Evaluation of Otta Seal Surfacing for Low-Volume Roads in Iowa

Final Report
June 2018

IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract

Low-volume roads represent a significant proportion of transportation infrastructure, and the cost of maintaining low-volume roads is quite high for secondary road departments. Traditional bituminous surface treatments (BSTS) for asphalt pavements require high-quality materials and specialized expertise, but Otta seal surfaces can be constructed using more economical local aggregates and regularly available equipment.

To evaluate the feasibility of Otta seals as an alternative surface treatment on Iowa's low-volume roads and gauge the cost-effectiveness and performance of Otta seals compared to BSTs, the first Otta seal construction project in Iowa was conducted using a double-layer Otta seal over a 6.4 km (4 mi) long existing asphalt pavement with cracks in Cherokee County during September 2017.

This study focused on the general background of this construction project, the Otta seal design details, the Otta seal construction procedures, and the many investigative tests conducted before, during, and after construction. Multiple in situ investigations, including loose aggregate tests, dustometer tests, roughness tests, and visual appearance inspections, were conducted over different construction periods to evaluate the performance of this Otta seal constructed in Iowa. Economic analyses using Minnesota and Iowa as case study locations indicate that Otta seals could be more cost-effective than BSTs (i.e., than chip seals).

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EXECUTIVE SUMMARY

This research focused on evaluating Otta seals as an alternative surface treatment for low-volume roads. The principal objectives of this study were to evaluate the following:

- Feasibility of Otta seals as an alternative surface treatment on low-volume roads using local aggregates, including lower-quality aggregates
- Cost-effectiveness and performance of Otta seals compared to traditional bituminous seal coat surfaces and with respect to maintenance of granular surfaced roads

The first principal task was to review and synthesize worldwide experience with the use of Otta seals to provide state-of-the-art information on its properties, design, and construction. Based on this work, design recommendations including material selection (aggregates and binders), Otta seal type (thickness, single- or double-layer), pre-construction preparations, and construction matters (spray rates, compaction, etc.) were developed for a local demonstration project, the first Otta seal construction project in Iowa.

The demonstration site was constructed with a double-layer Otta seal over a 6.4 km (4 mi) existing asphalt pavement with cracks in Cherokee County, Iowa. To monitor the performance of the constructed Otta seal, international roughness index (IRI) tests were conducted and dust induced by the passing traffic was measured. Key findings from the Phase I study were as follows:

- Otta seal design needs to follow the Øverby (1999) design guide, and gradation is the most critical property for aggregate selection. The allowed aggregate gradation limits vary widely, and the Otta seal type selected should fall within the specific limits. Extra-fine aggregate content is of concern because it may lead to unmanageable dust resulting from the Otta seal surface. Dustometer test results revealed that the test section constructed with low-fine-content aggregate produced the least amount of dust associated with passing traffic.
- In the Øverby (1999) design guide, the specified binder types are all cutback asphalt, but because of limitations and restrictions on using cutback asphalt in the US, asphalt emulsion was used in this study. To account for this change, the recommended binder spray rate in Øverby (1999) should be modified on the basis of asphalt content in the emulsion. The amount of asphalt per unit volume of emulsion should be equal to the equivalent amount recommended in Øverby (1999). In this study, the applied spray rate of binder for both layers was increased to 2.26 L/m^2 (0.50 gal/yd^2).
- Aggregate spreading is another critical aspect that influences Otta seal construction and resulting performance. First, the spread rate during construction should be carefully monitored. The amount of aggregate per unit area directly impacted the compaction and curing steps, the presence of extra aggregate particles led to a relatively rougher surface, and the binder also could not be squeezed upward to fully coat these particles.
- Even though the aggregate spreader was equipped with an automatic spread rate controller, there were additional factors influencing the actual spread rate, and, along with human factors, aggregate moisture content played a crucial role. Practical experience derived from this study showed that if the aggregate is too moist before spreading, there is a significant

chance that a portion of the spreader head could be blocked by moist aggregate. It will be important for engineers to keep the aggregate in a dry condition for at least one day before construction.

- A square steel plate with 0.84 m^2 (1 yd^2) area was fabricated for monitoring the aggregate spread rate. The actual spread rates were always higher than those in the design value (27.12 kg/m^2 or 50 lbs/yd^2), and the long-term performance of the Otta seal may be influenced by this discrepancy (i.e., improper operation due to insufficient binder coating on extra aggregate particles).
- Short-term performance test results indicate that the IRI values changed slightly after Otta seal construction. The IRI values before and after construction ranged from 3 to 5 m/km (190.1 to 316.8 in./mile), and, based on the short-term performance observed in this project, Otta seals are capable of providing a surface satisfying the same smoothness requirements as a hot-mix asphalt (HMA) pavement.
- The economic analyses using Minnesota and Iowa as case study locations indicate that Otta seals could be more cost-effective than chip seals.
- The results of economic analysis using Minnesota only as a case study location reveal that, in some cases, the additional investment required for Otta seals might be justified by maintenance savings alone.

After the first field demonstration site for Iowa was successfully constructed through this study, the project technical advisory committee (TAC) recommended Phase II research for establishing recommended specifications. This would include devising 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 representing a range of locally available aggregates in different areas of the state.

INTRODUCTION

Norway-based Otta (graded aggregate) seal technology, originally developed in the 1960s, has been used in northern Europe and Africa, among other locations, as an economical and practical alternative to traditional bituminous surface treatments (BSTs). It provides flexible, durable, and impervious surfacing more tolerant of the higher anticipated pavement deflections on low-volume roads constructed with lower-quality materials. Compared to traditional BSTs, which require high-quality materials and specialized expertise, Otta seals can often be constructed using more economical local aggregates and the readily available equipment (asphalt distributor, aggregate spreader, pneumatic-tired roller, and mechanical broom) that is typically used for asphalt maintenance. Otta seals are formed by a thin BST of graded aggregate, ranging from natural gravel to crushed stone, with a low-viscosity binder. Otta seals rely on a combination of mechanical particle interlock and the binding effect of bituminous binder.

Over time, Otta seals have exhibited reduced maintenance costs compared to traditional chip seals, with a typical service life of 8 to 12 years for a single-layer Otta seal, compared to 4 to 6 years for a single-layer chip seal (Øverby and Pinard 2013).

Iowa has over 117,160 km (72,800 miles) of unpaved secondary roads experiencing very low daily traffic volumes, and Iowa's county secondary road departments spend more than $110 million annually repairing and maintaining gravel roads alone. The excellent performance of Otta seal as a low-cost BST and dust mitigation technique has been documented by many international studies and in full-scale field studies conducted in Minnesota and South Dakota. Otta seals may be able to provide an alternative to a traditional BST as well as an alternative to maintaining granular roads with constant replenishment of granular materials.

Background

Otta seals were first developed and subjected to trials in Norway's Otta Valley in 1963. The treatment was developed by the Norwegian Road Research Laboratory (NRRL) in response to budgetary constraints to serve as a low-cost maintenance alternative for unpaved gravel roads with low bearing capacity during spring thaw periods (Øverby 1999). Otta seals can be constructed with various aggregate types, ranging from natural gravel to crushed limestone, using a soft (low-viscosity) binder of various formulations (Øverby and Pinard 2006). The aggregate layer is rolled into a sprayed asphalt binder layer using a roller with pneumatic tires or using loaded trucks two to three days after construction to achieve "mechanical interlocking" and "asphalt binding" capable of carrying traffic loads (Øverby 1999). During traffic opening periods up to 12 weeks after construction, the asphalt binder moves up through the matrix of aggregate voids, resulting in a surface appearance similar to that of cold mix asphalt concrete, as shown in Figure 1 (Johnson and Pantelis 2011).

Johnson and Pantelis 2011, MnROAD

Figure 1. Otta seal roadway surfacing

An Otta seal provides several advantages: (1) it allows the use of uncrushed aggregate, leading to cost reduction in aggregate production and transportation; (2) it acts as an impermeable surfacing material as the binder fills the aggregate voids, thus preventing water from penetrating moisture-susceptible gravel roads; (3) it does not require a prime coat during construction; (4) it can be opened to traffic immediately after construction; (5) fewer periodic maintenance activities are required between reseals; and (6) it has the capability for recycling as an unbound or stabilized material after pulverization. However, it adds no structural capacity to the roadway, so a sufficient substructure to support anticipated traffic loading is required (Johnson and Pantelis 2011, Weiss 2010).

Otta seals can be placed in either one or two layers, with or without a sand cover seal, depending on aggregate properties, traffic volume, construction cost, and required service life (Øverby 1999). The use of a sand cover seal is recommended to reduce the rate of oxidation of the surfacing asphalt binder under high-temperature conditions (Øverby and Pinard 2006). When applying two layers during the same season to accommodate higher traffic, it is recommended that the second layer be placed two to three months after the first (Weiss 2010). In Minnesota, in some cases a chip seal has been added to the Otta seal surface in lieu of a sand cover seal.

Since an Otta seal offers significant flexibility with respect to the use of local materials, as well as simplicity of construction, empirically based guidelines (Øverby 1999, Visser and Henning 2011) for design of Otta seal treatments have been developed. Under these guidelines (Øverby 1999, Visser and Henning 2011), an aggregate gradation that relies on expected traffic levels is a governing design factor that complements other material design factors such as aggregate spread rate, asphalt binder selection, and asphalt spray rate. Generally, the recommended aggregate gradation specifications are open (or coarse) for traffic levels less than 100 vehicles per day, medium for traffic levels higher than 100 and less than 1,000 vehicles per day, and dense for traffic levels higher than 1,000 vehicles per day. Other aggregate property requirements for Otta seals are not as strict as those for a traditional BST, like a chip seal. Relatively lower-strength aggregate can be used for an Otta seal if the gradation falls within a specified gradation area that allows the maximum amount of fine material (<0.075 mm) to be less than 10 percent. Aggregate spread rates ranging from 0.013 to 0.020 m^2/m^3 (0.012 to 0.018 yd^2/yd^3) are recommended.

The selection of asphalt binder types and the spray rate is dependent on the aggregate gradation selected for the expected traffic level. A soft asphalt binder should be used to coat the fine aggregate and move up through the aggregate matrix. Commonly suggested types of asphalt binder are MC 800 or MC 3000 for cutbacks produced from 80/100 or 150/200 penetration grade asphalt. Minnesota and South Dakota experiences (Johnson 2011, Weiss 2014) indicate that high-float, medium-set, and soft-emulsified binder (HFMS-2s) can be used, although emulsions have seen little use in other countries. The asphalt binder spray rate can be determined through road trials; it ranges from 0.9 to 2.0 L/m^2 (0.20 to 0.44 gal/yd^2) for various traffic levels and aggregate gradations. For steep uphill or downhill gradients, reducing the binder application rates is recommended when using open aggregate gradation to prevent the excessive bleeding and instability that can occur during early stages of construction (Øverby 1999).

Nordic counties have extensively used Otta seals with success (Øverby 1999) since its beginnings in the 1960s. 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). However, it has had only limited use in the US due to lack of knowledge and because the empirical design approach associated with this technique 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 resources and equipment instead of constructing a standard asphalt pavement (Weiss 2010). In this project, an Otta seal was placed on a newly graded 9 in. South Dakota Department of Transportation (SDDOT) standard specification base course. Since conducting this project, South Dakota has also used Otta seals as a surfacing material for unpaved road rehabilitation projects using an existing gravel surface as a base after improvement through recycling or addition of new virgin aggregate materials.

In 2009, the city of Pierre, South Dakota, employed an Otta seal in rehabilitating 2.01 km (1.25 miles) of a gravel-surfaced road with an annual daily traffic (ADT) volume of 526. This was done to address a city budget constraint that could not accommodate the cost of a standard paved asphalt surface. Results from the Pierre project indicate that construction costs, including those for Otta seal materials ($\$1.57/yd^2$) and agency-owned equipment and personnel, were considerably lower than the typical $\$10.35/yd^2$ for a 10.16 cm (4 in.) thick asphalt overlay (a traditional unpaved road rehabilitation strategy). To date, no occurrence of road distress has been reported for this Otta seal project since its construction in 2009 (Skorseth 2013).

Various agencies (city, county, and department of transportation) in Minnesota have used Otta seals for various traffic volumes ranging from very low up to an annual average daily traffic (AADT) of 2,000 since early 2000 (Johnson and Pantelis 2008, Johnson and Pantelis 2011). Most Otta seal-surfaced road sections constructed in Minnesota have performed well during their services lives, except when they have encountered unexpected situations such as unanticipated high traffic volumes or flood damage.

Research Objectives

The objectives of this project were as follows:

- Evaluate the feasibility of Otta seals as an alternative surface treatment on low-volume roads using local aggregate, including lower-quality aggregates.
- Evaluate the cost-effectiveness and performance of Otta seals compared to traditional bituminous seal coat surfaces and to the maintenance of granular surfaced roads.
- Develop a guide for road selection with regard to the use of Otta seals as an alternative and develop guidelines for construction of Otta seals.
- Identify local projects that could be sites for field demonstrations that represent a range of locally available aggregates in different areas of the state. The evaluation should include roadway characteristics, aggregate properties and characteristics, and performance under various conditions.
- Evaluate the performance of constructed Otta seals in a seasonally changing environment and under various traffic loading conditions through laboratory testing and field demonstration.

LITERATURE REVIEW

Overview of Traditional Asphalt-Based Surface Treatments for Road Maintenance

Federal funding has focused more on building new facilities rather than promoting and maintaining existing infrastructure (Saeed 2006). State and local governments have jurisdiction over almost 97 percent of all roads and streets in the US. From 1953 until now, total road and street mileage has increased about 18.3 percent, but paved mileage has increased by 183 percent (U.S. DOT 2014). Because much of the required infrastructure is already in place, getting better value from current roads should be prioritized. According to a FHWA 2016 budget estimate, "the percentage of funding applied to new construction is decreasing while funds for rehabilitation of the system are increasing" (FHWA 2015).

With the reduction in the building of new roads, further deterioration of the existing system is anticipated if current policies continue (Weingroff 2013), but current infrastructure systems can be maintained in a cost-efficient manner through a preventive maintenance program (U.S. DOT 2014). Pavement preventive maintenance is defined as "a program strategy to arrest light deterioration, retard progressive failures, and reduce the need for routine maintenance and service activities" (FHWA 2007). The objective of such strategies is to increase the service life of the pavement by applying treatments before the pavement deteriorates.

An effective pavement preservation strategy consists of a series of different treatments (Geoffroy 1996). Seal coatings are relatively inexpensive types of treatment that can provide a protective wearing surface on the existing pavement surface to increase its service life. There are different types of pavement sealers; e.g., coal tar-based, asphalt-based, and petroleum-based are three primary types of sealers (Geoffroy 1996) that all have pros and cons. While surface treatments are generally used to provide a relatively inexpensive surface for low-volume traffic roads, they are not designed to fix structural deficiencies of pavements (Peshkin et al. 2004), so having a strong base under the treated surface is extremely important. A clear understanding of the scope and limitations of asphalt-based surface treatments is necessary to obtain satisfactory results. ADT, AADT, climate conditions, material availability, and current pavement condition should all be taken into the account to select the most appropriate design and surface treatment type (Peshkin et al. 2004). The next section provides a brief overview of some of the asphalt-based surface treatments.

Surface Treatment Materials

Achieving a high-quality surface treatment lies in the selection of appropriate material properties. The two primary materials used in BST construction are the binder and the aggregate. The binder is normally an asphalt emulsion, and the cover aggregate can be either natural or crushed.

Binder (Asphalt Emulsion)

The three major components of asphalt emulsion are asphalt cement, water, and an emulsifying agent. Usually two-thirds of binder volume is asphalt cement, typically with the same characteristics as that used in hot mix asphalt (HMA). Water, the second main emulsion component, creates a condition for asphalt particle transfer and suspension (Wood et al. 2006). Addition of an emulsifying agent causes asphalt particles to form as small droplets that enable suspension of asphalt particles (Wood et al. 2006).

Wide ranges of binders are used by contractors and agencies in surface treatments. Agencies can either provide a choice of binder or contractors can select a type of binder by soliciting advice from an engineer. Some commonly used binders are as follows:

- CRS-2
- RS-2
- HFRS-2
- HFMS-2-s
- HFMS-1
- SS-1h
- MS-1
- MC 3000
- AC-20 5TR
- AC-15P
- Qs-1h

Proper selection of binder and application rate can have huge impact on the performance of a treated road. Asphalt binders like AC-20 5RT and AC-15P are usually used in warm climate conditions, and the emulsion grade CRS1-P is commonly used in cold weather conditions (Wood et al. 2006). The choice of binder application rate depends on the desired embedment of aggregate into the binder. For high traffic volume conditions, 30 percent embedment, recommended by Senadheera and Vignarajah (2007), might be sufficient, while for roads with low traffic volumes, 70 percent embedment is recommended by Wood et al. (2006). The percentage of desired design embedment depends on binder type, aggregate gradation, and ADT (Senadheera and Vignarajah 2007). When a larger aggregate size is used, a higher percentage of embedment is required to ensure that the binder is capable of retaining the aggregate (Wood et al. 2006, Senadheera and Vignarajah 2007). A lower binder application rate is desirable because of the binder expense, while using too much binder would cause flushing or bleeding and related deterioration over time (Gransberg and James 2005).

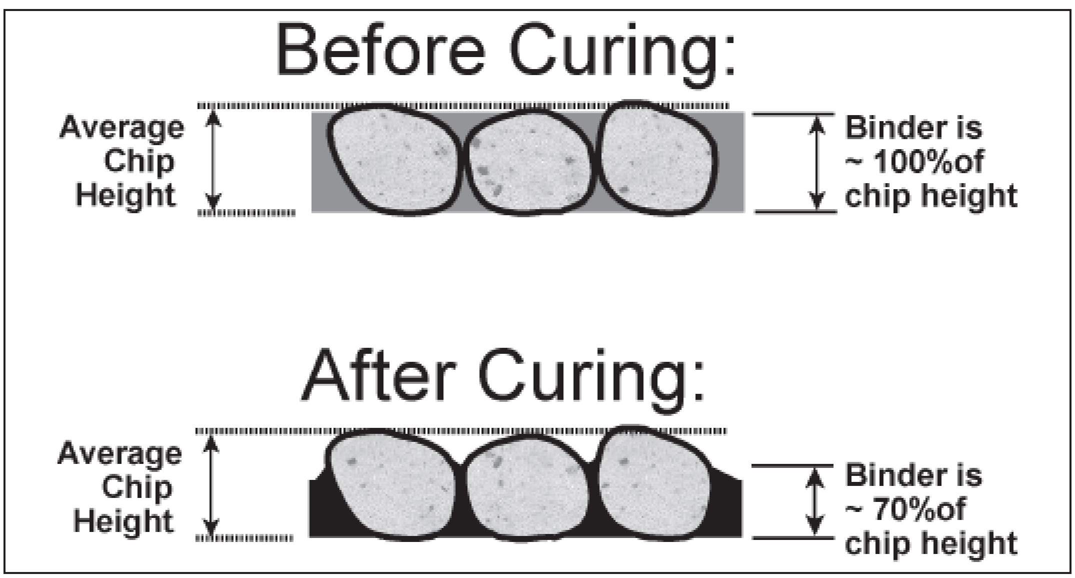
Aggregate

Typical aggregates used for most BSTs include natural gravels or crushed stones. In order for most surface treatment methods to deliver a durable and serviceable surface for traffic use, aggregates should be dust-free, stiff, and uniform. In most cases, dust will prevent the aggregate from bonding to the asphalt binder and create difficulties in terms of excessive material loss (Gransberg 2007).

Aggregate shape can be either flat or cubical and is sometimes described as angular. Aggregate gradation and size are factors key to the success of a surface treatment. Gradation refers to determination of the particle-size distribution for aggregate (Ljungstrom 1957). Grading limits and maximum aggregate size are specified, because these properties affect the amount of aggregate used, along with binder requirements, workability, and durability of BST (Gransberg 2007). It is common to limit the percent of material that can pass through a No. 200 sieve (with a diameter of 0.075 mm) to about 1 percent or less because excessive dust can present a serious adhesion issue for BSTs (Ljungstrom 1957).

Design

Surface treatments must be designed to ensure that the proposed BST has the required characteristics for a successful seal coat project. The design should determine the proper amount of binder and aggregate (Wood et al. 2006). For chip seal design, usually 70 percent of the aggregate (no lower than 50 percent) must be embedded in the binder to avoid excessive aggregate loss (Wood et al. 2006). The binder must be able to rise nearly to the top of the aggregate or else the strength of the remaining asphalt will be inadequate to appropriately embed the aggregate. The aim is to have the binder attain a height of about 70 percent of the aggregate after the binder has cured (Figure 2).



Wood et al. 2006, MnDOT

Figure 2. Change in volume after emulsion has cured

There are different design procedures for BST, including the one used by the Strategic Highway Research Program (SHRP) for designing special pavements across the US (Bullard et al. 1992, Wood et al. 2006).

Construction

Because seal coats add no structural capacity to roadways, the base/subbase layers should be capable of supporting the anticipated traffic loading. In the case of gravel roads, subgrade and base materials should be compacted and graded to provide a steady working surface before bituminous surface application. For damaged pavements, potholes must be patched, and other damaged areas on the existing pavement should also be repaired (Asphalt Institute 1979, Gransberg 2007, Ljungstrom 1957).

Prior to construction, the surface should be cleaned with a rotary broom or power sweeper if the existing surface is asphalt pavement, while prime coating but no brooming is needed for gravel road surfaces. The construction sequence is similar for all kinds of BST (Figure 3). The bituminous material is sprayed onto the prepared surface by the binder distributor. Then, the aggregate should be spread immediately onto the surface at the specified rate using an aggregate spreader. The last step is for the surface to be rolled properly and sufficiently so that the aggregate particles can embed in the binder (Asphalt Institute 1979, Gransberg 2007, Ljungstrom 1957).

Figure 3. Surface treatment operation sequence

BST Types

In this section, the following popular surface treatments will be briefly discussed:

- Sand seal
- Slurry seal
- Microsurfacing
- Chip seal
- Fog seal

Table 5 at the end of this section summarizes important points, including applications and uses, type of binder, and construction tips for each method shown.

Sand Seal

Sand seal can be beneficial in improving a number of pavement flaws by providing a barrier to prevent loss of material from the old surface by traffic abrasion. It can also help prevent intrusion of moisture and air into the pavement.

Sand seal is constructed by spray application of asphalt emulsion, usually RS-1, CRS-1, MS-1, or HFMS-1, followed by a covering of fine aggregate such as clean sand. Table 1 shows the required quantities of binder and aggregate for sand seal. Selecting sharp and angular fine aggregate would help in developing a skid-resistant surface texture.

Table 1. Quantities of binder and aggregate for sand seal

Bituminous surface treatment type	Usual emulsion applied	Aggregate type	Aggregate spreading rate kg/m^2 (lb/yd^2)	Binder spraying rate kg/m^2 (lb/yd^2)
Sand seal	RS-1, CRS-1, MS-1	Sand or screenings cover	5.5–12 (10–2)	0.70 to 1.25 (0.15–0.28)

Slurry Seal

Slurry seal is a maintenance practice used on the surfaces of older pavements (Figure 4). It fills surface cracks, stops raveling and loss of matrix, recovers skid resistance, generally reduces water and oxidation deterioration, and consequently increases overall pavement service life (McLeod et al. 1969). Slurry seal offers many advantages, such as rapid application, capability for quickly opening to traffic after construction, limitation of loose aggregate on the surface, good surface texture, and skid resistance (Wood et al. 2006).

Department of Public Works, County of Los Angeles, California 2018

Figure 4. Slurry-sealed road one hour after application

Slurry seal can be applied over a wide range of thicknesses (from 3 to 9 mm), and asphalt emulsion used in the slurry seal may be SS-1, CSS-1, SS-1h, QS-1h, CSS-1h, or CQS-1h. Cement-mixing testing is waived for CQS-1h and QS-1h emulsions. The binder spray rate varies from 0.25 to 0.45 L/m^2 (0.05 to 0.10 gal/yd^2) based on the sealing purpose. Based on usage, one of three types of aggregate gradations is typically used for slurry seal, and the International Slurry Surfacing Association (ISSA) recommends three types of gradation based on seal coating usage, as shown in Table 2.

Table 2. Slurry seal aggregate gradation and application rates

Gradation type	I	II	III
Usage	**Parking Areas Urban and Residential Streets Airport Runways**	**Urban and Residential Streets Airport Runways**	**Primary and Interstate Routes**
Sieve size	**Percent passing**	**Percent passing**	**Percent passing**
3/8 in.	100	100	100
No. 4	100	90–100	70–90
No. 8	90–100	65–90	45–70
No. 16	65–90	45–70	28–50
No. 30	40–65	30–50	19–34
No. 50	25–42	18–30	12-25
No. 100	15–30	10-21	7–18
No. 200	10–20	5–15	5–15
Application rate kg/m^2 (lb/yd^2)	4.3–6.5 (8–12)	5.4–9.8 (10–18)	8.1–12.0 (15–22)

Recommended by the International Slurry Surfacing Association

Type I gradation is a thin sealing course that excels in crack penetration. Type I slurry seal performs well on pavements with low traffic density. Type II is the most commonly used slurry seal gradation; it is used for areas with moderate traffic density to protect the existing pavement from oxidation. Type III gradation requires a heavy binder application rate and provides high skid resistance, making it a good candidate for roadways with heavy traffic density (International Slurry Surfacing Association 2010a).

Microsurfacing

Microsurfacing is an application that hardens quicker than slurry seals and can be used when circumstances do not permit slurry seal to be successfully placed. Roadways with a lot of shade and streets that have large traffic volumes can be appropriate candidates for microsurfacing.

Similar to slurry sealing, microsurfacing involves application of chemical additives to an existing asphalt concrete pavement surface along with binder and aggregate (Figure 5). To create better mixture properties, polymer is typically added to the binder in this case (International Slurry Surfacing Association 2010b).

Wood et al. 2006, MnDOT

Figure 5. Microsurfacing application

Similarly to slurry sealing, different types of aggregate gradations are recommended for microsurfacing (International Slurry Surfacing Association 2010b). The two generally accepted aggregate gradations for microsurfacing are shown in Table 3. Type II aggregate is often used for general resurfacing of streets and roadways with medium volume traffic loads. In areas with heavy traffic loads or where high-friction traction is desirable, Type III is recommended (International Slurry Surfacing Association 2010b).

Table 3. Microsurfacing aggregate gradation and application rates

Gradation type	II	III
Usage	General resurfacing, sealing and renewal of surface friction	High volume roadway resurfacing, and producing high-friction surfaces
Sieve Size	**Percent Passing**	**Percent Passing**
3/8 in.	100	100
No. 4	90–100	90–100
No. 8	65–90	65–90
No. 16	45–70	45–70
No. 30	30–50	30–50
No. 50	18–30	18–30
No. 100	10–21	10–21
No. 200	5–15	5–15
Application rate kg/m^2 (lb/yd^2)	5.4–10.8 (10–20)	8.1–16.3 (15–30)

Recommended by the International Slurry Surfacing Association

Chip Seal

Chip seal surface treatment may be used for several reasons, including providing a waterproof, skid-resistant surface over a current asphalt concrete pavement. While chip seal can be applied in multiple layers, a single-layer treatment is usually used for roads and streets with light to medium traffic as a protective or interim maintenance procedure (Gransberg and James 2005). For roadways with higher traffic volumes, using a polymer-modified emulsion with high-quality aggregate should be considered (Gransberg and James 2005). Multiple chip seal treatments can provide a surface thickness of about 12 to 20 mm (1/2 to 3/4 in.). If double-layer treatments are properly designed and constructed, the service life of the surface treatment can be significantly increased (about 3 times the service life of a single surface treatment) for only about 1.5 times the construction cost (Pierce and Kebede 2015).

Laboratory testing and mathematical calculations are usually employed to estimate the required quantities of binder and aggregate. The design must consider the amount of binder and cover aggregate to apply. “In order to prevent excessive chip loss, about 70 percent of the aggregate (and a minimum of 50 percent) must be embedded in the residual asphalt” (Gransberg and James 2005) (Figure 6).

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Figure 6. The goal is to achieve 70 percent chip embedment into the binder

Table 4 provides a general guideline regarding quantities of asphalt and aggregate for double surface treatments.

Table 4. General guideline regarding quantities of binder and aggregate for double-layer chip seal

Thickness		Aggregate size no.	Quantity of aggregate kg/m^2 (lb/yd^2)	Quantity of binder L/m^2 (gal/yd^2)
12.5 mm	First layer	8	14–19 (25–35)	0.9–1.4 (0.20–0.30)
(1/2 in.)	Second layer	9	5–8 (10–15)	1.4–1.8 (0.30–0.40)
16.0 mm	First layer	7	16–22 (30–40)	1.4–1.8 (0.30–0.40)
(5/8 in.)	Second layer	9	8–11 (15–20)	1.8–2.3 (0.40–0.50)
19.0 mm	First layer	6	22–27 (40–45)	1.6–2.3 (0.35–0.50)
(3/4 in.)	Second layer	8	11–14 (20–25)	2.3–2.7 (0.50–0.60)

Fog Seal

Fog seal is a maintenance treatment applied to surfaces on either an intermittent or a cyclical basis. Candidate roadways for fog seal treatment are usually those with minor cracking or faded color, where a fog seal would help extend the pavement life until resurfacing becomes necessary (Wood et al. 2006) (Figure 7).

Pavement Interactive 2018b, Copyright ©2012 Pavia Systems, Inc.

Figure 7. Maintenance patch on a longitudinal joint covered by a fog seal

While fog seal can be a valuable maintenance aid, it is not a substitute for asphalt surface treatments (such as chip seal or slurry seal) and should be used only to renew old asphalt surfaces that have become dry and hardened with age and to seal tiny cracks and surface voids. The asphalt emulsions normally used for fog seal are SS-1, SS-1h, CSS-1, and CSS-1h (Wood et al. 2006).

Asphalt emulsions used in fog seal applications contain globules of paving asphalt, water, an “emulsifying agent” or surfactant, and sometimes a “rejuvenator.” A rejuvenator is an asphalt additive that, when applied to the existing pavement, will slightly soften the pavement to create a better bond. The total quantity of fog seal is normally from 0.45 to 0.70 L/m^2 (0.10 to 0.15 gal/yd^2) of diluted material, and the surface condition or texture, dryness, and degree of cracking of the pavement determines the quantity required (McLeod et al. 1969).

Summary

Table 5 summarizes the different BST applications and uses, types of binder, and construction tips for each method discussed in more detail above. Note that a clear understanding regarding the benefits and limitations of different BSTs is essential to providing a surface with high skid resistance and good ride quality. Agencies and contractors should consider many factors, such as traffic count, condition of existing pavement, availability of BST materials, cost, safety, and climate condition, when designing or selecting a proper surface treatment.

Table 5. Summary and construction tips

BST type	Uses	Binder	Construction tips
Sand seal	Sand seal is used in city streets and to improve street sweeping and traffic line visibility. It can provide a barrier to prevent loss of material from the old surface by traffic abrasion. It can also help prevent intrusion of moisture and air into the pavement.	CRS-1, CRS-2 RS-1, RS-2, MS-1, HFMS-1, HFRS-2	Spray-applied with pneumatic roller. Avoiding excess binder is necessary.
Slurry seal	Mostly used in airport and city street maintenance where loose aggregate cannot be tolerated. Seals, fills minor depressions, and provides an easy-to-sweep surface.	DQS-1h, CSS-1h, QS-1h, SS-1h	Requires pretesting the aggregate and emulsion mix to reach anticipated workability, setting rate, and durability. Calibration of the equipment before starting the construction is also necessary.
Microsurfacing	Microsurfacing is a high-performance resurfacing method used in highway, city street, and airport maintenance where a durable, friction-resistant resurfacing is required. It can also be used as a rapid roadway surface correction.	CSS-1h (polymer modified)	A mix design should be required, along with calibration of equipment prior to starting the project. Experienced personnel required for proper application.
Chip seal	Chip seal provides a relatively inexpensive, all-weather surface treatment and improves skid resistance.	CRS-2, RS-2	The key factors in chip seal construction are using hard, clean aggregate and properly calibrated binder distributor.
Fog seal	Fog seal can be used on either an intermittent or cyclical basis. Fog seal treatments are usually used on roads with minor cracking or a faded color.	SS-1, SS-1h, CSS-1, CSS-1h	Emulsion can be sprayed either with or without sand cover. Diluting the emulsion with water can help in achieving coverage without adding excess binder.

Review of Otta Seal Technology

Otta seal was first developed and subjected to trials in Norway's Otta valley in 1963. It was developed by the NRRL in response to budgetary constraints to serve as a low-cost maintenance alternative to unpaved gravel roads with low bearing capacity during spring thaw periods (Øverby 1999).

Otta seal can be constructed with various aggregate types, ranging from natural gravel to crushed limestone, and with soft (low-viscosity) asphalt binder of many types (Øverby and Pinard 2006). The aggregate layer is rolled into a sprayed asphalt binder layer using a pneumatic-tired roller or loaded truck two to three days after construction to achieve mechanical interlocking and asphalt binding necessary to carry traffic loads (Øverby 1999). During traffic opening periods of up to 12 weeks after construction, the asphalt binder moves up through the matrix of aggregate voids, resulting in a surface appearance similar to that of cold mix asphalt concrete (Johnson 2011), as shown in Figure 8.

MnDOT (from FHWA Central Federal Lands Highway Division 2005)

Figure 8. Otta seal surfacing

Empirically based guidelines (Øverby 1999, Visser and Henning 2011) have been developed to design Otta seal treatments that provide flexibility with respect to the use of local materials and construction simplicity. Under these guidelines (Øverby 1999, Visser and Henning 2011), the aggregate gradation, which relies on expected traffic level, is a governing factor in designing to complement other material design factors such as aggregate spread rate, asphalt binder selection, and asphalt spray rate.

This section will provide state-of-the-art information on the properties, design, and construction of Otta seals and a review of worldwide experience in the use of Otta seals.

Brief History

In the early 1960s, a significant portion of the total public road network in Norway was comprised of unpaved gravel roads with low bearing capacity and carrying an AADT of 50 to 500 vehicles. With the arrival of the spring thaw period, the roadbed would soften and many road sections were impassable for vehicles, irrespective of weight. Considering the prevailing practices at that time, these road sections would normally have required reconstruction before bituminous surfacing was applied (Øverby and Pinard 2013).

Øverby (1999), however, reported that the road rehabilitation program actually progressed slowly because of budgetary constraints and difficulties associated with setting up heavy construction plants. In 1963, this situation led to a need to develop a method or treatment that could improve the quality of gravel roads at a relatively low cost. The Norwegian road authorities desired that such a surface treatment be cost-effective to provide a faster return on investment, perform in a manner similar to conventional bituminous surfacing as perceived by the road user, and comply with the following requirements (Øverby 1999):

- Be cheap and easy to implement
- Utilize locally available aggregate types
- Be impervious to prevent water incursion into the moisture-susceptible base material
- Be very flexible, durable, and easy to maintain

Such a bituminous surface treatment, referred to as Otta seal, was eventually developed by the NRRL in 1963, and initial field trials were carried out from 1963 to 1965 in the Otta Valley, Norway (Figure 9). Although Otta seal was originally intended to be used only as a temporary bituminous surfacing for unpaved gravel roads with low traffic volumes, its good performance resulted in it being adopted as a surfacing technique for both newly constructed and existing asphalt roads and for both low- and medium-traffic situations. From 1965 until 1985, more than 12,000 km of unpaved roads, constituting approximately 20 percent of the total Norwegian paved road network, have been surfaced using the Otta seal method.

Øverby1999, Norwegian Public Roads

Figure 9. Otta Valley, Norway, the place of Otta seal's origin

Based on its success in Norway, this practical, low-cost, sprayed bituminous seal began to be adopted in various parts of the world during the 25 years after 1985. The ability to modify the Otta seal method to conform to local environments and the lack of strict requirements for adhering to conventional standards for bituminous surfacing enabled its successful implementation in a variety of climates, ranging from freezing cold to hot/wet and dry/very hot. Norway, Sweden, Iceland, Bangladesh, Australia, Botswana, and other parts of Africa have all seen widespread use of Otta seal (Table 6).

Table 6. Countries with widespread use of Otta seal

Country	Length (km)
Norway	12,000
Sweden	4,000
Iceland	2,000
Kenya	500
Botswana	2,700 (one-third of the paved road network)
Zimbabwe	80
South Africa	25
Namibia	Trials
Mozambique	50
Ghana	30
Tanzania	100
Bangladesh	20
Nepal	40
Australia	Trials
New Zealand	Trials
Falkland Islands	15

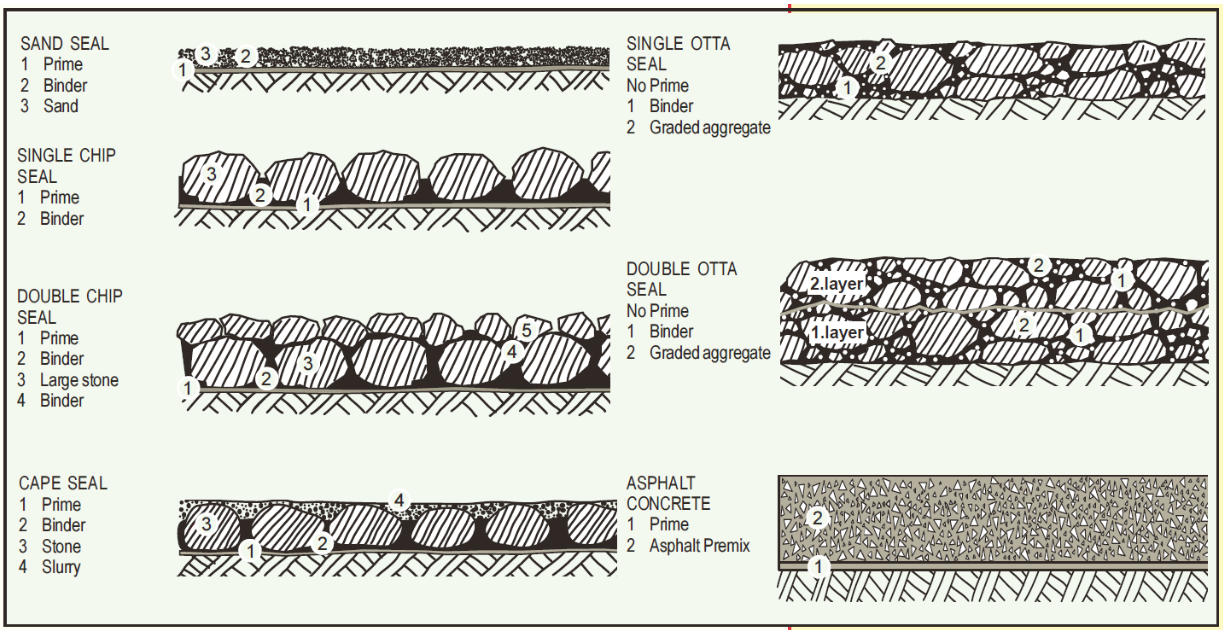
Øverby and Pinard 2013

Øverby's study (1999) was the first major effort by the Norwegian Directorate of Public Roads to provide practical and comprehensive state-of-the-art information on Otta seal properties, design, construction, and performance based on 25 years of worldwide experience.

General Description, Types, Advantages, and Limitations

Otta seal can be described as "a 16 to 32 mm thick bituminous surfacing constituted of an admixture of graded aggregates, ranging from natural gravel to crushed rock, in combination with relatively soft (low-viscosity) binders with or without sand seal cover" (Øverby and Pinard 2013). A significant advantage of Otta seal is that it can be constructed using more economical local aggregates and with the same commonly available equipment (asphalt distributor, aggregate spreader, pneumatic-tired roller, and mechanical broom) often used for asphalt maintenance.

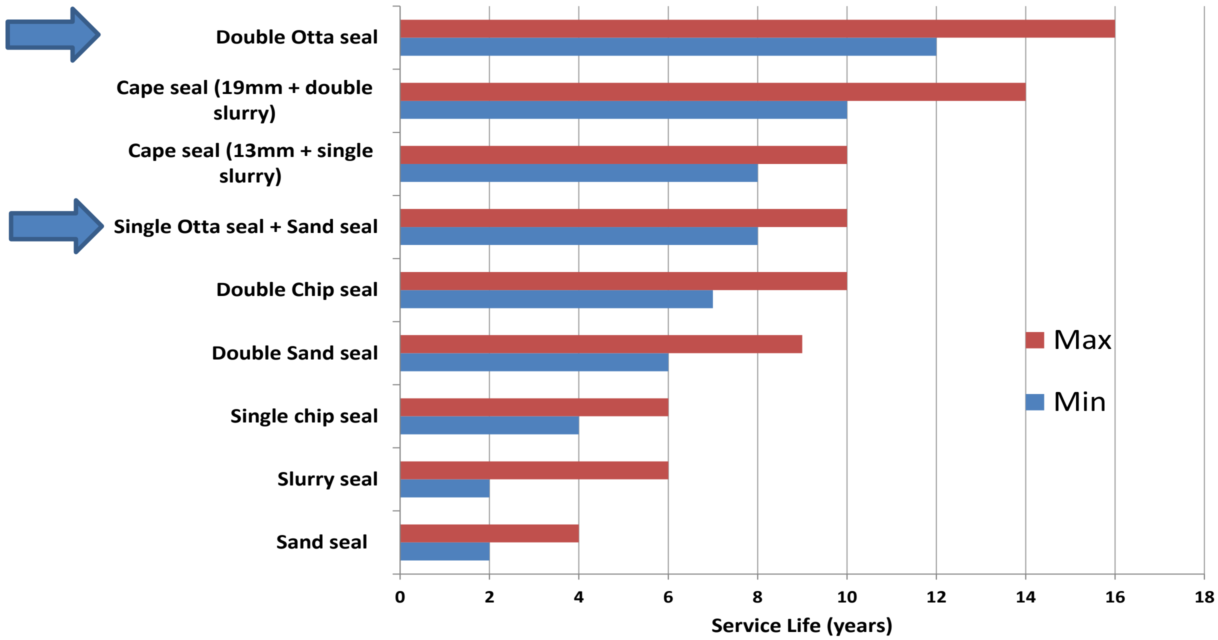
Otta seal can be placed in either one (single Otta seal) or two layers (double Otta seal) with or without a sand cover seal, depending on the aggregate properties, traffic volume, construction cost, and required service life (Øverby 1999). Aggregate grading can be open, either medium or dense, for both types of Otta seals. The use of a sand cover seal to reduce the rate of oxidation of the surfacing asphalt binder under high-temperature conditions is recommenced (Øverby and Pinard 2006). When applying two layers within a single season to accommodate higher traffic levels, it is recommended that the second layer be placed two to three months after the first (Weiss 2010). Figure 10 presents a schematic illustration of single and double Otta seals along with other types of BST.



Øverby1999, Norwegian Public Roads Administration

Figure 10. Schematic illustration of single and double Otta seals along with other types of BSTs

Typical service lives of various BSTs are compared in Figure 11. According to Øverby and Pinard (2013), the service life of the single and double Otta seal shown in Figure 11 could be considered conservative because experiences in Botswana and Kenya (warm and dry climate) have shown that double Otta seal and single Otta seal (with sand cover seal) can last more than 27 and 18 years, respectively.



Data from Øverby and Pinard 2013

Figure 11. Service life comparison of various bituminous surfacing

The relative differences between Otta seals and traditional seals are summarized in Table 7 (Øverby and Pinard 2013), which also highlights several advantages of using Otta seal over other BSTs as well as its limitations.

Table 7. Otta seals and traditional bituminous surface treatments: relative differences

Parameter	Category A (Otta seal)	Category B (Chip seal)
Aggregate quality	Relaxed requirements for: - strength - grading - particle shape - binder adhesion - dust content Maximizes the use of locally available natural gravel or of the crushed product.	Stringent requirements for: - strength - grading - particle shape - binder adhesion - dust content Maximized use of the crushed product is difficult; use of natural gravel is inappropriate.
Binder type	Relatively soft (low-viscosity) binders are required: 150/200 pen. grade or MC 3000 or MC 800 cutback bitumen (emulsions included).	Relatively hard (high viscosity) binders are required for aggregate retention: 80/100 penetration grade under hot conditions.
Design	Empirical approach. Relies on guideline and trial design on site. Amenable to design changes during construction.	Rational approach (note: not used in Iowa). Relies on confirmatory on-site trials. Not readily amenable to design changes during construction.
Construction	Relatively little sensitivity to standards of workmanship.	Sensitive to standards of workmanship.
Durability of seal	Enhanced durability due to use of relatively soft binders and a close-textured surface.	Reduced durability due to use of relatively hard binders and open-textured surface (in low-volume roads).
Aesthetics	Exhibits a non-uniform, patchy appearance that improves with traffic load.	Exhibits a very uniform, even appearance when well-constructed.
Skid resistance in wet weather	Initially exhibits relatively low skid resistance, which tends to be reduced (worsened) with traffic load.	Initially exhibits relatively high skid resistance that tends to be reduced (worsened) with traffic load.

Adapted from Øverby and Pinard 2013

Significant advantages of using Otta seal can be summarized as follows:

- It encourages the use of locally available materials.
- It does not need crushed nominal size aggregate (types of aggregate material that are generally costly). The use of uncrushed aggregate allows for cost reduction in aggregate production and transportation.
- It does not require a prime coat.
- The design is adaptable to local conditions because it can allow for various grades of material quality.
- It requires fewer periodic maintenance activities between reseals.

- It provides flexible and durable surfacing that can withstand higher pavement deflections than typically expected on low-volume roads built with lower-quality materials (Øverby and Pinard 2013).
- Construction faults resulting from over-application of binder are not as problematic as those that result from using conventional seals (Øverby and Pinard 2013).
- It is not as sensitive to workmanship quality and imposes fewer demands on contractor capacity and maintenance capability (Øverby and Pinard 2013).
- It can be opened to traffic immediately after construction.
- Its dense matrix offers resistance against intense solar radiation, thus enhancing its durability by slowing down rapid aging and binder hardening (Visser 2013).
- It has the capability to be recycled and used as an unbound or stabilized material after pulverization.
- Its dense matrix can combat high solar radiation that can cause rapid aging and hardening of the binder, thereby providing enhanced durability (Visser 2013).

Despite its many advantages, there are some limitations to Otta seal application:

- The time taken to assume final appearance is significant, and continuous rolling is required post construction for a period of up to eight weeks to ensure quality (Visser 2013).
- Considering the global picture, its worldwide use is still limited. It has been untried in many countries where particular environmental and climatic conditions are encountered (Wilkonson et al. 2013).
- Otta seal is not suitable for use on pavements where rutting or other significant/widespread defects are encountered due to heavy traffic (Wilkonson et al. 2013).
- Loose chips resulting from Otta seal construction can become a windshield hazard if proper care is not taken.
- Because double Otta seal is relatively quite expensive, this technique may not be suitable for low- and medium-traffic rural roads.
- Road marking is delayed until the curing process is completed (after the road has been opened to traffic).
- Little structural capacity is added to the roadway (although Otta seal can maintain the existing structural capacity by preventing moisture ingress), and therefore sufficient substructure support is required to support the anticipated traffic loading (Johnson and Pantelis 2011).

Design, Aggregate, and Binder Characteristics

Design

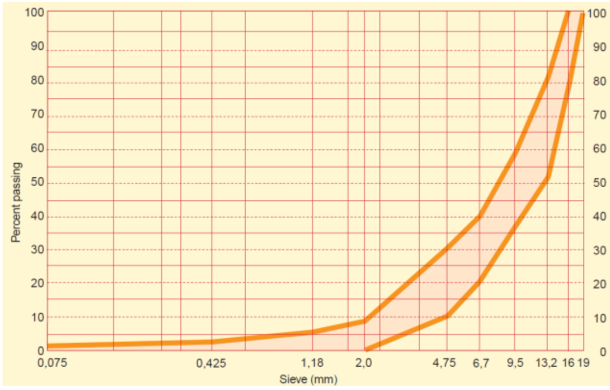
The design of Otta seal is relatively simple compared to that of conventional BSTs because it is primarily based on empirically determined binder type and aggregate application rate. Empirically based guidelines (Øverby 1999, Visser and Henning 2011) have been developed to design Otta seal treatments because they have flexibility with respect to the use of local materials and simplicity in construction. Aggregate gradation, which relies on expected traffic level, is a governing design factor to complement other material design factors such as aggregate spread rate, asphalt binder selection, and asphalt spray rate.

Aggregate

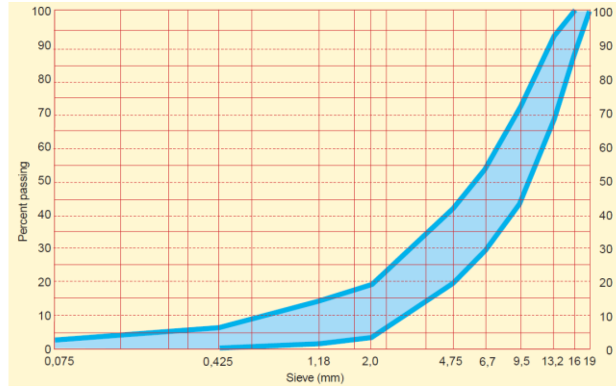
Local aggregates, typically of lower quality, are often used in the construction of Otta seal. Graded aggregate for Otta seal can be produced from crushed or uncrushed materials or a mixture of both (Øverby and Pinard 2013) to meet the required aggregate gradation. Øverby and Pinard (2013) provide typical examples of gravel/aggregate types that have been successfully used in the construction of Otta seals. These include crushed rock (e.g., gabbro, basalt, silcrete, and sandstone), screened or crushed gravel, and river and lake gravels. Note that Iowa's aggregate sources primarily include crushed stone (limestone or dolomite), natural and crushed gravel, and sand (Jahren et al. 2003).

As noted previously, there are three aggregate grading envelopes suitable for Otta seals: open, medium, and dense. Medium and dense are the preferred grading envelopes for Otta seals. It is suggested that dense grading be used for roads with an AADT in the range of 1,000 or more. Medium grading is best suited to cases where the AADT is in the range of 100 to 1,000, and open grading is preferred when the AADT is less than 100. The three aggregate grading envelopes are displayed in Figure 12 and summarized in Table 8 along with other requirements.

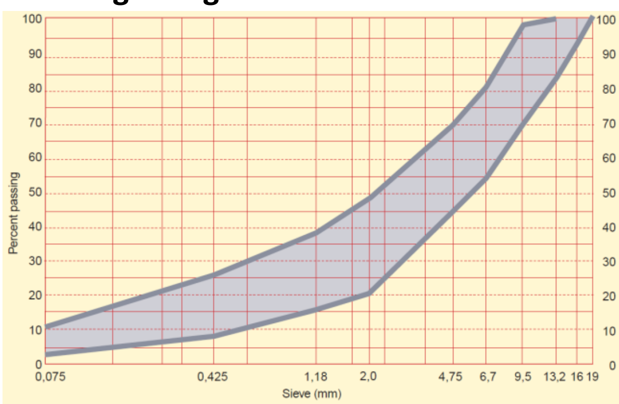
Open grading



Medium grading



Dense grading



AADT	Best suited grading
Less than 100	"Open"
100 - 1000	"Medium"
More than 1000	"Dense"

Aggregate strength requirements	Vehicles per day at the time of construction		BS Test Designation
	< 100	> 100	
Min. Dry 10% FACT	90 k N	110 k N	BS 812
Min. Wet/Dry strength ratio	0,60	0,75	

Adapted from Øverby 1999

Figure 12. Aggregate grading envelopes and strength requirements for Otta seals

Table 8. Aggregate gradation envelopes and other requirements for Otta seal

Sieve Sizes (mm)	Open percent Passing	Medium percent Passing	Dense percent Passing	Specification
19	100	100	100	AASHTO 146-49
16	80–100	84–100	93–100	
13.2	52–82	68–94	84–100	
9.5	36–58	44–73	70–98	
6.7	20–40	29–54	54–80	
4.75	10–30	19–42	44–70	
2.00	0–8	3–18	20–48	
1.18	0–5	1–14	15–38	
0.425	0–2	0–6	7–25	
0.075	0–1	0–2	3–10	
Material Properties		**Limit Values**		
Plasticity Index		Max 10		AASHTO 90-61
Flakiness Index		Max 30 (Only for crushed stones)		BS 812

Øverby 1999, Visser 2013

According to Øverby and Pinard (2013), the preferred aggregate gradation for Otta seals should fall within and desirably be parallel to the grading envelopes shown in Figure 12. Other preferred aggregate gradation requirements include a nominal maximum aggregate size of 16 mm (for single Otta seal) and 19 mm (for double Otta seal) and less than 10 percent of fine content (percent passing through a No. 200 sieve) (Øverby 1999). Also, oversized material should be screened out.

Table 9 summarizes the aggregate spread rates associated with the use of different grading envelopes.

Table 9. Aggregate application rates for Otta seals and sand cover seals

Type of Seal	Aggregate Spread Rates (m^3/m^2)		
	Open Grading	Medium Grading	Dense Grading
Otta seals	0.013–0.016	0.013–0.016	0.016–0.020
Sand Cover Seals	0.010–0.012	n/a	n/a

Øverby 1999

In general, the aggregate application rates vary from 0.013 to 0.020 m^3/m^2 (0.014 to 0.022 yd^3/yd^2), although application rates are often increased in practice to reduce the risk of bleeding (Øverby 1999). Any excess aggregate remaining after the initial curing period of the seal (two to four weeks for crushed aggregate and considerably longer periods for natural gravel) can be swept off (Visser 2013).

Binder

The choice of binder for achieving complete coating of mineral aggregates and successful performance of Otta seal requires that the binder type and application rate be tailored to the aggregate properties. Øverby (1999) lists the following desirable characteristics for binders used in Otta seal:

- It should be soft enough to initially coat the aggregate fines.
- It should be soft enough to allow for its rapid movement through the aggregate voids under the action of rolling and traffic.
- It should be soft enough to allow for its continued movement through the aggregate interstices over a period of four to eight weeks after the surface is opened to traffic.
- It should accommodate large-scale application in one spray operation.

Among the commonly available binders, Øverby and Pinard (2013) suggest that the following binders and related viscosities are most appropriate for Otta seal construction:

- MC 800 cut back bitumen (softest)
- MC 3000 cut back bitumen (medium)
- 150/200 penetration grade bitumen (hardest)

Table 10 summarizes information on the selection of a binder suitable for Otta seal with respect to aggregate grading and traffic. The guide by Øverby (1999) provides much useful information for on-site blending (in situations when reduction in binder viscosity is required, to improve the binder durability, etc.) and the recommended temperatures for storage and spraying of binders. Note that high-float, medium-set, and soft-emulsified asphalt binder (HFMS-2s) have been used as alternatives in US Otta seal projects in Minnesota and South Dakota.

Table 10. Choice of binder in relation to aggregate grading and traffic

AADT at the Time of Construction (sum both directions)	Type of Binder		
	Open Grading	**Medium Grading**	**Dense Grading**
> 1,000	Not applicable	150/200 Pen grade	MC 3000 MC 800 in cold weather
100–1,000	150/200 Pen grade	150/200 Pen grade in cold weather	MC 3000 MC 800 in cold weather
< 100	150/200 Pen grade	MC 3000	MC 3000

Øverby 1999

Anti-stripping agents are generally used to promote adhesion between the binder and the aggregate surface. By adding a small quantity of anti-stripping agent to the binder (dosage is normally in the range of 0.5 to 0.8 percent by weight of binder), the surface tension of the water is reduced, thus increasing the wettability of the aggregate surfaces by the binder. Although the use of an anti-stripping agent is recommended when using natural gravel with high fine content, good performance of Otta seal has been reported even without the use of such an additive (Øverby 1999). Because anti-stripping agents are generally expensive, their use should be determined on a case-to-case basis after performing appropriate laboratory tests on aggregates.

A number of parameters influence binder application rates in the construction of Otta seal, including traffic at the time of construction (AADT), aggregate grading (open/medium/dense), absorbency of aggregate particles, and whether or not the base layer in new construction has been primed (Visser 2013). In general, binder spray rates for Otta seal construction vary anywhere from 0.9 to 2.0 L/m^2 (0.20 to 0.44 gal/yd^2) for various traffic levels and aggregate gradations, as summarized in Table 11.

Table 11. Hot binder application rates (in L/m^2) for unprimed base course or reseal

Type of Otta seal		Open	Medium	Grading Dense AADT<100	Dense AADT>100
Double	1st spray*	1.6	1.7	1.8	1.7
	2nd spray	1.5	1.6	2.0	1.9
Single with Sand Seal	1st spray*	1.6	1.7	2.0	1.9
	2nd spray	0.9	0.8	–	0.7
Single without Sand Seal		1.7	1.8	1.8	1.9
Maintenance Reseal (Single)		1.5	1.6	2.0	1.7

Visser 2013
*On a primed base on new construction, the first spray rate is reduced by 0.2 L/m^2.
For aggregates with water absorbency of more than 2 percent, the hot spray rate should be increased by 0.3 L/m^2.
Hot spray rates lower than 1.5 L/m^2 should not be allowed.

The actual spray rate for a given project can be determined through preliminary road trials. Also, for steep uphill or downhill gradients, when using open aggregate gradation, reduction in binder application rates is recommended to prevent excessive bleeding and instability that could occur during early stages of construction.

Construction

Although the construction operations for an Otta seal are similar to those for a traditional BST, Otta seals differ in many respects from a traditional BST, e.g., a chip seal (see Table 7). Typically, binder distributors, self-propelled chip-spreaders, tipper trucks, pneumatic and steel rollers, front-end loaders, mechanical brooms, and motor graders are used in the construction of Otta seals. The following steps, also summarized in Figure 13, are involved in the construction of Otta seals:

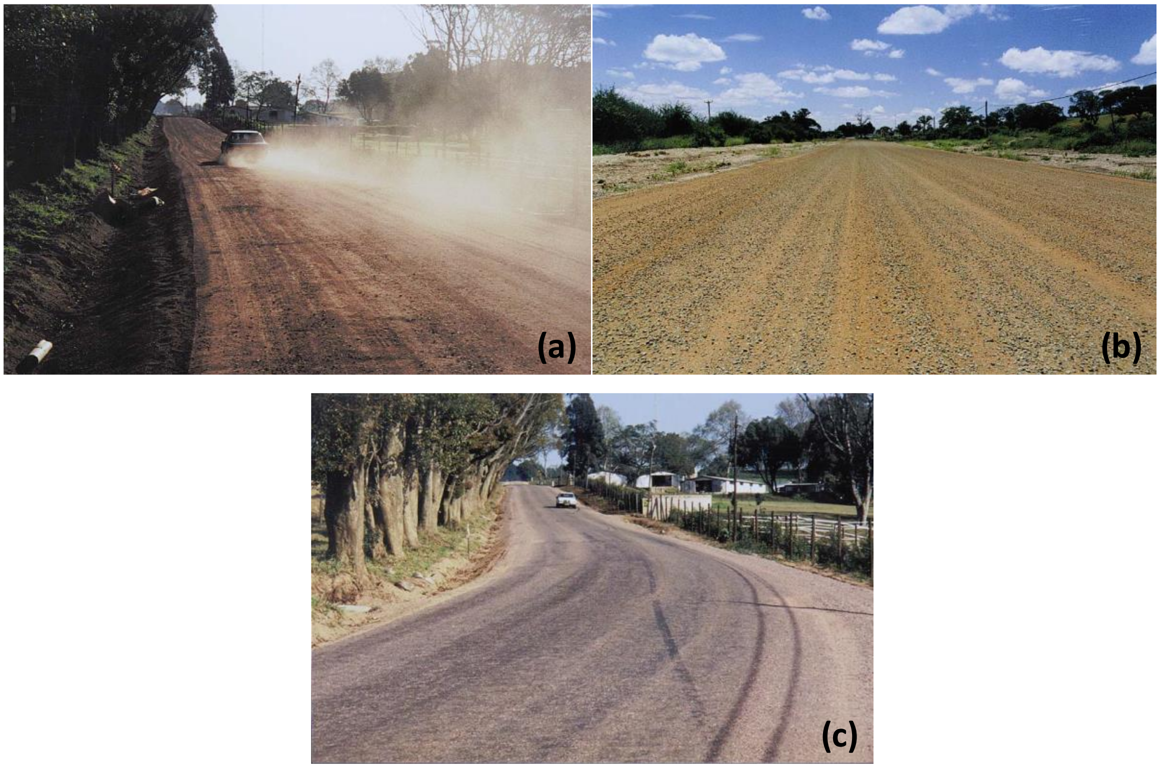
- Production of aggregate for the Otta seal
- Preparation (brooming) of the road base prior to sealing
- Loading of binder with on-site blending
- Spraying of binder
- Spraying of aggregate
- Rolling and compaction

(a) (b) (c) (d) (e)

(a and b) Øverby and Pinard, SSATP 2006, (c, d, and e) Visser 2013

Figure 13. Overall steps involved in the construction of Otta seal: (a) production of aggregate, (b) preparation of the road base prior to sealing, (c) spraying of binder, (d) spraying of aggregate, (e) rolling and compaction

Immediately after construction, the initial appearance of Otta seal is influenced by the aggregate color, but within weeks under the influence of traffic the binder moves up through the matrix of aggregate voids creating a look similar to cold mix asphalt concrete. The different stages in the maturation of Otta seal are depicted in Figure 14.



Overby and Pinard 2006

Figure 14. Different stages in the maturation of Otta seal: (a) immediately after construction, (b) 1 to 2 weeks after construction, and (c) 8 to 10 weeks after construction

Performance

The performance of Otta seal, like that of other surfacing seals, depends on a number of factors during and after construction, including materials, design, construction, traffic, and environmental variables (especially solar radiation). As mentioned previously, the typical performance of Otta seal has been reported to exceed that of other surfacing seals in terms of service life (Øverby and Pinard 2013).

Visser and Henning (2011) provided guidelines for performance monitoring of Otta seals. A performance evaluation program should be initiated even before the application of Otta seal through visual inspection for surface defects and documentation of the following construction information (Visser and Henning 2011):

- Milepost information (i.e., location of the participating project)
- Terrain type (flat, rolling, mountainous)
- Traffic count (including truck volume)

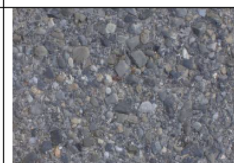
- Roadway characteristics (length and width of the section on which Otta seal is to be applied)
- Binder type and application rates for new Otta seal (as designed and actual)
- Aggregate type, source, and spray rates (first layer and second layer)
- Construction date and time
- Weather conditions both during and immediately following construction

A construction data sheet that will include these details should be prepared for this purpose. The attributes to be monitored through regular site (visual) inspection include the following:

- Surface and binder condition (surface texture, aggregate loss, binder bleeding/flushing, brittle binder)
- Cracking (longitudinal, traverse, alligator)
- Structural defects (potholes, edge break/repairs, shoulder drop-off)
- Subsurface drainage outlet conditions (any visible moisture-related surface distresses)

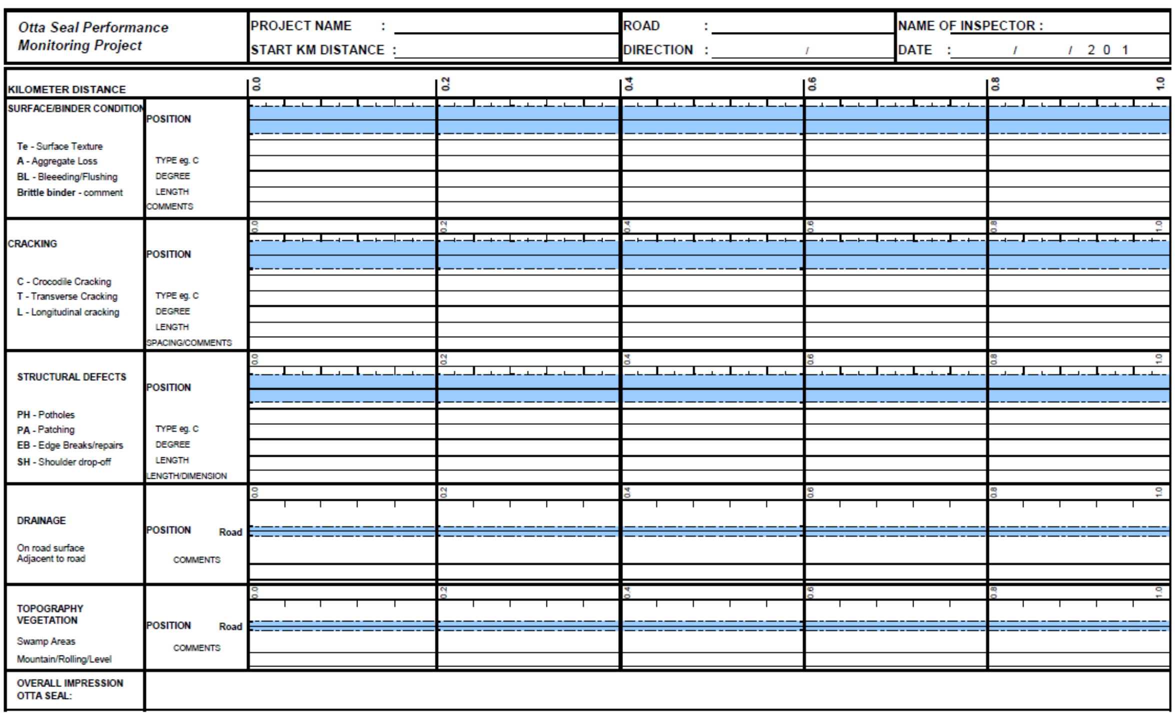
It is important to note that it takes about two weeks to achieve a consistent surface condition after construction of Otta seal surfacing because loose aggregate material will continue to be dislodged (especially with the use of cutback binders) during the two weeks post construction under traffic-induced compaction. Therefore, the following visual assessment and monitoring schedule has been suggested for field performance evaluation of Otta seal projects (Visser and Henning 2011): two weeks, three months, six months, and one year.

In addition to the information gathered through visual inspection, other useful data that could be collected (depending on availability) include local maintenance records, rainfall records from the nearest weather station, and actual traffic volume at the time of construction. Visser and Henning (2011) provide a quasi-visual inspection protocol (see Figure 15) and a visual inspection template (see Figure 16) for performance evaluation of Otta seal projects.

Defect	Description / Likely Cause	Definition of the Degree	Extent Measurement	Photos
Over-all Surface and Binder Condition				
Surface texture	Texture is important for road surfaces as it provides the required skid resistance for vehicle tires, especially in wet conditions. Texture loss may occur on Otta seals due to stones being lost from the surface or bitumen rising to the top of the surface.	**Coarse (1)** – The surface has a course appearance with significant stones being visible on the surface **Medium (2)** – There are some stones exposed to provide skid. This degree is still being classified as acceptable texture (see photo) **Fine (3)** – The surface has a smooth appearance with most of the stones being level with the surface	**Only the worst part of the section is rated.** The extent of the lowest texture rating is quantified by the actual size of the patch containing low texture (to the nearest 1 metre) Where a number of smaller smooth areas exist, the total areas of these parts have to be assessed.	 Medium texture (medium)
Aggregate loss/loose stones	Stone loss may occur for a number of reasons including: insufficient binder; vehicles performing turning movements; insufficient binding between stones and bitumen. This attribute is evaluated after construction, as loose material is swept	**Minor (1)** – only a limited number of stones are loose. (see photo) **Medium (2)** – loose stones can be observed on most of the section. **Serious (3)** –	**Only the worst part of the section is rated.** The extent of the worse affected area is quantified by the actual size of the patch containing stone loss (to the nearest 1 metre) Where a number of smaller affected	 Loose Chip (minor)

Visser and Henning 2011

Figure 15. Quasi-visual inspection protocol for monitoring Otta seal projects



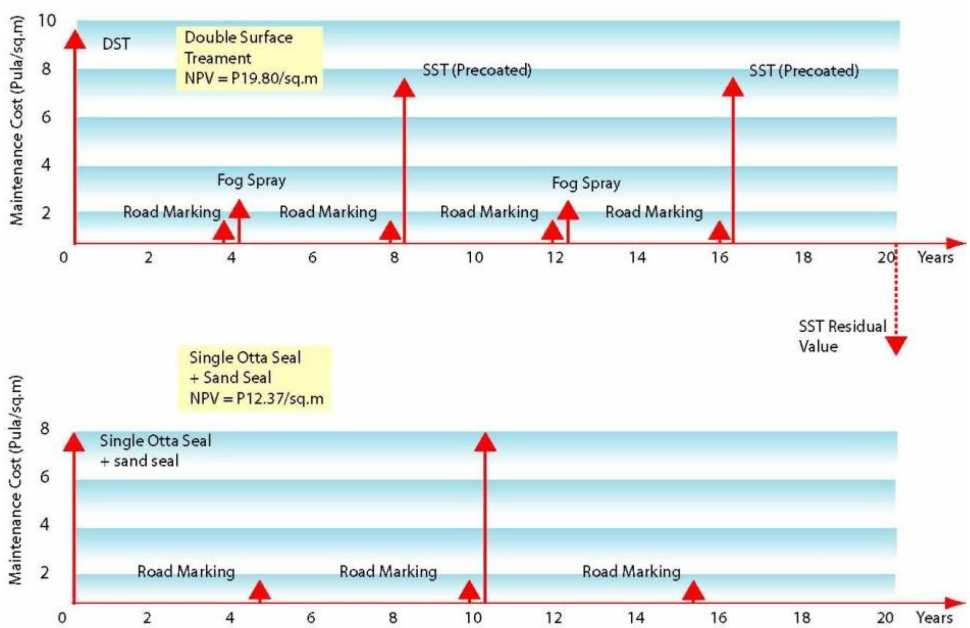
Visser and Henning 2011

Figure 16. A sample visual inspection template for performance monitoring of Otta seal projects

Economics

While several studies have reported that Otta seals achieve lower life-cycle costs compared to traditional seals and gravelling/re-gravelling (Øverby and Pinard 2013), the weakness of those studies lies in their assumptions. A deterministic analysis of life-cycle costs assumes a given cost for the materials used in the surface treatment, even though the assumption that inflating the cost of liquid asphalt binder at an annual rate of 3 to 5 percent over a period of a decade or more is a fundamental mistake. The price of diesel has nearly tripled over the past decade, as have the prices of asphalt products, and a study completed by Gransberg and Diekmann (2004) found that deterministic economic analysis was inadequate to be applied to highly volatile construction materials with any degree of confidence.

For any bituminous surface treatment, the following factors are somewhat important with respect to influencing service life (Øverby and Pinard 2013): surface type, quality of surfacing (aggregate strength, durability of binder, construction quality, etc.), bearing capacity of overall pavement structure, actual traffic, environment (especially solar radiation), and roadway characteristics. Single Otta seals and double Otta seals have typical service life ranges of 8 to 10 years and 12 to 16 years, respectively (Øverby and Pinard 2013). Because of the lower initial construction costs (attributed to greater utilization of crushed aggregate or screened gravel), longer service life, and lower maintenance costs, double Otta seals have generally proven to be more cost-effective than single Otta seals, as depicted in Figure 17.



Øverby and Pinard 2007

Figure 17. Single Otta seal with sand seal cover versus double chip seal: life-cycle cost comparison

US Experiences with Otta Seal

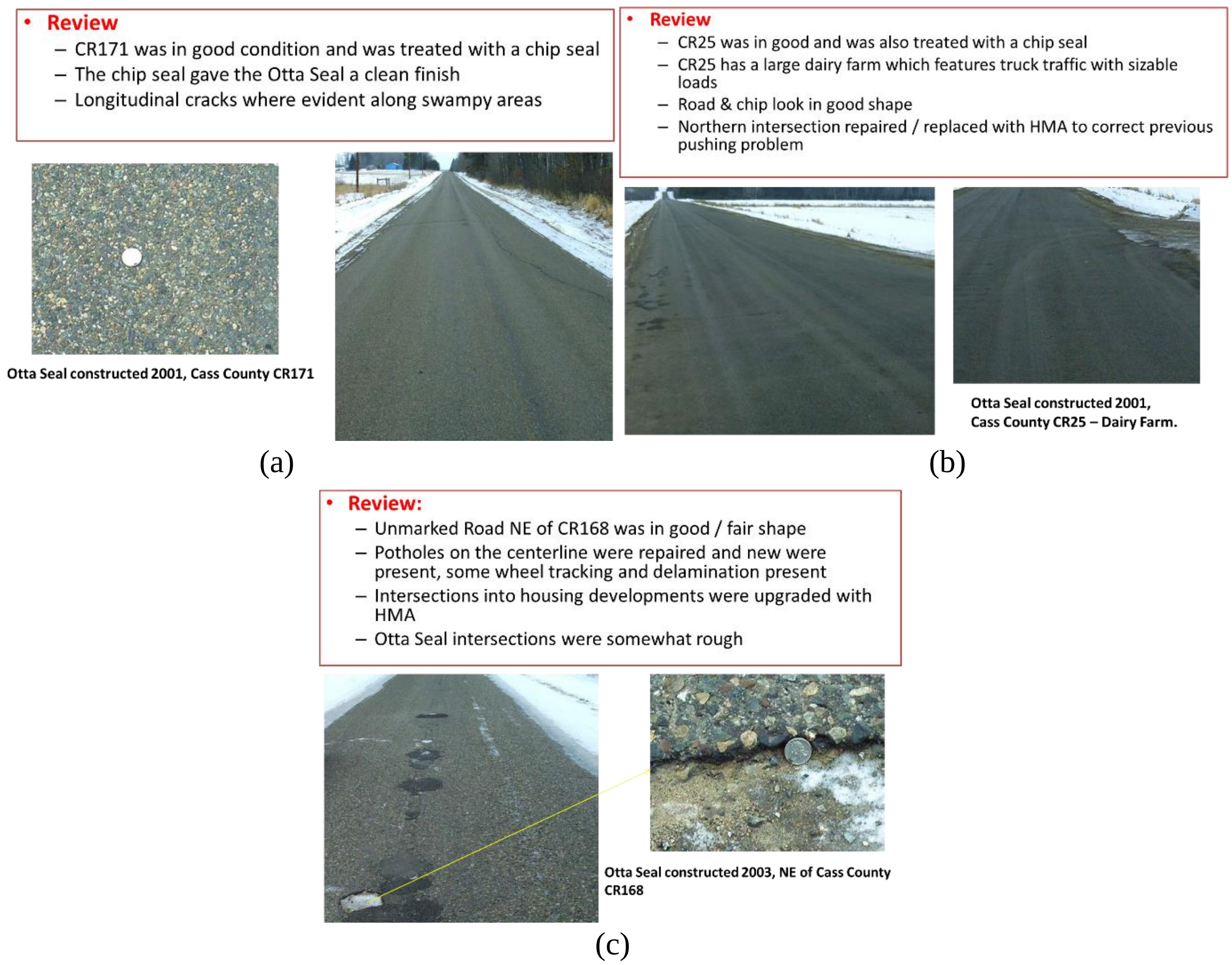
Although Nordic countries, Asia, Africa, New Zealand, and South America continue to see increasing use of Otta seal, its use in the US is currently limited (Øverby 1999, Visser 2013). This is related to lack of knowledge and the empirical design approach associated with this technique, which requires evaluation of trial or demonstration sections before deployment. Minnesota and South Dakota are currently the only two states that have completed Otta seal projects in the US. A discussion of their experiences with Otta seal is given in this section.

Minnesota

Various agencies (city, county, and department of transportation) in Minnesota have used Otta seals since early 2000 for traffic volumes ranging from very low up to an AADT of 2,000 (Johnson and Pantelis 2008, Johnson and Pantelis 2011, Johnson, 2014). Most Otta seal-surfaced road sections constructed in Minnesota have performed well, except when they experienced unexpected situations during their service lives such as unanticipated high traffic volumes or flood damage. A summary of the highlighted Otta seal project sections in Minnesota is provided in Table 12 and Figure 18.

Table 12. Summary of highlighted Otta seal projects in Minnesota

Road	State	County or City	Const. Year	ADT	Performance	Note
Trial section	MN	St. Louis County	2000	260	Potholes and wash boarding problems due to uniform aggregate application	Lessons learned: Use a chip spreader for accurate aggregate application rate; No driving on the emulsion before aggregate is applied
CR 168	MN	Cass County	2001	Less than 150	Good condition after 7 years; Thermal cracks had occurred at intervals of 50 ft	1 in. of aggregate maximum size without fine aggregate
Unmarked road	MN	Cass County: Northeast of CR 168	2001	Less than 150	Fair condition after 7 years; Pothole distress had developed in the centerline	Higher volume intersections with turning traffic had been upgraded to HMA sections
CR 171	MN	Cass County	2001	Less than 150	Good condition after 7 years; Longitudinal cracks were evident along swampy areas	
CR 25	MN	Cass County	2001	Less than 150	Good condition after 7 years	One intersection was replaced with HMA due to a surface shoving problem



Johnson and Pantelis, MnROAD 2008

Figure 18. Highlighted Minnesota Otta seal projects: (a) CR 171, (b) CR 25, and (c) CR 168

In addition to the overall Otta seal construction stages and operations summarized by Øverby (1999), Johnson (2003) provided additional construction guidelines based on Minnesota's experience (Table 13).

Table 13. Guidelines on Otta seal construction operations based on Nordic and Minnesota experiences

Steps of Construction	Suggestions
Preparation of Base Course	Unprimed base: the base should be broomed free of all dust or any foreign matter
On the Day of Construction: Sealing Operations	A minimum of 15 passes with a pneumatic-tired roller at a minimum weight of 12 tons is required (two pneumatic-tired rollers are recommended); 1 pass with a 10- to 12-ton static tandem steel roller (Johnson 2003) after the initial rolling can provide more benefit to knead the binder upwards into the aggregate particles. Commercial traffic should be allowed immediately following completion of the initial rolling
Follow-up Inspection	An inspection must be made during the first six to seven days following sealing to ensure that any defects are corrected
Immediate Post-Construction Care	During the initial two days after construction, a minimum of 15 passes with a pneumatic-tired roller are required
	For two to three weeks after construction, any aggregate dislodged due to traffic should be broomed back into the wheel tracks if cutback is used instead of emulsion. After two to three weeks, any excess aggregate can be swept off
Traffic Management	Early traffic load is a valuable contribution to the compaction of the seal
Lane Closure Requirement	Lane closure is required only during the construction
Additional Considerations	Double Otta seal: minimum of 8 to 12 weeks is recommended (Øverby 1999) after the first Otta seal layer, but most projects carried out in the US placed the second Otta seal layer right after the first Otta seal layer treatment with no adverse effect on performance
	Sand cover seal or chip seal: recommended several months after Otta seal to ensure performance of constructed Otta seal

Øverby 1999, Johnson 2003

Dayamba (2013) developed a system for selecting candidate roads for light surfacing (including Otta seal) and reviewed design methods for light road surfaces. In a review of case studies of successful and unsuccessful implementation, it was noted that Otta seal was most successful in areas of good soil support and modestly heavy vehicle loads. Dayamba’s selection method uses a combination of GIS information (soil type, buildings and land parcels likely to attract heavy traffic, traffic volumes, and material availability) and site visit documentation (verification of soil support, maintenance costs in comparison to existing surface, demand for sealed road surfaces by road users and landowners, and safety considerations). It was found that considerable information is available in GIS databases to inform decisions on light surfacing options such as Otta seal (Dayamba 2013).

Dayamba (2013) reviewed the following design methods for their applicability to light surfacing seals such as Otta seal: Minnesota Gravel Equivalent, the method used in MnPave software (mechanistic-empirically based) (MnDOT 2012), a method used by the American Association of State Highway and Transportation Officials (AASHTO), Rolt's method (TRL 1993), and Russell's method (Hitch and Russell 1977). It was found that while the first three methods were developed for standard pavements, and therefore their applicability to light surfacing seals such as Otta seal was questionable, they did produce results similar to those produced by Rolt's and Russell's methods, which were more specifically developed for light surfacing seals.

South Dakota

South Dakota's first Otta seal project was completed in Day County, South Dakota, in 2008 to provide a low-cost asphalt surface using in-house resources and equipment rather than constructing a standard asphalt pavement (Weiss 2010). In this project, Otta seal was placed on a newly placed 9 in. South Dakota Department of Transportation standard specification base course (Figure 19). Since this project, South Dakota has also used Otta seal as a surfacing material both for projects using new virgin aggregate materials and for an unpaved road rehabilitation project utilizing the existing gravel surface as a base after it was improved through recycling (Fromelt 2012).

(a)

(b)

Fromelt 2012, Day County, South Dakota

Figure 19. Otta seal project in Day County, South Dakota: (a) first surfacing with an Otta seal using a very heavy coat of high-float emulsion on CR12, (b) second surfacing with cutback asphalt and 3/8 minus pea stone to provide a good driving surface

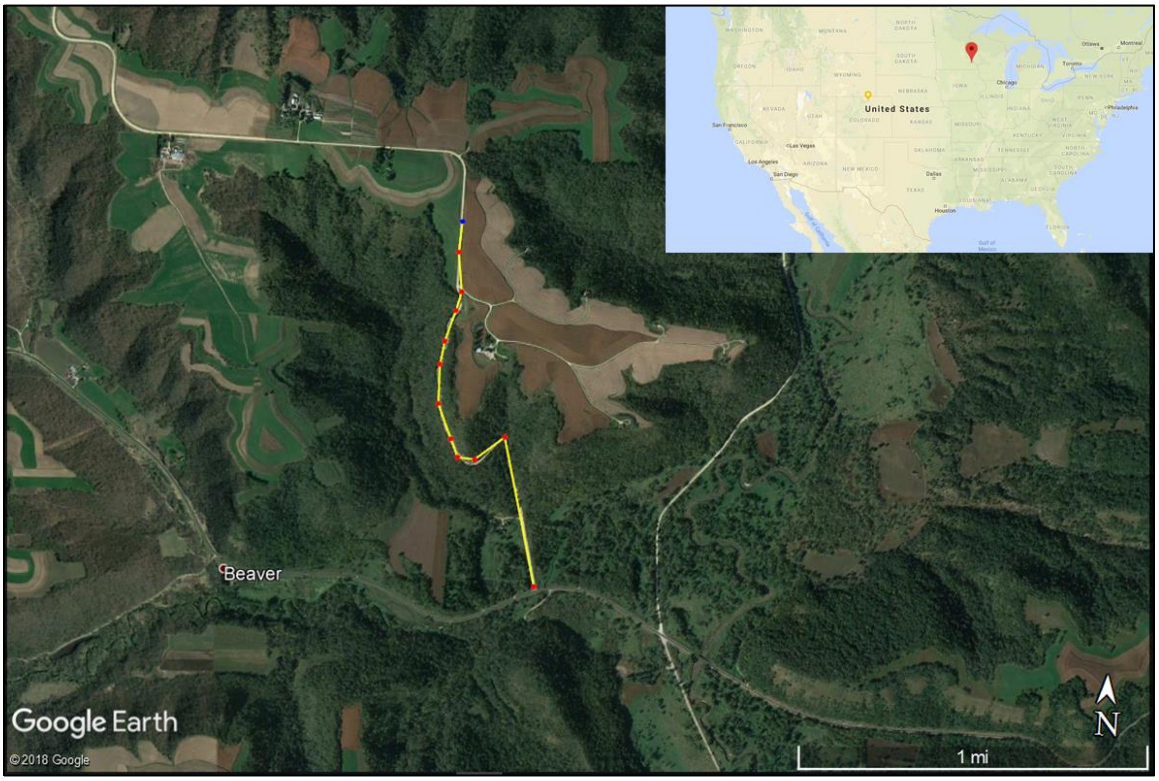
In 2009, the city of Pierre, South Dakota, employed Otta seal in rehabilitating 1.25 mi of a gravel-surfaced road with an ADT of 526. This was done to address a city budget constraint that could not accommodate a standard paved asphalt surface. The Pierre project results indicated that construction costs, including the Otta seal materials (\$1.57 per yd^2) and the agency's equipment and personnel, were considerably lower compared to the cost of \$10.35 per yd^2 for a 4 in. thick asphalt overlay (a traditional unpaved road rehabilitation strategy). To date, no distress has been reported for this Otta seal since its construction in 2009 (Skorseth 2013).

MINNESOTA OTTA SEAL STUDIES

Otta Seal Construction on CR 116, Winona County, Minnesota

Project Information

An Otta seal project was initiated in Winona County, Minnesota. The beginning GPS location of the start (north end) of the project was 44°09'12.3"N, and the end (south end) location was 92°00'57.3"W (Figure 20).



Google Earth © 2018

Figure 20. Location and topography of the project on CR 116, Winona County, Minnesota

The ADT was estimated at around 150. The total length of this project was 1.2 mi, and the constructed pavement was 22 ft wide. Based on the information provided by the Winona County engineer, the type of the existing road was an aggregate base course. The subgrade and base material were compacted and graded in 2016 (Figure 21).

Figure 21. Pre-construction appearance of CR 116, Winona County, Minnesota

Construction Description

There were three motivations for adopting Otta seal in this construction project:

- Otta seal requires fewer periodic maintenance activities between reseals.
- Otta seal acts as an impermeable surface.
- Otta seal can be recycled and used as an unbound or stabilized material after pulverization.

The construction of a double Otta seal surface was performed in August 2017. The bituminous binding agent used for CR 116 was an emulsified asphalt (HFMS-2s), and the aggregate applied was Minnesota Class 5 gradation (Figure 22).

Figure 22. Aggregate used for Otta seal on CR 116, Winona County, Minnesota

The construction equipment used in the project included an asphalt distributor to spray the required binder, a chip spreader to apply the required aggregate, three pneumatic rollers (12 tons) to compact the final surface, and a mechanical broom to remove loose aggregate immediately after placement (Figure 23 and Figure 24).

Figure 23. Equipment used for Otta seal on CR 116, Winona County, Minnesota

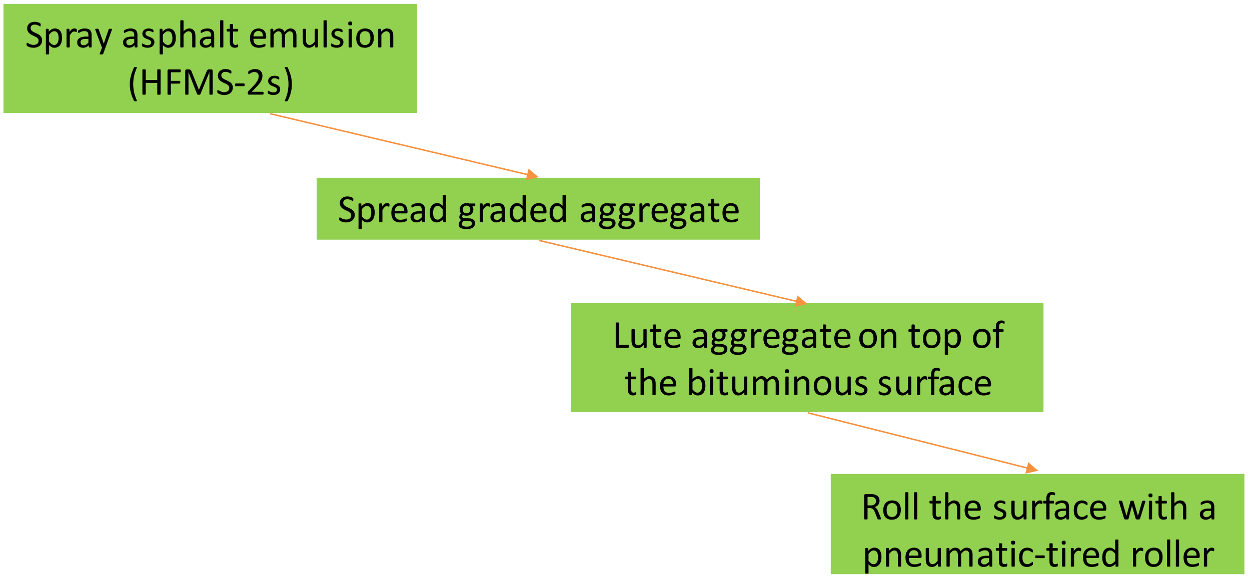


Figure 24. Construction sequence of Otta seal on CR 116, Winona County, Minnesota

The Otta seal's appearance was similar to that of a gravel road and was influenced by the aggregate color (Figure 25 and Figure 26). The second layer construction took place one month after the first layer and followed construction techniques similar to that of the first layer.

Figure 25. Newly placed Otta seal in Winona County, Minnesota

Figure 26. Otta seal surface texture immediately after constructing the first layer in Winona County, Minnesota

Lessons Learned and Key Findings

The motivations for using Otta seal in this project were the need for fewer periodic maintenance activities between reseals; Otta seal's ability to act as an impermeable surface by filling up aggregate voids, thus preventing water infiltration; and Otta seal's capability for recycling as an unbound or stabilized material after pulverization.

Several useful results related to construction were found:

- It is desirable for the contractor to furnish and install EXPECT DELAYS signage at the entrance to the work zone during construction.
- The first application of emulsion and aggregate should be completed after all subgrade preparation has been completed and accepted by the engineer in the field.
- It is acceptable to make fewer than five passes and leave the remaining compaction to public traffic.
- Constructing the second layer between 10 days and 3 weeks after constructing the first layer is recommended.
- It is necessary to broom the first layer's surface on the same day that the second layer is constructed.
- The construction procedure and equipment for the second layer are the same as those for the first layer.

Based on the construction process and the subsequent short-term visual observation of the Otta seal's performance, some critical lessons learned from this project can be summarized as follows:

- It is necessary to compact the top of the existing aggregate surface before placing the Otta seal.
- It is necessary to construct to a 3 percent minimum of crown.
- It is necessary to eliminate loose coarse aggregate, potholes, and washboards.
- It is necessary to keep the moisture content at 3 to 7 percent.
- The finished top of the subgrade should not vary by more than 1.52 cm (0.05 ft) from the established grade and cross‐ section.
- Otta seal should be constructed between May 1 and October 1.
- Otta seal should be constructed during daylight hours.
- Otta seal should be constructed when the pavement and air temperature is 1.7°C (35°F) and rising.
- Otta seal should be constructed when wind cannot cause uneven spraying of the bituminous material for mixture.
- There is a possibility that the aggregate cannot be well distributed at some spots on the surface (Figure 27).

Figure 27. Aggregate not well distributed on some spots of the surface

- During construction, wet aggregate decreases the production rate of the construction process.
- If there is a possibility of rainfall, construction should be canceled to avoid wet aggregates.
- However, rain causes no serious problems for sections already completed (Figure 28).

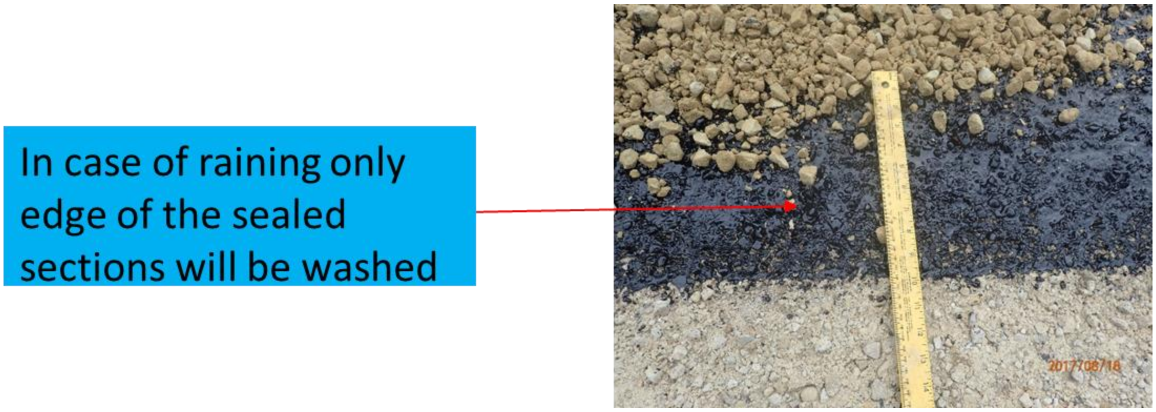


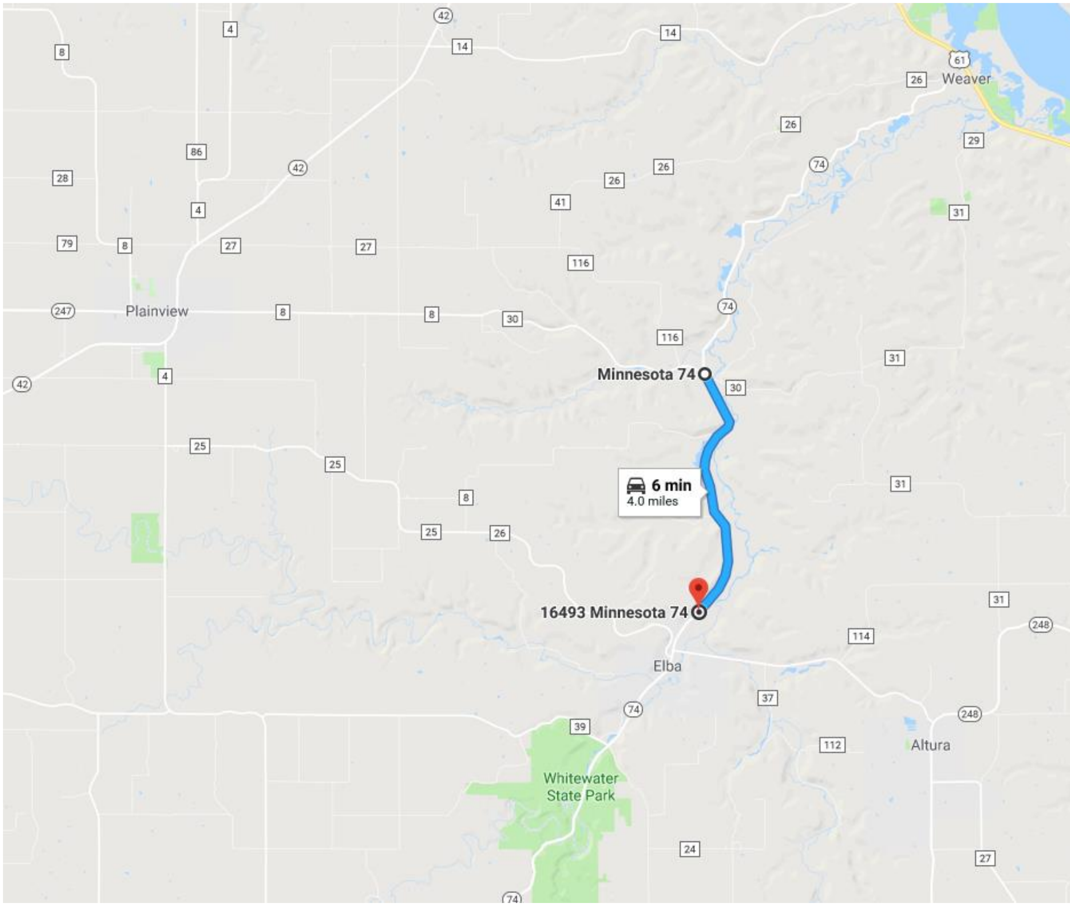
Figure 28. Completed sections showing a lack of rain-related damage

- The roadway lane being constructed must be closed during construction, so adequate traffic control is needed.
- The Otta seal surface can be opened to traffic as soon as construction is completed.
- Calibration of the aggregate spreading rate of the chip spreader is essential for achieving a successful Otta seal.
- Calibration of the asphalt spraying rate of the emulsion distributor is essential for achieving a successful Otta seal.
- If applying Otta seal over a previously treated surface, it is necessary to sweep off excess aggregate on the same day as construction.
- It is suggested that Otta seal only be applied during dry weather and with dry aggregate.

Performance of Minnesota Otta Seal-Surfaced Road

MN 74, Winona County, Minnesota

MN 74, an Otta seal-surfaced road, is located in Winona County, Minnesota. The length of the road segment is 4 mi, and it has an ADT of 395. The Otta seal on MN 74 continues to perform satisfactorily after 16 years in service (Figure 29 and Figure 30).



Map data ©2018 Google

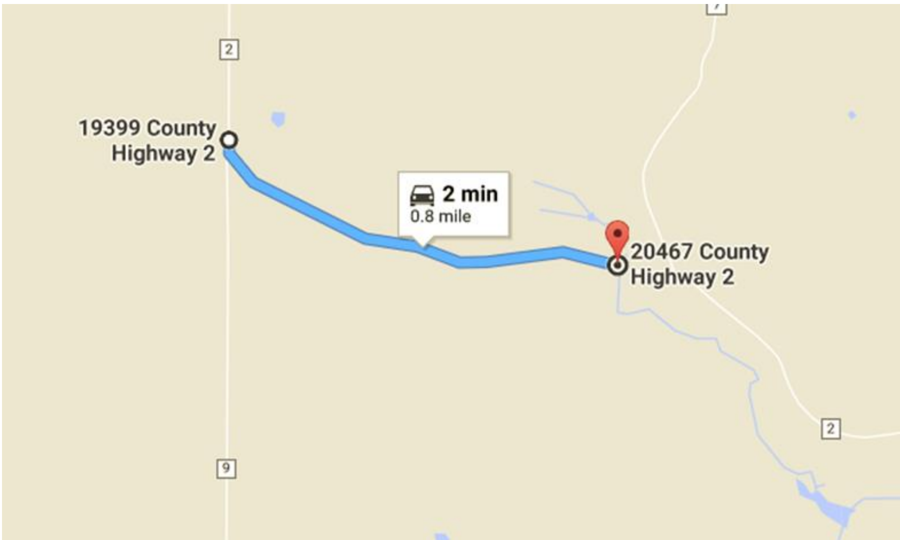
Figure 29. Location of the Otta seal project on MN 74 Winona County, Minnesota

Figure 30. Performance of Otta seal on MN 74 Winona County, Minnesota

Minor issues were observed on the road edges that required a resealing application to extend the service life of the Otta seal. Some surface potholes on the centerline that had formed after about 16 years of service were also noticed and repaired. Because of the good performance of MN 74 in Minnesota since 2001, the Minnesota Department of Transportation (MnDOT) has initiated many Otta seal projects to utilize locally available aggregate.

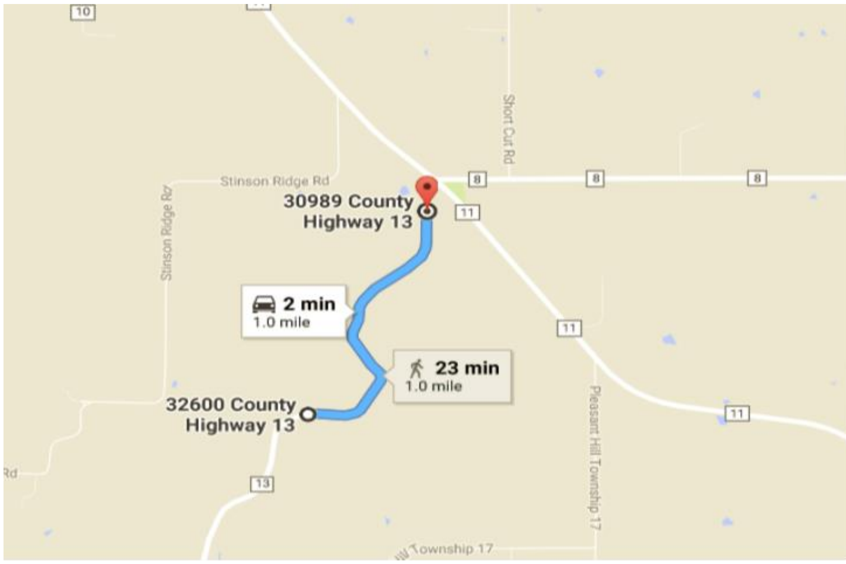
CSAH 2 and CSAH 13, Winona County

CSAH 2 (Figure 31) and CSAH 13 (Figure 32) are double Otta seal projects stretching for 1 mi each and are located in Winona County, Minnesota. The most recent ADT values are 85 and 100, respectively.



Map data ©2018 Google

Figure 31. Location of the Otta seal project on CSAH 2 Winona County, Minnesota



Map data ©2018 Google

Figure 32. Location of the Otta seal project on CSAH 13 Winona County, Minnesota

The Otta seals in CSAH 2 and CSAH 13 have performed in an excellent manner after one year in service, with no issues noticed on the surface of the road and no required maintenance scheduled for 2018. The aggregate used was a locally produced limestone, MnDOT Class 5 base course, with no recycling allowed. Figure 33 and Figure 34 illustrate the short-term performance of the Otta seals constructed on CSAH 2 and CSAH 13 in Winona County, Minnesota, respectively.

Figure 33. Performance of Otta seal on CSAH 2 Winona County, Minnesota

Figure 34. Performance of Otta seal on CSAH 13 Winona County, Minnesota

Based on these Otta seal projects in Minnesota, several key findings were noted during an August 7, 2017 on-site interview with Troy Drath, Assistant County Engineer of Winona County, Minnesota:

- The reduced maintenance frees staff to work on other needs of the county road system.
- Dust control is satisfactory for both residents and travelers.

- The need for placing new gravel to maintain in-service gravel roads is eliminated.
- There is safer travel with increased surface friction compared to dry gravel conditions on hilly roads.
- The surfacing allows more liberal use of sand and salt to increase friction and melt snow and ice without concern for the detrimental effects of these materials on gravel surfaces.

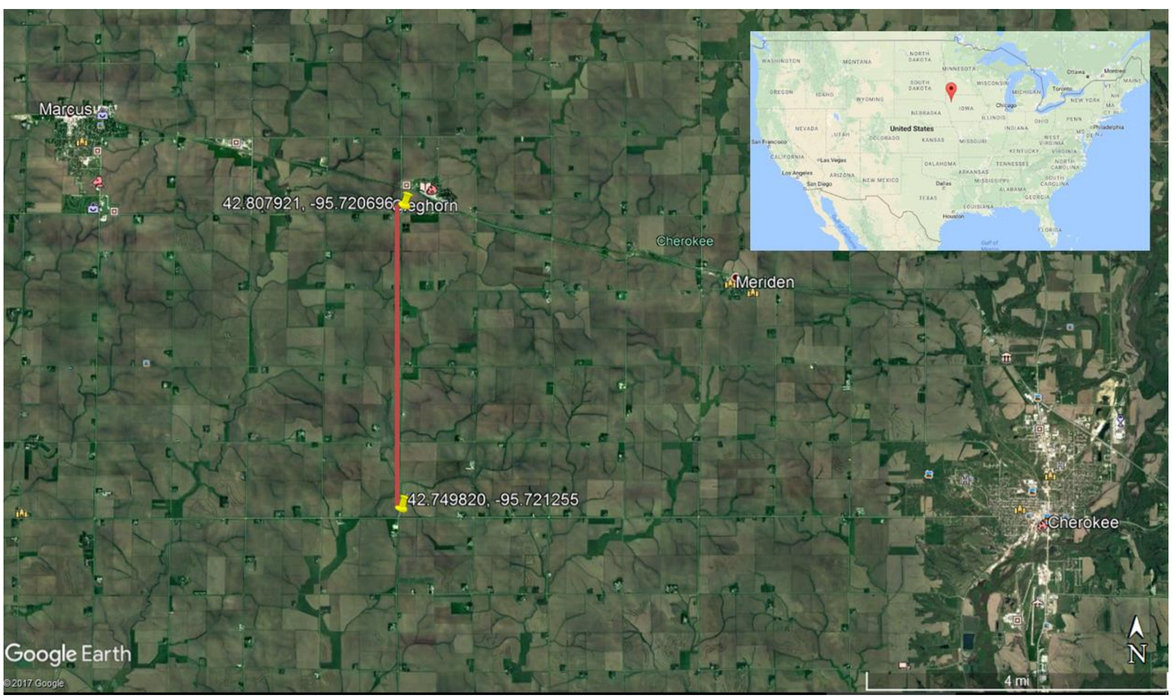
IOWA OTTA SEAL DEMONSTRATION CONSTRUCTION AND PERFORMANCE EVALUATION

To achieve the objectives of this project, several local low-volume road projects in Iowa were identified as potential sites for field demonstrations to represent the range of locally available aggregate in different areas of the state. The selected candidate site was constructed using Otta seal as a resurfacing strategy for extending road service life.

This chapter introduces the general background of this project, the Otta seal design details, the documented Otta seal construction procedures, and the multiple tests conducted before, during, and after construction. The evaluation included roadway characteristics, aggregate properties and characteristics, and performance under various conditions.

Background of the Otta Seal Project in Cherokee County, Iowa

CR L-40, the selected candidate site for this Otta seal demonstration project, is in Cherokee County, Iowa, at the location and GPS coordinates shown in Figure 35.



Google Earth © 2017

Figure 35. Location and topography of the Otta seal project on CR L-40, Cherokee County, Iowa

The starting point (north end) of the project is 42º48'28.87"N, 95º43'14.57"W, and the ending point (south end) is 42º44'59.38"N, 95º43'16.64"W. The ADT was estimated by the county engineer to be about 190, including up to 30 percent truck traffic. The road length represents about 6.43 km (4.0 mi) of an existing 6.71 m (22.0 ft) wide hot mix asphalt (HMA) road. The maintenance history of this road indicates crack seal only. Table 14 summarizes the general information about this road.

Table 14. Summary of the road information of CR L-40 in Cherokee County, Iowa

Question	Answer
Road name	CR L-40, Cherokee County, Iowa
ADT	ADT = 190 (up to 30 percent truck traffic)
Primary vehicles (resident vehicle primarily: farm equipment primarily or both?)	Both
Road length	6.43 km (4 miles)
Road width	22 ft
Surface type of existing road	HMA
Maintenance history	Crack seal only

With respect to climatic conditions, the air temperature history showed that the average air temperature near the project site was 9.4°C (49°F), while the annual air temperature range varied widely, from -30.5°C (-23°F) to 35.5°C (96 °F), indicating that the pavement underwent critical hot and cold situations and freeze-thaw cycles.

Before Otta seal construction, a visual inspection was conducted on the existing pavement. Various types of distresses were observed, including longitudinal and transverse cracking, rutting, alligator cracking, etc., on the pavement surface (Figure 36). At the time, the pavement was unable to provide satisfactory service to the public, posing a strong need to repair this road section to improve driving comfort and safety and extend the road service life.

Figure 36. Various types of distresses observed on CR L-40 Otta seal project site prior to any surface treatment, August 21–22, 2017

Design and Construction Description

Based on the traffic volume and truck traffic on CR L-40, it was recommended to apply a dense aggregate gradation, as specified in the Norwegian Road Technology Department manual (Øverby 1999), for Otta seal construction in Cherokee County. Table 15 lists the dense gradation limits specified in Øverby (1999). In consideration of the daily heavy agricultural truck traffic, a double Otta seal design was recommended.

Table 15. Dense gradation specified in NRRL manual

Sieve Size	Percent Passing (percent) Min.	Percent Passing (percent) Max.	Percent Passing (percent) Average
25	100	100	100
19	100	100	100
16	93	100	96.5
13.2	84	100	92
9.5	70	98	84
6.7	54	80	67
4.75	44	70	57
2	20	48	34
1.18	15	38	26.5
0.425	7	25	16
0.075	3	10	6.5

Øverby 1999

A pivotal goal of the investigation was to check the feasibility of the aggregate gradation used by Cherokee County for Otta seal. Because the gradation suggested by Cherokee County was open graded and could be used in Otta seal design only if the ADT were less than 100 and there would be no agricultural trucks on the road segment, it was recommended to employ dense gradation in accordance with the NRRL manual (Øverby 1999). Dense gradation is suitable for roadways with high ADT and agricultural truck traffic, while medium gradation is preferred if there is to be no agricultural traffic. The remainder of this section discusses design details in terms of aggregates and binders.

Aggregates

Because aggregates are a key component in Otta seal, the feasibility of using locally available aggregates is a principal question to be addressed. According to the design guide in Øverby (1999), gradation is the only Otta seal design criterion that must be characterized. After communications with local quarries, the county engineer, and the research team, seven types of aggregates from five sources were assessed:

- Source 1 aggregate
- Source 2 aggregate

- Source 3 aggregate
    - Two types of aggregates: Type A and Type B
- Source 4 aggregate
- Crushed limestone
    - Asphalt aggregate
    - Class A aggregate

In the Otta seal projects described in the previous chapter, aggregates following MnDOT Class 5 limits were used. To provide comparisons between the actual aggregate gradations, the gradations recommended by Øverby (1999), and MnDOT Class 5 gradations, the grain size distribution curves of the seven available aggregates were plotted to check whether or not these curves fall into the specific limits (Figure 37 through Figure 43).

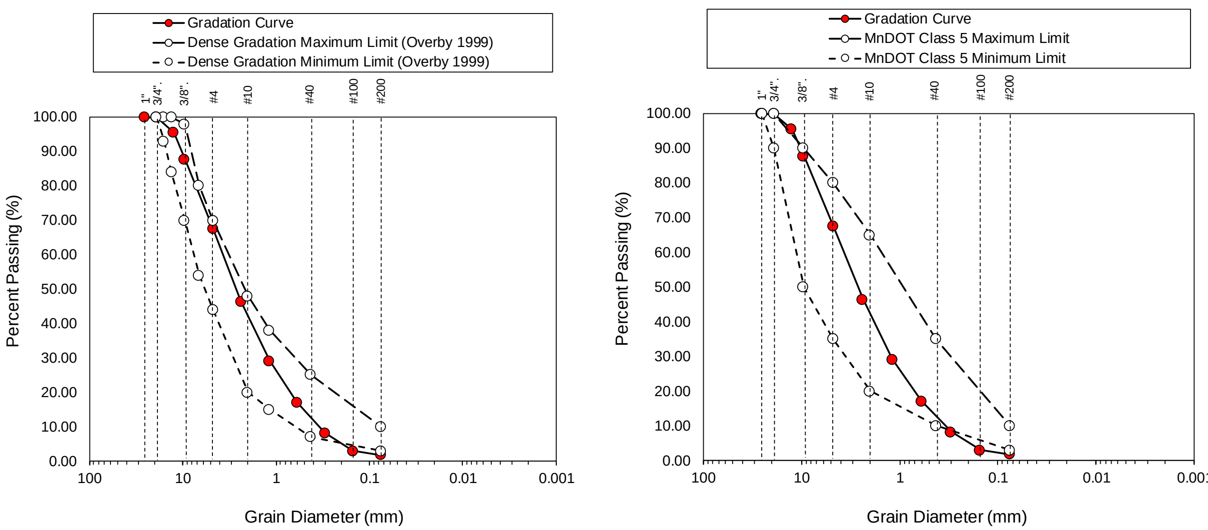


Figure 37. Gradation of Source 1 aggregate in comparison with Øverby (1999) limits and MnDOT Class 5 limits

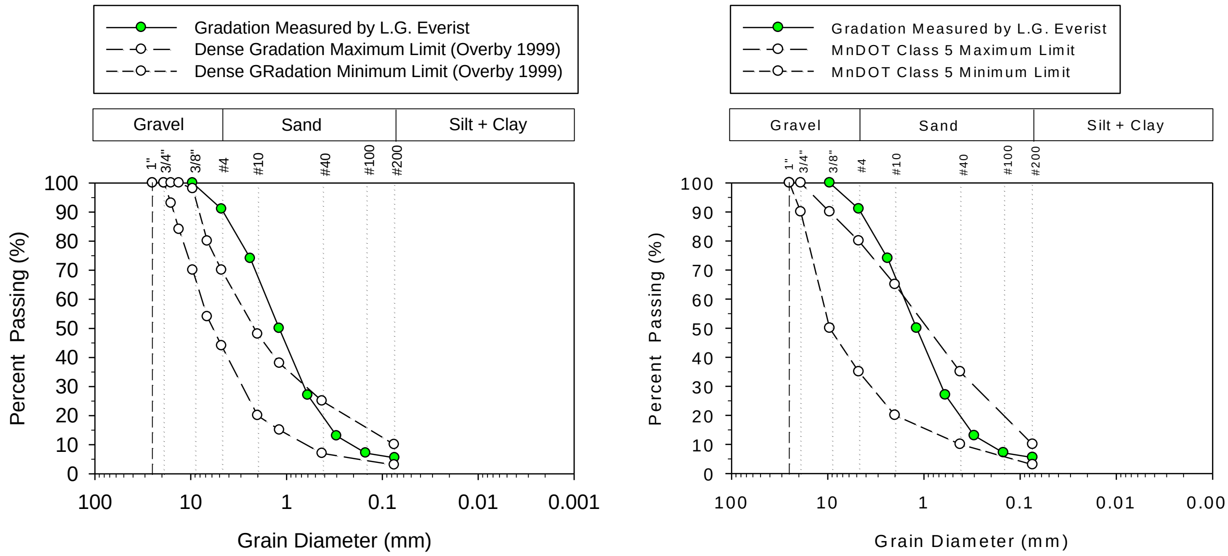


Figure 38. Gradation of Source 2 aggregate in comparison with Øverby (1999) limits and MnDOT Class 5 limits

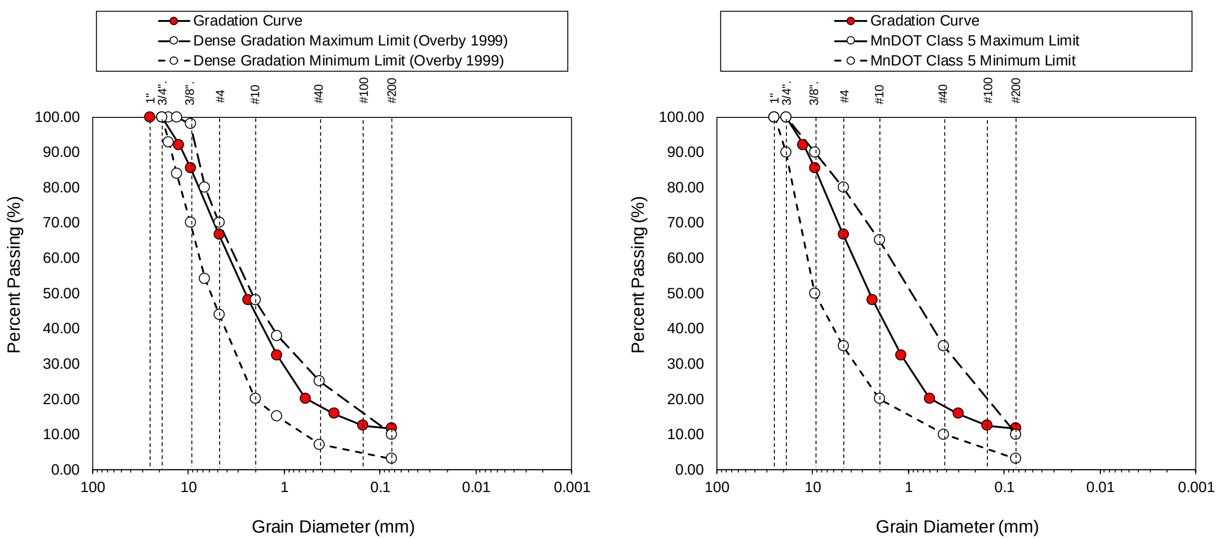


Figure 39. Gradation of Source 3 Type A aggregate in comparison with Øverby (1999) limits and MnDOT Class 5 limits

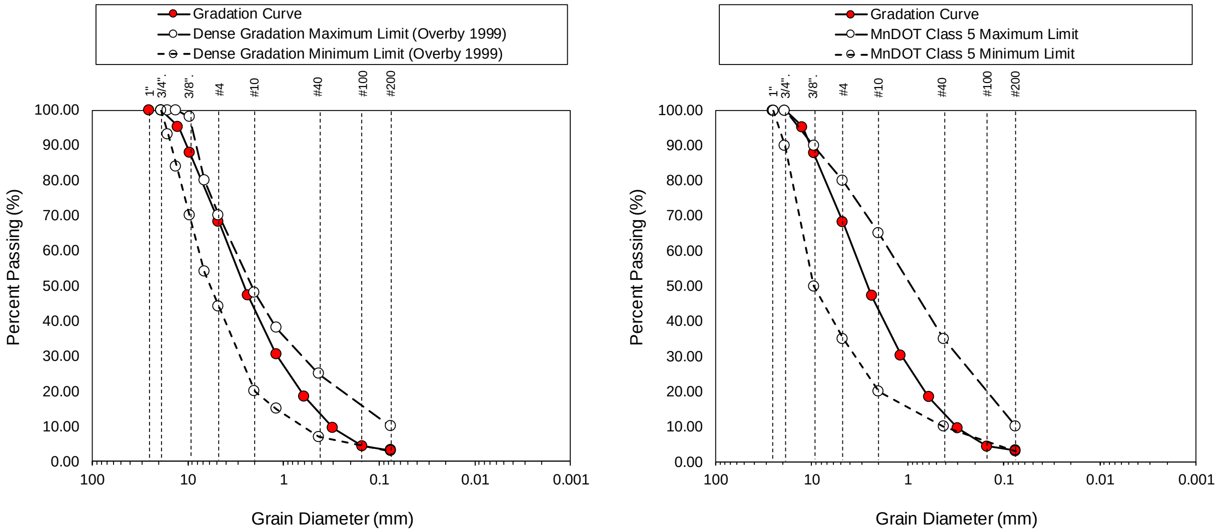


Figure 40. Gradation of Source 3 Type B aggregate in comparison with Øverby (1999) limits and MnDOT Class 5 limits

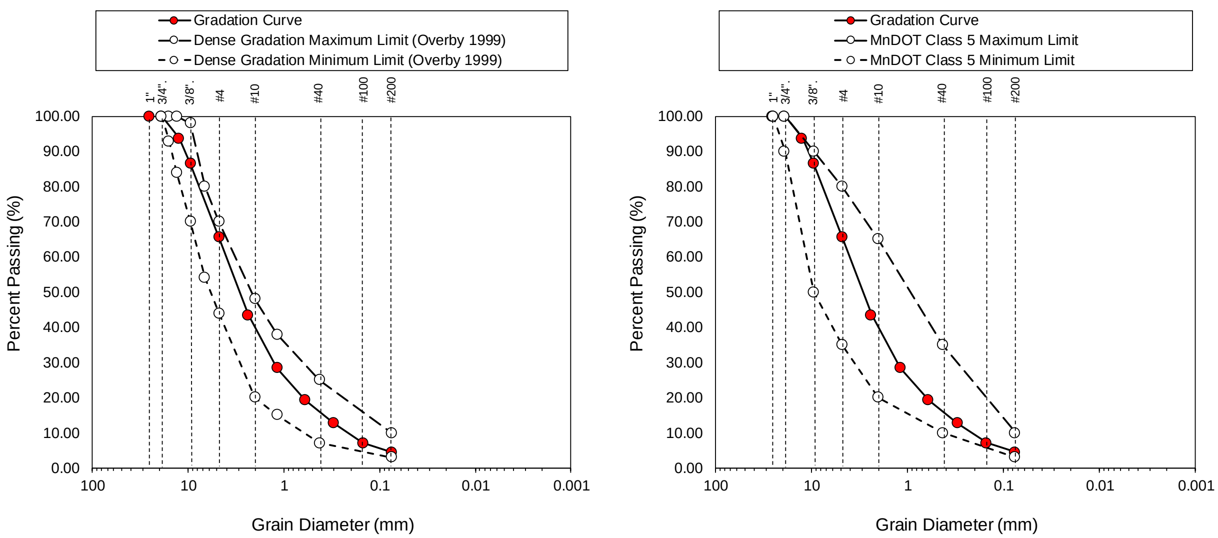


Figure 41. Gradation of Source 4 aggregate (the selected one for most of road sections in the Cherokee County Otta seal construction project) in comparison with Øverby (1999) limits and MnDOT Class 5 limits

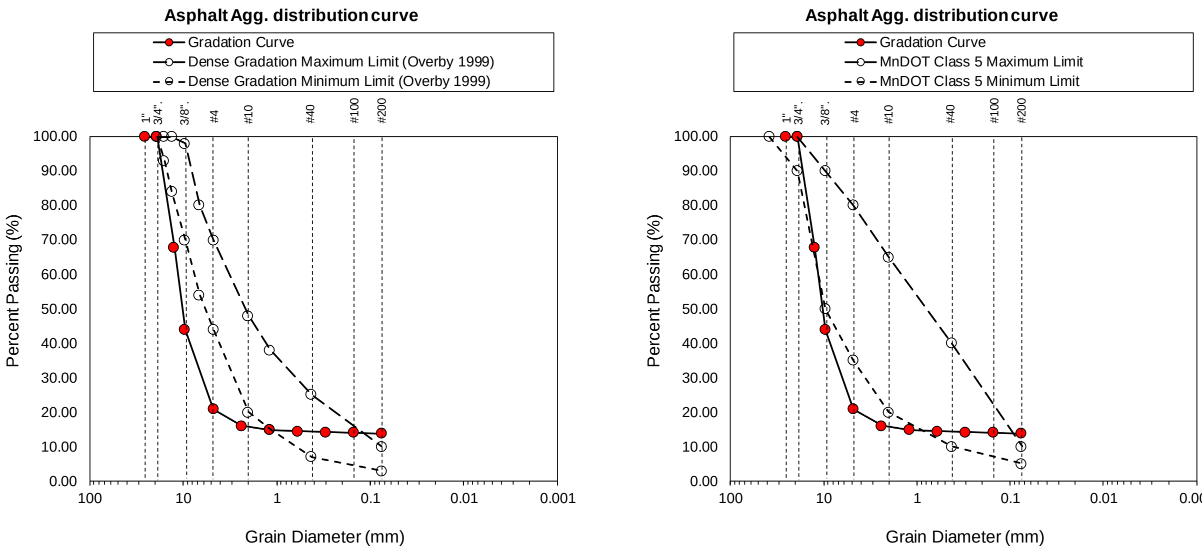


Figure 42. Gradation of crushed limestone – asphalt aggregate in comparison with Øverby (1999) limits and MnDOT Class 5 limits

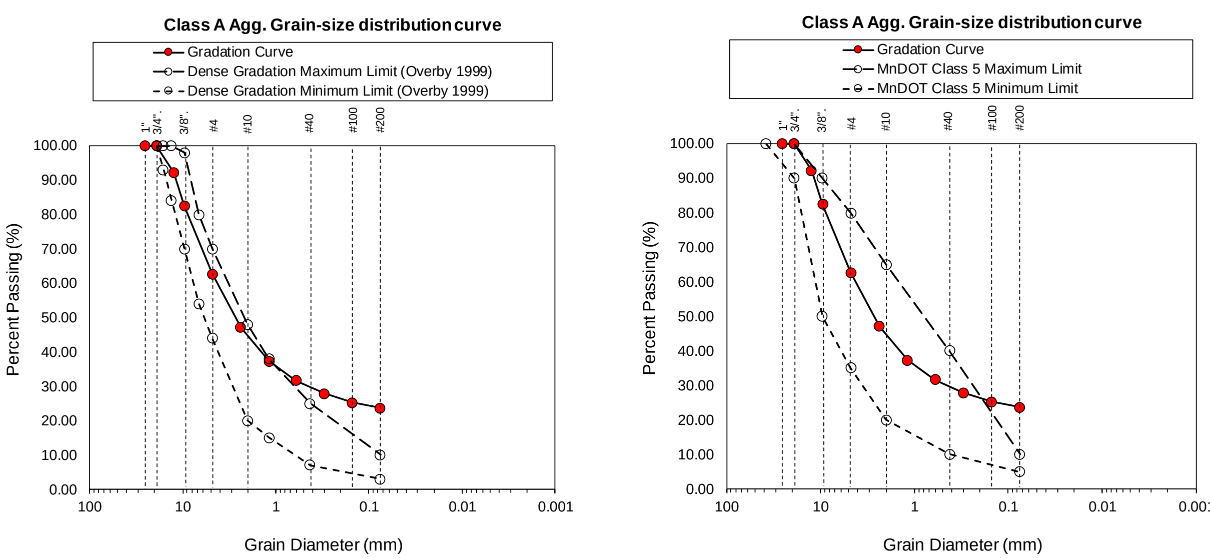


Figure 43. Gradation of crushed limestone – Class A aggregate in comparison with Øverby (1999) limits and MnDOT Class 5 limits

After comparing the gradations recommended by Øverby (1999) and the MnDOT Class 5 gradations, Source 4 aggregate was chosen for most road sections participating in the Cherokee County Otta seal construction. It was recommended that the aggregate spread rate be controlled at 27.1 kg/m^2 (50.0 lb/yd^2) in accordance with the design criteria given in Øverby (1999).

Binders

Asphalt emulsion and cutback asphalt are the two binder types commonly used for Otta seal. The type of binder recommended by Øverby (1999) was MC 3000, classified as a cutback asphalt. This type of binder has been commonly used in European and African Otta seal projects. It is a mixture of asphalt and petroleum solvent and typically contains a maximum of 15 percent of petroleum solvent. The Øverby experience indicates that MC 3000 requires 8 to 12 weeks to allow solvents to evaporate, and there are also environmental concerns about using it in the US because of its potential for greenhouse gas release.

HFMS-2s (Figure 44) was selected for use in this project because Minnesota and South Dakota have both applied this binder type for Otta seal projects, with satisfactory performance reported by the engineers involved.

Figure 44. The emulsion asphalt binder HFMS-2s applied for Otta seal construction on CR L-40, Cherokee County, Iowa

The acronym HFMS designates high float and medium set. HFMS-2s is a mixture of asphalt, water, and emulsified agent, typically containing up to 35 percent water. Based on the Minnesota experience, when it is applied for Otta seal, it requires 8 to 10 days for setting (allowing the water to evaporate), meaning that the second layer of Otta seal construction (for double Otta seal projects) is delayed at least 8 to 10 days after the first layer is constructed. South Dakota tried various binder spray rates on the first and second layers of Otta seal, and performance varied. Minnesota tried using rates of 2.3±0.02 L/m^2 (0.5±0.05 gal/yd^2), and, because most previous projects in Minnesota had performed satisfactorily, this spray rate was recommended for the Iowa project as well.

The proposed emulsion (HFMS-2s) to be used with the given proposed aggregates is characterized as high-float and medium-set with high viscosity and is an anionic medium rapid-setting emulsion that requires special care when in storage and during application to maintain optimal quality. Table 16 lists the suggested storage and application temperatures.

Table 16. Suggested storage and application temperature for Otta seal

	Min. Temperature	Max. Temperature
Storage Tank	122 °F or 50 °C	140 °F or 60 °C
Application	122 °F or 50 °C	185 °F or 85 °C

The suggested binder application rate is 0.5 ± 0.05 gal/yd^2 (2.2 ± 0.2 L/m^2). Table 17 provides a comparison of the emulsion spraying rates.

Table 17. Asphalt binder spraying rates

Case	Binder Application Rates
NRRL design guide: low traffic (ADT < 100)	1.5 to 1.6 L/m^2 (0.33 to 0.38 gal/yd^2)
NRRL design guide: medium traffic (ADT = 100 to 1,000)	1.6 to 1.8 L/m^2 (0.35 to 0.40 gal/yd^2)
NRRL design guide: high traffic (ADT > 1,000)	1.7 to 2.0 L/m^2 (0.38 to 0.44 gal/yd^2)
MN practice (ADT < 1,000)	2.2±0.2 L/m^2 (0.5±0.05 gal/yd^2)
SD practice (ADT < 1,000)	2.2 L/m^2 (0.5 gal/yd^2)
Suggestion for Otta seal demonstration in Cherokee County, Iowa (this project)	2.2±0.2 L/m^2 (0.5±0.05 gal/yd^2)

The binder spray rates for Otta seal depend on the following parameters (Øverby 1999):

- Traffic (ADT)
- Aggregate grading (open/medium/dense)
- The absorbency of aggregate particles; if it is more than 2 percent, the hot spray rate should be increased by 0.3 L/m^2 (0.07 gal/yd^2).
- The hot spray rate should be decreased by 0.2 L/m^2 (0.05 gal/yd^2) if the base course is primed.

Test Sections

Four test sections (TS) were proposed for applying and evaluating different types of aggregates (Figure 45).

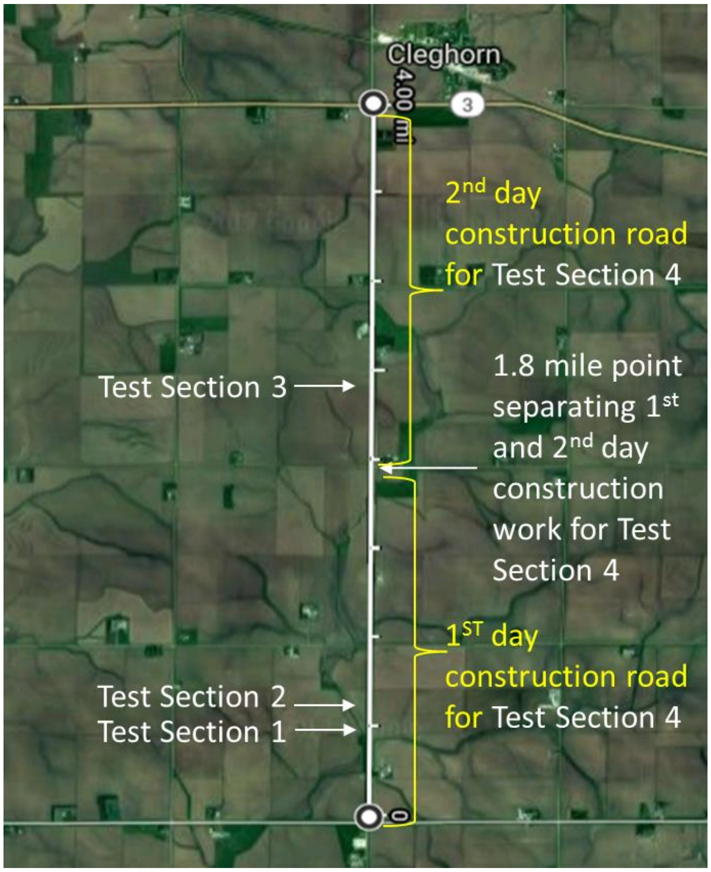


Figure 45. Test sections proposed for Otta seal construction on CR L-40

TS 1, TS 2, and TS 3 are approximately 137 m (450 ft) long. TS 4 covers the majority of the constructed road, a length of approximately 6.1 km (3.8 mi), and the construction process was separated into two days, with 2.9 km (1.8 mile) performed on the first day and the other 3.2 km (2.0 mile) on the second day. Table 18 displays the corresponding aggregate type applied in each of the TSs. The filter sand in the first layer of TS 2 construction was one of the non-recommended aggregates for Otta seal.

Table 18. Recommended aggregate application rate versus actual and billable

Road section	TS 1 ~137 m (450 ft)	TS 2 ~137 m (450 ft)	TS 3 ~137 m (450 ft)	TS 4 ~6.1 km (3.8 mile) (rest of the roads)
Recommended aggregate type for construction	Crushed limestone – asphalt aggregate	Source 1 aggregate	Crushed limestone - Class A aggregate	Source 4 aggregate
Actual aggregate type used for first layer construction	Crushed limestone – asphalt aggregate	Filter sand (not recommended)	Crushed limestone - Class A aggregate	Source 4 aggregate
Actual aggregate type used for second layer construction	Crushed limestone – Class A aggregate	Crushed limestone - Class A aggregate	Crushed limestone - Class A aggregate	Source 4 aggregate

Pre-Construction Repair

Approximately one week before construction of the first layer, the deteriorated asphalt pavement surface was slurry sealed at both transverse and longitudinal cracking locations (Figure 46). This operation was to prevent the potential for any reflective cracking from the existing asphalt pavements onto the Otta seal surface.

Figure 46. Slurry seal applied on the existing HMA pavement on CR L-40 before construction

First Layer Construction

The first layer of Otta seal construction was initiated on September 5, 2017, during which time the road was closed to traffic in both directions. In general, the construction can be classified into three steps; binder spraying, aggregate application, and rolling compaction (Figure 47).

Figure 47. Three key steps during Otta seal construction

The asphalt distributor began spraying the bituminous HFMS-2s material at a rate of 2.26 L/m^2 (0.50 gal/yd^2) on the existing asphalt surface, followed by aggregate application at a rate of 35.26 kg/m^2 (65 lbs/yd^2), about 30 percent higher than the recommended value, 27.12 kg/m^2 (50 lbs/yd^2). The actual binder spray rate was lower than the recommended rate, 2.49 L/m^2 (0.55 gal/yd^2). Immediately after placing the binder and the aggregate, a 10.89-metric ton (12-US ton) roller made 30 compaction passes on the first day and 15 passes on the second day. The entire Otta seal construction process is shown in Figure 48. The contractor was able to finish 2.89 km (1.80 miles) on the first day and continued with the remaining 3.22 km (2.0 miles) on the second day.

Figure 48. The entire Otta seal construction process

For better Otta seal performance, that is, ensuring that most of the aggregate was compacted and covered with the applied emulsion HFMS-2s, a 12.70-metric ton (14-US ton) pneumatic roller was used on the project after completing the first layer to compensate for the extra aggregate applied and the lack of compaction effort during construction. The construction sequence for the second day was rather similar to that of the first day.

Pictures of TS 1, TS 2, TS 3, and TS 4 are shown in Figure 49 through Figure 52. The aggregate used on TS 2 was not recommended for use. A color comparison between partially compacted and uncompacted lanes is shown in Figure 53.

Figure 49. TS 1 using crushed limestone – asphalt aggregate

Figure 50. TS 2 using filter sand

Figure 51. TS 3 using crushed limestone – Class A aggregate

Figure 52. Source 4 aggregate (TS 4), asphalt aggregate (TS 1), and filter sand (TS 2)

Figure 53. Partially compacted (left) versus uncompacted (right) lanes

The following recommendations, based on the construction of the first layer, were provided by the research team:

- The recommended aggregate spreading rate should be 27.12 kg/m^2 (50 lbs/yd^2).
- The recommended binder spraying rate should be 2.49 L/m^2 (0.55 gal/yd^2).
- Pneumatic rollers should be filled with aggregate to the required level to reach a sufficient weight.
- Pneumatic rollers should be limited to 4 mph for 30 passes on the construction day to ensure proper compaction quality.
- Filter sand applied in TS 2 was not recommended for construction of the second layer.
- The rollers should be filled to the required weight (Figure 54).

Figure 54. Roller was not filled to the required weight for first layer construction

Second Layer Construction

Two weeks after construction of the first layer (September 21 through September 22, 2017), the construction crew continued work at the site for placement of the second layer of Otta seal. The same techniques and procedures were followed, but additional quality control/quality assurance (QC/QA) operations were conducted to monitor the aggregate and binder application rates. The complete construction sequence is shown in Figure 55.

Figure 55. Construction of the second Otta seal layer: (a) binder spraying, (b) aggregate application, (c) rolling compaction, and (d) the complete process

Recommendations for construction of the second layer based on the experience with the first layer are as follows:

- The surface must be broomed prior to constructing the second layer.
- TS 2 should be constructed with Source 4 aggregate instead of sandy materials.
- The aggregate spreader should be calibrated to a spreading rate of 27.12 kg/m^2 (50 lbs/yd^2).
- The binder spraying rate should be calibrated to 2.49 L/m^2 (0.55 gal/yd^2).
- Contractors should prepare a proper quality control program to determine the optimum aggregate spreading rate, binder spraying rate, and actual aggregate gradation applied on-site.
- Pneumatic rollers should be filled to the maximum weight allowed.
- Pneumatic rollers should conduct 30 passes at a speed less than 4 mph.
- More rollers (perhaps three to four) should be assigned to construct the second layer to expedite the compaction process.
- Compaction should be continued into the next day of construction to achieve better quality.

The design of Otta seal on CR L-40 consisted mainly of aggregate application at the rate of 27.12 kg/m^2 (50 lbs/yd^2) and binder spraying at the rate of 2.49 L/m^2 (0.55 gal/yd^2). Rolling and compacting are also required to draw the binder upward toward the surface of the aggregate. However, the actual application rates applied in the field during construction varied due to issues with the aggregate spreader and the asphalt distributor.

To precisely determine the actual aggregate application rate, a square yard pan was proposed to perform quality control of the aggregate application rates (Figure 56).

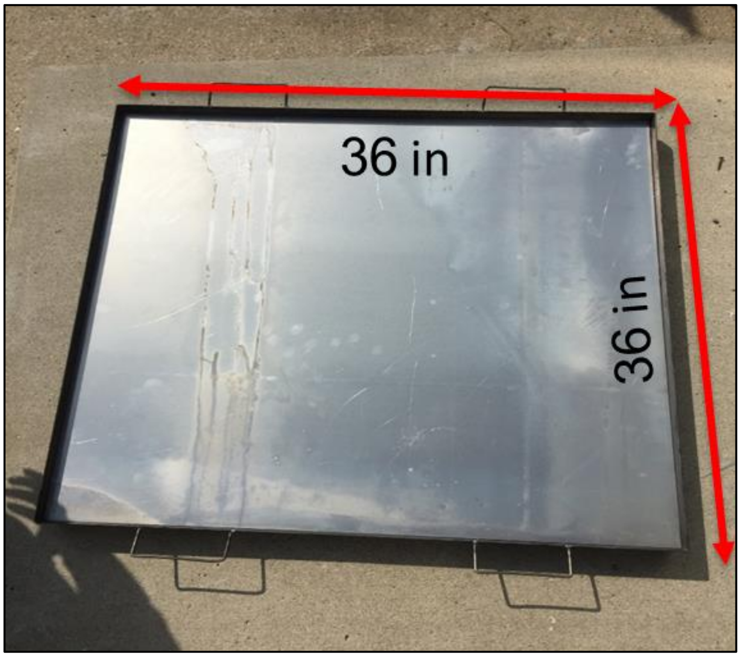


Figure 56. Square yard pan for conducting quality control measurement of aggregate application rates

The pan was repeatedly placed in front of the aggregate spreader, and after the machine passed over the pan (Figure 57), it was removed from the constructed area.

Figure 57. Aggregate spreader passing over the pan, with aggregates falling on the pan

First, the pan was weighed without aggregates and then weighed while full of aggregates, after which the actual weights of the aggregates spread by the aggregate spreader over a unit area could be directly measured (Figure 58).

Figure 58. Measurement of the weight of aggregate per unit area

While the recommended design aggregate application rate was 27.12 kg/m^2 (50 lbs/yd^2) for both the first and second layers, the actual application rates nevertheless varied due to issues with the aggregate spreader that were related to factors such as distribution uniformity and aggregate moisture contents. Table 19 presents the recommended aggregate application rates versus the actual and billable values for both the first and the second layers. The asphalt spreader was set to spray at the rate of 2.49 L/m^2 (0.55 gal/yd^2), but the billable quantity to the owner was 2.04 L/m2 (0.45 gal/yd^2).

Table 19. Recommended aggregate application rates versus actual and billable values

Road section	TS 1 ~450 ft	TS 2 ~450 ft	TS 3 ~450 ft	TS 4 ~3.8 Mile (rest of the roads)
Recommended aggregate application rate for construction	27.12 kg/m^2 (50.00 lbs/yd^2)	27.12 kg/m^2 (50.00 lbs/yd^2)	27.12 kg/m^2 (50.00 lbs/yd^2)	27.12 kg/m^2 (50.00 lbs/yd^2)
Actual aggregate application rate used for first layer construction	35.26 kg/m^2 (65.00 lbs/yd^2)	35.26 kg/m^2 (65.00 lbs/yd^2)	35.26 kg/m^2 (65.00 lbs/yd^2)	35.26 kg/m^2 (65.00 lbs/yd^2)
Actual aggregate application rate used for second layer construction	35.35 kg/m^2 (65.16 lbs/yd^2)	30.47 kg/m^2 (56.16 lbs/yd$^{2)}$	30.36 kg/m^2 (55.97 lbs/yd^2)	30.18 kg/m^2 (55.63 lbs/yd^2)
Billable quantity to the county	33.24 kg/m^2 (61.28 lbs/yd^2)	33.24 kg/m^2 (61.28 lbs/yd^2)	33.24 kg/m^2 (61.28 lbs/yd^2)	33.24 kg/m^2 (61.28 lbs/yd^2)

Information came from actual measurements, the contractor, and the county engineer.

Table 20 presents the recommended binder spray rates versus the actual and billable values for both the first and second layers.

Table 20. Recommended binder spray rates versus actual and billable values

Road section	TS 1 ~450 ft	TS 2 ~450 ft	TS 3 ~450 ft	TS 4 ~3.8 Mile (rest of the roads)
Recommended binder spraying rate for construction	2.49 L/m^2 (0.55 gal/yd^2)	2.49 L/m^2 (0.55 gal/yd^2)	2.49 L/m^2 (0.55 gal/yd^2)	2.49 L/m^2 (0.55 gal/yd^2)
Actual binder spraying rate used for first layer construction	2.25 L/m^2 (0.50 gal/yd^2)	2.25 L/m^2 (0.50 gal/yd^2)	2.25 L/m^2 (0.50 gal/yd^2)	2.25 L/m^2 (0.50 gal/yd^2)
Actual binder spraying rate used for second layer construction	2.25 L/m^2 (0.50 gal/yd^2)	2.25 L/m^2 (0.50 gal/yd^2)	2.25 L/m^2 (0.50 gal/yd^2)	2.25 L/m^2 (0.50 gal/yd^2)
Billable quantity to the county	2.08 L/m^2 (0.46 gal/yd^2)	2.08 L/m^2 (0.46 gal/yd^2)	2.08 L/m^2 (0.46 gal/yd^2)	2.08 L/m^2 (0.46 gal/yd^2)

Information came from the contractor and the county engineer.

Performance of Otta Seal on CR L-40 Cherokee Iowa

Multiple in situ tests were conducted before and after construction, including loose aggregate tests, dustometer tests, roughness tests, and visual appearance inspections, with the intent of evaluating the performance of Otta seal constructed on CR L-40.

Loose Aggregate Test

The appropriate time to conduct the loose aggregate test is three to four weeks after constructing the first layer to allow as much of the binder as possible to move upward to the surface through aggregate voids. The items of equipment required to conduct loose aggregate tests on the surface are listed below (Figure 59):

- Vacuum device
- Two wooden sticks (with lengths of 376 cm or 148 in.)
- Ruler
- Bucket for aggregate collection

To perform a test, two wooden sticks are placed to establish a single lane 4 in. wide. A vacuum device is then used to collect any loose aggregate between the area of the two wooden sticks, with a bucket used to store the collected aggregate. The bucket is then weighed using a scale (Figure 59).

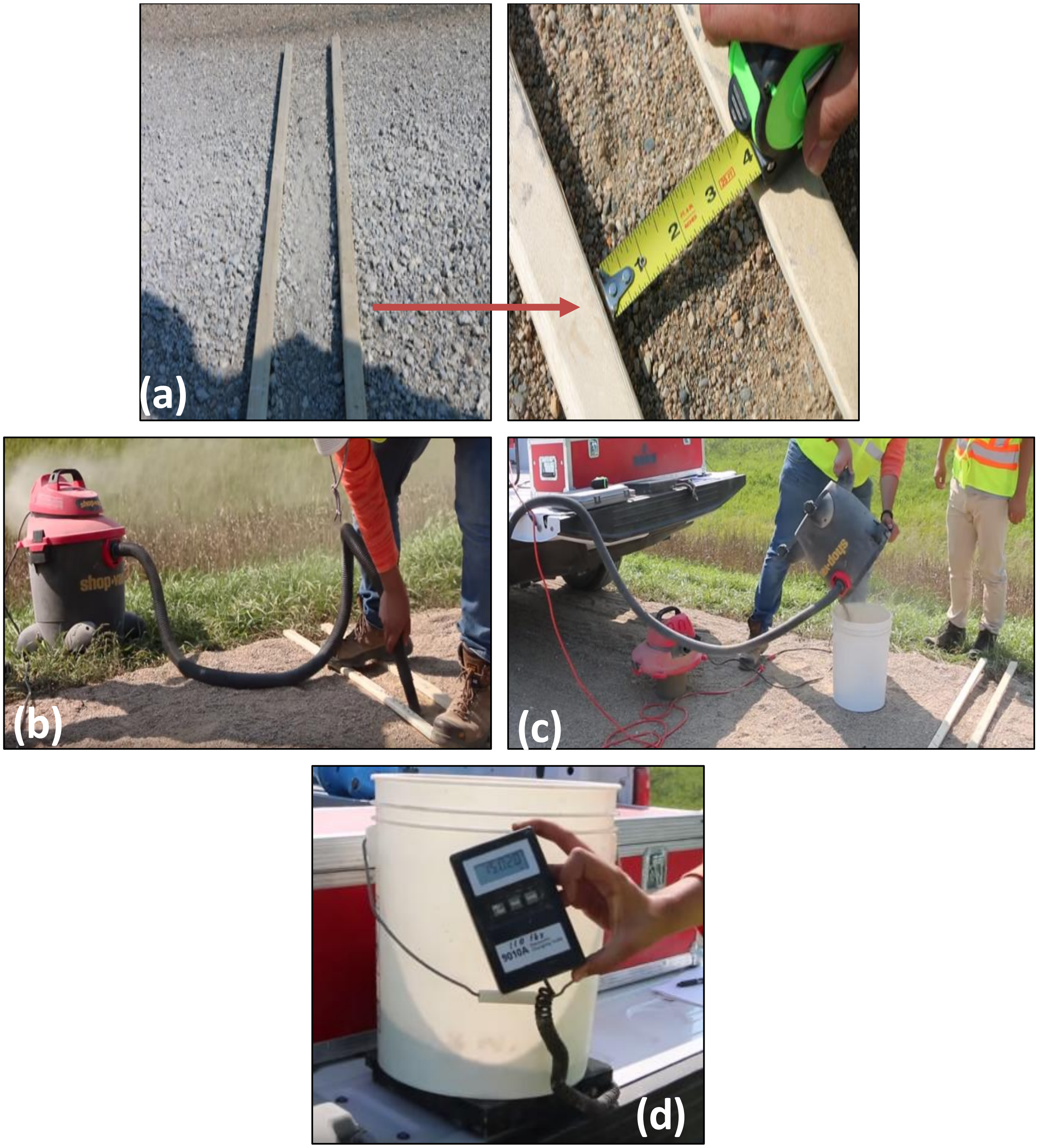


Figure 59. Equipment and steps of loose materials test: (a) making a single lane (148 in. × 4 in.), (b) collecting excessive aggregate between the surface of two wooden sticks, (c) placing collected aggregate, and (d) measuring the weight of collected aggregate

Multiple tests per section were conducted on the same day, resulting in the calculated averages and standard deviations presented in Table 21.

Table 21. First layer evaluation: loose materials on the surface of the first layer

Road Section (Construction Date)	Length	Average Loose Aggregate in kg (lbs) on area of 148 in. × 4 in.	Aggregate Loose Rate in kg/m^2 (lbs/yd^2)
Test Section 1 (9/5/2017)	115.8 m (380 ft)	3.13 (6.9)	8.21 (15.13)
Test Section 2 (9/5/2017)	123.4 m (405 ft)	6.81 (15.02)	19.82 (36.54)
Test Section 3 (9/6/2017)	114.3 m (375 ft)	1.50 (3.30)	3.92 (7.22)
Test Section 4 (9/5/2017)	2.9 km (1.8 mi)	3.40 (7.49)	8.90 (16.40)
Test Section 4 (9/6/2017)	3.2 km (2.0 mi)	2.08 (4.60)	5.46 (10.07)

These results indicate that aggregate placed on TS 3 performed best, i.e., had the least amount of loose materials three to four weeks after the Otta seal was constructed. TS 4/2.0 miles (second-day construction) exhibited better performance compared to TS 4/1.8 miles (first-day construction). Note that the aggregate spread rate was corrected to meet the design recommendation after the first day of construction.

Dustometer Test

A dustometer was used in this project to evaluate the effectiveness of Otta seal in controlling dust after construction is completed (Figure 60). The main components used in making dustometer measurements are a generator, a vacuum/suction pump, the dustometer device itself, and new filters. First, the dustometer was mounted behind the truck, and then the filter paper (weighed before the test) was placed into the dustometer. The truck was then driven at a speed of 40 km/h (25 mph) over the desired length, after which the filter was weighed to determine the accumulated dust per segment.

Figure 60. Three steps of installing the dustometer tester: installing the dustometer on a truck, preparing the vacuum, and placing filter paper in the tester

Figure 61 provides a comparison of the filter papers collected at two different locations at different testing times. Based on the results of the dustometer tests, TS 4, constructed on September 5, 2017, achieved the best performance with respect to dust control after the first layer was constructed.

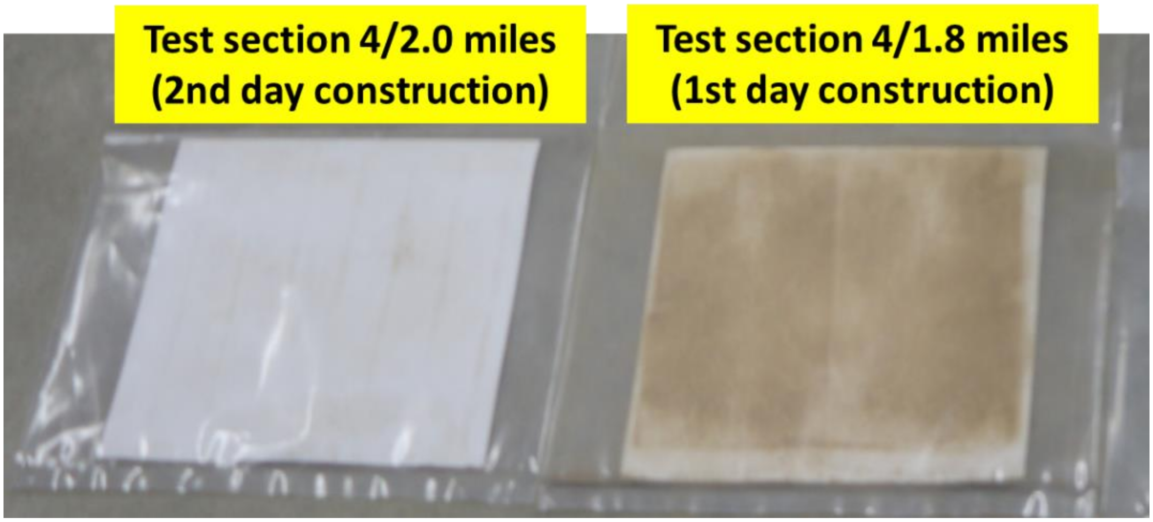


Figure 61. Comparison of collected filter papers

Table 22 summarizes the results of the filter weighing.

Table 22. Summary of dustometer test results

Road Section (Construction Date)	Length	Filter Weight before Testing (g)	Filter Weight after Testing (g)	Collected Dust (g/km)
One week after first layer application				
Test Section 1 (9/5/2017)	115.8 m (380 ft)	43.59	43.75	1.38
Test Section 2 (9/5/2017)	123.4 m (405 ft)	43.49	43.68	1.54
Test Section 3 (9/6/2017)	114.3 m (375 ft)	43.71	43.82	0.96
Test Section 4 (9/5/2017)	2.9 km (1.8 mi)	42.60	45.50	1.00
Test Section 4 (9/6/2017)	3.2 km (2.0 mi)	43.78	45.70	0.60
Two months after second layer application				
Test Section 4 (9/5/2017)	2.9 km (1.8 mi)	16.40	16.90	0.17
Test Section 4 (9/6/2017)	3.2 km (2.0 mi)	16.38	16.80	0.13

Road Roughness Test

Another parameter used to evaluate Otta seal performance is international roughness index (IRI), which was measured using a mobile device-based app called “Roadroid.” IRI measurements took place on the existing HMA pavement surface condition before construction, two weeks after the first layer of Otta seal construction, and two weeks after the second layer of Otta seal construction (Figure 62 through Figure 64). Results indicated either a slightly improved or equivalent level in ride quality after constructing the Otta seal, based on both estimated IRI (eIRI) and calculated IRI (cIRI) results.

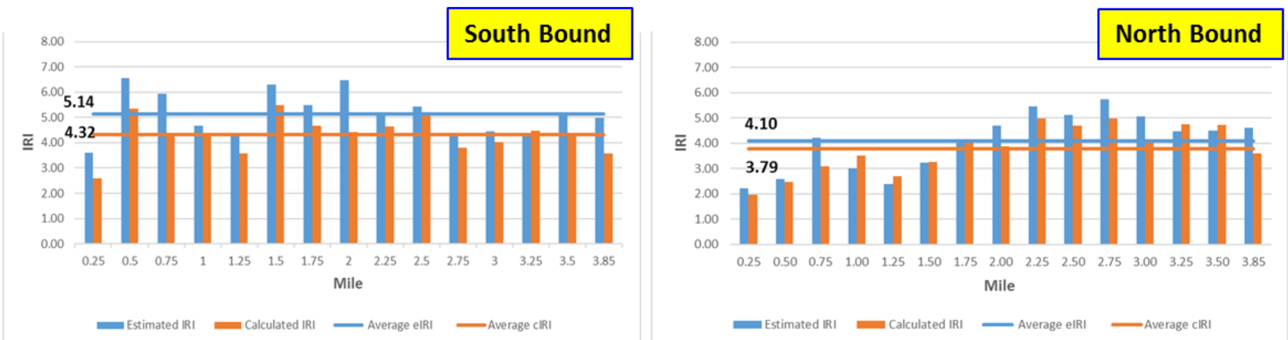


Figure 62. IRI data before Otta seal construction

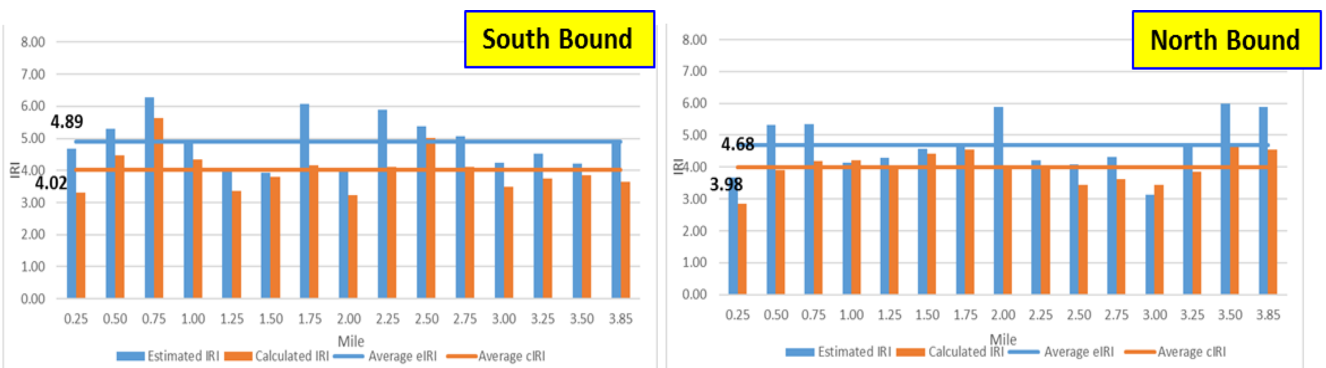


Figure 63. IRI data two weeks after first layer construction

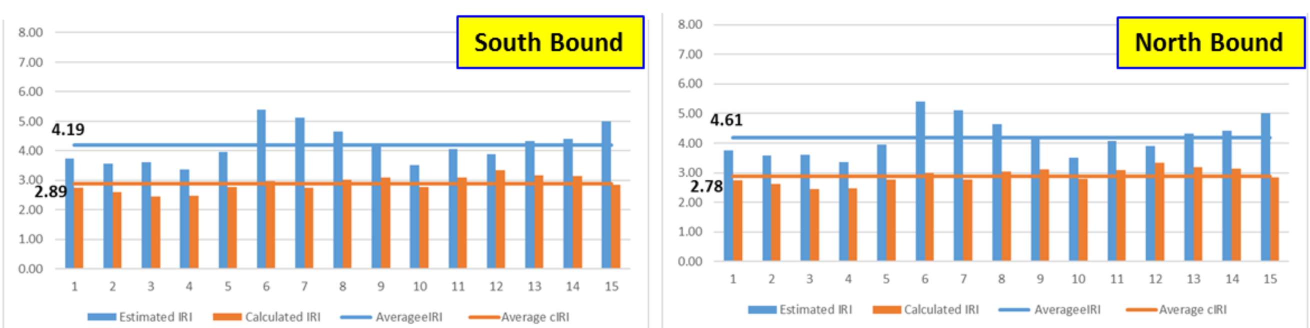


Figure 64. IRI data two weeks after second layer construction

Otta Sealed Road Appearance and Condition

Otta seal color changes can be an indicator of the state of the curing condition. A surface becoming dark means the binder was squeezed up to coat the aggregates. Figure 65 through Figure 72 show the road surface coloration at different times. It is obvious that the surfaces of both the first and second layers were a relatively light color immediately after construction and became darker as time elapsed.

Figure 65. First layer appearance: one day after application

Figure 66. First layer appearance: two days after application

Figure 67. First layer appearance: three days after application

Figure 68. First layer appearance in whole sections: one week after application

Figure 69. Second layer appearance in whole sections: two days after application

Figure 70. Second layer appearance in whole sections: two weeks after application

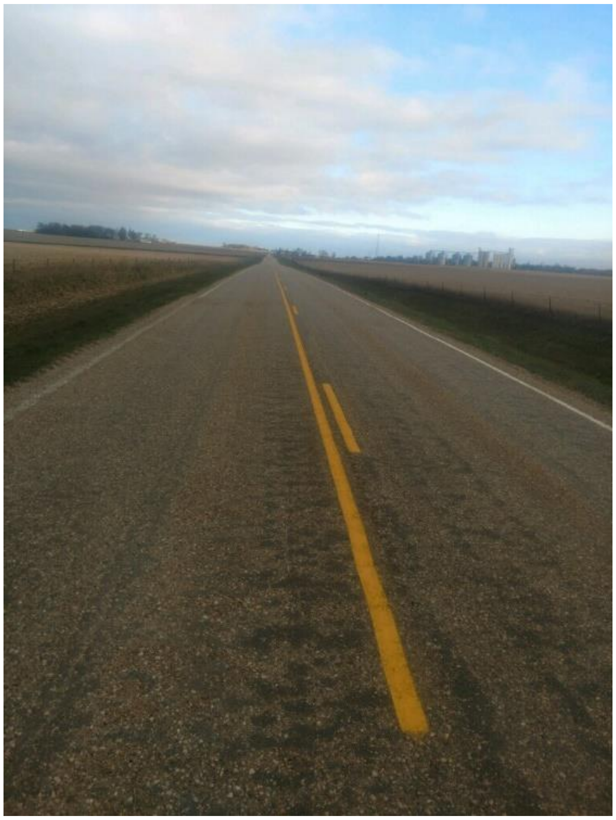



Figure 71. Three months after second layer construction

Figure 72. Six months after second layer construction

Construction Guidance for Field Implementation

Construction guidance for Otta seal field implementation, based on the empirically based NRRL guidelines by Øverby (1999), past US projects, and the field demonstration project in Iowa, is presented in this section. Figure 73 shows a flow chart for the Otta seal design process.

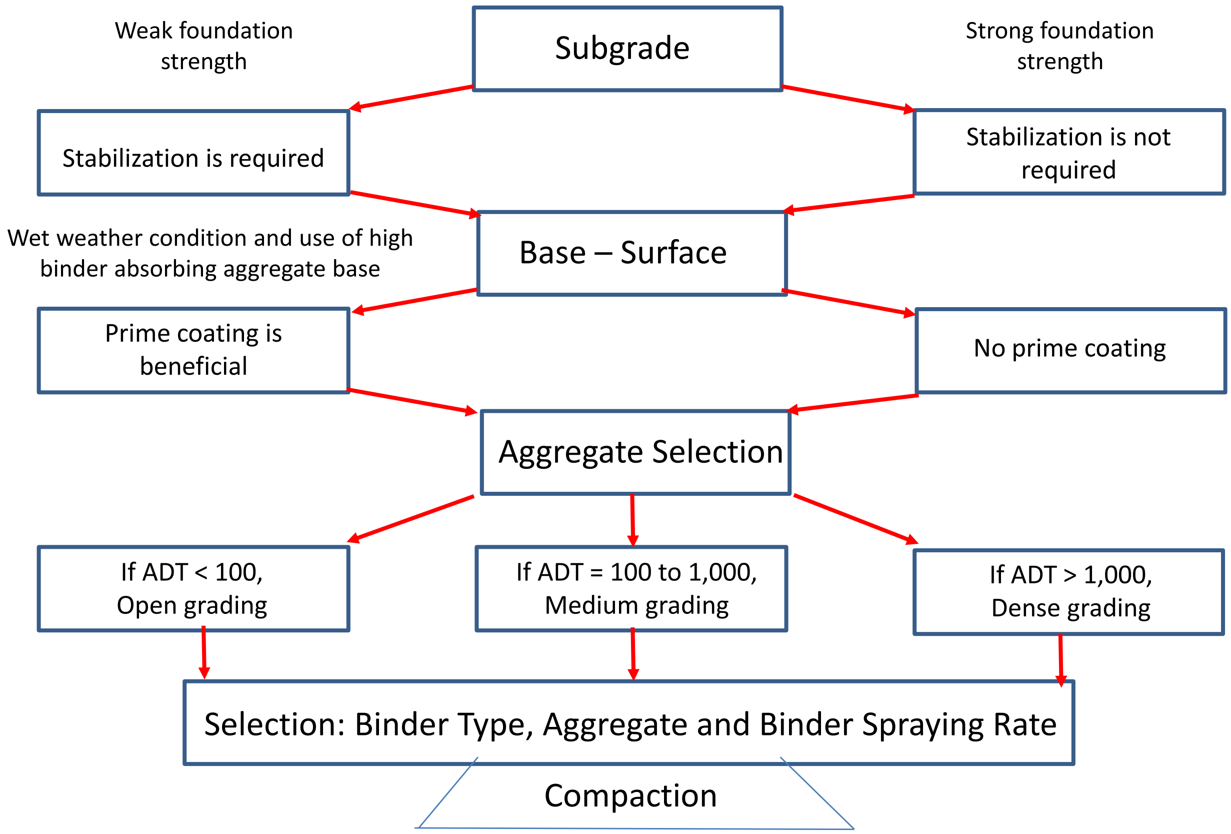


Figure 73. General flow chart for Otta seal design process

The Otta seal design types, layer structural features, aggregate types, aggregate gradations, binder types, construction equipment required, aggregate application rates, and binder spraying rates used in Nordic practice, US (Minnesota and South Dakota) practice, and the Iowa demonstration in Cherokee County are compared in Table 23 to Table 30, along with suggestions for Iowa roads.

Table 23. Comparison of Otta seal type between Nordic and US practices and Iowa demonstration

Case	Type of Otta seal
NRRL Design Guide: Low Traffic (ADT < 100)	Single Otta seal or single Otta seal with sand cover seal
NRRL Design Guide: Medium Traffic (100 to 1,000)	ADT < 500: single Otta seal with sand cover seal; ADT > 500: double Otta seal with/without sand cover seal
NRRL Design Guide: High Traffic (ADT > 1,000)	Double Otta seal with/without sand cover seal
MN Practice (ADT < 1,000)	Double Otta seal with chip seal as clean finish
SD Practice (ADT < 1,000)	Double Otta seal without prime coating
IA Demonstration (ADT < 1,000)	Double Otta seal without prime coating
Suggestion for IA Roads	Double Otta seal with/without chip seal and without prime coating

Table 24. Comparison of Otta seal layer structural features between Nordic and US practices and Iowa demonstration

Case	Layer Structural Features
NRRL Design Guide: Low Traffic (ADT < 100)	About 1.52 cm (0.6 in.) of single Otta seal surface thickness
NRRL Design Guide: Medium Traffic (ADT = 100 to 1,000)	About 1.52 cm (0.6 in.) of single Otta seal surface thickness and 3.05 cm (1.2 in.) of double Otta seal surface thickness
NRRL Design Guide: High Traffic (ADT > 1,000)	About 1.52 cm (0.6 in.) of single Otta seal surface thickness and 3.05 cm (1.2 in.) of double Otta seal surface thickness
MN Practice (ADT < 1,000)	About 3.18 cm (1.25 in.) of final surface thickness; 7.62 to 15.24 cm (3 to 6 in.) of aggregate base layer thickness
SD Practice (ADT < 1,000)	About 3.18 cm (1.25 in.) of final surface thickness; 22.86 to 35.56 cm (9 to 14 in.) of aggregate (with or without RAP) base layer thickness for heavy agricultural or industrial traffic
IA Demonstration (ADT < 1,000)	About 3.18 cm (1.25 in.) of final surface thickness; 7.62 to 15.24 cm (3 to 6 in.) of aggregate base layer thickness
Suggestion for IA Roads	About 3.18 cm (1.25 in.) of final surface thickness; Thicker base layer for heavy agricultural or industrial traffic

Table 25. Comparison of Otta seal aggregate type between Nordic and US practices and Iowa demonstration

Case	Type of Aggregate
NRRL Design Guide: Low Traffic (ADT < 100)	A screened aggregate (crushed, uncrushed, or blended)
NRRL Design Guide: Medium Traffic (ADT = 100 to 1,000)	A screened aggregate (crushed, uncrushed, or blended)
NRRL Design Guide: High Traffic (ADT > 1,000)	A screened aggregate (crushed, uncrushed, or blended)
MN Practice (ADT < 1,000)	A screened aggregate (crushed and uncrushed)
SD Practice (ADT < 1,000)	A screened aggregate (crushed and uncrushed)
IA Demonstration (ADT < 1,000)	A screened aggregate (crushed and uncrushed)
Suggestion for IA Roads	A screened aggregate (crushed, uncrushed, or blended)

Table 26. Comparison of Otta seal aggregate gradation between Nordic and US practices and Iowa demonstration

Case	Aggregate gradation
NRRL Design Guide: Low Traffic (ADT < 100)	Open
NRRL Design Guide: Medium Traffic (ADT = 100 to 1,000)	Medium
NRRL Design Guide: High Traffic (ADT > 1,000)	Dense
MN Practice (ADT < 1,000)	Dense or MnDOT class 5
SD Practice (ADT < 1,000)	Less than 1.91 cm (3/4 in.) minus aggregate as a large top-size aggregate
IA Demonstration (ADT < 1,000)	Dense
Suggestion for IA Roads	Dense, MnDOT class 5, IA DOT No. 10 – granular surface, or IA DOT No. 11 – granular surface & shoulder; Less than 1.91 cm (3/4 in.) minus aggregate as a large top-size aggregate

Table 27. Comparison of Otta seal binder type between Nordic and US practices and Iowa demonstration

Case	Type of Asphalt Binder
NRRL Design Guide: Low Traffic (ADT < 100)	150/200 penetration grade bitumen (hardest)
NRRL Design Guide: Medium Traffic (ADT = 100 to 1,000)	150/200 penetration grade bitumen (hardest)
NRRL Design Guide: High Traffic (ADT > 1,000)	MC 3000 cut back bitumen (medium); MC 800 cut back bitumen (softest) in cold weather
MN Practice (ADT < 1,000)	HFMS-2s
SD Practice (ADT < 1,000)	HFMS-2s
IA Demonstration (ADT < 1,000)	HFMS-2s
Suggestion for IA Roads	HFMS-2s

Table 28. Comparison of Otta seal construction equipment requirements between Nordic and US practices and Iowa demonstration

Case	Equipment Required
NRRL Design Guide: Low Traffic (ADT < 100)	Asphalt distributor, aggregate spreaders, pneumatic-tired roller, steel flat wheel rollers, and mechanical broom
NRRL Design Guide: Medium Traffic (ADT = 100 to 1,000)	Asphalt distributor, aggregate spreaders, pneumatic-tired roller, steel flat wheel rollers, and mechanical broom
NRRL Design Guide: High Traffic (ADT > 1,000)	Asphalt distributor, aggregate spreaders, pneumatic-tired roller, steel flat wheel rollers, and mechanical broom
MN Practice (ADT < 1,000)	Asphalt distributor, chip spreader, pneumatic-tired roller, and mechanical broom
SD Practice (ADT < 1,000)	Asphalt distributor, chip spreader, pneumatic-tired roller, and mechanical broom (Asphalt cold milling machines if using existing asphalt surface as recycled material)
IA Demonstration (ADT < 1,000)	Asphalt distributor, chip spreader, pneumatic-tired roller, and mechanical broom (Asphalt cold milling machines if using existing asphalt surface as recycled materials)
Suggestion for IA Roads	Asphalt distributor, chip spreader, pneumatic-tired roller, mechanical broom, and steel flat wheel rollers (if available)

Table 29. Comparison of Otta seal aggregate application rates between Nordic and US practices and Iowa demonstration

Case	Aggregate Application Rates
NRRL Design Guide: Low Traffic (ADT < 100)	33 to 40 kg/m^2, 0.013 to 0.016 m^3/m^2 (60 to 74 lb/yd^2)
NRRL Design Guide: Medium Traffic (ADT = 100 to 1,000)	33 to 40 kg/m^2, 0.013 to 0.016 m^3/m2 (60 to 74 lb/yd^2)
NRRL Design Guide: High Traffic (ADT > 1,000)	40 to 50 kg/m^2, 0.016 to 0.020 m^3/m^2 (74 to 92 lb/yd^2)
MN Practice (ADT < 1,000)	27 kg/m^2 (50 lb/yd^2)
SD Practice (ADT < 1,000)	27 kg/m^2 (50 lb/yd^2)
IA Demonstration (ADT < 1,000)	30-35 kg/m^2 (55-65 lb/yd^2)
Suggestion for IA Roads	27 kg/m^2 (50 lb/yd^2)

Table 30. Comparison of Otta seal binder application rates between Nordic and US practices and Iowa demonstration

Case	Binder Application Rates
NRRL Design Guide: Low Traffic (ADT < 100)	1.5 to 1.6 L/m^2 (0.33 to 0.38 gal/yd^2)
NRRL Design Guide: Medium Traffic (ADT = 100 to 1,000)	1.6 to 1.8 L/m^2 (0.35 to 0.40 gal/yd^2)
NRRL Design Guide: High Traffic (ADT > 1,000)	1.7 to 2.0 L/m^2 (0.38 to 0.44 gal/yd^2)
MN Practice (ADT < 1,000)	2.2±0.2 L/m^2 (0.5±0.05 gal/yd^2)
SD Practice (ADT < 1,000)	2.2 L/m^2 (0.5 gal/yd^2)
IA Demonstration (ADT < 1,000)	2.2-2.5 L/m^2 (0.50-0.55 gal/yd^2)
Suggestion for IA Roads	2.2±0.2 L/m^2 (0.5±0.05 gal/yd^2)

Table 31 summarizes the general construction procedures for Otta seal found in the literature (Øverby 1999, Johnson 2003) and observed in US practice. Table 32 shows the stages in the maturation of Otta seal reported in the literature (Øverby 1999) and observed in this study.

Table 31. General construction operations

Steps of Construction	Suggestions
Preparation of Base Course	Un-primed base: the base should be broomed Primed base: good practice should be adopted for placing any bituminous seal
On the Day of Construction: Sealing Operations	A minimum of 15 passes with a pneumatic-tired roller with a minimum weight of 10.89 metric tons (12 US tons) are required (two pneumatic-tired rollers are recommended); one pass with a 10- to 10.89 metric tons (12 US tons) static tandem steel roller (Johnson 2003) after the initial rolling can be more advantageous in kneading the binder upwards into the aggregate particles: Commercial traffic should be allowed immediately following completion of the initial rolling
Follow-up Inspection	An inspection must be made during the first six to seven days following sealing to ensure that any defects are corrected
Immediate Post-Construction Care	During the initial two days after construction, a minimum of 15 passes with a pneumatic-tired roller are required For two to three weeks after construction, any aggregate dislodged (due to traffic) should be broomed back into the wheel tracks if cutbacks are used instead of emulsion; After two to three weeks, any excess aggregate can be swept off
Traffic Management	Early traffic load makes a valuable contribution to the compaction of the seal
Lane Closure Requirement	Lane closure is required only during construction
Additional Considerations	Double Otta seal: up to 12 weeks are recommended (Øverby 1999) after the first Otta seal layer if using cutbacks. However, most projects carried out by using asphalt emulsions in the US placed the second Otta seal layer immediately after the first Otta seal layer treatment with no adverse effects on performance Sand cover seal or chip seal: Recommended about several months after Otta seal construction to ensure performance of constructed Otta seal

Table 32. Stages in maturation of Otta seal

Stages	Surface features	Suggested maintenance items
Immediately after construction	Appearance is influenced by the aggregate color	A minimum of 15 passes with a pneumatic-tired roller is required
two to three weeks after construction	Aggregate can be dislodged by traffic	During two to three weeks after construction, any dislodged aggregate (due to traffic) should be broomed back into the wheel tracks if cutbacks are used; After two to three weeks, any excess aggregate can be swept off
10 to 14 weeks after construction	The Otta seal bleeds down to produce the appearance of an asphalt concrete premix	The initial appearance of bleeding and isolated fatty spots should cause no concern, and can be blended off with fine aggregate and preferably rolled into the surfacing; Where bleeding is extensive, a coarser aggregate may be used and rolling application may be conducted during the hotter times of the day
6 months after construction	Seal is fully settled and shows excellent appearance	The entire sealed area should preferably be uniformly exposed to traffic
More than 1 year after construction	Any localized surface defects might be observed	Resealing intervals for Otta seal vary between 9 and 15 years depending on the type of seal

ECONOMIC ANALYSIS - OTTA SEAL VERSUS CHIP SEAL

Overall Description of Analysis Approach

The US has approximately 2,280,440 km (1,417,000 miles) of unpaved secondary roads that experience relatively low daily traffic volumes. To maintain these roads, US county secondary road departments spend millions of dollars annually for aggregate replacement alone. While Otta seal has been reported to be an effective, low-cost BST and dust mitigation technique by many international studies, only two US states—Minnesota and South Dakota—have reported on its construction and performance prior to this study, which describes the first Otta seal construction demonstration in Iowa. When considering this limited use in the US, Otta seal should be compared with chip seal, a commonly used BST in the US, from an economic viability perspective.

An existing study (Øverby and Pinard 2013) has reported on Otta seal's lower life-cycle costs compared to other BSTs, but the study's weakness lies in its assumptions. A deterministic analysis of life-cycle costs assumes a given cost for the materials used in the surface treatment, but assuming that today's cost of liquid asphalt binder is likely to be inflated at an annual rate of 3 to 5 percent over a period of a decade or more would be a fundamental mistake. The price of diesel fuel has nearly tripled over the past decade, as have the prices of bituminous products, and such instability means that a deterministic economic analysis cannot be performed with any degree of confidence when applied to highly volatile construction materials (Gransberg and Diekmann 2004, Gransberg and Kelly 2008, Gransberg and Scheepbouwer 2010).

Using Minnesota and Iowa as case study locations for life-cycle cost analysis (LCCA), an analysis was conducted at two levels: (1) deterministic life-cycle cost analysis and (2) stochastic life-cycle cost analysis. While various road and highway agencies in Minnesota have implemented Otta seal and provided access to the historical bid cost records needed to complete this study, few historical bid cost records are available in Iowa. Because the Otta seal demonstration project conducted through this study in Cherokee County, Iowa, was the first such construction project in Iowa, a cost breakdown approach was utilized as an alternative for estimating historical costs in Iowa.

Deterministic and stochastic LCCA approaches were employed to compare competing design alternatives. The specific approach for this study utilizes equivalent uniform annual cost (EUAC) analysis, permitting elimination of the many assumptions required when using the more common, and more problematic, net present worth LCCA (Walls and Smith 1998). Deterministic EUAC, the traditional method used for decision-making in pavement management, involves using point estimates that result in a single output value (Salem et al. 2003). The outcome of a deterministic LCCA depends on numerous estimates, forecasts, assumptions, and approximations, with each factor having some potential for introducing error into the results. The role of each such error in affecting the outcome of the EUAC must be known to a decision-maker if informed decisions are to be made with confidence. Moreover, the degree of uncertainty associated with each alternative is itself a factor to be considered when selecting among competing alternatives (Gransberg and Scheepbouwer 2010, Salem et al. 2003, Walls and Smith 1998).

Along with deterministic LCCA, this study included the use of a stochastic LCCA methodology (Pittenger et al. 2012) similar to that previously used in studies related to pavement management (Abdelaty et al. 2016, Gransberg and Diekmann 2004, Tighe 2001). This methodology has been specifically developed to accommodate the wide range of surface treatment alternatives found in pavement preservation and maintenance approaches (Tighe 2001). The issues associated with a deterministic EUAC model, such as sensitivity to discount rate or volatility of underlying commodity prices, could be addressed by developing a stochastic life-cycle cost model. A stochastic LCCA approach allows input variables to range across their more recent historic variations utilizing Monte Carlo simulation (MCS) (Reigle and Zaniewski 2002), which also supports quantification of the range of possible EUAC values using sensitivity analysis to identify how each particular input variable affects the overall EUAC model (Flanagan et al. 1987, Reigle and Zaniewski 2002).

Cost Estimations for LCCA

Input Values Determination

The first step in a stochastic approach is to determine which input values have associated uncertainty that could significantly impact the results (Peshkin et al. 2004, Pittenger et al. 2012). Such values should be treated probabilistically, while others can be treated deterministically to simplify the analysis (Pittenger et al. 2012). Initial construction costs, discount rates, and service life associated with pavement treatment methods were treated probabilistically in the stochastic LCCA study.

Service Life and Discount Rate

"Service life is considered the most superior performance measure because all other long-term effectiveness measures are computed on the basis of service life" (FHWA 2007). Service life uncertainty creates sensitivity in LCCA results (Peshkin et al. 2004), making service life a good candidate for stochastic treatment and deterministic sensitivity analysis.

Figure 74 summarizes the service lives of single chip seal, double chip seal, and double Otta seal for LCCA calculations, as reported in the literature (Gransberg 2007, Gransberg and James 2005, Johnson and Pantelis 2011, Mamlouk and Matild 2014, Øverby 1999, Øverby and Pinard 2013).

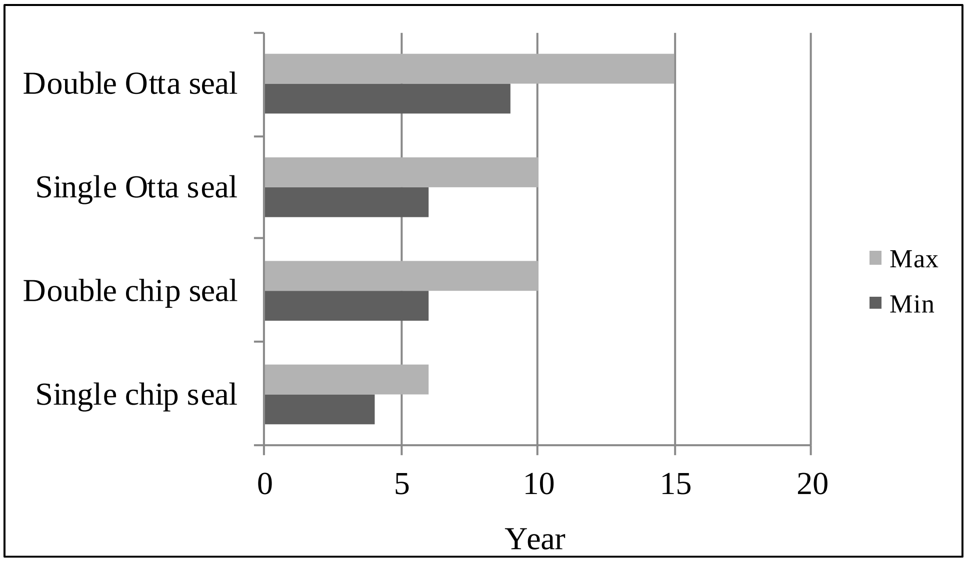


Figure 74. Typical service life ranges for bituminous surface treatments

FHWA suggests that a discount rate of 3 to 5 percent be used in determination of LCCA (FHWA Pavement Division 1998). In addition, previous 20-year discount rate data from the Federal Reserve (Federal Reserve 2017) were obtained for the stochastic LCCA approach.

Initial Construction Cost

Initial construction cost is one of the main components of LCCA (FHWA Pavement Division 1998). The cost estimation approach used for the Minnesota case study was to use historical bid tabs to create unit cost estimates. Due to the lack of Otta seal bid data in Iowa, the approach was to break down the construction cost into specific items, such as aggregate or transportation. Each item's quantity and cost were estimated for use in deterministic and stochastic LCCA models.

Case Study 1: Minnesota

The initial construction cost of BST was obtained from publicly available Minnesota bid tabs (Bid Express 2018). Bid data provide a simple, reliable, and quick method for estimating unit costs (Tehrani 2016). The data set used in this analysis contained bid records for the previous two-year period (September 2015 to August 2017). Figure 75 shows how unit costs of various Minnesota surface treatment options were distributed from September 2015 to August 2017.

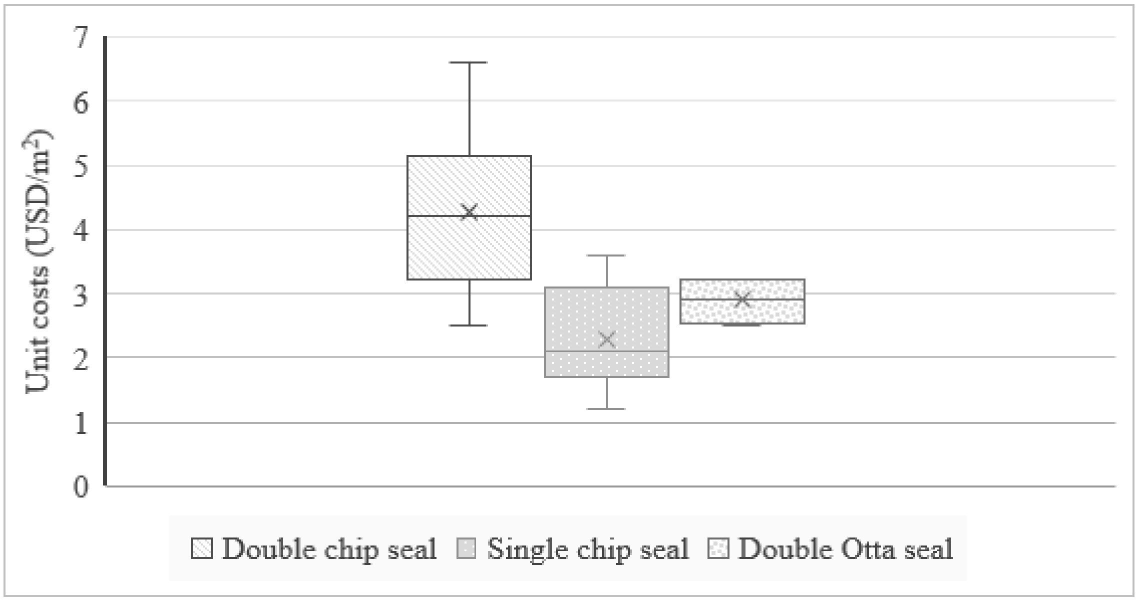


Figure 75. Unit cost of surface treatment options

According to design guidelines, the volume of binder in double Otta seal is usually close to 2.25 L/m^2 (0.50 gal/yd^2), virtually 50 per cent more than that of double chip seal (Gransberg and James 2005, Øverby 1999, Øverby and Pinard 2013). However, as shown in Figure 75, the mean values of unit costs for double Otta seal projects are much lower than those for double chip seal projects. According to discussions with contractors and Minnesota county engineers, the main reason for the difference between the unit prices of chip seal and Otta seal lies in the cost of hauling aggregate from aggregate producers' storage areas to job sites; in some chip seal cases, the hauling distance would be more than 300 km. Also, because Otta seal has a less restrictive requirement for aggregate gradation (unlike chip seal, which requires using a uniformly graded aggregate, as shown in Figure 76), using local aggregate for Otta seal surfacing is more often a viable option. Using local aggregate could result in aggregate production and haulage cost reductions (for locations not close to a good source of chip seal aggregate), reducing construction unit costs accordingly.

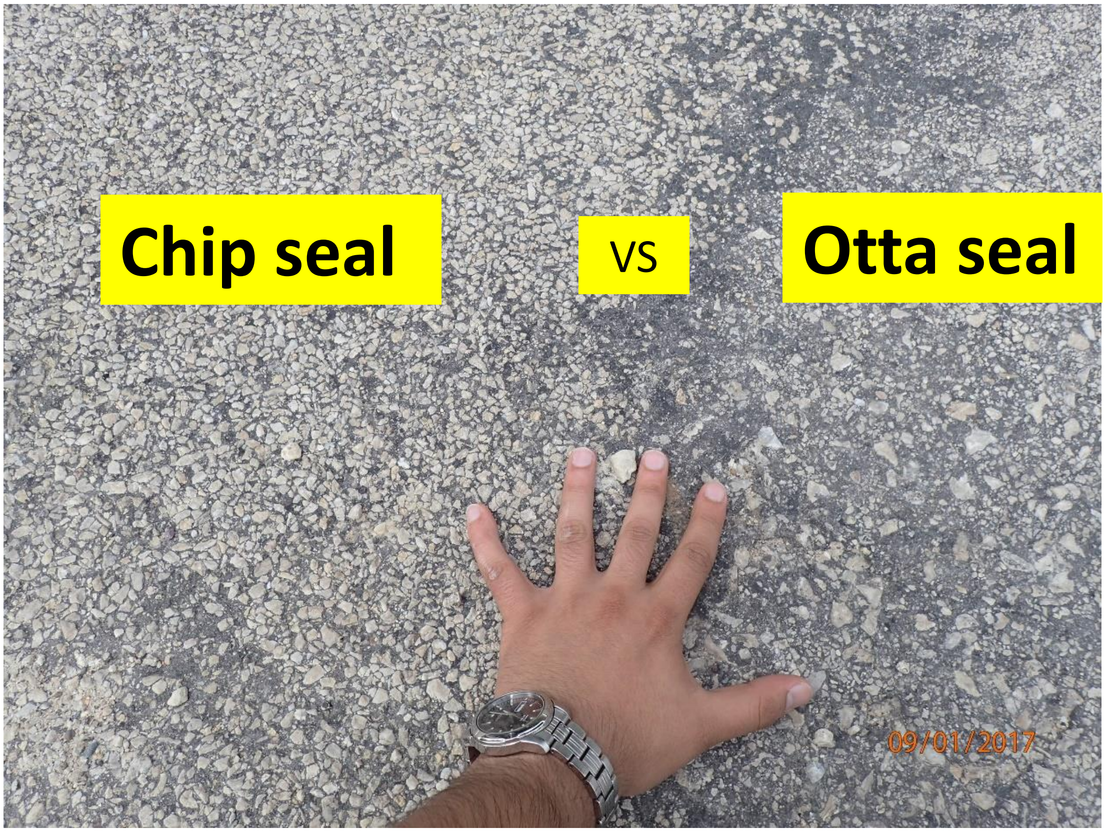


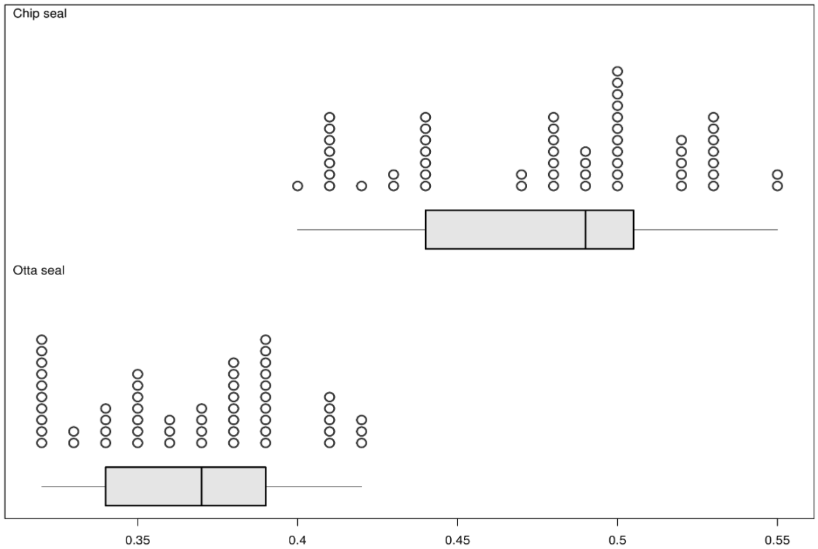
Figure 76. Uniform and non-uniform gradation of chip seal and Otta seal (MN 74, Winona County, Minnesota)

Case Study 2: Iowa

Because few historical cost records are available in Iowa, the initial installation costs of surface treatment methods were broken down into specific categories such as aggregate, transportation, and binder.

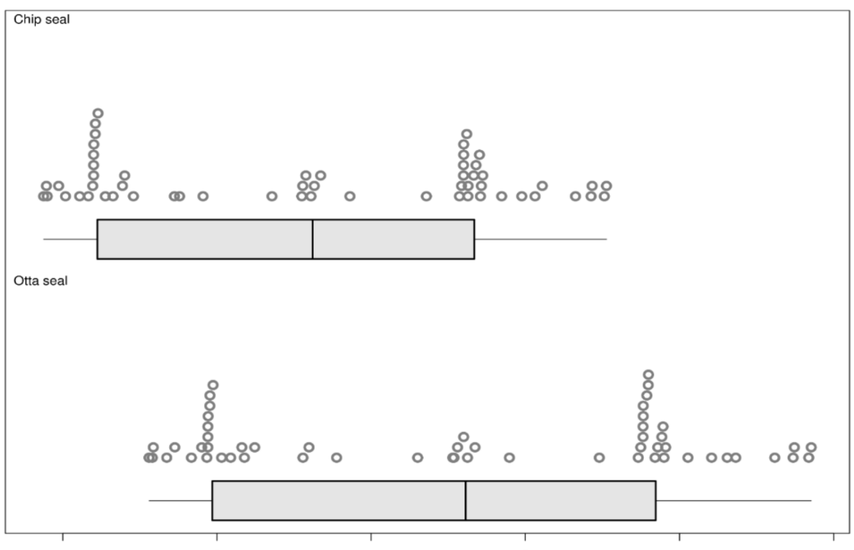
Both Otta seal and chip seal use aggregate spread on top of a bituminous binding agent, after which the surface is rolled with a pneumatic-tired roller, so the construction sequence and equipment required for Otta seal and chip seal construction are quite similar. Furthermore, the same equipment (asphalt distributor, chip spreader, pneumatic roller, and mechanical broom) can be used in either case, so equipment costs are likely to be similar for both methods. Otta seal production rate is a bit lower because it requires more material, and every time the distributor runs out of binder, there is a delay while it is refilled. If more aggregate spreading is needed, more trucks are required, and more truck changes slow down construction. However, these differences may not have a big impact on cost, so equipment and labor costs for both sealing methods would probably be close to one another and not likely to have a material effect on the comparison.

The main sources of initial cost difference between the methods are quantity of binder, aggregate haulage, and type and quantity of aggregate used. In this study those costs were determined from the U.S. Bureau of Labor Statistics (BLS) data (U.S. BLS 2017) and quarterly cost reports presented in the *Engineering News Record* (2017) (Figure 77).



USD/m^2

(a)



USD/m^2

(b)

Figure 77. Historical cost of required materials for sealing one square meter of surface during last five years: (a) aggregate: crushed aggregate for Otta seal and graded aggregate for chip seal, (b) cost of binder for chip seal and Otta seal

Figure 77a shows the historical cost of required aggregate per square meter for both Otta seal and chip seal. The aggregate spreading rate for Otta seal is approximately 27 kg/m^2 (50 lb /yd^2) (Johnson 2011, Øverby 1999, Øverby and Pinard 2013) and for chip seal the rate is approximately 16 kg/m^2 (50 lb/yd^2) (Gransberg and James 2005), and, as mentioned earlier, local aggregate materials are often used for Otta seal. In previous Minnesota Otta seal projects, crushed aggregate with a maximum size ranging from 1.25 to 2.5 cm (0.50 to 1.00 in.) (Johnson 2011) was used, while aggregate sizes used in chip seal construction ranged from 1 cm (0.385 in.) to 1.25 cm (0.50 in.) (Ozbay et al. 2004).

For a gravel road, the required amount of binder for Otta seal would be approximately 2.25 L/m^2 (0.5 gal/yd^2) (Johnson and Pantelis 2011, Øverby 1999, Øverby and Pinard 2013) and for chip seal the required amount would be approximately 1.6 L/m^2 (0.35 gal/yd^2) (Gransberg and James 2005). Figure 77b depicts the historical cost of required binder per square yard of Otta seal and chip seal.

Another factor affecting initial cost is the cost of hauling aggregate from quarries to job sites. The aggregate hauling rate per mile in Iowa for the last five years was obtained from the U.S. BLS data (U.S. BLS 2017). Figure 78 shows the cost per mile for hauling one truckload from an aggregate-producing location to a job site.

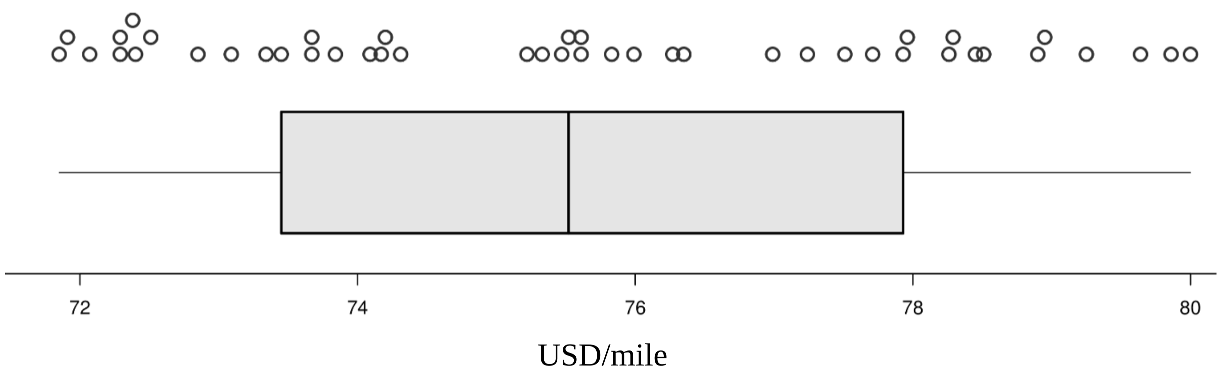


Figure 78. Hauling aggregate rate per mile for each truck load (7.2 metric tons)

Transportation cost is location-dependent and varies from one project to another. As shown in Figure 79, in the deterministic model, three different scenarios for representing transportation cost were evaluated. In the stochastic LCCA approach, transportation unit costs for all three possible scenarios were fitted to their best distributions and entered into the model.

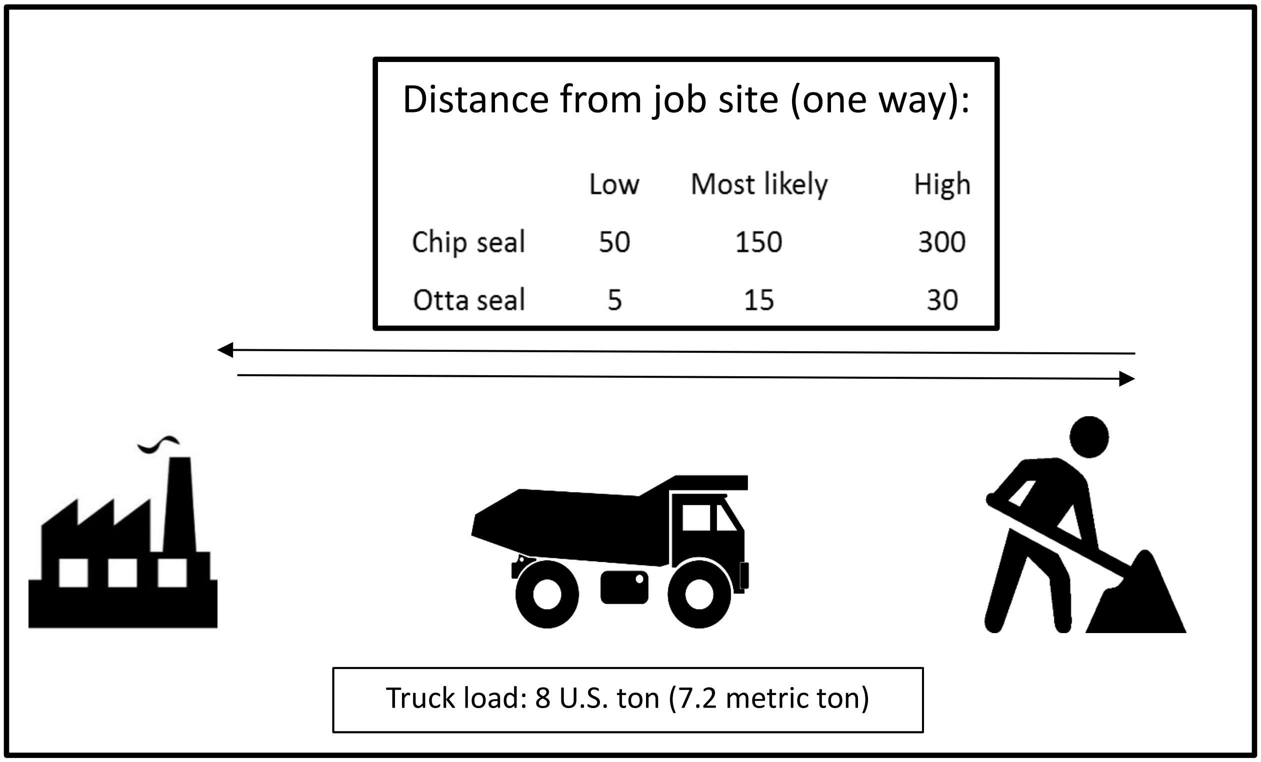


Figure 79. Different scenarios for transportation cost

User and Future Costs

According to FHWA, “if a pavement treatment is expected to incur costs, such as maintenance, comparable to the costs of other alternatives, and will not have a material effect on the output, they can be treated deterministically or ignored altogether” (Abdelaty et al. 2016, FHWA Pavement Division 1998).

However, according to the literature and discussion with county engineers, the wheel path of a new reseal surface will usually flush before chip seal has reached the end of its service life (Gransberg 2008, Gransberg and James 2005). This condition typically occurs roughly two to three years after construction (Gransberg 2008). The cost of removing excess binder in cases in which the wheel paths flush was estimated using average bid prices for projects awarded in Minnesota (MnDOT 2017a). The removal of excess binder also will typically add another year to chip seal service life.

Based on discussions with Minnesota and Iowa county engineers, all other maintenance costs associated with a road are assumed to be the same for both alternatives. In addition, because typical ADT will be quite low, costs associated with traffic control during construction and maintenance were not considered in this study.

Probability Distributions for Stochastic LCCA Results

Choosing an appropriate probability distribution for each input variable is an important step in using the stochastic LCCA approach. Input variables representing sufficient uncertainty and capability were fit into proper distributions and entered into the model.

In this study, two methods based on availability of data for different variables were used to identify the appropriate probability distribution for each input variable. Variables with sufficient data availability were placed in their best-fit distributions and entered into the model. The fitting process was enabled by goodness-of-fit tests based on statistical methods such as chi-square tests (Pearson 1992). For other inputs (e.g., service life), triangular distributions, commonly used for variables based on limited sample data (Pittenger et al. 2012), were used.

Because Otta seal is a relatively new technology in the US and only a few Otta seal projects have been implemented in Minnesota during the last two years, a triangular distribution was used in the MCS model to represent the initial costs of double Otta seal. The initial costs of single chip seal and double chip seal, obtained from the bid records, were fitted to their best theoretical distribution. Also, to make a same base comparison possible, chip seal alternatives were fitted triangularly, and the results were compared.

In the stochastic LCCA approach based on cost breakdown (Iowa case), the historical unit cost of materials and transportation cost were replaced with their probability distributions, and the output was estimated in a quantity variation format (as shown in Figure 80).

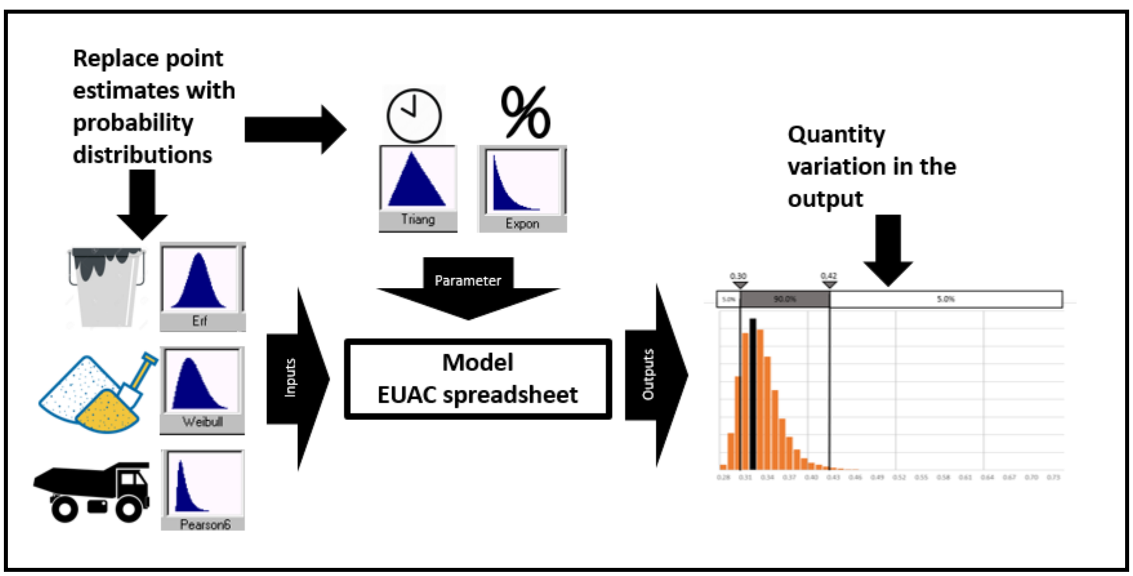


Figure 80. Stochastic cost model components

Deterministic LCCA Results

Case Study 1: Minnesota

The mean value of bid data unit costs was used for the initial costs. Table 33 shows the LCCA outputs in equivalent uniform annual cost format. The highest possible value of the double Otta seal option is lower than the lowest possible value of the chip seal options, as shown in Table 33. There is a theoretical possibility that a rapid change in the material price of chip seal could put its EUAC at the high end of its range, so further analysis is required before it can be concluded that double Otta seal would be the preferred alternative.

Table 33. Deterministic LCCA for Minnesota based on bid data approach through the inclusion of a sensitivity analysis, EUAC (USD/m^2)

Treatment method	Service life (years)	Discount rates		
		3 percent	4 percent	5 percent
Double chip seal	Low (6)	0.70	0.72	0.76
	Most likely (8)	0.56	0.59	0.61
	High(10)	0.48	0.50	0.53
Double Otta seal	Low (9)	0.42	0.43	0.44
	Most likely (12)	0.34	0.35	0.36
	High(15)	0.28	0.29	0.31
Single chip seal	Low (4)	0.83	0.85	0.86
	Most likely (5)	0.67	0.68	0.70
	High (6)	0.56	0.58	0.59

Case Study 2: Iowa

To illustrate situations where the EUAC will fall, the deterministic LCCA based on the FHWA model was performed using the lowest, the most likely, and the highest possible values for each input (Table 34). A discount rate of 3 percent was used in conformance with the FHWA technical report (FHWA Pavement Division 1998). A 3 percent discount rate also reflects the highest cost value for agencies within FHWA guidelines.

Table 34. Deterministic LCCA for Iowa based on cost breakdown approach through the inclusion of a sensitivity analysis, EUAC (USD/m^2)

Item		Low volume	Most likely	High value
Binder cost for chip seal (L/m^2)		3.89	5.60	7.50
Binder cost for Otta seal (L/m^2)		4.52	6.55	8.81
Aggregate cost for chip seal (kg/m^2)		0.81	0.99	1.13
Aggregate cost for Otta seal (kg/m^2)		0.63	0.72	0.86
Sealing types	**Service life (years)**	**EUAC (USD/m^2)**		
Double chip seal	High (6)	0.53	0.73	1.03
	Most likely (5)	0.43	0.59	0.84
	Low (4)	0.36	0.50	0.71
Double Otta seal	High (10)	0.20	0.28	0.35
	Most likely (8)	0.25	0.34	0.42
	Low (6)	0.32	0.44	0.54
Single chip seal	High (10)	0.40	0.58	0.84
	Most likely (8)	0.49	0.71	1.02
	Low (6)	0.64	0.91	1.32
Single Otta seal	High (15)	0.22	0.37	0.48
	Most likely (12)	0.24	0.44	0.58
	Low (9)	0.30	0.47	0.61

Similar to the deterministic analysis for Minnesota, for most scenarios the cost of Otta seal implementation is relatively lower than that of chip seal, although, as mentioned in the methodology section of this chapter, the deterministic LCCA could not adequately evaluate simultaneous variability (Pittenger et al. 2012).

Stochastic LCCA Results

Case Study 1: Minnesota

To conduct the stochastic LCCA, the model was developed using commercial simulation software, with each simulation iterated 1,000 times and each lasting from 20 to 55 seconds. Figure 81 shows the output of the simulations for double Otta seal.

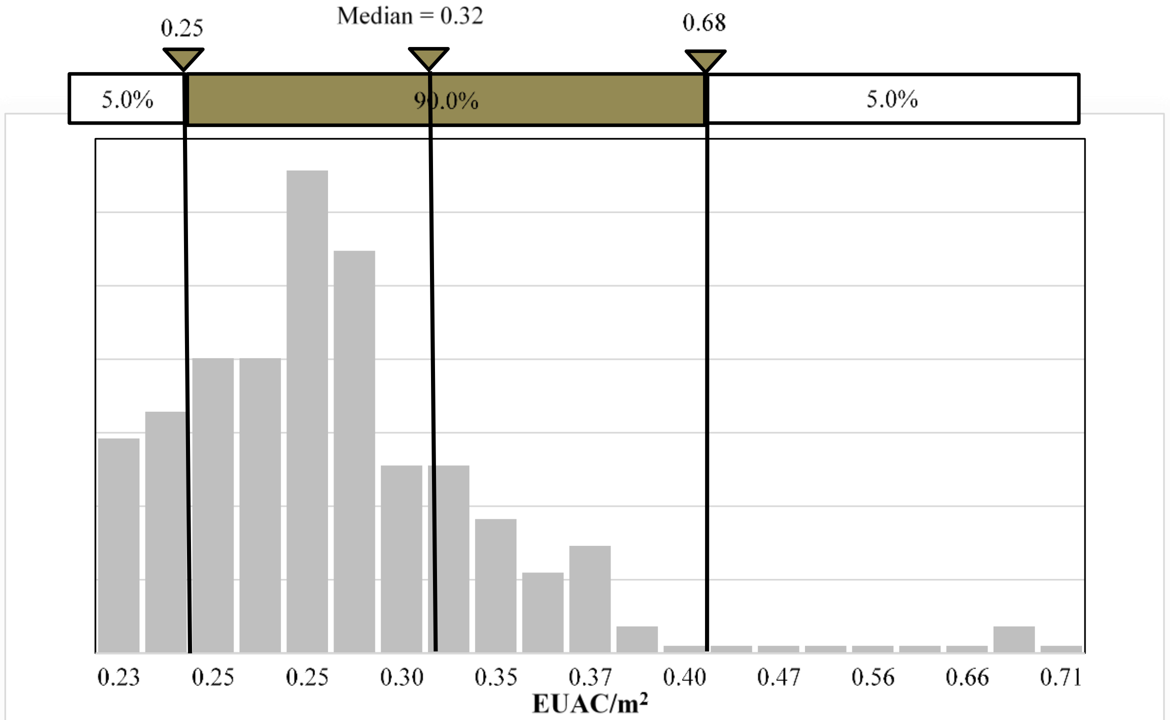


Figure 81. Probability distribution function for double Otta seal beads on the bid data

The simulation results for Minnesota are summarized in Table 35.

Table 35. Result of stochastic LCCA for state of Minnesota

Item	EUAC (USD/ m^2)				
	Pavement treatment type				
	Double Otta seal	Double chip seal best fit (Pareto distribution for initial cost)	Double chip seal with using triangular distribution for initial cost	Single chip seal best fit (exact value distribution for initial cost)	Single chip seal with using triangular distribution for initial cost
Median	0.32	0.53	0.55	0.64	0.65
Standard deviation	0.02	0.10	0.07	0.05	0.07
5th percent	0.25	0.41	0.44	0.50	0.53
95th percent	0.40	0.68	0.66	0.79	0.79
Max	0.73	0.79	0.77	0.90	0.84

The result from running a MCS is a probability density function (PDF) that provides a relative likelihood of EUAC. PDF variability is represented in Table 35. The standard deviation is an indicator of the amount of dispersion of EUAC values, and for double Otta seal, the estimate with a two-tailed 90 percent confidence interval ranges from 0.25 to 0.33, with a median value of 0.29. The median is a good measure because, regardless of distribution shape, half of the values are above the median and half are below the median (Boddy and Smith 2009). It can once again be seen that among the alternatives, double Otta seal has the lowest median life-cycle cost.

Case Study 2: Iowa

Similar to the previous section, point estimates in the deterministic EUAC model were replaced with probability distributions and the output was estimated in the quantity variation format. There were 1,000 iterations, with simulation times ranging from 18 to 53 seconds.

Table 36 shows the simulation outputs.

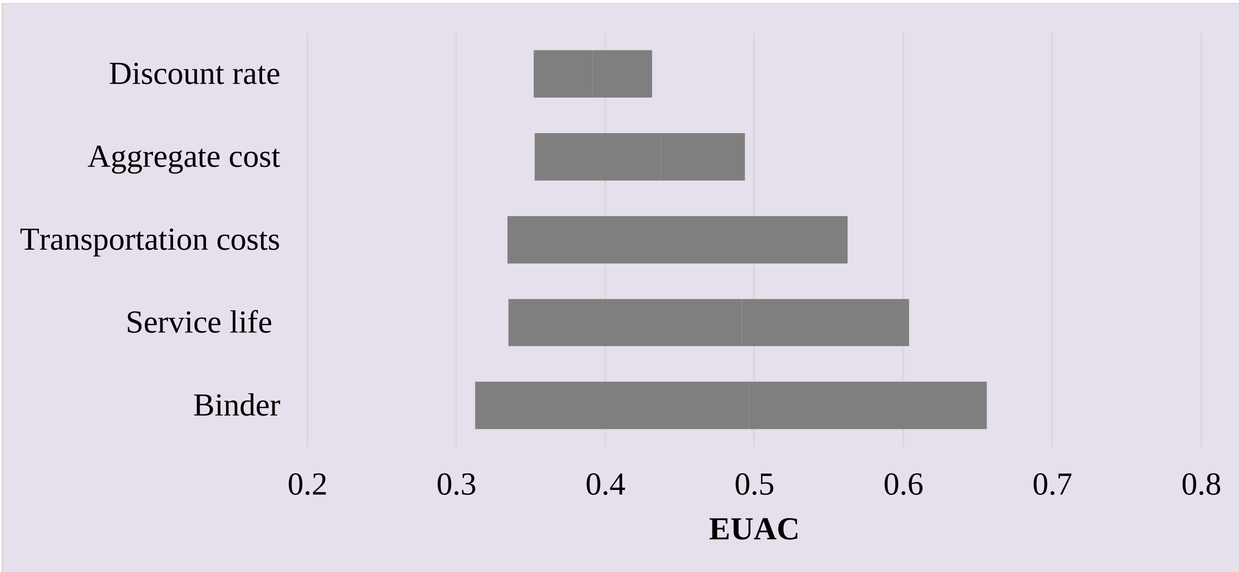
Table 36. Result of stochastic LCCA for state of Iowa

	EUAC (USD/ m^2)			
	Pavement treatment type			
Item	**Double Otta seal**	**Single Otta seal**	**Double chip seal**	**Single chip seal**
Median	0.33	0.36	0.48	0.56
Standard deviation	0.06	0.16	0.14	0.28
5th percent	0.23	0.33	0.32	0.44
95th percent	0.42	0.53	0.61	0.72
Max	0.49	0.64	0.75	0.91

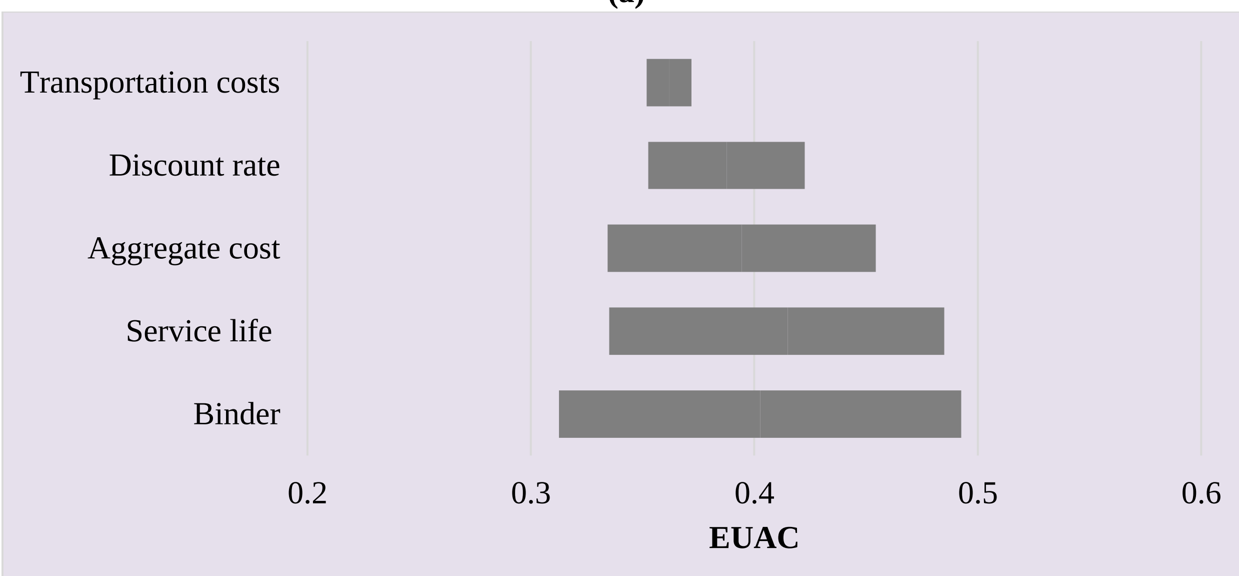
Similar to the previous results, it can be seen that, once again, double Otta seal has the lowest median life-cycle cost among the alternatives. In addition, for single-layer Otta seal, the estimate range with a two-tailed 90 percent confidence interval ranges from 0.23 to 0.53, with a median value of 0.36, which is lower than the cost of both double and single chip seal.

Another outcome of running a MCS is a determination as to which of the input variables has the greatest potential impact on the overall EUAC. Using the cost breakdown approach for cost estimation (the approach used for the Iowa case study) enables the quantification of the impact of different work package costs (i.e., costs for binder, aggregate, and transportation) on the total life-cycle.

As shown in Figure 82, the binder cost is a key factor influencing the EUAC in Iowa for both methods, and it is anticipated that the EUAC would decrease significantly as binder cost decreases. Another important factor is the sealed layer service life, which is directly related to construction quality. This highlights the importance of construction quality in both sealing methods. As shown in Figure 82b, the cost of hauling aggregate is the third factor driving variation in the chip seal life-cycle cost, reflecting the fact that the life-cycle cost of chip seal is location-dependent. However, because the use of local aggregate for Otta seal surfacing would be a viable option, transportation is not a key factor affecting EUAC (Figure 82b).



(a)



(b)

Figure 82. Sensitivity analysis results for Iowa: (a) double chip seal, (b) double Otta seal

Discussion

This study used both deterministic and stochastic LCCA approaches to evaluate the economic feasibility of using Otta seal in place of chip seal, with results leading to the conclusion that the use of Otta seal, a technology based on the use of local aggregate, would lead to reductions in transportation and material costs, thereby decreasing total construction costs. Because Otta seal technology is successfully being used in both Minnesota and Iowa, and because public agencies might be inclined to use it to reduce the maintenance costs of low-volume roads, the inputs can be modified and the method can be applied to these new inputs to produce results appropriate for other localities.

Although the analyses of the results reveal that Otta seal is more cost-effective than chip seal, this conclusion is limited only to Minnesota and Iowa because the relative unavailability of chip seal aggregate in some parts of these states could cause transportation cost to be a key factor affecting EUAC for chip seal. In states where high-quality aggregate would be locally available, the initial cost of chip seal would probably be significantly reduced. This study also was limited to only a cost-effectiveness evaluation of Otta seal compared to chip seal and did not investigate the performance aspects of sealed roads. For example, chip seal exhibits relatively higher skid resistance and is therefore said to reduce the incidence of skid-related accidents (Øverby and Pinard 2013), so the choice of Otta seal versus chip seal might not be clear and would depend on specific agency and user needs.

The methodology followed in this study provides agencies with the probability that a preferred alternative will actually produce the lowest life-cycle cost. Recommendations that may result from this research project will not only be founded in fundamental LCCA theory but can also provide various transportation agencies with an added level of confidence in predicting the financial results associated with pavement treatment alternatives of interest.

ECONOMIC ANALYSIS - OTTA SEAL VERSUS GRAVEL ROAD

This section compares the life-cycle cost of surfacing and maintaining a gravel road using a restored gravel road surface versus an Otta seal-coated surface. This study aims to provide guidance for local officials to decide at what point it would be desirable to promote a gravel road to an Otta seal-coated surface. This study can be modified and used to address local conditions. A methodology was chosen for estimating the cost of surfacing and maintaining gravel roads that is useful when requirements for labor, equipment, and materials can be predicted based on historical analysis (Jahren et al. 2005). For the sake of consistency with the previous chapter, and because historical performance and bid records for Otta seal were unavailable in Iowa, Minnesota was used as a case study for conducting the analysis.

Overall Descriptions of Analysis Approach

Although there have been attempts to use historical gravel road maintenance cost analysis on low-volume roads in Minnesota, historical cost analysis in Minnesota shows that in many cases cost data recorded by field crews were not placed in proper categories (Jahren et al. 2005). "Maintenance activities for bituminous roads were sometimes charged to gravel roads and vice versa" (Jahren et al. 2005). This study, therefore, used a deterministic cost estimation approach developed in another study (Jahren et al. 2005) to estimate the surfacing and maintenance costs of gravel roads.

As mentioned in the previous chapter, there are issues associated with a deterministic LCCA model, such as sensitivity to discount rates or volatility of underlying commodity prices, and these issues could be more satisfactorily addressed by developing a stochastic life-cycle cost model. This study chose to adopt the deterministic model described in the literature (Jahren et al. 2005) and, by using MCS, came up with a new stochastic LCCA model to compare gravel road and Otta seal life-cycle costs. In the remainder of this chapter, the cost estimation approaches and the results of the analysis are explained in detail.

Cost Estimations for LCCA

Cost estimates were made to develop the LCCA framework, and the cost estimation in this study assumed the roadway cross-section shown in Figure 83. As mentioned in the previous section, because of gravel road surfacing and maintenance cost estimations, this study adopted an approach first developed in a previous technical report. In addition, available bid records were used to estimate cost of Otta seal implementations on a 1 mi (1.6 km) road.

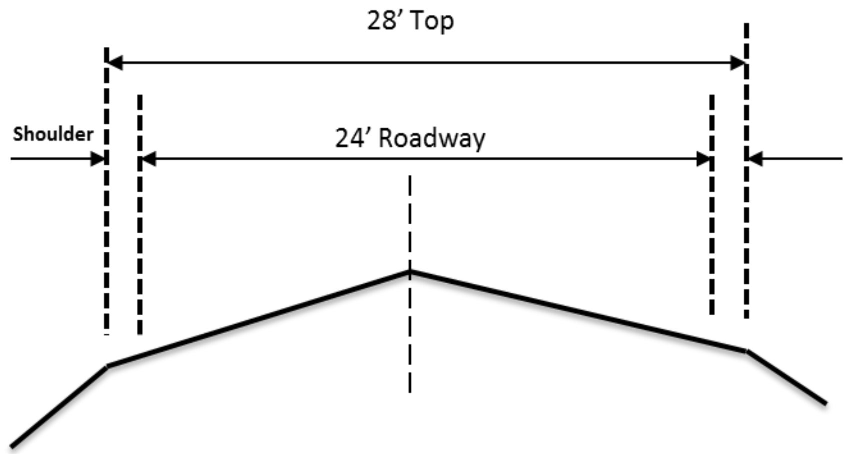


Figure 83. Roadway cross-section used in the analysis

Gravel Road

Assumptions were made in performing cost estimations for graveling a 1 mi road and maintaining the graveled surface, and calculations are based on methods described in the Caterpillar performance handbook (Caterpillar Inc. 2015). The set of assumptions used in the cost estimation are as follows:

- A 1.6 km (1 mi) long roadway with a 7.3 m (24 ft) top
- 5 cm (2 in.) of new gravel is assumed for graveling/re-graveling (480 m^3/km [1,000 yd^3/mi or 1,000 ton/mi])
- Gravel costs approximately 8.37 USD/m^3 (7 USD/yd^3)
- The cost for a motor grader is 50 USD/hr (including fuel)
- During grading operations, the motor grader travels at an average speed of 6.5 km/hr (4 mph).
- A 12 ft moldboard with a carry angle of 60 degrees is used.
- Three passes of the motor grader are needed per mile
- Operator cost was assumed to be 40 USD/hr
- Trucks (with 12 yd capacity) cost 50 USD/hr (includes fuel)
- Operator cost was assumed to be 30 USD/hr (round trip for each time in loading of aggregate would take 75 minutes).

Based on discussions with county engineers, the researchers found that the number of grading operations could vary from three times per month to three times per week, depending on daily traffic volume. In addition, grading months during a year could vary from one region to another, depending on severity of snow events and snowfall rates. Because of the uncertainty associated with the number of grading operations, this parameter was plugged into the stochastic analysis as one of the uncertain input variables.

To develop an estimate regarding labor and equipment cost, calculation of hourly operating area is necessary. The Caterpillar Performance Handbook (Caterpillar Inc. 2015) suggests the following equation for hourly operating area estimation:

$$A = S \times (l_e - l_o) \times 5280 \times E \qquad \text{Equation 1}$$

Where A is an hourly operation area, S is the operation speed, L_e is the effective blade length (10.4 ft [3.2 m]), L_o is the width of overlap (2.4 ft [0.75 m]), and E is the job efficiency (0.75). The calculation for hourly operating area can be found using the following:

$$A = 4 \times (10.4 - 2.4) \times 5280 \times 0.75 = 126.720\ ft^2/hr \qquad \text{Equation 2}$$

Using this hourly operating area, the time to blade for a 1 mi road can be calculated as shown in Equation 3.

$$t = \frac{Surface\ area}{Motorgrader\ rate} = \frac{24\ ft \times 5280\ ft\ (1\ mile)}{126.720\ ft^2/hr} = 1\ hr \qquad \text{Equation 3}$$

The time to blade a 1 mi road is 1 hour, meaning that a grading machine can cover three passes in an hour (taking into account a suggested efficiency factor of 0.75). Based on time-to-blade calculations, the time per year spent on a 1 mi roadway can be calculated using Equation 4. Because the number of required grading operations each year is quite uncertain, a deterministic value was not assigned to this variable in Equation 4.

$$T = 1.00\frac{hr}{mile} \times N\ miles \qquad \text{Equation 4}$$

After determining, the annual time spent on a 1 mi roadway, surfacing and maintaining (grading) costs can be calculated, with calculations for labor and equipment costs of surfacing (graveling) given by the following equations:

$$Number\ of\ gravel\ loads\ needed\ for\ one\ mile\ road = \left({}^{1\ load}/_{12\ yd^3}\right) \times \left({}^{1000\ yd^3}/_{mile}\right) \approx 84 \qquad \text{Equation 5}$$

$$Equipment\ cost = 84 \times 1.25\ hrs\ (time\ to\ load\ material) \times 50\ \left(\frac{USD}{hr}\right) = 5{,}250\ USD$$

$$Labor\ cost = 84 \times 1.25\ hrs\ (time\ to\ load\ material)\ \times 30 \left(\frac{USD}{hr}\right) = 3{,}150\ USD$$

$$Material = Gravel\ unit\ cost\ \left(\frac{7\ USD}{yd^3}\right) \times \left(\frac{1000\ yd^3}{mile}\right) = 7{,}000\ (\frac{USD}{Mile})$$

Otta Seal

The initial construction cost of a 1 mi double Otta seal was obtained from publicly available Minnesota bid tabs. The data set used in this analysis contained three bid records obtained over the past two-year period, and Table 37 shows the bid information used in this analysis. Note that only surface treatment cost was considered in the economic analysis, and non-related costs (e.g., miscellaneous, pipes and aprons extensions, or sub-drains) were not included.

Table 37. Costs for double Otta seal projects over the past two years in Winona County, Minnesota

Project location	Year	Double Otta seal cost in USD/km (USD/mile)
CSAH 2, Winona County, MN	2016	35,418 (57,000)
CSAH 13, Winona County, MN	2016	42,005 (67,600)
CR 31, 37, and 116, Winona County, MN	2017	37,158 (59,800)

From reviews of county cost data analysis (Jahren et al. 2005), the annual average maintenance expenditure for bituminous roads was assumed to be 1,491 USD/km (2,400 USD/mile) (value was adjusted using the price trend index for Iowa highway construction for the year 2017). Table 37 shows costs for double Otta seal projects over the past two years in Winona County, Minnesota.

When upgrading a gravel road to a BST road, the cost of some maintenance activities would change. For example, activities like grading, graveling, and the cost of dust suppressants would be eliminated, while the cost of snow removal operations on a paved road would be higher because more time is spent plowing them. Because snow and ice removal add a major cost to the maintenance of BST roads, this cost was included in the economic analysis. The following assumptions were made to estimate the additional cost of snow removal activities:

- Plowing would start when there is approximately 1 in. of snow on top of the road surface.
- Two passes with a snowplow on a paved road would be enough to clear the surface of snow.

Snow removal driving costs per mile were obtained from the MnDOT highway fund expenditures report for 2017 (MnDOT 2017b) (Figure 84). Note that costs were adjusted to a 2017 dollar value using a 3 percent annual inflation factor based on historic MnDOT maintenance and operations commodity and labor inflation.

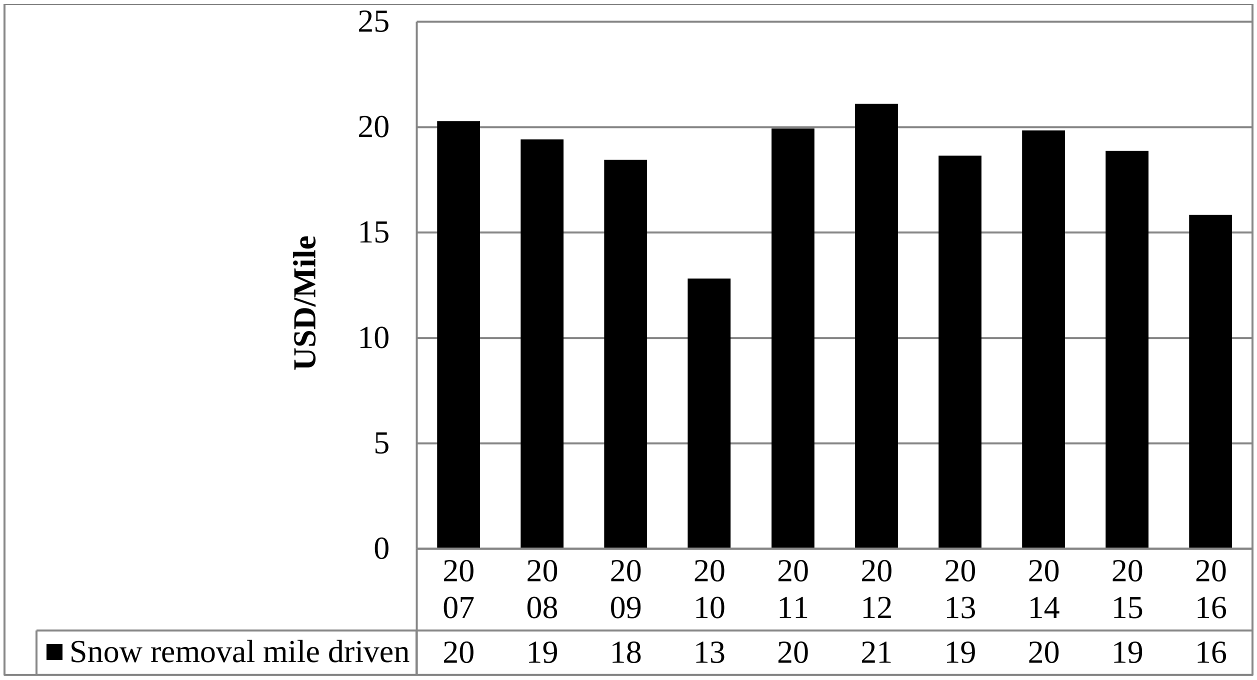
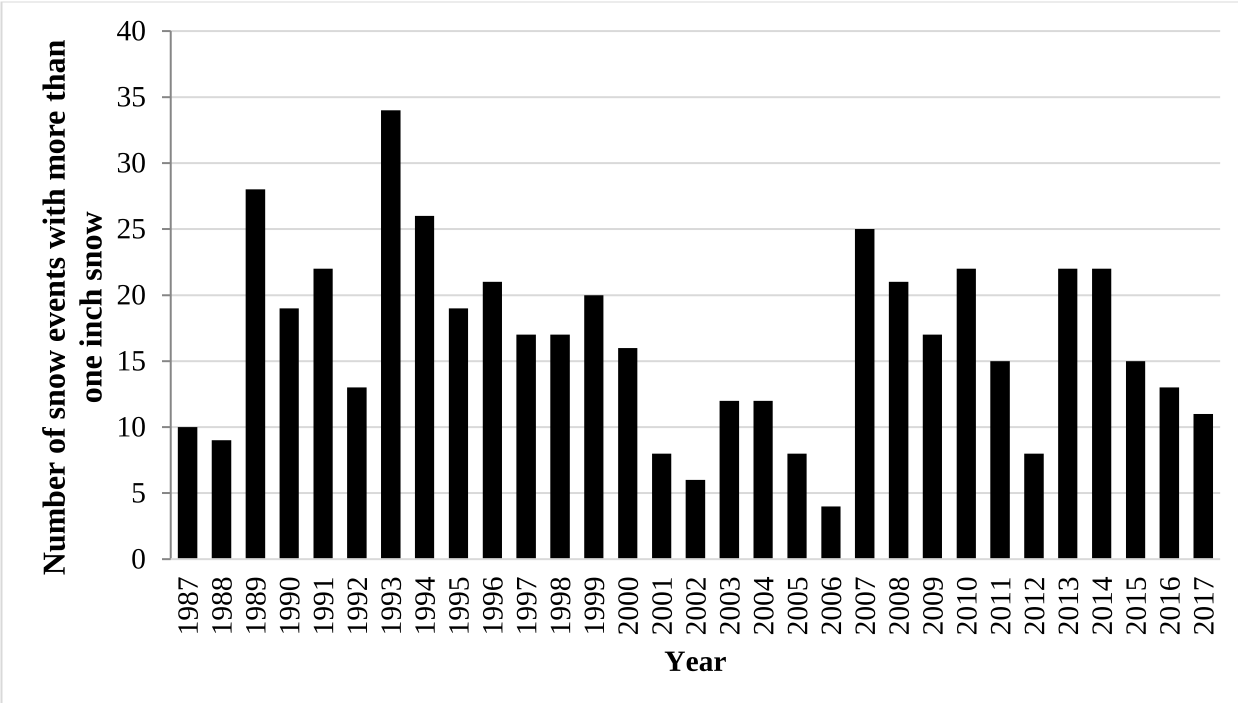


Figure 84. Snow removal driving cost per mile

Snow events over the last 30 years were determined using the automated surface observation system (IEM 2017) and are shown in Figure 85. The average number of snow events and snow removal driving costs per mile were used in the LCCA. Snow removal annual cost was calculated using the following equation:

$$Snow\ removal\ average\ annual\ cost = Average\ number\ of\ snow\ events \times Average\ snow\ removal\ driving\ cost\ \left(\frac{USD}{mile}\right) \times 2\ \text{(two passes of snowplow)} = 17 \times 19\ \left(\frac{USD}{mile}\right) \times 2 \approx\ 650\ USD \qquad \text{Equation 7}$$



Data from IEM 2017

Figure 85. Number of snow events with more than 1 in. snowfall

Economic Analysis

The economic analysis in this study can be modified by local authorities to reflect the costs and timing of many typical situations. The specific approach for this study uses EUAC analysis, allowing elimination of many assumptions required when using the more common, and more problematic, net present worth LCCA (Walls and Smith 1998). Similar to the previous chapter, the issues associated with a deterministic EUAC model, such as sensitivity to discount rate or volatility of underlying commodity prices, were addressed by developing a MCS-based economic analysis. In addition, for the stochastic LCCA approach, discount rate data for the previous 20 years from the Federal Reserve (Federal Reserve 2017) were obtained and included in the model.

Deterministic LCCA

The following assumptions were made in performing the deterministic LCCA for a 1 mi road treated with double Otta seal and gravel road:

- The design service lives of new graveled and new double Otta seal roads would be 5 and 12 years, respectively.
- A discount rate of 3 percent was used in accordance with an FHWA technical bulletin (FHWA Pavement Division 1998).

- A sensitivity analysis was performed with respect to the number of grading operations. The following three possible scenarios for the number of grading operations were evaluated:
  - Low value: The road is graded three times per month from April to October, a total of 21 times.
  - Most likely value: The road is graded five times per month from March to November, a total of 50 times.
  - High value: The road is graded seven times per month from March to November, a total of 70 times.
- Because the study is oriented to low-volume roads, the ADT would be so low that any user costs associated with traffic disruption during construction and maintenance operations would be trivial and were therefore eliminated from the model.

Table 38 shows the LCCA outputs in EUAC format. As shown in Table 38, the gravel road maintenance cost varied from 1,470 USD to 4,900 USD depending on the number of grading operations. In addition, the average annual cost for agencies and counties to upgrade a 1 mi gravel road to a 1 mi double Otta seal-surfaced road would vary from almost 1,500 USD to 5,000 USD based on gravel road annual maintenance costs.

Table 38. Deterministic LCCA

Item	Low value	Most likely value	High value
Number of grading operations	21	50	70
Gravel road maintenance cost in USD/km (USD/mile)	913 (1,470)	2,175 (3,500)	3,045 (4,900)
Double Otta seal cost in USD/km (USD/mile)	35,418 (57,000)	37,158 (59,800)	42,005 (67,600)
Otta seal EUAC in USD/km (USD/mile)	6,350 (10,220)	6,571 (10,575)	7,177 (11,550)
Gravel road EUAC in USD/km (USD/mile)	3,417 (5,500)	4,679 (7,530)	5,549 (8,930)

Stochastic LCCA

Because of the fluctuating number of grading operations, this variable was treated probabilistically in stochastic EUAC calculations. Triangular distribution was used in the model, following the same scenarios developed in the deterministic analysis, to describe the uncertain nature of this variable. In addition, costs associated with traffic control during construction and maintenance were not considered in this study. Moreover, unlike for Otta seal and chip seal, uncertainties associated with the service life of gravel roads have not been significantly reported in the literature, so service life for gravel roads was treated deterministically. Figure 86 shows the primary costs for maintaining a gravel road, including grading and resurfacing, for a five-year re-graveling cycle.

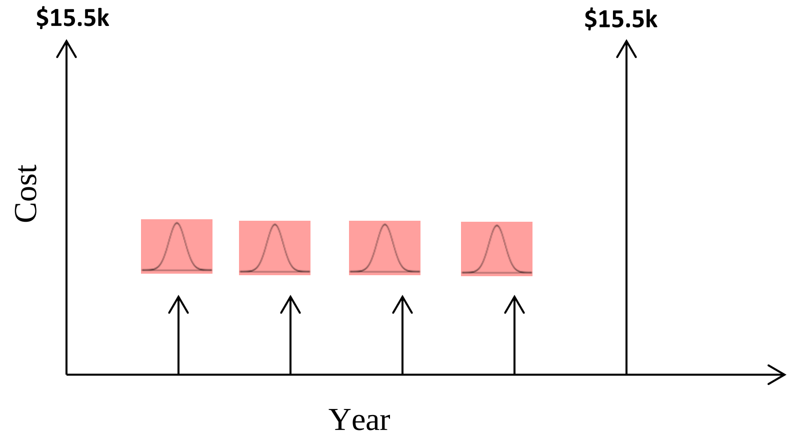


Figure 86. Maintaining and surfacing costs for five-year re-graveling cycle

Similar to gravel road EUAC calculations, maintenance was treated deterministically for Otta seal LCCA analysis. Based on bid records from Winona County, Minnesota, a triangular distribution was used to describe the construction cost of double Otta seal, and costs associated with traffic control during construction and maintenance were not considered. Service life uncertainty creates sensitivity in EUAC results (Peshkin et al. 2004), making service life a good candidate for stochastic analysis. The service life data presented in Figure 74 for double Otta seal was used in the economic analysis.

To conduct the stochastic LCCA, a MCS-based model was developed, with each simulation, ranging from 20 to 55 seconds, iterated 10,000 times. Figure 87 shows the EUAC results for both double Otta seal and gravel roads throughout their life-cycles. As shown in Figure 87, upgrading a 1 mile gravel road to a double Otta seal would require an average of 2,400 USD in annual expenditures. In addition, Figure 87 indicates that in nearly 20 percent of different possible scenarios, surfacing a road with a double Otta seal might incur the same cost as a gravel road.

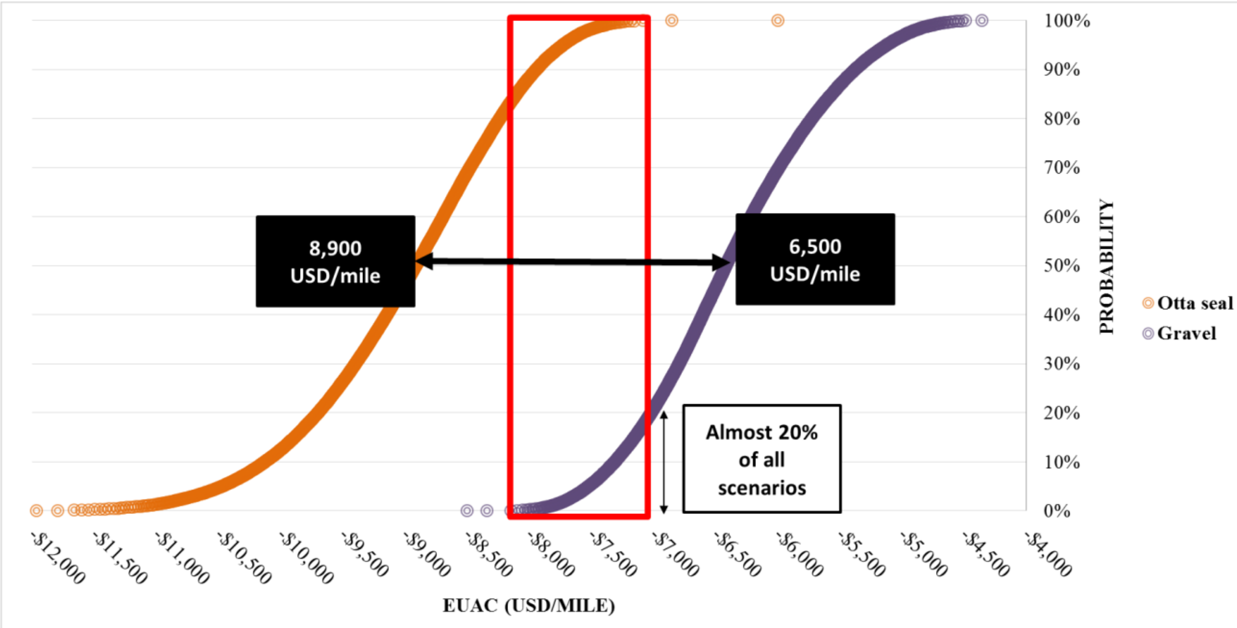


Figure 87. Stochastic LCCA results: double Otta seal versus gravel road

Indirect Benefits of Otta Seal over Gravel Road

It may not be possible to justify roadway surfacing decision-making based solely on economic analysis. There are many benefits associated with BSTs on an aggregate road that cannot be expressed in terms of monetary value. These benefits cannot be quantified and included in an economic analysis. Some of the benefits that should be considered in decision-making for roadway surfacing are the safety of the surface, driving efficiency, and dust control.

BST implementation on top of a gravel road would create a surface with higher skid resistance, and driving efficiency increases when a vehicle moves on a smooth, hard surface, unlike that of a loose gravel road. In contrast, driving on a gravel road creates a rougher ride and increases the amount of wear and tear on a vehicle's tires and undercarriage. Less dust in the car filters would result in greater fuel efficiency and reduced vehicle maintenance costs. Because BSTs, especially Otta seal, provide dust-free driving, with no dust coming from roadway travel, living conditions in the surrounding areas would improve, possibly reducing breathing-related health issues, creating less pollution in the water and the environment, and offering greater cleanliness for nearby homeowners.

Discussion

Stochastic and deterministic economic analyses were conducted to determine the investment needed to upgrade a gravel road to an Otta seal road. Because historical bid and performance records of Otta seal in Iowa were not available, Minnesota was used as a case study for conducting the analysis. Results of deterministic and stochastic economic analyses reveal that in some cases the investment in Otta seal might be justified by maintenance savings alone, though the results also show that in most cases maintenance savings alone would likely not be a good justification for investment. However, the upgrade from gravel road to Otta seal, or any other BST, might be justified in terms of improving the quality of life for nearby residents, improving safety for road users, and encouraging economic development that would benefit local areas. In addition, the results of the stochastic economic analysis indicate that in nearly 20 percent of different possible scenarios, surfacing a road with double Otta seal might incur the same cost as a gravel road. Local officials may use the cost estimating and economic analysis techniques described in this report to help target investments toward roads that would yield the most desirable results.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The principal objectives of this study were to evaluate the feasibility of Otta seals as an alternative surface treatment for Iowa's low-volume roads and to evaluate the cost-effectiveness and performance of Otta seals compared to traditional bituminous seal coat surfaces and to the maintenance of granular surfaced roads. The conclusions drawn from this study are summarized below.

Conclusions from Otta Seal Construction and Performance Evaluation

- Otta seals can be utilized as an alternative rehabilitation strategy for both unpaved roads and HMA pavements that are performing poorly.
- Properly constructed Otta seals can provide expected advantages, e.g., provision of a durable and impervious surface, prevention of aggregate loss, and deterrence of dust and mud.
- Gradation is the most critical property for aggregate selection, and because the allowed aggregate gradation limits vary over a wide range, the selected Otta seal type should fall within specific limits. Extra-fine content in the aggregate may cause the dust generated by the Otta seal surface to become unmanageable. The dustometer test results revealed that in the test section constructed with low-fine-content aggregate, passing traffic produced less dust.
- In the Øverby (1999) design guide, even though the specified binder types are all for cutback asphalt, asphalt emulsion was used in this study because of the limitations and restrictions on using cutback asphalt in the US. To reflect this change, the recommended binder spray rate in Øverby (1999) should be modified on the basis of the asphalt content in the emulsion. The amount of asphalt per unit volume of emulsion should be equal to the equivalent value recommended in Øverby (1999). In this study, the applied spray rate of binder was increased to 2.25 L/m^2 (0.50 gal/yd^2) for both layers.
- Aggregate spreading is another critical aspect that influences Otta seal construction and the resulting performance. First, the spread rate during construction must be carefully monitored. In the demonstration project, the amount of aggregate per unit area directly impacted the compaction and curing steps, and the presence of extra aggregates led to relatively rougher surfaces and binder that could not be squeezed upward to fully coat the aggregates.
- Even though the aggregate spreader featured an automatic spread rate controller, there were other factors that influenced the actual spread rate. In addition to human factors, aggregate moisture content played a crucial role. Practical experience derived from this study showed that if the aggregate is too moist before spreading, there is a significant chance that part of the spreader head can be blocked by moist aggregates, so it is important that aggregates be kept in a dry condition for at least one day before construction.
- A square steel plate with an area of 0.84 m^2 (1 yd^2) was fabricated for monitoring the aggregate spread rate. Compared to the design value 27.12 kg/m^2 (50 lbs/yd^2), the actual spread rates were always higher than the designed rates. The long-term performance of an

Otta seal may be influenced by this deviation because of insufficient binder to coat the extra aggregates.

- Short-term performance test results indicated that the IRI values changed slightly after Otta seal construction. The IRI values before and after construction ranged from 3 to 5 m/km (190.1 to 316.8 in./mile) and, based on the short-term performance of this project, the Otta seal seems capable of providing a surface that satisfies the smoothness requirements of a HMA pavement.

Conclusions from Economic Analysis Comparing Otta Seal, Chip Seal, and Granular Surfaced Roads

- Otta seal, a technology based on the use of local aggregate, would lead to a reduction in transportation and material costs, thereby decreasing total construction costs.
- The relative unavailability of chip seal aggregate in a region can significantly increase transportation cost, a key factor affecting EUAC for chip seal.
- Although the analyses reveal that Otta seal is more cost-effective than chip seal, this conclusion is limited only to geographic regions that have attributes that match the assumptions used in the calculations. In Minnesota and Iowa, the relative unavailability of good-quality aggregate in certain regions can result in transportation costs being a key factor affecting EUAC for chip seal, thus making the calculations presented here relevant.
- Stochastic and deterministic economic analyses were conducted to determine the investment needed to upgrade a gravel road to an Otta seal road. Because historical bid and performance records of Otta seals in Iowa were not available, Minnesota was considered as a case study for conducting the analysis. Although the results of the economic analysis reveal that, in some cases, an investment in an Otta seal might be justified by maintenance savings alone, in many cases maintenance savings alone do not provide good justification for upgrading to an Otta seal. However, Otta seals provide many other benefits that are difficult to quantify with great certainty but that are highly desirable, thus making an investment in an Otta seal desirable.
- The methodology followed in this study provides agencies with the probability that the preferred alternative will actually produce the lowest life-cycle cost. Therefore, recommendations that may result from this research project are not only founded in fundamental LCCA theory but can also provide various transportation agencies with an added level of confidence in predicting the financial results of pavement treatment alternatives of interest and explaining risk to stakeholders.

Recommendations

Based on the findings of this research and the recommendations of the project TAC, future research directions related to Otta seal applications for Iowa’s low-volume roads were identified and can be summarized as follows:

- A follow-up Phase II research study is needed to establish recommended specifications, including quality control/quality assurance procedures for Iowa Otta seal construction projects. Two concurrent research studies are suggested: (1) comprehensive laboratory evaluation and characterization and (2) field implementation projects representing a range of locally available aggregate possibilities in various regions of the state.

- Development of a rational or engineered approach is recommended for determining the optimum application rates for asphalt binder and aggregate in Otta seal applications.
- A set of field investigations of Otta seal construction is recommended to identify road surface/base preparation requirements before Otta seal application, to identify test and control procedures for checking and calibrating actual field application rates of asphalt binder and aggregate, and to evaluate the rolling operations (e.g., number of passes) necessary for achieving appropriate field compaction
- Curing periods are required between the first and second layers of Otta seal construction for double Otta seals to ensure that the maximum amount of aggregate particles is embedded into the soft asphalt binder during the evaporation of water (for asphalt emulsion) or the solvent (for cutback asphalt). However, because there is currently no standard test procedure for determining curing periods, research is needed to identify test procedures for determining curing times on Otta seals and to recommend optimum curing times between the first and second layers of double Otta seal construction
- Previous studies have shown that annual maintenance costs for a gravel road increase as the AADT increases (Skorseth et al. 2013), and because there is a general trend toward increasing traffic volumes, especially in urban areas, it is recommended that further studies be conducted on the best times for upgrading roads to BST while taking traffic volume into consideration.
- Other future research directions recommended by the project technical advisory committee (TAC) include investigating the feasibility of using reclaimed asphalt pavement as an alternative to virgin aggregate in Otta seals and evaluating the use of Otta seal layers as a holding strategy for Iowa county roads.

REFERENCES

Abdelaty, A., D. Jeong, B. Dannen, and F. Todey. 2016. Enhancing life cycle cost analysis with a novel cost classification framework for pavement rehabilitation projects. *Construction Management and Economics*, Vol. 34, No. 10, pp. 724–736.

IEM. 2017. ASOS-AWOS-METAR Data Download. Iowa Environmental Mesonet (IEM), Iowa State University. https://mesonet.agron.iastate.edu/request/download.phtml.

Asphalt Institute. 1979. *A Basic Asphalt Emulsion Manual*. Manual Series No. 19 (MS-19). Lexington, KY.

Bid Express Secure Internet Bidding. 2018. https://www.bidx.com/site/static?page=services#basic.

Boddy, R. and G. Smith. 2009. *Statistical Methods in Practice: For Scientists and Technologists*. John Wiley & Sons, West Sussex, UK.

Bullard, D. J., R. E. Smith, and T. J. Freeman. 1992. *Development of a Procedure to Rate the Application of Pavement Maintenance Treatment*. SHRP-M/FR-92-102. Strategic Highway Research Program, Washington, DC.

Caterpillar Inc. (2015). *Caterpillar Performance Handbook*. Caterpillar, Inc., Peoria, IL.

Dayamba, F. O. 2013. Improved processes for selection and design of lightly surfaced roads. MS thesis, Iowa State University, Ames, IA.

Department of Public Works, County of Los Angeles. 2018. *Slurry Seals*. Los Angeles, CA. http://dpw.lacounty.gov/gmed/lacroads/treatmentslurryseal.aspx.

Engineering News Record. 2017. Construction Economics: Construction Cost Index and Building Cost Index. *Engineering News Record*. https://www.enr.com/economics.

Federal Reserve. 2017. Board of Governors of the Federal Reserve System. Federal Reserve System, Washington, DC. https://www.federalreserve.gov/.

FHWA. 2002. *Life Cycle Cost Analysis Primer*. Office of Asset Management, Federal Highway Administration, Washington, DC.

FHWA. 2003. *Economic Analysis Primer*. Office of Asset Management, Federal Highway Administration, Washington, DC. https://www.fhwa.dot.gov/asset/lcca/010621.pdf.

FHWA. 2005. *Roadway Surfacing Options Photo Album: Companion Document to Context Sensitive Roadway Surfacing Selection Guide*. FHWA-CFL/TD-05-004A. Central Federal Lands Highway Division, Lakewood, CO.

FHWA Pavement Division. 1998. *Life-Cycle Cost Analysis in Pavement Design*. FHWA-SA-98-079. Federal Highway Administration, Washington, DC. https://www.fhwa.dot.gov/infrastructure/asstmgmt/013017.pdf.

FHWA. 2007. *Asset Management Overview*. Office of Asset Management, Federal Highway Administration, Washington, DC. https://www.fhwa.dot.gov/asset/if08008/assetmgmt_overview.pdf.

FHWA. 2015. *FHWA FY 2016 Budget Estimates*. Federal Highway Administration, Washington, DC. https://www.transportation.gov/mission/budget/fhwa-fy-2016-budget-estimates.

Flanagan, R., A. Kendell, G. Norman, and G. D. Robinson. 1987. Life cycle costing and risk management. *Construction Management and Economics*, Vol. 5, No. 4, pp. S53–S71.

Fromelt, C. 2012. Success with alternatives to paving. Paper presented at 2012 NDLTAP Regional Local Roads Conference, October, Bismarck, ND. http://www.ndltap.org/events/conference/downloads/9d_2012_Success_Alternatives_Paving.pdf.

Geoffroy, D. N. 1996. *NCHRP Synthesis 20-05/Topic 25-10 [Final (Synthesis)]: Cost-Effective Preventive Pavement Maintenance*. National Cooperative Highway Research Program, Washington, DC.

Gransberg, D. D. 2007. Using a New Zealand Performance Specification to Evaluate U.S. Chip Seal Performance. *Journal of Transportation Engineering*, Vol. 133, No. 12, pp. 688–695.

Gransberg, D. D. 2008. *Evaluate TxDOT Chip Seal Binder Performance Using Pavement Management Information System and Field Measurement Data – San Antonio District*. University of Oklahoma Transportation Research Report, Norman, OK.

Gransberg, D. D. and J. Diekmann. 2004. Quantifying pavement life cycle cost inflation uncertainty. *2004 AACE International Transactions*, pp. R.08.01–R.08.11.

Gransberg, D. D. and D. M. B. James. 2005. *NCHRP Synthesis 342: Chip Seal Best Practices*. National Cooperative Highway Research Program, Washington, DC.

Gransberg, D. D. and E. J. Kelly. 2008. Quantifying Uncertainty of Construction Material Price Volatility Using Monte Carlo. *Cost Engineering*, Vol. 50, No. 6, pp. 14–18.

Gransberg, D. D., and E. Scheepbouwer. 2010. Infrastructure Asset Life Cycle Cost Analysis Issues. *2010 AACE International Transactions*, pp. CSC.03.01–CSC.03.11.

Hitch, L. S. and R. B. C. Russell. 1977. *Bituminous Bases and Surfacings for Low-cost Roads in the Tropics*. Transport and Road Research Laboratory, Wokingham, Berkshire, UK.

International Slurry Surfacing Association. 2010a. *Recommended Performance Guidelines for Emulsified Asphalt Slurry Seal Surfaces*. A105. International Slurry Surfacing Association, Annapolis, MD. http://thebarnhardtgroup.com/wp-content/uploads/2010/07/A105-Slurry-Seal-Guidline-Specificaitons.pdf.

International Slurry Surfacing Association. 2010b. *Recommended Performance Guidelines for Micro-Surfacing*. A143. International Slurry Surfacing Association, Annapolis, MD. http://thebarnhardtgroup.com/wp-content/uploads/2010/07/A143-Microsurfacing-Guideline-Specifications.pdf.

Jahren, C. T., D. Smith, J. Thorius, M. Rukashaza-Mukome, D. White, and G. Johnson. 2005. *Economics of Upgrading an Aggregate Road*. Minnesota Department of Transportation, St. Paul, MN.

Jahren, C. T., W. A. Nixon, and K. L. Bergeson. *Thin Maintenance Surfaces: Phase Two Report with Guidelines for Winter Maintenance on Thin Maintenance Surfaces*. Iowa State University Department of Civil and Construction Engineering, Ames, IA. http://www.intrans.iastate.edu/reports/tr435.pdf

Johnson, G. and J. Pantelis. 2011. *Otta Seal – Thin Bituminous Surfacing Option for Aggregate Road*s. MnROAD, Minnesota Department of Transportation, Maplewood, MN. http://dotapp7.dot.state.mn.us/research/pdf/2011MRRDOC017.pdf.

Johnson, E. 2014. Overview of thin bituminous treatments: field performance of types used in Minnesota. Paper presented at 18th Annual TERRA Pavement Conference, February 5, Minneapolis, MN.

Johnson, G. 2003. Minnesota's experience with thin bituminous treatments for low-volume roads. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1819, pp. 333–337.

Johnson, G. and J. Pantelis. 2008. Otta Seal Surfacing of Aggregate Roads. MnROAD, Office of Materials & Road Research, Maplewood, MN. http://www.dot.state.mn.us/materials/bituminousdocs/Pavement%20Maintenance/OttaSeal_4-pagerMRR_2008.pdf.

Ljungstrom, F. 1957. Recovering sub-surface bituminous deposits by creating a frozen barrier and heating in situ. http://www.freepatentsonline.com/2777679.html.

Mamlouk, M. S. and D. Matild. 2014. Verification of effectiveness of chip seal as a pavement preventive maintenance treatment using LTPP data. *International Journal of Pavement Engineering*, Vol. 15, No. 10, pp. 879–888.

McLeod, N. W., C. W. Chaffin, A. E. Holberg, C. F. Parker, V. Obrcian, J. M. Edwards, W. H. Campen, and W. J. Kari. 1969. A General Method of Design for Seal Coats and Surface Treatments. *Association of Asphalt Paving Technologists Proceedings*, Vol. 38, pp. 537–628.

MnDOT. 2017a. *Bid Letting*. Minnesota Department of Transportation, St. Paul, MN. http://www.dot.state.mn.us/bidlet/average-bid-price.html.

MnDOT. 2017b. *Major Highway Projects, Trunk Highway Fund Expenditures and Efficiencies Report*. Minnesota Department of Transportation, St. Paul, MN.

MnDOT. 2012. *MnPave User's Guide*. Minnesota Department of Transportation, St. Paul, MN. https://www.dot.state.mn.us/app/mnpave/docs/MnPAVE_Users_Guide.pdf

Mirza, S. 2006. Durability and sustainability of infrastructure—A state-of-the-art report. *Canadian Journal of Civil Engineering*, Vol. 33, No. 6, pp. 639–649.

Øverby, C. 1999. *A Guide to the Use of Otta Seals*. Publication No. 93, Norwegian Directorate of Public Roads, Road Technology Department, International Division, Oslo, Norway.

Øverby, C. and M. I. Pinard. 2006. A brief of the Otta seal. Paper presented at the SSATP/World Bank Workshop of Knowledge Sharing and Promotion of Appropriate Pavements and Surfacing Technologies for Low-volume Roads in Ghana, Burkina Faso, and Sierra Leone, September 27–29, Accra, Ghana.

Øverby, C. and M. I. Pinard. 2007. *The Otta Seal Surfacing: An Economic and Practical Alternative to Traditional Bituminous Surface Treatments*. SSATP - Africa Transport Policy Program, The World Bank, Washington, DC. https://www.ssatp.org/sites/ssatp/files/publications/HTML/LVSR/English/Added-2007/2007-Otta-Seal-Guide-by-ChOverby-MPinard.pdf.

Øverby, C. and M. I. Pinard. 2013. Otta seal surfacing: practical and economic alternative to traditional bituminous surface treatments. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2349, pp. 136–144.

Ozbay, K., D. Jawad, N. Parker, and S. Hussain. 2004. Life-Cycle Cost Analysis: State of the Practice Versus State of the Art. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1864, pp. 62–70.

Pavement Interactive. 2018a. *Bituminous Surface Treatments*. http://www.pavementinteractive.org/bituminous-surface-treatments/.

Pavement Interactive. 2018b. *Fog Seals*. http://www.pavementinteractive.org/fog-seals/.

Pearson, K. 1992. On the Criterion that a Given System of Deviations from the Probable in the Case of a Correlated System of Variables is Such that it Can be Reasonably Supposed to have Arisen from Random Sampling. In *Breakthroughs in Statistics*. Springer, New York, NY.

Peshkin, D. G., T. E. Hoerner, and K. A. Zimmerman. 2004. *NCHRP Report 523: Optimal Timing of Pavement Preventive Maintenance Treatment Applications*. National Cooperative Highway Research Program, Washington, DC.

Pierce, L. M. and N. Kebede. 2015. *Chip Seal Performance Measures — Best Practices*. Washington State Department of Transportation, Olympia, WA.

Pittenger, D., D. D. Gransberg, M. Zaman, and C. Riemer. 2012. Stochastic Life-Cycle Cost Analysis for Pavement Preservation Treatments. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2292, pp. 45–51.

Reigle, J. and J. Zaniewski. 2002. Risk-Based Life-Cycle Cost Analysis for Project-Level Pavement Management. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1816, pp. 34–42.

Salem, O., S. AbouRizk, and S. Ariaratnam. 2003. Risk-based Life-cycle Costing of Infrastructure Rehabilitation and Construction Alternatives. *Journal of Infrastructure Systems*, Vol. 9, No. 1, pp. 6–15.

Senadheera, S. and M. Vignarajah. 2007. *Design and Construction Guide for Surface Treatments Over Base Courses*. Center for Multidisciplinary Research in Transportation, Texas Tech University, Lubbock, TX.

Skorseth, K. 2013. South Dakota experience in constructing alternatives to paved surfaces on local roads and streets. Paper presented at 2013 APWA Congress, June 27, Chicago, IL.

Tehrani, F. M. 2016. Engineer's estimate reliability and statistical characteristics of bids. *Cogent Engineering*, Vol. 3, No. 1, pp. 1–12.

Tighe, S. 2001. Guidelines for Probabilistic Pavement Life Cycle Cost Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1769, pp. 28–38.

TRL. 1993. *A Guide to the Structural Design of Bitumen- Surfaced Roads in Tropical and Sub-Tropical Countries*. Transport Research Laboratory, Overseas Centre, Crowthorne, Berkshire, UK.

U.S. BLS. 2017. *Commodity Data Database, Producer Price Index*. U.S. Bureau of Labor Statistics (BLS), Washington, DC. https://www.bls.gov/ppi/data.htm.

U.S. DOT. 2014. *2013 Status of the Nation's Highways, Bridges and Transit: Conditions and Performance*. Federal Highway Administration and Federal Transit Administration, Washington, DC. https://www.fhwa.dot.gov/policy/2013cpr/pdfs/cp2013.pdf.

Visser, A. T. 2013. Introducing Otta Seals for Low-Volume Roads in Tonga. Seminar on Otta Seals at World Bank. Washington D.C.

Visser, A. T. and T. F. P. Henning. 2011. *Guidelines for Performance Monitoring Otta Seal Resurfacings in the Pacific Island Countries.* Contractor draft report for World Bank, Meyerspark, South Africa.

Walls, J. and M. R. Smith. 1998. *Life-Cycle Cost Analysis in Pavement Design —Interim Technical Bulletin.* FHWA-SA-98-079. Federal Highway Administration, Washington, DC.

Weingroff, R. F. 2013. *Origins of the Interstate Maintenance Program*. Federal Highway Administration, Washington, DC. https://www.fhwa.dot.gov/infrastructure/intmaint.cfm.

Weiss, L. 2010. Otta seal in South Dakota: Between gravel and asphalt. *Government Engineering*, November-December, pp. 20–21.

Wilkonson, S. J., A. T. Visser, T. F. P. Henning, C. R. Bennett, and A. Faiz. 2013. *Introducing Otta Seals for low volume roads in Tonga*. Paper presented at the Transportation Research Board 92nd Annual Meeting, January 13-17, Washington, DC.

Wood, T. J., D. W. Janisch, and F. S. Gaillard. 2006. *Minnesota Seal Coat Handbook 2006*. Minnesota Local Road Research Board, Minnesota Department of Transportation, St. Paul, MN.

APPENDIX A. IMAGE LOG OF OTTA SEAL IN CHEROKEE COUNTY, IOWA

Figure 88. Condition of the road surface before implementing Otta seal in Cherokee, Iowa

Figure 89. Longitudinal and transverse cracking present before implementing Otta seal in Cherokee, Iowa

Figure 90. Severe alligator cracking on the HMA surface

Figure 91. Existing transverse cracking

Figure 92. Existing longitudinal cracking

Figure 93. Intersection of CR L-40 with 500th St in Cherokee, Iowa

Figure 94. Existing cracking at intersection area

Figure 95. During the process of applying slurry seal

Figure 96. Applying slurry seal

Figure 97. Slurry seal applied on the HMA cracking area

Figure 98. Slurry sealed area

Figure 99. Slurry seal in curing

Figure 100. View of slurry sealed sections

Figure 101. Slurry sealed cracking area

Figure 102. Binder application during the first layer construction

Figure 103. Aggregate application during the first layer construction

Figure 104. Compaction work during the first layer construction

Figure 105. The complete processes of Otta seal construction

Figure 106. Otta seal first layer construction near 530th Street

Figure 107. Otta seal first layer construction on CR L-40 near 530th Street

Figure 108. Otta seal first layer construction on CR L-40

Figure 109. Otta seal first layer construction

Figure 110. Binder, aggregate, and other construction equipment

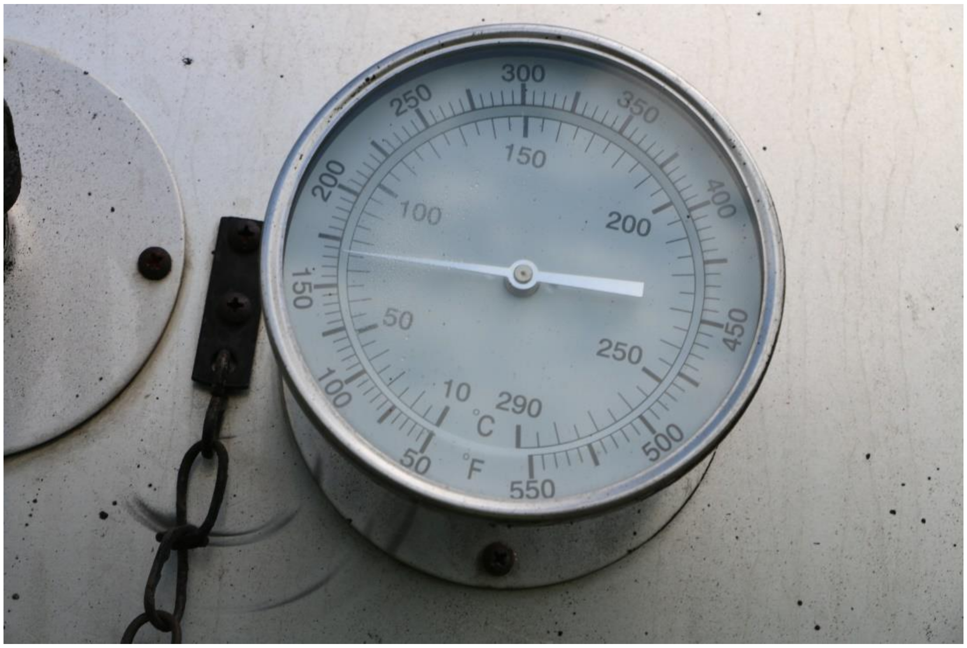


Figure 111. HFMS-2 application temperature

Figure 112. Binder and aggregate applications

Figure 113. Compaction after applying binder and aggregates

Figure 114. Compaction efforts during the first layer construction

Figure 115. Appearance of Otta seal first layer immediately after construction

Figure 116. Appearance of Otta seal first layer comparing two lanes with different compaction efforts

Figure 117. Appearance of Otta seal first layer after comparing test sections

Figure 118. Binder, aggregate, and construction equipment for second layer construction

Figure 119. Binder and aggregate application during second layer construction

Figure 120. Compaction immediately after applying binder and aggregates

Figure 121. Quality control test to insure an accurate application rate of aggregate

Figure 122. Appearance of Otta seal second layer immediately after construction

Figure 123. Binder spraying during second layer construction

Figure 124. Aggregate application during second layer construction

Figure 125. Appearance of Otta seal surface two days post construction

Figure 126. Long view of the second layer Otta seal two days post construction

Figure 127. Appearance at a slope area of Otta seal two days post construction

Figure 128. Appearance of Otta seal two days post construction showing color changes

Figure 129. Appearance of Otta seal two days post construction comparing two test sections

Figure 130. Appearance of Otta seal two days post construction showing dark areas near lane center

Figure 131. Appearance of Otta seal two days post construction – long view

Figure 132. Appearance of Otta seal two days post construction with wheel paths

Figure 133. Appearance of Otta seal two weeks post construction showing color change

Figure 134. Appearance of Otta seal two weeks post construction – long view

Figure 135. Appearance of Otta seal two weeks post construction showing one test section

Figure 136. Appearance of Otta seal two weeks post construction showing surface color differences

Figure 137. Appearance of Otta seal two weeks post construction, showing surface changed to darker color

Figure 138. Appearance of Otta seal two weeks post construction, with lane center a lighter color than other areas

Figure 139. Appearance of Otta seal surface two weeks post construction of test section using limestone

Figure 140. Appearance of Otta seal surface two weeks post construction, showing binder squeezed up to surface

Figure 141. Appearance of Otta seal surface two months post construction

Figure 142. Appearance of Otta seal surface two months post construction – long view with pavement markings

Figure 143. Appearance of Otta seal surface two months post construction, showing that surface continued to change to darker color

Figure 144. Appearance of Otta seal surface two months post construction, showing dark surface

Figure 145. Appearance of Otta seal surface two months post construction, with one test section showing relatively lighter color

Figure 146. Appearance of Otta seal surface six months post construction, showing deteriorated pavement marking

Figure 147. Appearance of Otta seal surface six months post construction

Figure 148. Appearance of Otta seal surface six months post construction – long view

Figure 149. Appearance of Otta seal surface six months post construction, shown with scale

Figure 150. Appearance of Otta seal surface on a test section six months post construction, shown with scale

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