# Alternate Design Methods to Renew Lightly Traveled Paved Roads

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Minnesota’s local highway agencies are tasked with maintaining their low-volume road networks with available financial resources, prompting increased interest in lower-cost pavement rehabilitation alternatives. In-place cold recycling technologies, such as cold in-place recycling (CIR) and full-depth reclamation (FDR), provide lower-cost opportunities to renew deteriorated roads than traditional rehabilitation methods, particularly if surfaced with a thin surface treatment such as a chip seal (seal coat) or microsurfacing rather than hot-mix asphalt. However, the resulting road surface may not meet some road users’ expectations.

This study investigated the performance and economics of four pavement rehabilitation alternatives involving recycling technologies. The alternatives included CIR and FDR treatments with either an asphalt overlay or thin surface treatment. Fifteen case study sections in Minnesota and neighboring states were selected for performance evaluation and lifecycle cost analysis (LCCA).

Pavement condition surveys were performed to evaluate the study sections’ pavement distresses and roughness. The results indicated satisfactory performance for fourteen sections, while a CIR section with a chip seal surface using quartzite as cover aggregate had extensive transverse cracking. The cause of the distress is not clear.

The LCCA results indicate a 14% to 42% lower lifecycle cost for CIR and FDR treatments with chip seal surfaces. Costs savings may be achieved if asphalt overlay thicknesses are reduced, though chip seal surfaces may be rougher and nosier and require more maintenance than asphalt overlays. A decision tree was developed to aid local agencies during the treatment selection process.

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# Alternate Design Methods to Renew Lightly Traveled Paved Roads

## Final Report

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# Executive Summary

The issue with the maintenance of Minnesota's low-volume roads is that continuously deteriorating pavement conditions have raised the demand for infrastructure investment. The increased need for pavement maintenance funding is unlikely to be addressed given current budget constraints, and the lack of investment will result in diminished road performance, which, in turn, will likely negatively affect the economy and road user satisfaction. This challenge has motivated local highway agencies to develop lower-cost alternatives that can be used in place of traditional pavement renewal methods.

Traditional pavement rehabilitation methods often include the application of an asphalt overlay, possibly on a milled pavement surface. The milling decreases the thickness of the pavement structure and to some extent mitigates but does not completely eliminate existing distress patterns, especially cracking. The overlay lift thickness should be thick enough to provide sufficient structural support and minimize the effects of distress patterns in the pre-existing pavement structure.

Some in-place cold recycling technologies, such as cold in-place recycling (CIR) and full-depth reclamation (FDR), are able to destroy the distress pattern by pulverizing the existing pavement and introducing recycling agents without significantly changing the road profile. Roads treated with these technologies can sometimes be surfaced with a thinner overlay in comparison to traditional methods. In some cases, the recycled surface can be protected with a thin surface treatment, such as a chip seal (seal coat), slurry seal, or microsurfacing, or a combination of these.

Noticeable cost savings and performance improvements may be realized by incorporating recycling technologies into pavement rehabilitation strategies. This project report reviews the current research efforts in using CIR and FDR recycling technologies as alternatives to conventional asphalt pavement rehabilitation methods and the state-of-the-practice for individual technologies involved in these rehabilitation alternatives.

Under this investigation, researchers conducted a search for case study roads that had been renewed using CIR and FDR in Minnesota and neighboring states. Fifteen road sections were selected for performance evaluation and lifecycle cost analysis (LCCA). The test sections include roads with a CIR- or FDR-treated base and an asphalt overlay or chip seal surface.

The pavement condition survey results indicated that the rehabilitation alternatives were able to provide satisfactory performance and pavement life extension. The long-term performance of the FDR with asphalt overlay sections was comparable to that of a newly constructed asphalt pavement. The most common distress type was transverse cracking. All sections had good ride quality, and the pavement quality indices (PQI) of most sections were in the good range. Two of the CIR roads with a chip seal surface had fair pavement quality, and one of them had extensive transverse cracking and a loss of cover aggregate. The cause of the unsatisfactory performance remains uncertain given the available information.

Extrapolations were used to estimate the life expectancy for each treatment method. The CIR and FDR with asphalt overlay methods are expected to provide a 25-year service life. The life expectancies for CIR and FDR with chip seal surfaces are 19 and 17 years, respectively.

The results of the LCCA with a 30-year and a 50-year analysis period indicate that the pavement rehabilitation alternatives discussed in this report were able to reduce the rehabilitation and maintenance costs by 14% to 42%.

Based on the LCCA results, a decision tree for treatment selection was developed. The decision tree can be used as a reference for local highway agencies when a lower-cost asphalt pavement rehabilitation alternative is considered.

# Chapter 1. Introduction

Local highway agencies in Minnesota are facing the challenge of maintaining their low-volume road networks with available financial resources. According to the Minnesota Department of Transportation (MnDOT) pavement condition report (MnDOT 2015), in 2014, 4.4% of the roads in Minnesota that are not included in the national highway system (NHS), which usually carry a low traffic volume, exhibited poor ride quality. Meanwhile, the percentages of Interstates and other NHS roads with poor ride quality were 1.9% and 3%, respectively. Under the current funding level, it is projected that more than 10% of the Minnesota non-NHS roads will have poor ride quality by 2018. In order to improve the road conditions and maintain the network at a more satisfactory level, local highway agencies are interested in developing lower-cost pavement rehabilitation alternatives.

Deteriorated low-volume paved asphalt roads in Minnesota and other Midwest states usually suffer from non-load–related distresses caused by environmental factors. Traditional rehabilitation methods involve milling 1 to 2 inches of existing asphalt and then applying a 3- to 5-inch asphalt overlay on the remaining existing pavement. In-place recycling technologies, such as cold in-place recycling (CIR) and full-depth reclamation (FDR), destroy distress patterns (especially cracking), maintain the thickness of pavement structure, and rejuvenate aged binder by adding recycling agents; when executed properly, these processes produce a stable base for surface layers. Because low-volume roads are less likely to fail due to fatigue failures or insufficient structural support, a thick asphalt overlay is often not required to complete the rehabilitation process. A thin surface treatment is sometimes sufficient to protect the recycled pavement layer from water penetration and weathering. In such cases, the pavement may perform satisfactorily for a time without an asphalt overlay. In comparison to a new pavement layer with the same thickness, recycling technologies require less virgin materials and usually result in lower construction costs. Therefore, recycling technologies can provide an opportunity to renew aged roads at lower costs.

This report describes an investigation of the costs and benefits of various pavement rehabilitation strategies associated with recycling technologies. The objective of the study was to document local experiences with recycling technologies in Minnesota and neighboring states and provide references for local highway agencies regarding how to properly consider pavement renewal strategies that could possibly include CIR and/or FDR with and without asphalt overlays.

As part of this study, a search was conducted for case study roads that had been rehabilitated using recycling technologies. It was found from an informational survey distributed to county-level highway agencies that CIR and FDR have been extensively used within Minnesota. These treatments are usually used as base preparation methods for asphalt overlays. A few locations were found where a thin surface treatment was applied directly on a recycled pavement surface. The performance of such treatments has not been extensively studied.

After a search for case study road sites, the research team selected fifteen test sections in Iowa, Minnesota, and North Dakota. The test sections include four types of rehabilitation strategies: CIR with asphalt overlay, CIR with thin surface treatment (chip seal), FDR with asphalt overlay, and FDR with thin surface treatment (chip seal). Pavement condition surveys were performed on these sections to evaluate the performance of each treatment method. A lifecycle cost analysis (LCCA) was employed to compare the present worth of the current and future costs of these treatments to the current and future costs of the conventional mill and fill method. A decision tree was developed as a reference to assist local agencies in their efforts to select effective and appropriate pavement renewal strategies.

# Chapter 2. Literature Review

A literature review was conducted regarding recent investigations into alternative pavement rehabilitation methods for low-volume roads. It was found that pavement recycling technologies have been successfully implemented for pavement rehabilitation projects, and a recycled layer can be covered by a surface treatment to provide a lower-cost alternative to current rehabilitation strategies. Some examples of disappointing performance are also documented. The literature review findings suggest that it would be desirable to develop better mix design methods for the recycling technologies and crew training programs. An investigation performed in Nevada and an ongoing research project sponsored by the Iowa Department of Transportation (DOT) are reviewed in detail in this chapter. The technologies that may be used in the recycling and surfacing treatments are also reviewed in terms of construction processes, life expectancies, design methods, specifications, and other factors.

## 2.1 Nevada Alternative Rehabilitation Strategies (Maurer et al. 2007)

The Nevada DOT constructed 29 test sections using CIR, FDR, cold-mix asphalt, and various surface treatments including chip seals, cape seals, microsurfacing, and flush seals. The treatments included stabilized full-depth reclamation (SFDR) with a chip seal, SFDR with a thin overlay and a chip seal, and CIR with a chip seal surface. The test sections were constructed on five low-volume roads throughout Nevada. The existing pavements of the roads were aged and suffered from various cracking and raveling distresses. Load-related distresses were not reported.

SFDR treatments were applied that involved pulverizing the bituminous layers of the existing pavements as well as a portion of the underlying base layers. Various asphalt emulsions, cement, and foamed asphalt, including two proprietary products, were used as the recycling agents. Six of the eight SFDR sections were reported to have failed, including the two sections using a proprietary liquid stabilizer, two sections using cement, a section using a proprietary asphalt emulsion, and a section using a CMS-2S asphalt emulsion. The manufacturer of the proprietary liquid stabilizer introduced the product as a stabilization agent that has considerable adaptability to soil conditions and does not require time to cure before a wearing course is placed. Raveling occurred immediately after the construction of the test sections. The test sections were overlaid with a 1.5-inch hot-mix asphalt (HMA) layer to correct the problem. For the cement-stabilized FDR sections, a dose of 3% and 4.5% of cement by weight was applied, which is higher than the typical 2% cement application rate in Nevada. The sections were designed to evaluate the effectiveness of a higher cement application rate. After considering the performance of the test sections, the researchers recommended that the cement application rate should not exceed 2%. The FDR test section using the proprietary asphalt emulsion product apparently did not cure properly. The issue was remedied by placing a 1.5-inch HMA overlay. The section using the CMS-2S asphalt emulsion showed signs of raveling after the construction of the SFDR layer. The treatment involved pulverizing 8 inches of the existing pavement and adding 1.5% asphalt emulsion to the top 2.5 inches of the FDR mat. Quicklime was also applied at a rate of 3% to the entire thickness. The cause of the failure was analyzed, and the researchers concluded that the emulsion content was too low. An emulsion content of 2.5% was recommended. The FDR sections that experienced satisfactory performance used foamed asphalt as the recycling agent.

The CIR sections were constructed with a CMS-2S asphalt emulsion or a proprietary polymer-modified asphalt emulsion. The CIR layers were 3 inches thick. Three percent lime was added to the CIR sections that were treated with asphalt emulsion. The proprietary asphalt emulsion provided satisfactory performance. The proprietary product also improved constructability by not requiring lime, compaction, and a fog seal and by allowing a lower surface temperature. In general, the CIR sections exhibited satisfactory performance. Isolated problems were identified, such as locations that had insufficient structural support for the CIR train, binder that set too quickly, raveling, and rutting. The researchers recommended that a minimum of 1.5 inches of the existing pavement should be left to support the CIR train. Other problems could be solved by carefully evaluating the binder properties and providing a better mix design. There was one CIR section where the construction process involved the incorporation of reclaimed asphalt pavements (RAP) from other locations. The result of this strategy was favorable.

The surface treatments that were applied to the test sections were primarily single or double chip seals with various emulsified asphalts and aggregate sizes. Other surface treatments include four cape seal treatments, four flush seal treatments, and microsurfacing. A double chip seal with a nonwoven geotextile was also constructed. This treatment proved not to be suitable for the hot, moist conditions that existed during the time of construction. Water vapor was trapped by the geotextile and formed bubbles, which resulted in aggregate loss. Some surface treatments were placed without a base treatment. The authors did not report a noticeable performance difference between the sections that had hot-mix asphalt surface and the sections that had received the thin surface treatments without a hot-mix asphalt layer.

Roughness tests and falling weight deflectometer (FWD) tests were performed to evaluate the performance of the test sections. Some FDR sections were reported to have a rough surface; however, it was concluded that the cause was an inexperienced motor grader operator. The performance evaluation results indicated that despite the aforementioned problems caused by poor mix designs and workmanship, the recycling and surfacing strategy successfully improved the road conditions and provided satisfactory serviceability. The present serviceability ratings (PSR) were improved 17% to 62% and 2% to 43% by the CIR and FDR treatments, respectively. The FWD test results indicated that the structural capacities were increased by 36% to 72% for the FDR sections. The sections using a cold-mix overlay and the MC-800 asphalt also showed evidence of improved performance. The laboratory material evaluations did not show clear correlations between the laboratory material properties and field performance. A lifetime cost analysis was employed considering a 20 year design life and periodic maintenance using thin surfacing treatments. The analysis showed that the average lifetime cost saving of using a recycling and surfacing strategy could be $100,000 per centerline mile in comparison to a conventional 2-inch HMA overlay and chip seal treatment.

## 2.2 Iowa Holding Strategies (Yu et al. 2015)

The Iowa DOT constructed 10 test sections in 2013 on a low-volume rural state highway. The objective of the research project was to evaluate various rehabilitation methods that could be used as holding strategy treatments to replace the conventional overlay approach. A holding strategy is a pavement management concept that involves postponement of major rehabilitation or reconstruction of a deteriorated road section using applications of treatments that are more aggressive than preventative maintenance treatments, have lower costs, and most likely have shorter service lives compared to rehabilitation strategies. The test sections included two mill-and-fill sections, one interlayer and ultrathin overlay section, four recycling and surfacing sections, one leveling and strengthening course section, and one mill and seal coat section. The recycling and surfacing sections included CIR and FDR treatments with a 1.5-inch HMA overlay or a double chip seal. Pavement condition surveys and FWD tests were conducted. The results have not been published yet; however, a cost analysis was presented at the 67th Iowa County Engineers Conference in December of 2013. The results suggest that a recycling and surfacing strategy could be an economical alternative to a 3-inch HMA overlay treatment, which is the conventional rehabilitation approach in Iowa. The construction cost for the FDR and HMA overlay section was slightly higher than the estimated cost for a 3-inch overlay, while the costs of the other recycling and surfacing sections were 15% to 45% lower.

## 2.3 Cold In-Place Recycling

### *Definition and Construction Process*

Cold in-place recycling is an asphalt pavement rehabilitation technology that involves pulverizing the top 2 to 4 inches of the existing pavement and mixing the pulverized materials with recycling agents (typically asphalt emulsion or foamed asphalt) to produce a recycled asphalt mixture that can be laid down and compacted to form a road base layer. A typical CIR operation is performed with a recycling train that includes one or multiple units. The single-unit trains consist of a cold reclamation machine, which is capable of pulverization, sizing, and blending (Thompson et al. 2009). A two-pass operation is generally conducted using a single-unit train. The stabilizer/reclaimer performs sizing on the first pass and mixes the RAP with the recycling agents and stabilizers on the second pass. Graders and compactors following the second pass restore the road profile and compact the CIR layer to achieve the desired density and strength. Multi-unit trains include two or more units. The multi-unit trains have a milling machine and allow the mixture to be placed with a paving system. A two-unit system has a pugmill mixer-paver, which performs recycling agent injection, mixing, and paving. The milling machine of a two-unit train also has the ability to crush RAP materials into the appropriate size. When there are more than two units in a system, more tasks are performed by the individual pieces of construction equipment. Such an operation may require a pavement profiler (pavement milling machine), a crusher, a pugmill, a paver, and compactors to fulfill the tasks of milling, sizing, mixing, paving, and compaction, respectively. The multi-unit trains comprise a mixture of pieces of both off-the-shelf and custom construction equipment. It has been found that the multi-unit trains produce more uniform materials and have a higher production rate than single-unit and two-unit trains (Caltrans 2008). However, the size of the multi-unit trains and traffic control requirements limit the use of these trains in urban areas. The single-unit and two-unit trains require specialized equipment and have more difficulty achieving constant process control than multi-unit trains. These two types of trains can be used in urban areas where high traffic volumes and small turning radii are encountered. The two-unit trains are able to weigh the RAP on the feeder belt and add an appropriate amount of recycling agent accordingly; therefore, these trains produce more uniform products than the single-unit trains. The primary advantages of the single-unit trains are their simplicity of operation and flexibility of use in urban areas.

### *Benefits and Limitations*

Compared to the conventional mill and fill method, CIR is often a lower cost, faster, and more environmental friendly alternative. The CIR construction process allows 100% of the recycled materials to be reused immediately after processing, resulting in no need for RAP handling and storage. The primary limitations of this technology are curing issues and the lack of a nationally accepted design method. A newly placed CIR surface usually requires a 2 hour minimum curing time before traffic is permitted. This curing time also limits the thickness of the CIR layer. It has been reported that CIR material may be difficult to cure if the layer thickness is greater than 4 inches (FHWA 2011). The moisture content can noticeably affect the performance of CIR treatments. A curing time of 7 to 14 days may be required in order for the CIR material to achieve the proper moisture content before any overlay or wearing course is placed. Therefore, CIR is more suited to maintaining low-volume roads where the traffic will not cause excessive load damage before curing is completed and the overlay or wearing course is placed. Moreover, lower nighttime temperatures considerably increase the initial curing time, which limits the desirability of CIR applications for projects that require nighttime construction.

The design of CIR has been described as "more of an art rather than science" (FHWA 2011). Although several design methods have been developed, the selection of the optimum binder content and moisture content still rely on the engineer's experience. The requirement of engaging a high-quality contractor that provides good workmanship is essential to the success of CIR construction. Other disadvantages include having a larger variation in construction material properties in comparison to materials provided using central plant recycling, the requirement of a wearing surface, and structural support issues for construction equipment. Because CIR pulverizes a considerable thickness of the existing pavement, which results in a temporary decrease in the pavement's structural capacity, the weight of the CIR train may cause structural damage to the road. Some agencies require a minimum remaining HMA thickness of 1 inch to prevent damage caused by construction equipment (FHWA 2011). In situ pavement structural tests, such as the dynamic cone penetrometer (DCP) test, California bearing ratio (CBR) test, and FWD test, can be employed to determine the adequacy of the structural support that can be expected from the pavement system.

### *Mix Design Methods*

CIR design methods have been developed by various institutions and highway and pavement organizations. Most of the methods are a modified Marshall mix design procedure. Design methods based on the Hveem method or using gyratory-compacted samples and indirect tensile tests have also been developed. The CIR design methods reviewed in this section include the AASHTO, Asphalt Institute, California, Chevron, Oregon, Pennsylvania, and US Army Corps of Engineers (USACE) methods. A CIR design method developed by Lee and Kim (2003) using foamed asphalt is also reviewed.

**AASHTO Method** (Salomon and Newcomb 2000)**.** The AASHTO method uses a modified Marshall procedure. RAP samples are procured through cold milling or by drilling and crushing cores. Crushed core sampling requires an extra step of gradation verification on the first construction day. RAP samples are mixed with asphalt emulsions at various emulsion contents that include the estimated target emulsion content. The trial emulsion content increments are set at 0.5%. The finished mixture samples have a target total water content of 3%, which includes the moisture in the RAP materials and emulsions as well as the additional water added to adjust the mixture's water content. A Marshall compactor is used to produce CIR specimens with a compaction effort of 50 blows per face. The compacted samples are cured for 6 hours at 60ºC and 12 hours at room temperature. Then, Marshall stability tests following AASHTO T 245 are performed at a 60ºC testing temperature to determine the optimum emulsion content. The optimum total water content is determined by testing the volumetrics of samples prepared at the optimum emulsion content and varying water contents. An acceptable water content is expected to result in an air void content between 9% and 14%.

**Asphalt Institute Method** (Epps and Allen 1990)**.** The Asphalt Institute method does not involve the evaluation of the physical properties of compacted samples. The target binder content is calculated using an aggregate surface area formula. In order to determine the application rate of the recycling agent, the RAP gradation and binder content must be evaluated. An ignition test or binder extraction process may be carried out. This method requires field adjustments.

**California Method** (Salomon and Newcomb 2000, Epps and Allen 1990)**.** The California method incorporates a modified Hveem method. The California method determines the grade of the base asphalt for asphalt emulsion and the optimum emulsion content. RAP samples are procured by crushing cores. One RAP sample is used for binder extraction and RAP binder content and aggregate gradation determination. The viscosity of the reclaimed asphalt is tested, and this information is used to calculate the expected viscosity of the blended binder. The selected base asphalt is required to result in a viscosity of 4,000 poises at 140ºF for the blended binder. An aggregate surface area formula is applied to estimate the approximate total bitumen requirement. Four RAP samples are oven dried and mixed with 2% water and various emulsion contents. The mixtures are cured at 60ºC for 16 hours. After curing, the samples are compacted using the California kneading compactor, with the sample temperature the same as the curing temperature. The Hveem stability test is conducted at 140ºC. The specimens that are considered to have proper emulsion content need to be free of surface flushing or bleeding and have a minimum air void content of 4% and minimum Hveem stability values of 30 and 25 for traveled ways and shoulders, respectively. The selected emulsion content is the highest number among those that satisfy the aforementioned requirements.

**Chevron Method** (Epps and Allen 1990)**.** The Chevron method is a modified Hveem method. The starting binder content is calculated using an aggregate surface area formula and the centrifuge kerosene equivalent test. The need for virgin aggregate materials is determined if the starting asphalt content requires less than 2% emulsion to be added. Sample specimens are prepared using the California kneading compactor and conventional Hveem design procedures. The specimens are tested for Hveem stability, resilient modulus, and cohesiometer value. The criteria for selecting the optimum binder content include a resilient modulus of 150,000 to 600,000 psi at 23ºC, a minimum Hveem stability value of 30 at 60ºC, and a minimum cohesiometer value of 100 at 60ºC.

**Oregon Method** (FHWA 2011, Epps and Allen 1990)**.** The Oregon method is a modified Hveem procedure. RAP samples are procured using a 16-inch milling machine and crushed to ensure that 100% of the particles pass the 1-inch sieve. The RAP binder is extracted and tested for viscosity and asphalt penetration. The gradation of the RAP sample is also determined. The method assumes a default emulsion content of 1.2%. Factors based on local experience in Oregon from 1984 and 1988 are applied to adjust the default emulsion content for the influences of aggregate gradation, RAP binder content, and RAP binder viscosity or penetration. The emulsion type is selected based on various binder and aggregate tests. The estimated trial emulsion content can be determined using Equation 1. Mixture samples are prepared at the estimated emulsion content and six other emulsion contents in increments of 0.3%, with three samples above and three samples below the estimated emulsion content. The total water content at each emulsion content is determined by conducting Oregon DOT Test Method TM126 (Oregon DOT 2014). The RAP material with the optimum water content is expected to exhibit a damp appearance at the surface while showing no signs of free water. The mixture samples are cured at 60ºC for one hour and compacted using the California kneading compactor. The compacted specimens are cured in molds for 24 hours at 60ºC and cured for an additional 72 hours at 22ºC without molds. The optimum emulsion content is determined by testing the specimens with the Hveem stability and resilient modulus tests. The determined optimum emulsion content needs to be adjusted according to field observations.

$$EC_{EST} = 1.2 + A_G + A_{A/C} + A_{P/V} \quad \textbf{(1)}$$

where:
$EC_{EST}$ = estimated emulsion content (%)
$A_G$ = adjustment for gradation (%)
$A_{A/C}$ = adjustment for asphalt content (%)
$A_{P/V}$ = adjustment for penetration or viscosity (%)

**Pennsylvania Method** (FHWA 2011, Epps and Allen 1990). The Pennsylvania method is a modified Marshall design procedure. Crushed cores or cold milling samples are collected from the existing pavement. Binder extraction is performed to procure reclaimed RAP binder samples and RAP aggregate samples. The RAP samples' binder viscosity and penetration are tested at 60ºC and 25ºC. When the extracted binders have penetration values of 15 to 20, which is typical for Pennsylvania, the recommended emulsion is CMS-2. If the viscosity and penetration tests indicate a stiffer RAP binder, a CSS-1h emulsion can be used. The Pennsylvania method allows virgin aggregate materials to be introduced. The addition of virgin aggregate is usually desired if the RAP gradation needs to be adjusted or the RAP materials have excessive binder content. In some cases, virgin aggregate is introduced to CIR materials to increase the layer thickness, which provides greater structural capacity. The optimum moisture content is determined with mixtures at 2.5% emulsion content and varying moisture contents. Virgin aggregate is not included in the mixtures when determining optimum moisture content. The optimum moisture content is the moisture content of the samples that have a minimum coating percentage of 90% and that do not show stripping, breaking, or segregation. Compacted specimens are prepared at the optimum moisture content and various emulsion contents ranging from 2% to 3.5%. The loose mixtures are cured at 41ºC for 45 minutes and compacted with the Marshall hammer at an energy level of 75 blows per face. The specimens are cured in molds at 23ºC for 15 to 24 hours. Then, the specimens are extruded from the molds and cured at 40ºC for three days. The optimum emulsion content is determined after examining the results from the bulk specific gravity, Marshall stability, resilient modulus, and soaked resilient modulus tests. The Marshall stability and resilient modulus tests are performed at 25ºC. The samples are vacuum saturated for 30 minutes before testing for the soaked resilient modulus.

**USACE Method** (Salomon and Newcomb 2000, Cross and Ramaya 1995)**.** The USACE method provides designs for CIR mixtures using the same approach as that used to design HMA pavements on low-volume roads with modified compaction parameters. If the Marshall compactor is used, the sample is compacted with 50 blows on each side. Specimens can also be made by a gyratory compactor with a 1º angle of gyration and 620 kPa (90 psi) compaction pressure for 150 revolutions. The optimum binder content is intended to ensure that a minimum shear strength of 100 kPa (14 psi) and a maximum gyratory elastic plastic index of 1.54 will be achieved.

**Iowa Method for CIR Using Foamed Asphalt** (Lee and Kim 2003)**.** This procedure is developed specifically for CIR construction projects using foamed asphalt as the recycling agent. The design method determines the optimum water content for asphalt forming, the optimum water content for RAP to achieve the maximum density, and the optimum asphalt content. Laboratory foaming tests are performed to develop an expansion ratio and foaming water content relationship and a half-life versus foaming water content curve. The optimum foaming water content is determined as the water content at the intercept point of the two curves. The modified proctor test following ASTM D1557 (ASTM 2012) is employed to determine the optimum water content for the RAP materials. The optimum water content is the water content for which the maximum dry unit weight is achieved. The Marshall hammer is used to fabricate the compacted specimens. The compaction energy level is 75 blows per face. Then, the compacted specimens are extruded from the molds and cured at 40ºC for 3 days. The samples are cooled to room temperature and tested for Marshall stability and flow and tensile strength at 25ºC. Indirect tensile tests are also performed on saturated samples to evaluate the moisture sensitivity of the material. A vacuum saturation time of 50 minutes is specified. The optimum asphalt content is selected based on the analyses of the sample strength, stability, bulk specific gravity, and moisture sensitivity.

### *Structural Design*

Designing the thickness of a CIR layer to meet the structural requirement to support the design traffic is not essentially different from designing the thickness of a conventional HMA pavement. However, the various structural coefficients, such as the American Association of State Highway and Transportation Officials (AASHTO) layer coefficient or granular equivalent value, should be appropriate for the CIR layer rather than a conventional HMA layer, which typically has a layer coefficient of 0.44. The AASHTO road test results indicated that a layer coefficient between 0.3 and 0.35 might be used for the thickness design of cold in-place recycled pavement (AASHTO 1986). However, the actual structural capacity of a CIR layer is dependent upon the properties of the subgrade soil and CIR material. Therefore, some state highway agencies (SHAs) have developed structural coefficient values based on local experience. In Nevada, a standard layer coefficient of 0.28 has been established for CIR thickness design (FHWA 2011). In Kansas, the typical CIR layer coefficient ranges between 0.25 and 0.28 (FHWA 2011). CIR is often used to correct pavement cracking. Sometimes, a minimum milling depth is needed to prevent reflective cracking. The California Department of Transportation (Caltrans) has developed an equation (Equation 2) to determine the minimum milling depth (Epps and Allen 1990).

$$X = (T - 2Y) \div 3 \qquad \textbf{(2)}$$

where:
$T$ = original pavement thickness (ft)
$Y$ = virgin asphalt concrete overlay thickness (ft)
$X$ = milling depth (ft)

### *CIR Experience in Various States*

Successful implementations of CIR technology have been reported in various states. A review of this technology conducted by the Federal Highway Administration (FHWA) summarizes the past experiences and current practices of CIR technology in New York, Nevada, and Kansas (FHWA 2011). CIR has been implemented in those states for more than 20 years.

In New York, CIR treatments are primarily used on low-volume rural roads in fair condition. Applications are limited to roads with less than 8,000 annual average daily traffic (AADT) and 10% trucks. The typical CIR pavement structure in New York includes a 4-inch CIR layer and a 1.5-inch HMA overlay. The life expectancy for such a pavement structure is 10 to 15 years with minimal maintenance activities.

CIR pavements in Nevada are usually constructed on roads with less than 300,000 equivalent single axle loads (ESALs). The Nevada DOT typically uses a 3-inch CIR layer. The wearing course is a double chip seal for roads with less than 400 average daily traffic (ADT) and a low truck percent or an open-graded friction course if the design ESALs exceeds 500,000. The Kansas DOT uses a typical CIR design depth of 4 inches and a 1.5-inch HMA overlay. The life expectancy is seven years for a typical CIR project.

Noticeable amounts of construction cost savings due to the implementation of CIR have been recognized in Nevada and Kansas. The Kansas DOT reported that $600 million has been saved through the use of cold milling recycling technologies, including CIR and FDR, in the past 20 years. The Nevada DOT reported that a CIR project costs about 45% less than a 4-inch HMA overlay, which is the conventional rehabilitation treatment in Nevada. Improved pavement smoothness has been reported by the Kansas DOT and is considered to be a benefit of CIR technology. CIR technology is successful in correcting full-depth cracking, low subgrade strength, and thermal cracking. The major reported performance problem related to CIR is asphalt stripping. Experience in Kansas has shown that the stripping problem can be lessened by adding lime slurry during mixing. The use of lime slurry also improves the overall pavement performance. A lime content of 1.5% is typically used. The states that were reviewed by the FHWA (2011) reported that engaging an experienced contractor is vital to the success of CIR construction. The requirements of high equipment investment and good workmanship can be an obstacle for the implementation of this technology.

A performance study conducted by Jahren et al. (1998) shows that CIR technology has been successfully implemented in Iowa since 1986. The study reviewed 18 sample roads that were rehabilitated with CIR treatments. Few cracks appeared on those roads in the first five years after rehabilitation. Better overall performance was observed compared to the roads before the treatments were applied. Few rutting problems were noted in the observations. The study also indicates that poor subgrade conditions may limit the use of CIR in Iowa. The CIR pavements in Iowa typically have a 3- to 4-inch CIR layer and a 2- to 4-inch HMA overlay. The construction cost of CIR is about one quarter of the cost of an HMA overlay with the same thickness. Typical candidate roads for CIR are rural low-volume roads with an AADT between 300 and 2,000. The life expectancies of the CIR projects in Iowa range from 15 to 26 years. A follow-up study indicated that the performance and life expectancy of CIR was affected by the engineering properties of the CIR mixture, including void ratio, modulus, and indirect tensile strength (Chen et al. 2010). It was found that the CIR layer acts as a stress relieving course. Better performance was observed for roads with higher air voids and lower moduli of the CIR layer.

The MnDOT started using CIR in late 1980s. The early attempts did not succeed due to rutting and curing time issues (Watson 2012). CIR technology has been implemented again in recent years because of financial pressures. The typical structure of CIR pavements consists of a 2- to 4-inch CIR layer and a 2- to 4-inch HMA overlay or chip seal. Both asphalt emulsion and foamed asphalt are used as a recycling agent, and the performance of these roads is still being monitored.

### *Specifications*

Various state transportation agencies (STAs) have developed specifications that establish criteria for RAP gradation, recycling agent type, mix design, equipment, compaction effort, weather conditions, and curing. A summary of the specifications for Iowa, Minnesota, Nevada, and New Mexico are presented in Table 1.

# Table 1. CIR specifications in various states

| | Iowa | Minnesota | Nevada | New Mexico |
|---|---|---|---|---|
| **RAP Gradation** | 98 to 100% passing 1.5 inch sieve; 90% to 100% passing 1 inch sieve | 100% passing 1.5 inch sieve; 90% to 100% passing 1 inch sieve | 100% passing 1.5 inch sieve | 100% passing 1.25 inch sieve; 90% to 100% passing 1 inch sieve |
| **Recycling Agent** | HFMS-2s on primary and interstate highways; CSS-1 on others; Foamed PG 52-34 or PG 46-34 asphalt on all roads | HFMS-2p or foamed asphalt | Not specified | Polymerized High Float Emulsion |
| **Recycling Agent Application Rate** | 0.3 gallons/yd$^2$/in (emulsion); 0.0011 tons/yd$^2$/in (foamed asphalt); or determined in mix design | 2% emulsion content and adjusted if necessary | 1.5% binder content and adjusted if necessary | Determined in mix design |
| **Lime Slurry** | Not specified | Not specified | 1.5% lime content | 1.5% lime content |
| **Rolling Requirements** | Field density >94% of lab sample density for interstate and primary roads; >92% of lab sample density for other roads | Test strip | Test strip | Field density >96% of lab sample density |
| **Surface Treatment of Compacted CIR Layer** | Not specified | Need for a fog seal is determined by Engineer | Fog seal is required | Fog seal is optional |
| **Equipment** | CIR train type is not specified; require at least two compactors including one double drum vibratory steel roller and one 25 ton or greater pneumatic tire roller | Multi-unit train is required; require at least two compactors including one 25 to 30 ton pneumatic roller and another pneumatic or steel drum roller | Multi-unit train is required; require at least two 25 ton or greater pneumatic tire rollers and one 10 ton or greater steel wheel roller | CIR train type is not specified; require at least one 30 ton or greater pneumatic roller |
| **Weather Restrictions** | Ambient temperature below 60ºF (15ºC); foggy or rainy weathers; October 1 to May 1 in the next year | Ambient temperature below 50ºF (10ºC); foggy or rainy weather | Ambient temperature below 60ºF (15ºC); ambient temperature will drop below 35ºF (2ºC) in 72 hours; foggy or rainy weather | Ambient temperature below 60ºF (15ºC); foggy or rainy weather |
| **Curing and Placement of Surface Course** | Curing time depends on field observations; place the surface course in 14 days after CIR construction is completed; moisture content in CIR layer must below 0.3% above the residual moisture content or 2% before placement of the surface course | Two hours minimum curing time before traffic is allowed; moisture content of CIR layer must below 1.5% before placement of the surface course | 1 to 2 hours curing time before compaction; 10 days minimum curing time before placement of the surface course; re-compact between 3 and 15 days after initial compaction | Two hours minimum curing time before traffic is allowed; moisture content must below 1% above the natural moisture of the material |

The RAP gradation requirements are similar because they mostly require a maximum particle size of 1.5 inches. High-float asphalt emulsion is favored by most STAs. The binder application rate is determined by the mix design or experience and adjusted according to field performance. Two out of four states in Table 1 require the use of lime slurry. The application rate of the lime slurry is intended to achieve a 1.5% lime content. Rolling criteria are based on either density requirements or a test strip. The sample preparation procedures for establishing the laboratory sample density vary between STAs. The specifications for Minnesota, Nevada, and New Mexico encourage the application of fog seal on the finished CIR surface to protect the new CIR layer before placement of the wearing course. Typically, a two-hour curing time is required before the road is opened to traffic. The placement of the wearing course requires that the CIR layer be dried to a specified moisture content. The Iowa DOT requires that the wearing course be laid within two weeks after CIR construction.

## 2.4 Full-Depth Reclamation

### *Definition and Construction Process*

FDR is a cold recycling technology similar to CIR. However, unlike CIR which only partially recycles HMA pavements and usually leaves at least 1 to 2 inches of the existing HMA to support the construction equipment, FDR recycles the entire thickness of the HMA layers and a portion of the underlying aggregate base. Therefore, FDR is also known as full-depth cold recycling, whereas CIR is partial-depth cold recycling. Some of the equipment and construction processes for applying CIR treatments can also be used for FDR construction. The single-unit train operation is more common for FDR, while CIR construction is usually conducted with a multi-unit train operation (Thompson et al. 2009). The thick FDR layer causes difficulties for curing and compaction. Stabilizing additives, such as lime and cement, are usually applied to reduce the material moisture content and improve the bonding strength between material particles. The product of FDR treatment is a stabilized aggregate base material.

### *Benefits and Limitations*

As an in-place recycling technology, FDR provides economic and environmental benefits. The construction of FDR requires less new aggregate and binder material compared to building a new HMA pavement and does not produce large amount of RAP materials that need to be transported, processed, and stored. The costs and energy for making new construction materials can be decreased. The number of pieces of equipment is also reduced by this in-place recycling procedure, which lowers the costs for equipment mobilization and reduces project management complexity. Compared to CIR, FDR is more effective in eliminating deep cracking patterns and reduces the chances of having reflective cracking. The primary limitation of FDR implementation is that this technology is relatively new. It can also become less economical when processing thicker pavements and can require a considerably higher cost per unit area because more stabilizing agent may have to be added in order to process a thicker layer. Long-term field performance has not been well evaluated, and nationwide design procedures have not yet been developed.

*Mix Design Methods*

Most mix design methods were developed for cold recycling technologies in general, including both partial- and full-depth in-place recycling methods. However, certain design methods may be more appropriate for one process than the other. The design methods that can be applied to both CIR and FDR include the Chevron and Pennsylvania methods (Epps and Allen 1990). The Asphalt Institute and USACE methods are more suited to the design of FDR materials. Some STAs have developed their own FDR mix design methods and have identified them in their specifications. The mix design methods in Colorado and Illinois are reviewed herein.

**Colorado Method**. The Colorado method requires the procurement and crushing of RAP materials to meet the gradation requirements shown in Table 2.

**Table 2. RAP sample gradation requirements**

| Sieve Size | % Passing, |
|---|---|
| 1.25 inch | 100 |
| 1 inch | 90 to 100 |
| 3/4 inch | 80 to 97 |
| No. 4 | 30 to 55 |
| No. 30 | 5 to 15 |

A modified proctor test following AASHTO T 180, Method D, is performed to determine the optimum moisture content. The RAP materials are mixed with water at 50% to 75% of the optimum moisture content for RAP material that has a sand equivalent value less than 30, and 40% to 65% of the optimum moisture content if the sand equivalent value is greater than 30. If the proctor test produces a dry density versus moisture content curve that does not have a peak point, the RAP materials should be mixed at 2% to 3% moisture content. RAP materials that have less than 4% of the particles passing the No.200 sieve should also be processed at a 2% to 3% moisture content. Then, the RAP samples are mixed with asphalt emulsion at four or more emulsion contents that bracket the estimated optimum emulsion content. The mixture samples are cured in plastic containers of 6 inches in diameter for 30 to 45 minutes at 40ºC. Six-inch sample specimens are then compacted with a gyratory compactor at 600 kPa pressure and a 1.25º angle of gyration for 30 gyrations. The compaction is performed at room temperature. Then, the specimens can be cured and conditioned for volumetric and performance tests. The performance tests used by the Colorado method include a modified Hveem cohesiometer test, resilient modulus test, indirect tensile strength test, and moisture sensitivity test following the standard AASHTO and ASTM standards shown in Table 3.

**Table 3. Colorado performance test criteria for selecting optimum emulsion content**

| Property | Criteria | |
|---|---|---|
| | For mixtures containing < 8% passing #200 sieve | For mixtures containing > 8% passing #200 sieve |
| Short-term strength test, 1 hour, modified cohesiometer, AASHTO T 246 (Part 13), g/25 mm of width | > 175 | > 150 |
| Indirect tensile strength (ITS), ASTM D4867, Part 8.11.1, 25ºC, psi | > 40 | > 35 |
| Conditioned ITS, ASTM D4867, psi | > 25 | > 20 |
| Resilient modulus, ASTM D4123, 25ºC, 1000psi | > 150 | > 120 |
| Thermal cracking (IDT), AASHTO T 322 | < -20ºC | < -20ºC |

The specimens for the cohesiometer test are cured at 25ºC for 60 minutes and 10% to 70% humidity. Other specimens are cured at 40ºC for 72 hours and then cooled at room temperature. The optimum emulsion content is selected if the sample meets the criteria in Table 3.

**Illinois Method**. The Illinois DOT does not have a step-by-step mix design method. Instead, the FDR specifications require certain criteria that the designed materials must meet. The method determines the optimum moisture content using the modified proctor test following ASTM D1557, Method C. Six-inch-diameter sample specimens are made with a gyratory compactor using a 1.25º angle of gyration, 600 kPa pressure, and 30 revolutions. The short-term strength (STS) test following ASTM D1560 is conducted, and the results are used as the stability indicator. Indirect tensile strength (ITS) tests following ASTM D4867 are also performed for both dry samples and moisture-conditioned samples. The binder content that allows the sample to meet the requirements in Table 4 is chosen for the application.

**Table 4. Illinois performance test criteria for selecting optimum binder content**

| Property | Criteria | |
|---|---|---|
| | For mixtures containing < 8% passing #200 sieve | For mixtures containing > 8% passing #200 sieve |
| Short-term strength test, ASTM D1560 | > 175 | > 150 |
| ITS, ASTM D4867, psi | > 40 | > 35 |
| Conditioned ITS, ASTM D4867, psi | > 25 | > 20 |

The specifications also establish requirements for asphalt emulsion, which must meet the criteria in Table 5.

**Table 5. Illinois emulsified asphalt material specification for FDR**

| Test | Procedure | Minimum | Maximum |
|---|---|---|---|
| Viscosity, Saybolt Furol, at 25ºC, SFS | AASHTO T 59 | 20 | 100 |
| Sieve Test, No. 20 (850µm), retained on sieve, % | AASHTO T 59 |  | 0.1 |
| Storage Stability Test, 24 hours, % | AASHTO T 59 |  | 1 |
| Distillation Test, Residue from distillation to 175ºC, % | AASHTO T 59 | 64 |  |
| Oil distillate by volume, % | AASHTO T 59 |  | 1 |
| Penetration, 25ºC, 100g, 5s, dmm | AASHTO T 49 | 75 | 200 |

### *Structural Design*

Unstabilized FDR materials (those without the addition of new binder materials or chemical stabilizing agents) are usually treated as a granular base during the structural design process. In Minnesota, a granular equivelant (GE) value of 1, which is equivalent to the structural capacity of a Class 5 aggregate, can be assumed for this type of FDR (Tang et al. 2012). Stabilization agents can noticeably increase the stiffness of FDR materials and, therefore, their structural capacity. A GE value of 1.5 is used for designing the thickness of a stabilized FDR (SFDR) layer (Tang et al. 2012). Nantung et al. (2011) studied the layer coefficient of SFDR using FWD test results (Nantung et al. 2011). The FWD data were collected from a lightly traveled test section with an 8-inch FDR base in Indiana. The results showed that the SFDR layer coefficient ranged from 0.16 to 0.22. A layer coefficient of 0.22 was recommended for SFDR. The strength of the SFDR layer at the time construction is completed is considerably lower than that measured at one or more years after construction. Diefenderfer and Apeagyei (2011a) found that SFDR material attains its ultimate structural capacity at one year after construction, and the ultimate structural capacity is 15% to 45% higher than that when the test sections are recently constructed.

### *FDR Experiences and Life Expectancy*

FDR was first used in the United States in late 1980s and early 1990s. The implementation of and research on FDR has increased rapidly in the last decade. Successful applications have been reported in terms of long-term performance and cost savings (SME 2012). FDR projects on several county roads have been constructed in Minnesota in the past few years (Watson 2012). The life expectancy of an FDR project varies for different material properties, climate conditions, and traffic volumes. In general, FDR treatments with HMA overlays can last for 15 to 20 years (Maher et al. 2005).

### *Specifications*

FDR specifications have been established to address the same issues discussed previously for CIR. The FDR specifications in Colorado, Illinois, Iowa, and Minnesota are reviewed in this section. In comparison to the CIR specifications, the FDR specifications have less strict requirements for RAP gradation, recycling agent type and application rate, equipment, and curing. However, most states have detailed requirements to ensure the quality of compaction.

The primary concern for establishing the compaction requirements is that the difficulty of compacting a thick FDR layer, which is typically more than 6 inches, is much greater than that of compacting a 2- to 4-inch CIR layer. Adequate and uniform compaction must be provided throughout the entire layer thickness. The FDR specifications in the reviewed states are summarized and compared in Table 6.

**Table 6. FDR specifications in various states**

| | Colorado | Illinois | Iowa | Minnesota |
|---|---|---|---|---|
| **RAP Gradation** | 99% to100% passing 1.5 inch sieve | 100% passing 2 inch sieve; 97% to 100% passing 1.5 inch sieve | 98% to 100% passing 1.5 inch sieve; 90% to 100% passing 1 inch sieve | 100% passing 3 inch sieve; 97% to 100% passing 2 inch sieve |
| **Recycling Agent** | Not specified | Determined in specified mix design | HFMS-2s; foamed PG52-34 or PG46-34 asphalt | Not specified |
| **Recycling Agent Application Rate** | Determined in specified mix design | Determined in specified mix design | Use 3% residue binder content or determined in mix design | Not specified |
| **Mineral Stabilizer** | Not specified | Fly ash; maximum 1% cement | Type I Portland cement; fly ash; hydrated lime; limestone fines | Not specified |
| **Rolling Requirements** | Field density > 95% of maximum dry density | Establish test strip and growth curve; compare the field density with the target density determined by the growth curve | Field density at 75% of reclaimed mat depth > 94% of lab sample density for interstate and primary roads; field density at 75% of reclaimed mat depth > 92% of lab sample density for other roads; field density at 2 inches depth > 97% of field density at 75% of reclaimed mat depth | Maintain 3% to 7% moisture content during compaction; DCP test requirements: 0.4 inches DCP index value and 1.5 inches seating value |
| **Equipment** | Require a motor grader, two vibratory pad foot rollers, one 20 ton or greater pneumatic tire roller, and one double drum vibratory steel roller | Require at least one 25 ton or greater pneumatic tire roller, one 10 ton or greater double drum vibratory roller, and one 10 ton or greater pad foot vibratory roller | Require at least one Sheepsfoot roller, one double drum roller, and one 25 ton or greater pneumatic roller | Require at least one 10 ton or greater pad foot vibratory roller and one 25 ton or greater pneumatic roller |
| **Weather Requirement** | Ambient temperature above 50ºF (10ºC) and rising; no rainy or foggy weather | Ambient temperature above 50ºF (10ºC) and rising; no rainy or foggy weather | Not specified | Not specified |
| **Curing and Placement of Surface Course** | Cure the placed FDR material until the moisture content is less than 2.5% or 50% of the optimum moisture content before placement of the surface course | Cure the placed FDR material until the moisture content is less than 2.5% or 50% of the optimum moisture content before placement of the surface course | Not specified | Not specified |

## 2.5 Thin Surface Treatment

Thin surface treatments (TSTs) are thin impermeable bituminous wearing courses that are used to protect the underlying pavement structures from oxidization and water damage. The wearing course thickness is typically about 0.5 inch or less (Li et al. 2007). TSTs are also known as light surface treatments (LSTs) or bituminous surface treatments (BSTs). Typical TST technologies include chip seal, slurry seal, cape seal, sand seal, bonded wearing course, and Otta seal.

### *Chip Seal*

Chip seal is the most common type of TST. A chip seal is constructed by applying an asphalt binder (recently mostly emulsion) and spreading a single-sized aggregate cover on the road surface. Compactors are used to embed the aggregate particles into the asphalt. Mix design procedures have been developed to determine the proper binder and aggregate application rates to achieve an optimum embedment of 70% (Caltrans 2008, Wood et al. 2006). The typical emulsion application rate is 0.25 to 0.44 gallons per square yard and is dependent upon the size of the aggregate and the condition of the substrate (Jahren et al. 2007). The cover aggregate is usually applied at 20 to 30 pounds per square yard. Sometimes a double chip seal is placed to provide additional protection for the pavement structural layers. A double chip seal is constructed by placing a single chip seal and then applying another chip seal treatment with a smaller size of cover aggregate. The life expectancy for a chip seal treatment ranges from three to five years (Maher et al. 2005) (Huang et al. 2009).

### *Slurry Seal*

Slurry seal is a thin film of asphalt mixture made of emulsified asphalt and a graded aggregate. A slurry seal usually provides better surface texture and skid resistance than other TSTs. A special slurry mixing pugmill is needed for producing slurry seal mixtures. Compaction is sometimes helpful for a slurry seal to develop early strength. Microsurfacing is a special type of slurry seal (Gransberg 2010). High-quality aggregates and polymer-modified asphalt emulsion are used to make a microsurfacing mixture. The method is used on roads with high traffic volumes, on which a conventional slurry seal may fail quickly. The typical life expectancy of a slurry seal is three to eight years (Maher et al. 2005) (Huang et al. 2009).

### *Cape Seal*

Cape seal is a treatment that combines a chip seal and a slurry seal. During construction, a chip seal is placed first and a slurry seal is applied on top of the chip seal. This treatment is favored for roads with relatively high traffic volumes and in climatic regions where snowplowing operations are frequent. Snowplowing usually causes noticeable damage to a chip seal surface because the cutting edge of the blade can scrape cover aggregate away from the road surface. The slurry seal has a smoother surface, which mitigates the aforementioned problem. Constructability is a concern for the implementation of a cape seal because it requires two separate operations and sets of equipment.

### *Sand Seal*

A sand seal is constructed by placing an asphalt binder followed by a finely graded aggregate cover. The construction process is similar to that of a chip seal. The treatment is often used as a temporary surface course. It can be applied on top of other TSTs to provide a smooth surface that can benefit from a fine cover aggregate gradation. The main problems related to this method are non-uniformly distributed sand and flushing.

### *Bonded Wearing Course*

A bonded wearing course (e.g., the proprietary product NOVACHIP) is an ultrathin open-graded HMA course overlaying a polymer-modified tack coat. A bonded wearing course is constructed by using a specialized paver that is able to apply the HMA mixture immediately after the tack coat is sprayed. Compaction is usually applied with two passes of a double drum roller. The life expectancy for a bonded wearing course is 10 to 12 years (Russell et al. 2008). The technology can be used for various traffic conditions, including both low-volume and high-volume roads. A cost study showed that the lifecycle cost of a bonded wearing course is less than that of a 2-inch HMA overly while noticeably higher than that of a chip seal (Russell et al. 2008).

### *Otta Seal*

Otta seal is a TST that is similar to a chip or sand seal. It is constructed by applying a soft binder and then placing a graded aggregate cover. The gradation of the cover aggregate is coarser than that of a sand seal, and an Otta seal typically uses locally available aggregates. Compared to a chip seal, an Otta seal layer is thicker and more flexible. The quality and gradation requirements for an Otta seal are less strict compared to those of a chip seal. The benefits of using an Otta seal include higher tolerance to construction quality control problems and better resistance to solar radiation (Overby 1999). However, immediately after construction an Otta seal has a bitumen-rich appearance, which may lead observers to believe that the treatment has a bleeding problem. The “bleeding” appearance will often be corrected by traffic six months after construction (Overby 1999).

# Chapter 3. Informational Survey and Case Study Road Section Selection

A search was conducted for low-volume roads that had been rehabilitated using FDR or CIR and covered with various surface treatments. The objectives were to identify the current extent to which alternative pavement renewal methods have been implemented in Minnesota as well as to locate potential test sections for possible subsequent use as case study sites for performance observations.

## 3.1 Online Survey

An online survey was distributed to the 87 counties in Minnesota. Sixteen counties responded to the survey, including five counties that invited researchers to make contact via a phone interview to provide more information about their experience with the pavement renewal technologies. The survey questions are shown in Appendix A. The survey results indicate that the most commonly used thin surface treatment method (not including an HMA overlay) in Minnesota for covering CIR or FDR is a chip seal. Other similarly used surface treatments include Otta seal, microsurfacing, and ultrathin overlay; however, no actual case study site was found where these treatments had been applied over CIR or FDR layers on paved roads. FDR has been extensively used by the survey respondents. Among the 16 counties that responded to the online survey, 15 counties have constructed roads using FDR. Only 4 of the 16 responding counties have roads that were rehabilitated with CIR technology. A summary of the use of various treatment methods by the respondent counties is shown in Table 7.

**Table 7. Number of roads treated with surface treatments and/or recycling technologies in Minnesota counties that responded to the online survey**

| County | Number of Roads Treated | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Otta Seal | Chip Seal | Slurry Seal | Micro-surfacing | Novachip | Ultrathin Overlay | FDR | CIR |
| Beltrami | 0 | 1 | 0 | 0 | 0 | 0 | 3 | 0 |
| Benton | 0 | 15 | 0 | 0 | 0 | 0 | 15 | 0 |
| Brown | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 6 |
| Dodge Center | 0 | 25 | 0 | 0 | 0 | 0 | 12 | 0 |
| Fillmore | 0 | 1 | 0 | 1 | 0 | 0 | 6 | 8 |
| Goodhue | 1 | 40 | 0 | 0 | 0 | 1 | 14 | 0 |
| Houston | 0 | 2 | 0 | 0 | 0 | 0 | 5 | 0 |
| Kittson | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 |
| Lake | 0 | 3 | 0 | 0 | 0 | 0 | 2 | 0 |
| Le Sueur | 0 | 50 | 0 | 0 | 0 | 0 | 3 | 20 |
| Nobles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Olmsted | 0 | 0 | 0 | 5 | 0 | 0 | 20 | 33 |
| Rock | 0 | 20 | 0 | 0 | 0 | 0 | 2 | 0 |
| St Louis | 0 | 0 | 0 | 0 | 0 | 1 | 400 | 0 |
| Watonwan | 0 | 30 | 0 | 0 | 0 | 0 | 1 | 0 |
| Wright | 0 | 15 | 0 | 0 | 0 | 0 | 15 | 0 |

Most of the respondents reported satisfactory performance for their FDR and CIR applications, while personnel in only one county observed considerable transverse cracking in FDR sections. Two respondents reported that they are still evaluating the long-term performance of their FDR roads. The majority of FDR projects did not involve the use of a stabilization agent. A problem that was reported for the stabilized FDR (SFDR) sections included having to process wet pavement material due to having the wrong consistency of oil; this resulted in poor performance and poor cost effectiveness. Moreover, Benton County indicated that the life expectancy of a chip seal treatment is five years. In addition to the treatment types that respondents could choose in the online survey, Nobles County applied a fog seal treatment, and this fog seal section has reportedly performed well.

The survey also investigated the current use of decision tools for selecting pavement renewal treatments within local agencies in Minnesota. Most counties select the type of treatment for pavement renewal based on past experience. Road surface condition, pavement age, and cost are the primary factors that are considered in order to make a decision. Some agencies also consider the output from pavement management information systems (PMIS), FWD test results, or cost analysis in the decision making process. Two counties, Benton and Brown, use a spreadsheet decision tool to assist in the selection of appropriate treatments for renewing deteriorated pavements.

### 3.2 Candidate Test Section Search

Candidate test sections with potentially high research value were identified through phone interviews with Minnesota county engineers, contacts in the pavement rehabilitation industry, and the literature. Appendix B documents the phone interview questions. The survey questions were sent via email to the five counties that expressed an interest in participating in a phone interview when responding to the online survey. Follow-up calls were made to schedule the calls to conduct the survey. County engineers in Beltrami County, Brown County, Goodhue County, Olmsted County, and St. Louis County in Minnesota; Barnes County in North Dakota; and Buffalo County in Wisconsin were contacted for the phone interviews. Three counties, including Beltrami, Brown, and Barnes, have constructed pavement sections with CIR or FDR and a surface treatment. Goodhue County has constructed pavement sections using FDR and an asphalt overlay. These sections are also included in this study and serve as a comparison group. The remaining counties did not report roads that were rehabilitated using treatments of interest for this research. Test sections on IA 93 in Iowa were also of interest for this study. The Iowa test sections were constructed for an Iowa DOT research project on pavement holding strategies in which the authors of this report participated. In this section of the report, project information such as treatment type, pavement structure, construction year, and subgrade soil condition is introduced for each candidate test section.

#### *Beltrami County*

The projects recommended by Beltrami County for this study are three FDR sections on CSAH 5, CSAH 34, and CSAH 36, respectively (Figure 1).

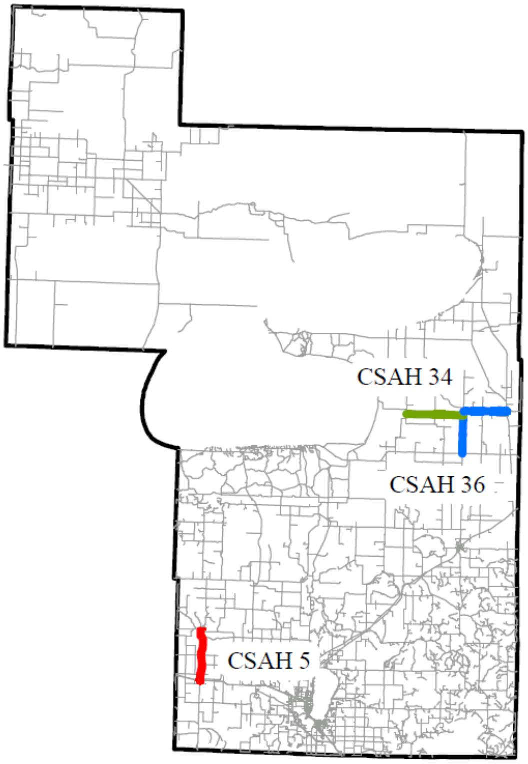

Figure 1. Beltrami County test sections

The treatments for the three sections were completed in the summer of 2014, and county personnel are currently monitoring performance. All three of these routes are two-lane rural roads. The project lengths are 5.6 miles, 6 miles, and 10.5 miles for CSAH 5, CSAH 34, and CSAH 36, respectively. The traffic levels, subgrade soil conditions, and design ESALs of the three sections are summarized in Table 8.

**Table 8. Traffic level, subgrade soil condition, and design ESALs of Beltrami County FDR sections**

| | ADT in 2014 | Heavy Commercial ADT (HCADT) in 2014 | Subgrade Soil R-Value | Soil Factor and AASHTO Classification | Design ESAL |
|---|---|---|---|---|---|
| **CSAH 5** | 557 | 75 | 20 | 100% (A-2, A-4) | 250,750 |
| **CSAH 34** | 580 | 78 | 10 | 130% (A-2) | 280,815 |
| **CSAH 36** | 242 | 32 | 12 | 130% (A-2) | 93,412 |

The R-values and soil factors in Table 2 are assumed to be typical design values for Beltrami County. Schematic illustrations of the pavement structures are shown in Figures 2 through 4.

**Figure 2. Schematic illustration of pavement structure for Beltrami County CSAH 5**

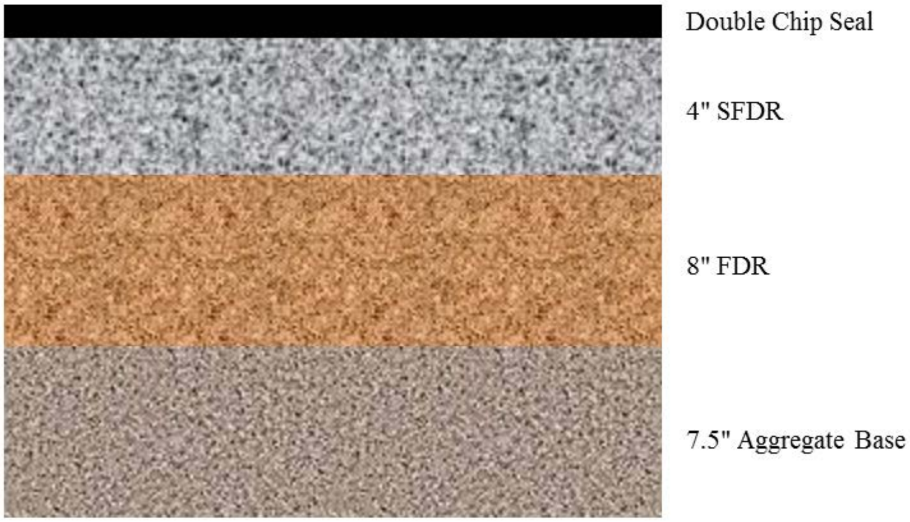

**Figure 3. Schematic illustration of pavement structure for Beltrami County CSAH 34**

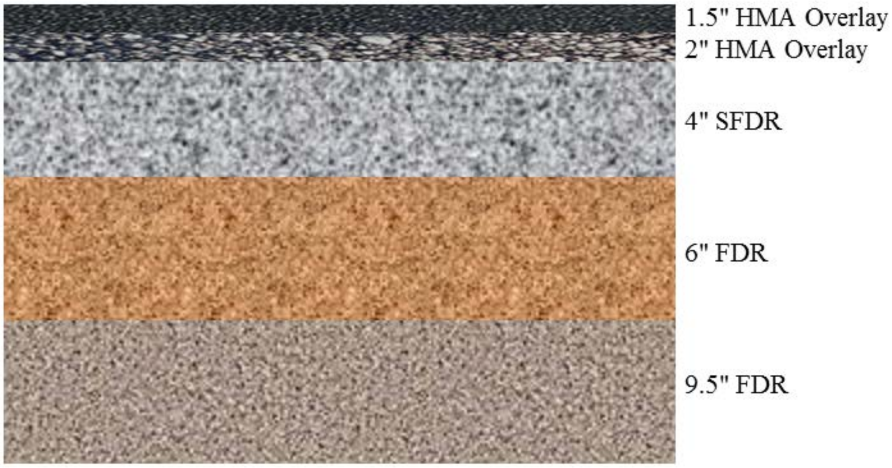

**Figure 4. Schematic illustration of pavement structure for Beltrami County CSAH 36**

The pre-existing pavement of CSAH 5 included a 4.5-inch bituminous surface and an 11-inch aggregate base. The rehabilitation treatment involved a 4-inch FDR layer and a 4-inch SFDR layer with a 3.5-inch overlay, including a 1.5-inch wearing course and a 2-inch binder course. The thickness of the existing structure of CSAH 34 was about 20 inches total. The bituminous layer of the pre-existing pavement varied from 3 to 6 inches. During the construction project, an 8-inch FDR layer and a 4-inch SFDR layer were applied, and then a double chip seal surface treatment was placed. A fog seal layer was applied over the double chip seal. In the summer of 2015, a third chip seal was placed. The pre-existing structure for CSAH 36 was 19.5 inches thick, total, including 5.5 inches of bituminous surface. The rehabilitation treatment involved constructing a 6-inch FDR layer and a 4-inch SFDR layer. A 1.5-inch overlay was placed as the wearing course with a 2-inch binder course underlying. BaseOne stabilization agent was applied to the SFDR layer for all three projects. The construction costs per road mile were reported by the county engineer as $270,000, $115,000, and $220,000 for CSAH 5, CSAH 34, and CSAH 36, respectively.

*Brown County*

The projects recommended by Brown County for this study are three CIR sections on CSAH 11, CSAH 22, and CSAH 27, respectively (Figure 5).

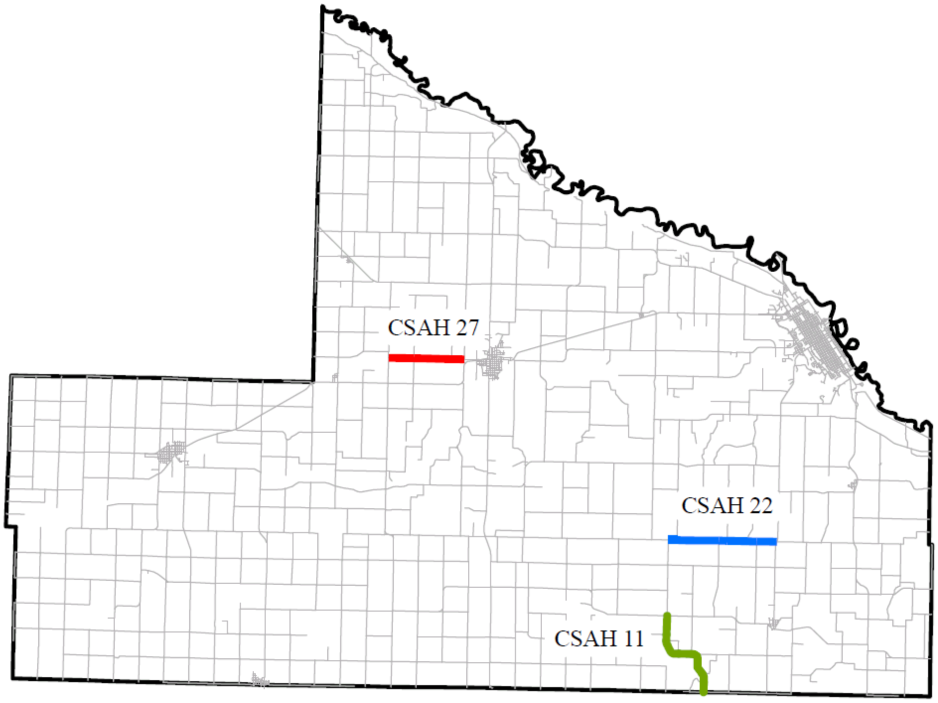

**Figure 5. Brown County test sections**

The three county roads are two-lane rural highways. Table 9 summarizes the year in which each treatment was constructed, project length, traffic level, and subgrade soil conditions for each road section.

### Table 9. Construction information and traffic and subgrade soil conditions of Brown County CIR sections

| | Year of Treatment Construction | Project Length | ADT | Percent Truck in ADT | Soil Factor | Subgrade Soil R-Value and Soil Classification |
|---|---|---|---|---|---|---|
| **CSAH 11** | 2013 | 4 miles | 160 | 10% | 100% | 12 (A-7-5, A-7-6) |
| **CSAH 22** | 2012 | 4.3 miles | 455 | 10% | 100% | 12 (A-4) |
| **CSAH 27** | 2010 | 2.3 miles | 800 | 10% | 100% | 12 (A-4) |

The R-values and soil factors in Table 9 are assumed to be typical design values for Brown County.

Schematic illustrations of the pavement structures are shown in Figures 6 through 9.

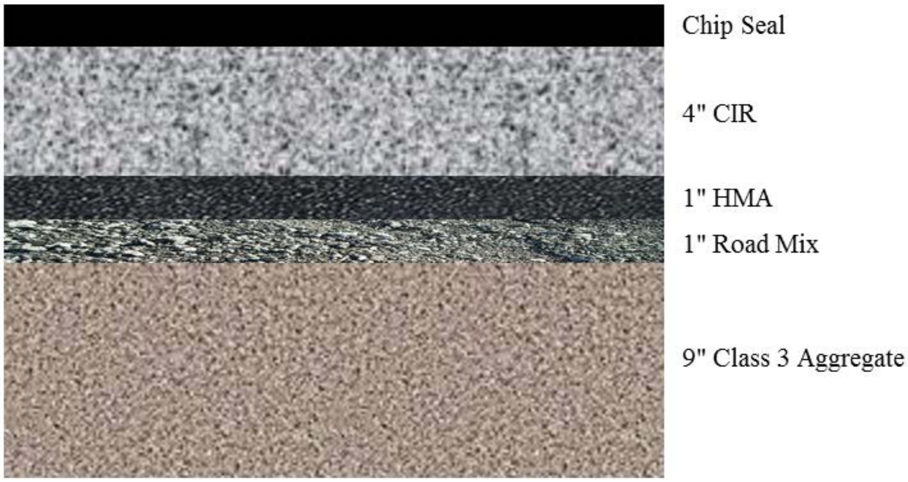

**Figure 6. Pavement structure for Brown County CSAH 11**

**Figure 7. Pavement structure for Brown County CSAH 22 Section I**

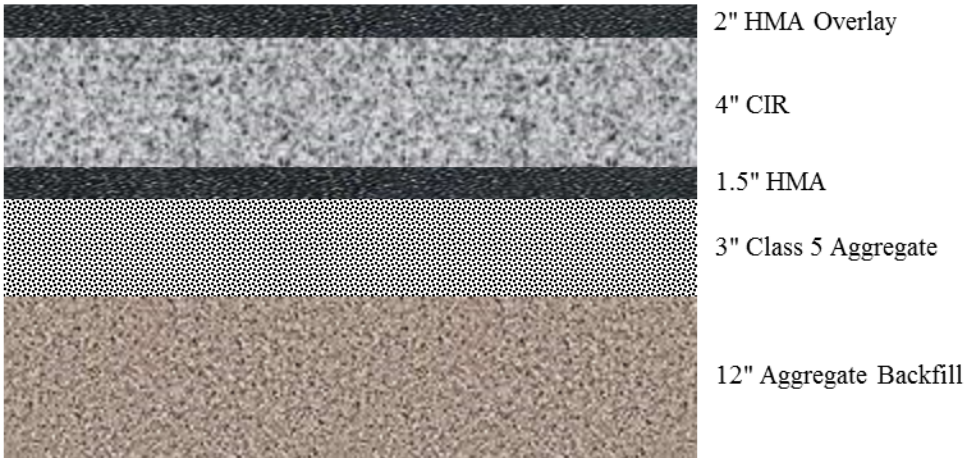

Figure 8. Pavement structure for Brown County CSAH 22 Section II

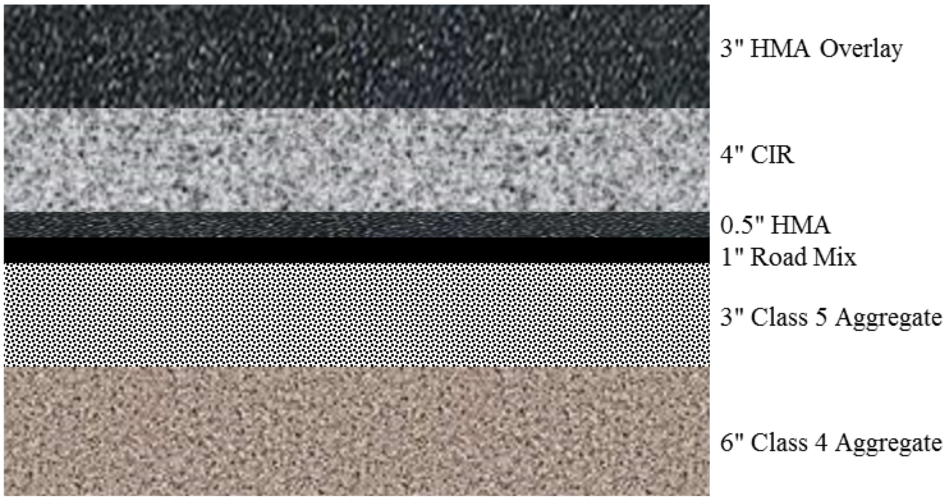

Figure 9. Pavement structure for Brown County CSAH 23

The pre-existing pavement section for CSAH 11 included a 4.5-inch bituminous surface, 1 inch of road mix (a cold mix asphalt concrete), and a 9-inch Class 3 aggregate base. The rehabilitation treatment involved a 4-inch CIR layer and a chip seal surface. CSAH 22 includes two sections that had different layer structures. Section I consisted of a 5.5-inch bituminous surface and a 9-inch Class 5 aggregate base. The pre-existing pavement of Section II included a 5.5-inch bituminous surface overlaying a 3-inch Class 5 aggregate base and 12 inches of aggregate backfill. Both sections received a 4-inch CIR treatment and a 2-inch HMA overlay. The pre-existing pavement section for CSAH 27 consisted of a 4.5-inch bituminous surface, 1 inch of road mix, a 3-inch Class 5 aggregate base, and a 6-inch Class 4 aggregate subbase. The section received a 4-inch CIR treatment and a 3-inch HMA overlay. The construction costs were reported by the county engineer as $359,287, $862,459, and $541,695 for CSAH 11, CSAH 22, and CSAH 27, respectively.

*Goodhue County*

The projects recommended by Goodhue County for this study are three FDR sections on CSAH 7 and CSAH 11 (Figure 10).

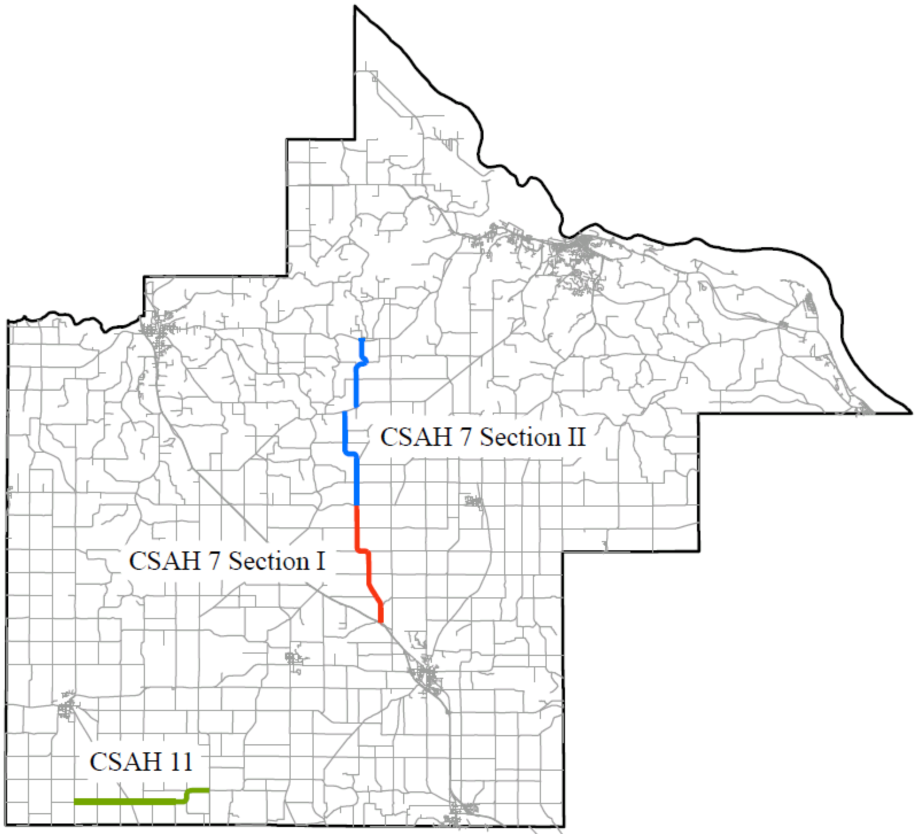

**Figure 10. Goodhue County test sections**

CSAH 7 and CSAH 11 are two-lane rural highways that are functionally characterized as minor collectors. Table 10 summarizes the year in which the treatment was constructed, project length, traffic level, and subgrade soil conditions for each road section.

**Table 10. Construction information and traffic and subgrade soil conditions of Goodhue County FDR sections**

| | Year of Treatment Construction | Project Length | ADT | Percent Truck in ADT | Soil Factor (%) or R-value and Soil Classification | Design ESAL |
|---|---|---|---|---|---|---|
| **CSAH 7 Section I** | 1998 | 5.6 miles | 441 | 5.9% | 130% (A-6) | 66,761 |
| **CSAH 7 Section II** | 2005 | 7.5 miles | 574 | 5.9% | 130% (A-6) | 66,761 |
| **CSAH 11** | 2012 | 6.2 miles | 513 | 5.9% | 20 (A-6) | 52,387 |

The R-values and soil factors in Table 10 are assumed to be typical design values for Goodhue County. Schematic illustrations of the pavement structures are shown in Figures 11 through 13.

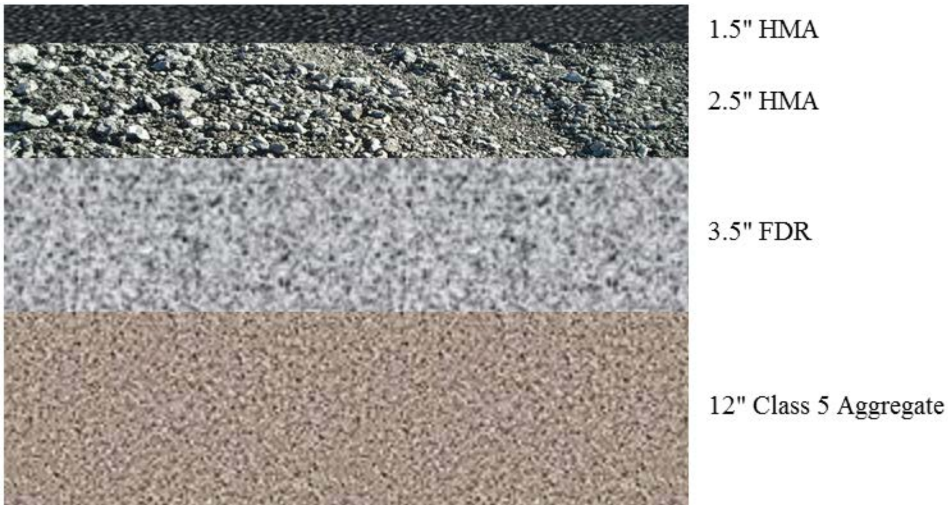

Figure 11. Pavement structure for Goodhue County CSAH 7 Section I

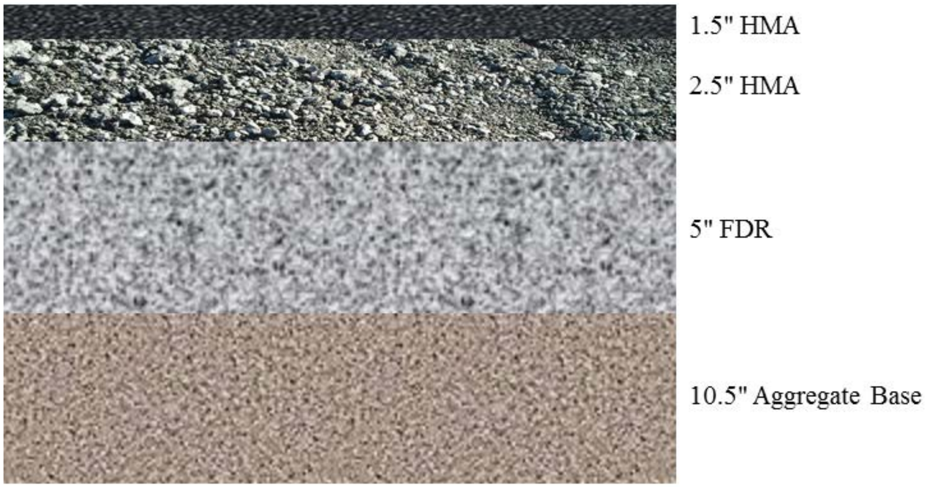

Figure 12. Pavement structure for Goodhue County CSAH 7 Section II

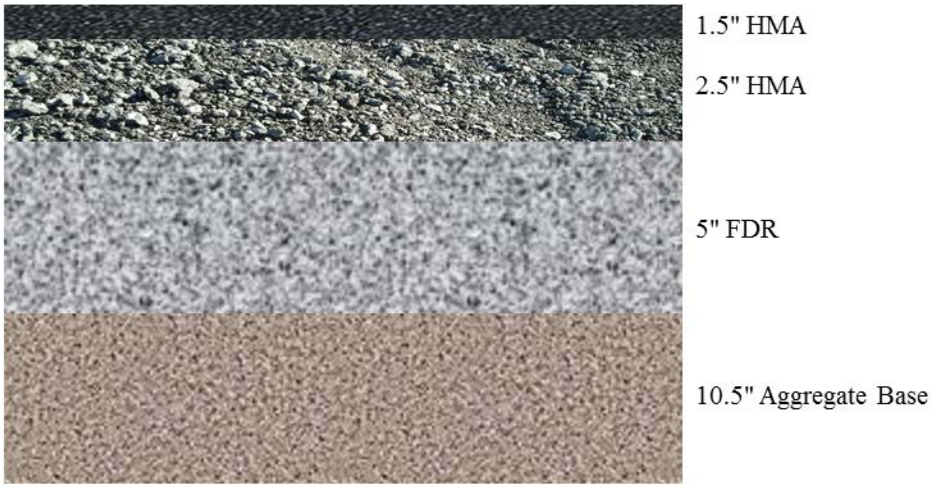

Figure 13. Pavement structure for Goodhue County CSAH 11

The pre-existing pavement of CSAH 7 included a 3.5-inch bituminous surface and a 12-inch Class 5 aggregate base. The rehabilitation treatment for Section I involved a 3.5-inch FDR layer and a 4-inch bituminous overlay. The 4-inch HMA overlay was constructed as two layers: a 1.5-inch wearing course and a 2.5-inch leveling course. The rehabilitation treatment for Section II used a 5-inch FDR layer and an HMA surface layer similar to that of Section I. The existing pavement of CSAH 11 consisted of a 6-inch bituminous surface and a 9-inch aggregate base. The section was milled 2 inches prior to reclamation. The FDR treatment reclaimed the remaining 4 inches of in-place bituminous material and 1-inch of aggregate base. A 2.5-inch leveling course and a 1.5-inch wearing course were placed to cover the FDR layer. The construction costs were reported by the county engineer as $484,519, $935,824, and $1,434,831 for CSAH 7 Section I, CSAH 7 Section II, and CSAH 11, respectively. The maintenance treatments and costs for each of the sections are summarized in Table 11.

**Table 11. Maintenance activities and costs for Goodhue County FDR sections**

| **CSAH 7 Section I** | **CSAH 7 Section II** | **CSAH 11** |
|---|---|---|
| Seal coat in 2000 cost $33,071 | Seal coat in 2007 cost $65,829 | Crack filling in 2014 cost $6,177 |
| Crack filling in 2003 cost $940 | Crack filling in 2007 cost $924 | Seal coat in 2014 cost $128,966 |
| Seal coat in 2007 cost $57,740 | Seal coat in 2011 cost $89,698 | |
| Crack filling in 2007 cost $845 | Crack filling in 2011 cost $806 | |
| Crack filling in 2012 cost $6,413 | | |

### *Barnes County (North Dakota)*

Barnes County constructed two CIR sections on County Road 21 (CO 21) in 2007 and 2009, respectively (Figure 13).

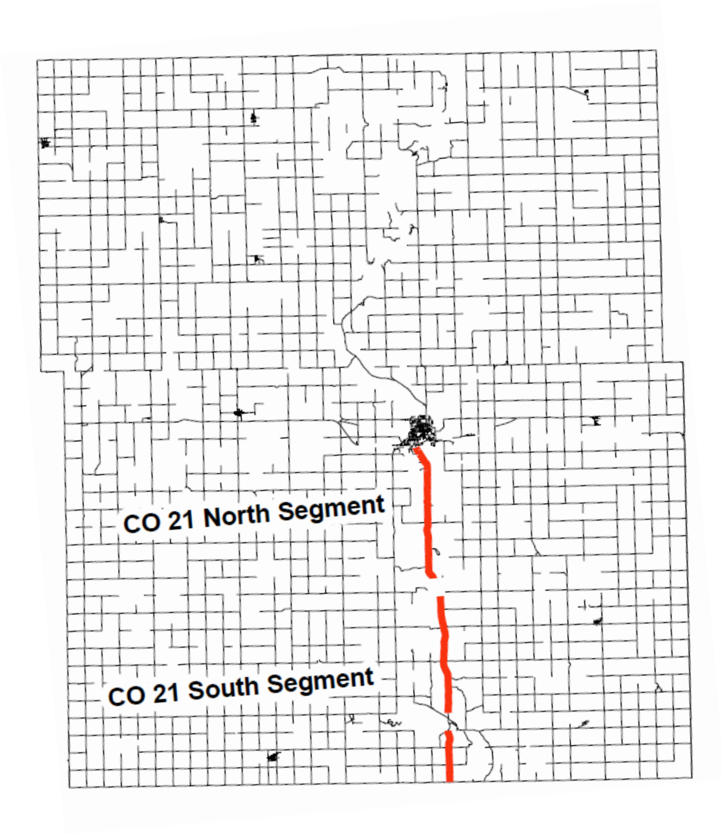

**Figure 14. Barnes County test sections**

The north segment, which was constructed in 2007, has an ADT of 584, including 14.5% trucks. The north one-third mile of the north segment, which is in the vicinity of the Valley City municipal area, is subjected to a high traffic volume of 1,861 ADT, including 16.6% trucks. The south segment, which was constructed in 2009, has an ADT of 830, including 3% trucks. The traffic and subgrade conditions are summarized in Table 12.

**Table 12. Traffic and subgrade soil conditions of Barnes County CIR sections**

| | Year of Treatment Construction | Project Length | ADT | Percent Truck in ADT | Subgrade Soil Condition |
|---|---|---|---|---|---|
| **CO 21 North Segment** | 2007 | 6.6 miles | 584 | 14.5% | CBR: 5.5–6<br>Modulus: 6800–7800 psi<br>AASHTO Classification: A-7-6 |
| **CO 21 North Segment (north 1/3 mile)** | 2007 | 0.3 miles | 1,551 | 16.6% | |
| **CO 21 South Segment** | 2009 | 7 miles | 830 | 3% | |

The existing pavement for the north segment had a 6-inch aggregate base and 5.5 inches of bituminous material. The construction process involved recycling 4 inches of the pre-existing pavement and applying a chip seal layer on the surface (Figure 15).

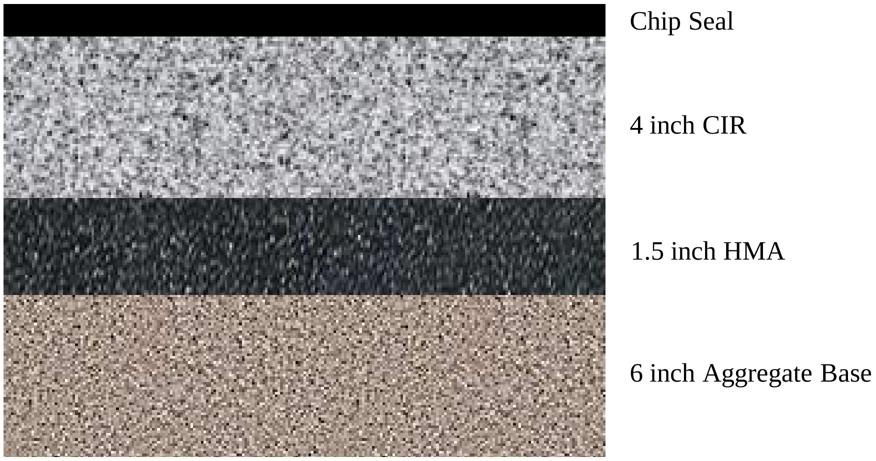

**Figure 15. Pavement structure for Barnes County CO 21 north segment**

A 1.5-inch asphalt overlay was placed on the north 2,500 feet of the north segment due to the higher traffic volume. In 2009, a microsurfacing layer was placed to correct rutting, which was thought to have resulted from large rain precipitation events that occurred before and during the curing of the chip seal layer. The pre-existing pavement for the south segment had a 6-inch aggregate base and 6.5 inches of bituminous material. A 4-inch CIR layer was constructed, and a chip seal surface was applied (Figure 16).

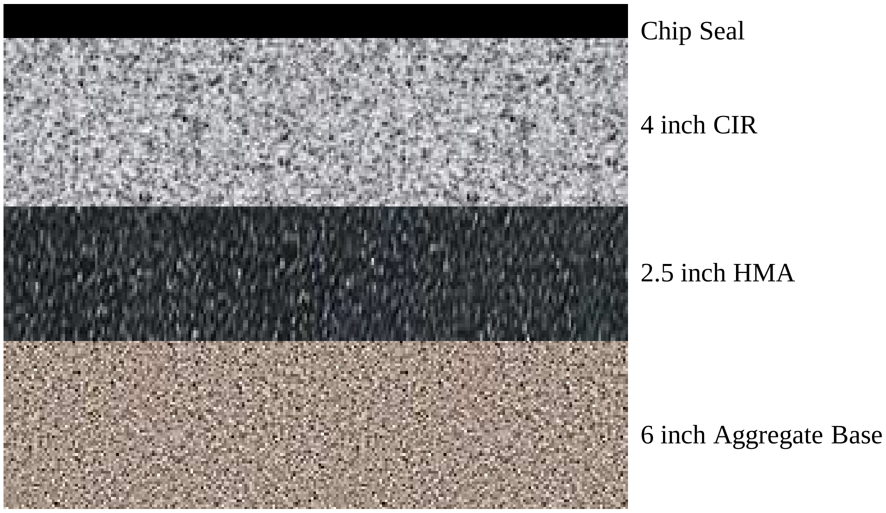

**Figure 16. Pavement structure for Barnes County CO 21 south segment**

During the construction process, approximately 2,500 feet of the south segment failed under the milling machine due to insufficient structural support. These areas were strengthened with a 1.5-inch asphalt overlay. Other than the aforementioned rutting problem on the north segment, both segments have performed satisfactorily. The cost for the CIR construction was $532,752 for the north segment and $644,158 for the south segment. The county did not provide the cost of the additional overlay and chip seal treatment. During a field visit conducted in August 2015, preparations were being made to place a hot-mix asphalt overlay on all of the aforementioned segments of CO 21.

### *IA 93 Sections*

IA 93 is a two-lane rural highway that connects Sumner and Fayette, Iowa, and carries an ADT of 1,040, with 3% heavy vehicles. The pre-existing pavement consisted of 7 to 8 inches of bituminous material and a 6-inch aggregate base. Ten holding strategy treatments were applied in 2013. The lengths and features of each treatment are summarized in Table 13.

**Table 13. IA 93 rehabilitation treatments**

| Base Treatment | Surface Treatment | Section Length, Mile |
|---|---|---|
| 1-inch scarification | 1.5-inch HMA overlay | 1.3 |
| 1-inch scarification | 1.5-inch HMA overlay and single chip seal | 2.0 |
| 1-inch scarification and 1-inch interlayer course | 0.75-inch ultrathin HMA overlay | 2.2 |
| 8-inch full depth reclamation | 1.5-inch HMA overlay | 1.0 |
| 8-inch full depth reclamation | double chip seal | 0.4 |
| 2.5-inch cold-in-place recycling | double chip seal | 1.4 |
| 2.5-inch cold-in-place recycling | 1.5-inch HMA overlay | 1.6 |
| none | 2-inch HMA overlay | 1.4 |
| 1-inch leveling and strengthening course | single chip seal | 1.9 |
| 1-inch scarification | single chip seal | 0.3 |

The subgrade soil has an average resilient modulus of 20 ksi. The cost for each section is shown in Table 14.

**Table 14. IA 93 test section construction costs**

| Treatment | Cost/Road Mile |
|---|---|
| 1-inch scarification + 1.5-inch HMA overlay | $104,189 |
| 1-inch scarification + 1.5-inch HMA overlay + chip seal | $130,699 |
| 1-inch scarification + 1-inch interlayer + 0.75-inch HMA overlay | $153,463 |
| 8-inch FDR + 1.5-inch HMA overlay | $181,938 |
| 8-inch FDR + double chip seal | $146,822 |
| 2.5-inch CIR + double chip seal | $94,048 |
| 2.5-inch CIR + 1.5-inch HMA overlay | $129,984 |
| 2-inch HMA overlay | $119,045 |
| 1-inch leveling and strengthening course + chip seal | $99,754 |
| 1-inch scarification + chip seal | $65,721 |

### 3.3 Selection of Case Study Projects

The test sections in Beltrami County and Brown County and on IA 93 were selected because they have high value from a research perspective. The traffic levels, climate conditions, and subgrade soils are very similar within the same county or area, which could minimize the performance variations caused by these factors. The sections have similar structural layers but different surface treatments, including lower-cost pavement rehabilitation alternatives that could serve as experimental test sections and conventional treatments that could serve as control sections. This variety could allow the research team to compare the effects of different surface treatments on pavement performance.

Of the IA 93 sections, the FDR and CIR sections were selected for this study. The FDR or CIR treatments with a chip seal surface are lower-cost rehabilitation alternatives that are of interest based on the results of the literature search and survey results. However, these sections have been very recently constructed, and long-term performance data are not available.

The test sections in Goodhue County are FDR sections with conventional thick HMA overlays. Although the treatments may not be low-cost alternatives, these sections were selected because the performance and maintenance information could help to provide comparison points. Both Barnes County and Brown County have constructed CIR layers with chip seal treatments. Satisfactory performance was reported for the Barnes County sections, while the test section in Brown County has experienced considerable cracking and loss of chip seal aggregate. These sections were selected because investigating the differences in the materials, pavement structures, traffic volumes, climates, and subgrade soil conditions will be useful for developing criteria for selecting good candidate roads or developing guidelines for alternative maintenance methods.

# Chapter 4. Pavement Condition Survey Results

This section summarizes the results of pavement condition surveys for the selected test sections (Table 15).

**Table 15. Test sections and treatments**

| County | Road ID | Treatment | Year of Construction |
|---|---|---|---|
| Barnes County (North Dakota) | CO 21 North | 4-inch CIR + chip seal + microsurfacing (placed in 2009) | 2007 |
|  | CO 21 South | 4-inch CIR + chip seal | 2009 |
| Beltrami County (Minnesota) | CSAH 5 | 4-inch FDR + 4-inch SFDR + 1.5-inch AC | 2014 |
|  | CSAH 34 | 4-inch FDR + 4-inch SFDR + double chip seal | 2014 |
|  | CSAH 36 | 6-inch FDR + 4-inch SFDR + 1.5-inch AC | 2014 |
| Brown County (Minnesota) | CSAH 11 | 4-inch CIR + chip seal | 2013 |
|  | CSAH 22 | 4-inch CIR + 2-inch AC | 2012 |
|  | CSAH 27 | 4-inch CIR + 3-inch AC | 2010 |
| Goodhue County (Minnesota) | CSAH 11 | 5-inch FDR + 4-inch AC | 2012 |
|  | CSAH 7I | 3.4-inch FDR + 4-inch AC | 1998 |
|  | CSAH 7II | 5-inch FDR + 4-inch AC | 2005 |
| Fayette County (Iowa) | IA 93 – MC 4 | 8-inch SFDR + 1.5-inch AC | 2013 |
|  | IA 93 – MC 5 | 8-inch SFDR + double chip seal | 2013 |
|  | IA 93 – MC 6 | 2.5-inch CIR + double chip seal | 2013 |
|  | IA 93 – MC 7 | 2.5-inch CIR + 1.5-inch AC | 2013 |

The performance of the test sections was evaluated qualitatively and quantitatively. The survey results were used to compare various rehabilitation treatments and analyze the cost-effectiveness of each treatment. For each test section with the exception of Goodhue County test section CSAH 7-II, three 500 foot survey sections were selected. Goodhue County test section CSAH 7-II is considerably longer and has two disconnected segments; therefore, road condition surveys were performed for three survey sections on both of the segments to account for the variations in the two segments.

The road performance properties that were assessed include surficial distresses and defects, such as transverse and longitudinal cracking, fatigue cracking, stripping, raveling, potholes, rutting, and road roughness. Total linear lengths and affected areas were recorded for transverse and longitudinal cracking and fatigue cracking, respectively. The severity of cracking was evaluated according to the FHWA’s *Distress Identification Manual for the Long-Term Pavement Performance Program* (Geiger 2005). Rutting was measured on wheel paths using a measuring device equipped with a 4 foot straight edge and a vertical ruler (Figure 17).

**Figure 17. Deflectometer for measuring rutting**

A smartphone-based application, Roadroid, was used to estimate the international roughness index (IRI) values of the test sections. Roadroid was developed by Swedish scientists Hans Jones and Lars Forslof. This smartphone application collects vibration data from the built-in acceleration sensor of the smartphone and correlates the vibration readings to IRI. The application is able to provide 80% reliability for an information quality level (IQL) of 3, which can be used for program analysis or detailed planning (Jonhes and Forslof 2014). During testing, a smartphone was attached to the windshield of a mid-size car (2014 Ford Taurus) using a car mount for a mobile phone. The application calibrates the vibration readings for vehicle type and speed. However, in order to achieve a higher consistency of data, the vehicle speed was maintained at 50 miles per hour while the phone recorded the readings.

## 4.1 Surficial Distresses

The results of the pavement condition surveys show that the predominant distress type for all of the test sections is transverse cracking. Therefore, transverse cracking is used as the primary performance indicator for analysis and comparison in this chapter. Figure 18 shows the linear length of transverse cracking on both traffic lanes per one mile of the test roads.

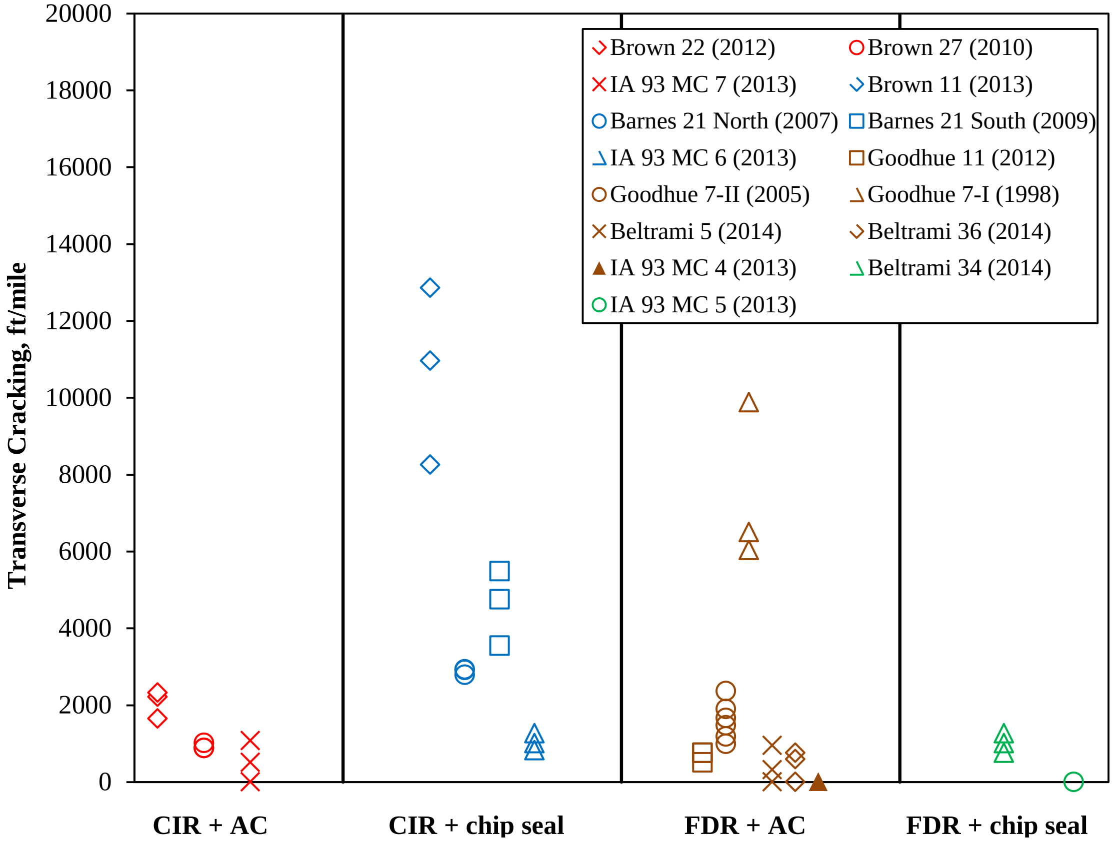

**Figure 18. Observed transverse cracking**

The roads that received a 3.5-inch FDR treatment and a 4-inch asphalt overlay in Goodhue County exhibited higher transverse cracking density than the other test roads, with exception of the road in Brown County, which received a 4-inch CIR treatment and a chip seal. However, the FDR road in Goodhue County (CSAH 7-I) was constructed in 1998, which was 7 to 16 years earlier than the other test roads. With the exception of Goodhue County CSAH 7-I, the roads with FDR treatments, regardless of surface type, or CIR treatments with an asphalt overlay showed better performance than the roads with CIR treatments and a chip seal surface. Figure 19 shows that, in general, the FDR sections exhibited better performance than the CIR sections, except for Goodhue County CSAH 7-I. This trend is more noticeable when the test sections within the same county are compared.

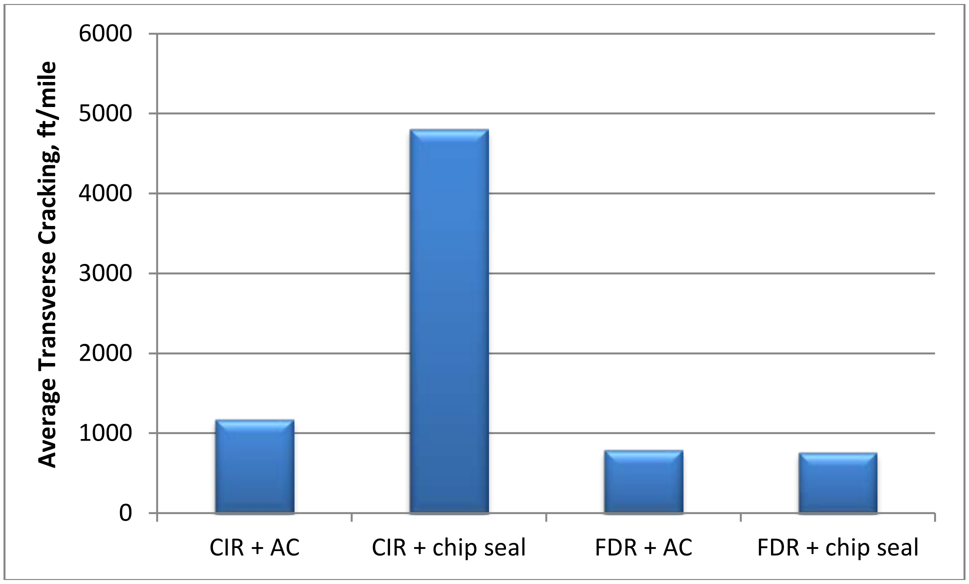

**Figure 19. Average transverse cracking densities for various treatments (Goodhue CSAH 7-I is excluded)**

The FDR roads with a double chip seal surface (Beltrami County CSAH 34 and IA 93 Test Section 5) performed comparably to other FDR roads. However, a p-value of 0.0587 was calculated for comparisons between Beltrami County CSAH 34 and the other FDR roads in Beltrami County. (A p-value smaller than 0.05 is considered statistically significant at the 95% confidence level.) This implies that a performance difference may exist between FDR roads with different types of surface. Given the fact that the treatments for Beltrami County CSAH 34 were applied recently, further monitoring of road performance will be required to fully evaluate the effectiveness of the treatment. Table 16 summarizes the average percent of transverse cracking of moderate and high severity for the test roads.

**Table 16. Crack severity of transverse cracking**

| County | Road ID | Transverse Crack Density, ft/mile | % Moderate and High Severity Transverse Crack | Coefficient of Variance (COV), % |
|---|---|---|---|---|
| Barnes | CO 21 North | 2,876 | 0 | Not applicable |
| | CO 21 South | 4,597 | 12 | 30 |
| Beltrami | CSAH 5 | 422 | 0 | Not applicable |
| | CSAH 34 | 1,014 | 0 | Not applicable |
| | CSAH 36 | 451 | 0 | Not applicable |
| Brown | CSAH 11 | 10,694 | 13 | 35 |
| | CSAH 22 | 2,063 | 56 | 53 |
| | CSAH 27 | 950 | 100 | Not applicable |
| Goodhue | CSAH 11 | 676 | 100 | Not applicable |
| | CSAH 7-I | 1,598 | 8 | 173 |
| | CSAH 7-II | 7,476 | 46 | 47 |
| Fayette | IA 93 MC 4 | 0 | 0 | Not applicable |
| | IA 93 MC 5 | 0 | 0 | Not applicable |
| | IA 93 MC 6 | 1,035 | 0 | 22 |
| | IA 93 MC 7 | 528 | 0 | 102 |

Cracks with less than a 6 mm opening are defined as low severity. High-severity cracking refers to crack openings that exceed 19 mm (Geiger 2005). The results show no correlation between the severity of cracking and cracking density. All high-severity cracks were properly filled using crack filling materials.

Figures 20 through 24 compare surficial distresses among the test sections in each of the counties, respectively.

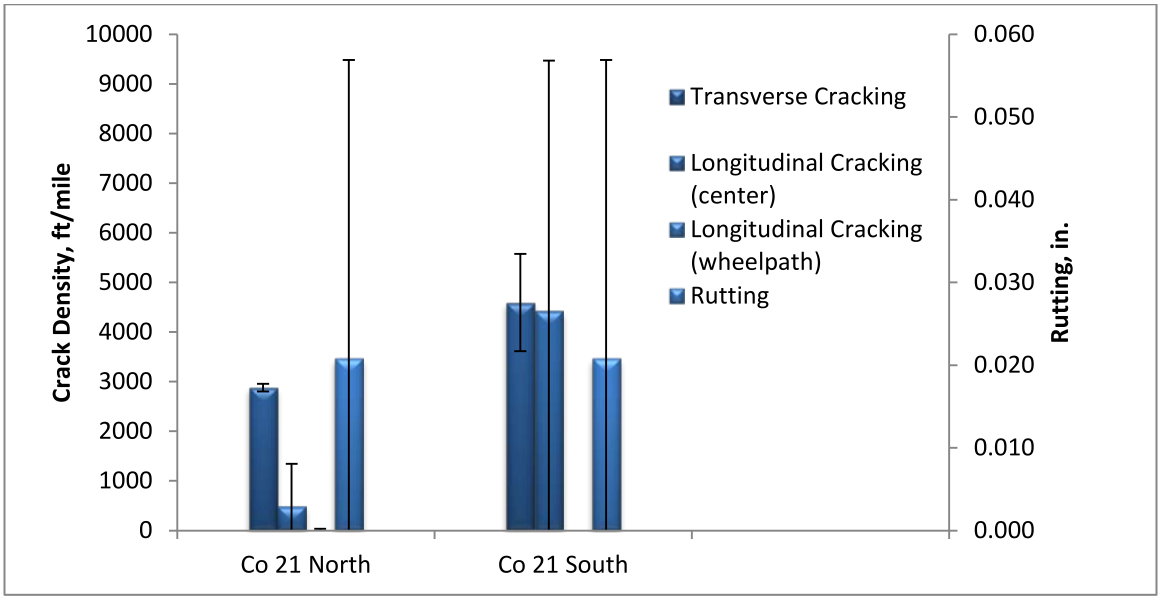

Figure 20. Survey results for cracking and rutting on Barnes County test sections

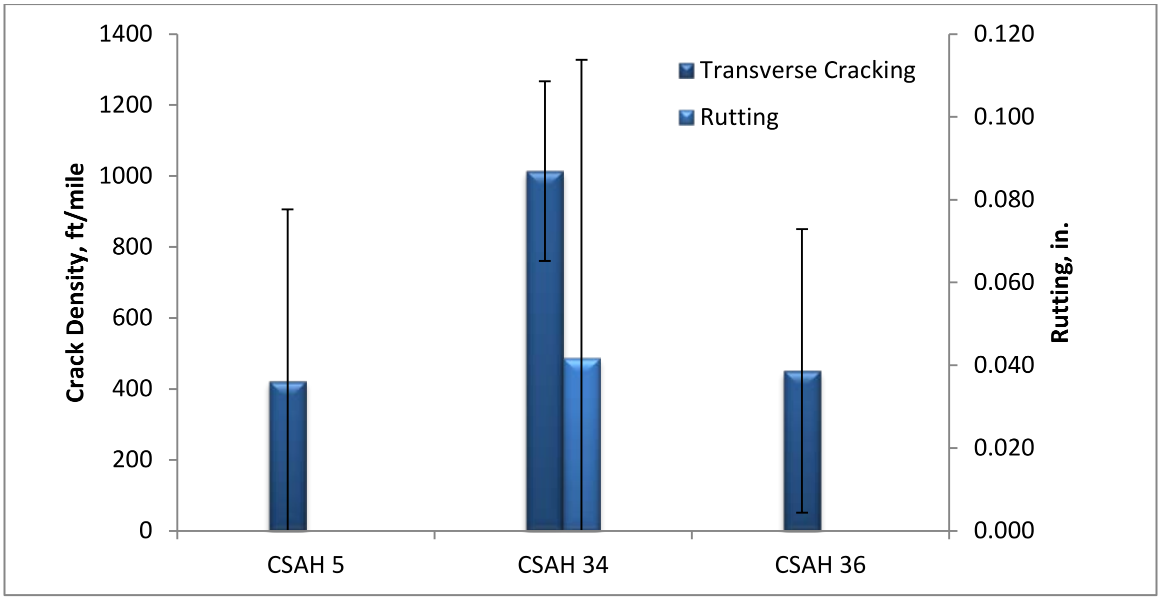

Figure 21. Survey results for cracking and rutting on Beltrami County test sections

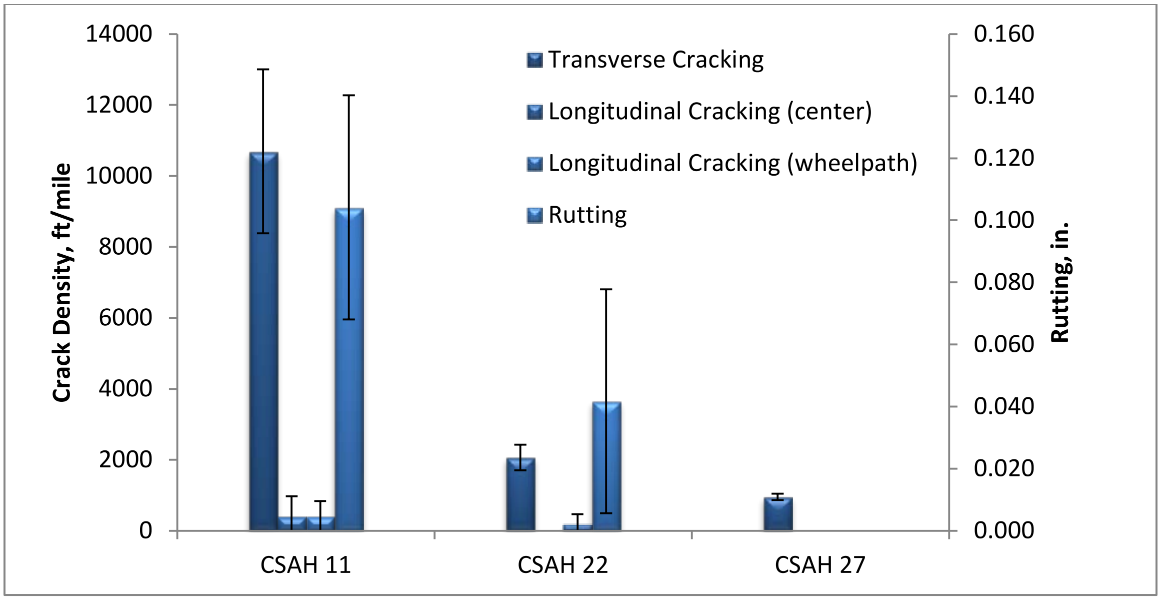

Figure 22. Survey results for cracking and rutting on Brown County test sections

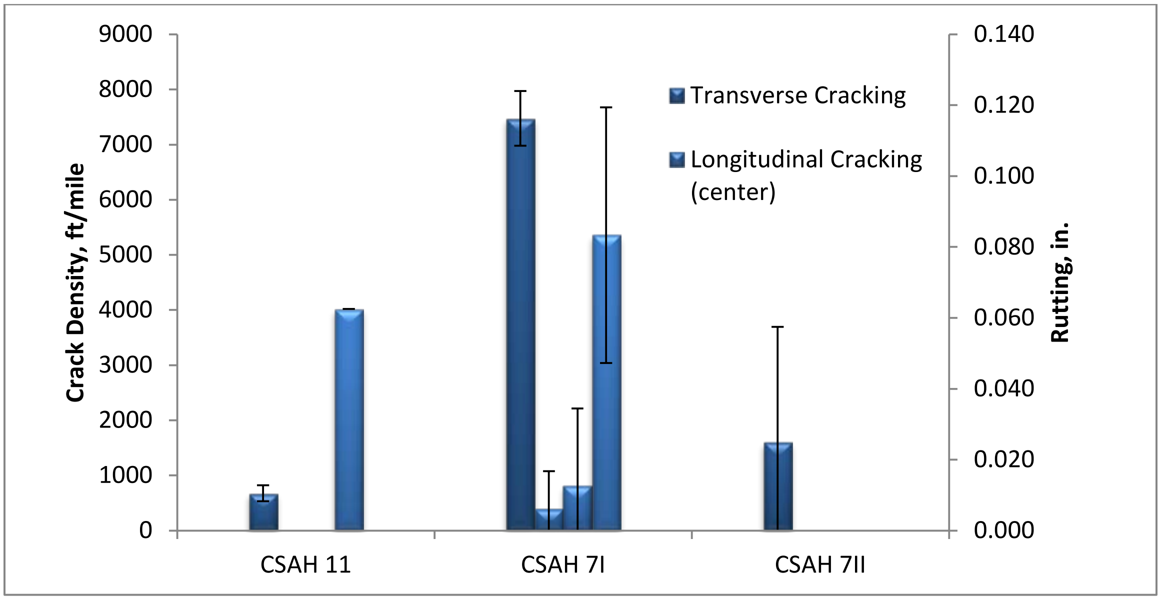

Figure 23. Survey results for cracking and rutting on Goodhue County test sections

The error bars in Figures 20 through 24 show one standard deviation of data. A large error bar indicates that the variations in the data are large. Longitudinal cracking in both wheel paths and between the wheel paths was found rarely except on Barnes County CO 21 South, which has an exceptionally high center lane longitudinal cracking density. However, the large variation indicates that the problem is localized. All longitudinal cracks are of low severity. Minor rutting was found on some of the test roads. The depths of rutting typically ranged between 1/16 and 1/8 of an inch.

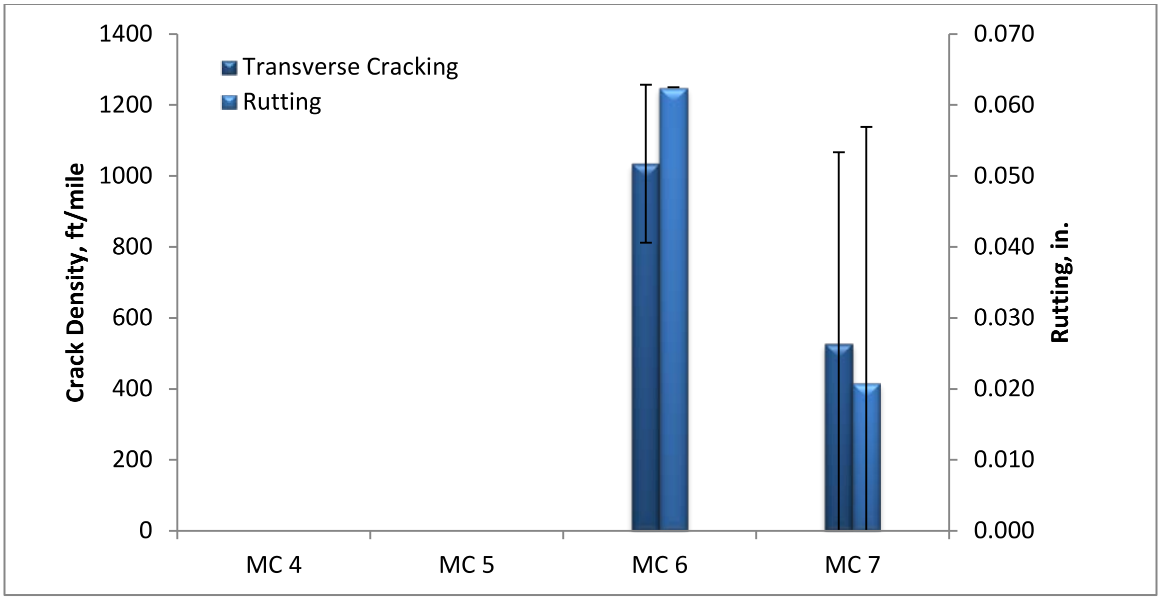

**Figure 24. Survey results for cracking and rutting on IA 93 test sections**

In addition to the aforementioned surficial distresses, other distresses found during the pavement condition survey include stripping of chip seals due to snow plowing operations, fatigue cracking, and potholes. Stripping was found on the two sections with a FDR and double chip seal treatment, while the other sections with a chip seal surface show no stripping problems. The stripping may have resulted from the rough surface of the FDR layer and the bonding behavior between the chip seal and the FDR layer. The other distresses are either minor or localized. A summary of the roads with these types of distresses are shown in Table 17.

**Table 17. Minor surficial distress issues**

| County | Road ID | Loss of Chip Seal Cover Aggregate | Fatigue Cracking | Pothole |
|---|---|---|---|---|
| Barnes | CO 21 North | | X | |
| | CO 21 South | | | |
| Beltrami | CSAH 5 | | X | |
| | CSAH 34 | X | | |
| | CSAH 36 | | | |
| Brown | CSAH 11 | | | |
| | CSAH 22 | | X | |
| | CSAH 27 | | | |
| Goodhue | CSAH 11 | | | |
| | CSAH 7-I | | | X |
| | CSAH 7-II | | | |
| Fayette (IA 93) | MC 4 | | | |
| | MC 5 | X | | X |
| | MC 6 | | | |
| | MC 7 | | | |

## 4.2 Surface Roughness

The estimated IRI measurements using Roadroid are shown in Figure 25.

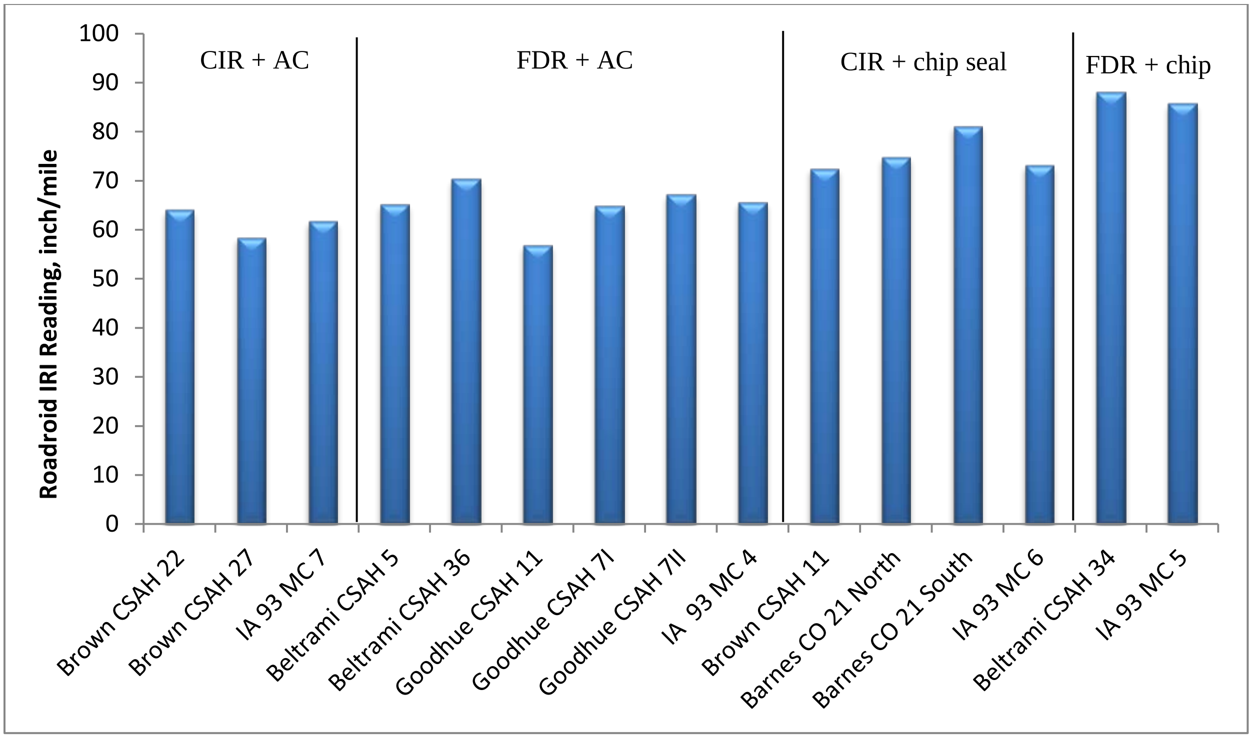

**Figure 25. Estimated IRI measurements using Roadroid**

Compared to an IRI value of 200 inches per mile, which is the AASHTO failure criteria for secondary roads (AASHTO 2008), all of the test roads performed satisfactorily in terms of roughness. In general, test sections with a CIR treatment or asphalt overlay surface tended to have lower IRI values than sections with a FDR treatment or chip seal surface. The roads treated with a combination of FDR and a chip seal exhibited the highest IRI values.

# Chapter 5. Lifecycle Cost Analysis and a Decision Tool

Based on treatment life expectancies and a lifecycle cost analysis, this chapter discusses the costs and benefits of various flexible pavement rehabilitation alternatives used on the test sections identified in the previous chapter. Five rehabilitation strategies, including four in-place recycling strategies and one conventional mill-and-fill strategy, were compared in an analysis period of 30 years and 50 years, respectively. Based on the LCCA results, a preliminary decision tree is proposed to assist in the decision process for treatment selection.

## 5.1 Treatment Life Expectancy

The life expectancies of the pavement rehabilitation alternatives are difficult to determine with the available information because (a) most of the test sections were constructed within the last five years, and therefore long-term performance data are not available; (b) the test sections over 10 years old were continuously maintained using preventive maintenance treatments, and therefore the natural deterioration rate of the road without preventive maintenance is not available; and (c) the projects using the same rehabilitation strategy vary in terms of subgrade type, construction methods, and materials. The treatment life expectancies are estimated through an extrapolation approach and rational analysis.

In order to evaluate pavement performance, the crack counts and IRI measures were converted to a single parameter, pavement quality index (PQI), by following the approach described in the *Mn/DOT Distress Identification Manual* (MNDOT 2007). Figure 26 shows the PQIs of the test sections.

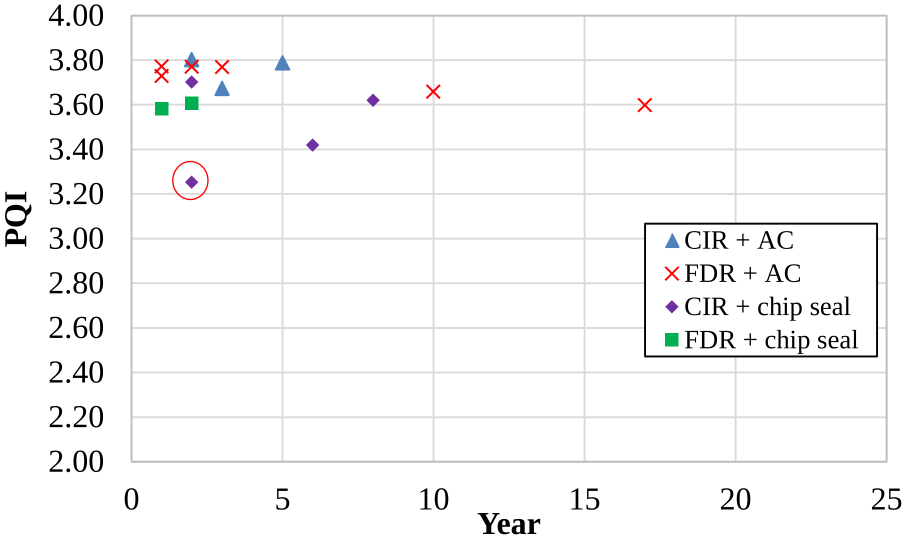

**Figure 26. PQIs of test sections**

The circled point in Figure 26 is the PQI of Brown County CSAH 11. The PQI of this road is considerably lower than that of the other road sections of the same age. It is also lower than that of other sections using the same rehabilitation method. The Brown County highway department engineer also found similar performance for four other roads that received the same treatment method. These roads were compared with the other test sections using the CIR and chip seal treatment. No noticeable differences were observed with regard to the climate and traffic conditions and subgrade soil types. However, the chip seal treatments in Brown County used a quartzite aggregate cover, while the other roads with satisfactory performance used limestone as cover aggregate. Meanwhile, aggregate loss was observed for Brown County CSAH 11 and was not found in the other sections. A comparison of the surface conditions is shown in Figure 27.

**Figure 27. Comparison of surface conditions for CIR sections with chip seal**

Aggregate loss is an indication of possible low bonding strength between the cover aggregate and binder asphalt. Loss of cover aggregate can result in a rough surface and may decrease the chip seal's ability to prevent water penetration. The cause of the difference in performance for Brown County CSAH 11 cannot be concluded based on the currently available information. Laboratory and in situ material testing are needed to identify the factors that have negatively affected the performance of this road section. This data point was not used to estimate the life expectancy of a properly constructed CIR with chip seal treatment. However, the difference in performance for Brown County CSAH 11 suggests that the performance of this treatment method may vary greatly.

Typically, a road with a PQI lower than 2 is considered to have failed and to be due for rehabilitation. The pavement is in good condition if the PQI of the pavement is above 3.5. Figure 26 indicates that the pavement conditions of the roads treated with FDR and an asphalt concrete (AC) overlay are rated in the "good" range in terms of PQI at 10 and 17 years after construction; in most cases, the roads have had regular preventive maintenance treatments since construction.

Such performance is comparable to that of a new asphalt pavement, which usually has 25 to 30 years of service life. Therefore, it is reasonable to believe that the FDR and AC overlay method can be effective in correcting pavement distresses and restoring the pavement condition so that it is close to its original state. Long-term performance observations are not available for the other rehabilitation strategies. However, the first two years of early-age performance of the test sections treated with CIR and an AC overlay is better than the performance of the sections treated with FDR and an AC overlay. Therefore, the long-term performance of the sections treated with CIR and an AC overlay is expected to be no worse than the performance of the sections treated with FDR and an AC overlay. Brown County also reported satisfactory performance for other roads that have had CIR treatments with AC overlays. The oldest road of this type was constructed over 15 years ago. A list of these roads and the other roads treated with CIR with a chip seal is shown in Table 18.

**Table 18. CIR Roads in Brown County**

| Road ID | Year | Miles | Location | Surface Type |
|---|---|---|---|---|
| 29 | 2000 | 11.01 | TH 4 to 1900 feet East of CSAH 12 | 3-inch Overlay |
| 4 | 2001 | 2.99 | TH 14 to North County Line | 3-inch Overlay |
| 8 | 2001 | 2.98 | CSAH 29 to CSAH 30 | 3-inch Overlay |
| 29 | 2004 | 6.728 | TH 68 to TH 4 | 3-inch Overlay |
| 102 | 2005 | 3.032 | CSAH 13 to TH 15 | 3-inch Overlay |
| 10 | 2007 | 4.008 | CSAH 24 to CSAH 27 | 3-inch Overlay |
| 8 | 2008 | 7.924 | South County Line to CSAH 24 | 3-inch Overlay |
| 5 | 2010 | 9.045 | South County Line to Springfield | 3-inch Overlay |
| 25 | 2010 | 2.962 | CSAH 13 to TH 15 | 3-inch Overlay |
| 27 | 2010 | 2.32 | CSAH 8 to Sleepy Eye | 3-inch Overlay |
| 28 | 2010 | 2.32 | West County Line to TH 68 | 3-inch Overlay |
| 20 | 2011 | 9.753 | CSAH 16 to TH 4 | Chip Seal |
| 10 | 2012 | 6.414 | South County Line to CSAH 20 | Chip Seal |
| 11 | 2012 | 3.506 | CSAH 22 to CSAH 24 | 2-inch Overlay |
| 22 | 2012 | 7.578 | CSAH 10 to CSAH 13 | 2-inch Overlay |
| 16 | 2013 | 10.801 | South County Line to TH 14 | 4-inch Overlay |
| 3 | 2013 | 4 | South County Line to 410 Ave | 2-inch Overlay |
| 3 | 2013 | 3.892 | 410 Ave to CSAH 23 | Chip Seal |
| 19 | 2013 | 2.594 | TH 15 to East County Line | Chip Seal |
| 30 | 2014 | 6.705 | West County Line to TH 4 | 3-inch Overlay |
| 13 | 2014 | 1.309 | KC Road to North County Line | 3-inch Overlay |
| 13 | 2014 | 1.669 | 220 St to Camels Back Road | 3-inch Overlay |
| 16 | 2014 | 1.332 | TH 14 to North County Line | 3-inch Overlay |
| 22 | 2014 | 3.254 | TH 4 to CSAH 10 | 2-inch Overlay |
| 29 | 2014 | 2.091 | CSAH 12 to New Ulm | 3-inch Overlay |
| 20 | 2015 | 2.583 | TH 15 to East County Line | 2-inch Overlay |
| 20 | 2015 | 2.985 | TH 4 to CSAH 10 | 2-inch Overlay |
| 24 | 2015 | 3.62 | Leavenworth to TH 4 | 3-inch Overlay |
| 24 | 2015 | 3.024 | TH 15 to East County Line | 2-inch Overlay |

The early-age PQI values of the sections treated with FDR and CIR and a chip seal are slightly lower than those of the sections treated with FDR and CIR and an AC overlay. The life expectancies of the in-place recycling with chip seal treatments can be expected to be less than the expected service life of the FDR or CIR with AC overlay treatments. Table 19 summarizes the average PQI for each treatment method in the first two years after construction.

**Table 19. Average PQI in the first two years after construction**

| Treatment Method | PQI |
|---|---|
| CIR + AC | 3.80 |
| FDR + AC | 3.76 |
| CIR + chip seal | 3.70 |
| FDR + chip seal | 3.59 |

To estimate the life expectancies of the aforementioned rehabilitation alternatives, the influence of the preventive maintenance activities must be taken into account. It was assumed that the pavement regains its initial PQI after a preventive maintenance treatment and deteriorates at the same rate as a new pavement immediately after the maintenance treatment was placed. The PQI values in Figure 26 are shifted by plotting them with the time elapsed from the most recent preventive maintenance to represent the pavement deterioration behavior without preventive maintenance. Figure 28 shows the shifted PQI values for sections treated with FDR or CIR and an AC overlay.

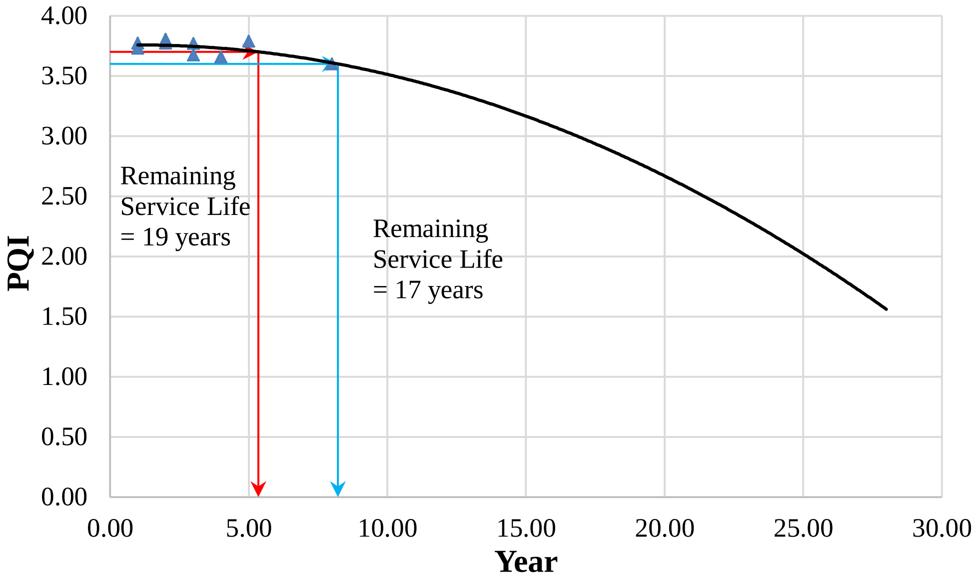

**Figure 28. Shifted PQI values of test sections with an in-place recycling and AC overlay treatment**

The extrapolated PQI curve indicates that the life expectancies of the CIR or FDR with AC overlay treatments are approximately 25 years. The literature review shows that the life expectancies for CIR and FDR treatments with a 2- to 4-inch overlay are 7 to 26 years (Jahren et al. 1998, Maher et al. 2005, Wu et al. 2010); therefore, the results of the extrapolation are reasonable according to the literature review.

The PQI curve in Figure 28 represents the deterioration behavior of the pavement for which the distresses have been completely corrected by the in-place recycling technologies and AC overlays. However, the differences in early-age performance indicate that the pavement conditions might not be restored to their initial state for sections that receive a chip seal treatment. It is assumed that the performance of the CIR or FDR with chip seal treatments follows a PQI curve similar to that shown in Figure 28. Their life expectancies would depend on the average PQI immediately after construction. Therefore, the estimated life expectancy is 19 years for a CIR with chip seal treatment and 17 years for a FDR with chip seal treatment.

### 5.2 Lifecycle Cost Analysis Case Study

A LCCA was performed for five rehabilitation strategies (Table 20), based on the assumption that each strategy involves a major rehabilitation treatment method and a series of preventive maintenance treatments.

**Table 20. Proposed rehabilitation alternatives for LCCA**

| Year (after construction) | Alternative A | Alternative B | Alternative C | Alternative D | Alternative E |
|---|---|---|---|---|---|
| 0 | CIR + AC | FDR + AC | CIR + Chip seal | FDR + Chip seal | 4-inch AC |
| 5 | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing |
| 10 | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing |
| 15 | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | 2-inch AC |
| 20 | 2-inch AC | 2-inch AC | 2-inch AC | 2-inch AC | Chip seal + Crack sealing |
| 25 | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing |
| 30 | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | 4-inch AC |
| 35 | CIR + AC | FDR + AC | CIR + Chip seal | FDR + Chip seal | Chip seal + Crack sealing - |
| 40 | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing - |
| 45 | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | Chip seal + Crack sealing | 2-inch AC |

The schedule of the treatments was developed based on the maintenance history of the Goodhue County test sections as well as a LCCA study on roads treated with FDR in Virginia (Diefenderfer and Apeagyei 2011b). The maintenance history of the Goodhue County sections and the maintenance schedule used in the Virginia LCCA study are shown in Table 21.

## Table 21. Pavement rehabilitation and maintenance schedule in Goodhue County and Virginia

| **Goodhue County Test Section Maintenance History** | | | **Virginia LCCA Study** | |
|---|---|---|---|---|
| **CSAH 7I** | **CSAH 7II** | **CSAH 11** | **Traditional Approach** | **FDR Approach** |
| 1998: FDR + AC | 2005: FDR + AC | 2012: FDR + AC | Year 0: 4-inch mill and overlay | Year 0: 2-inch mill, FDR and 3-inch overlay |
| 2000: Chip seal | 2007: Chip seal + crack filling | 2014: Chip seal + crack filling | Year 8: 2-inch mill and overlay | Year 12: 2-inch mill and overlay |
| 2003: Crack filling | 2011: Chip seal + crack filling | | Year 16: 2-inch mill and overlay | Year 22: 2-inch mill and overlay |
| 2007: Chip seal + crack filling | | | Year 24: 2-inch mill and overlay | Year 32: 2-inch mill, FDR and 3-inch overlay |
| 2012: Crack filling | | | Year 32: 4-inch mill and overlay | Year 40: 2-inch mill and overlay |
| | | | Year 40: 2-inch mill and overlay | |
| | | | Year 48: 2-inch mill and overlay | |

The test sections in Goodhue County were maintained with a chip seal in the second year after construction. Then, a crack filling or chip seal treatment, or a combination of these treatments, was applied every four to five years. In the Virginia LCCA study, the traditional 4-inch AC overlay approach required more frequent maintenance activities in comparison to the FDR and 3-inch overlay approach. The major rehabilitation treatments were reapplied at 32 years after the initial construction. The proposed CIR and FDR rehabilitation strategies include a schedule for crack filling, chip seal treatment, and 2-inch AC overlay. A reapplication of the initial rehabilitation treatment is performed at 35 years after the initial construction. Alternative E uses a conventional AC overlay strategy. The 2-inch AC overlay treatment is used at five years after two chip seal treatments have been applied. The reapplication of the 4-inch AC overlay is performed in the 30th year.

The thicknesses of the rehabilitation treatments vary from project to project and are dependent on the existing pavement structure. The typical milling depth for CIR is 2 to 4 inches. Pavement sections that include a thick HMA layer are more likely to be selected as candidates for a CIR treatment because a thin HMA layer may not have sufficient strength to support the CIR train during recycling and a thick HMA section is difficult to process using an FDR approach. The load bearing capacity of the pavement structure during recycling is affected by many factors, such as subgrade soil strength, base layer thickness, thickness and strength of the remaining pre-existing HMA pavement, and other items. Some local agencies do not recommend that CIR be constructed on roads with less than 6 inches of bituminous material. However, successful CIR applications have been found on some roads with existing pavements that had less than 6 inches of bituminous material. Therefore, a CIR treatment should be used with caution if the existing bituminous material thickness is less than 6 inches. The typical FDR layer thickness is 5 to 12 inches. The application depth of the FDR treatment should be enough to recycle the entire HMA layer as well as a few inches of the aggregate base. The pre-existing pavement thicknesses and treatment application thicknesses of the test sections are summarized in Table 22.

**Table 22. Pre-existing pavement thickness and treatment application thickness**

| County | Road ID | Pre-existing Pavement Thickness, inches | | Treatment Thickness, inches | | |
|---|---|---|---|---|---|---|
| | | HMA | Aggregate Base | AC | FDR | CIR |
| Beltrami | CSAH 5 | 4.5 | 11 | 1.5 | 8 | N/A |
| | CSAH 34 | 4.5 | 15.5 | N/A | 12 | N/A |
| | CSAH 36 | 5.5 | 14 | 1.5 | 10 | N/A |
| Brown | CSAH 11 | 5.5 | 9 | N/A | N/A | 4 |
| | CSAH 22 | 5.5 | 9 | 2 | N/A | 4 |
| | CSAH 27 | 5.5 | 9 | 3 | N/A | 4 |
| Goodhue | CSAH 11 | 6 (milled 2-inch) | 9 | 4 | 5 | N/A |
| | CSAH 7I | 3.5 | 12 | 4 | 3.5 | N/A |
| | CSAH 7II | 3.5 | 12 | 4 | 5 | N/A |
| Barnes | County RD 21 North Segment | 5.5 | 6 | N/A | N/A | 4 |
| | County RD 21 South Segment | 6.5 | 6 | N/A | N/A | 4 |
| Fayette | IA 93 MC-4 | 7.5 | 6 | 1.5 | 8 | N/A |
| | IA 93 MC-5 | 7.5 | 6 | N/A | 8 | N/A |
| | IA 93 MC-6 | 7.5 | 6 | N/A | N/A | 2.5 |
| | IA 93 MC-7 | 7.5 | 6 | 1.5 | N/A | 2.5 |

For this case study, the aforementioned rehabilitation strategies were employed to renew two hypothetical roads with different structures. The thicknesses of the treatments are designed based on the hypothetical pavement structure as well as the typical application thicknesses determined from Table 22. The existing pavements of the hypothetical roads are suffering from severe surface defects and loss of functionality. However, there were no indications of structural distresses found with the pavements. The first hypothetical road includes 5 inches of bituminous material and a 6-inch aggregate base. The second hypothetical road includes 8 inches of bituminous material and a 6-inch aggregate base. It is assumed that both roads carry the same level of traffic and have the same type of subgrade. The assumptions for the treatment thicknesses are shown in Table 23.

Table 23. Case study treatment thickness assumptions and estimated costs

| Treatment | Case 1: 5-inch pre-existing HMA and 6-inch aggregate base | | | | |
|---|---|---|---|---|---|
| | AC | FDR | CIR | Chip Seal | Estimated Cost, $ |
| FDR+AC | 2 | 6.5 | | | 195,800 |
| FDR + Chip seal | | 6.5 | | Double chip seal | 120,000 |
| CIR+AC | 2 | | 3.5 | | 173,600 |
| CIR + Chip Seal | | | 3.5 | Single chip seal | 81,100 |
| AC | 4 | | | | 255,500 |

| Treatment | Case 2: 8-inch pre-existing HMA and 6-inch aggregate base | | | | |
|---|---|---|---|---|---|
| | AC | FDR | CIR | Chip Seal | Estimated Cost, $ |
| FDR+AC | 2 | 10 | | | 216,600 |
| FDR + Chip seal | | 10 | | Double chip seal | 140,700 |
| CIR+AC | 2 | | 3.5 | | 173,600 |
| CIR + Chip Seal | | | 3.5 | Single chip seal | 81,100 |
| AC | 4 | | | | 255,500 |

The costs for the typical rehabilitation methods were estimated using the historical costs from these test section projects and recent bid prices from a recent reconstruction project in Carver County, Minnesota. The estimated costs are summarized in Table 24.

Table 24. Estimated treatment unit cost

| Treatment | Average Cost (for roads with two 12 foot lanes) |
|---|---|
| Single Chip Seal | $24,600/mile |
| Double Chip Seal | $41,300/mile |
| CIR | $32,100/mile |
| FDR | $40,100/mile |
| Stabilizer (FDR) | $5,900/inch/mile |
| Stabilizer (CIR) | $7,000/inch/mile |
| HMA | $58,500/inch/mile |
| Milling | $21,300/mile |
| Crack Filling | $500/mile |

MnDOT has typically used a 2% discount rate for cost analyses; therefore, that discount rate was applied in this study to convert the costs into 2015 dollars. The cost for each rehabilitation method was estimated based on the estimated treatment costs and the assumed application thicknesses. The average costs for chip seal and crack filling of the Goodhue County test sections were also used to estimate the costs for preventive maintenance. The typical rehabilitation and maintenance costs are also shown in Table 23.

A 30-year and a 50-year LCCA were conducted to evaluate the costs and benefits of each rehabilitation strategy. The equivalent annual costs (EQAC) of the rehabilitation strategies are shown in Figure 29.

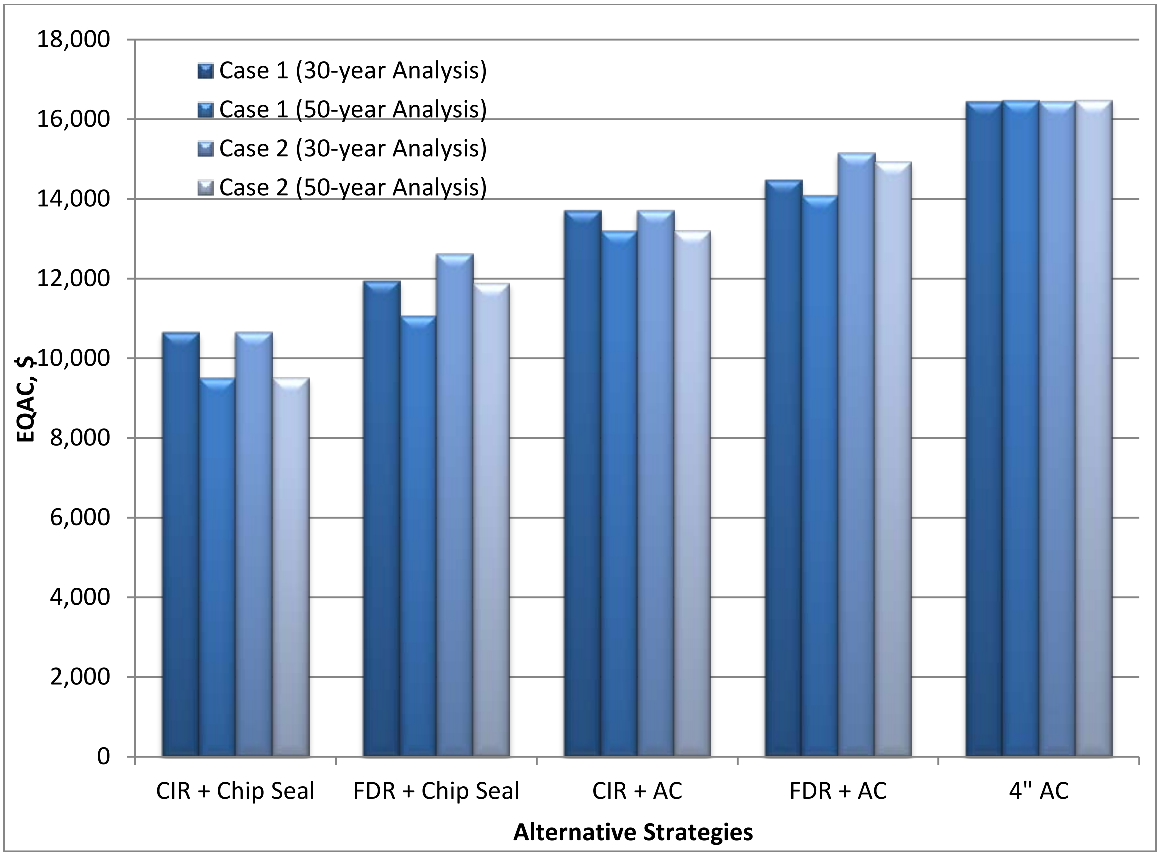

**Figure 29. EQAC of rehabilitation alternatives**

A base benefit was established as that of the EQAC of a 4-inch overlay treatment without preventive maintenance. The service life of such a treatment was assumed to be 12 years. The base benefit was established as $21,300 per year. This base benefit value was used for cost comparison and does not represent the user benefits generated from reduced tire wear, improved fuel efficiency, preferences for less road noise and smoother ride and safety. A benefit-to-cost (B/C) ratio was computed for each rehabilitation strategy and is shown in Table 25.

**Table 25. Benefit-to-cost ratio of rehabilitation strategies**

| Rehabilitation Strategy | Benefit-to-Cost Ratio | | | |
|---|---|---|---|---|
| | Case 1 | | Case 2 | |
| | 30-Year Analysis Period | 50-Year Analysis Period | 30-Year Analysis Period | 50-Year Analysis Period |
| CIR + AC | 2.22 | 2.13 | 2.22 | 2.13 |
| FDR + AC | 2.11 | 1.99 | 2.01 | 1.88 |
| CIR + Chip seal | 2.53 | 2.77 | 2.53 | 2.77 |
| FDR + Chip seal | 2.08 | 2.23 | 1.97 | 2.08 |
| Traditional AC | 1.34 | 1.42 | 1.34 | 1.42 |

A 4-inch overlay without any additional maintenance activities has a B/C ratio of 1. A B/C ratio higher than 1 indicates that such a maintenance strategy could provide a longer service life than a 4-inch overlay treatment with the same level of investment or provide the same service life as a

4-inch overlay treatment with lower costs. Periodic maintenance activities can considerably increase the B/C ratio of a road. The benefits in each B/C ratio only include the benefits that can be quantified with PQI. Pavement noise level and appearance are also considered to be functional benefits. However, such benefits are difficult to quantify and are not included in the B/C ratio.

The alternative rehabilitation strategies show lower EQACs and higher B/C ratios than the traditional AC overlay strategy. The CIR with chip seal strategy has the lowest EQAC and the highest B/C ratio. The annual cost savings for the other alternative rehabilitation strategies are approximately $2,000 to $5,800 per mile for a 30-year analysis period and $2,400 to $7,000 per mile for a 50-year analysis period. In comparison to the traditional overlay method, the percent cost savings are 12% to 35% and 14% to 42% for 30- and 50-year periods of analysis, respectively.

### 5.3 Preliminary Decision Tree

A preliminary decision tree is proposed in Figure 30.

The preliminary decision tree proposed in this section should be used only as a reference to assist with the selection of treatments for two-lane rural highways with an asphalt structure and low traffic volumes. All test sections included in this study carry daily traffic volumes lower than 1,100. Therefore, it is recommended that this decision tree be used with caution for roads with daily traffic volumes greater than 1,100. Future research needs to be performed to determine an appropriate traffic threshold and develop an advanced decision tool that can be applied as a guideline for treatment selection.

A traffic study and pavement structural analysis should be conducted to determine the adequacy of the current pavement structural capacity in terms of meeting the requirements of the design traffic volume. Load-related distresses, such as severe fatigue cracking, rutting, or longitudinal cracking on wheel paths, are indications of insufficient structural support. Nondestructive testing methods, such as FWD testing and laboratory material testing, can be used for structural evaluation at the project level. Conducting a pavement distress survey is a critical step in adding relevant information to the decision process. Field cores provide valuable information about the origins and causes of the distresses as well as actual pavement thicknesses. Pavements with bottom-up cracks or where cracking propagates to a considerable depth have distresses that may be difficult to correct with a CIR treatment; however, a FDR treatment can be very effective in treating such distresses because it pulverizes the pavement and breaks up the crack pattern for the entire depth of the pavement. In addition, constructability should be considered. CIR construction on pavements with less than 6 inches of existing bituminous material caries a higher risk of having insufficient support for construction equipment than CIR construction on pavements with thicker bituminous layers. The strength of the base layer and subgrade should be evaluated if CIR will be applied to roads with less than 6 inches of existing bituminous material.

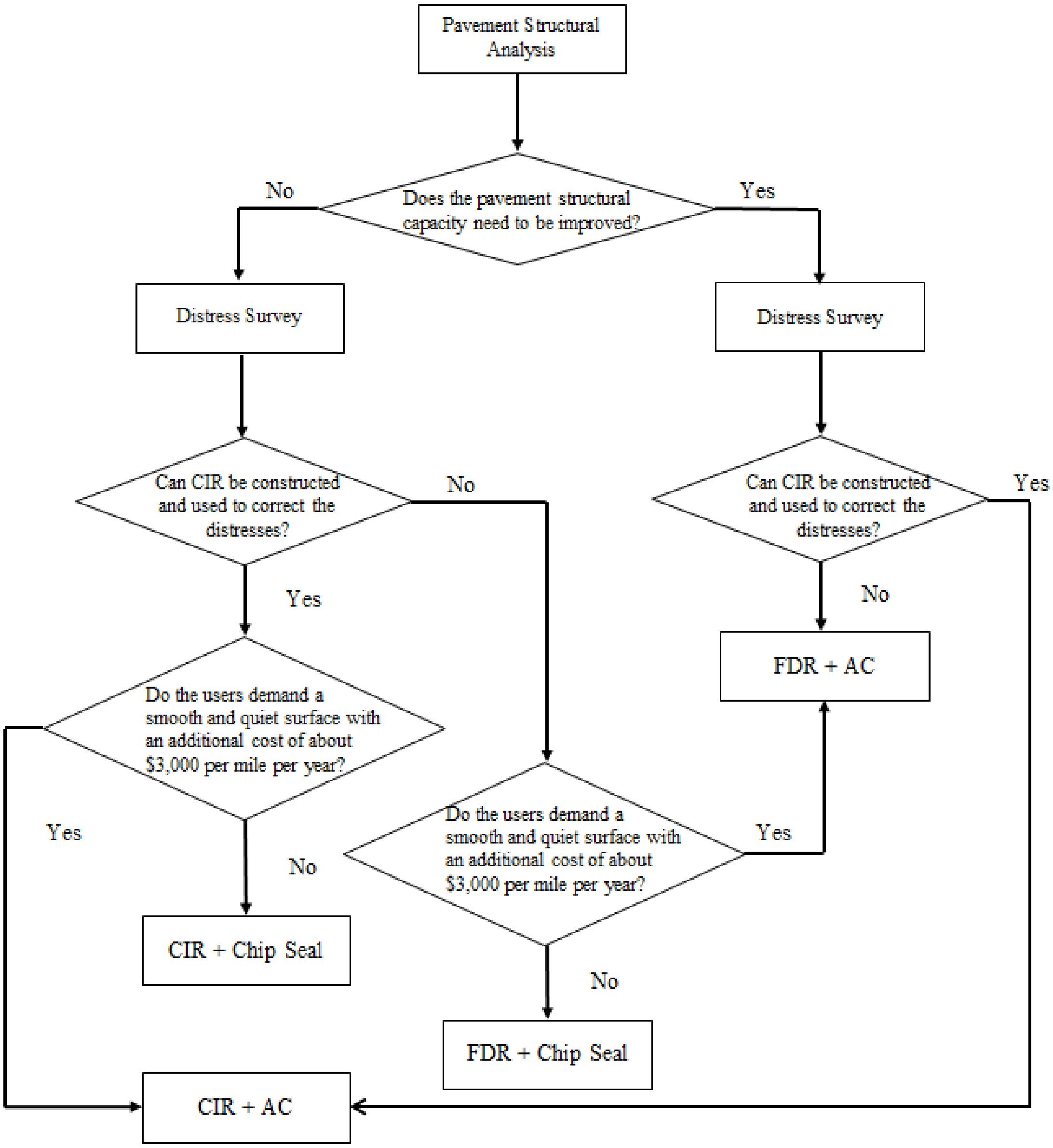

**Figure 30. Decision tree for selecting pavement rehabilitation strategy**

In some cases, a road may have a narrow shoulder width, which increases the difficulty of accommodating the grade change due to the addition of the pavement thickness. Such roads sometimes have a thick AC layer due to previous overlays. A milling and recycling method may be applied in such scenarios. A few inches of the top AC layer can be scarified, and CIR or FDR can be applied to the reaming pavement structure without raising the road profile. However, if the road does not have a sufficient pavement thickness, milling the top a few inches can weaken the pavement's load bearing capacity and lead to a construction failure. A traditional mill-and-fill method may be more appropriate for roads of this kind. User demand should also be considered in a decision tree. A chip seal surface is usually less expensive than an overlay surface. However, a smoother and quieter surface is typically expected for an AC surface in comparison to a chip seal surface. The smoothness and quietness of the road surface affects driving experience and user costs such as tire attrition and fuel economy.

# Chapter 6. Conclusions

Deteriorated low-volume roads in Minnesota and other Midwest states often suffer from non-load related distresses caused by environmental factors. In-place recycling technologies have been found to be an effective method for treating such distresses. Traditional pavement rehabilitation uses a mill-and-fill method, which involves milling of a few inches of the existing pavement and placing a 3- to 5-inch asphalt overlay. Milling of the existing pavement provides limited substrate improvements for the new asphalt overlay. Compared to milling, recycling technologies such as CIR and FDR produce a base that may require a thinner overlay lift or no overlay, because (a) the in-place recycling methods do not decrease the thickness of the existing pavement structure and (b) the recycling technologies destroy distress patterns and/or rejuvenate aged asphalt by adding recycling agents. It should be noted that for a thinner overlay to be used over a recycled layer, the recycled layer must be well compacted and cured in order to mitigate compaction rutting and other distresses in the overlay. A thin surface treatment can be used in place of an asphalt overlay to provide a surface for the recycled pavement; however, this surface may disappoint road users by producing more road noise and may not be as smooth as an asphalt overlay surface. The recycling technologies and/or thin maintenance surfaces provide alternative strategies for improving deteriorated low-volume roads with lower costs and environmental benefits.

This project included an informational survey of county engineers in Minnesota and neighboring states to understand current practices regarding the implementation of recycling technologies for low-volume asphalt road rehabilitation projects. Based on the survey results, 15 test sections were selected for a case study involving cost-benefit analyses of the alternative pavement renewal methods. A decision tree for treatment type selection was proposed in this report, according to the case study results.

The informational survey included two parts: an online survey and follow-up phone interviews. The online survey was distributed to the 87 counties in Minnesota; 16 responded to the survey. The survey results showed that CIR and FDR treatments have been extensively used on Minnesota roads, though fewer counties have had experience with CIR than with FDR. Chip seals were the only type of surface treatments that were applied directly to a CIR or FDR layer of paved road. Other surface treatments, such as microsurfacing, Otta seal, and ultrathin asphalt overlay, were also mentioned by respondents; however, these treatments were mostly used for pavement preservation.

The survey also indicated that the majority of the responding Minnesota counties select the type of pavement rehabilitation used based on past experience. Road surface condition, pavement age, and cost are the primary factors considered in the decision. Some agencies also consider the output from a PMIS, FWD test results, or cost analysis in the decision processes. Only two counties use a spreadsheet decision tool to assist in the selection of appropriate treatments for renewing deteriorated pavements.

Five of the online survey respondents invited the researchers to conduct phone interviews. Through the phone interviews, inquiries were made about the traffic, pavement structure, construction and maintenance costs, and subgrade soil conditions of the road sections with the alternative rehabilitation methods involving FDR or CIR. Barnes County in North Dakota was also contacted for further information regarding test sections that were of interest for this investigation. In addition, the researchers used data from IA 93 in Fayette County, Iowa, that were collected as part of a research project funded by the Iowa Highway Research Board. Based on the information collected through the interviews, 15 test sections were chosen for the case study analysis. The selected case study roads included seven CIR sections and eight FDR sections. Four CIR sections and two FDR sections received a chip seal treatment that was applied over the recycled pavement, while the other sections were overlaid with 1.5 to 4 inches of asphalt concrete.

A pavement condition survey was conducted to assess the performance of each treatment on each test section. The survey included a visual inspection of surficial distresses, rutting measurement, and a roughness evaluation. The IRI value of each test section was measured with a smartphone-based application, Roadroid. The pavement survey results showed that the primary type of distress was transverse cracking. Pavements exhibited satisfactory performance for all test sections, with the exception of one CIR road treated with a chip seal surface in Brown County, Minnesota. Considerably higher transverse cracking density and loss of cover aggregate were found for this road section compared to the other sections that had received similar treatments. Poor performance was also reported for several other roads within the same county that were treated using the same type of treatment method. The pavement structure, traffic levels, and environmental conditions for these poorly performing sections were compared with those of the sections in other counties that received similar treatments and experienced better performance. The comparison showed no considerable differences in these conditions. It is suspected that the use of hydrophilic quartzite cover aggregate for the Brown County sections treated with CIR and a chip seal may have resulted in lower bonding strength between the aggregate cover and asphalt binder, which caused a loss of aggregate particles under external forces like snow plowing operations. It should be noted that adjustments can be made to decrease the risk of stripping when quartzite is used as a chip seal cover aggregate and that quartzite has been successfully used as a chip seal cover aggregate at other locations.

All test sections exhibited good roughness characteristics and no noticeable rutting problems. In general, the roads with an asphalt overlay surface had lower roughness levels than the roads with a chip seal surface. The FDR with chip seal treatment produced slightly higher IRI values than the other treatment types.

PQI was calculated for each section based on the distress survey results and roughness measurements. Most sections had a PQI value above 3.5 and were therefore found to be in good condition. Two CIR roads with a chip seal surface, including the aforementioned section in Brown County with less than satisfactory performance, had PQI values within a range that indicated fair pavement condition. The other CIR road in fair pavement condition had construction issues caused by precipitation during construction.

The long-term performance of the CIR or FDR treatments with an AC overlay was comparable to that of a new asphalt road with a life expectancy of 25 to 30 years. Because long-term performance data were not available for the CIR or FDR treatments with a chip seal, the life expectancies of these treatments were estimated through extrapolation. The estimated life expectancies for CIR with chip seal and FDR with chip seal are 19 and 17 years, respectively.

A LCCA was employed for each of the alternative rehabilitation strategies studied in this project and a conventional 4-inch asphalt overlay. The EQACs of the alternative treatment strategies were lower than those of the conventional method, and the realized cost savings were 12% to 35% for a 30-year analysis period and 14% to 42% for a 50-year analysis period. The rehabilitation strategies involving CIR or FDR with a chip seal showed lower EQACs and higher B/C ratios than the strategies involving CIR or FDR with an AC overlay. However, roads with an AC overlay usually have a quieter surface and a preferred visual appearance for most road users when compared to a chip-seal surfaced road. Quietness and appearance are usually difficult to quantify but may affect user perceptions of road performance, which may also be an important consideration when a rehabilitation strategy is selected.

A preliminary decision tree was developed based on the LCCA results. Existing pavement distress types, construction and maintenance costs, constructability, treatment life expectancy, and user demands are considered in the decision process. This decision tool is proposed to help engineers in local highway agencies select an economical asphalt pavement rehabilitation strategy that meets performance requirements and user needs.

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# Appendix A
# Online Survey Questions

1. Please tell us your name, phone number, e-mail, and the county or township which you are working in.

2. Please check the following pavement renewal technologies that your county has applied on paved low-volume road. Please enter the number of roads that you know for each treatment in the box next to each treatment option.

   Otta Seal ( )    Chip Seal ( )    Slurry Seal ( )    Microsurfacing ( )    NovaChip ( )

   Ultrathin Overlay ( )    Full-Depth Reclamation ( )    Cold In-Place Recycling ( )

3. Please specify other methods, besides the conventional HMA overlay or mill and fill method, which your county has used for asphalt pavement rehabilitation.

4. Please provide a few more details about how you have used the above treatments.

5. Please briefly describe how the roads performed after the treatments were applied.

6. Does your agency use any decision tools to help select pavement renewal methods (decision tree, software, excel spreadsheet, etc.)? Please specify the decision tool, if applicable. Answers such as “good past experience” and “local preference” are acceptable.

7. Please select the option to invite a follow up call from our research team for future discussion.

   I would like to invite a follow up call. ( )
   No, thanks. ( )

# Appendix B
# Telephone Interview Questions

Please select up to three low-volume roads in your county that were maintained with full-depth reclamation or cold in-place recycling topped with chip seal, microsurfacing, or overlay for the following questions.

1. When and where were these roads constructed?

2. What is the traffic volume and percent truck on the roads?

3. Any information about the subgrade soils? (soil type, R-value, CBR value, etc.)

4. What’s the pavement structure of these roads? What are the layers’ thicknesses, material types, etc.?

5. How did the construction process go?

6. What was the construction cost for the rehabilitation treatment?

7. How is the road performing? If the roads are not performing well, what are the possible reasons?

8. Are these roads included in any type of a pavement management system? If not, what historical performance information is available?

9. How much is the actual maintenance cost for maintaining these roads?

10. Any other comments and/or suggestions?