Evaluate ODOT's Current Berm Compaction Process for Cost Effective Alternatives

Prepared by:
Munir D. Nazzal
Sang Soo Kim
Hassan Zahran
Mohammad Alkhasawneh
Hamzeh Saqer

Prepared for:
The Ohio Department of Transportation,
Office of Statewide Planning & Research

State Job Number 135496

April 2020

Final Report

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/OH-2020-14		
4. Title and Subtitle		5. Report Date:
Evaluate ODOT's Current Berm Compaction Process for Cost Effective Alternatives		**April 2020**
		6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No.
Munir D. Nazzal, Sang Soo Kim, Hassan Zahran, and Mohammad Al-khasawenh		
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)
Ohio University Department of Civil Engineering Athens, Ohio 45701		
		11. Contract or Grant No.
		SJN 135496
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered
Ohio Department of Transportation 1980 West Broad Street, MS 3280 Columbus, Ohio 43223		**Final Report**
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report summarizes the results of a research project that was completed to evaluate and analyze ODOT's current berm construction/repair process and provide recommendations on how to improve the safety, productivity and cost effectiveness of this process. This project was divided into two phases. The results of Phase 1 indicated that the main cause for the frequent berm reconditioning/repair is the erosion of the berm materials. The high stresses applied by oil and gas industry trucks as well as the very narrow width have accelerated the erosion of berms in ODOT Monroe County. Phase 1 also identified new equipment and materials that can help in improving the berm resistance to erosion and rutting and can enhance their performance and service life. Phase 2 of this study examined the improvement in berm performance and service life when using the different alternative materials and methods identified in Phase 1 for establishing berm materials, and evaluated the cost-effectiveness of these alternatives. The results of the Phase 2 indicated that the use of alternative materials and methods significantly improved the service life of berms. The highest improvement was achieved when using heated RAP or emulsified RAP materials. In addition, all alternative berm materials/methods resulted in significantly reducing the annual cost of berms. The highest cost benefits were obtained when heated RAP or emulsified RAP materials were used as berm materials. Based on the results of the of this study, recommendations for the alternative materials and methods for establishing or repairing berms were provided.

17. Keywords	18. Distribution Statement
Berms, erosion, compaction, RAP mixes	**No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161**

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**	**50**	

EVALUATE ODOT'S CURRENT BERM COMPACTION PROCESS FOR COST EFFECTIVE ALTERNATIVES

Prepared by:

Munir D. Nazzal, Ph.D., P.E.
Department of Civil and Architectural Engineering and Construction Management,
University of Cincinnati,
Cincinnati, OH 45221

Sang Soo Kim
Department of Civil Engineering
Ohio University
Athens, OH 45701

April 2020

Prepared in cooperation with the Ohio Department of Transportation, and the U.S. Department of Transportation, Federal Highway Administration

Acknowledgments

The researchers would like to thank the Ohio Department of Transportation (ODOT) and the Federal Highway Administration (FHWA) for sponsoring this study. The researchers would like also to thank the technical liaisons: Mr. Jamie Hendershot, Mr. Jim Wells, and Mr. David Molihan. Finally, the researchers would like to express their appreciation to Ms. Jacquelin Martindale for her time and assistance.

TABLE OF CONTENTS

List of Figures

Evaluate ODOT's Current Berm Compaction Process for Cost Effective Alternatives

Executive Summary

This report summarizes results of a project that was completed to evaluate and analyze ODOT's current berm construction/repair process and provide recommendations on how to improve the safety, productivity and cost effectiveness of this process. This project was divided into two phases. The results of Phase 1 indicated that the main cause for the frequent berm reconditioning/repair is the erosion of the berm materials. The high stresses applied by oil and gas industry trucks as well as the very narrow width have accelerated the erosion of berms in ODOT Monroe County. In addition, in some cases the berm materials were significantly weakened by erosion and excessively settled under the high stresses from the oil and gas industry trucks. Cost analysis of berm repairs indicated that the cost of these repairs was very high for short segments and decreased exponentially with the increase in the repaired berm segment length. Therefore, reducing the number of short berm segments repaired (spot berm repairs) will significantly reduce the average cost of berm repairs for ODOT county garages. Phase 1 also identified new equipment and materials that can help in improving the berm resistance to erosion and rutting and can enhance their performance and service life.

Phase 2 of this study examined the improvement in berm performance and service life when using the different alternative materials and methods identified in Phase 1 for establishing berm materials, and evaluated the cost-effectiveness of these alternatives. To achieve that, laboratory and field test program was conducted. The laboratory testing program included evaluating the erodibility of current and alternative berm materials using the turbulent flow test. In addition, berm test sections were constructed in ODOT Monroe and Vinton Counties in District 10. The obtained information was used to conduct a comprehensive cost analysis to evaluate the cost effectiveness of the different alternative materials and processes to construct berm.

The laboratory test results that unheated RAP material has poor resistance to erosion and should not be used for berm. The laboratory test results indicated that the compaction temperature of heated RAP material should be at least 100°C to achieve adequate resistance to erosion.
The results of the field testing program indicated that the use of alternative materials and construction methods significantly improved the service life of berms. The highest improvement was achieved when using heated RAP or emulsified RAP materials. In addition, all alternative berm materials/methods resulted in significantly reducing the annual cost of berms. The highest cost benefits were obtained when heated RAP or emulsified RAP materials were used as berm materials. Based on the results of this study, recommendations for the alternative materials and methods for establishing or repairing berms were provided.

1. Project Background

Berm compaction and placement is one of the procedures that the Ohio Department of Transportation (ODOT) maintenance crews commonly perform. This procedure is essential to maintain the traveling public safety as road side drop-off can affect vehicle stability and reduce a driver's ability to handle the vehicle resulting in fatalities, injuries and/or vehicle damages. In addition, proper berm compaction helps to maintain the structural capacity and longevity of pavement structures.

Berm materials settle or are washed away by runoff from road pavement surface causing road side drop-off. Berms can be quickly eroded due to roadway runoff especially if located adjacent to steep slopes. In some counties in Ohio such as Monroe and Vinton County, the berms are settling and being eroded more rapidly due to the increase in the heavy truck traffic from oil and gas industry as well as the topographical characteristics of the area, requiring more frequent placement and repair of these berms. Therefore, the maintenance crew form these counties are required to place and repair the berms in a timely and efficient manner.

Proper berm compaction is one of the most critical components to ensure its adequate performance, durability, and stability over time. For compaction of relatively level shoulder ODOT specification requires applying four compaction passes with crawler-type tractors, suitable pneumatic tire rollers, tamping rollers, trench rollers, or any other suitable compaction equipment weighing at least 6 tons. However, it is challenging and unsafe to use these compaction equipment for compaction of berms that have slopes.

The type of material used in berms also affects their stability and durability. Different types of materials can be used for berm compaction. These materials include natural soil, aggregates, and asphalt mixes. These materials have different resistance to deformation and movement under various traffic loads and weather conditions, which can significantly affect the performance and service life of berms. In addition, some materials are more erodible and susceptible to weather condition due to run-off and precipitation. The initial cost of some types of berm materials (such as asphalt mixtures) might be higher but their life cycle costs might be lower than those currently used. However, currently, there is no field data to document the performance or life cycle costs of berms when using different materials.

ODOT initiated the project entitled "Evaluate ODOT's Current Berm Compaction Process for Cost Effective Alternatives-Phase 1" (referred to as Phase 1 hereinafter) to evaluate and analyze ODOT's current berm construction/repair process and provide recommendations on how to improve the safety, productivity and cost effectiveness of this process. The results of Phase 1 indicated that the main cause for the frequent berm reconditioning/repair is the erosion of the berm materials. The high stresses applied by oil and gas industry trucks as well as the very narrow width have accelerated the erosion of berms in ODOT Monroe County. In addition, in some cases the berm materials were significantly weakened by erosion and excessively settled under the high stresses from the oil and gas industry trucks. Cost analysis of berm repairs indicated that the cost of these repairs was very high for short segments and decreased exponentially with the increase in the repaired berm segment length. Therefore, reducing the number of short berm segments repaired (spot berm repairs) will significantly reduce the average cost of berm repairs for ODOT county garages.

Phase 1 also identified new equipment, materials and alternative methods for berm placement and compaction that can help in improving the berm resistance to erosion and rutting and can enhance their performance and service life. The results of life cycle cost analysis conducted in Phase 1 indicated that these alternatives can reduce the average annual cost of repairing routes with heavy truck traffic by up to 60%. However, further evaluation should be performed to determine the improvement level in berm performance achieved when using these alternatives.

Phase 2 will evaluate the reliability, efficiency, and ease of use of different tools and equipment identified in Phase 1 for berm compaction and placement. In addition, it will assess the improvement in berm performance and service life when using the different alternatives identified in this Phase 1. This will be used to examine the cost effectiveness of these alternatives. The main outcome of this project will be to improve cost-effective, efficiency, and safety of berm placement and compaction process in Ohio.

2. Research Context

The main objective of this project is to conduct comprehensive evaluation and analysis of ODOT's current berm compaction process and provide recommendations on how to improve the safety, productivity and cost effectiveness of this process. Specific objectives of Phase 2 include:

1- Determine the improvement in berm performance and service life when using the different alternative methods identified in this Phase 1.
2- Determine the cost-effectiveness of the different alternative methods identified in this Phase 1 for berm compaction and placement.
3- Evaluate the reliability, efficiency, and ease of use of different tools and equipment identified in Phase 1.
4- Determine the rejuvenator to be used with RAP mix produced using the asphalt recycler for berm.

Phase 2 of this study included conducting the following tasks to achieve the outlined objectives:

Task 1. Purchase Equipment and Conduct Training
Task 2. Conduct Laboratory tests to determine berms materials used in the field
Task 3. Construct of Field test section
Task 4. Evaluation of Field Test Sections
Task 5. Evaluate the Cost Benefits of Alternative Methods for Berm Compaction and Placement
Task 6. Recommendations for Method to Construct/Repair Berms
Task 7. Prepare and Submit Report

Literature review conducted in Phase 1 indicated that the erodibility potential of berm materials is significantly affected by material type, gradation of unbound aggregates, degree of compaction, and magnitude and frequency of traffic loads. Increasing the density of aggregates can improve their resistance to erosion and rutting. The type of material used in berms affects their erosion and rutting potential as well. Asphalt mixes are much more resistant to erosion and rutting than unbound aggregate materials.

Berms are critical components of pavement structure as they provide lateral support for the entire pavement structure, an increased width to accommodate oversize trucks and equipment, and a recovery area when a vehicle's wheels leave the pavement (Jensen & Uerling 2015). Berm consisting of uncompacted berm materials suffer from different types of deterioration that include settlement and/or erosion. Compaction of berm materials improves their shear strength and stiffness. This makes them capable of resisting more stress with less deformation and, hence, it prevents or reduces the development of detrimental excessive settlement during service. In addition, compaction helps improve the erosion resistance of different soil types and decrease their susceptibility to environmental changes (Gu et al. 2015). However, placement and compaction of berms typically presents a challenge to maintenance crews due to the narrow width and slope of berm. A side-mounted vibratory roller or plate is best suited for compaction of berms. However, no previous study has reported the use or evaluation of such rollers for berm compaction. Different types of materials have been used for berm and shoulders, which include: concrete mixes, asphalt mixes, asphalt treated materials, unbound aggregates, stabilized aggregate, and vegetated or unstabilized soil (Jensen & Uerling 2015). Unbound aggregate is the most commonly used berm material. Asphalt mixes has much better resistance to erosion and rutting than unbound aggregate. While the initial cost of asphalt mixes is higher than that of unbound aggregates, the maintenance costs of shoulders constructed with asphalt mixes were reported to be three times lower than those constructed using unbound aggregates.

This report summarizes Phase 1 research work that was completed to evaluate and analyze ODOT's current berm construction/repair process and provide recommendations on how to improve the safety, productivity and cost effectiveness of this process. To achieve that, a survey was conducted to collect information from ODOT county garages on their current practices for berm construction and repairs. The results of this survey indicated that berm materials are typically compacted using the dump truck tires. Few county garages reported using a roller mounted on a tractor for berm compaction. However, the majority of ODOT county garages believe that berms materials are inadequately compacted. Most ODOT county garages believe that asphalt grindings/millings (recycled asphalt pavement (RAP)) are the best materials to be used in constructing/repairing berms. However, the county garages prefer using new grindings (less than one year old) and compact them during warm weather. Sand and gravely unbound aggregates were reported to be eroded easily by water and traffic. About half of ODOT county garages indicated that berms are being constructed with a minimum width of 2 ft. Many ODOT county garages indicated reconditioning the same berm once or twice a year.

Analysis of berm failures was also performed in Phase 1 indicated that the main cause for the frequent berm reconditioning/repair is the erosion of the berm materials. The high stresses applied by oil and gas industry trucks as well as the very narrow width have accelerated the erosion of berms in ODOT Monroe County. In addition, in some cases the berm materials were significantly weakened by erosion and excessively settled under the high stresses from the oil and gas industry trucks. Cost analysis of berm repairs indicated that the cost of these repairs was very high for short segments and decreased exponentially with the increase in the repaired berm segment length. Therefore, reducing the number of short berm segments repaired (spot berm repairs) will significantly reduce the average cost of berm repairs for ODOT county garages.

This study also identified new equipment and materials that can help in improving the berm resistance to erosion and rutting and can enhance their performance and service life. A preliminary analysis of different alternative processes to construct and repair berms using the identified equipment and materials was conducted. The results of the performed analysis indicated that the initial cost of alternatives that involves modifying current ODOT process by using a Roadwidener berm box to spread and place berm materials as well as using a Roadwidener offset vibratory roller to compact placed berm was slightly higher than that of current practice. However, both alternatives can help to significantly improve the safety and efficiency of berm compaction process and can also increase the resistance of berm materials to erosion and rutting. However, further evaluation should be performed to determine the level of improvement in berm performance achieved when using these alternatives. The initial cost of another alternative that involves using the Roadwidener berm box and the Roadwidener offset vibratory roller as well as replacing the current berm materials with RAP mix produced using Bagela BA10000 recycler was slightly lower than that of current practice for berm segments shorter than 1500 ft., but it was higher for berm segments longer than 1500 ft. Life cycle cost analysis indicated that this alternative practice can significantly reduce the average annual cost of repairing routes with heavy truck traffic.

Based on the results of the Phase 1 of this study, it is recommended that Phase 2 should be conducted to:

1- Evaluate the reliability, efficiency, and ease of use of different tools and equipment identified in Phase 1.
2- Evaluate the compaction level for different types of materials and at different field conditions that can be achieved using the Roadwidener offset vibratory roller. The Light Weight Deflectometer (LWD) can be used to assess the achieved level of compaction.
3- Determine the improvement in berm performance and service life when using the different alternatives identified in this Phase 1.
4- Determine the optimal rejuvenator type and dosage to be used with RAP mix produced using the asphalt recycler for berm as well as for other pavement repair applications.

3. Research Approach

Analysis of berm failures was also performed in Phase 1 indicated that the main cause for the frequent berm reconditioning/repair is the erosion of the berm materials. The high stresses applied by oil and gas industry trucks as well as the very narrow width have accelerated the erosion of berms in ODOT Monroe County. In addition, in some cases the berm materials were significantly weakened by erosion and excessively settled under the high stresses from the oil and gas industry trucks. Cost analysis of berm repairs indicated that the cost of these repairs was very high for short segments and decreased exponentially with the increase in the repaired berm segment length. Therefore, reducing the number of short berm segments repaired (spot berm repairs) will significantly reduce the average cost of berm repairs for ODOT county garages.

Phase 1 identified different alternative processes to construct and repair berms using new equipment and materials, which can help improving the berm resistance to erosion and rutting and can enhance their performance and service life. The identified alternative processes involved using a Roadwidener berm box to spread and place berm materials as well as using a Roadwidener offset vibratory roller to compact berm material. In addition, the identified processes involved using replacing the current berm materials with RAP mix produced using Bagela BA10000 recycler. The results of preliminary analysis conducted in Phase 1 indicated that the identified alternatives can significantly reduce the average annual cost of repairing berms on state routes. However, further evaluation of these alternative processes needs to be conducted of this study to validate the results of the analysis conducted in Phase 1. The following subsections summarize the research approach that was followed in this Phase 2 to evaluate the alternative methods and materials identified in Phase 1 to construct and repair berm materials.

3.1 Purchase of Equipment and Conduct Training Sessions

The equipment identified in Phase 1 were purchased, these included: Roadwidener 4ft offset vibratory roller, Roadwidener reduced neck skid steer road widener berm box, and Bagela BA10000 asphalt recycler. Several training sessions were held for ODOT personnel in Monroe and Vinton Counties that will be involved in this project. A training session was conducted for the Roadwidener offset vibratory roller and the Roadwidener berm box. In addition, two training sessions were held for the Bagela BA10000 asphalt recycler; one for each county garage. These sessions educated the attendees on the proper procedure for using and maintaining these equipment as well as the factors and measures that should be taken to ensure successful and efficient usage of equipment.

3.2 Laboratory Evaluation of Erodibility

The erodibility of materials was evaluated using the turbulent flow test. This test simulates the turbulent flows, particularly the action of wind and surface water runoff, that can influence the unbound aggregates and drag the fine materials causing erosion problems. The test involved letting the water run on the surface of the test material, then the erosion resistance can be calculated by measuring the weight of the dragged materials. The research team designed and fabricated the device for this test. Samples of the berm materials were obtained from ODOT Monroe and Vinton county garages. In addition, samples of ODOT Item No. 304 was obtained for comparison. The piles of Reclaimed Asphalt Pavement (RAP) in ODOT Monroe and Vinton county garages were also sampled. Erodibility tests were conducted on the obtained materials.

The use of heated RAP mixtures was also investigated in the laboratory. To this end, the effect of heating of RAP on their erodibility was evaluated. Tests were conducted on samples that are prepared using RAP materials that were unheated as well as heated to two different temperatures: 55 °C and 100 °C.

The use of emulsified RAP mixes was also investigated in the laboratory. To achieve this, RAP mixes were prepared with different emulsion contents of 2%, 3.5 %and 4.5%. The emulsion used was CSS-1hM. This is the type of emulsion used in micro-surfacing mixes.

3.3 Laboratory Evaluation of the Effect of Rejuvenator on Durability of RAP Mixes

The durability of RAP mixes produced using rejuvenators was evaluated. Two different rejuvenators were considered in this task, namely, aromatic extracts, and tall oil. Those rejuvenators have shown promising results in previous studies. The recommended dosage of 10% of the RAP binder content used. The evaluation included spraying each recycling agent on the RAP material with the specified dosage before heating it. Gyratory specimens of the obtained RAP mixtures were prepared to target air voids of 7%. Indirect tensile strength (IDT) test were performed on the prepared specimens in accordance with AASHTO T283 at a temperature of 25°C using a loading rate of 50 mm/min. The load as well as the vertical and lateral deformations were continuously recorded. IDT test results was analyzed to determine the indirect tensile strength

(ITS). The AASHTO T 283 (modified Lottman) test were used to evaluate the moisture susceptibility of the prepared specimens. At least six specimens will be tested. The specimens were split into two groups: unconditioned (dry) samples and conditioned (wet) samples. The wet conditioned samples were first partially saturated in a water bath to achieve 70% to 80% saturation. Each sample was then wrapped in plastic and placed in a plastic bag with 10 ml of water in it. The samples were then placed in an environmental chamber that was set at a temperature of 0°F (–18°C) for 17 hours. After that, the samples were placed in a water bath with a temperature of 140°F (60°C) for 24 hours. The water bath temperature was reduced to 77°F (25°C) 2 hours prior to testing. The IDT test was conducted on the dry and conditioned wet samples. The ratio between average indirect tensile strengths of the wet conditioned samples to that of the dry samples was computed. This ratio is typically known as the tensile strength ratio (TSR) and used as a measure of moisture susceptibility.

3.4 Berm Test Sections

Field test sections were constructed in ODOT Monroe County and ODOT Vinton County to evaluate the different berm material alternatives that were identified based on the laboratory tests conducted and the different methods recommended in Phase 1 of this study. Eight berm test section were constructed in the week of August 27th, 2018 on State Route (SR) 800 in ODOT Monroe County to evaluate the different alternative materials and methods for the berm construction and repair. Figure 1 provides the layout for the constructed test sections. Each test section was about 400 ft long. The constructed test sections were:

- Section 1 (control section): The berm was established using current method, equipment and materials used by ODOT Monroe County.
- Section 2: The berm was established using an alternative compaction and placement method that involves modifying current ODOT process by using a Roadwidener box attached to a skid steer to spread and place the current berm material as well as using an offset vibratory roller attachment on a skid steer to compact the placed berm materials.
- Section 3: The berm was established using the same method and equipment as in Section 2, but ODOT Item 304 aggregates (without any millings) was used.
- Section 4: The berm was established using the same method, material, and equipment as in Section 3, but a CSS-1hm emulsion was sprayed on the compacted berm material.
- Section 5: The berm was established using the same method and equipment as in Section 2 but using a mix of RAP and CSS-1hm emulsion that will be produced using Bagela BA10000 recycler.
- Section 6: The berm was established using the same method and equipment as in Section 2 but using recycled asphalt pavement (RAP) mix that was produced using Bagela BA10000 recycler.
- Section 7: The berm was established using the same method and equipment as in Section 2 but using RAP mix with an aromatic extract rejuvenator produced using Bagela BA10000 recycler.
- Section 8: The berm was established using the same method and equipment as in Section 2 but using RAP mix with No. 57 aggregates produced using Bagela BA10000 recycler. The No. 57 aggregates was added after RAP is heated and was mixed with RAP at a proportion of 3 parts RAP to 1 part No. 57 (3:1).

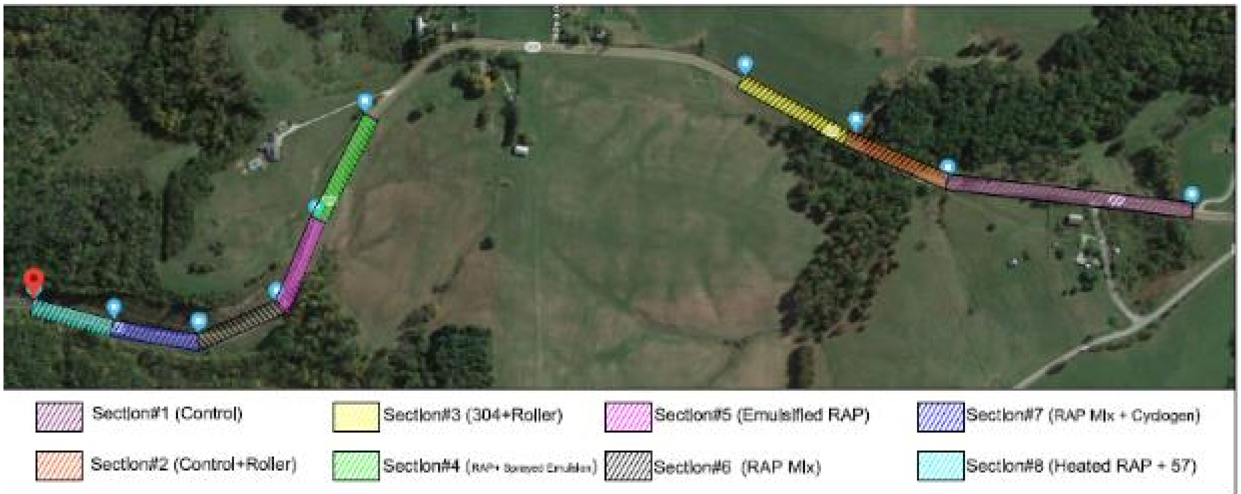


Figure 1. Layout of test section on SR 800 in ODOT Monroe County

Four berm test section were also constructed on October 22nd, 2018 on SR 160 in ODOT Vinton County to evaluate the different alternative materials and methods for the establishing berms. Figure 2 provides the layout for the constructed test sections in Vinton County. The constructed test sections were:

- Section 1: The berm was established using the same method and equipment as in SR 800 Test Section 2 but using a mix of RAP and CSS-1hm emulsion that will be produced using Bagela BA10000 recycler.
- Section 2: The berm was established using the same method and equipment as in SR 800 Test Section 2 but using RAP mix that was produced using Bagela BA10000 recycler.
- Section 3: The berm was established using the same method and equipment as in SR 800 Test Section 2, but ODOT Item 304 aggregates (without any millings) was used.
- Section 4 (control section): The berm was established using current method, equipment and materials used by ODOT Vinton County.

For each test section, the following information and data were recorded during the berm placement compaction: exact location of each test section, time and date of compaction, berm material type and volume used, climatic conditions, equipment used for placing and compacting the berm, duration of berm placement and compaction, and number of persons in maintenance crew involved in berm construction. Prior to constructing the berm, the stiffness of existing materials was evaluated using the Light Falling Weight Deflectometer (LWD). LWD was also used during compaction to determine the number of passes needed by offset vibratory roller to achieve the optimum stiffness for unbound granular materials. Based on that it was determined that the minimum of three passes of the offset vibratory roller was needed for unbound aggregate material. LWD was also conducted to determine the stiffness of berms after completion of compaction. Videos and photographs were also taken to document the berm compaction and placement process. All available information regarding the cost of constructing berm test sections were also obtained for use in the cost analyses conducted in this study.

Figure 2. Layout of test section on SR 160 in ODOT Vinton County

Field trials were also performed to evaluate the different applications of the RAP mixes produced using Bagela BA10000 recycler. To this end, RAP mixes were used to repair the berm and road edges on several locations on SR 145 in August 2018. RAP mixes were also used to patch potholes on SR 255 in March 2019.

3.5 Field Evaluation of Berm Test Sections

A field testing methodology was developed to evaluate the performance of the test sections constructed in ODOT Monroe and Vinton counties. The developed field methodology included evaluating the performance of the test sections by the research team during the duration of this project. All field evaluations involved examining the severity and extent of erosion in these sections. In addition, the drop-off in each test section was evaluated. The stiffness of each test section was evaluated after one year of construction using LWD. To this end, LWD was performed on at least 4 points within each test section.

3.6 Prediction of Rutting Performance of Berms Test Sections

Analysis was conducted using KENLAYER software to determine the distribution of vertical strain that develops within the different berm sections due to trucks with heavy loads. In this analysis, a tandem axle with 34 kips (maximum allowed load) was used. The modulus values that were obtained from LWD tests conducted on the berm test sections were used in the analysis. Damage models are then used to relate the vertical compressive strain, computed from the stress analysis, at the mid-depth of berm and the number of traffic applications to layer plastic strains. The overall permanent deformation is then computed using Equation 1 as sum of permanent deformation for each individual sub-layer.

$$PD = \varepsilon_p \times h \tag{1}$$

where:

PD = Rutting of the berm

ε_p = Total plastic strain berm

h= Thickness of berm (3 inches)

Three main damage models were used in this study, namely, one for the heated RAP mixes and emulsified RAP mixes (Equation 2), one for the unbound aggregate berm materials (Equation 4), and one for existing materials underneath the berm (Equation 5). The parameters of these models were determined through national calibration efforts using the Long-Term Pavement Performance (LTPP) database, and laboratory tests conducted on the different pavement materials used.

$$\frac{\varepsilon_p}{\varepsilon_v} = k_1 10^{-3.4488} T^{1.5606} N^{0.473844} \tag{2}$$

Where

ε_p = Accumulated plastic strain at N repetitions of load

ε_v = vertical strain of the asphalt material

N = Number of load repetitions

T = Berm temperature

k_1 = function of total asphalt layer(s) thickness and depth to computational point, to correct for the variable confining pressures that occur at different depths and is expressed as:

$$k_1 = (C_1 + C_2 \text{ * depth}) \text{ *}0.328196^{depth} \tag{3}$$

Where

C_1=-0.1039*h_{ac}^2+2.4868*h_{ac}-17.342

C_2=0.0172*h_{ac}^2-1.7331*h_{ac} - 27.428

h_{ac}= is the asphalt layer thickness

$$\frac{\varepsilon_p}{\varepsilon_v} = \beta_{GB}\left(\frac{\varepsilon_o}{\varepsilon_r}\right) \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \tag{4}$$

$$\frac{\varepsilon_p}{\varepsilon_v} = \beta_{SG}\left(\frac{\varepsilon_o}{\varepsilon_r}\right) \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \tag{5}$$

Where

β_{GB} = national model calibration factor for unbound base course material and is equal to 1.673

β_{SG} = national model calibration factor for subgrade material and is equal to 1.35

ε_0, β, and ρ = Material parameters

ε_r = resilient strain imposed in laboratory test to obtain material properties

3.7 Cost Analysis of Alternative Processes

The cost of materials, labor and equipment used for construction of test sections was obtained from ODOT Monroe and Vinton County garages. Equation 6 was also used to determine the hourly rate of the offset vibratory roller and the Roadwidener berm box.

$$A = \frac{P\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] + S\left[\frac{i}{(1+i)^n-1}\right] + AMC}{NHY} \tag{6}$$

Where;

A: Equivalent annual value

P: Purchase value

S: Salvage value
n: Service life of the equipment
i: Interest rate
AMC: annual maintenance cost
NHY: expected number of hours of usage per year.

The cost of producing RAP mixes using Bagela BA10000 recycler was calculated for each county. Based on the computed and obtained costs, the initial costs for constructing the different test sections were calculated. Cost analysis was performed to evaluate the life cycle cost of different test sections. The analyses considered the initial cost of berm placement and number of times that the berm needs to be repaired within the analysis period. An analysis period of five years was used in this study. The service life of different test sections was estimated based on the observed performance during the first year of service. The cost effectiveness of alternative materials and processes to construct berm were evaluated by comparing them to ODOT current process. This was achieved by computing the cost ratio using Equation 7.

$$\text{Cost Ratio} = \frac{\text{Annual Cost}_{\text{new material/method}}}{\text{Annual Cost}_{\text{current method}}} \tag{7}$$

4. Research Findings and Conclusions

Appendices A and B present a detailed summary of the survey, literature review, and analyses conducted in Phase 1 of this study, respectively. The main findings of this phase are summarized below.

- The laboratory test results indicated that the erosion resistance of ODOT Item No. 304 material was much better than materials typically used by ODOT for berms.
- The laboratory test results indicated that the unheated RAP material has much lower resistance to erosion than ODOT Item No. 617 and ODOT Item No. 304 materials. This suggested that unheated RAP materials should not be used for berm.
- The laboratory test results indicated that the compaction temperature of heated RAP material should be at least 100°C to achieve adequate resistance to erosion.
- The results of laboratory tests indicated that increasing the emulsion content have improved the RAP material resistance to erosion significantly, particularly when the emulsion content was more than 3%. Based on the results, the optimum emulsion content is between 3 and 3.5%, which is equate to about 7.25 to 7.5 gallons of emulsion per ton of RAP.
- The use of alternative materials and construction methods resulted in field test sections with higher stiffness than that of the control section constructed using current ODOT berm process. The highest stiffness was obtained when using heated RAP mixes and emulsified RAP material.
- The stiffness of berm sections with emulsified RAP materials increased with time during the first year of service.
- The results of analyses showed that sections with heated RAP mix and emulsified RAP materials will develop much less rutting under heavy truck traffic.

- The use of alternative materials and construction methods significantly improved the service life of berms. The highest improvement was achieved when using heated RAP or emulsified RAP materials.
- All alternative berm materials/methods resulted in significantly reducing the annual cost of berms. The highest cost benefits were obtained when heated RAP or emulsified RAP materials were used as berm materials.
- The results of analyses indicated that alternative berm materials/methods can reduce the time that ODOT personnel need to be in the field for repairing berms on state routes by up to 95%.
- The RAP mix produced with recycler can be used to install long lasting pothole patches.

5. Recommendations for Implementation

Based on the results of the of this study, the following recommendation are made:

- Figure 3 provides the alternatives that are recommended to be used when establishing or repairing berms. A decision tree is also provided in Figure 4 to be used for the selection of berm material.
- Continue to monitor the performance of berm sections constructed in this study to validate the conclusions made in this report.
- The use of emulsified RAP mix was found to significantly improve the performance and service life of berms, and significantly reduce their cost. Future research should explore methods to efficiently produce such mixes.
- Future research should evaluate the performance and service life of patches installed using the RAP mixes produced using the asphalt recycler.

6. References

- Ohio Department of Transportation. *Construction and Material Specifications Manual* (2016). Ohio Department of Transportation, Columbus, OH.
- Jensen, W., & Uerling, N. (2015). Mitigating Pavement Edge Drop-off.
- Glennon, J. C. (2005). A Primer on Pavement Edge Drop-offs, CrashForensics.com,
- AASHTO (2008). Driving Down Lane-Departure Crashes: A National Priority. American Association of State Highway and Transportation Officials, Washington, D.C. 20001.
- Holtz, R. D., Kovacs, W. D., & Sheahan, T. C. (2011). An introduction to geotechnical engineering.
- Guo, Y., Li, J., Huang, Q., & Yu, X. (2015). Experimental Study of Compaction Behaviors and Assessment of Berm Materials. In Innovative Materials and Design for Sustainable Transportation Infrastructure, pp. 128-142.
- Jahren, C.T., White, D.J., Phan, T.H., Westercamp, C., and Becker, P. (2011). Stabilization Procedures to Mitigate Edge Rutting for Granular Shoulders –Phase II. IHRB Project TR-591, Center for Transportation Research and Education, Iowa State University, Ames IA 50010-8664.

- White, D., Mekkawy, M., Jahren, C., Smith D., and Suleiman, M. (2007). Effective Shoulder Design and Maintenance, IHRB Project TR-531, Center for Transportation Research and Education, Iowa State University, Ames IA 50010-8664.

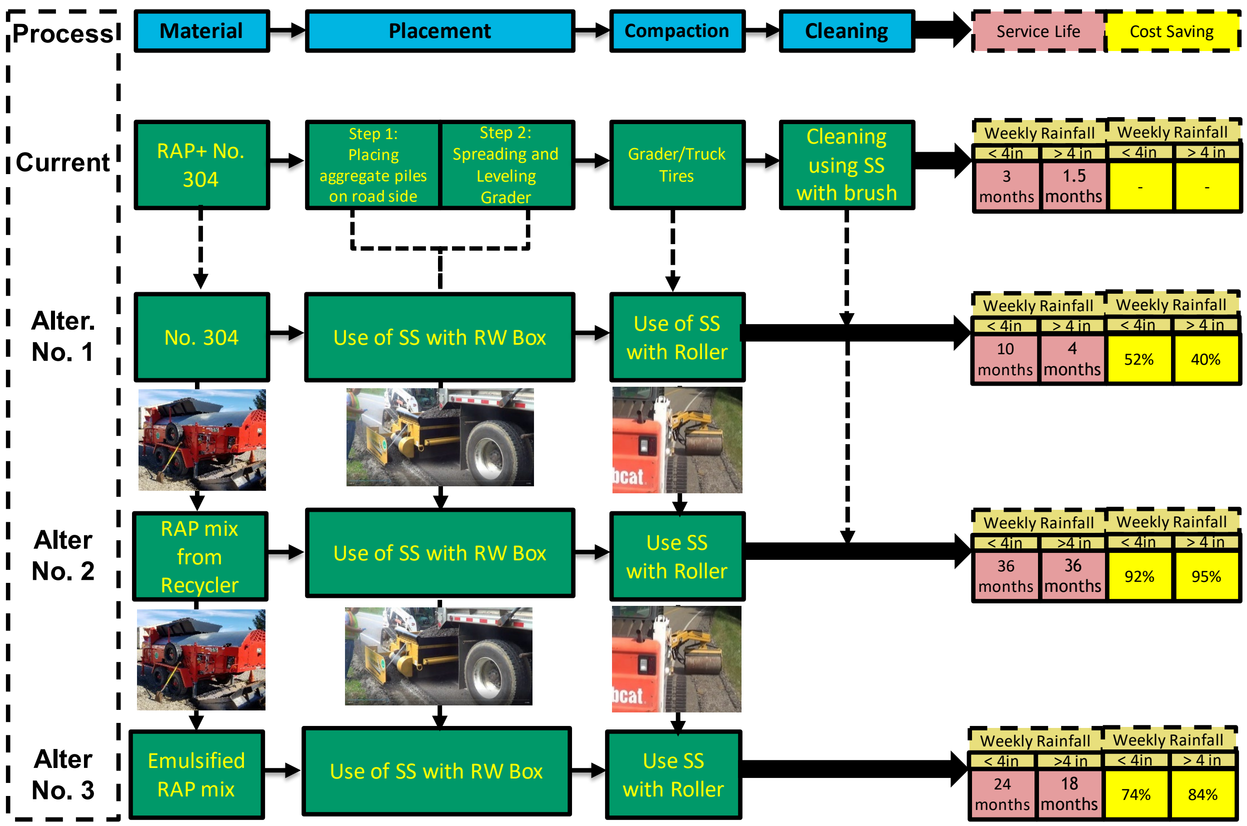


Figure 3. Recommended alternatives materials/methods for establishing berms

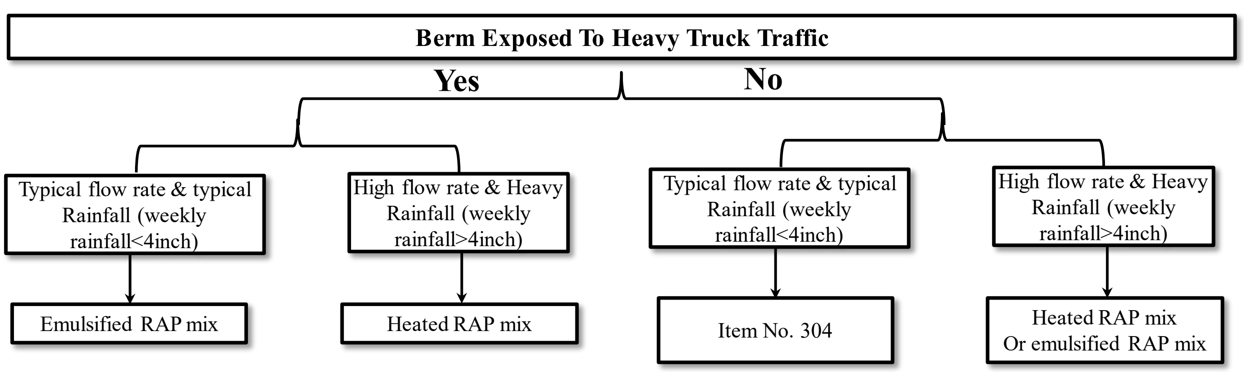


Figure 4. Recommended decision tree for selection of berm material

Appendix A Testing Program

A.1 Laboratry Evaluation of Erodobility

The erodibility of materials was evaluated using the turbulent flow test. This test simulates the turbulent flows, particularly the action of wind and surface water runoff, that can influence the unbound aggregates and drag the fine materials causing erosion problems. The test involved letting the water run on the surface of the test material, then the erosion resistance can be calculated by measuring the weight of the dragged materials. The research team designed and fabricated the device for this test, Figure A.1. The test device consisted of three main parts. The first part is the water tank to store the water before running the test. It is fixed at a specified height with a certain amount of water. The second part of the device is the pipe that connects the bottom of the water tank to the water outlet. The water flow can be controlled by the valve on the pipe. The last part is a hollow cylinder with its top covered. The cylinder has two vertical offset plates attached to the top cover and goes inside the cylinder until a depth of 0.25 inch from the sample surface. These two plates are used to maintain uniform flow rate.

The cylinder was designed to fit on the top of the modified proctor mold. The sample was placed and prepared in the proctor mold. The test starts after the valve is opened and ends by empty the water tank. As found in another study (Bilodeau et al. 2007), 7.0 liters of water were used to run the test and this quantity was found to be enough to get significant loses without having too much water to dry out later. The average test duration was 11.5 seconds. A metal container was used to collect the materials that dragged by the runoff water. The container was placed in the oven for one day to dry the collected material was drying. The dry weight corresponds to the amount of eroded material. Equation A.1 presents the equation used to determine the erosion rate (ER). The higher the ER values the greater the susceptibility of the tested material to erosion.

$$ER = \frac{M_S}{A \times t} \quad \text{A.1}$$

where
M_S: eroded dry mass (g)
A: proctor mold surface area (m^2)
t: time to empty the tank (second)

Samples of the berm materials were obtained from ODOT Monroe and Vinton county garages. In addition, samples of ODOT item No. 304 was obtained for comparison. The piles of Reclaimed Asphalt Pavement (RAP) in ODOT Monroe and Vinton county garages were also sampled. Erodibility tests were conducted on the uncompacted and compacted samples obtained materials.

The use of heated RAP mixtures was also investigated in the laboratory. To this end, the effect of heating of RAP on their erodibility was evaluated. Tests were conducted on samples that are prepared using RAP materials that were unheated as well as heated to two different temperatures: 55 °C and 100 °C.
The use of emulsified RAP mixes was also investigated in the laboratory. To achieve this, RAP mixes were prepared with different emulsion contents of 2%, 3.5 %and 4.5%. The emulsion used was CSS-1hM. This is the type of emulsion used in micro-surfacing mixes.

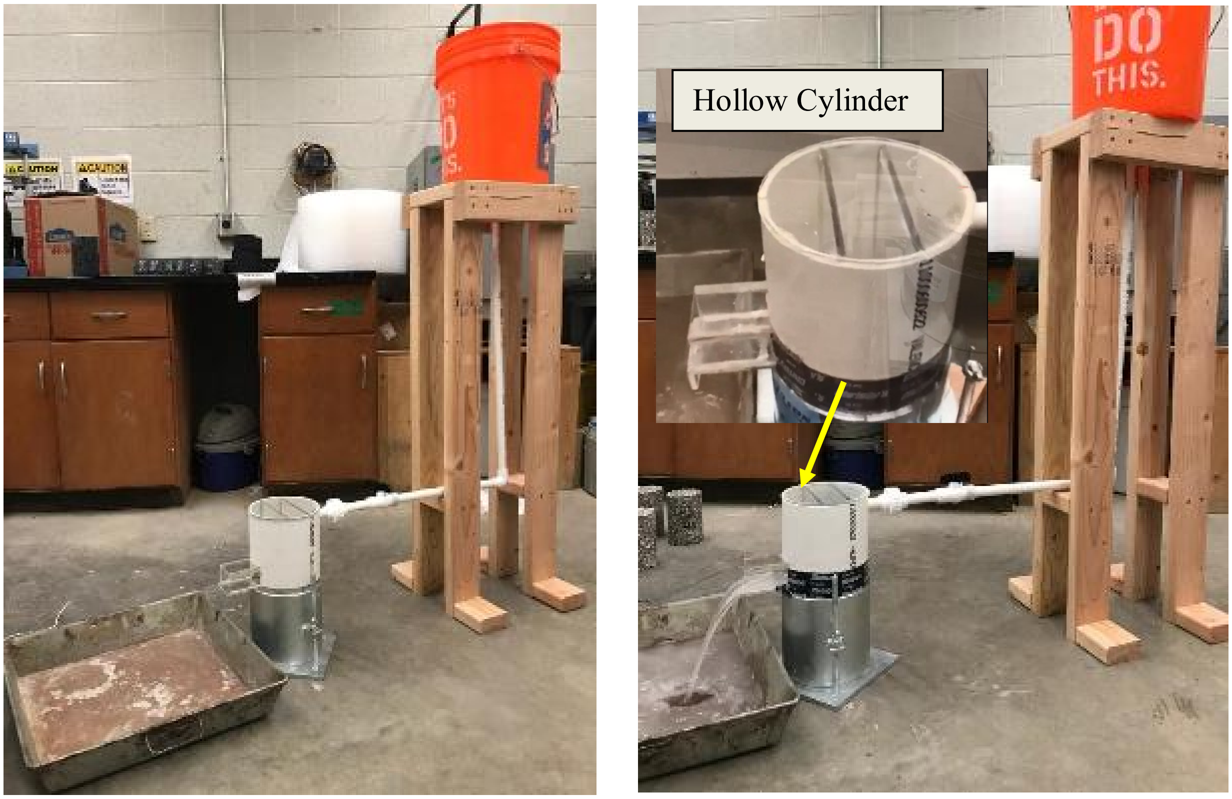


Figure A.1 Developed turbulent flow test

A.2 Laboratory Evaluation of Effect of rejuvenator on Durability of RAP Mixes

The durability of RAP mixes produced using rejuvenators was evaluated. Two different rejuvenators were considered in this task, namely, aromatic extracts, and tall oil. Those rejuvenators have shown promising results in previous studies. The recommended dosage of 10% of the RAP binder content was used. The evaluation included spraying each recycling agent on the RAP material with the specified dosage before heating it. Gyratory specimens of the obtained RAP mixtures were prepared at two target air voids of 7%. Indirect tensile strength (IDT) test were performed on the prepared specimens in accordance with AASHTO T283 at a temperature of 25°C using a loading rate of 50 mm/min. The load as well as the vertical and lateral deformations was continuously recorded. IDT test results were analyzed to determine the indirect tensile strength (ITS). The AASHTO T 283 (modified Lottman) test was used to evaluate the moisture susceptibility of the prepared specimens. At least six specimens were tested. The specimens were split into two groups: unconditioned (dry) samples and conditioned (wet) samples. The wet conditioned samples were first partially saturated in a water bath with vacuum to achieve 70% to 80% saturation. Each sample was then wrapped in plastic and placed in a plastic bag with 10 ml of water in it. The samples were then placed in an environmental chamber that was set at a temperature of 0°F (–18°C) for 17 hours. After that, the samples were placed in a water bath with a temperature of 140°F (60°C) for 24 hours. The water bath temperature was reduced to 77°F (25°C) 2 hours prior to testing. The IDT test was conducted on the dry and conditioned wet samples. The ratio between average indirect tensile strengths of the wet conditioned samples to that of the dry samples was computed. This ratio is typically known as the tensile strength ratio (TSR).

A.2 Descrption of Field Test Section

Field test sections were constructed in ODOT Monroe County and ODOT Vinton County to evaluate the different berm material alternatives that were identified based on the laboratory tests conducted and the different methods recommended in Phase 1 of this study. Eight berm test sections were constructed in the week of August 27th 2018 on State Route (SR) 800 in ODOT Monroe County to evaluate the different alternative materials and methods for the berm construction and repair. Figure A.2 provides the layout for the constructed test sections. The sections were about 400 ft long. The constructed test sections were:

- Section 1 (control section): The berm was established using current method, equipment and materials used by ODOT Monroe County.
- Section 2: The berm was established using an alternative compaction and placement method that involves modifying current ODOT process by using a Roadwidener box attached to a skid steer to spread and place the current berm material as well as using an offset vibratory roller attachment on a skid steer to compact the placed berm materials.
- Section 3: The berm was established using the same method and equipment as in Section 2, but ODOT Item 304 aggregates (without any millings) was used.
- Section 4: The berm was established using the same method, material, and equipment as in Section 3, but a CSS-1hm emulsion was sprayed on the compacted berm material.
- Section 5: The berm was established using the same method and equipment as in Section 2 but using a mix of RAP and CSS-1hm emulsion that was produced using Bagela BA10000 recycler.
- Section 6: The berm was established using the same method and equipment as in Section 2 but using recycled asphalt pavement (RAP) mix that was produced using Bagela BA10000 recycler.
- Section 7: The berm was established using the same method and equipment as in Section 2 but using RAP mix with an aromatic extract rejuvenator produced using Bagela BA10000 recycler.
- Section 8: The berm was established using the same method and equipment as in Section 2 but using RAP mix with No. 57 aggregates produced using Bagela BA10000 recycler. The No. 57 aggregates was added after RAP is heated and was mixed with RAP at a proportion of 3 part RAP to 1 part No. 57 (3:1).

Four berm test section were also constructed on October 22nd, 2018 on SR 160 in ODOT Vinton County to evaluate the different alternative materials and methods for the establishing berms. Figure A.3 provides the layout for the constructed test sections in Vinton County. The constructed test sections were:

- Section 1: The berm was established using the same method and equipment as in Monroe County Section 2 but using a mix of RAP and CSS-1hm emulsion that was produced using Bagela BA10000 recycler.
- Section 2: The berm was established using the same method and equipment as in Section 2 but using RAP mix that was produced using Bagela BA10000 recycler.
- Section 3: The berm was established using the same method and equipment as in Section 2, but ODOT Item 304 aggregates (without any millings) was used.
- Section 4 (control section): The berm was established using current method, equipment and materials used by ODOT Monroe County.

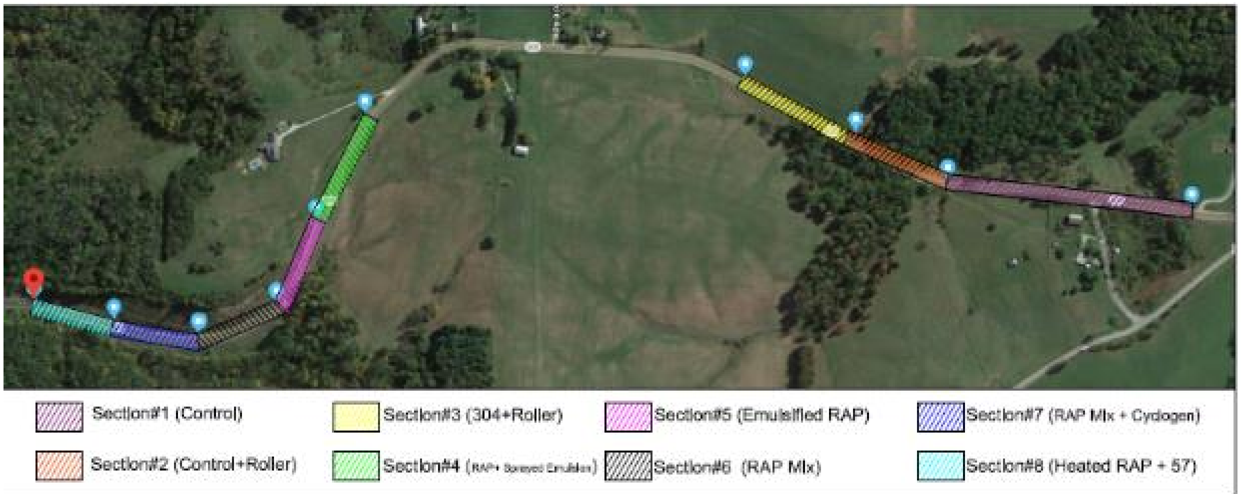


Figure A.2 Layout of test section on SR 800 in ODOT Monroe County

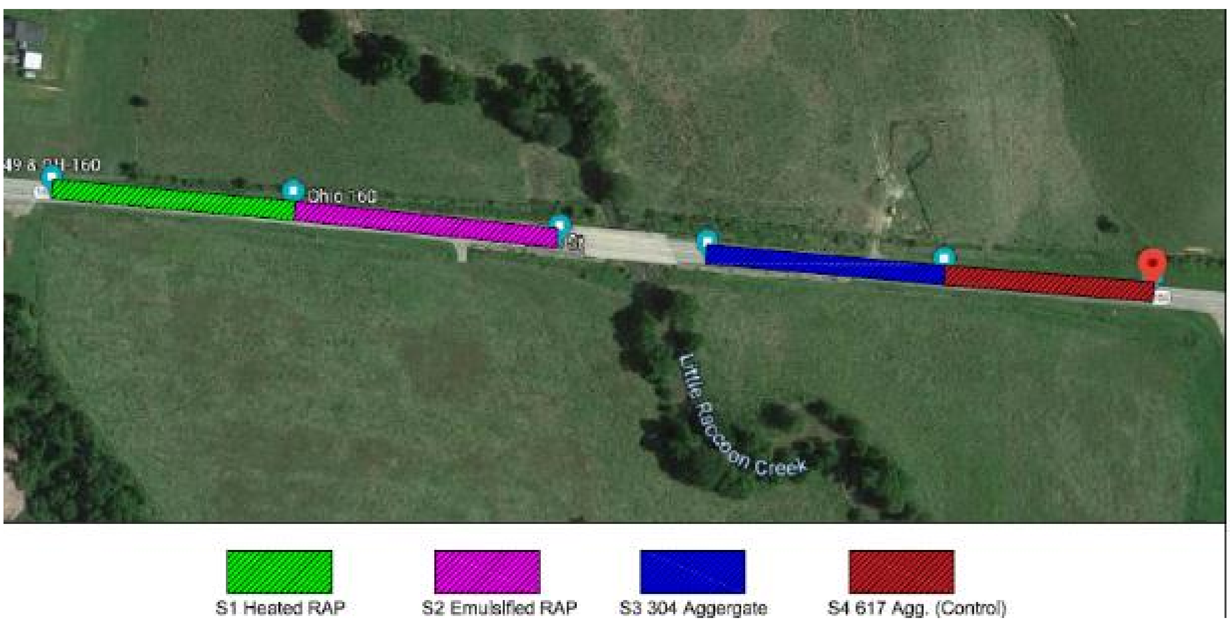


Figure A.3 Layout of test section on SR 160 in ODOT Vinton County

For each test section, the following information and data were recorded during the berm placement and compaction: exact location of each test section, time and date of compaction, berm material type and volume used, climatic conditions, equipment used for placing and compacting the berm, duration of berm placement and compaction, and number of workers in maintenance crew involved in berm construction. Prior to constructing the berm, the stiffness of existing materials was evaluated using the Light Falling Weight Deflectometer (LWD). LWD was also used during compaction to determine the number passes needed by offset vibratory roller to achieve the optimum stiffness for unbound granular materials. Based on that it was determined that three passes of the offset vibratory roller was needed for unbound aggregate material. LWD was also conducted to determine the stiffness of berms after completion of compaction. Videos and photographs were also taken to document the berm compaction and placement process. Figure A.4

presents some of the pictures taken during construction of test sections. All available information regarding the cost of constructing berm test sections were also obtained for use in the cost analyses conducted in this study.

Figure A.4 Pictures taken during construction of berm test section in Monroe County

A.2 Other Field Trials

Field trials were also performed to evaluate the different applications of the RAP mixes produced using Bagela BA10000 recycler. To this end, RAP mixes were used to repair the berm and road edges on several locations on SR 145 in August 2018. Figure A.5 presents some of the pictures of repaired area. RAP mixes were also used to patch potholes on SR 255 in March 2019. Figure A.6 presents some of the pictures of the installed patches.

A.4 Field Evaluation of Constructed Test Sections

A field testing methodology was developed to evaluate the performance of the constructed test sections at ODOT Monroe and Vinton counties. The developed field methodology included evaluating the performance of the test sections by the research team for the duration of this project. All field evaluations involved examining the severity and extent of erosion in these sections. In addition, the drop-off in each test sections was evaluated. The stiffness of each test sections was evaluated after one year of construction using LWD. To this end, LWD was performed on at least 4 locations within each test section.

Figure A.5 Picture of repairs on SR 148

Figure A.5 Picture of repairs on SR 255

A.5 Prediction of Rutting Performance

Analysis was conducted using KENLAYER software to determine the distribution of vertical strain that develop within the different berm sections due to trucks with heavy loads. In this analysis, a tandem axle with 34 kips (maximum allowed load) used. The modulus values that were obtained from LWD tests conducted on the berm test sections were used in the analysis. Damage models are then used to relate the vertical compressive strain, computed from the stress analysis, at the mid-depth of berm and the expected number of traffic applications to plastic strain of each layer. The overall permanent deformation is then computed using Equation A.1 as sum of permanent deformation for each individual sub-layer.

$$PD = \varepsilon_p \times h \qquad \text{A.1}$$

where:

PD = Rutting of the berm

ε_p = Total plastic strain berm

h= Thickness of berm (3 inches)

Three main damage models were used in this study, namely, one for the heated RAP mixes and emulsified RAP mixes (Equation A.2), one for the unbound aggregate berm materials (Equation A.4), and one for existing materials underneath the berm (Equation A.5). The parameters of these models were determined through national calibration efforts using the Long-Term Pavement Performance (LTPP) database, and laboratory tests conducted on the different pavement materials used.

$$\frac{\varepsilon_p}{\varepsilon_v} = k_1 10^{-3.4488} T^{1.5606} N^{0.473844} \qquad \text{A.2}$$

Where

ε_p = Accumulated plastic strain at N repetitions of load

ε_v = vertical strain of the asphalt material

N = Number of load repetitions

T = Berm temperature

k_1 = function of total asphalt layer(s) thickness and depth to computational point, to correct for the variable confining pressures that occur at different depths and is expressed as:

$$k_1 = (C_1 + C_2 * \text{depth}) * 0.328196^{\text{depth}} \qquad \text{A.3}$$

Where

$C_1 = -0.1039 * h_{ac}^2 + 2.4868 * h_{ac} - 17.342$

$C_2 = 0.0172 * h_{ac}^2 - 1.7331 * h_{ac} - 27.428$

h_{ac} = is the asphalt layer thickness

$$\frac{\varepsilon_p}{\varepsilon_v} = \beta_{GB}\left(\frac{\varepsilon_o}{\varepsilon_r}\right) \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \qquad \text{A.4}$$

$$\frac{\varepsilon_p}{\varepsilon_v} = \beta_{SG}\left(\frac{\varepsilon_o}{\varepsilon_r}\right) \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \qquad \text{A.5}$$

Where

β_{GB} = is national model calibration factor for unbound base course material and is equal to 1.673

β_{SG} = is national model calibration factor for subgrade material and is equal to 1.35

ε_0, β, and ρ = Material parameters

ε_r = Resilient strain imposed in laboratory test to obtain material properties

A.6 Cost Analysis of Alternative Processes

The cost of materials, labor and equipment used for construction of test sections was obtained from ODOT Monroe and Vinton County garages. Equation A.6 was also used to determine the hourly rate of the offset vibratory roller and the Roadwidener berm box. Table A.1 presents the computed and obtained hourly rates used in different alternatives.

$$A = \frac{P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] + S\left[\frac{i}{(1+i)^n - 1}\right] + AMC}{NHY} \qquad \text{A.6}$$

Where;

A: Equivalent annual value

P: Purchase value
S: Salvage value
n: Service life of the equipment
i: Interest rate
AMC: annual maintenance cost
NHY: expected number of hours per year.

The cost of producing RAP mixes using Bagela BA10000 recycler was calculated for each county. Tables A.1-2 show the costs of equipment, labor, and materials that were included in this calculation as well as all assumption made. Based on information shown in this table, it was estimated that the cost of produced RAP mixes using Bagela BA10000 recycler ranged between \$18.0 and \$24.5 per ton.

Based on the computed and obtained costs, the initial costs for constructing the different test sections was calculated. Cost analysis (LCCA) was performed to evaluate the life cycle cost of different test sections. The analyses considered the initial cost of berm placement and number of times of the berm need is repaired within the analysis period. An analysis period of five years was used in this study. The service life of different test sections was estimated based on the observed performance during the first year of service. The cost effectiveness of alternative materials and processes to construct berm were evaluated by comparing them to ODOT current process. This was achieved by computing the cost ration using Equation A.7.

$$\text{Cost Ratio} = \frac{\text{Annual Cost}_{\text{new material/method}}}{\text{Annual Cost}_{\text{current method}}} \quad \text{A.7}$$

Table A.1: Hourly rate for equipment included in the analysis

Equipment	Hourly rate	Production rate (miles/hour)	Source
Road widener box	\$4.35	1	Equation A.6
Offset roller	\$5.1	2	Equation A.6

Table A.2: Cost of RAP mixes produced using Bagela BA10000

Item Cost	Heated RAP	Heated RAP+ Rejuvenator	Heated RAP+ No. 57 Aggregate
Capital cost of equipment	\$ 180,000.00	\$ 180,000.00	\$ 180,000.00
Labor cost per hour	\$ 52.46	\$ 52.46	\$ 52.46
Loader hourly rate	\$ 50.00	\$ 50.00	\$ 50.00
Input material per ton	\$ 1.21	\$ 1.21	\$ 7.69
Fuel Cost per gallon	\$ 2.76	\$ 2.76	\$ 2.76
Depreciation Cost (per ton)	\$ 2.56	\$ 2.56	\$ 2.56
Maintenance Cost (per ton)	\$ 0.36	\$ 0.36	\$ 0.36
Total operating cost per ton	\$ 18.03	\$ 18.03	\$ 24.50
Rejuvenator price per kg		\$ 3.00	
Rejuvenator Density (kg/m^3)		930	
Amount of Rejuvenator per ton of RAP (m^3)		0.00095	
Amount of Rejuvenator per ton of RAP (kg)		0.8835	
Cost of Rejuvenator per ton of RAP	\$ -	\$ 2.65	\$ -
Total Cost of RAP mix per ton	\$ 18.03	\$ 20.68	\$ 24.50

Appendix B Results and Analysis

B.1 Reults of Erodbility Labortary tests

The erodibility of two different types of unbound aggregate materials (ODOT Item No. 617 and ODOT Item 304) that can be used by ODOT as berm materials was evaluated at different compaction level using the turbulent flow erodibility test. Figure B.1 presents the results of the average erodibility ratio (ER) that was obtained from conducted tests. It is noted that the lower the ER value the better the resistance of the martials to erosion. It is clear that the erosion resistance of ODOT No. 304 material was much better than ODOT No. 617 material. In addition, the effect of compaction on the erodibility of both aggregates is significant. Such that the compacting the materials to their maximum density obtained in a standard proctor results in decreasing the ER value and increasing the erodibility resistance. The improvement was more significant in the ODOT No. 304 aggregates.

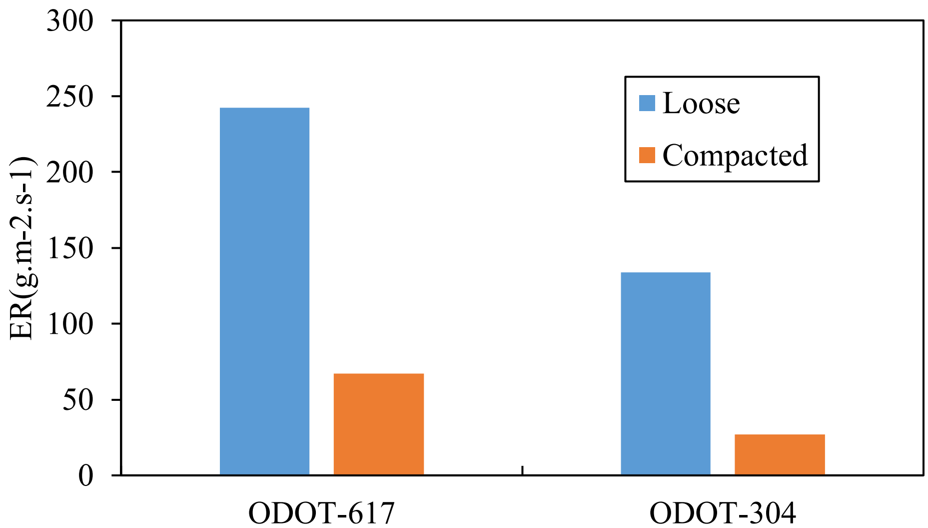


Figure B.1 Erodibility of unobund berm materials

The use of heated RAP material was one of the alternatives identified in Phase 1 to improve the performance and service life of berm materials. Erodibility tests were conducted on RAP materials that were unheated as well as heated to two different temperatures and then compacted to determine the minimum heating temperature to be used in the field. The temperatures used were 55°C and 100°C. Figure B.2 presents the ER ratio for the RAP material heated to different temperatures. It is clear that the unheated RAP material has much higher ER value and thus significantly lower resistance to erosion than ODOT No. 617 and ODOT No. 304 materials. This suggested that unheated RAP materials should not be used for berm. Heating the materials to 55°C will improve the erosion resistance significantly; however, the best resistance to erosion will be achieved at a temperature of 100°C. This result suggest that compaction temperature of heated RAP material should be at least 100°C.

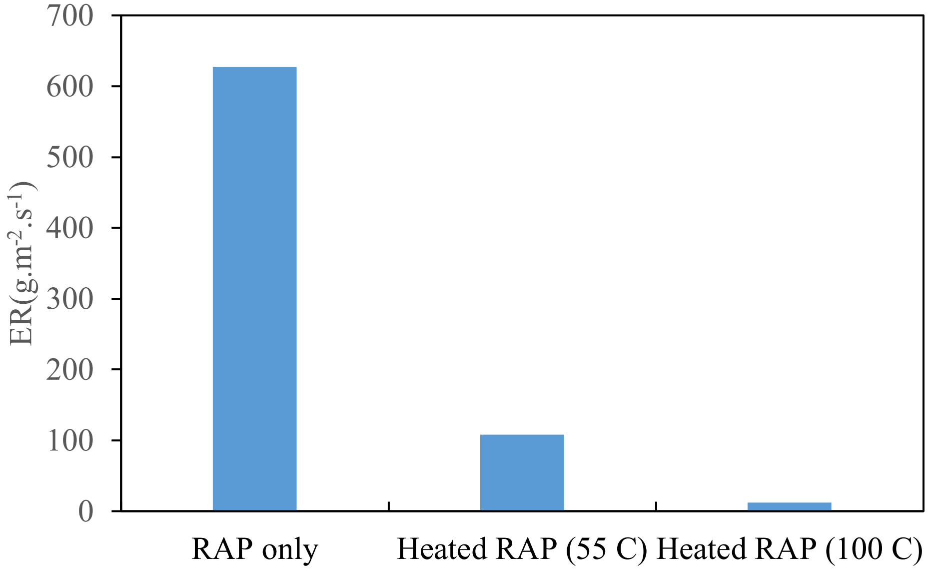


Figure B.2 Erodibility of heated RAP material

Phase 2 of this study also explored the use of emulsified RAP material for berm. Emulsified RAP materials are RAP materials that are mixed with an emulsion to form a mixture after curing. RAP materials obtained from ODOT county garages were mixed with four different emulsion contents: 2%, 3, 3.5%, and 4%. Emulsified RAP mixes were compacted and tested. Figure B.3 presents the ER ratio for the emulsified RAP mixes prepared using different emulsion contents. It is clear that increasing the emulsion have improved the RAP material resistance to erosion significantly, particularly when the emulsion content is more than 3%. Based on the results, the optimum emulsion content is between 3 and 3.5%.

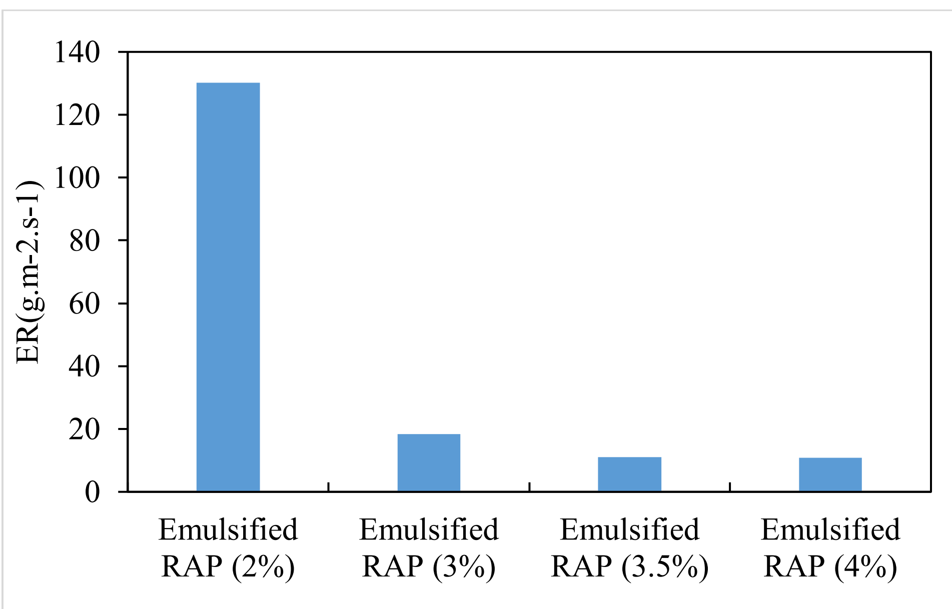


Figure B.3 Erodibility of Emulsified RAP material

B.2 Results of Laboratory Evaluation of Effect of rejuvenator on Durability of RAP Mixes

Indirect tensile strength (IDT) tests were conducted on dry and wet conditioned samples of the RAP mixes with two different rejuvenators at 25°C. Figure B.4 presents the average ITS values for tested samples. It is noted that the average ITS value for the dry samples of the RAP mix with aromatic extract rejuvenator was higher than 100 psi, which is the value recommended for mixes with acceptable tensile strength. However, RAP mix with tall oil rejuvenator had an average ITS value less than 100 psi for dry samples. This indicates that the tall oil has significantly softened the RAP mix, which might suggest it affects its cracking resistance. The wet conditioning resulted in lowering the ITS values of the samples of both mixes. However, the decrease in the ITS was slightly more in the mix with the tall oil rejuvenator. The tensile strength ratio (TSR), the ratio between average indirect tensile strengths of the wet conditioned samples to that of the dry samples, was computed. The average TSR values for the considered mixes are shown from Figure B.5. It is noted that all mixes exceeded the TSR limit set by ODOT at 80%, which indicates adequate resistance to freezing and thawing and thus, good durability. Based on the obtained results the aromatic extract rejuvenator was selected to be used in the RAP mixes for the field test section.

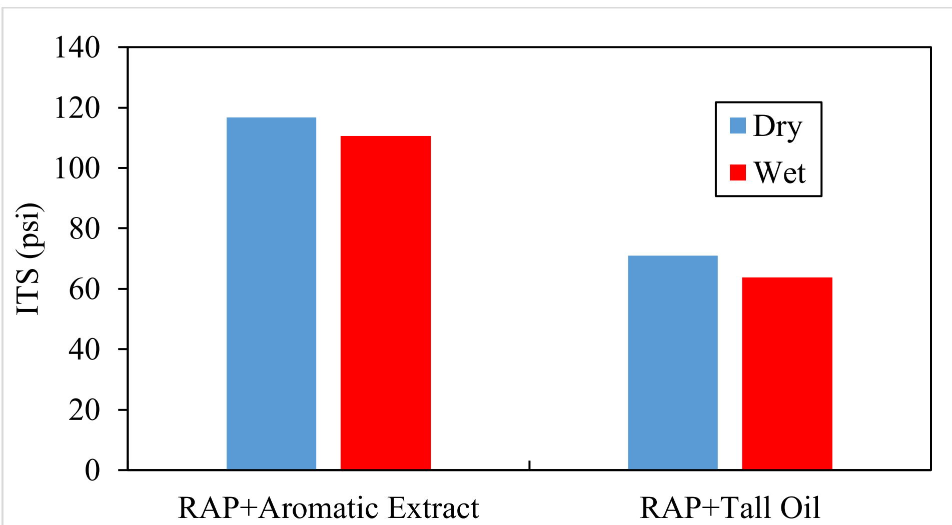


Figure B.4 ITS test results for RAP mixes

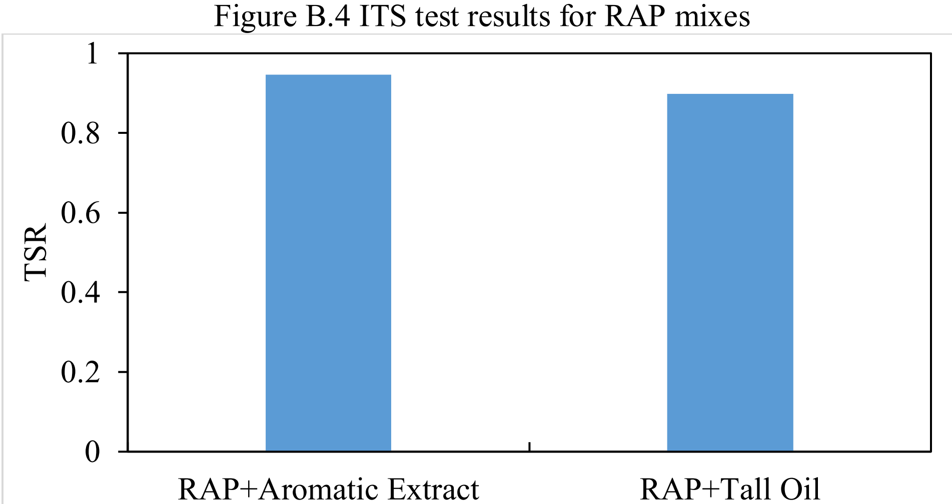


Figure B.5 TSR of RAP mixes

B.3 LWD Modulus After Contruction

Figure B.6 presents the average LWD modulus values of the berm test sections in ODOT Monroe County, which were back-calculated from the results of LWD tests conducted directly after construction. It is noted that sections with alternative berm materials and construction methods had higher modulus values than the control section, Section 1. This indicates that these materials and methods improved the stiffness of berm. The highest improvement was in sections that had heated RAP mixes followed by the section with emulsified RAP material. Section 6 had the highest modulus value among all sections. It is noted that Section 4 (wet), which had water sprayed prior to compaction, had higher modulus than Section 4. This suggests that adding water to unbound aggregate berm materials might be needed to achieve proper berm compaction, when the moisture content of these materials is much lower than their optimum moisture content.

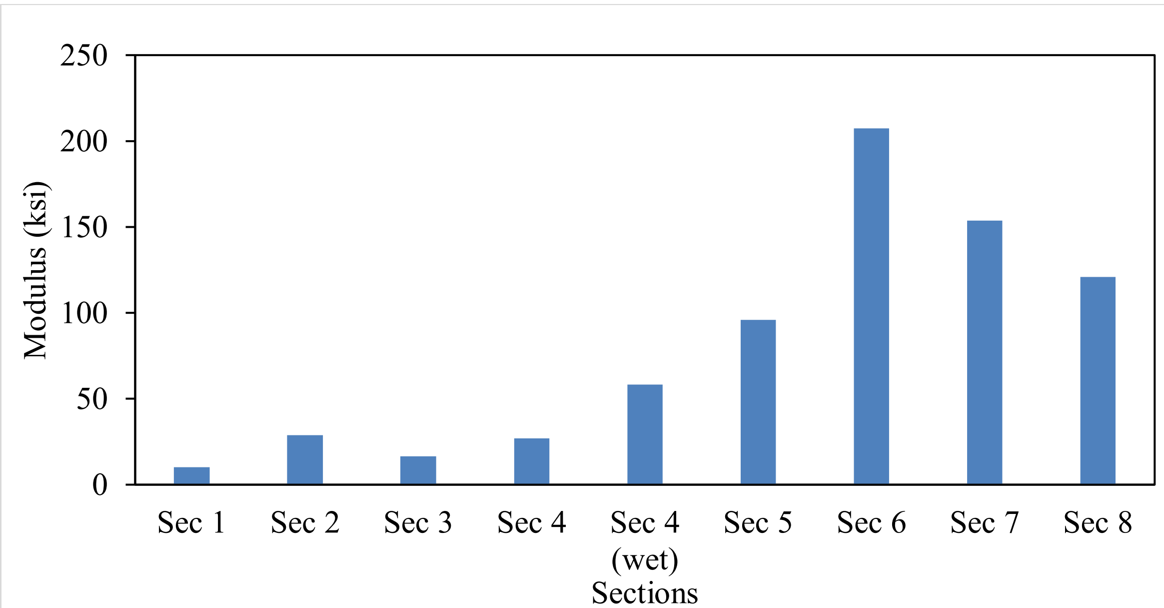


Figure B.6 LWD Modulus values for Monroe test section directly construction

Figure B.7 presents the average LWD modulus values of the berm test sections in Vinton County. It is noted that sections with alternative berm materials and construction methods had, in general, higher modulus values than the control section, Section 1. As for the section in Monroe County, the highest improvement was in sections that had heated RAP mixes. The section with emulsified RAP material had lower modulus values than those observed in Monroe County. This might be explained by fact that the lower temperatures during and after construction, which might have affected the curing of the emulsion in the emulsified RAP mix in Vinton County. The lower modulus of layer underneath the berm in this section might also contributed to the lower stiffness measured using the LWD.

B.3 Performance Evaluation

Periodical field evaluations were conducted during the first year of service of the berm test sections constructed at ODOT Monroe and Vinton counties. The evaluation included the level of erosion and drop-off that occurred in berm test section. The following sections summarize the results of field evaluation for each test section.

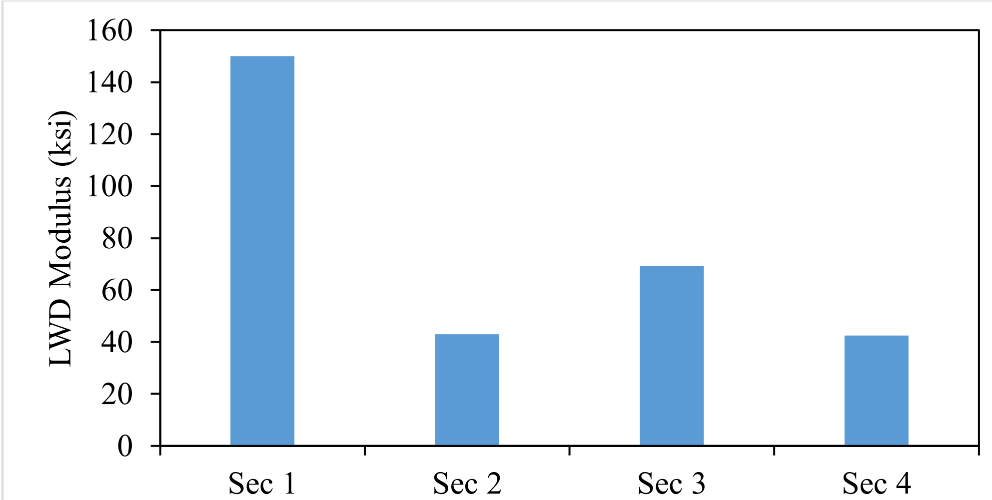


Figure B.7 LWD Modulus values for Vinton test section directly construction

B.3.1 Field Evaluation of Monroe Test Sections

Section One

This section is the control section which incorporates the using of limestone Item #304 mixed with RAP material. Berm materials were poorly placed and were not well compacted during the construction process. Berm materials were loose and soft after construction. After one month, the surface aggregate moved sideways. However, minor signs of drop-off and no erosion problems were noticed in the first-month evaluation. After four months, there were rutting caused by truck traffic. In addition, fines materials were washed out and eroded, and a drop-off with up to 1 inch were noticed in this section. As shown in Figure B.8c there was a failure in this berm test section at one spot. At this spot there was significant loss of the berm materials and pavement edges were broken due to lack of support from the berm. After seven months, the berm materials became looser and more fines of material were eroded. After one year, the drop-off in the berm section was increased and recorded to be more than 1.0 inches. Based on the results of the evaluation, the expected service life for this section was estimated to be less than four months.

Section Two

During the first month, there were no signs of erosion problems except for the outside of the berm next to the water stream which had severe aggregate migration as shown in Figure B.9a. Despite this, the berm materials were more intact compared to section one (control section). After four months, the section noticed to be stiffer and more stable. However, unbound materials and some fine material started to wash out. After seven months, there was a failure in second part of the berm test section (last 200 ft), as shown in Figure B.9b. The berm materials were completely eroded in failing part, and the pavement edges were broken due to lack of support. However, in the first part of section two, there were some signs of berm materials erosion characterized by washing of fine. In addition, the drop-off ranged between 0.25 and 0.5 inch in this part. The failure in the second part occurred in February 2019. The rainfall record was obtained for January, February, and March 2019 for the berm test section area. Table B.1 presents the obtained rainfall record. It is clear that during February 2019 the weekly rainfall was greater than 4 inch and the daily was more than 1.25 inch. This may suggest that a weekly rainfall more than 4 inch may result in significant flow rate that may cause erosion. It is worth noting that grade changed within the second part of section two from negative to positive indicating that this part was placed on a valley, Figure B.10. The failed part of berm section 2 was repaired using the heated RAP. It is noted that after three months of service the repaired part had no erosion or any damage, Figure B.9f. After one year, the berm materials became very loose and the drop-off along the edge increased and reached up to 1.5 inches. Additionally, pavement edges were broken due to lack of lateral support. The service life for this section was estimated to be about seven months.

Figure B.8 Pictures from section one evaluation after: a. One month b. Four months b. Four months (Failed section) c. One year

Figure B.9 Pictures from section two evaluation after: a. One month b. Four months c. Six months (first part of section) d. Six months (second part of section) e. One year f. 3 months (Repaired part

Table B.1 Rainfall record Jerusalem, OH

Parameter	January 2019	February 2019	March 2019
Total Monthly rainfall (in)	2.55	5.71	1.98
Maximum Weekly rainfall (in)	1.99	4.07	1.17
Maximum Daily rainfall (in)	0.87	1.38	0.45

Figure B.10 Slopes of section 2

Section Three

The berm material had no significant erosion or drop-off problems after one month of service, Figure B.11. However, a very small amount of washed out aggregate and migrated to the pavement. After four months, there was some signs rutting along the wheel path. The surface aggregate was loose, which is considered to be the first signs of erosion. In addition, drop-off depth was about 0.5 inches in few spots along the section. After seven months, a rutting increased and there were signs of a tractor wheel along the section. The drop-off depth reached up to 1.0 inch in few spots. After one year, there was significant erosion of fine materials, which caused the drop-off depth to increase to about 1.25 inches. In addition, cracks along the pavement edge were noticed due to the lack of support. As a result, the service life for this section was estimated to be less than one year.

Section Four

This section did not have any erosion or drop-off after one month. In addition, the berm material seemed to be stiffer than it was directly after the construction. There were no apparent differences in the performance between the wet and dry compacted parts of the section. The materials were loose and soft after four months of construction, Figure B.12b. In addition, some of the loose materials started to migrate towards the sideways of the section. A drop-off of up to 0.25 inches was observed in some spots of the berm. After one year, the berm material became looser, which resulted in some erosion and increase in the depth of the drop-off along the edge, which was found to be on average about 0.5 inches along the section but reached up to 2.0 inches in few locations. In addition, cracks developed along the pavement edges, which was caused by lack of support from the berm. The service life for this section was estimated to be one year.

Figure B.11 Pictures from section three evaluations after: a. One month b. Four months b. Seven months four months c. one year

Figure B.12 Pictures from section four evaluations after: a. One month b. Four months b. Seven months four months c. One year

Section Five

This berm test section had no significant erosion problems or drop-off during the first year of service, Figure B.13. The stiffness of berm materials (emulsified RAP mix) in this section seemed to increase with time; particularly in the first four months. In six months, the section was still stable and stiff without any apparent signs of significant erosion problems. There was a small amount of surface aggregate that stripped out from the berm and started to be loose easily moved on the surface after one year of service. This berm section had clearly better resistance to erosion than the first fours test sections. Based on the evaluation done, the service life for this section is estimated to be at least 2 years.

Figure B.13 Pictures from section five evaluations after: a. One month b. Four months b. Seven months four months c. One year

Sections Six

There was no erosion, rutting, or any drop-off during the first of year of service. Although there was a water stream next to berm test section, there was no erosion issues in the section. In general, the berm looked like a newly paved road, Figure B.14. However, some minor problems related to poor construction and not placing enough berm materials at few spots. Sections provided adequate lateral support to the pavement. Observing that, section seven was getting more stiffness, which found to be more durable than sections 6 and 8. There was low level raveling in the section 6 after one year of service. Based on evaluation done on this test section, it is estimated that the service life will be more than three years.

Figure B.14 Pictures from section six evaluations: a. One month b. Four months c. one year

Section Seven

As shown in Figure B.15, this section had very similar performance to the test section six. However, the section did not show any raveling after one year. Therefore, the service life of this section might be slightly better than section six.

Section Eight
There was a low-level erosion after one year of service, which results in drop-off less than 0.25 inches in some segments in this section. This section seemed to be less durable than sections six and seven, as shown in Figure B.16. Some of aggregates have started stripping out from the berm after one year of service, but this did not affect the performance. It is estimated that the service life of this section to be less than three years.

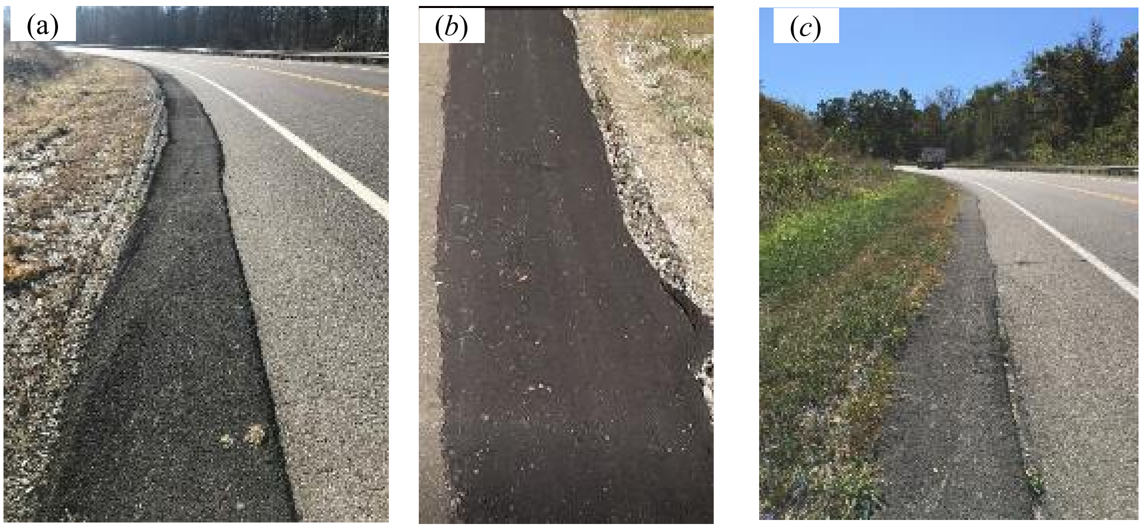


Figure B.15 Pictures from section seven evaluations: a. One month b. Four months c. One year

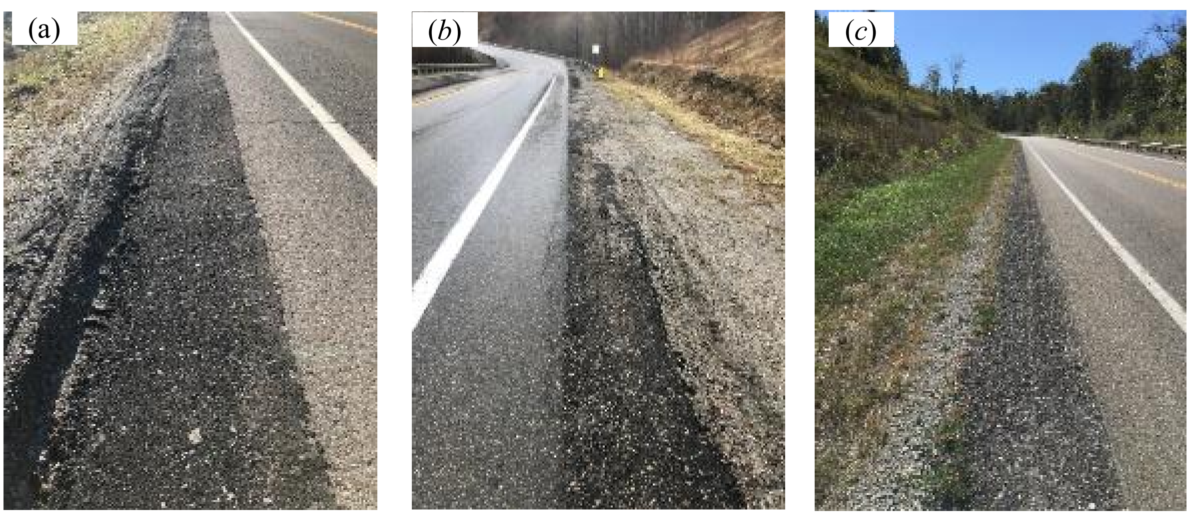


Figure B.16 Pictures from section eight evaluations: a. One month b. Four months c. One year

B.3.2 Field Evaluation of Vinton Test Sections
Section One
As shown in Figure B.17 During the first one year, there was no significant erosion or drop-off, and the berm was stiff and stable. However, there were some issues during the construction of the first 150 ft of the section which resulted in compacting the RAP mix at temperatures lower than

100°C. These issues might contributed to the development of some cracks on the surface after six months in that portion of this section. After one year, loose materials moved from the unpaved side to the surface but did not cause any problem to the berm. Therefore, the service life for this section is estimated to be 2.5 years.

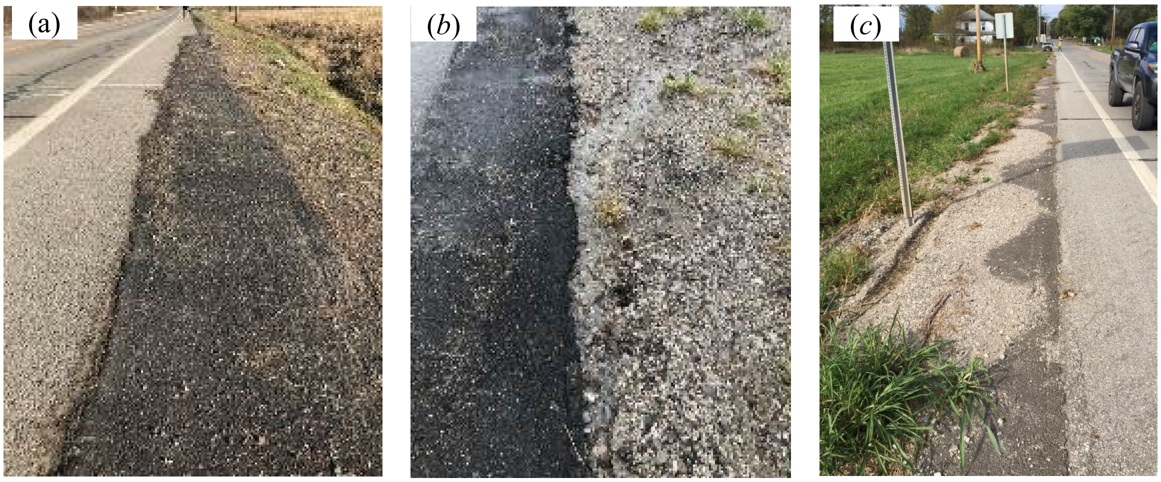


Figure B.17 Pictures from section one evaluations: a. Two months b. Six months c. One year

Section Two

The test section had no significant erosion or drop-off problems during the first year of service, Figure B.18. The berm materials seemed to gain strength with time. There was some low-level raveling. Loose materials stripped from the berm to the surface, which resulted in a drop-off with a depth of 0.25 at some spots. Concluded from that, the service for this life is estimated to be at least two years.

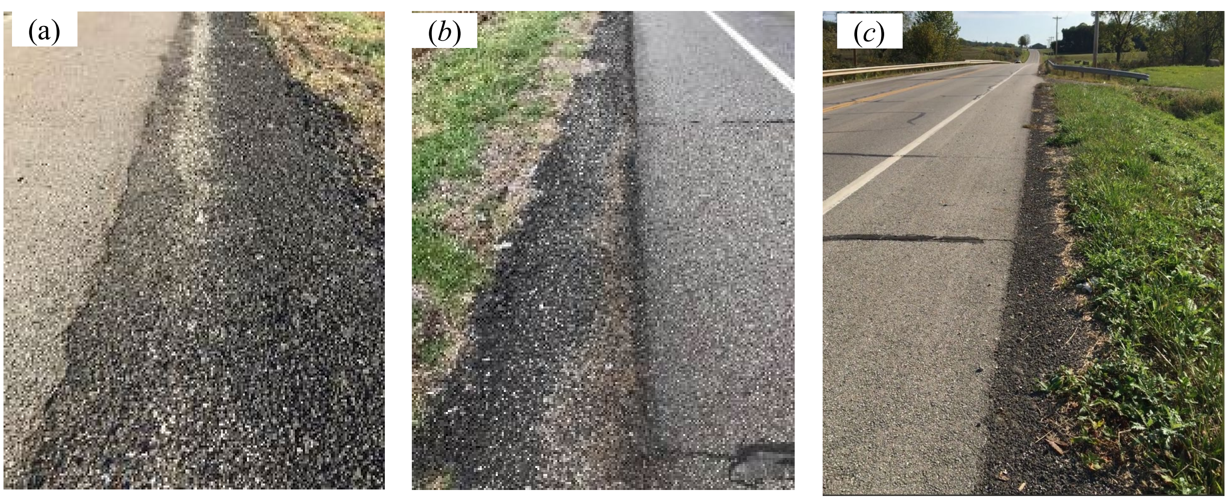


Figure B.18 Pictures from section two evaluations: a. Two months b. Six months c. One year

Section Three

This section had two parts. The first part (250 ft) of test section was constructed on a culvert. The second part (150 ft) was constructed on natural soil with a slope. After two months of service, some of the fine were eroded and migrated to the sides. However, there was no significant erosion or drop-off issues. After one year of service, the part that constructed on the culvert was found to be stiff and stable. However, some of the berm materials on the area with slope were eroded by the water runoff, which resulted in a drop-off of depth of more than 1 inch.

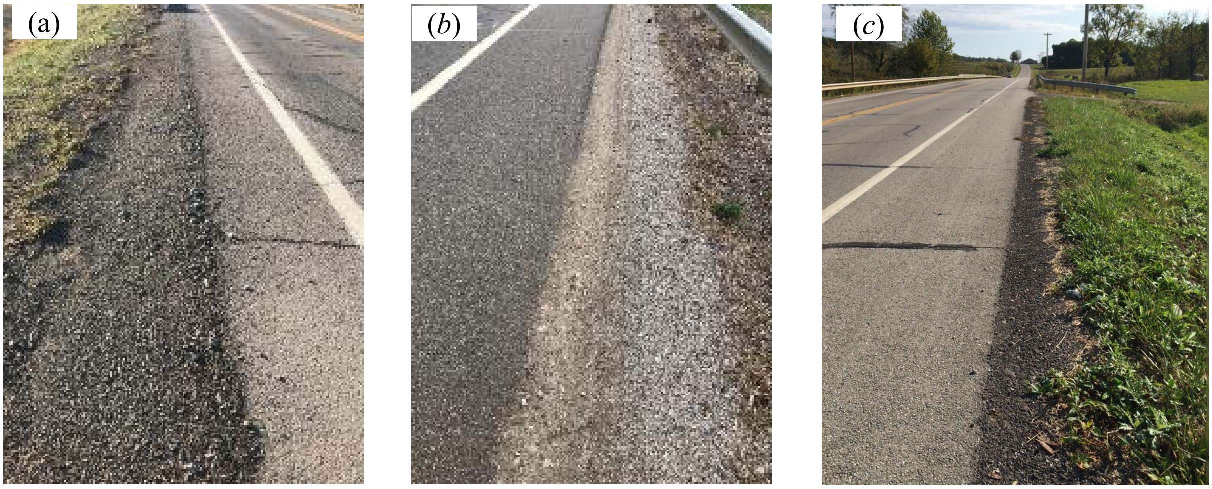


Figure B.19 Pictures from section three evaluations: a. Two months b. Six months c. One year

Section Four

This test section is the control section. It was constructed on area with a slope. As shown in Figure B.20, The berm material was loose due to erosion after two months of service. There was a drop-off of 0.25 inches along the entire berm edge. Also, signs for truck or tractor wheel observed in some spots. In the later evaluations, it was found that the section had a significant drop-off problem. After one year, the drop-off was more than 1.5 inches. It was clear that this section was more susceptible to erosion than the other three sections. It is estimated that the service life for this section to be six months.

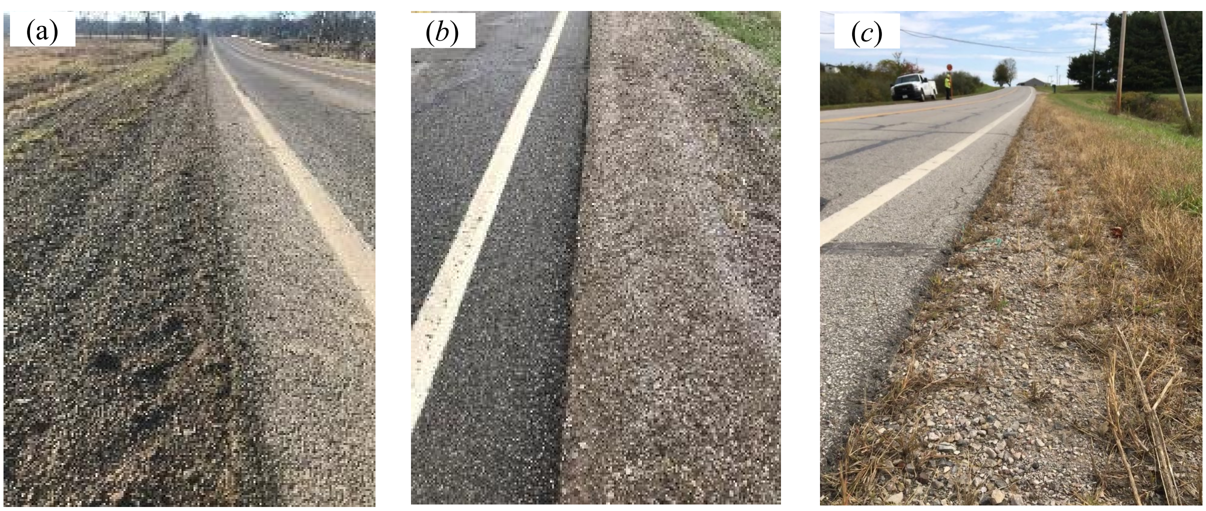


Figure B.20 Pictures from section four evaluations after: a. Two months b. Six months c. One year

B.4 LWD Modulus After one Year

Figure B.21presents the average LWD modulus values of the berm test sections, which were back-calculated from the results of LWD tests conducted after one year of construction. It is noted that section 2 had the same material as the control section but was compacted using the off-set vibratory roller had a higher modulus value after one year of construction, which was similar to what was observed directly after construction. In addition, the sections three and four with #304 material had much higher modulus values than the control section. It is noted that both sections had a significant increase in stiffness during the first year of service, which might be attributed to higher compaction that they might encountered from truck traffic. Section four had slightly higher modulus values than section three, which might be attributed to the emulsion that was sprayed on top of compacted berm material. Section five had significantly higher modulus values than that of section four. In addition, section five stiffness significantly increased with time and became very close to those with the heated RAP mixes (i.e. Section 6-8). All sections with the heated RAP mixes, had very high modulus values, but section seven (with the rejuvenator) had the highest modulus values. This might indicate that this section did not have any internal damage (i.e. crack initiation), which is attributed to the use of rejuvenator.

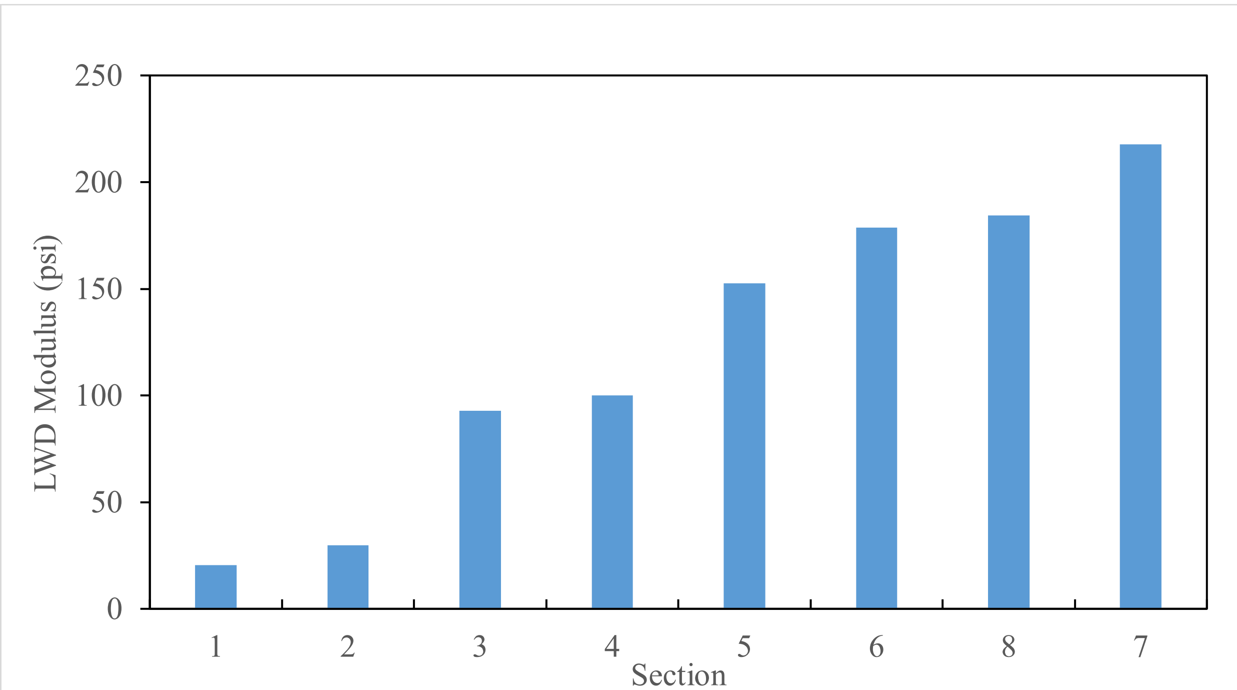


Figure B.21 LWD Modulus values for Monroe test section after one year of service

B.5 Rutting Performance Prediction

As rutting due to heavy truck traffic is a concern for test sections in ODOT Monroe County, the rutting was predicted for 5 years of service life. To achieve this, the LWD modulus was used to determine the vertical strains that will develop in the different test section due to truck traffic with maximum axle load of 34 kips. The computed vertical strain was used to compute the rutting. Figure B.22 presents the computed rutting in the berm test sections. It is clear that sections with current berm materials will result in rutting more than 3 inches. The use of ODOT No. 304 compacted using the offset vibratory roller will reduce the rutting to less than 1 inch. Finally, using emulsified RAP mixes or heated RAP mixes will result in rutting less than 0.5 inch. The lowest rutting will develop in the section with heated RAP mix that includes rejuvenator.

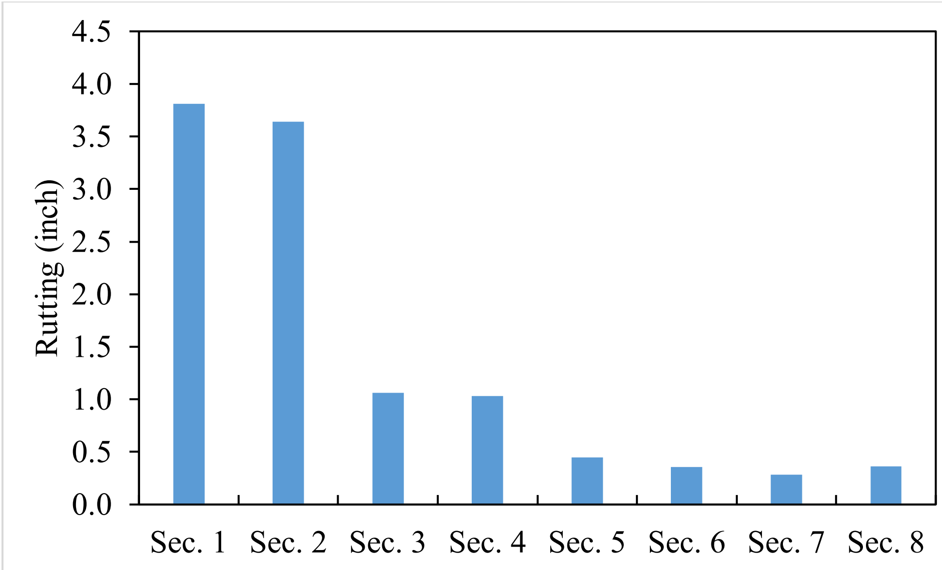


Figure B.22 Predicted rutting values for Monroe test section

B.6 Cost Amalysis

B.6.1 Initial Cost

All available cost information for construction of test sections was obtained from ODOT Monroe and Vinton County garages. Figure B.23 presents the construction cost for the test section in ODOT Monroe County. It is noted that all sections had similar cost to that of control section except sections three, four, and five. Section three had a higher cost since the ODOT item No. 304 cost much more than the berm material currently being used. In addition, section five's higher price was attributed to the long time it took to produce the emulsified RAP material using the recycler; mainly since the recycler has not been used for this application before. Figure B.24 presents the construction cost for the test section in ODOT Vinton County. It is noted that alternative sections had slightly higher cost to that of control section. Section three had the highest cost, which might be attributed to higher cost of the ODOT item No. 304 as compared to the berm materials currently being used.

B.6.2 Life Cycle Cost for Monroe Test Sections

To compute the life cycle costs of the Monroe test sections, the service life was estimated based on the observed performance of the test sections during the first year of service. Figure B.25 presents the estimated service life. It is noted that service life is estimated for areas with typical and heavy rainfall that results in high flow rate causing more erosion. The annual cost for test sections was computed based on the estimated service life. Figures B.26 and B.27 present the computed annual costs of sections for typical and heavy flow rate cases, respectively. It is clear that all alternative berm materials/methods resulted in significantly reducing the annual cost of berms. The highest reduction was obtained for sections with heated RAP. It is clear that the annual cost of test sections is higher for the heavy flow rate case. However, the control section had much higher increase in cost as compared to the other sections. The cost ratio was calculated for different sections and cases to quantify the benefits of different alternative berm materials and construction methods. Figures B.28 and B.29 present the computed cost benefit ratio for typical and heavy flow rate cases, respectively. It is noted that using the current berm material with the berm box and off-set vibratory roller will result in at least 40% reduction in annual berm cost due the increase in the service life. However, the cost ratio will be reduced to less than 20% in the heavy flow rate case. Emulsified RAP material will result in reduction in cost by 70% for regular flow rate case. In addition, the benefits will be improved for the heavy flow rate case. The heated RAP mixes will result in at least 90% reduction in annual cost of berms.

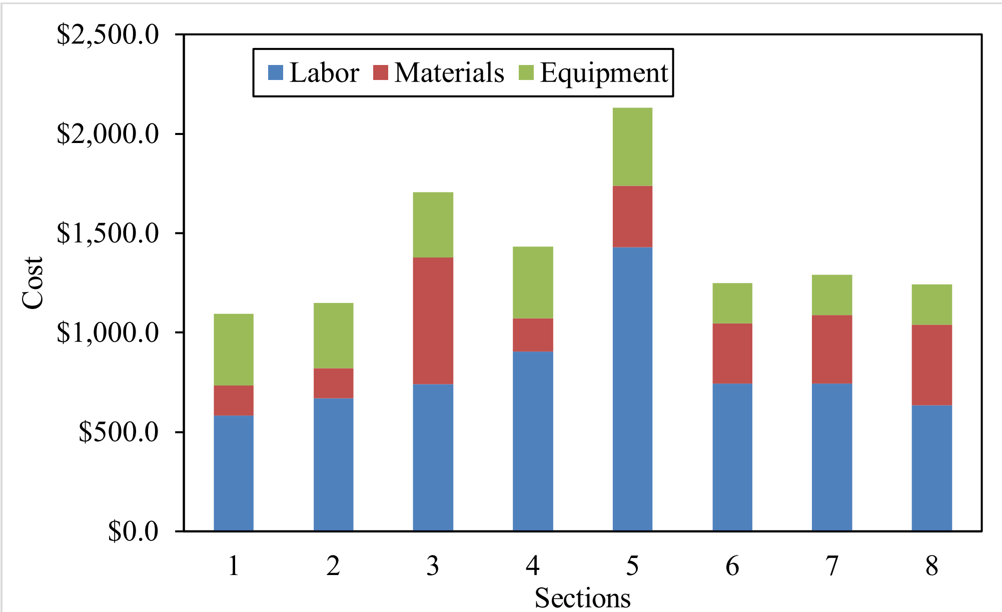


Figure B.23 Cost of construction for Monroe test section

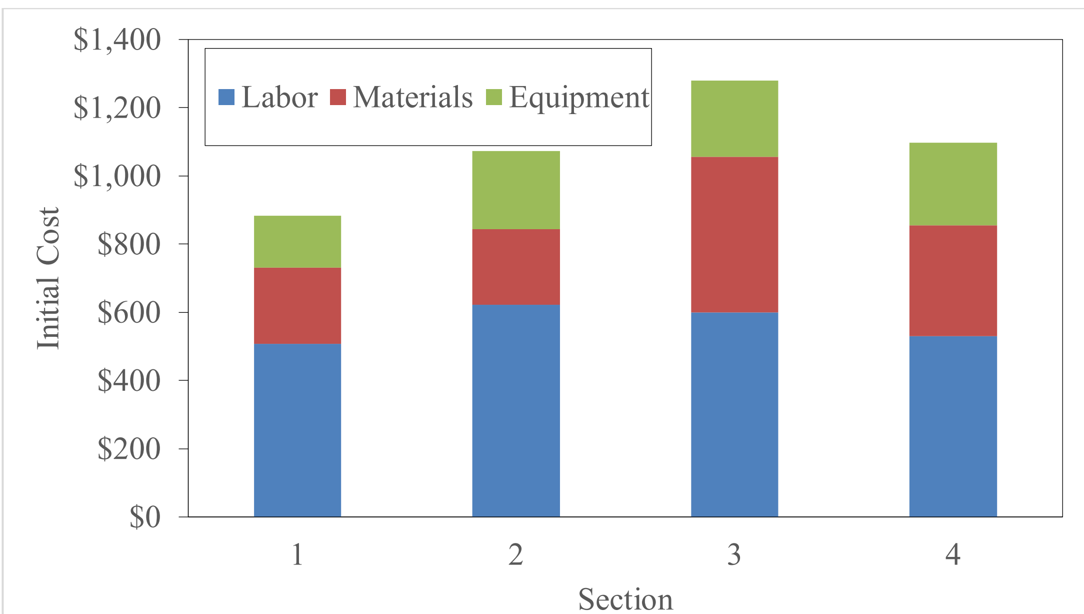


Figure B.24 Cost of construction for Vinton test section

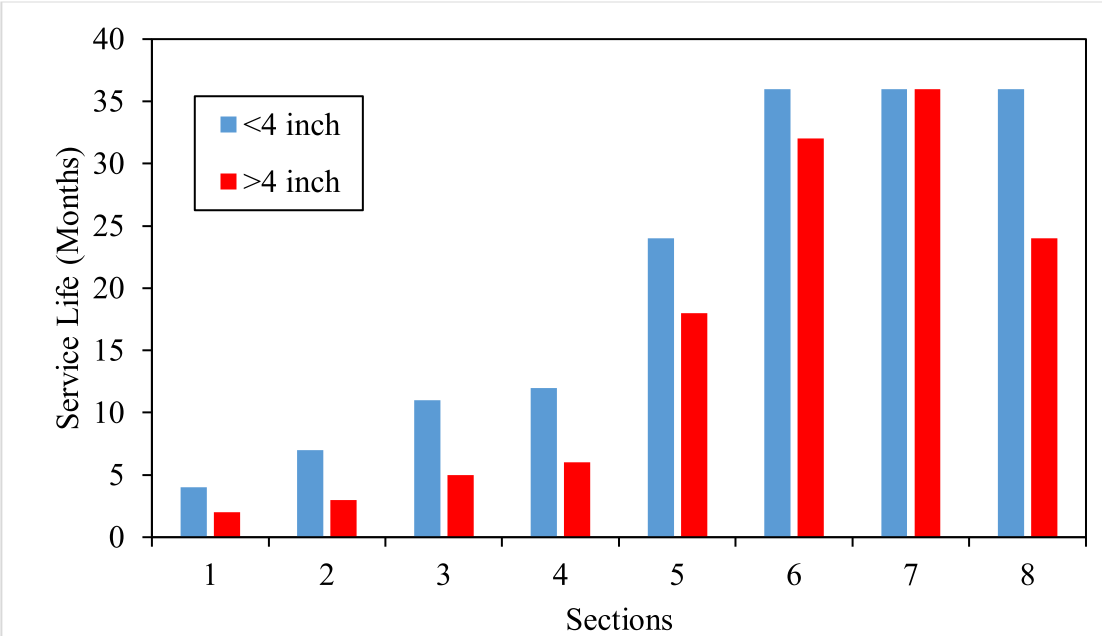


Figure B.25 Estimated service life for Monroe test section

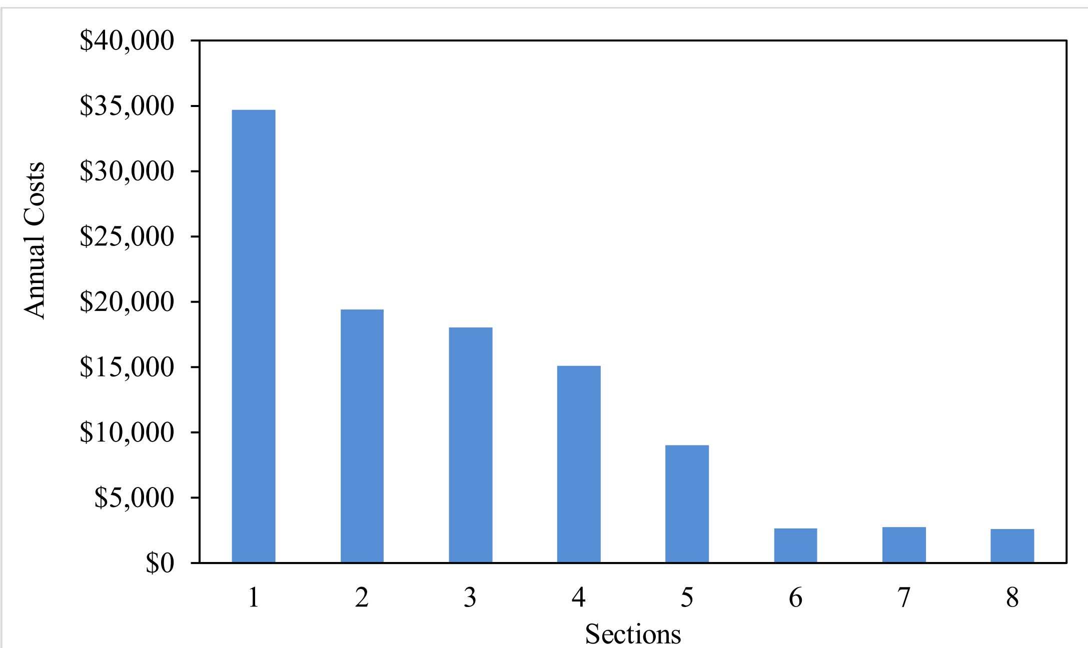


Figure B.26 Estimated annual costs for Monroe test section- typical rainfall

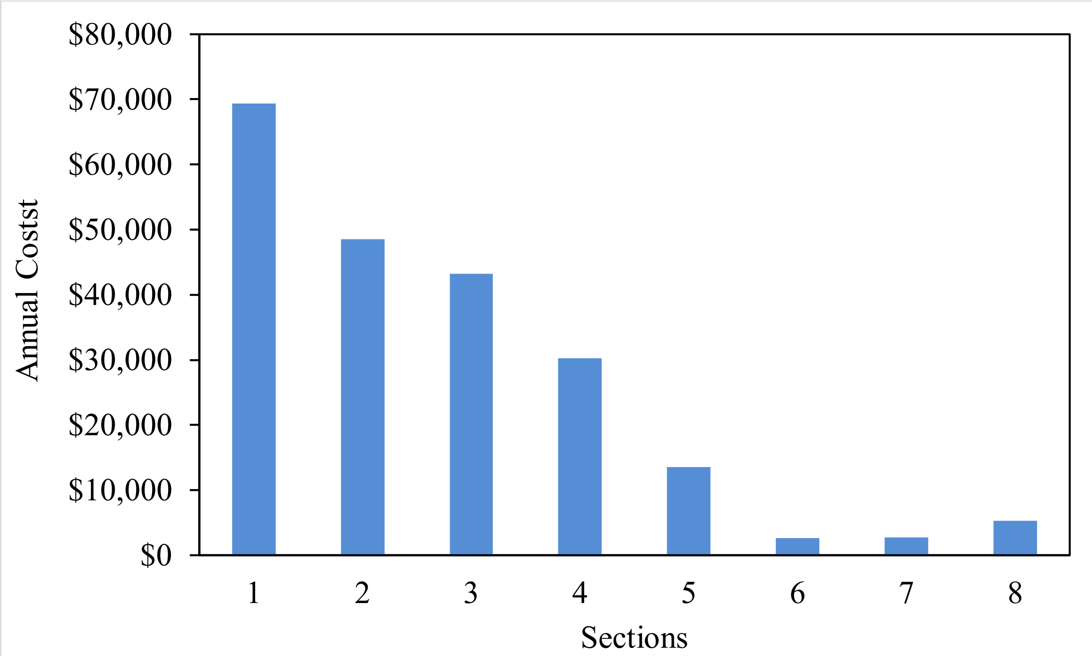


Figure B.27 Estimated annual costs for Monroe test section- heavy rainfall

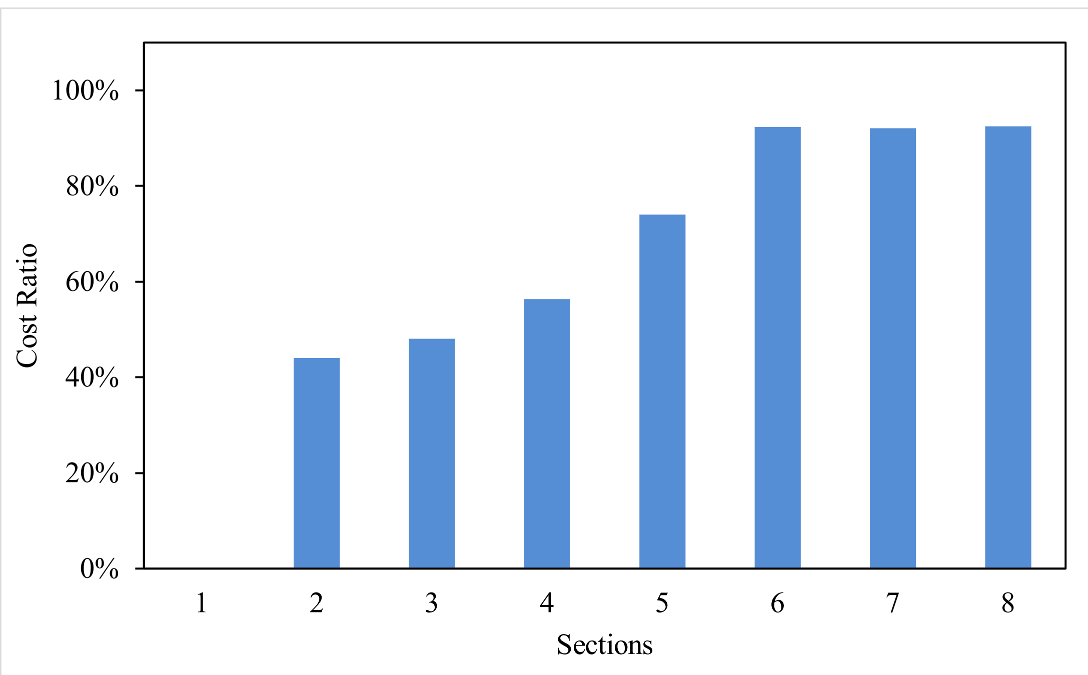


Figure B.28 Cost benefit ratio for Monroe test section-typical rainfall

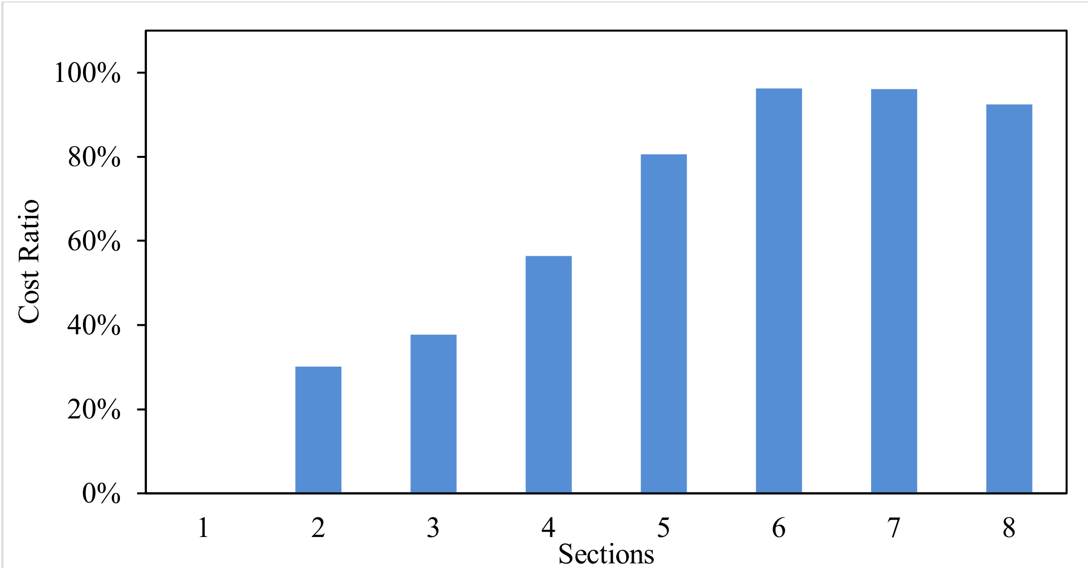


Figure B.29 Cost benefit ratio for Monroe test section-heavy rainfall

B.6.3 Life Cycle Cost Vinton Test Sections

The service life of the ODOT Vinton County test sections was estimated based on the observed performance of these sections during the first year of service. Figure B.30 presents the estimated service life. The annual cost for test sections was computed based on the estimated service life. Figure B.31 presents the computed annual costs for Vinton County sections. It is clear that all alternative berm materials/methods resulted in significantly reducing the annual cost of berms. The highest reduction was obtained for sections with heated RAP. The cost ratio was calculated for different sections and cases to quantify the benefits of different alternative berm materials and construction methods. Figure B.32 presents the computed cost benefit ratio. As in the Monroe test sections, the use of heated RAP mixes will result in a reduction of about 90% of the berm cost. In addition, the use of emulsified RAP will result in about 80% reduction in the annual cost of berms.

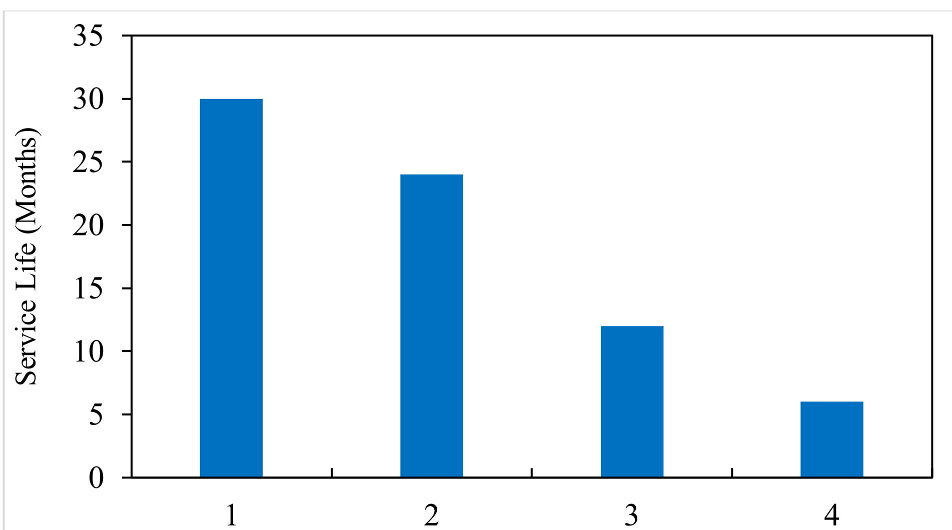


Figure B.30 Estimated service life for Vinton test section

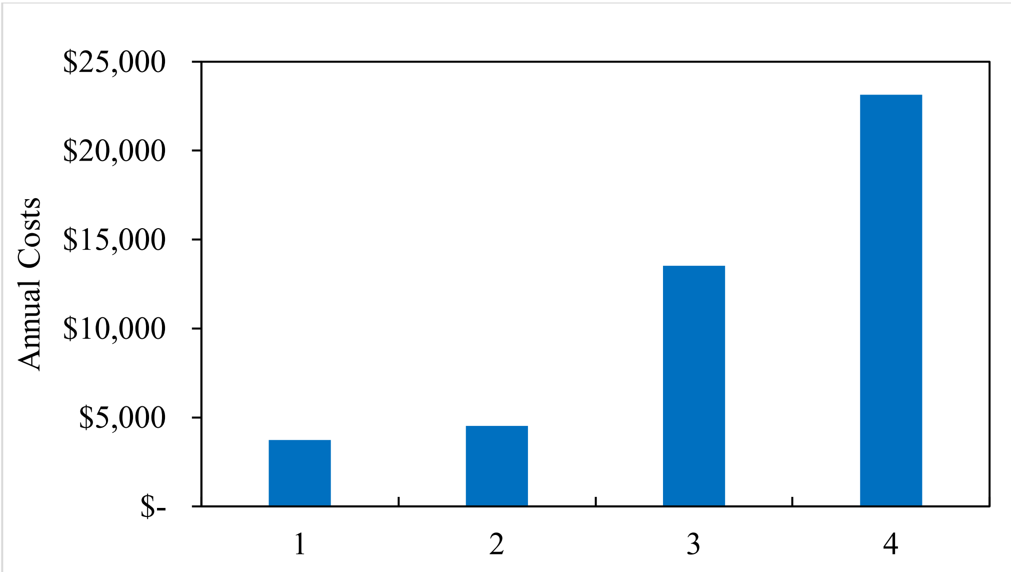


Figure B.31 Estimated annual costs for Vinton test section

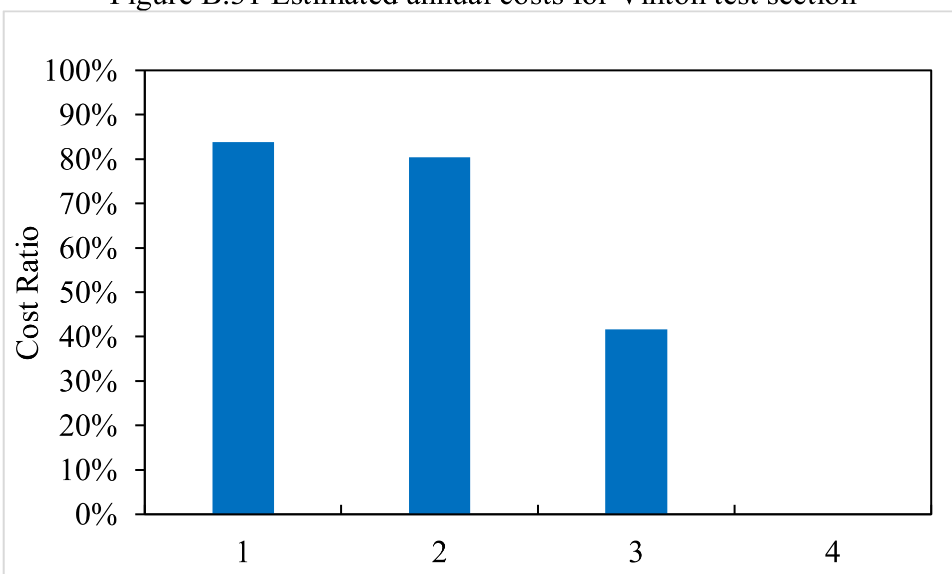
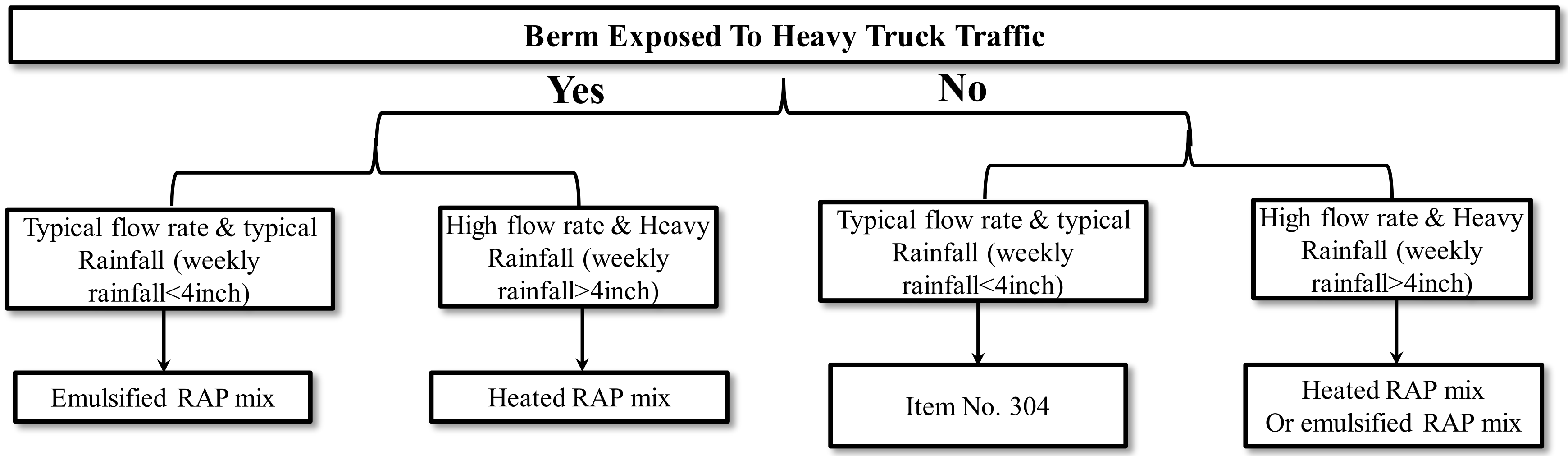


Figure B.32 Cost benefit ratio for Vinton test section

Appendix C Recommended Decision Tree



Recommended decision tree for selection of berm material