Evaluation of Roadway Subsurface Drainage on Rural Routes

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16. Abstract

Excess moisture has been identified as a cause for stripping, raveling, debonding, and rutting in flexible pavement [ODOT, 2016a]. The Ohio Department of Transportation (ODOT) has been getting substantially less than the expected 15 year service life after a resurfacing project, particularly on those routes without drainage. Providing drainage may help mitigate the premature failures ODOT is seeing on their rural routes. Section 205 of the 2016 Ohio DOT Pavement Design Manual (PDM) requires subsurface drainage on all new projects and recommends aggregate drains be used with bituminous surface treated and aggregate shoulders. Installing aggregate drains by contract during resurfacing has become costly for ODOT.

This project was completed in two phases. The first phase focused on current practices of drainage installation on rural routes and on identifying available equipment for use by county crews. Phase 2 included a field evaluation to evaluate cost effective options for drainage incorporating the findings and recommendations from Phase 1.

The Phase 1 evaluation identified aggregate drains as the appropriate drainage method and the rock saw as the most efficient equipment for aggregate drain installation. In Phase 2 aggregate drains were constructed by ODOT's Marion County personnel in forty test sections on State Route 529 using the rock saw and the backhoe. Drains were not installed in four sections which served as control sections, for a total of forty-four sections. Aggregate drains were installed using backfill meeting AASHTO #8, #57, and #4 gradations as well as a porous concrete backfill. Other factors evaluated included varied spacing between drains, trenches with and without fabric, compacted and un-compacted backfill, and narrow and wide trenches. Dynamic cone penetrometer testing was conducted before and after the monitoring period. The sections were monitored every four months for a one year period by testing with the falling weight deflectometer and measuring in-situ volumetric moisture.

Key Findings include:

- Total installation time, per drain, was reduced from an average of 32 minutes for the backhoe to 8 minutes for the rock saw.
- Field-measured moisture content and changes in base layer stiffness indicated water is moving from undrained areas to the drain, verifying aggregate drains aid in the removal of moisture from the pavement system.

Recommendations include:

- Data were collected for a one year period and only reflect short term changes, therefore monitoring of deflection and moisture measurements should be continued over an extended period of time.
- Aggregate drains be constructed with rock saw instead of the backhoe.
- Aggregate drains continue to be placed at the current specified spacing using the lowest cost backfill material.
- If compaction of the aggregate is desired, the width of the trench should match the width of the compaction equipment.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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EXECUTIVE SUMMARY

Many rural roads in Ohio were typically constructed 16 ft (4.9 m) to 20 ft (6.1 m) wide and have been widened over the years to meet current geometric standards. Where these widened sections were not properly drained, ODOT has been proactively installing aggregate drains (French drains) to extend the service life. The current process is time consuming and costly due to lack of productivity. The researchers evaluated equipment and materials which may provide improvements in productivity and drainage.

The goal of this project was to conduct a field evaluation of the equipment and installation techniques for subsurface drainage on local roads using aggregate drains. This project was completed in two phases. Specific objectives for each phase are listed below:

Phase 1

1. Conduct an in-depth analysis of ODOT's current method of addressing base saturation
2. Identify other equipment for constructing subsurface drainage for rural roads in Ohio
3. Compare the other equipment to the current ODOT equipment (the backhoe) and rank based on safety, training requirements, equipment cost, labor requirements, and production rates
4. Design an experiment to evaluate the effectiveness of aggregate drains constructed with varying parameters.

Phase 2

1. Evaluate effectiveness of aggregate drains for drains with varying installation parameters.
2. Evaluate the use of the best equipment option identified in Phase 1 relative to the backhoe method currently used in installation of aggregate drains.

The current ODOT procedure for constructing aggregate drains was reviewed in Phase 1. Five types of equipment were reviewed: backhoe/loader, trencher, horizontal directional drilling rig, rock saw, and vibratory plow. The equipment types were ranked based on safety, training, equipment cost, number of personnel needed to operate, and production rates. The most promising method, using a track loader with rock saw attachment, was identified and recommended for field evaluation in Phase 2. As a result, the rock saw was purchased for evaluation in Phase 2

Based on the findings in Phase 1, drains were constructed by ODOT on State Route 529 in Marion County in 2016. The project consisted of 44 test sections installed for the evaluation of equipment (rock saw and back hoe), compaction verses no compaction, backfill material (AASHTO #8, #57, #4, and cement treated permeable base), drain spacing (50 ft and 200 ft), and fabric wrap versus no fabric wrap. Subgrade and granular base stiffness and moisture were monitored for one year in the field using the dynamic cone penetrometer, falling weight deflectometer, and TDR moisture probes. Moisture content of the base and subgrade were measured in the laboratory using samples collected prior to installation and after one year.

Based on the results of the evaluation, the following conclusions were drawn.

Equipment Productivity and Cost Analysis:

- The average time of installation for the rock saw was only 8 minutes, or one-quarter the time needed for the backhoe.
    - Therefore, it is expected the rock saw will also reduce the time traffic is delayed during construction.
- A return on the investment of the rock saw would be achieved with the installation of at least 1,205 aggregate drains.

- Based on projected needs in one District 6 county, the use of the rock saw could reduce installation time by approximately 1936 work days, with a projected savings of approximately $458,000.

Effectiveness of Aggregate Drains:

- Field-measured moisture content at the drains was consistently higher than between the drains, indicating water is moving from undrained areas to the drains. Changes in layer stiffness relative to baseline values at the drains and in between tend to support this.
    - Movement of water from undrained areas to the drains serves to verify aggregate drains aid in the removal of moisture from the pavement system.
- Less than a third of the sections experienced a decrease in laboratory determined moisture content of the water-bound macadam base over the one year period. While more than two-thirds of the sections in the westbound direction experienced a decrease in laboratory determined moisture content in the subgrade.
- Although some trends were identified among the variables, no statistically significant relationships were found between the effectiveness of the drains and the spacing, the backfill material, usage of filter fabric, or usage of compaction based on layer stiffness determined from DCP testing.
- DCP, deflection, and moisture data were collected for a one year period and therefore, only reflect short term changes in performance.
- A potential long-term issue that should continue to be monitored is clogging of the drains with fines from the subgrade soil, where differences may not be evident after only one year.
- Compaction may be desirable to prevent settlement, however, findings for sections constructed with or without compaction were inconclusive.

The short-term data indicate a movement of water within the base to the aggregate drain outlets, indicating there are likely long term benefits. Therefore, the researchers have the following recommendations:

- No specific combination of factors could be identified as the most effective. Therefore, it is recommended the current specified spacing be used in combination with the lowest cost backfill material.
- Use the rock saw to install drains instead of the backhoe.
- It is recommended if compaction of the aggregate is desired, the width of the trench should match the width of the compaction equipment. A wider trench will make it difficult to achieve compaction.
- Previous research [Wolfe and Butalia, 2004] found moisture content in the soil stabilized two years after new construction. It is anticipated full benefits will be measurable at least two years after installation. Therefore it is recommended that deflection (FWD) and moisture (TDR) continue to be monitored on the test sections for an extended period of time (at least one additional year).
    - Collection of additional data over an extended period of time will better determine performance and allow for full stabilization of soil moisture content at the site, sufficient weather events, and enough sediment to see clogging.
    - Long-term monitoring for settlement of the patched areas is recommended to validate the effectiveness of compaction.

PROJECT BACKGROUND

Many rural roads in Ohio were constructed in the first half of the 20th century. These roads were typically narrow when constructed, i.e. 16 ft (4.9 m) to 20 ft (6.1 m) wide, but have been widened over the years to meet geometric standards. Rural routes have also been unintentionally widened during resurfacing as contractors pave slightly wider than the existing pavement width. These widened sections may be thinner than the existing pavement and/or may not be properly drained. Without proper drainage moisture can become trapped in the pavement structure.

Excess moisture has been identified as a cause for stripping, raveling, debonding, and rutting in flexible pavements and for pumping, faulting, cracking, and joint failure in rigid pavements [ODOT, 2016b]. Premature pavement failures such as rutting, wheel track cracking, edge cracking, and potholes have been observed on rural routes in Ohio. Ohio Department of Transportation (ODOT) has been getting substantially less than the expected 15 years of service life after a resurfacing project, particularly on those routes without drainage. Moreover, increasing traffic due to residential and commercial development has accelerated the development and growth of pavement distress, resulting in excessive demand for maintenance.

Providing drainage may help mitigate the premature failures ODOT is seeing on their rural routes. Section 205 of the ODOT Pavement Design Manual (PDM) [2016b] requires subsurface pavement drainage on all new or reconstructed pavement to reduce moisture in the base and subgrade. Types of drainage systems recommended for use include pipe underdrains, prefabricated edge underdrains, and aggregate drains. Pipe underdrains are typically used with paved shoulders and curbed pavement while aggregate drains are typically used with bituminous surface treated and aggregate shoulders. The prefabricated edge underdrains may be used for concrete pavements during resurfacing.

Typically, aggregate drains are constructed by contract for drainage on bridge replacement projects, to provide outlets for the granular base on two-lane routes, and to provide drainage for full-depth repairs, using the ODOT Construction and Materials Specifications Manual Item 605, Aggregate Drains. ODOT county garage crews are used to construct aggregate drains primarily to provide outlets for granular base on two-lane routes. Constructing drainage by contract during resurfacing has become costly for ODOT. While constructing aggregate drains in-house is a time consuming process. Therefore, there is a need to evaluate the cost effectiveness of current and available methods for installing of aggregate drains by ODOT's county crews. An analysis of available equipment that could reduce installation time, improve safety, and improve the process for country crews is also needed.

This project, initiated by ODOT, was completed in two phases. The first phase focused on current practices of subsurface drainage installation on rural routes, and identifying available equipment for use by county crews. Phase 2 included a field evaluation of aggregate drains to evaluate cost effective options for drainage incorporating the findings and recommendations from Phase 1.

RESEARCH CONTEXT

The goal of this project was to conduct a field evaluation of the equipment and installation techniques for subsurface drainage on local roads using aggregate drains. This project was completed in two phases. Specific objectives for each phase are listed below:

Phase 1

1. Conduct an in-depth analysis of ODOT's current method of addressing base saturation

2. Identify other equipment for constructing subsurface drainage for rural roads in Ohio
3. Compare the other equipment to the current ODOT equipment (the backhoe) and rank based on safety, training requirements, equipment cost, labor requirements, and production rates
4. Design an experiment to evaluate the effectiveness of aggregate drains constructed with varying parameters.

Phase 2

1. Construct an experiment comparing the current equipment (the backhoe) and the best equipment option identified in Phase 1.
2. Evaluate the use of the best equipment option identified in Phase 1 relative to the backhoe method currently used in installation of aggregate drains.

Moisture can enter the pavement system in a variety of ways: longitudinal seepage, rise and fall of the water table, infiltration through the pavement surface or construction joints, from the water table by capillary action, vapor movement from the water table, or lateral movement from the road shoulder and ditches [Queensland Department of Transport and Main Roads, 2013]. Typically, pavement drainage consists of a drainable layer to collect the moisture which is then removed either by daylighting the layer or installing an outlet.

Regardless of how moisture has entered the system, it has been found the removal of excess water from the pavement system can positively affect the performance of the pavement. Diefenderfer et al. [2005] concluded based on a limited field evaluation of drained and undrained sections in Virginia the drainage layer appeared to impact the in-situ structural number in a positive manner. Cedergren [1988] reviewed the effect of drainage on the performance of rigid and flexible test sections on the WASHO and AASHO Road Tests, concluding excess water was the prime factor in the failure of those test pavements.

Several factors have been found to be related to the effectiveness of pavement drainage systems. Generally, these include the characteristics and quality of the material chosen for the drainage layer, and a functioning outlet to allow water to escape the pavement system.

In the National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice 96 [Ridgeway, 1982] criteria to evaluate the effectiveness of a drainage layer were identified. While others identified aggregate base gradations which provide drainage and stability [Van Sambeek, 1989; FHWA, 1999; Randolph et al., 2000; and FHWA, 2002]. A study on the Ohio Strategic Highway Research Program (SHRP) test road found regardless of the permeability of the base layer, subgrade moisture content increases for several years after construction due to capillary action until it has reached complete saturation [Wolfe et al., 2010].

Finally, the importance of providing a positive outlet for the water in the base has been documented. Research conducted in Iowa [Ceylan et al., 2013] found many of the outlets were not effective due to damage, broken outlets, sediment, and tufa formation. They also reported that although blocked drainage did not result in observable distress in the pavement, shoulder drop off and cracking were observed near the blocked outlets [Ceylan, et al., 2013].

As noted, Section 205 of ODOT's PDM [2016b] identifies three methods for subsurface pavement drainage: pipe underdrains, prefabricated edge underdrains, and aggregate drains. Aggregate drains are constructed on rural, two-lane routes either by contract or by ODOT's county crews. While previous research has identified the ways moisture can enter the pavement, provided guidance on the selection of base type, and identified methods for outletting the base or drainage layer, little research has been done specific to aggregate drains.

Due to the increased need for aggregate drains, the time consuming process of installation, and the expense related to aggregate drains installed by contract, there is a need for research to specifically address cost effective procedures for aggregate drain installation by ODOT's county crews. To meet this need, a two-phase project was initiated with focus placed on aggregate drain installation by ODOT's county crews. Several tasks were identified for each phase to meet the objectives of this study, as presented below.

The specific tasks identified as part of Phase 1 are as follows:
Task 1: Review of Current ODOT Procedures
Task 2: Literature Search to Identify Alternative Methods for Providing Drainage to Rural Roads
Task 3: Evaluate Drainage Practices
Task 4: Prepare Final Report

An interim report was submitted at the end of Phase 1 for review by the technical advisory committee. Approval to proceed with Phase 2 was granted upon acceptance of the Phase 1 report. Based on the findings from Phase 1, the following tasks were included in Phase 2:
Task 1: Purchase Equipment for Field Evaluation
Task 2: Locate Test Sections and Perform Initial Evaluation
Task 3: Construct Aggregate Drains
Task 4: Field Monitoring
Task 5: Data Analysis
Task 6: Prepare Final Report

RESEARCH APPROACH

Phase 1

The primary focus of Phase 1 was to identify current practices within the state of Ohio and other available methods, and equipment being used for the installation that could be evaluated. As part of Phase 1, a literature search was conducted on the topic of pavement subsurface drainage. The full literature review is presented in Appendix A. Additionally, a review of all 50 state highway agencies specifications for subsurface drainage was conducted. Specifically, those agencies which had specifications for aggregate drains were identified. The associated specifications were summarized (in Appendix A) to identify other methods and requirements for aggregate drains.

Additionally, the current ODOT procedure for constructing aggregate drains was reviewed in Phase 1. As part of the review, the specification (Item 605) [ODOT, 2016a] and guidance described in ODOT's PDM [2016b] for aggregate drains were summarized and discussions were had with ODOT personnel in two counties that actively install aggregate drains. Details are provided in Appendix B. Through discussions with ODOT personnel, it was revealed the process includes sawing the pavement, trenching the pavement from the ditch, backfilling the trench with aggregate, and lastly, patching the pavement. Pictures of saw cutting the pavement and excavating the material during aggregate drain installation are shown in Figure 1. It was also found a backhoe is typically used for the majority of the process (digging the trench and backfilling with aggregate). However, the process is slow and using the backhoe to dig the trench can also result in the asphalt pavement being lifted up as the backhoe bucket pulls the pavement upward to excavate the trench, potentially damaging the asphalt pavement. Other disadvantages include the difficulty in maneuvering the backhoe while operating in the tight traffic control zone on two-lane routes, and due to the use of the backhoe, backfill material is not compacted and can settle at the edge of the pavement. One advantage was identified: the ODOT county garages currently installing aggregate drains have a backhoe and personnel trained on that equipment.

Figure 1. Backhoe Excavation.

Based on the disadvantages associated with the backhoe and the current procedure used for installing aggregate drains, various types of equipment for installing aggregate drains were identified and reviewed. Due to the lack of literature on aggregate drains, the type of equipment frequently used for the installation of pipelines and cable were reviewed to identify alternative equipment types for installation of aggregate drains. Five types of equipment were reviewed: backhoe/loader, trencher, horizontal directional drilling rig, rock saw, and vibratory plow. The equipment types were ranked based on safety, training, equipment cost, number of personnel needed to operate, and production rates, full details are presented in Appendix C. The most promising method, using a track loader with rock saw attachment, was identified and recommended for field evaluation in Phase 2.

To evaluate the current ODOT procedure for aggregate drain installation, the first step was to determine if aggregate drains are an effective method for draining the aggregate base. Therefore, a preliminary evaluation of aggregate drains was conducted in Phase 1. As part of this preliminary evaluation, two sites with similar pavement material type and buildup were selected. The first site, the westbound direction of route 95 in Marion County (MAR-95), had aggregate drains installed at an earlier date, while the second site, eastbound of route 529 in the same county (MAR-529), did not have aggregate drains installed. Moisture and stiffness in the granular base and subgrade were measured at both sites. Layer stiffness, represented by resilient modulus (M_R), was estimated from dynamic cone penetrometer (DCP) test results for each the granular base and subgrade. DCP testing was conducted in four locations in the wheelpath on the drained pavement (MAR-95) and in six locations (four in the wheelpath and two at the edge of pavement) on the undrained pavement (MAR-529). Granular base material was sampled from each test location after the completion of DCP testing to determine the gravimetric moisture content. The preliminary evaluation showed the site with drains had greater resilient modulus in the granular base material than the site without drains. Moisture is detrimental to the granular material and can result in a loss of stiffness, therefore greater stiffness at the drained site relative to the undrained site may indicate the aggregate drains are effectively removing excess moisture from the pavement, giving cause to conduct further evaluation of aggregate drains. Full details on the preliminary evaluation are presented in Appendix D, while conclusions and recommendations from Phase 1 are presented in Appendix E.

Phase 2

Based on the findings in Phase 1, an experimental plan was developed to construct aggregate drains in Phase 2 by varying a range of factors. As part of the plan, the effectiveness of the variations of aggregate drains were evaluated by conducting field testing prior to construction, periodically over a one-year monitoring period and at the conclusion of the monitoring period. Specifically, changes in layer stiffness of the granular base and subgrade as well as measured moisture in the granular base were investigated.

The plan was aimed at first evaluating the production rate and cost associated with using equipment other than the traditionally used backhoe, to determine the most cost effective equipment for the installation procedure. As a result of the review of applicable equipment in Phase 1, the rock saw was purchased by ODOT for evaluation in Phase 2. The experimental plan also incorporated some of the variations in procedure and materials identified in the review of current ODOT procedures and other state highway agencies' specifications. The following variables were included:

- Gradation: Aggregate meeting American Association of State Highway Transportation Officials (AASHTO) gradations No. 8, No. 57, and No. 4, and porous concrete
- Compaction and no compaction of aggregate or porous concrete
- Fabric wrap and no fabric wrap with aggregate or porous concrete
- Drain spacing: 50 ft (15 m) and 200 ft (61 m)
- Trench width: 8 in (20 cm) and 15 in (38 cm)
- Equipment: Rock saw and backhoe

As indicated in the CMS manual, materials for aggregate drains are to consist of granular material meeting AASHTO gradation "No. 8, 9, or 89 size air-cooled blast furnace slag, limestone, or gravel." However, it was found in Phase 1 of this study, the material commonly identified in the plans was gravel meeting AASHTO No. 57 gradation, although aggregate meeting the No. 8 gradation has been used by Marion County ODOT crews. Therefore, AASHTO No. 57 material was investigated and used most frequently to be consistent with current practice, and to provide a baseline for comparisons with the other variables of interest. Based on the literature review and review of the existing specifications conducted in Phase 1, granular materials with gradations meeting AASHTO No. 8, and No. 4 as well as porous concrete were also investigated.

The current ODOT procedure for aggregate drain installation which primarily utilizes a backhoe does not include compaction of the backfill material. However, it was found in the review of state specifications that compaction is often required in other states. Therefore, both, compaction and no compaction of the backfill material was investigated.

Although fabric is not typically used in the construction of aggregate drains in Ohio, the review of state specifications in Phase 1 revealed several other states require backfill material be wrapped with fabric. Therefore, drains constructed with and without fabric wrap were investigated. Details on the fabric selected are provided in Appendix I.

Aggregate drains installed to provide an outlet for the base are typically spaced at 50 ft (15.2 m) and staggered, to provide a drain on one side of the road every 25 ft (7.6 m), which are consistent with the spacing described in ODOT's PDM [2016b]. Due to the reported low production rate, a longer interval was also investigated to determine if it was as effective as the current spacing. Therefore, drain spacing of 50 feet (15 m) and 200 feet (61 m) were investigated.

The width of the trench is typically dictated by the equipment used to excavate the trench. Due to the size of the bucket on the backhoe, following current ODOT procedures aggregate drains are constructed at a width of approximately 15 inches (38 cm). Excavation with the rock saw, as shown in Figure 2, produces trench widths of approximately 8 inches (20 cm).

Figure 2. Rock Saw Excavation.

Aggregate drains were constructed primarily with a rock saw. Aggregate drains were also constructed with a T4 Bobcat E85 Compact Excavator (referred to as backhoe in this report). The equipment used to construct the "rock saw" sections was a T4 Bobcat Compact Track Loader with rubber tracks, upgraded with high flow hydraulics and a WS 24 wheel saw. A trench compactor accessory with an 8 in (20 cm) wide pad kit, was also purchased to compact trench backfill material.

Experimental matrices were developed to incorporate all of the above variables, shown in Tables 1 through 3 by backfill material. It was not practical to construct aggregate drains representing every permutation of these variables, nor was it necessary to evaluate the impact of each variable. Therefore, experimental matrices were reduced appropriately, full details are provided in the methodology for Phase 2, presented in Appendix F.

Table 1. Experimental Matrix for Aggregate Drains Constructed with No. 57 Aggregate (50 ft = 15 m, 200 ft = 61 m; 8 in = 20 cm, 15 in = 38 cm).

AASHTO Gradation	#57											
Fabric Wrap	Y											
Compaction	Y						N					
Drain Spacing (ft)	50			200			50			200		
Trench Width (in)	8	15	15	8	15	15	8	15	15	8	15	15
Equipment	R	B	R	R	B	R	R	B	R	R	B	R
Section Number	3	5	28	31	27	36	35	6	17	32	7	13
AASHTO Gradation	#57											
Fabric Wrap	N											
Compaction	Y						N					
Drain Spacing (ft)	50			200			50			200		
Trench Width (in)	8	15	15	8	15	15	8	15	15	8	15	15
Equipment*	R	B	R	R	B	R	R	B	R	R	B	R
Section Number	2	19	39	22	29	16	11	8	42	38	41	23

*R: Rock Saw; B: Backhoe

Table 2. Experimental Matrix for Aggregate Drains Constructed with No. 4 or No. 8 Aggregate (50 ft = 15 m, 200 ft = 61 m; 8 in = 20 cm, 15 in = 38 cm).

AASHTO Gradation	#8						#4					
Fabric Wrap	Y		N				Y		N			
Compaction	Y	N	Y		N		Y	N	Y		N	
Drain Spacing (ft)	50	50	50	200	50	200	50	50	50	200	50	200
Trench Width (in)	8	8	8	8	8	8	8	8	8	8	8	8
Equipment*	R	R	R	R	R	R	R	R	R	R	R	R
Section Number	30	40	34	12	24	25	43	15	20	1	26	44

*R: Rock Saw

Table 3. Experimental Matrix for Aggregate Drains Constructed with Porous Concrete (50 ft = 15 m, 200 ft = 61 m; 8 in = 20 cm, 15 in = 38 cm).

Material	Porous Concrete			
Fabric Wrap	Y		N	
Compaction	Y	N	Y	N
Drain Spacing (ft)	50	50	50	50
Trench Width (in)	8	8	8	8
Equipment*	R	R	R	R
Section Number	9	33	18	14

*R: Rock Saw

A segment of approximately 4.6 miles (7.4 km) on Ohio State Route 529 (MAR-529) beginning at the Mautz-Yeager intersection and running east to the Marion/Morrow County line was selected as the site for this project by ODOT and ORITE personnel. This stretch of asphalt pavement is located in a rural area east of the Marion city limits. The ODOT straight line diagram for this portion of MAR-529 indicates the pavement has a width of 18 ft. Additionally, it shows the base under the westbound lane is water-bound macadam while the base under the eastbound lane consists of water-bound macadam beginning the centerline of the pavement and extending 3 ft into the eastbound lane. For the remaining width of the eastbound lane (approximately 6 ft (2.4 m) wide) the base is shown as specification Item 304 or traffic compacted aggregate base. It is believed this is due to the pavement being widened at a later date. The asphalt pavement varied in thickness from 10 inches (254 mm) to 14 inches (355 mm).

Prior to construction of the aggregate drains, an initial evaluation was conducted to identify areas with similar structural conditions. To do so, falling weight deflectometer (FWD) testing was conducted in the eastbound lane every 50 ft (15 m). A statistical method was applied to then identify areas of the pavement which had similar subgrade responses to the impact load applied during FWD testing. These areas were selected for investigation and test sections were identified. A total of 44 test sections were assigned, such that 4 sections were left completely undrained to serve as control sections, and for the remaining 40 sections, aggregate drains were constructed following the matrices presented in Tables 1 through 3. Full details on the layout of the test sections are presented in Appendix F and J.

Aggregate drains were constructed in April and May of 2016. During construction the processes used based on the different variables applied were observed and recorded. The number of personnel and equipment required for each of the five operations (excavation, placing and wrapping fabric, backfill material, compacting material, and patching) were recorded. The durations to complete each operation were also recorded except the time to complete patching since it is independent of the process and equipment used for constructing the aggregate drain itself. Details on the processes used, personnel and equipment demands are provided in Appendix F. Recorded durations to complete each operation are presented in Appendix O. This information was collected to evaluate productivity and costs associated with the two types of equipment (backhoe and rock saw) used, allowing for a cost saving analysis to be conducted, as discussed in Appendix G.

To evaluate the effectiveness of the aggregate drains, two primary parameters were evaluated: stiffness of the granular base and subgrade, and measured moisture content. Resilient modulus, as an estimate of layer stiffness, was determined from DCP testing and FWD testing. Moisture was evaluated based on gravimetric moisture content of sampled granular base and subgrade material, as well as in-situ moisture measured with time domain reflectometer (TDR) probes.

DCP testing was conducted in the westbound direction of MAR-529 in the middle of each section prior to the installation of the aggregate drains to serve as a baseline for comparisons with DCP results from testing conducted at the conclusion of the one-year monitoring period. DCP test results were used to calculate resilient modules for each, the granular base and subgrade. FWD testing was conducted periodically over the one-year monitoring period. FWD testing was conducted in both lanes at six locations (three at the aggregate drain locations, and three midway between aggregate drains) within each experimental section, to determine if any differences in the structural conditions were evident in the immediate vicinity of the aggregate drains and in the areas in between drains. FWD testing was conducted in the control sections at six locations using the same spacing used for the experimental sections. Backcalculation was performed on the FWD test results to determine the resilient modulus for each pavement layer.

Immediately after DCP testing was conducted the granular base material and subgrade were sampled in each section for which gravimetric moisture content was determined in the laboratory for each material. This was done to determine if, over the one-year period, any notable changes in moisture resulted from the installation of the various aggregate drains. In the eastbound lane time domain reflectometer (TDR) probes were installed during construction in selected sections, including two undrained control sections. The TDR probes enabled measurements of the in-situ moisture content within the aggregate drains and in between the aggregate drains.

RESEARCH FINDINGS AND CONCLUSIONS

This study was aimed at identifying alternative equipment for improving production and cost effectiveness of aggregate drain installation by ODOT country crews. Additionally, numerous factors were varied in aggregate drain construction to evaluate the effectiveness and provide recommendations on improving the current procedure for aggregate drain installation. Based on the results detailed in Appendix G, the following conclusions were drawn. More detailed conclusions are presented in Appendix H.

Equipment Productivity and Cost Analysis:

- There is a significant difference in excavation time between the two pieces of equipment. Total time to complete the aggregate drain installation was also statistically different, the rock saw took an average of slightly less than 8 minutes and the backhoe took slightly more than 32 minutes to complete, on average.
    - It is anticipated that the reduction in installation time associated with the rock saw will also reduce the time traffic is delayed during construction.
- To recover costs of the rock saw, at least 1,205 aggregate drains would be needed for a return on the investment. If this work load is met, the rock saw is more economical than the backhoe for aggregate drain installation.
- Based on projected needs in one District 6 county, the use of the rock saw could reduce installation time by approximately 1936 work days, with a projected savings of approximately $458,000.

Effectiveness of Aggregate Drains:

- Field-measured moisture content at the drains was consistently higher than between the drains, indicating the water is moving from undrained areas to the drain. Generally, a greater increase in layer stiffness (determined by FWD testing) relative to baseline measurements was found between drains than at the drains. This supports the notion that water is moving towards the drains.
    - Movement of water from undrained areas to the drains serves to verify aggregate drains aid in the removal of moisture from the pavement system.
- Less than a third of the sections experienced a decrease in laboratory determined moisture content of the water-bound macadam base over the one year period. While more than two-thirds of the sections in the westbound direction experienced a decrease in laboratory determined moisture content in the subgrade.
- Some trends were identified among the variables considered as described herein. However, there were no statistically significant relationships found between the effectiveness of the drains and the spacing, the backfill material, usage of filter fabric, or usage of compaction based on layer stiffness determined from DCP testing.
- DCP, deflection, and moisture data were collected for a one year period. Thus, data collected only reflect short term changes in performance, giving a limited picture of the effects of the installation of drains on moisture content and material properties.
- A potential long-term issue in comparing the different installation conditions is clogging of the drains, where differences may not be evident after only one year.

- Compaction may be desirable to prevent settlement, however, findings for sections constructed with or without compaction were inconclusive.

RECOMMENDATIONS FOR IMPLEMENTATION OF RESEARCH FINDINGS

The short-term data indicate a movement of water within the base to the aggregate drain outlets, indicating there are likely long term benefits. Therefore, the researchers have the following recommendations:

- No specific combination of factors could be identified as the most effective. Therefore, it is recommended the current specified spacing be used in combination with the lowest cost backfill material.
- Use the rock saw to install drains instead of the backhoe.
- It is recommended if compaction of the aggregate is desired, the width of the trench should match the width of the compaction equipment. A wider trench will make it difficult to achieve compaction.
- Only short-term changes were captured in the one-year monitoring period. Previous research [Wolfe and Butalia, 2004] found moisture content in the soil stabilized two years after new construction. It is anticipated full benefits will be measurable at least two years after installation. Therefore it is recommended that deflection (FWD) and moisture (TDR) continue to be monitored on the test sections for an extended period of time (at least one additional year).
    - Collection of additional data over an extended period of time will better determine performance and allow for full stabilization of soil moisture content at the site, sufficient weather events, and enough sediment to see clogging.
    - Long-term monitoring for settlement of the patched areas is recommended to validate the effectiveness of compaction.

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APPENDIX A LITERATURE REVIEW (PHASE 1)

The topic of pavement subsurface drainage has been widely researched. A search of "pavement subsurface drainage" in TRIS produced 532 hits. A similar search in Google produced 154,000 hits. A brief review of some of the more relevant reports is presented below.

Ways by which the moisture can enter the pavement system include [Queensland Department of Transport and Main Roads, 2013]:

- Longitudinal seepage
- Rise and fall of the water table
- Infiltration through the pavement surface or construction joints
- Capillary action from the water table
- Vapor movement from the water table
- Lateral movement from the road shoulder and ditches

A drainable layer is typically constructed under the pavement to collect water which infiltrates through the surface or seeps in from the road shoulder or ditch. Outlets are installed or the layer is daylighted to remove the collected water.

The improvement in performance which can be realized from draining a pavement has been well documented. The second report published by the Ohio State Highway Department (now the ODOT) investigated the premature pumping distress in concrete pavements [Ohio State Highway Department and Portland Cement Association, 1951]. The research found subgrade or subbase layers will not pump if sand and gravel content exceeds 55% by weight, the soil is fairly well graded, and PI is 6 or less.

Diefenderfer et al. [2005] documented the effect of moisture on the performance of flexible pavement in Virginia. Cedergren [1988] reviewed the effect of drainage on the performance of rigid and flexible test sections on the WASHO and AASHO Road Tests. Chatti et al. [2005], Harrigan [2002], and Hall et al. [2003, 2007] documented the effect of drainage on the performance of rigid and flexible pavements constructed for the Strategic Highway Research Program (SHRP) SPS-1 and SPS-2 experiments.

The quality of drainage needed has also been documented. In the National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice 96 [Ridgeway, 1982] two criteria were identified to evaluate the effectiveness of a drainage layer: the time to drain from complete saturation down to a specified percentage level of saturation, and the drainage layer should be capable of draining water at a rate equal to or greater than the inflow rate without becoming completely saturated. Guidelines for the former criteria have been recommended by AASHTO, shown in Table 4 and ERES consultants, shown in Table 5 [FHWA, 1999].

Table 4. AASHTO Guidelines for Quality of Drainage [FHWA, 1999].

Quality of Drainage	Time to Drain from 100% to 50% saturation
Excellent	2 hours
Good	1 day
Fair	7 days
Poor	1 month
Very Poor	Does not drain

Table 5. ERES Consultants Guidelines for Quality of Drainage [FHWA, 1999].

Quality of Drainage	Time to Drain from 100% to 85% saturation
Excellent	Less than 2 hours
Good	2 to 5 hours
Fair	5 to 10 hours
Poor	Greater than 10 hours
Very Poor	Much greater than 10 hours

The characteristics of drainage layers in Ohio and nationally have been researched and documented [Van Sambeek, 1989; FHWA, 1999; Randolph et al., 2000; and FHWA, 2002]. These reports identify aggregate base gradations which provide drainage and stability.

While the time to drain a base is important, the effect of water table and capillary action cannot be ignored. Wolfe et al. [2010] monitored moisture in the subgrade directly under granular and high permeability drainable bases on the Ohio/SHRP Test road and various sections throughout Ohio and found the average moisture content increases for several years after construction, with seasonal fluctuations, until the subgrade became fully saturated (i.e. positive pore pressures were measured), regardless of the permeability of the base layer. Sargand, Wu, and Figueroa [2005, 2006] demonstrated the importance of understanding the stiffness of the underlying subgrade when selecting a base for a flexible pavement.

Finally, the importance of providing a positive outlet for the water in the base has been documented. Ceylan et al. [2013] evaluated the drainage system in Iowa. They found many of the outlets were not effective due to damage, broken outlets, sediment, and tufa formation. They also found the blocked drainage did not result in observable distress in the pavement, but shoulder drop off and cracking were observed near the blocked outlets [Ceylan, et al., 2013].

In summary, current research identifies the causes of moisture in the pavement and provides guidance on the selection of base type and characteristics, and methods of outletting the base. However, no research addressing cost effective procedures for providing drainage for widened pavement using aggregate drains was identified.

Review of State Specifications

The specifications for all 50 states were reviewed. Including Ohio, 17 states have developed specifications for aggregate drains. The most common maximum aggregate sizes specified are 1.5 in (38 mm) for 11 of the 17 states, 0.75 in (19 mm) for 9 of the 17 states, and 0.375 in (9.5 mm) for 8 of the 17 states. State specifications typically require compaction of the aggregate backfill as well as of the underlying soil. These specifications are summarized in Table 6.

Table 6. Summary of Specifications for Gradations of Aggregate used for Drainage.

Sieve	English units	3"	2"	1.5"	1"	3/4"	1/2"	3/8"	#4	#8	#10	#16	#30	#50	#100	#200
Size	(mm)	76	51	38	25	19	12.7	9.5	4.75	2.36	2.0	1.18	0.6	0.3	0.15	0.075
State	**Item #**	**Percent Passing sieve size above (%)**														
AL***	605			100	80-100	70-100	25-80		0-15	0-10						>1
CO*	605.05 (A)	100				20-90			0-20							0-3
	605.05 (B)			100					20-60			10-30		0-10		0-3
	605.05 (C)					100			60-100					10-30	0-10	0 - 3
DE	717 (Del 8)						100	85-100							10-30	
FL**	443		100	90-100	20-55	0-15		0-5								>3
	446 Draincrete			100	95-100		25-60		0-10	0-5						>3
IL	601.06 (FA 1)							100	94-100			45-85		3-29	0-10	
	601.06 (FA 2)							100	94-100			45-85		10-30	0-10	
	601.06 (FA 20)							100	94-100	60-100		35-65		10-30	3-17	0-8
	601.06 (CA 18)	100			90-100				50-100			30-80		0-20		0-4
IA	2502 (#29)					100	95-100	50-100	0-50	0-8						
KY*	704.03.01			100					0-30						0-5	>5
MD*	306.03.08 (57)			100	95-100		25-60		0-10	0-5						
MO***	605.3.3 (Gr. 3-A)		100	95-100		35-70		10-30	0-5							
	605.3.3 (Gr. 3-B)			100	95-100		25-60		0-8							
	605.3.3 (Gr. 3-D)				100	90-100		15-45	0-8							
	605.3.3 (Gr. 3-E)					100	80-100	40-70	0-10	0-4						
	605.3.3 (Gr. 4-A)			100	95-100		25-60		0-10	0-5						
	605.3.3 (Gr. 4-B)				100	90-100		20-55	0-10	0-5						
NM***	605 (Type I)				100	80-100			30-60		20-45					3-10
	606 (Type II)				100	85-95			40-70		30-55					6-15
NC*	815 (2S)							100	95-100	80-100		45-95	25-75	5-30	0-10	0-3
	815 (2MS)							100	95-100	80-100		45-95	25-75	5-35	0-20	0-8
	815 (78M)					100	98-100		20-45	0-15						
OH*	605.07 (8's)						100	85-100	10-30	0-10		0-5				
	605.07 (89's)						100	90-100	20-55	5-30		0-10		0-5		
	605.07 (9's)							100	85-100	10-40		0-10		0-5		
PA*	612 (57's)			100	95-100		25-60		0-10	0-5						

Sieve	English units	3"	2"	1.5"	1"	3/4"	1/2"	3/8"	#4	#8	#10	#16	#30	#50	#100	#200
Size	(mm)	76	51	38	25	19	12.7	9.5	4.75	2.36	2.0	1.18	0.6	0.3	0.15	0.075
State	**Item #**	**Percent Passing sieve size above (%)**														
SC	801 (57)			100	95-100		25-60		0-10	0-5						
	801 (789)					100	95-100	80-100	20-50			0-6			0-2	
	801 (FA-12)							100	90-100			50-86		2-20	0-5	
	801 (FA-13)							100	90-100			40-80		0-10	0-3	
TN*	710.05 (57)			100	95-100		25-60		0-10	0-5						
	710.05 (6)				100	90-100	20-55	0-15	0-5							
	710.05 (7)					100	90-100	40-70	0-15	0-5						
	710.05 (78)					100	90-100	40-75	5-25	0-10		0-5				
	710.05 (8)						100	85-100	10-30	0-10		0-5				
WV*	606.3.3 (57)			100	95-100		25-60		0-10	0-5						
	606.3.3 (67)				100	90-100		20-55	0-10	0-5						
	606.3.3 (7)					100	90-100	40-70	0-15	0-5						
	606.3.3 (78)					100	90-100	40-75	5-25	0-10						
WI*	612.3.9 (#2)		100	90-100	20-55				0-10	0-5						
* use fabric wrap																
** use pipe outlets																
*** use pipe outlets and fabric wrap																

APPENDIX B CURRENT ODOT PROCEDURE (PHASE 1)

The Department installs aggregate drains by contract, using the Ohio DOT Construction and Materials Specifications Manual Item 605, Aggregate Drains; or by ODOT County Garage crews. Aggregate drains installed by contract are typically used for drainage on bridge replacement projects, to provide outlets for the granular base on two-lane routes, and to provide drainage for full-depth repairs. Figures 3 and 4 show typical plan sheets for installing aggregate drains by contract. The drains installed to provide an outlet for the base are commonly spaced at 50 ft (15.2 m) and staggered, to provide a drain on one side of the road every 25 ft (7.6 m) as shown in Figure 3. Air-cooled blast furnace slag, limestone, or gravel aggregate meeting the AASHTO No. 8, 9, or 89 gradation was permitted for the aggregate drains under Item 605. However, several Districts modify the specification by plan note, as shown in Figure 4, limiting the granular material to gravel meeting AASHTO #57 gradation. From January, 2013 through November, 2015, the Department sold a total of 197 projects to install a total of 74,917 linear feet (22.8 km) of aggregate drains at an average cost of $11.84 per linear foot.

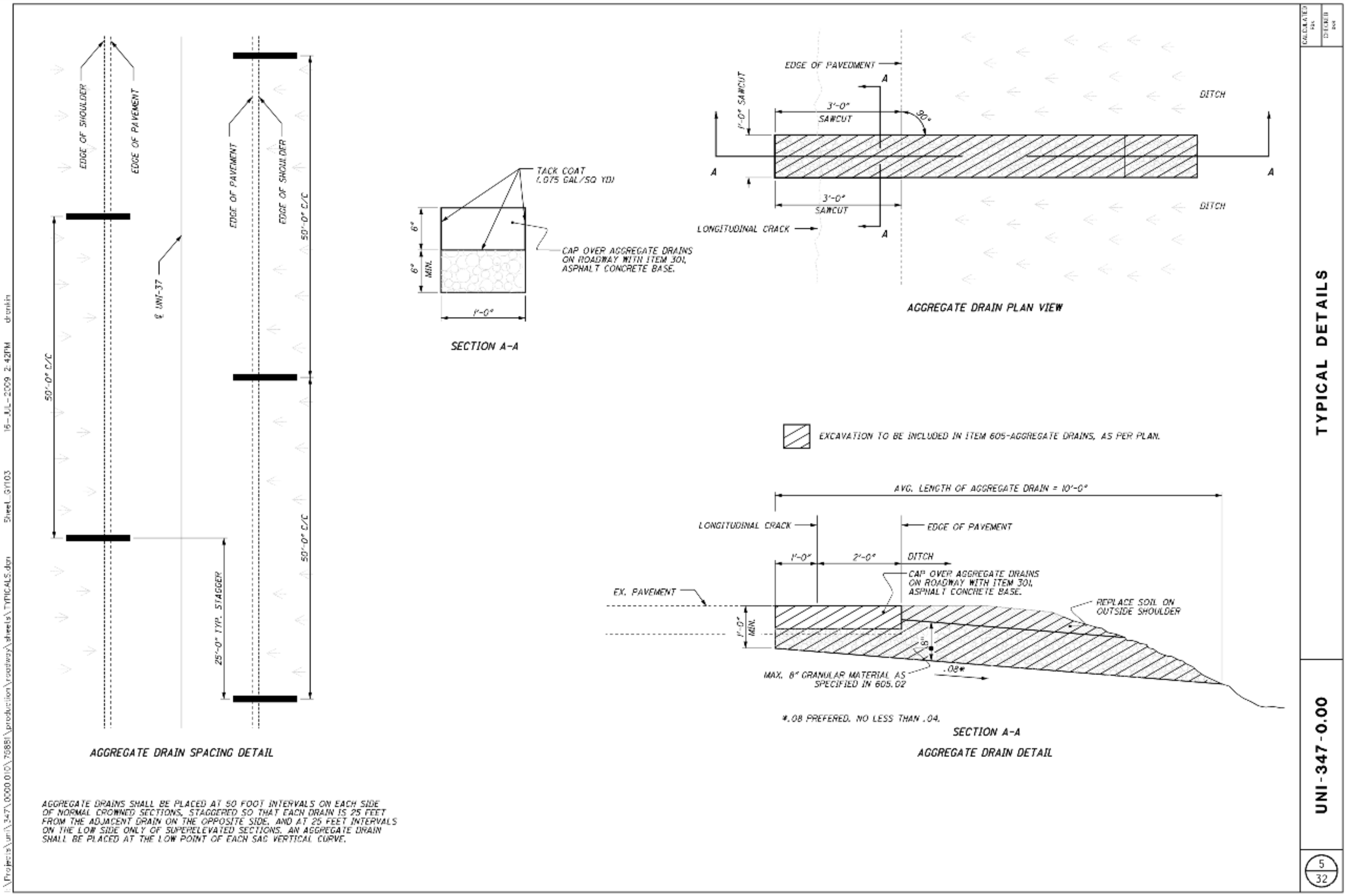

Figure 3. Typical Plan Sheet for Aggregate Drains for Rural Roads used by ODOT.

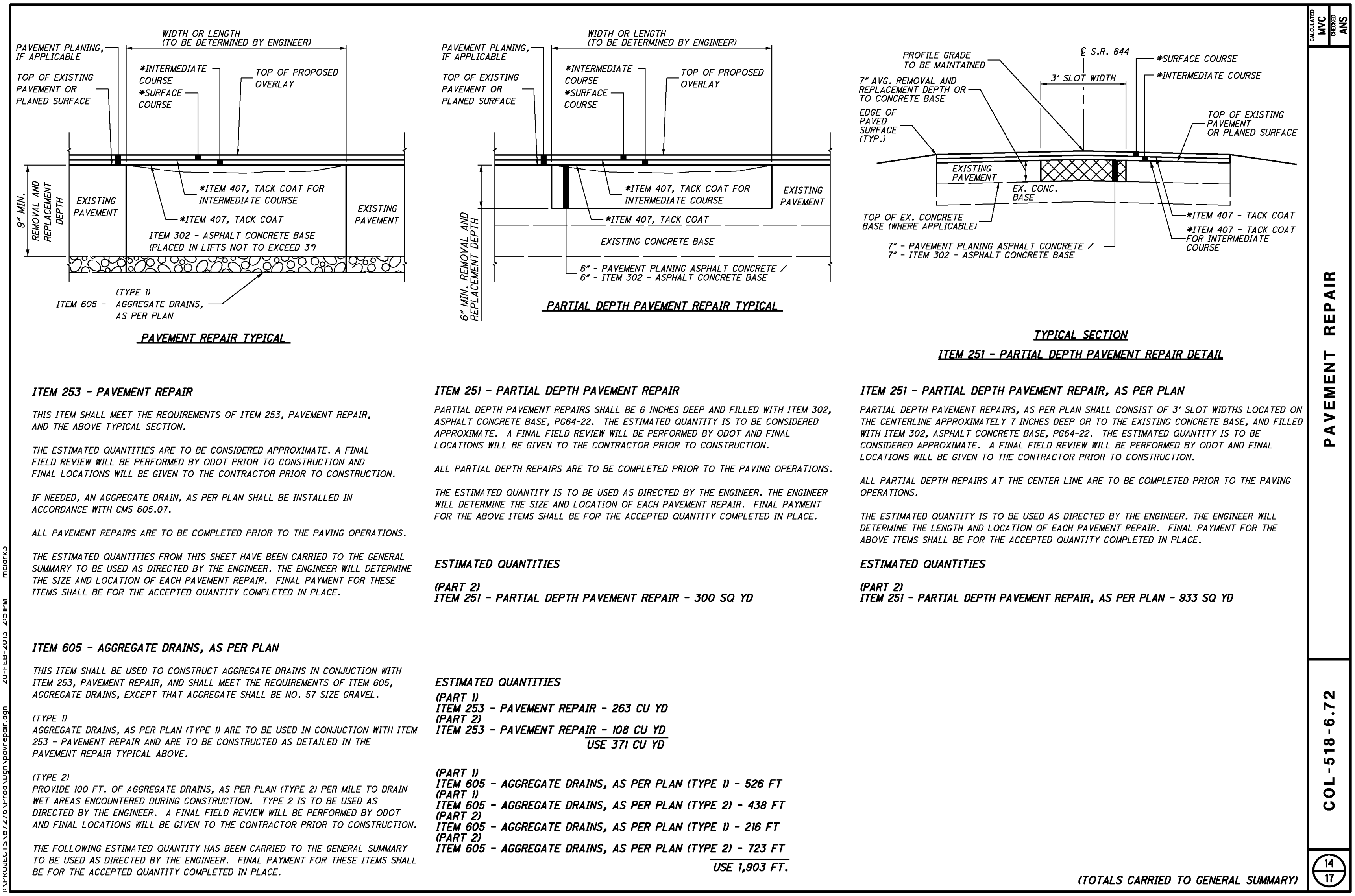

Figure 4. Typical Plan Sheet for Aggregate Drains for Rural Roads used by ODOT.

ODOT crews in two Ohio counties, Marion and Carroll, are actively installing aggregate drains. The crews in Carroll County, ODOT District 11, are installing aggregate drains whenever full-depth pavement repairs are constructed by county crews, typically to repair damage caused by increased traffic due to oil well hydraulic fracturing operations. Marion County ODOT crews, District 6, are proactively installing aggregate drains in undrained flexible pavements with aggregate bases. The process is time consuming. Parallel saw cuts, 12 in (30.5 cm) apart, are made from the edge of pavement, or paved shoulder, to the edge of the underlying granular base. A 12-in (30.5 cm) bucket on a backhoe, similar to that shown in Figure 5, is used to dig a trench from the ditch to the pavement. The trench is filled, without compaction, to the surface with aggregate meeting AASHTO #8 gradation. The finished drain is shown in Figure 6, with a close-up view shown in Figure 7. Production during a typical eight-hour work day is three to five drains. In addition to the low production rate, other disadvantages of this method are the need to dispose of removed soil; the trench is excavated towards the pavement; the sawn pavement is pulled upwards when removed, sometimes lifting the asphalt that remains in place; the length of the backhoe/loader makes the backhoe difficult to maneuver and operate in traffic control zone; and the uncompacted backfill and patch material settles at the edge of pavement. The advantages of this method include no need to purchase additional equipment or train the operator.

Figure 5. Backhoe with Bucket Excavating for Road Drainage [http://www.odotonline.org/photoarchive/].


Figure 6. Finished Aggregate Roadside Drain.


Figure 7. Close-up View of Finished Aggregate Roadside Drain.

APPENDIX C REVIEW OF APPLICABLE EQUIPMENT (PHASE 1)

Given the lack of literature on aggregate drains, the researchers looked at related construction fields. The installation of pipelines and cable has seen progress in recent years to meet the increased demand in buried power, telecommunication, internet, and television cables and construction of pipelines for oil and gas. The equipment considered for this project includes trenchers, horizontal directional drilling rigs, plows, and rock saws/microtrenching. The following information was gathered from websites of the manufacturers Ditch Witch and Bobcat as well as from discussions with local distributers. The information is summarized in Table 7, after the options have been presented.

A trencher consists of a chain of cutting teeth which moves around a guide bar. Trenchers may be self-contained, as in the Ditch Witch shown in Figure 8, or an attachment to multi-use equipment, such as the trencher mounted on the Bobcat shown in Figure 9. The Ditch Witch and Bobcat models can cut trenches up to 8 in (20 cm) and 12 in (30.5 cm), respectively (not necessarily the models shown). Estimated cost for the Ditch Witch ranged from $150,000 to $180,000. Estimated cost for the Bobcat is $66,000 for the track loader plus $10,000 for the trencher attachment. The distributer estimated the trencher production rate would be 25 to 30 aggregate drain trenches per 9-hour day in typical clayey Ohio soils. ODOT Districts currently operate Bobcats with a grinder head to remove humps in the pavement surface so minimal training would be needed to implement this equipment. Disadvantages of this method are the need to saw the pavement and remove asphalt to excavate to the granular base, the inability of the trencher to cut through any boulders encountered, and the length of the Ditch Witch trencher makes it difficult to maneuver and operate in a traffic control zone.

Figure 8. Ditch Witch Trencher. [https://www.ditchwitch.com/trenchers]

Figure 9. A Bobcat Track Loader with Trencher Attachment in use.
[http://www.directindustry.fr/prod/bobcat/product-31379-1180679.html]

Horizontal directional drilling (HDD), using equipment such as that shown in Figure 10, has seen increased use as more utilities move their cables underground. The machine drills a pilot hole using a controllable drilling head. If the hole needs to be enlarged, a cutter head is then pulled back through the hole. The pipe or cable is then pulled through the enlarged hole. For drainage, it was envisioned HDD could be used to install a drainage pipe either transversely, from one shoulder to the other, or longitudinally, drilling from the shoulder into the granular base, following the base at the edge of pavement for some distance, then exiting into the ditch. It is estimated HDD can install up to 400 ft (122 m) of 4 in (10 cm) pipe in a day in typical Ohio soil. Estimated cost for the equipment, including the equipment needed for mixing drilling mud, is $220,000. A two-member crew is usually required to operate the HDD equipment. Other disadvantages include the need to dig pits at the beginning and end of the installation, the drilling and reaming operation may hump the soil/pavement and there will be drainage outlets to maintain.

Figure 10. Horizontal Directional Drilling (HDD) Equipment. [http://assets.cougar.nineentertainment.com.au/imagegen/p/800/600/assets/traderspecs/2013/12/03/misc/vermeer_d24x40_2.jpg]

The rock saw – also known as the wheel saw, frost saw, or microtrencher – consists of carbide teeth mounted on the circumference of a large metal wheel. The Bobcat model, shown in Figure 11 is an attachment to the track loader and can cut trenches up to 8 in (20 cm) wide. Estimated cost for the Bobcat is $66,000 for the track loader plus $19,000 for the rock saw attachment. The distributer estimated the production rate would be 50 aggregate drain trenches per 9-hour day in typical Ohio clayey soils. The ODOT crew in Carroll County has used a smaller rock saw on a limited basis to construct temporary drains in failed or wet pavement areas until a more permanent solution can be constructed. Also, some ODOT Districts currently operate Bobcats with a grinder head to remove humps in the pavement surface so minimal training would be needed to implement this method. The rock saw, as the name implies, can cut through any boulder encountered as well as the pavement, eliminating the need to saw the pavement before cutting the trench. The cuttings produced are fine and can be spread over the shoulder rather than being hauled away. Trench depth is limited to 24 in (61 cm) maximum.

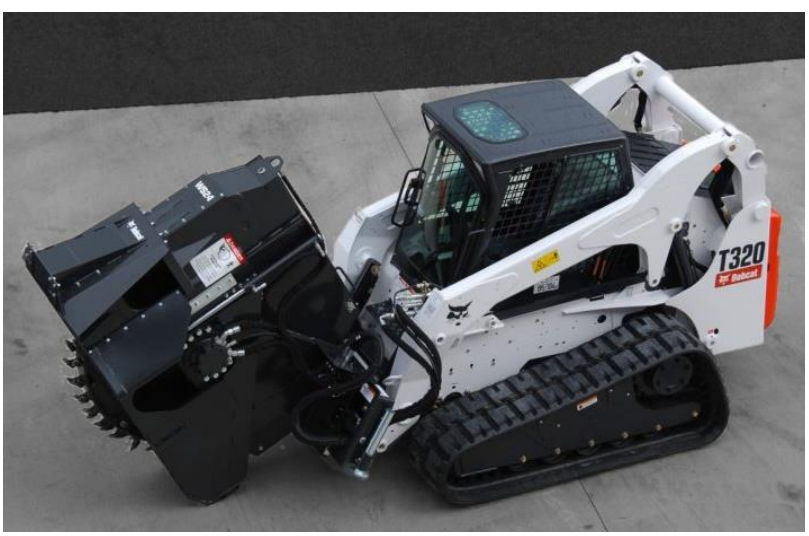

Figure 11. Rock Saw Attachment Mounted on a Bobcat.

[http://www.mtsplant.co.uk/products/attachments/sale/wheel-saw/]

The vibratory cable plow, shown in Figure 12, installs cable by using a narrow plow to slit and separate the soil, feeding a cable into the separation, and vibrating the soil to close and compact the soil. However, based on discussions with the distributors, this equipment is not capable of installing pipes of the diameter desired, 3 in (76 mm) or greater, to drain the base.

Figure 12. A vibratory Cable Plow. [http://williscable.com/services/]

Table 7. Summary of characteristics of subsurface drainage installation equipment.

Criterion \ Equipment	Backhoe/ loader	Trencher	Horizontal Directional Drilling	Rock Saw	Vibratory Plow
Safety	Length may interfere with traffic	Length may interfere with traffic			Length may interfere with traffic
Training	None	Minimal	Needed	None	Needed
Equipment Cost (2015)	$0	$76,000 - $180,000	$220,000	$85,000	
Operators	1	1	2	1	1
Daily production	3 to 5 drains	25 to 30 drains	400 ft (122 m)	50 drains	N/A
Outlets to maintain	No	No	Yes	No	Yes

To select equipment for further evaluation in Phase II, the researchers used a ranking system. The criteria used for the ranking were taken from the RFP or included by the researchers based on discussions with ODOT. For each criterion, the equipment which ranked best was assigned a rank of 1, the next best was assigned a 2, and so on. Ties were assigned the same value. The vibratory plow was not considered in the evaluation since it was not capable of installing underdrain outlets of diameters 4 in (10 cm) and 6 in (15 cm), typically installed by ODOT. The rating points were determined as follows:

- Safety
    - The rock saw is compact, and would not extend into the traffic lane, and the horizontal directional drilling rig would operate from the shoulder, so these two pieces of equipment were assigned a rating of 1.
    - The backhoe/loader and trencher are longer and may extend into the traffic lane during operation and were therefore assigned a ranking of 2.

Training
  - ODOT currently owns the backhoe/loader and operate Bobcat loaders similar to the one proposed for this project. Little or no operator training would be required so both were assigned a rating of 1.
  - A minimal amount of training would be required for the trencher since it is similar to current ODOT equipment, so the trencher was assigned a ranking of 2.
  - The horizontal directional drilling equipment would be new to ODOT and would require significant training, so this equipment was assigned a ranking of 3
- Equipment Cost
  - ODOT currently owns backhoe/loaders so there were be no additional cost, so the backhoe/loader was assigned a rank of 1
  - Estimated cost of the trencher was $76,000 and was assigned a rank of 2.
  - Estimated cost of the rock saw was $85,000 and was assigned a rank of 3
  - Estimated cost of the horizontal directional drill was $220,000 and was assigned a rank of 4
- Operators
  - The backhoe/loader, trencher, and rock saw all require one operator so they were assigned a rank of 1. The horizontal directional drill requires 2 operators and was therefore assigned a value of 2
- Production
  - The rock saw, trencher, backhoe/loader and horizontal directional drill can install an estimated 50, 25 to 39, 3 to 5, and one drain daily, respectively. The respective ranking of each piece of equipment was 1, 2, 3, and 4.
- Maintenance of outlets.
  - Drains installed with the backhoe/loader, trencher, and rock saw do not have outlets to maintain and therefore each piece of equipment was assigned a rank of 1. The drains installed with the horizontal directional drill would have outlets to maintain and therefore it was assigned a rank of 2.

The results are presented in Table 8. The Backhoe/loader and Rock Saw best addressed the evaluation criteria and are recommended for study in Phase II.

Table 8. Rankings for Characteristics of Subsurface Drainage Installation Equipment.

Equipment / Criterion	Backhoe/ loader	Trencher	Horizontal Directional Drilling	Rock Saw
Safety	2	2	1	1
Training	1	2	3	1
Equipment Cost	1	2	4	3
Operators	1	1	2	1
Production	3	2	4	1
Outlets to maintain	1	1	2	1
Total Score	9	10	16	8

APPENDIX D PRELIMINARY EVALUATION OF AGGREGATE DRAINS (PHASE 1)

The first step in the evaluation of the current ODOT procedure was to determine if an aggregate drain was an effective method to drain the aggregate base. Moisture in granular base and the subgrade will decrease the stiffness of the pavement structure. To determine if the aggregate drains are effective, the stiffness and moisture were measured in the base and subgrade at two sites with similar pavement material type and buildup. MAR-95 in Marion County (MAR) was selected to represent a pavement structure that had aggregate drains previously installed. MAR-529 in Marion County was selected to represent a pavement that did not have aggregate drains but needed them. The site on MAR-95 was located approximately 1.6 miles east of MAR-98. The site on MAR-529 was located approximately 0.8 mi (1.3 km) east of MAR-98 and approximately 2.75 mi (4.4 km) southwest of the MAR-95 site.

Dynamic Cone Penetrometer (DCP)

Data were collected with a trailer-mounted Vertek automated dynamic cone penetrometer (DCP) and used to estimate the modulus of the base and subgrade at each site, as well as the thickness of the base layer. Figure 13 shows the coring and DCP testing operations.

Figure 13. Coring (left) and Dynamic Cone Penetrometer (DCP) Testing (right).

DCP testing of MAR-95 was performed on September 24, 2015, and MAR-529 was tested the following day. The locations used for the DCP testing were strategically selected to identify the soil stiffness close to the aggregate drains on MAR-95 as well as midway between the aggregate drains. Stiffer base and soil near the aggregate drains are to be expected since they are likely to have less moisture. The coring and DCP layout for MAR-529 were duplicated to maintain consistent spacing between the two tests and allow for comparison. However, two additional locations were tested on MAR-529 closer to the edge of pavement to see if the results would differ near the edge. Locations of the DCP testing are shown are in Figure 14 for MAR-95 and in Figure 15 for MAR-529.

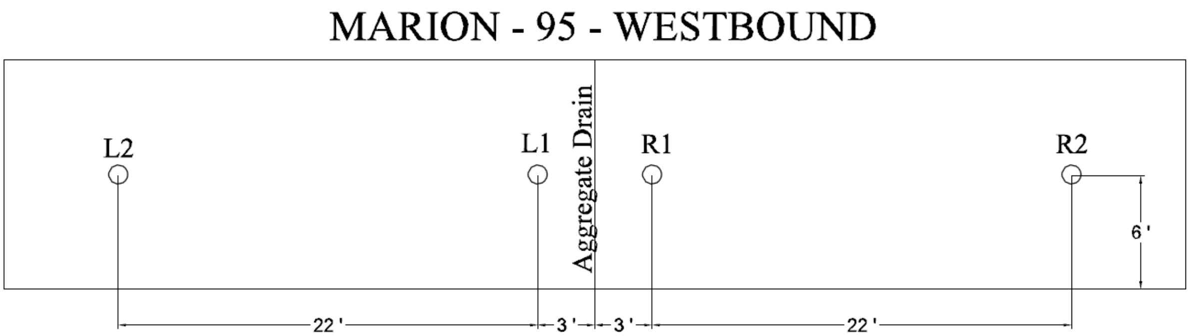

Figure 14. Coring and DCP Layout MAR-95 (1 ft = 0.305 m).

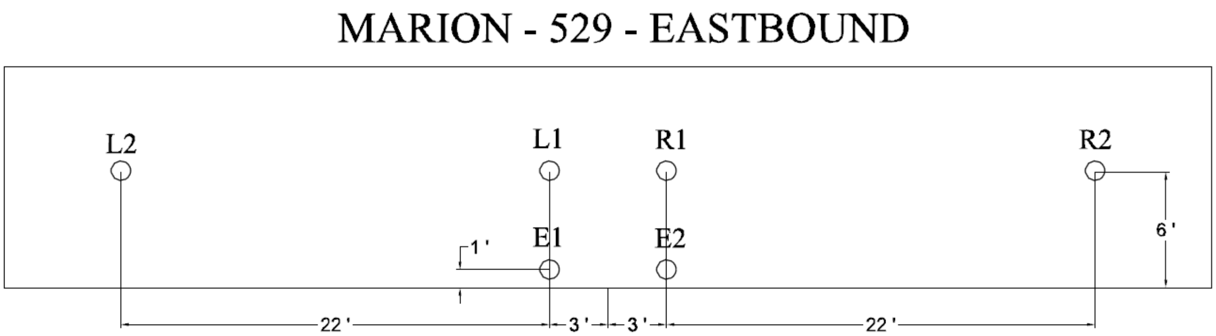

Figure 15. Coring and DCP Layout for MAR-529 (1 ft = 0.305 m).

DCP testing was conducted by first coring the pavement to remove the existing AC pavement layer. The DCP was then placed in the core hole with the pointed tip resting on the surface of the granular base. The hammer was then raised and dropped onto the rod, forcing the cone to penetrate the unbound layer. The depth of penetration was measured after each hammer drop to determine the penetration rate (PR), the distance the tip of the DCP travels per blow, in millimeters per blow (mm/blow) and converted to inches per blow (in/blow).

Uniform layers were identified using the cumulative differences method [AASHTO, 1986] based on the PR in mm/blow and depth in mm following the procedure described in Wu and Sargand [2007]. Once uniform layers were identified, the average PR of each layer was determined. Uniform layers are evident in the examples shown in Figure 16 and Figure 17 for DCP testing on MAR-95 and MAR-529, respectively. In these figures the average layer PR demarcates the uniform layers and the differences in PR are evident as a new layer of unbound material is reached. The first uniform layer, or the upper portion of the unbound layers in the structure was granular base material, while the lower portion or second uniform layer was the subgrade.

Once the average PR was determined for each material, the California Bearing Ratio (CBR) was then calculated using Equation 1, developed by the U.S. Army Corps of Engineers [Webster, Grau, and Williams, 1992] to relate CBR and PR. The CBR was in turn used to calculate resilient modulus (M_r) for the base and subgrade in each route. The M_r for the water-bound macadam base was determined using Equation 2, which follows the method used in the Mechanistic Empirical Pavement Design Guide developed under NCHRP 1-37A [2004]. Following the equation shown in Ohio DOT's Pavement Design Manual [2016], Section 203.1, M_r was calculated for the subgrade using Equation 3.

$$CBR = \frac{292}{PR^{1.12}} \quad (1)$$

$$M_r = 2555(CBR^{0.64}) \quad (2)$$

$$M_r = 1200 * CBR \quad (3)$$

where:
CBR = California Bearing Ratio
PR = Penetration Rate (mm/blow)
M_r = Resilient Modulus (psi)

The results for the granular base thickness (*h*) and resilient modulus of each layer are reported in Table 9 and Table 10 for MAR-95 (with aggregate drains) and MAR-529 (without aggregate drains), respectively. An example profile of the DCP measurements and layer averages found for one location on MAR-95 and one on MAR-529 are shown in Figure 16 and Figure 17, respectively.

Table 9. Resilient Moduli Based on DCP Testing, MAR-95 (with Aggregate Drains)

	Aggregate Base				Natural Subgrade	
Location	h (in)	h (cm)	M_r (psi)	M_r (MPa)	M_r (psi)	M_r (MPa)
L2	18.61	47.3	68079	469.39	13538	93.34
L1	16.23	41.2	70816	488.26	32803	226.17
R1	18.71	47.5	66437	458.07	10589	73.01
4R2	19.74	50.1	68225	470.40	10313	71.11
Average	18.32	46.5	68389	471.53	16811	115.91
Standard Deviation	1.48	3.8	1810	12.48	10761	74.20
COV	8.1%		2.6%		64.0%	

Table 10. Resilient Moduli Based on DCP Testing, MAR-529 (without Aggregate Drains)

	Aggregate Base				Natural Subgrade	
Location	h (in)	h (cm)	M_r (psi)	M_r (MPa)	M_r (psi)	M_r (MPa)
L2	13.99	35.5	69076	476.26	27949	192.70
L1	13.64	34.7	58120	400.72	13294	91.66
R1	13.02	33.1	68141	469.82	17365	119.73
E1 (Center)	12.06	30.6	61225	422.13	7796	53.75
R2	12.89	32.7	60420	416.58	10533	72.62
E2 (Right Edge)	12.82	32.6	58736	404.97	24851	171.34
Average	13.07	33.2	62620	431.75	16965	116.97
Standard Deviation	0.68	1.7	4781	32.96	8024	55.32
COV	5.2%		7.6%		47.3%	

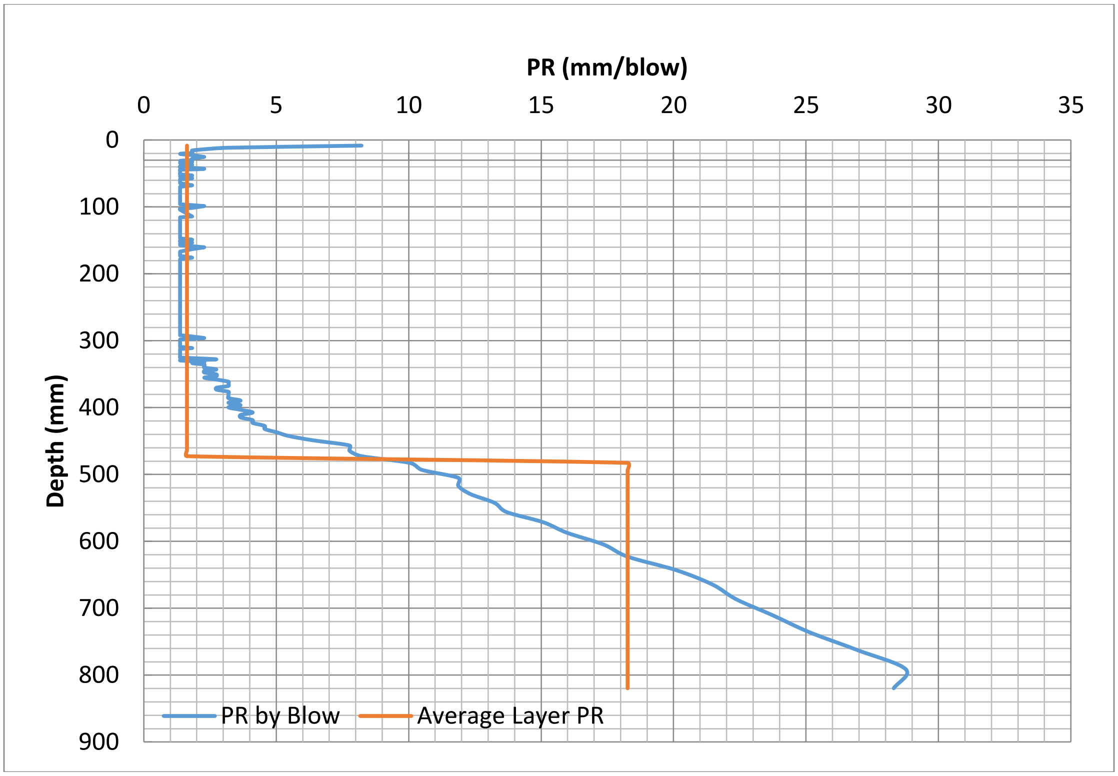

Figure 16. Example Profile of DCP Testing Results on MAR-95 (with Aggregate Drains) (1 in. = 2.54 cm).

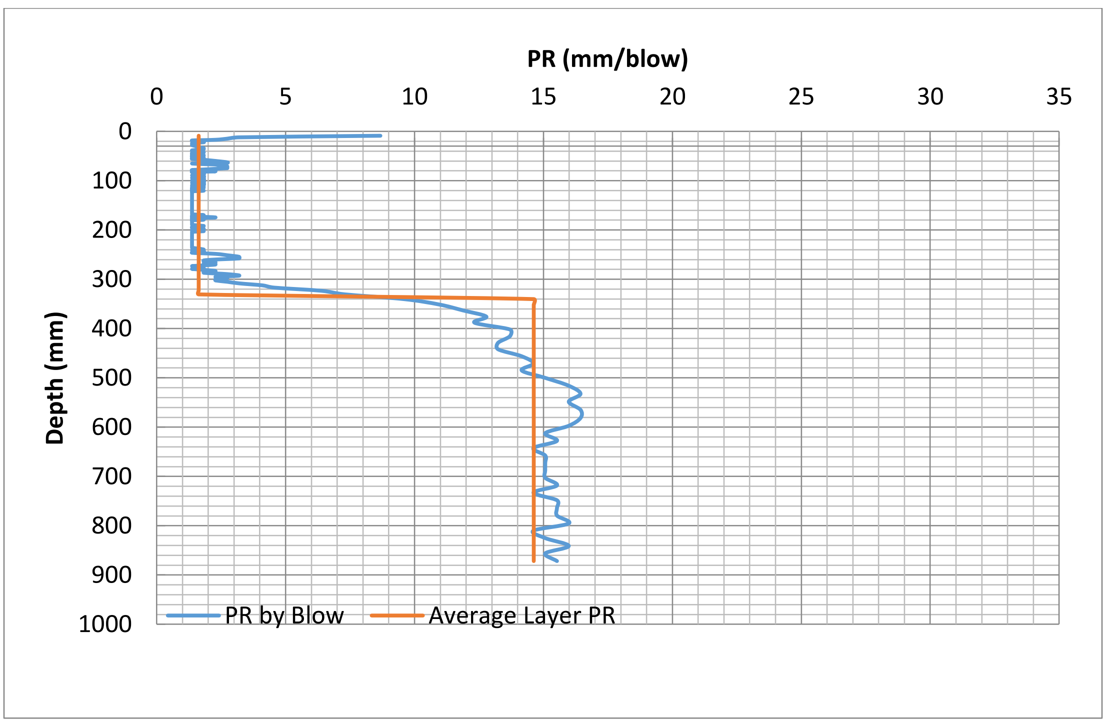

Figure 17. Example Profile of DCP Testing Results on MAR-529 (without Aggregate Drains) (1 in. = 2.54 cm).

The average base resilient modulus at the site with aggregate drains (MAR-95) was nearly 9% greater than the average base resilient modulus at the site without drains. Additionally, the base extended approximately 5 in (13 cm) deeper, on average, into the pavement structure. These results indicate the aggregate drains are beneficial in draining the pavement base, which results in a higher modulus. As a result, the tensile strains in the asphalt should be reduced, which extends the pavement fatigue life.

Laboratory Soil Testing

Granular base material was sampled from each core location after the completion of DCP testing. An example of the water-bound macadam base is shown in Figure 18. Sampled material was brought back to the lab for determination of moisture content, following procedures laid out in AASHTO T-265 "Laboratory Determination of Moisture Content of Soils". Gravimetric moisture contents (ω) in percent are shown in Table 11 for each location.

Figure 18. Water-bound Macadam Base.

Table 11. Moisture Content

MAR-95 wheelpath		MAR-529 wheelpath		MAR-529 Edge of Pavement	
Sample	ω %	Sample	ω %	Sample	ω %
L1	2.0%	L1	4.8%	E1	3.6%
L2	1.5%	L2	3.2%	E2	3.7%
R1	1.9%	R1	5.5%		
R2	2.0%	R2	3.8%		

Sieve analyses were completed in accordance with AASHTO T-88 "Particle Size Analysis of Soils" for the granular base material collected from the DCP test locations. Gradations for base material from each site are plotted in Figure 19.

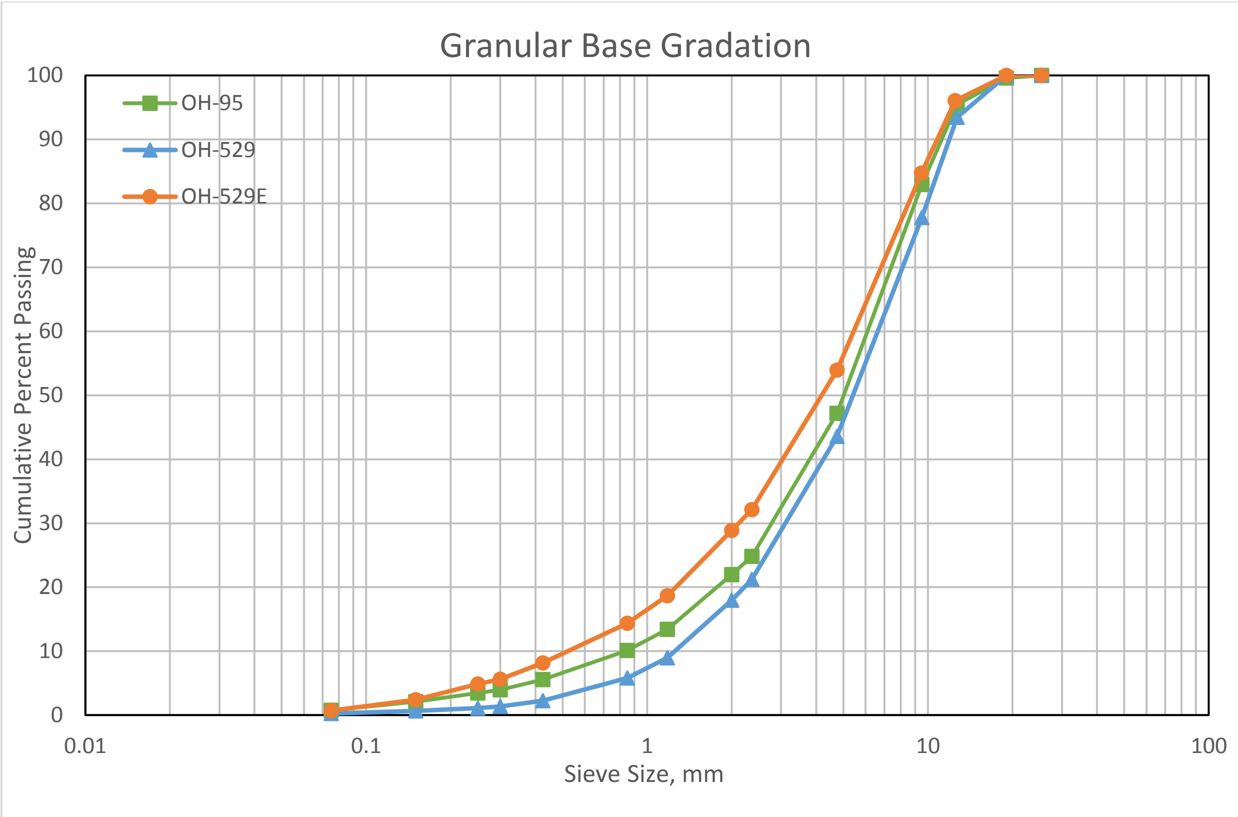

Figure 19. Gradations of Base Materials from MAR-95 and MAR-529 (MAR-529E is for specimens collected at the edge of the pavement) (25.4 mm = 1 in).

APPENDIX E PHASE 1 CONCLUSIONS AND RECOMMENDATIONS

- Based on a review of state DOT specifications, the most common maximum aggregate size specified are 1.5 in (38 mm) (11 of the 17 states), 0.75 in (19 mm) maximum aggregate size (9 of 17 states), and 0.375 in (9.5 mm) maximum aggregate size (8 of 17 states).
- State specifications typically require the backfill material be compacted
- DCP field testing and lab testing of samples obtained from similar routes in Marion County showed average modulus of the base at the site with aggregate drains was 8% higher than average modulus of base at the site without drains, and extended 5 in (13 cm) deeper into the pavement structure. These results indicate a higher base resilient modulus in areas aggregate drains were present.
- Five types of equipment; backhoe/loader, trencher, horizontal directional drill, vibratory plow, and rock saw, were evaluated for installation of aggregate drains. The use of the vibratory plow was not feasible due to limitations on the diameter of pipe which can be installed.
- A ranking system was used to evaluate the remaining equipment types. The rock saw and track loader/backhoe received the best ratings. However, the higher production rate and higher safety ranking of the rock saw would make this the preferred equipment.
- The researchers recommend the rock saw for further evaluation in Phase 2. The researchers recommend a limited number of aggregate drains be installed with the backhoe/loader in Phase 2 to provide a benchmark to determine change in productivity and pavement damage from current practice.

APPENDIX F METHODOLOGY (PHASE 2)

In Phase 1 of this project, the benefits of drainage were validated in the field, several pieces of equipment and techniques for installing drainage on rural roads were examined, and the most promising method, using a track loader with rock saw attachment, was selected for field evaluation in Phase 2. In Phase 2, aggregate drains were constructed by personnel from Ohio Department of Transportation (ODOT) Marion County Garage following the experimental matrix. As part of Phase 2, aggregate drains were also installed with a backhoe/loader to provide a baseline for determination of changes in production and pavement damage.

The experimental plan for Phase 2 research considered the following variables:

- Equipment: Rock saw and backhoe
- Gradation: #8, #57, and #4 aggregate and porous concrete
- Compaction and no compaction of aggregate or porous concrete
- Fabric wrap and no fabric wrap with aggregate or porous concrete
- Drain spacing: 50 ft (15 m) and 200 ft (61 m)
- Trench width: 8 in (20 cm) and 15 in (38 cm)

Six drains, alternating three on each side of the pavement, were installed for each of the variable combinations. A study including all variables for both pieces of equipment would require the construction of 960 drains taking an estimated 138 days to construct. However, the effect of gradation, compaction/no compaction, fabric/no fabric, spacing, and trench width are independent of equipment type. Therefore the experiment focused on the rock saw, which is more productive than the backhoe/loader.

If the aggregate drain is at least as permeable as the base material, the effect of drain spacing would depend on the time for the water to travel through the existing base. In this case, the aggregate drain gradation would be independent of spacing, and this condition was assumed for this experiment. Therefore, spacing was only varied for the intermediate gradation, AASHTO #57.

The experimental matrix shown in Table 12 was followed in constructing the drains. The sections built are indicated in the Equipment row by yellow shading and an R indicating the rock saw was used or by orange shading and a B indicating duplicate sections was built, one with rock saw and the other with backhoe, to compare production rates, the time each equipment requires to complete a step of the installation, i.e., excavate trench to the required width and depth. The unshaded sections marked with an X are redundant and were not constructed. In addition, two control sections, two of 125 ft (38 m) length and two of 500 ft (152 m) length, did not have drains installed but were tested as described in the work plan below. This plan required the installation of 228 drains along 2.1 mi (3.4 km) of pavement.

Table 12. Proposed matrix for evaluation of subsurface drainage methods in Phase 2 (Drain spacing: 50 ft = 15 m, 200 ft = 61 m; Trench width: 8 in = 20 cm, 15 in = 38 cm).

AASHTO Gradation	#8																#57															
Fabric Wrap	fabric wrapped								no fabric wrap								fabric wrapped								no fabric wrap							
Compaction	yes				no				yes				no				yes				no				yes				no			
Drain Spacing (ft)	50		200		50		200		50		200		50		200		50		200		50		200		50		200		50		200	
Trench Width (in)	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15
Equipment	R	X	X	X	R	X	X	X	R	X	R	X	R	X	R	X	R	B	R	B	R	B	R	B	R	B	R	B	R	B	R	B
AASHTO Gradation	#4																porous concrete															
Fabric Wrap	fabric wrapped								no fabric wrap								fabric wrapped								no fabric wrap							
Compaction	yes				no				yes				no				yes				no				yes				no			
Drain Spacing (ft)	50		200		50		200		50		200		50		200		50		200		50		200		50		200		50		200	
Trench Width (in)	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15	8	15
Equipment	R	X	X	X	R	X	X	X	R	X	R	X	R	X	R	X	R	X	X	X	R	X	X	X	R	X	X	X	R	X	X	X

Key to equipment:
R = Constructed with Rock Saw
B = Constructed with Both Rock Saw and Backhoe
X = Redundant experimental sections; therefore, not constructed

Evaluation of the effectiveness of the drainage was accomplished by measuring pavement stiffness using falling weight deflectometer (FWD) and dynamic cone penetrometer (DCP); determining base/subgrade moisture content using time domain reflectometer (TDR) sensors; and laboratory testing of samples of base and subgrade material.

Field testing was conducted prior to the construction of the aggregate drains and periodically after construction over a one-year monitoring period to capture changes in unbound layer stiffness and in-situ moisture. Field testing included readings from time domain reflectometer (TDR) probes, falling weight deflectometer (FWD) testing, and dynamic cone penetrometer (DCP) testing. In addition to field testing, gravimetric moisture contents of samples taken during DCP testing were determined in the laboratory.

Project Site

A segment of approximately 4.6 miles (7.4 km) on Ohio State Route 529 (MAR-529) beginning at the Mautz-Yeager intersection and running east to the Marion/Morrow County line was selected as the site for this project by ODOT and ORITE personnel. This stretch of asphalt pavement, located east of the Marion city limits in a rural area, is shown on the map in Figure 20.

Figure 20. Location of Project Site, MAR-529 [www.google.com/maps].

The ODOT straight line diagram for this portion of MAR-529 indicates the pavement has a width of 18 ft. Additionally, it shows the base under the westbound lane is water-bound macadam while the base under the eastbound lane consists of water-bound macadam beginning the centerline of the pavement and extending 3 ft into the eastbound lane. For the remaining width of the eastbound lane (approximately 6 ft (2.4 m) wide) the base is shown as specification Item 304 or traffic compacted aggregate base. It is believed this is due to the pavement being widened at a later date. The asphalt pavement varied in thickness from 10 inches (254 mm) to 14 inches (355 mm).

Characterization of Unbound Layers

Laboratory testing was completed on soil samples obtained during DCP testing conducted prior to construction of the aggregate drains. Laboratory testing included gravimetric moisture content of the water-bound macadam base and compacted subgrade, sieve analysis of the water-bound macadam base and subgrade, and classification of the subgrade soil.

After DCP testing (details are presented later in this report) was completed in the westbound lane, water-bound macadam base and natural subgrade were sampled from the core hole. To sample the material, a 4-inch (10 cm) core barrel was welded to a shaft, mounted on a skid steer, and pressed into the base/subgrade material. The extracted material was sealed in plastic bags. Material was sampled in 4 in (10 cm) depth increments, enabling the separation of water-bound macadam base from the natural subgrade. The water-bound macadam base and subgrade samples were transported to laboratories in Athens and Lancaster for testing.

Gravimetric moisture content of each sample of water-bound macadam base and subgrade soil was determined following AASHTO T 265, Laboratory Determination of Moisture Content of Soils. Once the moisture content was determined, sieve analyses were completed for water-bound macadam base samples following AASHTO T 27. Sieve analyses were completed on samples from selected sections to achieve a distribution along the project site: 1, 3, 9, 12, 14, 18, 19, 21, 24, 27, 42, and 44. For the subgrade soil the amount of material passing the No. 200 sieve (75 μm) was first determined following the AASHTO T 11, "Materials Finer than 75 μm (No. 200) Sieve in Mineral Aggregates by Washing". However, due to the time-consuming nature of the test, only samples obtained from Sections 1, 9, 12, 23, 34, and 44 were tested to represent the gradation of the natural subgrade. Once the amount of material passing the No. 200 (75μm) sieve was determined for the selected subgrade soil samples, sieve analyses were conducted following AASHTO T 27. The plastic limit (AASHTO T 90) and liquid limit (AASHTO T 89) were determined for the same subgrade samples to classify the soil following AASHTO M 145.

Variables Considered

To evaluate the effectiveness of aggregate drains, a range of variables were explored. These variables included the material used as backfill, the spacing of the drains, the width of the drains, the use of compaction, and the use of a filter wrap. Four types of backfill material were investigated: granular material meeting AASHTO gradation No. 57, No. 4, and No. 8, and porous concrete. Drain spacing of 50 feet (15 m) and 200 feet (61 m) were investigated, as well as trench widths of 8 inches (20 cm) and 15 inches (38 cm). It was not practical to construct aggregate drains representing every permutation of these variables, furthermore, it was not necessary to do so to evaluate the impact of each variable. Therefore, the experimental matrices were reduced appropriately, as discussed below. The experimental matrix for aggregate drain construction with each backfill material is shown in Table 13 through Table 15, which are adapted from Table 9 to include only those sections actually constructed. Section Numbers are given based on a randomized assignment discussed later under "Layout of Test Sections" and are generally in order from west to east, with the exception of Section 43 that was inserted between Sections 3 and 4.

Table 13. Experimental Matrix for Aggregate Drains Constructed with No. 57 Aggregate (50 ft = 15 m, 200 ft = 61 m; 8 in = 20 cm, 15 in = 38 cm).

AASHTO Gradation	#57											
Fabric Wrap	Y											
Compaction	Y						N					
Drain Spacing (ft)	50			200			50			200		
Trench Width (in)	8	15	15	8	15	15	8	15	15	8	15	15
Equipment	R	B	R	R	B	R	R	B	R	R	B	R
Section Number	3	5	28	31	27	36	35	6	17	32	7	13
AASHTO Gradation	#57											
Fabric Wrap	N											
Compaction	Y						N					
Drain Spacing (ft)	50			200			50			200		
Trench Width (in)	8	15	15	8	15	15	8	15	15	8	15	15
Equipment*	R	B	R	R	B	R	R	B	R	R	B	R
Section Number	2	19	39	22	29	16	11	8	42	38	41	23

*R: Rock Saw; B: Backhoe

Table 14. Experimental Matrix for Aggregate Drains Constructed with No. 4 or No. 8 Aggregate (50 ft = 15 m, 200 ft = 61 m; 8 in = 20 cm, 15 in = 38 cm).

AASHTO Gradation	#8						#4					
Fabric Wrap	Y		N				Y		N			
Compaction	Y	N	Y		N		Y	N	Y		N	
Drain Spacing (ft)	50	50	50	200	50	200	50	50	50	200	50	200
Trench Width (in)	8	8	8	8	8	8	8	8	8	8	8	8
Equipment*	R	R	R	R	R	R	R	R	R	R	R	R
Section Number	30	40	34	12	24	25	43	15	20	1	26	44

*R: Rock Saw

Table 15. Experimental Matrix for Aggregate Drains Constructed with Porous Concrete (50 ft = 15 m, 200 ft = 61 m; 8 in = 20 cm, 15 in = 38 cm).

Material	Porous Concrete			
Fabric Wrap	Y		N	
Compaction	Y	N	Y	N
Drain Spacing (ft)	50	50	50	50
Trench Width (in)	8	8	8	8
Equipment*	R	R	R	R
Section Number	9	33	18	14

*R: Rock Saw

ODOT specification for aggregate drains fall under Item 605 Underdrains in ODOT's Construction and Material Specifications (CMS) manual [2016]. As indicated in the CMS manual, materials for aggregate drains are to consist of granular material meeting AASHTO gradation "No. 8, 9, or 89 size air-cooled blast furnace slag, limestone, or gravel." However, it was found in Phase 1 of this study for aggregate drain construction, the material is commonly identified in the plans was gravel meeting AASHTO No. 57 gradation, although aggregate meeting the No. 8 gradation has been used by Marion County ODOT crews for aggregate drain construction. The experimental matrix was expanded at this gradation to construct aggregate drains consistent with current practice, thereby providing a baseline for comparisons with aggregate drains constructed with the variables of interest. Based on the literature review conducted in Phase 1 and the existing specification, granular materials with gradations meeting AASHTO No. 8, and No. 4 were also considered, as well as porous concrete. Additional information regarding the backfill materials is presented in the subsequent subsection.

For each backfill material aggregate drains were constructed with and without a filter wrap. According to ODOT's CMS manual for Item 605, Geotextile Fabric to be used as part of underdrain construction should be of Type A material. For this project the material used for filter wrap was Mirafi 140N, a nonwoven geotextile composed of polypropylene fibers, with technical information sheet given in Appendix I, which meets or exceeds the requirements for Type A Geotextile Fabric. Additionally, aggregate drains were constructed with and without compaction for each backfill material. Compaction consisted of rolling the backfill material with plates mounted on a wheel which is attached to the Bobcat mini-excavator. Equipment used for compaction is discussed under the "Equipment" subsection.

According to ODOT's Pavement Design Manual [2016], aggregate drains "should be located at 50-foot (15 m) intervals". As part of this study an additional interval distance of 200 feet (61 m) was evaluated. However, drain spacing was varied only on the middle gradation, No. 57 aggregate. It is assumed the aggregate drain is at least as permeable as the existing macadam base material, therefore, the effect of the drain spacing should be independent of the gradation. The length of the test sections were proportional to the interval distance between aggregate drains such that for 50-foot (15-m) spacing, sections were 125 feet (38 m) long, and for 200-foot (61-m) spacing, sections were 500 feet (152 m) long. Each test section included 6 drains, starting with a drain on the eastbound side and alternating sides within the section.

According to ODOT CMS manual [2016], aggregate drains are to be constructed at a minimum width of 12 inches (30.5 cm). For this study, the width of the trench for the aggregate drain was varied based on the type of equipment utilized to construct the drain. The more frequently used width, 8 in (15 cm), corresponds to that of the rock saw, whereas the 15 inch (38 cm) width corresponds to that of the backhoe bucket. Aggregate drains constructed using a rock saw to achieve a wider trench of 15 inches (38 cm) were also evaluated for the No. 57 aggregate, to provide direct comparisons with the aggregate drains constructed with a backhoe.

While the equipment used to construct the aggregate drains is of concern for addressing the second objective of this research, it should not impact the effectiveness of the aggregate drain itself. Therefore focus was placed on the rock saw to evaluate the effectiveness of the equipment. As shown in Table 13, aggregate drains constructed with a backhoe were evaluated for No. 57 aggregate to provide a baseline for comparisons.

To evaluate the effectiveness of the aggregate drains, sections of length 500 feet (152 m) and 125 feet (38 m) with no aggregate drains were reserved to serve as control sections for the experiment. The 500 ft (152 m) sections were Number 4 and 21, and the 125 ft (38 m) sections were Number 10 and 37.

Materials

Four types of material were utilized in the aggregate drains: porous concrete and three gradations of granular material meeting AASHTO Designations No. 4, No. 8, and No. 57. Samples of the No. 4, No. 8, and No. 57 aggregate were obtained and sieve analyses were completed. Aggregate gradations for each material are plotted in Figures 21 through 23. Material supplied for all three gradations was on the coarse side of the gradation criteria with the No. 4 aggregate being slightly out of specification.

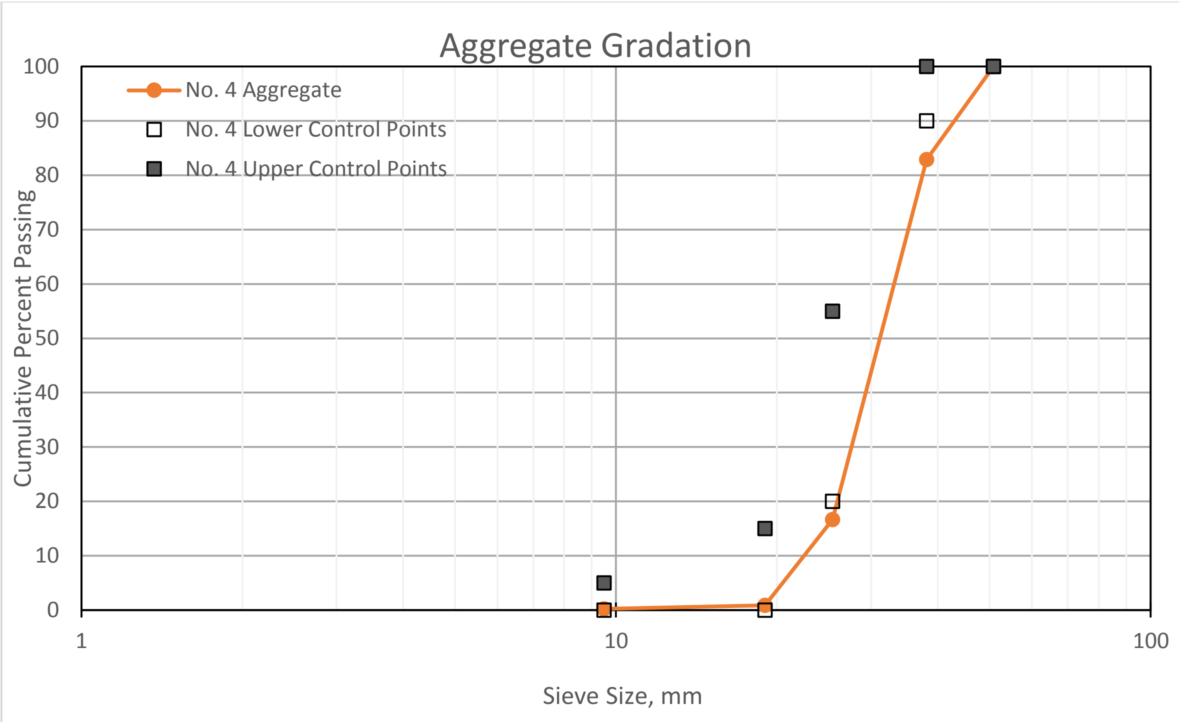

Figure 21. Gradation of No. 4 Aggregate used in Aggregate Drain (25.4 mm = 1 in).

Figure 22. Gradation of No. 57 Aggregate used in Aggregate Drain (25.4 mm = 1 in).

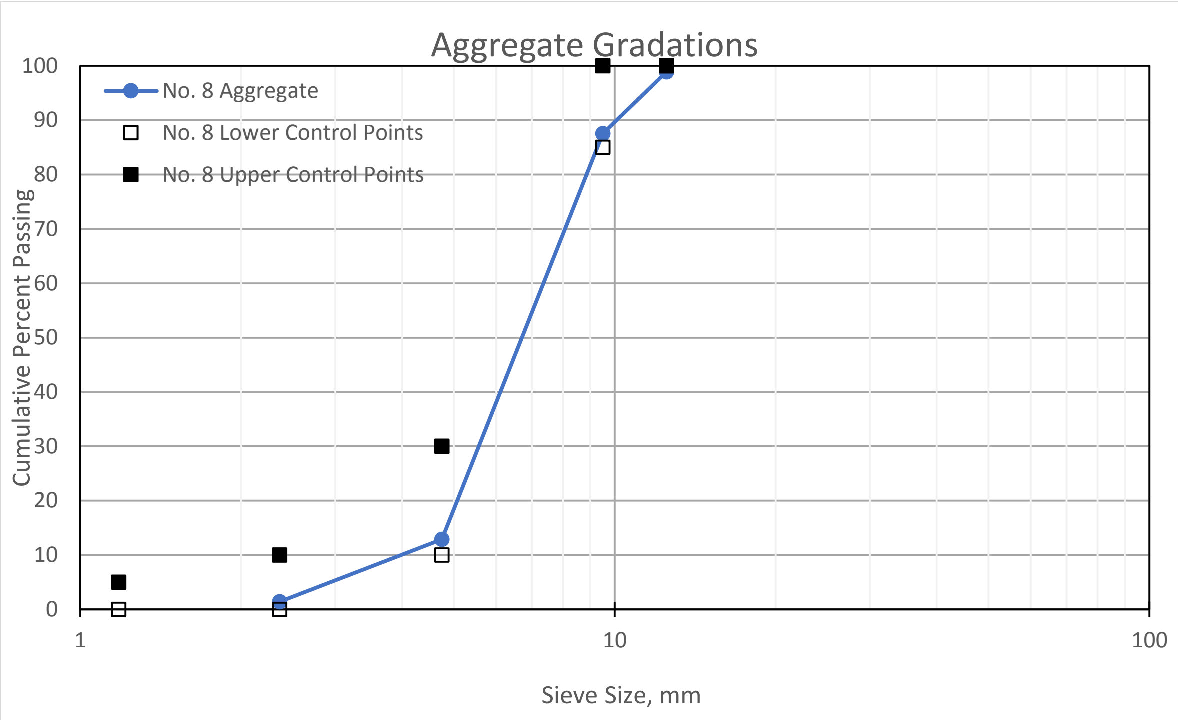

Figure 23. Gradation of No. 8 Aggregate used in Aggregate Drain (25.4 mm = 1 in).

The porous concrete drains were constructed using material meeting ODOT specification Item 306, Cement Treated Free Draining Base (CTFDB) except the cement content was 400 lb/yd^3 (237 kg/m^3) rather than 250 lb/yd^3 (148 kg/m^3). This specification is no longer used by ODOT and last appeared in the 2005 CMS. CTFDB used for the project used AASHTO No. 57 coarse aggregate. The specification and delivery tickets are reproduced in Appendix N.

Equipment

As part of Phase 1 of this study, the rock saw was selected for evaluation because the county crew familiarity with equipment reduced training needs; compact size results in less intrusion into adjacent lanes, improving safety; expected production rate; material can be wasted on site; and cost.

To meet the fifth objective of this study, aggregate drains were constructed primarily with a rock saw. As noted previously, aggregate drains were also constructed with a T4 Bobcat E85 Compact Excavator (referred to as backhoe in this report). Equipment used to construct the “rock saw” sections was a T4 Bobcat Compact Track Loader with rubber tracks. The equipment was upgraded with high flow hydraulics and a WS 24 wheel saw with an 8 inch (20 cm) wheel and trench cleaner accessory. The WS 24 can trench up to 8 in (20 cm) wide and up to 24 in (61 cm) deep. A trench compactor accessory with an 8 in (20 cm) wide pad kit, see Figure 24, was purchased to compact trench backfill material.

Figure 24. Bobcat with Compactor Attachment.

Layout of Test Sections

To compare the effectiveness of aggregate drains by various methods and materials, the initial soil conditions among all the test sections should be as similar as possible. To achieve this, preliminary FWD testing was performed. The goal was to identify areas along the site which had statistically similar soil responses to the FWD load.

On March 7th, 2016, FWD testing was conducted by ODOT using a Dynatest FWD model 8002. Drops of 9000 lb (40 kN) were made in the center of the eastbound lane every 50 ft (15 m) beginning at the MAR-529/Mautz-Yeager intersection (the zero point for the site) and ending at the Marion/Morrow county line, for a total of 463 drops. Deflections were measured at the surface using ODOT's standard arrangement of geophones, spaced as shown in Table 16. The third geophone, D3, is placed on the side of the load opposite to the other geophones.

Table 16. FWD Geophone Array.

Geophone	D1	D2	D3	D4	D5	D6	D7
Distance from load (inches)	0	12	-12	24	36	48	60
Distance from load (cm)	0	30	-30	61	91	122	152

The loads were first normalized to 9000 lb (40 kN) to enable comparisons among the locations. The "D5" deflection sensor, located 36 in (91 cm) from the center of the load plate, was selected to represent the condition of the natural subgrade. This sensor was chosen because it would best represent the response of soil located 24 in (61 cm) below the surface, assuming the stress bulb forms a 34^{o} angle with the surface [Irwin, 2010], rather than the asphalt concrete layer or base material.

Next, a statistical method of determining the boundaries of uniform units with the aid of the D5 deflection sensor was used to determine areas of similar soil types. This method is known as delineating statistical homogeneous units by the "Cumulative Differences Method" [AASHTO, 1986]. Using this method, the project site was separated into 10 regions. Each region was clearly defined by beginning and end measurements recorded by the FWD's Digital Measuring Instrument (DMI). T-tests were performed, comparing each of the 10 regions to one another. The t-tests showed there were six regions with similar soil responses. Based on the results of the analysis, regions with average deflections measured at the D5 sensor between 3.76 mil (95.5 µm) and 5.95 mil (151 µm) were included, whereas regions with average measured deflections outside of that window were rejected. A total of 3.1 mi (5 km) of the 4.6 mi (7.4 km) of the site were identified for use in the study.

To develop a layout of test sections, first, the total number of combinations of test variables was determined from the experimental matrices shown in Tables 13 through 15. A total of 40 different combinations were identified, each assigned to a test section. Additionally, four control sections, two for each section length being investigated, 125 ft (38 m) and 500 ft (152 m), were included, for a total of 44 sections. Section numbers were determined by assigning each combination of test variables a random number between 0.0000 and 1.0000 using the RAND function in Excel. These combinations were then sorted in ascending order based on the random number, and these were numbered as Section 1 through Section 44, with Section 1 nearest the Mautz-Yeager intersection progressing eastward. The one exception to this rule is Section 43, which was moved from its original position to between Section 2 and Section 3 to avoid conflicts with driveways at the original location. Start and end stations are listed for each section in Appendix J, with the stationing beginning at the Mautz-Yeager intersection and progressing eastward.

A coding system was developed to identify the variables included in each section so the Marion County crew could easily identify which treatment techniques were to be used in a given section during installation of the drains. An explanation of the coding system for a given section and an example of a designated code is shown below. Table 17 lists for each section the designated code and each variable investigated.

(1) (2) (3) (4) (5) (6) (7)

1 - R - #4 - NF - C - L - N

1) Arbitrary section number which was used for randomizing the sections.
2) Refers to the type of equipment used to excavate the trenches: Backhoe (B) or Rock Saw (R).
3) Material Type used in drains: #4, #57, #8 stone, or Porous Concrete (PC).
4) “F” or “NF” - Whether or not filter fabric was used: Fabric (F) or No Fabric (NF).
5) “C” or “NC” – Whether or not the material is compacted: Compaction (C) or No Compaction (NC).
6) “L” or “S” – Refers to the length of spacing used: Long (L) is 200 ft (61 m), and Short (S) is 50 ft (15 m).
7) “N” or “W” – Refers to the trench width: Narrow (N) is 8 in (20 cm) and Wide (W) is 15 in (38 cm).

Table 17. Section Information and Coding (Customary Units) (50 ft = 15 m, 200 ft = 61 m; 8 in = 20 cm, 15 in = 38 cm).

Section	Method	Material	Fabric	Compact	Spacing	Width	Code
1	Rock Saw	No. 4 Aggregate	No	Yes	200 ft (61 m)	8 in (20 cm)	R #4 NF C L N
2	Rock Saw	No. 57 Aggregate	No	Yes	50 ft (15 m)	8 in (20 cm)	R #57 NF C S N
3	Rock Saw	No. 57 Aggregate	Yes	Yes	50 ft (15 m)	8 in (20 cm)	R #57 F C S N
4	-	Control-500B	-	-	-	-	CNTRL-500B
5	Backhoe	No. 57 Aggregate	Yes	Yes	50 ft (15 m)	15 in (38 cm)	B #57 F C S W
6	Backhoe	No. 57 Aggregate	Yes	No	50 ft (15 m)	15 in (38 cm)	B #57 F NC S W
7	Backhoe	No. 57 Aggregate	Yes	No	200 ft (61 m)	15 in (38 cm)	B #57 F NC L W
8	Backhoe	No. 57 Aggregate	No	No	50 ft (15 m)	15 in (38 cm)	B #57 NF NC S W
9	Rock Saw	Porous Concrete	Yes	Yes	50 ft (15 m)	8 in (20 cm)	R PC F C S N
10	-	Control-125B	-	-	-	-	CNTRL-125B
11	Rock Saw	No. 57 Aggregate	No	No	50 ft (15 m)	8 in (20 cm)	R #57 NF NC S N
12	Rock Saw	No. 8 Aggregate	No	Yes	200 ft (61 m)	8 in (20 cm)	R #8 NF C L N
13	Rock Saw	No. 57 Aggregate	Yes	No	200 ft (61 m)	15 in (38 cm)	R #57 F NC L W
14	Rock Saw	Porous Concrete	No	No	50 ft (15 m)	8 in (20 cm)	R PC NF NC S N
15	Rock Saw	No. 4 Aggregate	Yes	No	50 ft (15 m)	8 in (20 cm)	R #4 F NC S N
16	Rock Saw	No. 57 Aggregate	No	Yes	200 ft (61 m)	15 in (38 cm)	R #57 NF C L W
17	Rock Saw	No. 57 Aggregate	Yes	No	50 ft (15 m)	15 in (38 cm)	R #57 F NC S W
18	Rock Saw	Porous Concrete	No	Yes	50 ft (15 m)	8 in (20 cm)	R PC NF C S N
19	Backhoe	No. 57 Aggregate	No	Yes	50 ft (15 m)	15 in (38 cm)	B #57 NF C S W
20	Rock Saw	No. 4 Aggregate	No	Yes	50 ft (15 m)	8 in (20 cm)	R #4 NF C S N
21	-	Control-500A	-	-	-	-	CNTRL-500A
22	Rock Saw	No. 57 Aggregate	No	Yes	200 ft (61 m)	8 in (20 cm)	R #57 NF C L N
23	Rock Saw	No. 57 Aggregate	No	No	200 ft (61 m)	15 in (38 cm)	R #57 NF NC L W
24	Rock Saw	No. 8 Aggregate	No	No	50 ft (15 m)	8 in (20 cm)	R #8 NF NC S N
25	Rock Saw	No. 8 Aggregate	No	No	200 ft (61 m)	8 in (20 cm)	R #8 NF NC L N
26	Rock Saw	No. 4 Aggregate	No	No	50 ft (15 m)	8 in (20 cm)	R #4 NF NC S N
27	Backhoe	No. 57 Aggregate	Yes	Yes	200 ft (61 m)	15 in (38 cm)	B #57 F C L W
28	Rock Saw	No. 57 Aggregate	Yes	Yes	50 ft (15 m)	15 in (38 cm)	R #57 F C S W
29	Backhoe	No. 57 Aggregate	No	Yes	200 ft (61 m)	15 in (38 cm)	B #57 NF C L W
30	Rock Saw	No. 8 Aggregate	Yes	Yes	50 ft (15 m)	8 in (20 cm)	R #8 F C S N
31	Rock Saw	No. 57 Aggregate	Yes	Yes	200 ft (61 m)	8 in (20 cm)	R #57 F C L N
32	Rock Saw	No. 57 Aggregate	Yes	No	200 ft (61 m)	8 in (20 cm)	R #57 F NC L N
33	Rock Saw	Porous Concrete	Yes	No	50 ft (15 m)	8 in (20 cm)	R PC F NC S N
34	Rock Saw	No. 8 Aggregate	No	Yes	50 ft (15 m)	8 in (20 cm)	R #8 NF C S N
35	Rock Saw	No. 57 Aggregate	Yes	No	50 ft (15 m)	8 in (20 cm)	R #57 F NC S N
36	Rock Saw	No. 57 Aggregate	Yes	Yes	200 ft (61 m)	15 in (38 cm)	R #57 F C L W
37	-	Control -125A	-	-	-	-	CNTRL-125A
38	Rock Saw	No. 57 Aggregate	No	No	200 ft (61 m)	8 in (20 cm)	R #57 NF NC L N
39	Rock Saw	No. 57 Aggregate	No	Yes	50 ft (15 m)	15 in (38 cm)	R #57 NF C S W
40	Rock Saw	No. 8 Aggregate	Yes	No	50 ft (15 m)	8 in (20 cm)	R #8 F NC S N
41	Backhoe	No. 57 Aggregate	No	No	200 ft (61 m)	15 in (38 cm)	B #57 NF NC L W
42	Rock Saw	No. 57 Aggregate	No	No	50 ft (15 m)	15 in (38 cm)	R #57 NF NC S W
43	Rock Saw	No. 4 Aggregate	Yes	Yes	50 ft (15 m)	8 in (20 cm)	R #4 F C S N
44	Rock Saw	No. 4 Aggregate	No	No	200 ft (61 m)	8 in (20 cm)	R #4 NF NC L N

Aggregate Drain Locations
According to the ODOT Pavement Design Manual [2016], Section 205.1.4, aggregate drains should be located at intervals of 50 ft (15 m) on each side of the pavement and staggered such that the longitudinal distance between the adjacent drain in the opposite lane is half the interval distance. For this study two interval distances were investigated: the standard distance of 50 ft (15 m), and a longer distance of 200 ft (61 m). Within each experimental section, three drains were located in each direction, for a total of six drains, with drains staggered in opposite lanes, as shown in Figure 25. The location of each drain is listed in Appendix J, such that the stationing, regardless of the lane the drain is in, progresses eastward.

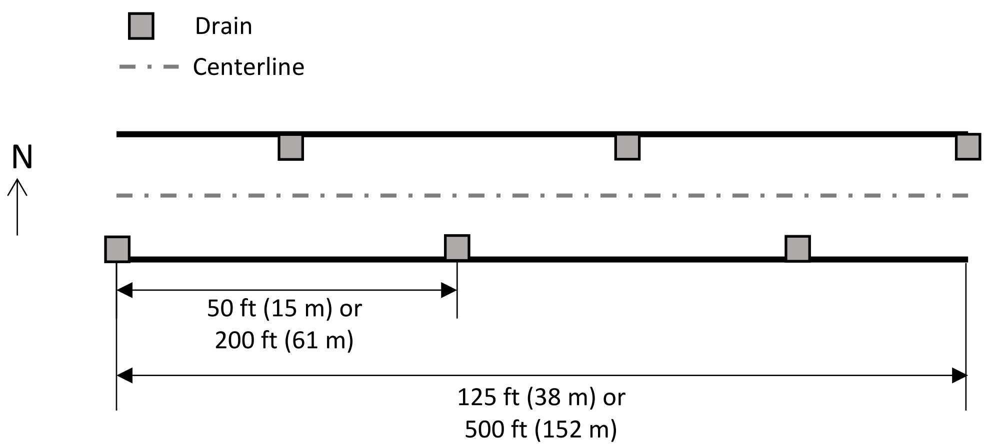

Figure 25. Aggregate Drain Layout (Not to Scale).

Aggregate Drain Construction

Aggregate drains were constructed in April and May of 2016, as detailed in Appendix K. Traffic control was established prior to construction to protect workers. A moving operation setup was used for traffic control which allowed the construction zone to progress down the road without having to reset.

The following describes the processes, people, and equipment needed to perform aggregate drain installation:

1. Saw Cutting (shown in Figure 26)
    a. Walk behind pavement saw and water truck to deliver water to the saw.
    b. One person to operate the saw and one person to drive the water truck
2. Excavation (shown in Figures 26 and 27)
    a. Backhoe with a 15 inch wide bucket or rock saw with 8” (20 cm) cutting head.
    b. One person to operate backhoe or rock saw.
    c. One person to operate truck for excavated material

Figure 26. Backhoe Excavation.

Figure 27. Rock Saw Excavation.

3. Trench Cleanout
    a. Two people with trench rakes and shovels to clean debris out of trench before placing fabric or backfilling.

4. Fabric Installation
    a. Two people to place fabric in trench. Typically the same people who cleaned out the trench. This process is shown in Figure 28.

Figure 28. Fabric Installation.

5. Backfill
    a. One person to drive and operate truck with drainage material. Typically the same people who cleaned out trench can backfill with shovels and rakes. This is shown in Figure 29.

Figure 29. Backfilling.

6. Compaction
    a. If compacted, the material will be placed in two lifts, compacting after each lift.
    b. One person to operate compactor.

Figure 30. Compaction.

7. Second Backfill
    a. Place second layer of drainage material, same process as step 5.

8. Second Compaction
    a. Compact second lift, same process as step 6.

9. Cold Mix Patching
    a. Truck with cold mix.
    b. Two people for patching.

When the rock saw was used, Step 1 was omitted. Step 4 was omitted when fabric was not installed. When backfill was not compacted, the backfill was placed in one lift and steps 6, 7, and 8 were omitted.

As part of the production analysis, the number of workers and the number and type of equipment required to accomplish each task were identified. The Table 18 summarizes each operation and the number of people and equipment to accomplish the task.

Table 18. Summary of Personnel and Equipment Needs.

Operation	No. of People Needed	No. of Pieces of Equipment Needed
Backhoe[1]	3	3
Rock Saw[2]	1	1
Fabric[3]	2	0
Backfill[4]	3	1
Compaction[5]	1	1
Patching[6]	2	1

1 Backhoe excavation requires the backhoe, pavement saw, and water truck along with people to operate all of them.
2 Rock saw excavation requires the rock saw and the operator.
3 Fabric placement requires two workers to install and no heavy machinery.
4 Backfilling requires a distribution truck and driver, as well as two ground workers operating the chute and distributing materials.
5 Compacting the material requires the compactor and operator.
6 Patching requires two workers and a truck for hauling cold mix.

The time required to complete each step of the drain installation was monitored and recorded for each section. Information recorded included the following:

- Section ID
- Date
- Excavation equipment type (rock saw or backhoe)
- Other equipment (i.e. pavement saw, dump truck, etc.)
- Begin and end time for
    - Excavation
    - Fabric installation
    - Backfilling trench
    - Compaction of backfill
    - Factors affecting construction (i.e. refueling equipment)

A Construction Production Sheet was developed to standardize the data collection. An example and the measured installation times are shown in Appendix O.

Field Monitoring

To evaluate the effectiveness of the aggregate drains, field testing was conducted at various times throughout the first year after installation.

DCP Testing

DCP testing was conducted to determine the effect, if any, of aggregate drains on underlying materials, and, if so, how stiffness varied for the various parameters (aggregate gradation, spacing, equipment, and trench width). Testing was conducted in each section in the westbound (WB) lane. The test location within a section was approximately the midpoint of the section, between two planned/installed drain locations, as shown in Figure 31. Stations associated with DCP testing in each section are listed in Appendix C. Prior to construction of the drains, DCP testing was conducted beginning on April 12, 2016 and concluding on April 13, 2016 to establish baseline stiffness of the base and subgrade layers. At the conclusion of the monitoring period, testing will be conducted.

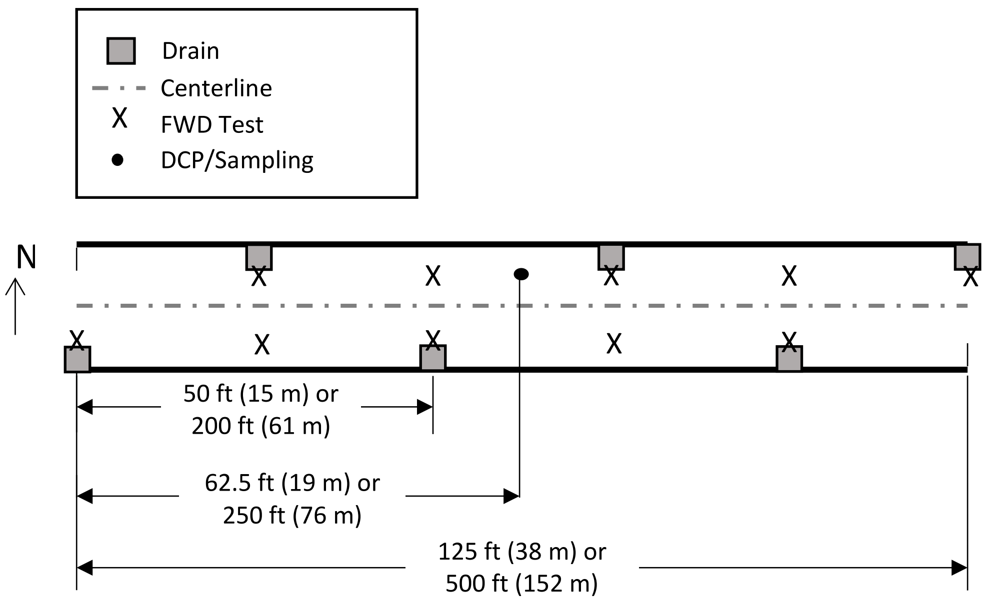

Figure 31. Typical Section Layout and Test Locations (Not to Scale).

DCP testing was conducted as described previously under Phase 1. The cores extracted from the pavement were retained and measured to determine AC pavement layer thickness for use in backcalculation of layer moduli using measured FWD deflections. The same method used in Phase 1 to estimate the resilient modulus for the granular base layer and subgrade was followed for Phase 2 work. Using the cumulative differences method [AASHTO, 1986] uniform layers were determined, as shown in Figure 32. The first uniform layer, or the upper portion of the unbound layers in the structure was the water-bound macadam base layer. In some cases a uniform layer of softer material (higher penetration rate) was found within the water-bound macadam base layer such that after passing through the softer material DCP results rebounded to PR values in line with the first uniform layer (water-bound macadam base). Similarly, in some cases, uniform layers of stiffer material were also identified within the subgrade material or the lower portion of the structure. In these cases, the resilient modulus was calculated for each blow using the average PR for the uniform layer. The resulting moduli were then averaged for all blows within the water-bound macadam base layer, and likewise for all blows that were within the subgrade material. In these cases, the average resilient modulus for the water-bound macadam base layer and for the subgrade was reported.

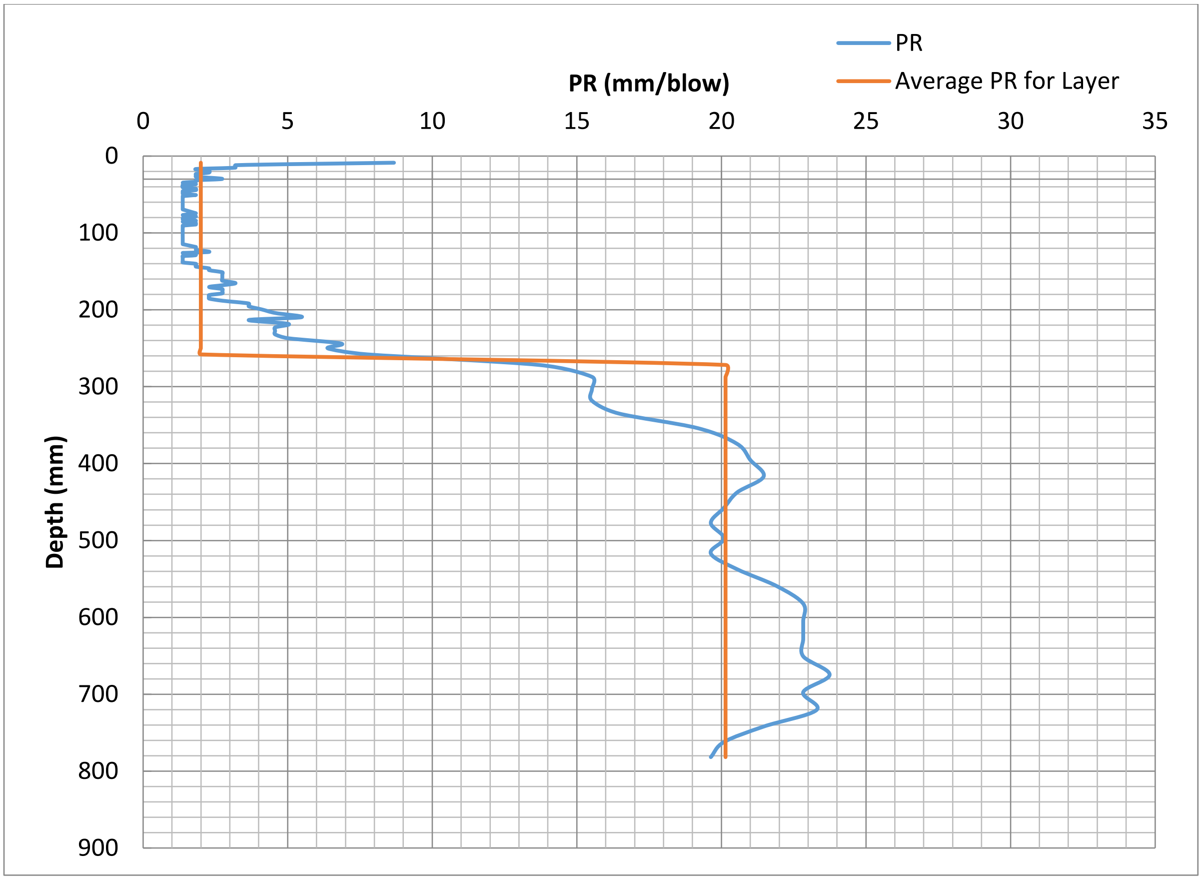

Figure 32. Example DCP Test Result from April, 2016.

FWD Testing

In addition to the initial FWD testing conducted to establish the layout of the test sections, FWD Testing was conducted periodically over the one-year monitoring period after the construction of the aggregate drains. Testing was conducted by ODOT using the same equipment and geophone array utilized in the initial FWD analysis and consisted of one drop with a 9000 lb (40 kN) load approximately 6 in (150 mm) to the left of the right wheel path. Testing was conducted at six locations, three at aggregate drain locations and three midway between aggregate drains, in each direction of each section, as shown in Figure 29. Stations of the FWD test locations coincide with the stationing for each aggregate drain, which are listed in Appendix J. Stations for FWD testing conducted between aggregate drains coincided with the stationing for the aggregate drains in the opposite lane.

Backcalculation was conducted to estimate the in-place moduli from measured FWD deflections. The measured FWD deflections at the 9000 lb (50 kN) load level in combination with the layer thicknesses were used to estimate in-place moduli for the AC layer, granular base layer, and subgrade for each test location. AC layer thicknesses were determined from the pavement cores extracted during DCP testing. Thicknesses for the granular base layers of each section were estimated from the DCP analysis.

First, the subgrade modulus was estimated following the procedure for a two-layer backcalculation presented in the 1993 AASHTO Design Guide using Equation 4 [AASHTO, 1993]. For this analysis deflections measured at the furthest sensor from the load (60 in (1.5 m), as shown in Table 16) was used to compute the modulus of the subgrade layer.

$$M_R = \frac{0.24P}{d_r r} \quad (4)$$

where:

M_R = Resilient Modulus of the subgrade (psi)
P = applied load (lbs)
d_r = deflection at a distance r from the center of the load (in)
r = distance from the center of load (in)

Once determined, the modulus of the subgrade was in turn used to estimate the modulus of the granular base layer following the Dorman and Metcalf relationship as presented in [Stubstad, Jiang, and Lukanen, 2006] using Equation 5:

$$E_{Base} = 0.86 \times {h_2}^{0.45} \times E_{sub} \quad (5)$$

where:

E_{Base} = Base Modulus (psi)
h_2 = Thickness of the intermediate base layer (in)
E_{sub} = Subgrade modulus (psi) (M_R from Equation 4)

Lastly, the asphalt layer moduli were estimated based on the AREA factor using the following equations as presented in [Stubstad, Jiang, and Lukanen, 2006]:

$$E_{AC} = \frac{\left[E_0 \times AF_{AC} \times {k_3}^{\left(\frac{1}{AF_{AC}}\right)}\right]}{{k_3}^2} \quad (6)$$

$$E_0 = \frac{1.5 \times a \times \sigma_0}{d_0} \quad (7)$$

$$AF_{AC} = \left[\frac{(k_2 - 1)}{\left\{k_2 - \left(\frac{AREA_{12}}{k_1}\right)\right\}}\right]^{1.35} \quad (8)$$

$$AREA_{12} = 2 \times \left[2 + 3 \times \left(\frac{d_8}{d_0}\right) + \left(\frac{d_{12}}{d_0}\right)\right] \quad (9)$$

where:

E_{AC} = Stiffness of modulus of the upper AC (bound) layer
E_0 = Composite modulus of the entire pavement system beneath the load plate
AF_{AC} = AREA factor (i.e., the improvement in AREA to the 1.35 power)
$AREA_{12}$ =AREA beneath the first 12 inches (305 mm) from the center of the load plate
k_1 = 6.85
k_2 = 1.752
k_3 = Thickness ratio of upper layer thickness/load plate diameter = $h_1/(2a)$
a = Radius of the FWD load plate
σ_0 = (Peak) pressure for FWD impact load under the load plate
d_0 = FWD deflection measured at the center of the FWD load plate
d_8 = FWD deflection measured 8 inches (203 mm) from the center of the plate
d_{12} = FWD deflection measured 12 inches (305 mm) from the center of the load plate

In computing $AREA_{12}$, the deflection at 8 inches (203 mm) from the load was not measured as part of ODOT's standard geophone array as shown in Table 16, therefore d_8 was interpolated from the d_0 and d_{12} measurement.

TDR Readings

Campbell Scientific CS659 Water Content Sensors were installed in the eastbound lane to enable measurement of the in-situ volumetric moisture content in the granular base material (ODOT Item 304 aggregate base according to straight-line diagrams) over time. The volumetric moisture content was measured by a Hydrosense II handheld reader, shown in Figure 33 attached to a sensor. The TDR probes were installed at the bottom of the cut for the aggregate drain, as shown in Figure 34. The excavated Item 304 aggregate base was used as bedding atop the existing subgrade. The sensor was placed on this bedding, just above the interface with the existing subgrade, and covered with approximately 1 in (25 mm) or more of 304 aggregate base material which was then hand compacted around the sensor. The aggregate backfill for the drain was then placed on top of the backfilled Item 304 aggregate base.

Figure 33. Soil Volumetric Water Content Sensor with Hydrosense II Reader. [http://www.campbellsci.com]

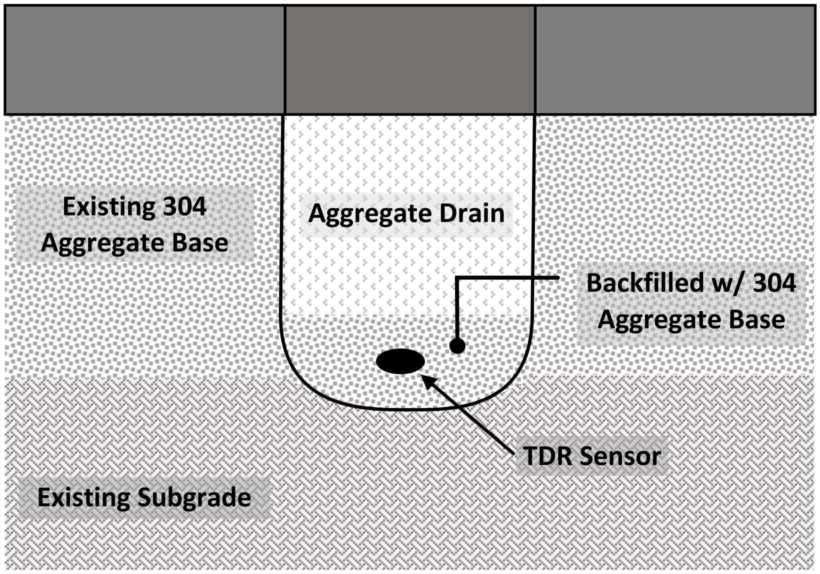

Figure 34. Example Cross-section of Aggregate Drain with TDR Sensor.

TDR sensors were also installed in control sections and between drains. For the locations which did not coincide with an aggregate drain, the TDR sensors were installed in the 304 aggregate base just above the interface with the existing subgrade. Access for sensor installation was achieved by excavating from the shoulder with the rock saw into the 304 aggregate base beneath the asphalt layer. This procedure was followed to ensure the sensor was installed within the 304 aggregate base and within the pavement structure, to be consistent with the installation of the TDR probe within the aggregate drains.

A total of 18 TDR sensors were installed in the EB lane of nine sections. Two of the sections were control sections (denoted as CNTRL) with no aggregate drains, as listed in Table 19. For the seven experimental sections, TDR sensors were installed at the second aggregate drain in the EB lane (drain No. 3), and in between the second (drain No. 3) and third drain (drain No. 5) in the EB lane. For the two control sections, the TDR sensors were installed in two locations at intervals proportional to the length of the section: 50 ft (15 m) and 100 ft (30 m) for section lengths of 125 ft (38 m) and 500 ft (150 m), respectively.

Table 19. Sections Selected for In-situ Moisture Monitoring.

Section	Code	Material	Fabric	Compaction	Length (ft (m))	Spacing (ft (m))	Trench Width (in (cm))
1	R #4 NF C L N	#4	N	Y	500 (152)	200 (61)	8 (20)
2	R #57 NF C S N	#57	N	Y	125 (38)	50 (15)	8 (20)
10	CNTRL-125B	CNTRL	CNTRL	CNTRL	125 (338)	N/A	8 (20)
12	R #8 NF C L N	#8	N	Y	500 (152)	200 (61)	8 (20)
18	R PC NF C S N	PC	N	Y	125 (38)	50 (15)	8 (20)
20	R #4 NF C S N	#4	N	Y	125 (38)	50 (15)	8 (20)
21	CNTRL-500A	CNTRL	CNTRL	CNTRL	500 (152)	N/A	8 (20)
22	R #57 NF C L N	#57	N	Y	500 (152)	200 (61)	8 (20)
34	R #8 NF C S N	#8	N	Y	125 (38)	50 (15)	8 (20)

APPENDIX G RESULTS AND DISCUSSION

Characterization of Unbound Layers

Sieve analysis and Atterberg limit tests were performed on samples of the water-bound macadam and subgrade soil to classify the materials distributed along the project. Results for the water-bound macadam base are presented in Table 20. Results for the subgrade soil are presented in Table 21 and shown in Figure 37. As shown in Table 20 and Figure 36, the gradation of the base material was highly variable with the highest variation in the material passing the 3/8" (9.5 mm) and #4 (4.75 mm) sieve. As seen in Figure 37, the gradations of the subgrade soils were more consistent and composed of A-2-4, A-2-6 and A-4 soils (Table 22).

Table 20. Sieve Analysis of Water-bound Macadam Base.

Sieve Size		Macadam Base Sections: Percent Passing (%)												Average
(US)	(mm)	1	3	9	12	14	18	19	21	24	27	42	44	
2"	50.800	100.0	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8
1 -1/2"	38.100	75.1	81.9	81.9	81.9	81.9	81.9	81.9	81.9	81.9	81.9	81.9	81.9	81.9
1"	25.400	61.9	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
3/4"	19.000	46.1	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9
3/8"	9.500	25.5	45.9	45.9	45.9	45.9	45.9	45.9	45.9	45.9	45.9	45.9	45.9	45.9
4	4.750	18.0	39.1	39.1	39.1	39.1	39.1	39.1	39.1	39.1	39.1	39.1	39.1	39.1
16	1.180	14.0	24.3	24.3	24.3	24.3	24.3	24.3	24.3	24.3	24.3	24.3	24.3	24.3
30	0.595	8.3	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4
50	0.300	4.1	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6
100	0.149	0.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
200	0.075	0.2	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5

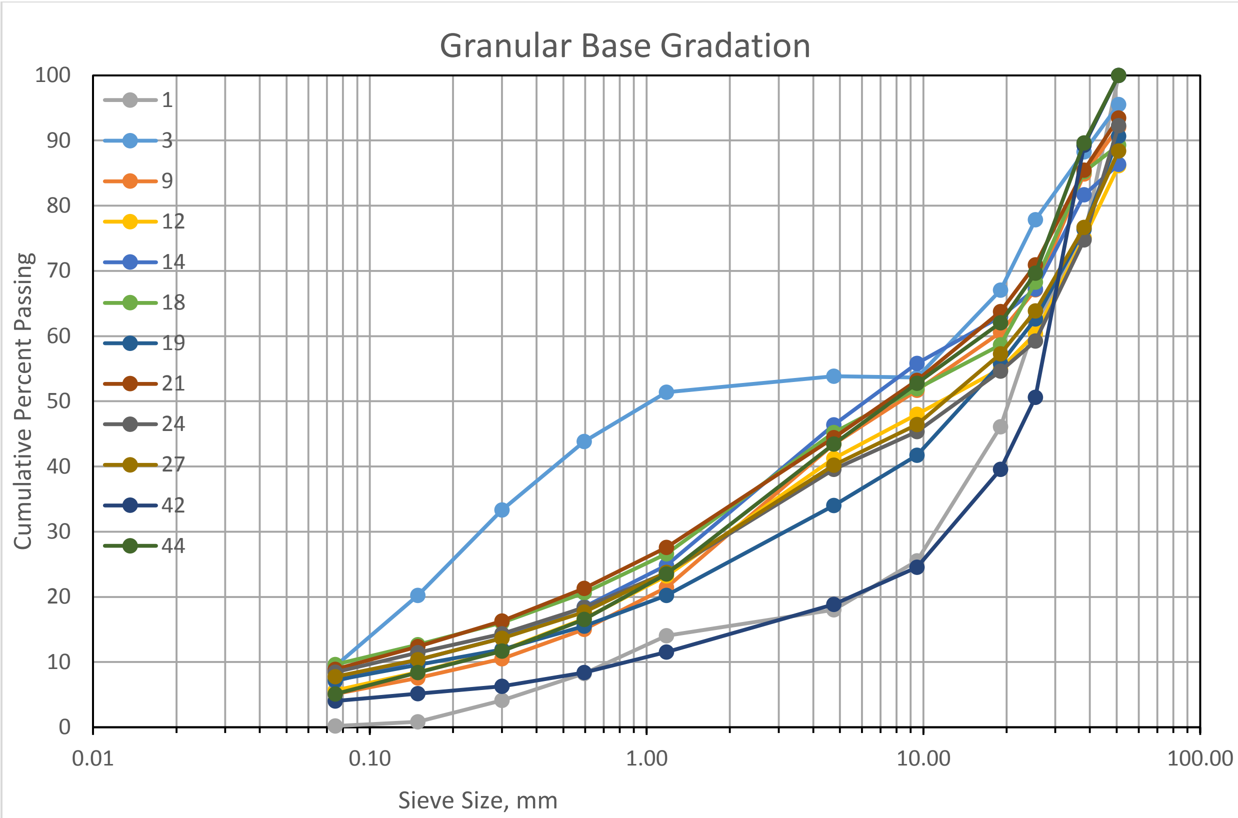

Figure 35. Water-bound Macadam Base Gradations.

Table 21. Sieve Analysis of Subgrade.

Sieve Size	Sieve Size	Subgrade Sections: Percent Passing (%)						Average
(US)	(mm)	1	9	12	23	34	44	
1"	25.400	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	19.000	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8"	9.500	100.0	100.0	100.0	100.0	100.0	100.0	100.0
4	4.750	100.0	99.9	100.0	100.0	99.8	96.1	99.3
8	2.360	99.9	98.4	99.9	99.7	99.4	91.9	98.2
16	1.180	99.8	96.4	99.8	99.6	99.2	90.6	97.5
30	0.595	99.8	93.6	99.7	99.2	98.7	89.8	96.8
50	0.300	85.2	78.7	87.0	81.8	81.2	74.0	81.3
100	0.149	58.1	52.9	58.2	53.3	56.3	53.7	55.4
200	0.075	35.5	34.0	31.1	35.0	38.3	37.8	35.3

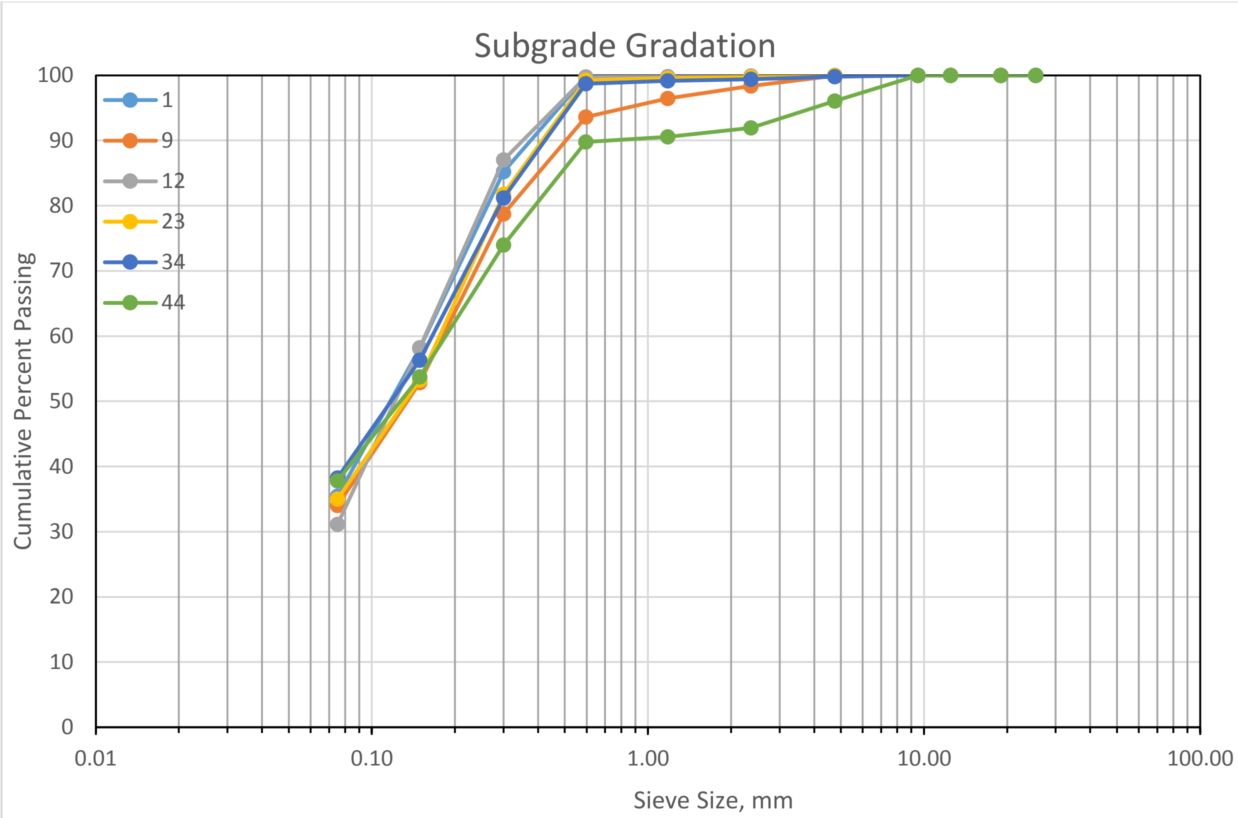

Figure 36. Subgrade Gradations.

Table 22. Subgrade Soil Classification.

Section	Passing #200 (0.075 mm) (%)	LL (%)	PI (%)	AASHTO Classification	AASHTO Description
1	35	19	7	A-2-4	silty or clayey gravel and sand
12	31	15	7	A-2-4	silty or clayey gravel and sand
23	35	19	11	A-2-6	silty or clayey gravel and sand
34	38	17	10	A-4	silty soils
44	38	15	8	A-4	silty soils

Evaluation of Equipment

During the compaction operation it was observed compaction in the narrow trench (8 in (20 cm)) appeared to be more effective due to confinement. However, in the wide trench (15 in (38 cm)) and in the shoulder portion of both the 8-in (20 cm) and 15-in (38 cm) trenches it was observed the material flowed around and over the compaction pad rather than densifying, it is believed this was due to the lack of lateral confinement.

Equipment Production Rates

A box plot, shown in Figure 37, summarizes the installation time data using the backhoe and the rock saw. The bottom and top of the box represents the 1st and 3rd quartiles, respectively. The line inside the box represents the median value and the dot inside the box represents the mean value. The two lines extending from the box represents values outside the 1st and 3rd quartile and the horizontal bars on the end of the vertical lines represent the minimum and maximum values. Box plots are useful for determining the spread and skew of the data. When comparing a variable, such as total time, if the boxes do not overlap, there is a statistical difference in the two procedures. If the boxes overlap, but do not include both medians, there is likely a difference in the time required to perform the two procedures. If the boxes overlap and include both medians, both procedures are considered to require the same time to perform. [Sargand et al., 2016]

The box plot clearly shows a significant difference in excavation time, with the rock saw completing the operation in an average of slightly less than 2 minutes while the backhoe took an average of slightly more than 13 minutes. Total time to complete the aggregate drain installation was also statistically different with the rock saw taking an average of slightly less than 8 minutes and the backhoe taking slightly more than 32 minutes to complete. Compacting the backfill took an additional 3 to 5 minutes for both the rock saw and backhoe with the exception of the compaction of the trench cut with the backhoe and lined with the fabric before backfilling, which took an additional 9 minutes on average to compact. Using fabric added 1 to 3 minutes to the installation time.

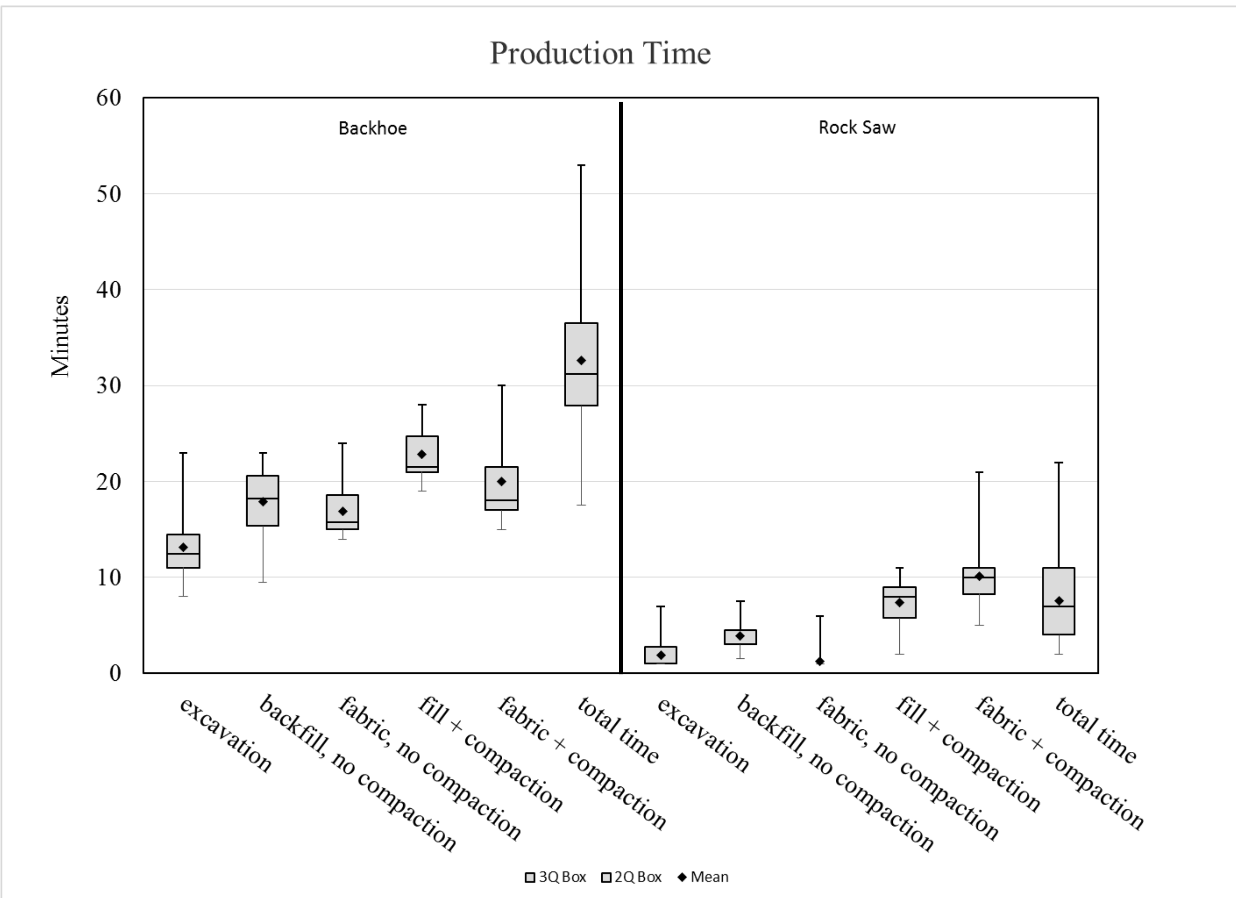

Figure 37. Production Time for Backhoe and Rock Saw.

Cost Savings Analysis

Most of the processes associated with the installation of the aggregate drains, such as placing fabric, back filling the trench, compacting the backfill, etc., are common regardless of the equipment used to create the trench and were not considered in the cost savings analysis. Therefore, only the equipment and labor which is unique to the trench excavation procedure were considered in the cost analysis. For the rock saw procedure, the rock saw equipped track loader was the only unique equipment. For the excavator procedure, a pavement saw with water truck, a dump truck to remove excavated material, and two additional laborers were unique to the process.

The cost of labor was determined from the Ohio Department of Administrative Services pay rate tables. A Highway Technician Equipment Specialist would have the skills to operate the pavement saw (DAS Classification Specifications, 2017). This position is a pay range 07 which has a maximum salary, without longevity, of $19.77 (DAS OSCEA Pay Range Schedule, 2017).

Equipment cost, other than the excavator and the rock saw (referred to by vendor as track loader with wheel saw), was taken from the Ohio Department of Transportation's 2016 Equipment Standard Rates (ODOT Equipment Standard Rates, 2017). The walk behind pavement saw is assigned a per hour rate of $16.00. A water tank, pump, and stake bed truck are assigned a combined rate of $46.74 per hour. A dump truck has a per hour rate of $50.15.

An average installation using the excavator took 13 minutes. The marginal cost for this installation when compared to the installation using the rock saw would be:

Marginal installation cost using excavator
= (additional labor rate + additional equipment rate) x 13 minutes
= ((2 x $19.77/hour) + ($46.74/hour + $50.15/hour)) X 13 minutes/(60 minutes/hour)
= $29.56/hour

The rock saw and compact excavator used on this project was purchased by ODOT for a total of $87,541 and $79,835, respectively, for a difference of $7,706.

Therefore, the additional cost of the rock saw would be recovered after operating for 261 hours ($7706/$29.56/hour = 261 hours). This time corresponds to the average time needed to install 1,205 aggregate drains.

To drain undrained sections in one county, District 6 estimated 400 miles of two lane pavement would require the installation of aggregate drains. If installed on alternating sides at a 25 ft spacing, the number of aggregate drains would be (400 mile) x (5280 ft/mile) x (1 drain/25 ft) =84,480 drains. If installed with a backhoe, the excavation time would be (84,480 drains) x (13 minutes) x (1 hour/60 minutes)=18,304 hours. Using the rock saw, the same excavations would take (84,480 drains)x(2 minutes)x(1 hour/60 minutes)=2,816 hours. A reduction of 1,936 eight hour work days. Projected savings would be (18,304 hours – 2,816 hours) x $29.56/hr = $457,825.

Results of DCP Testing

DCP testing was conducted on April 12, 2016 and April 13, 2016, prior to the installation of the aggregate drains and four days; May 25, May 26, June 1, and June 2 at the conclusion of the field monitoring period in 2017. DCP testing provides approximate layer thicknesses as well as a means to estimate the in-situ layer modulus using Equations 1 through 3 to convert PR to resilient modulus. The cumulative differences method (AASHTO, 1986) was used to identify uniform layers from which the layer thickness of the water-bound macadam base was determined for each section. Full results are shown in Appendix L. The thickness for the water-bound macadam base layer based on initial DCP testing ranged from 4.7 in (119 mm) to 16.0 in (406 mm), with an average layer thickness of 10.6 in (270 mm). The coefficient of variation (COV), calculated as the ratio of the standard deviation to the mean, was found to be 26.5% for the layer thickness of the water-bound macadam base. Final DCP testing resulted in uniform layer thicknesses for the water-bound macadam base slightly different than the initial results. The thicknesses from final DCP testing ranged from 4.6 in (118 mm) to 18.4 in (468 mm) with an overall average of 11.4 in (289 mm) and a COV of 25.5%. The differences are likely due, at least in part, to slight spatial variation in construction since the DCP test location for the final testing was offset from the initial test location. The other cause for the differences may be tied to the reduction in moisture in drained sections, as evident in the TDR readings shown later in the report.

Initial and final resilient moduli of the in-situ base determined from DCP testing are shown in Figure 36 at each station (and section). Similarly, initial and final subgrade moduli from DCP testing are shown in Figure 37 for each station (and section). Layer moduli are reported for each section in Appendix L. The layer moduli are summarized in Table 23. As shown in Figures 38 and 39, the water-bound macadam base moduli and the subgrade moduli vary along the length of the project site. To assess the variability, the COV of the moduli was determined for each layer. As shown in Table 23, the subgrade modulus was the most variable with a COV of 37.4% and 54.5% for the initial and final testing, respectively.

Table 23. Summary of Layer Moduli Based on DCP Test Results.

Layer	Reading	Minimum		Maximum		Average		Std. Dev.		COV
		(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(%)
Water-bound macadam base	Initial	20,234	139.51	67,077	462.48	47,007	324.10	11,136	76.78	23.7
	Final	26,205	180.68	60,267	415.53	46,507	320.66	8,608	59.35	18.5
Subgrade	Initial	6,391	44.07	24,851	171.34	12,588	86.79	4,712	32.48	37.4
	Final	4,950	34.13	40,499	279.23	13,065	90.08	7,122	90.08	54.5

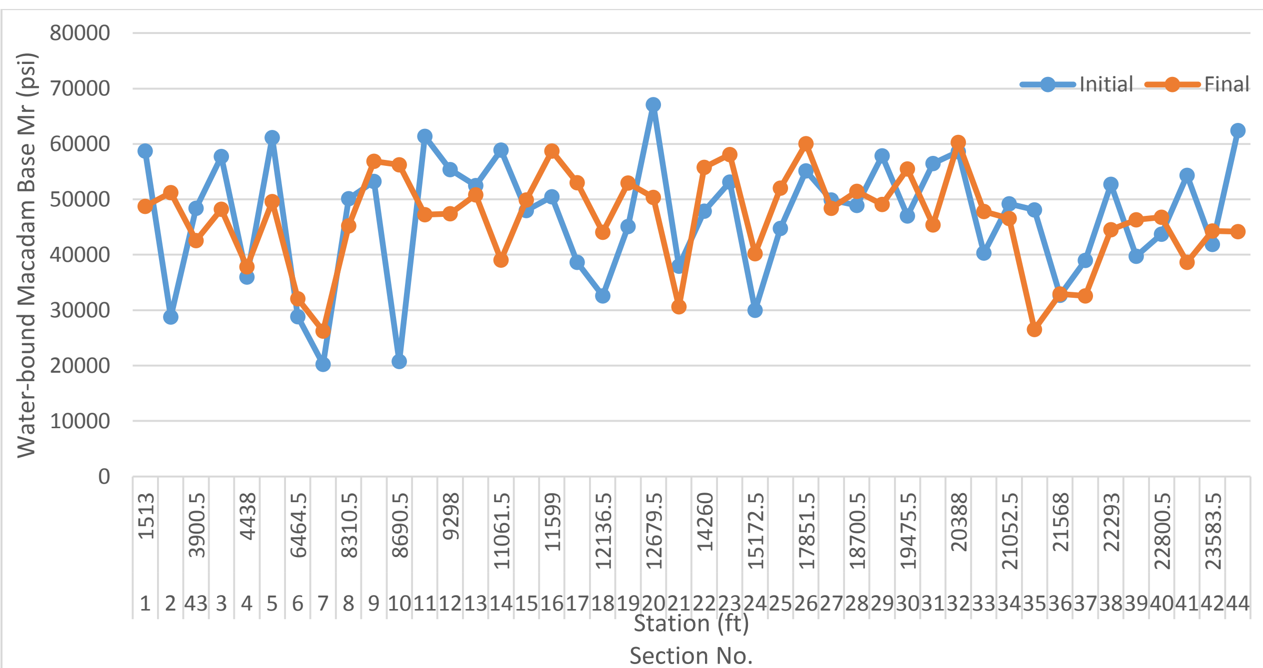

Figure 38. In-situ Base Resilient Modulus (M_r) (100 ft = 30.5 m; 100,000 psi = 689 MPa).

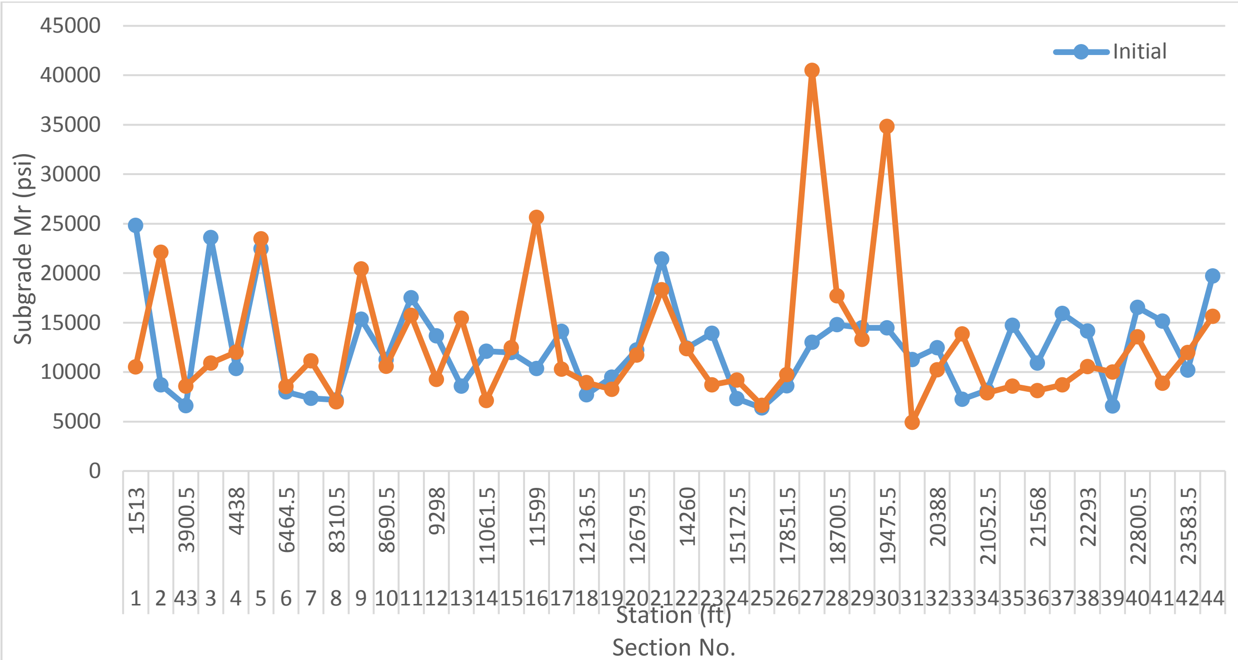

Figure 39. In-situ Subgrade Resilient Modulus (M_r) (100 ft = 30.5 m; 100,000 psi = 689 MPa).

Base and subgrade moduli are further explored for the individual variables included in this study: backfill material, aggregate drain spacing, use of compaction, and use of filter fabric. The following subsections provide comparisons between initial modulus values and final modulus values for each variable.

Water-bound Macadam Base Modulus – Backfill Material

Shown in Figure 40 are the moduli for the water-bound macadam base for each control section determined from DCP testing conducted prior to the start of the study, and at the conclusion of the one-year monitoring period. Although section 10 shows the greatest difference between initial and final base modulus, an analysis of variance (ANOVA) at an alpha of 0.05 found there was no statistical difference between initial moduli and final moduli for the control sections, full ANOVA results are shown in Appendix Q.

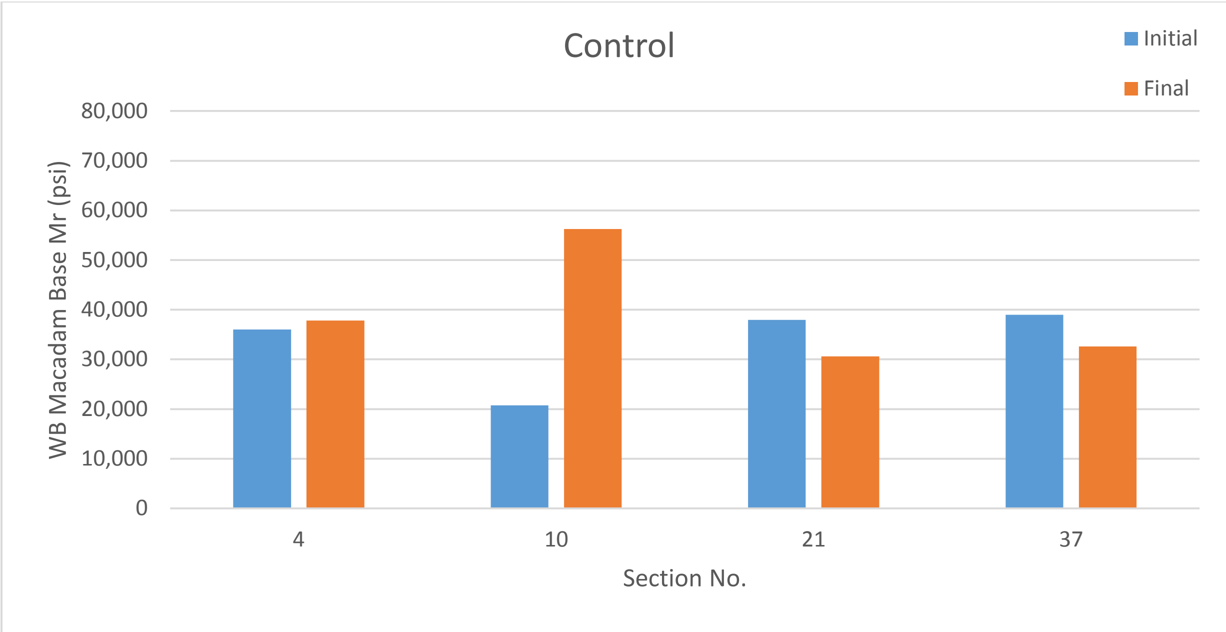

Figure 40. Comparison of Base DCP M_r for Control Sections (100,000 psi = 689 MPa).

Figures 41 through 44 show initial and final moduli for each section grouped by each backfill material investigated: No. 4 aggregate, No. 8 aggregate, No. 57 aggregate, and porous concrete, respectively. Although there are a few exceptions (e.g. Sections 2 and 35, shown in Figure 43) the final modulus for each section is very consistent with the initial modulus in terms of magnitude of the measurement. There are no obvious trends in the data, i.e. the moduli measured at the conclusion of the monitoring period are not consistently greater than (or less than) the initial modulus. An ANOVA (alpha = 0.05) conducted for each backfill material was conducted to determine if differences between the initial and final modulus values were significant. The results of each ANOVA indicated there were no statistical differences between initial and final moduli for each backfill material. Full ANOVA results are reported in Appendix Q for each backfill material.

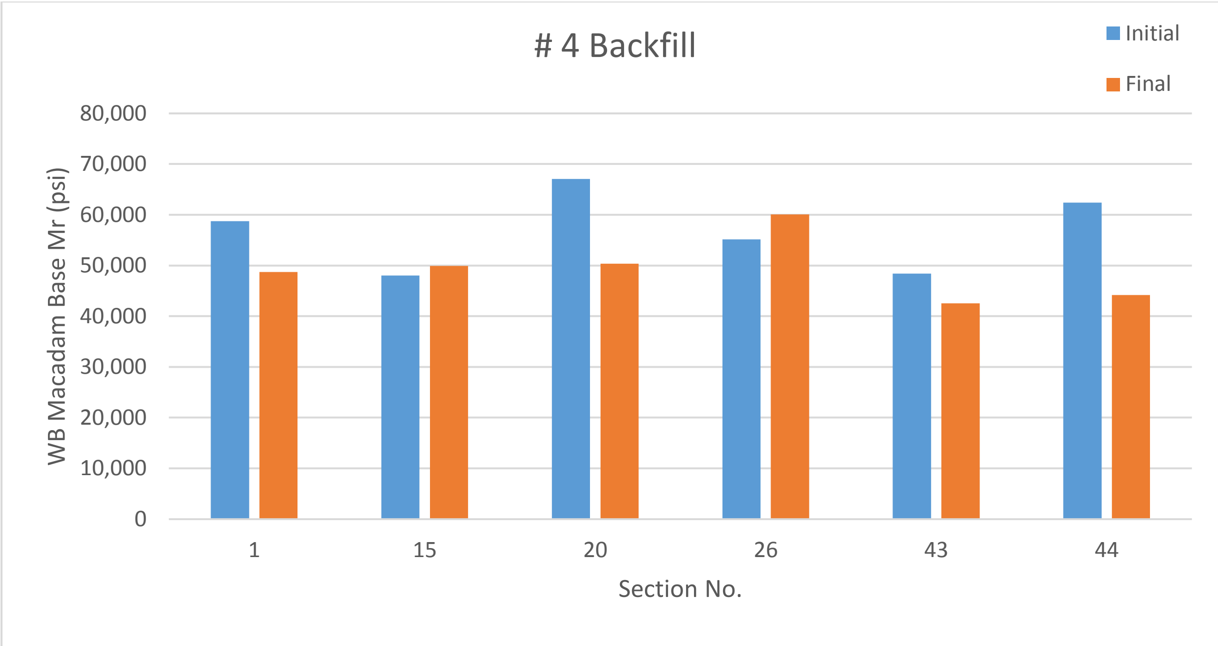

Figure 41. Comparison of Base DCP M_r for Sections Backfilled with No. 4 Aggregate (100,000 psi = 689 MPa).

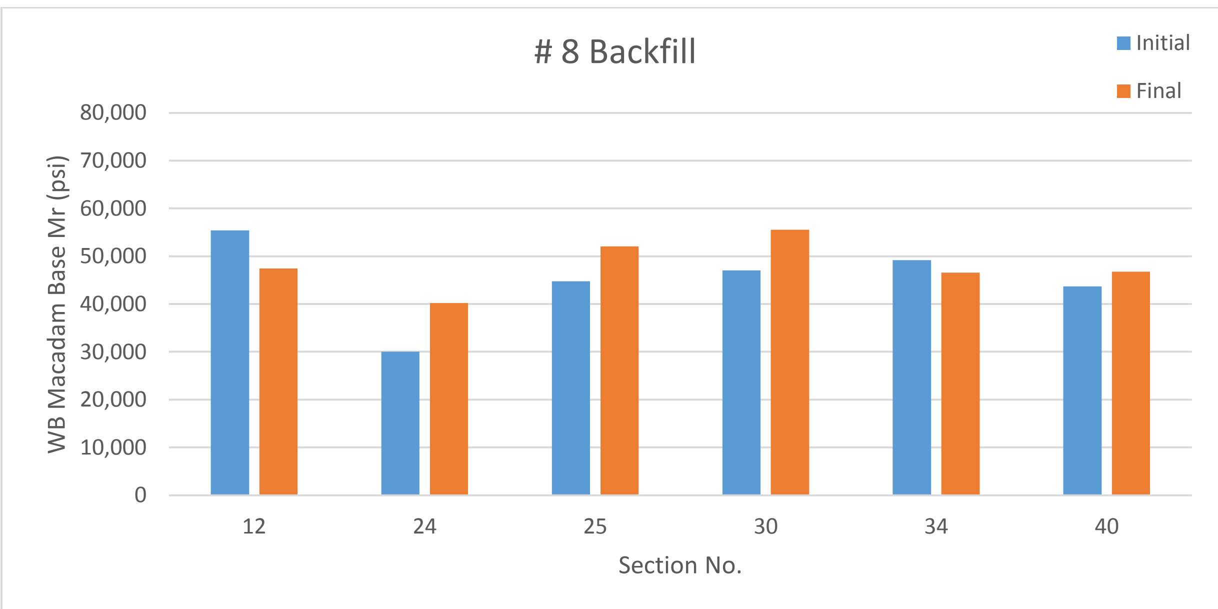

Figure 42. Comparison of Base DCP M_r for Sections Backfilled with No. 8 Aggregate (100,000 psi = 689 MPa).

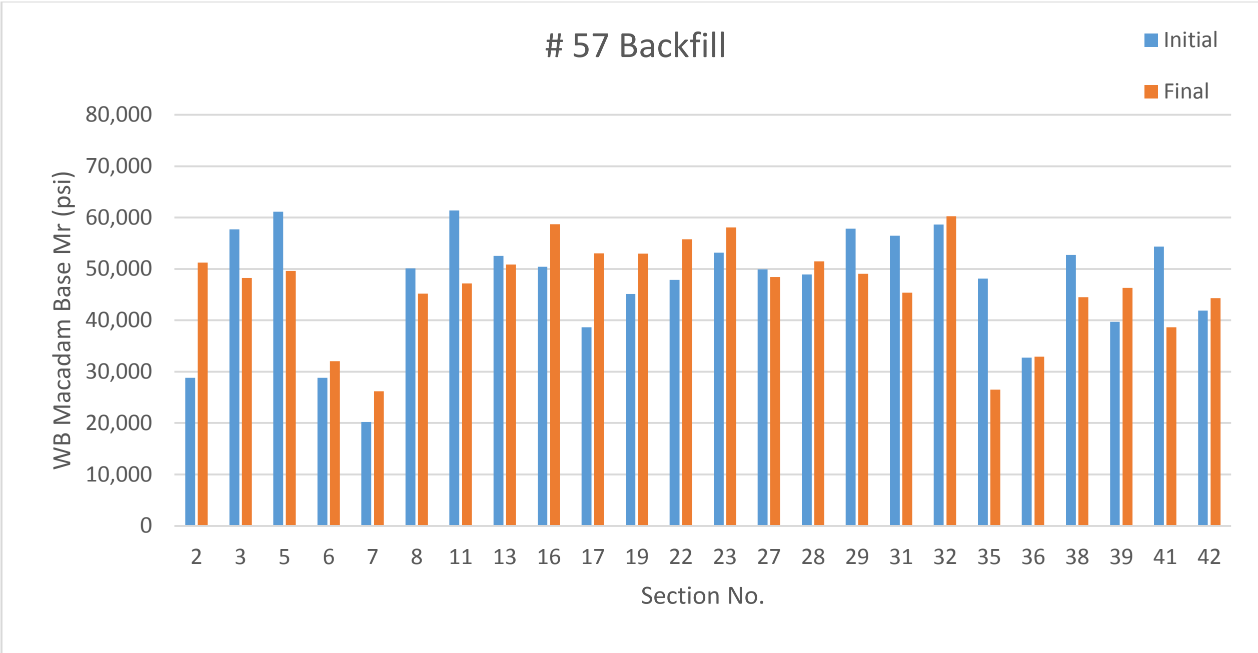

Figure 43. Comparison of Base DCP M_r for Sections Backfilled with No. 57 Aggregate (100,000 psi = 689 MPa).

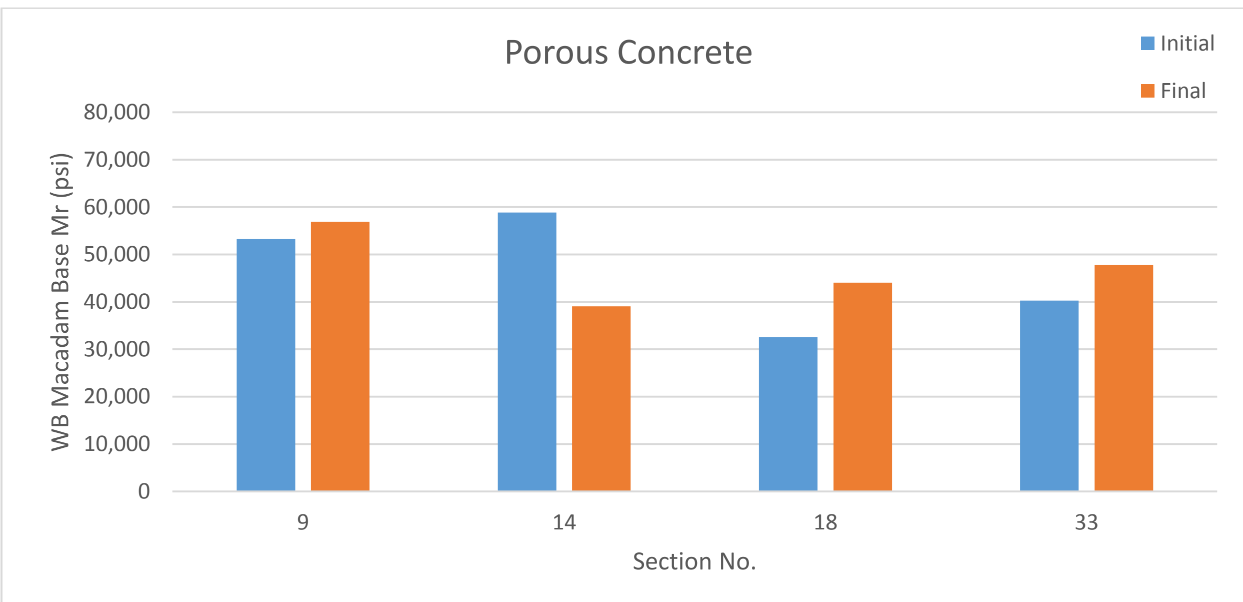

Figure 44. Comparison of Base DCP M_r for Sections Backfilled with Porous Concrete (100,000 psi = 689 MPa).

Water-bound Macadam Base Modulus – Aggregate Drain Spacing

Shown in Figures 45 and 46 are the moduli measured before aggregate drain installation and after the one-year monitoring period in each section, for the two distances used for aggregate drain spacing: 50 ft (15 m) and 200 ft (61 m). While some variability in moduli are noted from section to section, the final modulus is generally consistent with initial modulus measured in a given section. An ANOVA (alpha at 0.05) was conducted for each spacing, 50 ft (15 m) and 200 ft (61 m). The results showed there is no statistical difference between initial and final modulus values for sections with aggregate drains spaced at 50 ft (15 m), and no statistical difference between initial and final modulus values for those with aggregate drains spaced at 200 ft (61 m). Full ANOVA results are reported in Appendix Q.

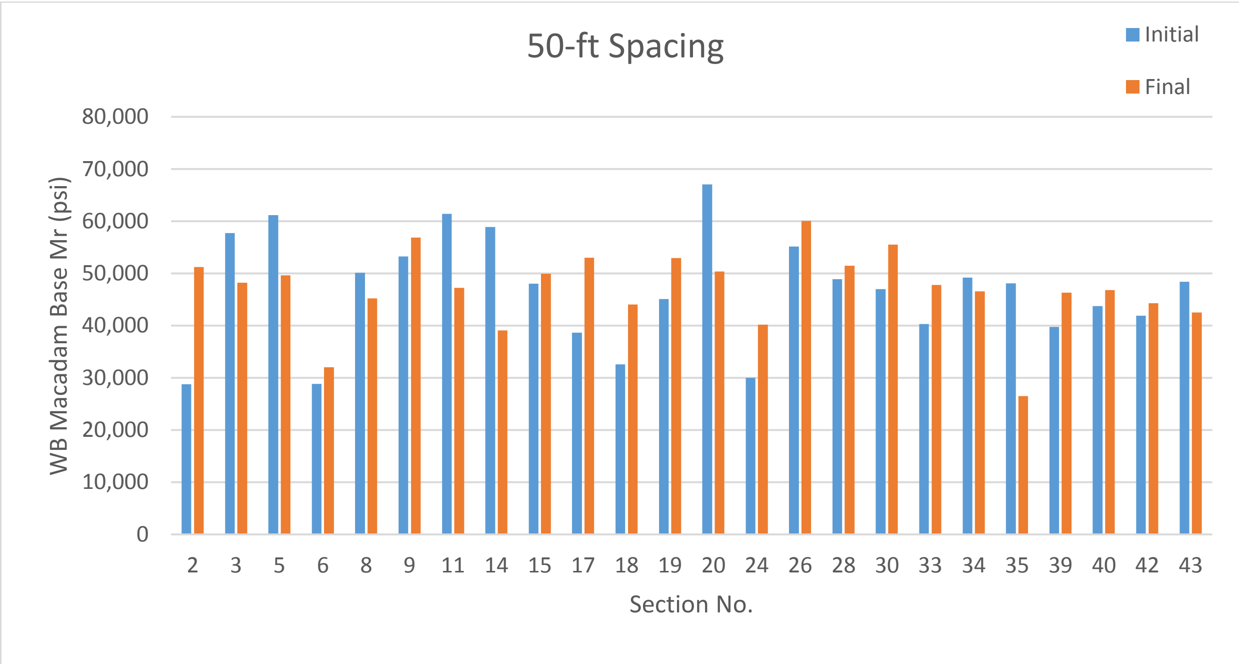

Figure 45. Comparison of Base DCP M_r for Sections with Aggregate Drains Spaced at 50 ft (15 m) (100,000 psi = 689 MPa).

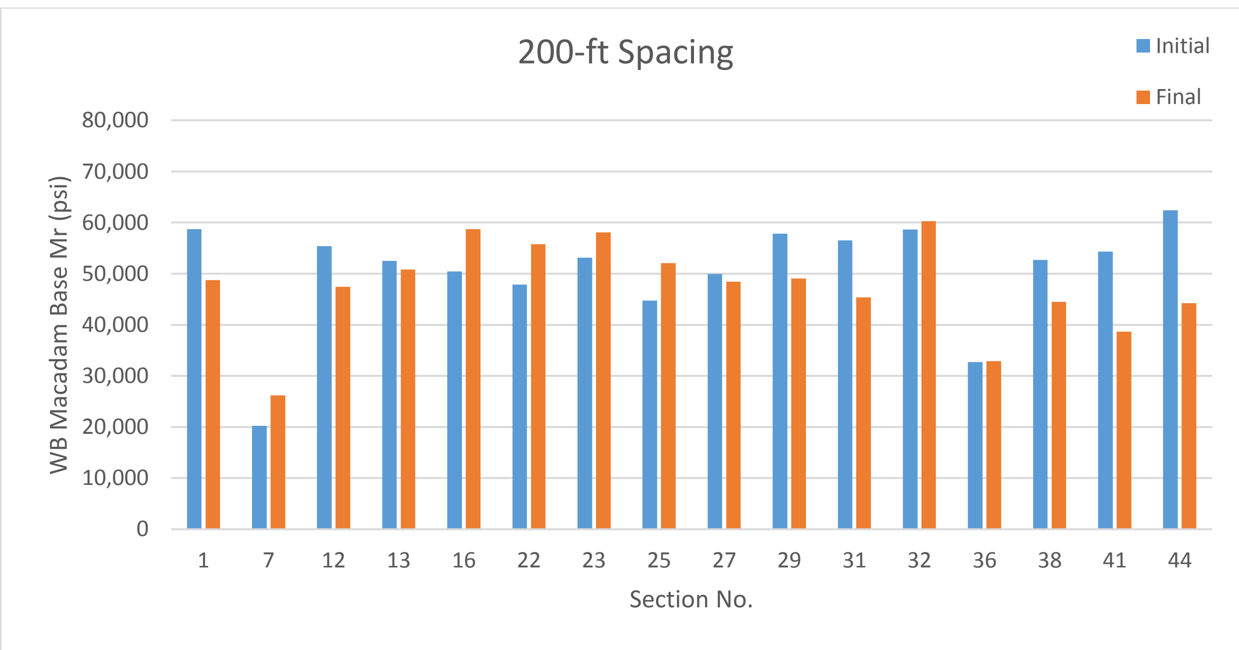

Figure 46. Comparison of Base DCP M_r for Sections with Aggregate Drains Spaced at 200 ft (61 m) (100,000 psi = 689 MPa).

Water-bound Macadam Base Modulus – Use of Compaction

Shown in Figures 47 and 48 are the moduli measured before aggregate drain installation and after the one-year monitoring period in each section, for backfill material compacted and not compacted during placement. While some variability in moduli are noted from section to section, the final modulus is generally consistent with initial modulus measured in a given section. An ANOVA (alpha at 0.05) was conducted for compaction and no compaction. The results showed there is no statistical difference between initial and final modulus values for sections with backfill not compacted during placement, and no statistical difference between initial and final modulus values for compacted during placement. Full ANOVA results are reported in Appendix Q.

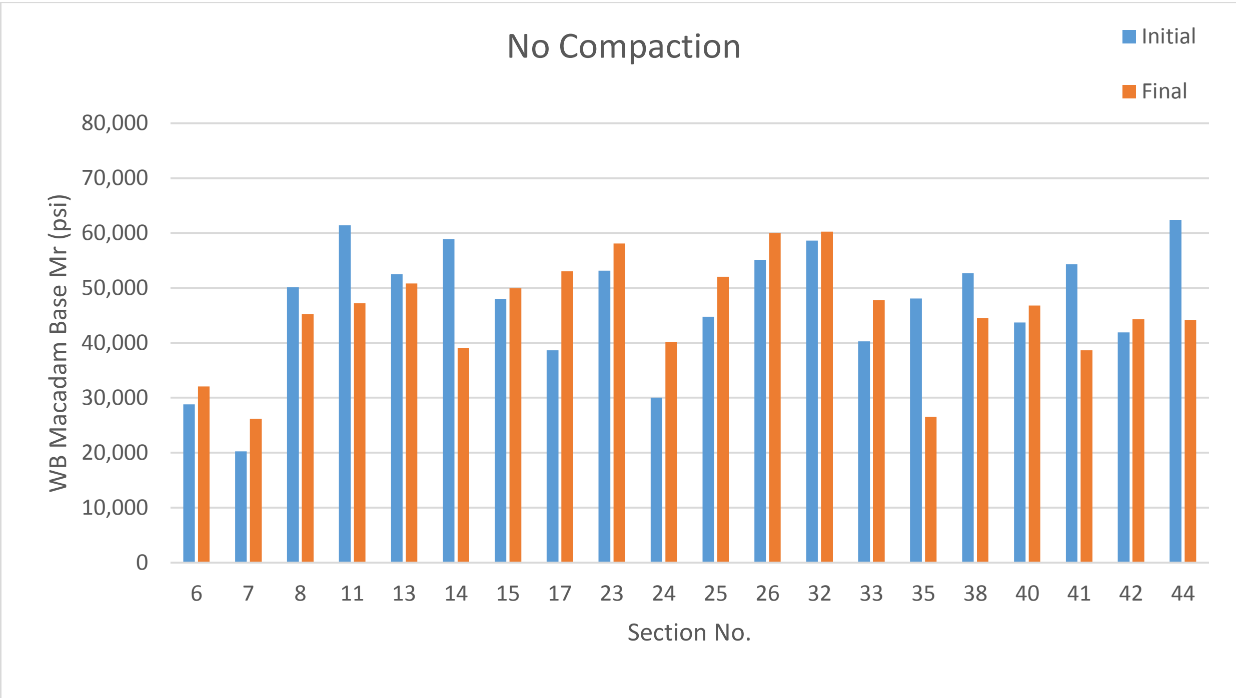

Figure 47. Comparison of Base DCP M_r for Sections with Aggregate Drains Constructed without Compaction (100,000 psi = 689 MPa).

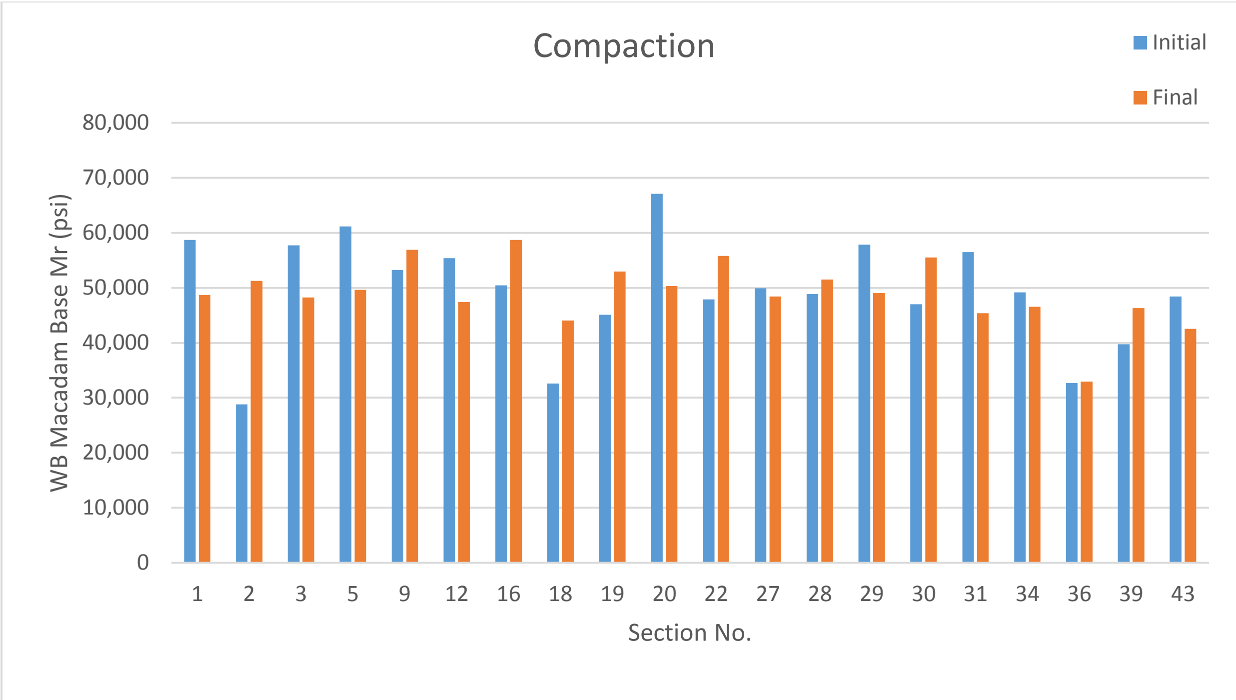

Figure 48. Comparison of Base DCP M_r for Sections with Aggregate Drains Constructed with Compaction (100,000 psi = 689 MPa).

Water-bound Macadam Base Modulus – Use of Filter Fabric

Shown in Figures 49 and 50 are the moduli measured before aggregate drain installation and after the one-year monitoring period in each section, for sections without filter fabric and sections with the backfill wrapped in filter fabric. While some variability in moduli are noted from section to section, the final modulus is generally consistent with initial modulus measured in a given section. An ANOVA (alpha at 0.05) was conducted for backfill without filter fabric and backfill wrapped in filter fabric. The results showed there is no statistical difference between initial and final modulus values for sections without filter fabric, and no statistical difference between initial and final modulus values for those with a filter fabric wrapped backfill. Full ANOVA results are reported in Appendix Q.

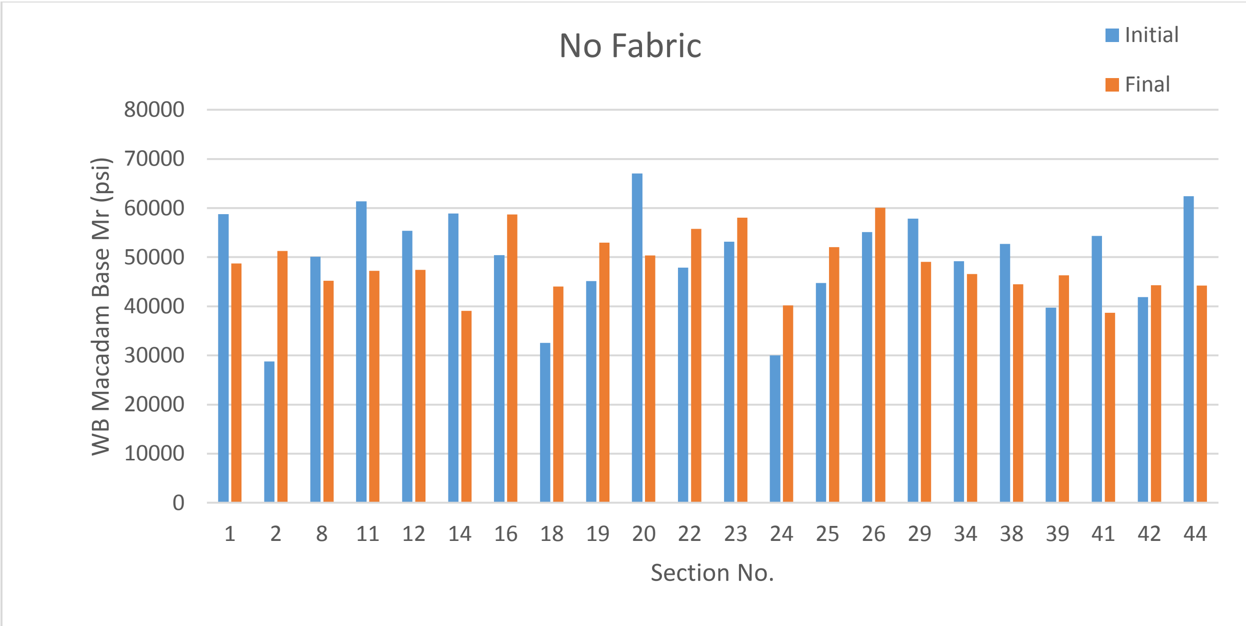

Figure 49. Comparison of Base DCP M_r for Sections with Aggregate Drains Constructed without Fabric (100,000 psi = 689 MPa).

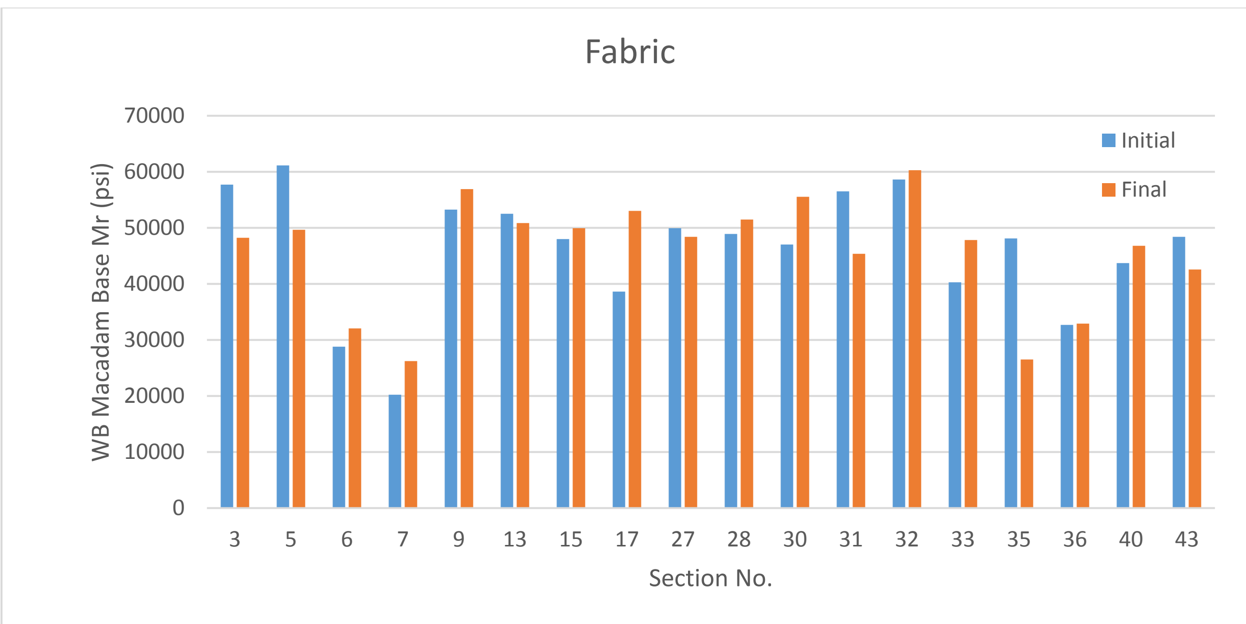

Figure 50. Comparison of Base DCP M_r for Sections with Aggregate Drains Constructed with Fabric (100,000 psi = 689 MPa).

Subgrade Modulus – Backfill Material

Shown in Figure 51 are the moduli for the subgrade for each control section determined from DCP testing conducted prior to the start of the study, and at the conclusion of the one-year monitoring period. Although section 37 shows the greatest difference between initial and final base modulus, an analysis of variance (ANOVA) at an alpha of 0.05 found there was no statistical difference between initial moduli and final moduli for the control sections, full ANOVA results are shown in Appendix R.

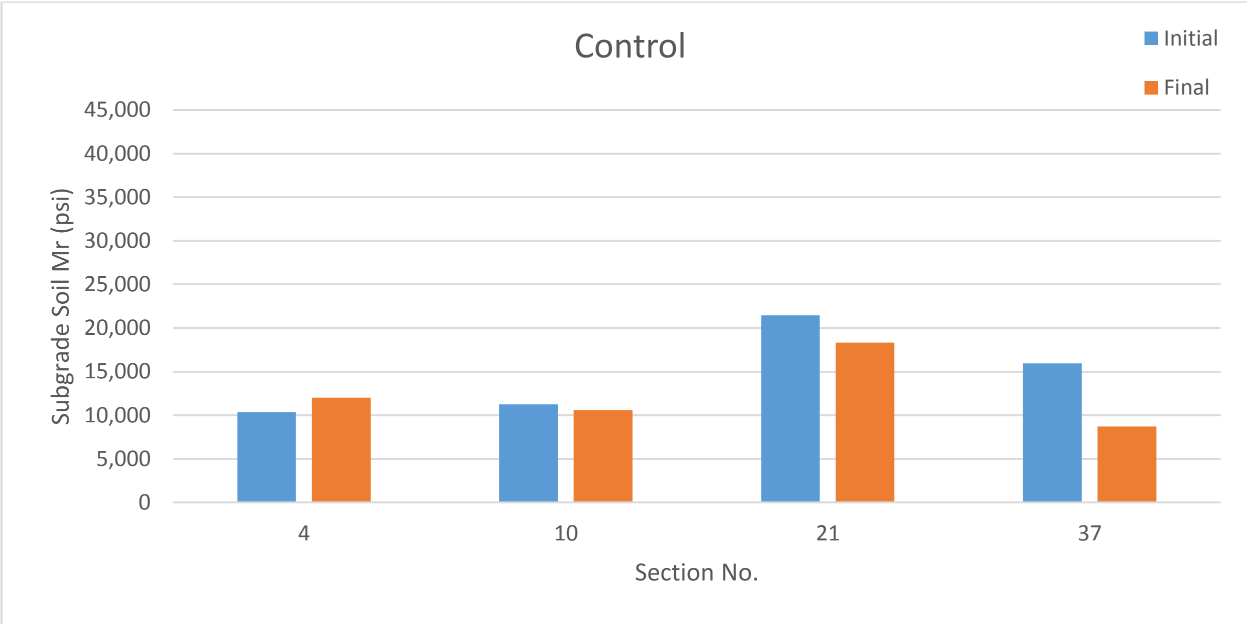

Figure 51. Comparison of Subgrade DCP M_r for Control Sections (100,000 psi = 689 MPa).

Figures 52 through 55 show initial and final moduli for each section grouped by each backfill material investigated: No. 4 aggregate, No. 8 aggregate, No. 57 aggregate, and porous concrete, respectively. Although there are a few exceptions (e.g. section 1 in Figure 52, section 30 in Figure 53, and sections 2, 3, 16, and 27 shown in Figure 54) the final modulus for each section is very consistent with the initial modulus in terms of magnitude of the measurement. There are no obvious trends in the data. An ANOVA (alpha = 0.05) conducted for each backfill material was conducted to determine if differences between the initial and final modulus values were significant. The results of each ANOVA indicated there were no statistical differences between initial and final moduli for each backfill material. Full ANOVA results are reported in Appendix R for each backfill material.

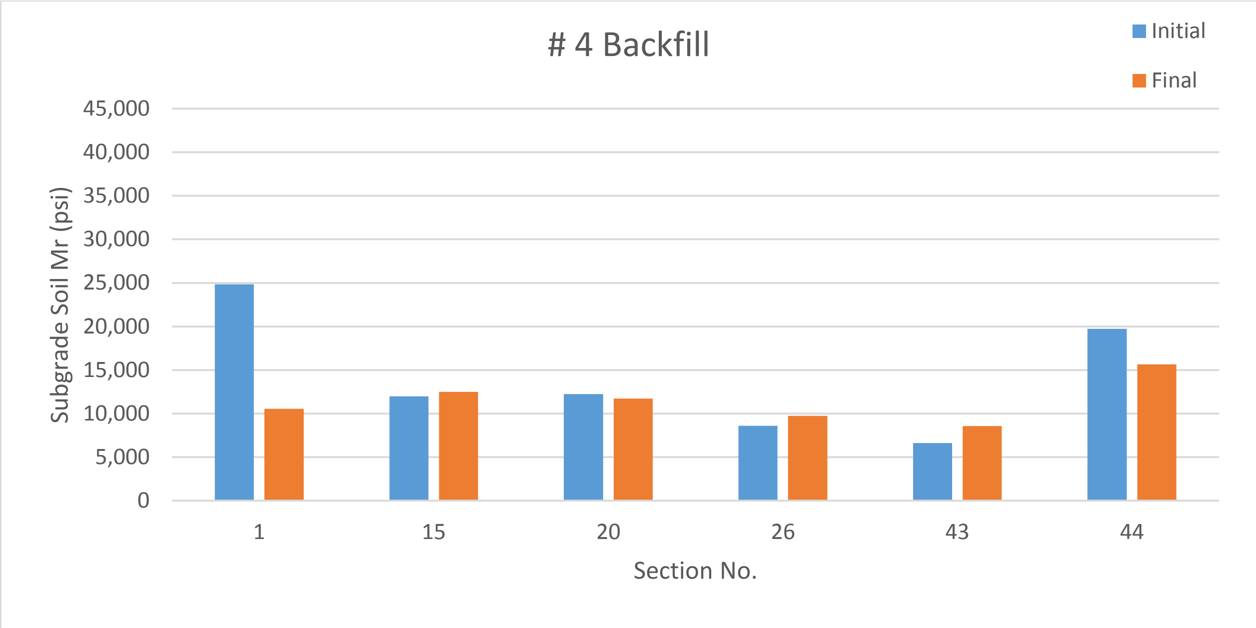

Figure 52. Comparison of Subgrade DCP M_r for Sections Backfilled with No. 4 Aggregate (100,000 psi = 689 MPa).

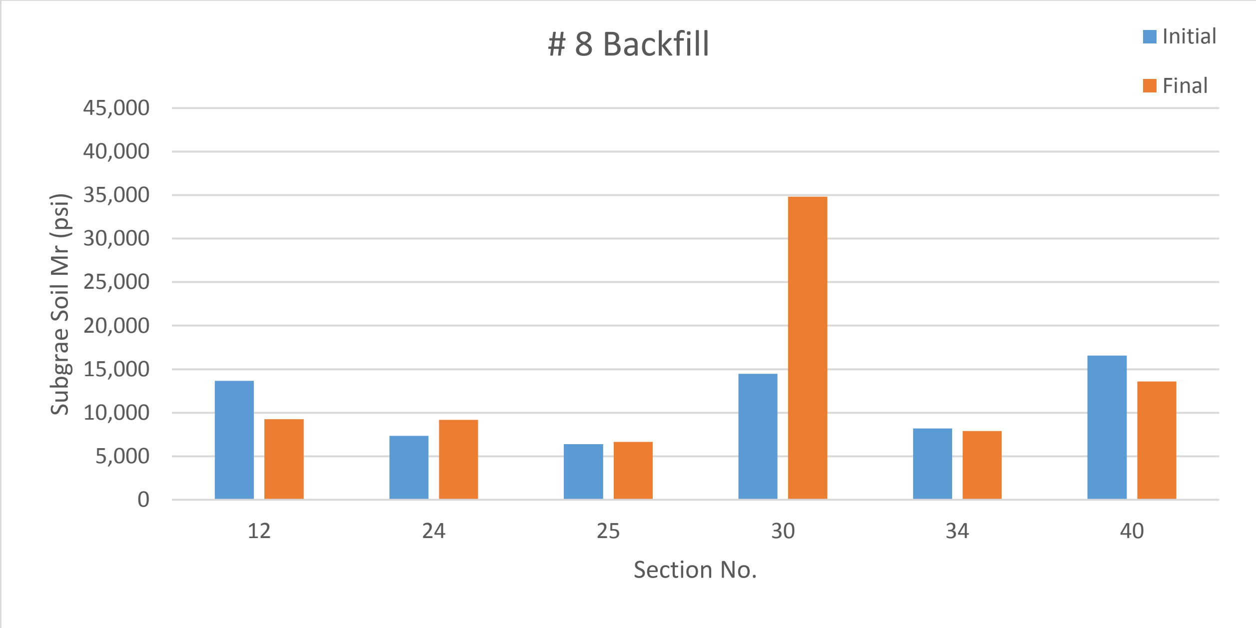

Figure 53. Comparison of Subgrade DCP M_r for Sections Backfilled with No. 8 Aggregate (100,000 psi = 689 MPa).

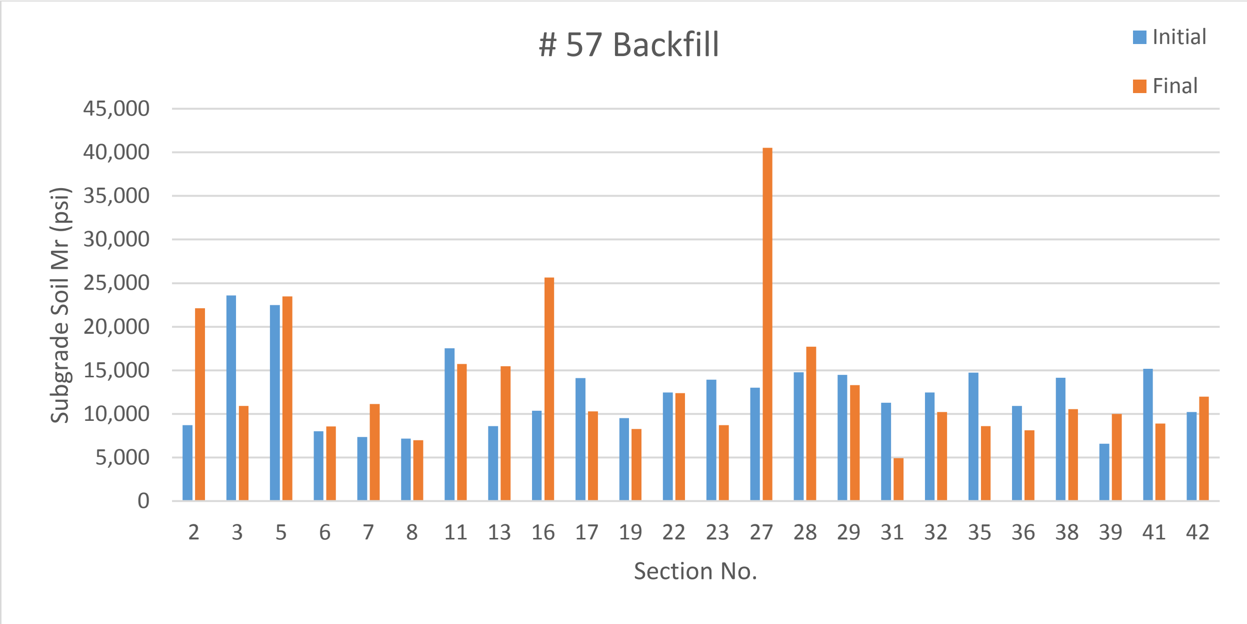

Figure 54. Comparison of Subgrade DCP M_r for Sections Backfilled with No. 57 Aggregate (100,000 psi = 689 MPa).

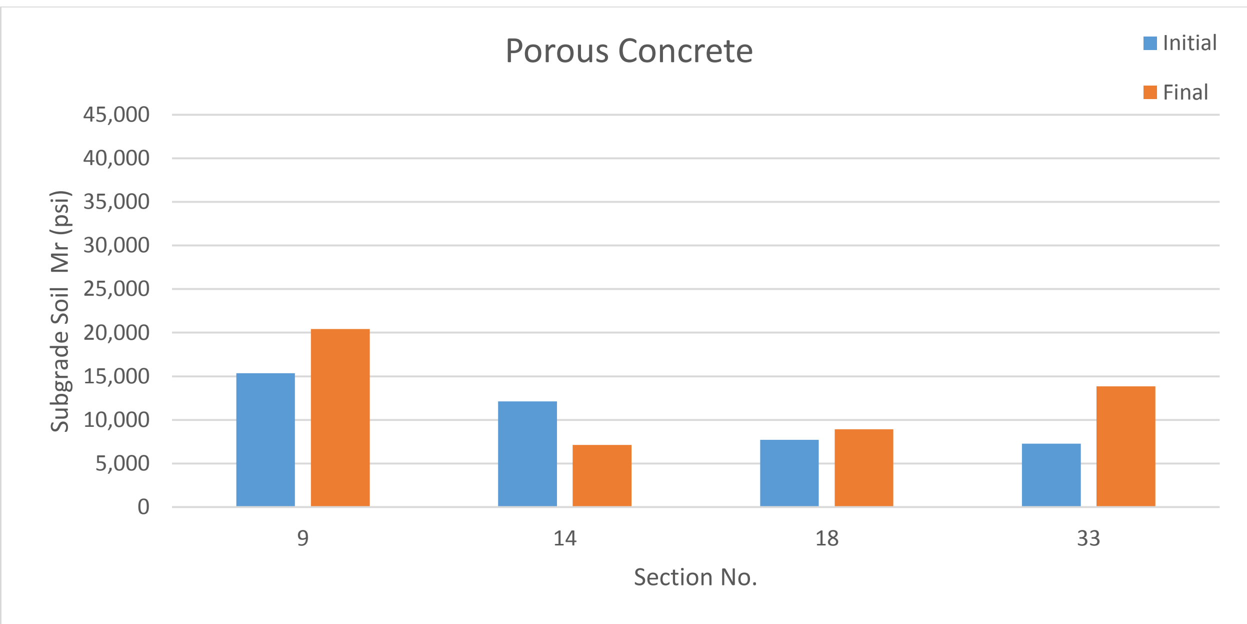

Figure 55. Comparison of Subgrade DCP M_r for Sections Backfilled with Porous Concrete (100,000 psi = 689 MPa).

Subgrade Modulus – Aggregate Drain Spacing

Shown in Figures 56 and 57 are the moduli measured before aggregate drain installation and after the one-year monitoring period in each section, for the two distances used for aggregate drain spacing: 50 ft (15 m) and 200 ft (61 m). While some variability in moduli are noted from section to section (e.g. section 30 in Figure 56 and Section 27 in Figure 57), the final modulus is generally consistent with initial modulus measured in a given section. An ANOVA (alpha at 0.05) was conducted for each spacing, 50 ft (15 m) and

200 ft (61 m). The results showed there is no statistical difference between initial and final modulus values for sections with aggregate drains spaced at 50 ft (15 m), and no statistical difference between initial and final modulus values for those with aggregate drains spaced at 200 ft (61 m). Full results are reported in Appendix R.

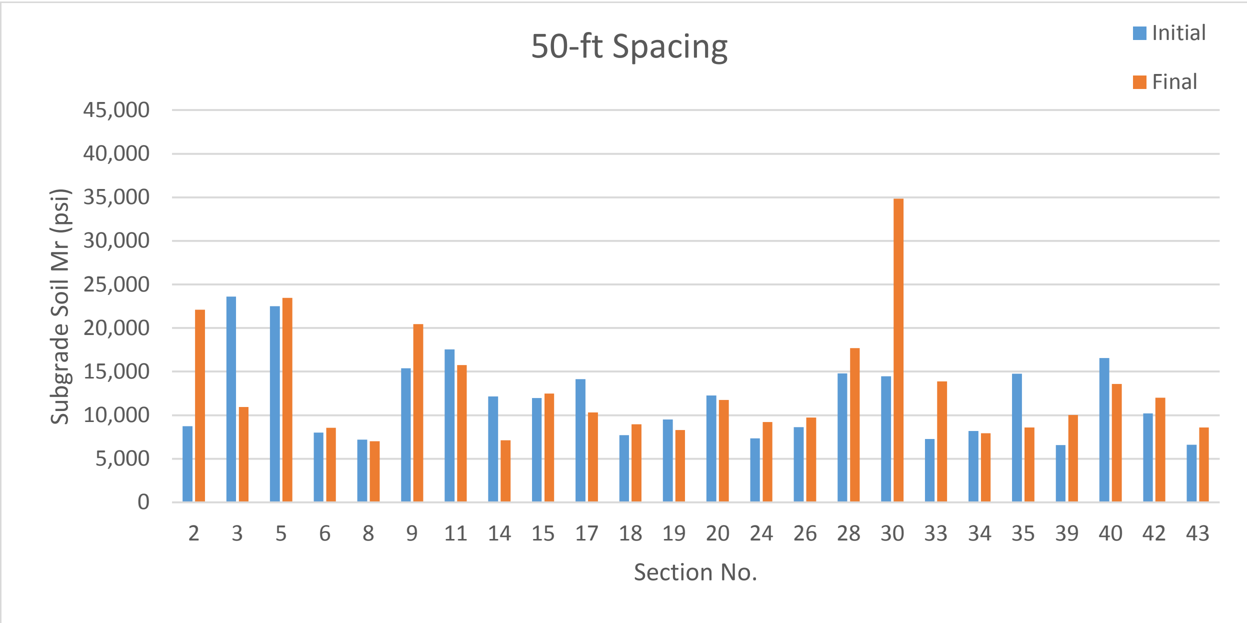

Figure 56. Comparison of Subgrade DCP M_r for Sections with Aggregate Drains Spaced at 50 ft (15 m) (100,000 psi = 689 MPa).

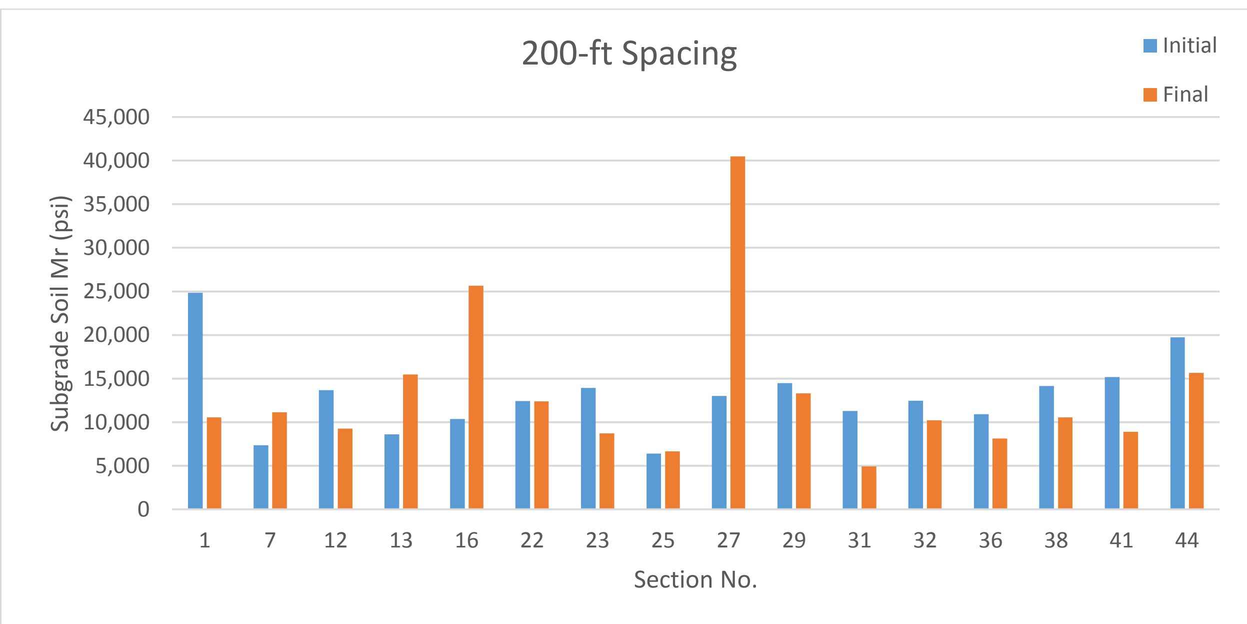

Figure 57. Comparison of Subgrade DCP M_r for Sections with Aggregate Drains Spaced at 200 ft (61 m) (100,000 psi = 689 MPa).

Subgrade Modulus – Use of Compaction

Shown in Figures 58 and 59 are the moduli measured before aggregate drain installation and after the one-year monitoring period in each section, for backfill material compacted and not compacted during placement. While some variability in moduli are noted from section to section (e.g. Sections 1, 16, 27 and 30 in Figure 59), the final modulus is generally consistent with initial modulus measured in a given section. An ANOVA (alpha at 0.05) was conducted for compaction and no compaction. The results showed there is no statistical difference between initial and final modulus values for sections with backfill not compacted during placement, and no statistical difference between initial and final modulus values for compacted during placement. Full ANOVA results are reported in Appendix R.

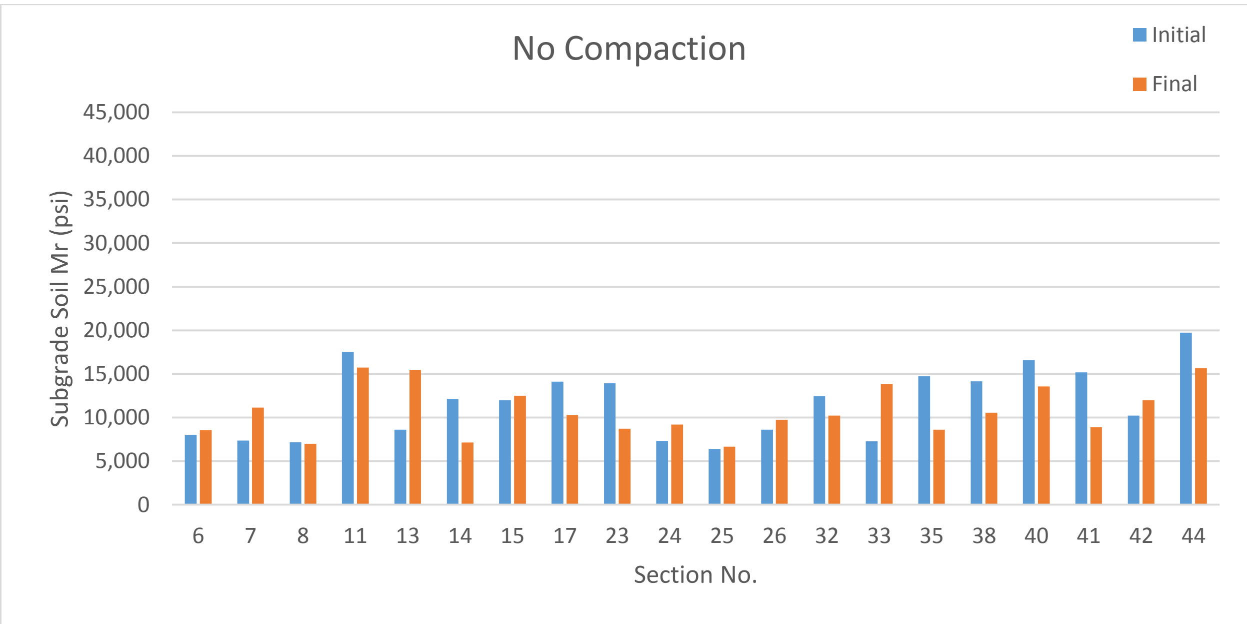

Figure 58. Comparison of Base DCP M_r for Sections with Aggregate Drains Constructed without Compaction (100,000 psi = 689 MPa).

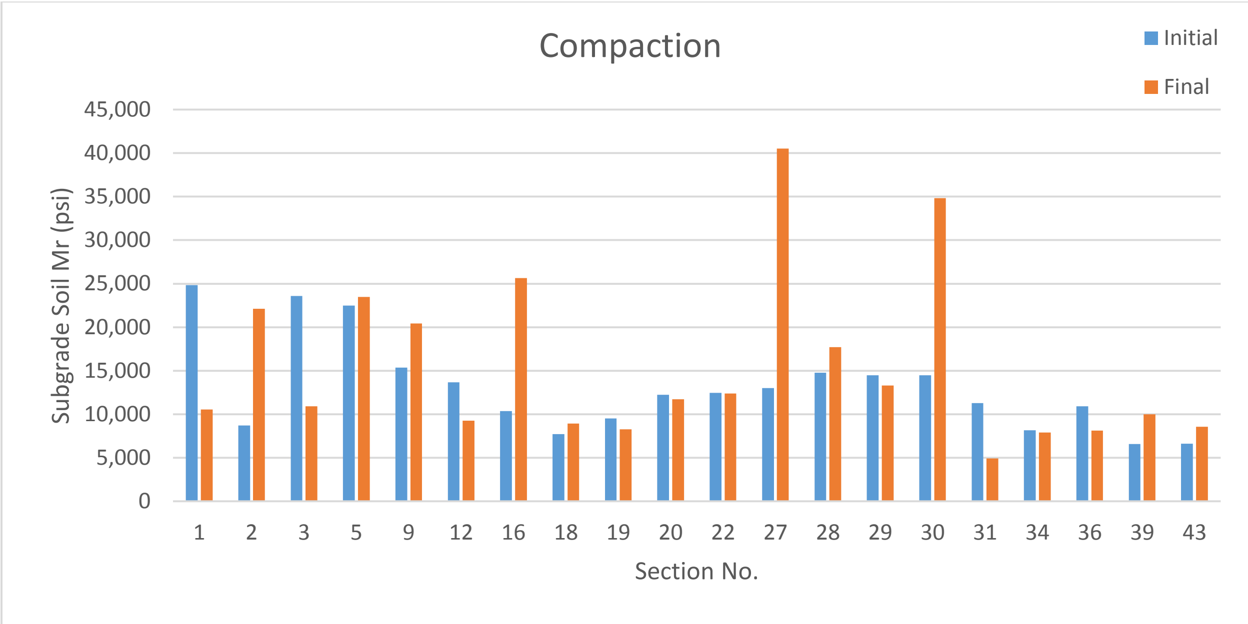

Figure 59. Comparison of Base DCP M_r for Sections with Aggregate Drains Constructed with Compaction (100,000 psi = 689 MPa).

Subgrade Modulus – Use of Filter Fabric

Shown in Figures 60 and 61 are the moduli measured before aggregate drain installation and after the one-year monitoring period in each section, for sections without filter fabric and sections with the backfill wrapped in filter fabric. While some variability in moduli are noted from section to section (e.g. Section1, 2, and 16 in Figure 60 and Sections 3, 27 and 30 in Figure 61) , the final modulus is generally consistent with initial modulus measured in a given section. An ANOVA (alpha at 0.05) was conducted for backfill without filter fabric and backfill wrapped in filter fabric. The results showed there is no statistical difference between initial and final modulus values for sections without filter fabric, and no statistical difference between initial and final modulus values for those with a filter fabric wrapped backfill. Full results are reported in Appendix R.

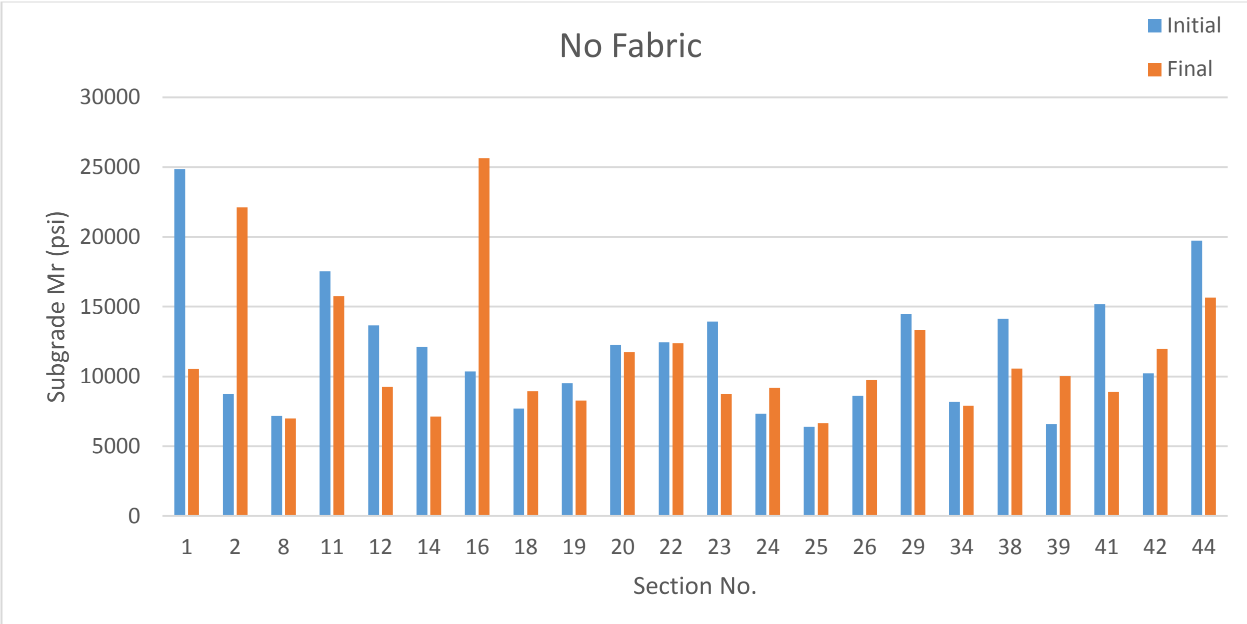

Figure 60. Comparison of Subgrade DCP M_r for Sections with Aggregate Drains Constructed without Fabric (100,000 psi = 689 MPa).

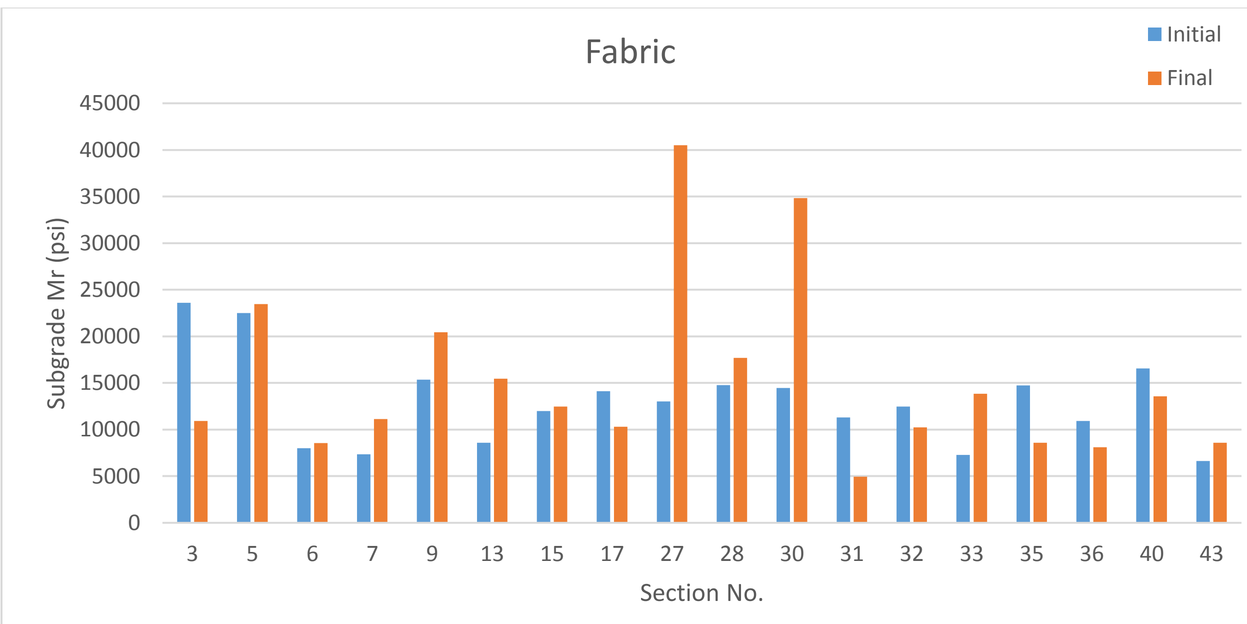

Figure 61. Comparison of Subgrade DCP M_r for Sections with Aggregate Drains Constructed with Fabric (100,000 psi = 689 MPa).

Results of FWD Testing

FWD testing was conducted on April 21, 2016 prior to construction of the aggregate drains to provide a baseline for relative comparisons. After the completion of aggregate drain construction FWD testing was conducted on four dates: August 30, 2016, January 19, 2017, May 31, 2017 (eastbound direction only) and June 7, 2017 (westbound direction only). Layer moduli were backcalculated for each date to investigate if any effects of the different aggregate drains could be detected in unbound layer moduli. FWD testing was conducted at 5 locations in each section in each direction. For the experimental sections, FWD testing was conducted at the aggregate drains and midway between the drains in each direction. For the control sections testing was conducted at equal intervals along the length of the section. Average backcalculated layer moduli at drain locations and between drain locations are reported for each section in each direction in Appendix P. For the control sections, the average backcalculated layer modulus are reported for the whole section.

It is expected the granular base layer would experience changes in modulus relative to changes in moisture content. Therefore, focus was placed on the base layer in evaluating the differences in moduli due to the use of drains. First, the average moduli for each control section in the eastbound and westbound lanes were determined at each FWD test date. The percent difference from the average modulus prior to construction of the aggregate drains (4/21/2016) were then determined for each test date after construction, and are plotted in Figure 62. This plot provides insight into how the unbound layer is changing throughout the seasons as there is no effect due to drainage in the control sections. The largest percent differences, which show an increase in base modulus, occur on the first test date post-construction (8/30/2016) in both the eastbound and westbound directions. It is expected seasonal variations in environmental conditions would be reflected in FWD deflections and therefore in backcalculated moduli. FWD results from the second test date, which occurred in the middle of winter (1/19/2017), show five of the eight control sections had lower base moduli than the initial moduli from 4/21/2016. These decreases are likely due to freeze-thaw effects.

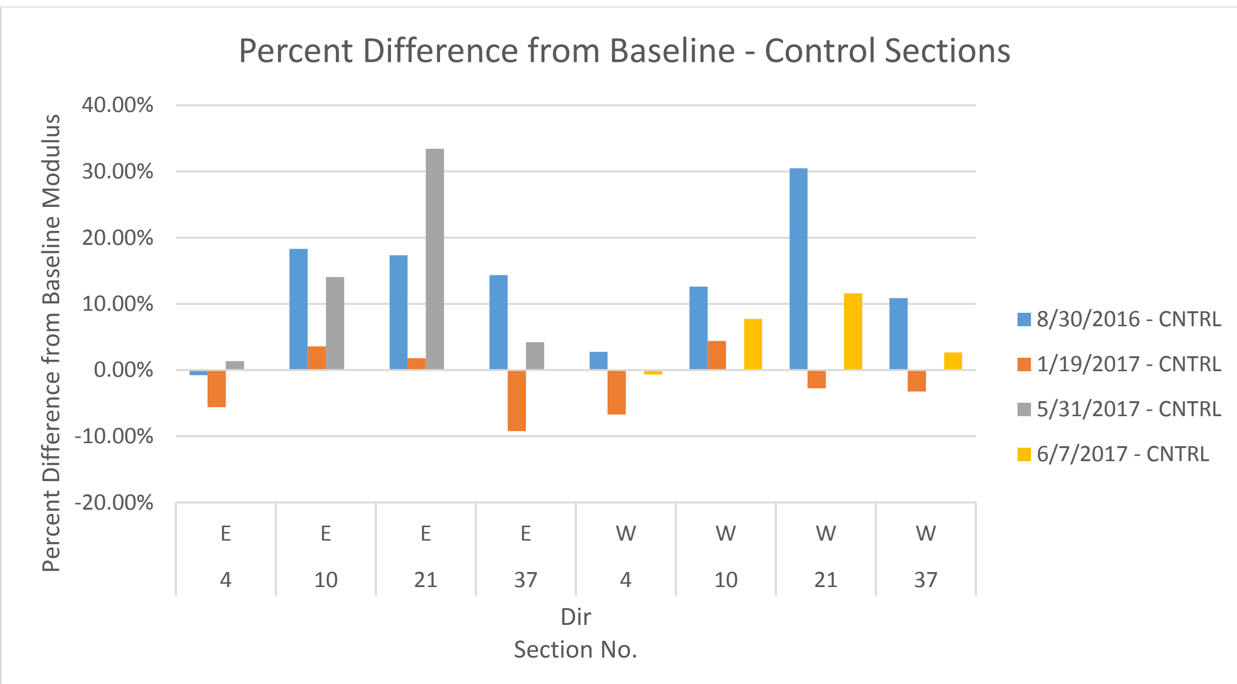

Figure 62. Average Percent Difference from Baseline for Control Sections.

Based on the plot in Figure 62, it can be expected seasonal variations will also be reflected in backcalculated moduli for sections with aggregate drains. It is also expected moisture moves toward the drain and therefore would be highest at drain locations, resulting in a decrease in modulus. To evaluate this, the average base modulus among the locations the drains were to be constructed were determined for the test date prior to construction, which serves as the baseline condition. The average base modulus among the same locations (drains) in each section were determined for each test date after construction. The percent difference between the average base modulus at the drains and the average base modulus at the drains prior to construction were determined in each section and for each date after construction. In the same manner the percent difference from the baseline condition was also determined for locations between the drains. The percent differences at the drains ("D") and between drains ("BD") are plotted for each experimental section in the eastbound direction in Figures 63 and 64, respectively. Percent differences from the baseline modulus at the drains and between drains in each section are plotted in Figures 65 and 66 for the westbound direction, respectively. Seasonal effects are evident in these plots as the percent differences on the coldest date, 1/19/2017, are mostly negative indicating moduli have gone down regardless of the presence of drains. Comparing the percent differences for moduli between drains and for moduli at the drains may be indicate changes in moisture. Comparing Figure 64 to Figure 63, it appears that in several sections (6, 9, 20, 30, 31, 34, 40, 42, and 43) the percent difference on the first and last test date after construction are slightly greater between drains (Figure 64) than at the drains (Figure 63). This implies that while both locations saw increases in base moduli over the baseline values, the base modulus between the drains saw a greater increase than base modulus at the drains. Higher percent differences are also observed between the drains compared to percent differences at the drains in the westbound direction for Sections 7, 11, 13, 15, 16, 17, 23, 35, 41, and 43. This follows logic that moisture would be flowing out of the pavement system at the drains which would result in increased moisture at the drains and a relative decrease between the drains. An increase in moisture at the drains should result in lower moduli.

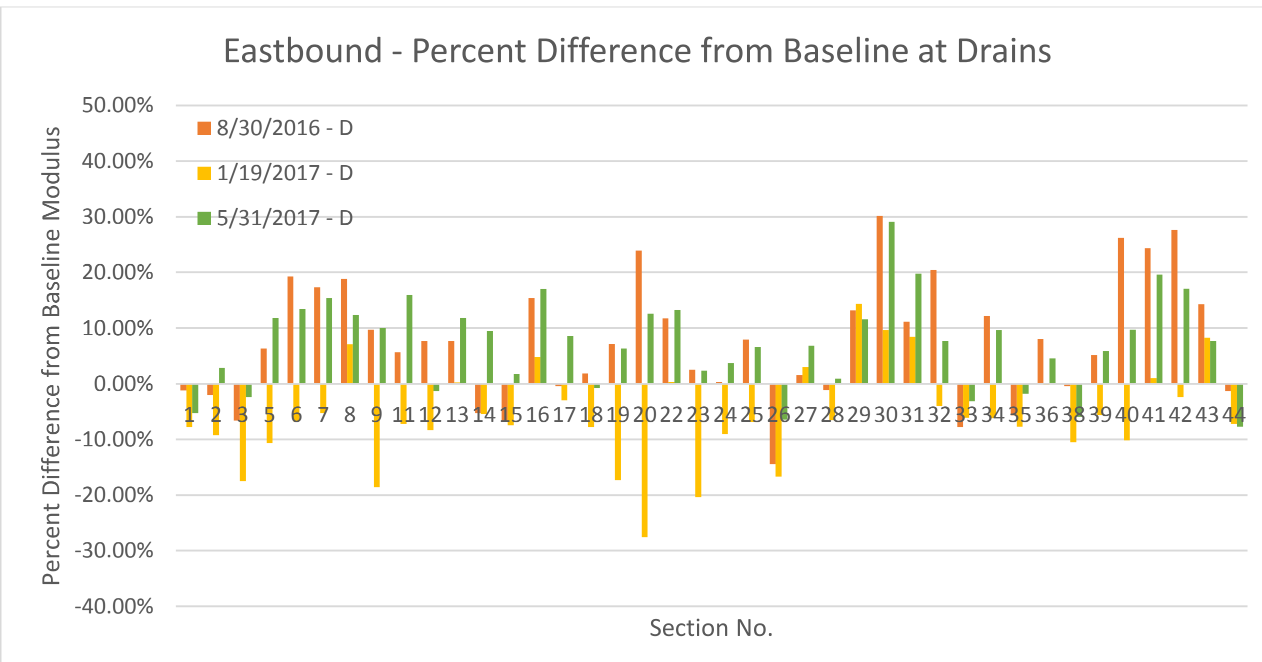

Figure 63. Percent Differences from Baseline Base Modulus at Drains, Eastbound Lane.

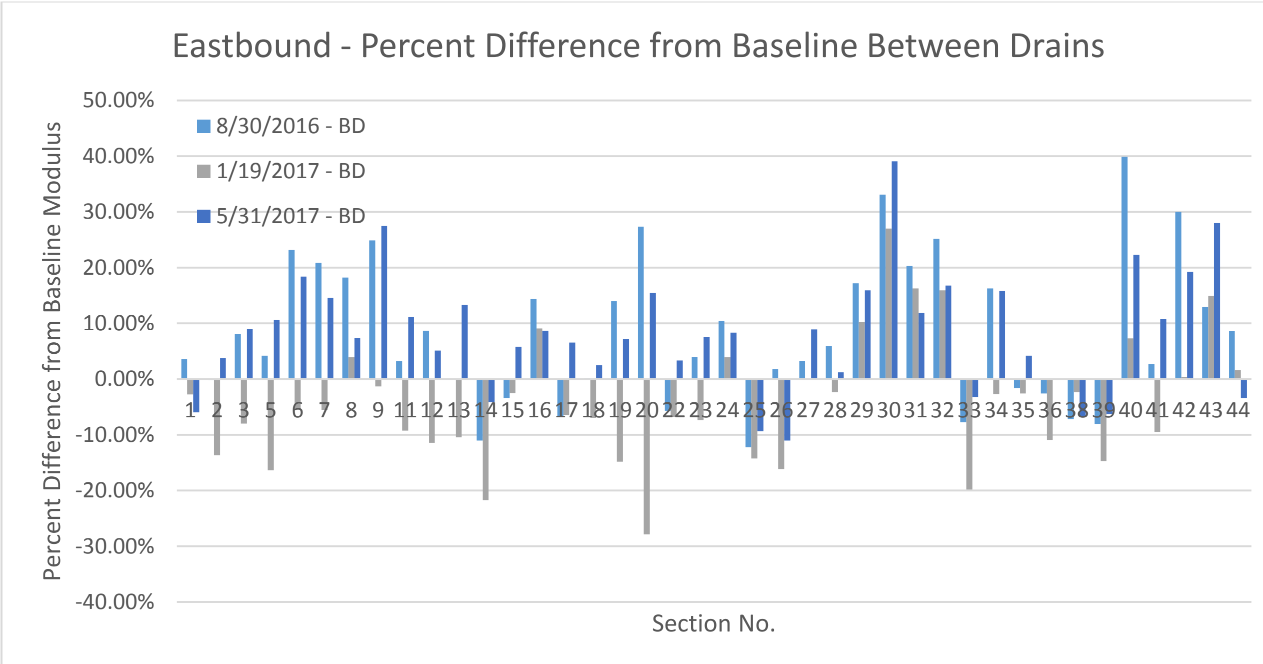

Figure 64. Percent Differences from Baseline Base Modulus Between Drains, Eastbound Lane.

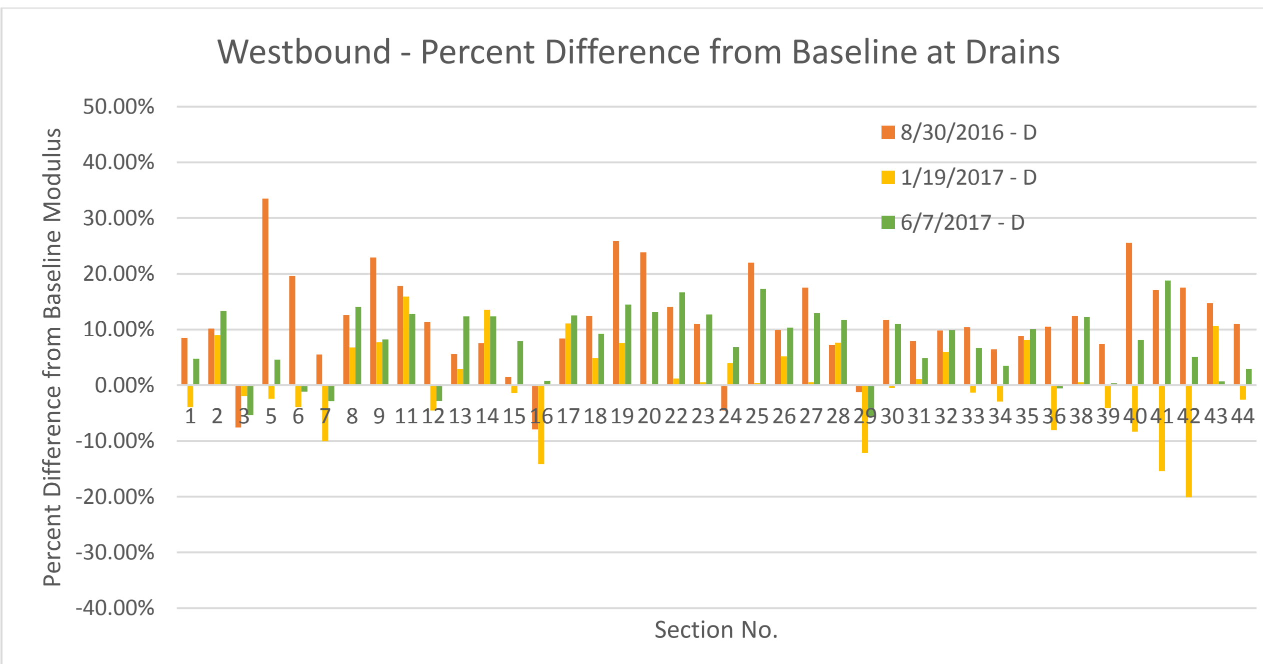

Figure 65. Percent Differences from Baseline Base Modulus at Drains, Westbound Lane.

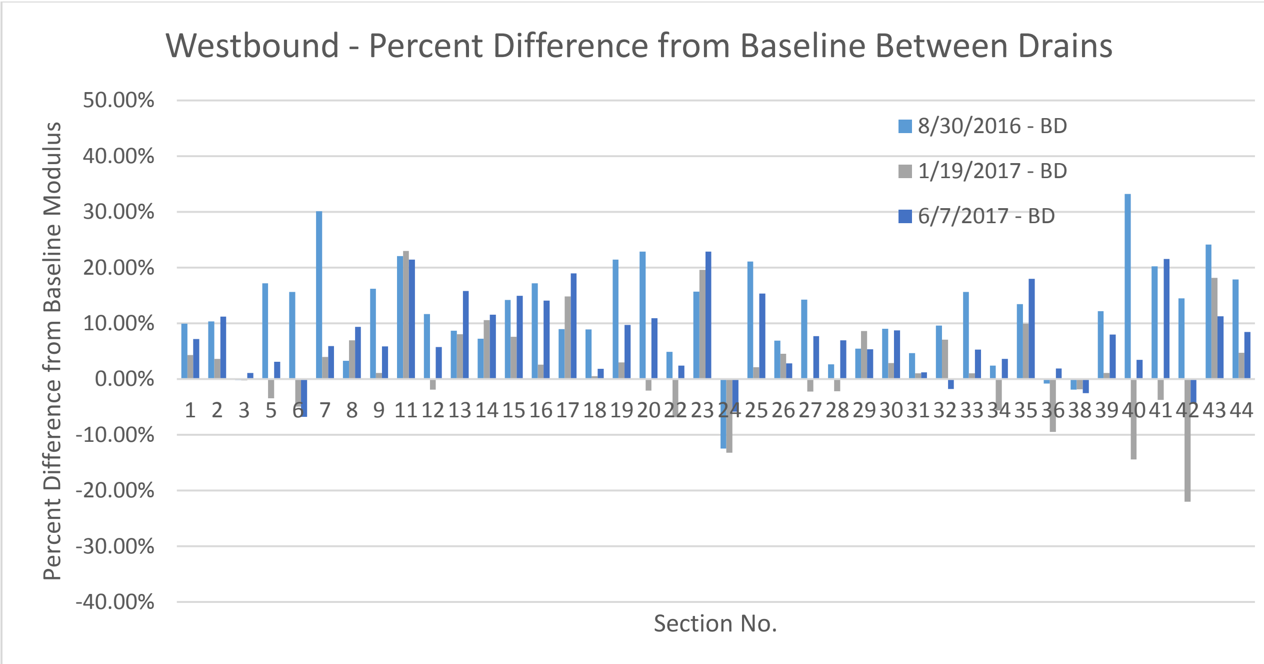

Figure 66. Percent Differences from Baseline Base Modulus Between Drains, Westbound Lane.

The percent differences from the baseline modulus at each location (drain or between drain) were averaged among sections with like variables (backfill material and aggregate drain spacing) to determine if any trends were evident that could provide insight into which combination of variables effectively remove moisture from the pavement system. Plotted in Figures 67 through 69 are the average percent differences for each location for each combination of variables for FWD testing conducted 4 months, 9 months, and 12 months post-construction, respectively. While there are some combinations of variables (e.g. No. 4 backfill material for aggregate drains spaced at 50 ft (15 m) in the eastbound lane and in the westbound lane, No. 8 backfill material for aggregate drains spaced at 50 ft (15 m) in the eastbound lane, and No. 4 backfill material for aggregate drains spaced at 200 ft (61 m) in the westbound lane) which consistently show a lower percent difference from the baseline moduli at the drains than between drains for all dates evaluated, there are other combinations which show the opposite trend (e.g. porous concrete backfilled drains spaced 50-ft (15-m) in the westbound lane).

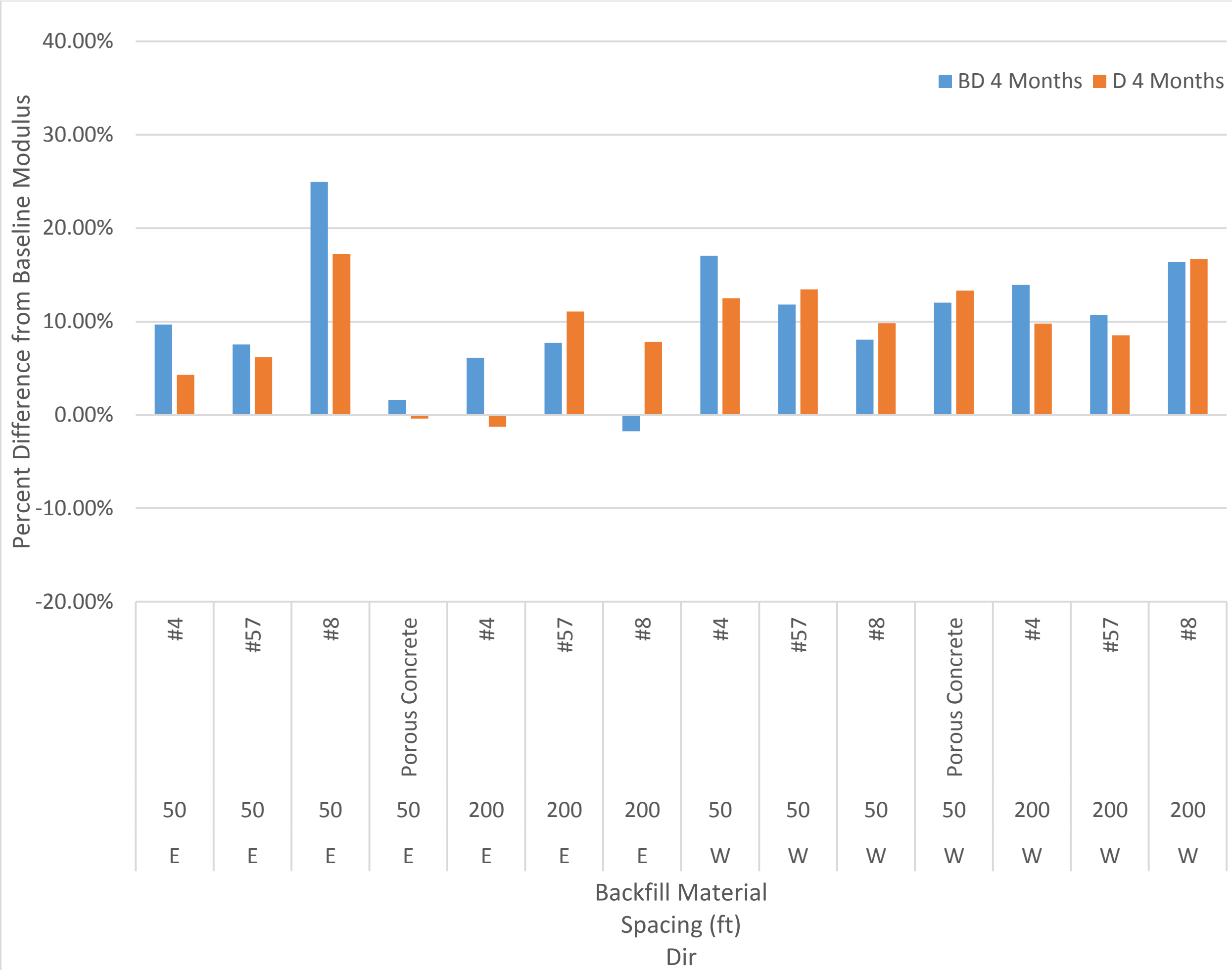

Figure 67. Average Percent Difference from Baseline at 4 Months (8/30/2016) (50 ft = 15 m, 200 ft = 61 m).

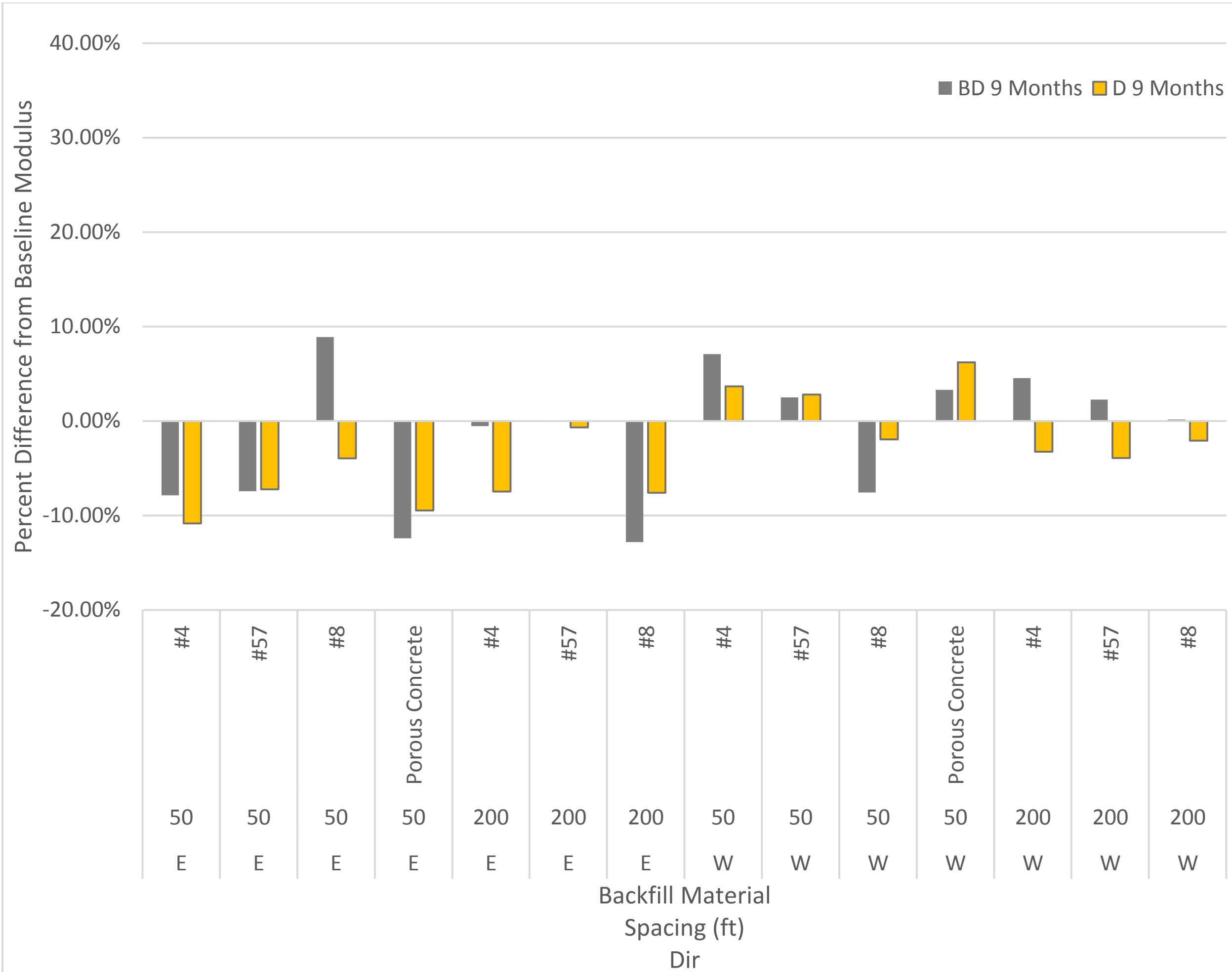

Figure 68. Average Percent Difference from Baseline at 9 Months (1/19/2017) (50 ft = 15 m, 200 ft = 61 m).

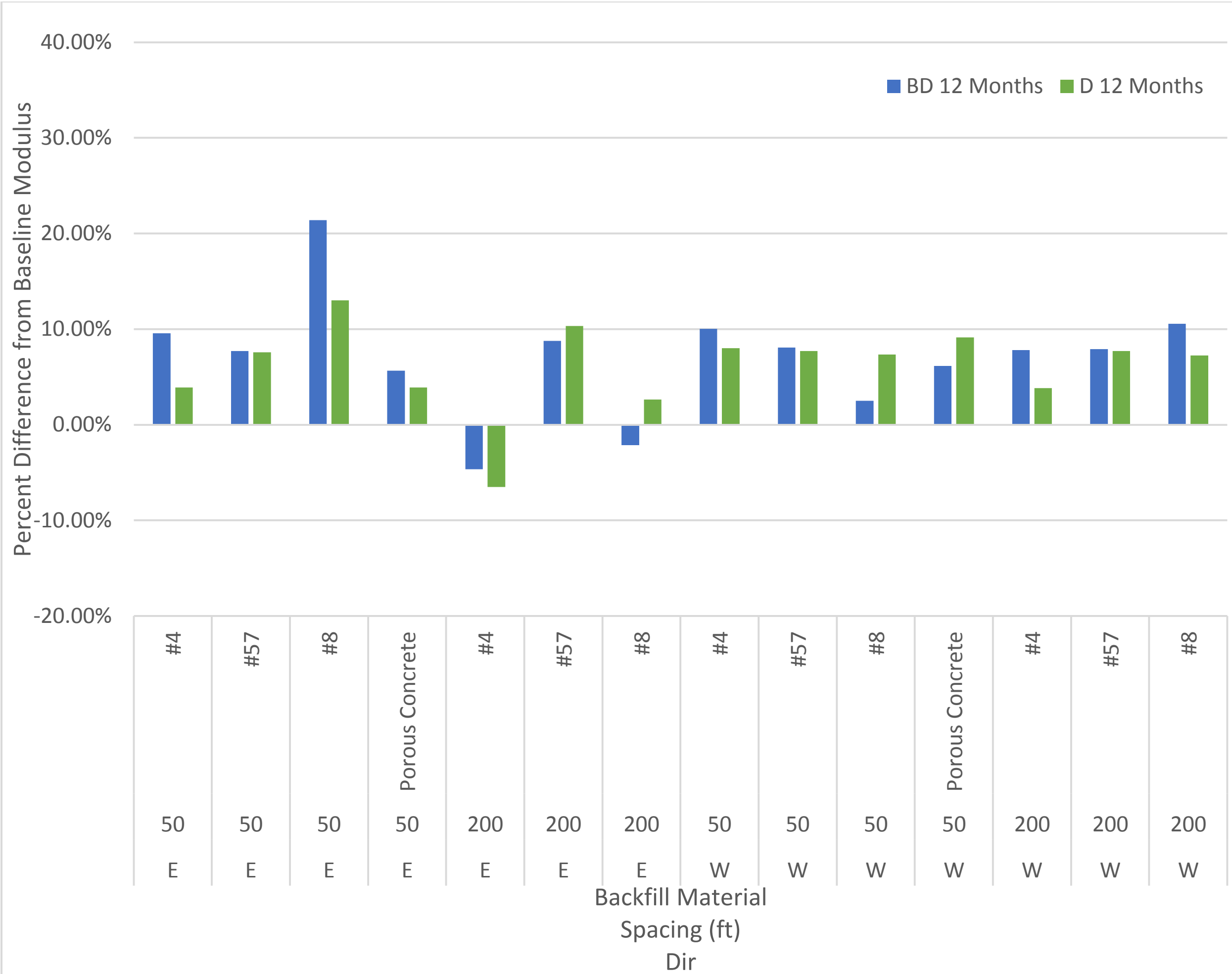

Figure 69. Average Percent Difference from Baseline at 12 Months (5/31/207 in EB and 6/7/2017 in WB) (50 ft = 15 m, 200 ft = 61 m).

Moisture in Unbound Layers

To assess the effectiveness of the aggregate drains to remove water from the pavement structure, moisture content was determined in two ways. Gravimetric moisture content was determined in the laboratory for the water-bound macadam base and subgrade prior to installation of the aggregate drains and again at the conclusion of the one year monitoring period. In-situ volumetric moisture content in aggregate drains and in the aggregate base were determined for selected sections in the eastbound lane using the TDR cables.

Laboratory Determined Moisture Content

Samples of water-bound macadam base and subgrade were collected at the conclusion of initial and final DCP testing conducted in the westbound lane for each test section. Gravimetric moisture content was determined following AASHTO T 265. The initial and final gravimetric moisture content for the water-bound macadam base and subgrade for each section are plotted in Figures 70 and 71, respectively. The moisture content of both the macadam base and subgrade varied along the project site. As was expected, the subgrade had greater moisture content than the base layer. The moisture content of the granular base layer ranged from 3% to nearly 13% by weight initially and from 4% to 14% after one year. Meanwhile, moisture content of the subgrade ranged from 6% to 40% initially and from 13% to 26% after one year. Initial base moisture content is missing for one section due to accidental disposal of the sample before testing was completed.

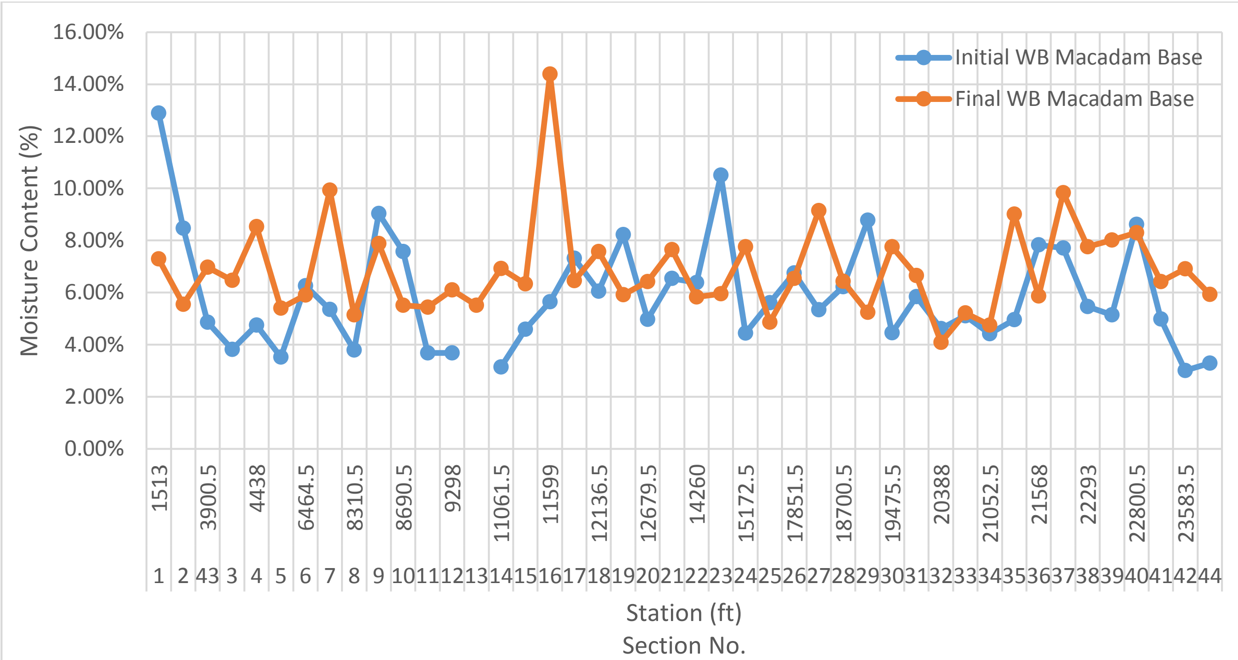

Figure 70. Laboratory Determined Gravimetric Moisture Content for Water-bound Macadam Base (Westbound Lane) (100 ft = 30.5 m).

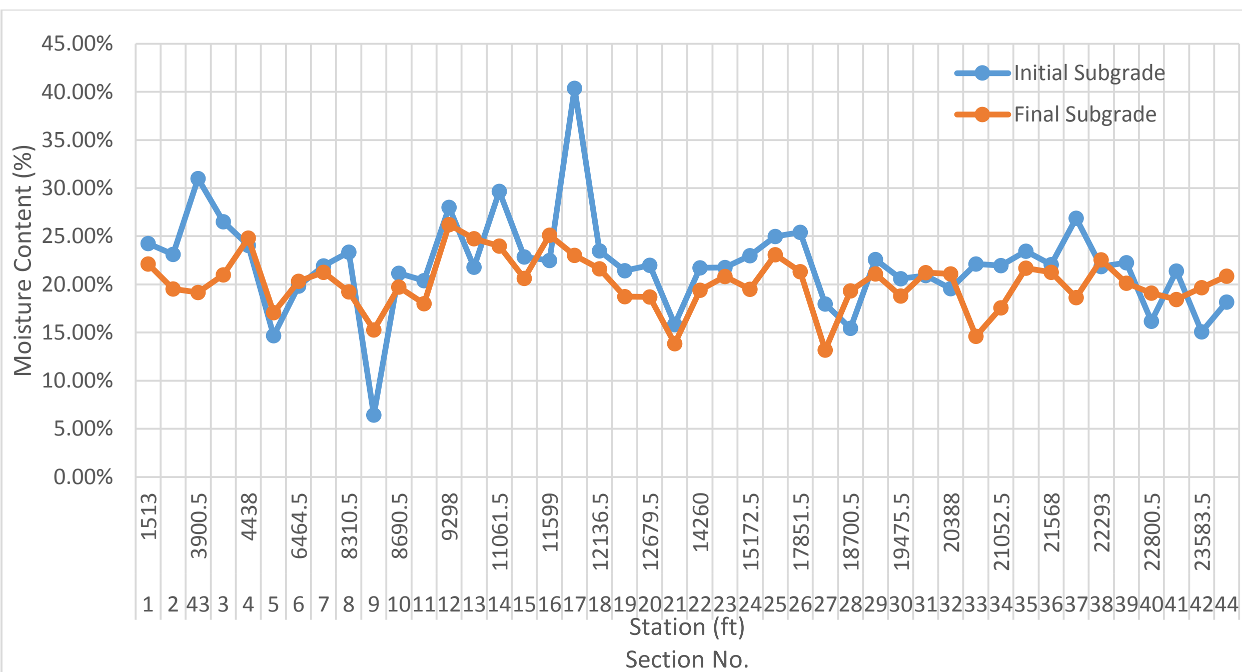

Figure 71. Laboratory Determined Gravimetric Moisture Content for Subgrade (Westbound Lane) (100 ft = 30.5 m).

Water-bound Macadam Base Gravimetric Moisture Content

The percent difference in gravimetric moisture content of the macadam base, from initial to one year later, for the control and each backfill material, are shown in Figures 72 through 76.

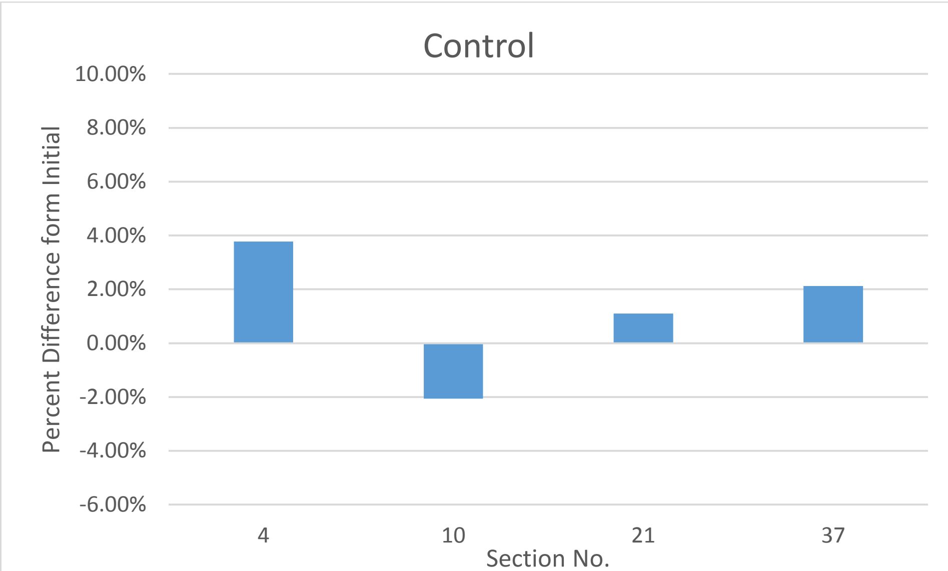

Figure 72. Difference from Initial Lab Gravimetric Moisture Content for Macadam Base, Control Sections.

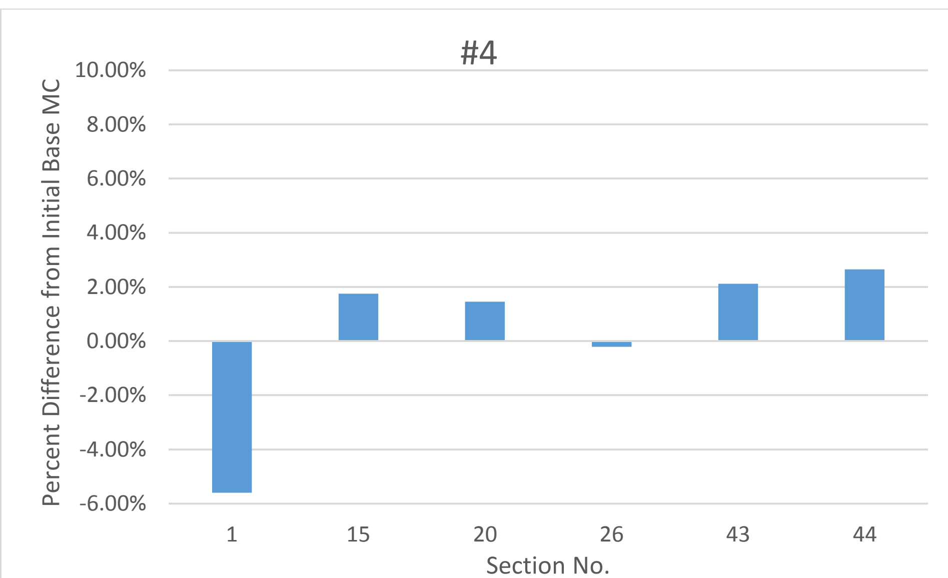

Figure 73. Differences from Initial Lab Gravimetric Moisture Content for Macadam Base, #4 Backfill.

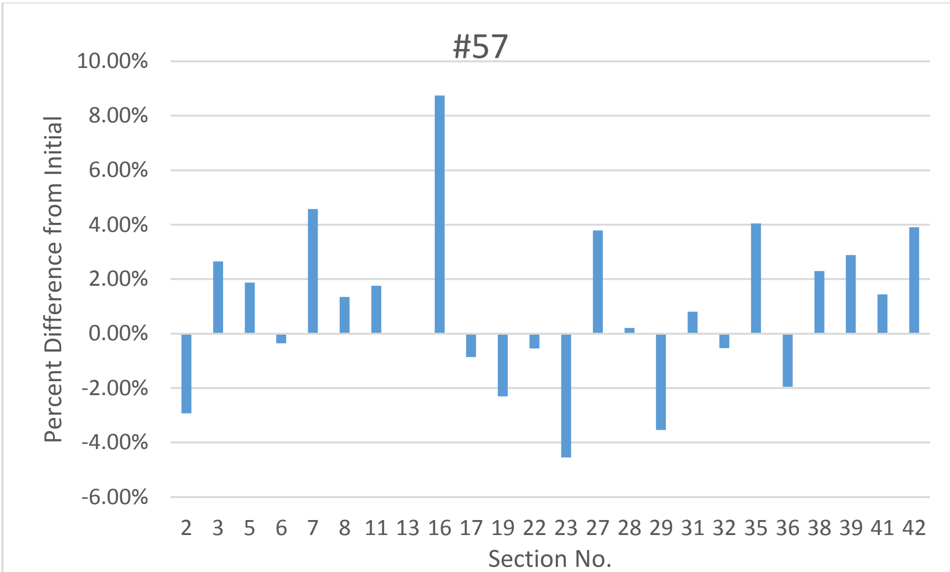

Figure 74. Differences from Initial Lab Gravimetric Moisture Content for Macadam Base, #57 Backfill.

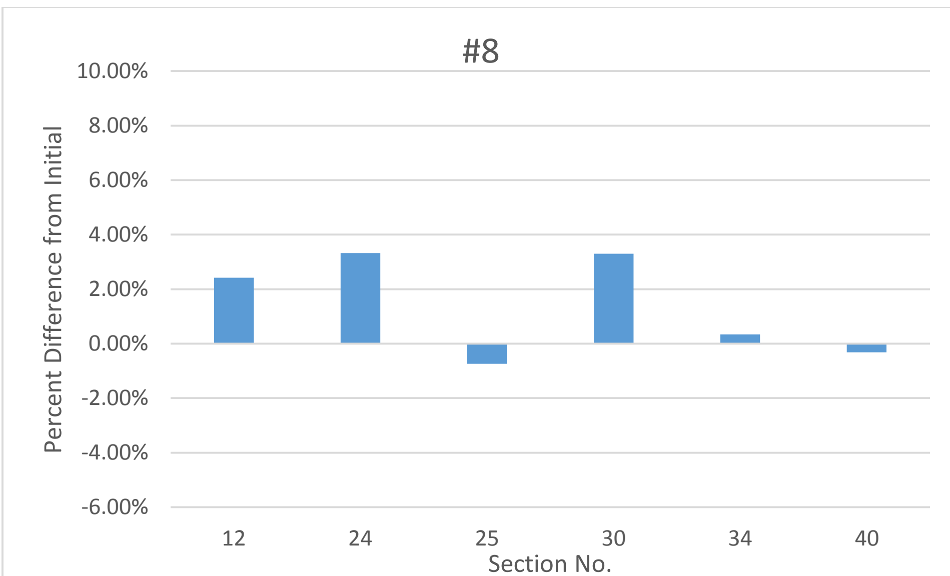

Figure 75. Differences from Initial Lab Gravimetric Moisture Content for Macadam Base, #8 Backfill.

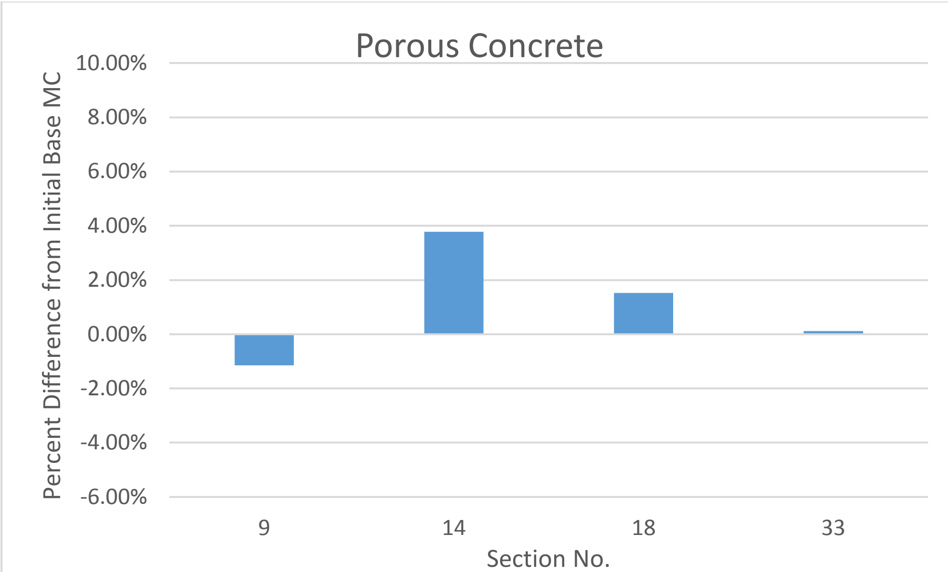

Figure 76. Differences from Initial Lab Gravimetric Moisture Content for Macadam Base, Porous Concrete Backfill.

Approximately 32% of the sections experienced a decrease in the moisture content of the macadam base. An additional 7% of the sections experienced only a slight increase.

Subgrade Gravimetric Moisture Content

The percent change in gravimetric moisture content of the subgrade, from initial to one year later, for the control and each backfill material, are shown in Figures 77 through 81.

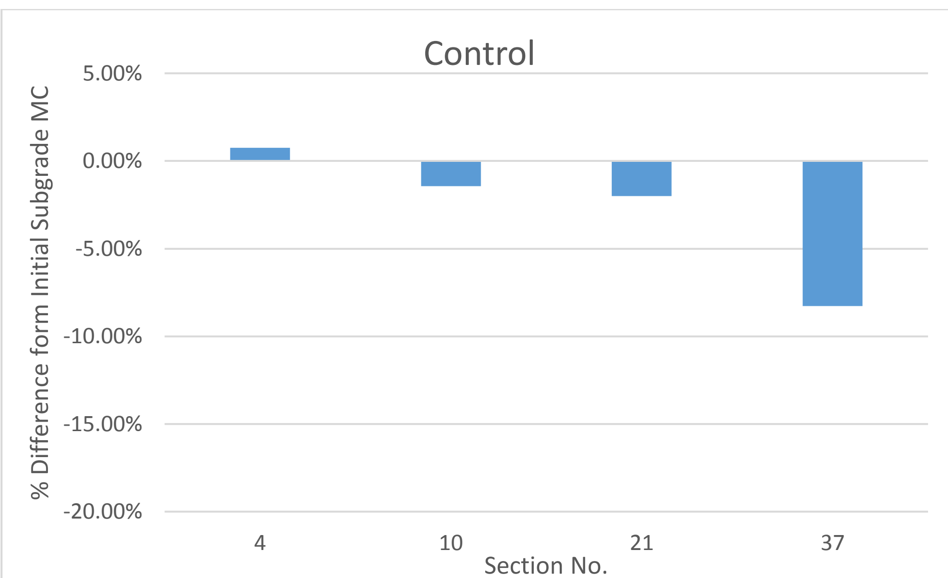

Figure 77. Difference from Initial Lab Gravimetric Moisture Content for Subgrade, Control Sections.

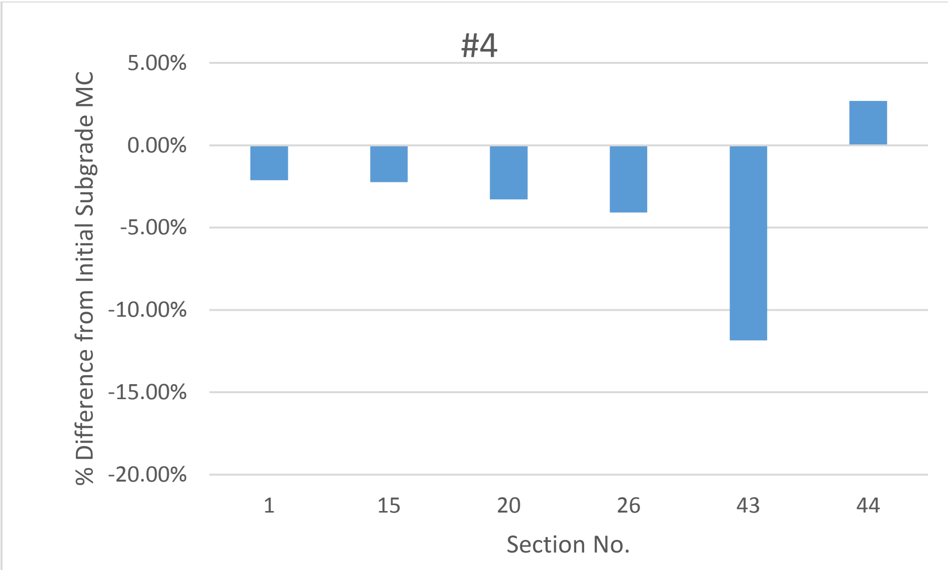

Figure 78. Differences from Initial Lab Gravimetric Moisture Content for Subgrade, #4 Backfill.

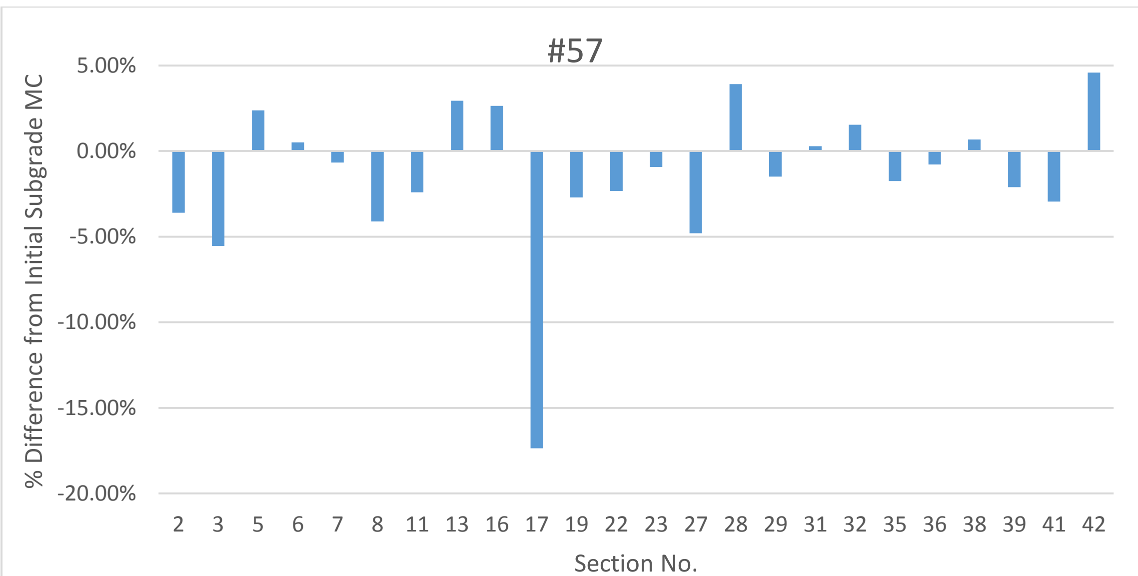

Figure 79. Differences from Initial Lab Gravimetric Moisture Content for Subgrade, #57 Backfill.

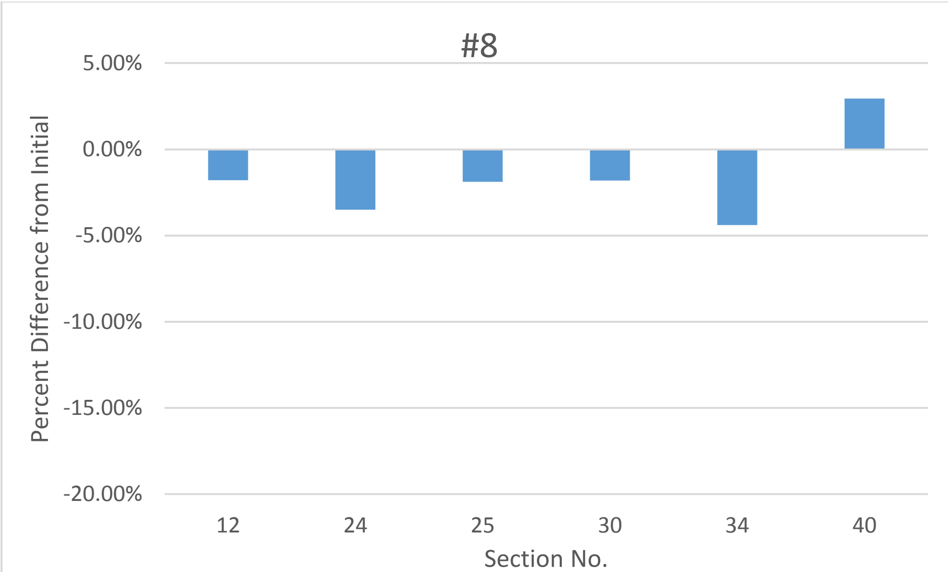

Figure 80. Differences from Initial Lab Gravimetric Moisture Content for Subgrade, #8 Backfill.

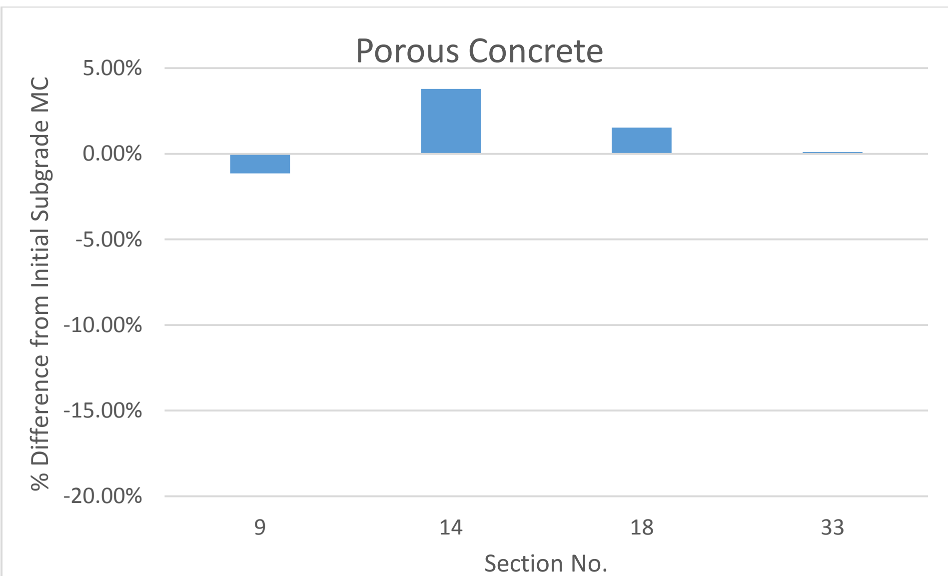

Figure 81. Differences from Initial Lab Gravimetric Moisture Content for Subgrade, Porous Concrete Backfill.

Approximately 64% of the sections experienced a decrease in the moisture content of the macadam base, measured from samples obtained before installation and one year later. Another 9% experienced only a slight increase. The granular base is more porous and would be influenced by short term events, i.e. rainfall, whereas the subgrade is less permeable and would be more indicative of long term trends.

In-situ Moisture of Granular Base

In-situ volumetric moisture content was determined using TDR sensors at approximately four-month intervals after the completion of aggregate drain construction. TDR sensors were installed in seven experimental and two control sections in the eastbound lane. In the experimental test sections, moisture content was measured by the TDR at the bottom of the aggregate drain. In the control sections sensors were installed at the bottom of the 304 aggregate base layer.

Moisture contents are summarized below in Table 24 for each date readings were obtained. In Table 24 values are summarized for the moisture content within the drains of the experimental sections and within the aggregate base in the control sections and between drains in the experimental sections. Full results are presented in Appendix M. As shown in Figure 82, not all of the TDR sensors were functioning on the last date. To put the moisture content in context with the amount of precipitation, weather data were obtained for the Marion Municipal Airport (KMNN) from Weather Underground [2017]. A correlation analysis was conducted for the in-situ moisture content in the control sections to determine the most influential precipitation parameter associated with measured volumetric moisture content. It was found the cumulative precipitation for the two days prior to the measurement (CP2) was most correlated with volumetric moisture content in the control sections. Values for CP2 are also shown in Table 24. Generally, greater cumulative precipitation was associated with higher volumetric moisture content in the aggregate base.

Table 24. Summary of Volumetric Moisture Content

Date	Location	No. of sensors	CP2, in (mm)	Volumetric Moisture Content (%)				
				Min	Max	Avg	Std. Dev.	COV
5/23/2016	CNTRL	4	0.12 (3.0)	12.24	14.2	12.93	0.88	6.8%
5/23/2016	BD	7	0.12 (3.0)	9.69	17.73	12.63	2.94	23.3%
5/23/2016	D	7	0.12 (3.0)	11.87	19.85	14.90	3.23	21.7%
10/19/2016	CNTRL	4	0.32 (8.1)	14.93	18.68	16.76	1.71	10.2%
10/19/2016	BD	7	0.32 (8.1)	12.42	22.71	18.47	3.52	19.1%
10/19/2016	D	7	0.32 (8.1)	24.07	32.47	28.06	3.40	12.1%
1/19/2017	CNTRL	3	0.37 (9.4)	16.81	17.91	17.50	0.60	3.4%
1/19/2017	BD	6	0.37 (9.4)	13.91	34.26	22.15	8.07	36.4%
1/19/2017	D	6	0.37 (9.4)	26.67	36.99	31.58	3.75	11.9%
5/31/17	CNTRL	2	0.26 (6.6)	15.39	18.25	16.82	N/A	N/A
5/31/17	BD	6	0.26 (6.6)	14.10	33.27	22.28	7.94	35.6
5/31/17	D	6	0.26 (6.6)	24.76	36.45	29.44	3.84	13.1
6/2/2017	CNTRL	3	0	13.08	15.15	14.33	1.10	7.7%
6/2/2017	BD	5	0	13.21	23.66	18.02	4.29	23.8%
6/2/2017	D	7	0	23.84	36.35	29.30	3.96	13.5%

CNTRL: Control sections
BD: Between drains
D: at Drain

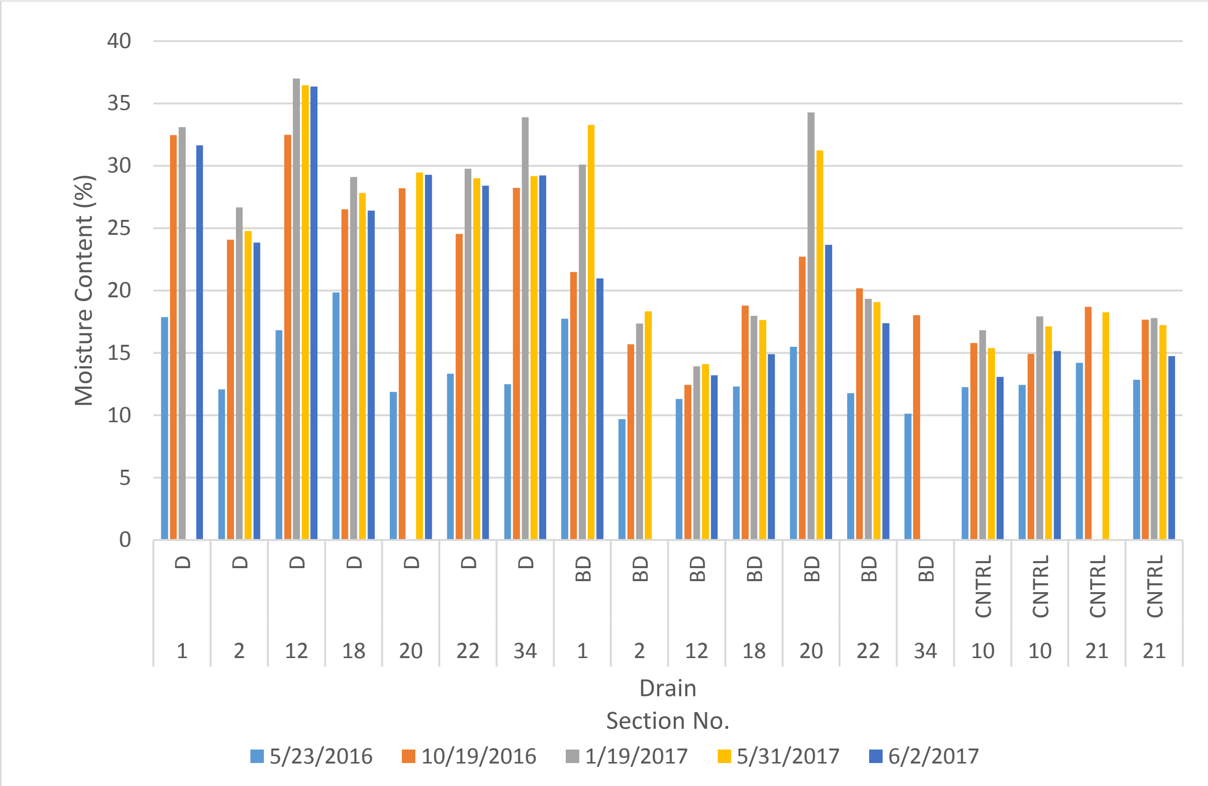

Figure 82. Volumetric Moisture Content.

The in-situ moisture contents were very consistent among the four sensors in the control sections for each date, evident by the low COV shown in Table 24. With the exception of the first date, May 23, 2016, average in-situ moisture contents were consistently greater at the aggregate drains than between the drains and in the control sections. This is also evident in Figure 82. This could be an indication moisture is migrating towards the aggregate drains. To explore this notion, the percent difference between in-situ moisture content measured at the drains and between drains were plotted in Figure 83. With the exception of Section 21 on May 23, 2016 and Section 18 on May 31, 2017, there is an increase in moisture at the aggregate drains relative to moisture measured between the drains. It should be noted that aggregate drains were installed in six of the seven sections only four days prior to the first reading on May 23, 2016. In Section 18, the TDR sensor was installed and read on May 23, 2016 when aggregate drain construction began, however construction of the drains in Section 18 was not complete until the following day. Therefore, the readings on the first date may not completely represent the change in moisture due to the presence of the drains in Section 18.

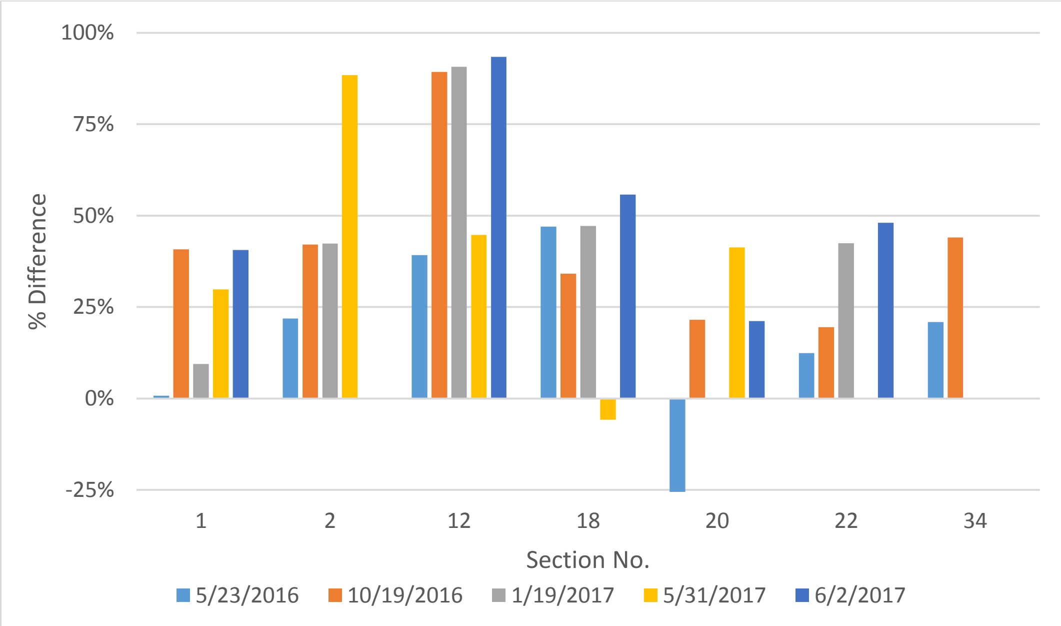

Figure 83. Percent Difference between In-situ Moisture at Drains and Between Drains.

As inferred from the COV of moisture readings shown in Table 24, the control sections had the least variability, whereas moisture readings between drains were the most variable. The variability could be associated with the various parameters investigated among the seven experimental sections. For aggregate drains constructed in these seven sections, filter fabric was not used in construction and the material was compacted. Parameters that were not held constant were the type of material, section length, and drain spacing. Although the section length was varied, the drain spacing was dependent on the section length, therefore, effectively there were only two variables of concern: material and drain spacing. To evaluate if any of the parameters was related to the differences shown between moisture measured at the drains and moisture measured between the drains, the sections were ranked by percent difference (with sections ranked as 1 were associated with the largest percent difference) for each date in Table 25. Sections ranked number one for each date are identified by bold font. Section 12, which featured aggregate drains constructed with No. 8 aggregate and spaced at 200 ft (61 m), saw the largest difference in moisture content and ranked the highest on all three dates.

Table 25. Rank of Sections Based on Percent Difference in Moisture

Date	Section	Percent Difference	Rank
5/23/2016	1	0.7%	5
	2	21.9%	2
	12	**39.2%**	**1**
	18*	47.0%	N/A
	20	-26.5%	6
	22	12.4%	4
	34	20.9%	3
10/19/2016	1	40.8%	4
	2	42.1%	3
	12	**89.3%**	**1**
	18	34.1%	5
	20	21.5%	6
	22	19.5%	7
	34	44.0%	2
1/19/2017	1	9.5%	5
	2	42.3%	4
	12	**90.7%**	**1**
	18	47.2%	2
	22	42.5%	3
5/31/17	2	29.8%	4
	12	**88.4%**	**1**
	18	44.8%	2
	20	-5.8%	5
	22	41.3%	3
6/2/17	1	40.6%	4
	12	**93.4%**	**1**
	18	55.8%	2
	20	21.2%	5
	22	48.1%	3

*Excluded due to timing of aggregate drain construction

The moisture content in the bases drained with the AASHTO No. 4 gradation, Section 1 and Section 20, had similar levels of moisture content at the drain and between the drains, and those levels were among some of the highest moisture contents recorded between drains.

Although the porous concrete drains in Section 18 were among the lower moisture content and high percent difference between the drain and the midpoint between drains, the values were similar to the AASHTO No. 8 and AASHTO No. 57 gradation backfill, and would therefore be more cost effective.

APPENDIX H SUMMARY AND CONCLUSIONS (PHASE 2)

DCP, deflection, and moisture data were collected for a one year period and only reflect short term changes in performance. Such a short period of monitoring gives a limited picture of the effects of the installation of drains on moisture content and material properties. Based on findings from Wolfe and Butalia [2004], at least two years are required for the moisture content in the soil to stabilize following a construction activity. A potential long-term issue in comparing the different installation conditions is clogging of the drains, where differences may not be evident after only one year. Collection of additional data over an extended period of time will better determine performance and allow for full stabilization of soil moisture content at the site, sufficient weather events, and enough sediment to see clogging.

Specifically, the following conclusions can be drawn from the findings in this study.

Equipment Production Rates:

- There is a significant difference in excavation time between the two pieces of equipment. The rock saw completed the trench excavation in an average of slightly less than 2 minutes while the backhoe took an average of slightly more than 13 minutes.
  - Total time to complete the aggregate drain installation was also statistically different, the rock saw taking an average of slightly less than 8 minutes and the backhoe taking slightly more than 32 minutes to complete, on average. In addition to increasing productivity, the reduction in installation time also reduces the time traffic is delayed during construction.
- Lining the trench with fabric required an additional 1 to 3 minutes over a standard installation time. Compacting the backfill took an additional 3 to 5 minutes for both the rock saw and backhoe.
- In order to recover costs of the rock saw, at least 1,205 aggregate drains would be needed for a return on the investment. If this work load is met, the rock saw is more economical than the backhoe for aggregate drain installation.
- Based on projected needs in one District 6 county, the use of the rock saw could reduce installation time by approximately 1936 work days, with a projected savings of approximately $458,000.

FWD Testing:

- Backcalculation from FWD data indicated increases in base moduli over the baseline values at both locations, at drains and between drains. The base modulus between the drains in many sections saw a greater increase relative to baseline moduli values than base modulus at the drains, likely due to the movement of moisture from the undrained areas to the drain.

DCP Testing:

- The ANOVA analyses of DCP data collected before installation and after a year of service showed the changes in the modulus of the subgrade and the macadam base were not of sufficient magnitude to reach statistical significance regardless of backfill material, drain spacing, filter fabric wrap, and/or compaction.

Laboratory Determined Moisture Content:

- Approximately 32% of the sections experienced a decrease in the moisture content of the macadam base, measured from samples obtained before installation and one year later. An additional 7% of the sections experienced only a slight increase.

- Approximately 64% of the sections experienced a decrease in the moisture content of the subgrade, measured from samples obtained before installation and one year later. Another 9% experienced only a slight increase.

In-situ Volumetric Moisture Measured in the 304 Aggregate Base:

- The moisture content was monitored in the granular material in the base. The moisture content at the drains were consistently higher than between the drains, indicating the water is moving from undrained areas to the drain.
    - The backcalculated base modulus between drains was generally greater than at the drains, which may also indicate the movement of water towards the drains. Movement of water from undrained areas to the drains serves to verify aggregate drains aid in the removal of moisture from the pavement system.

Variables Considered:

- Although some trends were identified among the variables considered as described herein, there were no statistically significant relationships established between the effectiveness of the drains and the spacing, the backfill material, usage of filter fabric, or usage of compaction.
- Compaction may be desirable to prevent settlement, however, findings for sections constructed with or without compaction were inconclusive. Long-term monitoring for settlement of the patched areas is recommended to validate the effectiveness of compaction.
- Filter fabric may be desirable when using larger sized aggregate and/or porous concrete as backfill material to prevent migration of the subgrade soils into the backfill material. Findings for sections constructed with or without filter fabric were inconclusive. Long-term evaluation of sections with aggregate drains constructed with No. 4 aggregate, and porous concrete and with and without filter fabric should be conducted to determine if this phenomenon is occurring and the effect on drainage.

APPENDIX I GEOTEXTILE FABRIC TECHNICAL INFORMATION

MIRAFI® _______________ *TECHNICAL DATA SHEET*

Mirafi® 140N

Mirafi® 140N is a nonwoven geotextile composed of polypropylene fibers, which are formed into a a stable network such that the fibers retain their relative position. 140N is inert to biological degradation and resists naturally encountered chemicals, alkalis, and acids.

Mechanical Properties	Test Method	Unit	Minimum Average Roll Value	
			MD	CD
Grab Tensile Strength	ASTM D 4632-91	kN (lbs)	0.53 (120)	0.53 (120)
Grab Tensile Elongation	ASTM D 4632-91	%	50	50
Trapezoid Tear Strength	ASTM D 4533-91	kN (lbs)	0.22 (50)	0.22 (50)
Mullen Burst Strength	ASTM D 3786-87	kPa (psi)	1550 (225)	
Puncture Strength	ASTM D 4833-00	kN (lbs)	0.30 (65)	
Apparent Opening Size (AOS)	ASTM D 4751-99A	mm (U.S. Sieve)	0.212 (70)	
Permittivity	ASTM D 4491-99A	sec^{-1}	1.8	
Permeability	ASTM D 4491-99A	cm/sec	0.21	
Flow Rate	ASTM D 4491-99A	$l/min/m^2$ ($gal/min/ft^2$)	5500 (135)	
UV Resistance (at 500 hours)	ASTM D 4355-02	% strength retained	70	

Physical Properties	Test Method	Unit	Typical Value	
Weight	ASTM D 5261-92	g/m^2 (oz/yd^2)	163 (4.8)	
Thickness	ASTM D 5199-01	mm (mils)	1.4 (55)	
Roll Dimensions (width x length)	--	m (ft)	3.8 x 110 (12.5 x 360)	4.5 x 110 (15 x 360)
Roll Area	--	m^2 (yd^2)	418 (500)	502 (600)
Estimated Roll Weight	--	kg (lb)	74 (164)	89 (197)

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APPENDIX J LOCATION OF AGGREGATE DRAINS

Table 26. Section and Aggregate Drain Stationing

Section No.	Code	Spacing (ft)	Length (ft)	Drain 1 (EB) (ft) [Start]	Drain 2 (WB) (ft)	Drain 3 (EB) (ft)	Drain 4 (WB) (ft)	Drain 5 (EB) (ft)	Drain 6 (WB) (ft) [End]
1	R #4 NF C L N	200	500	1263	1363	1463	1563	1663	1763
2	R #57 NF C S N	50	125	1859	1884	1909	1934	1959	1976
3	R #57 F C S N	50	125	4013	4038	4063	4088	4113	4138
4	CNTRL-500B	-	500	4188	-	-	-	-	4688
5	B #57 F C S W	50	125	4738	4763	4788	4813	4838	4863
6	B #57 F NC S W	50	125	6402	6427	6452	6477	6502	6527
7	B #57 F NC L W	200	500	6580	6680	6780	6880	6980	7068
8	B #57 NF NC S W	50	125	8248	8273	8298	8323	8348	8373
9	R PC F C S N	50	125	8444	8469	8494	8519	8544	8578
10	CNTRL-125B	-	125	8628	-	-	-	-	8753
11	R #57 NF NC S N	50	125	8828	8853	8878	8903	8928	8953
12	R #8 NF C L N	200	500	9048	9148	9248	9348	9441	9548
13	R #57 F NC L W	200	500	10449	10549	10649	10749	10849	10949
14	R PC NF NC S N	50	125	10999	11024	11049	11074	11099	11124
15	R #4 F NC S N	50	125	11174	11199	11224	11249	11274	11299
16	R #57 NF C L W	200	500	11349	11449	11549	11649	11749	11849
17	R #57 F NC S W	50	125	11899	11924	11949	11974	11999	12024
18	R PC NF C S N	50	125	12074	12099	12124	12149	12174	12199
19	B #57 NF C S W	50	125	12249	12274	12299	12324	12349	12374
20	R #4 NF C S N	50	125	12617	12642	12667	12692	12717	12742
21	CNTRL-500A	-	500	13460	-	-	-	-	13960
22	R #57 NF C L N	200	500	14010	14110	14210	14310	14410	14510
23	R #57 NF NC L W	200	500	14560	14660	14760	14860	14960	15060
24	R #8 NF NC S N	50	125	15110	15135	15160	15185	15210	15235
25	R #8 NF NC L N	200	500	17049	17149	17249	17349	17449	17549
26	R #4 NF NC S N	50	125	17789	17814	17839	17864	17889	17914
27	B #57 F C L W	200	500	17991	18091	18191	18291	18391	18491
28	R #57 F C S W	50	125	18638	18663	18688	18713	18738	18763
29	B #57 NF C L W	200	500	18863	18963	19063	19163	19263	19363
30	R #8 F C S N	50	125	19413	19438	19463	19488	19513	19538
31	R #57 F C L N	200	500	19588	19688	19788	19888	19988	20088
32	R #57 F NC L N	200	500	20138	20238	20344	20438	20538	20638
33	R PC F NC S N	50	125	20700	20725	20750	20775	20800	20825
34	R #8 NF C S N	50	125	20990	21015	21040	21065	21090	21115
35	R #57 F NC S N	50	125	21143	21168	21193	21218	21247	21268
36	R #57 F C L W	200	500	21318	21418	21518	21618	21718	21818
37	CNTRL-125A	-	125	21868	-	-	-	-	21993
38	R #57 NF NC L N	200	500	22043	22143	22243	22343	22443	22543
39	R #57 NF C S W	50	125	22578	22603	22628	22653	22678	22703
40	R #8 F NC S N	50	125	22738	22763	22788	22813	22838	22863
41	B #57 NF NC L W	200	500	22971	23071	23171	23271	23371	23471
42	R #57 NF NC S W	50	125	23521	23546	23571	23596	23621	23646
43	R #4 F C S N	50	125	3838	3863	3888	3913	3938	3963
44	R #4 NF NC L N	200	500	23696	23796	23896	23996	24096	24196

Section No.	Code	Spacing (m)	Length (m)	Drain 1 (EB) (m) [Start]	Drain 2 (WB) (m)	Drain 3 (EB) (m)	Drain 4 (WB) (m)	Drain 5 (EB) (m)	Drain 6 (WB) (m) [End]
1	R #4 NF C L N	61	152	385	415	446	476	507	537
2	R #57 NF C S N	15	38	567	574	582	589	597	602
3	R #57 F C S N	15	38	1223	1231	1238	1246	1254	1261
4	CNTRL-500B	-	152	1277	-	-	-	-	1429
5	B #57 F C S W	15	38	1444	1452	1459	1467	1475	1482
6	B #57 F NC S W	15	38	1951	1959	1967	1974	1982	1989
7	B #57 F NC L W	61	152	2006	2036	2067	2097	2128	2154
8	B #57 NF NC S W	15	38	2514	2522	2529	2537	2544	2552
9	R PC F C S N	15	38	2574	2581	2589	2597	2604	2615
10	CNTRL-125B	-	38	2630	-	-	-	-	2668
11	R #57 NF NC S N	15	38	2691	2698	2706	2714	2721	2729
12	R #8 NF C L N	61	152	2758	2788	2819	2849	2878	2910
13	R #57 F NC L W	61	152	3185	3215	3246	3276	3307	3337
14	R PC NF NC S N	15	38	3352	3360	3368	3375	3383	3391
15	R #4 F NC S N	15	38	3406	3413	3421	3429	3436	3444
16	R #57 NF C L W	61	152	3459	3490	3520	3551	3581	3612
17	R #57 F NC S W	15	38	3627	3634	3642	3650	3657	3665
18	R PC NF C S N	15	38	3680	3688	3695	3703	3711	3718
19	B #57 NF C S W	15	38	3733	3741	3749	3756	3764	3772
20	R #4 NF C S N	15	38	3846	3853	3861	3869	3876	3884
21	CNTRL-500A	-	152	4103	-	-	-	-	4255
22	R #57 NF C L N	61	152	4270	4301	4331	4362	4392	4423
23	R #57 NF NC L W	61	152	4438	4468	4499	4529	4560	4590
24	R #8 NF NC S N	15	38	4606	4613	4621	4628	4636	4644
25	R #8 NF NC L N	61	152	5197	5227	5257	5288	5318	5349
26	R #4 NF NC S N	15	38	5422	5430	5437	5445	5453	5460
27	B #57 F C L W	61	152	5484	5514	5545	5575	5606	5636
28	R #57 F C S W	15	38	5681	5688	5696	5704	5711	5719
29	B #57 NF C L W	61	152	5749	5780	5810	5841	5871	5902
30	R #8 F C S N	15	38	5917	5925	5932	5940	5948	5955
31	R #57 F C L N	61	152	5970	6001	6031	6062	6092	6123
32	R #57 F NC L N	61	152	6138	6169	6201	6230	6260	6290
33	R PC F NC S N	15	38	6309	6317	6325	6332	6340	6347
34	R #8 NF C S N	15	38	6398	6405	6413	6421	6428	6436
35	R #57 F NC S N	15	38	6444	6452	6460	6467	6476	6482
36	R #57 F C L W	61	152	6498	6528	6559	6589	6620	6650
37	CNTRL-125A	-	38	6665	-	-	-	-	6703
38	R #57 NF NC L N	61	152	6719	6749	6780	6810	6841	6871
39	R #57 NF C S W	15	38	6882	6889	6897	6905	6912	6920
40	R #8 F NC S N	15	38	6931	6938	6946	6953	6961	6969
41	B #57 NF NC L W	61	152	7002	7032	7063	7093	7123	7154
42	R #57 NF NC S W	15	38	7169	7177	7184	7192	7200	7207
43	R #4 F C S N	15	38	1170	1177	1185	1193	1200	1208
44	R #4 NF NC L N	61	152	7223	7253	7284	7314	7344	7375

APPENDIX K AGGREGATE DRAIN CONSTRUCTION DATES

Table 27. Aggregate Drain Construction Dates

Date	Section No.	Direction	Drain #	Location (ft)	Location (m)
4/26/2016	35	W	6	21268	6482.5
4/26/2016	36	W	6	21818	6650.1
4/26/2016	36	W	4	21618	6589.2
4/26/2016	36	W	2	21418	6528.2
4/26/2016	38	W	6	22543	6871.1
4/26/2016	38	W	4	22343	6810.1
4/26/2016	38	W	2	22143	6749.2
4/26/2016	39	W	6	22703	6919.9
4/26/2016	39	W	4	22653	6904.6
4/26/2016	39	W	2	22603	6889.4
4/26/2016	40	W	6	22863	6968.6
4/26/2016	40	W	4	22813	6953.4
4/26/2016	40	W	2	22763	6938.2
4/26/2016	42	W	6	23646	7207.3
4/26/2016	42	W	4	23596	7192.1
4/26/2016	42	W	2	23546	7176.8
4/26/2016	44	W	6	24196	7374.9
4/26/2016	44	W	4	23996	7314.0
4/26/2016	44	W	2	23796	7253.0
5/3/2016	23	W	6	15060	4590.3
5/3/2016	23	W	4	14860	4529.3
5/3/2016	23	W	2	14660	4468.4
5/3/2016	24	W	6	15235	4643.6
5/3/2016	24	W	4	15185	4628.4
5/3/2016	24	W	2	15135	4613.1
5/3/2016	25	W	6	17549	5348.9
5/3/2016	25	W	4	17349	5288.0
5/3/2016	25	W	2	17149	5227.0
5/3/2016	26	W	6	17914	5460.2
5/3/2016	26	W	4	17864	5444.9
5/3/2016	26	W	2	17814	5429.7
5/3/2016	28	W	6	18763	5719.0
5/3/2016	28	W	4	18713	5703.7
5/3/2016	28	W	2	18663	5688.5
5/3/2016	30	W	6	19538	5955.2
5/3/2016	30	W	4	19488	5939.9
5/3/2016	30	W	2	19438	5924.7
5/3/2016	31	W	6	20088	6122.8
5/3/2016	31	W	4	19888	6061.9
5/3/2016	31	W	2	19688	6000.9
5/3/2016	32	W	6	20638	6290.5
5/3/2016	32	W	4	20438	6229.5
5/3/2016	32	W	2	20238	6168.5
5/3/2016	35	W	4	21218	6467.2
5/3/2016	35	W	2	21168	6452.0

Date	Section No.	Direction	Drain #	Location (ft)	Location (m)
5/4/2016	13	W	6	10949	3337.3
5/4/2016	13	W	4	10749	3276.3
5/4/2016	13	W	2	10549	3215.3
5/4/2016	15	W	6	11299	3443.9
5/4/2016	15	W	4	11249	3428.7
5/4/2016	15	W	2	11199	3413.5
5/4/2016	16	W	6	11849	3611.6
5/4/2016	16	W	4	11649	3550.6
5/4/2016	16	W	2	11449	3489.7
5/4/2016	17	W	6	12024	3664.9
5/4/2016	17	W	4	11974	3649.7
5/4/2016	17	W	2	11924	3634.4
5/4/2016	20	W	6	12742	3883.8
5/4/2016	20	W	4	12692	3868.5
5/4/2016	20	W	2	12642	3853.3
5/4/2016	22	W	6	14510	4422.6
5/4/2016	22	W	4	14310	4361.7
5/4/2016	22	W	2	14110	4300.7
5/5/2016	1	W	6	1763	537.4
5/5/2016	1	W	4	1563	476.4
5/5/2016	1	W	2	1363	415.4
5/5/2016	2	W	6	1976	602.3
5/5/2016	2	W	4	1934	589.5
5/5/2016	2	W	2	1884	574.2
5/5/2016	3	W	6	4138	1261.3
5/5/2016	3	W	4	4088	1246.0
5/5/2016	3	W	2	4038	1230.8
5/5/2016	11	W	6	8953	2728.9
5/5/2016	11	W	4	8903	2713.6
5/5/2016	11	W	2	8853	2698.4
5/5/2016	12	W	6	9548	2910.2
5/5/2016	12	W	4	9348	2849.3
5/5/2016	12	W	2	9148	2788.3
5/5/2016	43	W	6	3963	1207.9
5/5/2016	43	W	4	3913	1192.7
5/5/2016	43	W	2	3863	1177.4
5/6/2016	3	E	1	4013	1223.2
5/6/2016	3	E	3	4063	1238.4
5/6/2016	3	E	5	4113	1253.6
5/6/2016	11	E	1	8828	2690.8
5/6/2016	11	E	3	8878	2706.0
5/6/2016	11	E	5	8928	2721.3
5/6/2016	13	E	1	10449	3184.9
5/6/2016	13	E	3	10649	3245.8
5/6/2016	13	E	5	10849	3306.8
5/6/2016	15	E	1	11174	3405.8
5/6/2016	15	E	3	11224	3421.1

Date	Section No.	Direction	Drain #	Location (ft)	Location (m)
5/6/2016	15	E	5	11274	3436.3
5/6/2016	16	E	1	11349	3459.2
5/6/2016	16	E	3	11549	3520.1
5/6/2016	16	E	5	11749	3581.1
5/6/2016	43	E	1	3838	1169.8
5/6/2016	43	E	3	3888	1185.1
5/6/2016	43	E	5	3938	1200.3
5/9/2016	17	E	1	11899	3626.8
5/9/2016	17	E	3	11949	3642.1
5/9/2016	17	E	5	11999	3657.3
5/9/2016	23	E	1	14560	4437.9
5/9/2016	23	E	3	14760	4498.8
5/9/2016	23	E	5	14960	4559.8
5/9/2016	24	E	1	15110	4605.5
5/9/2016	24	E	3	15160	4620.8
5/9/2016	24	E	5	15210	4636.0
5/9/2016	25	E	1	17049	5196.5
5/9/2016	25	E	3	17249	5257.5
5/9/2016	25	E	5	17449	5318.5
5/9/2016	26	E	1	17789	5422.1
5/9/2016	26	E	3	17839	5437.3
5/9/2016	26	E	5	17889	5452.6
5/9/2016	28	E	1	18638	5680.9
5/9/2016	28	E	3	18688	5696.1
5/9/2016	28	E	5	18738	5711.3
5/9/2016	30	E	1	19413	5917.1
5/9/2016	30	E	3	19463	5932.3
5/9/2016	30	E	5	19513	5947.6
5/10/2016	31	E	1	19588	5970.4
5/10/2016	31	E	3	19788	6031.4
5/10/2016	31	E	5	19988	6092.3
5/10/2016	32	E	1	20138	6138.1
5/10/2016	32	E	3	20344	6200.9
5/10/2016	32	E	5	20538	6260.0
5/10/2016	34	W	6	21115	6435.9
5/10/2016	34	W	4	21065	6420.6
5/10/2016	34	W	2	21015	6405.4
5/10/2016	35	E	1	21143	6444.4
5/10/2016	35	E	3	21193	6459.6
5/10/2016	35	E	5	21247	6476.1
5/10/2016	36	E	1	21318	6497.7
5/10/2016	36	E	3	21518	6558.7
5/10/2016	36	E	5	21718	6619.6
5/10/2016	38	E	1	22043	6718.7
5/10/2016	38	E	3	22243	6779.7
5/10/2016	38	E	5	22443	6840.6
5/10/2016	39	E	5	22678	6912.3

Date	Section No.	Direction	Drain #	Location (ft)	Location (m)
5/11/2016	39	E	1	22578	6881.8
5/11/2016	39	E	3	22628	6897.0
5/11/2016	40	E	1	22738	6930.5
5/11/2016	40	E	3	22788	6945.8
5/11/2016	40	E	5	22838	6961.0
5/11/2016	41	E	1	22971	7001.6
5/11/2016	41	E	3	23171	7062.5
5/11/2016	41	E	5	23371	7123.5
5/11/2016	42	E	1	23521	7169.2
5/11/2016	42	E	3	23571	7184.4
5/11/2016	42	E	5	23621	7199.7
5/11/2016	44	E	1	23696	7222.5
5/11/2016	44	E	3	23896	7283.5
5/11/2016	44	E	5	24096	7344.5
5/12/2016	29	E	1	18863	5749.4
5/12/2016	29	E	3	19063	5810.4
5/12/2016	29	E	5	19263	5871.4
5/12/2016	29	W	6	19363	5901.8
5/12/2016	29	W	4	19163	5840.9
5/12/2016	29	W	2	18963	5779.9
5/12/2016	41	W	6	23471	7154.0
5/12/2016	41	W	4	23271	7093.0
5/12/2016	41	W	2	23071	7032.0
5/13/2016	19	W	6	12374	3771.6
5/13/2016	19	W	4	12324	3756.4
5/13/2016	19	W	2	12274	3741.1
5/13/2016	19	E	1	12249	3733.5
5/13/2016	19	E	3	12299	3748.7
5/13/2016	19	E	5	12349	3764.0
5/13/2016	27	E	5	18391	5605.6
5/13/2016	27	E	3	18191	5544.6
5/13/2016	27	E	1	17991	5483.7
5/13/2016	27	W	2	18091	5514.1
5/13/2016	27	W	4	18291	5575.1
5/13/2016	27	W	6	18491	5636.1
5/17/2016	7	W	6	7068	2154.3
5/17/2016	7	W	4	6880	2097.0
5/17/2016	7	W	2	6680	2036.1
5/17/2016	7	E	1	6580	2005.6
5/17/2016	7	E	3	6780	2066.5
5/17/2016	7	E	5	6980	2127.5
5/17/2016	8	W	6	8373	2552.1
5/17/2016	8	W	4	8323	2536.9
5/17/2016	8	W	2	8273	2521.6
5/17/2016	8	E	1	8248	2514.0
5/17/2016	8	E	3	8298	2529.2
5/17/2016	8	E	5	8348	2544.5

Date	Section No.	Direction	Drain #	Location (ft)	Location (m)
5/18/2016	5	W	6	4863	1482.2
5/18/2016	5	W	4	4813	1467.0
5/18/2016	5	W	2	4763	1451.8
5/18/2016	5	E	1	4738	1444.1
5/18/2016	5	E	3	4788	1459.4
5/18/2016	5	E	5	4838	1474.6
5/18/2016	6	W	6	6527	1989.4
5/18/2016	6	W	4	6477	1974.2
5/18/2016	6	W	2	6427	1958.9
5/18/2016	6	E	1	6402	1951.3
5/18/2016	6	E	3	6452	1966.6
5/18/2016	6	E	5	6502	1981.8
5/19/2016	1	E	1	1263	385.0
5/19/2016	1	E	3	1463	445.9
5/19/2016	1	E	5	1663	506.9
5/19/2016	2	E	1	1859	566.6
5/19/2016	2	E	3	1909	581.9
5/19/2016	2	E	5	1959	597.1
5/19/2016	12	E	1	9048	2757.8
5/19/2016	12	E	3	9248	2818.8
5/19/2016	12	E	5	9441	2877.6
5/19/2016	20	E	1	12617	3845.7
5/19/2016	20	E	3	12667	3860.9
5/19/2016	20	E	5	12717	3876.1
5/19/2016	22	E	1	14010	4270.2
5/19/2016	22	E	3	14210	4331.2
5/19/2016	22	E	5	14410	4392.2
5/19/2016	34	E	1	20990	6397.8
5/19/2016	34	E	3	21040	6413.0
5/19/2016	34	E	5	21090	6428.2
5/24/2016	9	E	1	8444	2573.7
5/24/2016	9	E	3	8494	2589.0
5/24/2016	9	E	5	8544	2604.2
5/24/2016	14	E	1	10999	3352.5
5/24/2016	14	E	3	11049	3367.7
5/24/2016	14	E	5	11099	3383.0
5/24/2016	18	E	1	12074	3680.2
5/24/2016	18	E	3	12124	3695.4
5/24/2016	18	E	5	12174	3710.6
5/24/2016	33	E	1	20700	6309.4
5/24/2016	33	E	3	20750	6324.6
5/24/2016	33	E	5	20800	6339.8
5/25/2016	9	W	6	8578	2614.6
5/25/2016	9	W	4	8519	2596.6
5/25/2016	9	W	2	8469	2581.4
5/25/2016	14	W	6	11124	3390.6
5/25/2016	14	W	4	11074	3375.4

Date	Section No.	Direction	Drain #	Location (ft)	Location (m)
5/25/2016	14	W	2	11024	3360.1
5/25/2016	18	W	6	12199	3718.3
5/25/2016	18	W	4	12149	3703.0
5/25/2016	18	W	2	12099	3687.8
5/25/2016	33	W	6	20825	6347.5
5/25/2016	33	W	4	20775	6332.2
5/25/2016	33	W	2	20725	6317.0

APPENDIX L DCP TEST LOCATIONS AND RESULTS

Table 28. Stationing of DCP Testing

Section No.	Direction	Station	Code
1	WB	1513.0	R #4 NF C L N
2	WB	1917.5	R #57 NF C S N
3	WB	4075.5	R #57 F C S N
4	WB	4438.0	CNTRL-500B
5	WB	4800.5	B #57 F C S W
6	WB	6464.5	B #57 F NC S W
7	WB	6824.0	B #57 F NC L W
8	WB	8310.5	B #57 NF NC S W
9	WB	8511.0	R PC F C S N
10	WB	8690.5	CNTRL-125B
11	WB	8890.5	R #57 NF NC S N
12	WB	9298.0	R #8 NF C L N
13	WB	10699.0	R #57 F NC L W
14	WB	11061.5	R PC NF NC S N
15	WB	11236.5	R #4 F NC S N
16	WB	11599.0	R #57 NF C L W
17	WB	11961.5	R #57 F NC S W
18	WB	12136.5	R PC NF C S N
19	WB	12311.5	B #57 NF C S W
20	WB	12679.5	R #4 NF C S N
21	WB	13710.0	CNTRL-500A
22	WB	14260.0	R #57 NF C L N
23	WB	14810.0	R #57 NF NC L W
24	WB	15172.5	R #8 NF NC S N
25	WB	17299.0	R #8 NF NC L N
26	WB	17851.5	R #4 NF NC S N
27	WB	18241.0	B #57 F C L W
28	WB	18700.5	R #57 F C S W
29	WB	19113.0	B #57 NF C L W
30	WB	19475.5	R #8 F C S N
31	WB	19838.0	R #57 F C L N
32	WB	20388.0	R #57 F NC L N
33	WB	20762.5	R PC F NC S N
34	WB	21052.5	R #8 NF C S N
35	WB	21205.5	R #57 F NC S N
36	WB	21568.0	R #57 F C L W
37	WB	21930.5	CNTRL-125A
38	WB	22293.0	R #57 NF NC L N
39	WB	22640.5	R #57 NF C S W
40	WB	22800.5	R #8 F NC S N
41	WB	23221.0	B #57 NF NC L W
42	WB	23583.5	R #57 NF NC S W
43	WB	3900.5	R #4 F C S N
44	WB	23946.0	R #4 NF NC L N

Table 29. Results of Initial DCP Analysis: Macadam Base Thickness and Resilient Moduli of Unbound Layers

Date	Section No.	Station		Macadam Base Thickness		Water-bound Macadam Base Resilient Modulus "M_r"		Natural Subgrade Resilient Modulus "M_r"	
		(ft)	(m)	in	mm	(psi)	(MPa)	(psi)	(MPa)
4/12/2016	1	1513.0	461	12.82	325.6	58736	404.97	24851	171.34
4/12/2016	2	1917.5	584	4.69	119.2	30681	211.54	8734	60.22
4/12/2016	43	3900.5	1189	12.42	315.5	48398	333.70	6620	45.64
4/12/2016	3	4075.5	1242	9.46	240.2	57716	397.94	23605	162.75
4/12/2016	4	4438.0	1353	9.37	237.9	35985	248.11	10380	71.57
4/12/2016	5	4800.5	1463	9.31	236.5	61144	421.57	22488	155.05
4/12/2016	6	6464.5	1970	9.80	248.9	28819	198.70	8017	55.28
4/12/2016	7	6824.0	2080	12.17	309.1	20234	139.51	7351	50.68
4/12/2016	8	8310.5	2533	15.23	386.8	50113	345.52	7186	49.54
4/12/2016	9	8511.0	2594	9.94	252.5	53255	367.18	15368	105.96
4/12/2016	10	8690.5	2649	5.36	136.1	20727	142.91	11263	77.66
4/12/2016	11	8890.5	2710	9.47	240.6	61402	423.35	17535	120.90
4/12/2016	12	9298.0	2834	8.97	227.9	55402	381.98	13668	94.23
4/12/2016	13	10699.0	3261	6.24	158.4	52513	362.06	8593	59.25
4/12/2016	14	11061.5	3372	10.16	258.0	58890	406.03	12132	83.64
4/12/2016	15	11236.5	3425	8.32	211.4	48014	331.05	11984	82.63
4/12/2016	16	11599.0	3535	15.98	405.9	50451	347.85	10370	71.50
4/13/2016	17	11961.5	3646	8.77	222.8	38636	266.39	14123	97.37
4/13/2016	18	12136.5	3699	9.46	240.2	32588	224.68	7710	53.16
4/13/2016	19	12311.5	3753	11.18	284.0	45120	311.09	9511	65.57
4/13/2016	20	12679.5	3865	12.15	308.7	67077	462.48	12255	84.49
4/13/2016	21	13710.0	4179	6.60	167.6	38611	266.21	21438	147.81
4/13/2016	22	14260.0	4346	8.68	220.5	47892	330.20	12444	85.80
4/13/2016	23	14810.0	4514	7.91	200.9	53134	366.34	13927	96.02
4/13/2016	24	15172.5	4625	11.94	303.2	30005	206.87	7334	50.57
4/13/2016	25	17299.0	5273	12.62	320.5	44759	308.60	6391	44.07
4/13/2016	26	17851.5	5441	12.98	329.7	55143	380.20	8617	59.41
4/13/2016	27	18241.0	5560	6.99	177.6	49917	344.17	13015	89.73
4/13/2016	28	18700.5	5700	12.62	320.5	48897	337.13	14789	101.97
4/13/2016	29	19113.0	5826	9.78	248.4	57849	398.85	14486	99.88
4/13/2016	30	19475.5	5936	12.44	316.0	47021	324.20	14478	99.82
4/13/2016	31	19838.0	6047	12.67	321.9	56490	389.49	11289	77.83
4/13/2016	32	20388.0	6214	9.83	249.8	58620	404.17	12472	85.99
4/13/2016	33	20762.5	6328	15.95	405.0	40289	277.78	7265	50.09
4/13/2016	34	21052.5	6417	14.72	374.0	49180	339.08	8181	56.41

Date	Section No.	Station		Macadam Base Thickness		Water-bound Macadam Base Resilient Modulus "M_r"		Natural Subgrade Resilient Modulus "M_r"	
		(ft)	(m)	in	mm	(psi)	(MPa)	(psi)	(MPa)
4/13/2016	35	21205.5	6463	10.14	257.5	48100	331.64	14745	101.66
4/13/2016	36	21568.0	6574	10.03	254.8	32706	225.50	10911	75.23
4/13/2016	37	21930.5	6684	4.80	121.9	38999	268.89	15951	109.98
4/13/2016	38	22293.0	6795	12.69	322.4	52707	363.40	14146	97.53
4/13/2016	39	22640.5	6901	14.49	368.0	39731	273.93	6579	45.36
4/13/2016	40	22800.5	6950	11.36	288.6	43716	301.41	16557	114.16
4/13/2016	41	23221.0	7078	11.31	287.2	54336	374.63	15166	104.57
4/13/2016	42	23583.5	7188	11.86	301.4	41893	288.84	10213	70.42
4/13/2016	44	23946.0	7299	13.97	354.8	62430	430.44	19721	135.97
Average				**10.63**	**270.0**	**47007**	**324.10**	**12588**	**86.79**

Table 30. Results of Final DCP Analysis: Macadam Base Thickness and Resilient Moduli of Unbound Layers

Date	Section No.	Station		Macadam Base Thickness		Water-bound Macadam Base Resilient Modulus "Mr"		Natural Subgrade Resilient Modulus "Mr"	
		(ft)	(m)	in	mm	(psi)	(MPa)	(psi)	(MPa)
6/2/2017	1	1513.0	461	9.46	240.2	48722	335.93	10544	72.70
6/2/2017	2	1917.5	584	8.23	209.1	51245	353.32	22111	152.45
6/2/2017	43	3900.5	1189	10.79	274.0	42546	293.35	8579	59.15
6/2/2017	3	4075.5	1242	9.71	246.6	48222	332.48	10931	75.37
6/2/2017	4	4438.0	1353	9.73	247.0	37821	260.77	12024	82.90
6/2/2017	5	4800.5	1463	8.14	206.8	49621	342.13	23476	161.86
6/2/2017	6	6464.5	1970	11.94	303.2	32050	220.98	8568	59.08
6/2/2017	7	6824.0	2080	12.89	327.4	26205	180.68	11141	76.82
6/2/2017	8	8310.5	2533	14.24	361.6	45211	311.72	7000	48.26
6/2/2017	9	8511.0	2594	9.35	237.4	56905	392.35	20437	140.91
6/2/2017	10	8690.5	2649	11.70	297.3	56225	387.66	10592	73.03
6/1/2017	11	8890.5	2710	11.51	292.2	47214	325.53	15742	108.54
6/1/2017	12	9298.0	2834	11.83	300.5	47411	326.89	9264	63.87
6/1/2017	13	10699.0	3261	8.20	208.2	50843	350.55	15460	106.59
6/1/2017	14	11061.5	3372	11.58	294.1	39056	269.28	7127	49.14
6/1/2017	15	11236.5	3425	9.64	244.7	49922	344.20	12485	86.08
6/1/2017	16	11599.0	3535	15.62	396.8	58701	404.73	25636	176.75
6/1/2017	17	11961.5	3646	11.54	293.2	53014	365.52	10313	71.11
6/1/2017	18	12136.5	3699	10.96	278.3	44054	303.74	8938	61.63
6/1/2017	19	12311.5	3753	10.66	270.8	52971	365.22	8277	57.07

Date	Section No.	Station		Macadam Base Thickness		Water-bound Macadam Base Resilient Modulus "*Mr*"		Natural Subgrade Resilient Modulus "*Mr*"	
		(ft)	(m)	in	mm	(psi)	(MPa)	(psi)	(MPa)
6/1/2017	20	12679.5	3865	11.63	295.4	50347	347.13	11739	80.94
6/1/2017	21	13710.0	4179	6.89	174.9	30620	211.12	18346	126.49
6/1/2017	22	14260.0	4346	9.55	242.5	55783	384.61	12386	85.40
6/1/2017	23	14810.0	4514	12.15	308.7	58083	400.47	8731	60.20
6/1/2017	24	15172.5	4625	13.59	345.2	40178	277.02	9195	63.40
6/1/2017	25	17299.0	5273	4.64	117.8	52058	358.93	6646	45.82
6/1/2017	26	17851.5	5441	9.33	237.0	60039	413.96	9743	67.18
6/1/2017	27	18241.0	5560	14.98	380.4	48405	333.74	40499	279.23
6/1/2017	28	18700.5	5700	11.29	286.8	51473	354.89	17701	122.04
6/1/2017	29	19113.0	5826	18.41	467.6	49077	338.37	13310	91.77
6/1/2017	30	19475.5	5936	11.18	284.0	55511	382.73	34829	240.14
6/1/2017	31	19838.0	6047	15.68	398.2	45382	312.90	4950	34.13
6/1/2017	32	20388.0	6214	12.21	310.0	60267	415.53	10238	70.59
5/26/2017	33	20762.5	6328	16.83	427.4	47791	329.51	13857	95.54
5/25/2017	34	21052.5	6417	14.96	379.9	46559	321.01	7912	54.55
5/25/2017	35	21205.5	6463	8.41	213.7	26520	182.85	8601	59.30
5/25/2017	36	21568.0	6574	9.20	233.8	32907	226.89	8124	56.01
5/25/2017	37	21930.5	6684	12.21	310.0	32578	224.62	8719	60.11
5/25/2017	38	22293.0	6795	10.14	257.5	44506	306.86	10568	72.86
5/25/2017	39	22640.5	6901	14.35	364.4	46329	319.43	10012	69.03
5/25/2017	40	22800.5	6950	8.23	209.1	46791	322.61	13576	93.60
5/25/2017	41	23221.0	7078	18.00	457.1	38662	266.57	8890	61.29
5/25/2017	42	23583.5	7188	10.09	256.2	44290	305.37	11994	82.70
5/25/2017	44	23946.0	7299	9.51	241.6	44204	304.78	15650	107.91
Average				**11.39**	**289.29**	**46507**	**320.66**	**13065**	**90.08**

APPENDIX M TDR SENSOR LOCATIONS AND RESULTS

Table 31. TDR Probe Locations

Section	Direction	Station	Drain #	Code
1	EB	1463	3	R #4 NF C L N
1	EB	1563	BD	R #4 NF C L N
2	EB	1909	3	R #57 NF C S N
2	EB	1934	BD	R #57 NF C S N
10	EB	8678	N/A	CNTRL-125B
10	EB	8703	N/A	CNTRL-125B
12	EB	9248	3	R #8 NF C L N
12	EB	9348	BD	R #8 NF C L N
18	EB	12124	3	R PC NF C S N
18	EB	12149	BD	R PC NF C S N
20	EB	12667	3	R #4 NF C S N
20	EB	12692	BD	R #4 NF C S N
21	EB	13660	N/A	CNTRL-500A
21	EB	13760	N/A	CNTRL-500A
22	EB	14210	3	R #57 NF C L N
22	EB	14310	BD	R #57 NF C L N
34	EB	21040	3	R #8 NF C S N
34	EB	21065	BD	R #8 NF C S N

BD: Between Drains
N/A: Not Applicable

Table 32. Volumetric Moisture Content (500 ft = 152 m; 125 ft = 38 m; 200 ft = 61 m; 50 ft = 15 m)

Date	Section	Location	Material	Length (ft)	Spacing (ft)	Moisture (%)
5/23/2016	1	BD	#4	500	200	17.73
5/23/2016	2	BD	#57	125	50	9.69
5/23/2016	12	BD	#8	500	200	11.31
5/23/2016	18	BD	PC	125	50	12.30
5/23/2016	20	BD	#4	125	50	15.49
5/23/2016	22	BD	#57	500	200	11.76
5/23/2016	34	BD	#8	125	50	10.12
5/23/2016	10	CNTRL	CNTRL	125	N/A	12.24
5/23/2016	10	CNTRL	CNTRL	125	N/A	12.43
5/23/2016	21	CNTRL	CNTRL	500	N/A	14.20
5/23/2016	21	CNTRL	CNTRL	500	N/A	12.83
5/23/2016	1	D	#4	500	200	17.86
5/23/2016	2	D	#57	125	50	12.07
5/23/2016	12	D	#8	500	200	16.82
5/23/2016	18	D	PC	125	50	19.85

Date	Section	Location	Material	Length (ft)	Spacing (ft)	Moisture (%)
5/23/2016	20	D	#4	125	50	11.87
5/23/2016	22	D	#57	500	200	13.32
5/23/2016	34	D	#8	125	50	12.48
10/19/2016	1	BD	#4	500	200	21.47
10/19/2016	2	BD	#57	125	50	15.70
10/19/2016	12	BD	#8	500	200	12.42
10/19/2016	18	BD	PC	125	50	18.79
10/19/2016	20	BD	#4	125	50	22.71
10/19/2016	22	BD	#57	500	200	20.18
10/19/2016	34	BD	#8	125	50	18.03
10/19/2016	10	CNTRL	CNTRL	125	N/A	15.78
10/19/2016	10	CNTRL	CNTRL	125	N/A	14.93
10/19/2016	21	CNTRL	CNTRL	500	N/A	18.68
10/19/2016	21	CNTRL	CNTRL	500	N/A	17.66
10/19/2016	1	D	#4	500	200	32.46
10/19/2016	2	D	#57	125	50	24.07
10/19/2016	12	D	#8	500	200	32.47
10/19/2016	18	D	PC	125	50	26.51
10/19/2016	20	D	#4	125	50	28.19
10/19/2016	22	D	#57	500	200	24.54
10/19/2016	34	D	#8	125	50	28.21
1/19/2017	1	BD	#4	500	200	30.09
1/19/2017	2	BD	#57	125	50	17.35
1/19/2017	12	BD	#8	500	200	13.91
1/19/2017	18	BD	PC	125	50	17.98
1/19/2017	20	BD	#4	125	50	34.26
1/19/2017	22	BD	#57	500	200	19.33
1/19/2017	34	BD	#8	125	50	N/A
1/19/2017	10	CNTRL	CNTRL	125	N/A	16.81
1/19/2017	10	CNTRL	CNTRL	125	N/A	17.91
1/19/2017	21	CNTRL	CNTRL	500	N/A	N/A
1/19/2017	21	CNTRL	CNTRL	500	N/A	17.79
1/19/2017	1	D	#4	500	200	33.08
1/19/2017	2	D	#57	125	50	26.67
1/19/2017	12	D	#8	500	200	36.99
1/19/2017	18	D	PC	125	50	29.09
1/19/2017	20	D	#4	125	50	N/A
1/19/2017	22	D	#57	500	200	29.75

Date	Section	Location	Material	Length (ft)	Spacing (ft)	Moisture (%)
1/19/2017	34	D	#8	125	50	33.88
5/31/2017	1	BD	#4	500	200	33.27
5/31/2017	2	BD	#57	125	50	18.33
5/31/2017	12	BD	#8	500	200	14.1
5/31/2017	18	BD	PC	125	50	17.64
5/31/2017	20	BD	#4	125	50	31.23
5/31/2017	22	BD	#57	500	200	19.08
5/31/2017	34	BD	#8	125	50	
5/31/2017	10	CNTRL	CNTRL	125	N/A	15.39
5/31/2017	10	CNTRL	CNTRL	125	N/A	17.13
5/31/2017	21	CNTRL	CNTRL	500	N/A	18.25
5/31/2017	21	CNTRL	CNTRL	500	N/A	17.23
5/31/2017	1	D	#4	500	200	
5/31/2017	2	D	#57	125	50	24.76
5/31/2017	12	D	#8	500	200	36.45
5/31/2017	18	D	PC	125	50	27.81
5/31/2017	20	D	#4	125	50	29.46
5/31/2017	22	D	#57	500	200	29
5/31/2017	34	D	#8	125	50	29.18
6/2/2017	1	BD	#4	500	200	20.96
6/2/2017	2	BD	#57	125	50	
6/2/2017	12	BD	#8	500	200	13.21
6/2/2017	18	BD	PC	125	50	14.89
6/2/2017	20	BD	#4	125	50	23.66
6/2/2017	22	BD	#57	500	200	17.39
6/2/2017	34	BD	#8	125	50	
6/2/2017	10	CNTRL	CNTRL	125	N/A	13.08
6/2/2017	10	CNTRL	CNTRL	125	N/A	15.15
6/2/2017	21	CNTRL	CNTRL	500	N/A	
6/2/2017	21	CNTRL	CNTRL	500	N/A	14.75
6/2/2017	1	D	#4	500	200	31.64
6/2/2017	2	D	#57	125	50	23.84
6/2/2017	12	D	#8	500	200	36.35
6/2/2017	18	D	PC	125	50	26.41
6/2/2017	20	D	#4	125	50	29.27
6/2/2017	22	D	#57	500	200	28.39
6/2/2017	34	D	#8	125	50	29.22

ITEM 306 CEMENT TREATED FREE DRAINING BASE

306.01 Description. This work consists of constructing a cement treated free draining base (CTFDB) on a prepared base course.

306.02 Materials. Use CTFDB consisting of a mixture of aggregate, portland cement, and water. Use portland cement conforming to 701.01 or 701.04. Do not substitute pozzolans for portland cement. Furnish aggregate conforming to 703.12.

306.03 Proportioning, Mixing, and Transporting. Proportion, mix, and transport CTFDB according to Item 499, except prepare a mix design conforming to the following requirements:

A. Ensure that the minimum cement content by weight is 250 pounds per cubic yard (148 kg/m^3) when using No. 57 gradation and 220 pounds per cubic yard (130 kg/m^3) when using No. 67 gradation.

B. Ensure that the water-cement ratio is approximately 0.36. This ratio is the amount of water, exclusive of that absorbed by the aggregates, to the amount of cement, by weight. The Contractor may change this water-cement ratio depending on the workability of the mixture.

C. The Contractor may use water-reducing admixtures according to 705.12.

D. Prewet, as necessary, the mixer fins and chute to allow discharge of the CTFDB.

306.04 Verification of Design. A minimum of 30 days before the production of CTFDB, submit a computed blend of aggregates, cement content, admixture, and water content for the necessary testing to determine the mix design acceptance. Have an independent private laboratory perform the required tests to check the yield of the mix design.

The Department will take random samples of the material at the discharge of the mixer and following the spreading operation to ensure conformance to the mix design. The Department will check the yield using a bulk density test for aggregate (ASTM C 29) to determine the unit weight of the mix.

306.05 Equipment. Provide all equipment necessary to mix, transport, place, compact, and finish CTFDB. Receive approval for this equipment before work can start.

306.06 Placing and Spreading. When the Contract Documents do not require the base to be primed, sprinkle it with water so it is thoroughly moistened when CTFDB is placed.

Do not allow workers to walk in freshly mixed CTFDB with boots or shoes coated with earth or other foreign material.

Before compaction, spread the mixed CTFDB to produce a smooth uniform layer.

If the width of the CTFDB being placed in one operation is more than 12 feet (3.5 m) or the total area of any given width on the project exceeds 5000 square yards (4000 m^2), use a spreader.

The Department will test for in place gradation after spreading, but before compaction testing, according to Supplement 1090.

306.07 Limitations on Placing Operations. Spread CTFDB only when the atmospheric temperature is above 35 °F (2 °C). Do not spread on frozen material.

Do not place the CTFDB when rain is imminent. If rain occurs during placement of the CTFDB, cease all operations. Do not place the CTFDB when rain has softened the underlying base course or subgrade.

Do not place the CTFDB during any weather conditions that would cause its degradation, segregation, or contamination.

306.08 Compaction and Shaping. Compact and shape CTFDB to produce uniform density and cross-section. Use approved methods of compaction and shaping.

Compact the CTFDB using steel wheel rollers, modified slip-form pavers (using vibratory plates), or high-density screed pavers. Firmly seat the CTFDB into place by using the above equipment or combination thereof. Compact the CTFDB without crushing the aggregate or segregating the materials.

Perform the final compaction using steel wheel rollers weighing from 6 to 10 tons (5 to 9 metric tons). The Contractor may use vibratory rollers meeting the above requirements provided the vibration is turned off. Make at least two passes over any given point on the surface with the rollers. More passes may be required to ensure compaction.

Begin compaction within 1/2 hour of the spreading operation. Provide sufficient spreading and compaction equipment to complete compaction within 1 1/2 hours after water is added to the aggregate and cement.

Make construction joints by cutting a straight transverse joint in the completed work to form a vertical face at the end of each day's work or when work is suspended for more than 3 hours. Cut the CTFDB using a diamond blade saw. The Contractor may use a bulkhead instead of this procedure.

306.09 Curing. Place 6-mil (150 μm) white opaque polyethylene sheeting conforming to 705.06 over the completed CTFDB course immediately after compaction, and keep the sheeting in place for 3 days. Do not use concrete curing membranes.

If the next layer of pavement is placed without loading the CTFDB with construction or compaction equipment, the Engineer may allow a 2-day curing period. In this case, do not allow more than 4 hours to elapse between the removal of the curing and the placement of the pavement.

When the next layer of pavement is asphalt or a pavement layer that requires compaction equipment, cure the CTFDB for 3 days.

A cure day is defined as 24 consecutive hours. Maintain the temperature of the CTFDB above 40 °F (5 °C) during the curing period. For every day that the temperature of the CTFDB falls below 40 °F (5 °C) for any length of time, add an additional cure day.

306.10 Protection of the Underdrains. Do not allow equipment to crush any part of the underdrain system as a result of the placement or compaction of CTFDB. Repair or replace damaged underdrain pipe at no expense to the Department.

Ensure a positive connection between the underdrain backfill and the CTFDB at all times.

306.11 Protection of the Cement Treated Free Draining Base. The Department has not designed CTFDB for use as a haul road. Provided there is no significant displacement, breakup, or contamination, the Contractor may operate hauling units and other construction vehicles on the CTFDB.

If significant displacement, breakup, or contamination of the CTFDB is occurring, cease operating the hauling units and construction vehicles on the CTFDB. The Department will not allow hauling units and construction vehicles to travel on the CTFDB until the Contractor has satisfactorily demonstrated that displacement, breakup, or contamination is not expected to recur.

The use of the CTFDB by hauling vehicles or construction equipment is at the risk of the Contractor. Repair or replace all damage to the CTFDB, base, subgrade, or underdrains caused by the hauling units and construction vehicles at no expense to the Department.

Protect the CTFDB from fine material contamination at all times.

Provide adequate surface and subsurface drainage for the CTFDB, base, and subgrade at all times.

If constructing asphalt concrete pavement on the CTFDB, place the first course using a paver mounted on tracks. Allow the first course to cure overnight before placing the succeeding pavement courses.

306.12 Thickness Tolerances. Ensure that the compacted depth of CTFDB is 4 ± 1/2 inch (100 ± 13 mm). Ensure that the compacted depth conforms to the plans.

Verify the specified depth by randomly checking the CTFDB's depth during construction for at least every 2000 square yards (1650 m^2). If the depth is less than the specified depth by more than 1/2 inch (13 mm), remove and replace it with CTFDB within tolerance at no expense to the Department.

306.13 Surface Tolerance. Use templates, slope boards, or other devices to verify the surface tolerance.

Ensure that the finished surface is uniform and does not vary more than 1/2 inch (13 mm) from a 10-foot (3 m) straightedge applied to the surface parallel to the centerline of the pavement. If an area is out of tolerance, remove the areas and replace it with CTFDB within the specified tolerance at no expense to the Department.

306.14 Exposure to the Elements. Place the next layer of pavement within 40 days of the end of the CTFDB's curing period.

The Contractor may construct the CTFDB at any time that complies with the temperature restrictions specified in 306.07. However, completely cover the CTFDB with the next layer of pavement, and place the underdrain system and have it functioning before the atmospheric temperature falls below 35 °F (2 °C) or by the end of the construction season in any given calendar year.

Remove and replace CTFDB, base, subgrade, and underdrain system damaged by exposure to temperatures below 35 °F (2 °C) at no expense to the Department.

306.15 Method of Measurement. The Department will measure the 4-inch (100 mm) Cement Treated Free Draining Base by the number of square yards (square meters) computed from the profile grade and typical sections accepted in place.

306.16 Basis of Payment. The Department will pay for accepted quantities at the contract price as follows:

Item	unit	Description
306	Square Yard (Square Meter)	4 inch (100 mm) Cement Treated Free Draining Base

DELIVERY TICKET — CUSTOMER COPY

Buckeye Ready-Mix, L.L.C.
7657 Taylor Road • Reynoldsburg, Ohio 43068
1-800-876-0522 • 614-575-2132 (Columbus/Reynoldsburg)

WARNING
CEMENT IS INJURIOUS TO EYES; MAY CAUSE CHEMICAL BURNS.
READ THIS WARNING BEFORE USING. CONTAINS PORTLAND CEMENT

[illegible]

KEEP OUT OF REACH OF CHILDREN. [illegible]

DATE	TIME ON JOB	TIME BATCHED	CUSTOMER CODE	JOB NUMBER	P.O. #
05/24/16	9:45 AM	9:22 AM	COD	JOB	AUTH#056212

CUSTOMER NAME: OHIO DEPT OF TRANSPORTATION — PREVIOUS TRUCK:

DELIVERY INSTRUCTIONS:
UNKNOWN JOB
SR 529
SR 98 SOUTH, EAST ON 529 EAST ABOUT 1.5 MILES..

490066

ZONE: MARION

TRUCK	PLANT	ORDER #	TICKET #	CLASS/USAGE	DRIVER NAME	SLUMP
323	14	77191	480066	(UNKNOWN)	BANKS, TODD	1.00 in

LOAD QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UNIT O.M.	CUMULATIVE QUANTITY	UNIT PRICE	AMOUNT
4.00	DOTCTFDB	ODOT CEMENT TREATED FREE	yd	4.00	125.00	$500.00
1.00	BURNWARN	CHEM BURN WARN	LD	1.00		
1.00	HC	HAUL CHARGE	EA	1.00	$75.00	$75.00
1.00	MSDS SHE	SDS SHEET X________	LD	1.00		
						$575.00

LV. PLANT	ARR. JOB	START POUR	UNUSUAL INCIDENT OF NOTE ON THIS DELIVERY	SUBTOTAL	$575.00
END POUR	LV. JOB	ARR. PLANT		TAX	
				TOTAL	
WATER ADDED	SLUMP POURED	TEST CYLINDERS MADE ☐ YES ☐ NO		PREV. BALANCE	
				OVERTIME/ADJ.	
				GRAND TOTAL	$575.00

UNLOADING: Ten (10) minutes per yard allowed with a maximum of sixty (60) minutes. Overtime charges at a rate of $70.00 per hour. This concrete designed in accordance with customer specifications. Any alteration of the job relieves producer of responsibility for designed strength. Water added at customer's request.

CUSTOMER ACKNOWLEDGES RECEIPT OF THE CONCRETE IN GOOD CONDITION. CUSTOMER AGREES TO PURCHASE AND PAY FOR THE CONCRETE AT THE PRICE STATED AND UPON THE TERMS AND CONDITIONS DESCRIBED ON THE REVERSE SIDE OF THIS TICKET. CUSTOMER EXPRESSLY AGREES TO CONVEY THE ABOVE WARNING TO ALL PERSONS WHO COME IN CONTACT WITH WET (UNHARDENED) CONCRETE.

Authorized Representative of Customer ____ Time ____

CONTROL # 308754

```
Truck    Driver   User   Disp Ticket Num   Ticket ID   Time   Date
323      1811     user   480066            130549      9:22   5/24/16
Load Size   Mix Code   Returned   Qty   Mix Age   Seq   Load ID
4.00 CY     DOTCTFDB                               D     2647
Material   Required    Batched    % Var    % Moisture
CEMENT 1   1600 LB     1585 LB    -0.94%
57 LS      9550 LB     9500 LB    -0.60%   0.50% M
WATER      453.0 LB    445.0 LB   -1.77%
WR         48.00 OZ    47.00 OZ   -2.08%
Actual          Num Batches: 1
Load Total:  11533 lb     Design 0.365  Water/Cement 0.363 A   To Add: 0.3 lb
Slump:  1.00 in   *
```

DELIVERY TICKET

INSPECTOR'S COPY

BUCKEYE READY-MIX

Buckeye Ready-Mix, L.L.C.
7657 Taylor Road • Reynoldsburg, Ohio 43068
1-800-876-1522 • 614-575-2132 (Columbus/Reynoldsburg)

WARNING
CEMENT IS INJURIOUS TO EYES; MAY CAUSE CHEMICAL BURNS.
READ THIS WARNING BEFORE USING. CONTAINS PORTLAND CEMENT.

[illegible]

KEEP OUT OF REACH OF CHILDREN. [illegible]

DATE	TIME ON JOB	TIME BATCHED	CUSTOMER CODE	JOB NUMBER	P.O. #
05/25/16	9:54 AM	9:26 AM	COD	JOB	AUTH#083550

CUSTOMER NAME
OHIO DEPT OF TRANSPORTATION PREVIOUS TRUCK:

DELIVERY INSTRUCTIONS
UNKNOWN JOB
SR 529
SR 98 SOUTH, EAST ON 529 TURN AROUND @ 746 GOING BACK
WEST. THEYARE ON WEST SIDE OF SR 529 //

480355

ZONE: MARION

TRUCK	PLANT	ORDER #	TICKET #	CLASS/GRADE	DRIVER NAME	SLUMP
323	14	77194	480355	4000 PSI	BANKS, TODD	1.00 in

LOAD QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UNIT C.M.	CUMULATIVE QUANTITY	UNIT PRICE	AMOUNT
4.00	DOTCTFDB	ODOT CEMENT TREATED FREE	yd	4.00	125.00	$500.00
1.00	BURNWARN	CHEM BURN WARN	LD	1.00		
1.00	HC	HAUL CHARGE	EA	1.00	75.00	$75.00
1.00	MSDS SHE	SDS SHEET X____________	LD	1.00		
						$575.00

LV. PLANT	ARR. JOB	START POUR	UNUSUAL INCIDENT OF NOTE ON THIS DELIVERY
END POUR	LV. JOB	ARR. PLANT	
WATER ADDED	SLUMP POURED	TEST CYLINDERS MADE ☐ YES ☐ NO	

UNLOADING: Ten (10) minutes per yard allowed with a maximum of sixty (60) minutes. Overtime charges at a rate of $72.00 per hour. [illegible]

CUSTOMER ACKNOWLEDGES RECEIPT OF THE CONCRETE IN GOOD CONDITION. CUSTOMER AGREES TO PURCHASE AND PAY FOR THE CONCRETE AT THE PRICE STATED AND UPON THE TERMS AND CONDITIONS DESCRIBED ON THE REVERSE SIDE OF THIS TICKET. CUSTOMER EXPRESSLY AGREES TO CONVEY THE ABOVE WARNING TO ALL PERSONS WHO COME IN CONTACT WITH WET (UNHARDENED) CONCRETE.

Authorized Representative of Customer ______ Time ______

SUBTOTAL	$575.00
TAX	
TOTAL	
PREV. BALANCE	
OVERTIME/MISC.	
GRAND TOTAL	$575.00

CONTROL # 308774

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
323	1811	user	480355	130569	9:26	5/25/16

Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
4.00 CY	DOTCTFDB				D	2667

Material	Required	Batched	% Var	% Moisture
CEMENT 1	1600 LB	1585 LB	-0.94%	
57 LS	9558 LB	9480 LB	-0.81%	0.50% M
WATER	453.0 LB	445.0 LB	-1.77%	
WR	48.00 OZ	48.00 OZ	0.00%	

Actual Num Batches: 1
Load Total: 11513 lb Design 0.365 Water/Cement 0.363 A To Add: 8.4 lb
Slump: 1.00 in #

APPENDIX O CONSTRUCTION PRODUCTION

MAR 529 - Aggregate Drains   Construction Production Sheet   B. Jordan

Section ID ______________________   Date: ________

Excavation

equipment ________ (R - rocksaw, B - backhoe)

begin time ________ end time ________

other equipment (type/number): ______________________

# of people ________

notes:

Fabric

begin time ________ end time ________

other equipment (type/number): ______________________

# of people ________

notes:

Compaction

begin time ________ end time ________

other equipment (type/number): ______________________

# of people ________

notes:

Backfill

begin time ________ end time ________

other equipment (type/number): ______________________

# of people ________

notes:

Table 33. Installation Times for Each Aggregate Drain.

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/5/2016	1	W	6	8	Rock Saw	12:59	13:00	01:00				13:04	13:13	0:09			
5/5/2016	1	W	4	8	Rock Saw	13:16	13:17	01:00				13:18	13:27	0:09			
5/5/2016	1	W	2	8	Rock Saw	13:30	13:31	01:00				13:34	13:44	0:10			
5/19/2016	1	E	1	8	Rock Saw	9:21	9:22	01:00				9:24	9:33	0:09			
5/19/2016	1	E	5	8	Rock Saw	9:39	9:40	01:00				9:45	9:55	0:10			
5/5/2016	2	W	6	8	Rock Saw	12:13	12:15	02:00				12:16	12:24	0:08			
5/5/2016	2	W	4	8	Rock Saw	12:29	12:30	01:00				12:30	12:41	0:11			
5/5/2016	2	W	2	8	Rock Saw	12:44	12:45	01:00				12:47	12:55	0:08			
5/19/2016	2	E	5	8	Rock Saw	10:09	10:10	01:00				10:11	10:19	0:08			
5/19/2016	2	E	1	8	Rock Saw	9:56	9:57	01:00				10:00	10:06	0:06			
5/5/2016	3	W	6	8	Rock Saw	10:17	10:18	01:00	10:19	10:20	0:01	10:20	10:28	0:08			
5/5/2016	3	W	4	8	Rock Saw	10:32	10:33	01:00	10:33	10:34	0:01	10:34	10:46	0:12			
5/5/2016	3	W	2	8	Rock Saw	10:50	10:51	01:00	10:52	10:53	0:01	10:53	11:02	0:09			
5/6/2016	3	E	5	8	Rock Saw	10:07	10:08	01:00	10:09	10:10	0:01	10:10	10:17	0:07			
5/6/2016	3	E	1	8	Rock Saw	9:41	9:42	01:00	9:43	9:44	0:01	9:44	9:52	0:08			
5/6/2016	3	E	3	8	Rock Saw	9:54	9:55	01:00	9:55	9:56	0:01	9:56	10:05	0:09			
5/13/2016	5	W	2	15	Backhoe	11:02	11:12	10:00	11:12	11:13	0:01	11:14	11:17	0:03			
5/12/2016	5	E	5	15	Backhoe	11:02	11:12	10:00	11:12	11:13	0:01	11:14	11:17	0:03			
5/12/2016	5	W	4	15	Backhoe	10:48	10:59	11:00	10:59	11:00	0:01	11:01	11:05	0:04			
5/13/2016	5	E	3	15	Backhoe	10:48	10:59	11:00	10:59	11:00	0:01	11:01	11:05	0:04			
5/12/2016	5	W	6	15	Backhoe	10:29	10:40	11:00	10:41	10:42	0:01	10:43	10:48	0:05			
5/17/2016	5	E	1	15	Backhoe	10:29	10:40	11:00	10:41	10:42	0:01	10:43	10:48	0:05			
5/13/2016	6	W	4	15	Backhoe	8:52	9:02	10:00	9:02	9:03	0:01				9:03	9:05	0:02
5/17/2016	6	W	6	15	Backhoe	8:38	8:48	10:00	8:48	8:49	0:01				8:50	8:54	0:04

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/18/2016	6	E	1	15	Backhoe	9:29	9:39	10:00	9:39	9:40	0:01				9:41	9:44	0:03
5/18/2016	6	E	3	15	Backhoe	9:42	9:53	11:00	9:53	9:54	0:01				9:55	9:57	0:02
5/18/2016	6	E	5	15	Backhoe	9:55	10:06	11:00	10:06	10:07	0:01				10:08	10:10	0:02
5/12/2016	6	W	2	15	Backhoe	9:04	9:16	12:00	9:16	9:17	0:01				9:17	9:21	0:04
5/18/2016	7	W	6	15	Backhoe	11:11	11:21	10:00	11:21	11:22	0:01				11:23	11:25	0:02
5/17/2016	7	W	4	15	Backhoe	11:24	11:34	10:00	11:34	11:35	0:01				11:36	11:39	0:03
5/18/2016	7	W	2	15	Backhoe	11:39	11:51	12:00	11:51	11:52	0:01				11:53	11:55	0:02
5/18/2016	7	E	3	15	Backhoe	12:18	12:30	12:00	12:30	12:31	0:01				12:32	12:36	0:04
5/18/2016	7	E	5	15	Backhoe	12:29	12:42	13:00	12:42	12:43	0:01				12:44	12:47	0:03
5/17/2016	7	E	1	15	Backhoe	12:01	12:18	17:00	12:18	12:19	0:01				12:20	12:24	0:04
5/17/2016	8	W	2	15	Backhoe	9:53	10:01	08:00							10:02	10:03	0:01
5/18/2016	8	E	3	15	Backhoe	10:26	10:38	12:00							10:39	10:41	0:02
5/18/2016	8	E	5	15	Backhoe	10:39	10:52	13:00							10:54	10:55	0:01
5/18/2016	8	W	4	15	Backhoe	9:31	9:45	14:00							9:46	9:48	0:02
5/13/2016	8	E	1	15	Backhoe	10:11	10:25	14:00							10:26	10:27	0:01
5/13/2016	8	W	6	15	Backhoe	9:11	9:27	16:00							9:28	9:31	0:03
5/25/2016	9	W	6	8	Rock Saw	9:14	9:15	01:00	10:38	10:39	0:01	10:40	10:47	0:07			
5/24/2016	9	E	1	8	Rock Saw	8:30	8:31	01:00	8:31	8:32	0:01	9:40	9:47	0:07			
5/24/2016	9	E	3	8	Rock Saw	8:33	8:34	01:00	8:34	8:35	0:01	9:47	9:51	0:04			
5/24/2016	9	E	5	8	Rock Saw	8:38	8:39	01:00	8:40	8:41	0:01	9:51	9:59	0:08			
5/25/2016	9	W	4	8	Rock Saw	9:22	9:23	01:00	10:48	10:49	0:01	10:50	10:54	0:04			
5/25/2016	9	W	2	8	Rock Saw	9:24	9:25	01:00	9:25	9:26	0:01	10:55	11:02	0:07			
5/5/2016	11	W	6	8	Rock Saw	9:23	9:25	02:00							9:27	9:29	0:02
5/5/2016	11	W	2	8	Rock Saw	9:40	9:41	01:00							9:43	9:44	0:01
5/6/2016	11	E	1	8	Rock Saw	10:38	10:39	01:00							10:41	10:42	0:01

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/6/2016	11	E	3	8	Rock Saw	10:44	10:45	01:00							10:46	10:47	0:01
5/6/2016	11	E	5	8	Rock Saw	10:48	10:49	01:00							10:50	10:51	0:01
5/5/2016	11	W	4	8	Rock Saw	9:31	9:32	01:00							9:35	9:36	0:01
5/5/2016	12	W	6	8	Rock Saw	8:35	8:37	02:00				8:43	8:53	0:10			
5/5/2016	12	W	2	8	Rock Saw	9:10	9:11	01:00				9:13	9:19	0:06			
5/19/2016	12	E	5	8	Rock Saw	11:04	11:05	01:00				11:06	11:14	0:08			
5/19/2016	12	E	1	8	Rock Saw	10:45	10:46	01:00				10:55	11:03	0:08			
5/5/2016	12	W	4	8	Rock Saw	8:56	8:57	01:00				8:59	9:06	0:07			
5/4/2016	13	W	2	15	Rock Saw	13:00	13:03	03:00	13:03	13:04	0:01				13:04	13:08	0:04
5/6/2016	13	E	5	15	Rock Saw	11:21	11:24	03:00	11:24	11:25	0:01				11:25	11:30	0:05
5/4/2016	13	W	6	15	Rock Saw	12:34	12:37	03:00	12:38	12:39	0:01				12:39	12:43	0:04
5/4/2016	13	W	4	15	Rock Saw	12:47	12:50	03:00	12:50	12:51	0:01				12:52	12:55	0:03
5/6/2016	13	E	1	15	Rock Saw	11:00	11:02	02:00	11:04	11:05	0:01				11:05	11:08	0:03
5/6/2016	13	E	3	15	Rock Saw	11:11	11:13	02:00	11:13	11:14	0:01				11:14	11:19	0:05
5/24/2016	14	E	1	8	Rock Saw	8:45	8:46	01:00							10:00	10:02	0:02
5/24/2016	14	E	3	8	Rock Saw	8:47	8:48	01:00							10:03	10:04	0:01
5/25/2016	14	W	4	8	Rock Saw	9:02	9:03	01:00							10:32	10:34	0:02
5/25/2016	14	W	2	8	Rock Saw	9:04	9:05	01:00							10:34	10:36	0:02
5/24/2016	14	E	5	8	Rock Saw	8:50	8:51	01:00							10:04	10:06	0:02
5/25/2016	14	W	6	8	Rock Saw	8:56	8:57	01:00							10:29	10:32	0:03
5/4/2016	15	W	6	8	Rock Saw	11:51	11:53	02:00	11:53	11:54	0:01				11:54	11:59	0:05
5/6/2016	15	E	1	8	Rock Saw	11:36	11:38	02:00	11:39	11:40	0:01				11:40	11:46	0:06
5/4/2016	15	W	4	8	Rock Saw	12:15	12:16	01:00	12:16	12:17	0:01				12:17	12:22	0:05
5/4/2016	15	W	2	8	Rock Saw	12:23	12:24	01:00	12:24	12:25	0:01				12:25	12:29	0:04
5/6/2016	15	E	3	8	Rock Saw	11:47	11:48	01:00	11:49	11:50	0:01				11:50	11:54	0:04

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/6/2016	15	E	5	8	Rock Saw	11:55	11:56	01:00	11:57	11:58	0:01				11:59	12:02	0:03
5/4/2016	16	W	4	15	Rock Saw	11:10	11:14	04:00				11:16	11:23	0:07			
5/4/2016	16	W	2	15	Rock Saw	11:26	11:30	04:00				11:32	11:43	0:11			
5/6/2016	16	E	3	15	Rock Saw	12:20	12:24	04:00				12:26	12:35	0:09			
5/4/2016	16	W	6	15	Rock Saw	10:55	10:58	03:00				10:59	11:09	0:10			
5/6/2016	16	E	1	15	Rock Saw	12:03	12:05	02:00				12:06	12:17	0:11			
5/6/2016	16	E	5	15	Rock Saw	12:39	12:41	02:00				12:44	12:53	0:09			
5/4/2016	17	W	6	15	Rock Saw	10:17	10:21	04:00	10:21	10:22	0:01				10:22	10:25	0:03
5/4/2016	17	W	4	15	Rock Saw	10:31	10:35	04:00	10:36	10:37	0:01				10:37	10:41	0:04
5/4/2016	17	W	2	15	Rock Saw	10:42	10:45	03:00	10:46	10:47	0:01				10:49	10:51	0:02
5/9/2016	17	E	3	15	Rock Saw	9:04	9:07	03:00	9:08	9:09	0:01				9:09	9:13	0:04
5/9/2016	17	E	5	15	Rock Saw	9:15	9:18	03:00	9:19	9:20	0:01				9:20	9:23	0:03
5/9/2016	17	E	1	15	Rock Saw	8:52	8:55	03:00	8:56	8:57	0:01				8:57	9:02	0:05
5/25/2016	18	W	6	8	Rock Saw	8:41	8:42	01:00				10:07	10:13	0:06			
5/24/2016	18	E	1	8	Rock Saw	9:01	9:02	01:00				10:11	10:15	0:04			
5/24/2016	18	E	3	8	Rock Saw	9:03	9:04	01:00				10:16	10:18	0:02			
5/24/2016	18	E	5	8	Rock Saw	9:05	9:06	01:00				10:18	10:25	0:07			
5/25/2016	18	W	4	8	Rock Saw	8:46	8:47	01:00				10:13	10:21	0:08			
5/25/2016	18	W	2	8	Rock Saw	8:48	8:49	01:00				10:22	10:26	0:04			
5/17/2016	19	E	5	15	Backhoe	12:15	12:24	09:00				12:24	12:34	0:10			
5/17/2016	19	E	3	15	Backhoe	11:53	12:04	11:00				12:04	12:14	0:10			
5/17/2016	19	W	4	15	Backhoe	10:45	10:58	13:00				10:58	11:06	0:08			
5/12/2016	19	E	1	15	Backhoe	11:33	11:46	13:00				11:46	11:56	0:10			
5/17/2016	19	W	2	15	Backhoe	11:01	11:15	14:00				11:16	11:22	0:06			
5/12/2016	19	W	6	15	Backhoe	10:20	10:38	18:00				10:38	10:48	0:10			

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/4/2016	20	W	6	8	Rock Saw	9:17	9:21	04:00				9:22	9:31	0:09			
5/4/2016	20	W	4	8	Rock Saw	9:39	9:43	04:00				9:45	9:55	0:10			
5/4/2016	20	W	2	8	Rock Saw	9:56	10:00	04:00				10:00	10:10	0:10			
5/19/2016	20	E	1	8	Rock Saw	11:36	11:37	01:00				11:38	11:43	0:05			
5/19/2016	20	E	5	8	Rock Saw	11:44	11:45	01:00				11:46	11:52	0:06			
5/4/2016	22	W	2	8	Rock Saw	8:42	8:47	05:00				8:54	9:02	0:08			
5/4/2016	22	W	6	8	Rock Saw	8:23	8:26	03:00				8:35	8:40	0:05			
5/4/2016	22	W	4	8	Rock Saw	8:35	8:38	03:00				8:46	8:53	0:07			
5/19/2016	22	E	1	8	Rock Saw	12:06	12:07	01:00				12:08	12:15	0:07			
5/19/2016	22	E	5	8	Rock Saw	12:20	12:21	01:00				12:22	12:27	0:05			
5/9/2016	23	E	3	15	Rock Saw	9:56	10:01	05:00							10:02	10:07	0:05
5/3/2016	23	W	4	15	Rock Saw	12:59	13:03	04:00							13:03	13:08	0:05
5/9/2016	23	E	5	15	Rock Saw	10:11	10:15	04:00							10:17	10:19	0:02
5/9/2016	23	E	1	15	Rock Saw	9:43	9:46	03:00							9:47	9:50	0:03
5/3/2016	23	W	6	15	Rock Saw	12:52	12:55	03:00							12:55	12:59	0:04
5/3/2016	23	W	2	15	Rock Saw	13:07	13:10	03:00							13:10	13:15	0:05
5/9/2016	24	E	1	8	Rock Saw	10:23	10:26	03:00							10:27	10:29	0:02
5/3/2016	24	W	6	8	Rock Saw	12:39	12:41	02:00							12:41	12:43	0:02
5/3/2016	24	W	4	8	Rock Saw	12:44	12:46	02:00							12:46	12:49	0:03
5/3/2016	24	W	2	8	Rock Saw	12:48	12:50	02:00							12:50	12:52	0:02
5/9/2016	24	E	3	8	Rock Saw	10:32	10:33	01:00							10:34	10:35	0:01
5/9/2016	24	E	5	8	Rock Saw	10:36	10:37	01:00							10:39	10:40	0:01
5/3/2016	25	W	4	8	Rock Saw	12:18	12:21	03:00							12:21	12:23	0:02
5/3/2016	25	W	2	8	Rock Saw	12:24	12:26	02:00							12:26	12:28	0:02
5/9/2016	25	E	3	8	Rock Saw	10:58	11:00	02:00							11:00	11:02	0:02

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/3/2016	25	W	6	8	Rock Saw	12:11	12:12	01:00							12:13	12:15	0:02
5/9/2016	25	E	1	8	Rock Saw	10:51	10:52	01:00							10:52	10:54	0:02
5/9/2016	25	E	5	8	Rock Saw	11:05	11:06	01:00							11:07	11:09	0:02
5/9/2016	26	E	1	8	Rock Saw	11:14	11:16	02:00							11:16	11:20	0:04
5/3/2016	26	W	6	8	Rock Saw	11:50	11:52	02:00							11:52	11:56	0:04
5/9/2016	26	E	3	8	Rock Saw	11:24	11:26	02:00							11:26	11:28	0:02
5/9/2016	26	E	5	8	Rock Saw	11:31	11:33	02:00							11:34	11:37	0:03
5/3/2016	26	W	2	8	Rock Saw	12:02	12:03	01:00							12:03	12:07	0:04
5/3/2016	26	W	4	8	Rock Saw	11:58	11:59	01:00							11:59	12:02	0:03
5/17/2016	27	W	2	15	Backhoe	8:25	8:36	11:00	8:36	8:37	0:01	8:37	8:42	0:05			
5/13/2016	27	W	6	15	Backhoe	12:39	12:51	12:00	12:51	12:52	0:01	12:53	13:00	0:07			
5/12/2016	27	E	1	15	Backhoe	8:55	9:07	12:00	9:07	9:08	0:01	9:08	9:15	0:07			
5/13/2016	27	E	5	15	Backhoe	9:44	9:57	13:00	9:57	9:58	0:01	9:58	10:06	0:08			
5/11/2016	27	W	4	15	Backhoe	12:55	13:11	16:00	13:11	13:12	0:01	13:12	13:21	0:09			
5/13/2016	27	E	3	15	Backhoe	9:16	9:39	23:00	9:39	9:40	0:01	9:40	9:45	0:05			
5/9/2016	28	E	3	15	Rock Saw	12:13	12:16	03:00	12:17	12:18	0:01	12:18	12:24	0:06			
5/9/2016	28	E	5	15	Rock Saw	12:29	12:32	03:00	12:32	12:33	0:01	12:33	12:45	0:12			
5/3/2016	28	W	4	15	Rock Saw	11:23	11:26	03:00	11:26	11:27	0:01	11:27	11:35	0:08			
5/3/2016	28	W	6	15	Rock Saw	11:04	11:06	02:00	11:06	11:07	0:01	11:07	11:20	0:13			
5/3/2016	28	W	2	15	Rock Saw	11:35	11:37	02:00	11:37	11:38	0:01	11:38	11:45	0:07			
5/9/2016	28	E	1	15	Rock Saw	11:52	11:54	02:00	11:54	11:55	0:01	11:56	12:09	0:13			
5/13/2016	29	E	3	15	Backhoe	11:32	11:43	11:00				11:45	11:56	0:11			
5/11/2016	29	E	5	15	Backhoe	11:52	12:05	13:00				12:06	12:17	0:11			
5/12/2016	29	E	1	15	Backhoe	11:10	11:23	13:00				11:23	11:31	0:08			
5/11/2016	29	W	2	15	Backhoe	10:38	10:52	14:00				10:53	11:00	0:07			

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/13/2016	29	W	4	15	Backhoe	10:11	10:27	16:00				10:29	10:40	0:11			
5/12/2016	29	W	6	15	Backhoe	9:42	9:59	17:00				10:00	10:10	0:10			
5/3/2016	30	W	6	8	Rock Saw	10:19	10:21	02:00	10:21	10:22	0:01	10:22	10:32	0:10			
5/3/2016	30	W	4	8	Rock Saw	10:32	10:34	02:00	10:34	10:35	0:01	10:38	10:46	0:08			
5/3/2016	30	W	2	8	Rock Saw	10:47	10:49	02:00	10:49	10:50	0:01	10:50	10:59	0:09			
5/9/2016	30	E	1	8	Rock Saw	12:47	12:48	01:00	12:48	12:49	0:01	12:49	13:09	0:20			
5/9/2016	30	E	5	8	Rock Saw	13:24	13:25	01:00	13:26	13:27	0:01	13:27	13:39	0:12			
5/9/2016	30	E	3	8	Rock Saw	13:11	13:12	01:00	13:12	13:13	0:01	13:13	13:23	0:10			
5/3/2016	31	W	6	8	Rock Saw	9:44	9:45	01:00	9:45	9:46	0:01	9:48	9:54	0:06			
5/3/2016	31	W	2	8	Rock Saw	10:10	10:11	01:00	10:11	10:12	0:01	10:12	10:18	0:06			
5/10/2016	31	E	1	8	Rock Saw	8:39	8:40	01:00	8:41	8:42	0:01	8:43	8:55	0:12			
5/10/2016	31	E	5	8	Rock Saw	9:15	9:16	01:00	9:16	9:17	0:01	9:18	9:27	0:09			
5/3/2016	31	W	4	8	Rock Saw	9:56	9:57	01:00	9:57	9:58	0:01	10:00	10:07	0:07			
5/10/2016	31	E	3	8	Rock Saw	8:58	8:59	01:00	9:00	9:01	0:01	9:03	9:12	0:09			
5/3/2016	32	W	4	8	Rock Saw	9:25	9:28	03:00	9:29	9:30	0:01	0:00	0:00	-	9:30	9:36	0:06
5/3/2016	32	W	6	8	Rock Saw	9:10	9:12	02:00	9:12	9:13	0:01	0:00	0:00	-	9:14	9:24	0:10
5/3/2016	32	W	2	8	Rock Saw	9:36	9:38	02:00	9:38	9:39	0:01	0:00	0:00	-	9:39	9:43	0:04
5/10/2016	32	E	3	8	Rock Saw	9:56	9:58	02:00	9:59	10:00	0:01	0:00	0:00	-	10:00	10:03	0:03
5/10/2016	32	E	5	8	Rock Saw	10:08	10:09	01:00	10:10	10:11	0:01	0:00	0:00	-	10:12	10:15	0:03
5/10/2016	32	E	1	8	Rock Saw	9:31	9:32	01:00	9:33	9:34	0:01	0:00	0:00	-	9:34	9:38	0:04
5/24/2016	33	E	1	8	Rock Saw	10:30	10:31	01:00	10:31	10:32	0:01	0:00	0:00	-	10:32	10:35	0:03
5/24/2016	33	E	3	8	Rock Saw	10:32	10:33	01:00	10:33	10:34	0:01	0:00	0:00	-	10:35	10:39	0:04
5/24/2016	33	E	5	8	Rock Saw	10:36	10:37	01:00	10:38	10:39	0:01	0:00	0:00	-	10:39	10:43	0:04
5/25/2016	33	W	6	8	Rock Saw	8:14	8:15	01:00	9:46	9:47	0:01	0:00	0:00	-	9:48	9:51	0:03
5/25/2016	33	W	4	8	Rock Saw	8:18	8:19	01:00	9:50	9:51	0:01	0:00	0:00	-	9:51	9:53	0:02

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/25/2016	33	W	2	8	Rock Saw	8:20	8:21	01:00	9:54	9:55	0:01	0:00	0:00	-	9:55	9:57	0:02
5/10/2016	34	W	6	8	Rock Saw	10:55	10:57	02:00				11:01	11:06	0:05	0:00	0:00	-
5/10/2016	34	W	2	8	Rock Saw	10:30	10:31	01:00				10:37	10:41	0:04	0:00	0:00	-
5/10/2016	34	W	4	8	Rock Saw	10:42	10:43	01:00				10:50	10:54	0:04	0:00	0:00	-
5/19/2016	34	E	1	8	Rock Saw	12:45	12:46	01:00				13:02	13:07	0:05	0:00	0:00	-
5/19/2016	34	E	5	8	Rock Saw	12:48	12:49	01:00				13:07	13:14	0:07	0:00	0:00	-
5/3/2016	35	W	4	8	Rock Saw	8:36	8:38	02:00	8:38	8:39	0:01				8:40	8:49	0:09
5/3/2016	35	W	2	8	Rock Saw	8:52	8:54	02:00	8:54	8:55	0:01				8:56	9:05	0:09
4/26/2016	35	W	6	8	Rock Saw	13:23	13:24	01:00	13:24	13:25	0:01				13:25	13:30	0:05
5/10/2016	35	E	3	8	Rock Saw	11:32	11:33	01:00	11:35	11:36	0:01				11:36	11:39	0:03
5/10/2016	35	E	5	8	Rock Saw	11:43	11:44	01:00	11:44	11:45	0:01				11:45	11:48	0:03
5/10/2016	35	E	1	8	Rock Saw	11:22	11:23	01:00	11:24	11:26	0:02				11:27	11:29	0:02
4/26/2016	36	W	6	15	Rock Saw	12:27	12:34	07:00	12:35	12:36	0:01	12:36	12:46	0:10			
4/26/2016	36	W	4	15	Rock Saw	12:48	12:52	04:00	12:54	12:55	0:01	12:55	13:05	0:10			
4/26/2016	36	W	2	15	Rock Saw	13:06	13:10	04:00	13:10	13:11	0:01	13:11	13:21	0:10			
5/10/2016	36	E	5	15	Rock Saw	12:29	12:31	02:00	12:32	12:33	0:01	12:34	12:44	0:10			
5/10/2016	36	E	1	15	Rock Saw	11:53	11:55	02:00	11:57	11:58	0:01	11:58	12:07	0:09			
5/10/2016	36	E	3	15	Rock Saw	12:10	12:12	02:00	12:14	12:15	0:01	12:15	12:25	0:10			
4/26/2016	38	W	2	8	Rock Saw	12:19	12:21	02:00							12:21	12:25	0:04
5/10/2016	38	E	5	8	Rock Saw	13:06	13:07	01:00							1:08	1:10	0:02
4/26/2016	38	W	6	8	Rock Saw	12:03	12:04	01:00							12:04	12:09	0:05
4/26/2016	38	W	4	8	Rock Saw	12:12	12:13	01:00							12:14	12:17	0:03
5/10/2016	38	E	1	8	Rock Saw	12:50	12:51	01:00							12:52	12:55	0:03
5/10/2016	38	E	3	8	Rock Saw	12:57	12:58	01:00							12:59	13:01	0:02
4/26/2016	39	W	6	15	Rock Saw	11:21	11:25	04:00				11:32	11:35	0:03			

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/11/2016	39	E	3	15	Rock Saw	13:30	13:34	04:00				13:35	13:43	0:08			
4/26/2016	39	W	2	15	Rock Saw	11:49	11:52	03:00				11:54	11:59	0:05			
5/10/2016	39	E	5	15	Rock Saw	8:59	9:02	03:00				9:07	9:15	0:08			
4/26/2016	39	W	4	15	Rock Saw	11:32	11:35	03:00				11:39	11:46	0:07			
5/11/2016	39	E	1	15	Rock Saw	13:13	13:15	02:00				13:16	13:25	0:09			
4/26/2016	40	W	6	8	Rock Saw	10:49	10:52	03:00	10:56	10:59	0:03				10:59	11:02	0:03
4/26/2016	40	W	4	8	Rock Saw	11:00	11:02	02:00	11:02	11:08	0:06				11:09	11:13	0:04
4/26/2016	40	W	2	8	Rock Saw	11:10	11:11	01:00	11:11	11:16	0:05				11:16	11:18	0:02
5/11/2016	40	E	1	8	Rock Saw	9:21	9:22	01:00	9:29	9:30	0:01				9:30	9:32	0:02
5/11/2016	40	E	3	8	Rock Saw	9:41	9:42	01:00	9:43	9:44	0:01				9:44	9:46	0:02
5/11/2016	40	E	5	8	Rock Saw	9:50	9:51	01:00	9:52	9:53	0:01				9:53	9:55	0:02
5/18/2016	41	W	6	15	Backhoe	8:47	9:00	13:00							9:01	9:03	0:02
5/17/2016	41	E	3	15	Backhoe	12:36	12:52	16:00							12:52	12:55	0:03
5/17/2016	41	E	5	15	Backhoe	12:50	13:08	18:00							13:08	13:10	0:02
5/13/2016	41	E	1	15	Backhoe	12:15	12:33	18:00							12:34	12:35	0:01
5/18/2016	41	W	2	15	Backhoe	9:06	9:26	20:00							9:26	9:28	0:02
5/13/2016	41	W	4	15	Backhoe	8:55	9:15	20:00							9:16	9:18	0:02
4/26/2016	42	W	6	15	Rock Saw	9:51	9:58	07:00							9:58	10:01	0:03
4/26/2016	42	W	4	15	Rock Saw	10:03	10:08	05:00							10:12	10:17	0:05
4/26/2016	42	W	2	15	Rock Saw	10:20	10:25	05:00							10:26	10:31	0:05
5/11/2016	42	E	1	15	Rock Saw	10:15	10:17	02:00							10:18	10:21	0:03
5/11/2016	42	E	3	15	Rock Saw	10:25	10:27	02:00							10:28	10:30	0:02
5/11/2016	42	E	5	15	Rock Saw	10:34	10:36	02:00							10:38	10:40	0:02
5/5/2016	43	W	6	8	Rock Saw	11:06	11:07	01:00	11:07	11:08	0:01	11:09	11:20	0:11			
5/6/2016	43	E	1	8	Rock Saw	8:55	8:56	01:00	8:58	8:59	0:01	9:00	9:08	0:08			

Date	Section #	Direction	Drain #	Trench Width (in)	Excavation				Fabric			Backfill with Compaction			Backfill, No Compaction		
					Type	Time			Time			Time			Time		
						Beg.	End	Total	Beg.	End	Total	Beg.	End	Total	Beg.	End	Total
5/5/2016	43	W	2	8	Rock Saw	11:42	11:43	01:00	11:44	11:45	0:01	11:46	11:56	0:10			
5/6/2016	43	E	5	8	Rock Saw	9:24	9:25	01:00	9:26	9:27	0:01	9:27	9:37	0:10			
5/5/2016	43	W	4	8	Rock Saw	11:24	11:25	01:00	11:26	11:27	0:01	11:28	11:39	0:11			
5/6/2016	43	E	3	8	Rock Saw	9:11	9:12	01:00	9:12	9:13	0:01	9:14	9:23	0:09			
4/26/2016	44	W	6	8	Rock Saw	9:11	9:17	06:00							9:23	9:28	0:05
4/26/2016	44	W	2	8	Rock Saw	9:42	9:46	04:00							9:47	9:48	0:01
4/26/2016	44	W	4	8	Rock Saw	9:32	9:36	04:00							9:36	9:40	0:04
5/11/2016	44	E	5	8	Rock Saw	11:00	11:01	01:00							11:02	11:04	0:02
5/11/2016	44	E	3	8	Rock Saw	10:52	10:53	01:00							10:54	10:55	0:01
5/11/2016	44	E	1	8	Rock Saw	10:43	10:44	01:00							10:46	10:49	0:03

APPENDIX P BACKCALCULATION RESULTS

Table 34. Average Backcalculated Moduli, Eastbound Direction (1 ksi = 6.895 MPa)

No.	D/BD	4/21/2016			8/30/2016			1/19/2017			5/31/2017		
		E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)
1	BD	2263.43	31.06	14.81	2187.38	32.20	16.35	3820.13	30.22	14.39	1697.24	29.27	16.49
1	D	1877.44	35.34	16.57	1613.63	34.92	18.38	2583.19	32.70	16.03	1618.52	33.51	18.89
2	BD	3973.07	39.12	17.85	1962.59	39.06	22.01	3028.38	34.11	19.23	2243.03	40.61	22.89
2	D	2563.88	37.34	19.47	2061.37	36.59	20.62	5323.78	34.03	17.91	2126.29	38.42	21.65
3	BD	2106.31	32.22	15.39	2132.18	34.95	17.81	5182.89	29.74	16.76	2889.26	35.25	19.87
3	D	2397.83	37.29	17.01	1873.21	34.91	18.47	5683.50	31.28	17.63	2881.98	36.39	20.51
4	CNTRL	1518.31	37.09	18.02	1358.45	36.80	18.88	2219.25	35.07	17.92	1822.36	37.59	20.43
5	BD	921.34	44.25	22.59	1184.31	46.15	26.01	1582.27	37.55	21.17	1541.24	49.23	27.75
5	D	1331.83	44.11	20.12	1369.59	47.00	24.99	2039.39	39.66	20.98	1617.93	49.65	27.98
6	BD	1919.36	43.94	24.77	2371.41	55.46	31.26	3173.95	41.60	23.45	2191.11	52.85	29.79
6	D	1776.72	44.67	25.17	2094.95	54.20	30.55	2901.95	41.72	23.51	1483.21	51.07	28.78
7	BD	3007.48	41.95	23.64	1742.58	51.74	29.16	4396.33	39.70	22.37	1808.80	48.57	27.37
7	D	2181.00	39.39	22.20	1815.60	46.85	26.41	2436.52	37.36	21.06	2447.90	45.96	25.90
8	BD	1808.10	27.05	13.55	1927.07	32.47	14.81	3282.16	28.14	13.35	1901.20	29.12	16.41
8	D	2103.65	25.76	12.90	1931.92	31.13	15.35	2650.92	27.65	13.35	2049.36	29.15	16.43
9	BD	2167.07	42.12	23.74	1786.82	54.11	30.50	3635.10	41.58	23.43	1939.93	55.53	31.30
9	D	2449.04	47.40	23.26	1953.73	52.23	29.44	4468.78	39.34	22.17	2205.57	52.40	29.53
10	CNTRL	2831.44	38.03	21.43	2334.07	45.69	25.75	5897.71	39.42	22.22	2462.30	43.78	24.67
11	BD	2050.86	37.46	19.05	2230.91	38.68	21.80	3849.99	34.15	19.25	1992.78	41.88	23.60
11	D	2073.56	35.02	18.57	2229.68	37.06	20.89	3535.83	32.59	18.37	1948.23	41.09	23.16
12	BD	1443.52	43.47	22.33	1497.06	47.43	26.73	2208.53	38.76	21.85	1657.08	45.75	25.78
12	D	1627.23	34.46	16.17	1620.49	37.21	19.40	2771.54	31.70	15.85	1732.60	34.01	19.17
13	BD	3121.30	34.02	17.46	2247.38	34.00	19.16	5231.54	30.65	17.27	2048.48	38.88	21.91
13	D	2995.24	34.94	18.44	2098.19	37.71	21.25	4260.60	35.02	18.53	1913.26	39.35	22.18
14	BD	2575.37	35.68	16.28	1758.43	31.96	18.01	4286.80	28.69	16.17	1845.07	34.25	19.30
14	D	2643.40	32.85	16.05	1696.96	31.16	17.56	5213.18	31.12	16.34	1747.74	36.13	20.36
15	BD	3346.75	34.05	17.18	1977.87	32.92	18.55	5142.68	33.21	18.72	2000.15	36.09	20.34
15	D	3677.99	36.72	16.75	2103.32	34.38	19.38	4762.06	34.08	19.21	1918.38	37.38	21.07
16	BD	2221.51	30.79	16.47	1541.33	35.55	18.04	4041.38	33.72	17.13	1429.49	33.59	18.93
16	D	2483.79	37.86	20.78	1895.47	44.16	23.61	4585.85	39.74	21.21	1726.14	44.91	25.31
17	BD	3423.68	33.86	15.44	2528.51	31.68	17.85	7026.42	31.76	17.90	3087.08	36.16	20.38
17	D	3317.63	32.14	15.75	2292.89	31.99	18.03	6370.45	31.19	17.58	2042.68	35.01	19.73
18	BD	1276.35	33.78	16.09	1410.94	33.85	19.08	3704.04	31.51	17.76	1831.06	34.64	19.52
18	D	2410.76	35.54	16.65	1922.33	36.20	19.08	5893.51	32.88	17.38	1807.77	35.27	19.88

No.	D/BD	4/21/2016			8/30/2016			1/19/2017			5/31/2017		
		E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)
19	BD	1694.71	47.77	21.79	1501.91	54.96	30.97	3781.99	41.19	23.21	1462.81	51.35	28.94
19	D	2158.32	46.09	21.02	1504.03	49.51	27.90	4663.97	38.74	21.83	1548.49	49.09	27.67
20	BD	1778.72	52.26	27.79	1183.40	68.83	38.79	3984.34	39.49	22.25	1303.76	61.01	34.39
20	D	1936.48	50.10	24.59	1261.24	63.74	35.92	4069.28	37.96	20.03	1404.24	56.83	32.03
21	CNTRL	3202.02	48.06	27.09	2163.06	57.18	32.23	5888.64	48.93	27.58	2497.57	67.34	33.45
22	BD	2785.26	38.69	19.59	1679.26	36.56	20.60	4357.86	36.16	20.38	1614.04	40.02	22.55
22	D	2874.08	35.20	19.84	1837.95	39.58	22.31	4723.69	35.32	19.91	1966.67	40.20	22.65
23	BD	1421.13	36.96	18.66	969.21	38.46	21.68	2546.99	34.34	17.41	1186.16	39.88	22.48
23	D	1864.52	39.75	19.76	1210.87	40.75	21.58	2965.29	32.40	17.89	1212.07	40.68	22.93
24	BD	945.84	35.55	16.21	1128.11	39.47	22.25	3124.00	36.97	16.86	1108.68	38.65	21.78
24	D	1397.10	38.09	17.38	1172.71	38.21	21.54	3786.93	34.79	16.99	1231.15	39.51	22.27
25	BD	2214.16	38.48	17.55	1583.58	34.05	19.19	2720.22	33.37	17.03	1406.24	35.04	19.75
25	D	1650.77	42.64	21.57	1247.94	46.16	26.01	2569.48	39.81	22.44	1562.25	45.54	25.67
26	BD	2733.71	33.27	15.18	2145.81	33.87	15.45	4135.53	28.31	15.95	1381.40	29.80	16.80
26	D	3698.44	34.93	15.93	1593.43	30.22	17.03	3780.84	29.54	16.65	1947.68	32.75	18.46
27	BD	2347.02	35.25	15.29	1265.33	36.43	20.53	3743.09	35.27	19.88	1481.12	38.54	21.72
27	D	1987.78	39.27	19.43	1136.01	39.89	22.48	2935.57	40.46	21.57	1282.65	42.05	23.70
28	BD	2898.31	31.43	15.97	1653.03	33.35	16.95	4294.59	30.69	17.30	1508.48	31.81	17.93
28	D	3112.30	33.97	16.75	1811.18	33.58	17.68	5374.63	31.82	17.93	1789.18	34.28	19.32
29	BD	1451.30	32.96	17.64	904.37	39.16	20.18	3529.29	36.52	16.66	1324.26	38.67	21.80
29	D	1508.86	29.28	15.28	969.37	33.42	17.53	3150.51	33.82	16.49	1194.19	32.88	18.53
30	BD	381.07	24.68	13.91	619.60	34.46	17.42	3111.54	32.38	18.25	1584.70	36.67	20.67
30	D	617.29	29.51	15.40	536.63	39.98	21.11	2997.44	32.48	18.31	1340.59	39.57	22.30
31	BD	1448.37	26.61	13.81	956.79	32.62	14.88	3972.18	31.33	14.94	1001.23	29.98	16.90
31	D	923.53	37.47	17.91	744.46	41.90	23.61	2443.54	40.79	20.17	1251.73	45.71	25.76
32	BD	1120.25	30.06	15.05	1036.49	38.72	17.66	2937.00	35.26	16.08	1106.83	35.56	18.15
32	D	2206.54	36.59	17.72	1085.28	44.91	23.98	4701.79	35.17	18.63	1354.98	39.52	22.28
33	BD	1787.62	37.35	17.04	1162.30	34.57	19.49	3294.67	30.62	17.26	1635.39	36.18	20.39
33	D	2131.66	36.48	16.64	1091.83	33.75	19.02	3536.49	34.32	16.65	1602.98	35.34	19.92
34	BD	1002.90	40.92	23.06	985.78	48.16	27.15	2583.21	39.85	22.46	1336.23	47.96	27.03
34	D	1177.66	46.19	24.74	1137.08	52.20	29.42	2689.99	43.41	24.47	1466.27	50.86	28.66
35	BD	641.99	32.02	14.61	944.97	31.51	17.76	2290.80	31.21	17.59	1254.25	33.40	18.82
35	D	775.77	33.47	15.27	907.18	31.61	17.81	2817.73	30.98	17.46	1323.03	32.87	18.52
36	BD	1475.69	31.63	14.43	1303.94	30.82	17.37	3335.88	28.37	15.99	1852.02	31.63	17.83
36	D	1208.06	30.85	14.49	1254.64	33.42	17.52	3468.60	30.80	16.15	1719.03	32.27	18.19
37	CNTRL	1671.61	38.11	19.73	1482.04	44.01	24.80	3067.46	34.76	18.06	1777.11	39.75	22.40
38	BD	2118.47	33.44	15.26	1309.88	31.13	17.55	3806.00	32.68	16.71	1475.10	31.23	17.60

No.	D/BD	4/21/2016 E1 (ksi)	E2 (ksi)	E3 (ksi)	8/30/2016 E1 (ksi)	E2 (ksi)	E3 (ksi)	1/19/2017 E1 (ksi)	E2 (ksi)	E3 (ksi)	5/31/2017 E1 (ksi)	E2 (ksi)	E3 (ksi)
38	D	2308.66	34.37	15.68	1195.05	34.22	19.28	3541.63	30.94	17.44	1649.59	32.39	18.25
39	BD	1499.88	37.81	17.25	1196.52	34.90	19.67	3611.66	32.63	18.39	1734.52	35.53	20.02
39	D	1118.44	34.51	16.88	1234.38	36.32	20.47	3050.06	32.62	18.38	1614.51	36.59	20.62
40	BD	1486.88	47.43	26.73	1330.51	71.09	40.06	3550.15	51.03	28.76	1368.61	59.35	33.45
40	D	1144.57	53.78	28.57	1064.93	70.01	39.45	3983.32	48.57	27.37	1307.86	59.26	33.40
41	BD	728.63	35.63	18.03	676.68	36.60	20.63	2597.75	32.41	18.27	1029.41	39.68	22.36
41	D	1305.44	37.35	19.53	912.99	47.71	26.89	3991.99	37.71	21.25	1721.86	45.46	25.62
42	BD	3098.22	50.35	28.38	1523.30	68.12	38.39	4724.58	50.57	28.50	1812.14	61.06	34.42
42	D	3039.79	49.36	27.82	1519.69	65.18	36.74	5136.28	48.17	27.15	1819.62	58.60	33.02
43	BD	731.35	23.88	11.96	890.04	27.19	12.90	2191.64	27.75	13.21	1632.38	31.65	16.04
43	D	711.68	27.22	13.20	1035.40	31.41	14.33	2223.41	29.58	13.89	1536.64	29.40	16.57
44	BD	2106.85	36.66	16.72	984.63	39.97	20.30	4555.12	37.26	17.00	1198.28	35.44	19.98
44	D	2583.62	36.12	16.48	1019.78	35.64	18.70	3224.30	33.62	16.45	998.05	33.44	18.84

E1: Surface layer modulus
E2: Base layer modulus
E3: Subgrade layer modulus

Table 35. Average Backcalculated Moduli, Westbound Direction (1 ksi = 6.895 MPa)

No.	D/BD	4/21/2016 E1 (ksi)	E2 (ksi)	E3 (ksi)	8/30/2016 E1 (ksi)	E2 (ksi)	E3 (ksi)	1/19/2017 E1 (ksi)	E2 (ksi)	E3 (ksi)	6/7/2017 E1 (ksi)	E2 (ksi)	E3 (ksi)
1	BD	1654.21	32.89	17.63	1022.67	36.34	20.48	1727.41	34.34	17.65	1820.01	35.34	19.92
1	D	1741.07	37.00	19.02	865.04	40.29	22.71	2282.69	35.57	19.42	1853.48	38.79	20.55
2	BD	1062.01	35.80	20.17	695.97	39.71	22.38	1458.21	37.12	20.92	1628.04	40.05	22.57
2	D	1193.94	34.85	19.64	642.18	38.58	21.74	2051.88	38.12	21.48	1654.34	39.84	22.45
3	BD	1120.19	31.34	14.30	1431.29	31.30	17.64	2001.64	31.27	15.78	2403.83	31.69	17.86
3	D	1695.43	33.79	15.41	1201.70	31.31	17.65	2409.84	33.13	16.16	1998.75	32.04	18.06
4	CNTRL	2246.70	37.99	19.10	927.53	39.05	22.01	2879.00	35.52	20.02	2009.29	37.73	21.26
5	BD	2558.92	63.32	35.69	940.38	75.26	42.41	2882.48	61.17	34.48	1977.75	65.32	36.81
5	D	2767.14	58.93	33.21	1016.55	82.66	39.15	3761.11	57.54	32.43	2264.29	61.70	34.78
6	BD	1886.03	51.68	29.13	1044.99	60.47	34.08	2545.56	49.20	27.73	2043.90	48.30	27.22
6	D	2102.45	51.83	29.21	902.89	63.09	35.56	3017.25	49.84	28.09	1952.73	51.23	28.87
7	BD	1885.29	35.00	19.73	932.07	47.43	26.73	3725.66	36.42	20.53	1636.40	37.14	20.93
7	D	2007.85	42.57	22.27	860.64	45.00	25.36	3319.83	38.51	21.70	1785.49	41.38	23.32
8	BD	2995.65	29.14	14.79	1332.14	30.12	16.98	5226.16	31.25	17.61	2249.34	32.01	18.04
8	D	2482.75	29.04	15.34	1418.05	32.95	17.40	3844.74	31.08	17.52	2520.21	33.44	18.84
9	BD	2231.49	50.12	28.24	1741.33	58.95	33.22	2746.69	50.68	28.56	2609.48	53.15	29.95
9	D	1966.35	44.25	24.94	1370.42	55.70	31.39	2811.48	47.80	26.94	2451.42	48.03	27.07

No.	D/BD	4/21/2016			8/30/2016			1/19/2017			6/7/2017		
		E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)
10	CNTRL	2277.62	36.51	20.58	1126.65	41.42	23.34	3111.11	38.15	21.50	1979.48	39.45	22.23
11	BD	2114.58	33.98	19.15	1239.33	42.43	23.91	4270.90	42.81	24.13	2487.10	42.14	23.75
11	D	2513.05	34.95	19.70	1292.78	41.78	22.38	4686.61	41.00	23.11	2400.84	39.73	22.39
12	BD	2140.77	32.86	16.58	1071.11	36.94	20.82	3126.47	32.26	18.18	2137.15	34.82	19.62
12	D	1674.37	37.99	18.81	1126.38	42.58	24.00	2860.89	36.29	19.12	2346.08	36.94	20.82
13	BD	1814.62	32.48	18.30	931.51	35.43	19.97	3418.96	35.21	19.84	2403.66	38.06	21.45
13	D	2677.47	32.18	16.86	1060.73	34.02	19.17	3735.66	33.14	18.68	2631.75	36.42	20.52
14	BD	3189.27	31.27	17.62	1559.38	33.63	18.95	6253.24	34.75	19.59	2594.93	35.09	19.78
14	D	2782.58	30.62	17.26	1369.10	33.01	18.61	5207.81	35.08	19.77	2675.88	34.66	19.54
15	BD	1101.18	29.24	14.64	965.63	33.71	16.99	2659.66	31.55	17.78	2757.18	33.97	19.15
15	D	1044.93	32.70	15.34	1062.92	33.20	17.40	2768.88	32.26	18.18	2530.32	35.41	19.96
16	BD	2557.11	32.21	16.53	1493.00	38.27	19.64	5139.06	33.06	18.63	2346.86	37.10	20.91
16	D	1935.73	35.33	16.12	1087.04	32.65	18.40	2829.74	30.67	17.28	2347.69	35.63	20.08
17	BD	1034.62	26.61	13.33	1011.34	29.11	16.41	3980.12	30.87	17.40	3147.64	32.18	18.14
17	D	1104.05	28.71	13.92	1012.72	31.22	16.36	4450.42	32.08	18.08	3610.52	32.55	18.35
18	BD	2118.34	34.53	17.62	1279.57	37.75	21.27	3809.10	34.71	19.56	2951.74	35.18	19.83
18	D	2156.80	32.54	17.26	1128.44	36.86	20.77	4594.40	34.17	18.13	2856.02	35.70	20.12
19	BD	2620.95	38.10	21.47	1139.64	47.24	26.63	5692.17	39.26	22.13	3058.11	42.00	23.67
19	D	3709.97	41.36	23.31	1293.00	53.65	30.24	5036.28	44.63	25.15	2948.10	47.81	26.94
20	BD	3894.15	48.69	27.44	1536.62	61.27	34.53	5833.56	47.70	26.88	3023.08	54.33	30.62
20	D	3573.46	47.68	26.87	1602.96	60.57	34.14	5363.92	47.78	26.93	2882.07	54.38	30.65
21	CNTRL	2090.92	47.29	26.65	891.43	64.30	36.24	3871.36	46.00	25.93	2944.97	53.10	29.93
22	BD	2402.98	37.20	19.13	1318.97	39.07	22.02	3678.03	34.75	19.59	2386.27	38.13	21.49
22	D	2251.71	33.99	18.49	1191.19	39.15	22.06	2750.97	34.40	19.39	2802.86	40.18	22.64
23	BD	1498.98	29.89	16.85	1003.79	34.99	19.72	3329.96	36.38	20.51	1825.89	37.62	21.20
23	D	1469.92	36.05	18.79	1271.84	40.27	22.70	2674.33	36.23	20.42	2174.65	40.94	23.07
24	BD	1535.20	41.14	18.76	725.30	36.32	20.47	2646.34	36.04	18.24	1818.42	38.80	21.87
24	D	1424.27	35.23	17.23	666.56	33.67	18.97	2656.64	36.65	16.72	1835.79	37.72	21.26
25	BD	2845.96	35.62	18.13	1379.80	44.03	24.81	3405.19	36.39	20.51	2253.23	41.54	23.41
25	D	3236.47	37.94	21.39	1585.47	47.33	26.67	4628.26	38.10	21.47	2560.12	45.13	25.44
26	BD	1652.42	29.11	13.28	1429.93	31.19	15.81	3446.79	30.47	15.55	2683.28	29.95	16.88
26	D	2183.73	28.80	13.51	1447.42	31.81	15.49	3956.02	30.33	16.01	2860.56	31.94	18.00
27	BD	2134.41	38.41	21.65	1064.92	44.31	24.97	3291.24	37.56	21.17	2402.75	41.50	23.39
27	D	2124.28	36.70	20.08	958.53	43.74	23.41	2950.28	36.89	19.62	2195.51	41.78	23.55
28	BD	1589.63	31.60	15.02	1085.81	32.44	16.52	3097.13	30.93	17.43	2090.78	33.87	19.09
28	D	1813.25	29.49	16.03	1136.37	31.71	16.65	3009.63	31.84	17.94	1957.27	33.15	18.69
29	BD	1633.70	31.03	16.61	893.86	32.78	18.48	2215.87	33.83	17.27	1523.46	32.73	18.45

No.	D/BD	4/21/2016			8/30/2016			1/19/2017			6/7/2017		
		E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)	E1 (ksi)	E2 (ksi)	E3 (ksi)
29	D	1748.57	36.95	18.11	974.61	36.48	20.56	2584.29	32.73	18.45	1999.23	34.96	19.70
30	BD	2078.45	38.63	21.77	1097.60	42.28	23.83	3466.68	39.77	22.41	1893.39	42.15	23.76
30	D	1759.56	39.51	22.27	1031.41	44.44	25.05	2821.28	39.34	22.17	1681.71	44.10	24.86
31	BD	1222.75	36.78	18.62	1033.57	38.54	21.72	2203.08	37.17	18.99	1957.54	37.22	20.98
31	D	2214.78	34.75	19.59	1021.26	37.62	21.20	2039.02	35.13	19.80	1704.69	36.50	20.57
32	BD	2523.41	35.54	20.03	1343.99	39.13	22.05	3853.71	38.16	21.51	1918.43	34.93	19.68
32	D	2315.25	30.92	17.43	1335.31	34.12	19.23	3312.53	32.83	18.50	1949.21	34.13	19.24
33	BD	897.62	31.79	17.92	930.11	37.19	20.96	1508.18	32.13	18.11	1736.36	33.52	18.89
33	D	1060.99	33.51	17.78	1055.87	37.19	20.96	1982.07	33.08	18.64	1969.79	35.82	20.19
34	BD	833.36	38.02	18.04	835.48	38.96	21.96	2222.29	35.95	20.26	1826.85	39.44	22.23
34	D	1056.54	41.18	21.14	845.55	43.91	24.75	2227.38	39.98	22.53	1885.58	42.65	24.04
35	BD	988.95	27.02	13.53	860.06	30.93	17.43	1579.03	29.85	15.90	2146.58	32.38	18.25
35	D	1208.11	30.67	14.88	860.39	33.49	17.50	2035.27	33.28	16.89	1962.04	33.92	19.12
36	BD	1627.71	33.11	15.10	1148.28	32.86	18.52	2259.22	30.11	15.31	2477.85	33.76	19.03
36	D	1445.66	31.61	15.27	861.33	35.12	17.32	1994.96	29.16	14.79	2263.40	31.42	17.71
37	CNTRL	1425.86	34.82	18.02	988.19	38.83	21.89	3054.95	33.71	18.25	2341.69	35.77	20.16
38	BD	2484.37	34.63	15.80	1377.06	33.99	19.16	4286.18	34.01	15.51	2885.49	33.77	19.03
38	D	2191.69	33.59	17.18	1258.70	38.03	21.43	4361.33	33.76	19.02	2536.34	37.97	21.40
39	BD	1363.70	32.98	16.81	1052.69	37.25	21.00	1810.35	33.35	16.94	2399.97	35.72	20.13
39	D	1364.40	36.16	17.90	1139.59	38.95	21.95	2114.54	34.71	17.05	2910.37	36.29	20.45
40	BD	2391.42	51.12	28.81	1247.82	71.49	40.29	4052.47	44.25	24.94	1848.57	52.93	29.83
40	D	1930.53	55.20	31.11	1158.55	71.40	40.24	3271.13	50.78	28.62	1893.92	59.87	33.74
41	BD	3084.67	37.39	21.07	1343.56	45.81	25.82	5250.18	36.02	20.30	2700.75	46.42	26.16
41	D	2307.32	39.49	21.13	928.20	46.86	26.41	4164.25	33.84	18.50	2000.22	47.68	26.87
42	BD	2082.06	48.16	24.16	1254.27	55.67	31.38	4300.65	38.61	21.76	1850.16	46.16	26.01
42	D	1876.20	45.13	21.73	1106.77	53.80	30.32	4398.97	36.89	20.79	2013.64	47.49	26.76
43	BD	1926.21	26.53	13.28	1217.90	33.82	15.43	3005.36	31.83	14.52	1773.00	29.70	16.74
43	D	1819.07	28.84	13.95	1127.80	33.42	15.24	3483.16	32.08	14.63	2141.90	29.04	16.36
44	BD	2671.21	32.89	17.59	1358.24	39.34	20.16	3700.41	34.48	19.43	2114.53	35.79	20.17
44	D	3005.87	42.19	22.00	1336.66	47.12	26.55	5175.74	41.12	23.17	2651.99	43.44	24.48

E1: Surface layer modulus
E2: Base layer modulus
E3: Subgrade layer modulus

APPENDIX Q ANOVA RESULTS FOR DCP TESTING – WATER-BOUND MACADAM BASE

Table 36. ANOVA Results Water-bound Macadam Base Mr, Control Sections

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	4	157244.68	39311.171	136393135.3
Initial	4	133671.05	33417.7635	73142298.06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	69464505	1	69464504.6	0.663033488	0.446596	5.987378
Within Groups	628606300	6	104767717			
Total	698070805	7				

Table 37. ANOVA Results Water-bound Macadam Base Mr for Sections Backfilled with No. 4 Aggregate

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	6	295781.30	49296.88	37747060.01
Initial	6	339799.62	56633.27	58285039.42

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	161467734	1	161467734	3.362786713	0.096575	4.964603
Within Groups	480160497	10	48016049.7			
Total	641628231	11				

Table 38. ANOVA Results Water-bound Macadam Base Mr for Sections Backfilled with No. 57 Aggregate

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	24	1116984	46541.0004	87411338.08
Initial	24	1137210	47383.7491	121169782.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8522704.1	1	8522704.05	0.081720762	0.776262	4.051749
Within Groups	4.797E+09	46	104290560			
Total	4.806E+09	47				

Table 39. ANOVA Results Water-bound Macadam Base Mr for Sections Backfilled with No. 8 Aggregate

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	6	288507.55	48084.5922	27581057.56
Initial	6	270082.39	45013.732	71266035.02

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	28290546	1	28290545.7	0.572410275	0.466753	4.964603
Within Groups	494235463	10	49423546.3			
Total	522526009	11				

Table 40. ANOVA Results Water-bound Macadam Base Mr for Sections Backfilled with Porous Concrete

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	4	187806.61	46951.6531	56834834.28
Initial	4	185021.95	46255.4871	143676200

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	969294.25	1	969294.25	0.009668238	0.924875	5.987378
Within Groups	601533103	6	100255517			
Total	602502397	7				

Table 41. ANOVA Results Water-bound Macadam Base Mr for Sections with Aggregate Drains Spaced at 50 ft

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	24	1127862	46994.26	55283046
Initial	24	1123939	46830.8	1.11E+08

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	320617.402	1	320617.4	0.003849	0.950802	4.051749
Within Groups	3832142487	46	83307445			
Total	3832463104	47				

Table 42. ANOVA Results Water-bound Macadam Base Mr for Sections with Aggregate Drains Spaced at 200 ft

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	16	761217.3	47576.08	84970856
Initial	16	808174.7	50510.92	1.13E+08

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	68906256.12	1	68906256	0.696508	0.410556	4.170877
Within Groups	2967929614	30	98930987			
Total	3036835870	31				

Table 43. ANOVA Results Water-bound Macadam Base Mr for Sections with Aggregate Drains Constructed without Compaction

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	20	906907.3	45345.37	93630103
Initial	20	943753.3	47187.66	1.29E+08

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	33940613	1	33940613	0.305229	0.583858	4.098172
Within Groups	4.23E+09	38	1.11E+08			
Total	4.26E+09	39				

Table 44. ANOVA Results Water-bound Macadam Base Mr for Sections with Aggregate Drains Constructed with Compaction

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	20	982172.2	49108.61	33091098
Initial	20	988360.7	49418.03	99354790

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	957441.6	1	957441.6	0.014458	0.904926	4.098172
Within Groups	2.52E+09	38	66222944			
Total	2.52E+09	39				

Table 45. ANOVA Results Water-bound Macadam Base Mr for Sections with Aggregate Drains Constructed without Filter Fabric

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	22	1064701	48395.52	36908630
Initial	22	1097628	49892.18	1.08E+08

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	24640010	1	24640010	0.340408	0.562714	4.072654
Within Groups	3.04E+09	42	72383825			
Total	3.06E+09	43				

Table 46. ANOVA Results Water-bound Macadam Base Mr for Sections with Aggregate Drains Constructed with Filter Fabric

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	18	824378.1	45798.78	1E+08
Initial	18	834486	46360.33	1.17E+08

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2838032	1	2838032	0.026058	0.872713	4.130018
Within Groups	3.7E+09	34	1.09E+08			
Total	3.71E+09	35				

APPENDIX R ANOVA RESULTS FOR DCP TESTING – SUBGRADE

Table 47. ANOVA Results Subgrade Mr, Control Sections

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	4	49679.85	12419.96235	17437668.95
Initial	4	59031.51	14757.87679	25809901.18

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	10931687.9	1	10931687.87	0.50553998	0.503765	5.987378
Within Groups	129742710	6	21623785.07			
Total	140674398	7				

Table 48. ANOVA Results Subgrade Mr for Sections Backfilled with No. 4 Aggregate

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	6	68740.39	11456.73179	6154673.473
Initial	6	84047.41	14007.90101	48207607.09

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	19525393.2	1	19525393.16	0.718343416	0.416512	4.964603
Within Groups	271811403	10	27181140.28			
Total	291336796	11				

Table 49. ANOVA Results Subgrade Mr for Sections Backfilled with No. 57 Aggregate

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	24	324659.3	13527.47116	60763363.89
Initial	24	301695.2	12570.63226	19102189.26

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	10986488.1	1	10986488.08	0.275124572	0.602433	4.051749
Within Groups	1836907722	46	39932776.57			
Total	1847894211	47				

Table 50. ANOVA Results Subgrade Mr for Sections Backfilled with No. 8 Aggregate

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	6	81421.84	13570.30728	113913945.8
Initial	6	66608.99	11101.49848	18531531.06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	18285050.6	1	18285050.63	0.276114384	0.610712	4.964603
Within Groups	662227384	10	66222738.44			
Total	680512435	11				

Table 51. ANOVA Results Subgrade Mr for Sections Backfilled with Porous Concrete

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	4	50359.21	12589.80359	35450926.64
Initial	4	42474.9	10618.72454	14850461.12

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7770305.22	1	7770305.225	0.308949934	0.598425	5.987378
Within Groups	150904163	6	25150693.88			
Total	158674469	7				

Table 52. ANOVA Results Subgrade Mr for Sections with Aggregate Drains Spaced at 50 ft

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	24	313143	13047.63	43360508
Initial	24	286026.8	11917.78	23450665

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	15318559	1	15318559	0.458563	0.501688	4.051749
Within Groups	1.54E+09	46	33405587			
Total	1.55E+09	47				

Table 53. ANOVA Results Subgrade Mr for Sections with Aggregate Drains Spaced at 200 ft

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	16	212037.7	13252.36	75298680
Initial	16	208799.7	13049.98	20327399

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	327653.4	1	327653.4	0.006853	0.934575	4.170877
Within Groups	1.43E+09	30	47813040			
Total	1.43E+09	31				

Table 54. ANOVA Results Subgrade Mr for Sections with Aggregate Drains Constructed without Compaction

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	20	215525.3	10776.26	8332369
Initial	20	233475.8	11673.79	15898174

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8055494	1	8055494	0.664904	0.419916	4.098172
Within Groups	4.6E+08	38	12115271			
Total	4.68E+08	39				

Table 55. ANOVA Results Subgrade Mr for Sections with Aggregate Drains Constructed with Compaction

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	20	309655.5	15482.77	91965634
Initial	20	261350.7	13067.53	28162719

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	58333766	1	58333766	0.971191	0.330617	4.098172
Within Groups	2.28E+09	38	60064177			
Total	2.34E+09	39				

Table 56. ANOVA Results Subgrade Mr for Sections with Aggregate Drains Constructed without Filter Fabric

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	22	251416.9	11428.04	22691674
Initial	22	261156.9	11870.77	21693173

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2156053	1	2156053	0.097153	0.756816	4.072654
Within Groups	9.32E+08	42	22192424			
Total	9.34E+08	43				

Table 57. ANOVA Results Subgrade Mr for Sections with Aggregate Drains Constructed with Filter Fabric

Groups	*Count*	*Sum*	*Average*	*Variance*
Final	18	273763.8	15209.1	88771452
Initial	18	233669.6	12981.64	22871090

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	44654076	1	44654076	0.799947	0.377397	4.130018
Within Groups	1.9E+09	34	55821271			
Total	1.94E+09	35				

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