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Design, Construction, and Preliminary Investigations of Otta Seal in Iowa

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Abstract
Faced with limited financial resources, pavement engineers constantly seek more durable and economical technologies for road preservations and rehabilitations. Consequently, there have been many efforts to study resurfacing strategies, including various types of sealing for local roads. Among different sealing methodologies, Otta seal is a technique that has not yet been sufficiently studied in the U.S.A. For this investigation, the first Otta seal site in the state of Iowa was constructed using a double-layer Otta seal design over 6.4 km of cracked asphalt pavement. Otta seal design and construction details are documented and discussed, and test sections using various aggregates are compared for performance. The key lesson learned was that proper aggregate selection within gradation limits and aggregate spread rates were critical factors for Otta seal performance. Otta seal capability for holding loose aggregate particles and for dust control were examined, and there were indications that excessive proportion of fine aggregate particles could lead to diminished performance associated with fugitive dust emissions and unbound aggregate particles. Although the Otta seal provided a smooth surface satisfying road user and agency requirements, it did not significantly add structural capacity to the existing asphalt pavement. The findings from this study will benefit road officials and other decision makers who need to consider alternatives for resurfacing distressed low-volume asphalt roads.

Low-volume roads represent a large proportion of the route mileage of the transportation infrastructure system, and the cost to secondary road departments of maintaining such roads can be quite important. Over time, Otta seal has exhibited reduced maintenance costs by providing a typical service life of 8 to 12 years for a single-layer Otta seal, compared with 4 to 6 years for single-layer chip seal (1–3).

Norway-based Otta seal (graded aggregate) technology, originally developed in the 1960s and used in Scandinavian countries, Africa, and other continents, is an economical and practical alternative to traditional bituminous surface treatments (BSTs). It provides flexible, durable, and impervious surfacing that is more tolerant of higher anticipated pavement deflections on low-volume roads that are sometimes constructed with lower-quality materials (4). Compared with traditional BSTs requiring high-quality materials and specialized expertise, Otta seal can often be constructed using more economical local aggregates and readily available equipment (asphalt distributor, aggregate spreader, pneumatic-tired roller, and mechanical broom) typically used for asphalt maintenance (4). Otta seal, formed by a thin bituminous surface treatment (BST) of graded aggregates, ranging from natural gravel to crushed stone, with a relatively low-viscosity binder, relies on a combination of mechanical particle interlock and the binding effect of asphalt binder to provide a resilient, waterproof membrane over the road surface.

The state of South Dakota completed its first Otta seal project in Day County in 2008 to provide a low-cost surface using in-house resources and equipment in place of a standard hot-mix asphalt (HMA) pavement surface (5). Various agencies (city, county, and state department of transportation) in Minnesota have also applied Otta seal for traffic volumes ranging from 100 up to 2,000 vehicles average daily traffic (ADT) since early 2000 (6, 7). Most road sections surfaced with Otta seal in Minnesota have performed well except when they encountered unexpected situations such as unanticipated high traffic volumes or flood damage during their service lives (7). Otta seal construction was also found reasonably affordable compared with HMA or Portland cement concrete (PCC) pavement systems for use on low-volume roads; Otta seal has been considered a cost-effective and durable approach to dust control for gravel roads. In particular for developing countries, the available evidence suggests that Otta seal, surface dressings, and Cape seal are the most cost-effective and durable forms of dust control in relation to life-cycle costs (8–10).

The Norwegian Public Roads Administration (NPRA) Guideline 93 (4) was compiled using empirical data and experience from many trials and full-scale projects worldwide. However, in the U.S.A., few states have used the Otta seal, and hence, it is felt that a more comprehensive research along with full documentation is necessary to assist in the implementation of Otta seals in Iowa and many other states in the U.S.A.

Keywords
Otta seal, Low-volume road, Design, Construction, Performance evaluation

Disciplines
Construction Engineering and Management | Polymer and Organic Materials | Transportation Engineering

Comments
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ABSTRACT

Facing with limited financial resources, pavement engineers constantly seek more durable and economical technologies for road preservations and rehabilitations, so there have been many efforts to study resurfacing strategies, including various types of sealing for local roads. Among different sealing methodologies, Otta seal is a technique that has not yet been sufficiently studied in the US. For this investigation, the first Otta seal site in the state of Iowa was constructed using a double layer Otta seal design over a 6.4 km of cracked asphalt pavement. Otta seal design and construction details are documented and discussed, and test sections using various aggregates were compared for performance. The key lesson learned was that proper aggregate selection within gradation limits and aggregate spread rates were critical factors for Otta seal performance. Otta seal capability for holding loose aggregate particles and for dust control were examined, and there were indications that excessive proportions fine aggregate particles could lead to diminished performance associated with fugitive dust emissions and unbound aggregate particles. While the Otta seal provided a smooth surface satisfying road user and agency requirements, it did not significantly add structural capacity to the existing asphalt pavement. The findings from this study will benefit road officials and other decision makers who need to consider alternative for resurfacing distressed low volume asphalt roads. (218 words)

Keywords: Otta seal, Low-volume road, Design, Construction, Performance evaluation

INTRODUCTION

Low-volume roads represent a large proportion of the route mileage of the transportation infrastructure system, and the cost to secondary road departments of maintaining such roads can be quite important. Over time, Otta seal has exhibited reduced maintenance costs by providing a typical service life of 8 to 12 years for a single layer Otta seal, compared to 4 to 6 years for single layer chip seal (*1–3*).

Norway-based Otta seal (graded aggregate) technology, originally developed in the 1960s, used in Scandinavian countries, Africa, and other continents, is an economical and practical alternative to traditional bituminous surface treatments (BSTs). It provides flexible, durable, and impervious surfacing that is more tolerant of higher anticipated pavement deflections on low-volume roads that are sometimes constructed with lower-quality materials (*4*). Compared to traditional BSTs requiring high-quality materials and specialized expertise, Otta seal can often be constructed using more economical local aggregates and readily available equipment (asphalt distributor, aggregate spreader, pneumatic-tired roller, and mechanical broom) typically used for asphalt maintenance (*4*). Otta seal, formed by a thin BST of graded aggregates, ranging from natural gravel to crushed stone, with a relatively low-viscosity binder, relies on a combination of mechanical particle interlock and the binding effect of asphalt binder to provide a resilient, waterproof membrane over the road surface.

The state of South Dakota (SD) completed its first Otta seal project in Day County, SD, in 2008 to provide a low-cost surface using in-house resources and equipment in place of a standard hot mix asphalt (HMA) pavement surface (*5*). Various agencies (city, county, and state department of transportation) in Minnesota (MN) have also applied Otta seal for traffic volumes ranging from 100 up to 2,000-vehicles average daily traffic (ADT) since early 2000 (*6*, *7*). Most Otta seal surfaced road sections constructed in MN have performed well except when they encountered unexpected situations such as unanticipated high traffic volumes or flood damage during their service lives (*7*). Otta seal construction was also found reasonably affordable compared to an HMA or Portland cement concrete (PCC) pavement systems for use on low-volume roads; has been considered a cost-effective and durable approach to dust control for gravel roads. In particular for developing countries, the available evidence suggests that Otta seal along with surface dressings and Cape seal are the most cost-effective and durable form of dust control in terms life-cycle costs (*8–10*).

The Norwegian Public Roads Administration (NPRA) Guideline 93 (*4*) was compiled using empirical data and experience from many trials and full scale projects worldwide. However in the US, few states have used the Otta seal, and hence, it is felt that a more comprehensive research along with full documentation is necessary to assist in the implementation of Otta seals in Iowa and many other states in the US.

OBJECTIVE AND SCOPE

To evaluate the feasibility of Otta seal as an alternative surface treatment for local low-volume roads and to gauge the performance of Otta seal, the first Otta seal construction project in Iowa was conducted using a double layer Otta seal over a 6.4 km (4 mi) long section, consisting of a heavily distressed existing asphalt pavement with cracks. The average overall thickness of Otta seal depends on the average least dimension of the aggregate and the application type of Otta seal, e.g., double or single layer. In this project, double Otta seal layers were applied and the average in-place thickness for each layer was 1.90 cm (0.75 inch).

This study focused on the general background of this resealing project, Otta seal design details, construction procedures, and the investigative tests conducted before, during, and after construction. Multiple in situ observations and tests, including loose aggregate tests, dustometer tests, roughness tests, light weight deflectometer (LWD) tests, and visual appearance inspections, were conducted over different construction periods to evaluate the performance of this Otta seal application.

SITE CONDITION FOR OTTA SEAL PROJECT

County Road (CR) L-40, was the selected candidate site for this Otta seal demonstration project, is in Cherokee County, Iowa. Its ADT was estimated by the county engineer to be about 190 vehicles, 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 reflects use of crack seal only where cracks existed. TABLE 1 summarizes general information of the road.

TABLE 1 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 (approximately 4 miles)
Road width	6.7 m (approximately 22ft)
Surface type of existing road	HMA with longitudinal and horizontal cracks
Maintenance history	Crack seal only

Before Otta seal construction, the visual inspection conducted on the existing pavement, various types of pavement surface distress were observed, including longitudinal and transverse cracking, rutting, fatigue cracking, etc. (FIGURE 1a). Otta seal surfacing treatment was selected for this road to seal it, improve driving comfort and safety, and extend the road’s service life. Altitude and slope grade of this road are presented in FIGURE 2.

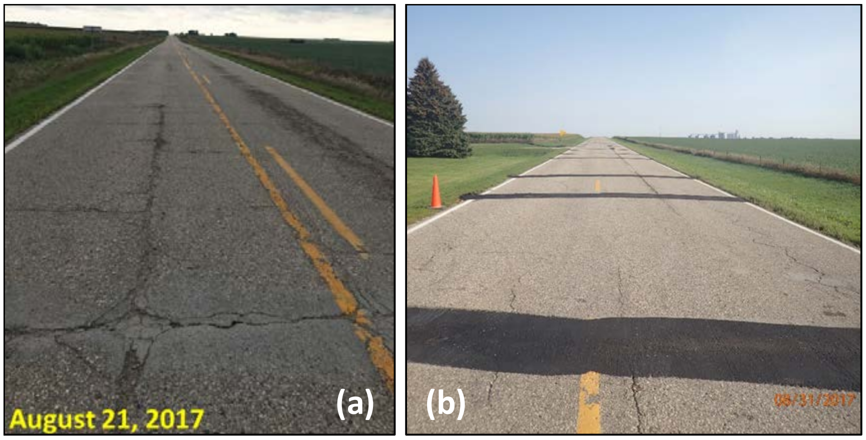

FIGURE 1 Pictures of the site before construction: (a) various cracks on existing pavement and (b) slurry seal applied before Otta seal.

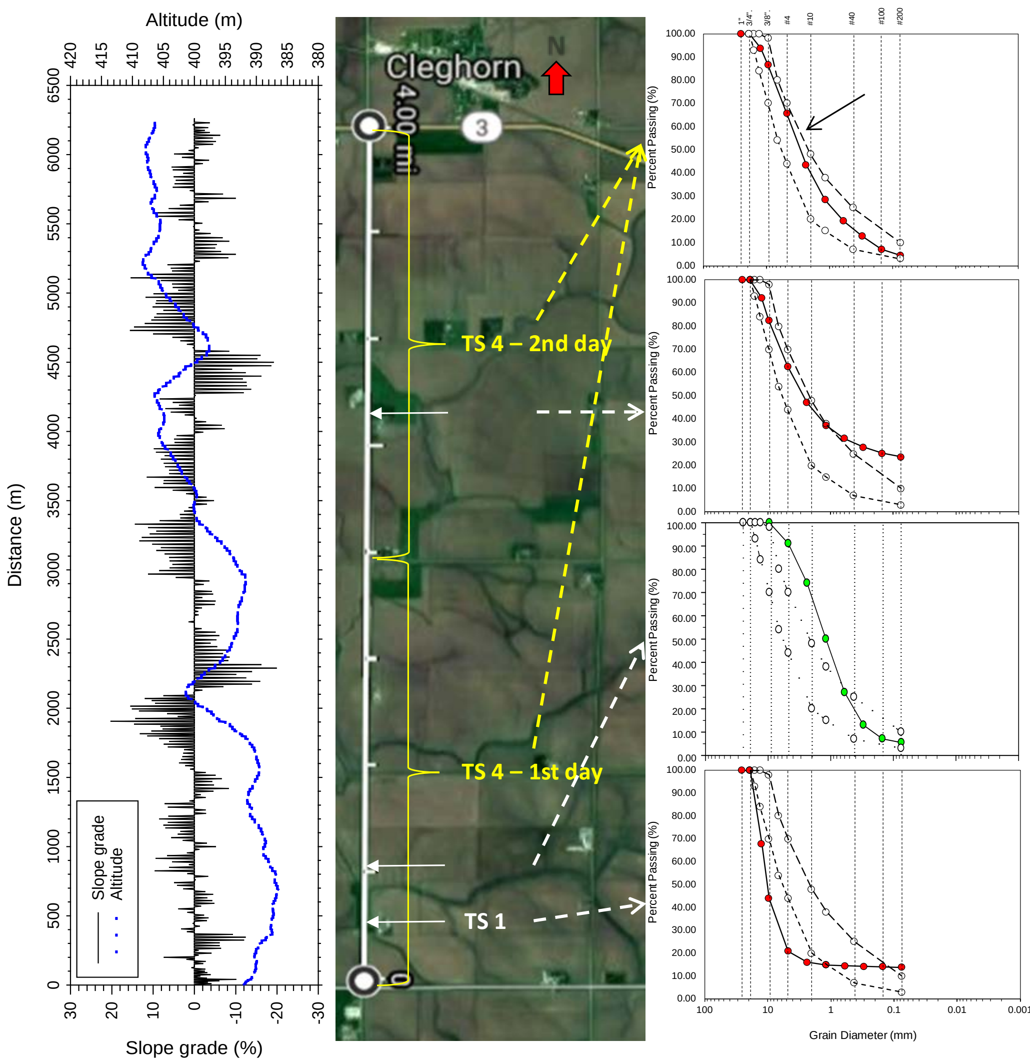

FIGURE 2 Site information in terms of altitude, slope grade (longitudinal road slope), and Otta seal test sections.

OTTA SEAL DESIGN

Aggregate

Since Otta seal offers significant flexibility with respect to the use of local materials, as well as simplicity of construction, empirically-based guidelines (*4, 11*) for design of Otta seal treatments have been developed. Under these guidelines (*4, 12*), using 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 greater than 100 and less than 1,000 vehicles per day, and dense for traffic levels greater than 1,000 vehicles per day. Other aggregate property requirements such as aggregate strength for Otta seals are not as strict as those for a traditional BST such as chip seal. Relatively lower-strength aggregate can be used for Otta seal if gradation falls within a specified gradation band that allows the maximum amount of fine material (<0.075 mm) to be less than 10 percent. The main difference between Otta seal and chip seal is the selected gradation. Unlike chip seal, Otta seal does not require a high quality gradation (i.e., a more single size gradation) making this method of bituminous surface treatment more economically suitable, because the local aggregates can be obtained from the nearest quarry and often less material processing is required.

Local aggregates, often of lower quality, have often been used in Otta sealed roads. To meet the required aggregate gradation, graded aggregate for Otta seal can be produced from crushed or uncrushed materials or a mixture of both (*3*). Øverby (*4*) provided typical examples of aggregate types that have been successfully used in the construction of Otta seal. Accounting for the traffic condition of the selected road, the aggregate utilized for this project was required to be within the maximum and minimum limits of the dense gradation specified by the Øverby (*4*) design, and the engineers identified multiple local sources of available aggregates for use in the project. The recommended aggregate application rate was 27 kg/m^2 for both layers, in accordance with Øverby (*4*) and also the Class 5 aggregate gradation specified in MnDOT (*13*).

The dense aggregate gradation was carefully selected rather than open or medium gradations for several reasons. The main reason was the availability of stockpiles within the city limit, which made it more economical for Cherokee County in Iowa to use Otta seal for the first time. Another reason for the selection of such aggregate gradation was due to the fact that the dense gradation, after curing, will create matrixes of aggregate and binder to withstand the anticipated traffic count and heavier agricultural equipment. Lastly, the dense gradation matrixes reduce the porosity of Otta seal surface, which then reduces water infiltration into the pavement layers.

In FIGURE 2, the gradations of the four selected aggregates for the four test sections (TSs) are compared with the criteria (*4*). The gradation curve of TS 4 aggregate properly falls within the Øverby (*4*) dense gradation, and the percentage of particles passing through a #200 sieve meets the minimum requirement of Øverby (*4*), while aggregates for the other three TSs in various extents do not fall within the gradation requirements. TABLE 2 lists the Otta seal aggregate spread rates among several previous applications in comparison with those recommended in this study.

Asphalt Binder

Asphalt emulsion and cutback asphalt are the two binder types commonly used for Otta seal (*4*). The type of binder recommended by Øverby (*4*) were MC 800, MC 3000 are classified as a cutback asphalt and Pen. Bitumen 150/200. These types of binders, commonly used both in Scandinavian and African Otta seal projects, are a mixture of asphalt and petroleum solvent and typically proportioned with 8-15 % solvent.

TABLE 2 Comparison of Otta Seal Aggregate Application Rates between NPRA Guideline 93 and US Practices and the First Otta Seal Project in Iowa

Case	Aggregate Application Rates
NPRA Guideline 93 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)
NPRA Guideline 93 Design Guide: Medium Traffic (ADT = 100 to 1,000)	33 to 40 kg/m^2, 0.013 to 0.016 m^3/m^2 (60 to 74 lb/yd^2)
NPRA Guideline 93 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)
First IA Project (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)

The selections of asphalt binder types and the spray rate are dependent on the aggregate gradation selected for the expected traffic level. A soft asphalt binder should be used to coat the finer aggregate (dense grading) and move up through the aggregate matrix. Commonly suggested types of asphalt binders are MC 800 or MC 3000 for cutbacks produced from 80/100 or 150/200 penetration grade asphalt. Experience in Minnesota and South Dakota (*5*, *14*) indicate that high-float, medium-set, emulsion (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, ranging from 0.9 to 2.0 L/m^2 (0.20 to 0.44 gal/yd^2) depending on traffic level and aggregate gradation. For roads with relatively steep gradients, reducing the binder application rate is recommended when using open aggregate gradation to mitigate the tendency for the binder to flow through the voids in the aggregate before the sets up (*4*). The Øverby (*4*) experience indicates that cutback bitumen requires 8 to 12 weeks after application to allow solvents to evaporate so that the binder is fully set or cured.

It is also important to consider and evaluate the site prior to construction. In this project, the existing asphalt surface condition was drastically pocked (porous and oxidized). Therefore, the site was slurry sealed where wider cracks were present so that the Otta seal could be applied. As result of the pre-construction measures taken, the emulsion application rate was increased to the highest end range of 2.26 L/m2 (0.5 gal/yd2) to compensate any binder infiltration to narrower cracks that were not pre-sealed. The aggregate must be in a dry damp condition, because higher moisture within the dense aggregate gradation may cause segregation, blockage of the aggregate in the chip spreader gate, and delay the evaporation of water from the emulsion. Where the aggregate has a water absorption of more than 2%, the bitumen spray rate shall be increased by 0.3 l/m2 (Øverby, 1999).The weather must be in good condition during construction to avoid wet and windy conditions, which may negatively influence the binder throughout construction and curing periods.

Because of greenhouse-gas release that accompanies the evaporation of solvent, there are also environmental concerns about using cutbacks in the US; thus emulsions are preferred for use asphalt binders. HFMS-2s asphalt emulsion was selected for use in this project, with reference successful use of this binder in both Minnesota and South Dakota Otta seal projects. The recommended cutback asphalt binder spray rate in Øverby (*4*) should be modified on the basis of asphalt content in the emulsion. The amount of asphalt applied to the road should be equal to the equivalent amount recommended in Øverby (*4*). The proportion of water required to emulsify asphalt is higher than the proportion of solvent required to liquefy cutback. Therefore application rates must be increased accordingly with emulsions are used in place of cutbacks.

The acronym HFMS designates high float and medium set emulsion. HFMS-2s bitumen penetration grade of 200 is a mixture of asphalt, water, and emulsifying agent, typically containing up to 35 percent water, and is an anionic emulsion that requires special care to maintain optimal quality both when in storage and during application. Based on the Minnesota experience, when it is applied for Otta seal, it requires 8 to 10 days (depending on temperature and weather conditions) for setting (allowing water to evaporate), meaning that the second layer of Otta seal construction (for double Otta seal projects) could take place 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 (*5*). The emulsion was heated to 76°C (168.8°F) prior to spraying.

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 also recommended for this Iowa project. TABLE 3 lists various Otta seal asphalt binder spray rates used in practice compared with that recommended by this study.

TABLE 3 Comparison of Otta Seal Binder Application Rates between NPRA Guideline 93 and US Practices and the First Otta Seal Project in Iowa

Case	Net Binder Hot Application Rates
NPRA Guideline 93: Low Traffic (ADT < 100)	1.5 to 1.6 L/m^2 (0.33 to 0.38 gal/yd^2)
NPRA Guideline 93: (ADT = 100 to 1,000)	1.6 to 1.8 L/m^2 (0.35 to 0.40 gal/yd^2)
NPRA Guideline 93: 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)
First IA Project (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)

OTTA SEAL CONSTRUCTION

Description of Construction Process

Approximately one week before first layer construction, the deteriorated asphalt pavement surface was slurry sealed at both transverse and longitudinal crack locations (FIGURE 1b) to mitigate the potential for reflective cracking from existing asphalt pavements to be transferred to the Otta seal surface. The cracking is considered to be none-active and only associated with the HMA. The objective of applying the slurry seal at existing longitudinal and transverse cracks is to fill the cracks and to provide an overall smoother ride quality after applying the double Otta seal. Also, the application of slurry seal on the cracks will prevent the emulsion from flowing into cracks.

The first layer of Otta seal construction was initiated on September 5, 2017, during which the road was closed to traffic in both directions. In general, the construction can be classified as three sequential steps (FIGURE 3(a), (b), and (c)): binder spraying, aggregate spreading, and rolling compaction.

FIGURE 3 Construction of Otta seal: (a) binder spraying, (b) aggregate spreading, (c) rolling compaction, and (d) the complete construction process.

The asphalt distributor began by spraying bituminous HFMS-2s emulsion 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 of 27.12 kg/m^2

(50 lbs/yd^2). The application rate of 35.26 kg/m^2 (65 lbs/yd^2) was corrected after (1.80 mi) during the first layer application. It is also worth noting that, Otta seal compaction method is different from that of chip seal construction in that: 1) for Otta seal, the aggregate layer needs more compaction relatively more compaction compared to chip seals (e.g., 30 round trips), and 2) the vehicles that are not involved in the construction project have a key role in the compaction process, i.e., the more the number of vehicles passing, the better the degree of compaction. The actual binder spray rate was lower than the recommended rate of 2.49 L/m^2 (0.55 gal/yd^2). Immediately after placing the binder and the aggregate, a 7.26-metric ton (8-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 3(d). The contractor was able to complete 2.89 km (1.80 mi) on the first day and continued to finish the remaining 3.22 km (2.0 mi) on the second day. The appropriate rollers of 12 tons minimum are required for Otta seal, but in this project 8 tons rollers were utilized based on the contractor availability. During the construction process, aggregate spreading was noticed as a critical aspect influencing Otta seal construction and its resulting performance. 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.

Although the aggregate spreader was equipped with an automatic spread rate controller, there were challenges controlling the spread rate including some human errors. Moist aggregate had a tendency to clog the spreader head especially when the fines content was high and the plasticity of the fines was high. To ensure better compaction, a 12.70-metric ton (14-US ton) pneumatic roller was used after completing the first layer.

Two weeks after construction of the first layer (September 21 through 22, 2017), the construction crew continued the work of placing the second layer of Otta seal. The same techniques and procedures were followed. Actual application rates applied in the field during construction varied somewhat due to issues with the aggregate spreader and the asphalt distributor. Regular traffic was allowed to return as soon as the compaction process was completed.

EARLY STAGE OTTA SEAL PERFORMANCE EVALUATION

In situ tests, included roughness (FIGURE 4a), loose aggregate (FIGURE 4b), and dustometer tests (FIGURE 4c) were conducted. Visual appearance inspections, were conducted both before and after Otta seal construction to evaluate the performance of the Otta seal placed on CR L-40.

FIGURE 4 (a) Measuring IRI using Roadroid software installed in a mobile phone, (b) loose aggregate test equipment, (c) installing dustometer test equipment, (d) filter papers from dustometer tests.

Visual Inspections at Different Construction and Service Periods

The changes in Otta seal color can be an indicator of the state of the curing condition, because a surface that becomes dark indicates that the binder was squeezed up to coat and hold the aggregates. FIGURE 5 shows the road surface colors at different times, and it can clearly be seen that the surface had a relatively light color immediately after construction.

In general, the Otta seal surface became darker as time elapsed. Two weeks after second layer construction, the surface turned from its regular dusty color (light brown) to grey, and continued to change to nearly black after three months of service. In that regard, the appearance of the Otta seal surface became quite similar to that of regular HMA pavement. Pavement marking was applied on the surface three months after construction (FIGURE 5c). FIGURE 5d shows a close view of TS 3 six months after implementation, at which point crushed limestone was applied (referring to FIGURE 2 for gradation). The surface color here was slightly lighter than other sections, due to the natural color of the aggregates.

FIGURE 5 Otta seal surface appearance: (a) second day, (b) two weeks, (c) three months, and (d) six months after construction.

International Roughness Index

The international roughness index (IRI) is a parameter used to assess the road roughness IRI was measured using a mobile device-based app, the "Roadroid" (*15*), and measurements took place on the existing HMA pavement surface before construction and at different intervals after Otta seal construction. FIGURE 6 shows the comparisons among the average IRI values of existing deteriorated HMA pavements before slurry seal application, values measured immediately after first and second layer construction, and six months after construction.

The results indicate that IRI was approximately 4 m/km before Otta seal implementation on both lanes , while some values noticeably increased immediately after Otta seal, reflecting poorer ride quality and drive comfort. However, similar to surface appearance changes during service time, these values dropped to 2 to 3 m/km after six months, reflecting lower values than those before applying Otta seal. This finding indicated that Otta seal surface is capable of providing a lower IRI index than before applying the Otta seal.

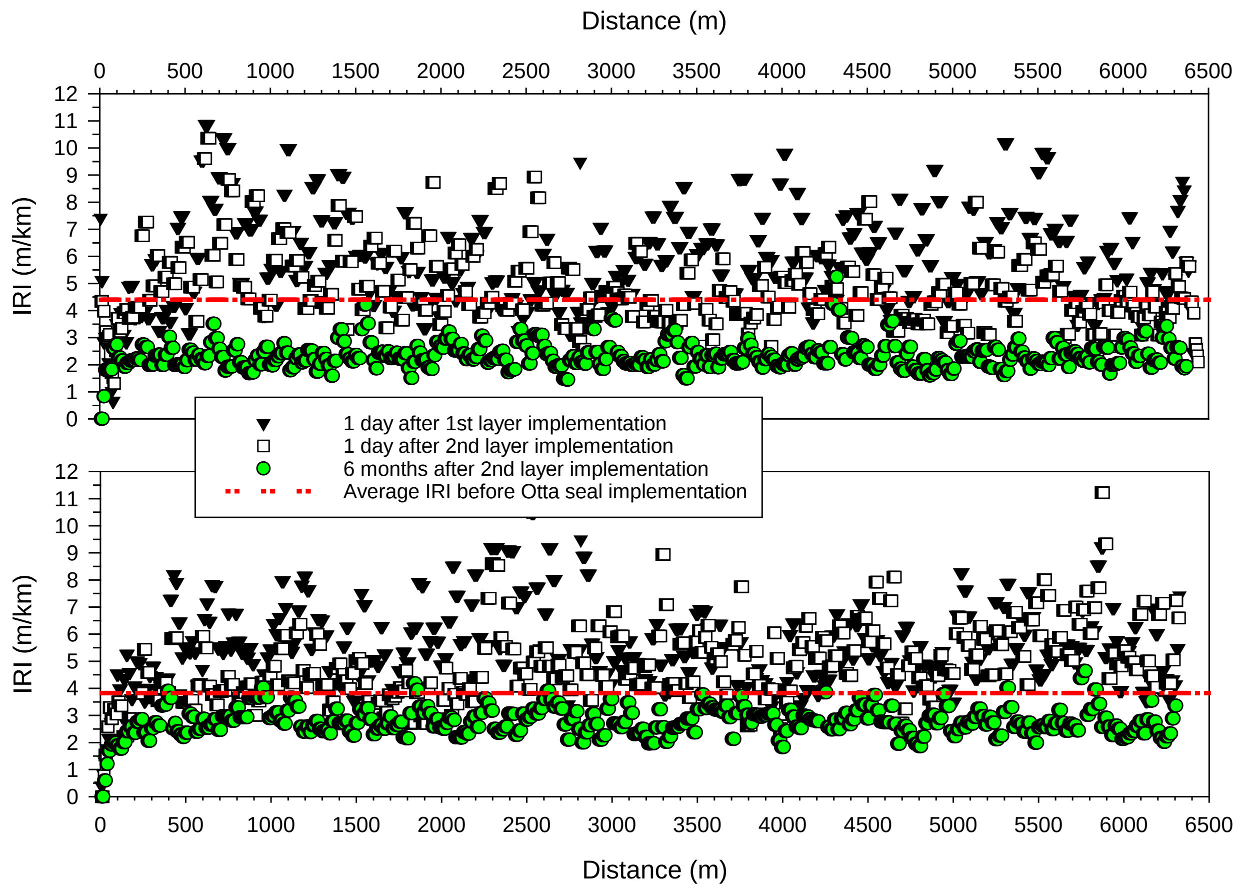

FIGURE 6 IRI measurements of (a) north bound and (b) south bound before and after Otta seal implementation.

Dustometer and Loose Aggregate Tests

A dustometer was used to evaluate the effectiveness of Otta seal in controlling dust after construction completion (FIGURE 4c). A pickup truck installed with a dustometer was driven at a speed of 40 km/h (about 25 MPH) over the desired length, after which dust-vacuumed filter papers were weighed to determine the accumulated dust content per segment (FIGURE 4d). FIGURE 7 shows the amounts of dust in unit length for each test section. It was reported that the typical mean value of dust measured on gravel roads by dustometer is 1.70 g/km (2.74 g/mi) (*21*). The results in this research indicated that Otta seal is capable of controlling dust at a level lower than 1.6 g/km. TS 4 achieved the best capability to control dust, especially TS 4 constructed at the second day, possibly due to use of a heavier compactor during the second day. However, TS 1 and TS 2 presented relatively poor capacity for dust control, possibly due to use of improper aggregates in these two sections.

To perform a loose aggregate test (FIGURE 4b), two wooden sticks were placed to establish a single 4-inch wide lane, and a vacuum device used to collect loose aggregate between the two wooden sticks into a bucket. The results indicated that the test section using crushed limestone (TS 3) provided the lowest amount of loose materials. In contrast, TS 2 presented 4 to 5 times more loose aggregate per unit area compared to the other sections, strongly indicating that the application of filter sand at TS 2 was likely not appropriate because apparently the asphalt binder was not able bind the sand particles in this section.

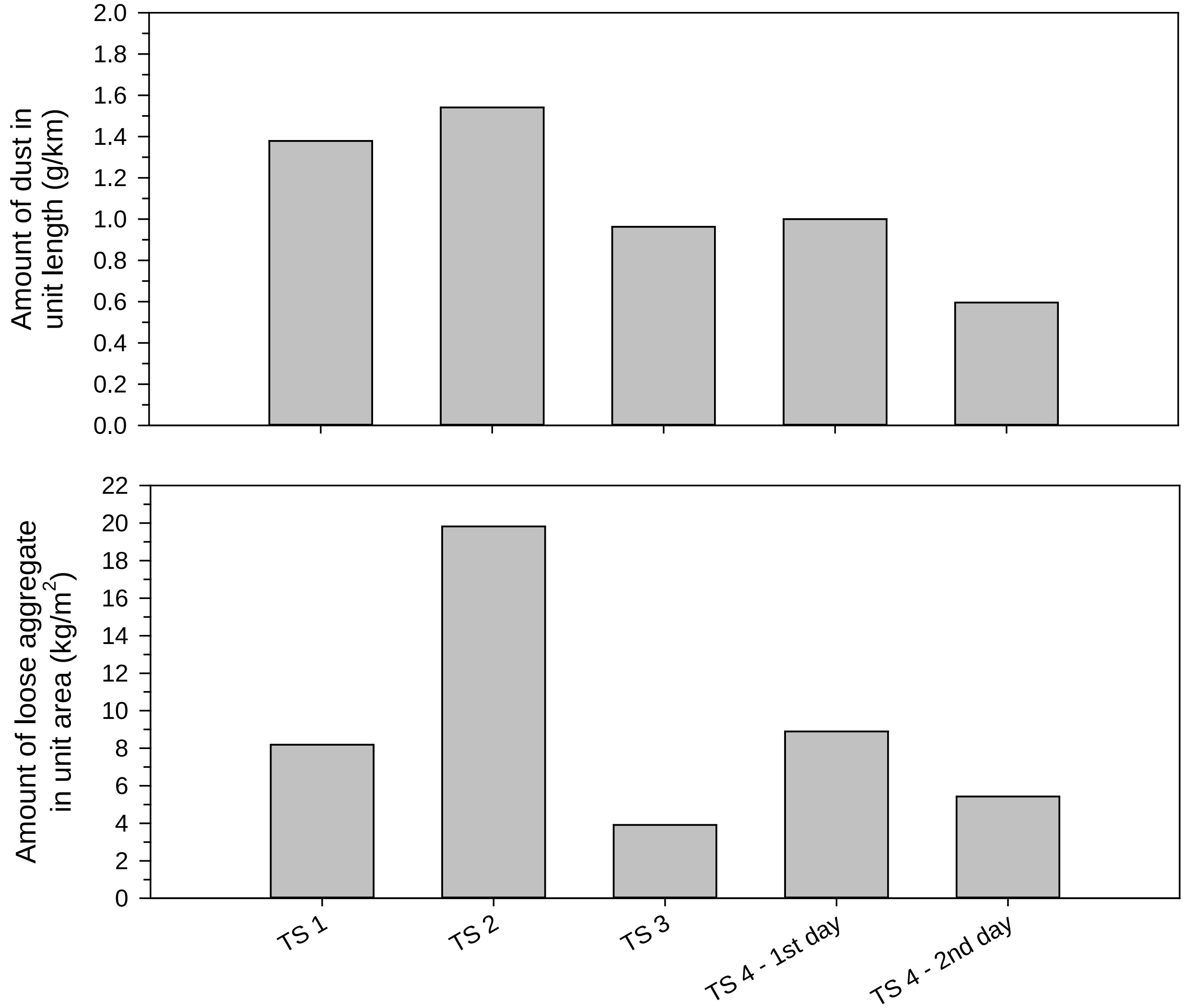

FIGURE 7 Results of (a) dustometer tests and (b) loose aggregate tests.

Lightweight Deflectometer Test

Seal coatings are relatively inexpensive treatment types that can provide a protective wearing surface on an existing pavement surface to increase its service life. There are various types of pavement sealers, e.g., coal tar-based, asphalt-based, and petroleum-based are three primary types of sealers (*9*), all with pros and cons. While surface treatments can generally be used to provide a relatively inexpensive surface for low-volume traffic roads, they are not intended to address pavement structural deficiencies (*17*). Similarly, Otta seal has been described in the literature as a resurfacing layer that will not provide structural improvement (*5*, *7*). To confirm this statement, LWD tests were conducted on the existing pavement and two weeks after first layer and second layer Otta seal implementations. The tests were performed following ASTM E2583 (*18*), and elastic modulus values were calculated according to Vennapusa and White (*19*), producing the results plotted in FIGURE 8.

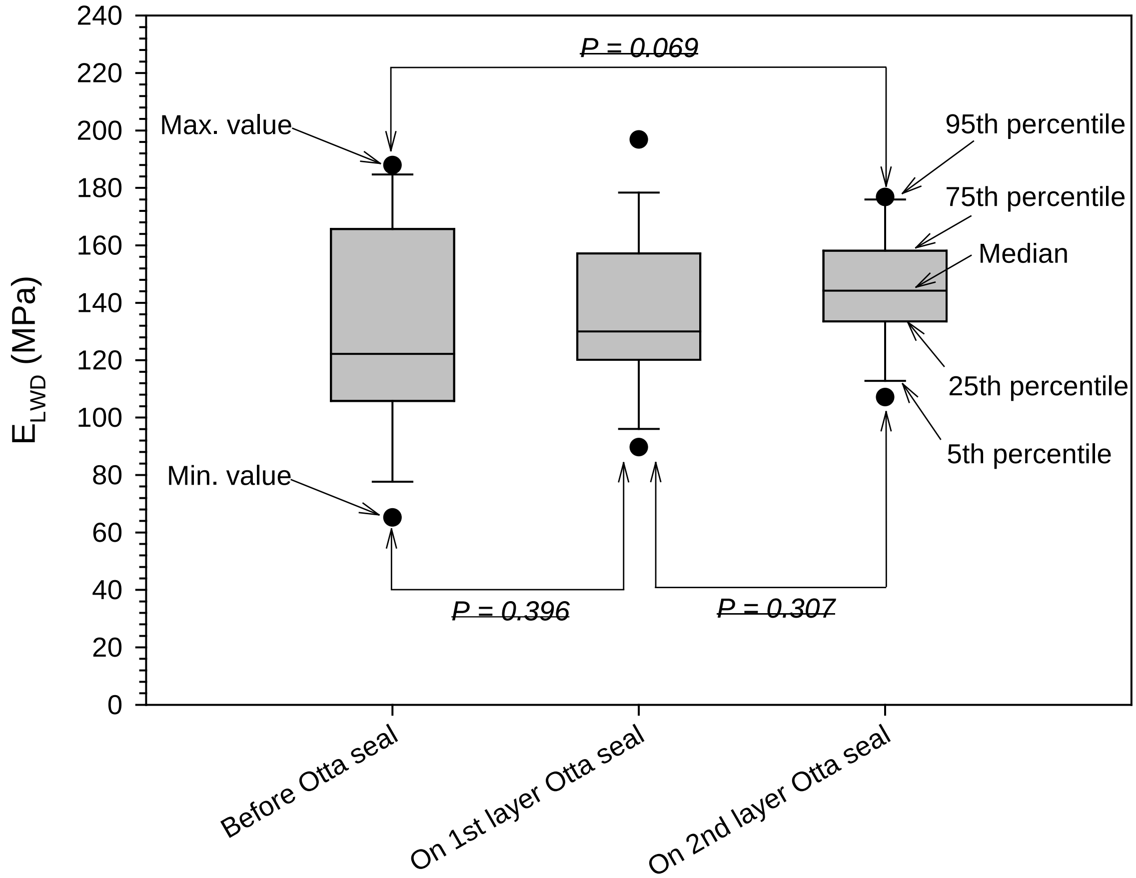

FIGURE 8 LWD results conducted on existing HMA pavement, first and second layers of Otta seal.

It is visually difficult to note whether or not Otta seal improved the elastic modulus of the road. While in comparing the median values of the E_{LWD} only slight increases were noticed after first and second layer implementation, to analyze the data in a more scientific manner, student t-tests were demonstrated in accordance with Ott and Longnecker (*20*). The P values statistically comparing the E_{LWD} values before Otta seal fabrication, after the first layer, and after the second layer, were 0.069, 0.396, and 0.307, respectively. All these P values are higher than the critical value, 0.05, indicating no significant difference between the three sets of E_{LWD} values. In other words, as indicated in FIGURE 8, the LWD measurement results showed an increase in the EWD, while this increasing effect is considered insignificant within a confidence interval of 95%. While this finding matches results reported in literature (5, 7), some uncertainty remains in terms of the influence of the asphalt binder hardening process on this finding. For this project Otta seal was applied on a HMA road, the structural capacity added by Otta seal was not surprisingly, negligibly low in comparison with the composite modulus of the existing pavement.

OTTA SEAL SERVICE LIFE AND CONSTRUCTION COST

The expected service life for a road surface is an important consideration when road surface section decisions are made. Indeed, most other long-term effectiveness considerations are influence by this service life (*22*). FIGURE 9 summarizes expected service lives of single chip seal, double chip seal, single Otta seal, and double Otta seal, as reported in the literature (*3*, *23–25)*.

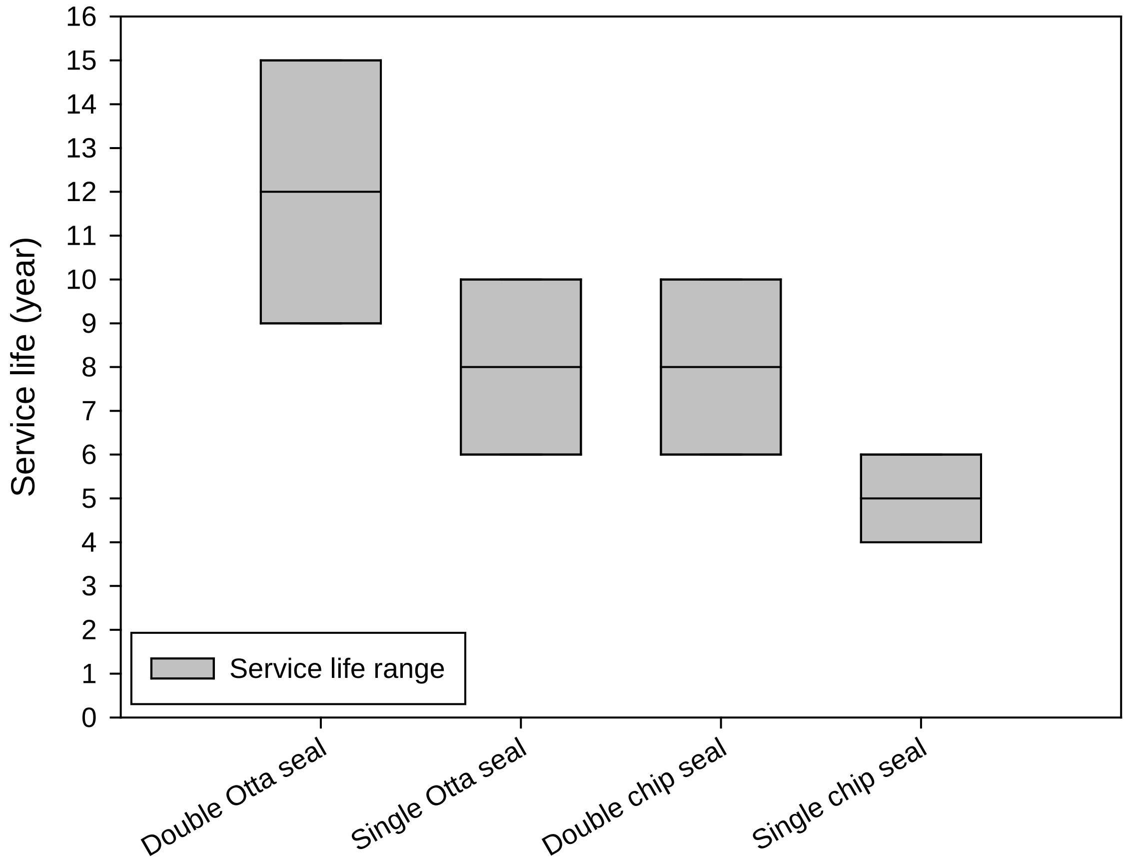

FIGURE 9 Typical service life ranges for bituminous surface treatments.

In addition to the literature review, several site visits were conducted to assess the longevity of Otta seal and chip seal roads. The results of site visits show that Otta seal and chip seal service life was found to be within ranges mentioned in the literature. TABLE 4 summarizes the visited sites indicating roads locations, current condition of the visited site sections, and the construction year.

The initial construction cost of Otta seal and chip seal were obtained from Minnesota and Iowa bid tabs that are publicly available (*26*). Bid data provide a simple, reliable, and quick method for estimating unit costs (*27-31*). The data set used in this analysis was obtained over the previous three-year period (June 2015 to June 2018). In total, seven bid records for double Otta seal, eleven for double chip seal, and six for single chip seal were found. FIGURE 10 shows how unit costs of various Minnesota surface treatment options were distributed from September 2015 to August 2017.

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). This would be virtually 50 percent more than that of double chip seal (*3*). However, as shown in , the mean values of unit costs for double Otta seal projects is much less than that for double chip seal. According to discussions with contractors and Minnesota and Iowa county engineers, the main reason for this difference between 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, since Otta seal has a less restricted requirement for aggregate gradation and strength (unlike chip seal that requires using a uniformly graded aggregate), using local aggregate for Otta seal surfacing is more often a viable option that could result in aggregate production and haulage cost reduction (for locations not close to a good source of chip seal aggregate), reducing hauling cost accordingly.

TABLE 4 Summary of Otta Seal Site Information in Minnesota

Road	County or City	Const. Year	ADT	Performance
Trial section	St. Louis County	2000	260	Potholes and wash boarding problems due to non-uniform aggregate application
CR73	Wabash County	2003	200	Good condition
CR 168	Cass County	2001	Less than 150	Good condition
Unmarked road	Cass County: Northeast of CR 168	2001	Less than 150	Good condition
CR 171	Cass County	2001	Less than 150	Good condition; Thermal cracks existed at intervals of 50 ft
CR 25	Cass County	2001	Less than 150	Good condition; Thermal cracks existed

The total construction cost for Otta seal application in Cherokee County was almost 2.5 (USD/m2) for 6.4 km (4 mi) road. In addition, to compare the cost of a previously Otta seal constructed in the state of Minnesota (with the case study discussed in this paper (L40)) cost of previous Otta seal projects were obtained from Minnesota bid tabs that are publicly available *(26)*. Also, Minnesota and Iowa bid records were used to obtain chip seal initial cost to provide insights on difference between Otta seal and chip seal construction costs (The bid records obtained over Jun 2015 to Jun 2018). Figure 10 shows the construction cost of Otta seal and chip seal that were obtained from Minnesota and Iowa bid tabs that are publicly available *(26)*. In total, seven bid records for double Otta seal, eleven for double chip seal, and six for single chip seal were obtained.

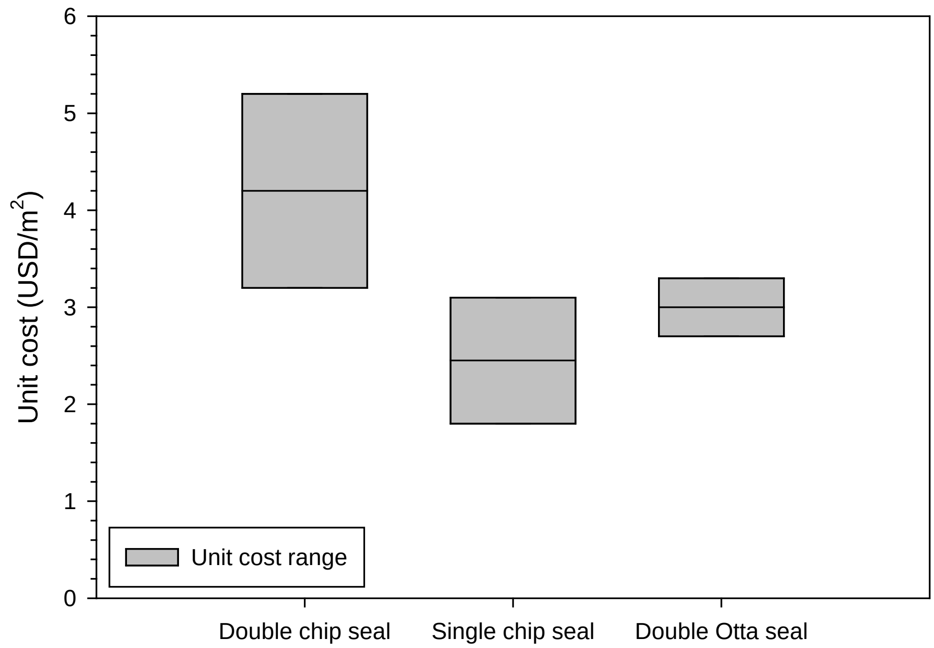

FIGURE 10 Construction unit costs of chip seal and Otta seal projects in Minnesota, obtained from Bid Express bid recordings (*26*).

As it is shown in Figure 10, the Otta seal construction cost is close to the cost of previous Otta seal projects conducted in Minnesota. However, as shown in Figure 10, double chip seal projects usually cost more than Otta seal construction. Also, the construction cost of chip seal projects fluctuates more than cost of Otta seal applications. 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). This would be virtually 50 percent more than that of double chip seal (*3*). However, as shown in , the mean values of unit costs for double Otta seal projects is much less than that for double chip seal. According to discussions with contractors and Minnesota and Iowa county engineers, the main reason for this difference between 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, since Otta seal has a less restricted requirement for aggregate gradation and strength (unlike chip seal that requires using a uniformly graded aggregate), using local aggregate for Otta seal surfacing is more often a viable option that could result in aggregate production and haulage cost reduction (for locations not close to a good source of chip seal aggregate), reducing hauling cost accordingly.

CONCLUSIONS

Otta seal has been reported as a more economical and durable alternative bituminous surface treatment technology for low-volume roads compared to conventional ones, such as chip seal. In this study, the demonstration site was constructed in accordance with a standard double layer Otta seal design over a 6.4 km (4 mi) existing deteriorated asphalt pavement with extensive cracking. To assess the performance of the constructed Otta seal, IRI tests were conducted and loose aggregates and dust induced by passing traffic were measured. LWD tests were performed to evaluate structural capacity improvement of Otta seal. Key lessons and findings from this study are as follows.

- Otta seal design should follow the design guide (*4*), with gradation being the most critical property for aggregate selection. The allowed aggregate gradation limits vary widely, and the type selected should fall within the specific limits. Use of extra-fine aggregate content is of concern because it could lead to considerable fugitive dust emissions and relatively larger amount of loose aggregates from and on 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 design guide (*4*), the specified binder types are all cutback asphalt, but because of concerns with the use of cutback asphalt in the US, asphalt emulsion was used in this study. To account for this change, the recommended binder spray rate in the design guide (*4*) 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 the design guide (*4*). 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 and checked. The amount of aggregate per unit area is directly impacted by the compaction and curing processes, and the presence of extra aggregate particles led to a relatively rougher surface at the earlier stage; the binder also could not be squeezed sufficiently far upward to fully coat and bind these particles. The moisture content of aggregates should be critically monitored before construction to prevent any chance that a portion of the spreader head could be clogged by wet aggregate particles. Although 10.89-metric ton (12-US ton) minimum rollers are required for Otta seal, the contractor could only supply an 8 tons roller on the first day or construction. Subsequently a 14 ton roller was supplied by better results.
- Short-term performance test results indicate that the IRI values changed slightly after Otta seal construction, with values after construction ranging from 2 to 3 m/km (126.72 to 190.08 in/mi) after six months; based on the short-term performance observed in this project, Otta seal surface is capable of providing satisfactory skid resistance and acceptable IRI values. However, LWD results revealed that the constructed Otta seal did not significantly add structural capacity to the existing HMA pavement.
- Otta seal surface appearance changes over service life. It appeared to be similar to regular granular roads immediately after construction, but became darker after a few months of service. The final appearance of Otta seal was similar to that of an HMA surface.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Ceylan, H., Kim, S., Jahren, C. T., Gransberg, D. D.; data collection: Gushgari, S. Y., Nahvi, A., Zhang, Y., Ceylan, H., Kim, S.; analysis and interpretation of results: Gushgari, S. Y., Zhang, Y., Nahvi, A., Ceylan, H., Kim, S.; draft manuscript preparation: Gushgari, S. Y., Zhang, Y., Nahvi, A., Ceylan, H., Kim, S., Øverby, C., Arabzadeh, A. All authors reviewed the results and approved the final version of the manuscript.

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