Determining Optimum Time for Application of Surface Treatments to Asphalt Concrete Pavements

Final Report

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## TABLE OF CONTENTS

### Task 1 Literature Review 1

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURFACE TREATMENT CONCEPT</td>
<td>1</td>
</tr>
<tr>
<td>REVIEW OF SURFACE TREATMENTS TECHNIQUES</td>
<td>3</td>
</tr>
<tr>
<td>Crack Seals</td>
<td>3</td>
</tr>
<tr>
<td>Fog Seals</td>
<td>3</td>
</tr>
<tr>
<td>Rejuvenators</td>
<td>3</td>
</tr>
<tr>
<td>Seal Coats</td>
<td>6</td>
</tr>
<tr>
<td>Slurry Seals</td>
<td>7</td>
</tr>
<tr>
<td>Microsurfacings</td>
<td>9</td>
</tr>
<tr>
<td>Thin Hot-Mix Overlays</td>
<td>9</td>
</tr>
<tr>
<td>RESEARCH PROGRAMS AND PROJECTS</td>
<td>9</td>
</tr>
<tr>
<td>NCHRP Project 14-14 [1]</td>
<td>9</td>
</tr>
<tr>
<td>Lead States Survey</td>
<td>12</td>
</tr>
<tr>
<td>Winslow Arizona Sealer/Rejuvenator Study [22]</td>
<td>14</td>
</tr>
<tr>
<td>Aging/Optimization Study (Minnesota)</td>
<td>15</td>
</tr>
<tr>
<td>Seal Coat on HMA pavements (TH 56)</td>
<td>15</td>
</tr>
<tr>
<td>Seal Coat and Rejuvenators on HMA Shoulders</td>
<td>17</td>
</tr>
<tr>
<td>Fog Seal on HMA Shoulders</td>
<td>18</td>
</tr>
<tr>
<td>Texas Chip Seal Study</td>
<td>18</td>
</tr>
<tr>
<td>Louisiana’s Maintenance Chip Seal and Microsurfacing Program</td>
<td>20</td>
</tr>
<tr>
<td>Chip Seal Study in South Dakota</td>
<td>22</td>
</tr>
<tr>
<td>Arizona State University Study (Arizona, Colorado, and Utah)</td>
<td>24</td>
</tr>
<tr>
<td>Iowa Surface Treatments Study</td>
<td>25</td>
</tr>
<tr>
<td>Fully Optimized Road Maintenance (FORMAT) (Europe)</td>
<td>27</td>
</tr>
</tbody>
</table>

### Task 2 Literature Review 2

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGING, HEALING, AND MOISTURE SENSIVITY OF ASPHALT MATERIALS</td>
<td>29</td>
</tr>
<tr>
<td>Aging</td>
<td>29</td>
</tr>
<tr>
<td>Steric Hardening</td>
<td>29</td>
</tr>
<tr>
<td>Oxidative Age Hardening</td>
<td>30</td>
</tr>
<tr>
<td>Oxidative Age Hardening in the Presence of Hydrated Lime</td>
<td>31</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Healing</td>
<td>32</td>
</tr>
<tr>
<td>Surface Free Energy</td>
<td>33</td>
</tr>
<tr>
<td>Moisture Damage - Stripping</td>
<td>35</td>
</tr>
<tr>
<td>Polymer Modifiers</td>
<td>39</td>
</tr>
<tr>
<td>Colored Pavements</td>
<td>41</td>
</tr>
<tr>
<td>Surface Friction and Skid Resistance</td>
<td>42</td>
</tr>
<tr>
<td>RESEARCH IN OTHER ENGINEERING FIELDS</td>
<td>43</td>
</tr>
<tr>
<td>POTENTIAL TEST METHODS</td>
<td>44</td>
</tr>
<tr>
<td>Task 3 Site Identification and Documentation</td>
<td>47</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>47</td>
</tr>
<tr>
<td>Site 1: I-35</td>
<td>47</td>
</tr>
<tr>
<td>Site 2: TH 56</td>
<td>48</td>
</tr>
<tr>
<td>Site 3: I-90</td>
<td>50</td>
</tr>
<tr>
<td>Site 4: I-35 Shoulder</td>
<td>50</td>
</tr>
<tr>
<td>Site 5: I-35</td>
<td>51</td>
</tr>
<tr>
<td>Site 6: TH 251</td>
<td>52</td>
</tr>
<tr>
<td>Task 4 Guidelines for Phase II Project</td>
<td>54</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>54</td>
</tr>
<tr>
<td>PHASE II OBJECTIVE</td>
<td>54</td>
</tr>
<tr>
<td>RESEARCH APPROACH</td>
<td>55</td>
</tr>
<tr>
<td>WORK PLAN</td>
<td>55</td>
</tr>
<tr>
<td>Task 1. Field Sample Collection</td>
<td>56</td>
</tr>
<tr>
<td>Task 2. Experimental Investigation - Surface Condition (Aging and Cracking) Assessment</td>
<td>56</td>
</tr>
<tr>
<td>Task 3. Experimental Investigation – Mechanical Characterization</td>
<td>57</td>
</tr>
<tr>
<td>Task 4. Experimental Investigation - Environmental Factors</td>
<td>57</td>
</tr>
<tr>
<td>Task 5. Data Analysis</td>
<td>58</td>
</tr>
<tr>
<td>Task 6. Draft Final Report</td>
<td>58</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>61</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1.1. Most used preventive maintenance techniques...................................................... 14
Table 1.2. Materials used in South Dakota study ................................................................. 23
Table 1.3. PCI values for Iowa study .................................................................................... 26
Table 3.1. Minnesota Surface Treatment Sites ..................................................................... 47
Table 3.2. TH 56 Seal Coat Data .......................................................................................... 49
LIST OF FIGURES

Figure 1.1. Example of preventive maintenance program [2] ......................................................... 2
Figure 1.2. Pavement surface before application of Reclamite ® .................................................. 4
Figure 1.3. Application of Reclamite ® ......................................................................................... 4
Figure 1.4. Pavement surface after application of Reclamite ® .................................................... 5
Figure 1.5. CRF applied to the pavement surface ......................................................................... 5
Figure 1.6. Spreading sand over CRF .......................................................................................... 6
Figure 1.7. Sand applied to CRF ................................................................................................ 6
Figure 1.8. Seal Coats [6] ............................................................................................................ 8
Figure 1.9. Concept of benefit. ..................................................................................................... 11
Figure 1.10. TH56 study ............................................................................................................ 16
Figure 1.11. Seal coat applied in 2000 to the pavement constructed in 1995 and 1999 .............. 16
Figure 1.12. Seal coat applied in 2001 to the pavement constructed in 1995 and 1999 .......... 16
Figure 1.13. Seal coat applied in 2002 to the pavement constructed in 1995 and 1999 .......... 17
Figure 1.14. Seal coat applied in 2003 to the pavement constructed in 1995 and 1999 .......... 17
Figure 2.1. Local Fracture Test [38] .......................................................................................... 33
Figure 2.2. Wilhelmy plate method .......................................................................................... 34
Figure 2.3. PATTI device principle .......................................................................................... 37
Figure 2.4. Two types of failure in pull-off test: cohesive and adhesive [42] ......................... 37
Figure 2.5. Schematic of Thin Film Tack test .......................................................................... 38
Figure 2.6. LPDS (Layer-Parallel Direct Shear) ........................................................................ 45
Figure 3.1. Cracking History on I-35 Conventional and NovaChip ® Surfaces ....................... 48
Figure 3.2. TH 56 Study – Test Section Layout ...................................................................... 49
Figure 3.3. I-35 Surface Treatments Near Stacy ..................................................................... 52
EXECUTIVE SUMMARY

An extensive literature review has been performed on the surface treatment methods. Research studies that are focused on the timing of the application of treatments to asphalt concrete pavements have shown that current maintenance practice is based on the construction phase and monitoring of the performance of the treatment over time. Some of the most recent studies also address the economic issues involved in the selection process and the timing of the application of treatments.

Several test sites has been identified and documented for the implementation in the second phase of this project. Detailed work plan has been proposed in order to better understand the mechanism by which surface treatments protect the existing pavement from further aging and deterioration due to traffic and environmental loadings and to reasonably predict the optimum time for the application of these treatments.
SURFACE TREATMENT CONCEPT

The many years of intensive pavement construction in the US have created a very large pavement network that needs to be constantly maintained and preserved to fulfill its critical role in the US economy [1, 2, 3]. Pavement preservation is a general term used in the literature for the set of activities that has the following goals [2]:

- Provide and maintain serviceable roadways,
- Extend pavement life,
- Enhance pavement performance,
- Ensure cost-effectiveness,
- Reduce user delays.

Pavement preservation includes both preventive maintenance and small rehabilitation activities. Major rehabilitation activities are not part of the preservation program. Preventive maintenance is part of the pavement preservation and represents a well–defined strategy of cost-effective treatments that preserve the pavement system, postpone deterioration, and maintain or improve functional condition of the pavement without increasing structural capacity [1, 2]. Because preventive maintenance activities of flexible pavements are usually applied towards the pavement surface they are also called ‘surface treatments’ or ‘surface rehabilitation techniques’ [4]. The most popular surface treatment activities reported in the literature for flexible pavements in the US are as follows:

- Crack seals,
- Fog seals,
- Rejuvenators,
- Slurry seals,
- Seal coats,
- Microsurfacings,
- Thin hot mix overlays.

The detailed description for each of them is presented in the next chapters.

One of the crucial aspects of the surface treatment approach is the proper timing. The key is to apply the treatment when the pavement is still in relatively sound condition with no
structural damage [2]. Numerous research projects showed [1, 2] that preventive maintenance activities performed at the right time represent the most cost-effective approach to pavement preservation. As a consequence, many states have implemented preventive maintenance programs into their strategies to help them maintain their road network. A schematic representation of this concept is presented in Figure 1:

![Figure 1.1. Example of preventive maintenance program [2]](image)

This figure illustrates one of two competing philosophies on proper timing of the application of surface treatments. The second theorizes that the application of a surface treatment on a bituminous pavement will retard the onset of surface deterioration and top-down cracking and extend not only the life of the pavement, but also the time at the highest condition indicator. This approach is currently used by Montana in their chip-sealing program: they apply the treatment to all of their new overlays and bituminous pavements as soon as possible after construction.
REVIEW OF SURFACE TREATMENTS TECHNIQUES

Crack Seals
Crack seals are used to fill individual surface cracks and prevent the entry of water or other materials in the cracks [5]. This technique is recommended for pavements with low to medium crack deterioration levels. Hot-pour asphalt rubber or polymer modified sealant are typically used as the sealant. Similar to any other type of crack sealing, it is necessary to clean the cracks before sealant application to ensure proper performance. Either a route-an-seal or a "blow-and-go" that is clean the crack with compressed air/heat lance and fill with the sealant are used.

Fog Seals
Fog seals consist of the light application of a diluted slow-setting asphalt emulsion to the pavement surface [5, 6]. The most common emulsions are SS-1, SS-1h, CSS-1 and CSS-1h. They are diluted with water for better control of the lower asphalt application rate. Polymer modified and medium-setting emulsions can be used in some applications. Fog seals are primary used on low-volume roads in order to:

- Seal the pavement surface,
- Rejuvenate the aged surface,
- Inhibit raveling,
- Provide shoulder delineation,
- Provide better contrast (visibility) for the centerline and edge line striping on a new seal coat,
- Postpone the use of a different surface treatment.

Rejuvenators
The primary reason for using rejuvenators is to restore the original properties of the aged pavement surface. Many rejuvenators contain maltenes because their quantity is reduced by the oxidation process. For most of these products the composition represents proprietary information that is not available in the literature.

One of the most common rejuvenator products is Reclamite ® [7]. It is used for relatively new pavements with minor severity of cracks or raveling. This product contains maltenes and is designed to penetrate the pavement to some depth to restore the maltene to asphaltene ratio to proper balance. According to the producer [7] Reclamite ® can be used for new pavements as
well as for preventive maintenance. The product is sprayed on the pavement surface at the rate of about 0.10 gal/yd\(^2\) and is followed by a light sand cover at a rate of 1-2 lbs / yd\(^2\). The sand is used to prevent tracking and eliminate the excess Reclamite ®. The following figures show examples of Reclamite ® application on the State Hwy 251 in Minnesota:

![Figure 1.2. Pavement surface before application of Reclamite ®](image1)

![Figure 1.3. Application of Reclamite ®](image2)
CRF is a different rejuvenator product from the same producer [8]. It is applied to pavements that have more severe deterioration than the ones targeted by Reclamite ®, such as pavements with alligator cracking and/or raveling. According to the producer the CRF both rejuvenates and seals the pavement surface. It can be used also as a preparation technique before applying a major treatment, such as seal coat or slurry seal. CRF is applied by a distributor truck and after curing the sand is drag-broom over the pavement surface to ensure sealing performance. The following pictures present the application of CRF on State Hwy 251 in Minnesota:
Seal Coats

Seal coats represent one of the most widely used surface treatment techniques and numerous references describe and document their use [3, 4, 5, 6, 9, 10, 11, 12]. This technique is also called bituminous surface treatment (BST), chip seal, “armor coating” or surface dressing (Europe). In general, a seal coat is an application of asphalt binder to the pavement surface followed immediately by aggregate cover. This technique is used in order to:

- Prevent the surface from further oxidation,
- Keep water out of the pavement structure,
- Increase the surface friction,
✓ Seal small cracks.

Originally, this technique was used only for low-volume roads due to potential vehicle damage by loose aggregate torn out by tires on high-traffic and high-speed highways. Today, seal coats are used, with special precautions, on higher volume roads as well [9]. The pavement candidates for seal coating should be in good structural condition without load related distresses such as rutting and alligator cracking. The pavement can have low severity raveling, transverse or longitudinal cracking.

The procedure to apply a single seal coat requires the following steps:
✓ Repair load-related distresses,
✓ Clean pavement surface,
✓ Spray the asphalt emulsion,
✓ Spread the aggregate chips,
✓ Embed the aggregates with pneumatic rollers,
✓ Remove excess aggregates.

It should be mentioned that aggregate chips have to be spread and rolled before the asphalt emulsion breaks in order to ensure that chips are sufficiently embedded in the asphalt layer.

Figure 8 presents different types of seal coat techniques [6].

**Slurry Seals**

A slurry seal is a homogenous mixture of asphalt emulsion, water, fine aggregate and mineral filler. The most commonly used mineral filler is the Portland cement. Slurry seals are applied to the pavement surface for the following purposes:
✓ Retard surface oxidation and raveling,
✓ Improve surface friction,
✓ Seal minor cracks.

Slurry seals should not be applied to pavements that contain extensive cracking.

A thin film of water is sometimes applied to the surface prior to the slurry seal application to ensure proper breaking of the emulsion and improve the bonding between the slurry seal layer and the original pavement surface. Slurry seal is produced and placed from either self-propelled or truck-mounted slurry machine. Proper machine calibration is crucial to obtain satisfactory performance and service life.
Figure 1.8. Seal Coats [6]
**Microsurfacing**

Microsurfacing [13, 14, 15, 16, 17, 18] is a mix of polymer-modified emulsion, water, well-graded crushed aggregate, mineral filler (normally Portland cement) and chemical additives that control the breaking process. In this application the breaking process is chemically controlled as opposed to the slurry seal and seal coat techniques that rely on the natural breaking process controlled by the field atmospheric temperature and humidity. Microsurfacing is used on moderate to heavy traffic roads for reasons similar to slurry seal application. Construction is performed using a microsurfacing machine similar to the slurry seal machine. Because of the chemical nature of the breaking process, the material selection and the mix design are of great importance for the proper performance of microsurfacing.

**Thin Hot-Mix Overlays**

Thin hot-mix overlays [4, 5, 19] consist of the asphalt cement and aggregate blended together. They are constructed in a similar way as regular hot-mix layers. According to the aggregate gradation the thin hot-mix overlays can be categorized as follows:

✓ Dense-graded,

✓ Gap-graded, such as SMA and Novachip,

✓ Open-graded friction course (OGFC).

They are primarily used on high-volume highways for functional improvements.

**RESEARCH PROGRAMS AND PROJECTS**

A number of research projects have investigated the benefits of using surface treatments to improve the performance of asphalt pavements and to prolong their service life. The majority of the projects focus on the construction activities and on the calculation of economic benefits of surface treatment application. Presently, there is no published research that documents the mechanism by which surface treatments seal and protect the existing pavement from further aging and deterioration from cracking, with implications on the pavement resistance to low temperature cracking and fatigue cracking.

**NCHRP Project 14-14 [1]**

The primary objective of this research was to develop a procedure for determining the optimal timing for the application of preventive treatments to both flexible and rigid pavements.
Numerous treatment techniques were considered and a flexible implementation tool was created. It was established that agencies used the following approaches to determine the right time for applying preventive treatments:

- A predetermined treatment schedule,
- The time elapsed since the previous maintenance or rehabilitation event,
- Maintenance surveys,
- Pavement management system.

Since these approaches are based mainly on the local experience, there is little supporting evidence that these approaches provide the optimal timing for the preventive maintenance.

The study emphasized that the agencies should consider the following treatment ‘attributes’ when considering suitable treatment techniques:

- Treatment purpose,
- Applicability:
  - traffic,
  - environment,
  - actual pavement condition,
- Contraindications,
- Construction considerations,
- Expected performance and costs,
- Customer satisfaction.

The optimal timing procedure in this project is based on the concept that the same treatment applied to a pavement at various stages of its life will have a different effect. There is a range of time when the applied treatment will result in the maximum benefit. A treatment applied at a different time will provide either less benefit or no benefit at all. The benefit is defined as the difference in condition over time between the pavement with applied treatment and the performance of the same pavement without any treatment (do-nothing performance). Thus, the treatment effect (benefit) can be either positive or negative. The pavement condition is measured using ‘condition indicators’, such as cracking, rutting, friction, etc. The selected condition indicator should satisfy the following requirements:

- Could be tracked over time,
- Could indicate the functional performance of the pavement,
Could change its value after applying a preventive treatment.

Because different condition indicators are usually expressed in different units, the recommended procedure normalizes all individual condition indicator benefit values by dividing the benefit area by the original do-nothing area. Then all individual benefit values are expressed as percentages. This concept is presented in Figure 9. For every combination of the condition indicator and treatment application age, the performance relationship (i.e. condition versus age) should be defined.

![Figure 1.9. Concept of benefit.](image)

When more than one condition indicator is used in the analysis, ‘benefit weighting factors’ are used to combine the benefit values associated with the different condition indicators. The sum of the benefit weighting factors has to be 100%. The individual benefit values are multiplied by the assigned benefit weighting factors and the total overall benefit is computed as the sum of the products from every condition indicator. The benefit weighting factors are primarily selected based on engineering judgment. The total overall benefit together with the associated cost analysis is used to assess the effectiveness of different timing scenarios. The costs that might be included in the analysis are as follows:

- Treatment cost (agency cost),
- Rehabilitation costs,
✓ User delay costs,
✓ Cost of the routine maintenance activities.

A simple life-cycle cost analysis (LCCA) is performed on every preventive treatment scenario. Both the Present Worth (PW) and the Equivalent Uniform Annual Cost (EUAC) are computed. The optimal time for the preventive maintenance has to maximize the benefit and simultaneously minimize costs. Thus, the maintenance scenario with the highest benefit-to-cost ratio represents the most appropriate treatment using the approach assumed in this research. The proposed procedure was validated using data from the following states:
✓ Arizona,
✓ California,
✓ Kansas,
✓ Michigan,
✓ North Dakota.
Reasonable results in specifying the optimal treatment timing were obtained.

The procedure proposed in this research has the following steps:
✓ Identify the specific objectives of the preventive maintenance program,
✓ Select the preventive maintenance treatments and define guidelines for their appropriate use,
✓ Define the typical performance of the pavements for the do-nothing case as well as for the applied treatment case,
✓ Calculate the optimal timing for the selected preventive maintenance treatments.

Lead States Survey
The American Association of State Highway and Transportation Officials (AASHTO) Task Force on SHRP Implementation developed and instituted the Lead State Program in 1996 [1, 20, 21]. The program was developed by the Task Force to ensure that practical, real world experience with the SHRP products was shared among all states. The Lead States Team on Pavement Preservation surveyed the transportation agencies in the 50 States about their pavement preventive maintenance (PPM) programs and local practices. 41 agencies responded to the survey in 1999 and it was found that: 36 (85%) agencies have established PPM programs; 2 others are in the process of developing a program; all 41 are using a variety of preventive treatments. 31 agencies reported that their pavement preservation programs were integrated with
their pavement management systems (PMS). 26 states had specific guidelines for PPM activities and most agencies were applying PPM techniques to the pavements in good or fair condition. 23 states reported that they had dedicated test sections for PPM techniques. Table 1 presents the cumulated number of answers for the most used preventive maintenance techniques.
Table 1.1. Most used preventive maintenance techniques

<table>
<thead>
<tr>
<th>Number of answers</th>
<th>Preventive Maintenance Method</th>
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<tbody>
<tr>
<td>38</td>
<td>Mill and overlay</td>
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<tr>
<td>37</td>
<td>Bituminous (asphalt) overlay (&lt; 40 mm or 1 1/2 inch)</td>
</tr>
<tr>
<td>34</td>
<td>Cold milling &amp; bituminous overlay (&lt; 40 mm or 1 1/2 inch)</td>
</tr>
<tr>
<td>33</td>
<td>Single course chip seal</td>
</tr>
<tr>
<td>30</td>
<td>Bituminous crack treatment (saw and seal or route and seal)</td>
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<tr>
<td>28</td>
<td>Single course micro-surfacing</td>
</tr>
<tr>
<td>25</td>
<td>Profile milling</td>
</tr>
<tr>
<td>24</td>
<td>Bituminous shoulder work (remove &amp; replace shoulder)</td>
</tr>
<tr>
<td>21</td>
<td>Multiple course micro-surfacing</td>
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<tr>
<td>21</td>
<td>Cold-in-place recycling</td>
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<tr>
<td>19</td>
<td>Overband crack fill</td>
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<tr>
<td>18</td>
<td>Multiple course chip seal</td>
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<tr>
<td>14</td>
<td>Ultra-thin bituminous overlay (&lt; 20 mm and ¾ inch)</td>
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<tr>
<td>14</td>
<td>Hot in-place bituminous recycling (&lt;40 mm or 1 1/2 inch)</td>
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<td>14</td>
<td>Slurry seal</td>
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<td>12</td>
<td>Fog seal</td>
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<tr>
<td>11</td>
<td>Paver placed surface seal (NovaChip)</td>
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<td>7</td>
<td>Scrub seal</td>
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<td>2</td>
<td>Cape seal</td>
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**Winslow Arizona Sealer/Rejuvenator Study [22]**

In September 2001 the National Center for Asphalt Technology, the Foundation for Pavement Preservation, the Arizona Department of Transportation, and the Federal Highway Administration established a national study on the optimal timing for surface treatments. Test sections were chosen in approximately 8 states mainly to evaluate the effectiveness of sealers and rejuvenators used for preserving the pavements.

The scope of the project was to evaluate in the first phase the test sections after three to four years from the time the sealers/rejuvenators were applied. In the second phase, new
Sealers/rejuvenators are applied to a half of every test section. The length of the original test sections is 500 ft with the transition zones varying from 84 ft to approximately 250 ft.

A comprehensive work plan for laboratory testing was also developed. The work plan consists of non-destructive techniques, such as nuclear magnetic resonance, spectral wave analysis, and sophisticated chemical materials characterization as well as advanced devices for both texture and friction evaluation of the asphalt pavements. A description of these tests is given in the next task.

At this time very little information is available about this national study.

**Aging/Optimization Study (Minnesota)**

In 2000 MnDOT started a research study to evaluate the cost effectiveness and proper timing for three different surface treatments techniques:

- Seal coat on HMA pavements (TH 56),
- Seal coat and rejuvenators on HMA shoulders (I-35 NB),
- Fog seal on HMA shoulders (I-90 WB).

In this study every test section was divided into one-mile segments and new treatments were applied every year on portions of each section. At the end of the study every section will consist of one-mile segments with different surface treatment ages.

The sections were evaluated in 2001 and 2004 in terms of the oxidation, loss of aggregate (for the seal coat section), pop-outs in the asphalt, ride quality, appearance, crack severity and overall performance of the treatment.

**Seal Coat on HMA pavements (TH 56)**

The test section for this study is a 24-mile long section of trunk highway 56. The test sections were constructed in two phases: in 1995 and in 1999, respectively. The first seal coat was applied to both parts in 2000. Every year since then a new application of the seal coat was performed and new one-mile segments were created in both parts of the test sections. A diagram of the test sections is presented in Figure 10. Figures 11 to 14 show pictures of the different test sections taken on April 29, 2004.
Figure 1.10. TH56 study.

Figure 1.11. Seal coat applied in 2000 to the pavement constructed in 1995 and 1999.

Figure 1.12. Seal coat applied in 2001 to the pavement constructed in 1995 and 1999.
Seal Coat and Rejuvenators on HMA Shoulders

The test section in this project is the north bound shoulder on Interstate 35. The shoulder was constructed in 1998 and the first seal coat was applied in 2000. The study found that almost 100% of the seal coat aggregate was lost after the first winter in 2000 due to snowplow damage. As a consequence, the next application of the seal coat in 2001 had a smaller aggregate size. Very little aggregate loss was observed in this case after the following winter. The rejuvenator applied in 2002 showed satisfactory performance after two months. However, the inspection performed in 2004 showed that the rejuvenated section looked similar to the control section.
**Fog Seal on HMA Shoulders**

The west bound shoulder on Interstate 94, constructed in 1999, had a fog seal applied in 2000. After one winter satisfactory performance of the treatment was observed.

**Texas Chip Seal Study**

The goal of this study was to compare the performance of the seal coat projects constructed between 1996 and 2001 in the Atlanta District in Texas [23, 24]. A total of 342 projects were considered; in 165 of these projects a CRS-2P asphalt emulsion was used as the binder, and in 177 projects an AC15-5TR asphalt binder was used. Since other potentially significant factors, such as contractors and aggregate type, were kept almost identical, a direct comparison of the performance of the emulsion and the asphalt in the seal coats was possible. The only significant difference was that the seal coats with conventional asphalt used a lightweight aggregate that was precoated with a specific bituminous material. The following data was collected for every project:

- type of binder,
- type of aggregate,
- specifications for emulsion and asphalt cement,
- average rate shot in the main lanes,
- specifications for aggregate,
- year of installation,
- average temperature, rainfall and freeze-thaw cycles during project life (National Weather Service),
- contract requirements,
- contract amount,
- amount of material used,
- location of project,
- length in feet,
- length in miles
- area of main lanes shot,
- area of intersections shot,
- area of miscellaneous locations such as drives and turnouts shot,
The following data was integrated and is available in the Pavement Management Information System (PMIS) program database for most of the projects in this study:

- type of underlying pavement,
- percent deep and shallow rutting,
- patching percent,
- base failure percent,
- block cracking percent,
- alligator cracking percent,
- longitudinal cracking percent,
- transverse cracking percent,
- raveling percent,
- flushing percent,
- average 18 kip wheel loads,
- average annual maintenance cost,
- date of last surface,
- distress score,
- ride score,
- surface index,
- skid number,
- pavement condition score.

The Pavement Condition (PC) Score information was obtained for 150 emulsion projects and 157 asphalt cement projects. Skid Numbers (SN) values were obtained for 62 of the emulsion projects and 104 of the asphalt cement projects. It was assumed that the number of projects with PC and SN values was sufficient and representative and a reliable statistical analysis of the data could be performed. Three different types of project performance metrics were incorporated:

- discreet metrics that are mathematical averages of the PMIS information and the financial information for each project,
weighted average metrics that used covered project areas as weights,

Cost Index Number metrics that combine cost and engineering measurements into a single index that two alternatives, i.e. emulsion and asphalt can be compared.

It was found that the emulsion seal coats are more cost effective compared to conventional asphalt seal coats. Even though the emulsion seal coats are generally used on roads that are in poorer condition, the results showed that on average the cured surface had higher skid resistance and a marginally better ride quality at a lower total cost. Both alternatives performed similar in the overall pavement condition score category.

**Louisiana’s Maintenance Chip Seal and Microsurfacing Program**

The major objective of this study performed in 2001 by Louisiana Department of Transportation and Development (DOTD) was to evaluate the effectiveness of seal coat and microsurfacing techniques in terms of their performance and cost [25].

Preventive treatments were applied to the selected pavements in 1995/6. Most of the seal coat projects used the polymer-modified emulsion CRS-2P and a single layer of lightweight clay or in some instances crushed stone or crushed gravel. The main reason for applying the seal coat was to establish a waterproof layer. The microsurfacing projects used polymer-modified emulsified asphalt cement, well graded crushed mineral aggregate, mineral filler and water. The microsurfacing was used to eliminate rutting and improve skid resistance. The data collected in this study was divided into three main categories:

**Inventory/Historical Data:**

- project identification information,
- pavement type,
- pavement geometrics,
- age,
- pavement cross section,
- climate,
- traffic (ADT).

**Pavement Condition Data:**

- surface distress,
- roughness,
surface friction.

Cost Data:
✓ cost of improvement,
✓ routine maintenance cost.

A number of field surveys of the project sites were performed. Test sections of 500-700 ft, chosen from every project site, were evaluated in terms of severity and extent of pavement distresses, and a pavement Condition Index was derived for every project site. It was assumed that the following factors have a considerable influence on the performance of the surface treatments:
✓ age since construction,
✓ pavement type (asphalt, composite),
✓ existing pavement condition,
✓ total pavement thickness,
✓ location (north, south),
✓ traffic.

The performance of the surface treatments was expressed by three different indicators:
✓ pavement distress in terms of PCI,
✓ pavement roughness in terms of IRI,
✓ safety in terms of skid resistance (FN).

The study found that:
✓ after 52 months of service 75% of the seal coat projects had still good to excellent condition,
✓ most of the seal coat projects lasted at least 4-6 years,
✓ all seal coat projects provided good friction performance,
✓ the equivalent annual cost (EAC) of a chip seal is about $0.27/year (assuming 5 year life expectancy),
✓ the lowest PCI value for microsurfacing projects after 60 months of service was 75,
✓ the expected life of microsurfacing projects was 4-7 years,
✓ microsurfacing projects with limestone aggregate had low Friction Numbers (FN),
✓ the equivalent annual cost (EAC) is about $0.49/year (assuming 6 year life expectancy).
Chip Seal Study in South Dakota

This study focused on the application of the seal coats on high-speed and high-volume roads in South Dakota [6, 26]. This preventive maintenance technique is primarily used for the low-volume roads because on high-volume roads it can lead to:

✓ vehicle damage due to loose chips,
✓ excess dust,
✓ excess noise and roughness,
✓ shortened life expectancy (compared to low-volume roads).

The study was performed on State Route 50. Seal coat treatments were applied in 2000 and 12 test sections were created that varying the aggregate type (quartzite and natural aggregate) and design processes (aggregate gradation and emulsion rate). The original pavement was evaluated shortly before the seal coat application and the seal coat performance was evaluated immediately after construction and three months later. The emulsion and the aggregate rates were determined in order to satisfy two primary concerns:

✓ The emulsion should fill the voids between the aggregate to about the top of an average-sized particle; after the breaking of the emulsion and the loss of water, the voids should be filled in proportion of 70%,
✓ A single layer of chips should be placed with minimal excess of particles.

Table 2 presents the design and the actual values of the emulsion and aggregate rates. The lag time between the application of the emulsion and the aggregate was 10 to 15 seconds, and the lag time between the application of the aggregate and the initial roller pass was typically less than 1 minute. Rolling was generally completed within 20 minutes. The excess aggregate was swept the next day after construction. The following evaluation procedures were used in order to monitor performance of the test sections:

✓ condition survey that focused on the number and length of the cracks, bleeding, raveling, and rutting,
✓ bonding evaluation between aggregate particles and the binder,
✓ macrotexture depth measurement using sand patch test,
✓ aggregate retention determination using weight of the excess aggregate from a standard area of the pavement,
✓ aggregate embedment into the binder.
<table>
<thead>
<tr>
<th>Application</th>
<th>Aggregate type</th>
<th>Aggregate Rate, lb/yd^2</th>
<th>Emulsion type</th>
<th>Emulsion Rate, gal/yd^2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured</td>
<td>Design</td>
<td>Measured</td>
</tr>
<tr>
<td>Seal coat</td>
<td>Quartzite</td>
<td>21.5</td>
<td>19.0</td>
<td>CRS-2P</td>
</tr>
<tr>
<td></td>
<td>Quartzite</td>
<td>18.1</td>
<td>19.0</td>
<td>CRS-2</td>
</tr>
<tr>
<td></td>
<td>Quartzite</td>
<td>19.9</td>
<td>19.0</td>
<td>CRS-2</td>
</tr>
<tr>
<td></td>
<td>Quartzite</td>
<td>19.0</td>
<td>19.0</td>
<td>CRS-2</td>
</tr>
<tr>
<td></td>
<td>Quartzite</td>
<td>16.3</td>
<td>19.0</td>
<td>CRS-2</td>
</tr>
<tr>
<td></td>
<td>Quartzite</td>
<td>23.0</td>
<td>24.0</td>
<td>CRS-2</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>26.1</td>
<td>24.0</td>
<td>AE150S</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>22.0</td>
<td>19.0</td>
<td>HFRS-2</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>23.4</td>
<td>19.0</td>
<td>HFRS-2</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>17.7</td>
<td>19.0</td>
<td>HFRS-2</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>19.8</td>
<td>19.0</td>
<td>HFRS-2</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>19.8</td>
<td>19.0</td>
<td>HFRS-2P</td>
</tr>
<tr>
<td>Fog seal</td>
<td>Quartzite</td>
<td>n/a</td>
<td>n/a</td>
<td>CSS-1</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>n/a</td>
<td>n/a</td>
<td>CSS-1</td>
</tr>
<tr>
<td>Choke Stone</td>
<td>Quartzite</td>
<td>8.7</td>
<td>8.2</td>
<td>CRS-2</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>8.6</td>
<td>8.2</td>
<td>HFRS-2</td>
</tr>
</tbody>
</table>

The study found that:

- The polymer-modified emulsion provided the strongest bond with both the quartzite and the natural aggregate; thus, the use of polymer-modified emulsion is encouraged on high-volume/high-speed roadways,

- A design procedure for the seal coat should be developed in South Dakota, possibly similar to Minnesota procedure that employs a modified McLeod design procedure that accounts for specific material properties, traffic volumes, and pavement condition.

- Precoated aggregates improve bonding, helps preventing aggregate loss, and reduce cracking; however, it was recommended to keep the roadway closed overnight after construction because the aggregates were still tacky and could be picked up by vehicles tires.
Arizona State University Study (Arizona, Colorado, and Utah)

A two-year study performed by Arizona State University involved six test sites selected in Arizona, Colorado, and Utah [19]. The test sites were divided into test sections and the following preventive treatments were applied in 1997:

- seal coat,
- seal coat followed by fog seal,
- reclamite,
- scrub seal,
- crack seal,
- rejuvenators,
- SS-1 fog seal.

In order to be consistent with the preventive maintenance concept only pavements in relative good condition were selected as test sites. Based on the periodical visual inspection and the final evaluation in 1999 the following conclusions were drawn:

**Arizona site #1 (seal coat, Reclamite, scrub seal):**

- All treated sections showed better performance than the control section,
- The Reclamite section with the rate 0.3l/m² showed the most satisfactory performance,
- The seal coat showed some cracks and aggregate dislodging,
- Mays-meter roughness increased on all sections and the highest value was measured on the scrub seal section.

**Arizona site #2 (crack sealing):**

- Almost all seals cracked after 4 months after construction due to probably an expansive type of clay that was used as a subgrade.

**Arizona site #3 (seal coat, rejuvenators, chip seal,:)**

- All treated sections except for the seal coat were in very good condition after two years,
- The emulsion binder used in the seal coat was absorbed by the original open graded friction course and thus the aggregate was lost shortly after construction,
- Mays-meter roughness increased on all sections.
Colorado site (seal coat with and without fog seal):

✓ All test sections exhibited reflective cracking four months after treatment construction despite the fact that all cracks in the original pavements were sealed before applying surface treatments,
✓ High skid numbers were obtained on all section using K.J. Law skid trailer.

Utah site #2 (scrub seal):

✓ The scrub seal improved the performance of pavement, even in the case of a pavement that had a large amount of cracks before the treatment; it was recommended to seal the cracks before applying the scrub seal treatment to enhance the performance of the treatment.

Iowa Surface Treatments Study

The study performed in Iowa and sponsored by Iowa Highway Research Board and the Iowa Department of Transportation focused on the performance of Thin Maintenance Surfaces (TMS) [27]. The following maintenance techniques were applied with different variations of the aggregate and binder:

✓ single seal coat,
✓ double seal coat,
✓ slurry seal,
✓ microsurfacing,
✓ cape seal.

This project was divided into two phases as follows:

✓ Phase 1, that covered US 30 and US 151 with treatments applied in 1997 and US 69 with treatments construction in 1998,
✓ Phase 2, that included US 218 where surface treatments were applied in 1999.

Both phases included control sections. The test sections ranged from 1,600 to 10,560 feet. Based on the performance monitoring the following conclusions have been made:

US 30 (microsurfacing, slurry seal, seal coat with and without fog seal, double seal coat, cape seal, thin lift)

✓ all test section but the thin lift had lower PCI values in 2000 than the values for the original pavement in 1997 as presented in Table 2. It is believed that the PCI for microsurfacing test
section dropped rapidly between 1997 and 1998 due to raveling. It can be noticed that the rest of treatments showed similar deterioration rates,

- it was observed only for the microsurfacing and the thin lift that the skid resistance in 2000 had a higher value than before construction.

### Table 1.3. PCI values for Iowa study

<table>
<thead>
<tr>
<th>Survey date</th>
<th>Control 2</th>
<th>Microsurfacing</th>
<th>Thin Lift</th>
<th>Seal Coat + Fog Seal</th>
<th>Seal Coat</th>
<th>Cape Seal</th>
<th>Control 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/97</td>
<td>83</td>
<td>79</td>
<td>77</td>
<td>75</td>
<td>70</td>
<td>55</td>
<td>68</td>
</tr>
<tr>
<td>10/97</td>
<td>83 (0)</td>
<td>94 (+15)</td>
<td>93 (+16)</td>
<td>93 (+18)</td>
<td>87 (+17)</td>
<td>80 (+25)</td>
<td>68 (0)</td>
</tr>
<tr>
<td>05/98</td>
<td>72 (-11)</td>
<td>66 (-13)</td>
<td>89 (+12)</td>
<td>89 (+14)</td>
<td>74 (+4)</td>
<td>66 (+11)</td>
<td>63 (-5)</td>
</tr>
<tr>
<td>11/98</td>
<td>69 (-14)</td>
<td>42 (-37)</td>
<td>86 (+9)</td>
<td>72 (-3)</td>
<td>58 (-12)</td>
<td>53 (-2)</td>
<td>63 (-5)</td>
</tr>
<tr>
<td>05/99</td>
<td>69 (-14)</td>
<td>40 (-39)</td>
<td>85 (+8)</td>
<td>72 (-3)</td>
<td>58 (-12)</td>
<td>53 (-2)</td>
<td>62 (-6)</td>
</tr>
<tr>
<td>05/00</td>
<td>67 (-16)</td>
<td>38 (-41)</td>
<td>82 (+5)</td>
<td>68 (-7)</td>
<td>56 (-14)</td>
<td>51 (-4)</td>
<td>55 (-13)</td>
</tr>
</tbody>
</table>

Values in the parentheses represent change in PCI value compared to July 1997.

**US 69 (microsurfacing, single and double seal coat, thin lift)**

- All PCI values recorded immediately after construction were above 95 but after the first winter all dropped to around 80. After that all treatments started to deteriorate with a rate comparable to the deterioration rate of the control sections. It was observed that most of the deterioration resulted from cracking, raveling, bleeding, and snowplowing.

- The single and double seal coats exhibited higher PCI values in 2000 compared to the PCI of the original pavement,

- The microsurfacing sections were severely damaged by raveling and snowplowing due to the small amount of fine particles in the aggregate mix.

The following general conclusions were drawn at the end of the study:

- It was observed that the following factors were critical for the satisfactory performance of TMS on high-volume roads:
  - proper TMS selection,
- materials selection,
- construction quality,

- The seal coats designed according to the method used by Mn/DOT [9] were more effective than the seal coats with standard application rates,
- The seal coats with graded aggregate mix rather than just one-size aggregate provide more resistance for the snowplowing and help reducing the noise,
- The treatments with the quartzite aggregate provided the best skid resistance.

**Fully Optimized Road Maintenance (FORMAT) (Europe)**

The Fully Optimized Road Maintenance project (FORMAT) is a 3 year 4.5 million Euro research study that started in February 2002. Approximately 45% of the funding came from the European Commission and the rest came from a consortium of 20 organizations from 14 European countries and United States that is conducting the research. The FORMAT consortium consists of national highway research organizations, road owners, universities, contractors, consultants and trade associations [28]. The study is divided into four phases or Work Packages:

- Road Maintenance Techniques and Procedures (WP3 ‘Technology’),
- Associated Cost Benefit Analysis Methods (WP4 ‘Cost Benefit Analysis’),
- Safety at Road Works (WP5 ‘Safety’),
- High Speed Monitoring of Road Pavement Condition (WP6 ‘Monitoring’).

The first (WP3) and the last (WP6) Work Package contain information relevant to the current literature search. WP3 consists of the following steps:

- The review of pavement maintenance technology in Europe and North America,
- The selection and evaluation of the promising treatment techniques through accelerated loading testing (ALT) in specialized full scale road pavement test facilities,
- Conducting pilot road trials.

Within WP6 the following research was planned:

- The review of recent developments in pavement evaluation devices that operate at normal-speed and evaluate pavements in terms of surface condition and structural capacity,
- The implementation of the results from these devices into a pavement maintenance planning system.
The Accelerated Load Test experiments are to be performed in the facilities at DWW (Netherlands), LAVOC (Switzerland), TRL (UK) and LCPC (France). The following techniques have been chosen as ‘innovative’ and have been conducted in these facilities:

- **DWW**: cement mortar grouted porous asphalt as a pavement overlay (80mm). The procedure is to first apply a porous asphalt layer and then fill the voids with cementations.
- **LAVOC**: high modulus asphalt binder course as an overlay (60mm) plus a thin asphalt surface layer (20mm),
- **TRL**: high modulus asphalt binder course, applied as an overlay to the wheel path alone, plus a thin asphalt wearing course,
- **LCPC**: Use of a thin bituminous overlay (< 40 mm) with geotextile.

The results from DWW and LAVOC tests that were performed in 2003 were recently presented at the Eurobitume congress this year. The treatment performance was monitored before, during, and after loading in terms of:

- cracking,
- pavement profile,
- deflections,
- texture,
- skid resistance.

Under extreme conditions, i.e. heavy wheel load and high temperature, it was observed that:

- The cement mortar grouted porous asphalt experienced progressive failure and large deformations combined with cracking at low-speed sections,
- The combination of the high modulus binder course and thin wearing course at LAVOC provided much higher resistance to rutting than the standard Swiss technique for pavements with rutting problems.
Task 2

Literature Review 2

AGING, HEALING, AND MOISTURE SENSIVITY OF ASPHALT MATERIALS

Numerous studies have identified and quantified the significant effect of materials physical properties to pavement performance. However, the effect of the chemical composition of asphalt materials on pavement performance is not well understood although chemical properties significantly affect the physical properties responsible for pavement performance. This is primarily due to the very complex mechanisms of change in the chemical composition of these materials with time due to external factors such as temperature, solar radiation, moisture, and asphalt-aggregate interaction.

Aging

Aging represents the main mechanism of change in the chemical structure of asphalt binders used in asphalt pavements. Asphalt aging increases the stiffness of the mixture, which benefits the pavement resistance to rutting. However, when the mixture becomes “too stiff”, the cracking resistance to fatigue and low temperature diminishes considerably.

Aging of asphalt is the result of a complicated set of events involving oxidation at the molecular level and structuring at the intermolecular level. The primary chemical species formed are ketones and sulfoxides. More severe oxidation produces carboxylic anhydrides and small amounts of other highly oxidized species. As temperature increases, the amount of structuring decreases and reactivity increases. However, the rate of aging decreases in time at any given temperature [29]. There are two types of asphalt aging [30]:

- Steric hardening that occurs upon prolonged standing at ambient and low temperatures,
- Hardening caused by the chemical oxidation of the asphalt during the pavement service life, due to exposure to the ambient air and to solar radiation (oxidative age hardening).

Steric Hardening

Steric hardening occurs at ambient and low temperatures and is a result of the rearrangement of some of the asphalt molecules which create a more solid structure. This process is reversed when enough heat is supplied in the system.
At ambient temperatures, polar molecules slowly assemble themselves into the lowest energy state. Thus, the intermolecular bonding is the highest and the association among molecules is the strongest. In this state the asphalt stiffness is the greatest but external factors, such as heat or shear stresses can break the internal structure and disorient the molecules. Heating the asphalt binder to about 100°C can totally reverse steric hardening.

At low temperatures, the more neutral components, such as waxes, become crystalline and amorphous solids and increase the asphalt stiffness. The stiffening rate varies and depends on the asphalt source, i.e. crude oil source. When heated the solid structures ‘melt’ reversing the process. Recent research has shown that for certain asphalt binders steric hardening is also influenced by asphalt film thickness and aggregate type [31].

**Oxidative Age Hardening**

Oxidative hardening (oxidation) is an irreversible process that occurs in the asphalt during its service life. Polar molecules driven by their dipole moments slowly re-orient until they reach a thermodynamic stable state (equilibrium). In this state the intermolecular bonding is strong and the asphalt is stiff. The aggregate particles can distort the thermodynamic state of the asphalt due to their polar surfaces. Asphalt molecules can reach other thermodynamic states that can cause either an increase or decrease in asphalt stiffness.

In real field conditions the thermodynamic equilibrium of the mixture is a very complex process. A number of mutually dependent factors influence this phenomenon:

- Oxidation of the asphalt distorts the polarity of the molecules,
- Temperature changes both oxidation rate and thermodynamic state,
- Traffic disorients molecular species.

Most asphalt binders experience a significant increase in viscosity with oxidation, especially in the first years after construction; with time, the increase in viscosity slows down and it becomes almost zero. This time strongly depends on the crude oil source and the performance of two binders with the same PG grade but from two different sources can be very different. Recent comparison study [32] used X-ray Photoelectron Spectroscopy (XPS) to detect the oxygen concentration for two pavements. It was shown that there is a significant difference in oxygen concentration for a newly constructed pavement and 14 years old pavement.

The principal species in the asphalt that oxidize under pavement field conditions are [30]:

30
Benzyl carbon, which oxidizes to benzyl ketone, and
Sulfidic sulfur, i.e. organic sulfide, which oxidizes to sulfoxide.

The oxidation rate of organic sulfide is much faster than benzyl carbon, and therefore the products from the organic sulfide oxidation (i.e. sulfoxides) consume most of the oxygen in the early stages of the pavement life. Considering that sulfoxides are causing minor changes of asphalt stiffness one can conclude that benzyl ketones are responsible for the age hardening of the asphalt binders. However, oxidation rates for both species change with temperature. At higher temperatures, both species have similar rates and relatively large amounts of ketones are formed. Thus age hardening proceeds much faster at higher temperatures.

Because of the difference in oxidation for benzyl carbon and sulfidic sulfur a dual, sequential oxidation mechanism for asphalt was introduced [33]. It was confirmed that oxidation process is highly temperature- and oxygen concentration dependent and PAV aging test at elevated temperatures does not correspond to the age hardening that occurs in less compatible asphalt binders in the pavements.

Oxidative Age Hardening in the Presence of Hydrated Lime

Hydrated lime (HL) can be added to the asphalt mixture as an active filler [34, 35, 36]. Among others beneficial effects HL can effectively reduce the oxidative age hardening. HL interacts with an asphalt to develop interactive molecular layer around HL particles. The interaction strongly depends on the asphalt type, time and temperature of the reaction [34]. In the study it was found that HL creates the interactive layer with ‘compatible’ asphalts (i.e. SHRP core binders AAD and AAG) and HL is effective at high temperatures. More recent study [35, 36] found that adding HL to the asphalt (AAD) not only reduces oxidative age hardening but also preserves elasticity during long-term oxidation aging. It was concluded that HL reduces the rate of hardening in two ways. First, HL absorbs oxidation catalysts in the asphalt and thus reduces the progress rate of oxidation. Second, polar asphalt components layer around HL particles improves component compatibility of asphalt and thus minimizes viscosity sensitivity to the oxidation products. However, there were no beneficial effects in terms of reducing the oxidative age hardening for AAD asphalt with HL. This was explained by the low level of asphaltenes in this binder type and high amount of solvent phase between molecules. One should keep in mind...
that other independent beneficial effect of HL on asphalt mixtures is a reducing the loss of pavement capacity from moisture damage.

**Healing**

Healing is an important factor that affects the fatigue life of asphalt mixtures. Under repeated traffic loading asphalt mixes deteriorate and the stiffness decreases. However due to the healing effect asphalt mixes demonstrate strength recovery. The major contributor to healing is the asphalt binder and mastic component of the mixture. In a recent study [37], cylindrical sand-asphalt mixture specimens were tested using a dynamic mechanical analyzer (DMA) to characterize the fatigue damage and to analyze the healing effects during strain-controlled, torsional testing. A fatigue life prediction model that accounts for the healing effect was developed for the torsional shear mode. Five binders were tested in this study:

- AC-20, unaged,
- AR-4000, unaged,
- PG 70-28 with rubber particles, unaged,
- PG 70-28 with rubber particles, aged for three months in the laboratory which is assumed to be equivalent to three years in the field,
- PG 70-28 with rubber particles, aged for six months in the laboratory which is assumed to be equivalent to six years in the field.

Each binder was mixed with Ottawa sand to form a sand asphalt mixture. The asphalt content was kept at 8% in order to maintain about 10 microns of film thickness. Controlled-shear strain cyclic fatigue tests were performed in the DMA at 25°C and at 10 Hz. Several different levels of strain were applied with and without rest periods. The results showed that:

- The modified binders with PG 70-28 base asphalt have longer fatigue life than SHRP binders (AC-20 and AR-4000) even though the two modified binders were aged,
- The longer the aging the steeper the fatigue curve (fatigue life vs. strain level),
- The dynamic modulus increased after the rest period, which may result in a decrease in microcracking rate and a longer fatigue life,
- The modified binders behaved differently due to their chemical composition.

In a different study on healing [38] a “Local Fracture Test on Bitumen” was developed. The principle of this test is presented in Figure 1.
In this test the asphalt binder specimen is subjected to successive tension loads at constant strain rates. Rest period are applied between load phases to examine the healing effect. Two steel hemispheres simulate two aggregate particles. One binder, an unmodified 50/70 penetration graded, was used for testing. It was shown that when the rest period increases the healing capacity increases as well. It was observed that the healing effects are present when the test temperature was higher than -10°C and the displacement rate was greater than 110µm/s.

One of the drawbacks of this test method is the interface between the steel and the binder, which is not representative of the real interface between an aggregate particle and the binder that is more complex due to aggregate surface texture and aggregate absorption properties that vary for different aggregate sources.

**Surface Free Energy**

The surface energy concept was applied in a recent study to asphalt materials used in pavement applications [39]. By definition, the surface free energy of a solid or liquid is the work done to increase the surface by one unit area. There is a relationship between the interface bonding between asphalt binder and aggregate particles in the asphalt mix and the surface free energy of the system. The surface free energy cannot be measured directly. In this study the surface free energy was determined using two methods:

- Wilhelmy plate for the asphalt,
Universal gas adsorption to estimate surface free energy for the aggregate; a Universal Sorption Device (USD) was developed to take into account the irregular shape of the aggregate particles

**Wilhelmy plate method**

The Wilhelmy plate method can be used to measure the contact angle between asphalt and the liquid (solvent). In this method a very thin plate of asphalt binder is immersed or withdrawn from liquid solvent at a very slow constant speed as shown in Figure 2.

![Figure 2.2. Wilhelmy plate method](image)

There is a relatively simple procedure [39] to compute the contact angle and then the surface free energy of the solid asphalt if the surface energy values for three different solvents are known. In this study [39], formamide, glycerol and distilled water were chosen as solvents and three different asphalt binders were tested: AAD and AAM (SHRP core asphalts) and High Cure Rubber (HCR) with two aging options: unaged and aged for six months in the laboratory. The study found that aging had a great influence on the surface free energy results and thus on the healing potential.
Universal Sorption Device (USD)

The USD was developed in order to estimate the surface free energy of aggregates. The USD device consists of: Rubotherm magnetic suspension balance system, computer, temperature control unit, high quality vacuum, pressure transducer, solvent container and a vacuum dissector. The aggregate sample with particles between 2.36mm and 4.75mm is immersed into solvent and the amount of solvent absorbed by the aggregate is measured in specific pressure and temperature conditions. After calculations, the total surface free energy of the aggregate can be determined. In this study three aggregates were used: Texas Limestone, Colorado Limestone, and Georgia Granite. It was found that the surface free energy values for the three aggregates were significantly different and that the surface free energy is indeed a material property of the aggregate.

Adhesion and Cohesion

The free energy of cohesion and the free energy of adhesion are related to the interfacial surface free energy. Based on the results from Wilhelmy plate method and USD method one can calculate all mentioned energies and conclude that if the value of free energy of cohesion or adhesion is positive, then the two phases, i.e. asphalt and aggregate, tend to bond together and the higher the value of the energy the higher the bonding strength. The study found that:

- AAM asphalt had the highest free energy of cohesion,
- Aging significantly reduced the cohesion,
- All free energies of cohesion and adhesion were positive for tested materials,
- Moisture damage potential can be estimated from the free energy of adhesion when comparing the adhesion energy between asphalt – aggregate and water – aggregate.

Two identical mixtures with two different aggregates were prepared and then tested in repeated load permanent deformation both in dry and wet conditions. The test results qualitatively agreed with the adhesion energy calculations that indicated the mixtures with more negative adhesion were more susceptible to moisture damage and performed worse in permanent deformation test.

Moisture Damage - Stripping

One of the major environmental factors that cause the deterioration of surface treatments is moisture. The most common moisture damage distress is stripping. Stripping involves
separation and removal of the asphalt binder film from the aggregate surface due to the action of moisture. Three classical phases of the stripping failure can be observed in a pavement [40]:

- The appearance of water-transported fines or dust from partially stripped mix on the pavement surface,
- The migration of the asphalt binder to the pavement surface or flushing,
- The development of potholes in the flushed areas.

In a recent study [40] the careful examinations of four highways with stripping problems showed that the presence of moisture saturation conditions in the pavement layers results most likely in stripping failure. Proper drainage and the use of an asphalt treated permeable material (ATPM) base course are highly recommended. The study also underlined that before designing any overlay the stripping potential should be evaluated by checking moisture contents in all existing pavement layers.

Research was also performed [41] to analyze the effects of moisture damage on the asphalt adhesion and the asphalt cohesion. Water can enter the interface phase between the asphalt film and the aggregate, break the adhesive bond between them, and eventually strip the binder from the aggregate. Water can also affect the internal chemical structure of the asphalt cement that results in decreasing cohesion within the asphalt cement. This can lead to the loss of stability of the whole asphalt mixture.

To evaluate the adhesion properties of the asphalt cement in various conditions a pull-off test (ASTM D 4541) known also as Pneumatic Adhesion Tensile Testing Instrument (PATTI) was used. The schematic drawing of this device is presented below.
Air pressure is pumped between a reaction plate and the metal blocks. Since the pull-stub and the reaction plate are screwed together the air pressure induces an airtight seal between the asphalt binder and the aggregate surface. When the air pressure exceeds the adhesive strength of the bond between asphalt and aggregate failure occurs at the interface. The pressure at failure is converted into the pull-off tensile strength in Pa. Two types of failure were recorded and are presented in the following figure.

Figure 2.4. Two types of failure in pull-off test: cohesive and adhesive [42]
To quantitatively evaluate the cohesive properties of the asphalt binder a Thin Film Tack test was used in the study. The idea of this test is presented in Figure 5.

![Figure 2.5. Schematic of Thin Film Tack test](image)

The upper holder is moved at a constant speed of 0.01 mm/sec. The induced force in the binder is plotted against time and a tack factor, $C_T$, can be computed by integrating the area under the curve. Both plain and modified asphalt binders were tested with and without conditioning in water. It was found that:

*For the pull-off test:*
- All unconditioned specimens experienced cohesive failure whereas all specimens conditioned in water had adhesive type of failure,
- Adding antistripping agents to the asphalt binder improves pull-off strength,
- The longer the conditioning time in water the lower the pull-off strength of the binder is,
- The pull-off test yields results with variability of about 10%.

*For the Thin Film Tack test*
- The test has very good repeatability,
- The higher temperature of the test the smaller the tack factor of the binder is,
- Modified binders have higher tack factors at every temperature than the plain binders,
- The addition of anti stripping agent did not improve the tack factor.

The results from PATTI and the Thin Film Tack test were next correlated with the strength results obtained using AASHTO T-283 method. Very strong correlations were found between
the maximum tensile strength of the unconditioned specimens and the tack factor, and between the maximum tensile strength of conditioned specimens and a combined function of the tack factor and pull-off strength ratio.

In a different study [42] researchers focused on the development of a new type of anti-stripping agent. The need for new agents is caused by the fact that older types of agents have small thermal stability and they might quickly degrade when mixed with asphalt binder and stored at high temperatures. The new agents were evaluated using the following test procedures:

- Boiling adhesion test,
- Dynamic immersion test,
- Immersion-compression test.

The first two methods require the aggregate particles to be fully coated with asphalt and anti-stripping agent. In the boiling test the conditioned coated particles are heated to the boiling point for a specific time. The percent aggregate surface area that remained coated represents the boiling adhesion value. In the dynamic immersion test, the coated particles are placed in a rotating vessel. The adhesion is expressed as the percent area that remained coated. The immersion-compression test is similar in principle to the standard tensile strength test on both dry and wet specimens. The tests results obtained in this study showed that the new anti-stripping agents provided excellent thermal stability as well as good adhesion properties of the asphalt binders.

**Polymer Modifiers**

One of the polymer additives used in asphalt emulsions is the Styrene-Butadiene-Rubber (SBR). The addition of SBR improves the properties of emulsions by increasing the resistance to cracking at low temperatures and the resistance to deformation at higher temperatures. The SBR expands the temperature range in which the asphalt acts as an elastic material and extends the service life of the surface treatments. A recent study [43] showed that in a polymer modified emulsion the SBR particles remained in the aqueous phase and transformed into a continuous polymer film around asphalt particles during the breaking process. Thus, the polymer modified emulsion can be considered as an emulsion containing dispersed asphalt and SBR particles. It was also observed that an incorrect recovery procedure can completely alter the residue structure. The study proposed the use of a Forced Airflow Drying procedure in order to obtain a
representative emulsion residue. DSR test results indicated that the addition of 3% of a newly developed SBR to the asphalt improved the PG grade by three grades at high temperature.

Further investigation [44] of the SBR modified emulsion residue proposed a new DSR procedure to evaluate the resistance of the residue to repeated high-strain deformations that occur in the seal coat applications under heavy-load traffic and snowplow operations. It was observed that the modified emulsions prevent chip loss and demonstrate early strength development. The proposed DSR strain-sweep procedure incorporates incremental strain increase from 0.1 to 30%. The sample is subjected to approximately 5,500 stress cycles during the total test time of 45 minutes. The DSR testing was complemented with a new brush test for seal coat treatment (ASTM D7000-04). It was found that there is a good correlation between the water absorption capability of the aggregate (ASTM C 127-88) and the aggregate retention in the brush test. It was also observed that the modified emulsions prevented chip loss and showed early strength development compared to the unmodified emulsions.

A comparative experiment performed in Europe [45] also showed that polymer modified asphalt provides excellent performance when used in thin maintenance courses. The objective of this study was to compare the resistance to rutting and reflective cracking for four different binders:
- pure 20/30 penetration graded asphalt cement,
- special multigrade asphalt cement HM 20/30 penetration graded,
- polymer modified binder EC,
- asphaltite bitumen G 20/30 penetration graded.

Four 400-meter test sections were located on a heavy-traffic highway with a high percentage of trucks (35%). The pavement temperature varied between -20°C and +60°C during the experiment. Asphalt mixture samples were collected from the original mix, after 6 and after 36 months after the construction in October 1999. The original binders were aged in RTFOT and PAV and tested as follows:

*Original binder*
- penetration at +25°C,
- ring and ball temperature (RBT),
- IP (Index of Penetration),
- Fraass temperature,
**RTFOT binder**

- penetration at +25°C,
- RBT,
- IP,

**RTFOT plus PAV binder**

- penetration at +25°C,
- RBT,
- IP,
- BBR (critical temperature).

Original mixes were tested in terms of:

- rutting in LCPC (French Central Laboratory for Roads and Bridges) wheel track tester,
- modulus in MAER press direct tensile test,
- low temperature resistance in restrained cooling test by measuring rupture temperature and rupture stress.

The extracted binders from the pavement after 6 and 36 months after construction were tested in terms of penetration and RBT. It was found that results differed from those obtained after RTFOT and PAV for all binders except for the pure binder 20/30. It was also observed that the special multigrade asphalt cement HM 20/30 aged the least.

Distress surveys of cracking and rutting after 36 months after construction showed good performance of the asphalt mixtures with multigrade asphalt cement HM 20/30 and polymer modified binder EC. Macro texture was evaluated using the sand patch test. The results showed small differences between the four test sections. It was concluded that the PMB binder and the multigrade binder provided the best performance and ensured a longer service life for thin maintenance courses.

**Colored Pavements**

Colored asphalt surfaces have been used in Europe for more than 10 years [46]. Recent developments of synthetic binders and advanced dyes enabled engineers to design pavements not only in terms of the load capacity but also for aesthetic reasons. The effect of color pavements can be obtained by applying one of the following techniques:

- seal coat with colored fine aggregate,
✓ very thin overlay with pigmentable asphalt binder or synthetic asphalt binder [46],
✓ microsurfacing with adding mineral pigment or using colored asphalt emulsion [47].

The primary use of colored pavements is related to safety and esthetic/visual improvements. It was however shown [46] that a colored pavement surface can significantly reduce pavement temperature, which can provide better rutting resistance and less aging of the asphalt mixture.

It was observed [47] that the nature of the colored pigment added to the aggregate can significantly influence the workability and cohesion properties of the microsurfacing mix or very thin asphalt concrete mix. On the other hand, synthetic binders have high water-damage resistance.

Preliminary observations on the use of colored pavements in Europe suggest that this technique is a very promising tool to provide safe and comfortable driving conditions. These techniques are relatively new and are still under development; therefore, more research is needed to evaluate the real cost-benefit of these materials in terms of reducing the pavement temperature, reducing aging, and influencing asphalt pavement performance [47].

**Surface Friction and Skid Resistance**

Surface friction predictions play a key role in Pavement Management Systems. A recent study in Europe [48] focused on the development of a prediction model for the surface friction on two different wearing courses:
✓ conventional asphalt concrete,
✓ experimental high performance modified asphalt concrete.

The surface friction and surface macrotexture deteriorate mainly due to the polishing action of the moving traffic and environmental conditions. Generally, the variation of the skid resistance can be divided into the following categories [48]:
✓ spatial variations:
  - longitudinal, due to road geometric design, e.g. sharp curves, intersections,
  - transversal, due to traffic wander,
✓ temporal variations:
  - short term, due to removable dirt on the surface, like dust,
  - long term, due to environmental and traffic polishing.
In this study the following experimental data was collected for a two-year period:

- traffic data that included magnitude, spectrum and vehicle lateral position,
- surface condition data that consisted of surface friction measured with British Pendulum Tester, and surface macrotexture measured with the Sand Patch Test.

Two methods were used to quantify the total damage in terms of the accumulated number of equivalent light vehicles, \( n_{eq} \):

- Method 1 assumed that damage is proportional to the total tire footprint area of the vehicle,
- Method 2 was based on the approach that damage is proportional to the total load exerted on the surface by the vehicle.

Traffic wander was assumed to be normally distributed. For field data the following models were assumed:

- logarithmic model for the British Pendulum Number:
  \[
  BPN = a + b \cdot \log(n_{eq})
  \]
- exponential model for the macrotexture data:
  \[
  HS(n_{eq}) = HS_0 \cdot e^{-k \cdot n_{eq}} + HS_t,
  \]
  where
  - \( HS \) - height of sand,
  - \( HS_0 \) - initial value of the Estimated (mean) Texture Depth (ETD) measured on the site using Sand Patch Test,
  - \( HS_t \) - terminal value of the ETD, assumed to be equal to 0.2mm.

It was shown that:

- method 1 models friction deterioration better than method 2,
- the proposed deterioration models have a good correlation with field data,
- the wearing course with modified asphalt concrete mix exhibits better performance than the conventional AC,
- for macrotexture a more refined model should be developed.

**RESEARCH IN OTHER ENGINEERING FIELDS**

The literature review searched other engineering fields for potential test methods that can be adapted to test the properties of surface treatments. A very limited number of tests were identified and are enumerated below:

- pull-off test,
✓ scratch test,
✓ interfacial indentation test [49],
✓ three- and four-point bending test with stiffener (for thin substrates),
✓ Double Cantilever Beam (DCB) test.

Some of the above test methods are not applicable to asphalt-aggregate system. Some of the tests, e.g. pull-off test, have been already applied to the asphalt mixes. The authors believe that the indentation test has great potential to provide more fundamental knowledge about the interface properties of the asphalt-aggregate system that play the critical role in surface treatment applications.

**POTENTIAL TEST METHODS**

The following list summarizes the test methods found during the literature search that were used to examine surface treatment behavior:

✓ X-ray Photoelectron Spectroscopy [32], see section on ‘Aging ...’,
✓ Local Fracture Test on Bitumen [38], see section on ‘Healing’,
✓ Pull-Off device [41, 50, ASTM D 4541], see section on ‘Stripping’,
✓ Thin Film Tack Test [41], see section on ‘Stripping’,
✓ Boiling Adhesion Test [42, 51, 52], see section on ‘Stripping’,
✓ Dynamic Immersion Test [42, 51, 52], see section on ‘Stripping’,
✓ Immersion – Compression Test [42, 51, 52], see section on ‘Stripping’,
✓ Wilhelmy plate test [39], see section on ‘Surface free energy’,
✓ Universal Sorption Device (USD) [39], see section on ‘Surface free energy’. 
✓ Layer-Parallel Direct Shear Device [50] fits into a standard Marshall testing machine, as shown in Figure 6. One part of the cylindrical sample is held by a semicircular pneumatic clamp. Shearing is applied by a steel plate at the pre-defined plane with a constant deformation rate and the maximum shearing force at the failure is recorded.
Nuclear Magnetic Resonance (NMR) [22]; recently a portable version of this device was developed; it is hoped that NMR will be able to detect changes in the asphalt layers caused by aging,

Portable Seismic Pavement Analyzer (PSPA) [22]; it can measure pavement modulus and give a quantitative evaluation of the changes in the asphalt layers caused by aging and/or moisture,

Schulze - Breuer & Ruck Test (SBR) [53]; this test is used in the design of microsurfacing to check the compatibility of the filler and asphalt binder. A defined 0/#10 aggregate mix, including reactive filler, is prepared, cured, compacted and then subjected to water immersion, abrasion (by shaking) and boiling stripping tests. The results of the tests are combined to give an overall compatibility score,

Wet Track Abrasion Test [53, 54, ASTM D3910]; this test is used to determine the minimum asphalt content and resistance to stripping. After ageing in the oven the asphalt mixture
specimens are placed in water for a specific time. The test determines the amount of material lost when the samples are subjected to a predetermined abrasive effort,

✓ Fretting test (Abrasion Cohesion Test Esso, ACTE) [13, 44, 55, 56, ASTM D7000-04], mentioned in the section on SBR modification; the asphalt emulsion is poured into a felt disk and aggregate is embedded into it. After specimen conditioning a nylon brush is abrading the surface treatment for one minute. Then, the loose aggregate is removed and the percentage of mass loss is calculated. This test is especially useful for specifying the time required to allow traffic after construction,

✓ Vialit Plate Shock Test [51, 57]; asphalt emulsion or hot asphalt cement is applied to standard size stainless-steel pans. 100 aggregates particles are embedded into the binder and the specimen is allowed to cure under specified conditions. After curing the specimen is conditioned at -22°C for 30 minutes. Then a 500 g ball is dropped 3 times from a distance of 50 cm on the inverted specimen. The results are recorded as percent aggregate retention, which represents a qualitative evaluation of the cohesion between the binder and aggregate,

✓ Hilt Cohesion Test (H.C.T.) [17]; a microsurfacing rectangular specimen is prepared and placed partially on the support with about half hanging in the air. A specific temperature is maintained and the time until the specimen breaks is measured. The time represents the H.C.T. cohesion of the mix,

✓ Cohesion tester [ASTM D6372]; an unconfined mix specimen is prepared and placed on a flat surface. A rubber-ended rod is placed on the upper surface of the specimen and connected to a torque meter. The torque required twisting the torque meter at 90° and 120° is recorded and the values are used to evaluate the asphalt mixture internal cohesion,

✓ SCREG Surface Cohesion Test [17, 55]; this is a modified Wet Track Abrasion Test. The specimen is prepared in a rounded mold and cured. The specimen is placed in a mechanical mixer with the abrading dual wheel head and the specimen is covered with water. The specimen surface is dried and the mass loss after the test is measured.

✓ The Dynamic Friction Tester (DFT) [22] is a portable device that measures the friction over a range of speeds by applying a braking force to pads revolving in a circular motion.
Task 3
Site Identification and Documentation

INTRODUCTION
In preparation for the second phase of this project that involves field and laboratory evaluation of different surface treatments, it is necessary to identify surface treatments field sites for which well documented construction and performance records are still available. This task identifies several sites in Minnesota that have the potential to be used in the second part of the project.

Table 1 lists the sites identified for further study. These are sites for which good supporting information is mostly available.

<table>
<thead>
<tr>
<th>Site #</th>
<th>Highway</th>
<th>Direction</th>
<th>Location</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>I-35</td>
<td>Southbound</td>
<td>Near Albert Lea</td>
</tr>
<tr>
<td>2</td>
<td>TH 56</td>
<td>Westbound</td>
<td>Near Austin</td>
</tr>
<tr>
<td>3</td>
<td>I-90 shoulder</td>
<td>Westbound</td>
<td>Near Austin</td>
</tr>
<tr>
<td>4</td>
<td>I-35 shoulder</td>
<td>Northbound</td>
<td>Near Albert Lea</td>
</tr>
<tr>
<td>5</td>
<td>I-35</td>
<td>Northbound</td>
<td>Near Stacy</td>
</tr>
<tr>
<td>6</td>
<td>TH 251</td>
<td>Eastbound</td>
<td>Near Albert Lea</td>
</tr>
</tbody>
</table>

Sites 2, 3, and 4 are part of an ongoing aging/optimization study being performed by the Minnesota Department of Transportation (Mn/DOT). Site 6 is part of the Winslow Arizona Sealer/Rejuvenator Study. Construction and field performance records are available at these sites. These two studies were detailed in the Task 1 report for this project.

Site 1: I-35
In 2001 an overlay was placed on a six-mile stretch of southbound Interstate 35 near Albert Lea. The northern and southern two miles consisted of a 4.5 inch conventional mixture with a PG 64-28 binder. The center two miles consisted of the same overlay with a ½ inch ultrathin bonded wearing course. This paving process, developed by Koch Pavement Solutions, is referred to as NovaChip®.

Figure 1 shows the cracking history of the three pavement sections after three winters. This review shows a significant reduction in the need to seal and perform maintenance on the cold joint or construction joints between the mainline and shoulder. There was no sealing along
the joint in the NovaChip® section, but the other two conventional sections required sealing and repair in nearly the entire section. Similar results were present in the transverse cracking counts.

![Cracking History on I-35 Conventional and NovaChip® Surfaces](image)

**Figure 3.1. Cracking History on I-35 Conventional and NovaChip® Surfaces**

**Site 2: TH 56**

TH 56 is a 24-mile long two-lane rural highway near Austin with an ADT of 2000. The test sections were constructed in two phases. The section between reference posts (r.p.) 2 and 15 was constructed in 1999, and the section from r.p. 15 to 26 was constructed in 1995. Because of the different ages of the two sections, it was decided to seal coat two different segments each year. The first segments were constructed according to the original work plan starting at r.p. 14 to 15 for the one-year-old section. The additional section was constructed at r.p. 15 to 16. By adding a similar seal coat on the older pavement, approximately four years time can be gained in determining the aging process in the asphalt pavement. The first seal coat was applied to both parts in 2000. Every year since then a new application of the seal coat was performed and new
one-mile segments were created in both parts of the test sections. A diagram of the test sections is presented in Figure 2.

![Figure 2](image)

**Figure 3.2. TH 56 Study – Test Section Layout**

Table 2 contains a summary of construction data for the test sections. After the seal coat on each section, a fog seal was applied with CSS-1H emulsion diluted 50:50 with water, at an application rate of 0.11 gallons/yd². In 2003 the fog seal was applied at 0.13 gallons/yd².

**Table 3.2. TH 56 Seal Coat Data**

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<th>12 to 13</th>
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<td>18</td>
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</table>
Site 3: I-90

Interstate 90 is a rural interstate highway near Austin with an ADT of 10,800. The treatments were applied on the 8-foot wide, right hand shoulder traveling westbound. The shoulders were replaced in 1999. Reference post 176 to 175 was the control section, paved in 1999. The next section (r.p. 175 to 174) was fog sealed in 2000 with a CSS-1H emulsion, diluted to a final product of one part water to three parts emulsion. The application rate was 0.12 gallons per square yard. Even though the shoulder was only one year old at the time of treatment, numerous popouts were present. After one winter satisfactory performance of the treatment was observed.

A panel of researchers evaluated the shoulder condition in the spring of 2004. A number of observations were made for the following sections:

- r.p. 177-176: Taken as new control section. Pavement was old with severe alligator cracking and wedge paving present.
- r.p. 176-175: Old control section. A portion of this section was fog sealed in 2003
- r.p. 175-174.6: A portion of the old fog seal section was re-treated in 2003 with a heavy CRS-2P emulsion.
- r.p. 174.6-174: A lighter fog seal was apparent. This may be a remnant of the original CSS-1H fog seal applied in 2000.
- r.p. 174-173: This section was fog sealed in 2003 with a CRS-2P emulsion.

All of the sections that were fog sealed appeared to be in satisfactory condition. The fog seal enhanced the performance of the shoulder.

Site 4: I-35 Shoulder

Interstate 35 is a rural interstate highway near Albert Lea with an ADT of 17,500. The surface treatments were applied on the northbound, 8 foot 6 inch wide, right hand shoulder. The section from r.p. 14-15 was taken as the control section. It was placed in 1998. A seal coat was applied in 2000 to the section from r.p. 15-16. The seal coat used approximately 17 lbs/yd2 of 3/8” New Ulm quartzite chip and 0.34 gallons per square yard of CRS-2P emulsion. The construction methods used were the same as the proper methods for seal coating a highway. Later reviews of the section showed almost a complete loss of the aggregate cover due to
snowplow damage. It appeared that the difference in the slope that the mainline was paved at versus the shoulder allowed the snowplows to attack the chips very aggressively. Based on physical appearance, the seal coat can be considered to be a complete failure. However, the seal coat was placed to protect the shoulder from aging and cracking. The emulsion from the seal coat still provided excellent protection to the shoulder.

A seal coat was applied in 2001 to the section from r.p. 16-17. Due to the loss of aggregate on the previous section, a smaller aggregate was used in this application. A seal coat with taconite tailings and CRS-1P was constructed. The taconite tailings all passed the #4 sieve, which provided a very smooth surface. Construction began with 0.18 gallons per square yard of emulsion and 8.5 lbs/yd2 of tailings. Excessive roller pickup and “waves” of the aggregate required less emulsion and more rock. Due to the small size of the tailings, the taconite could not be placed at the design rate from the seal coat design program. The emulsion was cut back to 0.14 gallons per square yard, and the aggregate increased to 12 lbs/yd2. Based on rolling, pickup, and curing time, it was recommended to apply future seal coats at starting rates of 0.10 gallons per square yard of emulsion and 15 lbs/yd2 of chips.

A rejuvenator was placed in 2002 from r.p. 17 to 18. A proprietary product called Reclamite was placed by CAM, LLC. Reclamite is marketed as a preservative seal that penetrates and rejuvenates oxidized pavements. It was applied at 0.10 gallons per square yard followed by a light coating of sand at 0.5 lbs/yd2. A survey performed two months after treatment showed that the pavement surface treated with Reclamite appeared darker than the untreated pavement past r.p. 18. One year after treatment, the Reclamite section looked similar to the control section, with no noticeable spalling or cracking. Another section of Reclamite was placed by CAM, LLC from r.p. 18 to 19 in July 2004.

**Site 5: I-35**

Interstate 35 near Stacy contains several sections of different surface treatments. An eight-mile stretch on both the northbound and southbound lanes contains micro surfacing, slurry leveling, and micro leveling sections. Very little information is available about this project. Figure 3 shows the different sections.
Site 6: TH 251

TH 251 is part of a larger sealer/rejuvenator study sponsored in part by the Foundation for Pavement Preservation. The idea was to apply seven different types of surface treatment (along with a control section) on sections along TH 251 to measure their performance side by side. The eight sections were to use the following surface treatments:

1. Mega-tec
2. Control (no treatment)
3. CSS-1H fog seal
4. GSB – type B
5. Pass-oil
6. Reclamite

<table>
<thead>
<tr>
<th>Southbound</th>
<th>Reference Post</th>
<th>Northbound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Surfacing (single pass)</td>
<td>141</td>
<td>Micro Surfacing (1999)</td>
</tr>
<tr>
<td>Slurry Leveling</td>
<td>140 (Stacy)</td>
<td>139</td>
</tr>
<tr>
<td>Nova Chip</td>
<td>138</td>
<td>single pass</td>
</tr>
<tr>
<td>Micro Leveling</td>
<td>137</td>
<td>quartzite</td>
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<tr>
<td>Control</td>
<td>135</td>
<td>Fog Seal</td>
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<td>133</td>
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Figure 3.3. I-35 Surface Treatments Near Stacy
7. CRF

8. Seal coat (traditional Minnesota design)

In 2002 these eight sections were constructed along eastbound TH 251. The test sections were 200 feet long starting at r.p. 9. The Mega-tec section was rather slippery after the application, but it looked like it was performing well. It is a plastic-based sealer produced by a company in Lakeville. The CSS-1H fog seal was applied too heavily and did not perform well. Little information was provided about the other sections. Cores were taken from four of the sections, and Mathy Technology & Engineering Services, Inc. performed torsion bar experiments on the mixtures in the dynamic shear rheometer. The goal was to measure how well the surface treatments prevented aging in the upper layers of the pavement. The test results from this study have not yet been made public.

In 2004 only two sections were constructed. ASI, who produced the GSB – type B treatments opted not to continue in the study. Minnesota Department of Transportation District 6 maintenance did not apply a fog seal or chip seal. The only supplier to return was CAM, LLC. They applied Reclamite and CRF to two sections 100 feet long. Cores were taken on these sections before the rejuvenator applications, and cores will again be taken after one year to study aging effects in the asphalt surface.
Task 4

Guidelines for Phase II Project

INTRODUCTION

The literature review performed in Task 1 has shown that most of the work done in the area of surface treatments focused on the construction practice and on the monitoring of the performance of the treatment over various periods of times. Some of the most recent studies also address the economic issues involved in the selection process and the timing of the application of treatments. To date there are no research studies that investigated the deterioration process of pavements in terms of crack formation and propagation related to traffic and environmental loading as well as environmental deterioration, to better select the appropriate application time of surface treatments. Also, there is very little information with respect to the role played by surface treatments in preventing or delaying the aging process in the treated pavement. This important issue needs to be further investigated to better understand and quantify the benefits of applying various types of treatments.

PHASE II OBJECTIVE

The objective of Phase II work is to provide a better understanding of the mechanism by which surface treatments protect the existing pavement from further aging and deterioration due to traffic and environmental loadings and to reasonably predict the optimum time for the application of these treatments. This requires a reasonable understanding of the progression of the complex aging mechanism in asphalt materials as well as the effect of aging on their fracture resistance. This research will provide guidelines on how to determine the optimum timing of surface treatment application based of surface distress evolution and make recommendations in terms of type of treatment to be used. Similar to any other pavement performance analyses and recommendations a follow up of this work by continuously monitoring the field performance combined with additional laboratory investigations and data analysis will be a necessary step in improving the prediction of the optimum times for the application of surface treatments to asphalt pavements in Minnesota. It is expected that the database and the field and laboratory
experiments performed in Phase II will provide the basis for routine type of activities part of the pavement management operations of the future.

**RESEARCH APPROACH**

The research methodology involves a mixture of fundamental analyses, laboratory experiments as well as field investigations. The timing of the surface treatment is related to the aging and distresses that develop in asphalt pavements with time. Ideally, a surface treatment should be applied not too soon (too expensive) and not too late (reduced life) to provide a balance between maximum life and minimum cost. The evolution of the asphalt pavement surface condition is mostly related to the aging characteristics of the asphalt binder and to the evolution of the mechanical properties of the binder with aging. Both destructive and nondestructive tests will be performed to assess the changes in the surface condition with time and to evaluate the influence of important environmental factors such as temperature and moisture.

The work will focus on providing reasonable answers to the following two questions:

1. When is the best time to apply a treatment based on a comprehensive evaluation of the pavement surface and of the processes that take place in the top surface layer of the pavement?
2. Do surface treatments in addition to “sealing the pavement surface” significantly delay the detrimental aging process of the treated pavement and are some treatments better than others?

As part of this research, information about the aging and mechanical distresses observed within the surface treatments will be collected and stored, whenever possible; however, no analysis of these data will be performed as part of this study.

**WORK PLAN**

The work plan will be divided into six tasks, as shown next. MnDOT will perform the coring of the field samples and provide guidelines on how to obtain historical information about the selected test sections. MnDOT chemical lab will also perform the extraction and recovery of the asphalt binders from the field samples. Gerald Reinke (Mathy Construction) will perform the binder FTIR characterization and some mechanical testing and will provide access to the data obtained in the national effort previously described.
**Task 1. Field Sample Collection**

During the first year samples will be collected for laboratory investigation from the following sites that were selected based on the information provided in phase I of the project: all ten sections from TH 56 and four sections, selected by the project TAP, from TH251. Six cores per site will be obtained for the experimental investigation. For some of the test sections, selected by the TAP and research team, milling will be performed to further refine the resolution of the aging effect with pavement depth at millimeter scale.

In addition, performance, construction and maintenance data, traffic and weather data and any other type of information relevant to this research produced by other parties will be collected and included in a database for further evaluation and analysis. One example is the MnROAD aging study. Particular attention will be given to information related to the presence of moisture in the test sections prior to the application of the surface treatment and during the application process; a number of studies has indicated the presence of moisture in the pavement as the lead contributor to the rapid failure of the treated pavements.

Up to three additional sections identified on Minnesota local roads may be included in the study if the TAP and the research team find well documented sections that will improve the outcome of the study.

**Task 2. Experimental Investigation - Surface Condition (Aging and Cracking) Assessment**

This task will consist of a set of experiments to evaluate the surface condition of the pavement. The experiments will focus on investigating two critical factors that affect pavement performance: pavement surface cracking and pavement surface aging.

For cracking, two methods will be used. The first one will identify the presence of microcracks using Scanning Electron Microscope (SEM) on samples cut from the field sites, as described in task 2 of phase I. This analysis will be performed at different depths within the cores obtained from the field sites. Considering the complexity of the sample preparation for the SEM analysis, the option of using a portable digital microscope to detect micro cracks in the surface layer will be explored to determine if a simple practical method can be developed to analyze the surface of a pavement.

For aging, two methods will be used also. The first one performs the surface aging evaluation directly on the field samples using X-ray Photoelectron Spectroscopy (XPS) analysis,
as described in task 2 of phase I. The other method requires the extraction and recovery of the binders from the field mixture samples followed by the FTIR analysis of the recovered binder to determine the level of oxidation. This method will be used with mixture slices cut from the field cores at different depths as well as with milled material from the surface of the selected pavements. Depending on the availability of the original binders for some of the selected sections, FTIR analysis will be performed on the laboratory aged binders for further comparison with the field samples. The results from the XPS and FTIR tests on the field samples will be compared to better understand their capabilities and limitations.

**Task 3. Experimental Investigation – Mechanical Characterization**

This task will consist of the mechanical characterization of the field samples obtained in task 1. The extracted cores will be first evaluated in terms of their volumetric properties. The experimental work will consist of tests performed on both the asphalt mixtures and the asphalt binders extracted and recovered from the mixtures. For the asphalt binders, DSR (master curves), BBR, DTT and fracture tests using the Single Edge Notched Beam (SENB) method will be performed on the binders extracted from the millings and mixture samples cut at different depths of the pavement. Fracture tests using the Semi Circular Bend (SCB) test will be performed on 1" slices of mixture cut from the field cores. Creep tests and repeated torsional fatigue tests on thin beams of mixture will also be performed to evaluate the aging effect with depth under different surface treatments.

**Task 4. Experimental Investigation - Environmental Factors**

The data collected in task 1 to quantify the most important environmental factors that influence the surface condition of asphalt pavements will be analyzed in this task. Weather parameters such as incident solar radiation, reflected radiation, air temperature, dew point, temperature, precipitation and wind speed will be used together with temperature profiles in the pavements. Ideally the temperature sensors in the pavement should be spaced vertically millimeters to centimeters apart to obtain relevant information about the thermal processes in the surface of the pavement. Most likely this information is not available in the existing instrumented field sections. The research team will perform a literature search to identify if such information is available. Next, the temperatures in pavements in response to weather and traffic conditions will
be simulated by a heat transfer model that will be one-dimensional (vertical) in space and unsteady in time. This model will use exceptionally high resolution in the space. Of particular interest will be the formulation of the surface heat flux budget, which has to include solar and atmospheric radiation, reflection, back radiation, convection, and under wet conditions evaporation. The available data will be used to determine parameters and coefficients in this model by calibration. Such parameters will include surface reflectivity and emissivity of pavement surfaces, wind convection coefficients, and thermal conductance values which will differ from one pavement type to another.

**Task 5. Data Analysis**

Description: This task will put together the results and analyses performed in the previous tasks. Of particular interest will be the development of correlations among the key parameters investigated in the proposed research such as:

- Variation of aging effects with pavement age
- Variation of aging effects along the pavement thickness and quantification of the reduction in aging provided by the application of surface treatments
- How well do the laboratory tests predict aging in the field; this analysis will be based on both the comparison of mechanical properties of field aged versus laboratory aged binders as well as FTIR analysis of the field and laboratory aged binders whenever original binders are available
- Microcracking evolution with pavement age
- Microcracking evolution along the pavement thickness and quantification of the reduction in cracking provided by the application of surface treatments
- Variation of aging and microcracking with the environmental factors
- Development of correlation between aging level and crack formation

These analyses will be used to develop a model for predicting the optimum time application of surface treatments and possibly recommend the best type of treatment for the job.

**Task 6. Draft Final Report**

A draft final report will be prepared following the Mn/DOT publication guidelines, to document project activities, findings, and recommendations. This report will be submitted through the
publication process for technical and editorial review. A database that contains all the data
acquired and generated as part of this project will be also delivered.
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