Evaluation of Otta Seal Surfacing for Low-Volume Roads in Iowa, Phase II Study: Comprehensive Laboratory Evaluation and Characterization and Full-Scale Field Implementation

Final Report
December 2023

IOWA STATE UNIVERSITY
Institute for Transportation

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7. Author(s)

Md Jibon (orcid.org/0000-0003-4239-0812), Bo Yang (orcid.org/0000-0002-7774-5233), Masrur Mahedi (orcid.org/0000-0002-3423-5524), Halil Ceylan (orcid.org/0000-0003-1133-0366), Sunghwan Kim (orcid.org/0000-0002-1239-2350), Yang Zhang (orcid.org/0000-0002-1150-5595), and Charles T. Jahren (orcid.org/0000-0003-2828-8483)

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Ames, IA 50010-8664

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16. Abstract

Iowa has over 110,000 miles of roads, and they frequently support local residential vehicles as well as heavy trucks. Traditional bituminous surface treatments (BST) could be employed to maintain these roads properly, but these treatments typically require high-quality materials and standard construction equipment. Otta seal is a relatively new BST that allows for the use of more economical local aggregates and commonly available equipment. To evaluate the feasibility of Otta seal implementation, a Phase I study was launched to design and construct Iowa's first Otta seal-surfaced road in Cherokee County in 2017. The successful construction of the first Otta seal road in Iowa provided valuable experience and knowledge for local public agencies, and a follow-up Phase II study was initiated in 2018. The Phase II study described in this report aimed to establish the recommended specifications through comprehensive laboratory evaluation and characterization and additional field implementation projects. In the Phase II study, more than 50 Otta seal sites constructed since 2017 were evaluated. These sites had various local aggregate and binder types, as well as various application rates. Five consecutive years of field measurements were executed in this Phase II study, including lightweight deflectometer-derived elastic modulus, International Roughness Index, dust generation, and skid resistance. The field evaluation in 2023 indicated that all Phase II Otta seal sites still exhibit satisfactory performance. A detailed laboratory investigation was conducted to establish a rational methodology for designing Otta seal road surfaces utilizing locally available materials. Four distinct aggregate types were considered in this study: limestone, recycled concrete aggregate (RCA), slag, and river aggregates. The McLeod method was modified to determine optimal rates for aggregate and binder application. The laboratory study primarily assessed Otta seal performance through a sweep test exploring the impact of material type, aggregate gradation, binder type, and application rate on aggregate loss. Key findings include the significance of aggregate gradation in reduced aggregate loss, the comparable performance of HFMS-2s and MC 3000 binders, the suitability of recycled materials (especially slag), and the effectiveness of the modified McLeod method. A life-cycle cost analysis revealed that the lowest cost was associated with Otta seal designed using the modified McLeod method. These findings contribute to a more efficient Otta seal design, enhancing road surface longevity while utilizing locally sourced materials.

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Principal Investigator
Halil Ceylan, Professor and Director
Program for Sustainable Pavement Engineering and Research (PROSPER)
Institute for Transportation, Iowa State University

Co-Principal Investigators
Sunghwan Kim, Research Scientist
Charles T. Jahren, Professor
Iowa State University

Research Assistants
Md Jibon, Bo Yang, and Masrur Mahedi

Authors
Md Jibon, Bo Yang, Masrur Mahedi, Halil Ceylan,
Sunghwan Kim, Yang Zhang, and Charles T. Jahren

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Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
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EXECUTIVE SUMMARY

Iowa has over 110,000 miles of roads, and they support not only the basic traveling needs of local residents but also heavy trucks. To properly maintain such a large amount of low-volume roads, Iowa's local public agencies have employed various bituminous surface treatments (BSTs), such as chip seal, micro-surfacing, slurry seal, and others. However, such traditional surfacing techniques are typically costly because they require high-quality materials and standard construction equipment, which are not always locally available.

Otta seal is a relatively new surfacing technique that involves placing a graded aggregate layer on top of a bitumen emulsion layer and then rolling it into the bitumen emulsion to form a seal. The Norwegian Road Research Laboratory (NRRL) initially developed the technique in the 1960s, and Overby (1999) subsequently established empirically based Otta seal design guidelines that have become the standard reference for Otta seal construction. This technique's most significant advantage is that it allows for the use of locally available equipment and aggregate, including nonstandard, marginal, and even recycled materials such as steel slag, to provide satisfactory surface conditions at a relatively low cost compared to conventional surfacing techniques, thereby decreasing construction cost and improving life-cycle benefits.

To explore the feasibility of this affordable pavement surface treatment technology in Iowa, the Iowa Highway Research Board (IHRB) launched a Phase I research project that successfully constructed Iowa's first Otta seal site in Cherokee County in 2017. This attempt provided valuable experience and knowledge for local public agencies, and a follow-up Phase II study was initiated in 2018 to establish recommended specifications through comprehensive laboratory evaluation and characterization and additional field implementation projects. In the Phase II study, more than 50 Otta seal sites constructed since 2018 in eight counties were evaluated. These sites had various local aggregate and binder types and had used various application rates. Five consecutive years (2018 through 2023) of field assessments were performed to track surface conditions in terms of lightweight deflectometer (LWD)-derived elastic modulus, International Roughness Index (IRI), dust generation, and skid resistance. The field evaluation showed that an Otta seal surface could provide a stable elastic modulus, improved IRI values, reduced dust generation, and enhanced skid resistance, all reflecting satisfactory performance. The most common distresses, which included cracks, potholes, bleeding, raveling, and loss of aggregate cover, were also identified through the extensive field assessments. Appropriate maintenance strategies should be established in the future to prolong the service life of Otta seal-surfaced roads.

Preparation for the Phase II study included outlining an experimental plan for Otta seal design focusing on two key components: laboratory investigation of Otta seal specimens and full-scale field implementation.

The primary objective of the laboratory investigation was to determine optimal application rates for aggregate and binder in Otta seal design using rational design techniques. The performance metric for assessing laboratory-scale Otta seal specimens was aggregate loss during sweep tests. The materials used in the construction of the Otta seal specimens included graded aggregate and

asphalt binder. The study explored various aggregate types, including limestone, recycled concrete aggregate (RCA), slag, and river aggregate, sourced from different counties in Iowa. Asphalt binders such as MC 3000 and HFMS-2s were utilized, and their environmental impact and performance characteristics were considered. Laboratory characterization of aggregates involved assessing properties such as particle size distribution, plasticity, bulk specific gravity, voids in loose aggregate, and flakiness index, all properties critical for understanding the suitability of aggregates for Otta seal construction. The McLeod method was adapted and modified to accommodate the unique characteristics of local aggregates used in Iowa Otta seal construction. Laboratory sweep tests based on ASTM D7000 were modified for use with the nonuniformly graded aggregates used in the Otta seal specimens. Modifications included adjusting the preheating temperatures, application rates, compaction methods, curing conditions, and aggregate sizes and gradations. Aggregate loss during sweep tests was measured using a mechanical brush assembly, and the results were used to assess the durability and performance of the Otta seal specimens.

The field study, conducted in Page County, Iowa, was aimed at investigating and implementing a rational mix design method for application of Otta seal on Iowa's low-volume roads. The primary objective of this field study was to assess the effectiveness and performance of Otta seal as a surfacing option while considering the properties of local materials to calculate binder and aggregate application rates. The study focused on County Road J55, a road with an annual average daily traffic (AADT) of 270 vehicles, mainly comprised of heavy truck traffic from a nearby quarry. Three test sections were constructed: TS-1 (following the Overby method), TS-2 (following a modified McLeod method), and TS-3 (following the Overby method without base stabilization). Field data collection involved various tests over time: roughness measurements using a Surface Systems and Instruments (SSI) high-speed profiler, the British pendulum test to assess skid resistance, dust generation measurement using a dustometer, loose aggregate collection to evaluate aggregate loss, LWD tests to assess structural capacity, and visual distress surveys to evaluate surface conditions.

An economic analysis considering factors such as construction, maintenance, and rehabilitation costs over the pavement's life cycle was conducted to evaluate different approaches to Otta seal construction on County Road J55 in Page County, Iowa. This economic analysis revealed that the modified McLeod design method (used to construct the Otta seal on TS-2) offered the most cost-effective solution over the pavement's life cycle.

The valuable field experience gained from the Phase II study was summarized and used to develop the Iowa Otta seal specifications presented in Appendix A of this report. These specifications incorporate Overby's empirically based design approach, a simplified method for selecting aggregate and binder and determining their application rates by aggregate gradation type. It is worth noting that the Iowa Otta seal specifications also introduce a laboratory-based design approach established during the Phase II study that was employed on one road segment on County Road J55 in Page County.

1 INTRODUCTION

1.1 Background and Motivation

Iowa has over 71,000 miles of unpaved secondary roads carrying very low daily traffic volumes but frequently supporting heavy vehicles (e.g., farm equipment). Iowa's county road departments spend more than $110 million annually for aggregate replacement on gravel roads alone. The excellent performance of Otta seal has recently gained significant interest from road engineers, who are always in search of economical approaches for low-volume road repair.

Otta seal (first developed and trialed in the Otta valley in Norway) was developed in 1963 by the Norwegian Road Research Laboratory (NRRL) as a low-cost surface maintenance alternative for unpaved gravel roads with low bearing capacities during spring thaw periods (Overby 1999). Consequently, Otta seal has been used in northern Europe and Africa, among other places, as an economical and practical alternative to traditional bituminous surface treatments (BSTs). Existing studies (Overby and Pinard 2013) have reported Otta seal's lower life-cycle costs in comparison to other BSTs. However, before the Iowa Highway Research Board (IHRB) initiated Phase I of the present study, only two states in the United States—Minnesota and South Dakota—had reported experience with Otta seal construction, while county engineers in Iowa expressed a desire to implement this technology to verify its short- and long-term performance.

Because of their flexibility with respect to the use of local materials and simplicity in construction, empirically based guidelines (Overby 1999, Visser and Henning 2011) have been developed to design Otta seal treatments. Under these guidelines (Overby 1999, Visser and Henning 2011), aggregate gradation dependent on expected traffic levels is a governing factor in design, complementing other material design factors such as aggregate application rate, asphalt binder selection, and asphalt application rate. Generally, recommended aggregate gradations are classified as "open (or coarse)" for traffic levels less than 100 vehicles per day (VPD), "medium" for traffic levels higher than 100 and less than 1,000 VPD, and "dense" for traffic levels higher than 1,000 VPD.

Other aggregate property requirements for Otta seal are not as strict as they are for traditional BSTs such as a chip seal. Relatively lower strength aggregate can be used for Otta seal if the gradation falls within a specified gradation classification that allows the maximum amount of fine material (<0.075 mm) to be less than 10%. Aggregate application rates ranging from 50 to 90 lb/yd^2 (about 30 to 50 kg/m^2), depending on aggregate gradation types and expected traffic levels, are recommended.

Selection of asphalt binder types and application rates are dependent on the aggregate gradation selected for an expected traffic level. Soft asphalt binder should be used to coat the fines and to move up through the aggregate matrix. Common types of asphalt binder suggested are MC 800 or MC 3000 for cutbacks produced from 80/100 or 150/200 penetration-grade asphalt. The experience of Minnesota and South Dakota (Johnson and Pantelis 2011, Weiss 2010) indicates that while high-float, medium-set, and soft-emulsified binders (HFMS-2s) can be used, emulsions have seen little use in other countries. Asphalt binder application rates ranging from

0.30 to 0.50 gal/yd^2 (1.5 to 2.0 l/m^2) for various traffic levels and aggregate gradations can be determined through road trials. For steep uphill or downhill gradients, reducing binder application rates is recommended when using an "open" aggregate gradation to prevent the excessive bleeding and instability that can occur during the early stages of construction (Overby 1999). Nordic counties have extensively used Otta seal with success (Overby 1999) since its origin in the 1960s. While recent studies reported in the literature indicate that it has also been applied successfully in trial sections in Asia, Africa, New Zealand, and South America (Visser 2013), Otta seal has seen limited use in the United States due to a lack of knowledge about the technology and the constraints of the empirical design approach associated with this technique, which requires evaluation of trial or demonstration sections before deployment.

South Dakota completed its first Otta seal project in Day County, South Dakota, in 2008 to provide a low-cost asphalt surface using in-house crews and equipment instead of constructing a standard asphalt pavement (Weiss 2010). For the project, Otta seal was placed on a newly graded 9 in. South Dakota Department of Transportation standard specification base course. Following this project, South Dakota also used Otta seal as a surfacing material for unpaved road rehabilitation projects utilizing the existing gravel surface as a base after improving it through recycling or the addition of new virgin aggregate materials. In 2009, the city of Pierre, South Dakota, employed Otta seal in rehabilitating 1.25 miles of a gravel-surfaced road with an average daily traffic (ADT) volume of 526. This was done to address a city budget constraint that could not afford a standard asphalt-paved surface. The Pierre project's results indicated that construction costs, including the Otta seal materials ($1.57/yd^2) and agency-owned equipment and personnel, were considerably lower in comparison to the $10.35/yd^2 cost for a 4 in. thick asphalt overlay (a traditional rehabilitation strategy for unpaved roads). Up to the present, no distress has been reported for this Otta seal since its construction in 2009 (Skorseth 2013).

Since the early 2000s, various agencies (city, county, and state) in Minnesota have used Otta seal for roads with various annual average daily traffic (AADT) volumes ranging from very low up to 2,000 (Johnson and Pantelis 2008, Johnson 2014). Most Otta seal-surfaced road sections constructed in Minnesota have performed well during their service lives except when they experienced unexpected situations such as unanticipated traffic volume increases or flood damage. Several advantages of using Otta seal have been reported in the literature (Overby 1999, Johnson 2014, Weiss 2010, Overby and Pinard 2013):

- It allows the use of uncrushed aggregate (up to 1 in. diameter), resulting in cost reduction in aggregate production and transportation.
- It acts as an impermeable surface by filling aggregate voids, thus preventing water from penetrating moisture-susceptible gravel roads.
- It does not require the use of a prime coat in construction.
- It can be opened to traffic immediately after construction.
- Fewer periodic maintenance activities are required between reseals.
- It can be recycled and used in place of an unbound or stabilized material after pulverization.

Encouraged by such successful experiences in other states, the Iowa Department of Transportation (DOT) and the IHRB sponsored a Phase I Otta seal project in 2014 to evaluate the feasibility of Otta seal as an alternative surface treatment on Iowa’s low-volume roads. In the Phase I study, the first Otta seal site in Iowa was successfully constructed on County Road L40 in Cherokee County in September 2017 (Ceylan et al. 2018). Based on the Phase I findings, an expanded Phase II project was initiated to address additional technical questions related to use of the Otta seal technique in new construction and rehabilitation projects for Iowa’s low-volume roads, such as utilization of various local aggregate types, determination of optimum aggregate and binder applications rates, and other considerations.

Existing empirical guidelines for Otta seal construction established in 1963 by the NRRL are primarily based on the performance of Otta seal sites in Norway (Overby 1999, Visser and Henning 2011), and given variations in local aggregates and climatic conditions, these guidelines may not be entirely applicable to other countries. Therefore, a more scientifically grounded approach is needed to consider local factors when determining Otta seal design parameters. Such an approach should address common forms of bituminous surface treatment distress, including issues such as aggregate loss, premature bleeding, thermal cracking, and rutting. Aggregate retention is a crucial factor influencing Otta seal performance and lifespan, making early aggregate loss an important performance indicator.

In this study, the sweep test method, commonly used for conventional bituminous surface treatments, was adopted for laboratory assessments of Otta seal. The traditional sweep test outlined in ASTM D7000 prescribes fixed binder application rates and the use of single-size aggregates, which are inadequate for evaluating the diverse range of aggregate gradations and binder types typically employed in Otta seal applications. Previous research has explored the sensitivity of sweep tests in evaluating chip seal applications, investigating factors such as aggregate type and gradation, asphalt binder type and application rate, curing time, and temperature (Lee and Kim 2008, Johannes et al. 2011). These studies demonstrated the sweep test’s sensitivity to emulsion application rate and aggregate gradation, particularly in the context of chip seal design. Based on this prior research, it has been suggested that, with some minor modifications, the sweep test can be effectively utilized to assess the compatibility of aggregates and emulsions for Otta seal design.

1.2 Research Objectives

This Phase II study is a follow-up investigation to the completed IHRB Project TR-674, Evaluation of Otta Seal Surfacing for Low-Volume Roads in Iowa (Ceylan et al. 2018). The primary objectives of this Phase II study were to establish recommended specifications, including quality control/quality assurance (QC/QA) procedures, for Iowa Otta seal construction projects through two concurrent research studies: (1) comprehensive laboratory evaluation and characterization and (2) field implementation projects.

Specific objectives established to achieve this primary objective include the following:

- Evaluate various local aggregate types in Iowa suitable for Otta seal construction.
- Develop a rational or engineered approach for determining optimum application rates for asphalt binder and aggregate systems in Otta seal applications.

- Identify road surface/base preparation requirements for Otta seal application.
- Identify test and control procedures for checking and calibrating actual field application rates of asphalt binder and aggregate.
- Evaluate rolling operations (e.g., number of passes) for achieving appropriate field compaction.
- Determine Otta seal curing times and recommend an optimum curing time between placement of the first and second layers for double Otta seal construction.
- Evaluate the feasibility of using recycled materials as an alternative to virgin aggregate in Otta seal applications.

1.3 Research Plan

In this Phase II study, the proposed research plan consisted of three major components: field evaluation of Otta seal sites constructed in Iowa, laboratory investigation of Otta seal specimens, and a life-cycle cost analysis (LCCA). Field evaluation was focused on visual examination of the Otta seal sites' appearance and nondestructive field testing, including elastic modulus measurement using a lightweight deflectometer (LWD), surface dust measurement using a dustometer, surface friction measurement using a British pendulum test, and roughness measurement using the commercial mobile application Roadroid (Forslöf 2012, Forslöf and Jones 2015) and a high-speed profilometer. Laboratory testing investigated the aggregate loss of Otta seal specimens with different combinations of aggregate and binder by performing the sweep test. The effects of aggregate type, binder type, grading envelope, and application rate on aggregate-binder bonding properties were evaluated. An LCCA was conducted based on field performance and construction cost data to determine the life-cycle benefits of Otta seal implementation in Iowa.

2 PERFORMANCE SUMMARY OF IOWA OTTA SEAL SITES

2.1 Background of Otta Seal Projects in Iowa

Based on the Phase I study's findings and recommendations, since 2017 Iowa has constructed more than 50 Otta seal sites in eight counties, as shown in Figure 1. These sites utilized various aggregate and binder types, material application rates, layer structures, and base stabilization strategies and were constructed following Overby's empirically based guidelines. Details of existing Otta seal sites in Iowa are summarized in Table 1. Among these sites, L40 in Cherokee County was constructed during the Phase I study as the first Otta seal demonstration site in Iowa. The 232nd St. and Old Highway 150 sites in Buchanan County are the first Otta seal implementations on existing pavements in Iowa. The Louisa County sites, K Ave. and 142nd St., are the first nationwide pilot Otta seal sites to use recycled steel slag (Yang et al. 2022). The M44 site in Page County is the first Otta seal site constructed on a cement-stabilized base in Iowa. These Otta seal construction projects have helped local public agencies (LPAs) gain experience in utilizing this surfacing alternative. During this Phase II study, the Iowa State University (ISU) research team collaborated with these LPAs and contractors in Otta seal design and construction and execution of the follow-up field evaluation through 2023.

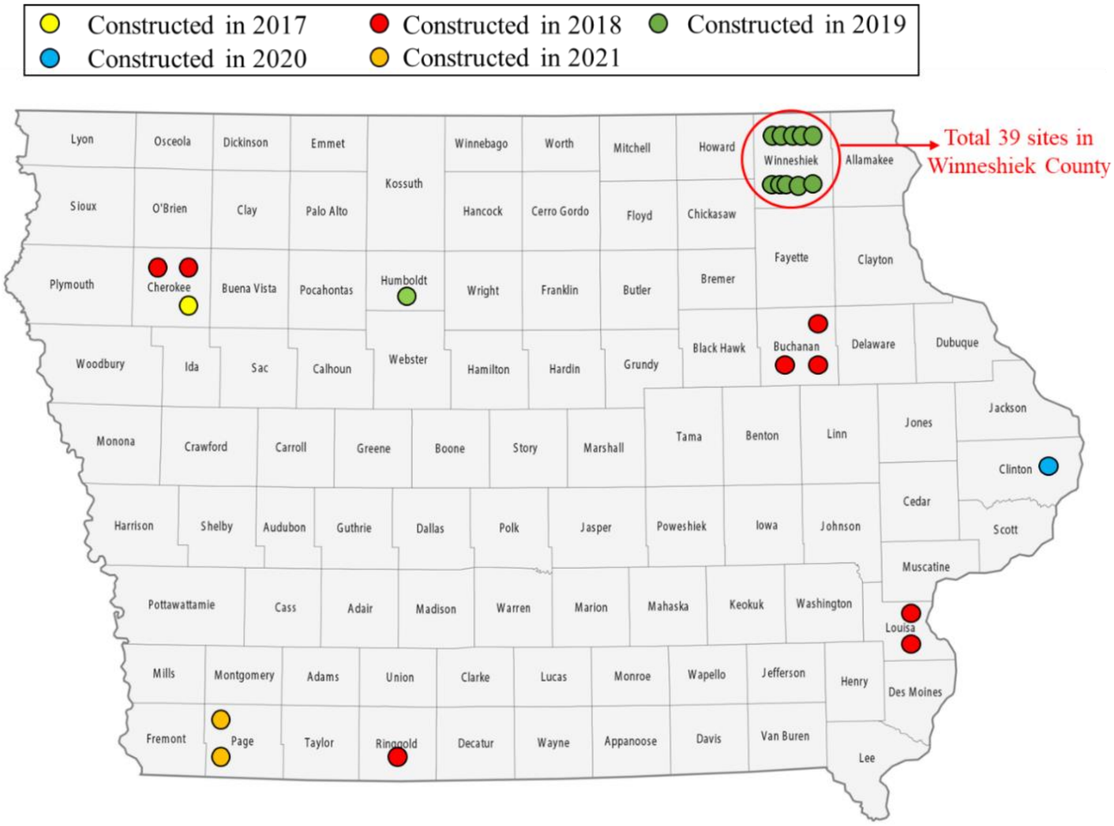


Figure 1. Iowa Otta seal site distribution map

Table 1. Otta seal sites designed and constructed in Iowa following the Overby method

County	Site	Length (miles)	Description
Cherokee	L40	4.0	Constructed in Sept. 2017. The first Otta seal field application in Iowa.
	Old 21 Rd.	2.6	Constructed in July 2018.
	O Ave.	3.1	Constructed in July 2018.
Buchanan	232nd St.	0.2	Constructed in July 2018. The first Otta seal application for rehabilitating deteriorated pavements.
	Old Hwy 150	0.5	
	Kentucky Ave.	0.6	Constructed in July 2018.
Louisa	K Ave.	0.5	Constructed in Aug. 2018. The first Otta seal field application using slag aggregate.
	142nd Ave.	0.5	
Ringgold	P68	6.0	Constructed in Aug. 2018. The first Otta seal field demonstration with county in-house crews and equipment (i.e., without contractors) in Iowa.
Winneshiek	Village Rd.	0.9	Constructed in June 2019.
	Others	8.5	The first Otta seal field application for large numbers of sites (39 sites in total).
Humboldt	Sheldon Park Rd	0.8	Constructed in July 2019.
Clinton	420th Ave.	0.3	Constructed in Oct. 2020.
Page County	M44	3.8	Constructed in Sept. 2021. The first Otta seal field site on a cement-stabilized base.

2.2 Design Overview

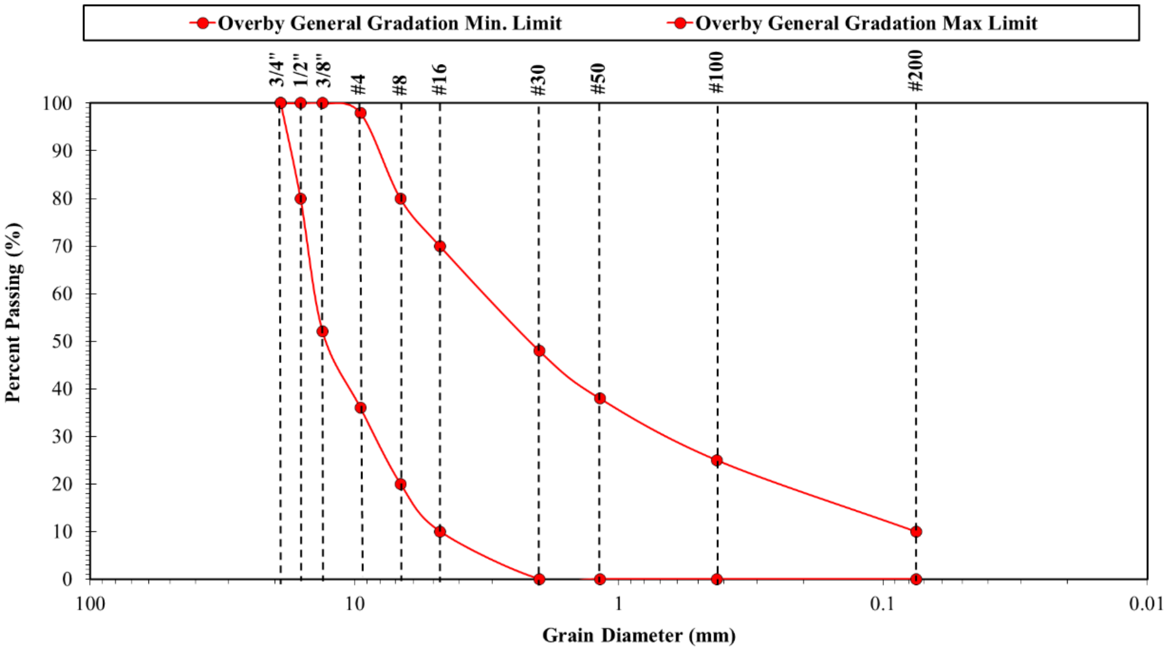
As introduced earlier, Otta seal surfacing technology was initially developed by the NRRL in the 1960s. Overby (1999) developed the first comprehensive Otta seal design and construction guidelines, which have become a critical reference for other countries seeking to employ this surfacing technology. In the Phase I study (Ceylan et al. 2018), the first Otta seal site in Iowa was successfully constructed in Cherokee County by following Overby’s guidelines.

The valuable field experience gained from the Phase II study has been summarized and used to develop Iowa Otta seal specifications (Appendix A). The specifications incorporate Overby’s empirically based design approach, a simplified method for selecting aggregate and binder and determining their application rates by aggregate gradation type. It is worth noting that the Iowa Otta seal specifications also introduce a laboratory-based design approach established during the Phase II study and employed on one road segment on County Road J55 in Page County.

In summary, all of the completed Phase II Otta seal sites in Iowa except for County Road J55 were designed by following the Iowa Otta seal specifications, which use Overby’s empirically based design approach. These design procedures are detailed in the developed Iowa Otta seal specifications presented in Appendix A and can briefly be introduced as follows:

1. Gather information about the project site, including primary use, existing surface, and traffic volume and type.

2. Determine the use of either a single course or double courses of Otta seal.
3. Determine the recommended aggregate gradation.
4. Select the locally available aggregate. Note that the selected aggregate should meet the general gradation limits shown in Figure 2.
5. Determine the recommended aggregate spreading rate.
6. Select a locally available binder.
7. Determine the recommended asphalt binder spray rate.



Overby 1999

Figure 2. General gradation limits for Otta seal

Based on collected records, as of 2021 a total of 55 roadways in Iowa have been surfaced with Otta seal; they all are low-volume roads with less than 300 ADT and are primarily used for resident vehicles, quarry trucks, and farm equipment. Table 2 summarizes historical site information and shows that these sites had various existing surfaces, ranging from granular to paved, before Otta seal implementation. Buchanan, Louisa, Ringgold, Clinton, and Page Counties also tried geo-stabilization, which has not been thoroughly investigated in other countries, before Otta seal implementation; geo-stabilization uses different stabilization methods, including geo-fabric, cement, and proprietary products, to provide a desirable foundation for the Otta seal surface.

Table 2. Iowa Otta seal sites information

County	Site	Length (mi)	Width (ft)	ADT	X-Surface	Geo-stabilization	Stabilization Date
Cherokee	L40	4	22	190	HMA	N/A	N/A
	Old 21 Rd.	2.6	22	150	Gravel	N/A	N/A
	O Ave.	3.1	22	240	Gravel	N/A	N/A
Buchanan	Kentucky Ave	0.6	26	120	Gravel	Claycrete + 2% Cement	7/24/2019
	232nd St	0.2	26	150	PCC	Geo-fabric	7/24/2018
	Old Hwy. 150	0.4	26	80	HMA over PCC	N/A	N/A
Louisa	K Ave.	0.5	26	200	Gravel	Base One	7/17/2018
	142nd Ave.	0.5	26	150	Gravel	Base One	7/18/2018
Ringgold	P-68	6	26	120	Gravel	Claycrete/Base One	7/20/2018
Winneshiek	Village Rd.	0.9	22	200	HMA	N/A	N/A
Humboldt	Sheldon Pkwy.	0.75	22	50	Gravel	N/A	N/A
Clinton	420th Ave.	0.3	25	160	Seal coat*	Base One	9/3/2018
Page	M44	3.8	24	100	Seal coat*	6% cement	9/8/2021

* The seal coat was reclaimed and blended with a chemical agent before Otta seal implementation.

The design of Otta seal in Iowa depends significantly on traffic conditions and availability of materials from local areas. Due to its wide availability, crushed limestone was the primary aggregate source utilized for Iowa Otta seal construction, with a few sites utilizing river rocks and slag for construction. Figure 3 shows the variety of Otta seal aggregates and gradations used in different counties. As shown in Table 2, all of Iowa's Otta seal sites have an ADT value of less than 300, reflecting the suitability of open and medium aggregate gradations based on the Iowa Otta seal specifications (Appendix A). However, since the local candidate sites typically serve resident cars and heavy vehicles such as quarry trucks and agricultural equipment, many LPAs preferred and selected dense-graded aggregates to make the Otta seal-surfaced roads more durable. For binder type, documentation of the constructed Iowa Otta seal sites indicates that emulsion asphalt (HFMS-2s) was utilized more often than cutback (MC 3000). It is worth noting that all 39 Otta seal sites in Winneshiek County used a combination of crushed limestone and asphalt emulsion.

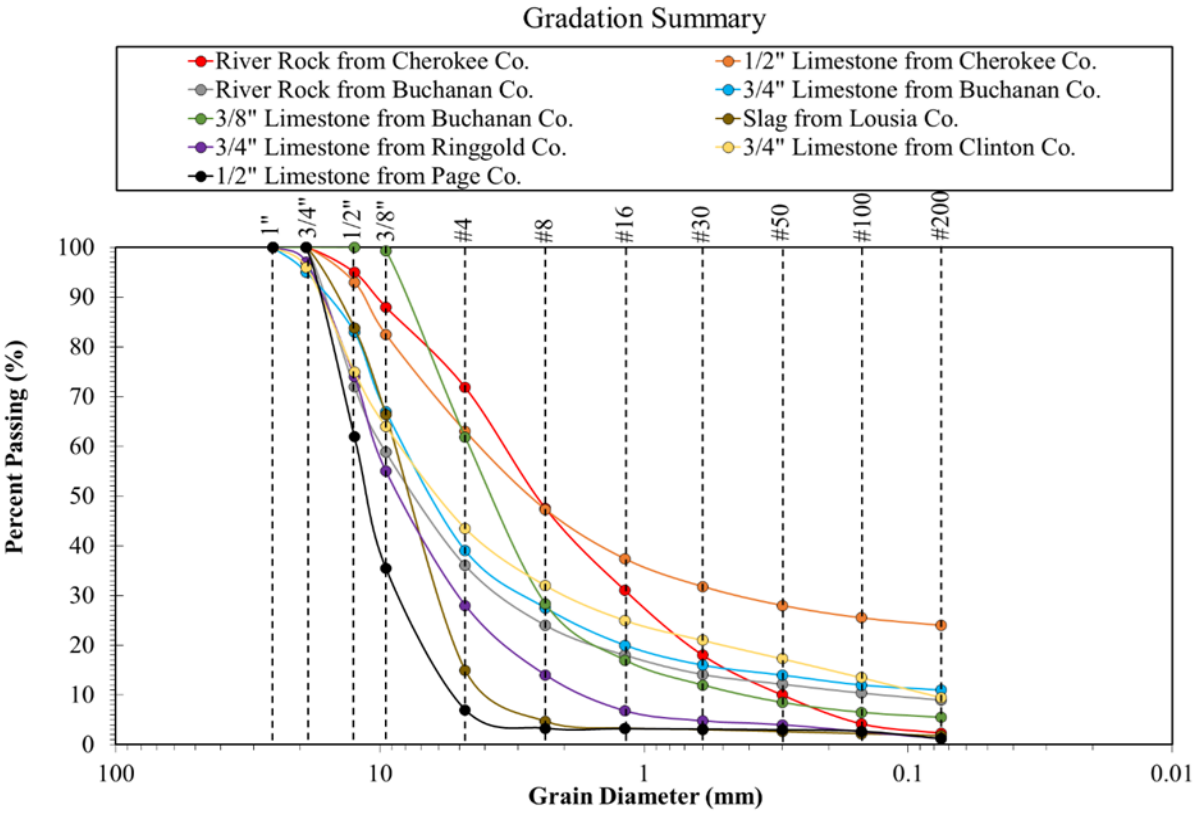


Figure 3. Aggregate gradations utilized in different counties in Iowa

Table 3 and Table 4 present the design and construction information for these Iowa Otta seal sites, including information on the first and second layers. Table 3 and Table 4 also illustrate that Iowa Otta seal practices reflect an aggregate spreading rate ranging from 47 to 65 lb/yd^2. Humboldt County selected 90 lb/yd^2 as the aggregate spreading rate for Shelton Park Road, but this is unique and not the representative value in Iowa. Among these 55 Otta seal sites, 39 are single-layer Otta seals primarily located in Winneshiek County. For double-layer Otta seals, the time gap between the two layers varied from two weeks to nearly one year. The Iowa Otta seal specifications (Appendix A) suggest a time gap of at least two weeks so the water or cut in the binder of the first course can fully evaporate.

Table 3. First-layer Otta seal design and construction information in Iowa

County	Site	Const. Date	Agg. Type	Agg. Gradation	Agg. Rate, lb/y^2	Binder Type	Binder Rate, gal/y^2
Cherokee	L40	9/5/2017	River rock	Dense	65	HFMS-2s	0.55
	Old 21 Rd.	7/2/2018	River rock	Dense	50	HFMS-2s	0.52
	O Ave.	7/6/2018	Limestone	Dense	50	HFMS-2s	0.52
Buchanan	Kentucky Ave.	7/24/2018	Limestone	Dense	50	HFMS-2s	0.5
	232nd St.	7/24/2018	River rock	Dense	50	HFMS-2s	0.5
	Old Hwy. 150	7/24/2018	Limestone	Dense	50	HFMS-2s	0.5
Louisa	K Ave.	8/1/2018	Slag	Open	50	MC 3000	0.4
	142nd Ave.	8/1/2018	Slag	Open	50	MC 3000	0.4
Ringgold	P-68	8/5/2018	Limestone	Open	57	HFMS-2s	0.5
Winneshiek	Village Rd.	6/4/2019	Limestone	Dense	45	HFMS-2s	0.5
Humboldt	Sheldon Pkwy.	7/18/2019	Limestone	Dense	90	HFMS-2s	0.61
Clinton	420th Ave.	10/21/2020	Limestone	Dense	56	MC 3000	0.45
Page	M44	9/17/2021	Limestone	Medium	47	MC 3000	0.4

Table 4. Second-layer Otta seal design and construction information in Iowa

County	Site	Const. Date	Agg. Type	Agg. Gradation	Agg. Rate, lb/y^2	Binder Type	Binder Rate, gal/y^2
Cherokee	L40	9/21/2017	River rock	Dense	55.6	HFMS-2s	0.5
	Old 21 Rd.	8/23/2018	Limestone	Dense	50	HFMS-2s	0.52
	O Ave.	8/23/2018	Limestone	Dense	50	HFMS-2s	0.52
Buchanan	Kentucky Ave	8/21/2019	Limestone	Dense	50	MC 3000	0.6
	232nd St.	6/26/2019	Limestone	Medium	50	MC 3000	0.5
	Old Hwy. 150	Single layer only					
Louisa	K Ave.	9/18/2018	Slag	Open	50	MC 3000	0.4
	142nd Ave.	9/18/2018	Slag	Open	50	MC 3000	0.4
Ringgold	P-68	8/15/2018	Limestone	Open	N/A	HFMS-2s	0.5
Winneshiek	Village Rd.	Single layer only					
Humboldt	Sheldon Pkwy.	N/A	N/A	N/A	N/A	N/A	N/A
Clinton	420th Ave.	8/24/221	Limestone	Dense	52	MC 3000	0.48
Page	M44	9/28/2021	Limestone	Medium	47	MC 3000	0.4

2.3 Construction Overview

The Otta seal construction process used in Iowa has no significant variations and generally follows the developed Iowa Otta seal specifications (Appendix A). The entire construction process can be categorized into three stages: site preparation (pre-construction), field construction, and post-construction.

Proper site preparation prior to construction is critical to the success of Otta seal construction. To prepare the project site for the upcoming Otta seal construction, three steps are required. First, the LPA should determine whether the existing road surface needs to be reclaimed and stabilized using chemicals. If soil/base stabilization is required and implemented, Otta seal construction should be delayed for a sufficient curing period to allow the surface to become firm. If no reclamation or stabilization is executed and construction on an existing surface is planned, the LPA should repair surface distresses to create an excellent platform before field construction. Second, on the day of construction, the road surface should be adequately cleaned using a motorized broom to remove loose aggregate and dust and minimize their effects on the binder. Third, the road closures and detour signs should be checked to ensure that they are presented correctly and that all required materials, equipment, and personnel are on site. Completing these steps will prepare the site for Otta seal construction.

Field construction of Otta seal is not a complex process. Figure 4 illustrates the general construction steps:

1. Calibrate the aggregate spread and asphalt distributor prior to Otta seal construction.
2. Spray asphalt binder on the cleaned road surface.
3. Spread aggregate on the bituminous layer.
4. Compact the Otta seal layer.

Application rate calibration for the construction equipment, including the aggregate spreader and asphalt distributor, is mandatory because this can significantly influence the quality of the Otta seal. In the calibration process, a metal pan is placed within the given area, and materials are spread on it, as shown in Figure 4a. The measured material weight in the metal pan can be converted into actual field application rates (lb/yd^2 or gal/yd^2) and utilized to achieve the targeted rates. Using incorrect application rates may cause bleeding, aggregate loss, or other related deterioration, thereby decreasing road performance and raising maintenance costs. After application rate calibration, Otta seal construction can begin with spraying of the asphalt binder, as shown in Figure 4b, and the aggregate spreader can follow the asphalt distributor and spread the aggregate on the binder layer (Figure 4c). Rolling compaction is the last step, as shown in Figure 4d. Rolling passes that follow the requirements of the Iowa Otta seal specifications (Appendix A) should be used to ensure compaction quality. If an insufficient number of rolling passes are conducted, the aggregate may not fully bond with the binder, resulting in a weak mixture and a rough surface. This rolling process can utilize different roller types, including a fully loaded truck if a standard roller is unavailable.

Figure 4. Typical Otta seal field construction procedures in Iowa

During the post-construction stage, the main action item is to sweep the surface again to broom the aggregate dislodged by the construction traffic onto the roadsides. Additional aggregate can be spread on the wheel paths to prevent the potential for bleeding. Once a newly constructed Otta seal project is opened to the public, traffic vehicles can play a role in follow-up compaction.

Table 5 summarizes the construction practices used for Otta seal projects in Iowa. The table indicates that pneumatic rollers are widely available in Iowa and can be utilized for rolling Otta seal surfaces. Although the Iowa Otta seal specifications (Appendix A) recommend using both a pneumatic roller and a steel roller, a steel roller may not be available in some districts, and in this case a fully loaded truck or tractor can be used as an alternative. As shown in Table 5, the number of rolling passes may also vary by site. Securing an accurate rolling record can often prove to be a daunting task, as operators of the machinery frequently do not keep a tally of the number of rolling passes. Instead, they tend to depend heavily on their accumulated knowledge and personal expertise in the field. Therefore, good communication with the contractor and proper field documentation is vital to the success of Otta seal construction.

Table 5. Compaction information for Otta seal practices in Iowa

County	Site	1st Layer Rolling	Roller Type	Rolling Pass	2nd Layer Rolling	Roller Type	Rolling Pass
Cherokee	L40	9/5/2017	Pneumatic roller	45	9/21/2017	Pneumatic roller	N/A
	Old 21 Rd.	7/2/2018	Pneumatic roller	20	8/23/2018	Pneumatic roller	N/A
	O Ave.	7/6/2018	Pneumatic roller	20	8/23/2018	Pneumatic roller	N/A
Buchanan	Kentucky Ave.	7/24/2018	Pneumatic roller	N/A	8/21/2019	N/A	30
	232nd St.	7/24/2018	Pneumatic roller	N/A	6/26/2019	Pneumatic roller + Loaded Truck	30 + 30
	Old Hwy. 150	7/24/2018	Pneumatic roller	N/A	Single layer only		
Louisa	K Ave.	8/1/2018	Pneumatic roller	N/A	9/18/2018	N/A	N/A
	142nd Ave.	8/1/2018	Pneumatic roller	N/A	9/18/2018	N/A	N/A
Ringgold	P-68	8/5/2018	Pneumatic roller + Steel roller	N/A	8/15/2018	Steel roller	N/A
Winneshiek	Village Rd.	6/4/2019	Pneumatic roller + Steel roller	N/A	Single layer only		
Humboldt	Sheldon Pkwy.	7/18/2019	Pneumatic roller	N/A	N/A	N/A	N/A
Clinton	420th Ave.	10/21/2020	Pneumatic roller + Loaded tractor	48	8/24/221	Pneumatic roller + Loaded tractor	N/A
Page	M44	9/17/2021	Pneumatic roller + Steel roller	N/A	9/28/2021	Pneumatic roller + Steel roller	N/A

2.4 Summary of Field Investigations

In this Phase II study, the ISU research team continuously monitored the field performance of 12 Iowa Otta seal project sites constructed between 2018 and 2021. Although Winneshiek County has 39 Otta seal sites, only Village Road was selected as the representative site in this county for field performance monitoring because it was constructed on an existing hot-mix asphalt (HMA) pavement and had a single Otta seal layer. The LWD-derived elastic modulus, International Roughness Index (IRI), amount of dust generated, and surface friction were documented through 2023.

Figure 5 illustrates the elastic modulus values of the monitored Otta seal project sites in Iowa. Each project site had different base and subgrade conditions, leading to the various elastic moduli. For most of the Otta seal project sites, an age increase of up to five years does not lead to significant variations in elastic moduli, indicating that the base course and subgrade of the Otta seal sites are still in good condition and that no structural damage was detected. It should be noted that 232nd Street and 420th Avenue sites exhibit a high elastic modulus during the second year due to the construction of a second course that increased the thickness of the Otta seal layer.

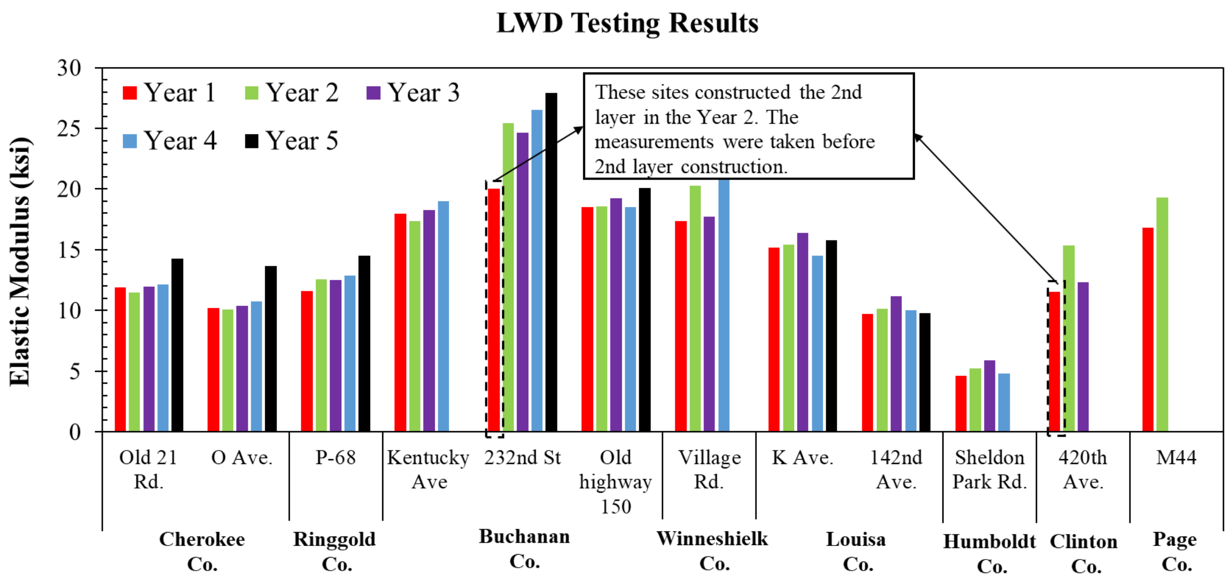


Figure 5. Field results summary for LWD-derived elastic modulus

Figure 6 presents the IRI results measured using the commercial mobile application Roadroid and a high-speed profiler. The newly constructed Otta seal sites achieved typical IRI values ranging from 150 to 200 in./mile during the initial stage, acceptable for low-volume roads. As shown in Figure 6, many Otta seal project sites still exhibit IRI values of less than 200 in./mile after a few years while exhibiting a steady and slight increase over time. The highest IRI values were documented at the 232nd Street and 420th Avenue sites; these were probably caused by insufficient compaction effort (lack of a steel roller, less than required number of rolling passes, etc.), heavy truck damage, and existing pavement cracking before Otta seal implementation.

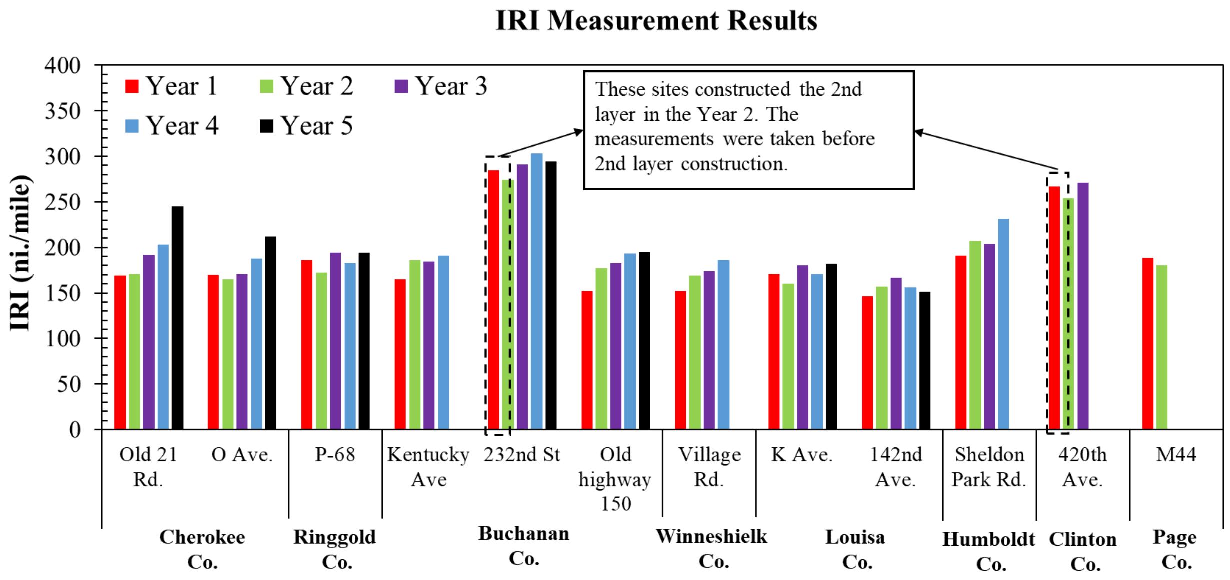


Figure 6. Field results summary for IRI measurements

Figure 7 indicates the amount of dust generated by traffic at the Otta seal sites. Dust is very common for granular roads, causing negative impacts on human health, vegetation, and air and water quality (Alsheyab et al. 2023). Based on field observations, Otta seal has been found to effectively reduce dust generation for existing granular roads. Yang et al. (2022) compared the dust generated before and after Otta seal placement and reported a 90% decrease one week after construction. As shown in Figure 7, the dust generated at different Otta seal sites varies from 0.2 to 2.8 g/mile, with Otta seal age having no significant effect. Variation in the amount of dust generated at different sites is typically influenced by the fines content in the aggregate and the binder application rate.

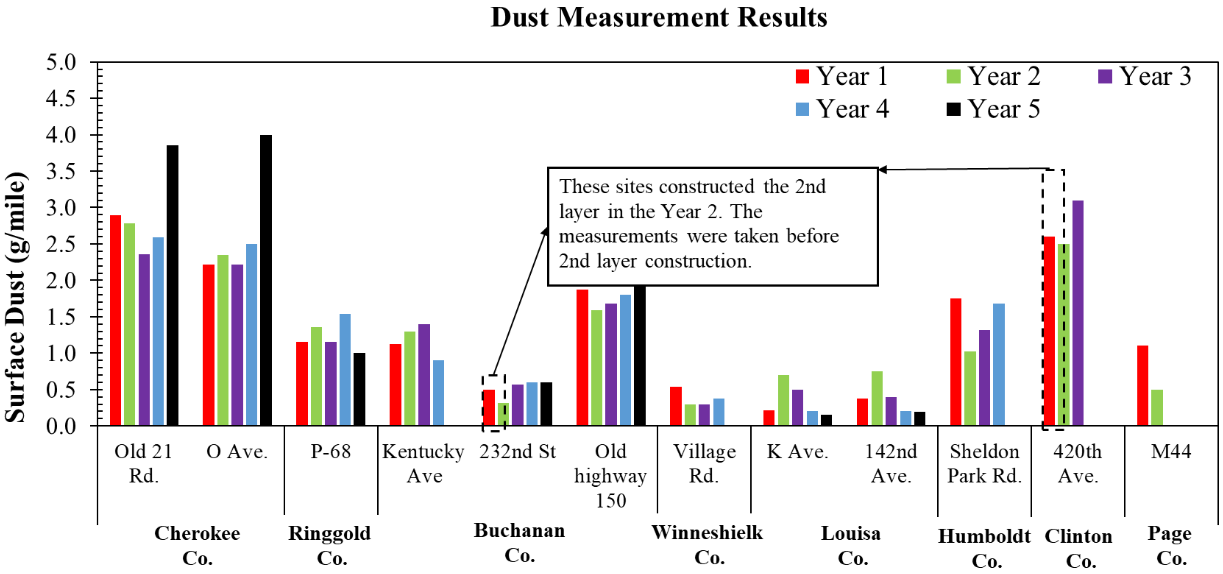


Figure 7. Field results summary for dust generation

The surface friction of roadways is critical to safety and should be examined to determine whether it meets the minimum requirements (Yang et al. 2020, Yang et al. 2022). In this Phase II study, the surface friction at the Otta seal sites was measured using the standard British pendulum test and expressed as the British pendulum number (BPN). Figure 8 illustrates the measured BPN for Iowa’s Otta seal sites, indicating that Otta seal produces a surface with high friction and provides good safety in terms of skid resistance.

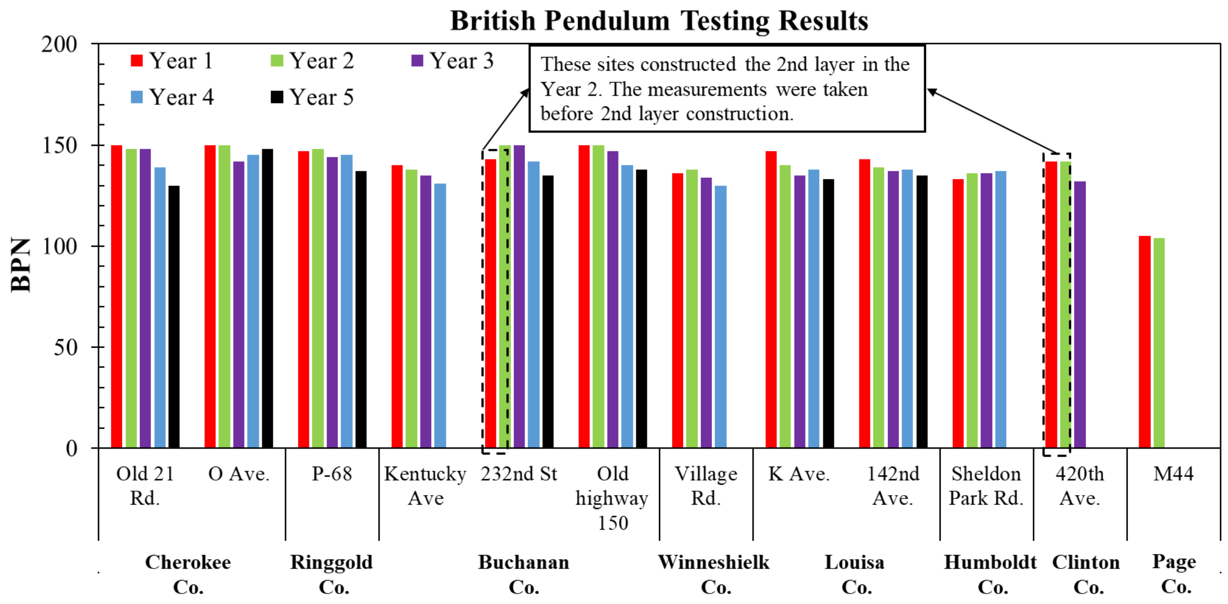


Figure 8. Field results summary for surface friction

The appearance of each site was evaluated to gauge the overall distress evident at the sites. Field images from the evaluation are presented in Appendix B. Based on the field observations, the ISU team categorized the overall surface condition of the Otta seal sites into five levels: very good, good, fair, bad, and very bad. The evaluation depended on the surface appearance and severity of various types of deterioration, such as cracking, aggregate loss, bleeding, raveling, and rutting. A very good appearance indicates that no obvious deterioration was observed and the entire surface was in good shape. If a site exhibited some distress at a few road segments but the entire road was still in good shape, it was categorized as having a good appearance. A fair condition indicates that some medium- and high-severity distress was observed at many road segments, causing a limited impact on road serviceability. A bad condition indicates that the road surface exhibited a great deal of distress and needs appropriate preservation strategies to maintain its serviceability. If a road reaches a very bad condition, the LPA should take remedial measures such as rehabilitation or reconstruction. Table 6 presents the overall condition for 13 representative Otta seal sites in Iowa, showing that none of the newer sites (constructed after 2017) is in bad or very bad condition except for the Phase I study site, L40. Some Phase II sites, such as K Avenue and 142nd Avenue, still appeared well preserved after five years. Although L40 exhibited massive cracking, the LPA sealed it in time to prevent further deterioration.

Table 6. Field condition rating for Otta seal practices in Iowa (as of August 2023)

County	Site	Age (years)	Overall condition of site appearance
Cherokee	L40*	6	Bad. Exhibited a lot of bleeding and cracking, but all distresses were sealed.
	Old 21 Rd.	5	Fair. Some sections exhibited serious loss of aggregate cover and frost boils. Placed a new aggregate surface.
	O Ave.	5	Fair. Some sections exhibited serious loss of aggregate cover and frost boils. Placed a new aggregate surface.
Buchanan	Kentucky Ave.	4	Fair. Bleeding was the primary issue at this site.
	232nd St.	5	Fair. Reflective cracking was the primary issue at this site.
	Old Highway 150	5	Good. A few raveling issues were observed.
Louisa	K Ave.	5	Good. Exhibited some micro-cracks, edge cracks, and some raveling.
	142nd Ave.	5	Very Good. No noticeable cracking or potholes.
Ringgold	P-68	5	Good. Exhibited a few bleeding, raveling, longitudinal, and edge cracks.
Winneshiek	Village Rd.	4	Fair. Exhibited many longitudinal and transverse cracks.
Humboldt	Sheldon Park Rd.	4	Fair. Exhibited a few longitudinal and micro-cracks. Some segments exhibited potholes.
Clinton	420th Ave.	3	Fair. Exhibited some loose aggregate, rutting, and potholes.
Page	M44	2	Good. Exhibited a few bleeding issues.

* Phase I study site constructed in 2017

As shown in Figure 9a through Figure 9g, multiple types of distress were identified at the Otta seal sites in Iowa. The primary cause of longitudinal cracking (Figure 9a) is heavy and repeated traffic loading in rural areas. As with many other low-volume roads, Otta seal sites typically have traffic volumes of less than 250 VPD, but many farming and quarry trucks use these roads frequently between spring and fall, resulting in load-related damage on the Otta seal surface. Transverse cracking (Figure 9b) is one of the most common issues for bituminous surfaces, and declining temperature is a widely known cause of this type of cracking. The reflective cracking shown in Figure 9c occurs due to cracks or joints in the underlying portland cement concrete (PCC) or HMA layer. Loss of aggregate cover (Figure 9d) is another common problem with BSTs such as Otta seal. Potential causes may be dusty aggregate, insufficient binder quantity, or insufficient rolling compaction. Bleeding (Figure 9e) occurs during hot weather, when the surface may become shiny and glasslike due to binder expansion. This is typically a design problem related to the use of excessive asphalt binder or an incorrect binder spray rate. Figure 9f depicts edge cracking at an Otta seal site, which primarily results from poor drainage practices. Figure 9g shows a pothole, another common distress for BSTs. Poor drainage, insufficient surface thickness, and heavy traffic loads, or some combination of these, could lead to pothole formation. Once these problems are observed and identified, appropriate maintenance actions should be taken.

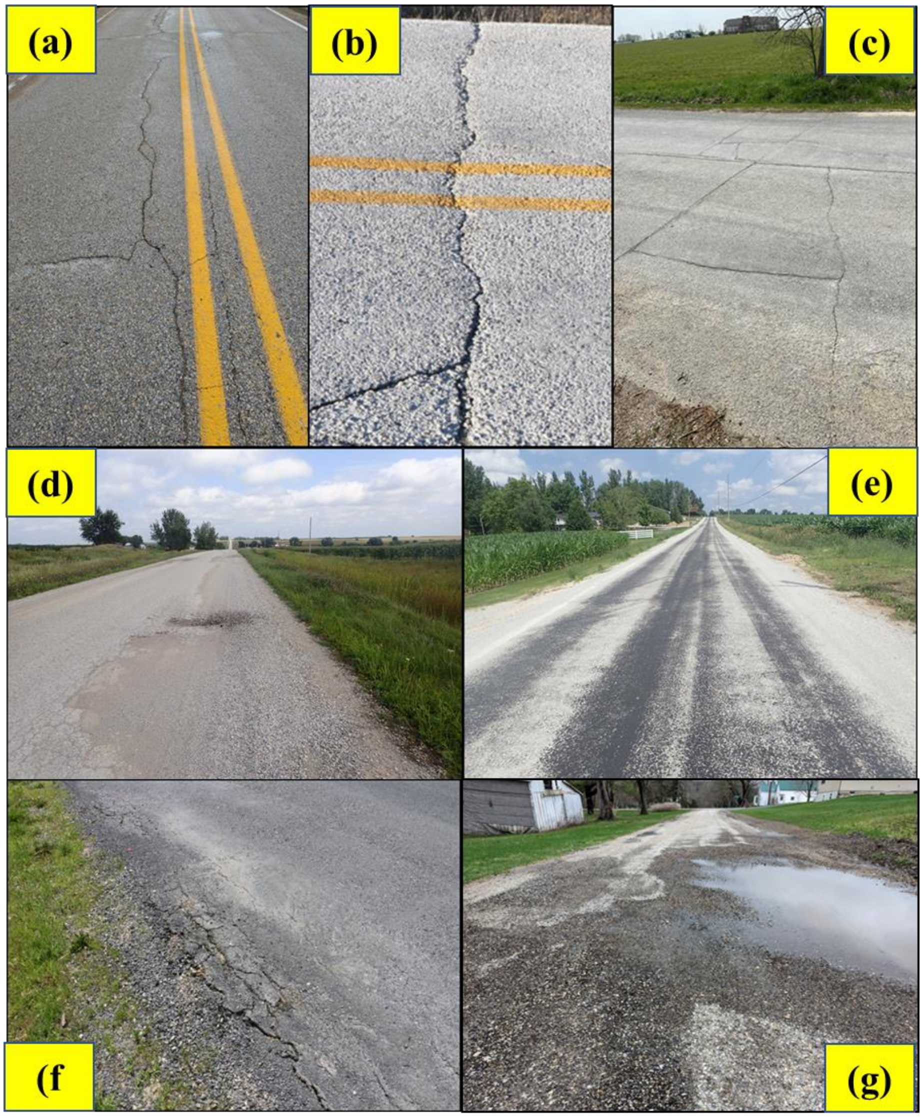


Figure 9. Distresses at Otta seal sites: (a) longitudinal crack, (b) transverse crack, (c) reflective cracking, (d) loss of cover aggregate, (e) bleeding, (f) edge crack, and (g) pothole

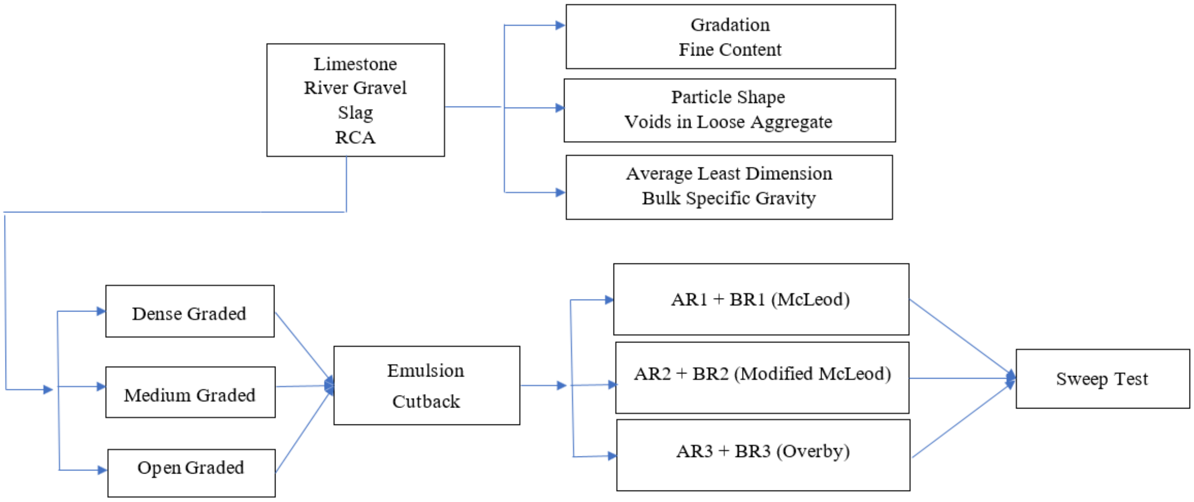
The full-scale field evaluation provides a global view of Otta seal performance in Iowa. As mentioned previously, the design and construction practices used for the Iowa Otta seal sites and documented during the Phase II study were incorporated into the Iowa Otta seal specifications (Appendix A). A combination of five years of field testing results and visual documentation demonstrated satisfactory field performance for these in-service Otta seal roads, proving that Otta seal can be an effective BST alternative if the Iowa Otta seal specifications are properly followed.

The Phase II study also identified a rational design method for evaluating the bonding properties between aggregate and asphalt binder, which can be used to determine the application rates of aggregate and binder. The following chapters discuss the laboratory and field studies for identifying and evaluating a rational design method tailored to Iowa’s conditions.

3 LABORATORY INVESTIGATION TO DEVELOP A RATIONAL DESIGN APPROACH FOR IOWA

3.1 Experimental Plan

Developing an experimental plan for evaluating Otta seal design involved two key components: (1) laboratory characterization of aggregate materials and (2) execution of sweep tests on laboratory-scale Otta seal specimens. The primary objective of the laboratory investigation was to determine optimal application rates for both aggregate and binder in Otta seal design utilizing the rational design techniques introduced in this study. The performance metric chosen for assessing the laboratory-scale Otta seal designs was the aggregate loss observed during the sweep test. As a reference point, the empirically based application rate calculation guidelines proposed by Overby (1999) were employed as the baseline for comparing the performance of Otta seal designs based on rational design techniques. The well-known chip seal design method developed by McLeod (1960) was also considered in calculating both aggregate and binder application rates for Otta seal. A modification to the McLeod method to accommodate the Otta seal design requirements was also proposed. This study presents a comparative analysis of the performance of Otta seal specimens designed using Overby’s empirical guidelines, the McLeod method, and the modified McLeod design method. Figure 10 illustrates the detailed experimental plan adopted in this study for laboratory investigation.



Note:

RCA = Recycled Concrete Aggregate
AR = Aggregate Application Rates
BR = Binder Application Rates
AR1 and BR1 = McLeod
AR2 and BR2 = Modified McLeod
AR3 and BR3 = Overby
AR4 and BR4 = Field application

Figure 10. Detailed experimental plan for the laboratory investigation of Otta seal

3.2 Materials

Otta seal is composed of two primary components: graded aggregate and asphalt binder. This combination of materials forms the integral structure of the Otta seal, with the aggregate providing the main structural support and the asphalt binder serving as the adhesive that holds the aggregate particles together. The versatile nature of Otta seal construction allows for the use of various aggregate types that can be crushed, uncrushed, or a combination of both. To ensure the successful application of Otta seal, Overby’s (1999) guidelines offer specific gradation requirements for locally available aggregates.

In the state of Iowa, where Otta seal is a prevalent surfacing choice, two primary aggregate types have gained widespread use: limestone and river aggregates. While these materials have demonstrated their effectiveness in Otta seal construction over time, Iowa pioneered a groundbreaking innovation in 2018 by introducing steel slag as an aggregate for Otta seal road construction. Remarkably, this steel slag-based Otta seal continues to exhibit excellent performance (Yang et al. 2022). Moreover, Iowa boasts an extensive network of concrete pavements spanning thousands of miles, and this substantial infrastructure has spurred a growing interest in exploring sustainable and cost-effective options for pavement rehabilitation. One such alternative gaining prominence is the utilization of recycled concrete aggregate (RCA). A diverse range of aggregate materials were selected for this study, including limestone, RCA, slag, and river aggregates, all meticulously sourced from various counties within Iowa. This comprehensive effort allowed for a thorough investigation into the characteristics and suitability of these materials for Otta seal construction in Iowa. Figure 11 shows the collected aggregate for laboratory characterization, including limestone, RCA, slag, and river aggregate.

(a) Limestone **(b) RCA**

(c) Slag **(d) River Aggregate**

Figure 11. Collected oven-dry (a) limestone, (b) RCA, (c) slag, and (d) river aggregate for laboratory characterization

The development of asphalt binders spans centuries, resulting in a wide range of properties and behaviors attributed to their various types and compositions (Roberts et al. 1996). Notably, cutback asphalts represent a class of asphalt binders composed of a mixture of solvents and asphalt cement. They can be categorized based on the percentages of added solvents, leading to distinctions such as slow-curing (SC), medium-curing (MC), or rapid-curing (RC) products. In the context of Otta seal construction, Scandinavian and African regions commonly employ binders such as MC 3000, MC 800, 80/100, and 150/200 penetration-grade bitumen (Manheche and Mukura 2010). Among these, MC 3000 and MC 800 fall into the categories of high-viscosity and low-viscosity cutbacks, respectively. It is worth noting that high-viscosity cutbacks raise environmental concerns due to the potential release of greenhouse gases from evaporating solvents.

In contrast, asphalt emulsion emerges as another prevalent binder type with fewer environmental implications. Asphalt emulsions consist of asphalt cement, water, and emulsifying agents. Notably, HFMS-2s, an anionic emulsion with a high float and medium set (HFMS), is widely used for Otta seal construction in regions such as Minnesota, South Dakota, and Iowa (Gushgari et al. 2019). This particular emulsion exhibits lower viscosity compared to cutback asphalt, contributing to its popularity. Moreover, asphalt emulsions are dispersions of asphalt droplets in water, typically containing 40% to 80% asphalt by weight, and they require lower heat during application in surface treatments, resulting in reduced greenhouse gas emissions compared to cutback asphalt. The versatility of asphalt emulsion allows for various pavement applications, including fog seal, slurry seal, chip seal, tack coat, cold central plant recycling (CCPR), cold in-place recycling (CIR), and full-depth reclamation (FDR) (Ahmed Kazmi et al. 2021 and Orosa et al. 2023).

In the context of this study, Otta seal specimens were prepared in the laboratory using MC 3000 and HFMS-2s binders. Notably, the residual asphalt content in the MC 3000 cutback and HFMS-2s emulsion was measured at 88.5% and 66.5%, respectively. To ensure accurate application rates, the design for HFMS-2s was adjusted based on its residual asphalt content, reflecting the precise and methodical approach taken in this investigation.

3.3 Laboratory Characterization of Aggregates

Laboratory characterization of aggregates includes the assessment of readily measurable aggregate properties that represent a range of essential factors, including gradation or particle size aggregate distribution, fines content within the sample, individual particle shape, the presence of voids within loose aggregate, the bulk specific gravity of the material, and the average least dimension of the aggregate particles. Particle size distribution analysis for each aggregate was conducted in accordance with ASTM C136, and ASTM D 4318 was rigorously followed to assess aggregate plasticity. Notably, all materials employed in this study exhibited a nonplastic classification, indicating their limited capacity for deformation under varying moisture conditions. In alignment with the American Association of State Highway and Transportation Officials (AASHTO) and Overby (1999) gradation envelopes, the collected limestone and RCA were classified as A-1-a and categorized as dense-graded aggregates. Slag was classified as A-1-a and identified as a medium-graded aggregate, and river aggregate was classified as A-1-a and designated as an open-graded aggregate. These classifications help in understanding the suitability of these aggregates for Otta seal construction.

Figure 12 shows the particle size distribution curve for the limestone aggregate obtained from wet and dry sieve analyses performed on the collected materials. Otta seal often utilizes local aggregates, generally of lower quality. As demonstrated by Overby (1999), graded aggregate for Otta seal can be produced from crushed or uncrushed materials, or a combination of both, to achieve the necessary gradation requirements. Overby (1999) recommended maximum and minimum limits for aggregate gradation, shown in Figure 12, along with the gradation curve of limestone aggregate. Similar information is shown for RCA, slag, and river aggregate in Figure 13, Figure 14, and Figure 15, respectively.

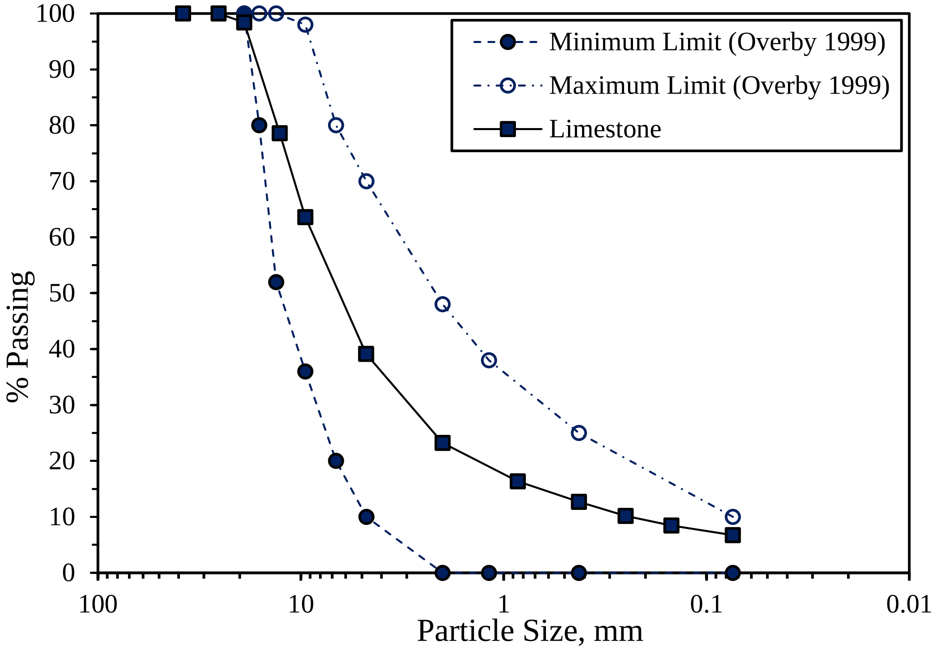


Figure 12. Particle size distribution of limestone aggregate along with the recommended limits by Overby (1999)

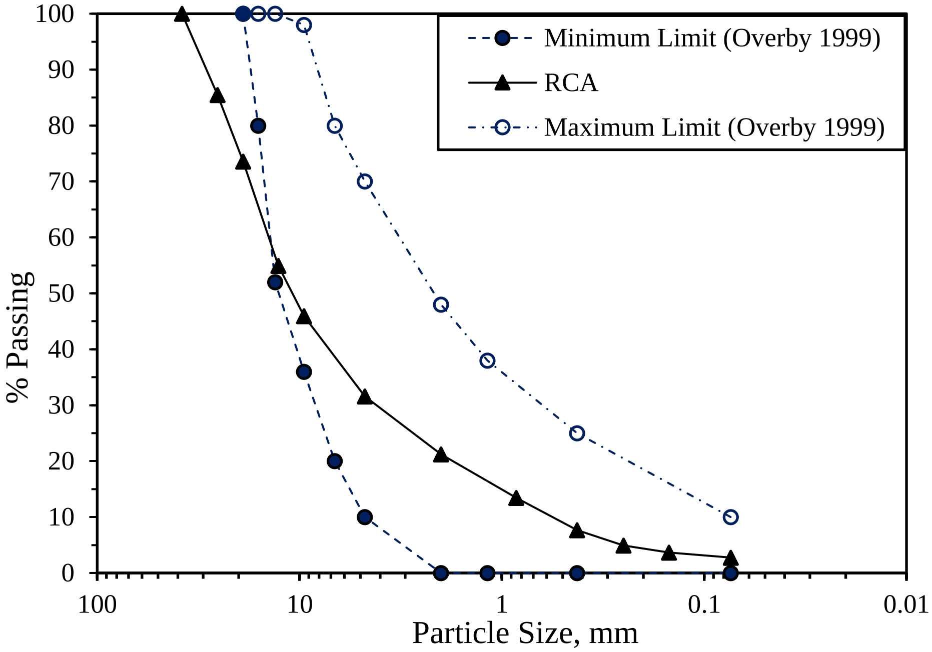


Figure 13. Particle size distribution of RCA along with the recommended limits by Overby (1999)

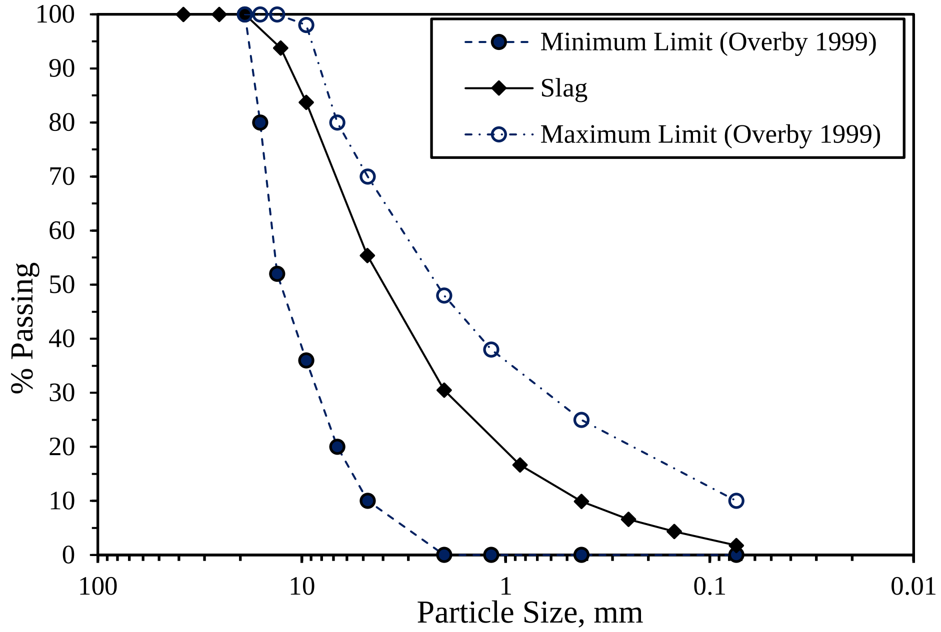


Figure 14. Particle size distribution of slag along with the recommended limits by Overby (1999)

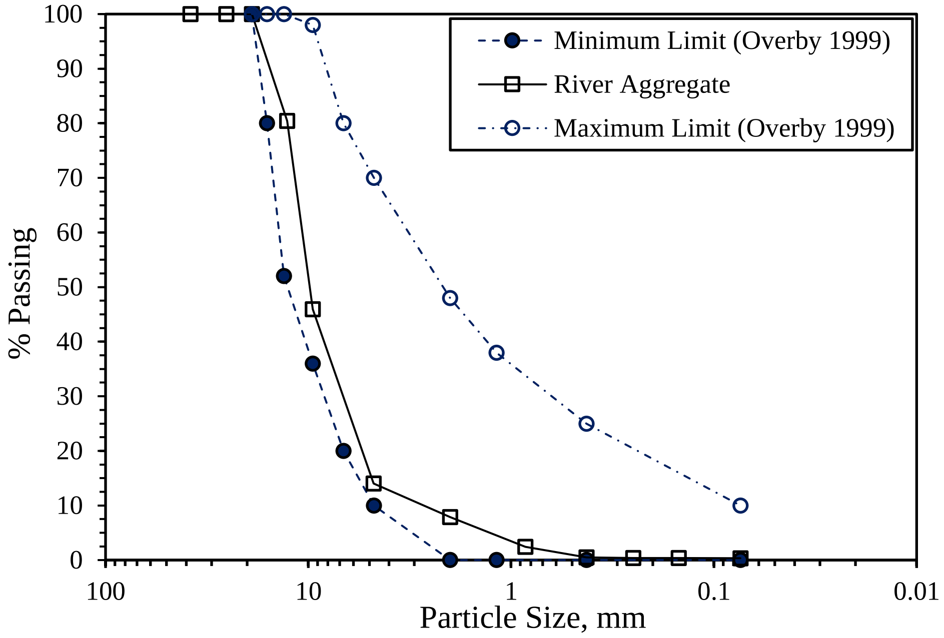


Figure 15. Particle size distribution of river aggregate along with the recommended limits by Overby (1999)

In Otta seal construction, three distinct gradation envelopes come into play: dense, medium, and open grade. These gradation categories play a pivotal role in determining the quality and effectiveness of the Otta seal application. Providing valuable insights into this aspect of Otta seal design, Overby (1999) meticulously outlined comprehensive guidelines specifying maximum and minimum limits for aggregate gradation, which are essential for achieving optimal Otta seal performance. To ensure strict adherence to these critical grading criteria, the present study excluded any oversized particles, defined as those exceeding 19 mm in size. A meticulous process of segregation and reclassification of the collected aggregates was undertaken. This reclassification resulted in the categorization of aggregates into three primary groups: dense, medium, and open grade. Figure 16 through Figure 18 provide comprehensive particle size distribution curves for dense-, medium-, and open-graded aggregate, along with maximum and minimum limits set by Overby (1999).

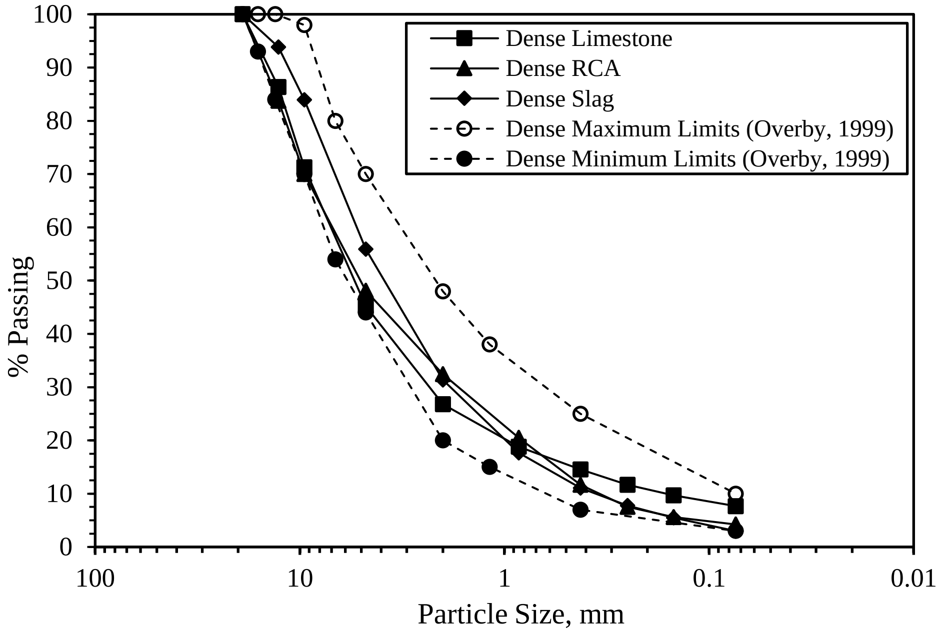


Figure 16. Particle size distribution of dense-graded aggregate along with the recommended limits by Overby (1999)

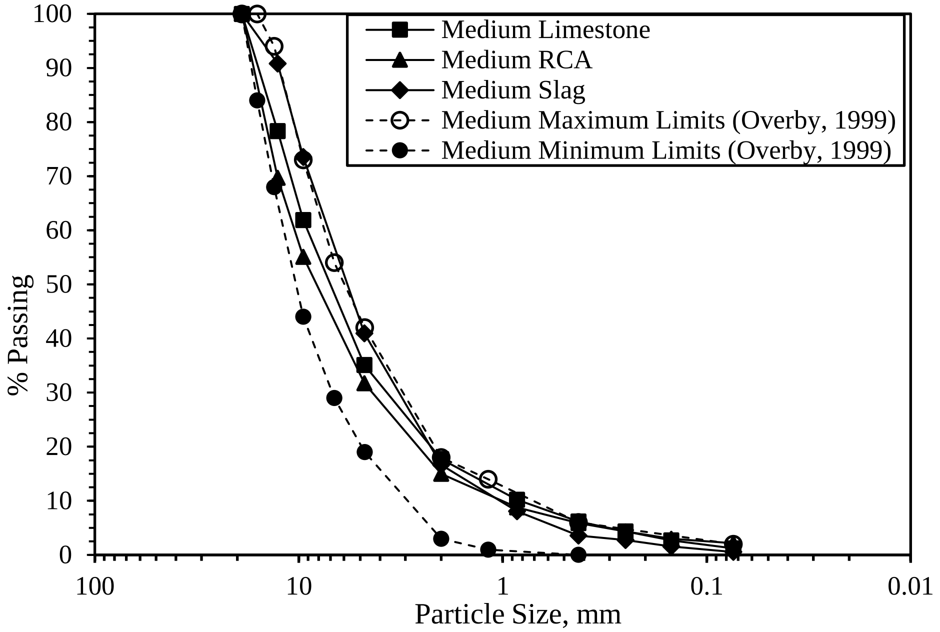


Figure 17. Particle size distribution of medium-graded aggregate along with the recommended limits by Overby (1999)

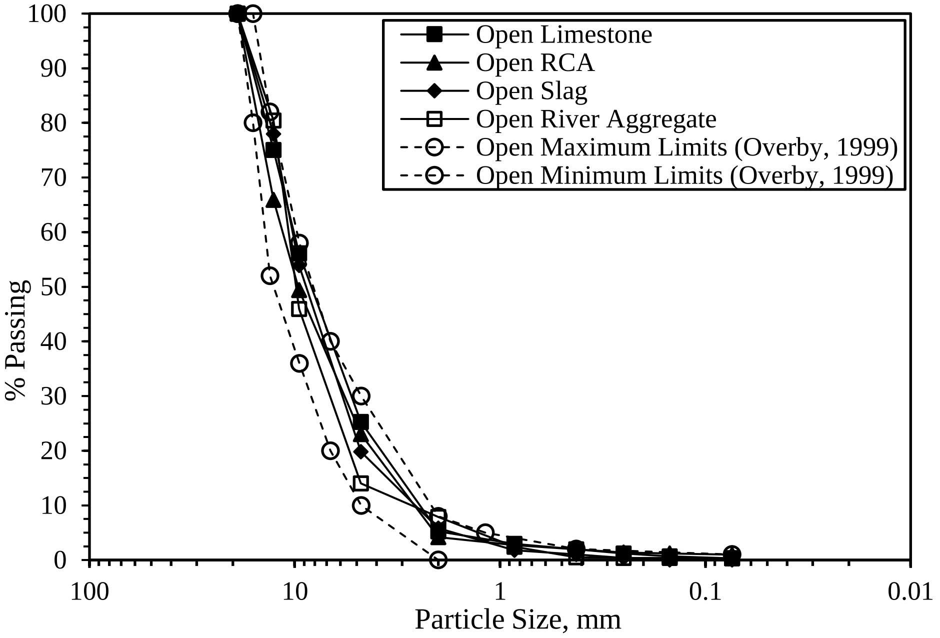


Figure 18. Particle size distribution of open-graded aggregate along with the recommended limits by Overby (1999)

However, it is important to note that, despite these efforts, challenges arose when working with river aggregates. The inherent composition of river aggregates presented a unique hurdle.

Specifically, a deficiency of sand and fine particles in the river aggregate proved to be a limiting factor. As a result, the dense and medium gradations for river aggregates proved to be unattainable within the scope of this study.

Bulk specific gravity is an important property of aggregates used in construction because it provides insights into the compactness and void content of the material. This test is commonly used in quality control and mix design for asphalt concrete. The bulk specific gravity (bulk density) of the coarse and fine aggregates evaluated in this study was determined by following ASTM C127. The specific gravity of the fine fraction of the aggregate was measured using a pycnometer, and a water tank with a wire mesh basket was used to measure the specific gravity of the coarse fraction. Aggregates were dried in an oven at a temperature between 110°C and 121°C until they reached a constant weight.

The procedure for the coarse aggregate includes placing a known volume of water in the water bath and bringing it to a specified temperature (73.4±1.8°C). Then the aggregate sample is suspended in the water bath using the wire basket or a basket with holes and is allowed to soak for a period sufficient for the sample to reach thermal equilibrium with the water. The saturated aggregate sample is removed from the water bath with excess water allowed to drain, then the saturated aggregate is weighed along with the container and the weight recorded. The bulk specific gravity of the aggregate is then calculated using the following formula:

$$G_{mb} = \frac{W_2 - W_1}{W_3 - W_1} \tag{1}$$

where G_{mb} is bulk specific gravity, W_1 is the weight of the empty container/pycnometer, W_2 is the weight of the saturated aggregate and container/pycnometer, and W_3 is the weight of the aggregate in air (saturated surface-dry condition). Figure 21 depicts the apparatus used for measuring the specific gravity of the fine and coarse fractions of aggregate.

(a) (b)

Figure 19. Measuring the bulk specific gravity of (a) the fine aggregate fraction using a pycnometer and (b) the coarse aggregate fraction in a water tank

Measuring the voids in loose aggregate and the unit volume of aggregate is essential for determining the properties and characteristics of aggregates that are crucial for designing asphalt mixtures. ASTM C29 outlines the procedure for measuring the bulk volume, loose unit weight, and voids in loose aggregate. First, the weight of an empty and dry mold is taken, and then loose aggregate is placed into the mold. The weight of the mold filled with loose aggregate is then measured, and the container filled with aggregate is suspended in a water bath at a controlled temperature (73.4±1.8°C). The sample is allowed to soak for a minimum of 15 hours, ensuring that the aggregate is completely saturated, and the container with the saturated aggregate is then removed from the water bath, with excess water allowed to drain. The container containing the saturated aggregate is then weighed. The bulk specific gravity and the voids in the loose aggregate can then be calculated using equations (2) and (3).

$$G_{lb} = \frac{W_2 - W_1}{W_3 - W_1} \tag{2}$$

$$V = 1 - \frac{G_{lb}}{G_{mb}} \tag{3}$$

where G_{lb} is loose bulk specific gravity, W_1 is the weight of the empty container, W_2 is the weight of the container with loose aggregate in air, W_3 is the weight of the container with saturated aggregate in water, and G_{mb} is the bulk specific gravity of the aggregate particles. Figure 20 shows the apparatus, including the cylindrical mold and tamping rod, used to measure the loose unit weight and voids in loose aggregate.

Figure 20. Apparatus used to measure the loose unit weight and voids in loose aggregate

The flakiness index of aggregates is a measure of the percentage of particles in an aggregate sample with a length (longest dimension) less than 0.6 times the nominal size of the aggregate.

Aggregates with a high percentage of flat and elongated (i.e., flaky) particles are considered less desirable. Flaky particles can affect the performance and workability of asphalt mixtures, and this index helps assess the quality of the aggregates being used. The flakiness index of the aggregates used in this study was measured following ASTM D4791. To represent the coarse fraction of aggregate, samples of more than 200 particles retained on the 3/8 in. sieve were obtained. The maximum and minimum dimensions of the individual particles were measured using a thickness gauge, and the flakiness index was then calculated using equation (4). Figure 21 depicts the procedure for measuring the flakiness index of the limestone aggregate.

$$Flakiness\ Index\ (\%) = \frac{\text{Total weight of flat and elongated particles}}{\text{Total weight of all particles in the size fraction}} \times 100 \tag{4}$$

Figure 21. Measuring the flakiness index of limestone aggregate by following ASTM D4791

Table 7 presents a summary of the results obtained from the comprehensive laboratory tests conducted on locally available aggregate. These index properties serve as crucial parameters for estimating the material application rate for Otta seal. These properties also provide insights into how the aggregate will interact with the binder and perform within the Otta seal structure.

Table 7. Results of laboratory characterization tests conducted on collected aggregate

Aggregates		Bulk Specific Gravity, G_{mb}	Loose Unit Weight (lb/f^3)	Voids in Loose Aggregates, V (%)	Flakiness Index (%)
Limestone	Dense	2.61	104.9	23.5	35.6
	Medium	2.60	103.2	24.0	36.4
	Open	2.57	96.5	25.0	39.8
RCA	Dense	2.61	99.0	17.0	39.2
	Medium	2.61	92.5	18.5	42.3
	Open	2.59	84.2	19.2	47.9
Slag	Dense	2.92	121.3	24.3	33.4
	Medium	2.89	110.4	25.2	38.8
	Open	2.87	101.9	25.7	43.1
River Aggregate	Open	2.51	93.7	39.0	40.2

3.4 Material Application Rate

The empirical construction guidelines currently in use for Otta seal were originally formulated in 1963 by the NRRL. Since the aggregate and binder application rates recommended in these guidelines are based on the performance of Otta seal sites in Norway (Overby 1999, Overby and Pinard 2013), determining a rational mix design technique for Otta seal that considers local aggregate and binder properties is essential. By following a rational mix design method, Otta seal performance can be optimized, providing longer lasting and more reliable solutions for enhancing the resilience and functionality of low-volume roads in Iowa.

3.4.1 Application Rate Based on Empirical Guidelines

The guidelines presented by Overby (1999) for determining aggregate and binder application rates in Otta seal construction have been widely adopted in Norway and other regions. Depending on traffic volume, three types of aggregates, i.e., dense-, medium-, or open-graded, can be utilized. Overby (1999) suggested that dense-graded aggregate is suitable for roads with AADT values exceeding 1,000. Medium-graded aggregate is recommended for roads with AADT values ranging from 100 to 1,000, while open-graded aggregate is preferred for roads with AADT values below 100. A nominal maximum aggregate size of 0.6 in. is preferred for a single Otta seal, while a double Otta seal calls for a 0.8 in. aggregate. Table 8 provides an overview of the binder and aggregate application rates for Otta seal, considering traffic levels and aggregate gradation.

Table 8. Binder and aggregate application rate according to empirical guidelines

Type of Otta Seal		Dense (AADT> 1000)	Medium (100<AADT < 1,000)	Open (AADT <100)
Binder Application Rate (gal/yd^2)				
Double	1st Spray	0.38	0.38	0.35
	2nd Spray	0.42	0.35	0.33
Single	1st Spray	0.42*	0.38*	0.35*
Aggregate Application Rate (ft^3/ft^2)				
Otta Seal		0.043–0.052 (0.052*)	0.043–0.052 (0.052*)	0.052–0.066 (0.059*)

* Adapted rates for specimen preparation.
Source: Overby 1999

3.4.2 Application Rate Based on Rational Guidelines

In this study, the widely recognized McLeod method (McLeod 1960) was employed as the primary approach for calculating the application rates of both binder and aggregate. This determination was based on a comprehensive assessment of the aggregate properties and the specific binder types considered in this study. It is important to note that Otta seal, compared to conventional chip seal, permits a higher proportion of fines content within its aggregate framework. Recognizing this distinction, it was necessary to adapt and enhance the McLeod method to better suit the unique requirements of Otta seal applications. The refined version of the McLeod method that resulted from this modification is referred to in this report as the modified McLeod method.

During the early 1960s, Norm McLeod introduced a design method for conventional BSTs that was later adopted by the Asphalt Institute and referred to as the McLeod method (McLeod 1960). This method, based on Hanson's theory (Hanson 1934), was aimed at ensuring adequate embedding of aggregate into the binder (Johannes et al. 2011). Hanson's theory introduced the concept of the average least dimension of aggregate particles because Hanson (1934) observed that aggregates tend to settle on their flattest sides after being subjected to traffic loads. According to Hanson (1934), the initial voids between the aggregates after spraying are assumed to be 50% of the material volume, while the final voids after substantial traffic activity are expected to decrease to 20%. The fundamental principle of the McLeod method is to fill 70% of the final void space with asphalt residue by applying an optimal asphalt binder. The McLeod method provides a means to calculate the aggregate and binder application rates through equations (5) and (6), respectively (Johannes et al. 2011). Equation (5) utilizes parameters such as voids in the loose aggregate, the average least dimension of the aggregate, and the specific gravity of the aggregate to determine the cover aggregate application rates, while equation (6) considers key parameters such as residual asphalt binder content, voids in the loose aggregate, and aggregate absorption factor to calculate the binder application rates. These equations serve as valuable tools for determining appropriate aggregate and binder application rates according to the McLeod method.

$$C = \left[1 - \left(\frac{0.2}{0.5} \times V\right)\right] HGE \times 46736 \tag{5}$$

$$B = \frac{\left(\frac{0.2}{0.5} \times V\right) H \times 25.4 \times T + S + A \times 4.53}{R} \times 0.221 \tag{6}$$

where C = cover aggregate application rate (lb/yd^2), B = binder application rate (gal/yd^2), V = voids in the loose aggregate, H = average least dimension (mm), G = bulk specific gravity of the aggregate, E = wastage factor for traffic whip-off = 1.10 for 10% aggregate loss, T = traffic factor = 0.65, S = surface condition factor (gal/yd^2), A = aggregate absorption factor (gal/yd^2) = 0.03 gal/m^2, and R = residual asphalt content in decimal form.

Table 9 lists the traffic factor values (T) suggested by McLeod (1960) for different traffic volumes. Asphalt cutback and asphalt emulsion exhibit variations in residual asphalt content (R), and it is advisable to verify this aspect with prospective suppliers. For this study, the residual asphalt contents were 0.88 for cutback (MC 3000) and 0.65 for asphalt emulsion (HFMS-2s).

Table 9. Traffic factor values, T

AADT	Traffic Factor, T
< 100	0.85
100 – 500	0.75
500-1,000	0.70
1,000-2,000	0.65
>2,000	0.60

Source: McLeod 1960

A correction factor (S) must be applied depending on the existing surface condition of the aggregate. Table 10 lists correction factors to be added or subtracted from the calculated binder application rate considering the existing surface condition of the aggregate. Note that the collected aggregate for this study required no correction factor.

Table 10. Surface condition correction factor values, S

Textural Rating of the Existing Surface	Operation	S (gal/yd^2)
Black (may have a bleeding issue)	Subtract	Up to 0.06
Smooth (no loss of binder)	Nil	Nil
Hungry 1h (loss of binder for aggregate smaller than 3/8”)	Add	0.03
Hungry 2h (loss of binder for aggregate between 3/4” and 3/8”)	Add	0.06
Hungry 3h (loss of binder for 3/4” aggregate)	Add	0.09

Source: McLeod 1960

The McLeod method was developed for single-size aggregates, while Otta seal uses the local graded aggregate with typically fewer voids in the aggregate skeleton (Shuler and Lord 2009). Due to the lower aggregate and binder application rates resulting from the McLeod method, it becomes necessary to modify the method to accommodate the specific characteristics of the local aggregates to ensure that the McLeod method accurately accounts for the unique properties and behaviors of the local aggregates used in Otta seal. Jibon et al. (2023) proposed a modification to the McLeod method to accommodate the use of local aggregates in Otta seal. Equation (7) gives the modified McLeod method for calculating aggregate application rate, and equation (8) gives the same method for binder application rate.

$$C = \left[1 - \left(\frac{0.2}{0.5} \times V_m\right)\right] H_m G Y_W E \tag{7}$$

$$B = \frac{\left(\frac{0.2}{0.5} \times V_m\right) H_m T + S + A}{R} \tag{8}$$

The modified McLeod equation considers the voids in a 0.5 in. particle skeleton (V_m) by excluding particle sizes larger than 0.5 in. from the aggregate structure. Determination of the void content in loose aggregates, V_m, was carried out in accordance with ASTM C29. It is important to note that this determination specifically excluded particles with a size smaller than 0.5 in. as part of the testing process.

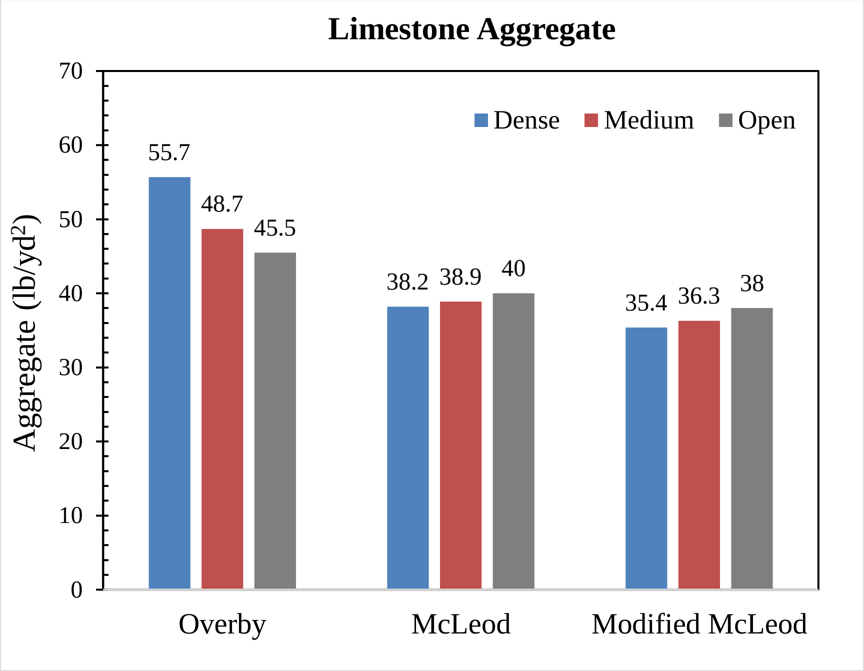
The modified average least dimension (H_m) in both equations (7) and (8) represents the average least dimension of particles larger than 0.5 in. The modified McLeod equation incorporates the consideration of voids within the 0.5 in. particle skeleton, assuming a 70% embedment of the largest aggregate particle (with a nominal maximum aggregate size of 12.7 mm) of the Otta seal within the residual asphalt (Jibon et al. 2023). The average least dimension of each aggregate type was measured in the laboratory after excluding particles passing through a 3/8 in. sieve from the aggregate skeleton. In total, approximately 100 particles were separated by the sieving process, and the least dimension of those particles was measured using a thickness gauge, as shown in Figure 22. The average of the measured dimensions of these particles was noted and listed as the modified average least dimension. Table 11 lists aggregate properties that were used in the modified McLeod method for the calculation of material application rates.

Figure 22. Measuring the average least dimension of aggregate using a thickness gauge

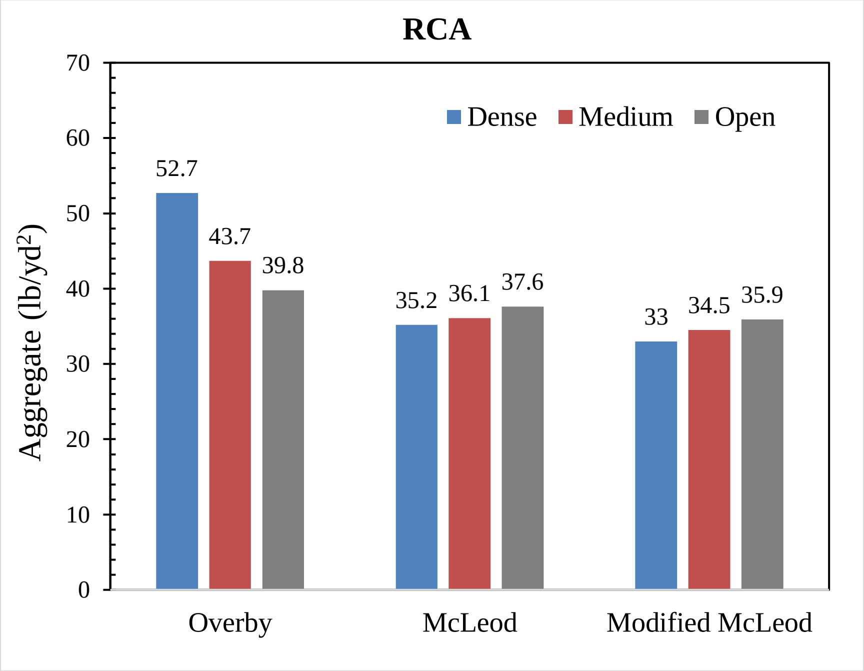
Table 11. Summary of the aggregate properties used in the modified McLeod method

Aggregates		**Modified Voids in Loose Aggregates, V_m (%)**	**Modified Average Least Dimension, H_m (in.)**
Limestone	Dense	50.0	0.33
	Medium		0.34
	Open		0.36
RCA	Dense	52.2	0.31
	Medium		0.32
	Open		0.34
Slag	Dense	53.1	0.28
	Medium		0.31
	Open		0.34
River Aggregate	Open	54.0	0.30

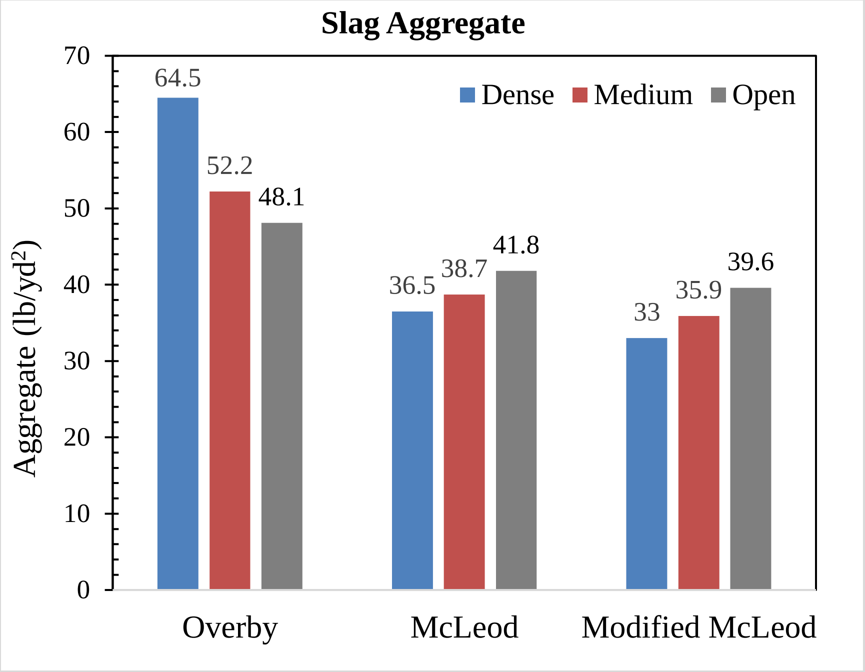
Figure 23 depicts the aggregate application rates calculated according to the Overby, McLeod, and modified McLeod methods. The modified McLeod method resulted in the lowest aggregate application rate for limestone, RCA, slag, and river aggregate. Figure 24 illustrates the HFMS-2s binder application rates calculated according to the Overby, McLeod, and modified McLeod methods. The modified McLeod method resulted in a lower HFMS-2s binder application rate for limestone, RCA, slag, and river aggregate compared to the Overby method’s suggested application rate. The MC 3000 binder application rates calculated according to the Overby, McLeod, and modified McLeod methods are shown in Figure 25. The modified McLeod method resulted in a lower MC 3000 binder application rate than the Overby method’s suggested application rate, with the aggregate gradation playing a significant role in the material application rate calculation. The application rate of the open-graded aggregate was higher compared to that of the dense-graded aggregate for the McLeod and modified McLeod methods, but the Overby method exhibited the reverse trend for the aggregate application rate. The binder application rate of the open-graded aggregate was also higher compared to that of the dense-graded aggregate for the McLeod and modified McLeod methods, while the Overby method again exhibited the reverse trend for the binder application rate.



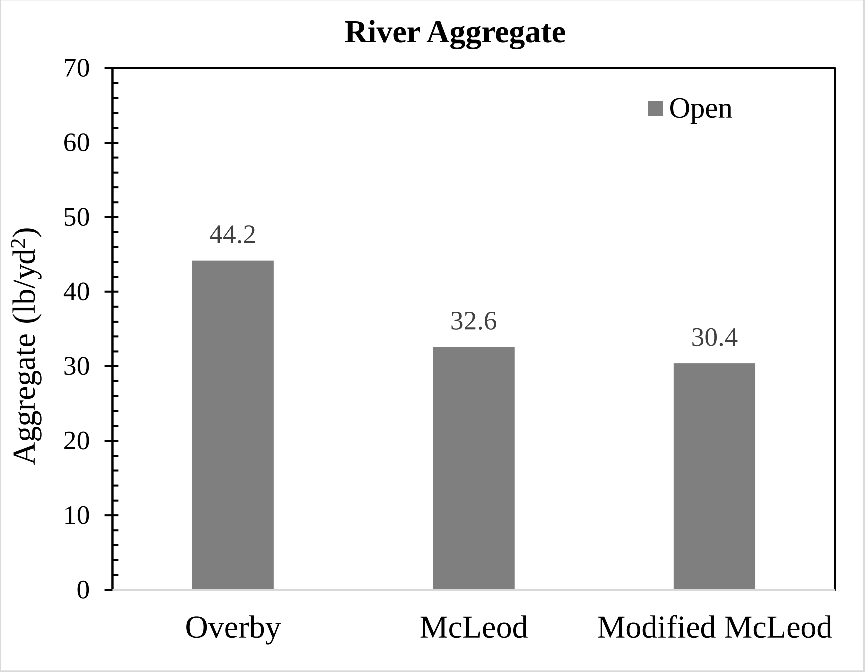
(a)



(b)

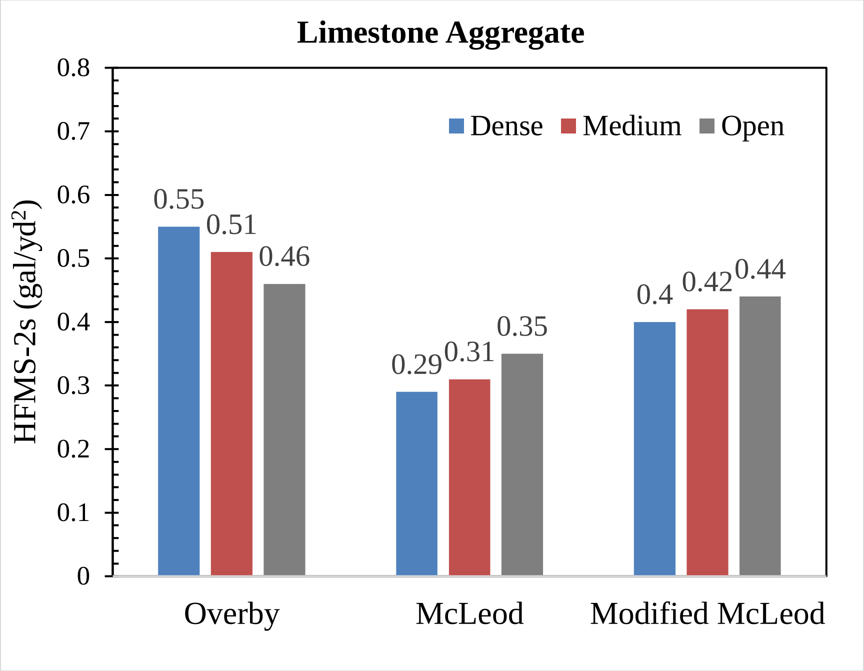


(c)

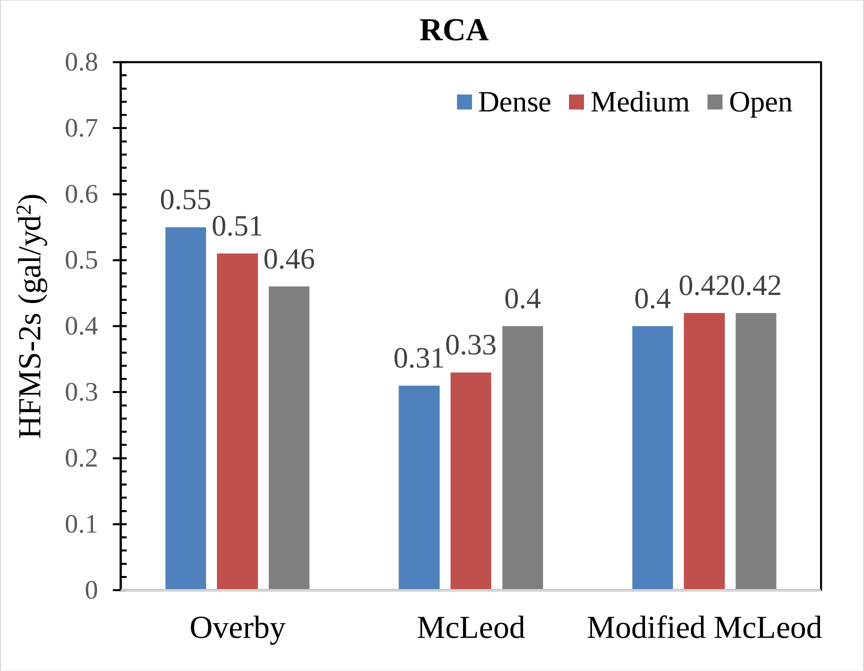


(d)

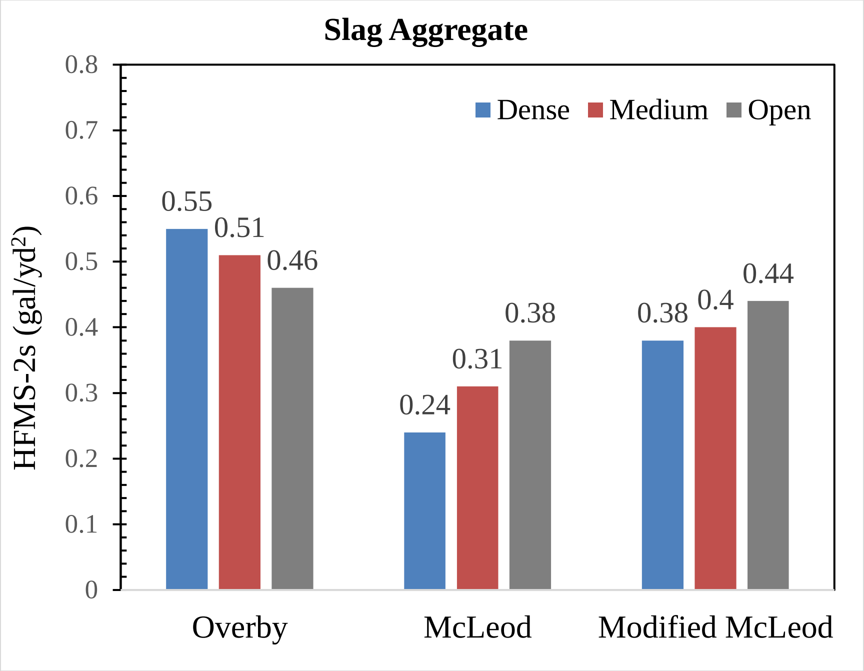
Figure 23. Calculated aggregate application rates for (a) limestone, (b) RCA, (c) slag, and (d) river aggregate


Limestone Aggregate
HFMS-2s (gal/yd²)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Dense
Medium
Open
0.55
0.51
0.46
0.29
0.31
0.35
0.4
0.42
0.44
Overby
McLeod
Modified McLeod

(a)


RCA
HFMS-2s (gal/yd²)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Dense
Medium
Open
0.55
0.51
0.46
0.31
0.33
0.4
0.4
0.42
0.42
Overby
McLeod
Modified McLeod

(b)



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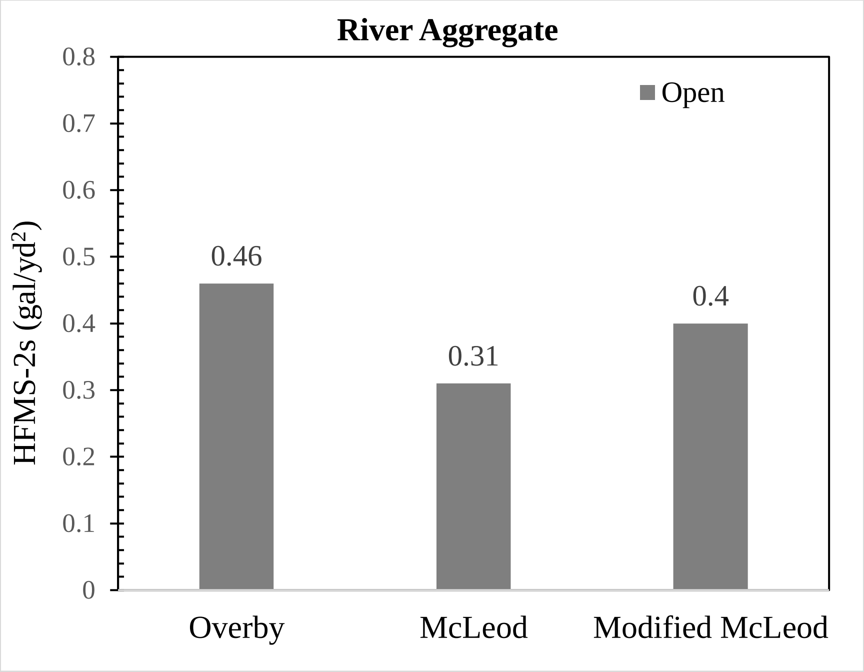
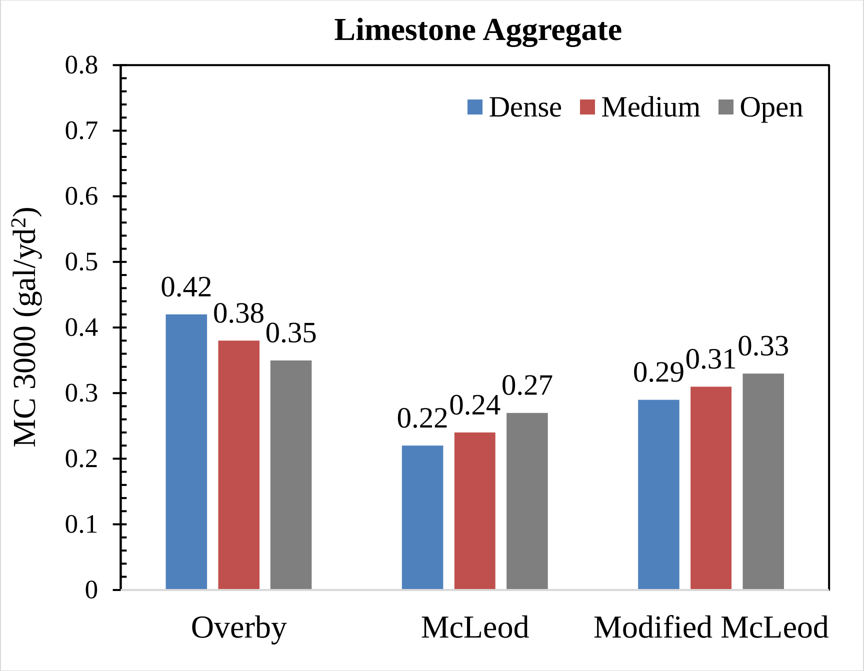
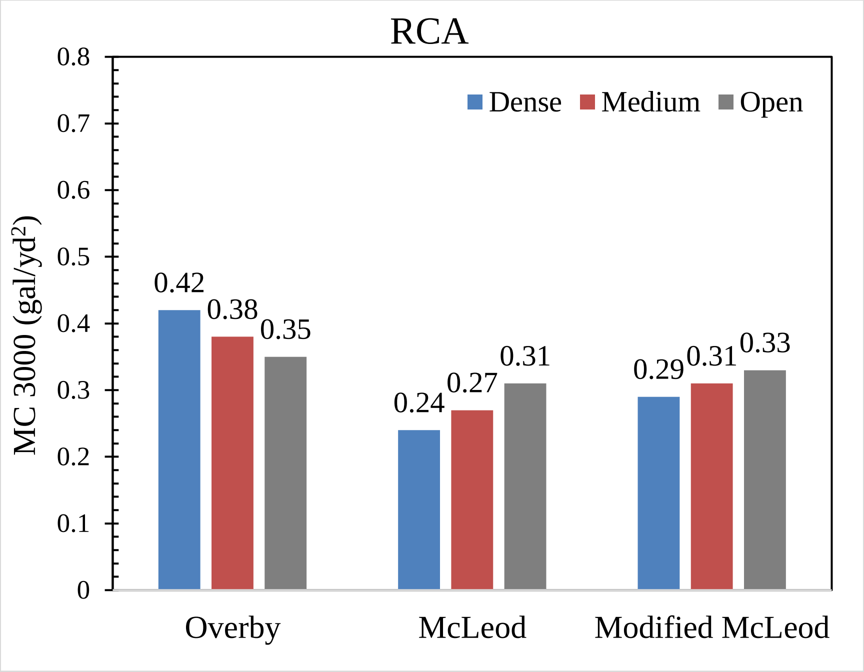


(d)

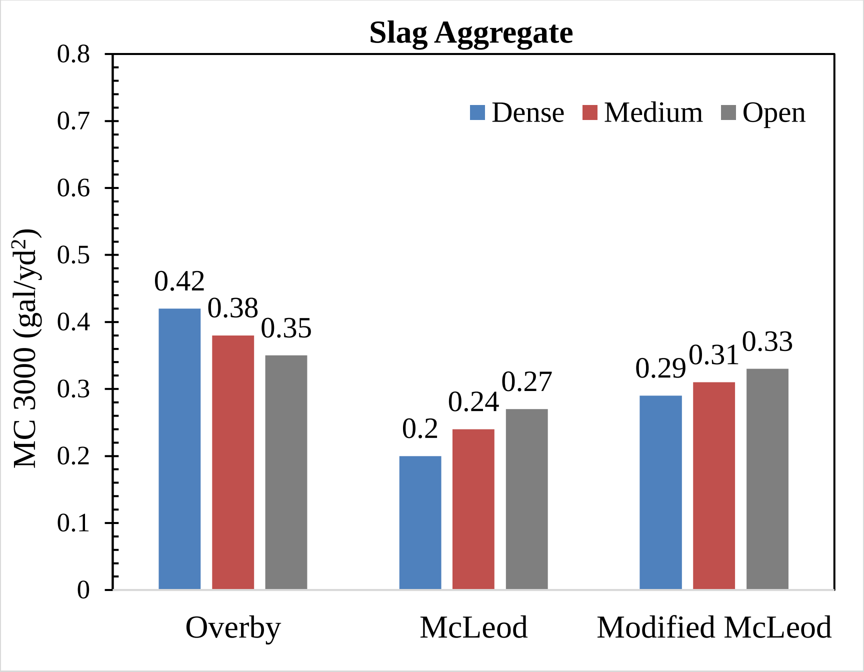
Figure 24. Calculated HFMS-2s application rates for (a) limestone, (b) RCA, (c) slag, and (d) river aggregate


Limestone Aggregate
MC 3000 (gal/yd²)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Dense
Medium
Open
0.42
0.38
0.35
0.22
0.24
0.27
0.29
0.31
0.33
Overby
McLeod
Modified McLeod

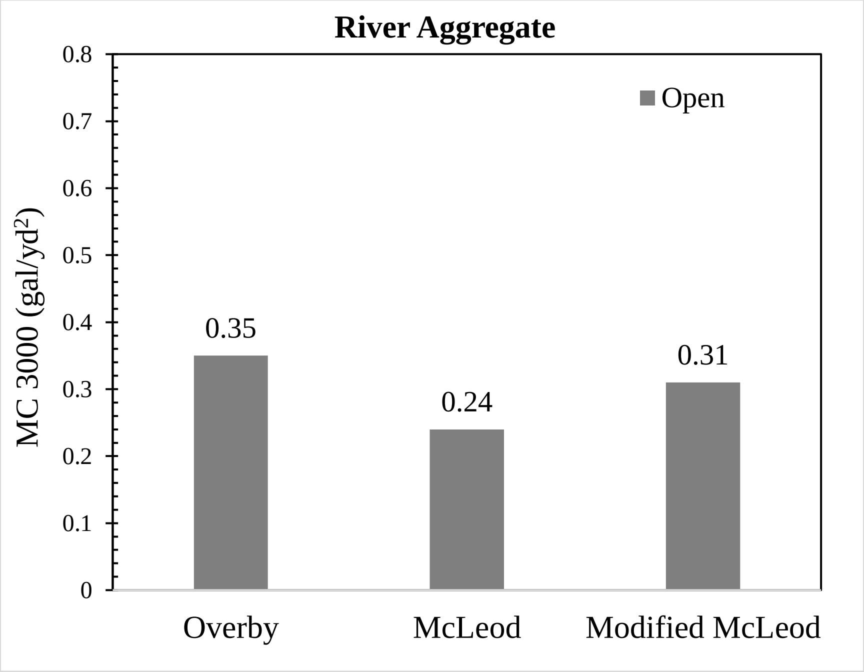
(a)


RCA
MC 3000 (gal/yd²)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Dense
Medium
Open
0.42
0.38
0.35
0.24
0.27
0.31
0.29
0.31
0.33
Overby
McLeod
Modified McLeod

(b)



(c)



(d)

Figure 25. Calculated MC 3000 application rates for (a) limestone, (b) RCA, (c) slag, and (d) river aggregate

3.5 Laboratory Sweep Tests

ASTM D7000 is a standard test method that provides guidelines for conducting a sweep test for chip seal surfaces or conventional asphalt-treated surfaces. A sweep test involves sweeping a mechanical device or tool over an asphalt-treated surface to simulate the effects of traffic and abrasion. According to ASTM D7000, the sweep test for chip seal applications is significant for quality control and for assessing durability, safety, cost-effectiveness, environmental impact, and public satisfaction. It helps ensure that chip seal applications are constructed correctly, resulting in longer lasting and safer road surfaces, in turn benefiting both transportation agencies and road users. This study adopted the sweep test methods specified in ASTM D7000 to evaluate the performance of Otta seal specimens. The study aimed to understand how much aggregate material is lost or worn away from Otta seal surfaces due to abrasion, which is important information for assessing the durability and performance of Otta seal road surfaces.

3.5.1 Modification of the ASTM D7000 Sweep Test

Since this study used locally sourced aggregates with a wide range of particle sizes rather than the uniformly graded aggregate used in chip seal applications, the existing sweep test method had to be adapted and modified to accommodate the use of nonuniformly graded aggregates. This modification involved adjusting the testing procedures and criteria to suit the specific characteristics of the Otta seal specimens being tested. Modifications included changes in the preheating temperatures, application rates, compaction methods, curing conditions, and aggregate sizes and gradations, all adjustments necessary to ensure that the research objectives were accurately met.

The first modification, involving adjusting the preheating temperatures for the binders used in the Otta seal specimens, was aimed at optimizing the binder's properties for the specific conditions of the study. Unlike the constant emulsion application rate specified in ASTM D7000 (0.31 gal/yd^2), variable application rates for both binders and aggregates were used in this study to assess how different application rates affected aggregate loss, a crucial aspect of the research. The method of compaction for preparing the specimens was modified by assembling a steel compactor with a rubber pad. This modification was intended to prevent the breakage of larger aggregate particles during compaction, ensuring specimen integrity. The curing conditions for the specimens were adjusted based on the setting time of each binder to ensure that the curing process was aligned with the binder's properties and allowed for the appropriate development of the Otta seal samples. ASTM D7000 calls for single-size aggregates with specific gradation requirements (100% passing through a 3/8 in. sieve, with fewer than 1% passing through a No. 4 sieve). This study used different aggregate sizes and gradations based on established guidelines drawn from the Overby, McLeod, and modified McLeod methods. The quantities of aggregate and binder required for preparing the Otta seal specimens are listed in Figure 23 through Figure 25.

3.5.2 Specimen Preparation

The Otta seal specimen preparation process described in ASTM D7000 involves several specific steps. Initially, a predetermined quantity of binder was weighed and applied to a felt disk, and a strike-off rod was used to ensure even distribution. In this case, the MC 3000 and HFMS-2s binders were preheated to temperatures of 110℃ and 80℃, respectively. Preheating helped to achieve sufficient fluidity of the binder during specimen preparation. After the hot binder was evenly spread on the felt disk, a predetermined amount of aggregate was applied. This was done by moving back and forth evenly to ensure uniform distribution of the aggregate over the hot binder.

A modified steel compactor was then employed to compact the Otta seal specimens. This compaction process was carried out over six cycles in both the horizontal and perpendicular directions. The number of compaction cycles was selected based on two important considerations. First, there must be sufficient compaction to achieve the desired density and stability of the specimen while minimizing aggregate loss. Second, it was crucial to prevent the breakage of aggregate particles during compaction.

The conditioning process for the Otta seal specimens involved placing them in an oven set to specific temperature and time conditions. Otta seal specimens prepared with the MC 3000 binder were cured at 35°C for 1 hour, a temperature and time combination selected for proper conditioning. Due to the higher water content of the HFMS-2s binder, a two-stage conditioning process was selected for Otta seal specimens using this binder. First, they were cured at 35℃ for 1 hour, then they went through an additional 48 hours of curing at 25℃. The longer curing time for the HFMS-2s specimens was necessary because the higher water content of the binder could affect the curing process. The choice of these specific curing conditions for the HFMS-2s and MC 3000 specimens was determined through a preliminary laboratory investigation aimed at ensuring that the binder had been set adequately to hold the aggregate particles firmly in place.

Figure 26 provides a visual representation of the Otta seal specimen preparation process for the sweep test. This illustration serves as a visual aid for better understanding the described specimen preparation procedure.

(a) (b)

(c) (d)

(e)

Figure 26. Otta seal specimen preparation: (a) aggregate weighed in pan, (b) binder spread on felt disk, (c) rubber pad on modified steel compactor, (d) top of modified steel compactor, and (e) specimen curing in the oven

3.5.3 Measuring Aggregate Loss

After subjecting the Otta seal specimens to the specified conditioning process, the aggregate loss was measured using a sweep test apparatus designed to replicate the wear and tear experienced by road surfaces due to traffic. This apparatus incorporated a mechanical brush assembly affixed to a carriage that moved across each specimen’s surface for 1 minute. During the test, the brush assembly was smoothly swept over the Otta seal specimen, maintaining a consistent speed and pressure. As the brush moved, its action served to dislodge any loose aggregate particles present on the surface, and a collecting pan or tray was strategically positioned beneath the specimen to capture these dislodged particles. Figure 27 illustrates the sweep test used on the Otta seal specimens and the resulting loose aggregate after abrasion from the sweeping brush.

(a) **(b)**

Figure 27. Sweep test: (a) conducting sweep test on Otta seal specimen and (b) collecting loose aggregate after sweep test

Once the sweep test was complete, the aggregate collected in the pan was meticulously weighed, and the formula shown in equation (9) was applied to determine the aggregate loss following the sweep test.

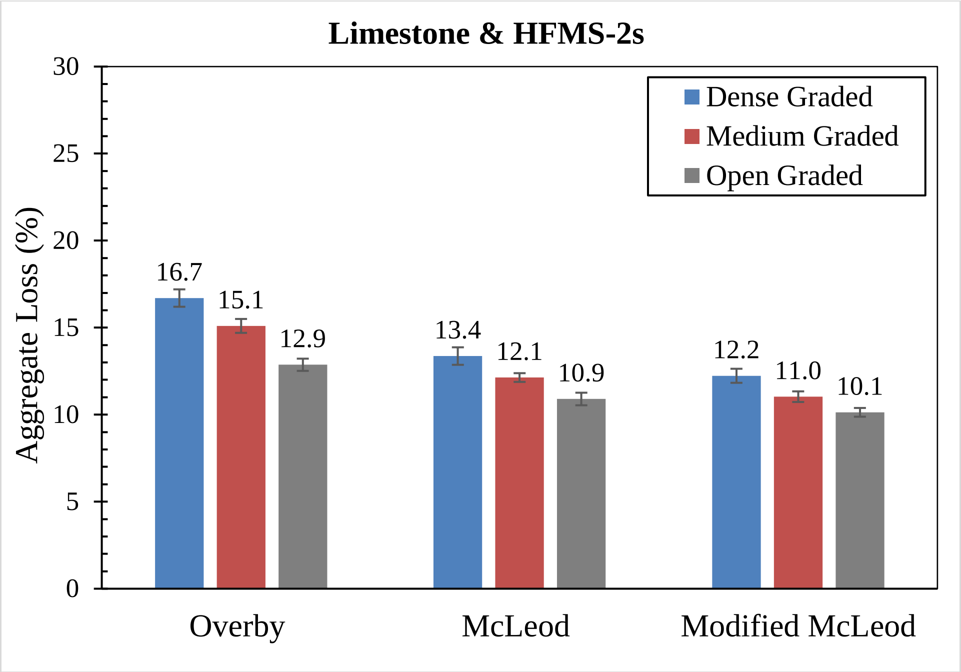
$$\%\ Aggregate\ Loss = \left[\frac{A-B}{A-C}\right] \times 100 \times 1.33 \tag{9}$$

where A = initial specimen weight before the sweep test, B = final specimen weight after the sweep test, and C = weight of felt disk used in specimen preparation.

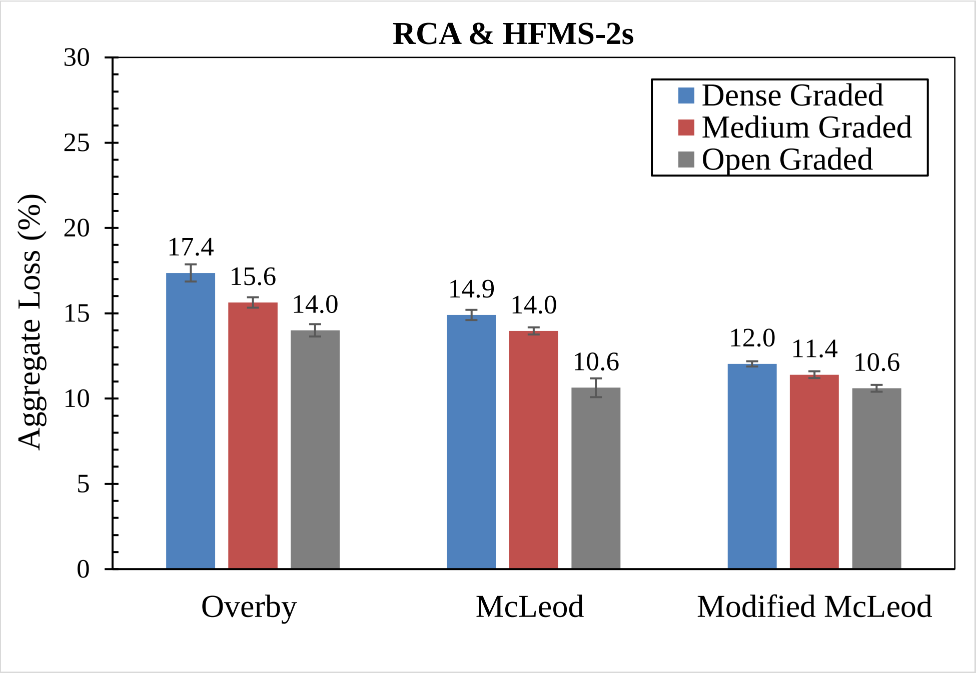
3.6 Results and Discussion

The percentage aggregate loss obtained from the sweep tests is shown in Figure 28 and Figure 29 for Otta seal specimens made with HFMS-2s or MC 3000 binder, respectively.

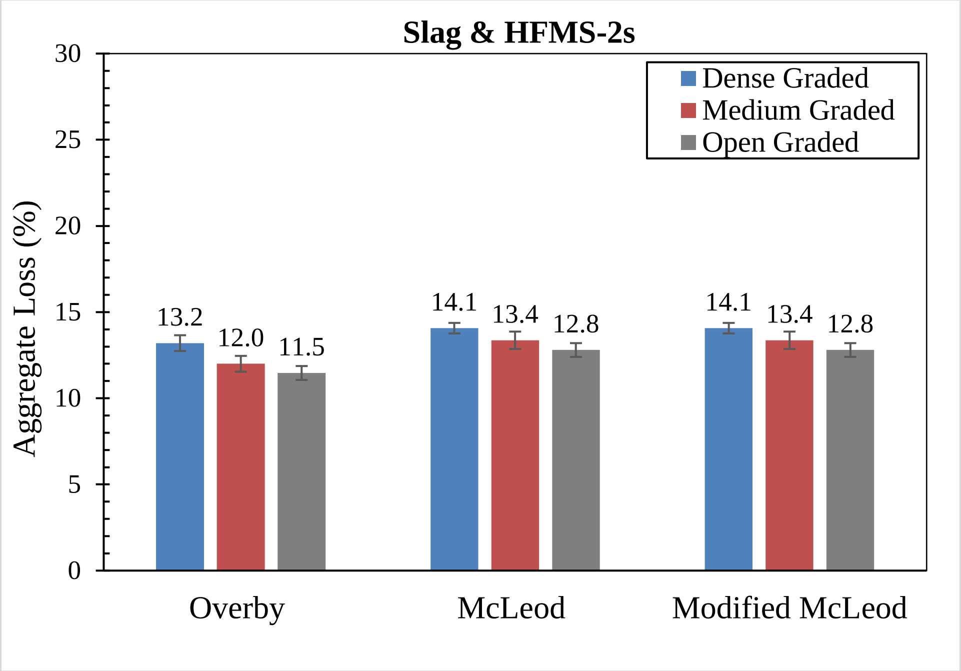
The aggregate loss of the Otta seal specimens prepared using HFMS-2s binder with limestone, RCA, slag, and river aggregate is shown in Figure 28, where the difference in aggregate loss among specimens prepared by following the Overby, McLeod, and modified McLeod methods is evident.


Limestone & HFMS-2s
Aggregate Loss (%)
0
5
10
15
20
25
30
Dense Graded
Medium Graded
Open Graded
16.7
15.1
12.9
13.4
12.1
10.9
12.2
11.0
10.1
Overby
McLeod
Modified McLeod

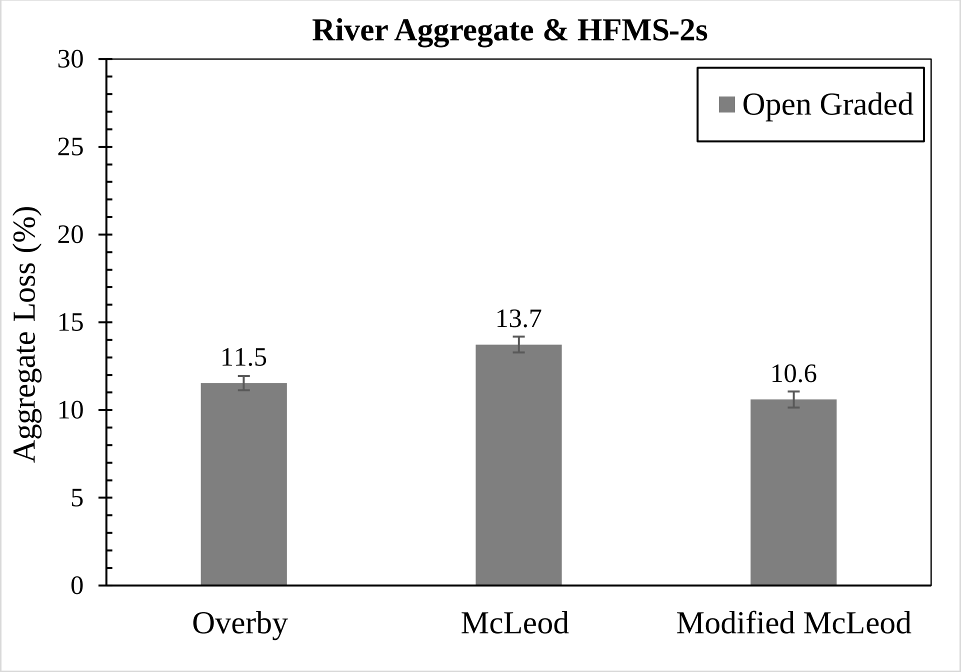
(a)


RCA & HFMS-2s
Aggregate Loss (%)
0
5
10
15
20
25
30
Dense Graded
Medium Graded
Open Graded
17.4
15.6
14.0
14.9
14.0
10.6
12.0
11.4
10.6
Overby
McLeod
Modified McLeod

(b)



(c)



(d)

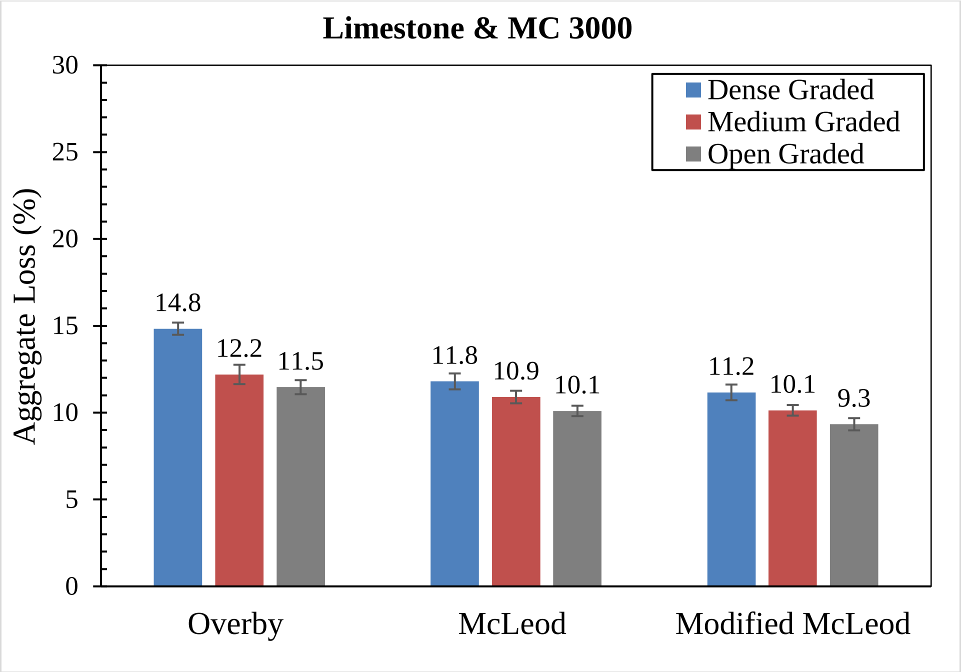
Figure 28. Effect of material application rate calculation method on aggregate loss from Otta seal specimen prepared with HFMS-2s binder for (a) limestone aggregate, (b) RCA, (c) slag aggregate, and (d) river aggregate

The modified McLeod method resulted in the lowest aggregate loss for the Otta seal specimens containing limestone, RCA, and river aggregate. This outcome was expected because the application rates determined using the modified McLeod method result in increased binder rate-to-aggregate rate (BR/AR) ratios. These elevated BR/AR ratios validate the importance of adequately embedding larger aggregate particles in the asphalt binder.

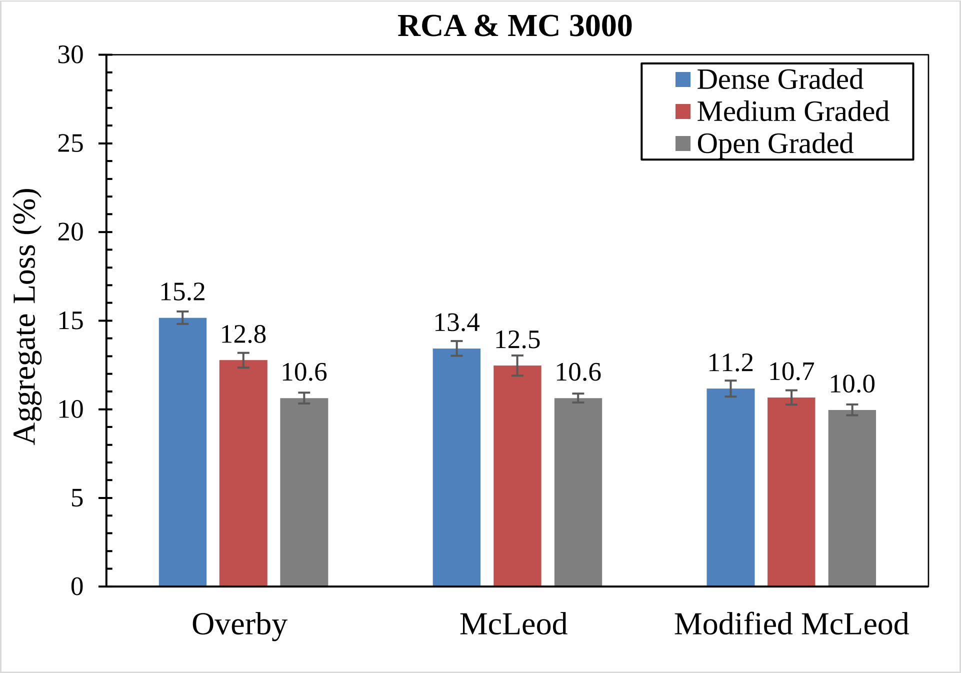
It was noted that fewer voids were present in loosely packed slag aggregates, resulting in a lower rate of binder application using the modified McLeod method. It was also observed that the average smallest dimensions of the slag aggregates were smaller compared to those of the limestone, RCA, and river aggregates. These two factors, i.e., the smaller aggregate dimensions and the reduced voids, had a direct influence on the modified McLeod application rate for slag aggregate. The reduced binder application rate of the modified McLeod method resulted in a higher aggregate loss for the slag aggregate specimen prepared using this method compared to the slag aggregate specimen prepared using the Overby method. It is evident that material gradation plays a significant role in aggregate loss, particularly with respect to the McLeod and modified McLeod application rates.

Open-graded limestone, RCA, slag, and river aggregate specimens demonstrated lower levels of aggregate loss compared to medium- and dense-graded aggregate specimens, a discrepancy attributed to the fact that open-graded aggregates required lower levels of aggregate application due to higher binder application rates. This resulted in a higher BR/AR ratio and reduced aggregate loss for open-graded aggregate specimens, primarily because a larger surface area of the aggregate was coated with binder. In contrast, dense gradations featured higher concentrations of fine and sand particles within the matrix, leading to a greater specific surface area. Such characteristics may result from inadequate coating and bonding between the aggregates and asphalt cement, leading to increased aggregate loss. Since aggregate gradation directly affects interlocking within the aggregate skeleton, the presence of fines and sand-sized particles fills the voids between the gravel elements, so dense-graded materials may be more suitable for high-volume traffic scenarios (with AADT volumes exceeding 1,000 vehicles) despite their elevated potential for aggregate loss. Achieving adequate compaction and an optimal BR/AR ratio are expected to be crucial factors in mitigating these adverse effects.

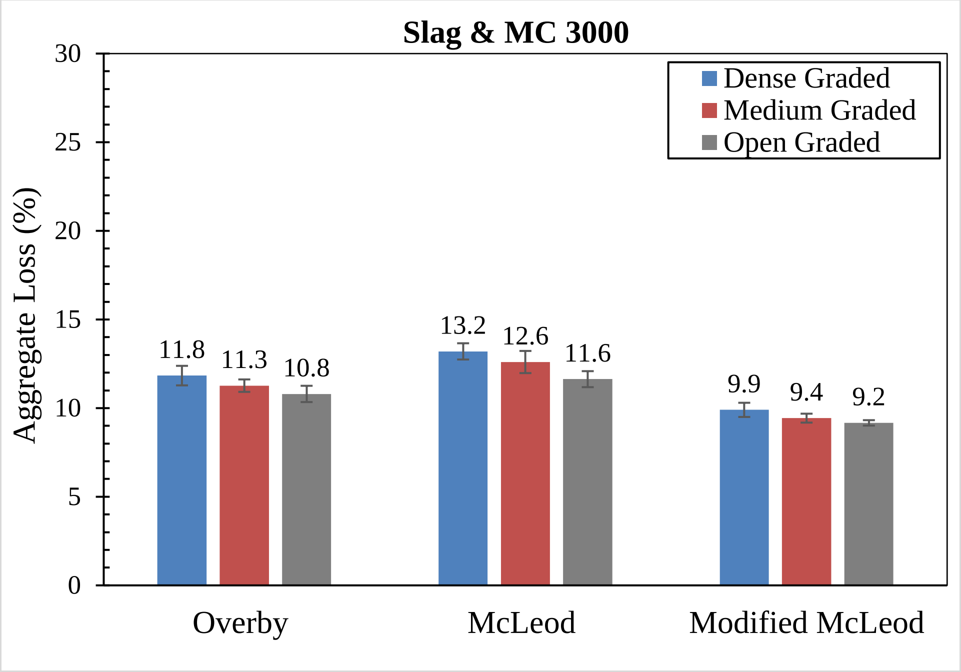
Figure 29 illustrates the aggregate loss of Otta seal specimens prepared using MC 3000 binder with limestone, RCA, slag, and river aggregate. These Otta seal specimens showed a trend in aggregate loss similar to that of the specimens prepared using the HFMS-2s binder, except for the slag aggregate specimen.


Limestone & MC 3000
Dense Graded
Medium Graded
Open Graded
Aggregate Loss (%)
30
25
20
15
10
5
0
14.8
12.2
11.5
11.8
10.9
10.1
11.2
10.1
9.3
Overby
McLeod
Modified McLeod

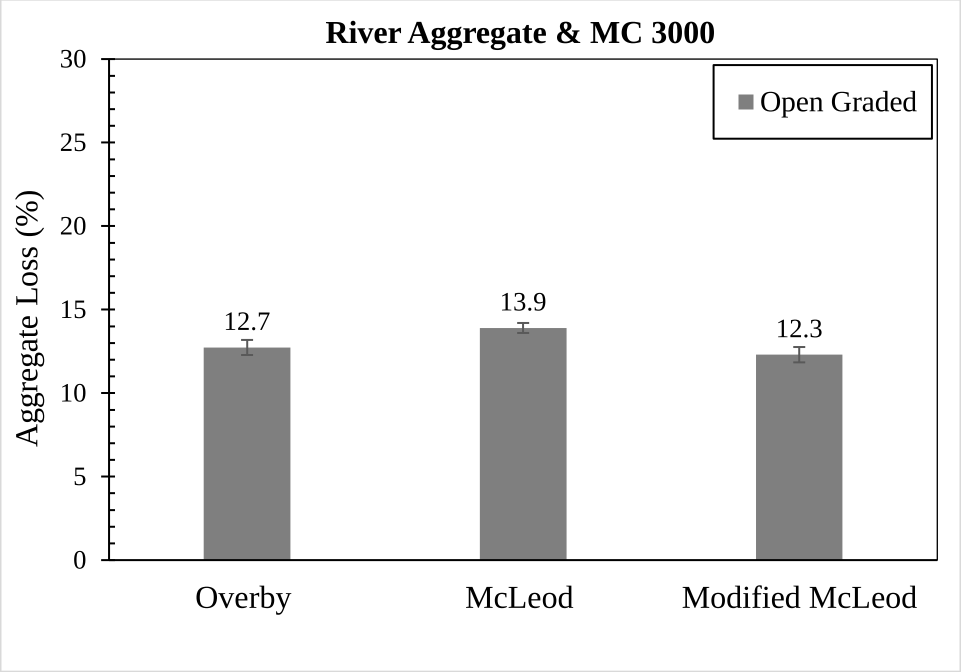
(a)


RCA & MC 3000
Dense Graded
Medium Graded
Open Graded
Aggregate Loss (%)
30
25
20
15
10
5
0
15.2
12.8
10.6
13.4
12.5
10.6
11.2
10.7
10.0
Overby
McLeod
Modified McLeod

(b)



(c)



(d)

Figure 29. Effect of material application rate calculation method on aggregate loss from Otta seal specimen prepared with MC 3000 binder for (a) limestone aggregate, (b) RCA, (c) slag aggregate, and (d) river aggregate

Otta seal specimens prepared according to the modified McLeod method exhibited the lowest aggregate loss for limestone, RCA, slag, and river aggregate. Similarly to the HFMS-2s specimens, open-graded limestone, RCA, slag, and river aggregate specimens exhibited reduced aggregate loss levels compared to medium- and dense-graded aggregate specimens. Of the three methods evaluated in this study, the Overby method necessitated larger quantities of aggregates and binders for construction. Conversely, the modified McLeod method was linked to the highest BR/AR ratio. Because a higher binder content in the asphalt mixture can lead to improved coating and binding with aggregate particles, it was expected that an increase in the BR/AR ratio would consequently decrease aggregate loss.

Among the four aggregates, slag aggregate specimens exhibited the lowest aggregate loss, particularly in specimens prepared with MC 3000 binder. This can be attributed to the high porosity and voids in slag, which absorbed more asphalt cement and formed a robust adhesive bond with the MC 3000 binder. Limestone and RCA had higher fines contents compared to the other aggregates, leading to increased mass loss in these specimens during the sweep test. The aggregate loss results from the RCA and slag specimens exhibited a potential for adapting recycled aggregate for Otta seal road construction with performance comparable to that of conventional limestone aggregate.

3.7 Key Findings

The primary goal of this study was to establish a rational method for designing Otta seal road surfaces using locally available materials. Four different types of aggregates, i.e., limestone, RCA, slag, and river aggregates, were collected and categorized into dense, medium, and open grades. The McLeod, modified McLeod, and Overby methods were utilized to determine the optimal aggregate and binder application rates. Otta seal performance was assessed primarily by measuring aggregate loss through sweep tests. The study explored the impact of various factors, including aggregate type and gradation, binder type, and aggregate and binder application rate, on aggregate loss. The key findings of this study can be summarized as follows:

- Aggregate gradation had a more significant influence on aggregate loss than the presence of a specific binder. Aggregate loss decreased as the aggregate gradation shifted from dense to open. Using open-graded aggregates, characterized by their low fines content, allowed for improved coating of larger aggregates, resulting in reduced aggregate loss.
- Binder type had a notable impact on Otta seal aggregate loss. Otta seal samples prepared with both HFMS-2s and MC 3000 binders exhibited comparable performance. However, it is worth noting that specimens prepared with HFMS-2s required a longer curing time to achieve their desired performance levels compared to those prepared with MC 3000.
- Aggregate loss was not significantly affected by the specific type of aggregate used in specimen preparation. Specimens containing both recycled materials, namely slag and RCA, performed well in the sweep tests. Notably, when the Overby application rate was used, slag specimens demonstrated the lowest aggregate loss among all of the aggregate specimens, and when the modified McLeod application rate was used, RCA specimens showed aggregate loss results very similar to those of limestone aggregate specimens.
- Otta seal specimens prepared using the modified McLeod application rates exhibited superior performance in terms of aggregate loss during the sweep tests. The higher BR/AR ratios used in the modified McLeod method enabled adequate coating and bonding of the aggregates, effectively minimizing the aggregate mass loss.

4 FIELD INVESTIGATION TO EVALUATE THE RATIONAL DESIGN APPROACH FOR IOWA

The objective of this field study was to investigate and implement the rational mix design method for the application of Otta seal to low-volume roads in Iowa. The primary aim was to evaluate the effectiveness and performance of Otta seal as a surfacing option for low-volume roads in Iowa while considering specific local material properties in calculating binder and aggregate application rates.

4.1 Otta Seal Site in Page County, Iowa

County Road J55 in Page County, Iowa, was selected for Otta seal construction, and three test sections were constructed for investigation of the effectiveness of the proposed rational mix design method. Figure 30 shows the test sections built on County Road J55 in Page County, Iowa. Test section TS-1 was built based on the application rates recommended by Overby (1999), and test section TS-2 was constructed based on the application rates recommended by the modified McLeod method. Prior to Otta seal construction, the base layers of both test sections were stabilized by applying cement. An additional test section, TS-3, the control section, was built on a nonstabilized layer and was also based on the application rates recommended by Overby (1999). The AADT for County Road J55 is 270, including mostly heavy truck traffic from a nearby quarry. The length of each test section is shown in Figure 30.

Figure 30. Location of Otta seal test section on County Road J55 near Braddyville in Page County, Iowa

The existing surface conditions before applying Otta seal are shown in Figure 31, where several distresses, including cracking, potholes, rutting, and faulting, can be observed.

Figure 31. Condition of County Road J55 in Page County, Iowa, before implementing Otta seal (August 2020)

4.2 Design and Construction Methods

4.2.1 Material Selection

Aggregate and asphalt binder are the two materials used for Otta seal construction according to the Overby (1999) guidelines. Both crushed and uncrushed materials, and a combination of both, are suitable for producing the graded aggregate used in Otta seals, giving emphasis to the use of locally available materials (Overby 1999). Aggregate for Otta seal construction was collected from the nearby Schildberg quarry located in Braddyville, Page County, Iowa, 0.25 miles from the Otta seal construction site. Aggregate gradation following ASTM C136 was performed in the laboratory. To facilitate comparison between the actual aggregate gradation and the gradations suggested by Overby (1999), a grain size distribution curve for the available limestone aggregate was plotted, as shown in Figure 32. The purpose of this plot was to determine whether the curve aligns with the specified limits. The gradation curve for the aggregate used in Otta seal construction in Page County largely follows the medium gradation limits specified by Overby (1999), except that the aggregate contains oversized particles (i.e., particles larger than 3/4 in.).

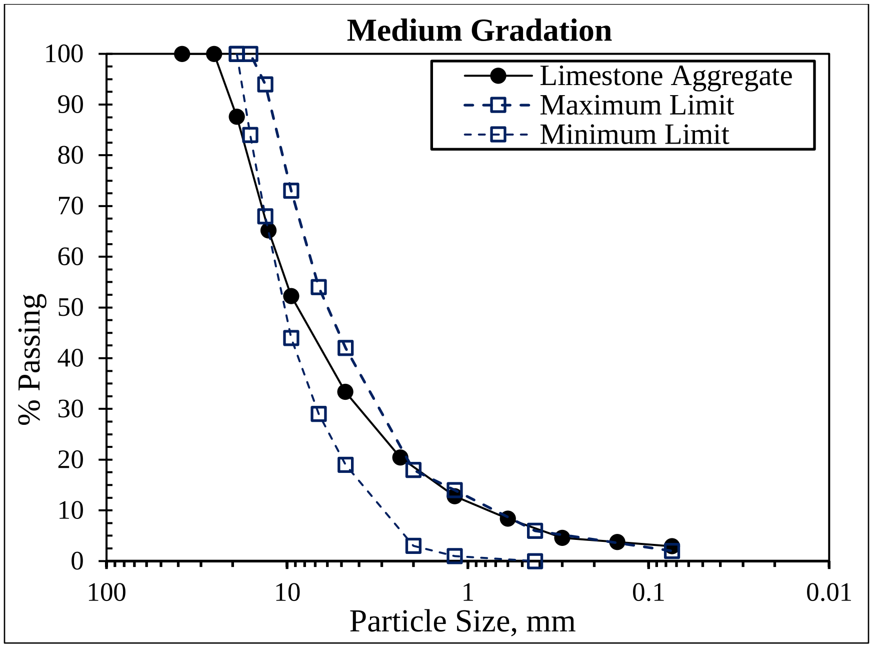


Figure 32. Particle size distribution of limestone aggregate along with recommended limits by Overby (1999)

The selection of appropriate asphalt binders for Otta seal construction plays a vital role in creating a stable, durable, and water-resistant surface that can withstand traffic loads and environmental conditions. Historically, cutback and asphalt emulsion have been successfully used in Otta seal construction in Africa and Scandinavian countries (Wilkinson et al. 2013 and Overby 1999). MC 3000 cutback binder was selected for Otta seal construction in this study to provide a sufficient coating for the aggregate particles. MC 3000 belongs to the medium-curing (MC) class of asphalt binders, with a medium to high viscosity and a moderate curing rate.

4.2.2 Material Application Rate Calculation

The various engineering properties of the selected aggregate were measured in the laboratory to determine the appropriate binder and aggregate application rate according to the modified McLeod method. The laboratory tests characterized the flakiness index, average least dimension, loose unit weight, voids in the loose aggregate, and bulk specific gravity of the aggregate. The voids in the loose aggregate (V_m) were determined following ASTM C29, which involves excluding particles smaller than 12.7 mm from the aggregate skeleton. A thickness gauge, used to measure the average least dimensions of the aggregates, was employed for flakiness testing, and the procedure followed ASTM D4791. The measurements were taken from 100 particles larger than 0.5 in. The bulk specific gravity of the aggregate and the flakiness index were estimated using ASTM C127 and ASTM C29, respectively. The modified McLeod application rates were calculated using equation (7) for the aggregate and equation (8) for the asphalt binder. Table 12 lists the required engineering properties of the aggregate, the calculated modified McLeod application rates, and the adapted Overby application rates. The application rates recommended by Overby (1999) were selected for field construction based on the traffic level and aggregate gradation.

Table 12. Summary of aggregate properties and material application rates

Aggregates	Flakiness Index (%)	Average Least Dimension, H_m (in.)	Loose Unit Weight (lb/ft^3)	Voids in Loose Aggregate (%)		Bulk Specific Gravity, G
				V	V_m	
Limestone	22.0	0.35	98.8	37.3	49.2	2.61
	Overby Recommended Rate (TS-1 and TS-3)		Modified McLeod Rate (TS-2)			
	AR (lb/yd^2)	BR (gal/yd^2)	AR (lb/yd^2)		BR (gal/yd^2)	
	46.6	0.38	41.5		0.35	

4.2.3 Construction of Test Section

The Otta seal construction process for County Road J55 adhered closely to the Iowa Otta seal specifications (Appendix A) developed in this research and can be broken down into three main stages: site preparation (pre-construction), field construction, and post-construction. The first step involved reclamation of the existing road surface and application of 6% cement to an 8 in. lift to provide a cement-stabilized base layer before Otta seal construction. Figure 33 illustrates the cement stabilization process used for the existing base layer prior to Otta seal construction. The Otta seal on County Road J55 in Page County was constructed in October 2020.

(a) (b)

(c)

Figure 33. Cement stabilization of the base layer prior to Otta seal application: (a) spraying and mixing cement with the base layer, (b) compacting with a sheepsfoot roller, and (c) checking the density of the base layer

On the day of construction, the road surface was thoroughly cleaned using a motorized broom, an essential step to remove loose aggregate and dust that could negatively impact binder adhesion. Before starting Otta seal construction, calibration of the equipment, including the aggregate spreader and asphalt distributor, was conducted to ensure accurate and consistent application rates. Figure 34 shows the calibration process used to adjust the application rates of the aggregate and binder spreaders. The next step was to spray asphalt binder onto the cleaned road surface to serve as an adhesive that would hold the aggregate in place. Following distribution of the asphalt binder, the aggregate was spread evenly on the binder layer. Uniform distribution of the aggregate was critical to ensuring the quality of the Otta seal. Compaction of the Otta seal layer was provided by two pneumatic rubber tire rollers and one steel drum roller to ensure that the aggregate was fully bonded with the binder.

(a) **(b)**

Figure 34. Calibration of equipment prior to Otta seal application: (a) adjusting aggregate application rate and (b) adjusting binder application rate

The step-by-step Otta seal construction process on County Road J55 is illustrated in Figure 35.

Figure 35. Otta seal construction on County Road J55: (a) spraying of MC 3000 binder, (b) distribution of limestone aggregate, (c) compaction using pneumatic rubber tire roller, and (d) center line compaction using steel drum roller

After providing sufficient compaction, the next step involved inspecting the completed Otta seal, addressing any issues or deficiencies, and using a mechanical broom to remove loose aggregate from the surface.

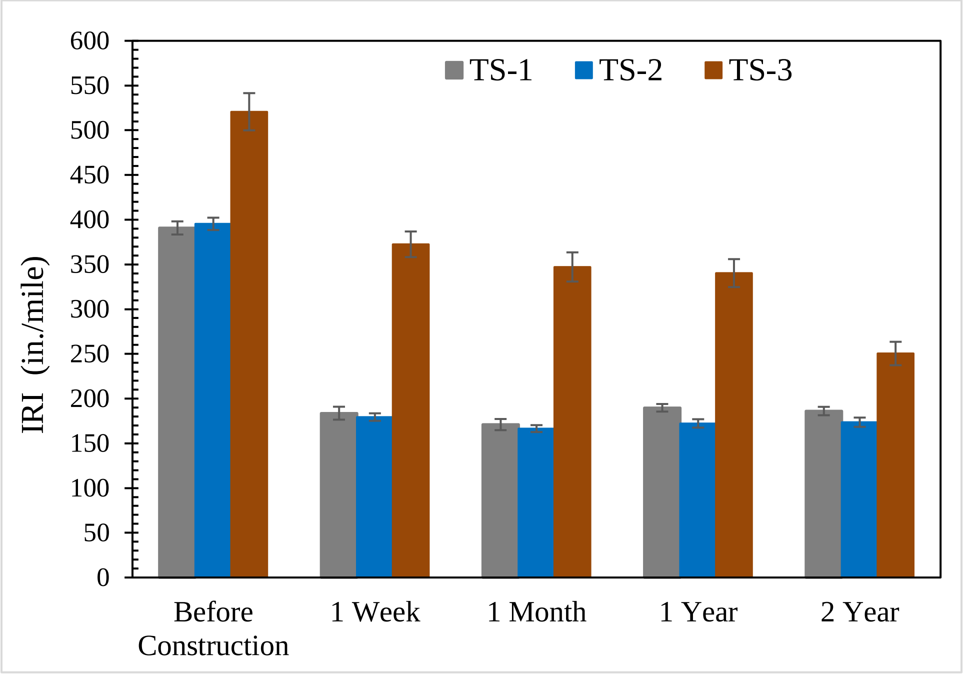
4.3 Field Data Collection on County Road J55

4.3.1 Roughness

Surface Systems and Instruments (SSI) high-speed profilers are used extensively for pavement management, road condition assessment, and maintenance planning because of their ability to rapidly collect road surface data at high speeds and provide valuable information for identifying rough pavement sections, evaluating pavement performance, and prioritizing maintenance and rehabilitation activities (Karamihas and Gillespie 2002, Tian et al. 2021, Akhter et al. 2003, SSI 2012). A CS9300 Portable Bumper Mount Inertial Profiler utilizing laser sensors to measure vertical deviations in the road surface was used in this study. Figure 36(a) shows three laser sensor units positioned at the front of the data collection truck, allowing documentation of the left, central, and right road tracks. This advanced device has the capability to obtain high-resolution profile data, with a longitudinal profile resolution of 1 in. and a transverse profile resolution of 0.01 in. (SSI 2012).

The roughness data collected from the SSI high-speed profiler were processed and analyzed using SSI profiler software to calculate the IRI values of the Otta seal test sections on County Road J55, quantifying the roughness based on vertical deviations over a defined length of road. Figure 36(b) shows the calculated IRI values for test sections TS-1, TS-2, and TS-3 measured at different times, including immediately before Otta seal construction and one week, one month, one year, and two years after Otta seal construction. The control section without base stabilization (TS-3) exhibited consistently higher IRI values compared to the other sections because it was constructed with a non-smooth base aggregate layer immediately below the Otta seal surface layer. The high IRI values for TS-3 signified the importance of having a well-prepared base aggregate layer before applying Otta seal surfacing. The modified McLeod section (TS-2) provided the lowest IRI values one week, one month, and one year after Otta seal construction.

(a)



(b)

Figure 36. Measuring roughness of test sections on County Road J55: (a) SSI-high speed profiler for IRI measurement and (b) IRI values of Otta seal surface at different times

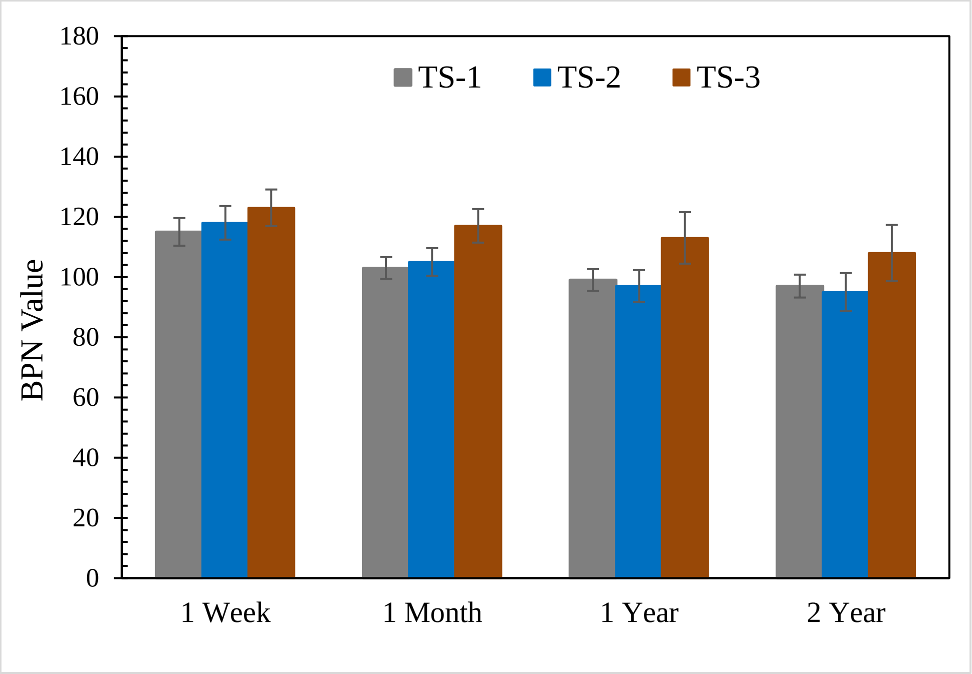
4.3.2 Skid Resistance

Skid resistance refers to the ability of a road surface to provide sufficient friction or traction between vehicle tires and the road surface. A road surface with high skid resistance allows vehicle tires to maintain better contact and grip, reducing the likelihood of skidding and preventing accidents (Mayora and Piña 2009, AASHTO 2010, Hall et al. 2009). The British pendulum test is a commonly used method for measuring the skid resistance of asphalt roads.

The test uses a pendulum device that swings across the road surface and measures the frictional resistance encountered during the skid. The distance traveled by the pendulum after the skid is converted into a BPN representing the road surface’s skid resistance.

The British pendulum test was performed following ASTM E303-93 to measure the skid resistance of the Otta seal test sections on County Road J55. Figure 37(a) shows the British pendulum test device used in the field to measure the BPN, and Figure 37(b) presents the BPN values for test sections TS-1, TS-2, and TS-3. While the control section (TS-3) exhibited the highest BPN values, all test sections satisfied the minimum requirements for skid resistance, ensuring adequate safety for vehicles.

(a)



(b)

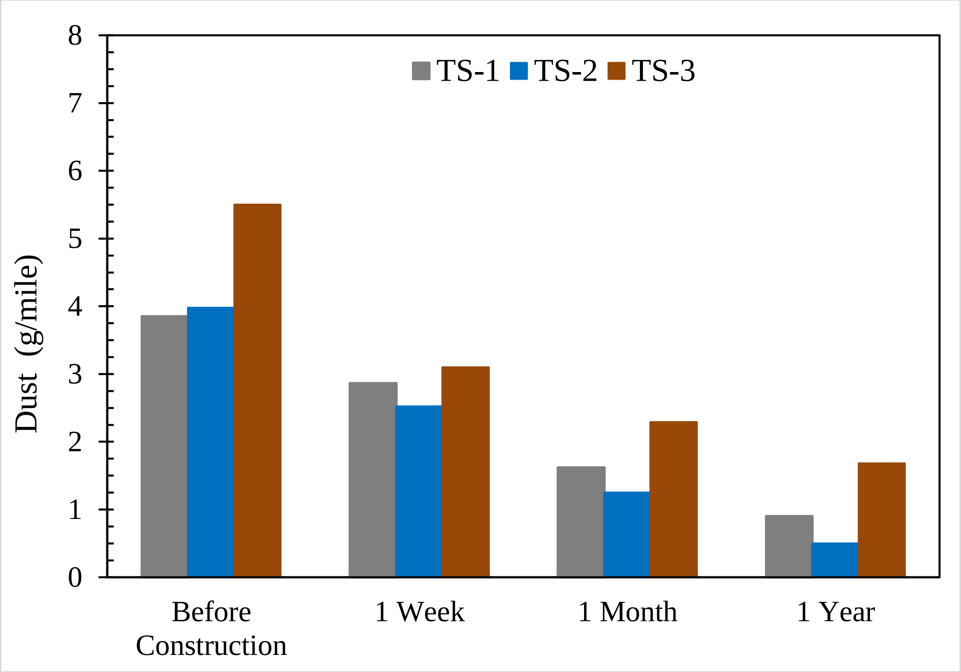
Figure 37. Measuring skid resistance of test sections on County Road J55: (a) British pendulum test device and (b) results of British pendulum tests

4.3.3 Dust

A Colorado State University dustometer was utilized in this study to measure the dust generated by the Otta seal test sections on County Road J55. This dustometer was developed as part of a Colorado Department of Transportation research project performed by Colorado State University (Sanders et al. 1997, Sanders and Addo 2000). The Colorado State University dustometer includes the following elements: a fabricated metal box containing a 25.4 x 20.32 cm sheet of glass fiber filter paper, a metal bracket to attach the device to the rear bumper of a data collection truck, an electrical generator, a standard high-volume suction pump, and a flexible tube running between the filter box and suction pump (Sanders and Addo 2000). This device has been successfully used in many studies, including Iowa DOT-funded research projects, to monitor the performance of low-volume roads (Sanders et al. 2015, Alsheyab et al. 2023, Ceylan et al. 2018, Yang et al. 2022).

Figure 38(a) shows the dustometer mounted behind the truck used in this study to collect dust from the Otta seal test sections. First, the dustometer was positioned at the rear of the truck, and a sheet of filter paper was weighed and subsequently inserted into the dustometer. The truck was then driven at a speed of 25 mph (40 km/h) along the desired distance. Following this, the filter paper was weighed once again to determine the amount of dust accumulated along the test section. To observe the effectiveness of Otta seal in controlling dust over time, dust from the surface was collected during different time periods. Figure 38(b) presents the amount of dust obtained from the different test sections of the Otta seal-surfaced road. Otta seal application significantly reduced the amount of dust generated, with a decreasing trend in dust generation over time. The modified McLeod section (TS-2) generated the lowest amount of dust compared to the other two sections one week, one month, and one year after Otta seal application. The lowest amount of dust production of 0.5 g/mile was recorded for test section TS-2 after one year. Note that no dust was generated on County Road J55 two years after construction.

(a)



(b)

Figure 38. Measuring dust generated by test sections on County Road J55: (a) dustometer mounted behind the truck and (b) amount of dust generated at different times

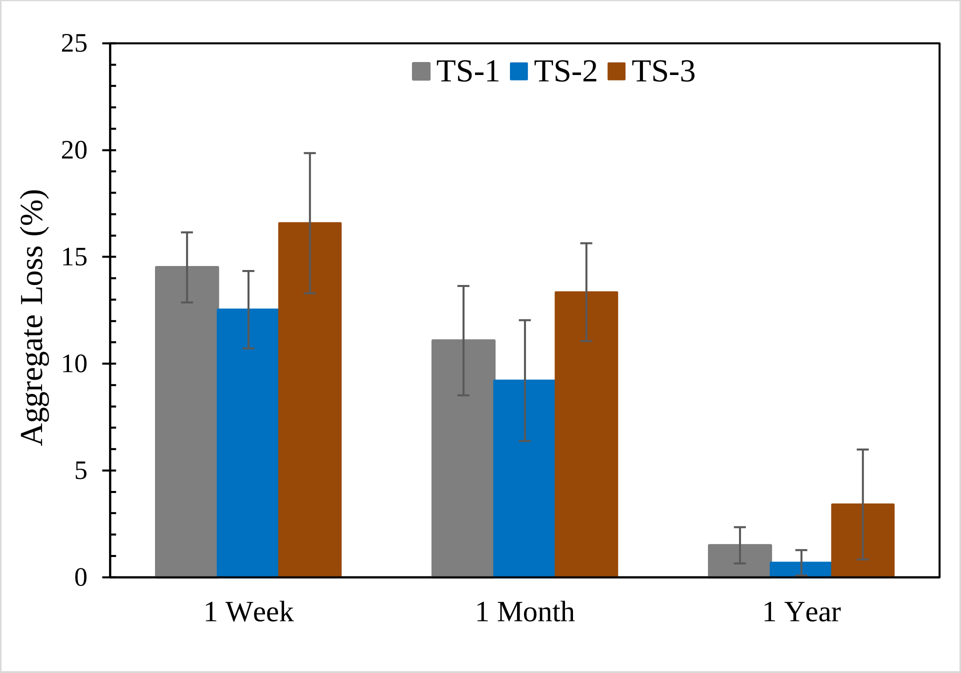
4.3.4 Loose Aggregate

Measuring the performance of Otta seal-surfaced roads through the collection of loose aggregate plays a crucial role in achieving quality assurance, enhancing safety, assessing durability and longevity, planning maintenance activities, and analyzing cost-effectiveness. The amount of loose aggregate collected can be used to determine the percentage aggregate loss from the surface, which maintenance agencies can use to identify sections of an Otta seal-surfaced road that require reapplication of the treatment or application of additional aggregate to maintain performance standards (Ceylan et al. 2018, Jibon et al. 2023, Johannes et al. 2011, Lee and Kim 2008).

The equipment used to perform the loose aggregate tests in this study included a vacuum device, a portable generator, two wooden beams (each 12 ft in length), a ruler, and a bucket for collecting the aggregate. To perform the tests, the two wooden beams were positioned to define a 6 in. wide corridor running transversely across the road, and the vacuum device was then used to gather loose aggregate within the designated area between the two wooden beams. Figure 39(a) shows the loose aggregate collection procedure being performed on one of the Otta seal test sections on County Road J55. The collected aggregate was stored in a bucket, and the weight of the loose aggregate from the designated area was measured. The total amount of aggregate in each designated area was estimated from the Otta seal application rates. Then the measured loose aggregate weight was converted to the percentage aggregate loss for the section.

The first loose aggregate tests were conducted on the Otta seal test sections on County Road J55 one week after construction to allow sufficient time for the binder to migrate upward through the aggregate voids and reach the surface. Figure 39(b) shows the percentage of loose aggregate obtained from the Otta seal test sections at three different times. The control section (TS-3) generated the highest percentage of loose aggregate compared to the TS-1 and TS-2 test sections. The well-prepared, stabilized base aggregate layer had a significant impact on Otta seal performance. The test section prepared with the modified McLeod design approach (TS-2) generated a lower amount of loose aggregate from the road surface compared to the test section prepared with the Overby design approach (TS-1). The higher BR/AR ratio in the modified McLeod design approach provided a sufficient coating for the cover aggregate, which resulted in the lowest amount of loose aggregate for the TS-2 test section.

(a)



(b)

Figure 39. Measuring loose aggregate from test sections on County Road J55: (a) collecting loose aggregate using vacuum suction and (b) loose aggregate generation trends over time

4.3.5 Structural Capacity and Compaction Quality

An LWD is a portable, nondestructive testing device used to assess the structural capacity and compaction quality of newly constructed pavements (Schwartz et al. 2017, Commuri et al. 2012, Volovski et al. 2014). The LWD operates based on a principle that involves the application of a dynamic load and measurement of the resulting pavement deflection. The elastic modulus computed from the LWD test has been utilized by many researchers to predict the resilient modulus of the pavement layer, which is used as the primary input for unbound material properties in mechanistic-empirical pavement design (Jibon and Mishra 2021, Jibon et al. 2020, Kuttah 2021, Ebrahimi and Edil 2013).

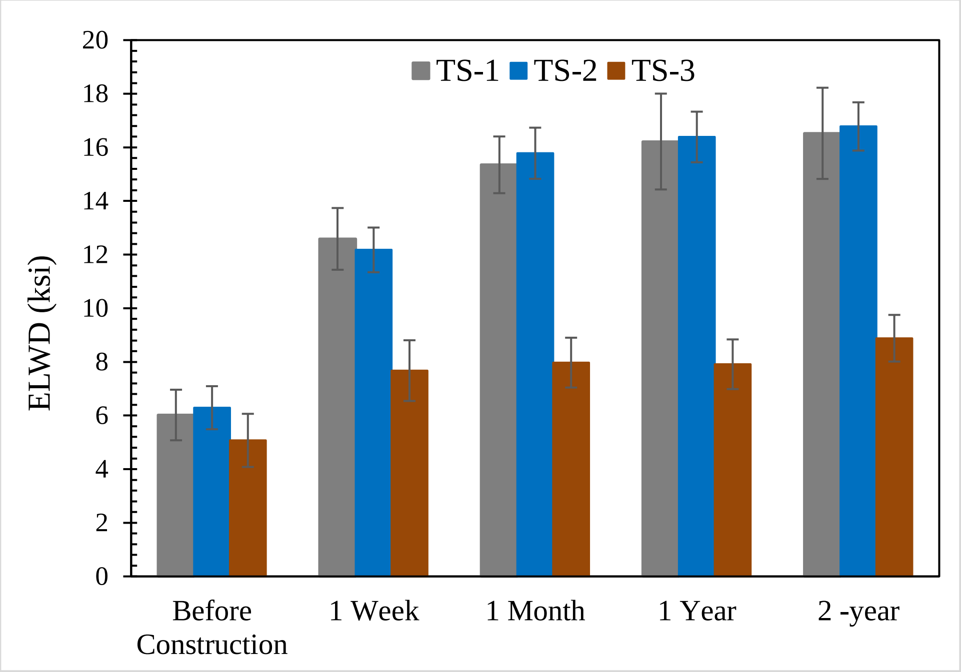
This study utilized a Zorn 3000 LWD device equipped with a 10 kg hammer having a drop height of 72.4 cm and a base plate diameter of 300 mm. Considering that the zone of influence for an LWD extends to a depth 1.5 to 2 times the diameter of the LWD plate, the elastic modulus values determined through these tests represent the composite elastic modulus of both the surface and subgrade layers (Schwartz et al. 2017). Figure 40(a) depicts the LWD test setup implemented in this study. The composite elastic modulus values for the pavement sections were computed using equation (10).

$$E_{LWD} = \frac{(1-\vartheta^2)\sigma_0 A f}{d_0} \tag{10}$$

where E_{LWD} is the elastic modulus calculated from the LWD tests, σ_0 is the vertical stress applied to the top of the LWD plate, ϑ is Poisson's ratio, d_0 is the diameter of the plate, f is the shape factor, and A is the stress distribution factor (Schwartz et al. 2017).

The measured composite elastic modulus (E_{LWD}) values from the LWD tests performed on the Otta seal test sections on County Road J55 are presented in Figure 40(b). Though the main function of applying Otta seal is not to increase the strength or stiffness of the pavement, conducting LWD tests on the Otta seal test sections provided insight into how the strength of the underlying pavement layers affects Otta seal performance. The composite elastic modulus values for test sections TS-1 and TS-2 increased significantly one week after construction, reflecting the benefit of cement-based stabilization. The slight improvement in elastic modulus for the control section (TS-3) was due to compaction during Otta seal construction and the presence of the bonded Otta seal layer itself. Test sections TS-1 and TS-2 exhibited an increasing trend in structural stiffness over time because the cement-stabilized layers experienced time-dependent strength gain. Test sections TS-1 and TS-2 exhibited very similar pavement structure stiffness values, demonstrating that differences in the performance of these test sections resulted from differences in the aggregate and binder application rates.

(a)



(b)

Figure 40. Structural evaluation of test sections on County Road J55 using LWD: (a) performing LWD tests and (b) results of LWD tests at different times

4.3.6 Surface Condition

A visual distress survey, including evaluations of bleeding, cracking, rutting, and potholes, was conducted on the Otta seal test sections on County Road J55 at various intervals to assess changes in surface conditions over time. Figure 41 provides visual representations of the surface conditions at different times, including before Otta seal construction and immediately after, one month after, and two years after construction.

TS-1 TS-2 TS-3

(a) Before Otta seal construction

TS-1 TS-2 TS-3

(b) Immediately after Otta seal construction

TS-1 TS-2 TS-3

(c) One month after Otta seal construction

TS-1 TS-2 TS-3

(d) Two years after Otta seal construction

Figure 41. Surface conditions of test sites on County Road J55 (a) before Otta seal construction, (b) immediately after Otta seal construction, (c) one month after Otta seal construction, and (d) two years after Otta seal construction

Table 13 presents the results of the visual distress survey in tabular format. Note the bleeding potential of test sections TS-1, TS-2, and TS-3 one year after construction. The observed bleeding in certain areas of County Road J55 was attributed to cold weather construction (late October 2021), which prevented the binder (MC 3000) from fully melting and adequately coating the aggregate particles so that loose aggregate on the Otta seal surface was displaced by abrasion from heavy truck traffic. During the following summer, the MC 3000 binder began to melt but did not achieve sufficient aggregate coverage, leading to bleeding issues in some spots on County Road J55 one year after construction. After two years, a few spots in the test sections also exhibited longitudinal wheel path depressions, likely due to heavy truck traffic from the nearby quarry.

Table 13. Summary of visual distress survey results on County Road J55 in Page County, Iowa

Distress	Test Section	1 Week	1 Month	1 Year	2 Years
Bleeding	TS-1	×	×	√	×
	TS-2	×	×	√	×
	TS-3	×	×	√	×
Cracking	TS-1	×	×	×	×
	TS-2	×	×	×	×
	TS-3	×	×	×	×
Rutting	TS-1	×	×	×	√
	TS-2	×	×	×	√
	TS-3	×	×	×	√
Pothole	TS-1	×	×	×	×
	TS-2	×	×	×	×
	TS-3	×	×	×	×

4.4 Summary Results

The key findings from this study are listed below:

- The modified McLeod section (TS-2) demonstrated the lowest IRI values one week, one month, and one year after Otta seal construction. The control section (TS-3), lacking base stabilization, consistently exhibited higher IRI values compared to the other sections, highlighting the importance of establishing a well-prepared base aggregate layer before applying Otta seal for optimal road smoothness.
- All test sections (TS-1, TS-2, and TS-3) met minimum skid resistance requirements, ensuring safe driving conditions despite varying road conditions. The modified McLeod section (TS-2) consistently had the lowest amount of loose aggregate, which was attributed to the higher BR/AR ratio used by modified McLeod method and, consequently, superior coating of the aggregate particles.

- Otta seal application significantly reduced dust generation over time, with the lowest amount of dust production recorded for the modified McLeod section (TS-2) one year after construction.
- Test sections TS-1 and TS-2 demonstrated increasing structural stiffness over time, largely due to time-dependent strength gain in the cement-stabilized layers. Both test sections TS-1 and TS-2 exhibited similar pavement structure stiffness values, suggesting that differences in performance were primarily influenced by variations in the aggregate and binder application rates.
- The visual distress survey identified issues such as bleeding and wheel path depressions in certain areas of County Road J55 after Otta seal construction. These observations highlighted the importance of considering construction timing, temperature, and traffic conditions when applying Otta seal to ensure the optimal performance and durability of the road surface.

This study validated the effectiveness of the rational design method by comparing the performance of Otta seal surfaces constructed based on the modified McLeod design method to the performance of Otta seal surfaces constructed based on the Overby guidelines. The results of this study also suggest guidelines for implementing the rational mix design method for Otta seal construction in a way that enhances the sustainability, cost-effectiveness, and longevity of the road network. Through these results, this study contributes to the body of knowledge on Otta seal surfacing techniques and provides practical insights for implementing rational mix design methods for Otta seal construction in Iowa.

5 ECONOMIC ANALYSIS OF OTTA SEAL

5.1 Description of Economic Analysis

Economic analysis plays a pivotal role in evaluating the financial feasibility, efficiency, and sustainability of various projects, policies, and strategies across a wide range of industries and sectors. It is a fundamental tool used by decision-makers to assess the allocation of resources, estimate costs and benefits, and make informed choices that maximize value and minimize risk. The key components of an economic analysis include considering various scenarios and variables and ultimately offering insights that can guide decision-makers toward sustainable, cost-effective, and economically sound solutions.

An economic analysis was conducted on the Otta seal test sections constructed on County Road J55 in Page County, Iowa, to determine the economic benefit of using the modified McLeod method for Otta seal design.

5.2 Cost Estimation

A roadway's typical life-cycle cost includes three major components: initial construction cost, maintenance and preservation costs during the roadway's service life, and end-of-life strategies. As mentioned in the previous chapter, Otta seal construction in Page County consisted of reclamation of the existing pavement, base stabilization using cement, and construction of the new Otta seal surface. Construction cost information was obtained from the Page County Engineer's Office and is presented in Table 14, where the information is broken down into sections for the three life-cycle cost components. Because aggregate loss is one of the common issues observed at the other Otta seal sites surveyed in this study, the primary assumed maintenance activity is spraying of the surface aggregate. The application rates and aggregate replacement costs for each section are based on the documented field performance and are summarized in Table 14. The pavement end-of-life strategy could be determined by many factors, such as budget, performance, and local community needs. In Iowa, cold in-place recycling is a prevalent option for low-volume roads and has been adopted in this economic analysis. The typical cost of \$48/m^2 for this treatment was chosen based on the local engineer's information. A design life of eight years was assumed for the Otta seal sections with cement stabilization (TS-1 and TS-2), while the nonstabilized section (TS-3) only has six years of design life (Nahvi et al. 2019, Gransberg 2008).

Table 14. Itemized cost of Otta seal construction, maintenance, and rehabilitation in Page County, Iowa

Item	Section	Activities	Unit Cost ($/km)
Otta Seal Construction	T1	47.0 lb/yd^2 Agg. + 0.38 gal/yd^2 Binder + Cement stabilization	$163,794
	T2	40.9 lb/yd^2 Agg. + 0.35 gal/yd2 Binder + Cement stabilization	$156,648
	T3	47.0 lb/yd^2 Agg. + 0.38 gal/yd2 Binder	$63,629
Otta Seal Maintenance	T1	4.6 lb/yd^2 Agg.	$13,981
	T2	3.7 lb/yd^2 Agg.	$11,185
	T3	5.5 lb/yd^2 Agg.	$16,777
Otta Seal Rehabilitation	T1	Cold in-place recycling, $57/yd^2	$320,794
	T2	Cold in-place recycling, $57/yd^2	$320,794
	T3	Cold in-place recycling, $57/yd^2	$320,794

5.3 Life-Cycle Cost Analysis

LCCA is a common technique utilized to evaluate the financial viability of various pavement construction, maintenance, and rehabilitation strategies (Yang et al. 2023, Lu et al. 2018, Pittenger et al. 2011). In the LCCA model created for this study, several indices were developed to assess the economic benefits of design and construction practices, such as the benefit/cost ratio, net present value (NPV), and equivalent uniform annual cost (EUAC), given the specific discount rate and analysis context (Babashamsi et al. 2016, Li et al. 2019). The EUAC is an evaluation index that transforms present and future costs into an annual-based cost, and it was employed in this study to compare the life-cycle benefits of different Otta seal design and construction approaches in Page County. The alternative of a low EUAC is expected because it means the annual cost for the practice is lower. Equation (11) is used to calculate EUAC.

$$EUAC = \sum P \times [(i(1+i)^n \div (1+i)^n - 1)]\ , \tag{11}$$

where P is the present cash value ($), i is the selected discount rate (%), and n is the design life of the surface treatment (years).

Cash flow models are essential to LCCA. For the purpose of evaluating all possible cases, this study developed the four scenarios with various maintenance frequencies shown in Figure 42. Scenario A assumes the worst case, in which the local public agency must replace the aggregate yearly until the end of life (Figure 42a). Scenarios B and C assume a maintenance activity every two years and three years, respectively, as shown in Figure 42b and Figure 42c. The best performing Otta seal case is illustrated in Scenario D, which assumes that only one maintenance activity is needed during the whole life cycle (Figure 42d).

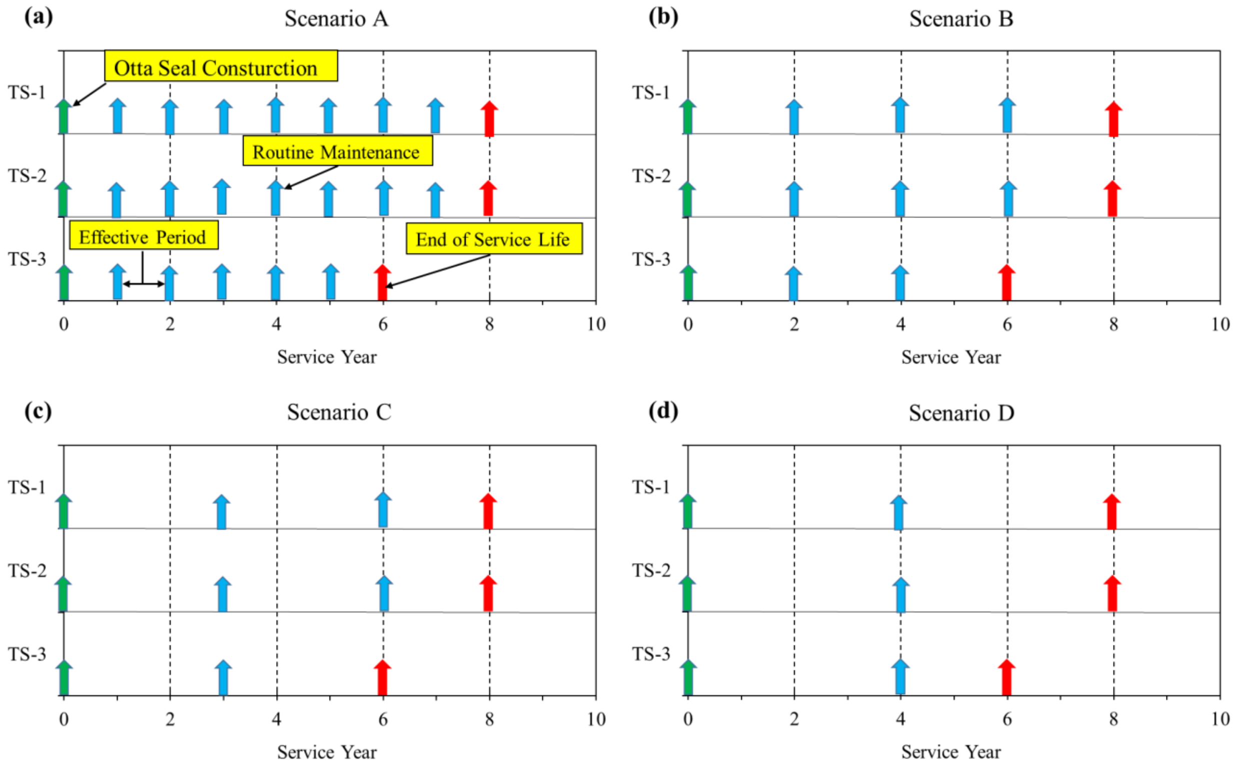


Figure 42. Cash flow scenarios for Otta seal construction, maintenance, and rehabilitation on County Road J55 in Page County, Iowa

Figure 43 shows that Scenario A exhibited the highest EUAC for all sections due to the frequent maintenance activities in this scenario, while Scenario D was associated with the lowest EUAC. Among the three test sections, TS-2, which used the McLeod design method, presented the lowest EUAC because the documented field performance had already indicated that TS-2 was the best performing section with the lowest usage of aggregate and asphalt binder, thereby resulting in the lowest construction and maintenance costs compared to the other two sections. It should also be noted that as the discount rate increased, the differences in EUAC between stabilized and nonstabilized sections decreased, indicating a decrease in the financial benefit of stabilization. In summary, TS-2 in Scenario D with a 7% discount rate represented the best practice with respect to achieving the lowest EUAC. By comparison, TS-3 in Scenario A with a 3% discount rate represented the worst practice because it reached the highest EUAC of $\$15.1/m^2$.

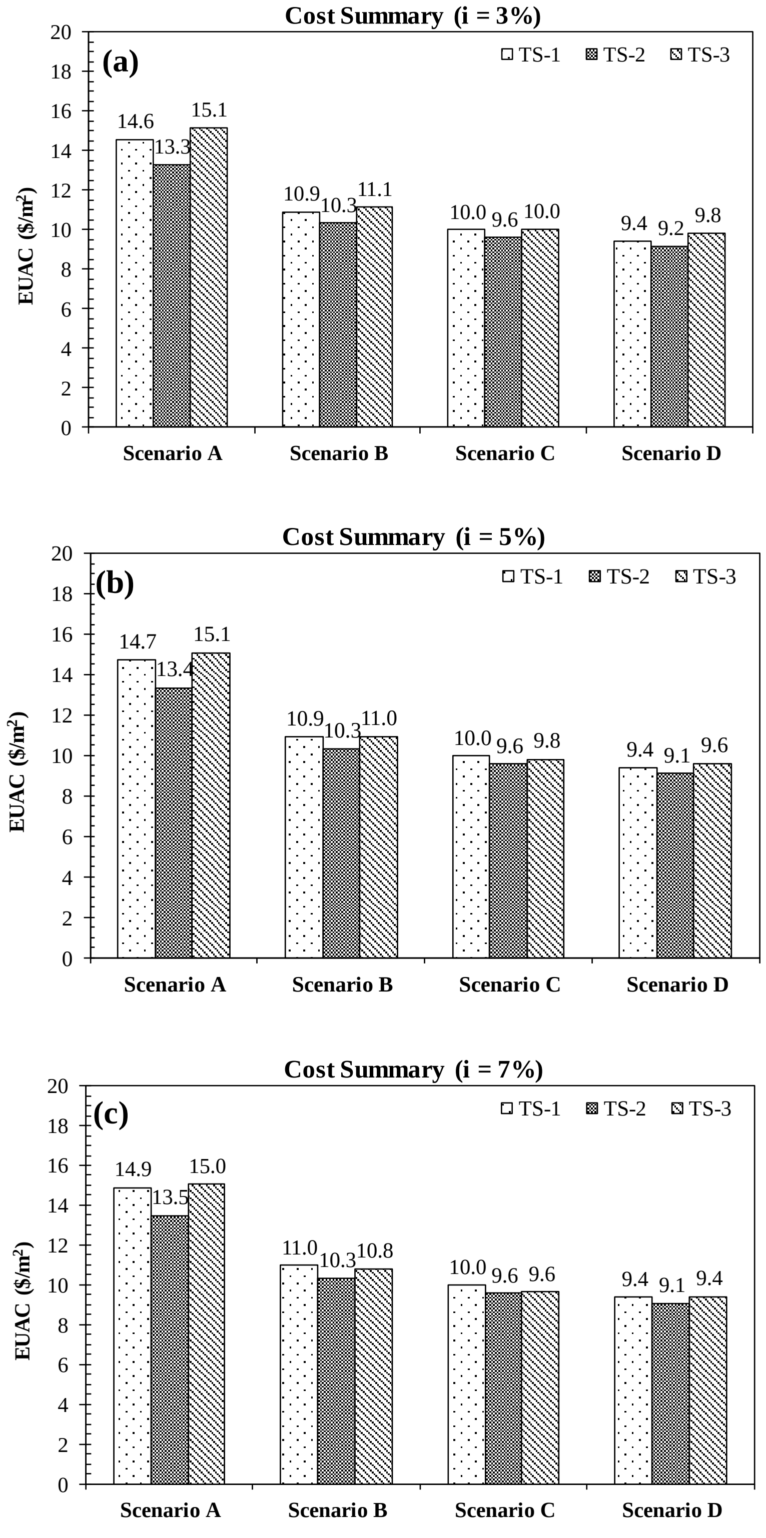


Figure 43. EUAC for different scenarios with (a) 3% discount rate, (b) 5% discount rate, and (c) 7% discount rate

5.4 Discussion

Through an LCCA, this study evaluated the different Otta seal design and construction approaches used in Page County, Iowa. This investigation included a breakdown of the initial construction costs, ongoing maintenance expenses, and end-of-life strategies for pavement sections both with and without cement stabilization. Among the three pavement test sections, TS-2, which utilized the modified McLeod design method, consistently demonstrated the lowest EUAC. This superior performance can be attributed to the reduced aggregate and asphalt binder usage, which resulted in cost savings throughout this test section’s life cycle. The findings highlight the critical role of maintenance frequencies and discount rates in shaping the EUAC for each scenario. Scenario D, characterized by minimal maintenance, emerged as the most cost-effective practice, boasting the lowest EUAC. In contrast, Scenario A, which features annual maintenance, exhibited the highest EUAC.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The Iowa DOT and LPAs have been exploring affordable pavement preservation maintenance technologies for years, and this Phase II research project was initiated in 2018 to continue investigating the use of Otta seal for local low-volume roads and establish Iowa Otta seal specifications.

Over 50 Otta seal field sites have been constructed in the past six years using various local aggregates, even recycled materials such as steel slag, to provide generally satisfactory surface conditions with a relatively lower cost compared to conventional technologies. A periodic evaluation process was performed to track the surface conditions of these sites. The results showed that Otta seal could provide satisfactory performance and could be a relatively cost-effective pavement preservation technology for Iowa's low-volume roads.

In addition to evaluating previously constructed Otta seal sites, another objective of this study was to develop a rational approach for designing Otta seal road surfaces using locally sourced materials. This aspect of the study involved laboratory and field investigations. A detailed laboratory investigation of Otta seal specimens was conducted to determine the most effective application rates for both aggregates and binders. The Otta seal specimens were created using the McLeod, modified McLeod, and Overby methods, and the performance of the specimens was primarily evaluated through a sweep test to examine how various factors, including material type, aggregate gradation, binder choice, and application rate, influenced aggregate loss. Based on the results of the laboratory investigation, three Otta seal test sections were constructed on County Road J55 in Page County, Iowa, to evaluate the rational design approach in the field. An LCCA was also conducted to assess the economic benefits of different Otta seal design and construction approaches.

Based on successful field implementation practices and the laboratory and field investigations conducted for this study, the Iowa Otta seal specifications presented in Appendix A were established to assist LPAs in employing this cost-effective BST.

The key findings from the performance evaluations of the constructed Otta seal sites are summarized as follows:

- Iowa has successfully constructed more than 50 Otta seal sites since 2017. After a few years in service, many of these sites are still in good shape and exhibit good performance.
- The Otta seal sites constructed in Iowa have proved that local aggregates (limestone and river gravel), and even recycled aggregate like slag, can be utilized for this surfacing technique.
- Otta seal can be implemented on different road types, including gravel, concrete, and asphalt roads.

- The most common issues observed at Otta seal sites constructed in Iowa are bleeding and loss of aggregate cover. The selection of proper BR/AR ratios and sufficient compaction could effectively reduce such problems.
- Otta seal has proved to be a relatively cost-effective surfacing technique, and its use in many circumstances where conventional asphalt surfacing would have been too expensive or impossible has allowed the construction of roads under unfavorable conditions.

The key findings from the laboratory study for the development of a rational design approach for Iowa are summarized as follows:

- Laboratory testing revealed that aggregate gradation played a crucial role in determining aggregate loss in Otta seal road surfaces. Shifting from dense to open gradation resulted in reduced aggregate loss. Open-graded aggregates, characterized by their lower fines content, enabled the binder to better coat the larger aggregates, leading to decreased aggregate loss.
- The specific type of aggregate used in specimen preparation had no significant effect on aggregate loss. Specimens containing recycled materials such as slag and RCA performed well in sweep tests. Notably, when the Overby application rate was used, specimens containing slag demonstrated the lowest aggregate loss among all aggregate specimens. When the modified McLeod application rate was used, RCA exhibited aggregate loss results similar to those of limestone aggregate specimens.
- Otta seal specimens prepared using the modified McLeod application rates exhibited superior performance in terms of aggregate loss during sweep tests. The higher BR/AR ratios used in the modified McLeod method facilitated better coating and bonding of the aggregates, effectively reducing aggregate mass loss.

The key findings from the field study for the evaluation of the rational design approach for Iowa are summarized as follows:

- The field study showed that the modified McLeod test section (TS-2), which featured a well-prepared base aggregate layer, consistently exhibited the lowest IRI values one week, one month, one year, and two years after Otta seal construction. In contrast, the control section (TS-3), which was constructed without proper base stabilization, consistently exhibited the highest IRI values. These results emphasize the importance of a well-prepared base for achieving optimal road smoothness with Otta seal surfacing.
- Otta seal application significantly reduced dust generation and loose aggregate over time, with the lowest amount of dust production recorded for the modified McLeod test section (TS-2) one year after construction.
- The LCCA revealed that TS-2, which utilized the modified McLeod design method, consistently demonstrated the lowest EUAC among the three pavement sections analyzed. This superior performance in terms of cost can be attributed to the reduced aggregate and asphalt binder usage, which resulted in cost savings throughout this test section’s life cycle.

6.2 Recommendations

Recommendations for employing Otta seal in Iowa are as follows:

- When selecting aggregate, oversized aggregates and aggregates with high fines contents should be avoided. Further research could focus on identifying the optimal gradation that minimizes aggregate loss, enhances the ability of the binder to coat the aggregate particles, and ensures long-lasting road surfaces.
- It is highly recommended that Otta seal be applied in Iowa during early summer to ensure a high enough temperature to melt the binder and coat the aggregate surfaces by upward movement of the binder.
- Because the modified McLeod method demonstrated greater economic benefits and better performance than the other Otta seal design methods evaluated in this study, it is suggested that the modified McLeod method be considered for calculating aggregate and binder application rates for Otta seal construction.

Recommendations for future study include the following:

- Given the success of Otta seal on Iowa’s low-volume roads, future studies should continue to monitor the long-term performance of these sites over an extended period. This will provide valuable insight into the durability and maintenance characteristics of Otta seal surfaces under varying traffic and climate conditions.
- While some international experience suggests that Otta seal can last at least eight years, this has yet to be validated under Iowa’s conditions. It is recommended that the serviceability of existing Otta seal sites in Iowa be tracked until their end of life.
- Preservation and maintenance strategies for Otta seal have not been extensively studied in Iowa, and comprehensive guidelines for the proper maintenance and preservation of Otta seal-surfaced roads are still needed to extend the longevity of this treatment.
- This study conducted a life-cycle cost analysis based on the two-year field study in Page County, Iowa. The life-cycle benefits found in this analysis should be validated through long-term field evaluations. Additional life-cycle cost analyses of other Iowa Otta seal sites could also provide critical insights.
- It is recommended that LPAs construct additional Otta seal sites using the modified McLeod method for Otta seal design and subsequently evaluate their performance.
- Appropriate maintenance strategies should be identified and established in the future to prolong the service life of Otta seal-surfaced roads.
- The use of recycled aggregates (RCA, reclaimed asphalt pavement [RAP], etc.) for Otta seal implementation should be investigated. Based on the positive results obtained in this study with recycled materials such as slag and RCA, further research could investigate the suitability of other locally available recycled aggregates for Otta seal construction. This could reduce the environmental impact of road construction and the cost of construction.
- The performance of Otta seal in diverse climates within Iowa should be investigated. Weather conditions such as extreme cold or heat can affect pavement materials differently, and an understanding of how Otta seal responds to various climates can guide its application in different regions.

- Examining the integration of Otta seal with other surfacing techniques, such as slurry seal and micro-surfacing (for instance, cape seal), has great potential to improve the performance and extend the service life of these treatments.
- Recently, counties in Iowa such as Jefferson, Louisa, and Fayette have constructed Otta seal sites. It would be advantageous to incorporate these sites into any future field evaluation plans to gain a broader understanding of Otta seal performance.
- The advantages of soil stabilization, using chemicals or geosynthetics, before Otta seal application require further evaluation to be quantified and validated.
- There is a need for definitive guidelines on the use of oversized aggregates or aggregates with high fines contents in Otta seal applications.
- It is suggested that a training workshop be prepared to introduce Otta seal construction practices and specifications to all counties in Iowa.

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APPENDIX A: OTTA SEAL SPECIFICATION FOR MATERIALS AND CONSTRUCTION IN IOWA

1. SCOPE

a) Otta seal is a thin bituminous surface treatment used for protecting the base and subgrade courses of a road from deterioration and for providing smooth ride quality, especially when applied on low-volume roads. There are two main types of Otta seal, single and double, which are similar in construction except for the number of courses. This specification covers the design, testing, and construction of Otta seal mixtures for the surface treatment of granular roads and pavements.

b) This specification introduces two methods for the design of Otta seal in terms of determining aggregate and binder application rates: the Overby design method and the modified Iowa design method, both of which can be utilized to determine the application rates of aggregate and asphalt binder for Otta seal implementation. The laboratory-based modified Iowa design method is recommended because it typically recommends lower application rates for materials, which in turn provides greater life-cycle benefits. However, the empirically based Overby design method can be followed if the modified Iowa design method cannot be used due to the unavailability of laboratory test results.

c) This specification also introduces standard construction practices for Otta seal, including required construction equipment and appropriate steps to follow.

d) The values stated in US customary units (English units) are to be regarded as standard. No other units of measurement are included in this standard.

e) This standard does not purport to address safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

AASHTO T 26, Standard Method of Test for Quality of Water to Be Used in Concrete.
ASTM C29/C29M-97, Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate.
ASTM C127-15, Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate.
ASTM C128-15, Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate.
ASTM D977-17, Standard Specification For Emulsified Asphalt.
ASTM D2027/D2027M–19, Standard Specification for Cutback Asphalt (Medium-Curing Type).
ASTM D4791-19, Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate.
ASTM D5624-13, Standard Practice for Determining the Transverse-Aggregate Spread Rate for Surface Treatment Applications.

Iowa Department of Transportation (DOT). 2023. *Standard Specifications for Highway and Bridge Construction with GS-15016 Revisions*. Iowa Department of Transportation, Ames, IA.
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3. TERMINOLOGY

3.1 Definitions of Terms Specific to this Specification

3.1.1. Locally available aggregates: local aggregates, including nonstandard or marginal materials, for pavement surface treatment. These could include crushed limestone, river rock, steel slag, or other recycled construction materials such as recycled concrete aggregate (RCA) and reclaimed asphalt pavement (RAP).

3.1.2. Otta seal mixtures: as related to this specification, mixtures of locally available coarse aggregate, with or without fines, uniformly mixed with asphalt cutback or asphalt emulsion.

3.1.3. Overby design method: empirically based design guidelines developed by Overby (1999) summarizing a simplified design approach based on previous field practices for selecting aggregate and binder. This design method also addresses typical construction practices for Otta seal implementation.

3.1.4. Modified Iowa design method: design method developed based on McLeod’s (1960) method for seal coat design. This design method is laboratory based and was developed, modified, and validated by the Iowa Highway Research Board (IHRB) and Iowa Department of Transportation (DOT) under sponsored project TR-753, Evaluation of Otta Seal Surfacing for Low-volume Roads in Iowa, Phase II Study: Comprehensive Laboratory Evaluation and Characterization and Full-Scale Field Implementation.

4. SIGNIFICANCE AND USE

This specification is intended for use in designing and constructing Otta seal surfaces for low-volume roads with deteriorated granular, portland cement concrete, or asphalt surfaces. It is applicable to surface treatments that require the use of locally available construction materials and equipment with a low cost and a quick return to traffic flow.

5. DESIGN

5.1 Aggregates

5.1.1. Select a suitable locally available aggregate gradation for Otta seal construction corresponding to the annual average daily traffic (AADT) values shown in Table A1. Dense grading is recommended if the Otta seal candidate site must frequently support heavy trucks.

Table A1. Recommended aggregate gradation for design purposes according to the local traffic volume

AADT	Best suited grading
< 100	Open
100 – 1,000	Medium
>1,000	Dense

Source: Overby 1999

5.1.2. Locally available aggregates should meet the required aggregate gradation specifications recommended by Overby (1999), shown in Table A2.

Table A2. Grading envelopes

	Open Grading		Medium Grading		Dense Grading	
Sieve No.	Max. % passing	Min. % passing	Max. % passing	Min. % passing	Max. % passing	Min. % passing
3/4”	100	100	100	100	100	100
5/8”	100	80	100	84	100	93
1/2”	82	52	94	68	100	84
3/8”	58	36	73	44	98	70
1/4”	40	20	54	29	80	54
No.4	30	10	42	19	70	44
No.10	8	0	18	3	48	20
No.16	5	0	14	1	38	15
No.40	2	0	6	0	25	7
No.200	1	0	2	0	10	3

Source: Overby 1999

5.1.3. The aggregate type can be crushed limestone, river rock, or steel slag.

5.1.4. Follow Sections 5.5.1.1 or 5.5.2.1 to determine the application rates of aggregate.

5.2 Bituminous Materials

5.2.1. The materials used depend on the climate and condition of the site and should be selected based on the Otta seal application type. The two common types of binder that have been used In Iowa are:

5.2.1.1. If asphalt cutback (MC 3000) is provided, it should meet the requirements of ASTM D2027/D2027M–19, Standard Specification for Cutback Asphalt (Medium-Curing Type).

5.2.1.2. If asphalt emulsion (HFMS-2s) is provided, it should meet the requirements of ASTM D977-17, Standard Specification For Emulsified Asphalt.

5.2.1.3. The penetration grade of base asphalt binder used for producing either emulsion or cutback should be within the range of 150 to 200 (0.1 mm).

5.2.2. Follow Sections 5.5.1.2 or 5.5.2.2 to determine the application rates of asphalt binder.

5.3 Water

5.3.1. Potable water is compatible with Otta seal and should meet the requirements of AASHTO T 26, Standard Method of Test for Quality of Water to Be Used in Concrete.

5.4 Otta Seal Type

5.4.1. Otta seal can be applied in a single course or double courses, depending on the traffic level and the type of sealing work. Overby (1999) recommends the types of Otta seal shown in Table A3 for specific applications. Note that this recommendation is flexible and can be changed in accordance with specific project requirements.

Table A3. Recommended type of Otta seal in relation to traffic level and type of sealing work

Traffic levels and type of work	Otta Seal Type
Temporary seal (diversions, haul roads, temporary accesses, etc.).	Single Otta Seal
Maintenance resealing (all traffic classes to which sprayed surfacing is applicable)	Single Otta Seal
AADT < 500	Single Otta Seal + Sand Cover Seal
AADT > 500	Double Otta Seal

Source: Overby 1999

5.5 Application Rates of Aggregate and Asphalt Binder

5.5.1. Overby design method (Overby 1999): this method provides a simplified approach for selecting an aggregate application rate based on aggregate gradation. Because lb/yd^2 is the unit commonly used in Iowa's design practices, the volumetric-based application rate used in Overby (1999), expressed in a volume-based SI unit, m^3/m^2, has been converted into a mass-based unit, lb/yd^2, in this specification by applying conversion factors.

5.5.1.1. Determining the aggregate application rate. The first step of this design method requires determining aggregate loose unit weight (LUW) in accordance with ASTM C29/C29M-97, Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate. The calculation is shown in equation (1):

$$\text{Aggregate's LUW} = \text{Volume} \div \text{Weight (lb/ft}^3\text{)} \tag{1}$$

After determining the aggregate's LUW, the application rate can be determined using equations (2) to (4):

$$\text{Aggregate with open grading (lb/yd}^2\text{)} = \text{LUW (lb/ft}^3\text{)} \times 0.383858 \tag{2}$$

$$\text{Aggregate with medium grading (lb/yd}^2\text{)} = \text{LUW (lb/ft}^3\text{)} \times 0.47244 \tag{3}$$

Aggregate with dense grading (lb/yd^2) = LUW (lb/ft^3) × 0.59055 (4)

5.5.1.2. Determining the spray rate of asphalt binder. The spray rate of asphalt binder is determined following the Overby design method as summarized in Table A4 and Table A5. The spray rate is dependent on the binder type. If asphalt cutback (MC 3000) is used, follow Table A4. If emulsion (HFMS-2s) is used, follow Table A5. The original unit of binder spray rate utilized in the Overby design method (Overby 1999) is the SI unit, l/m^2, which has been converted to the US customary unit, gal/yd^2, in this specification.

Table A4. Cutback asphalt spraying rates (gal/yd^2) for Otta seal

Type of Otta Seal		Aggregate Gradation Type			
		Open	**Medium**	**Dense (AADT < 100)**	**Dense (AADT > 100)**
Double	First Layer	0.35	0.38	0.40	0.38
	Second Layer	0.33	0.35	0.44	0.42
Single		0.38	0.40	0.44	0.42
Maintenance reseal (Single)		0.33	0.35	0.40	0.38

Note: If the aggregate has a water absorption percentage of more than 2%, the cutback spray rate should be increased by 0.07 gal/yd^2.
Source: Overby 1999

Table A5. Emulsion spraying rates (gal/yd^2) for Otta seal

Type of Otta Seal		Aggregate Gradation Type			
		Open	**Medium**	**Dense (AADT < 100)**	**Dense (AADT > 100)**
Double	First Layer	0.45	0.48	0.51	0.48
	Second Layer	0.43	0.45	0.57	0.54
Single		0.38	0.40	0.44	0.42
Maintenance reseal (Single)		0.33	0.35	0.40	0.38

Note: If the aggregate has a water absorption percentage of more than 2%, the emulsion spray rate should be increased by 0.1 gal/yd^2.
Source: Overby 1999

5.5.2. Modified Iowa design method (McLeod 1960): this method provides a modified approach for selecting an aggregate application rate based on laboratory-based testing properties. Follow Sections 5.5.2.1 to 5.5.2.2 to calculate aggregate and asphalt binder application rates. All units have been converted into US customary units.

5.5.2.1. Determining the aggregate application rate. Follow the listed laboratory testing protocol for the selected aggregate:

- Measure the bulk specific gravity of the aggregate coarse fraction by following ASTM C127-15, Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate, as shown in Figure A1a.

- Measure the bulk specific gravity of the aggregate fine fraction by following ASTM C128-15, Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate, as shown in Figure A1b. Then, measure the bulk specific gravity (G) of the aggregate by taking a weighted average of the specific gravity of the coarse and fine fractions.
- Utilize the measured specific gravity to estimate the voids in loose aggregate ($V_{1/2}$) for particles larger than ½ in. in size in accordance with ASTM C29/C29M-97, Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate, as shown in Figure A1c.
- Measure the average least dimension (ALD) of aggregate using a thickness gauge as specified in ASTM D4791-19, Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate, as shown in Figure A1d. During this testing, take 50 representative pieces of aggregate retained on a 3/8 in. sieve and measure the smallest dimensions of the individual aggregate pieces. The average of these smallest dimensions is the average least dimension of that aggregate.

Figure A1. Required laboratory testing for determining (a) bulk specific gravity of aggregate coarse fraction, (b) bulk specific gravity of aggregate fine fraction, (c) voids in loose aggregate for particles larger than ½ in., and (d) average least dimension of aggregate

After obtaining the required laboratory properties, use the modified McLeod equation (5) for calculating the aggregate application rate in lb/yd^2.

$$C = \left[1 - \left(\frac{0.2}{0.5} \times V_{1/2}\right)\right] HGE \times 46736 \quad (5)$$

where

C = aggregate application rate (lb/yd^2),
$V_{1/2}$ = voids in loose aggregate,
H = average least dimension (in.), and
E = wastage factor for traffic whip-off = 1.10 for 10% aggregate loss.

5.5.2.2. Determine the binder application rate. Determine the application rate of the binder by following equation (6). Note that equation (6) can be used for both cutback and emulsion, depending on the residual asphalt content of the binder (R).

$$\mathrm{B} = \frac{\left[\left(\frac{0.2}{0.5}\times V_{1/2}\right)\right]H\times 25.4\times T+S+A\times 4.53}{R}\times 0.221 \tag{6}$$

where

B = binder application rate (gal/yd^2),
$V_{1/2}$ = voids in loose aggregate,
H = average least dimension (in.),
S = surface condition factor (see Table A6),
T = traffic factor (see Table A7),
A = aggregate absorption factor (gal/yd^2) = 0.03 gal/yd^2 (McLeod 1960), and
R = residual asphalt content of binder.

The residual asphalt content differs between asphalt cutback and asphalt emulsion; check this content with suppliers. If such information is unavailable, use typical values of 0.85 and 0.67 for cutback (MC 3000) and asphalt emulsion (HFMS-2s), respectively.

Table A6. Value of surface condition factor, S

Textural rating of the existing surface	Operation	S (gal/yd^2)
Black (may have a bleeding issue)	Subtract	Up to 0.06
Smooth (no loss of binder)	Nil	Nil
Hungry 1h (loss of binder for aggregate smaller than 3/8”)	Add	0.03
Hungry 2h (loss of binder for aggregate between 3/4” and 3/8”)	Add	0.06
Hungry 3h (loss of binder for 3/4” aggregate)	Add	0.09

Note: Depending on the existing surface texture, a correction factor (S) must be applied to the quantity of asphalt binder used in Otta seal construction. The existing surface can be rated as black, smooth, or hungry, and the corresponding correction factor may be negative, nil, or positive, respectively. A black surface may have the potential to bleed, possibly requiring a correction factor of as much as 0.06 to be subtracted from the binder application rate. Since a smooth existing surface will not allow the asphalt binder to be lost into it, no adjustment is needed, and the correction factor is nil. To estimate the loss of asphalt binder on the surface, the surface can be rated as Hungry 1h, Hungry 2h, or Hungry 3h, and a corresponding correction factor from Table 7 must be added to the quantity of asphalt binder used in Otta seal construction. A large size aggregate of 3/4” might require a textural rating of Hungry 3h, while an aggregate size ranging from 3/4” to 3/8” requires a rating of Hungry 2h. For an aggregate size smaller than 3/8”, Hungry 1h can be selected.
Source: McLeod 1960

Table A7. Value of traffic factor, T

AADT	Traffic factor, T
< 100	0.85
100 – 500	0.75
500-1,000	0.70
1,000-2,000	0.65
>2,000	0.60

Source: McLeod 1960

6. CONSTRUCTION REQUIREMENTS

The construction requirements detailed below are summarized from the Overby design method (Overby 1999) and field practices for Otta seal construction in Iowa.

6.1 Weather Limitations

6.1.1. Construction of Otta seal surfaces from May 1 to October 31 (late spring to late fall) and during the daytime is recommended.

6.1.2. The road surface and air temperatures should be above 35°F.

6.1.3. Wind should not be allowed to cause uneven spraying of the bituminous material.

6.1.4. No Otta seal construction should be attempted when rain/snow is expected on the day of construction.

6.2 Equipment

6.2.1. Distributor: use an asphalt distributor equipped with spray bars and handheld nozzles. Spray bars shall be used to the fullest extent possible, with handheld nozzles used only in areas not accessible by the spray bar (Figure A2).

Figure A2. Asphalt distributor

6.2.2. Aggregate spreader: use a self-propelled aggregate spreader capable of distributing the aggregate uniformly at the required width and at the designated rate. The truck aggregate haul box must be clean and free of other materials (Figure A3). The aggregate spreader and the truck hookup hitches must be in workable condition to apply the aggregate uniformly.

Figure A3. Aggregate spreader

6.2.3. Rollers: A minimum of three 12-ton pneumatic-tired rollers are required to compact the main lanes of newly constructed Otta seal-surfaced roads (Figure A4a). Roller tire sizes, ratings, and pressures must comply with the manufacturer's recommendations. The tire pressure must be the same in all tires, and the tire surfaces must be smooth. A static steel wheel roller is recommended to compact the centerline joint (Figure A4b). If a pneumatic-tired or steel roller is unavailable, a fully loaded tractor or truck can be used for rolling (Figure A4c).

Figure A4. Rollers: (a) pneumatic-tired roller, (b) steel roller, and (c) fully loaded tractor

6.2.4. Broomer: If applying Otta seal to an existing surfaced road, use a motorized broom (Figure A5) with a positive means of controlling vertical pressure to clean the road surface prior to spraying bituminous material and to remove loose particles after treatment as required.

Figure A5. Motorized broom

6.3 Subgrade and Base Requirements

6.3.1. Otta seal is intended to protect the base and subgrade material from deterioration, so design the subbase and subgrade to withstand the anticipated traffic load.

6.3.2. Follow Division 21. Earthwork, Subgrades, and Subbases in the *Iowa DOT Standard Specifications for Highway and Bridge Construction* (Iowa DOT 2023) for any preparatory subgrade and base work.

6.3.3. Compact the top of the existing aggregate surface prior to placing Otta seal.

6.3.4. Level the subgrade/base to obtain a minimum crown of 3%.

6.3.5. Ensure that the course beneath the Otta seal is free of loose coarse aggregate, potholes, and washboards.

6.3.6. Keep the moisture content within a range of 3% to 7%.

6.3.7. Construct the aggregate layer to ±0.6 in. of both the profile and cross-section as required by the contract in accordance with Division 21. Earthwork, Subgrades, and Subbases in the *Iowa DOT Standard Specifications for Highway and Bridge Construction* (Iowa DOT 2023) for any preparatory subgrade and base work so that the evenness criteria can be met.

6.4 Before Construction of the First Otta Seal Course

6.4.1. Record ambient and surface temperatures.

6.4.2. Ensure that all quantities of required materials are available on site.

6.4.3. Make sure that a sufficient number of personnel are present on site.

6.4.4. Make sure that both road closure and detour signs are present.

6.4.5. Determine wind speed and direction.

6.4.6. Ensure that a backup team consisting of two people follows the construction operation to correct any problem that may occur during construction so that delays and any future problems can be avoided.

6.4.7. Calibrate the application rates for the aggregate spreader and asphalt distributor to ensure that the application rates of the materials are correct. Figure A6a and A6b demonstrate the examination and calibration of the field application rates for aggregate spreaders and asphalt distributors in accordance with ASTM D5624-13, Standard Practice for Determining the Transverse-Aggregate Spread Rate for Surface Treatment Applications. As shown in Figure A6, this process requires placing a square metal pan on the ground to receive spread aggregate and sprayed asphalt binder. The measured weight and area of the metal pan can be utilized to calculate the actual spreading rate.

Figure A6. Calibration of (a) aggregate spreader and (b) asphalt distributor

7. OTTA SEAL CONSTRUCTION PROCEDURE

The construction procedures detailed below are summarized from the Overby design method (Overby 1999) and field practices for Otta seal construction in Iowa.

7.1 Single-Course Otta Seal Construction

7.1.1. Spreading Binder Bitumen.

a) Apply bitumen to the prepared base or surface at the rate shown in the contract document, or as shown in Table A4 and Table A5 in Section 5.5.1 for the Overby design method, or as shown in equation (6) in Section 5.5.2 for the modified Iowa design method.

b) Inspect the aggregate in the wheel paths of the chip spreader to ensure that the binder is coating at least 70% of the aggregate surface area.

c) The spraying rate must be confirmed by the field engineer. Conducting a quality control test as described in Section 6.4.7 is recommended.

d) Heating temperatures for bituminous materials are shown in Table A8.

Table A8. Bituminous material temperatures

Designation	Temperature (°F)
MC 3000 Cut	275–310
HFMS-2s	120–185

e) Continue spraying the emulsion or cutback asphalt if the above requirements are met.

f) If the base course is calcareous (e.g., if a cement-stabilized base course is used), application of an emulsion tack coat using MC 30 or MC 70 is recommended due to the high amount of bitumen absorption. The application rate of tack coat bitumen should be between 0.17 to 0.26 gal/yd^2, and there should be a 12-hour minimum curing period prior to placement of the Otta seal surface.

7.1.2. Spreading Cover Aggregate

a) Prior to construction, calibrate the aggregate spreader in accordance with Section 6.4.7. The aggregate application rate should deviate by no more than ±1 lb/yd^2 from the planned rate in either the transverse or longitudinal direction.

b) The engineer may adjust the aggregate application rate during construction.

c) Uniformly spread cover aggregate of the size specified over the treated area promptly after the spreading of bitumen has been completed on any section.

d) Unless otherwise specified, use a rate of 50 lb/yd^2 for all applications.

e) When a bituminous seal coat is to be placed on two lanes, spread the aggregate with a 2 to 4 in. overlap of the lanes to prevent longitudinal cracking.

7.2 Double-Course Otta Seal Construction

7.2.1. First Course Construction.

7.2.1.1. Spreading Binder Bitumen.

a) Apply bitumen to the prepared base or surface at the rate shown in the contract document, or as shown in Table A4 and Table A5 in Section 5.5.1 for the Overby design method, or as shown in equation (6) in Section 5.5.2 for the modified Iowa design method.

b) Inspect the aggregate in the wheel paths of the chip spreader to ensure that the binder is coating at least 70% of the aggregate surface area.

c) The spraying rate must be confirmed by the field engineer. Conducting a quality control test as described in Section 6.4.7 is suggested.

d) Heating temperatures for bituminous materials are shown in Table A8.

e) Continue spraying the emulsion or cutback asphalt if the above requirements are met.

f) If the base course is calcareous (e.g., if a cement-stabilized base course is used), application of an emulsion tack coat using MC 30 or MC 70 is recommended due to the high amount of bitumen absorption. The application rate of tack coat bitumen should be between 0.17 to 0.26 gal/yd^2, and there should be a 12-hour minimum curing period prior to placement of the Otta seal surface.

7.2.1.2. Spreading Cover Aggregate

a) Prior to construction, calibrate the aggregate spreader in accordance with Section 6.4.7. The aggregate application rate should deviate by no more than ±1 lb/yd^2 from the planned rate in either the transverse or longitudinal direction.

b) The engineer may adjust the aggregate application rate during construction.

c) Uniformly spread cover aggregate of the size specified over the treated area at the rate listed in the contract document or 50 lb/yd^2 promptly after the spreading of bitumen has been completed on any section.

d) When a bituminous seal coat is placed on two lanes, spread the aggregate with a 2 to 4 in. overlap of the lanes to prevent longitudinal cracking.

e) When the full width is surfaced integrally, spread the aggregate to a width such that the junction of the two aggregate spreads is offset 12 in. from the center of the full-width surface.

7.2.2. Second Course Construction

7.2.2.1. Preparation of Roadbed.

a) After a minimum of 8 weeks or a time interval approved by the engineer, prepare the roadbed for the second course by either:

- Using a vacuum machine, or
- Lightly brooming the full width of the surface with a power broom to remove loose materials.

b) Complete the preparation of the roadbed in sections just prior to the application of bitumen for the second course.

7.2.2.2. Spreading Binder Bitumen.

a) Apply bitumen to the prepared base or surface at the rate shown in the contract document, or as shown in Table A4 and Table A5 in Section 5.5.1 for the Overby design method, or as shown in equation (6) in Section 5.5.2 for modified Iowa design method.

b) Inspect the aggregate in the wheel paths of the chip spreader to ensure that the binder is coating at least 70% of the aggregate surface area.

c) The spraying rate must be confirmed by the field engineer. Conducting a quality control test as described in Section 6.4.7 is suggested.

d) Heating temperatures for bituminous materials are shown in Table A8.

e) Continue spraying the emulsion or cutback asphalt if the above requirements are met.

7.2.2.3. Spreading Cover Aggregate.

a) Prior to construction, calibrate the aggregate spreader in accordance with Section 6.4.7. The aggregate application rate should deviate by no more than ±1 lb/yd^2 from the planned rate in either the transverse or longitudinal direction.

b) The engineer may adjust the aggregate application rate during construction.

c) Uniformly spread cover aggregate of the size specified over the treated area at the rate listed in the contract document or 50 lb/yd^2 promptly after the spreading of bitumen has been completed on any section of the roadbed.

d) When a bituminous seal coat is placed on two lanes, spread the aggregate with a 2 to 4 in. overlap of the lanes to prevent longitudinal cracking.

7.3 Compaction and Rolling Mechanism

7.3.1. Extensive rolling and compaction with 12-ton pneumatic rollers are important for bonding the aggregate with the binder.

7.3.2. Fully loaded heavy tractors or trucks should be used for rolling and compaction only if mechanical compactors are not available.

7.3.3. The entire crew involved in the operation should be arranged in a “train” during construction.

7.3.4. After the aggregate has been spread and on the day of construction, 30 passes on each lane using pneumatic rollers with a minimum weight of 12 tons are required.

7.3.5. After the aggregate has been spread and on the day of construction, at least one pass on the centerline joint using a steel roller is recommended.

7.3.5. Operate rollers at a speed of no more than 5 mph.

7.3.6. On the second day after construction, 15 passes on each lane using pneumatic rollers with a minimum weight of 12 tons are required.

7.3.7. On the third day after construction, another 15 passes on each lane using pneumatic rollers with a minimum weight of 12 tons are required.

7.3.8. If the conditions for compaction are not suitable in the days following construction, the compaction efforts should be postponed to the first subsequent days when the weather is suitable for compaction.

7.3.9. Alternatively, agencies can continue compaction on the second and third day after construction using agency-owned compaction equipment if the contractors have difficulty with the compaction process.

7.3.10. Any delay during the compaction and rolling process will minimize the bond between the aggregate and the residual binder, possibly resulting in potholes and an excess amount of loose aggregate on the surface.

7.4 Sweeping

7.4.1. For a single-course Otta seal, it is important to sweep the surface one month after construction. For a double-course Otta seal, it is required that the surface be swept before the second course is applied.

7.4.2. During the first few months after Otta seal construction, it is required that aggregate dislodged by traffic be broomed to the side of the road. The aggregate should then be spread on the wheel paths on the road surface to prevent any potential bleeding in the future.

8. TRAFFIC CONTROL

Specifications for handling traffic during Otta seal construction are as follows:

a) Direct traffic through restricted portions of the project using pilot cars as described in Section 2528.03 D. Furnish Pilot Cars and Pilot Car Signs in the *Iowa DOT Standard Specifications for Highway and Bridge Construction* (Iowa DOT 2023).

b) Station one flagger immediately ahead of the section where bitumen is being applied, one immediately behind that section, and one immediately behind the section being rolled. Display suitable warnings, speed limits, and fresh oil signs. Move the signs forward with the flaggers as the work progresses.

c) After the bituminous seal coat has been spread, smoothed, rolled, and cured for a minimum of 2 hours, the road may be opened to traffic.

d) In some areas, it may be more practical to apply the bituminous seal coat in short sections and to allow traffic to use the completed bituminous seal coat immediately after the surface treatment has been completed. In such areas, limit traffic speed on the newly placed bituminous seal coat to no more than 25 mph for a minimum of 2 hours. The engineer may specifically authorize such areas. The engineer may extend the minimum 2-hour period due to low temperature and visually observed damage to the bituminous seal coat under traffic or when turning movements may damage the bituminous seal coat. The intent of traffic control is to prevent traffic on completed bituminous seal coat sections until they are satisfactorily cured; curing requires a minimum of 2 hours, depending on climatic conditions.

e) The cost of implementing traffic control will be paid per Section 2528 in the *Iowa DOT Standard Specifications for Highway and Bridge Construction* (Iowa DOT 2023).

APPENDIX B: SITE APPEARANCE

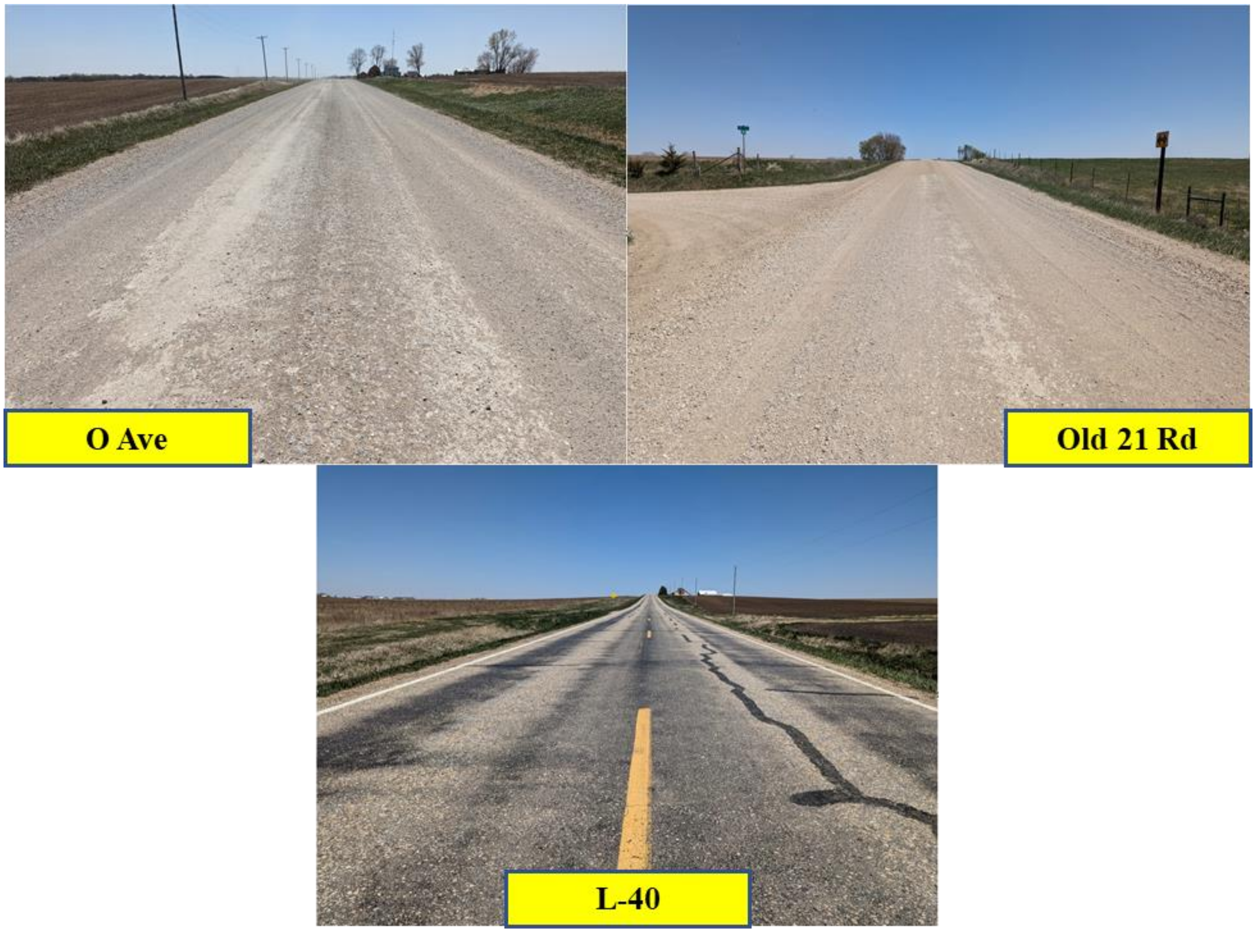

Figure B1. Otta seal site appearance in Cherokee County (photos taken on May 3, 2023)

Figure B2. Otta seal site appearance in Buchanan County (photos taken on April 21, 2023)

Figure B3. Otta seal site appearance in Louisa County (photos taken on July 31, 2023).

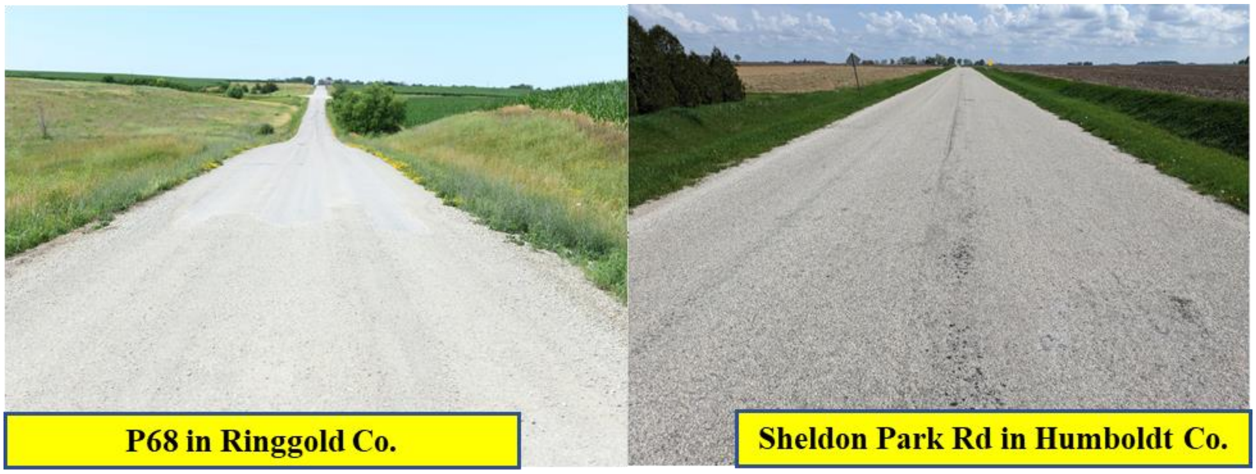

Figure B4. Otta seal site appearance in Ringgold County (photo taken on June 29, 2023) and Humboldt County (photo taken on May 12, 2023)

Figure B5. Otta seal site appearance in Winneshiek County (photo taken on April 21, 2023), Clinton County (photo taken on June 2, 2023), and Page County (photo taken on June 29, 2023)

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