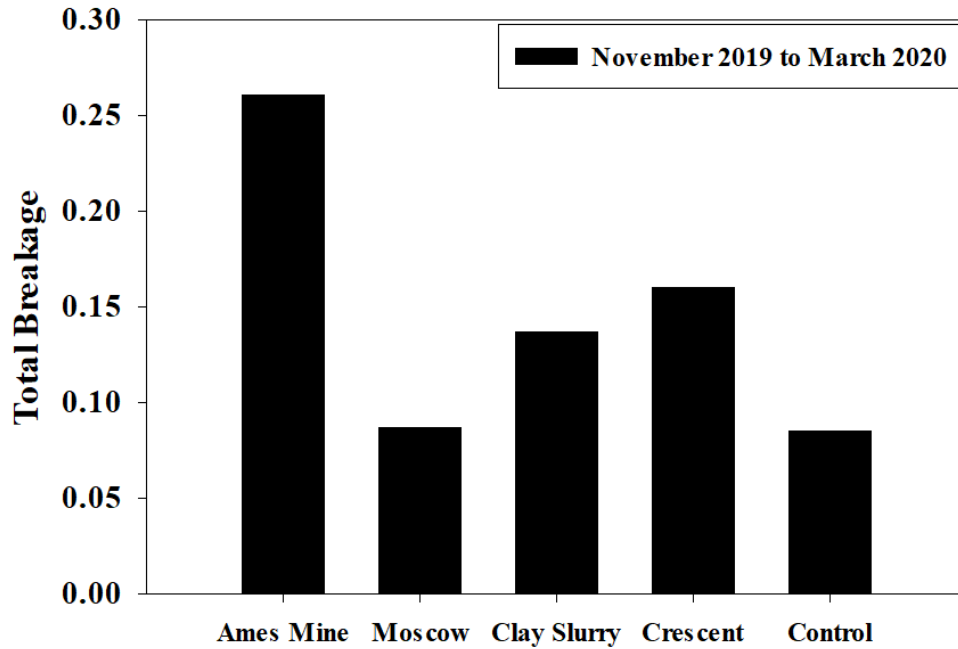
Figure 37. Total breakage of surface materials in Boone County test sections

The Moscow and control sections had the lowest total breakage at around 8%, while the Ames Mine section had the highest total breakage of approximately 26%. The total breakage of the Clay Slurry and Crescent sections were similar at approximately 13% and 16%, respectively.

6.1.2. Jones County

The fines content of the surface aggregate materials from the test sections in Jones County is shown in Figure 38.
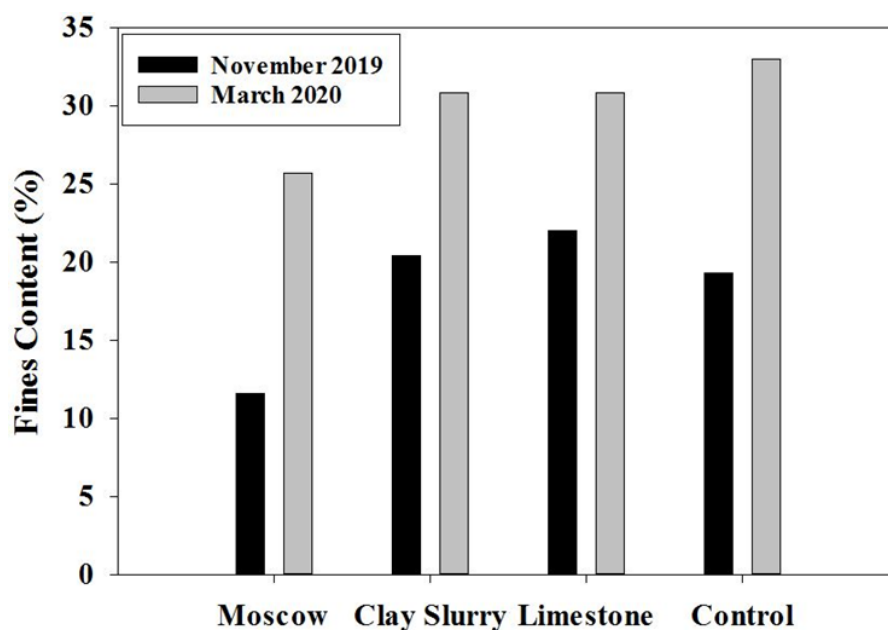
Figure 38. Fines content of surface materials in Jones County test sections

Similar to Boone County, the fines content of all sections increased from November 2019 to March 2020 as expected. The increase was greatest for the Moscow and control sections and lowest for the Clay Slurry and Limestone sections. After construction in November 2019, the Moscow section started out with the lowest fines content, while the Limestone section had the highest fines content, and all sections had values between 12% and 22%. However, after the winter and spring seasons, the control section ended up with the highest fines content while that of the Moscow section remained the lowest, and all sections had values between 26% and 33%.

As detailed in Table 11, the relative percent increase in fines content was highest at 122% for the Moscow section and lowest at 40% for the Limestone section.

Table 11. Changes in fines content of the surface materials in Jones County test sections

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

The sand content of the Jones County test sections is shown in Figure 39.
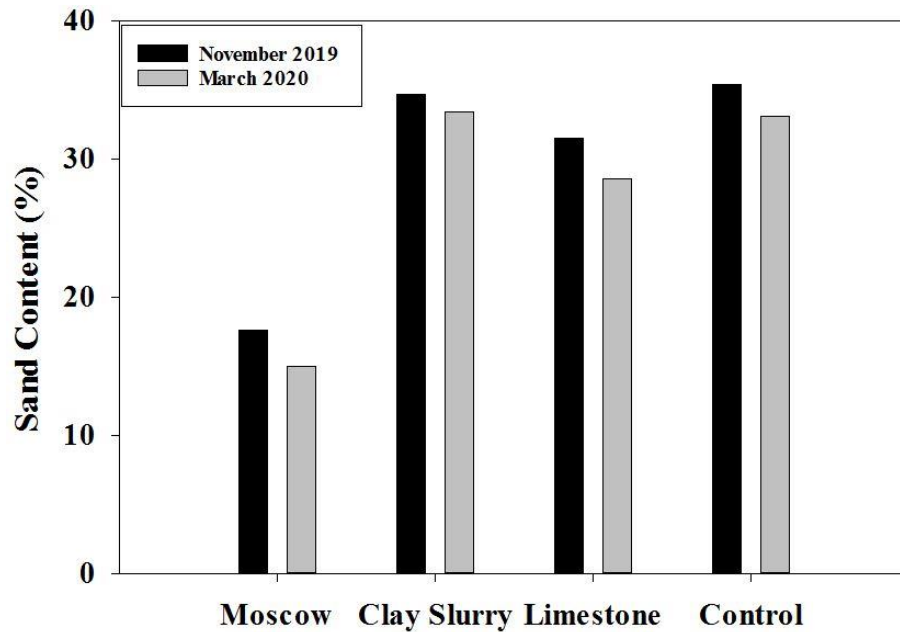
Figure 39. Sand content of surface materials in Jones County test sections

Overall, the Clay Slurry, Limestone, and control sections had similar sand content values that were approximately twice that of the Moscow section. From November 2019 to March 2020, all sections exhibited decreases in sand content of a few percent as detailed in Table 12.

Table 12. Changes in sand content of the surface materials in Jones County test sections

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

Because of its lower initial sand content, the corresponding relative percent change was greatest for the Moscow section at -15%, while the relative change for the Clay Slurry section was lowest at -4%.

Figure 40 shows the gravel content for the Jones County test sections.
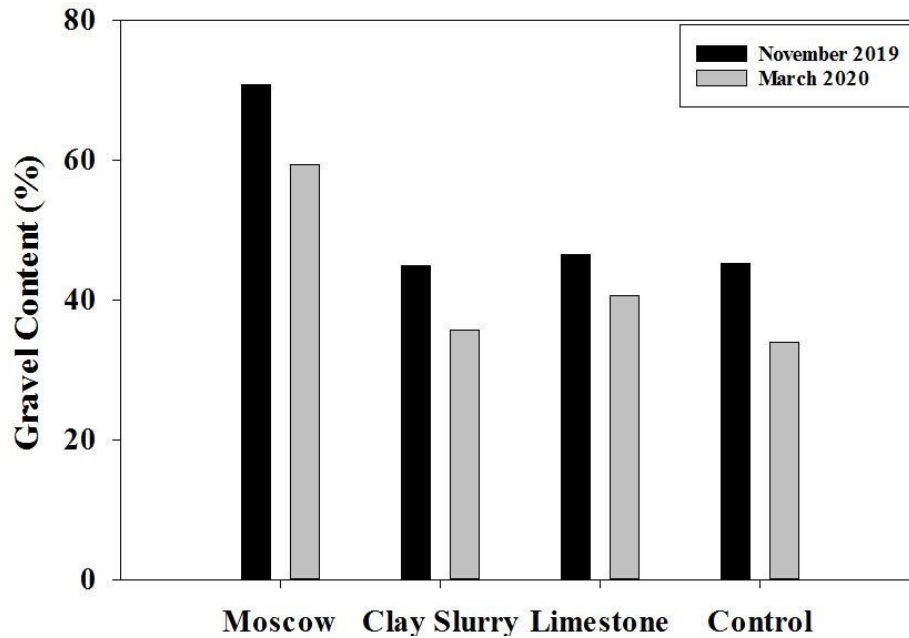
Figure 40. Gravel content of surface materials in Jones County test sections

Similar to the observations in Boone County, all sections had a decrease in gravel content from November 2019 to March 2020 due to aggregate deterioration during the freeze-thaw period, abrasion by traffic loads, and gravel loss accelerated by segregation. The Moscow section had the highest gravel content at both the beginning and end of the study. By March 2020, the control section experienced the greatest percent decrease in gravel content, leaving it with a lower final value than all the demonstration sections, although the value for the Clay Slurry section was only a few percent higher (Table 13).

Table 13. Changes in gravel content of the surface materials in Jones County test sections

Section	November 2019	March 2020	Change (%)
Moscow	71	59	-17
Clay Slurry	45	36	-20
Limestone	47	41	-13
Control	45	34	-24

Figure 41 shows the G/S ratio for all sections in Jones County in November 2019 and March 2020.
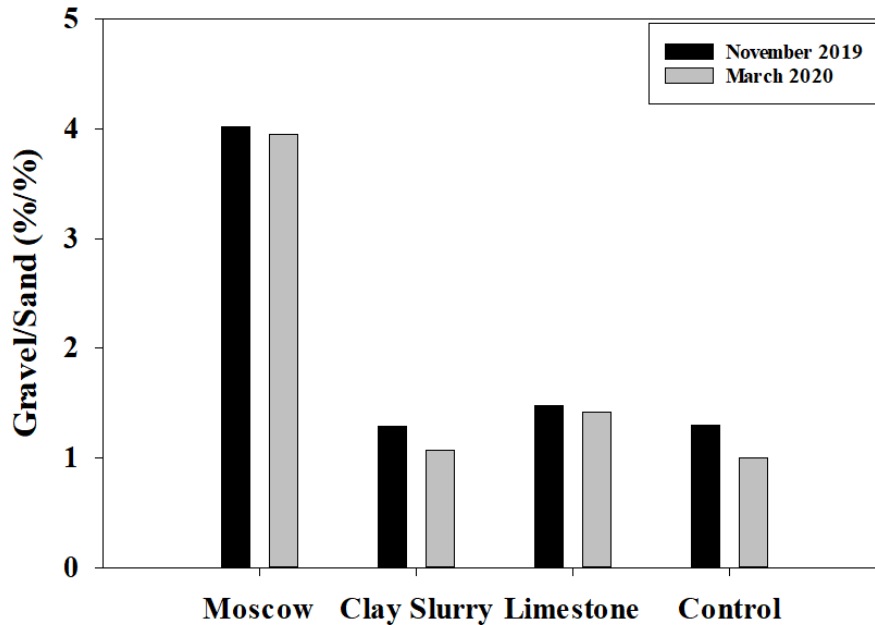
Figure 41. G/S ratio of surface materials in Jones County test sections

Overall, the Moscow section had the highest G/S ratio, while the Clay Slurry section had the lowest. The control section had the greatest decrease in G/S ratio over time, followed by the Clay Slurry section, whereas the Limestone and Moscow sections had the smallest decreases in G/S ratios from November 2019 to March 2020.

Table 14 shows the summary of the G/S ratios for all sections in Jones County in November 2019 and March 2020.

Table 14. Changes in G/S ratio of the surface materials in Jones County test sections

Section	November 2019	March 2020	Change (%)
Moscow	3.94	3.93	-0.25
Clay Slurry	1.28	1.09	-15
Limestone	1.47	1.41	-4
Control	1.29	1.03	-20

The results show that the control and Clay Slurry sections started out with practically the same G/S ratio of 1.3, while the Limestone section was slightly higher at 1.47, and the Moscow section had the highest ratio of 3.94. The G/S ratios of all sections decreased from November 2019 to March 2020, and this rate of change was the lowest for Moscow section (-0.25%) and highest for the control section (-20%).

Figure 42 shows the results of total breakage for all sections in Jones County from November 2019 to March 2020.

50
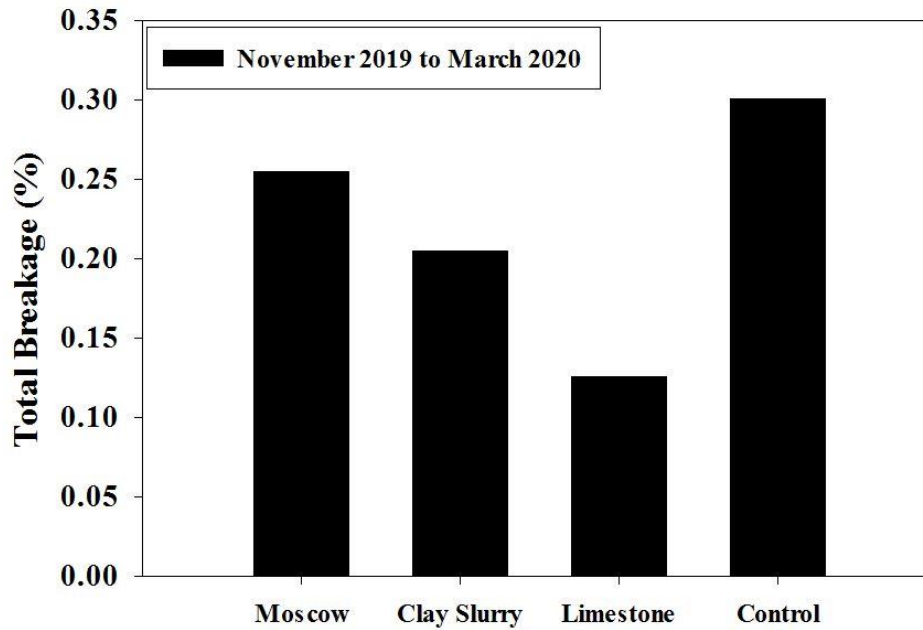
Figure 42. Total breakage of surface materials in Jones County test sections

The Limestone section had the lowest breakage, and the control section had the highest total breakage.

6.2. Nuclear Density Gauge Tests

The nuclear density gauge tests were performed by Iowa DOT personnel at 10 points distributed equally within each test section for both Boone and Jones counties. The results are reported as wet unit weights and moisture content of the surface materials, from which the dry unit weights were calculated.

6.2.1. Boone County

Table 15 shows the average values of the 10 test results within each section in Boone County in March 2020.

Table 15. Nuclear gauge results for Boone County test sections in March 2020

Section	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	137	128	7

γ_w = wet unit weight, γ_d = dry unit weight, and ω = water content

The maximum wet (142 pcf) and dry unit weight (134 pcf) were both observed in the Clay Slurry section, while the minimum wet (137 pcf) and dry unit weight (128 pcf) were measured in the control section. The water content values ranged from a low of 5% for the Ames Mine section to a high of 7% for the control section.

6.2.2. Jones County

Table 16 shows the average values of the 10 test results within each section in Jones County in March 2020.

Table 16. Nuclear gauge results for Jones County test sections in March 2020

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

γ_w = wet unit weight, γ_d = dry unit weight, and ω = water content

The maximum wet (141 pcf) and dry unit weight (130 pcf) were both observed in the Limestone section, while the minimum wet (136 pcf) and dry unit weight (124 pcf) were measured in the Clay Slurry section. The water content values ranged from 8% for the Moscow and control sections to 10% for the Clay Slurry section.

6.3. DCP Tests

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 from sudden changes in the slopes of cumulative blows versus depth plots, as well as CBR values based on empirical correlations given in ASTM D6951 (2015). As an example, Figure 43 shows the cumulative blows, DCPI, and correlated CBR values versus depth for the first test point of the Ames Mine section in Boone County.

(a)

(b)

53

(c)
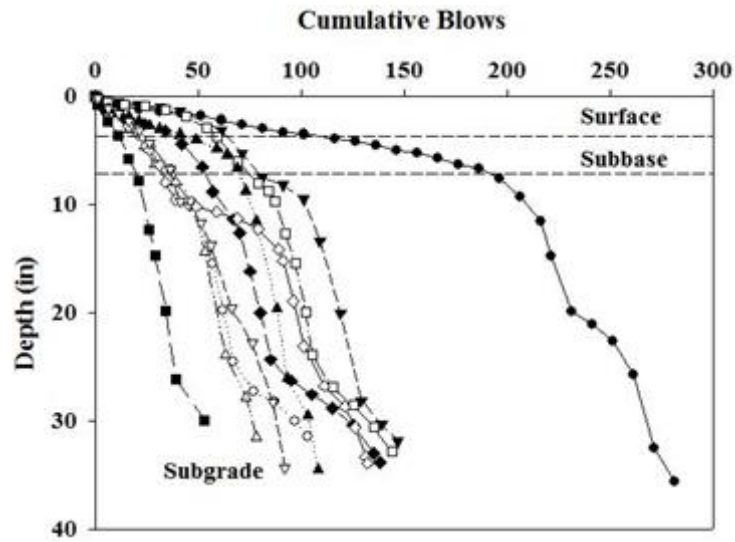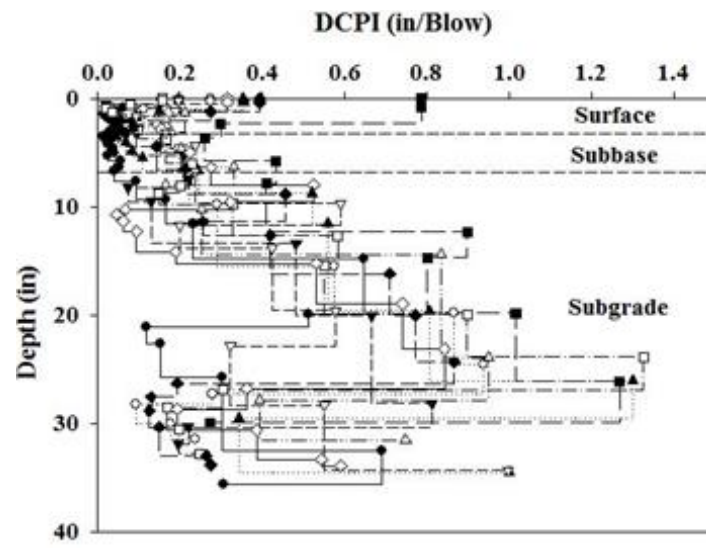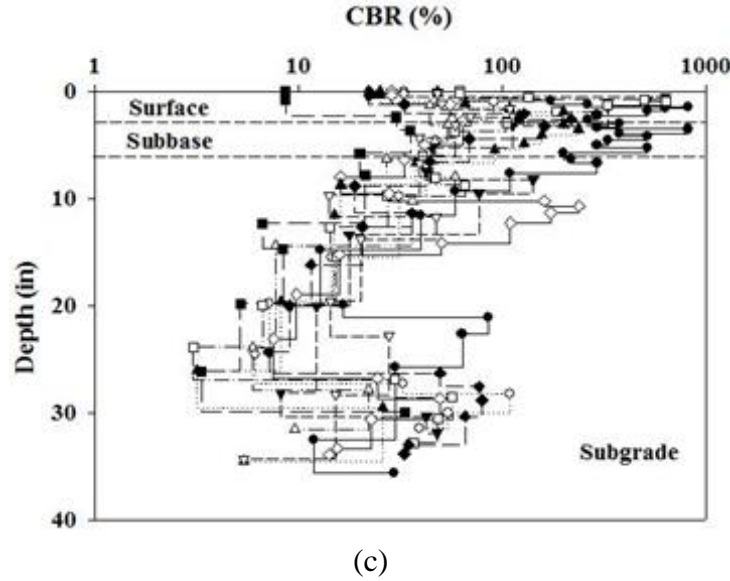
Figure 43. Ames Mine first test point in Boone County: (a) cumulative blows, (b) DCPI, and (c) correlated CBR versus cumulative depth in November 2019

Complete plots of cumulative blows, DCPI, and correlated CBR values versus depth are presented in Appendix C for all testing points of Boone and Jones counties. Using the average CBR values in each layer, relative strength ratings were determined for each test section using the criteria in Table 17, adopted from the Iowa Statewide Urban Design and Specifications (SUDAS) Design Manual (SUDAS 2015).

Table 17. Relative strength ratings of subbase and subgrade layers based on CBR values

CBR (%)	Material	Strength 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

Source: Adopted from SUDAS 2015

The ratings in the SUDAS manual were originally developed for relative ratings of supporting strengths of pavement subbase and subgrade soils.

6.3.1. Boone County

DCP tests were performed in Boone County in November 2019 and June 2020. The distance between test points was 100 ft, with 10 test points used per section. The DCP data were interpreted as a three-layered system consisting of surface, subbase, and subgrade layers for all

stabilized test sections. The control sections were interpreted as a two-layered system consisting of only surface and subgrade layers.

6.3.1.1. DCP Tests of November 2019

DCP tests were performed in November 2019 to investigate the strength of the surface, subbase, and subgrade layers as well as the thickness of the surface and subbase layers after construction of the test sections. Detailed results for the thickness, average CBR value, and corresponding relative strength rating of each layer are shown in Table 18.

Table 18. DCP results for Boone County test sections from November 2019

November 2019	Thickness (in.)		Median CBR (%)			Strength rating		
	Surface	Subbase	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade
Ames Mine	3.2	6.4	112	48	18	Excellent	Good	Fair-good
Moscow	2.7	4.6	70	52	14	Very good	Very good	Fair-good
Clay Slurry	3.3	12.2	71	34	29	Very good	Good	Very good
Crescent	3.3	8.3	52	48	13	Very good	Good	Fair-good
Control	12.0	NA	21	NA	20	Below good	NA	Fair-good

For the calculations, the bottom of the subgrade layer was taken as the maximum measurement depth reached in each test (typically around 36 in.). Statistical boxplots of the CBR values within each of the surface, subbase, and subgrade layers are shown in Figure 44.

(a)

55

Figure 44. CBR values for (a) surface, (b) subbase, and (c) subgrade layers from DCP tests in Boone County in November 2019

The boxplots illustrate graphically the highest, median, and lowest values measured, along with the other percentiles labeled. Figure 44a shows that the CBR of the surface layer of the Ames Mine section results in a relative strength rating of excellent, and this section had the highest median surface CBR value among the Boone County test sections. The Moscow, Clay Slurry, and Crescent sections had similar median surface CBR values that all rated as very good, whereas the control section had the lowest CBR and rated below the threshold for good. Therefore, all the quarry fines types examined in Boone County improved the CBR, with the Ames Mine fines resulting in the greatest improvement.

The median CBR values of the subbase layers were similar across all sections, resulting in good and very good relative strength ratings (Figure 44b). This behavior was expected, because all subbase layers had the same thicknesses of 5 in. and were constructed at the same time. The Moscow section had the widest overall range of CBR values, while the Clay Slurry section had the least variation.

The relative strength ratings from median CBR values for the subgrade layers were fair-good for all the sections, except for the Clay Slurry section, which was very good (Figure 44c).

The average surface thicknesses for all demonstration sections was between 2.7 and 3.3 in., while the thickness of the subbase layers ranged between 4.6 in. for the Moscow section and 12.2 in. for the Clay Slurry section. The average surface thickness of the control section was 12 in.

6.3.1.2. DCP Tests of June 2020

Another set of DCP tests was performed in June 2020, well after the freeze-thaw season had taken place. The resulting median CBR values for all surface layers of the treated sections had increased significantly and were rated as excellent, while the control section was rated as good (Figure 45a).

(a)

57

(b)

(c)
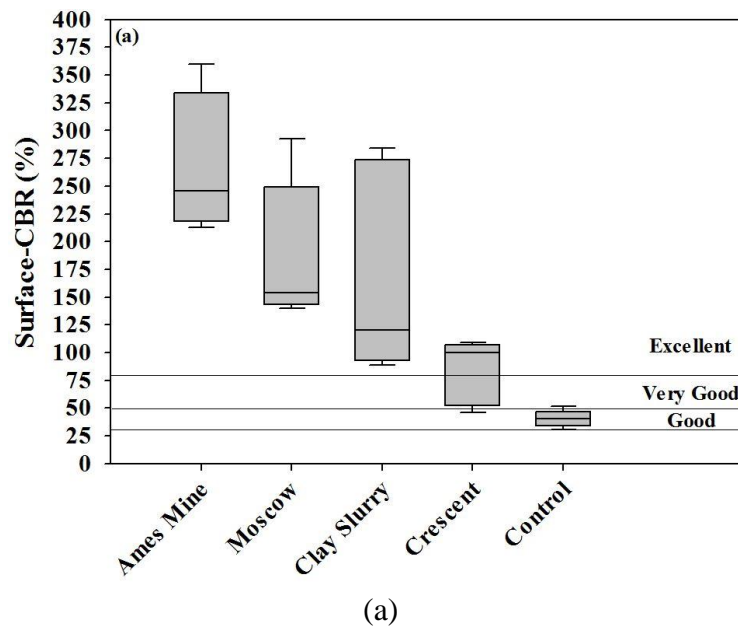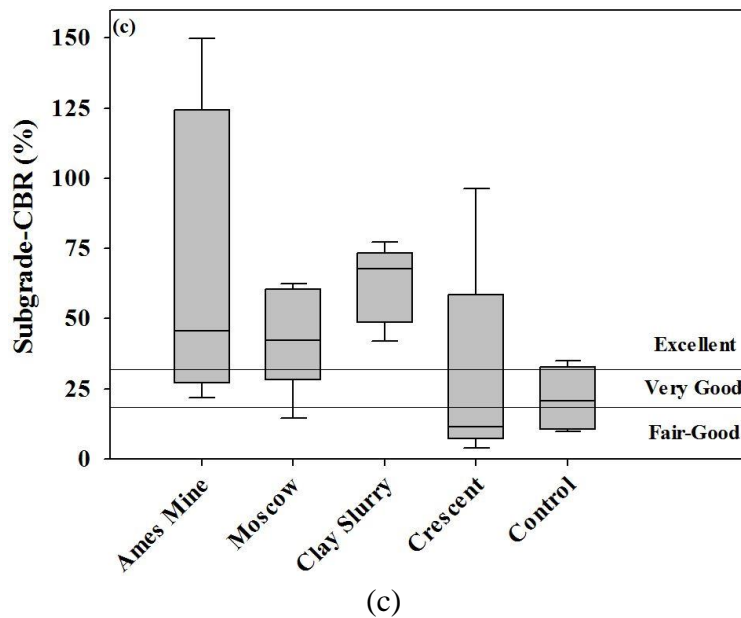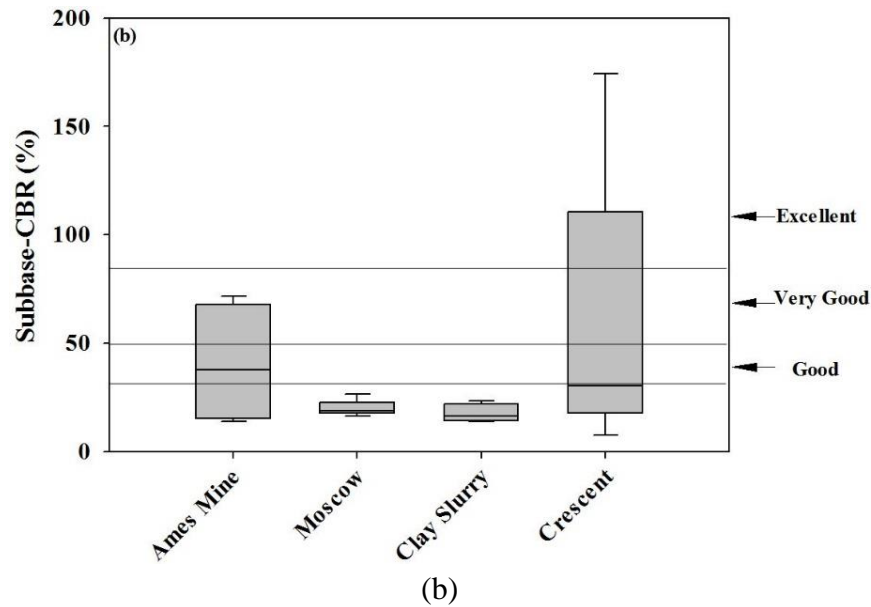
Figure 45. CBR values for (a) surface, (b) subbase, and (c) subgrade layers from DCP tests in Boone County in June 2020

The Clay Slurry section had the widest range of surface CBR values, while the control section had the smallest range. The results show that all the treated sections experienced improvements in their surface CBR values relative to those measured in November 2019. The reason for this trend could be the occurrence of continuing cementation reactions between the quarry fines and surface aggregate materials.

The median CBR values for the subbase layers for all quarry fines sections were rated as below good based on the SUDAS system, except for the Ames Mine section which was rated good (Figure 45b). These results indicate that all sections underwent a decrease in their subbase shear

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strength compared to November 2019. Despite the subbase materials becoming weaker, the surface courses of the quarry fines-treated sections all improved as noted previously, indicating that the treatments were beneficial.

The median CBR values for the subgrades of the Ames Mine, Moscow, and Clay Slurry sections were rated excellent, while the Crescent subgrade was rated fair-good and the control section rated very good (Figure 45c). The Ames Mine section had the widest range of CBR subgrade values among all sections.

The measured surface course thickness of all sections decreased from November 2019 (given previously in Table 18), and in June 2020, they ranged from 0.6 in. for the Ames Mine section to 4.7 in. for the control section (Table 19).

Table 19. DCP results for Boone County test sections from June 2020

June 2020	Thickness (in.)		Median CBR (%)			Strength rating		
	Surface	Subbase	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade
Ames Mine	0.6	9.0	245	38	45	Excellent	Good	Excellent
Moscow	1.0	12.0	153	19	42	Excellent	<Good	Excellent
Clay Slurry	1.2	13.8	119	16	68	Excellent	<Good	Excellent
Crescent	1.1	5.9	99	29	11	Excellent	<Good	Fair-good
Control	4.7	NA	40	NA	21	Good	NA	Very good

Over the same time period, the corresponding subbase layer thickness for all sections increased, except for the Crescent section, which decreased from 8.3 in. in November 2019 to 5.9 in. in June 2020.

6.3.2. Jones County

DCP tests were performed in November 2019 and June 2020 in Jones County. For both series of tests, the distance between test locations was 100 ft, with 10 test locations per section. Similar to Boone County, the DCP results were interpreted as a three-layered system consisting of surface, subbase, and subgrade layers for the stabilized sections and as a two-layered system consisting of surface and subgrade layers for the control section.
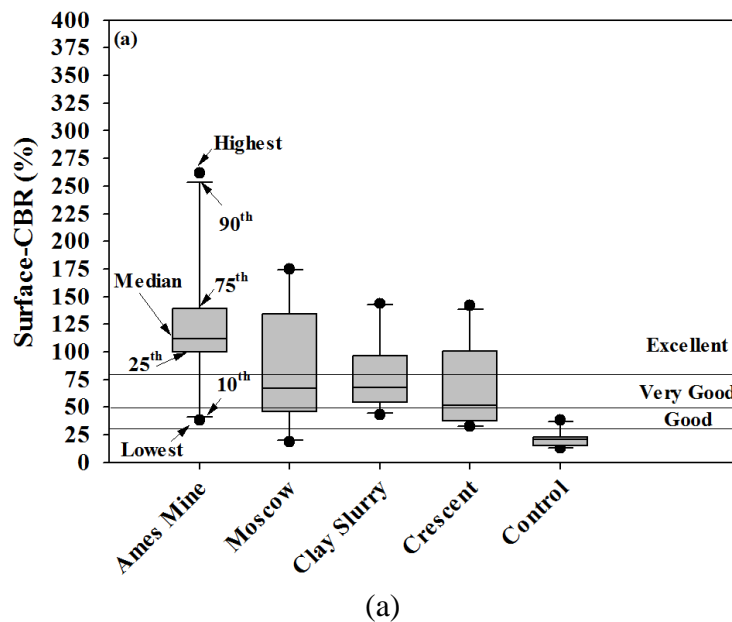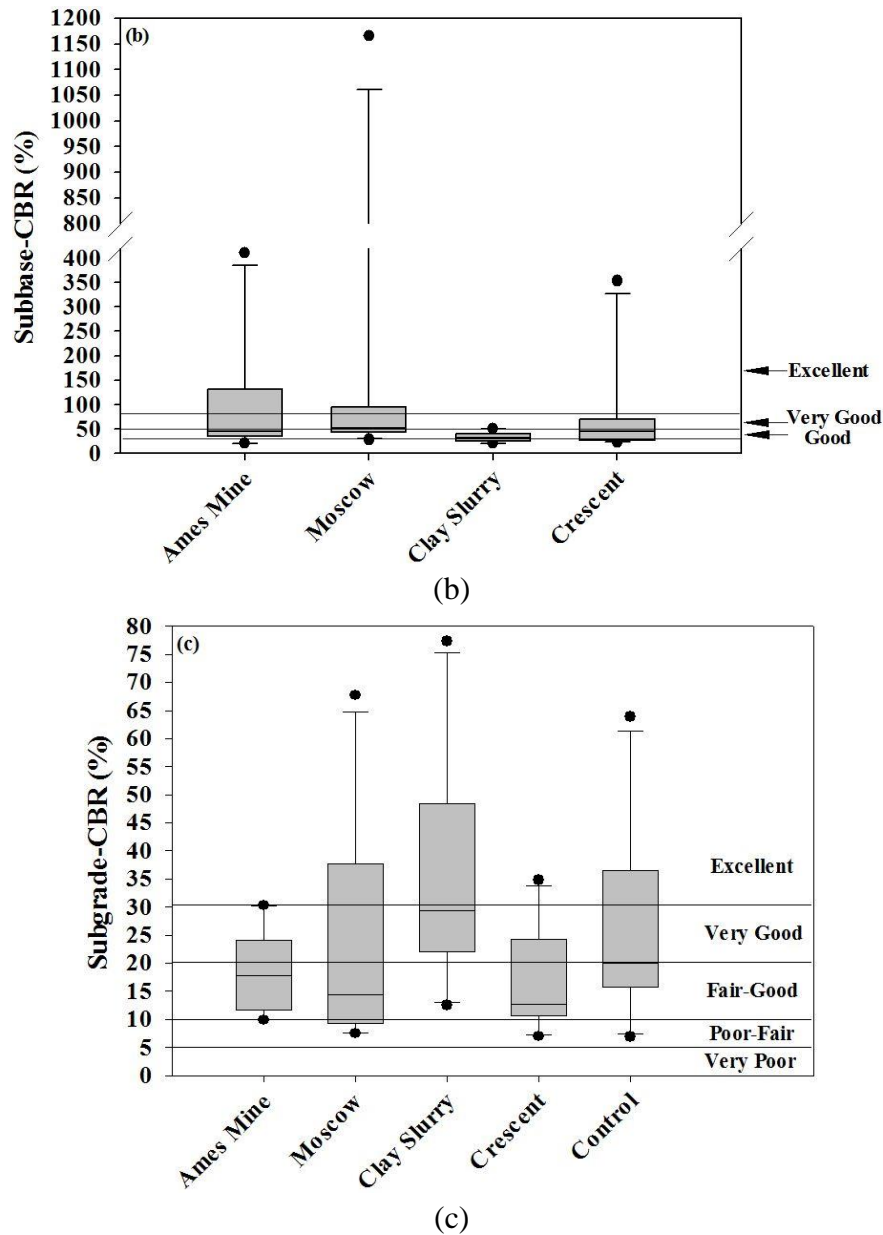
6.3.2.1. DCP Tests of November 2019

DCP tests were performed in November 2019 to investigate the strength and thickness of the surface, subbase, and subgrade layers soon after construction of the test sections. The detailed results for the thickness, average CBR values, and corresponding relative strength ratings are shown in Table 20.

Table 20. DCP results for Jones County test sections from November 2019

November 2019	Thickness (in.)		CBR (%)			Strength rating		
	Surface	Subbase	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade
Moscow	5.7	12.9	102	18	33	Excellent	<Good	Excellent
Clay Slurry	7.9	11.7	34	45	22	Good	Good	Very good
Limestone	2.9	10.3	38	52	16	Good	Very good	Fair-good
Control	7	NA	56	NA	8	Very good	NA	Poor-fair

The distributions of CBR values for the surface, subbase, and subgrade layers are shown as boxplots in Figure 46.

(a)

(b)

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(c)
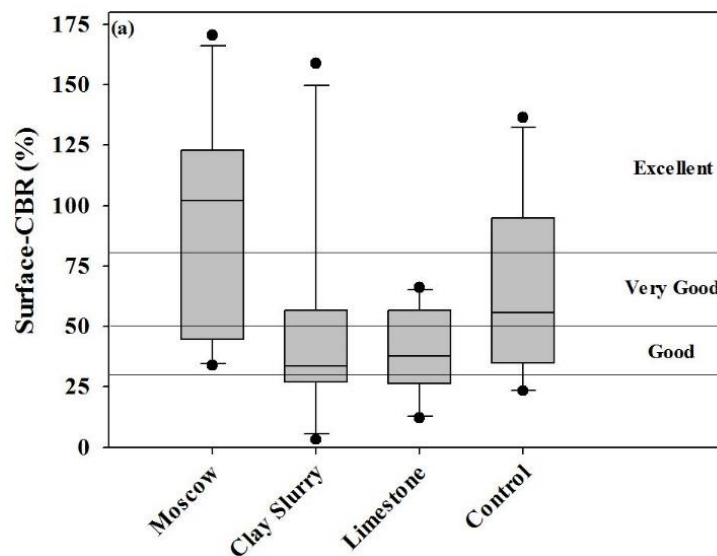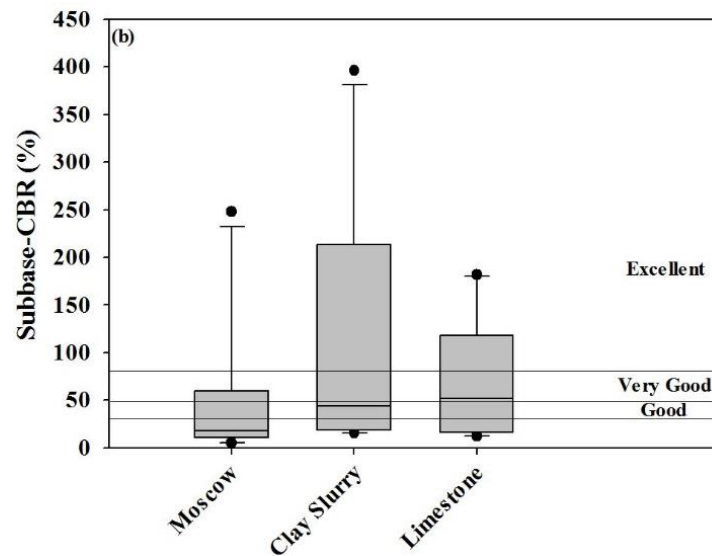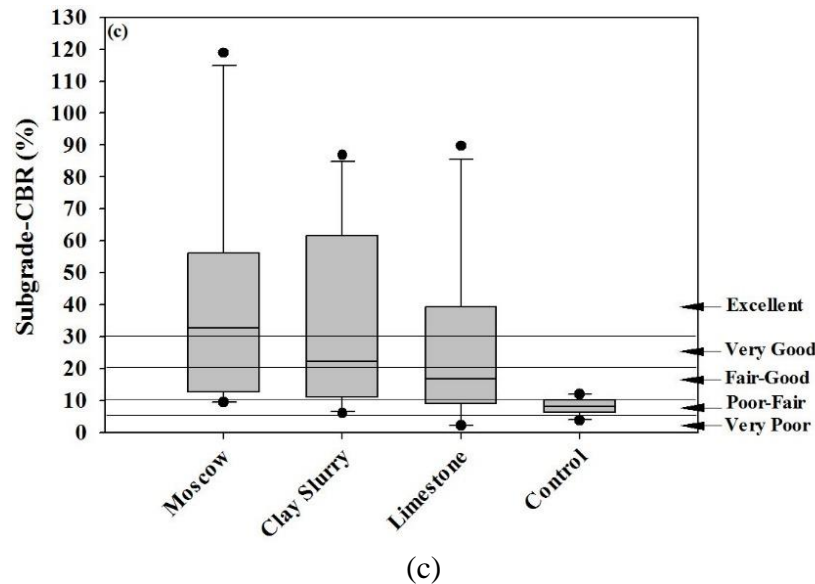
Figure 46. CBR results for (a) surface, (b) subbase and (c) subgrade layers from DCP tests in Jones County in November 2019

Figure 46a shows that the median CBR value of the surface layer for the Moscow section was rated as excellent, while the Clay Slurry and Limestone sections were rated as good, and the control section was rated as very good. The Clay Slurry section had the widest range of surface CBR values, while the Moscow and control sections had somewhat similar ranges. The Limestone section had the most consistent data (narrowest range) for the surface CBR.

For the subbase layers, the median CBR values of the Limestone, Clay Slurry, and Moscow sections corresponded to ratings of very good, good, and below good, respectively (Figure 46b). A more consistent narrow range of data was also observed for the Limestone section compared to the other two sections. However, the Clay Slurry section had the highest maximum subbase CBR values.

The median CBR values for the subgrades of the control, Limestone, Clay Slurry, and Moscow sections were rated as poor-fair, fair-good, very good, and excellent, respectively (Figure 46c). The control section had the most consistent (narrowest) range of subgrade CBR values, while the other sections had similarly wider ranges.

The average thickness of the surface courses ranged from 2.9 in. for the Limestone section to 7.9 in. for the Clay Slurry section (see Table 20), while the subbase thicknesses for all three stabilized sections ranged between 10.3 in. for the Limestone section and 12.9 in. for the Moscow section.

6.3.2.2. DPC Tests of June 2020

A second set of DCP tests were performed in June 2020, well after the end of the freeze-thaw

season. At that time, the CBR values of the surface layers of all sections were rated as good, except for the Moscow section which was rated excellent (Figure 47a).

(a)

(b)
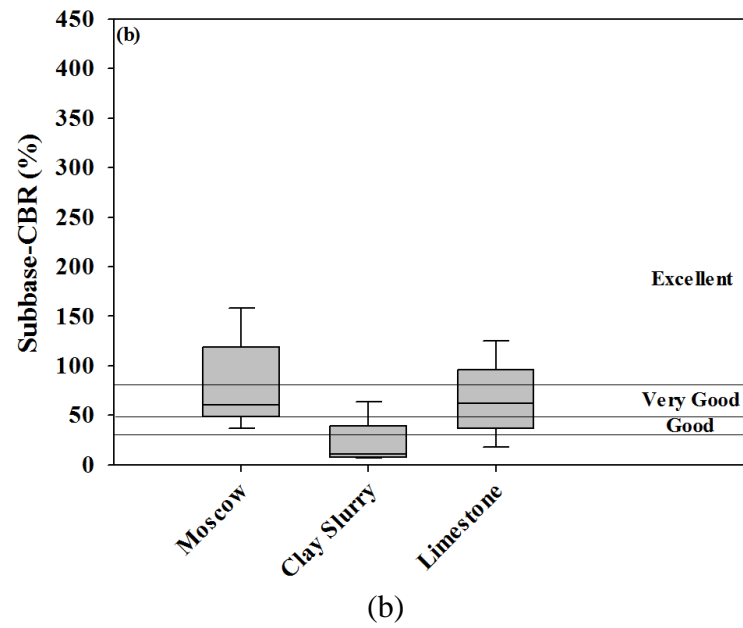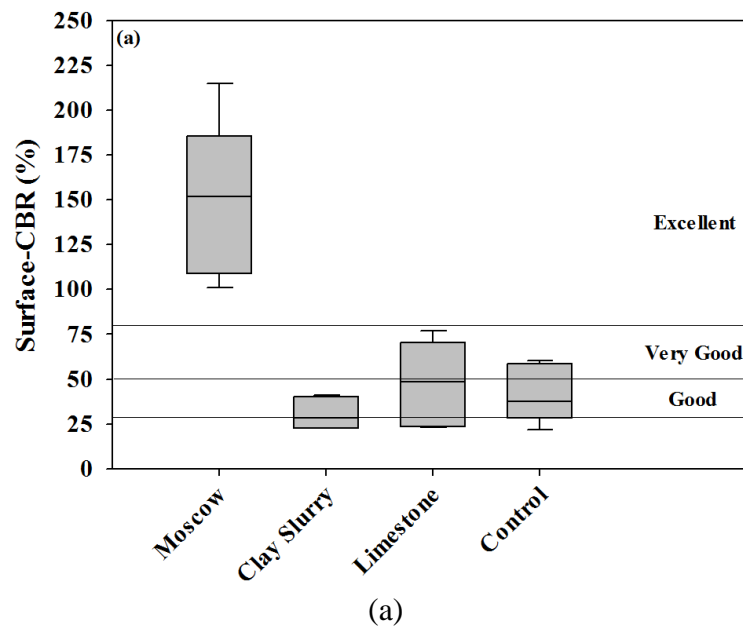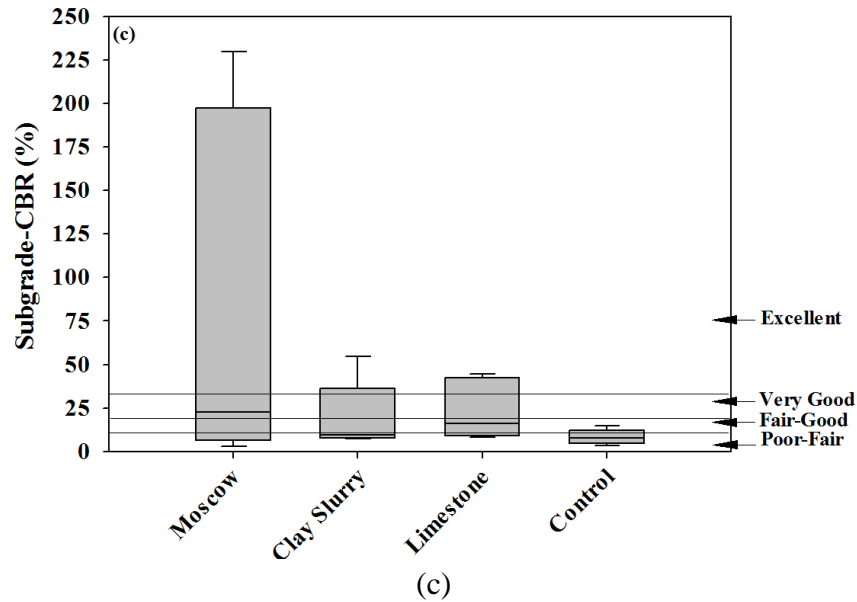
Figure 47. CBR values for (a) surface, (b) subbase, and (c) subgrade layers from CBR tests in Jones County in June 2020

The CBR values for the Moscow surface course were higher than those of all other sections, with all 10 test points of this section falling in the excellent strength range. The Clay Slurry section, on the other hand, had the lowest surface CBR values with a median value that rated on the border between good and below good. The surface CBR values for the Limestone and control sections were rated higher, with median values falling in the good range.

The subbase CBR data for the Moscow and Limestone sections had similar median values, which both rated as very good, although the Limestone section had a lower minimum value (Figure 47b). The Clay Slurry section, on the other hand, had the minimum median value for the subbase layer, which rated below good.

For the subgrade CBR values, the control and Clay Slurry sections had the lowest median values with ratings of very poor and poor-fair, respectively, whereas the Limestone section was rated as fair-good, and the Moscow section was rated as very good (Figure 47c). The subgrade CBR data for the Moscow section had the widest range and highest maximum values, and the most individual test points rating as excellent (Figure 47c).

The thickness of the layers was again determined based on the June 2020 DCP test data (Table 21), from which it was observed that all surface and subbase layers decreased in thickness from November 2019 to June 2020.

Table 21. DCP results for Jones County test sections from June 2020

Section	Thickness (in.)		CBR (%)			Strength rating		
	Surface	Subbase	Surface	Subbase	Subgrade	Surface	Subbase	Subgrade
Moscow	1.2	10.8	152	62	23	Excellent	Very good	Very good
Clay Slurry	1.0	8.8	30	12	9	Good	<Good	Poor-fair
Limestone	1.3	6.5	48	63	16	Good	Very good	Fair-good
Control	3.9	NA	42	NA	4	Good	NA	Very poor

Despite starting out with the thickest surface layer in 2019, the Clay Slurry ended up with the thinnest surface layer at 1 in., whereas the control section ended with the thickest surface layer at 3.9 in. The final subbase thickness for the Limestone section was the smallest at 6.5 in. (although this section also started out with the smallest thickness), and the thickness was greatest for the Moscow section at 10.8 in. The Limestone section experienced the smallest reduction in surface layer thickness (from 2.9 to 1.3 in.), whereas the Moscow surface layer reduced from 5.7 to 1.2 in., and the Clay Slurry surface layer reduced from 7.9 in. to 1.0 in.

6.4. FWD Tests

FWD tests were conducted at 10 locations in each test section after the first freeze-thaw period in March 2020 in both counties. The FWD is the most common test used to simulate traffic loads and evaluate the elastic modulus of the roadway layers.

The three-layered system assumption (surface, subbase, and subgrade) was employed for the back-calculation of FWD data using BAKFAA software. The Poisson's ratios of the surface, subbase, and subgrade layers were assumed to be 0.4, 0.35, and 0.3, respectively. In the following sections, the test results are summarized for each county and the modulus values of each section are compared.

6.4.1. Boone County

6.4.1.1. FWD Tests of March 2020

The back-calculated FWD moduli results for the surface, subbase, and subgrade layers in Boone County in March 2020 are shown in the following few figures. The corresponding median, maximum, and minimum Young's modulus values as well as the standard deviation (σ) and range are shown in Table 22 for Boone County.

Table 22. Surface elastic modulus values from FWD tests in Boone County in March 2020

Section	E_{Median}	E_{Max}	E_{Min}	σ	Range
Ames Mine	77	89	10	24	80
Moscow	64	95	38	20	57
Clay Slurry	47	74	28	14	46
Crescent	40	88	32	20	56
Control	20	28	11	6	18

From the results, the Ames Mine (77 ksi) and Moscow (64 ksi) sections had relatively higher median surface elastic modulus values compared to the other sections, and the control section had the lowest median value (20 ksi) (see Table 22). The Ames Mine section also had the widest range and highest standard deviation for the surface course, whereas the control section had the smallest range and lowest standard deviation. Figure 48 shows the surface results of the FWD tests in Boone County.
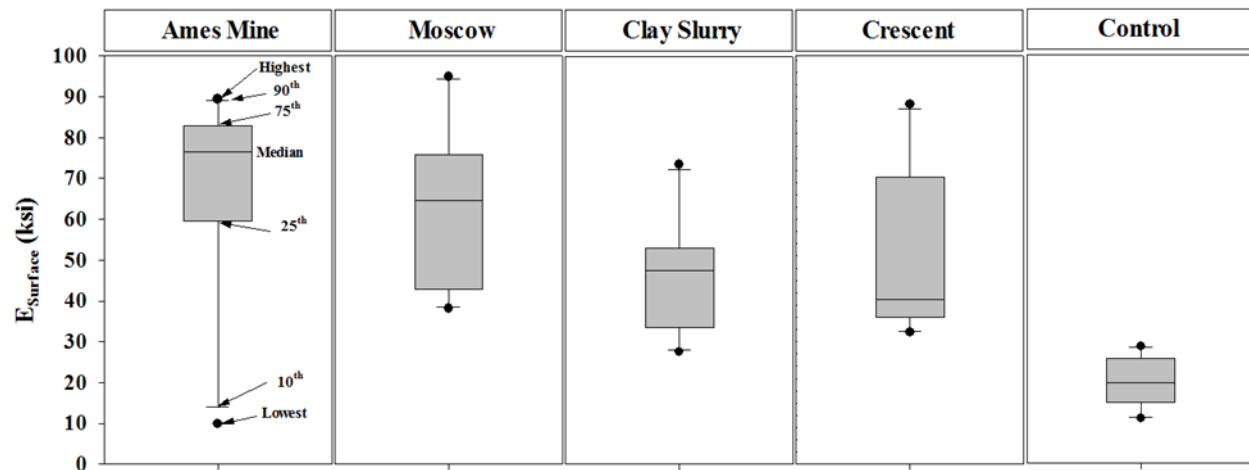
Figure 48. Surface elastic modulus values from FWD tests in Boone County in March 2020

Table 23 and Figure 49 show the median, maximum, minimum, standard deviation, and range of subbase elastic modulus values for Boone County in March 2020.

Table 23. Subbase elastic modulus values from FWD tests in Boone County in March 2020

Section	E_{Median}	E_{Max}	E_{Min}	σ	Range
Ames Mine	25	40	14	8	26
Moscow	21	32	12	7	19
Clay Slurry	19	37	10	9	27
Crescent	16	43	12	10	31
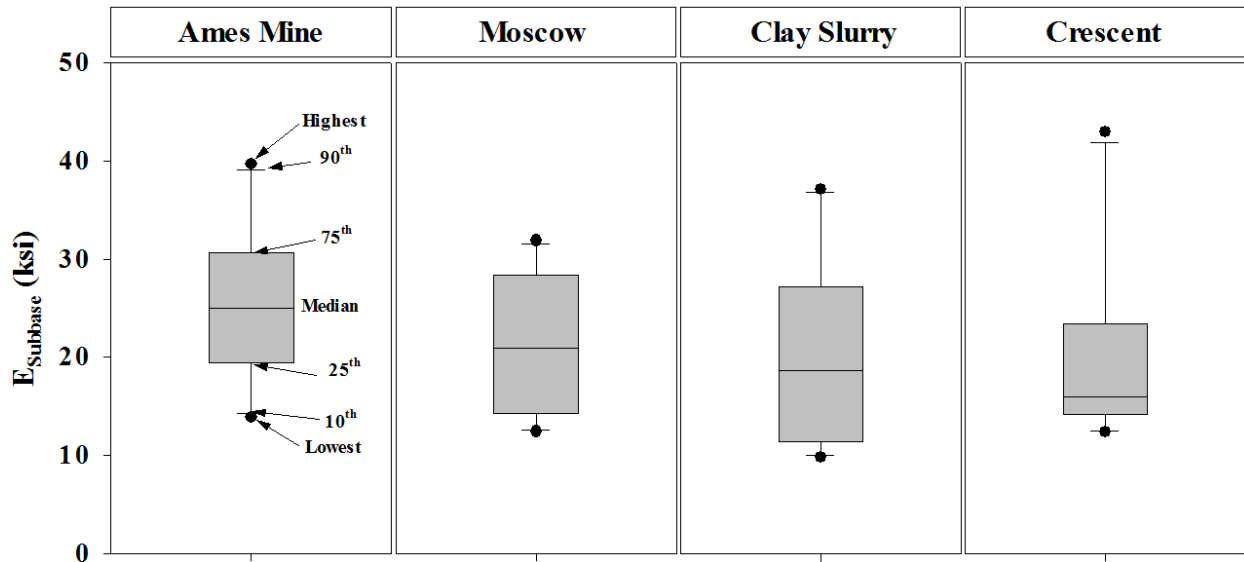
Figure 49. Subbase elastic modulus values from FWD tests in Boone County in March 2020

All the sections had very close median subbase elastic modulus values ranging between 21 and 25 ksi. This outcome was expected due to the use of the same material and methods for construction of the subbase layers in all sections.

For the subgrades beneath each test section, the median values of back-calculated elastic moduli were within a close range, from a minimum of 12 ksi for the Ames Mine section to a maximum of 16 ksi for the control section (Figure 50).
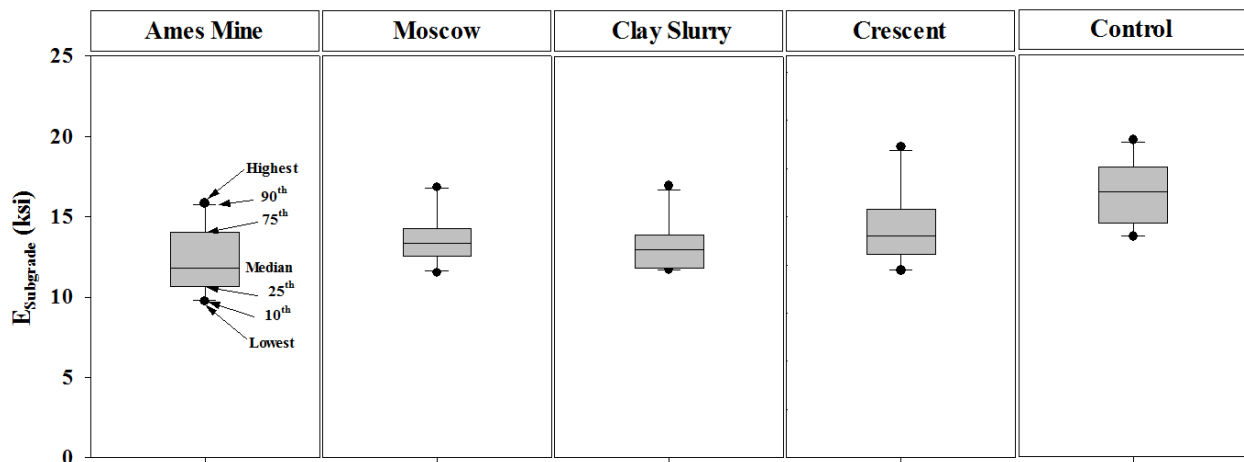
Figure 50. Subgrade elastic modulus values from FWD tests in Boone County in March 2020

The standard deviations were consistently 2 ksi for all sections, and the range of elastic modulus values within each section were fairly consistent at between 5 and 8 ksi (Table 24).

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Table 24. Subgrade elastic modulus values from FWD tests in Boone County in March 2020

Section	E_{Median}	E_{Max}	E_{Min}	σ	Range
Ames Mine	12	16	10	2	6
Moscow	13	17	12	2	5
Clay Slurry	13	17	12	2	5
Crescent	14	19	12	2	8
Control	16	20	14	2	6

This close range of subgrade elastic moduli was expected, as all test sections were constructed on the subgrade layer within the same 1 mi stretch of road.

6.4.2. Jones County

6.4.2.1. FWD Tests of March 2020

The back-calculated FWD results for the surface elastic moduli of the test sections in Jones County in March 2020 are presented in Table 25 and Figure 51.

Table 25. Surface elastic modulus values from FWD tests in Jones County in March 2020

Section	E_{Median}	E_{Max}	E_{Min}	σ	Range
Moscow	72	175	39	45	135
Clay Slurry	39	83	24	17	59
Limestone	87	206	23	67	183
Control	35	106	14	29	91
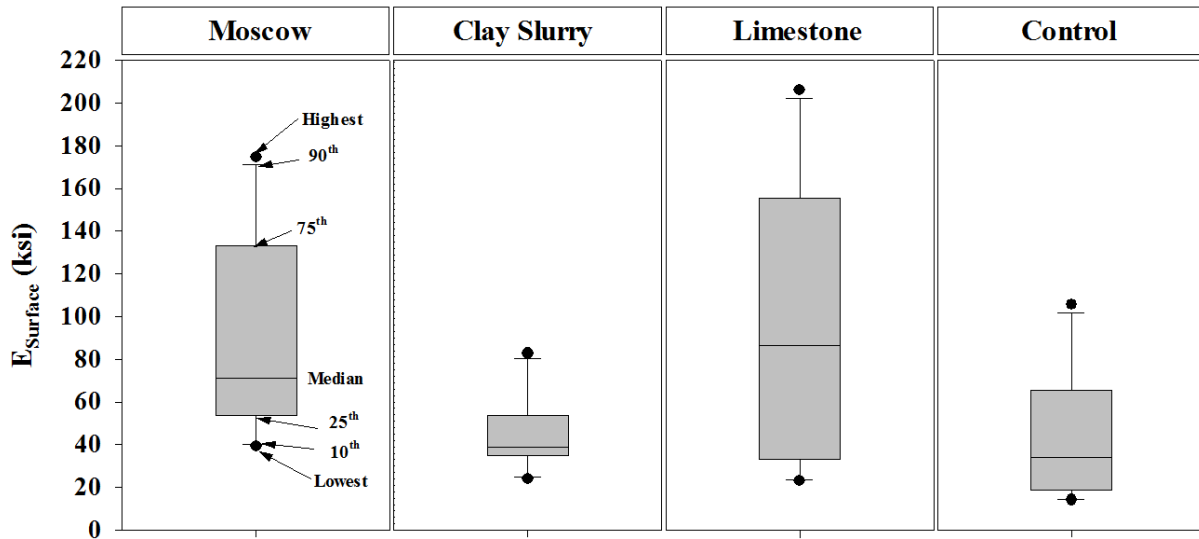
Figure 51. Surface elastic modulus values from FWD tests in Jones County in March 2020

The results show that the Limestone (87 ksi) and Moscow (72 ksi) sections had the highest median surface elastic moduli. However, these two sections also exhibited the greatest standard deviations and range of values. On the other hand, the Clay Slurry (39 ksi) and control sections (35 ksi) had similar median surface elastic modulus values. The highest surface elastic modulus was observed for the Limestone section (175 ksi).

For the subbases below the stabilized sections in Jones County, Table 26 and Figure 52 summarize the back-calculated elastic moduli in March 2020.

Table 26. Subbase elastic modulus values from FWD tests in Jones County in March 2020

Section	E_{Median}	E_{Max}	E_{Min}	σ	Range
Moscow	24	58	16	13	42
Clay Slurry	16	31	9	6	22
Limestone	36	85	10	26	75
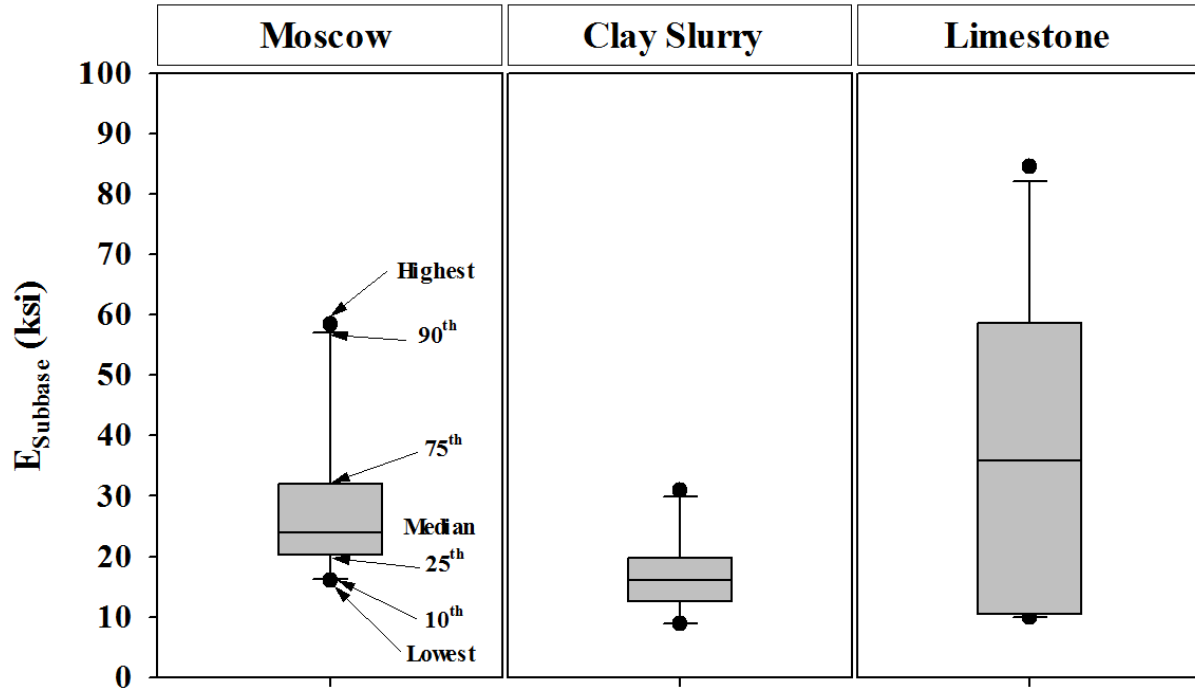
Figure 52. Subbase elastic modulus values from FWD tests in Jones County in March 2020

All four stabilized sections had similar median subbase elastic moduli ranging between 16 and 36 ksi. This observation was expected due to the use of the same construction materials and thickness (5 in.) for the subbase layers in all sections. The Limestone section had the highest median and maximum values as well as the largest standard deviation and range, while the Clay Slurry section had the lowest median, maximum, standard deviation, and range, and the corresponding values for the Moscow section were in between.

For the subgrades beneath the Jones County test sections, the median elastic modulus values were within a close range, from a minimum of 11 ksi for the control section to a maximum of 20 ksi for the Clay Slurry section (Table 27 and Figure 53).

Table 27. Subgrade elastic modulus values from FWD tests in Jones County in March 2020

Section	E_{Median}	E_{Max}	E_{Min}	σ	Range
Moscow	15	24	11	4	13
Clay Slurry	18	38	14	7	24
Limestone	13	25	9	5	16
Control	11	13	9	1	4
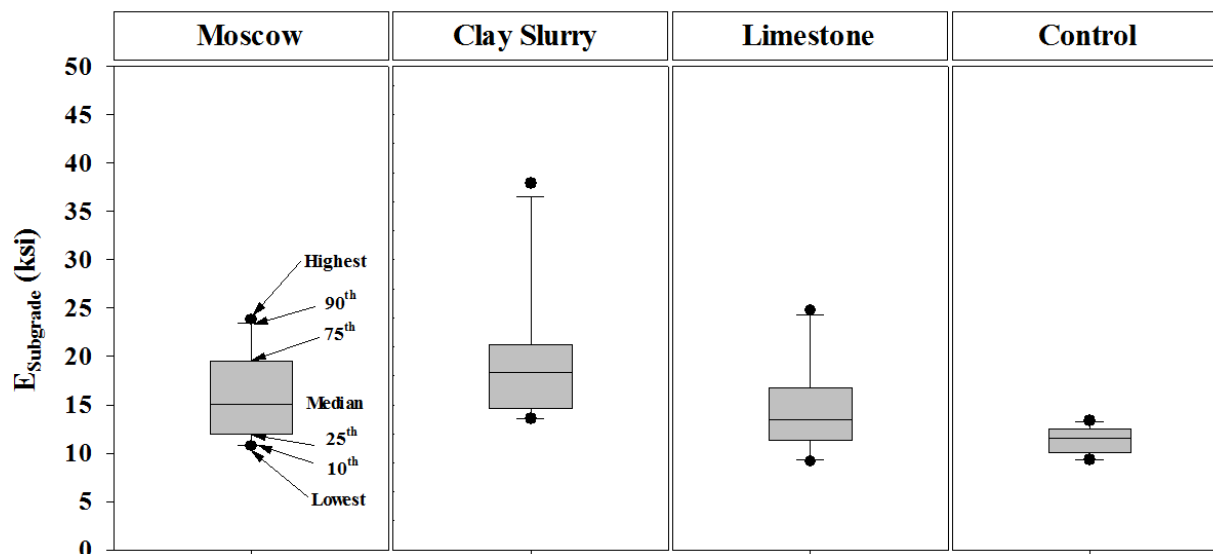
Figure 53. Subgrade elastic modulus values from FWD tests in Jones County in March 2020

The Clay Slurry section also had the largest range of values, while the control section had the smallest range. The standard deviations for subbase elastic moduli were very low for all sections, ranging from 1 ksi for the control section to 7 ksi for the Clay Slurry section. This result seems reasonable given all sections were constructed over the same 1 mi stretch of subgrade.

6.5. IRI Tests

Surface roughness is an important parameter to evaluate the performance of granular roadways. The IRI is widely used to quantify the surface roughness of pavements, and its use is increasing for management and research of granular-surfaced roads. The IRI values for all test sections were measured in this project using the Roadroid mobile application (Gopisetti 2017). Roadroid measures the vertical and horizontal movement of a vehicle using a smartphone affixed to the vehicle's windshield by a firm mount. For consistency, the same type of vehicle (a one-ton pickup truck) was used to measure the IRI each time it was performed in this study.

The Roadroid application can produce both estimated IRI (eIRI) and cIRI results. The difference between these two measures is the range of vehicle speeds over which the software can measure the IRI values. The speed range for eIRI is broader (between 12 and 62 mph) than for cIRI (between 37 and 50 mph) (Forslöf and Jones 2015). Therefore, the cIRI method provides better accuracy, and it was selected for use in this study. Table 28 shows four different surface roughness classifications based on measured IRI values.

Table 28. Surface roughness ratings based on IRI values

Roughness ratings	IRI value (in./mi)
Good	<253
Fair	253–380
Poor	380–507
Bad	>507

Source: Forslöf and Jones 2015

The cIRI values used in this study are all reported with units of inches per mile. The results of IRI measurements over time for both counties are presented in the following sections.

6.5.1. Boone County IRI Values

The IRI results for November 2019 and March 2020 in Boone County are shown in Figure 54 and Table 29.
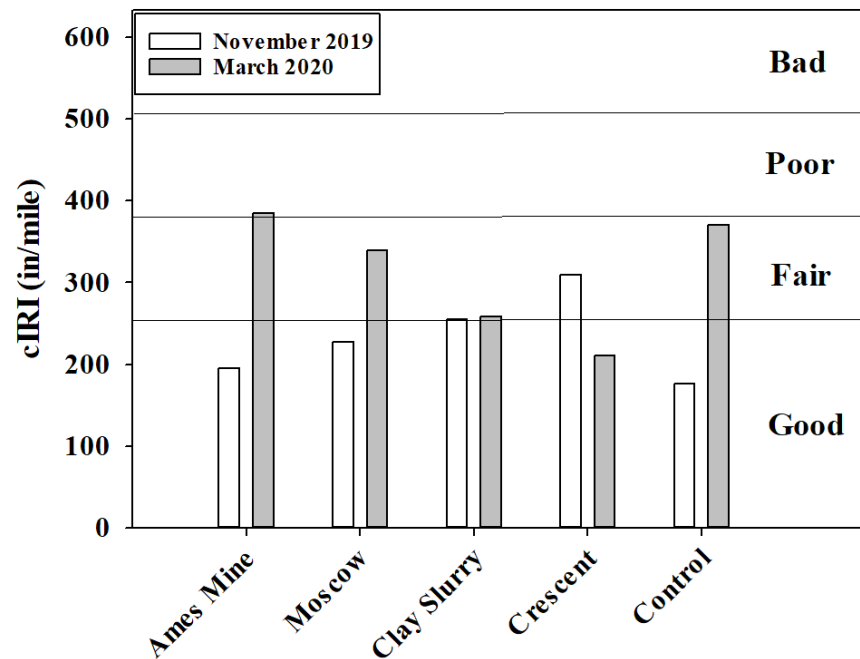
Figure 54. Average cIRI values for Boone County test sections

Table 29. Average cIRI values for Boone County test sections

Section	November 2019	March 2020	Change (%)
Ames Mine	195	385	97
Moscow	227	339	49
Clay Slurry	255	258	1
Crescent	309	210	-32
Control	176	370	110

According to the data, the surface roughness increased appreciably in the Ames Mine, Moscow, and control sections from November 2019 to March 2020. The Clay Slurry section did not have a significant change in its cIRI value, indicating a high consistency and reliability of this section due to the clay providing a bond between the aggregates that survived the freeze-thaw season. The surface roughness of the Crescent section was the only one to decrease over time, indicating that ride quality in this section improved from fair to good, possibly due to compaction under traffic loads and different deterioration rates compared to the other materials. The Ames Mine, Moscow, and control sections all started out with good surface roughness ratings in November, and by March these ratings decreased to fair for the Moscow and control sections and to poor for the Ames Mine section. The Clay Slurry surface rating remained in the fair category and very close to a rating of good for both November and March.

The cIRI values as well as their percent change from November 2019 to March 2020 are detailed in Table 29 for all Boone County sections. The Ames Mine, Moscow, and control sections experienced increases in their average cIRI values of 97%, 49%, and 110%, respectively, corresponding to increases in roughness and reductions in ride quality. On the other hand, the Clay Slurry section had a cIRI increase of only 1%, while the Crescent section had decrease of 32% in roughness corresponding to an increase in ride quality.

6.5.2. Jones County IRI Values

The IRI results for the Jones County test sections in November 2019 and March 2020 are shown in Figure 55 and Table 30.
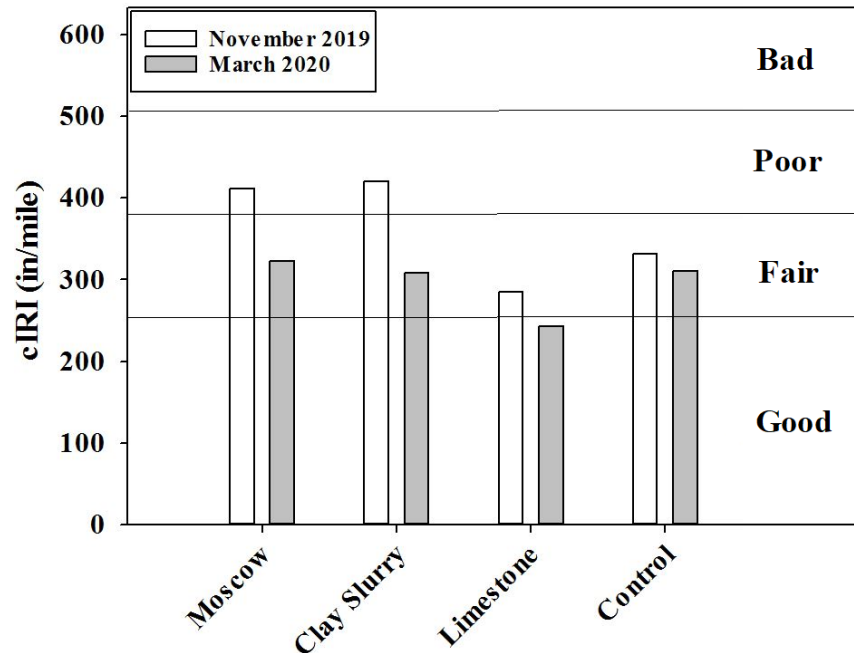
Figure 55. Average cIRI values for Jones County test sections

Table 30. Average cIRI values for Jones County test sections

Section	November 2019	March 2020	Change (%)
Moscow	412	323	-22
Clay Slurry	420	308	-27
Limestone	285	243	-15
Control	332	311	-6

According to Figure 55, the surface roughness of all sections decreased from November 2019 to March 2020, indicating increases in ride quality for all sections. The change was most significant for the Moscow and Clay Slurry sections, as they had poor ratings in November and fair ratings in March. This could possibly be due to blading of these sections to repair the distresses such as rutting and potholes. The Limestone section had the lowest surface roughness and best rating in both November 2019 and March 2020, and its rating improved from fair in November to good in March. The control section had a consistent rating of fair in both November 2019 and March 2020.

The average cIRI results for all test sections in Jones County in November 2019 and March 2020 are shown in Table 30. All sections experienced a decrease in their average cIRI values from November 2019 to March 2020 ranging from -6% for the control section to -27% for the Limestone section.

6.6. LWD Tests

LWD tests were performed in both counties to evaluate the composite elastic modulus ($E_{Comp.}$) of the test sections soon after construction in November 2019 and again after the freeze-thaw season in March 2020. The results of the tests are described in the following sections.

6.6.1. Boone County LWD Tests

The results of the Boone County LWD tests are shown as statistical boxplots in Figure 56.
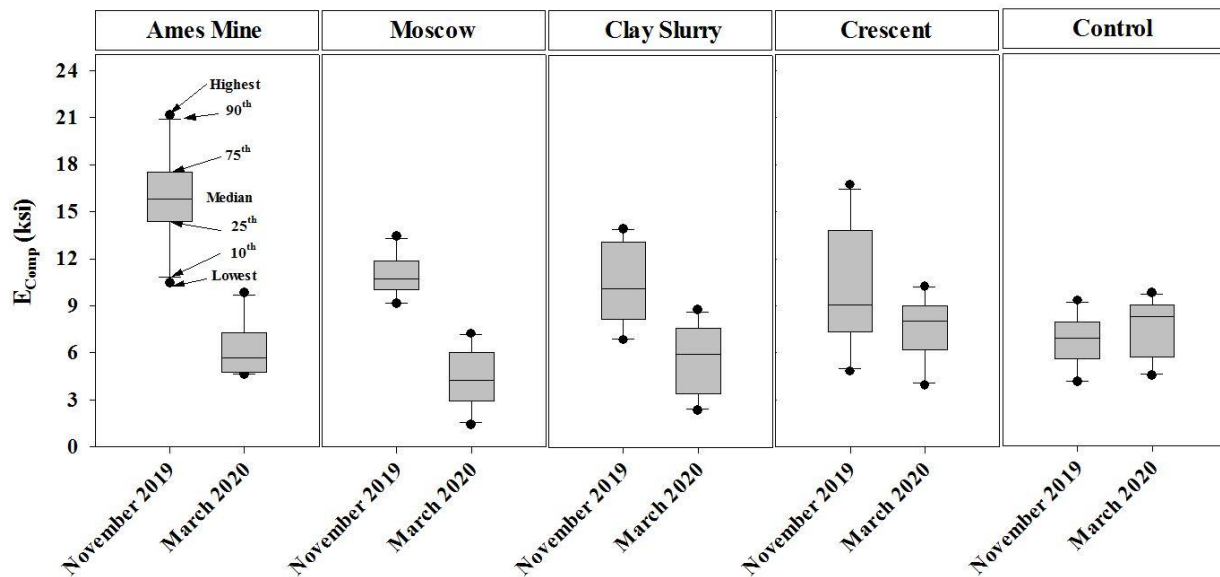
Figure 56. Composite elastic modulus values from LWD tests in Boone County

According to the plots, all sections experienced a decrease in their median $E_{Comp.}$ values over time, except for the control section, which experienced a slight increase. In November 2019, the Ames Mine section had the highest median $E_{Comp.}$ value, and all other stabilized sections had higher values than the control section. By March 2020, only the Crescent section had a higher median $E_{Comp.}$ value than the control section, while the Ames Mine, Clay Slurry, and Moscow sections were all lower.

The median, maximum, and minimum $E_{Comp.}$ values as well as their ranges and standard deviations are detailed in Table 31 (all rounded to the nearest 1 ksi).

Table 31. Composite elastic modulus values from LWD tests from November 2019→March 2020 in Boone County

	Section				
	Ames Mine	**Moscow**	**Clay Slurry**	**Crescent**	**Control**
E_{Median}	16→6	11→4	10→6	10→8	7→8
E_{Min}	10→5	9→1	7→2	5→4	4→4
E_{Max}	21→10	13→7	14→9	17→10	9→10
Range	11→5	4→6	7→6	12→6	5→5
σ^1	3→2	1→2	2→2	4→2	2→2

[1]Standard deviation

The results show that the median $E_{Comp.}$ values in November 2019 varied from a minimum of 7 ksi for the control section to a maximum16 ksi for the Ames Mine section. By March 2020, the median, maximum, and minimum $E_{Comp.}$ values all decreased for the quarry fines-treated sections, whereas they increased slightly for the control section.

In November 2019, the Crescent and Ames Mine sections had the highest ranges of $E_{Comp.}$ at 12 and 11 ksi, respectively, while the Moscow and control sections had the lowest ranges of 4 and 5 ksi, respectively, and the Clay Slurry section had an intermediate range of 7 ksi. By March 2020, however, the ranges of $E_{Comp.}$ values were consistently between 5 and 6 ksi for all sections, and all sections possessed the same standard deviation of 2 ksi.

6.6.2. Jones County LWD Tests

The results of LWD tests in Jones County are shown in Figure 57 and Table 32.
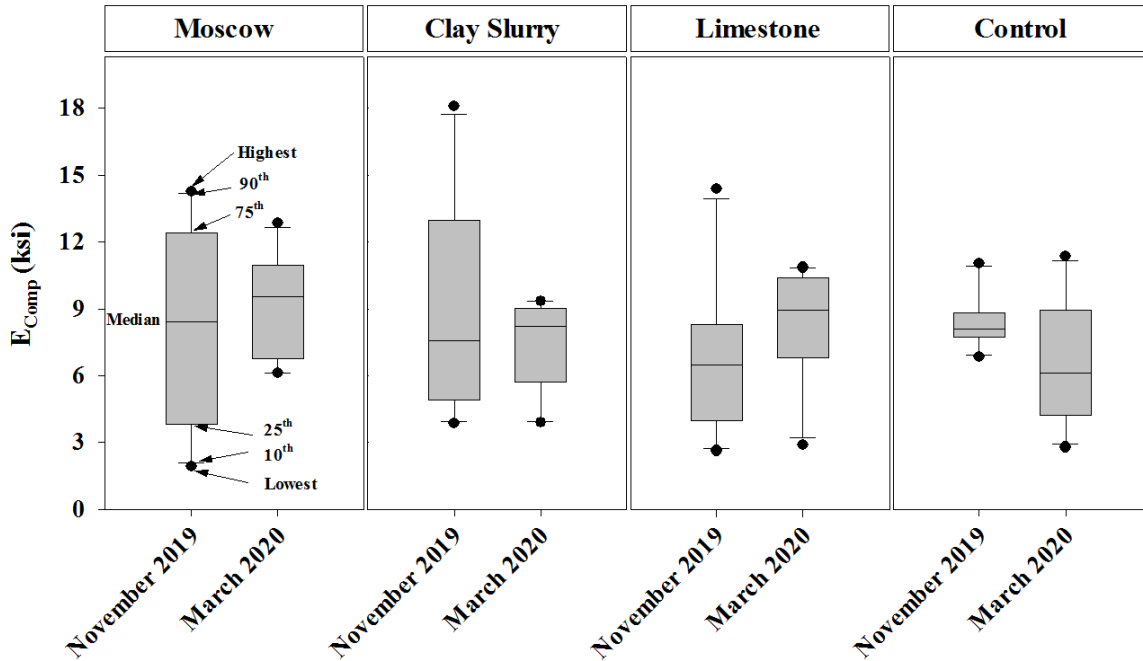
Figure 57. Composite elastic modulus values from LWD tests in Jones County

Table 32. Composite elastic modulus values from LWD tests from November 2019→March 2020 in Jones County

	Section			
	Moscow	**Clay Slurry**	**Limestone**	**Control**
E_{Median}	8→9	9→7	7→8	8→7
E_{Min}	2→6	4→4	3→3	7→3
E_{Max}	14→13	18→9	14→11	11→11
Range	12→7	14→5	12→8	4→9
σ^1	4→2	5→2	3→2	1→3

[1]Standard deviation

From November 2019 to March 2020, all three quarry fines-treated sections experienced an increase in median $E_{Comp.}$ value, while the control section experienced a decrease. By March 2020, the three treated sections all had median $E_{Comp.}$ values a few ksi greater than that of the control section.

Similar to Boone County, the range of $E_{Comp.}$ values in each treated section also decreased over time and ended up with the same standard deviation of 2 ksi, whereas the range in the control section increased, and the final standard deviation was 3 ksi. Overall, the quarry fines had the effect of increasing the stiffness of all three treated sections over time, while the control section's stiffness decreased.

6.7. Dustometer Tests

The dustometer test is a well-known indicator of dust emission and provides a way to compare the performance of different test sections based on their dust production. Dustometer tests were conducted in Boone and Jones counties twice in November 2019 after construction of the sections, and once in June 2020 after the freeze-thaw period.

6.7.1. Boone County Dustometer Tests

The measured dust emission (given in 10^{-3} lb/mi) for all test sections in Boone County are shown in Figure 58.
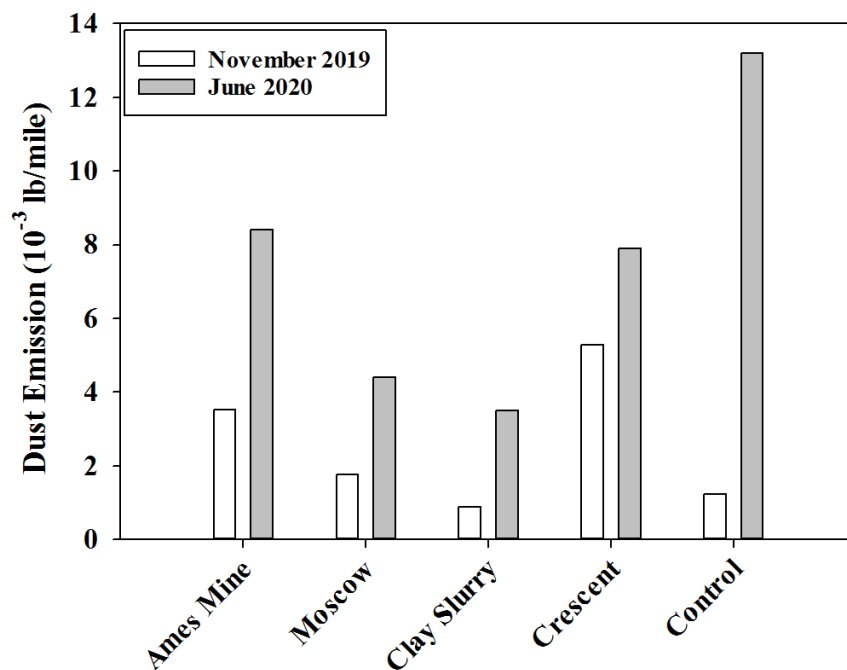
Figure 58. Dust production for all sections in Boone County

The results show that all sections in Boone County experienced an increase in dust emission after the freeze-thaw season. This increase may be attributed to aggregate deterioration occurring throughout and after the freeze-thaw season, as well as lower moisture content of the granular surfaces in June 2020 compared to November 2019. Despite the potential differences in moisture content on different test dates, the relative dust emission values of the various test sections provide useful insights on their relative performance. For instance, in November 2019, the dust emission was highest in the Crescent and Ames Mine sections and lowest in the control and Clay Slurry sections. By June 2020, however, the control section had the highest dust emission, while the Clay Slurry retained its ranking of lowest dust emission among all the test sections. The Moscow section ended up in June 2020 with a slightly higher dust emission than the Clay Slurry section, while the Ames Mine and Crescent sections had the largest dust emission among the treated sections.

Table 33 shows a summary of the results of dustometer tests in Boone County.

Table 33. Dust production for all sections in Boone County

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

The data show that among the treated sections, the Crescent section had the smallest percent increase in dust at 42%, while the Clay Slurry section had the largest increase at 289%. On the other hand, the control section had the largest increase among all sections at 525%.

6.7.2. Jones County Dustometer Tests

The results of the dustometer tests (given in 10^{-3} lb/mi) in Jones County are shown in Figure 59.
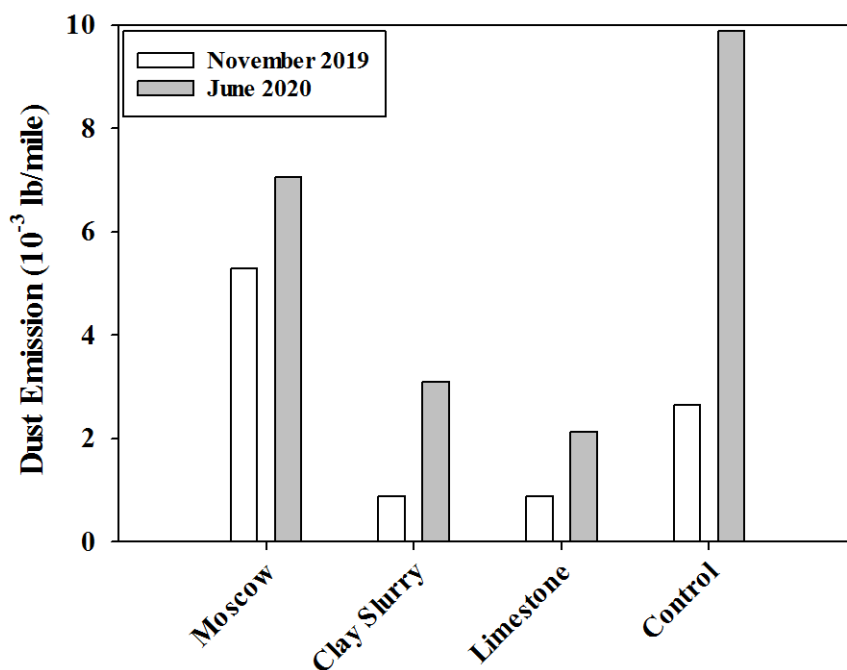
Figure 59. Dust production for all sections in Jones County

The data show that the Clay Slurry and Limestone sections had the lowest dust emission values among all sections in both November 2019 and June 2020. Similar to Boone County, the control section had the greatest increase in dust emission and ended up with the largest value in June

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2020. The Moscow and control sections had the highest dust emission values in both November 2019 and June 2020.

Table 34 contains a summary of the dustometer data for Jones County.

Table 34. Dust production for all sections in Jones County

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

The data show that while the Moscow and control sections had the highest dust emissions as noted previously, the Moscow section experienced the smallest increase in dust emission at 34%, while the control section had the greatest increase at 281%. The Limestone and Clay Slurry sections consistently had the lowest dust emission values and had increases in their dust emissions of 133% and 244%, respectively.

CHAPTER 7. COST AND BENEFIT ANALYSES

This chapter first examines the labor, equipment, hauling, and materials costs for each test section in Boone and Jones counties, then explains the methodology used to determine the benefits and cost-effectivity of choosing the various types of quarry fines for mixing with surface aggregates.

The quarry fines materials in this study were hauled from four quarries to the test sites in Boone and Jones counties as shown previously in Figure 1. In general, Jones County was relatively closer to the quarry locations compared to Boone County.

The previously given Table 6 shows the approximate hauling times between the quarries and test site locations in Boone and Jones counties.

The hauling times for the Clay Slurry, Moscow, and Crescent fines to the Boone County test site were between 2 and 3 hours, while the Ames Mine source was only 15 minutes away from this location. Consequently, the Ames Mine fines had the lowest hauling cost for Boone County. The Clay Slurry and Limestone quarry fines came from the same Frenchtown quarry and therefore had the same hauling time of 1 to 2 hours for the Jones County test site, while the Moscow fines were also near the Jones County site (1 hour away). Therefore, the Moscow fines material was a slightly more economical option than Clay Slurry and Limestone fines for constructing a test section in Jones County.

7.1. Construction Costs: Boone County

The test section construction procedures required road construction equipment including a motor grader, tandem truck, tractor/roller, and water truck. The hourly combined labor and equipment costs in Boone County for this equipment are presented in Table 35.

Table 35. Boone County labor and equipment unit costs

Category	Unit cost
On-site labor	$43.15/hr
Motor grader	$76.15/hr
Tandem dump truck	$59.55/hr
Water truck	$49.85/hr
Tractor and roller	$35.04/hr

The recorded times and costs for the labor and equipment used in the construction of the Boone County test sections are shown in Table 36.

Table 36. Time and labor/equipment costs to construct Boone County test sections

Section	Variable	Labor	Motor grader	Tandem truck	Tractor/ Roller	Water truck
Ames Mine	Time	4	2	2	1	-
	Cost	$173	$152	$119	$35	-
Moscow	Time	4	2	2	1	-
	Cost	$173	$152	$119	$35	-
Clay Slurry	Time	28	12	12	4	-
	Cost	$1,208	$914	$715	$140	-
Crescent	Time	10	2	4	2	2
	Cost	$431.5	$152	$238	$70	$100

Note: Time is given in hours.

The results show that the Clay Slurry section had the longest construction time due to the high water content of the Clay Slurry, which required extensive blade mixing and tractor/roller compaction. In addition, 120 tons of dry surface aggregates were spread over the surface of this section at the end of construction to reduce sticking of the material to tires. The Ames Mine and Moscow sections had the same labor and equipment costs, while the Crescent section required more time due to the use of a water truck for this section.

The unit costs and hauling times for the quarry fines materials as well as previously obtained fresh aggregates are shown in Table 37 for Boone County.

Table 37. Unit cost and hauling time for the Boone County materials

Materials	Unit cost ($/ton)	Hauling time (hr)
Aggregates	10.50	-
Moscow	8.30	2.6
Ames Mine	7.95	0.25
Crescent	3.00	2.5

The quarry fines costs were lower than the aggregate cost, as expected. Moreover, the unit cost of the Crescent fines was significantly less than that of the Moscow and Ames Mine fines. The Clay Slurry fines were delivered in two water tanker loads at a material cost of $100 each (hauling costs are discussed later). As described previously, the proximity of the Ames Mine quarry fines resulted in a lower hauling time of 15 minutes for these materials. The fresh surface aggregates were previously purchased and stockpiled by Boone County, and there was no hauling time considered for them due to the proximity of the stockpile to the test site location.

Table 38 shows the weights and corresponding costs of the surface aggregates and quarry fines used in construction of the Boone County test sections, as well as the associated hauling costs including labor.

Table 38. Material weights and costs for test section construction in Boone County

Section	Fresh aggregates		Quarry fines		Hauling costs		Existing surface aggregates	
	Tons	Cost	Tons	Cost	Labor	Truck	Tons	Cost
Ames Mine	0	-	39	$310	$17	$30	352	$3,694
Moscow	0	-	40	$332	$175	$310	362	$3,805
Clay Slurry	120	$1,260	7 (2 loads[1])	$200	$1,550	$1,125	343	$3,604
Crescent	24	$252	7	$21	$169	$298	343	$3,604
Control	-	-	-	-	-	-	363	$3,814

[1] Clay Slurry materials were delivered in water tankers.

The Clay Slurry section required the addition of 120 tons of fresh aggregates, and the Crescent section required 24 tons of fresh aggregates to decrease the moisture content of these sections during construction. Based on the design calculations, the Moscow and Ames Mine sections required 40 tons and 39 tons of quarry fines, respectively, while the Crescent and Clay Slurry sections needed only 7 tons of quarry fines each. The Clay Slurry fines were hauled and sprayed by self-unloading water tankers and required two tanker loads. Among all the quarry fines test sections, the Clay Slurry materials had the highest hauling costs, whereas the Crescent and Moscow sections had similar hauling costs that were much lower, and the Ames Mine section had very low hauling costs due to its close proximity to the test site.

7.2. Construction Costs: Jones County

The test section construction procedures in Jones County employed similar road construction equipment including a motor grader, skid loader, water truck, and tractor/roller. The unit costs of the equipment per hour including labor are presented in Table 39.

Table 39. Jones County labor and equipment unit costs

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

The recorded times and costs for the labor and equipment used in the construction of the Jones County test sections are shown in Table 40.

Table 40. Time and labor/equipment costs to construct Jones County test sections

Section	Variable	Labor	Motor grader	Skid loader	Tractor/ Roller	Water truck
Moscow	Time	3	2	1	0.25	1
	Cost	$107	$152	$33	$8	$73
Clay Slurry	Time	22	7	-	0.5	-
	Cost	$781	$533	-	$15	-
Limestone	Time	3	2	1	0.25	1
	Cost	$107	$152	$33	$8	$73

Note: Time is given in hours.

The results reflect the fact that the Clay Slurry section required more labor and equipment time due to the high water content of the Clay Slurry. Consequently, more time was required for the grader to mix the slurry with existing aggregates until the water content was reduced sufficiently and for the tractor/roller to compact the mixture. The Limestone and Moscow sections had the same labor and equipment costs, and a water truck was used for both sections to achieve the optimum moisture content of the surface materials.

Table 41 shows the unit costs and hauling time for the Moscow fines and the fresh aggregates used in Jones County.

Table 41. Unit cost and hauling time for Jones County materials

Materials	Unit cost ($/ton)	Time (hr)
Aggregates	8.40	-
Moscow	8.30	1

The unit cost of the Moscow fines was only slightly lower than the cost of the fresh aggregates. The Clay Slurry and Limestone fines were delivered in loads and their costs per load are discussed in the following section. As previously noted, the quarries selected for this project were relatively closer to the Jones County site compared to the Boone County site. The surface aggregates were from Stone City, which is in close proximity to the test site, so no hauling time was considered for surface aggregates.

Table 42 shows the weights and costs of the surface aggregates and quarry fines used in construction of the Jones County test sections, along with the hauling costs including labor.

Table 42. Material weights and costs for test section construction in Jones County

Section	Fresh aggregates		Quarry fines		Hauling costs		Existing surface aggregates	
	Tons	Cost	Tons	Cost	Labor	Truck	Tons	Cost
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	$250	$550		368	$3,94
Control	-	-	-	-	-	-	358	$3,003

[1] Clay Slurry materials were delivered in two water tanker loads.

The Clay Slurry section required 61 tons of fresh aggregates during construction, while the Moscow section required 91.5 tons, in order to decrease the moisture content and provide smoother surfaces. Based on the design calculations, the Moscow section required 55 tons of quarry fines, while the Limestone and Clay Slurry sections required only 7 tons and 8 tons of fines, respectively. The Clay Slurry was delivered in two tanker loads and was spread using a smaller self-unloading tanker truck. The Limestone fines were dewatered on site and had a moisture content of approximately 20% at the time of construction. The Limestone fines came out of the dump truck as a large mass and needed to be picked up and spread over the test section by a skid loader before being bladed with a motor grader. Among all the quarry fines materials, the Clay Slurry had the highest hauling costs, whereas the Limestone and Moscow fines had similar hauling costs that were much lower.

7.3. BCA

To determine the cost-efficiency of stabilizing granular road surfaces using various sources of quarry fines, this project examined materials from two quarries to construct test sections in Jones County and four quarries to construct test sections in Boone County. Three stabilized sections were constructed in Jones County and four were constructed in Boone County, with each section having different material properties, subgrade conditions, and costs.

The important factors considered in the BCA model were the construction costs, durability as assessed through the gradation change and total breakage, dust production, and engineering properties in the form of stiffness and CBR strength. The BCA begins by defining a base case, which was taken as the control sections in Boone and Jones counties for this study. The second step in the BCA is to quantify the benefits of using the different types of quarry fines and determine the best option for each county. This is done by comparing the test sections in terms of their environmental and serviceability factors (dust emission, ride quality), mechanical properties of the surface layers (strength and stiffness), and durability as measured by size characteristics (total breakage, fines content, G/S ratio, and gravel loss). The third step in the BCA model is to calculate the present values of the costs and benefits. These steps for BCA analyses are discussed in more detail in the following sections. In addition, a sample BCA spreadsheet is included in Appendix D.

7.4. Defining the Benefits

7.4.1. User Cost Savings

Granular roadways in seasonally cold regions undergo freezing and thawing, which accelerates deterioration of their surface aggregates under traffic loading. For the present BCA, it was therefore assumed that maintenance of the control sections would require the renewal of at least 2 in. of surface aggregates per year. It was also assumed that the maintenance procedures caused traffic delays that would double the usual travel time. The travel time associated with maintenance of a 0.25 mi test section was assumed to be 3 minutes, and the travel time during maintenance considering the delay was assumed to be 6 minutes. Therefore, the traveling public's user time could be saved by performing maintenance less frequently on roads that are stabilized. The travel time savings outcome is a user cost savings, and its specific value depends on vehicle type. The U.S. Bureau of Labor Statistics recommends that user cost savings be calculated based on rates of $54/hr for trucks and $25/hr for passenger cars (U.S. BLS 2018). According to the Boone and Jones counties' engineering offices, truck traffic is approximately 25% of the AADT for both roads. Moreover, the total AADT of the roads in Boone and Jones counties were 70 and 80 VPD, respectively, based on the Iowa Traffic Map (Iowa DOT 2007).

7.4.1.1. Maintenance Cost Savings

Performing regular maintenance, including adding new aggregates, can result in additional cost savings. Renewing the surface layer of gravel roads in cold regions is typically necessary for at least the top 2 in. of surface aggregates due to aggregate loss and abrasion, as well as surface distresses such as rutting, potholes, and washboarding (Cetin et al. 2019, Mahedi et al. 2020, Satvati et al. 2019). Improving the binding between the aggregates by utilizing quarry fines helps to minimize such issues by reducing aggregate loss and abrasion. Therefore, the maintenance costs for the quarry fines sections were reduced in the BCA by delaying the regular maintenance procedures (Satvati et al. 2020a, Wu et al. 2020). The reduced maintenance frequency was selected based on the observed performance and serviceability of each section, and the intervals between maintenance operations were chosen to be one year for low-performance sections, two years for medium-performance sections, and three years for high-performance sections. Moreover, three different scenarios were considered, including a worst-case, most likely, and best-case scenario. For a given test section, the maintenance interval for the most likely scenario was selected corresponding to the section's observed performance category (low, medium, or high), then this interval was reduced by one year for the worst-case scenario and increased by one year for the best-case scenario.

7.4.2. NPV Calculation for BCA

After defining the base case and benefits, the next step is to calculate the annual values of the costs and benefits. Equation 7 shows how to calculate the NPV considering the construction costs, maintenance costs, and salvage value. The service life (*n*) and the discount rate are two main factors in NPV calculations.

$$NPV = \text{Construction Costs}$$

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

where *i* is the discount rate and *n* is the service life of the project in years. 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 assumed that the surface materials would have no remaining life beyond the service life of the road.

The BCR is defined as the ratio between the NPV of the benefits divided by the NPV of the total costs. The user cost savings and maintenance cost savings were defined as benefits for the BCR calculations. A spreadsheet was developed and used to calculate the BCR values for each quarry fines alternative corresponding to one test section. Several alternative values were considered for the service life of the project (20, 30, 40, and 50 years). Moreover, a discount rate of 3% and maintenance intervals of one, two, three, four, and five years were additional inputs for the BCA model.

7.4.3. Performance-Based BCA

Along with the primary performance measures of breakage and gravel content, the laboratory and field test results including surface stiffness from FWD tests, surface strength from DCP tests, dust emission from dustometer tests, ride quality (IRI), and size characteristics (fines content and G/S ratio) were divided into three different secondary groups based on their degree of importance for influencing maintenance procedures. To combine all the BCA results and finally select the most beneficial alternative, relative weighting factors were assigned to each performance measure. The total breakage and change in gravel content were considered to be the most important considerations for choosing when to perform maintenance, so a relative weighting factor of 1.0 was assigned to these materials. The other performance measures, including fines content, G/S ratio, FWD modulus, DCP-CBR value, ride quality, and dust emission were placed into three groups based on their relative importance for maintenance considerations (Table 43).

Table 43. Classification of the laboratory and field results for BCA

	Primary measures	**First group**	**Second group**	**Third group**
Performance measures	Breakage, Gravel content	Fines content, G/S ratio	FWD, DCP	Dustometer, IRI
Weighting factor	1	0.75	0.5	0.25

The average fines content and G/S ratio within each test section were considered as the first group due to their importance to the shape characteristics and resulting performance of the surface aggregates, and they were assigned a weighting factor of 0.75. The FWD surface elastic

modulus and CBR value from DCP tests were placed in the second group, given they are representative of the structural properties of the surface layer, and they were assigned a weighting factor of 0.50. Finally, results of dustometer and IRI tests (dust emission and surface roughness/ride quality) were assigned to the third group with a weighting factor of 0.25. The following sections explain the results of the BCA for all test sections in both counties.

7.5. Results and Discussion for Boone County

Figure 60 shows the costs per 0.25 mi for equipment, aggregates, quarry fine materials, and hauling for all alternative sections in Boone County.
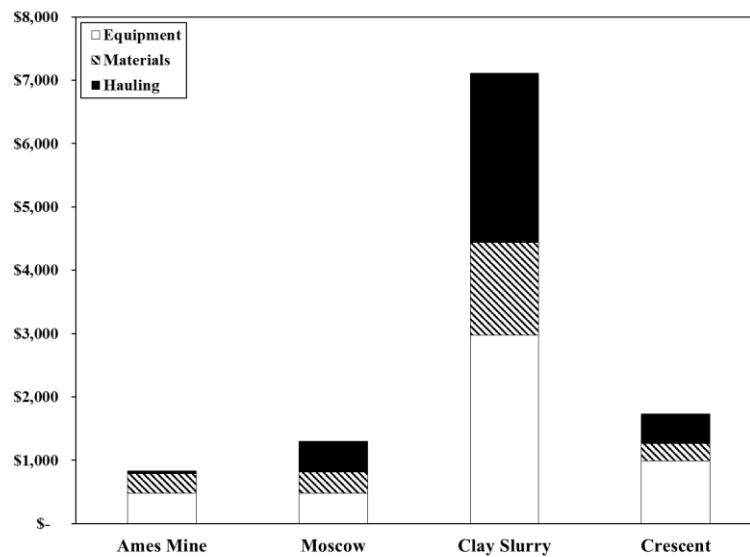
Figure 60. Construction costs for equipment, materials, and hauling in Boone County

The total construction cost for the Clay Slurry section was $7,112, which was the highest due to the greater hauling, equipment, and materials costs for this section. On the other hand, the Ames Mine section had the lowest total cost of $836, mostly attributed to its lower hauling costs. The material costs for the Ames Mine, Moscow, and Crescent sections were almost the same, though the Ames Mine and Moscow sections had the lowest equipment costs compared to the others.

The following sections describe the different performance measures considered to evaluate the serviceability of the sections for various maintenance scenarios, and based on each measure's performance, BCR values were determined. An overall BCR was calculated to select the most beneficial quarry fines option for Boone County.

7.5.1. Change in Gravel Content

The change or loss in gravel content (particle size >US Sieve #4 [4.76 mm]) was considered as one of the main indicators of deterioration of the granular road test sections. The gravel content

change from November 2019 to March 2020 is shown in Figure 61 for the treated sections in Boone County.
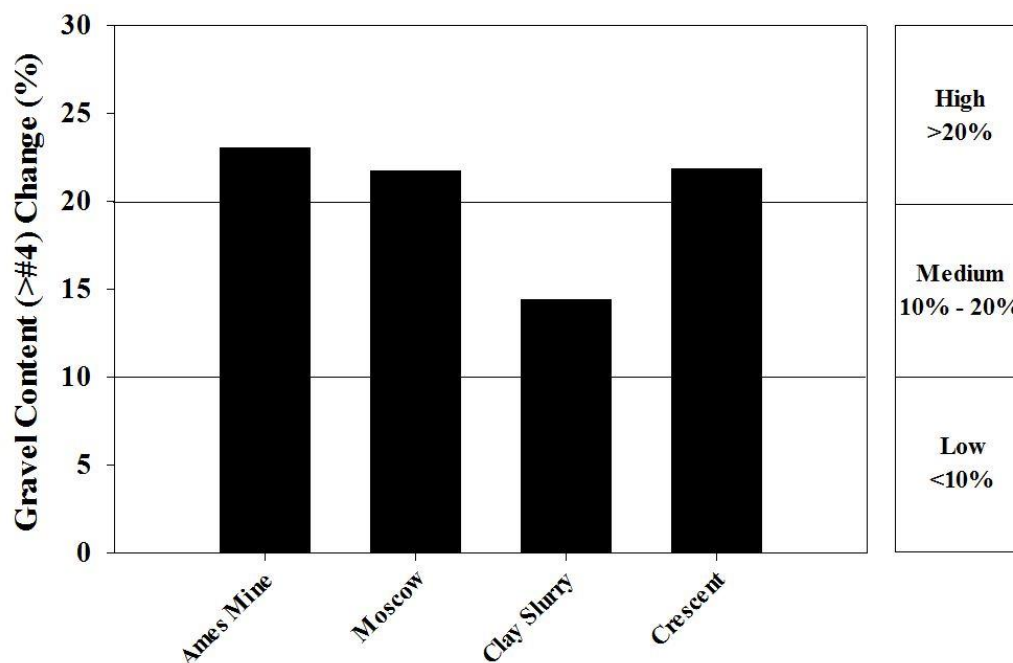
Figure 61. Change in gravel content for Boone County test sections

As shown in the figure, the sections were categorized as having either high (>20%), medium (10% to 20%), or low (<10%) gravel loss. Accordingly, the Ames Mine, Moscow, and Crescent sections had high gravel loss, while the Clay Slurry had only a medium gravel loss due to the clay particles improving the binding of the gravel particles.

Table 44 shows the different scenarios based on the results of gravel content change for each section.

Table 44. Maintenance scenarios based on gravel loss for Boone County sections

Section	Worst case	Most likely	Best case
Ames Mine	1	2	3
Moscow	1	2	3
Clay Slurry	2	3	4
Crescent	1	2	3

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

For the sections with high gravel loss (Ames Mine, Moscow, and Crescent), major maintenance could be performed every one, two, or three years, with two years being the most likely scenario. However, for the Clay Slurry section with only medium gravel loss, maintenance could be performed every two, three, or four years, with three years being the most likely scenario.

The BCA results for the previous scenarios based on gravel content change are shown in Figure 62.
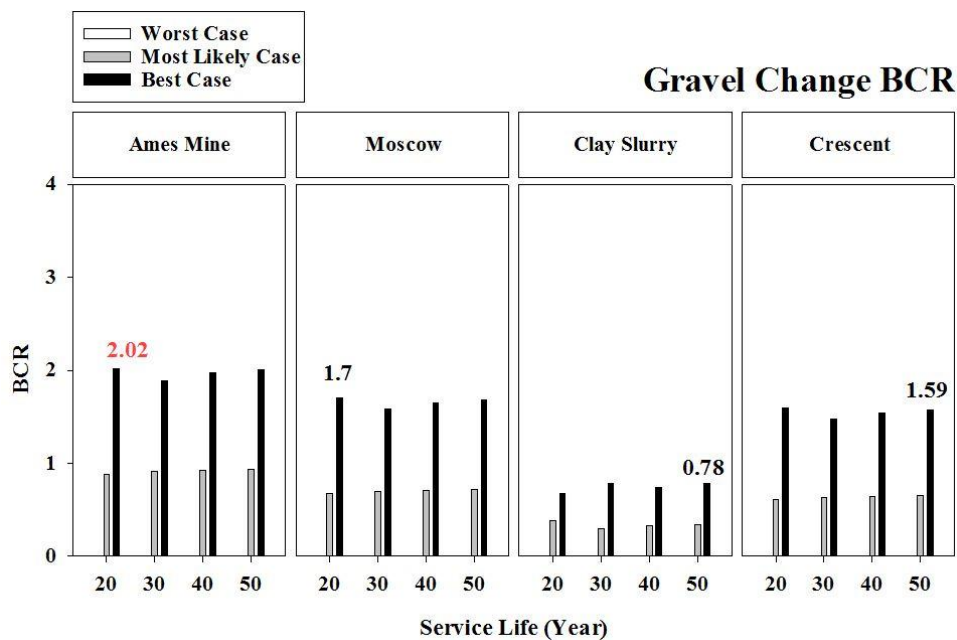

Figure 62. BCR values for gravel content change in Boone County sections

According to the results, the Ames Mine, Moscow, and Crescent sections could be considered beneficial alternatives to the base case (control section) for the best-case scenarios, because their BCR values were greater than 1 for such scenarios for all service life values. The BCR values for the Clay Slurry section, on the other hand, were lower than 1 for all scenarios due to the higher construction costs. The highest BCR values were observed for the Ames Mine (2.02) and Moscow (1.70) sections for their best-case scenario and a service life of 20 years.

7.5.2. Total Breakage

Total breakage is defined as the area between two PSD curves measured at different times and is an indicator of material degradation over time (Hardin 1985). Figure 63 shows the total breakage values for all treated Boone County test sections from November 2019 to March 2020.
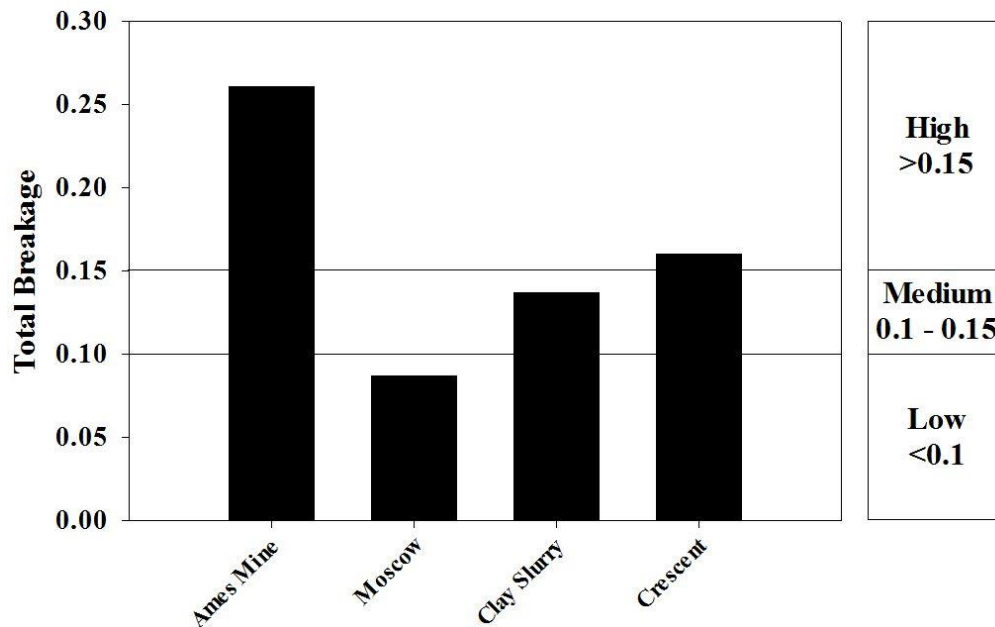
Figure 63. Total breakage values for Boone County sections

The test sections were categorized into three groups based on their total breakage values, whereby the Ames Mine and Crescent sections had high breakage (>0.15), the Clay Slurry section had medium breakage (0.1 to 0.15), and the Moscow section had low breakage (<0.1).

Table 45 shows the different maintenance scenarios based on the total breakage results.

Table 45. Maintenance scenarios based on total breakage for Boone County sections

Section	Worst case	Most likely	Best case
Ames Mine	1	2	3
Moscow	3	4	5
Clay Slurry	2	3	4
Crescent	1	2	3

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

For the Ames Mine and Crescent sections with high total breakage, the scenarios assumed that maintenance could be performed every one, two, or three years. For the Clay Slurry section with medium total breakage, maintenance could be performed every two, three, or four years, and for the Moscow section with low total breakage, maintenance could be performed every three, four, or five years.

Figure 64 shows the BCA results based on the total breakage for the previous scenarios.
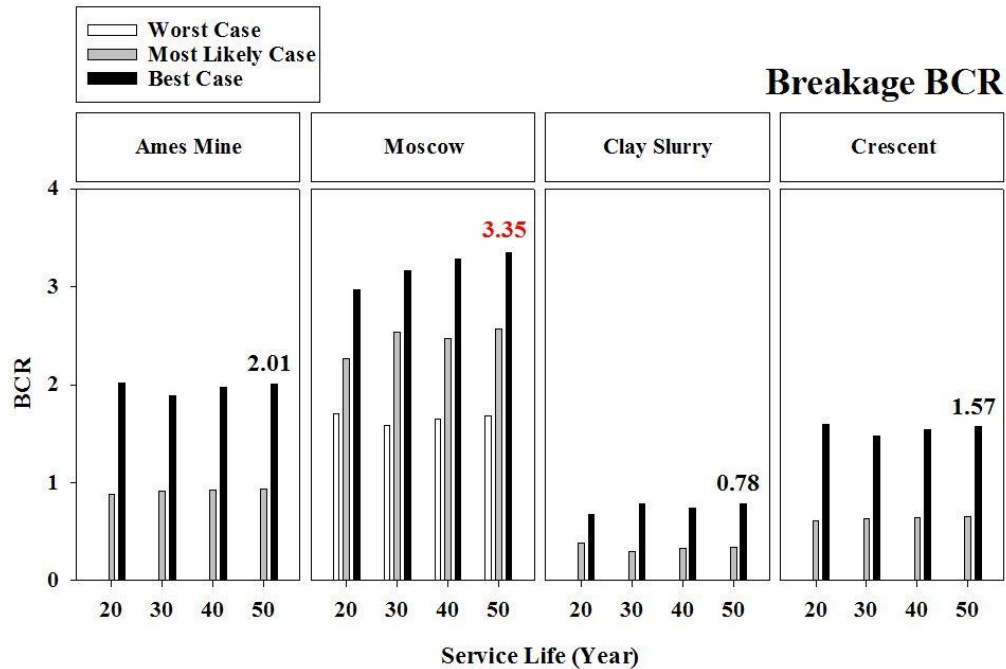
Figure 64. BCR values for total breakage in Boone County sections

The Moscow fines were found to always be beneficial compared to the base case (control section), as their BCR was greater than 1 for all scenarios and service life values. The Clay Slurry fines had the lowest BCR values, which were less than 1 for all scenarios and service life values. The Ames Mine fines were the second most beneficial option after the Moscow fines, with BCR values higher than 1 for all service life values for the best-case scenario. The third most beneficial option was Crescent fines, which also had BCR values greater than 1 for all service life values and the best-case scenario. However, both the Ames Mine and Crescent fines would not be beneficial options for any of the service life values for the worst-case and most likely scenarios.

7.5.3. Fines Content

The fines content of the surface aggregate materials has a relatively strong connection to the dust emission and occurrence of severe distresses. Therefore, the average fines content of the sections over the November 2019 to March 2020 time frame was selected as one of the important factors by which to compare BCR results for the alternative sections relative to the base case (control section). Figure 65 shows the average fines content values of the alternative test sections. Three ranges were considered for categorizing the fines content values.
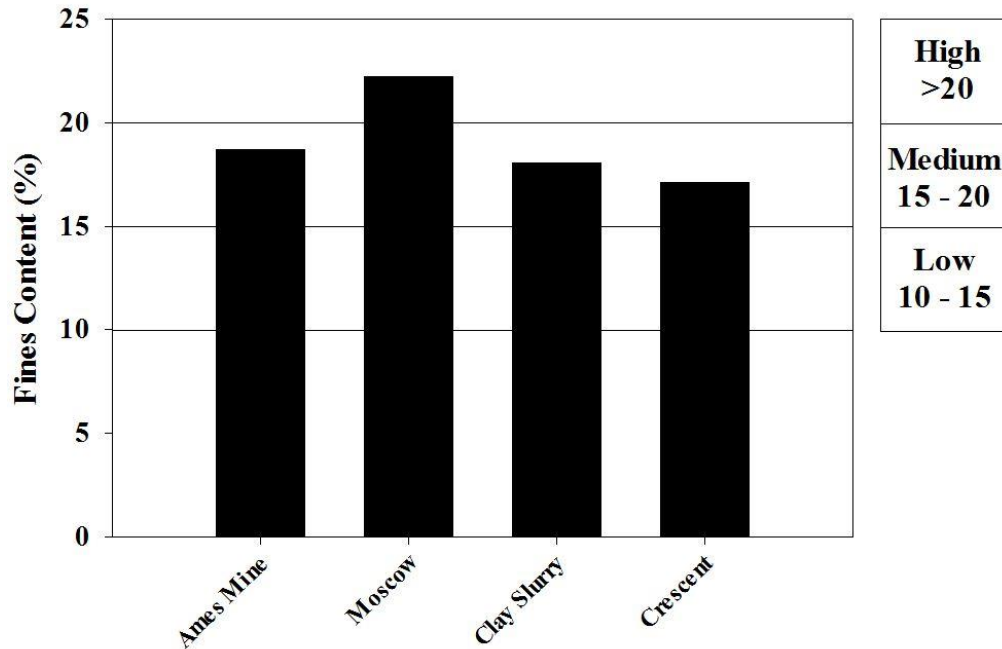
Figure 65. Average fines content values of Boone County sections

The Moscow section had a high (>20%) average fines content, while the Ames Mine, Clay Slurry, and Crescent sections had medium (15% to 20%) average fines content values.

Table 46 shows the different maintenance scenarios based on the average fines content values.

Table 46. Maintenance scenarios based on average fines content for Boone County sections

Section	Worst case	Most likely	Best case
Ames Mine	2	3	4
Moscow	1	2	3
Clay Slurry	2	3	4
Crescent	2	3	4

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

The Moscow section with high average fines content could have maintenance performed every one, two, or three years. The sections with medium fines content (Ames Mine, Clay Slurry, and Crescent) could have maintenance performed every two, three, or four years.

BCA results for the average fines content scenarios are shown in Figure 66.
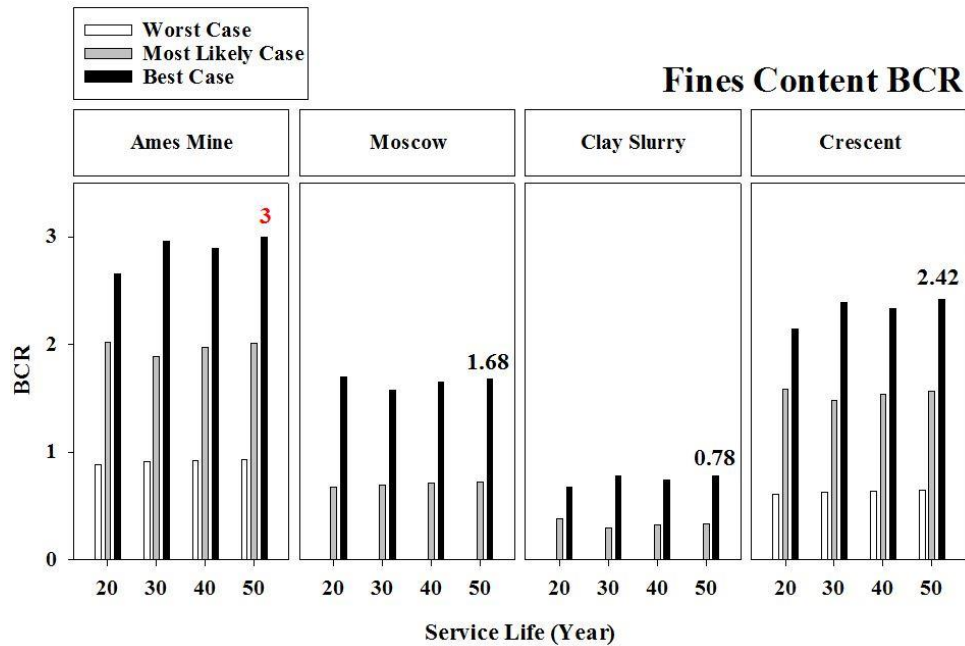
Figure 66. BCR values for average fines content of Boone County sections

The Ames Mine and Crescent sections were found to always be beneficial compared to the base case, as their BCR values were greater than 1 for the most likely and best-case scenarios for all service life values. However, Ames Mine had the highest BCR value among all sections. The Clay Slurry section would not be a cost-effective option based on average fines content, as its BCR was below 1 for all scenarios and service life values. The Moscow section only had a BCR greater than 1 for the best-case scenario.

7.5.4. G/S Ratio

The G/S ratio is closely related to particle packing, which influences the strength of a gradation (Li et al. 2018), and the change in the G/S ratio is an indicator of the breakage and loss of gravel sized particles over time. The G/S ratio was considered as another factor to evaluate the alternative sections relative to the base case. Figure 67 shows the average G/S ratios based on the sieve analysis results from samples collected in November 2019 and March 2020.
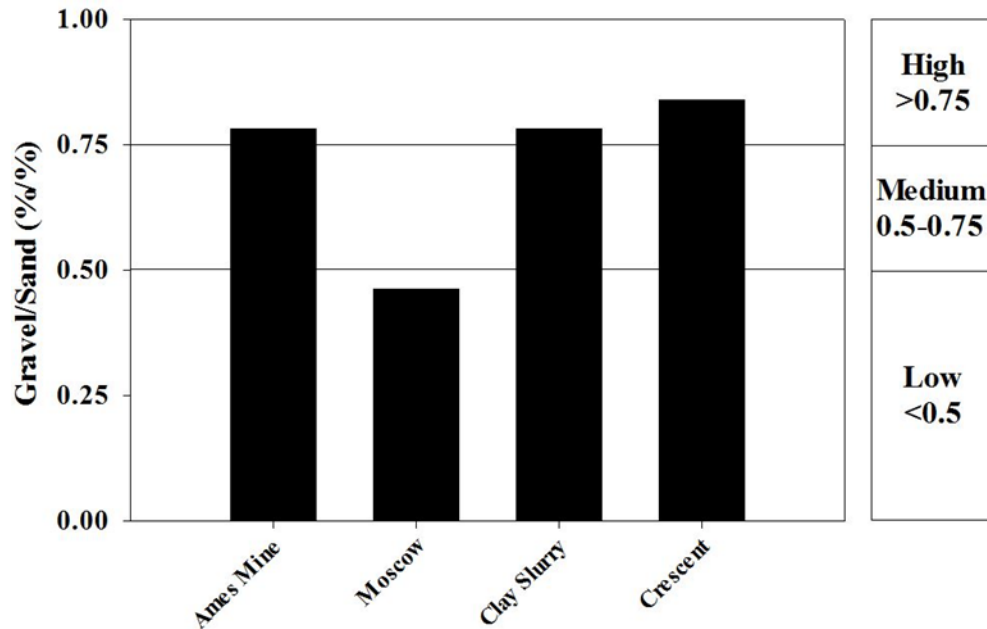
Figure 67. Average G/S ratio values for Boone County sections

As shown in the figure, the test sections were categorized into three groups whereby the Ames Mine, Clay Slurry, and Crescent sections had high average G/S ratios (>0.75), and the Moscow section had a low average G/S ratio (<0.5).

Table 47 shows the different maintenance interval scenarios based on the results of the average G/S ratios.

Table 47. Maintenance scenarios based on average G/S ratio for Boone County sections

Section	Worst case	Most likely	Best case
Ames Mine	3	4	5
Moscow	1	2	3
Clay Slurry	3	4	5
Crescent	3	4	5

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

For the assumed scenarios, the Moscow section with a low average G/S ratio could have maintenance performed every one, two, or three years, while the Ames Mine, Clay Slurry, and Crescent sections with high average G/S ratios would require maintenance less often (every three, four, or five years).

The BCA results for the scenarios based on average G/S ratios are shown in Figure 68.
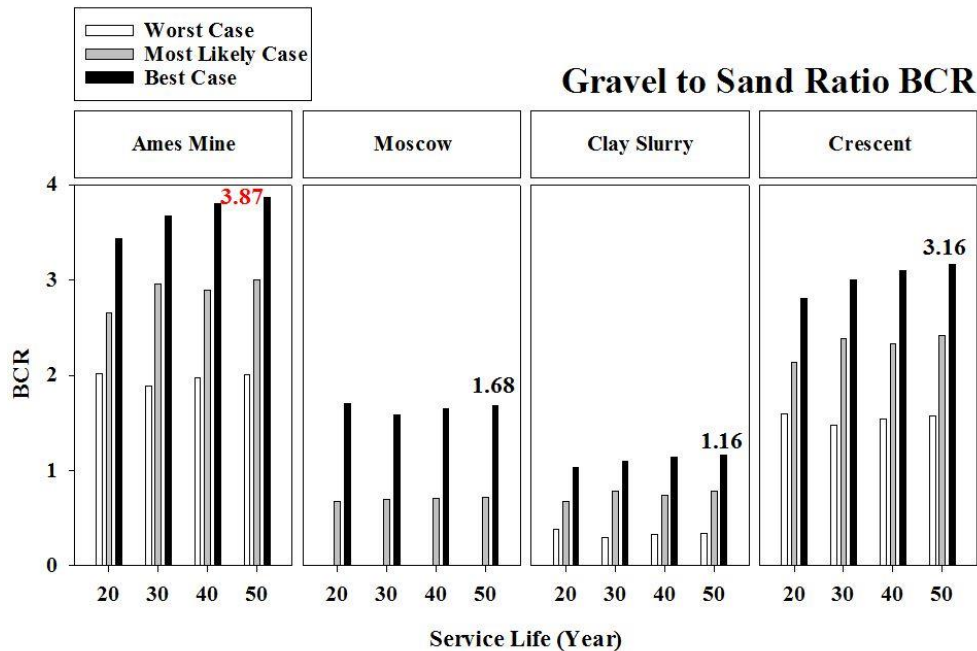
Figure 68. BCR values for average G/S ratio for Boone County sections

All sections had BCR values greater than 1 for their best-case scenarios. However, the Ames Mine (3.87) and Crescent (3.16) sections had the highest BCR values while the Clay Slurry (1.16) and Moscow (1.68) sections had the lowest. The Crescent and Ames Mine sections had BCR values greater than 1 for all scenarios and service life values. However, the Clay Slurry and Moscow sections were beneficial only for their best-case scenarios.

7.5.5. Surface Elastic Modulus from FWD Tests

Surface elastic modulus is an indicator of the performance of a road system, with a higher modulus generally being associated with better performance. In this section, the effects of back-calculated surface elastic moduli from FWD tests on the frequency of maintenance procedures were analyzed for the alternative sections.

The performance of the sections was categorized into three groups based on their surface elastic modulus as shown in Figure 69, whereby the Ames Mine, Moscow, and Crescent sections had high (>50 ksi) surface modulus, while the Clay Slurry section had a medium (25 ksi to 50 ksi) modulus.

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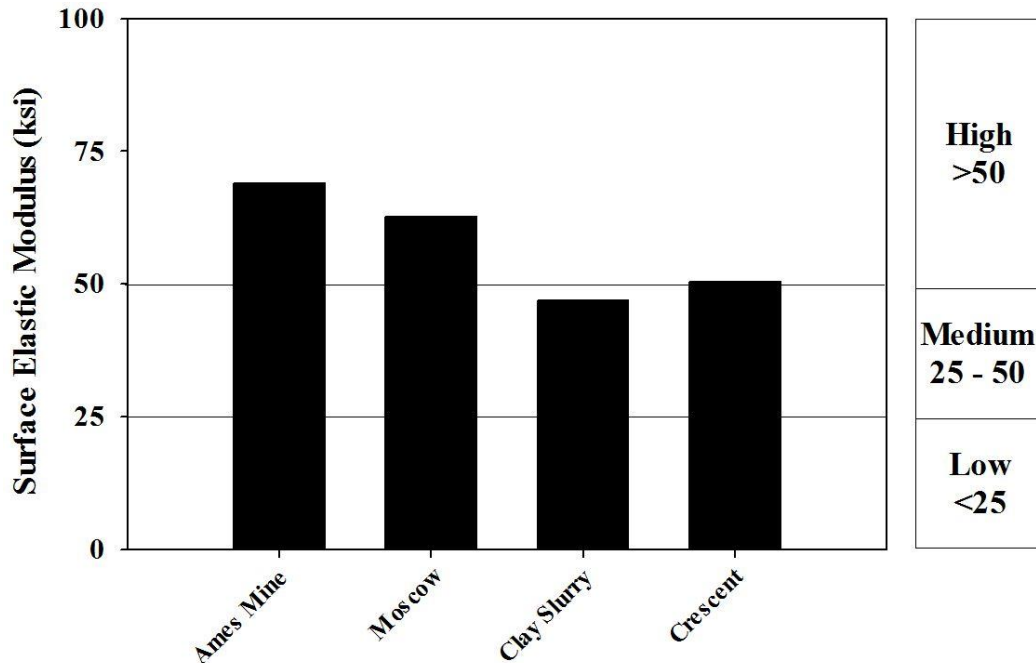
Figure 69. Average back-calculated surface elastic moduli for Boone County sections

Table 48 shows the different scenarios based on the average back-calculated surface elastic modulus.

Table 48. Maintenance scenarios based on average surface elastic modulus for Boone County sections

Section	Worst case	Most likely	Best case
Ames Mine	3	4	5
Moscow	3	4	5
Clay Slurry	2	3	4
Crescent	3	4	5

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

For the Clay Slurry section with medium average surface elastic modulus, maintenance could be applied every two, three, or four years, and for the Ames Mine, Moscow, and Crescent sections with high average surface elastic modulus, maintenance could be performed less often (three, four, or five years).

The BCA results based on the maintenance scenarios for the back-calculated surface elastic modulus are shown in Figure 70.
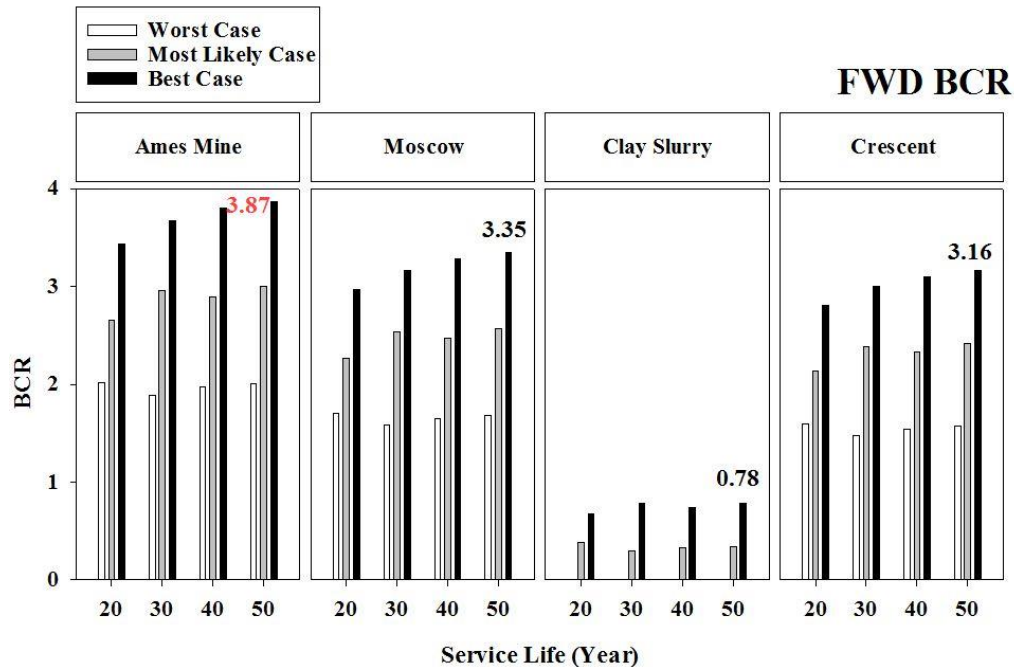
Figure 70. BCR values for average back-calculated surface elastic modulus for Boone County sections

The Ames Mine, Moscow, and Crescent sections were always beneficial to use compared to the base case, as their BCR values were greater than 1 for all scenarios and service life values. Among these three sections, the Ames Mine section had the highest BCR. Conversely, the Clay Slurry section always had a BCR lower than 1 for all maintenance scenarios and service life values due to its relatively higher hauling and material costs.

7.5.6. Surface CBR Strength from DCP Tests

The average CBR of the surface layer was also used to evaluate the advantages of using the quarry fines alternatives relative to the base case. Figure 71 shows the surface CBR strength of all sections from correlations to the DCP test results.
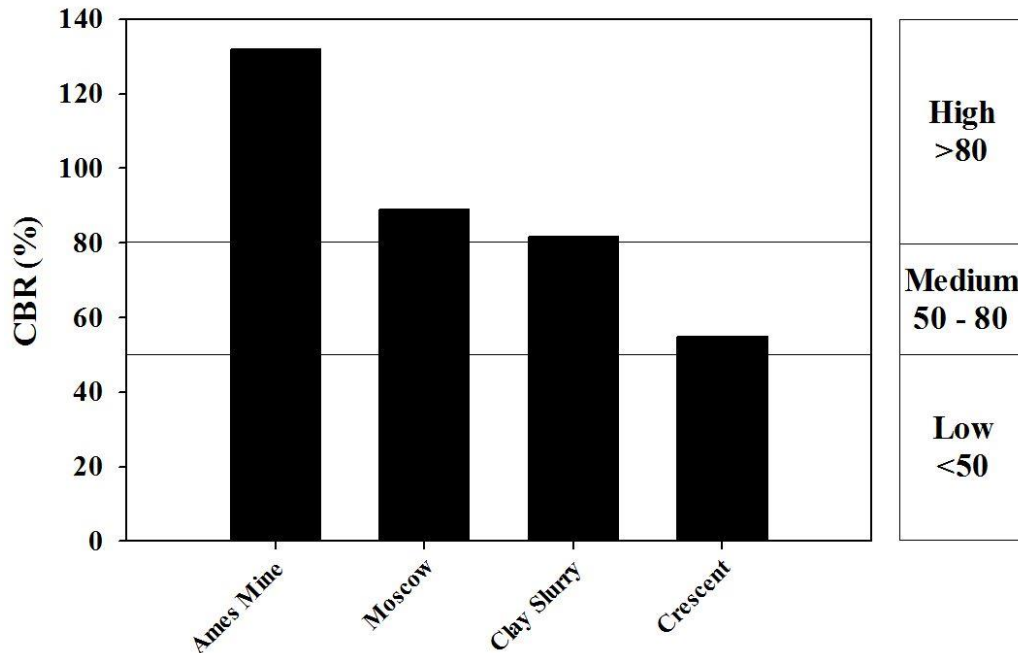
Figure 71. Average surface CBR values for Boone County sections

As shown in the figure, the test sections were categorized into three groups, whereby the Ames Mine, Moscow, and Clay Slurry sections had high (>80%) average surface CBR values, while the Crescent section had a medium (50% to 80%) value.

Table 49 summarizes different maintenance scenarios based on the results of the average surface CBR strength.

Table 49. Maintenance scenarios based on average surface shear strength for Boone County sections

Section	Worst case	Most likely	Best case
Ames Mine	3	4	5
Moscow	3	4	5
Clay Slurry	3	4	5
Crescent	2	3	4

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

The Ames Mine, Moscow, and Clay Slurry with high average surface CBR values could have maintenance procedures every three, four, or five years, while the Crescent section with a medium CBR could have maintenance every two, three, or four years.

Figure 72 summarizes the BCA results for all the maintenance scenarios based on average surface CBR values.
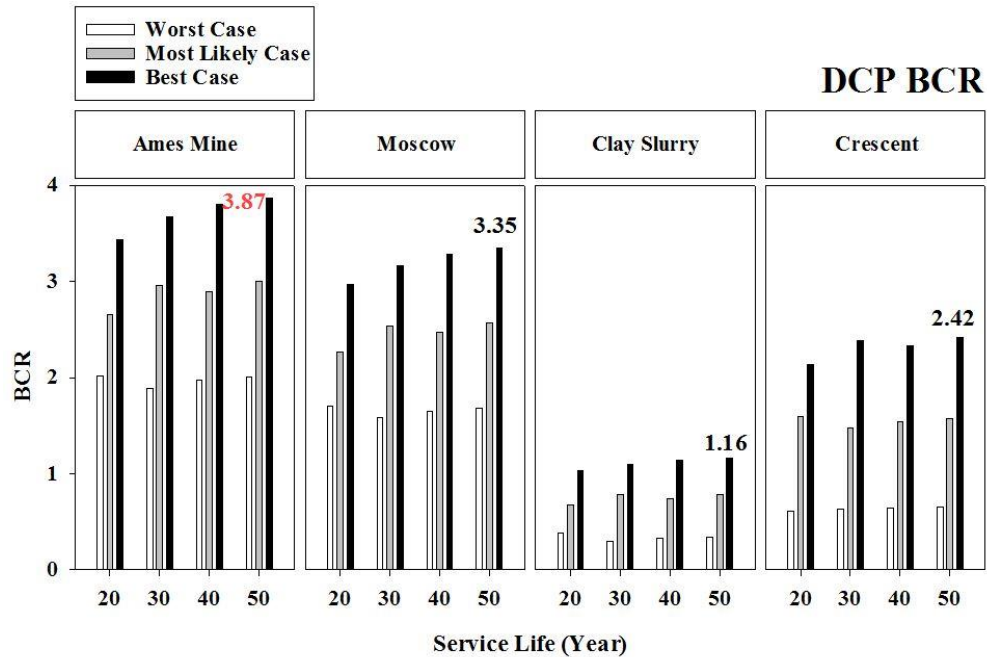
Figure 72. BCR values for average surface CBR value for Boone County sections

The BCR values for the Ames Mine and Moscow sections were always greater than 1 for all maintenance scenarios and all service life values, and the Ames Mine section had the highest BCR value among all sections. The Crescent section could also be beneficial compared to the control section, as its BCR values were greater than 1 for the most likely and best-case scenarios for all service life considerations. The Clay Slurry section could possibly be a beneficial alternative, as its BCR was greater than 1 for the best-case scenarios over all service life values.

7.5.7. Dust Production from Dustometer Tests

Dust emission is one of the most commonly associated problems with granular roadways, and it is preferable to use surface aggregate materials with low dust emissions. Figure 73 compares the average measured dust emission values for all alternative sections.
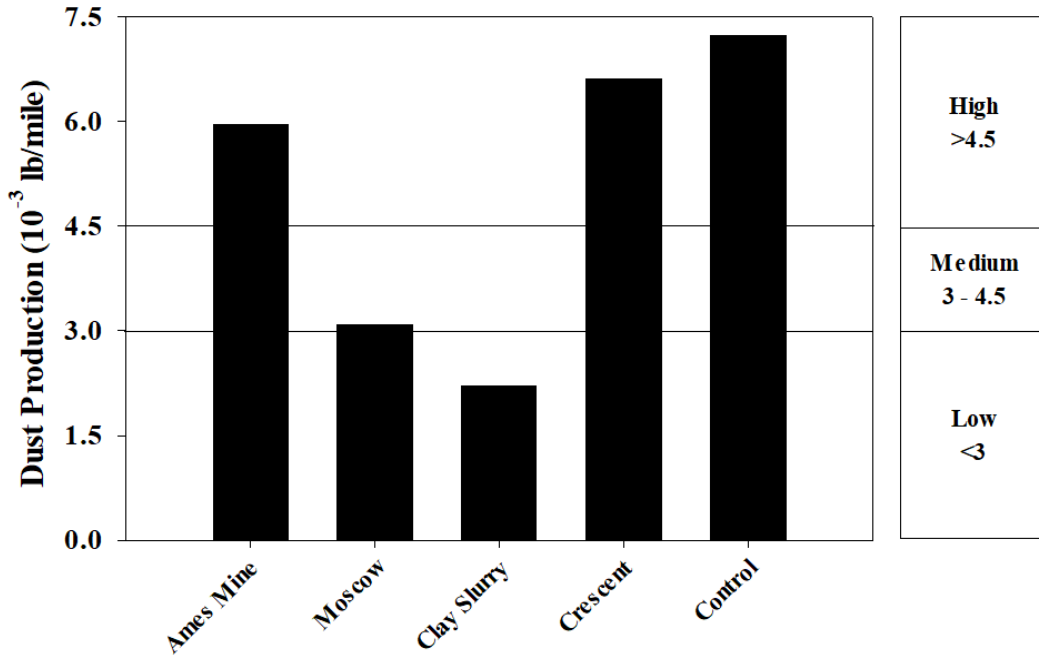
Figure 73. Average dust emission for Boone County sections

Three different categories of dust emission were selected, according to which the control, Crescent, and Ames Mine sections had high ($>4.5\times10^{-3}$ lb/mi) average dust emission, while the Moscow section had medium (3×10^{-3} to 4.5×10^{-3} lb/mi) and the Clay Slurry section had low ($<3\times10^{-3}$ lb/mi) average dust emission.

The different maintenance scenarios based on the average dust emission values are shown in Table 50.

Table 50. Maintenance scenarios based on average dust emission for Boone County sections

Section	Worst case	Most likely	Best case
Ames Mine	1	2	3
Moscow	2	3	4
Clay Slurry	3	4	5
Crescent	1	2	3

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

The Clay Slurry with low average dust emission could have maintenance every three, four, or five years. The Moscow section with medium average dust emission could have maintenance every two, three, or four years, and the Ames Mine and Crescent sections with high average dust emission could have more frequent maintenance every one, two, or three years.

Figure 74 summarizes the BCA results for all maintenance scenarios based on average dust emission values.
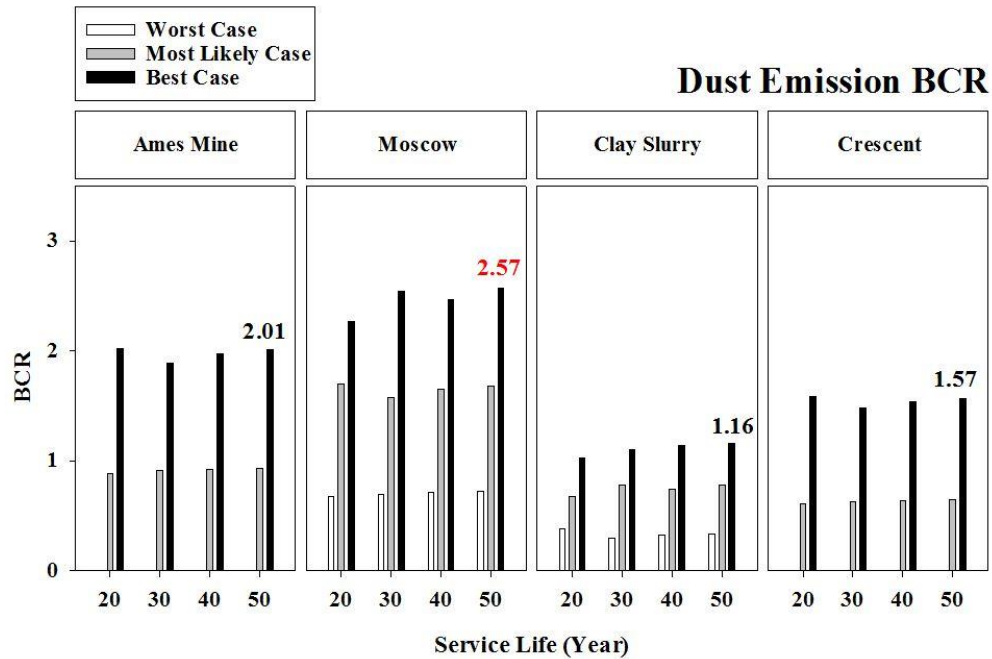
Figure 74. BCR values for average dust emission for Boone County sections

All sections could be considered beneficial alternatives for their best-case scenarios for all service life values examined, and the Moscow section had the highest BCR value. The Clay Slurry section again had the lowest BCR value among all sections. However, none of the sections were beneficial for their worst-case and most likely case scenarios for any of the service life values, as they all had BCR values less than 1.

7.5.8. Surface Roughness –IRI

Surface roughness or ride quality based on IRI is an indicator of serviceability of the roads. In this study, all sections had fair ride quality ratings based on the cIRI values obtained (Figure 75).

101
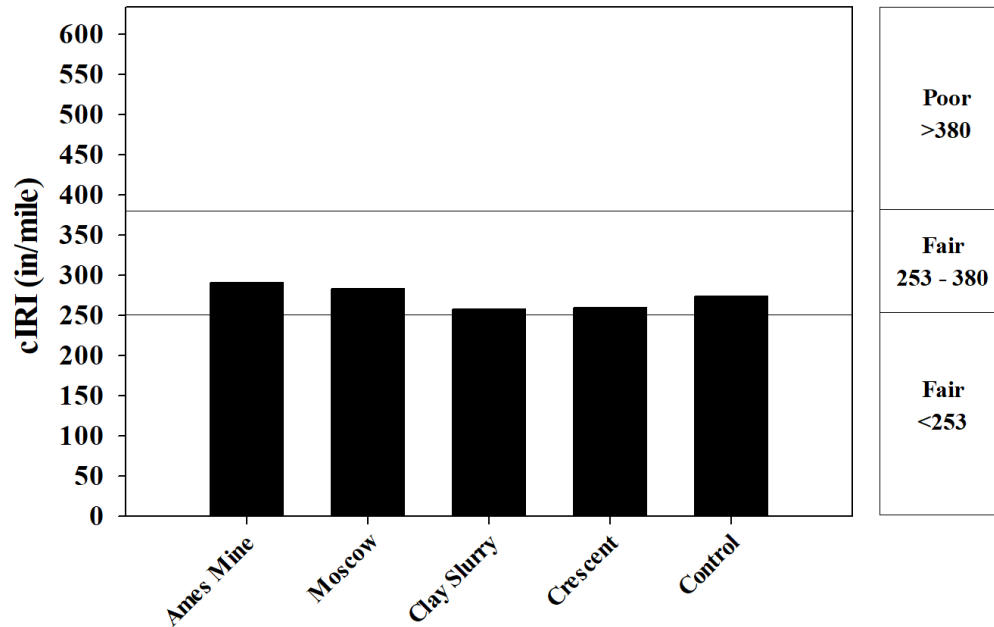
Figure 75. Average surface roughness values for Boone County sections

However, each section had different construction costs, and their BCR values for the same maintenance scenarios can therefore be different.

The proposed maintenance scenarios based on the average cIRI values are shown in Table 51.

Table 51. Maintenance scenarios based on average cIRI values for Boone County sections

Section	Worst case	Most likely	Best case
Ames Mine	2	3	4
Moscow	2	3	4
Clay Slurry	2	3	4
Crescent	2	3	4

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

Because all sections had fair ratings based on cIRI values, their maintenance intervals are all the same at two years for the worst-case scenario, three years for the most likely case, and four years for the best-case scenario.

The summary of the BCA results for the different maintenance scenarios and service life values based on their average surface roughness ratings are shown in Figure 76.

Figure 76. BCR values for average surface roughness for Boone County sections

The Ames Mine, Moscow, and Crescent sections were the most beneficial sections for their best-case and most likely scenarios. However, the Clay Slurry section consistently had BCR values below 1 and therefore could not be considered beneficial for any of the maintenance scenarios and service life values considered.

7.5.9. Overall Performance-Based BCR Values

While the BCA results of the previous sections provide an understanding of how BCR values vary with the individual performance factors, the overall performance of a granular road should take into consideration all the performance factors while recognizing that some are more important than others. To perform such an overall assessment, the gravel content change and total breakage measures were considered the most important performance factors and were therefore assigned a relative weight of 1.0. The previously described first group (fines content and G/S ratio) were considered the next most important group of factors and were weighted at 0.75, while the second group (FWD and DCP-CBR) were weighted at 0.5, and the third group (dustometer and IRI) were weighted at 0.25 (Figure 77).
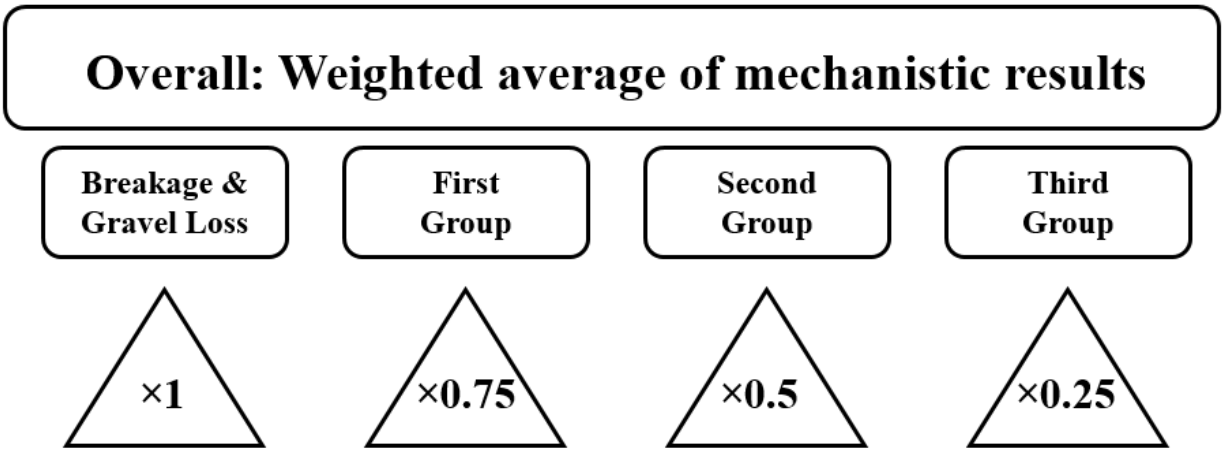
Figure 77. Relative weights for the four groups of performance factors

An overall BCA was then performed using these weights to reflect the perceived relative importance of the various factors contributing to the performance of the granular road sections.

Figure 78 shows the resulting BCR values using the relative weights applied to the average values of performance measures for different maintenance scenarios and service life values.
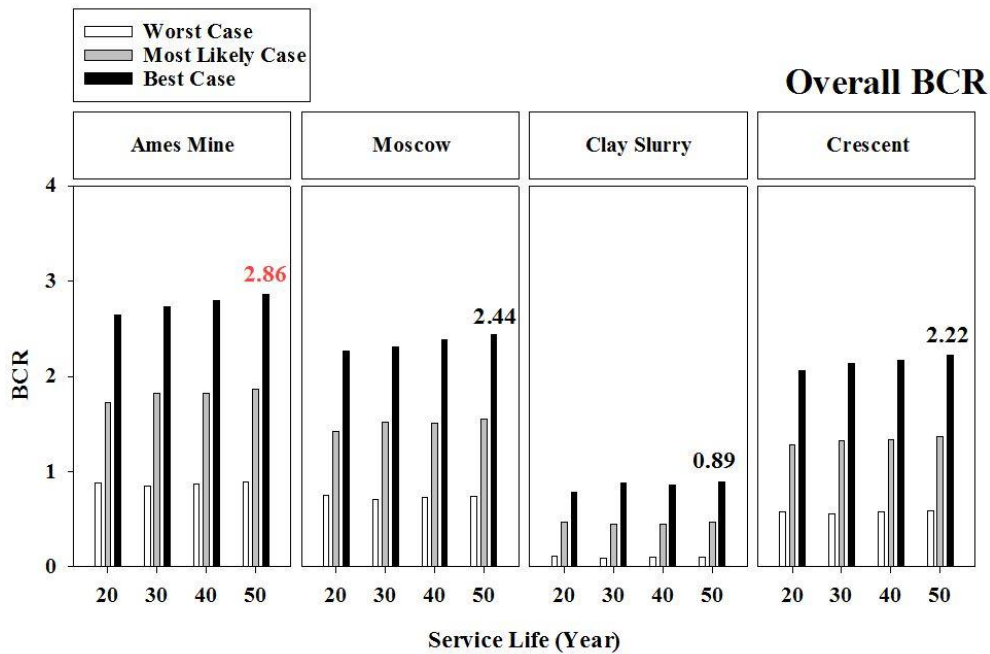
Figure 78. Overall BCR values for the weighted performance measures

The results show that the Ames Mine, Moscow, and Crescent sections had the highest BCR values and could be considered beneficial compared to the control section for their most likely and best-case scenarios for the entire range of service life values. On the other hand, the Clay

Slurry section did not produce BCR values greater than 1 and therefore could not be considered beneficial due to its high hauling and material costs.

7.6. Results and Discussion for Jones County

Figure 79 shows the costs per 0.25 mi for equipment, aggregates, quarry fine materials, and hauling for all alternative sections in Jones County.
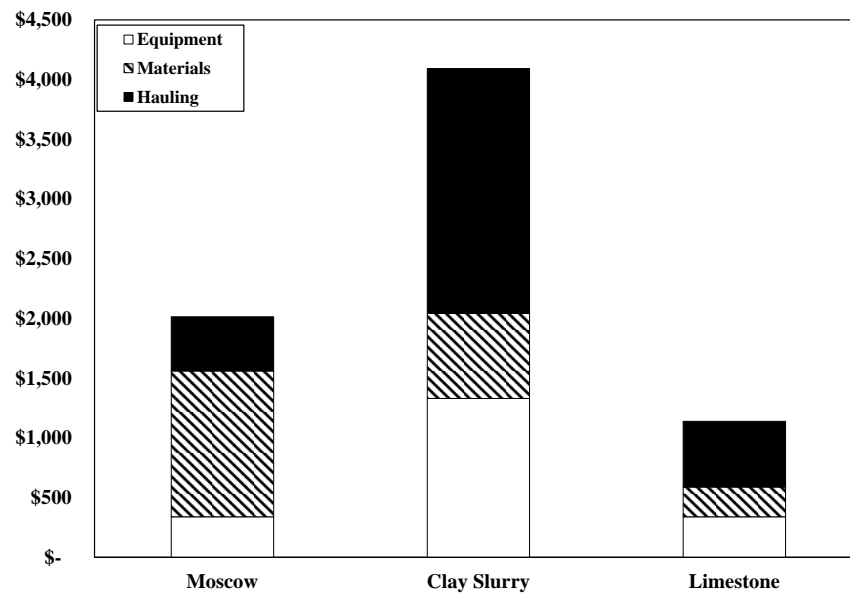
Figure 79. Construction costs for equipment, materials, and hauling in Jones County

The construction costs for the Clay Slurry ($4,091) were the highest among all sections due to the higher hauling, equipment, and materials costs required. On the other hand, the Limestone section had the lowest total construction costs ($1,173), most specifically because of the lesser amount of materials required to construct this section. The Moscow section had the highest material costs, while the Limestone section had the lowest and the Clay Slurry section had the highest hauling costs.

The following sections describe the different performance measures considered to evaluate the serviceability of the sections for various maintenance scenarios, and based on each measure's performance, BCR values were determined. An overall BCR was calculated to select the most beneficial quarry fines option for Jones County.

7.6.1. Change in Gravel Content

The gravel content change from November 2019 to March 2020 is shown in Figure 80 for the quarry fines sections in Jones County.
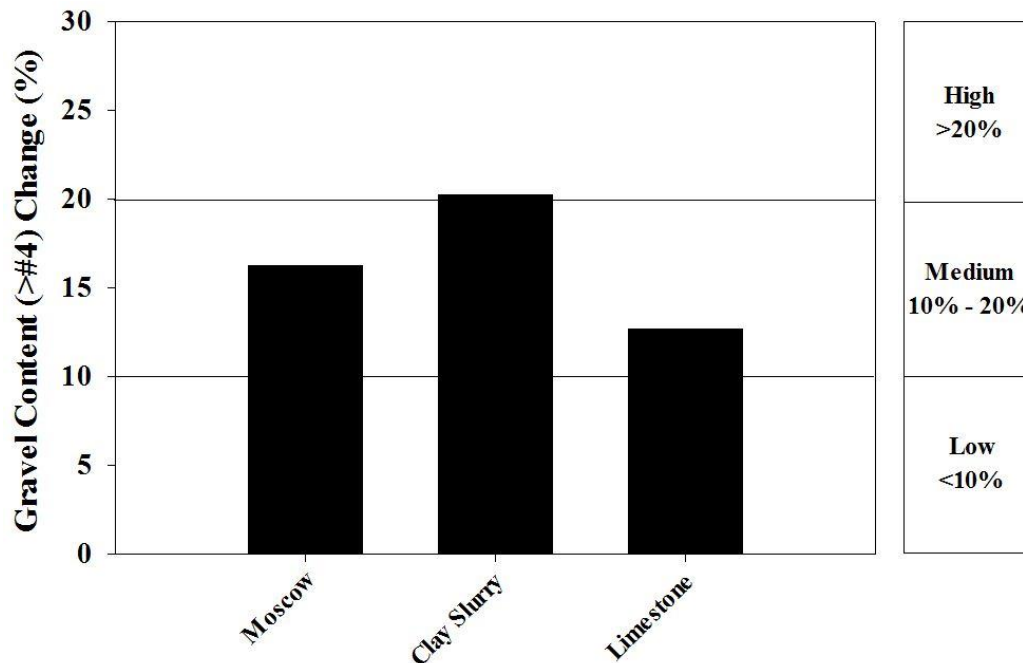
Figure 80. Change in gravel content for Jones County test sections

The sections were categorized as having high (>20%), medium (10% to 20%), or low (<10%) gravel loss, according to which the Clay Slurry section had high gravel loss, while the Moscow and Limestone sections had medium gravel loss.

Table 52 shows the different scenarios based on the results of gravel content change for each section.

Table 52. Maintenance scenarios based on gravel loss for Jones County sections

Section	Worst case	Most likely	Best case
Moscow	2	3	4
Clay Slurry	1	2	3
Limestone	2	3	4

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

For the Clay Slurry section with high gravel loss, maintenance could be performed every one, two, or three years for the worst-case, most likely, and best-case scenarios, respectively. However, for the Moscow and Limestone sections with medium gravel loss, maintenance could be performed every two, three, or four years.

The BCA results for the proposed maintenance scenarios based on gravel loss are shown in Figure 81.
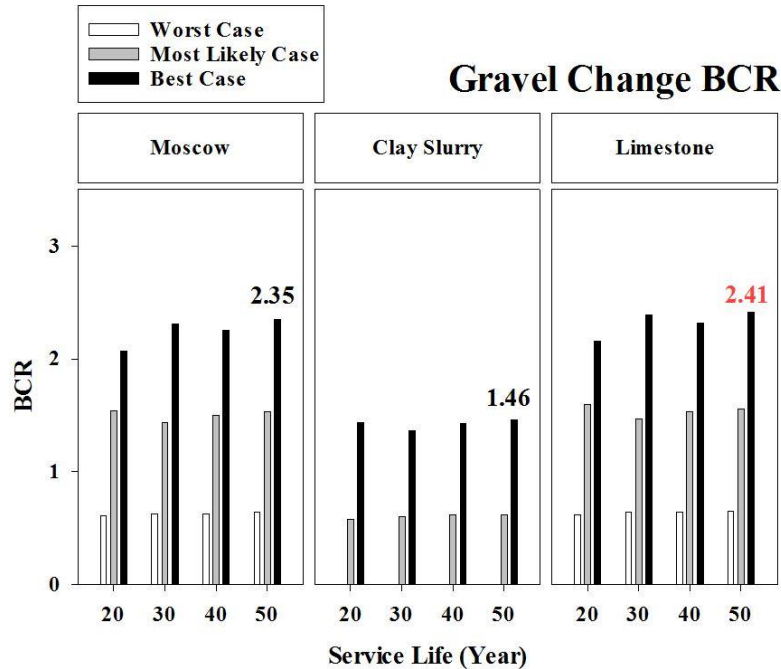
Figure 81. BCR values for gravel content change in Jones County sections

According to the results, the Limestone and Moscow sections could be beneficial alternatives to the base case (the control section) as their BCR values were greater than 1 for the best-case and most likely scenarios for all service life values considered. The BCR values for the Clay Slurry section, on the other hand, were less than 1 for all scenarios except for the best-case scenario. The highest BCR value was observed for the Limestone (2.41) and Moscow (2.35) sections for their best-case scenarios at a service life of 50 years.

7.6.2. Total Breakage

The total breakage values based on the measured PSD curves for all treated test sections from November 2019 to March 2020 in Jones County are shown in Figure 82.

107
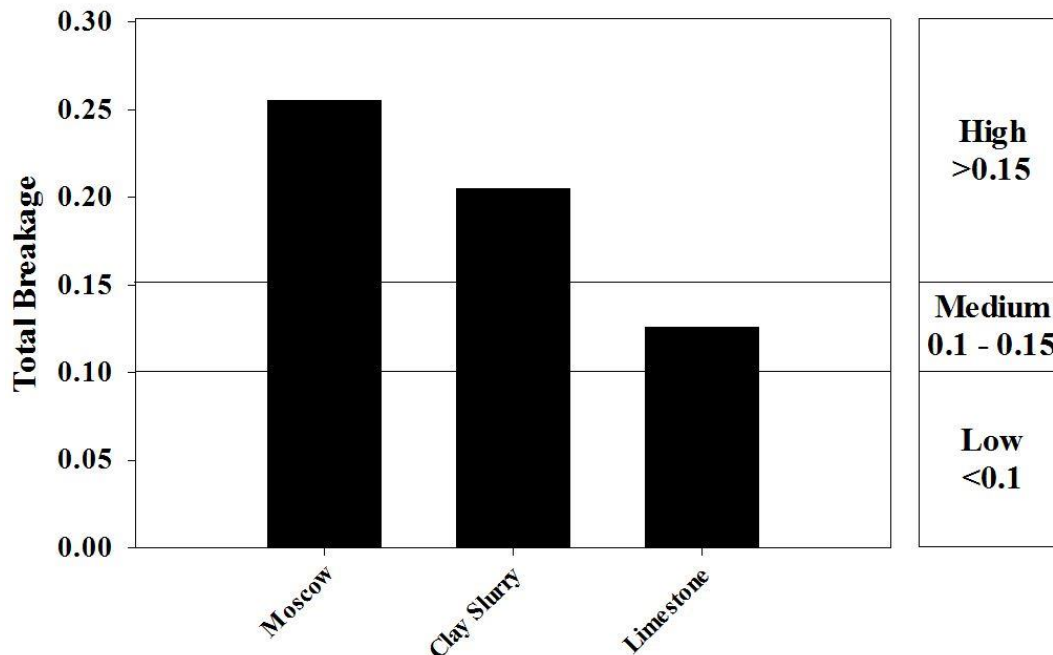
Figure 82. Total breakage values for Jones County sections

The test sections were categorized based on their breakage values, whereby the Moscow and Clay Slurry sections had high total breakage (>0.15), and the Limestone section had low total breakage (<0.1).

Table 53 shows the maintenance scenarios based on the total breakage results.

Table 53. Maintenance scenarios based on average total breakage for Jones County sections

Section	Worst case	Most likely	Best case
Moscow	1	2	3
Clay Slurry	1	2	3
Limestone	2	3	4

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

For the Moscow and Clay Slurry sections with high average total breakage, maintenance could be performed every one, two, or three years. For the Limestone section with medium average total breakage, maintenance could be performed every two, three, or four years.

Figure 83 shows the BCA results based on the total breakage for the previously given maintenance scenarios.
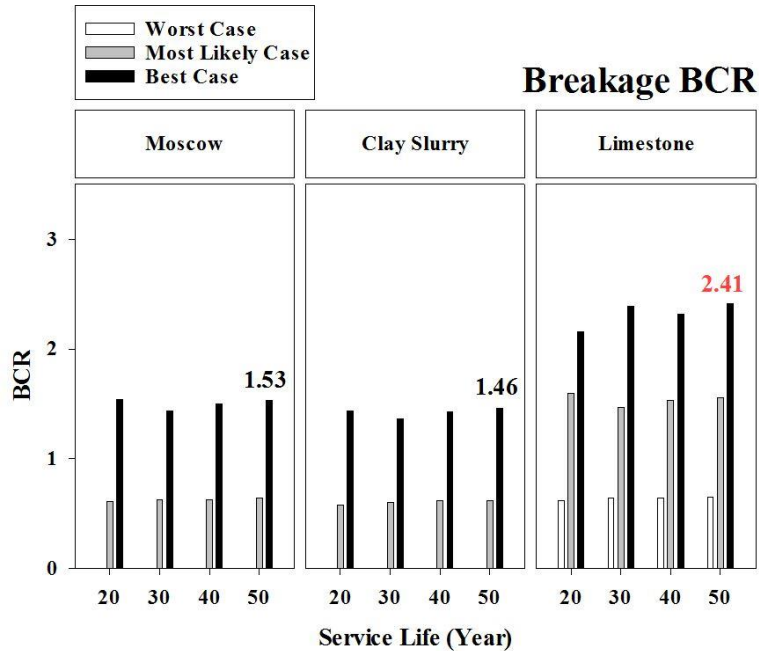
Figure 83. BCR values for total breakage in Jones County sections

The Limestone section could be considered beneficial for the most likely and best-case scenarios for all service life values. In addition, the Limestone section had the highest BCR value among all alternatives. On the other hand, the Moscow and Clay Slurry sections were beneficial only for their best-case scenarios for all service life values. The BCR values for the Clay Slurry and Moscow sections were similar.

7.6.3. Fines Content

The average fines content values over the November 2019 to March 2020 time frame for the alternative test sections in Jones County are shown in Figure 84.
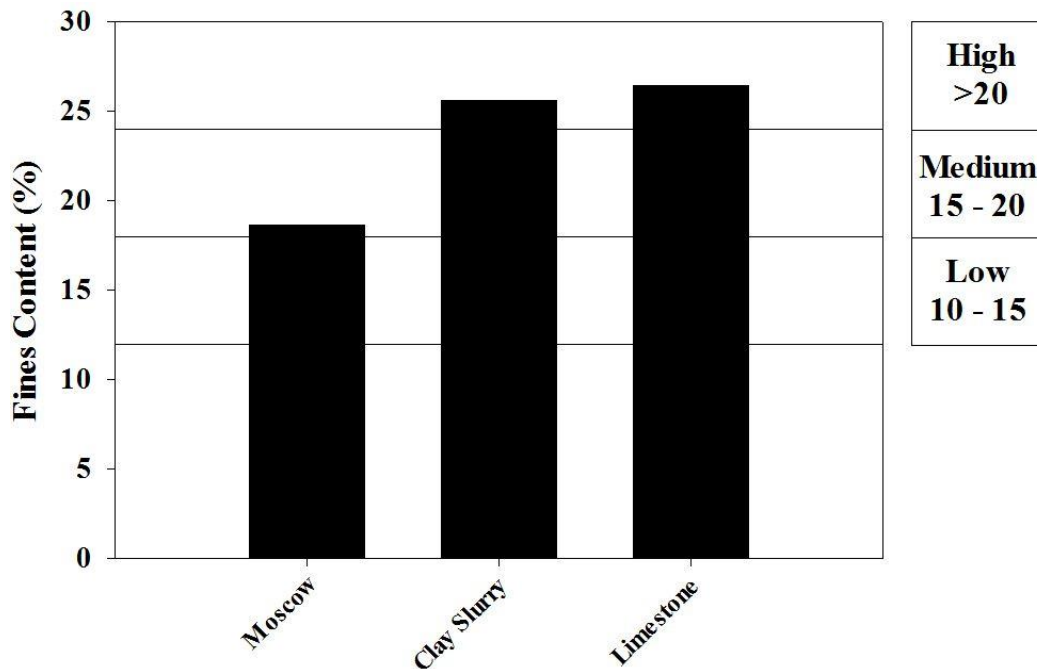
Figure 84. Average fines content values of Jones County sections

Based on the results, the Clay Slurry and Limestone sections had high (>20%) average fines content values, while the Moscow section had a medium (15% to 30%) average fines content value.

Table 54 shows the different maintenance scenarios based on the average fines content values.

Table 54. Maintenance scenarios based on average fines content for Jones County sections

Section	Worst case	Most likely	Best case
Moscow	2	3	4
Clay Slurry	1	2	3
Limestone	1	2	3

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

The Clay Slurry and Limestone sections, with high average fines content, could have maintenance performed every one, two, or three years, while the Moscow section with medium average fines content could have maintenance performed every two, three, or four years.

BCA results for average fines content scenarios are shown in Figure 85.
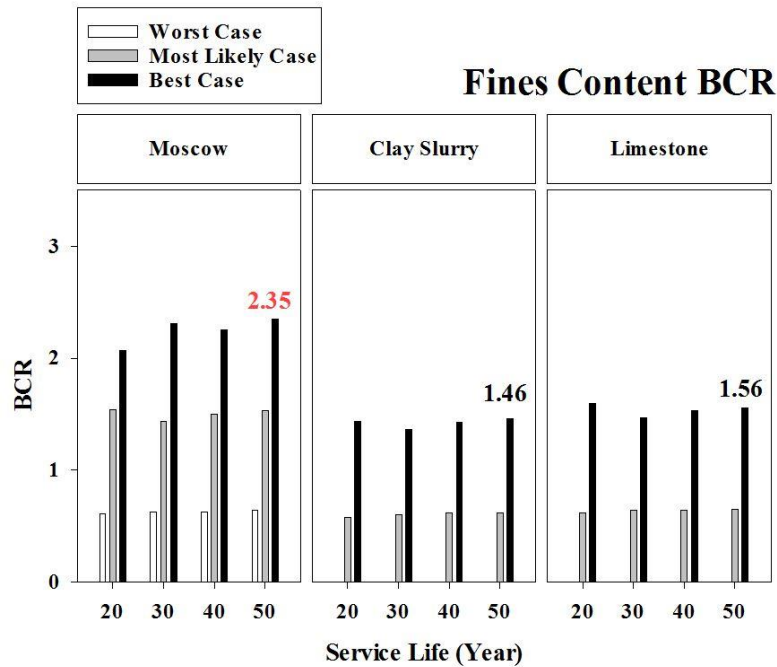
Figure 85. BCR values for average fines content of Jones County sections

The Moscow section had the highest BCR values compared to the other sections, and the BCR values for this section were always greater than 1 for the most likely and best-case scenarios for all service life considerations. On the other hand, the Clay Slurry and Limestone sections had relatively close BCR values, which were greater than 1 for their best-case scenarios and all service life considerations. Moreover, these two sections could not be considered beneficial for the worst and most likely cases.

7.6.4. G/S Ratio

The average G/S ratios based on the sieve analysis results from samples collected in November 2019 and March 2020 are shown in Figure 86.
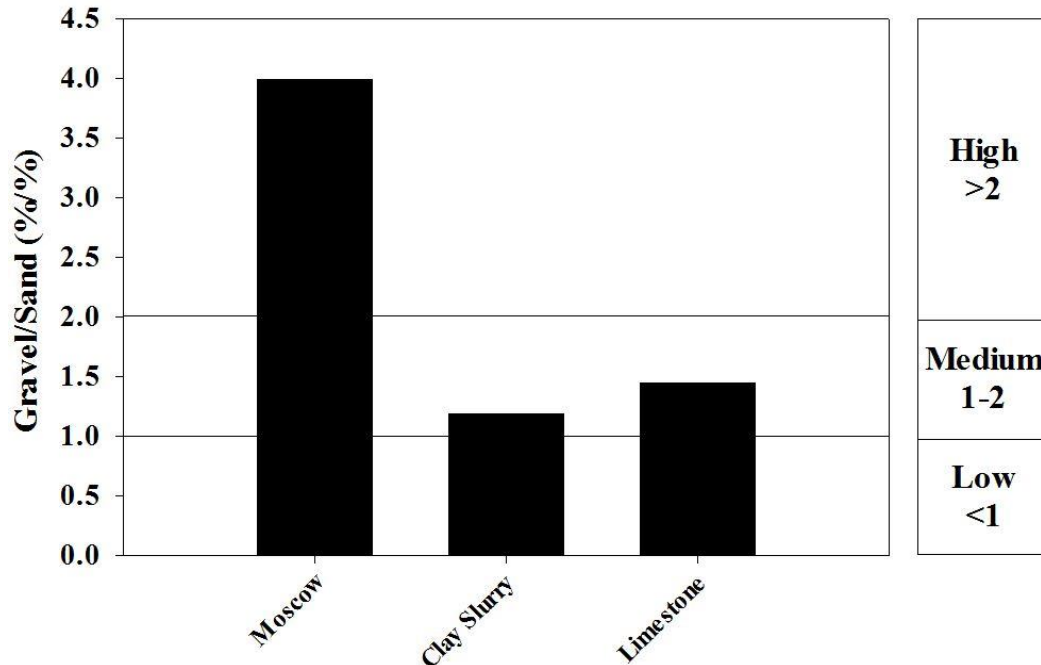
Figure 86. Average G/S ratio values for Boone County sections

According to the classification ranges shown in the figure, the Moscow section had a high (>2) average G/S ratio, while the Clay Slurry and Limestone sections had medium (1 to 2) average G/S ratios.

Table 55 shows the different maintenance scenarios based on the average G/S ratios.

Table 55. Maintenance scenarios based on average G/S ratio for Jones County sections

Section	Worst case	Most likely	Best case
Moscow	3	4	5
Clay Slurry	2	3	4
Limestone	2	3	4

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

The Clay Slurry and Limestone sections with medium average G/S ratios could have maintenance performed every two, three, or four years, while the Moscow section with a high average G/S ratio could have maintenance less often (three, four, or five years).

The BCA results for the maintenance scenarios based on average G/S ratios are shown in Figure 87.

112
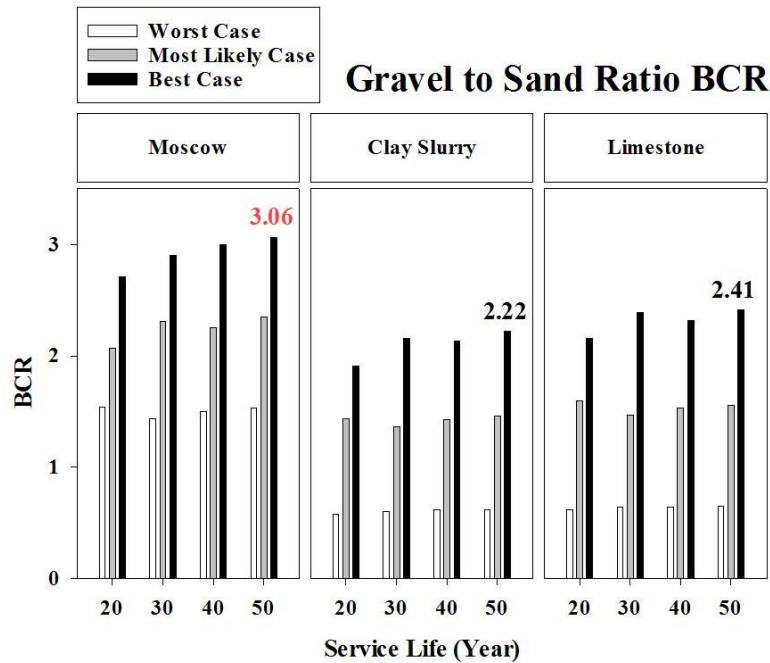
Figure 87. BCR values for average G/S ratio for Jones County sections

The Moscow section consistently had BCR values greater than 1 for all maintenance scenarios and service life values. The Clay Slurry and Limestone sections had similar BCR values, which were greater than 1 for their most likely and best-case scenarios.

7.6.5. Surface Elastic Modulus from FWD Tests

The average of the back-calculated surface elastic modulus values from FWD tests in November 2019 and March 2020 are shown in Figure 88 for the Jones County test sections.
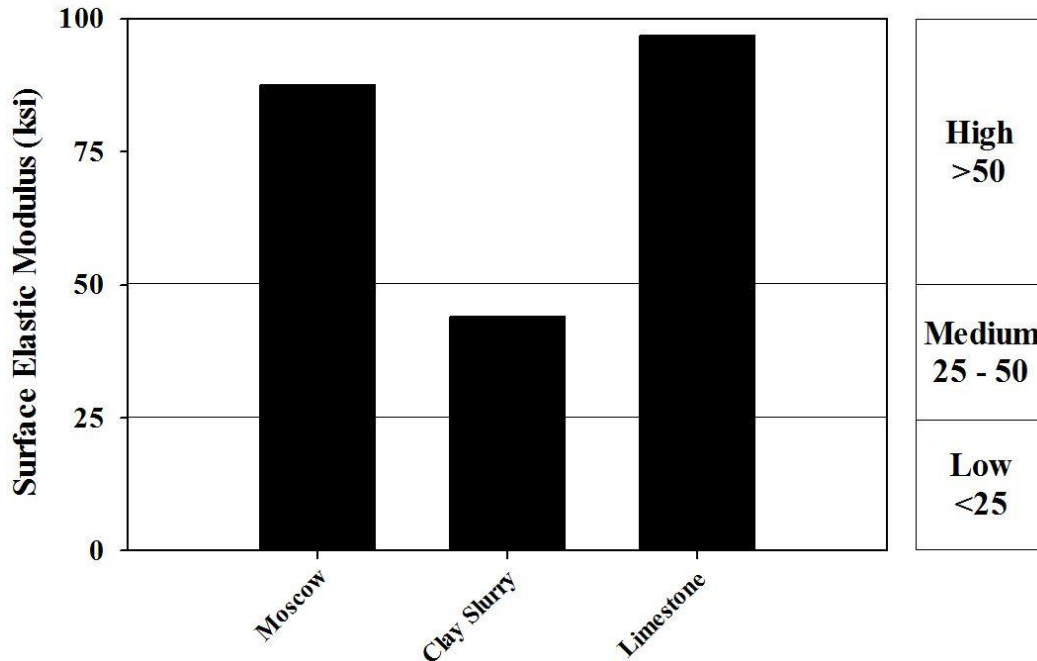
Figure 88. Average back-calculated surface elastic moduli for Jones County sections

The Moscow and Limestone sections had high (>50 ksi) average surface modulus values, while the Clay Slurry section had a medium (25 ksi to 50 ksi) average value.

Table 56 shows the different maintenance scenarios based on the average back-calculated surface elastic modulus values.

Table 56. Maintenance scenarios based on average surface elastic modulus for Jones County sections

Section	Worst case	Most likely	Best case
Moscow	3	4	5
Clay Slurry	2	3	4
Limestone	3	4	5

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

For the Clay Slurry section with medium average modulus, maintenance could be applied every two, three, or four years, and for the Moscow and Limestone sections with high average modulus values, maintenance could be performed less often (three, four, or five years).

The BCA results based on the maintenance scenarios for the back-calculated surface elastic modulus values are shown in Figure 89.
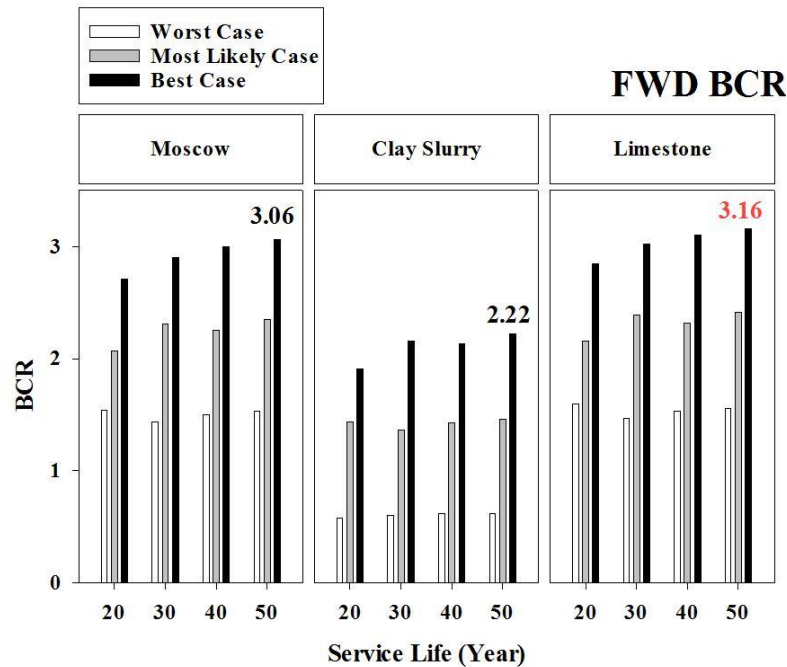
Figure 89. BCR values for average back-calculated surface elastic modulus for Jones County sections

The Moscow and Limestone sections were always beneficial compared to the base case, as their BCR values were greater than 1 for all scenarios and service life values. The Limestone section had the highest BCR (3.16) among all these sections. On the other hand, the Clay Slurry section had BCR values greater than 1 for the most likely and best-case maintenance scenarios for all service life values.

7.6.6. Surface CBR Strength from DCP Tests

The average CBR values of the surface layers as determined from DCP tests are shown in Figure 90.
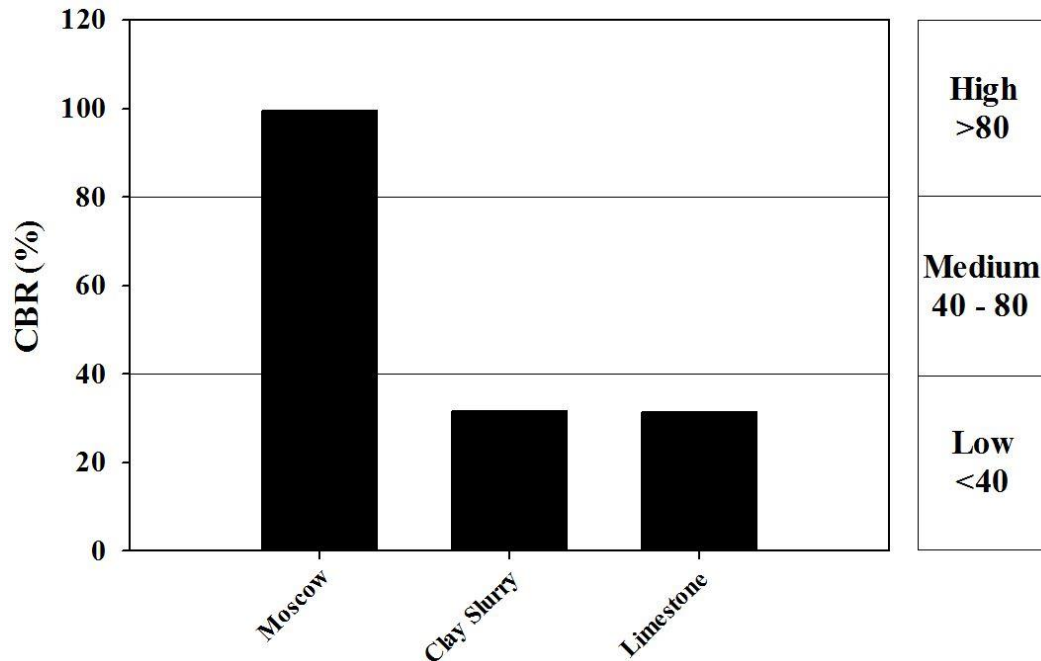
Figure 90. Average surface CBR values for Jones County sections

The test sections were categorized into three groups, whereby the Moscow section had a high (>80%) average CBR, and the Clay Slurry and Limestone sections had low (<40%) average CBR values.

Table 57 summarizes different maintenance scenarios based on the average CBR values.

Table 57. Maintenance scenarios based on average surface shear strength for Jones County sections

Section	Worst case	Most likely	Best case
Moscow	3	4	5
Clay Slurry	1	2	3
Limestone	1	2	3

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

The Moscow section with a high average CBR could have maintenance procedures every three, four, or five years, while the Clay Slurry and Limestone sections low average CBR values could have maintenance every one, two, or three years.

Figure 91 summarizes the BCA results for all the maintenance scenarios based on average surface CBR values.
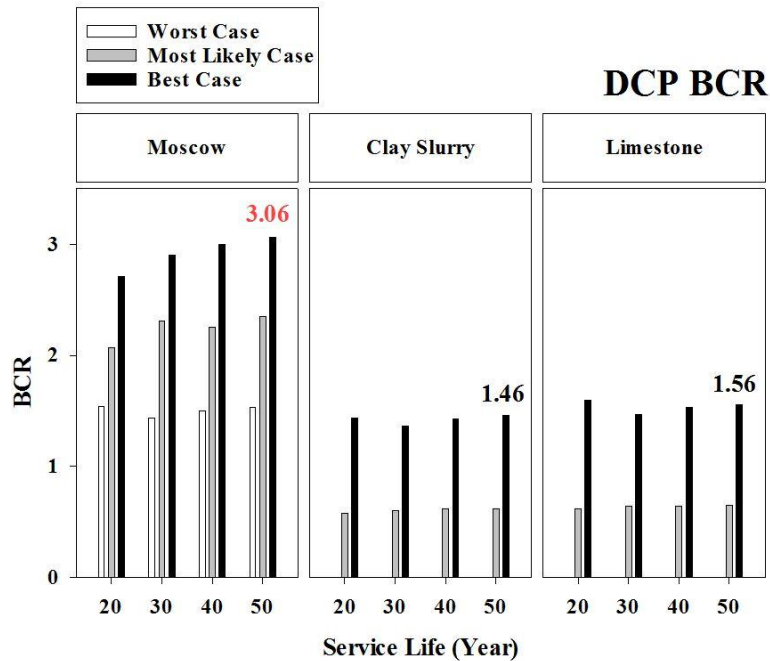
Figure 91. BCR values for average surface CBR for Jones County sections

The BCR values for the Moscow section were greater than 1 for all maintenance scenarios and all service life values considered. The Clay Slurry and Limestone sections could also be beneficial alternatives to the control section, as their BCR values were greater than 1 for the best-case scenarios for all service life considerations.

7.6.7. Dust Production from Dustometer Tests

The average dust emission values over the project duration for Jones County are shown in Figure 92.

117
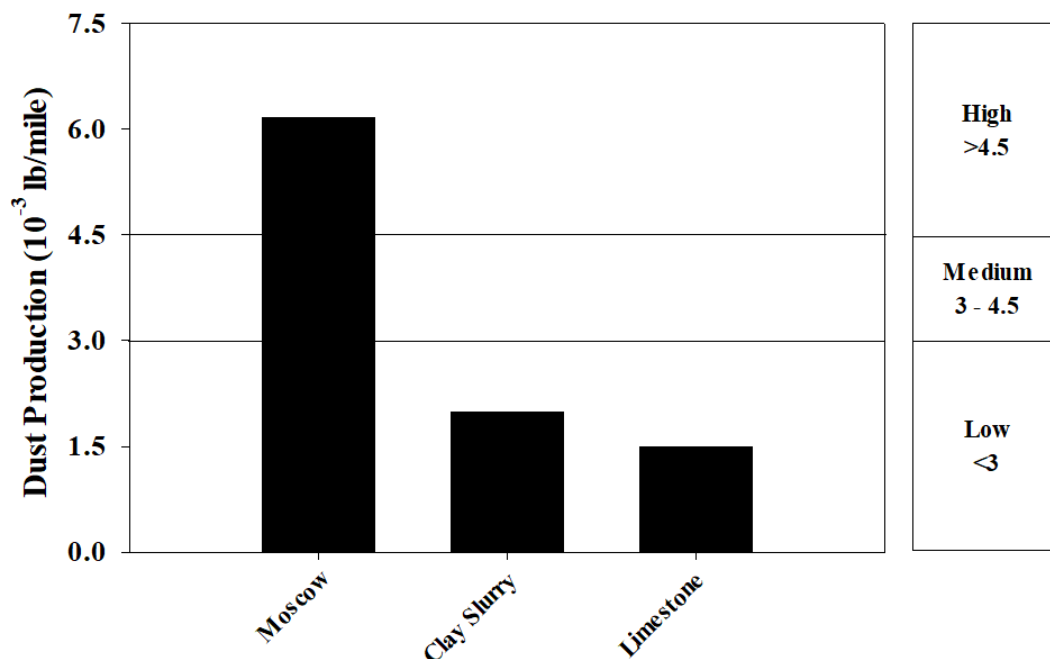
Figure 92. Average dust emission for Jones County sections

According to the classification values shown in the figure, the Moscow section had high average dust emission ($>4.5 \times 10^{-3}$ lb/mi), while the Clay Slurry and Limestone sections had low average dust emission ($<3 \times 10^{-3}$ lb/mi).

The different maintenance scenarios based on the average dust emission values are shown in Table 58.

Table 58. Maintenance scenarios based on average dust emission for Jones County sections

Section	Worst case	Most likely	Best case
Moscow	1	2	3
Clay Slurry	3	4	5
Limestone	3	4	5

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

The Clay Slurry and Limestone sections with low average dust emission could have maintenance every three, four, or five years for the three scenarios, while the Moscow section with high average dust emission could have a higher maintenance frequency of every one, two, or three years.

Figure 93 summarizes the BCA results based on the average dust emission values.
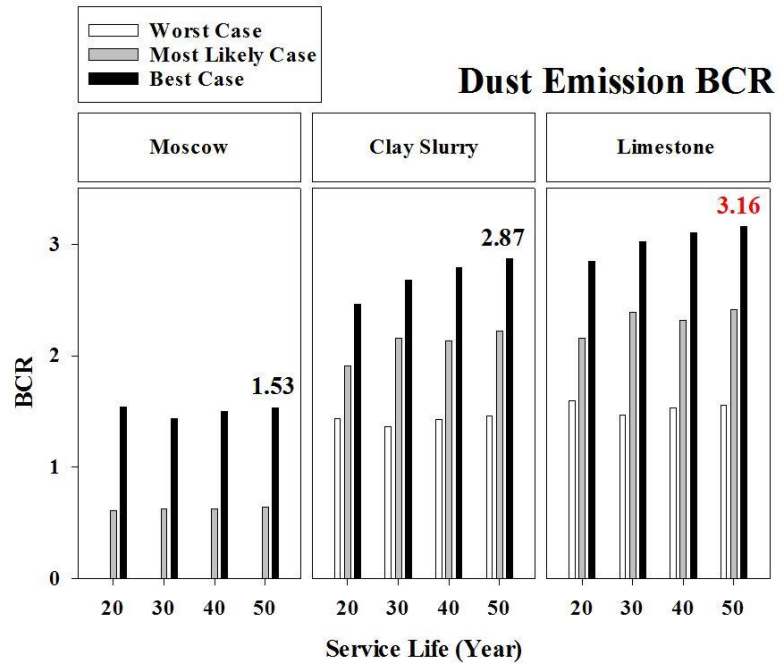
Figure 93. BCR values for average dust emission for Jones County sections

The Clay Slurry and Limestone sections could be beneficial alternatives for their best-case scenarios for all service life values considered. However, the Limestone section had the highest BCR values compared to the other sections. The Moscow section had the lowest BCR values among all sections and was only beneficial for its best-case maintenance scenario.

7.6.8. Surface Roughness –IRI

All of the Jones County sections had fair ride quality ratings based on their average cIRI values over the project duration, as shown in Figure 94.
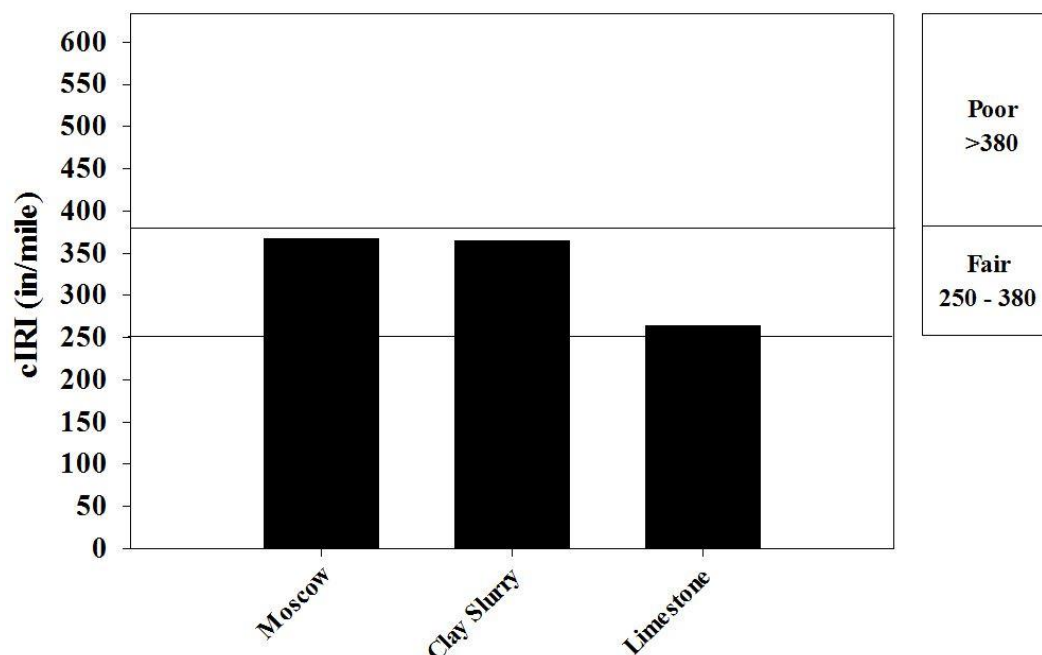
Figure 94. Average surface roughness values for Jones County sections

However, they had different construction costs, which will result in different BCR values for the same maintenance scenarios.

Table 59 shows the different maintenance scenarios based on the cIRI ratings.

Table 59. Maintenance scenarios based on average cIRI values for Jones County sections

Section	Worst case	Most likely	Best case
Moscow	2	3	4
Clay Slurry	2	3	4
Limestone	2	3	4

Note: The maintenance scenario intervals are given in years between 2 in. surface renewal.

Because all sections had the same rating of fair, their maintenance intervals are the same at two years for the worst-case, three years for the most likely case, and four years for the best-case scenario.

The summary of the BCA results for the different maintenance scenarios based on cIRI values are shown in Figure 95.
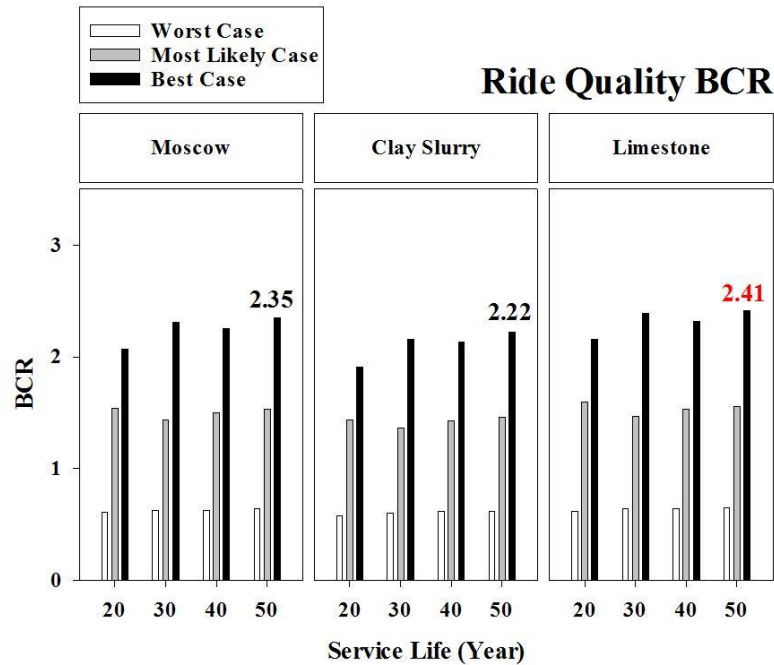
Figure 95. BCR values for average surface roughness values for Jones County sections

The Limestone, Moscow, and Clay Slurry sections were all found to be beneficial alternatives for their best-case and most likely scenarios for all service life values considered.

7.6.9. Overall Performance-Based BCR Values

An overall performance-based BCA was performed using the same relative weighting factors discussed in Section 7.5.9 and shown previously in Figure 77, which were 1.0 for gravel loss and total breakage, 0.75 for the first group consisting of fines content and G/S ratio, 0.5 for the second group consisting of FWD modulus and DCP, and 0.25 for the third group consisting of dustometer and IRI.

Figure 96 shows the resulting overall performance-based BCR values.
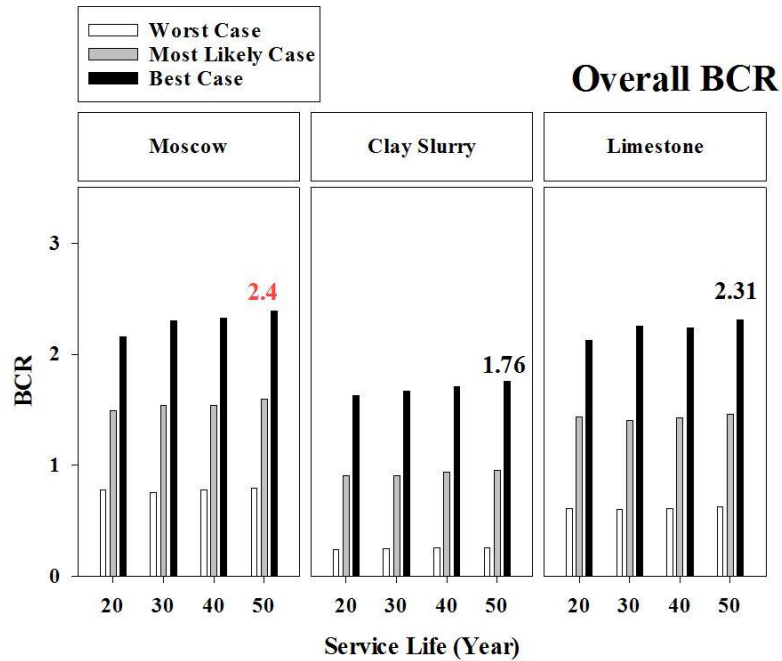
Figure 96. Overall BCR values for the weighted performance measures

The results show that the Moscow and Limestone sections had the highest BCR values and could be considered beneficial compared to the control section for their most likely and best-case scenarios for all service life values considered. The Clay Slurry section could also be beneficial but only for its best-case maintenance scenario.

CHAPTER 8. CONCLUSIONS

This chapter summarizes the results of the laboratory tests, field tests, and cost analyses for the granular-surfaced test sections constructed with quarry fines from various sources. In addition, recommendations for future studies are provided.

8.1. Field Observations

Based on the observations throughout construction and the field tests and surveys conducted over the fall to spring period of 2019–2020, it was concluded that the Ames Mine and Moscow sections in Boone County as well as the Moscow and Limestone sections in Jones County had the best overall performance and cost-efficiency. The Clay Slurry section had the highest construction costs, and its performance, with the exception of dust emission, was similar to those of the other sections in both counties. It should be noted that the supplier has since developed a method for pre-applying the clay slurry to aggregates that are then dried in piles, which will eliminate the need to haul a slurry consisting of 65% water and should bring the construction cost for this quarry fines source in line with the others.

8.2. Laboratory Test Results

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

- According to the USCS and AASHTO 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 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 to some extent. The PI of the subgrade soils 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 the Crescent, 6% of the Moscow, and 10% of the Ames Mine fines by dry weight with the Boone County surface aggregates increased their shear strength. Similarly, mixing 2% of the Limestone and 10% of the Moscow fines with Jones County surface aggregates increased their shear strength. These quarry fines mixing ratios, along with 2% for the Clay Slurry, were selected as the optimum values used for design of the field test sections.

- The pocket penetrometer results showed that the Crescent and Moscow fines reached their maximum penetration resistance faster than the other quarry fines, and the Clay Slurry had the slowest rate to reach its maximum penetration resistance.

- The results of the mini-vane shear tests also showed that the Crescent and Moscow fines had the highest shear strength, while the Ames Mine and Clay Slurry fines had the lowest shear strength values among the fines types selected for this project.

- Slaking times for the surface aggregate materials from Boone County were lower than those in Jones County. Mixing the Limestone fines with the surface aggregates in Boone County and Crescent fines with the surface aggregates in Jones County significantly increased their slaking times, while mixing the Clay Slurry with surface aggregates in both counties did not affect their slaking times.

8.3. Field Test Results

Field testing included sample collection, nuclear density/moisture gauge, FWD, LWD, dustometer, IRI, and DCP tests, which were performed once after construction and once after the freeze-thaw season on the sections in Boone and Jones counties. Samples collected from the sections were used for sieve analysis and hydrometer tests to evaluate the changes in gradation, fines content, and G/S ratio, as well as total breakage of the surface materials over time.

- In Boone County, the Crescent section had the lowest average fines content, while the Moscow and control sections had the highest average fines content. The Ames Mine section had the greatest increase in fines content, while the Moscow section had the smallest increase. In Jones County, the Moscow section had the lowest average fines content, while the other sections had similar average fines content values. The Moscow section had the greatest increase in fines content in Jones County, while the Limestone section had the smallest increase.

- In Boone County, the control and Moscow sections had the lowest average G/S ratios, while the Ames Mine, Clay Slurry, and Crescent sections had similar average G/S ratios. Additionally, the control and Ames Mine sections had the smallest decreases in G/S ratio, while the Crescent section had the greatest decrease in G/S ratio. In Jones County, the Moscow section had the highest G/S ratio, while the rest of the sections had similar G/S values. The control section had the greatest decrease in G/S ratio, while the Moscow section had the smallest decrease in G/S ratio. In Boone County, all quarry fines sections were generally effective in maintaining a higher G/S ratio than the control sections. In Jones County, however, the same was only true for the Moscow section.

- The Moscow section had the lowest total breakage, while the Ames Mine and Crescent sections had the highest total breakage values in Boone County. In Jones County, the control section had the highest total breakage and the Limestone section had the lowest. The increased binding of the quarry fines therefore had the intended effect of reducing the total breakage of aggregates in Jones County, while the same was not true for the Boone County test sections.

- The Ames Mine, Moscow, and Clay Slurry sections had the highest median surface CBR values, while the control section had the lowest in Boone County. In Jones County, the Moscow section had the highest and the Limestone and Clay Slurry sections had the lowest median CBR values. All of the quarry fines types were effective at increasing the median CBR strength of the surface layers in Boone County, while the same was only true for the Moscow section in Jones County.

- LWD test results showed that all sections in Boone and Jones counties had similar results for the composite elastic moduli after the spring thaw. However, FWD results showed that the Ames Mine section had the highest surface elastic modulus value, while the control section had the lowest in Boone County. In Jones County, the Limestone and Moscow sections had the highest surface elastic moduli, while the control and Clay Slurry sections had the lowest. Subbase and subgrade elastic moduli were nearly the same for all sections in both Boone and Jones counties.

- Dustometer test results showed that the Clay Slurry sections generally had the lowest dust emission, while the control sections had the highest dust emission in both counties.

8.4. Cost Analysis Results

Several BCAs were conducted based on the observed performance measures including gravel loss, total breakage, fines content, G/S ratio, surface stiffness, surface CBR, dust emission, and surface roughness, to determine the most cost-effective quarry fines options. Different maintenance scenarios were considered based on the relative performance of the sections for 20, 30, 40, and 50 years of service life. Finally, overall performance-based BCR values were calculated by assigning weighting factors to the individual BCR values based on the relative importance of each of the performance measures.

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

- All quarry fines in Jones County had a similar hauling time, while the hauling costs were greatest for the Clay Slurry.

- In Boone County, the Moscow section had the highest BCR for total breakage and dust emission considerations. In contrast, the Ames Mine section had the highest BCR values for ride quality, CBR, FWD modulus, G/S ratio, gravel loss, and fines content. Overall, the Ames Mine section was the most cost-effective quarry fines option in Boone County due to its good performance and lower hauling costs.

- In Jones County, the Limestone section had the highest BCR values for gravel loss, dust emission, total breakage, FWD, and ride quality. The Moscow section had the highest BCR values for G/S ratio, fines content, DCP, and for overall performance measures.

- The Clay Slurry section, due to its high material, equipment, and hauling costs, was not a cost-effective option for both counties. However, the Clay Slurry construction approach was experimental at the time of this study, and the supplier now sells pre-treated aggregates, which should make the hauling and construction costs comparable to the other quarry fines types.

8.5. Recommendations for Further Research

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

- Build new test sections in different regions to examine a broader range of local quarry materials, traffic loads, and subgrade conditions
- Find quarry fines with higher plasticity and cementitious behaviors from other quarries and around new site locations to reduce the hauling costs
- Mix quarry fines with recycled materials instead of virgin aggregates alone to reduce construction costs and improve sustainability
- Investigate the binding effect of subgrade and subbase materials stabilized by quarry fines to help reduce freeze-thaw effects on the subsurface layers
- Perform additional BCA studies on construction and maintenance of low-volume roads with different materials, stabilization methods, or other conditions
- Investigate the effects of maintenance costs for projects related to stabilization with quarry fines and over longer durations (e.g., two to five years)
- Develop 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 by such materials, which can help reduce gravel and thickness loss. Thereby, the required amount of materials for maintenance procedures will be lower for stabilized sections than sections having only existing surface aggregates. Moreover, obtaining quarry fines from nearby sources would decrease construction costs by reducing hauling costs. In this study, five different types of quarry fines were mixed with surface aggregates in two counties, and the performance of the sections was monitored. However, it would also be useful to investigate the effectiveness of mixing additional types of quarry fines with surface aggregates in more locations, over more extended periods, and with different subgrade and subbase, weather, and traffic conditions. In doing so, 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 CONSTRUCTION AND FIELD SURVEYS

A.1. Project Equipment

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

Figure A-2. Water tanker in Jones County

Figure A-3. Motor grader used in Boone County

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

Figure A-5. Skid-steer loader used for spreading Limestone fines in Jones County

A.2. Boone County Sections

A.2.1. Section 1: Existing Aggregates and Ames Mine Section

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

A.3. Jones County Sections

A.3.1. Section 1: Existing Aggregates and Moscow Section

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

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

Figure A-27. Moscow section in Jones County, June 2020
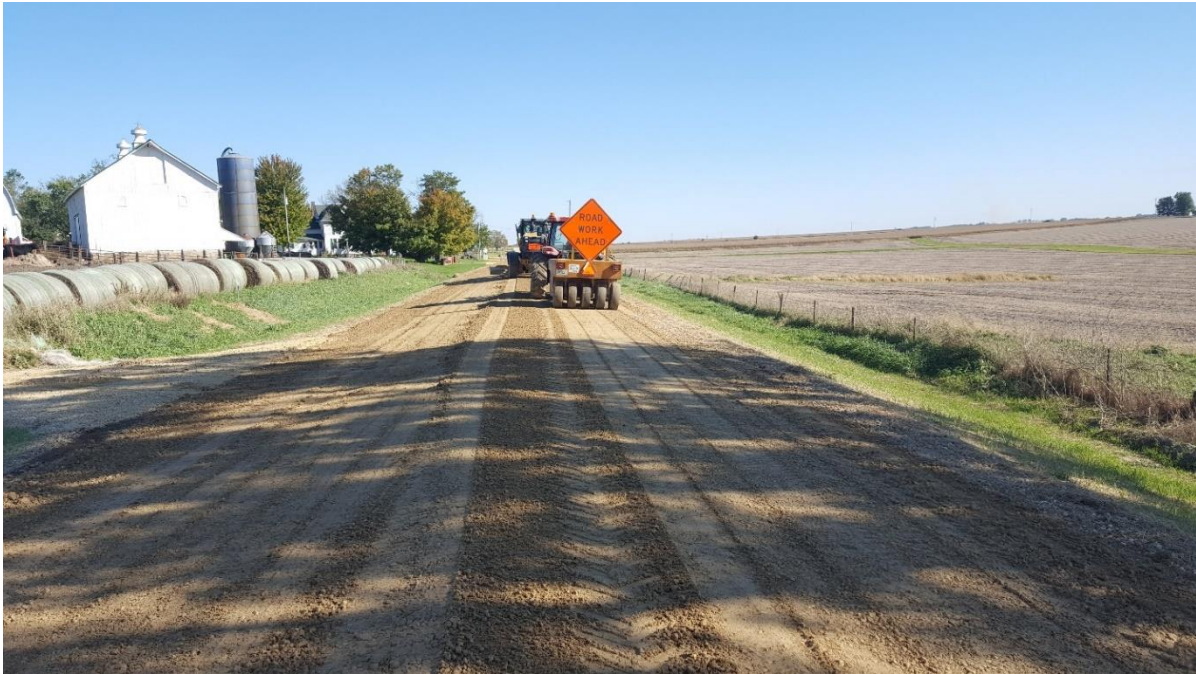
Figure A-28. Clay Slurry section in Jones County, during the construction, November 2019

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

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

A.3.3. Section 3: Existing Aggregates and Limestone Section

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

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

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

Figure A-34. Control section in Jones County, November 2019
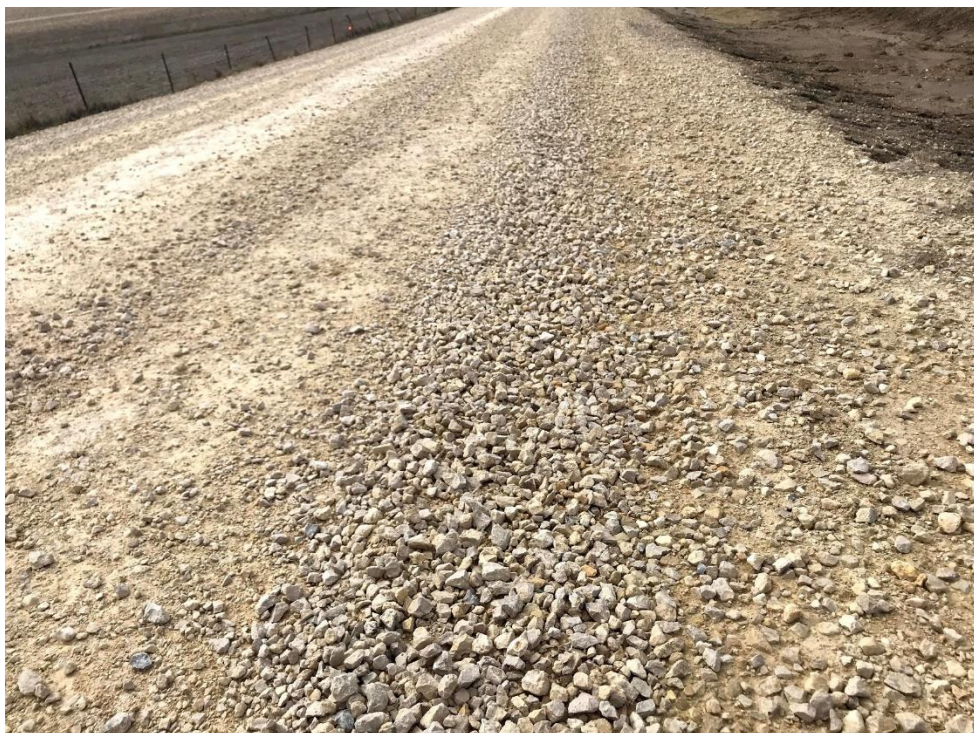
Figure A-35. Control section in Jones County, March 2020

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

APPENDIX B. PARTICLE SIZE ANALYSIS RESULTS
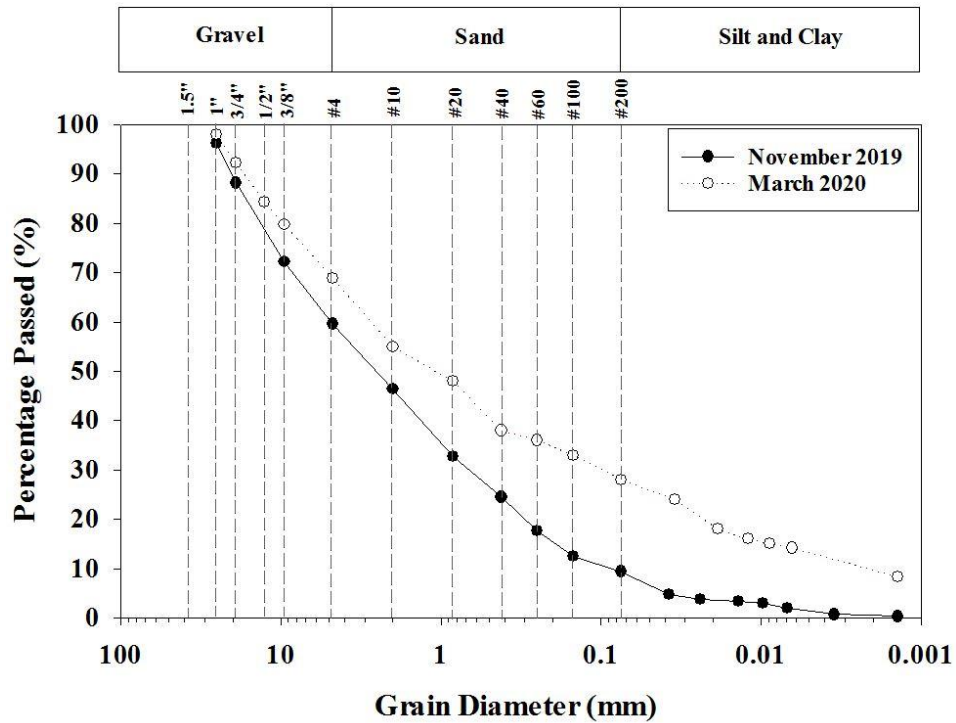
Figure B-1. Boone County Ames Mine section particle size distribution
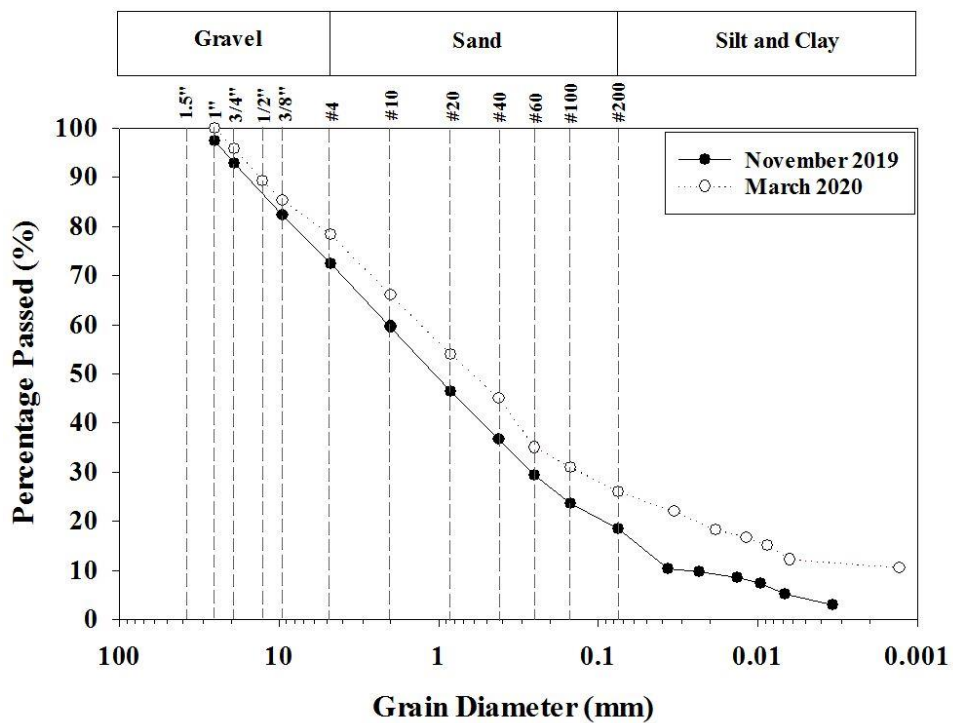
Figure B-2. Boone County Moscow section particle size distribution
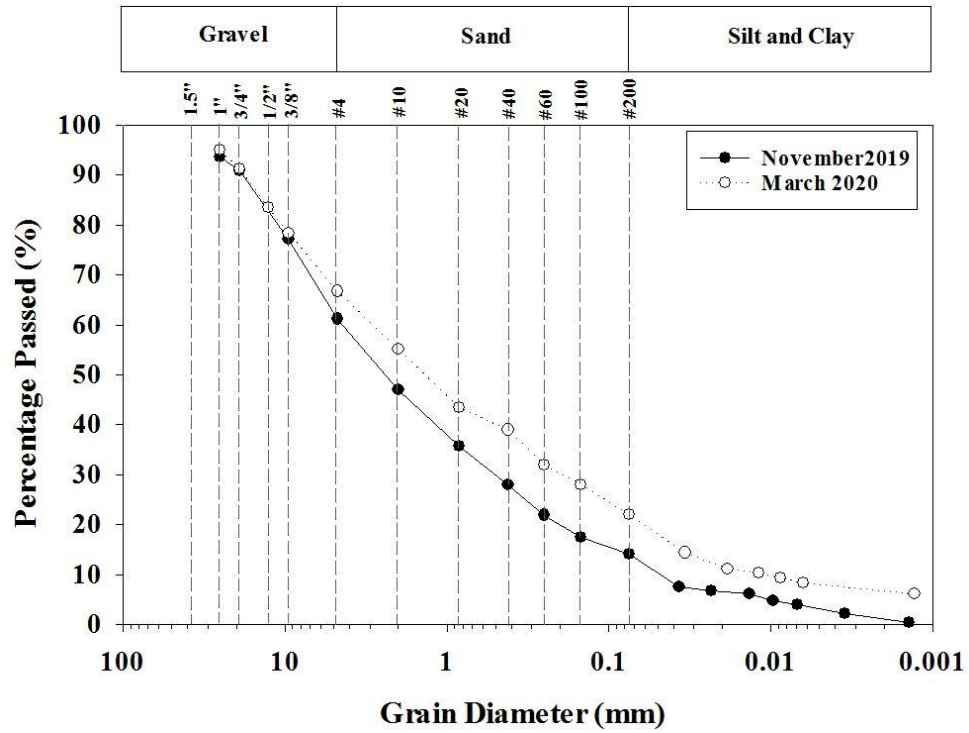
Figure B-3. Boone County Clay Slurry section particle size distribution
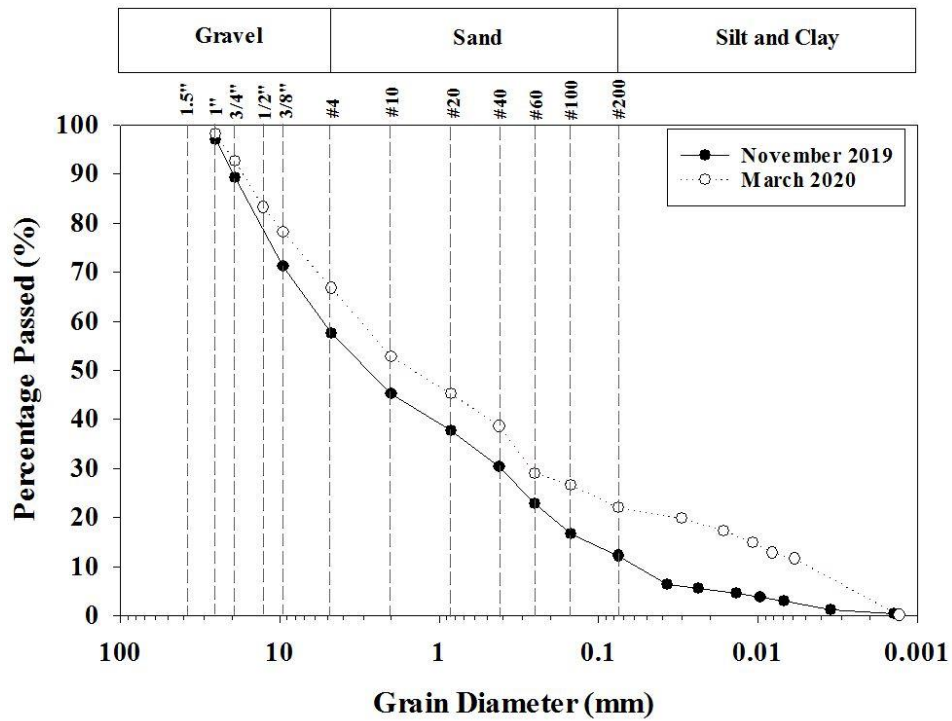
Figure B-4. Boone County Crescent section particle size distribution

162

Figure B-5. Boone County control section particle size distribution

Figure B-6. Jones County Moscow section particle size distribution
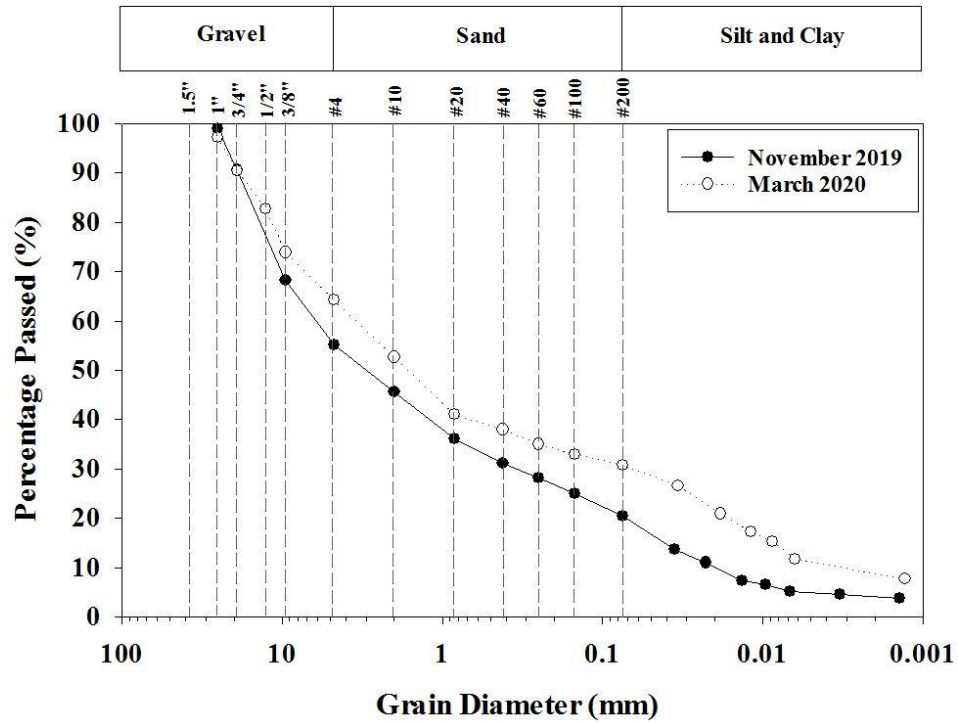
Figure B-7. Jones County Clay Slurry section particle size distribution
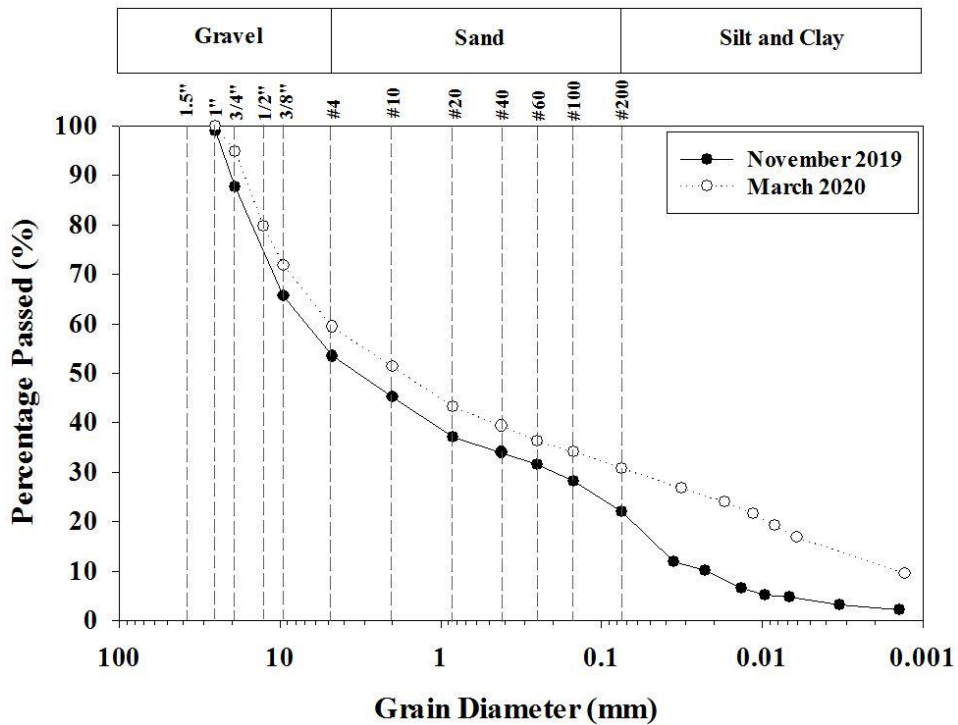
Figure B-8. Jones County Limestone section particle size distribution

164
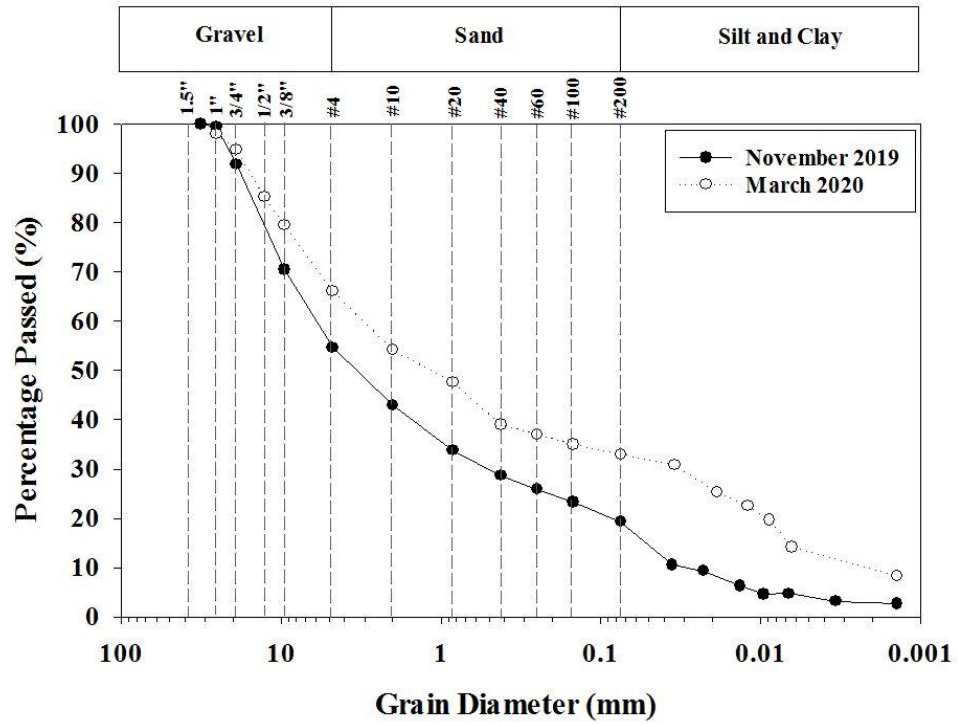
Figure B-9. Jones County control section particle size distribution
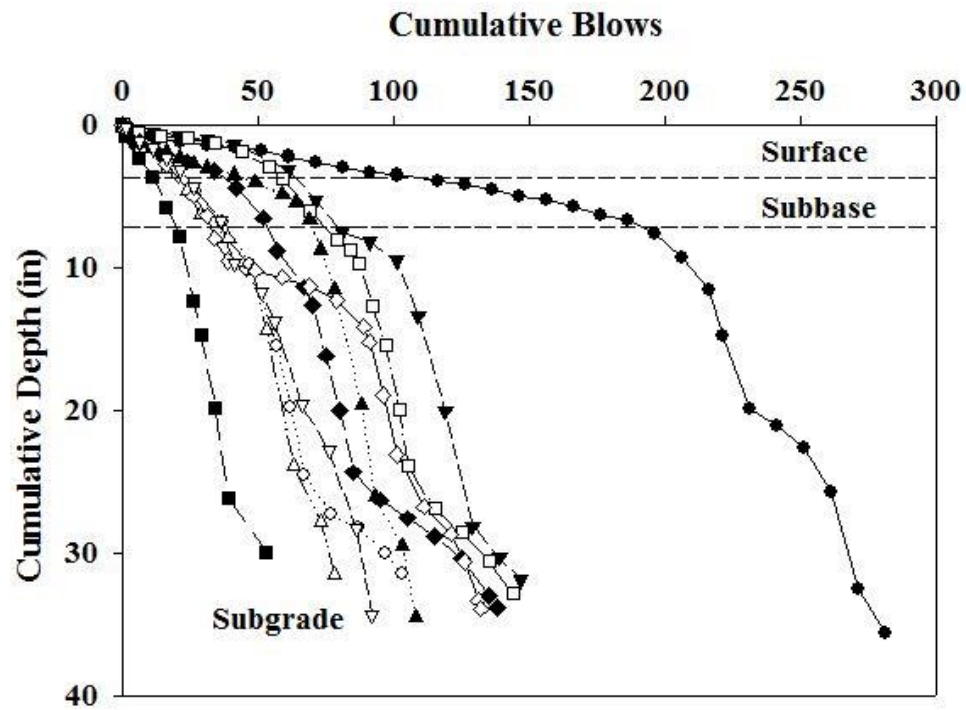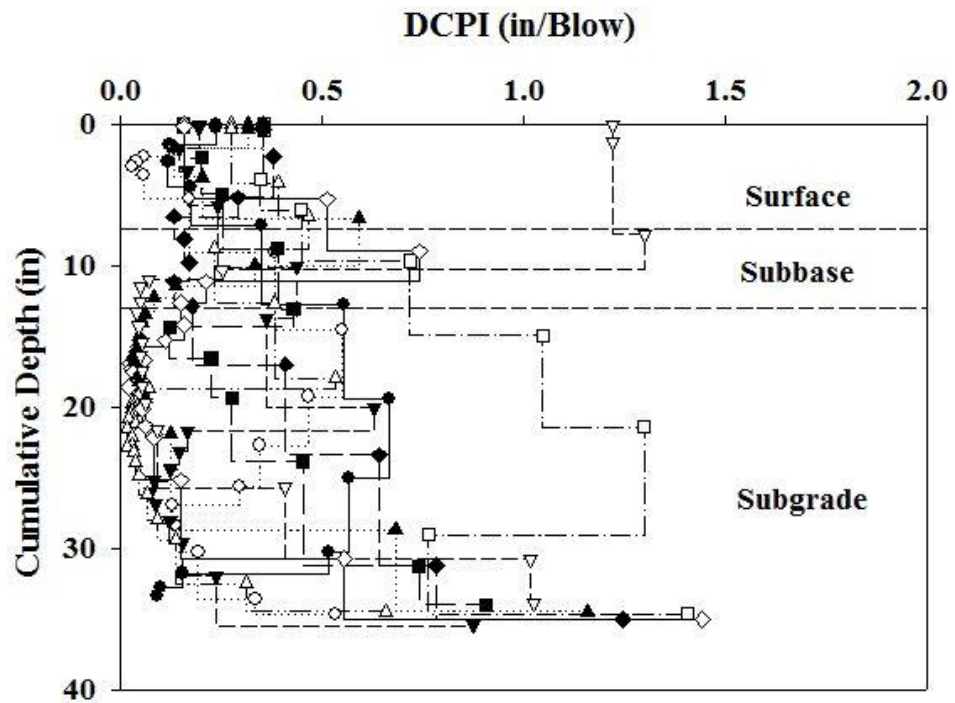
(a)
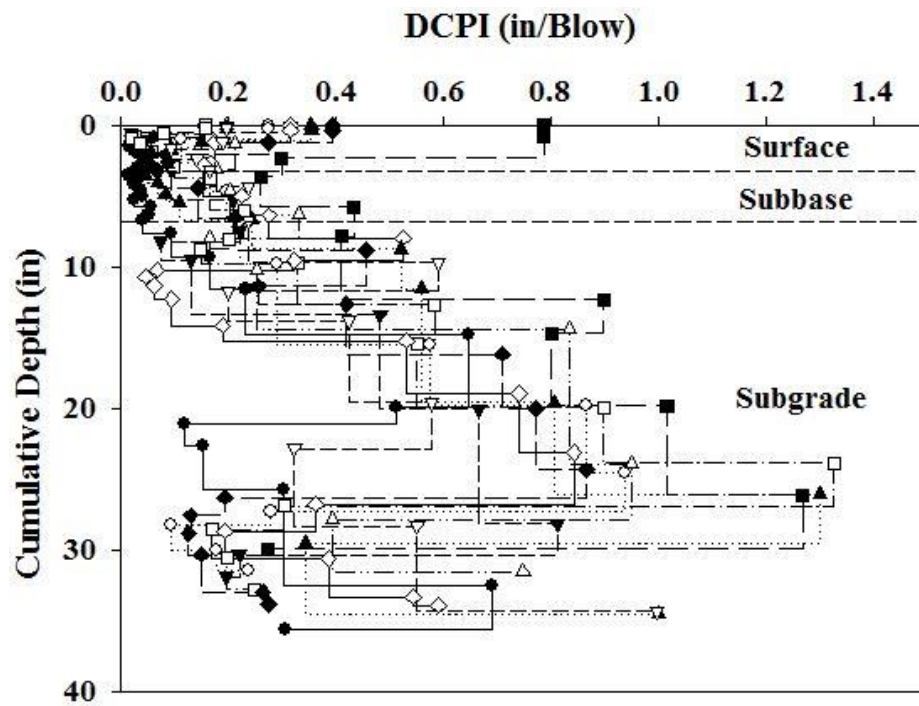
(b)
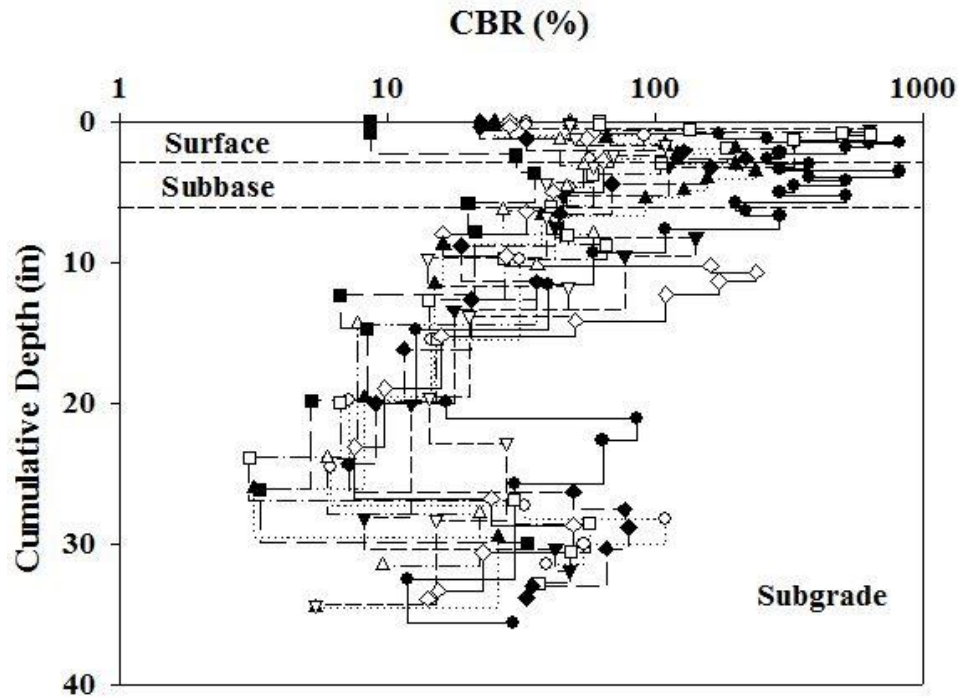
(c)

Figure C-1. Boone County Section 1 (Ames Mine): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019
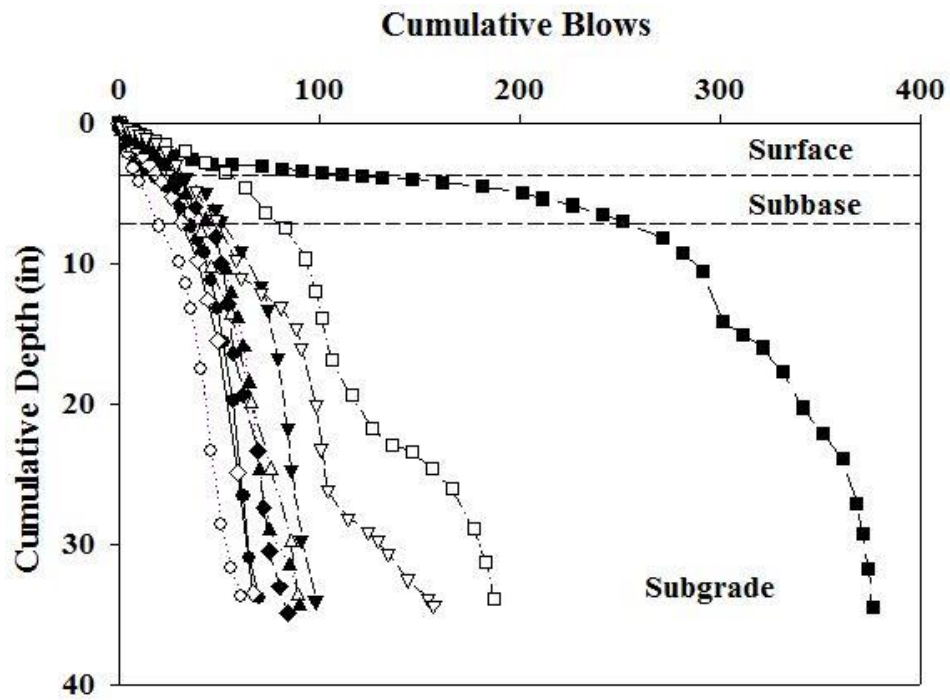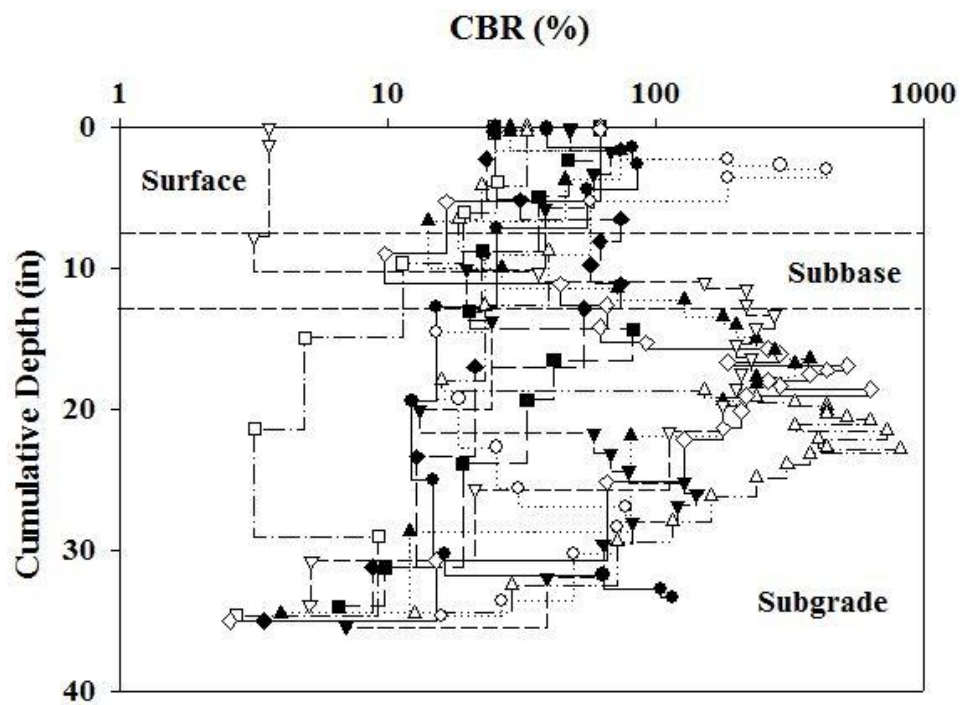

(a)
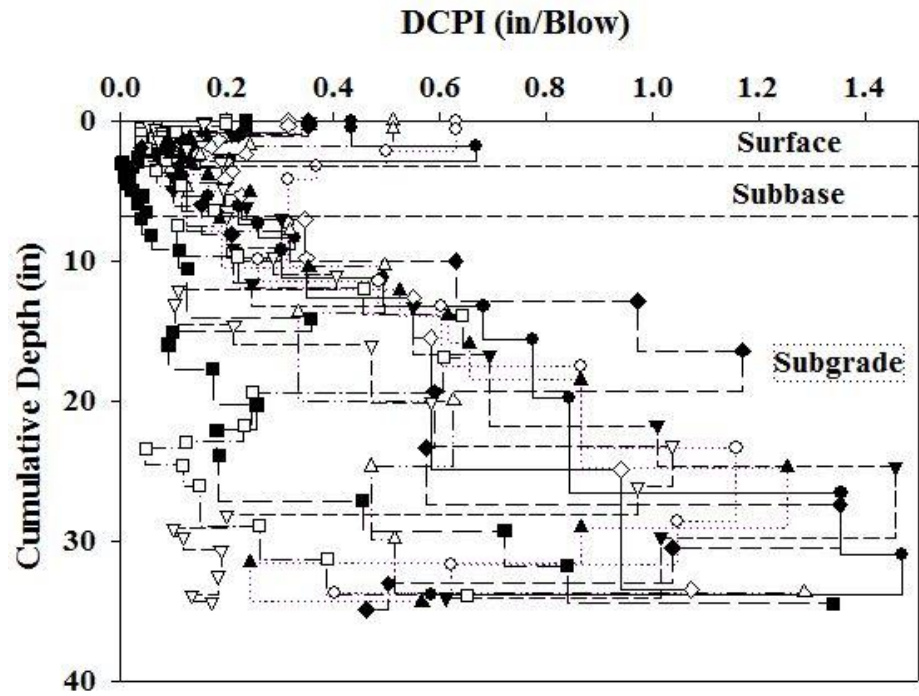
(b)
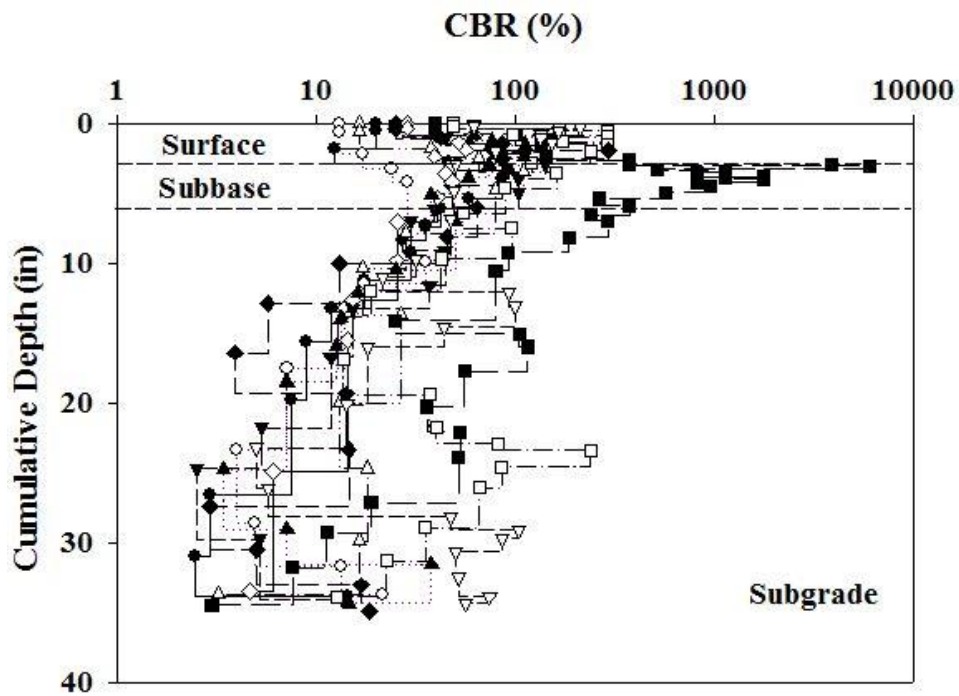
(c)

Figure C-2. Boone County Section 2 (Moscow): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019
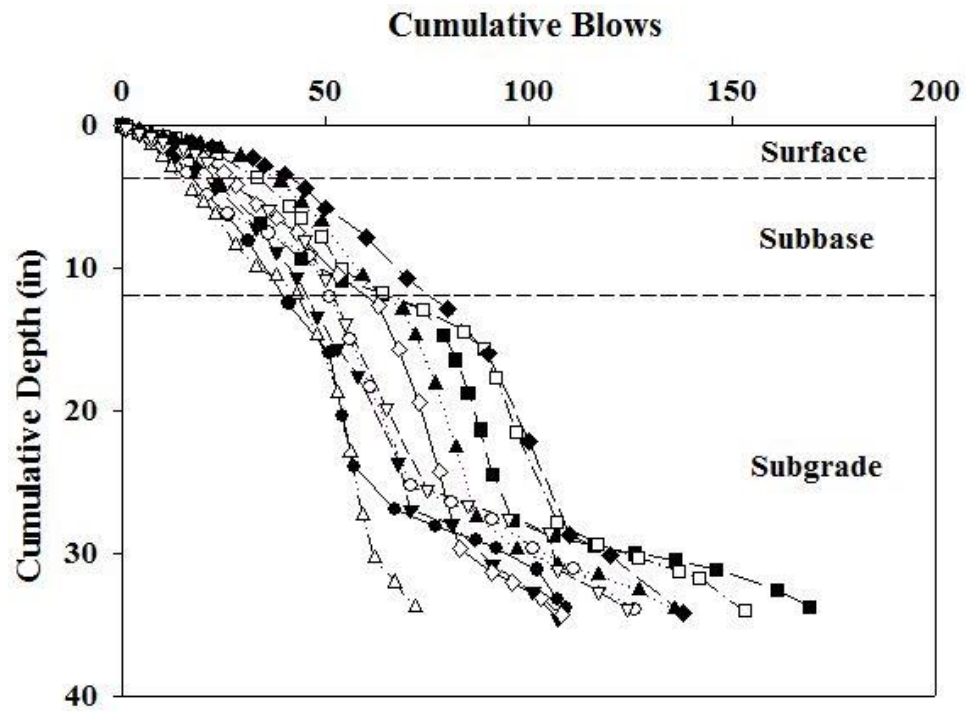
(a)
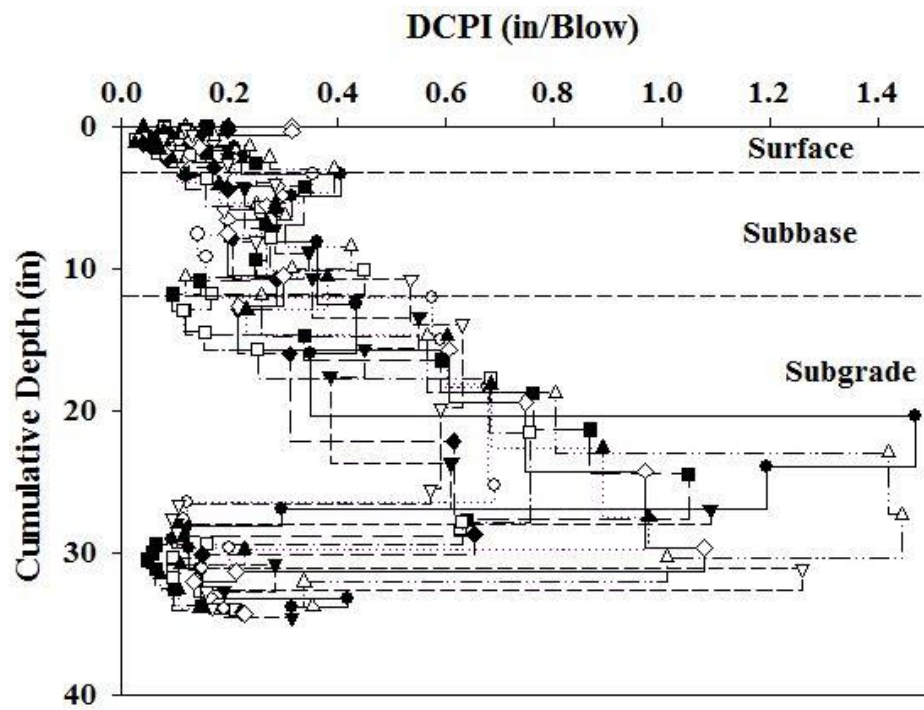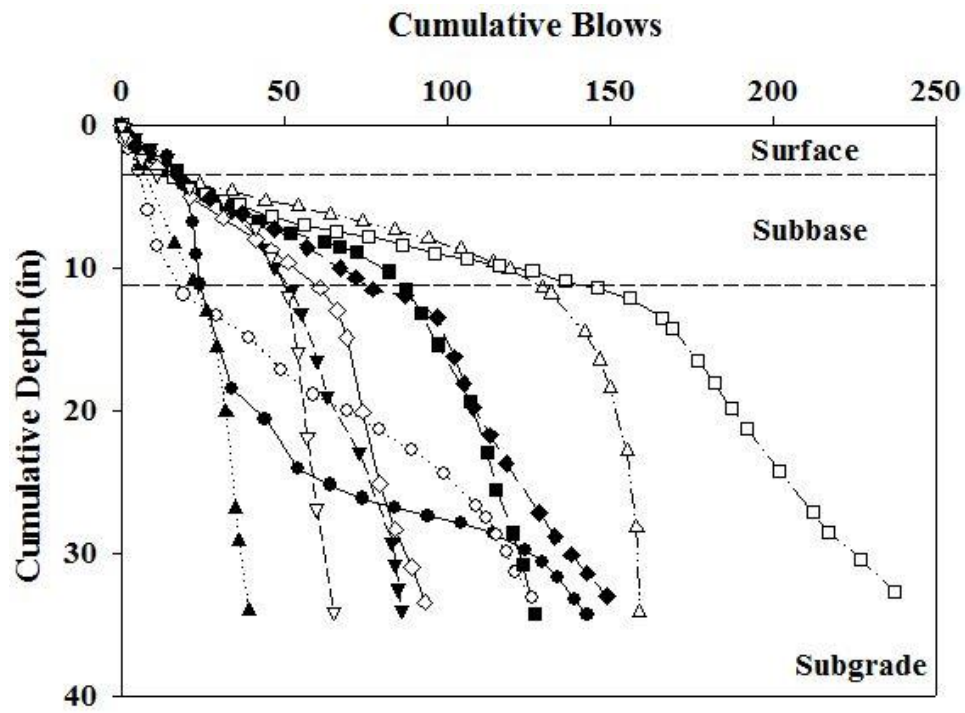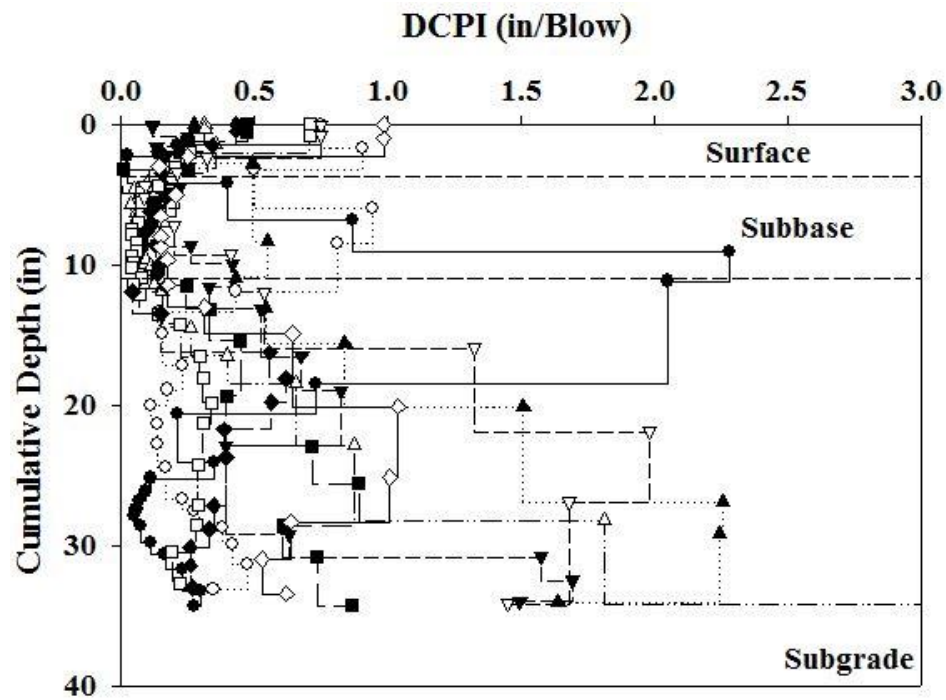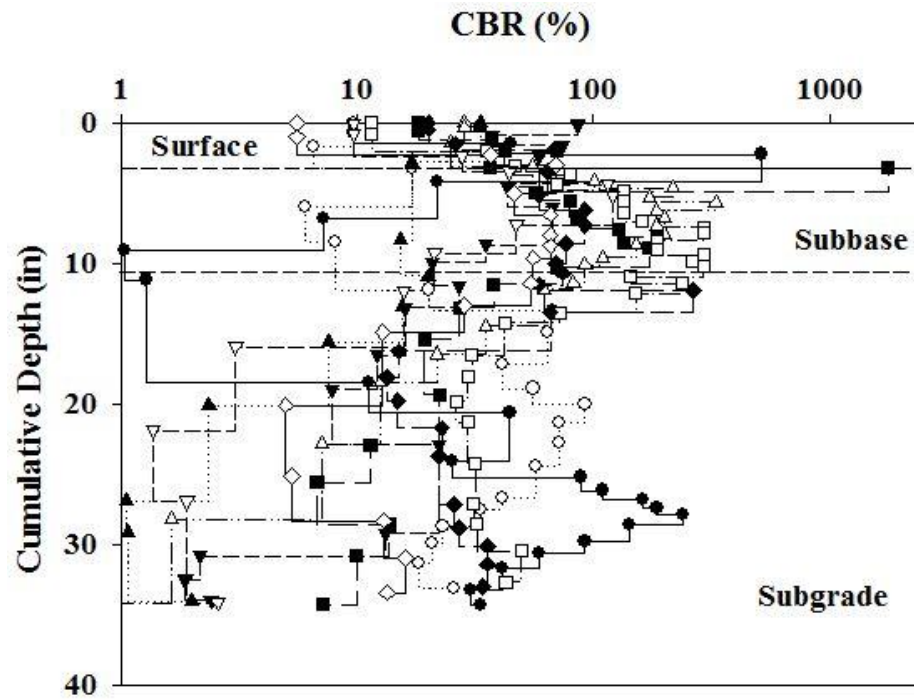

(b)
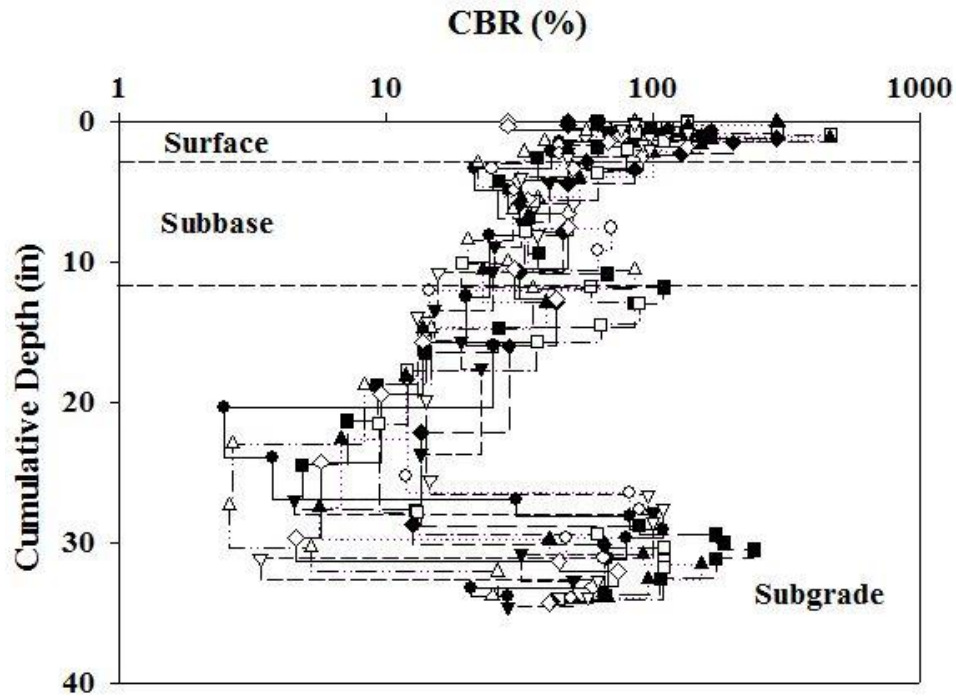
(c)

Figure C-3. Boone County Section 3 (Clay Slurry): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019
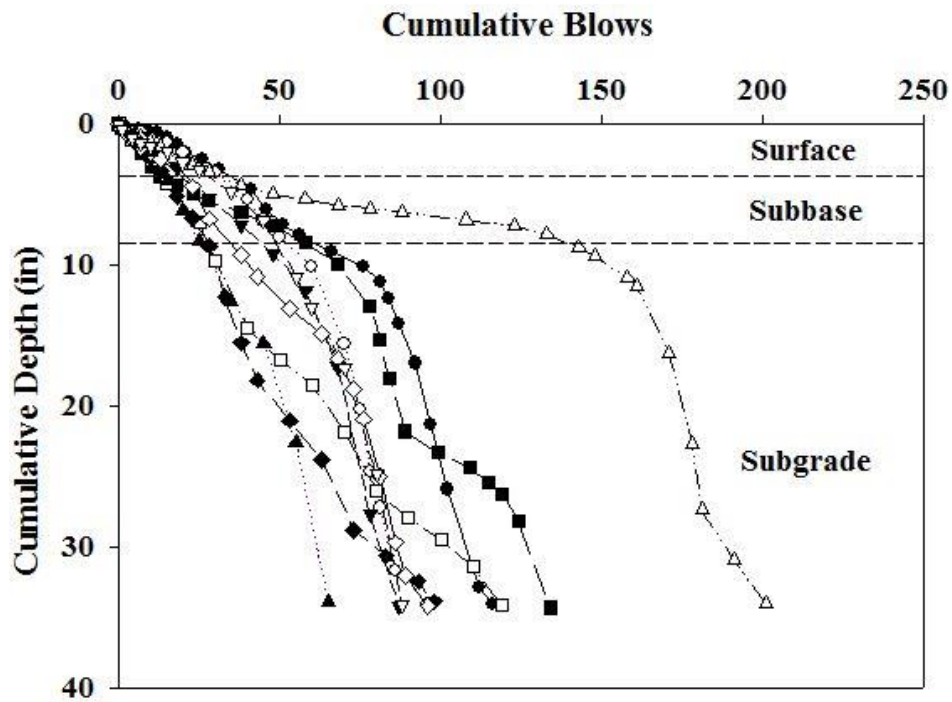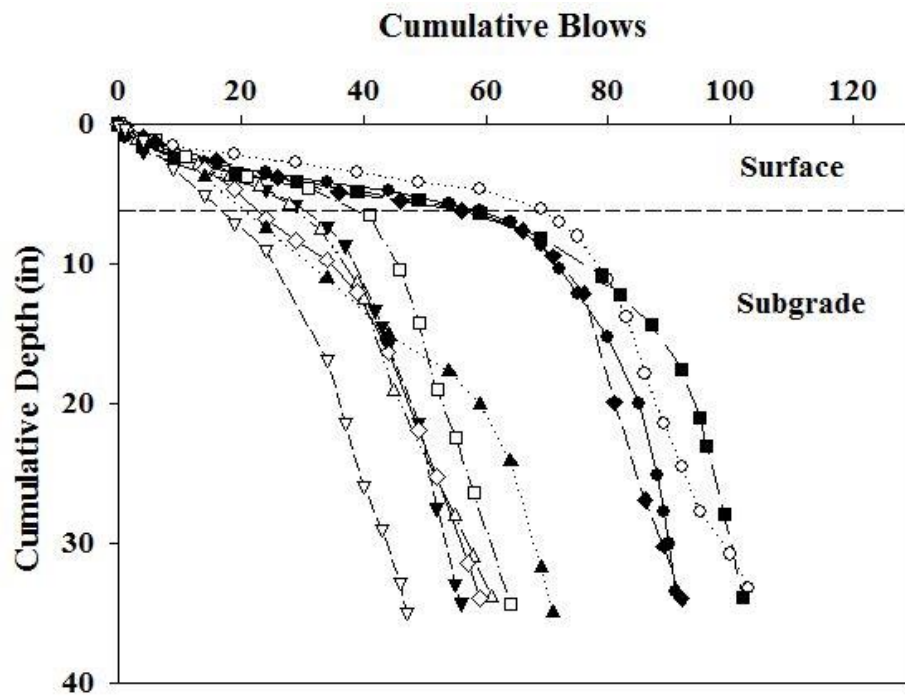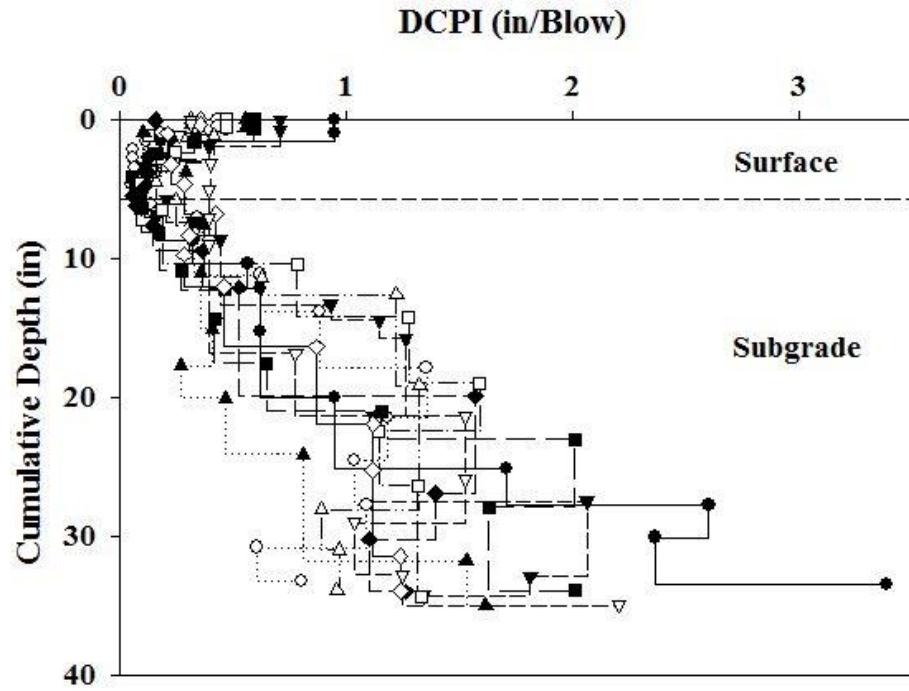

(a)
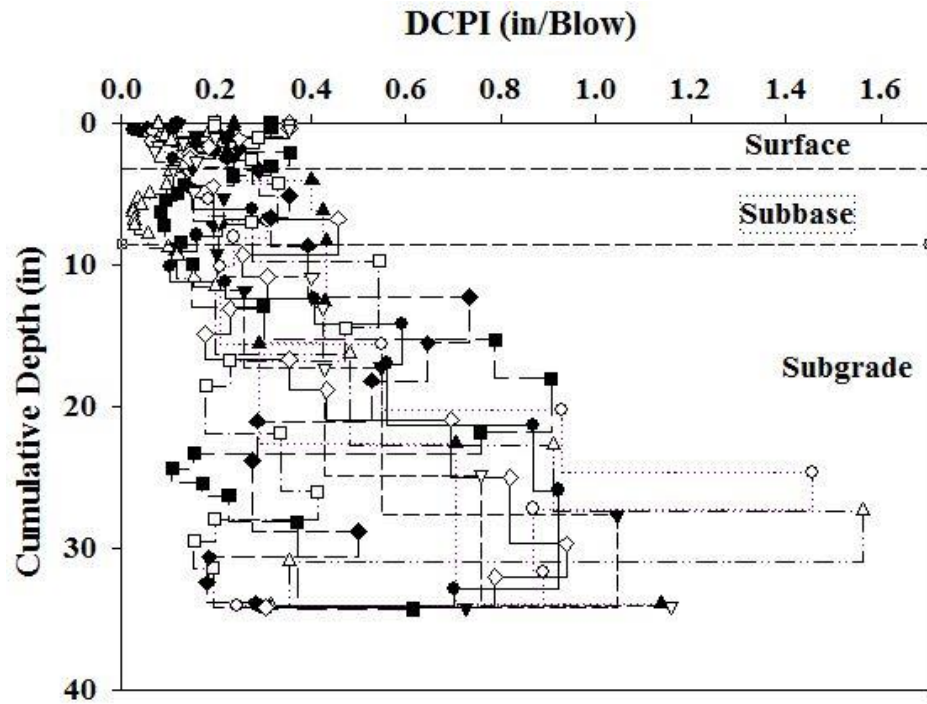
(b)
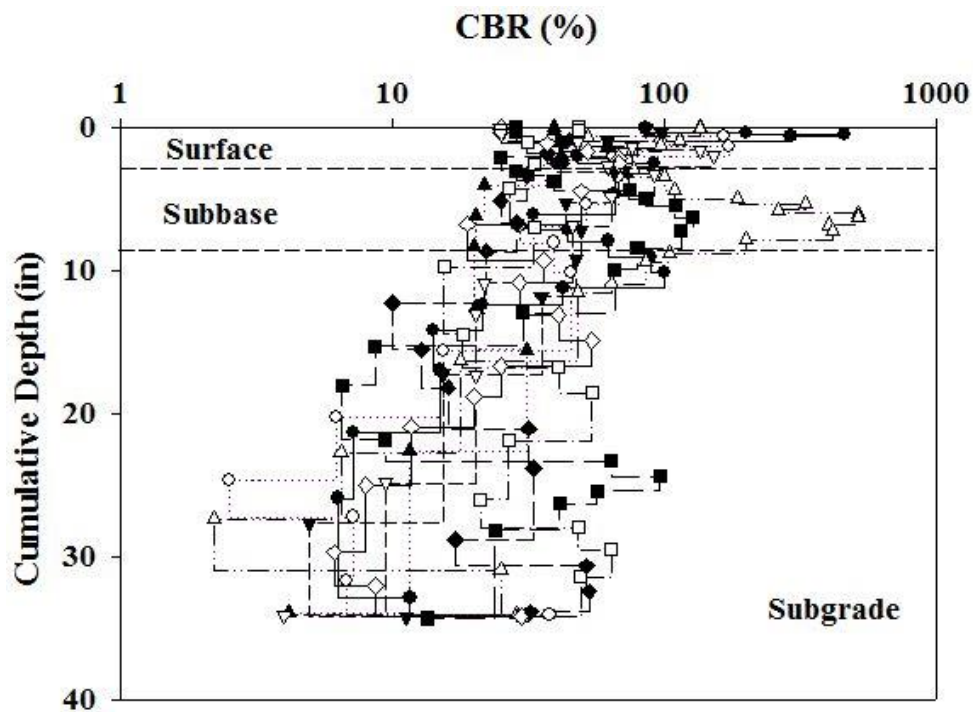
(c)

Figure C-4. Boone County Section 4 (Crescent): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019

Cumulative Blows

(a)

DCPI (in/Blow)

(b)

173
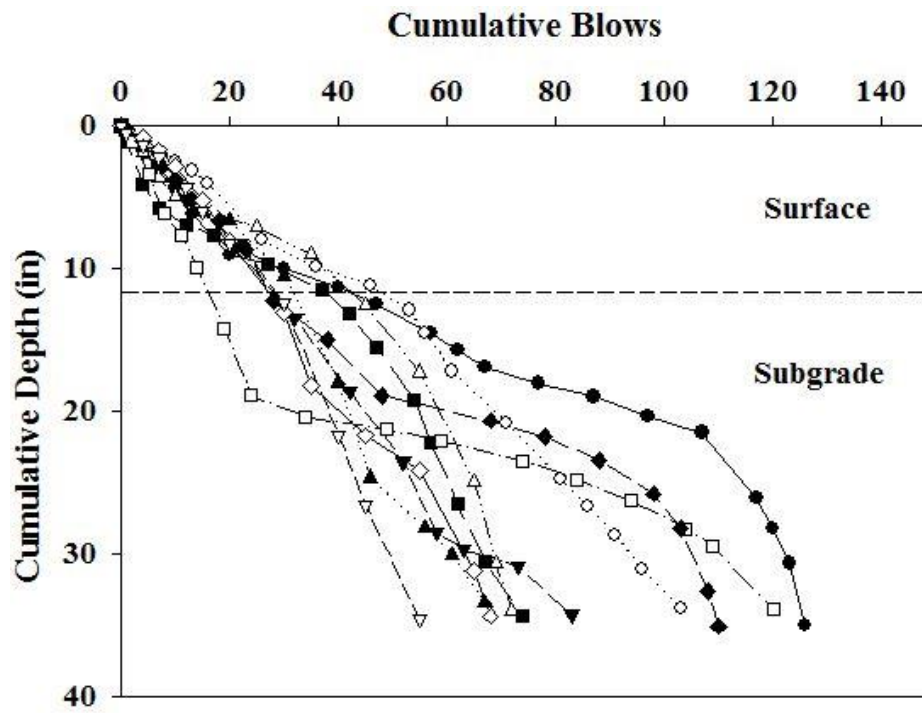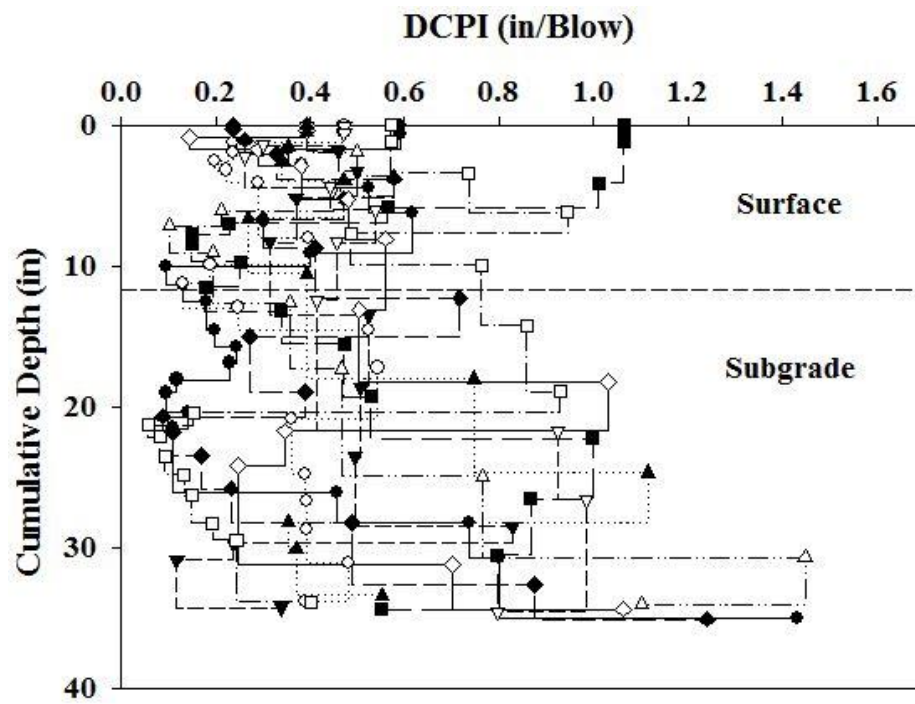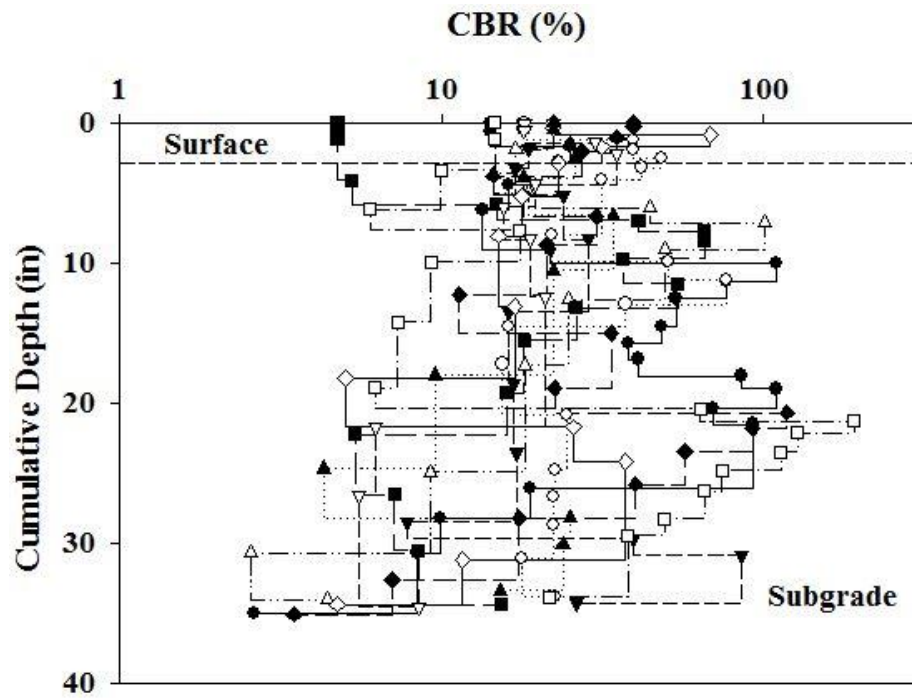
(c)

Figure C-5. Boone County Section 5 (Control): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019

(a)

174
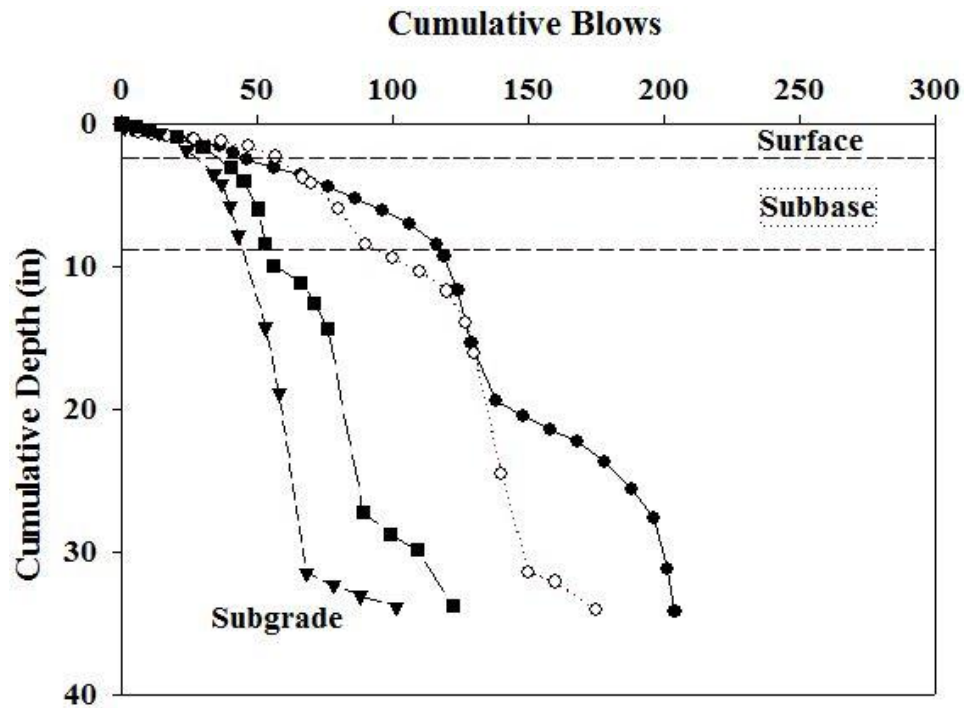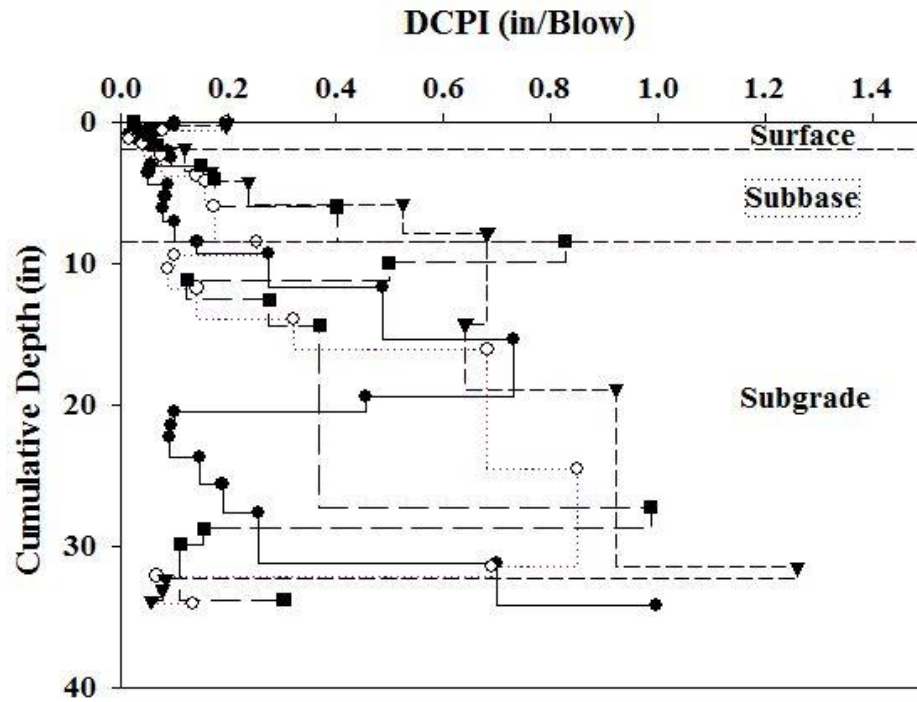
(b)
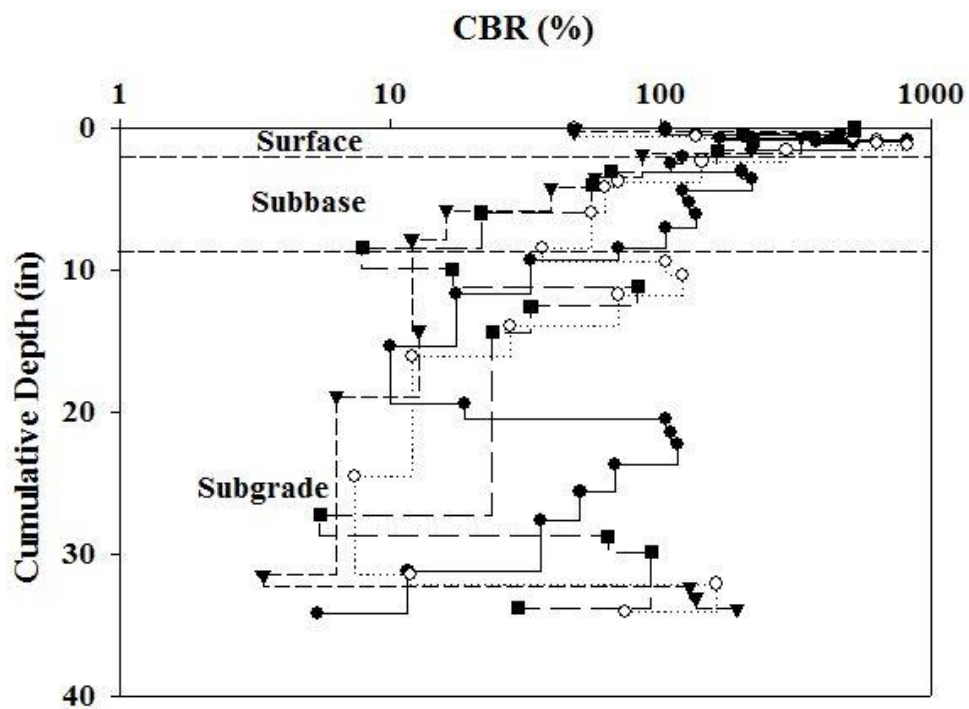
(c)

Figure C-6. Boone County Section 1 (Ames Mine): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020

175

(a)

(b)

176
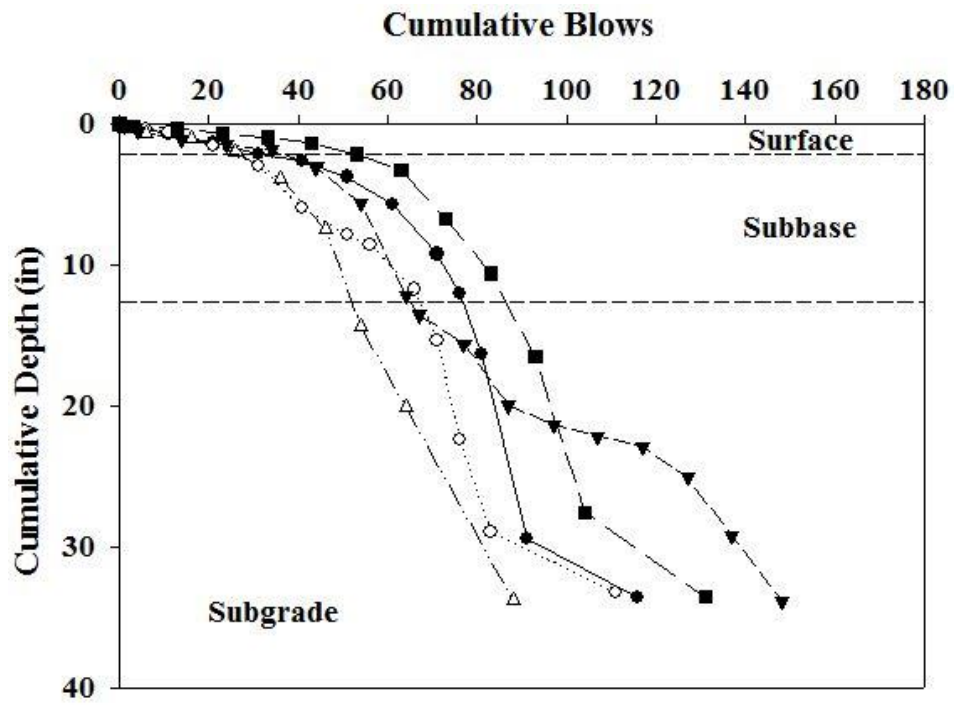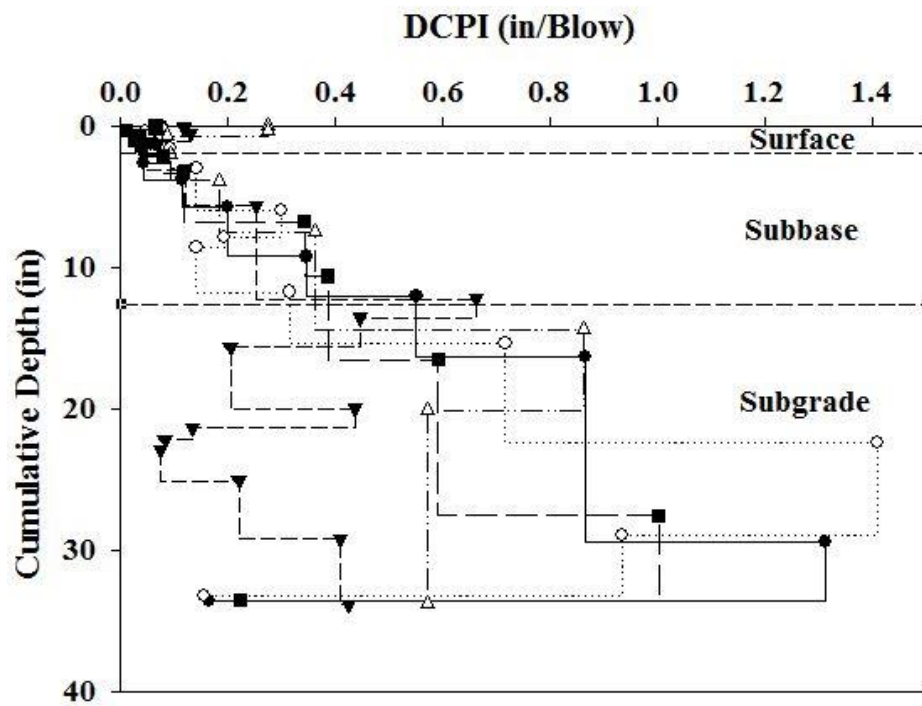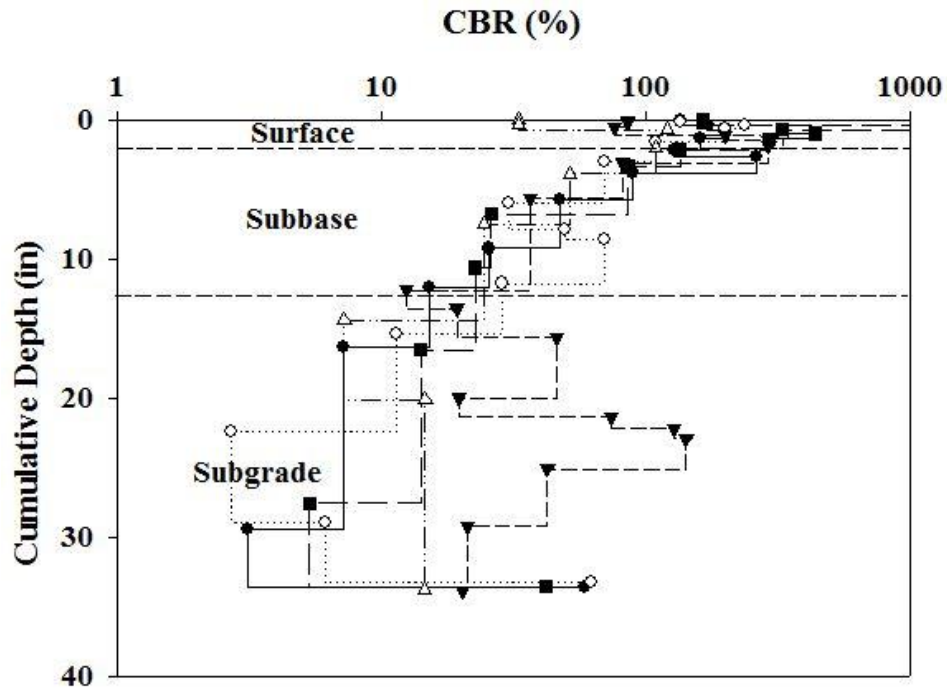
(c)

Figure C-7. Boone County Section 2 (Moscow): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020

(a)

177
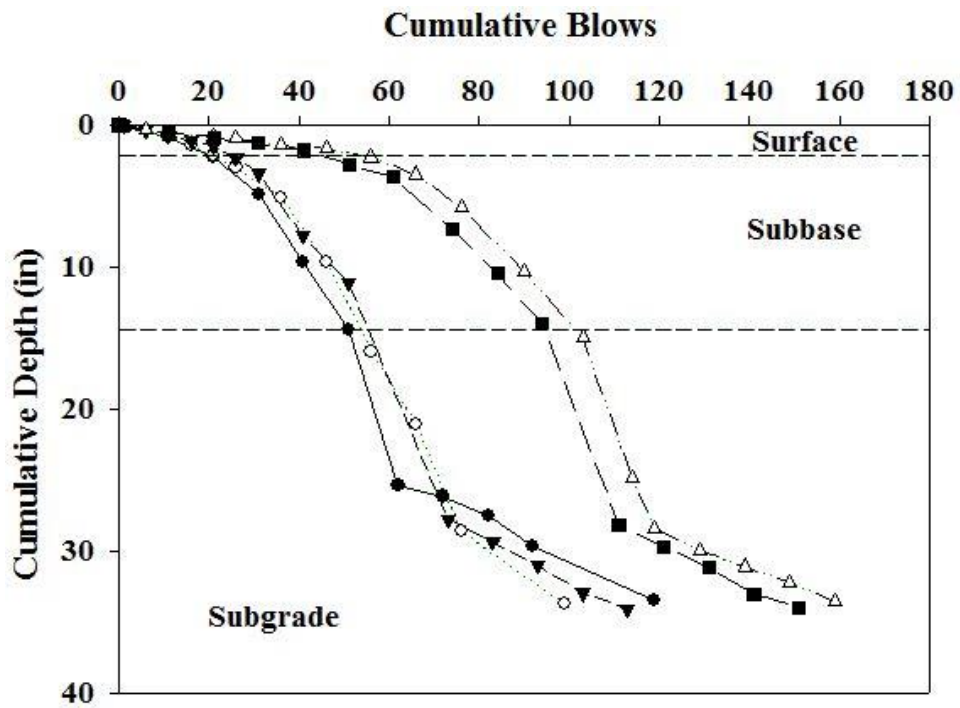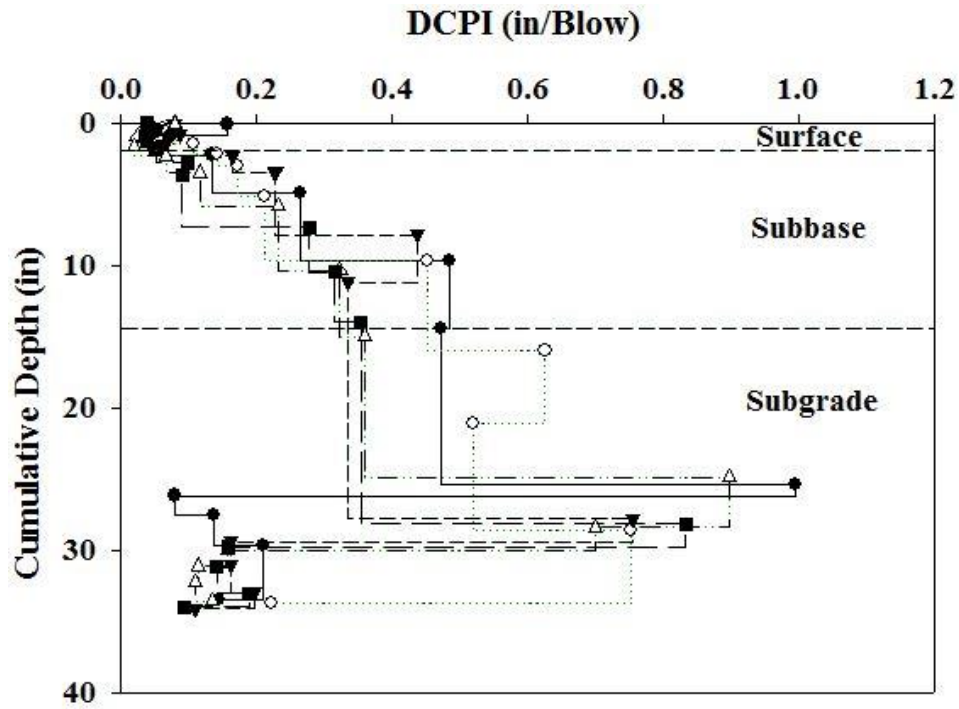
(b)
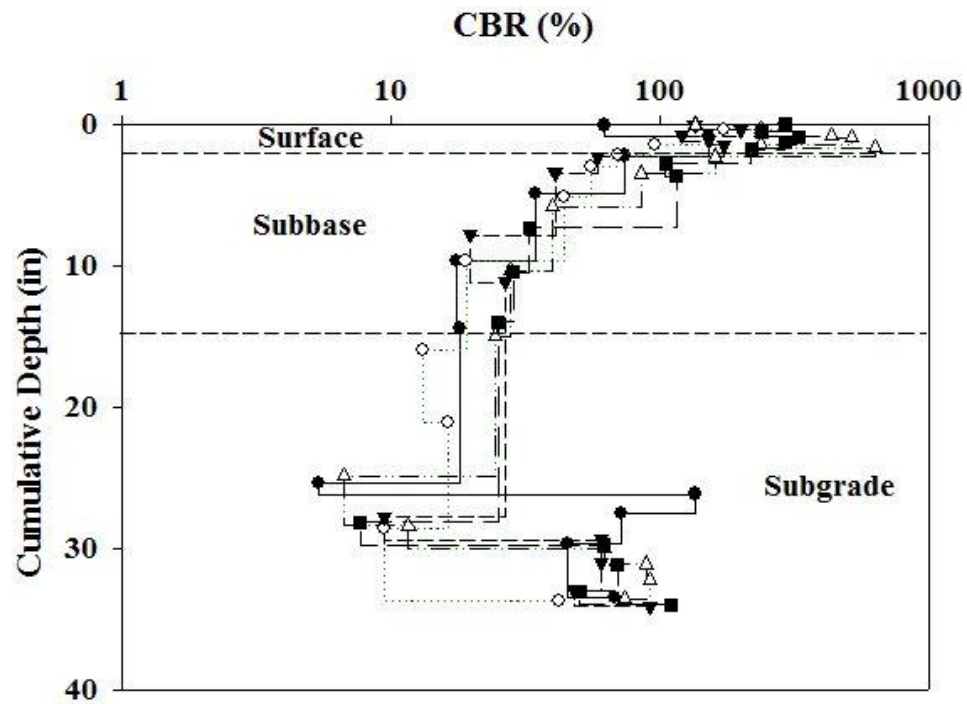
(c)

Figure C-8. Boone County Section 3 (Clay Slurry): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020
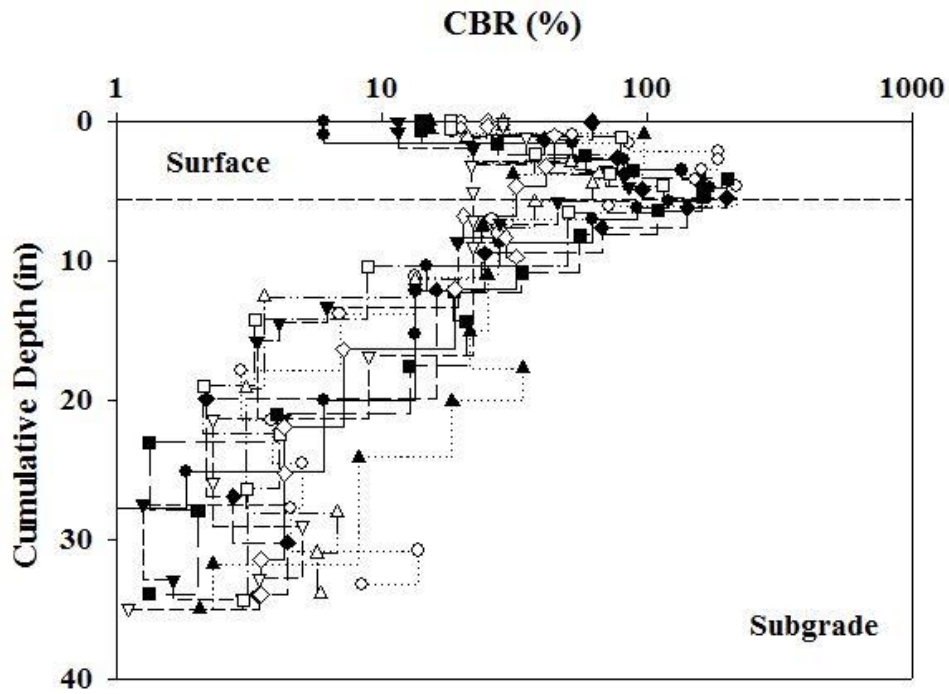
178
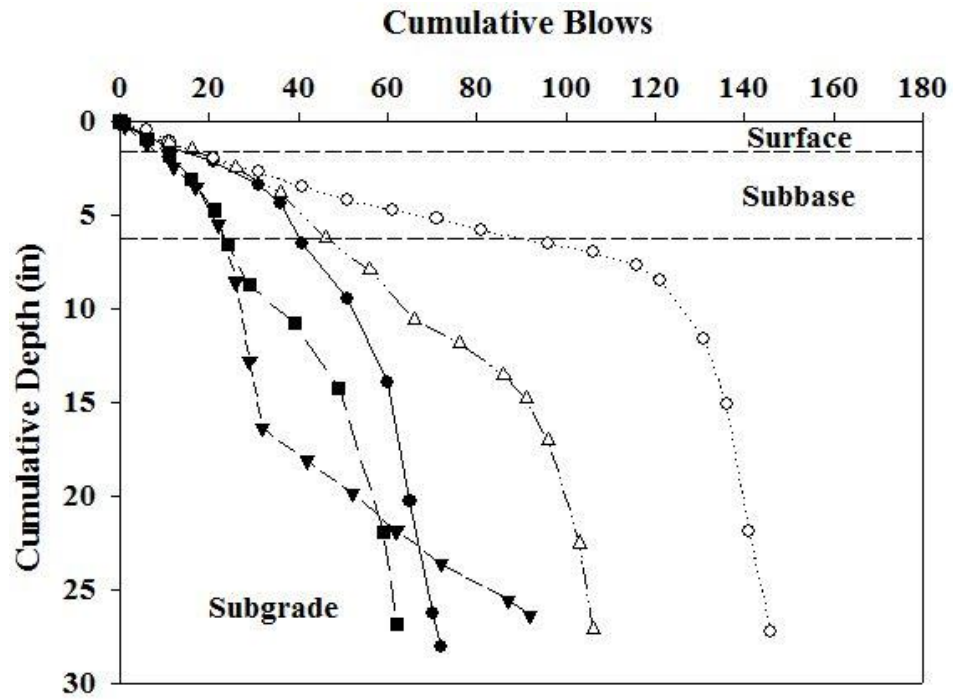
(a)
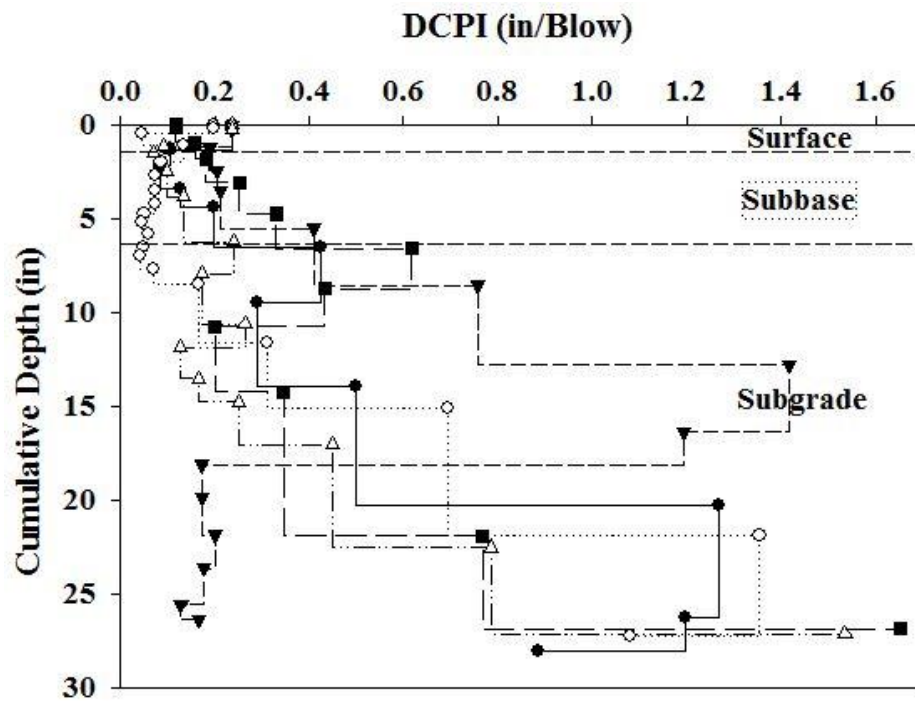
(b)
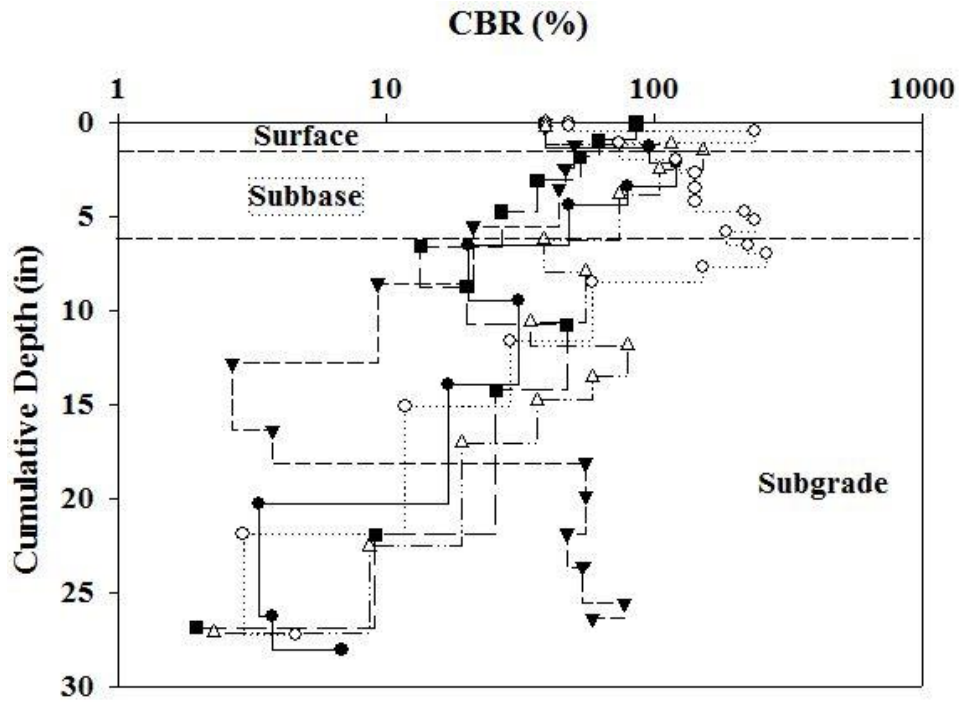
(c)

Figure C-9. Boone County Section 4 (Crescent): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020
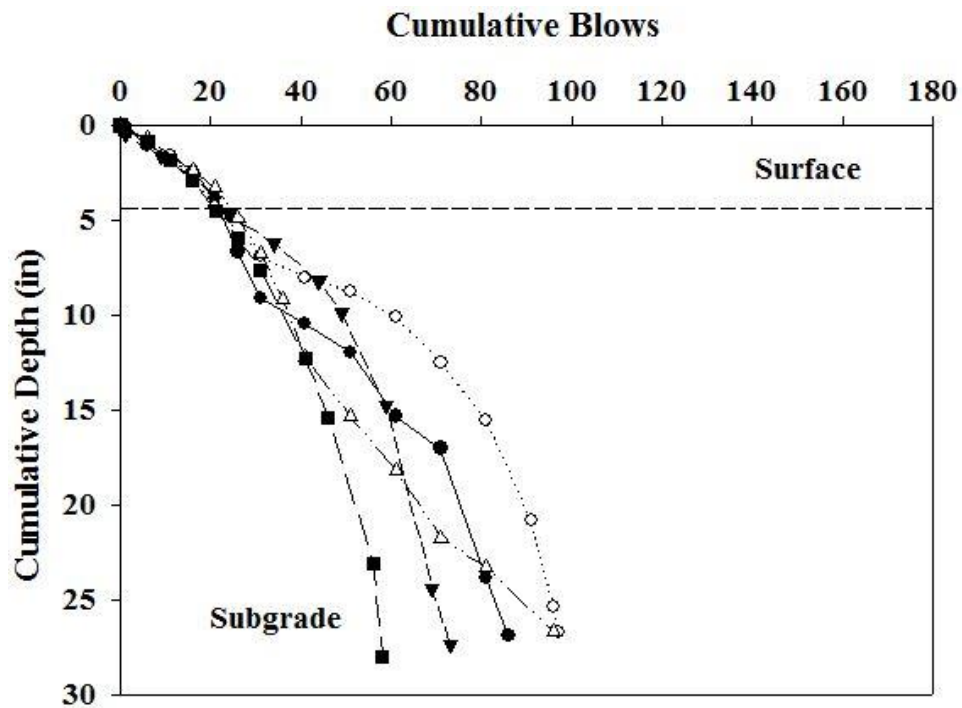
(a)
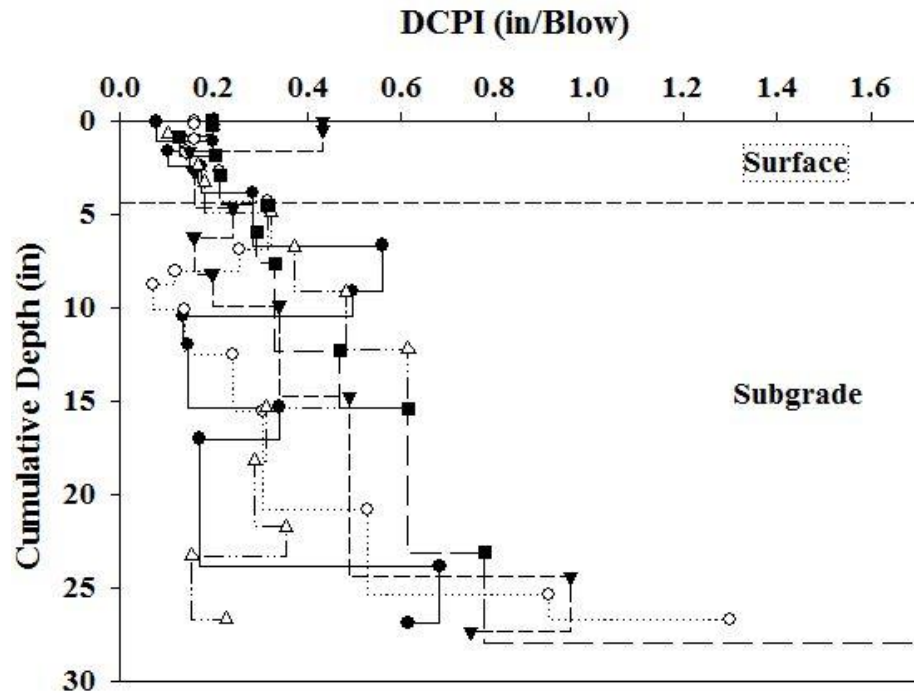
(b)
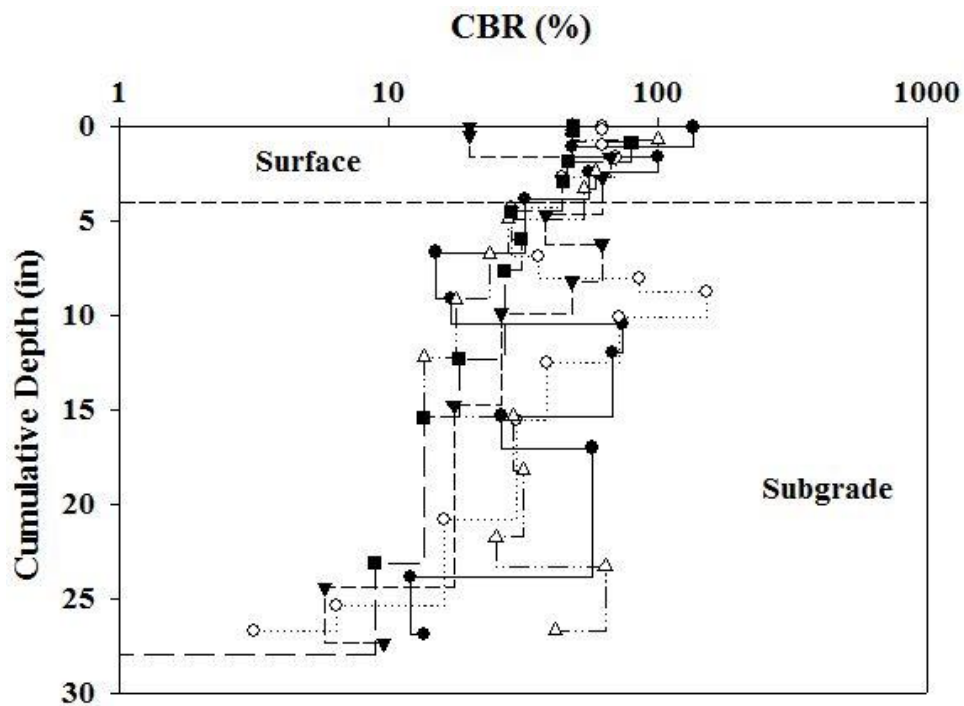
(c)

Figure C-10. Boone County Section 5 (Control): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020
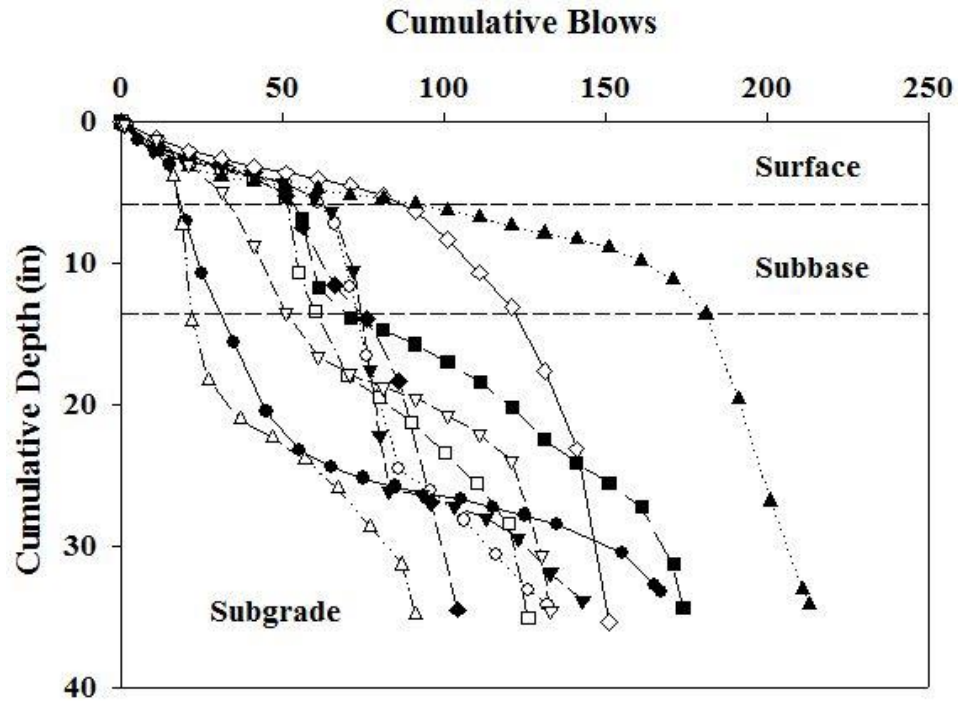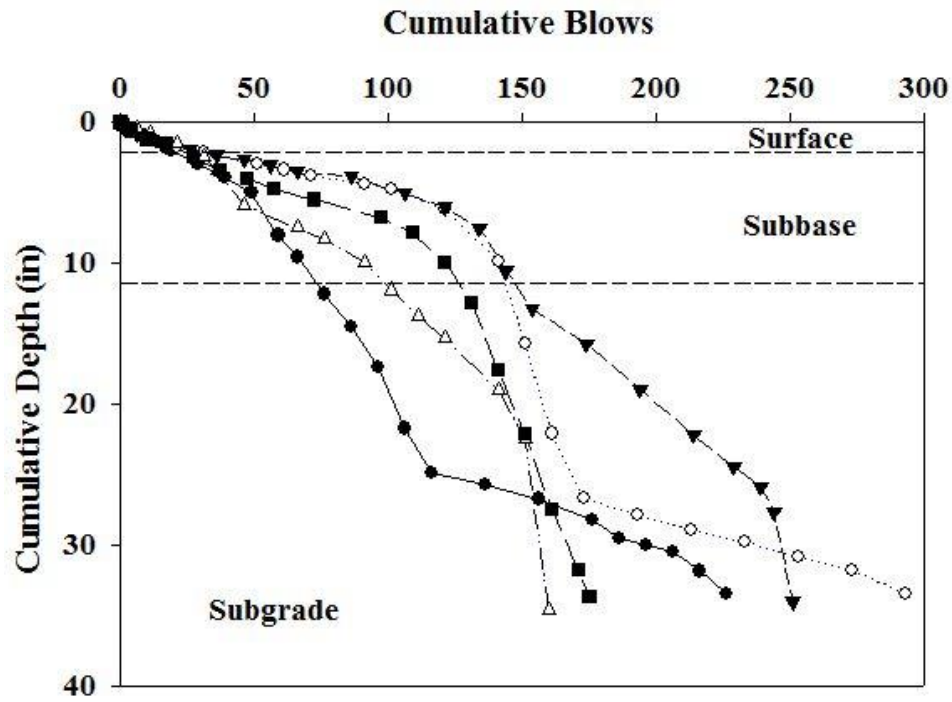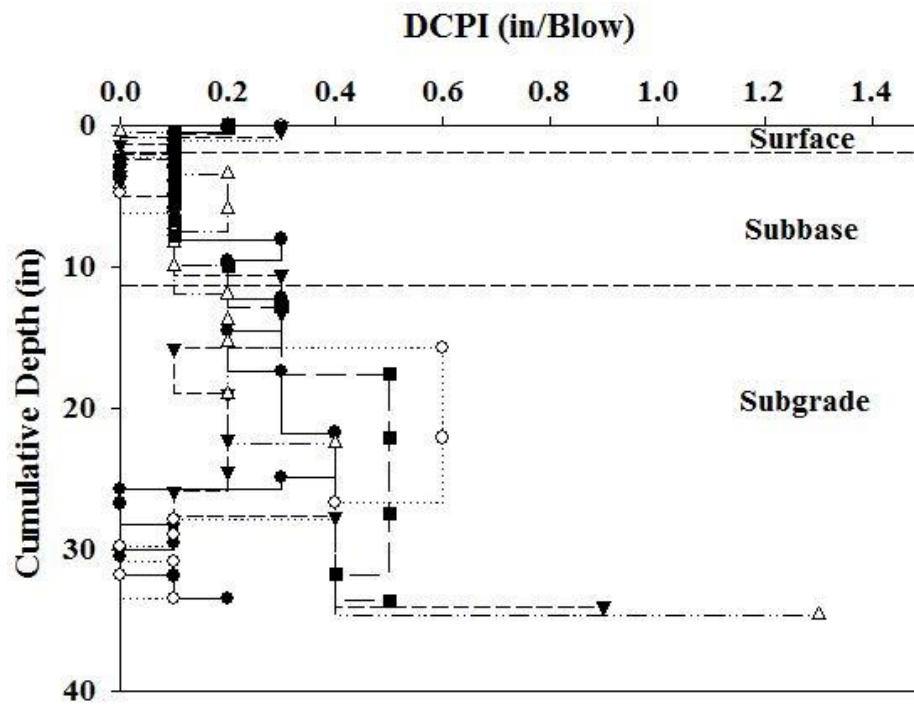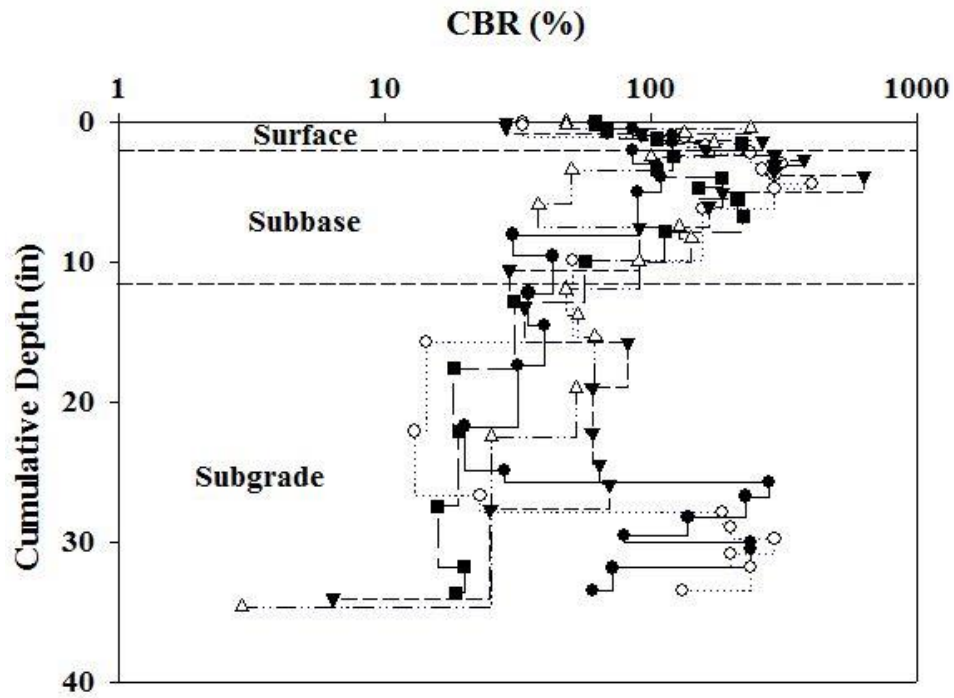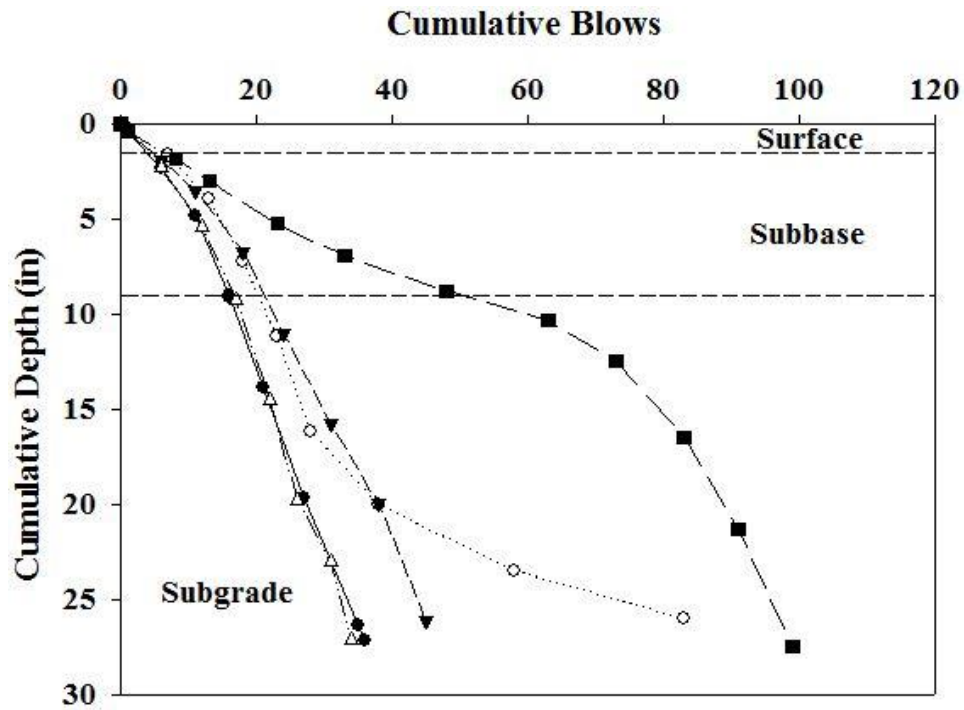
(a)
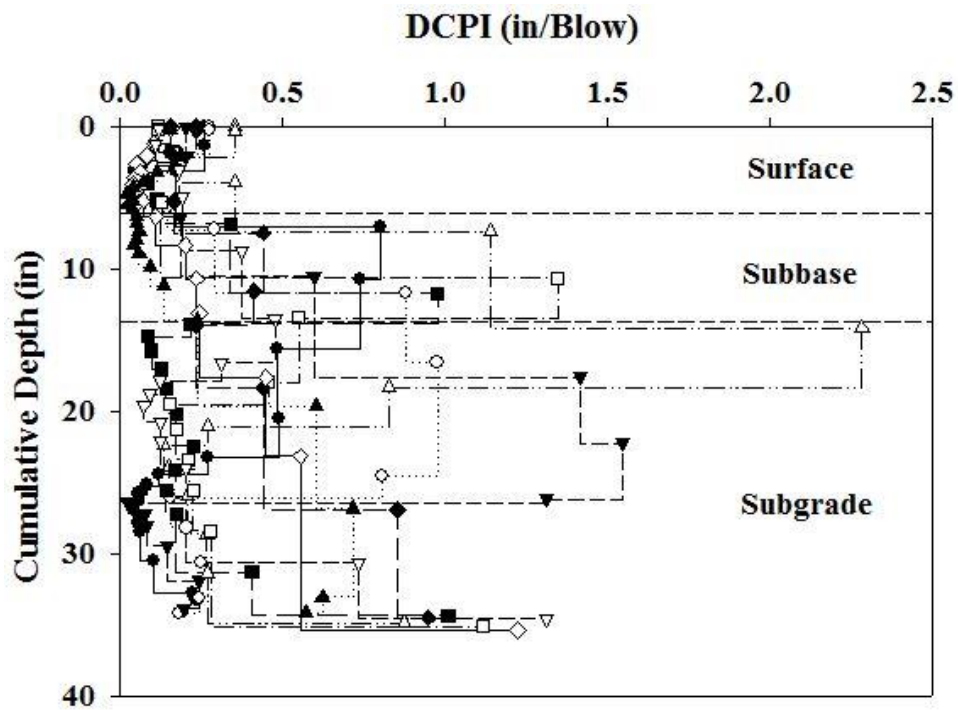
(b)
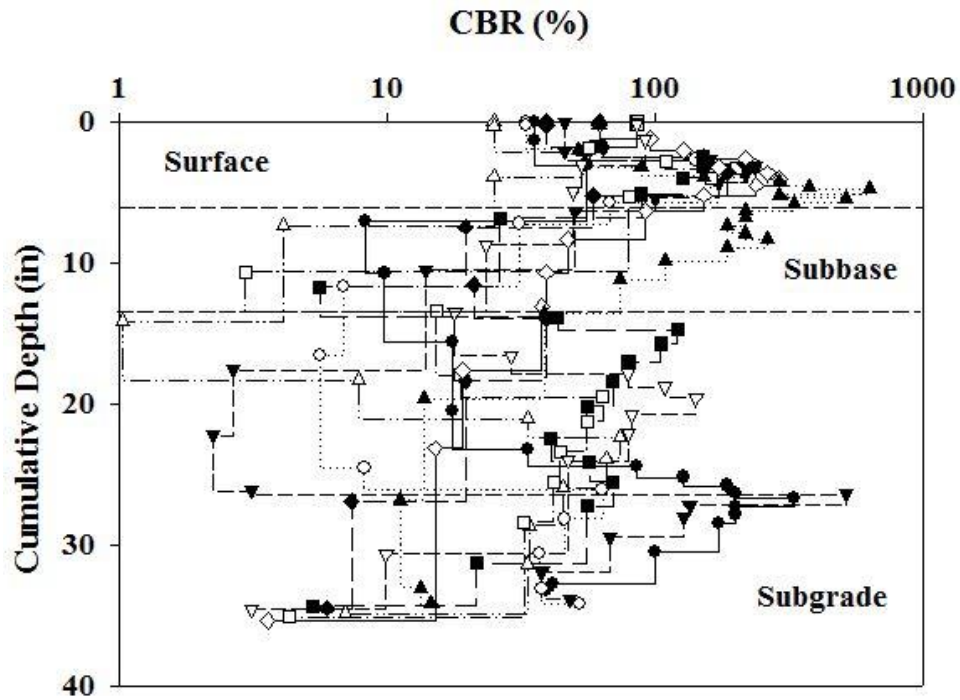
(c)

Figure C-11. Jones County Section 1 (Moscow): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019
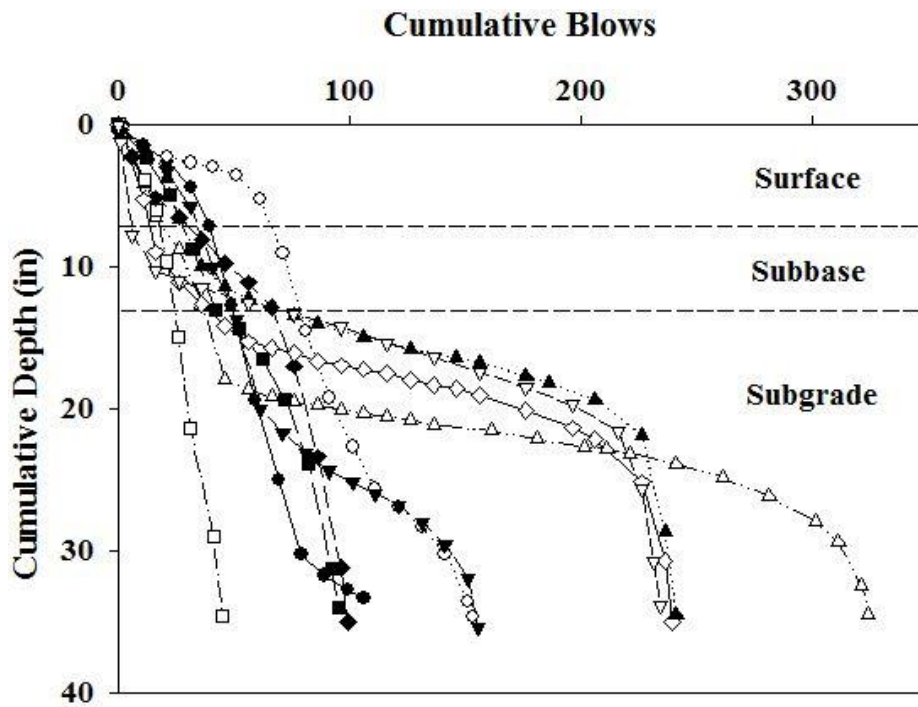
(a)

(b)

(c)

Figure C-12. Jones County Section 2 (Clay Slurry): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019

184

Cumulative Blows

(a)

DCPI (in/Blow)

(b)

185

CBR (%)

(c)

Figure C-13. Jones County Section 3 (Limestone): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019

Cumulative Blows

(a)

186

(b)

(c)

Figure C-14. Jones County Section 4 (Control): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in November 2019
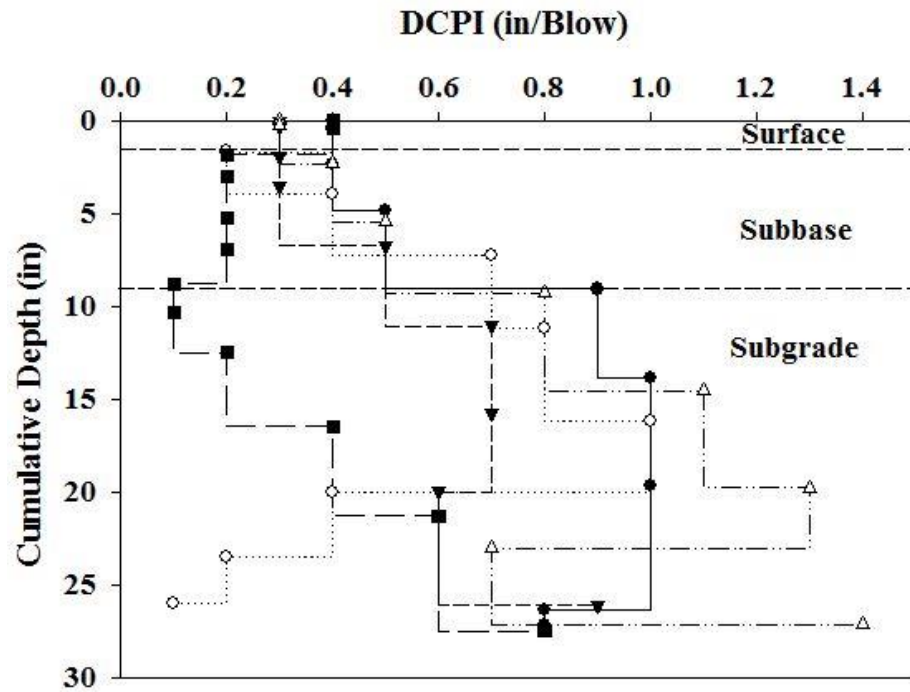
(a)

(b)
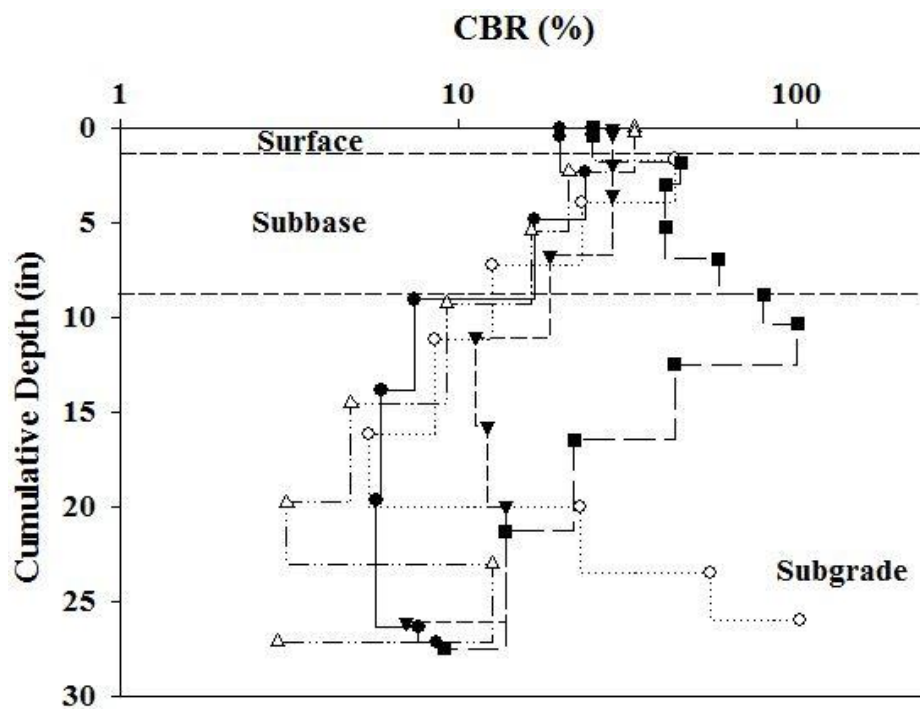
CBR (%)

(c)

Figure C-15. Jones County Section 1 (Moscow): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020
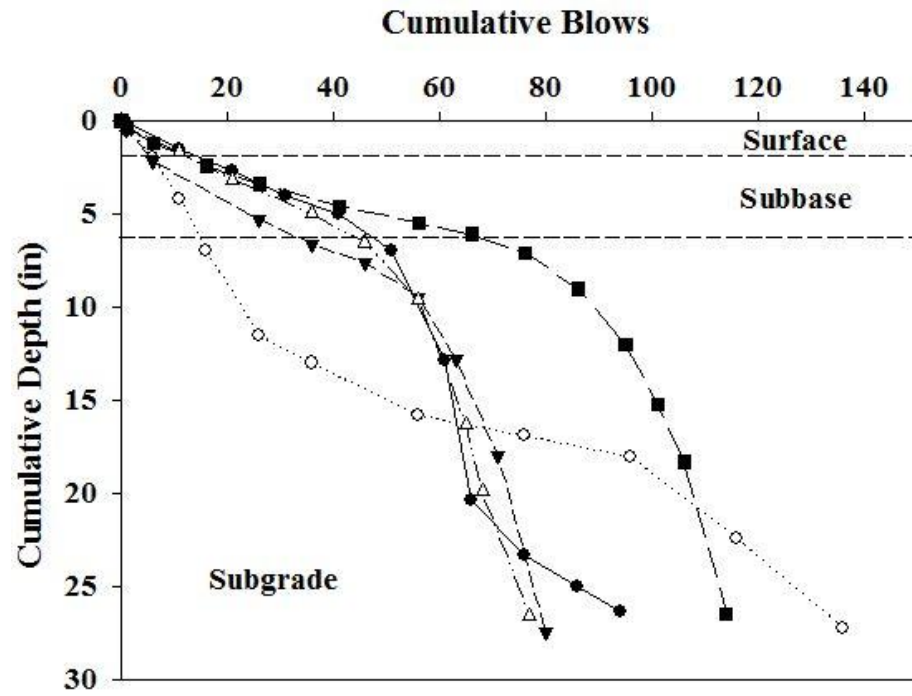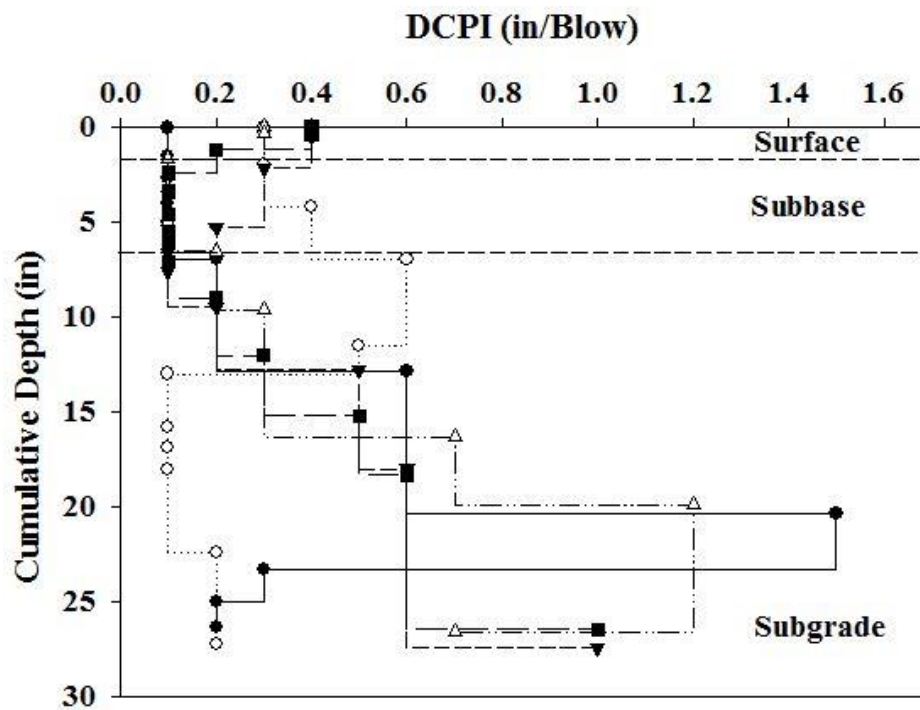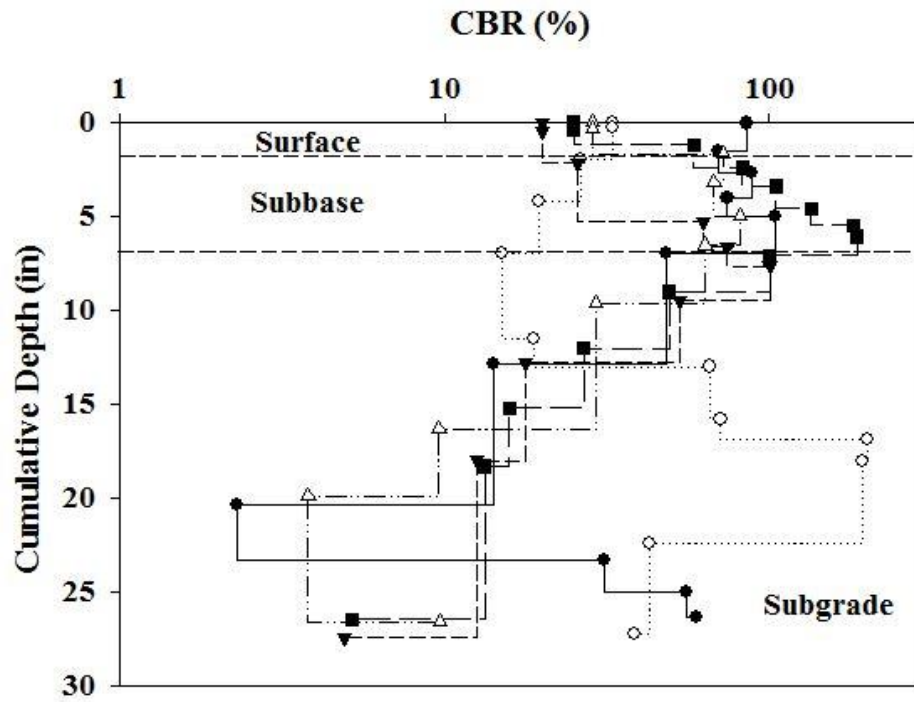

Cumulative Blows

(a)

(b)

(c)

Figure C-16. Jones County Section 2 (Clay Slurry): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020
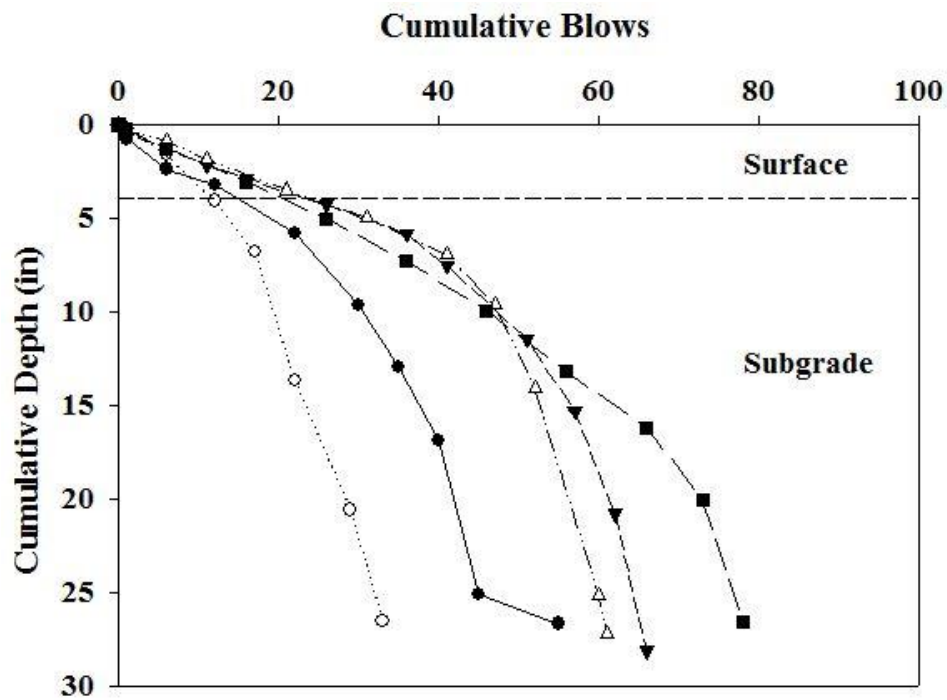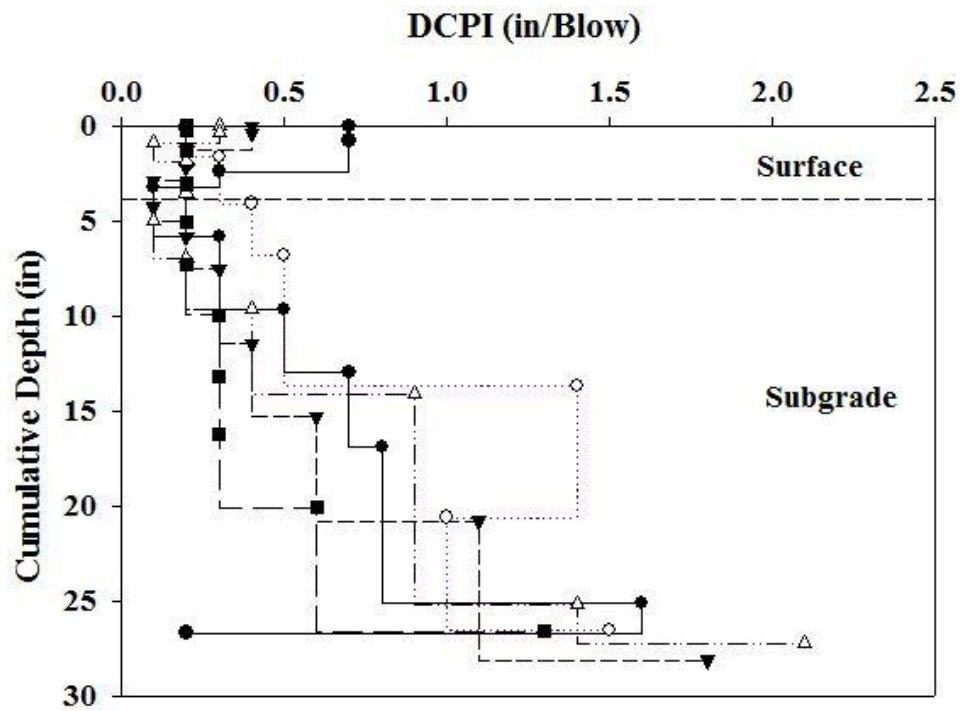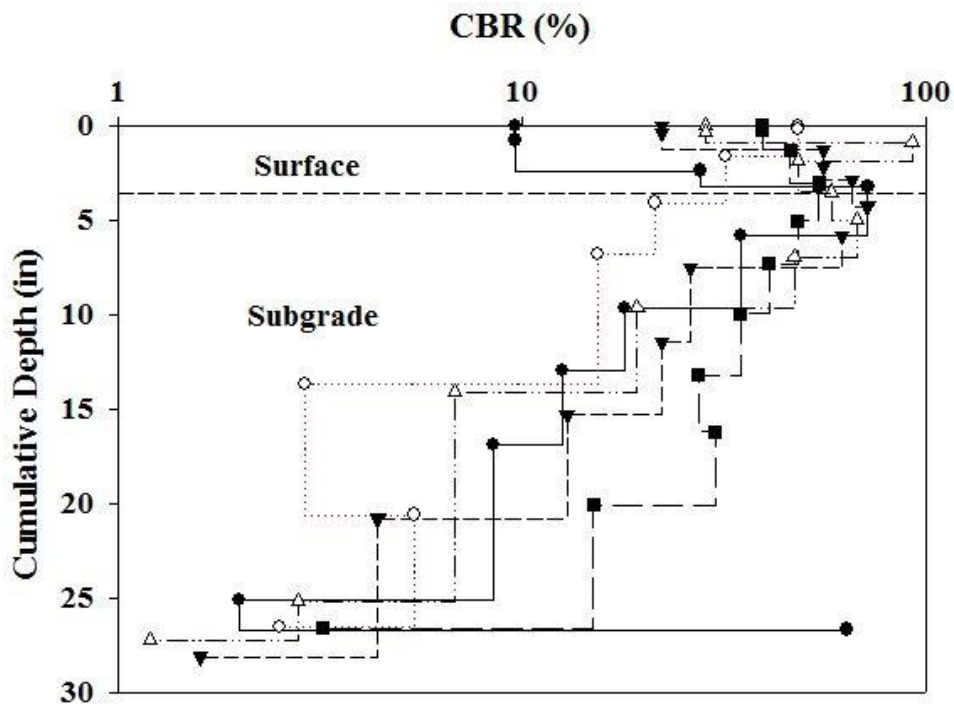
(a)

(b)

(c)

Figure C-17. Jones County Section 3 (Limestone): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020

(a)

(b)

(c)

Figure C-18. Jones County Section 4 (Control): (a) cumulative blows, (b) DCPI, and (c) DCP-CBR with depth in June 2020

193

APPENDIX D. SAMPLE 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

Figure D-1. BCR calculator spreadsheet

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