Long-Term Performance of Reflective Cracking Mitigation Techniques in Nevada

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Hot-mix asphalt (HMA) overlay is one of the commonly used methods for rehabilitating deteriorated pavements. The Nevada Department of Transportation (DOT) uses HMA overlays as a rehabilitation technique for the majority of the state's flexible pavements. One major type of distress influencing the life of an overlay is reflective cracking. In the past, Nevada DOT has experimented with a number of techniques—such as cold in-place recycling, reinforced fabrics, stress relief courses, and mill and overlay—to reduce the impact of reflective cracking on HMA overlays. Several projects were constructed under each category. The long-term field performance of various Nevada DOT reflective cracking mitigation techniques was evaluated; the techniques were used on flexible pavements at 33 field projects. Performances of the various projects were analyzed by fatigue, transverse, and block cracking measurements from Nevada DOT's pavement management system data. In addition, the statistical approach called principal component analysis was used to asses the effectiveness of each of the reflective cracking techniques. The study indicated that cold in-place recycling and mill and overlay were the most effective treatments for reflective cracking of HMA overlays over HMA pavements under Nevada's conditions, except when the existing pavement experiences severe alligator cracking. In such situations, it is recommended that HMA pavement be subjected to reconstruction or full-depth reclamation.

Pavement rehabilitation is rapidly becoming one of the most important issues facing many highway departments. Hot-mix asphalt (HMA) overlay is one of the commonly used methods for rehabilitating deteriorated pavements. The Nevada Department of Transportation (DOT) uses HMA overlays as a rehabilitation technique for the majority of the state's flexible pavements.

One major type of distress influencing the life of an overlay is reflective cracking (*1*). When asphalt overlays are placed over jointed or severely cracked existing rigid and flexible pavements, cracks reflect to the surface in a relatively short period. Physical tearing of the overlay occurs because of movements under heavy wheel loads at joints and cracks in the underlying pavement layer. Therefore, long-term performance of the HMA overlays depends on their ability to resist reflective cracking. Reflective cracking in the overlay allows water to percolate into pavement structure and to weaken the HMA and the supporting layers, hence contributing to many forms of pavement deterioration.

Numerous previous efforts have been undertaken to reduce or prevent reflective cracking of HMA overlays, including increased thickness of HMA overlay, use of a stress-absorbing membrane interlayer (SAMI); use of fabrics and geotextiles membranes; and fracturing of the existing concrete slabs. The basic principle of reflective cracking is that tensile stresses at the interface of the crack and the new HMA overlay are significantly increased due to the discontinuity at the tip of the crack. The developed tensile stresses rapidly exceed the tensile strength of the HMA layer, and the crack forms at the interface and quickly propagates to the surface. Combating reflective cracking can be achieved by either one of two approaches: (*a*) reduce the magnitude of the tensile stresses at the crack–overlay interface or (*b*) increase the tensile strength of the HMA overlay.

The increase of thickness of the HMA overlay, as well as placing a SAMI, follows the approach of reducing the magnitude of the tensile stresses at the crack–overlay interface. The SAMI usually consists of a single or double chip seal. The chip seal is a highly flexible layer that reduces the magnitude of the tensile stresses before they intersect with the new HMA layer. The ability of the SAMI to reduce the tensile stresses increases as its thickness increase (i.e., single versus double chip seal), as its binder content increases, and as the flexibility of the binder increases. However, having a thick, rich, and highly flexible SAMI may cause potential rutting and shoving problems under heavy traffic. An optimum design must be established to effectively mitigate reflective cracking without negatively affecting the long-term performance of the HMA overlay.

The fabrics and geotextiles technique follows the approach of increasing the tensile strength of the HMA overlay. Those materials have high tensile strengths and if they are effectively bonded to the HMA layer, they will improve the tensile strength of the overlay. Numerous brands of fabrics and geotextiles currently are on the market, covering a wide range of cost and strength properties. Selecting the best type of fabric or geotextile requires an in-depth assessment of their relative properties and long-term performance.

The research effort documented in this paper was directed toward identifying an effective method to eliminate and retard the propagation of the cracks from the old surface layer through the new HMA overlay. In 2006, Nevada DOT initiated a two-phase research project. Phase I identified the most promising techniques to mitigate reflective cracking in HMA overlays. Phase II identified an analytical model that could be used to predict the resistance of HMA overlays to reflective cracking and predict their long-term performance. Also, that phase reviewed the laboratory and field tests being used to evaluate the resistance of HMA overlays to reflective cracking. On the basis of such review and in-depth investigation of the problem, and at completion of both phases, a system will be recommended for implementation in Nevada. This paper summarizes the findings and recommendations of Phase I of this study.

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BACKGROUND

Numerous studies have been conducted throughout the years to assess the effectiveness of various techniques currently available in the industry. In 1982, FHWA reported a study on the performance of fabrics in asphalt overlays from Colorado test sections (2). The report revealed that the control section (1.5-in. AC overlay) developed 10% cracking in 1.25 years and 50% within 3.25 years, while the fabric section (1.5-in. AC overlay and fabric) developed less than 2% reflection cracking in 1.25 years and 30% within 3.25 years.

In 1984 and 1985, the evaluation of HMA overlays over deteriorated PCC pavements in Georgia indicated that 20% of the cracking area occurred in 6 years for a 6-in. HMA overlay compared with 2 years for a 4-in. HMA overlay (*3, 4*). Reflective cracking appeared almost immediately after construction for a 2-in. overlay.

In 1989, Scofield documented in a research report the history, development, and performance of asphalt rubber (AR) mixtures in Arizona (*5*). In that report, the conclusion was stated that "asphalt rubber has successfully been used as an encapsulating membrane to control pavement distortion due to expansive soils and to reduce reflection cracking in overlays on both rigid and flexible pavements." The research also indicated that during 20 years of AR use, Arizona DOT treatment evolved from using slurry applied asphalt rubber chip seals to using reacted asphalt rubber as a binder in open and dense-graded HMA. In 1990, Arizona DOT designed and constructed a large-scale, gap-graded AR test project in Flagstaff, Arizona, on the very heavily trafficked Interstate 40 (*6, 7*). In 1999, the traffic exceeded 20,000 vehicles per day with 35% heavy trucks. The purpose of the test project was to determine whether a relatively thin overlay with AR and without a SAMI could reduce reflective cracking. AR is a mixture of 80% hot paving grade asphalt and 20% ground tire rubber. It was reported that the AR overlay has performed beyond original expectations.

The California Department of Transportation (Caltrans) evaluated the increase of HMA thickness overlays to minimize reflective cracking. Research conducted by Predoehl in California showed that 4.8 in. of overlay is required to retard reflective cracking for 10 years (*8*). In 1992, Caltrans evaluated the effectiveness of glass-grid in retarding reflective cracking caused by thermal fatigue (*9*). As a result, the glass-grid retarded reflective cracking in the area of high tensile stresses. Therefore, Caltrans now considers glass-grid application for the overlay strategy.

In 1999, Buttlar et al. evaluated the cost-effectiveness of Illinois DOT's reflective cracking control system consisting of a nonwoven polypropylene paving fabric (*10*). The performance monitoring indicated an increase in life spans by 1.1 and 3.6 years for paving fabric strip (over lane widening) and area applications (over the entire pavement), respectively. Lane-widening and entire pavement applications were expected to have life spans of 12 and 14 years, respectively.

In 2002, the Texas Transportation Institute performed a research project in cooperation with Texas DOT and FHWA to investigate and develop information that will aid in evaluating the relative effectiveness of commercially available geosynthetic materials in reducing the severity or delaying the appearance of thermally induced reflective cracking in HMA overlays (*11*). Results showed that the performance of geosynthetics in addressing reflection cracking in HMA overlays has ranged from highly successful to disastrous failures.

In 2004, an experiment to assess the economy of various types of reflective cracking reduction techniques was conducted on I-25 near Colorado Springs, Colorado (*12*). The performance of the various methods was widely variable, but in general, geotextile, reinforced fabrics, fiberglass tape, and crack sealer showed less reflective cracking than the control section did.

REVIEW OF NEVADA DOT EXPERIENCE

In the past 15 years, Nevada DOT experimented with different techniques to reduce the impact of reflective cracking on HMA overlays. That research effort identified and reviewed the performance of the field projects where Nevada DOT has implemented reflective cracking mitigation techniques. The design, construction, and traffic details of those projects were collected along with their corresponding long-term field performance. Information was analyzed to assess the effectiveness of various techniques in mitigating reflective cracking under Nevada's conditions.

Performance-Related Data

Pavement roughness, rutting, and cracking represent major components of Nevada DOT's pavement conditions survey program. Nevada DOT's pavement management system (PMS) uses the present serviceability index (PSI) to monitor performance of various pavement sections throughout the state. The PSI is heavily dependent on the roughness of the pavement and it does not give enough weight to the cracking distresses, which makes it not useful in assessing the effectiveness of treatments for mitigation of reflective cracking in HMA overlays. For the purpose of this research, individual data collected on fatigue, transverse, and block cracking monitored over the service life of the selected pavements were used to asses the actual performance of various reflective cracking mitigation techniques. The cracking types, extent, and severity as defined by Nevada DOT's *Flexible Pavements Distress Identification Manual* are summarized as follows (*13*).

Fatigue Cracking

Fatigue cracking is caused by repeated traffic loading of the pavement. These cracks initiate at the bottom of the HMA layer and slowly work their way to the surface. Fatigue cracking usually starts as a longitudinal crack in the wheelpath, which Nevada DOT classifies as Type A. Further weakening of the HMA and base layers, coupled with repeated traffic loading, leads to progression of longitudinal crack and formation of interconnected cracks referred to as alligator cracking, which Nevada DOT classifies as Type B. The extent of Type A fatigue cracking is measured as the total linear feet of that type of cracking in the wheelpath of the pavement area being surveyed. The extent of Type B fatigue cracking is measured as the total square feet of that type of cracking in the wheelpath of the pavement being surveyed (i.e., 10-ft × 100-ft area at every milepost).

Transverse Cracking

Transverse cracking is primarily caused either by thermal stresses or reflection from cracks and joints in the layer underneath. The extent is measured as the total linear feet of cracking throughout the pavement area being surveyed (i.e., 10-ft × 100-ft area at every milepost).

Block Cracking

Block cracking starts as a combination of short transverse and non-wheelpath longitudinal cracking, which Nevada DOT classifies as Type A. It is caused by age hardening and shrinkage of the HMA layer. Although traffic loading is not the primary cause of that type of distress, continued loading on the brittle surface will accelerate the distress and break the larger pieces into smaller pieces, which Nevada DOT classifies as Types B and C. The extent of Type A is measured as the total linear feet of this type of cracking throughout the pavement area being surveyed. The extent of Types B and C is measured as the total square feet of this type of cracking throughout the pavement area being surveyed.

Long-Term Field Performance of Selected Nevada DOT Projects

The following section represents a summary of various reflective cracking mitigation techniques that Nevada DOT has evaluated within the past 15 years. These are

- Cold in-place recycling (CIR),
- Reinforced fabrics (RFs),
- Stress relief courses (SRCs), and
- Mill and overlay (MOL).

A total of 33 projects were constructed under all categories. Project locations varied between the northern and southern parts of Nevada, covering different environmental and traffic conditions. Table 1 summarizes the project contract number, project location, applied reflective cracking mitigation technique, date of construction (DOC), and 2005 annual average daily traffic (AADT). The DOC of projects varied between 1990 and 2003. Of the 33 projects, 19 were located in northern Nevada. All of the long-term field performances were obtained from the Nevada DOT's PMS. The following paragraphs present brief descriptions of various treatments evaluated in this study.

Cold In-Place Recycling Projects

CIR is carried out using specialized recycling machines, the heart of which is a milling drum equipped with a large number of hardened steel picks. Generally, CIR technology is used to build a strong, flexible base course. CIR is believed to strengthen the existing pavement by treating many types and degrees of distresses. Originally, the CIR projects were constructed on low traffic volume roads ranging from 30 to 300 AADT. However, some agencies,

TABLE 1 Summary of Nevada DOT Projects Analyzed in Study

Treatment	DOC[a]	Contract	Route	Location	Thickness of Surface Layer (in.)[b]	Binder Grade	AADT[c]
CIR-A-1	1998	2808a	US-50	North	2-in. CIR + 2.5-in. DGHMA	AC-20P	2,950
CIR-A-2	1997	2808b	US-50	North	2-in. CIR + 2.5-in. DGHMA	AC-20P	2,950
CIR-A-3	1999	2838	SR-396	North	2-in. CIR + 2.5-in. DGHMA	AC-20P	1,100
CIR-A-4	1999	2935	SR-360	South	2-in. CIR + 3-in. DGHMA	AC-20P	800
CIR-B-1	1998	2819	US-95	South	3-in. CIR + 3-in. DGHMA	AC-20P	5,550
CIR-B-2	1998	2873	US-95	South	3-in. CIR + 3-in. DGHMA	AC-20P	5,550
CIR-B-3	1999	2961	US-6	South	3-in. CIR + 3-in. DGHMA	AC-20P	2,000
CIR-B-4	1999	3013	US-95A	North	3-in. CIR + 3-in. DGHMA	AC-20P	14,500
CIR-C-1	2003	3025a	US-93	North	2-in. CIR + 2-in. DGHMA	AC-20P	5,000
CIR-C-2	2001	3025b	US-93	North	2-in. CIR + 2-in. DGHMA	AC-20P	1,000
CIR-C-3	2001	3025c	SR-208	North	2-in. CIR + 2-in. DGHMA	AC-20P	1,000
CIR-C-4	2001	2876	SR-208	North	2-in. CIR + 2-in. DGHMA	AC-20P	1,500
RF-1	1999	2761	SR-443	North	Fabric + 2-in. DGHMA	AC-20P	9,600
RF-2	1999	2932	US-95	South	Fabric + 2-in. DGHMA	AC-20P	2,850
RF-3	2000	2980	US-50	North	Fabric + 2-in. DGHMA	AC-20P	1,000
RF-4	2000	2980	US-95	North	Fabric + 2-in. DGHMA	AC-20P	4,400
RF-5	2001	3006	IR-80	North	Fabric + 2-in. DGHMA	AC-20P	7,200
RF-6	2001	3008	SR-227	North	Fabric + 2-in. DGHMA	AC-20P	10,000
SRC-1	1997	2723	US-95	South	1-in. SRC + 2-in. DGHMA	AC-20P	40,000
SRC-2	2000	3031	US-395	North	1-in. SRC + 2-in. DGHMA	AC-20P	15,600
SRC-3	2000	3048	SR-157	South	1-in. SRC + 2-in. DGHMA	AC-20P	2,700
SRC-4	2001	3045	US-50	North	1-in. SRC + 2-in. DGHMA	AC-20P	1,900
SRC-5	2003	3162	US-395	North	1-in. SRC + 2-in. DGHMA	PG 64-28NV	29,100
MOL-A-1	1990	2384a	US-95	North	1.0-in. DGHMA	AC-10	40,000
MOL-A-2	1993	2384b	US-95	North	1.0-in. DGHMA	AC-20	5,500
MOL-A-3	1993	2432	SR-157	South	1.0-in. DGHMA	AC-20	2,700
MOL-A-4	1993	2505	US-95	South	1.0-in. DGHMA	AC-20P	3,350
MOL-B-1	1995	2651a	US-95	South	1.5-in. DGHMA	AC-20P	2,000
MOL-B-2	1996	2651b	US-95	South	1.5-in. DGHMA	AC-20P	1,700
MOL-B-3	1996	2651c	US-95	South	1.5-in. DGHMA	AC-20P	1,700
MOL-B-4	1997	2679	US-95	South	1.5-in. DGHMA	AC-20P	6,750
MOL-C-1	2000	3028	SR-512	North	1.5-in. DGHMA	AC-20P	7,250
MOL-C-2	2003	2070	SR-160	South	1.5-in. DGHMA	AC-20P	7,500

[a] DOC denotes date of construction.

[b] DGHMA denotes dense graded hot-mix asphalt.

[c] AADT denotes annual average daily traffic.

including Nevada DOT, currently apply this treatment to roads with traffic varying from 1,000 to even 10,000 AADT. A total of 12 Nevada DOT CIR projects constructed between 1992 and 2001 were analyzed in this study. Following is a description of various CIR treatments applied:

- CIR-A—Contracts 2808a, 2808b, 2838, and 2935. CIR the top 2.0 in. of the existing HMA layer and overlaying it with 2.5-in. dense graded HMA and 0.75-in. open graded friction course (OGFC).
- CIR-B—Contracts 2819, 2873, 2961, and 3013. CIR the top 3.0 in. of the existing HMA layer and overlaying it with 3.0-in. dense graded HMA and 0.75-in. OGFC.
- CIR-C—Contracts 3025a, 3025b, 3025c, and 2876. CIR the top 2.0 in. of the existing HMA layer and overlaying it with 2.0-in. dense graded HMA and 0.75-in. OGFC.

Nevada DOT's standard practice is to place a 0.75-in. OGFC within the first year of construction.

Reinforced Fabrics Projects

Paving fabrics are a special class of geosynthetic that provide the generally acknowledged functions of a stress-absorbing interlayer and a waterproofing membrane. A total of six Nevada DOT projects with paving fabrics constructed between 1999 and 2001 were analyzed in this study. The construction consisted of cold milling 2.0 in. of the existing HMA layer, placing fiberglass yarns, and overlaying with 2.0-in. Type II dense graded HMA and 0.75-in. OGFC.

Stress Relief Course Projects

The SRC consists of a Nevada DOT Type III (0.5 in. maximum size) dense graded HMA layer. The SRC is placed between the existing pavement and the overlay layer; it is supposed to act as a separator layer between the cracked surface and the overlay. A total of five Nevada DOT projects with an SRC constructed between 1997 and 2003 were analyzed in this study. Following is a description of the various SRC treatments applied. This treatment consisted of cold milling 2.0 in. of the existing HMA layer, placing a 1.0-in. SRC, and overlaying with 2.0-in. Type II dense graded HMA and 0.75-in. OGFC.

Mill and Overlay Projects

This technique consists of cold milling up to 2 in. of the existing HMA layer and replacing it with an HMA overlay. The intention is to reduce reflective cracking by eliminating surface cracks through cold milling and replacing with new HMA material. A total of 10 Nevada DOT projects constructed between 1990 and 2003 were analyzed in this study. A description of the various applied HMA overlays is as follows:

- MOL-A—Contracts 2384a, 2384b, 2432, and 2505. Cold milling 1.0 in. of the existing HMA layer and overlaying with 1.0-in. Type III dense graded HMA and 0.75-in. OGFC.
- MOL-B—Contracts 2651a, 2651b, 2651c, and 2679. Cold milling 1.5 in. of the existing HMA layer and overlaying with 1.5-in. Type II dense graded HMA and 0.75-in. OGFC.
- MOL-C—Contracts 3028 and 2070. Cold milling 1.0 in. of the existing HMA layer and overlaying with 1.5-in. Type II dense graded HMA and 0.75-in. OGFC.

Overall Summary of Performance of Selected Projects

Table 2 summarizes the long-term field performance of the various Nevada DOT projects analyzed in this study. Pavement distresses in regard to surface cracks before and after application of the treatment are summarized for each project. In addition, Table 2 shows, for each project, the severity of each type of distress considered along with the number of years after construction that cracks appeared on pavement surface. Generally, all projects experienced prerehabilitation surface cracks ranging from minor to severe.

CIR treatment was mainly used on roadways with an AADT less than 6,000, except one project on US95 with 14,500 AADT. Performance data in Table 2 indicate the following trends for the CIR projects:

- The CIR project with the lowest AADT (CIR-A-4) did not experience any distresses after 6 years in service. However, the CIR project with the highest AADT (CIR-B-4) was among the best performers after 6 years in service.
- Reflective transverse cracking was the most common type of distress on CIR projects. Seven CIR projects experienced reflective transverse cracking 1 to 2 years after construction. Three CIR projects experienced reflective transverse cracking 6 to 7 years after construction.
- Two CIR projects with medium AADT experienced fatigue cracking after 3 and 7 years in service.

RF treatment was used on roadways with AADT of between 1,000 and 10,000. Performance data in Table 2 indicate the following trends for the RF projects:

- Three of six RF projects did not experience any distresses after 4 to 6 years in service.
- Reflective transverse cracking was the most common type of distress on the RF projects. Three of six RF projects experienced reflective transverse cracking after 1 to 3 years in service.
- The two RF projects with the highest AADT (RF-1 and RF-6) were among the worst performers.

The 1-in. SRC after cold milling and before application of overlay was used on roadways with AADT between 1,900 and 40,000. Performance data in Table 2 indicate the following trends for the SRC projects. Three of the five SRC projects did not experience any distresses. One of those projects is 8 years old and has the highest AADT (SRC-1), while the other two are 2 and 4 years old. Also, two of the five SRC projects experienced reflective transverse cracking after 5 years in service.

MOL treatment was used on roadways with AADT between 1,700 and 40,000. Performance data in Table 2 indicate the following trends for the HMA projects:

- One MOL project did not experience any distresses after 12 years in service (MOL-A-4).
- Reflective transverse cracking was the most common type of distress on the MOL projects. The length of time after construction for the transverse cracking to reflect to the surface ranged from 1 to 5 years.
- The MOL projects were the only ones that experienced block cracking after 5 to 6 years in service.
- The worst performing MOL project was the one that had the highest AADT (MOL-A-1); it experienced reflective fatigue cracking after 1 year in service.

TABLE 2 Pavement Distresses Summary of Selected Nevada DOT Projects

			Pavement Distresses Before Treatment Application (severity)						Pavement Distresses After Treatment Application (severity/time in years to develop)		
			Fatigue Cracking Type			Block Cracking Type					
Treatment	AADT	Age at 2005 (years)	A	B	Transverse Cracks	A	B	C	Fatigue Cracking Type A	Transverse Cracks	Block Cracking Type A
Cold In-Place Recycling											
CIR-A-1	2,950	7	Sev.	—	Mod.	Min.	—	—	—	Min./7	—
CIR-A-2	2,950	8	Min.	Sev.	Mod.	—	—	Min.	—	Min./2	—
CIR-A-3	1,100	6	—	—	Sev.	Sev.	Sev.	Sev.	—	Min./1	—
CIR-A-4	800	6	Sev.	Mod.	Min.	Min.	Mod.	Mod.	—	—	—
CIR-B-1	5,550	7	—	Sev.	Mod.	—	Min.	Min.	Min./3	Min./2	—
CIR-B-2	5,550	7	Min.	—	Min.	Min.	Sev.	Min.	Min./7	Min./7	—
CIR-B-3	2,000	6	Min.	—	Min.	Sev.	Sev.	Sev.	—	—	—
CIR-B-4	14,500	6	Min.	—	Min.	Mod.	—	—	—	Min./6	—
CIR-C-1	5,000	2	Min.	Min.	Min.	—	—	—	—	Min./1	—
CIR-C-2	1,000	4	Min.	Mod.	Min.	Mod.	Mod.	Min.	—	Min./1	—
CIR-C-3	1,000	4	Min.	Min.	Min.	Mod.	Mod.	Min.	—	Min./1	—
CIR-C-4	1,500	4	Min.	—	Sev.	Mod.	—	Min.	—	Min./1	—
Reinforced Fabric											
RF-1	9,600	6	Min.	Sev.	Mod.	Sev.	Mod.	—	Min./5	Min./1	—
RF-2	2,850	6	Min.	Min.	Sev.	—	—	—	—	—	—
RF-3	1,000	5	Min.	Min.	Sev.	—	Min.	Min.	—	—	—
RF-4	4,400	5	Min.	Min.	Min.	—	—	—	—	Min./3	—
RF-5	7,200	4	Min.	Min.	Min.	—	—	—	—	—	—
RF-6	10,000	4	Min.	Min.	Min.	—	—	—	—	Min./2	—
Stress Relief Course											
SRC-1	40,000	8	Mod.	Sev.	Mod.	Mod.	Min.	—	—	—	—
SRC-2	15,600	5	Min.	Min.	Mod.	Sev.	—	—	—	Min./5	—
SRC-3	2,700	5	Mod.	—	Mod.	—	—	—	—	Min./5	—
SRC-4	1,900	4	Min.	Mod.	Mod.	—	—	—	—	—	—
SRC-5	29,100	2	—	—	Min.	—	—	—	—	—	—
Mill and Overlay											
MOL-A-1	40,000	15	—	Sev.	Min.	Mod.	—	—	Mod./1	Mod./1	—
MOL-A-2	5,500	12	Mod.	Sev.	Mod.	Min.	—	—	Min./4	Min./2	—
MOL-A-3	2,700	12	Mod.	—	Mod.	—	—	—	—	Min./5	—
MOL-A-4	3,350	12	—	Sev.	—	Mod.	—	Sev.	—	—	—
MOL-B-1	2,000	10	—	Mod.	—	Mod.	—	Min.	—	—	Min./5
MOL-B-2	1,700	9	—	—	—	—	Sev.	Sev.	—	Min./5	—
MOL-B-3	1,700	9	Mod.	—	Mod.	Mod.	Sev.	Sev.	Min./5	Min./5	—
MOL-B-4	6,750	8	Mod.	—	Min.	Mod.	Min.	—	—	Mod./1	Min./6
MOL-C-1	7,250	5	—	—	Mod.	—	—	—	—	Min./3	—
MOL-C-2	7,500	2	Min.	Min.	Min.	Mod.	Mod.	—	—	—	—

NOTE: Min. denotes minor, mod. denotes moderate, sev. denotes severe.

Statistical Analysis of Surface Cracking Data by Principal Component Analysis

Principal component analysis (PCA) is a way of identifying patterns in data and expressing them in such a way as to highlight their similarities and differences. A formal definition indicates that PCA is a method that reduces data dimensionality by performing a covariance analysis among factors. Thus, it is suitable for data sets in multiple dimensions, such as a large data set of pavement distresses. The main applications of PCA are to (*a*) reduce the number of variables and (*b*) detect structure in the relationships among variables, that is, to rank variables.

An example for understanding PCA is provided for combining two variables into a single factor. Typically, the correlation between two variables can be presented in a scatter-plot. A regression line can then be fitted that represents the best summary of the linear relationship between the variables. If one could define a factor that approximates the regression line in such a plot, then that factor would capture most of the essence of the two variables. Therefore, single scores on that new factor, represented by the regression line, could then be used in future data analyses to represent the essence of the two items. In a sense, the two variables have been reduced to one factor. Note that the new factor is actually a linear combination of the two variables.

The example as provided, combining two correlated variables into one factor, illustrates the basic idea of PCA. If one extend the two-variable example to multiple variables, then the computations become more involved, but the basic principle of expressing two or more variables by a single factor remains the same.

The most valuable product obtained from PCA is a linear parameter estimated from a linear combination of the original variables. The objective of the PCA is to reduce dimensionality by extracting the smallest number of variables (factors) that account for most of the variation in the original multivariate data and to summarize the data with little loss of information. In the present case, the multivariate data correspond to Nevada DOT's cracking surveys for each year, while the dimensionality represents the extent, severity, and years of occurrence of the various types of cracking. Therefore, in the case of cracking, PCA tries to provide a combined indicator or a factor that interprets simultaneous effects of fatigue, transverse, and block cracking in regard to their extent, severity, and years of occurrence.

Overall Ranking of Performance of Selected Nevada DOT Projects

PCA analysis was conducted on all projects combined at 1 year before rehabilitation (−1) and at 1 (+1) 3 (+3); and 5 years (+5) after treatment application based on their measured surface cracks (fatigue, transverse, and block cracking). The SAS Macro called factor was used to perform the PCA analysis (*14*).

Table 3 shows the ranking of the various treatments based on PCA of the cracking data for the various projects. First, all 33 projects were ranked based on their pretreatment conditions (−1) and their condition at 1 year (+1) after treatment application. At (−1), the projects were ranked between 1 and 33, with a rank of "1" indicating the best conditions project and a rank of "33" indicating the worst conditions

TABLE 3 Nevada DOT Projects Information and Ranking of Treatments According to PCA

Treatment	DOC[a]	AADT[b]	Ranking[c]					
			−1	+1	−1	+3	−1	+5
CIR-A-1	1998	2,950	2	1	1	1	1	2
CIR-A-2	1997	2,950	7	1	8	10	7	12
CIR-A-3	1999	1,100	28	2	27	2	22	6
CIR-A-4	1999	800	21	1	20	1	16	2
CIR-B-1	1998	5,550	5	1	3	8	5	11
CIR-B-2	1998	5,550	26	1	26	1	19	2
CIR-B-3	1999	2,000	30	1	29	1	23	2
CIR-B-4	1999	14,500	16	1	15	1	12	2
CIR-C-1	2003	5,000	12	3	N.A.	N.A.	N.A.	N.A.
CIR-C-2	2001	1,000	22	4	22	1	N.A.	N.A.
CIR-C-3	2001	1,000	24	4	23	7	N.A.	N.A.
CIR-C-4	2001	1,500	19	4	19	7	N.A.	N.A.
RF-1	1999	9,600	27	5	25	7	18	9
RF-2	1999	2,850	6	1	4	1	4	2
RF-3	2000	1,000	17	1	17	1	15	2
RF-4	2000	4,400	9	1	12	2	10	4
RF-5	2001	7,200	9	1	11	1	N.A.	N.A.
RF-6	2001	10,000	10	1	13	4	N.A.	N.A.
SRC-A-1	1997	40,000	11	1	9	1	6	2
SRC-A-2	2000	15,600	18	1	18	1	13	8
SRC-A-3	2000	2,700	8	1	10	1	9	3
SRC-A-4	2001	1,900	3	1	4	1	N.A.	N.A.
SRC-B-1	2003	29,100	14	1	N.A.	N.A.	N.A.	N.A.
MOL-A-1	1990	40,000	4	6	6	9	8	12
MOL-A-2	1993	5,500	1	1	2	5	2	10
MOL-A-3	1993	2,700	6	1	5	1	3	12
MOL-A-4	1993	3,350	25	1	24	1	20	2
MOL-B-1	1995	2,000	20	1	21	1	17	1
MOL-B-2	1996	1,700	31	1	30	1	24	7
MOL-B-3	1996	1,700	29	1	28	1	21	13
MOL-B-4	1997	6,750	15	4	16	6	14	7
MOL-C-1	2000	7,250	13	1	14	3	11	5
MOL-C-2	2003	7,500	23	1	N.A.	N.A.	N.A.	N.A.

NOTE: For ranking categories, −1 represents previous year to construction, and +1, +3, and +5 represent 1, 3, and 5 years, respectively, after construction.

[a] DOC denotes date of construction.

[b] AADT denotes annual average daily traffic.

[c] Ranking is from best to worst; that is, the projects ranked as 1 had the best performance.

N.A. = project is younger than the indicated long-performance year.

project. However, the data in Table 3 show that the maximum ranking is "31" instead of "33". This occurred because projects RF-2 and MOL-A-3 were both ranked as "6" and projects RF-4 and RF-5 were both ranked as "9"—indicating that conditions of the similarly ranked projects are statistically the same.

Then the projects were ranked at +3 and +5 years after treatment application by conducting PCA again at both −1 year and the analysis year (+3 or +5), excluding the projects that were younger than the indicated long-performance year. Subsequently, the ranking was based on the same total number of projects before (−1) and after (+3, +5) treatment application. A total of 30 and 24 projects were ranked at −1 and +3 years, and at −1 and +5 years, respectively. It should be noted that the ranking at −1 year changes across Tables 3 and 4 because the number of projects that are ranked in −1 year is not constant; not all projects have performance data at years +3 and +5. As the number of projects used in the relative ranking process changes, the ranking of the individual projects also changes.

In the case of the ranking of projects at the +1, +3, and +5 years, there are several occasions in which several projects are given the same rank. This occurred due to the statistically similar performances of those projects. For example, in the case of ranking based on 1 year after construction (+1) in Table 3, a ranking of "1" is assigned to each project that did not experience any cracking 1 year after construction. However, if two projects showed cracking 1 year after construction, the extent and severity of cracking would then play a role in the ranking. For example, projects CIR-C-1 and CIR-C-2 both showed minor transverse cracking in Year 1, but PCA assigned a ranking of "3" and "4," respectively. The reason for the worse ranking of project CIR-C-2 is that the extents of the minor transverse cracking of project CIR-C-2 is higher than the extent of the minor transverse cracking in project CIR-C-1. In summary, the projects are first ranked based on the year of cracking occurrence, followed by severity of the cracking, and finally by extent of the cracking. In the cases in which all three factors are the same, then the projects are assigned similar ranks.

Figure 1*a* through 1*c* shows a comparison between the ranking of the various treatments at 1 year before construction versus the ranking at 1, 3, and 5 years after construction. The objective of

TABLE 4 Nevada DOT Projects Information and Percent Ranking of Treatments According to PCA

Treatment	DOC[a]	AADT[b]	PCA Ranking[c] (%) −1	+1	−1	+3	−1	+5
CIR-A-1	1998	2,950	3	0	0	0	0	4
CIR-A-2	1997	2,950	22	0	24	100	26	87
CIR-A-3	1999	1,100	91	78	90	62	91	57
CIR-A-4	1999	800	69	0	66	0	65	4
CIR-B-1	1998	5,550	13	0	7	93	17	83
CIR-B-2	1998	5,550	84	0	86	0	78	4
CIR-B-3	1999	2,000	97	0	97	0	96	4
CIR-B-4	1999	14,500	53	0	48	0	48	4
CIR-C-1	2003	5,000	41	81	N.A.	N.A.	N.A.	N.A.
CIR-C-2	2001	1,000	72	84	72	0	N.A.	N.A.
CIR-C-3	2001	1,000	78	84	76	83	N.A.	N.A.
CIR-C-4	2001	1,500	63	84	62	83	N.A.	N.A.
RF-1	1999	9,600	88	97	83	83	74	74
RF-2	1999	2,850	16	0	10	0	13	4
RF-3	2000	1,000	56	0	55	0	61	4
RF-4	2000	4,400	28	0	38	62	39	48
RF-5	2001	7,200	28	0	34	0	N.A.	N.A.
RF-6	2001	10,000	34	0	41	72	N.A.	N.A.
SRC-A-1	1997	40,000	38	0	28	0	22	4
SRC-A-2	2000	15,600	59	0	59	0	52	70
SRC-A-3	2000	2,700	25	0	31	0	35	43
SRC-A-4	2001	1,900	6	0	10	0	N.A.	N.A.
SRC-B-1	2003	29,100	47	0	N.A.	N.A.	N.A.	N.A.
MOL-A-1	1990	40,000	9	100	21	97	30	87
MOL-A-2	1993	5,500	0	0	3	76	4	78
MOL-A-3	1993	2,700	16	0	17	0	9	87
MOL-A-4	1993	3,350	81	0	79	0	83	4
MOL-B-1	1995	2,000	66	0	69	0	70	0
MOL-B-2	1996	1,700	100	0	100	0	100	61
MOL-B-3	1996	1,700	94	0	93	0	87	100
MOL-B-4	1997	6,750	50	84	52	79	57	61
MOL-C-1	2000	7,250	44	0	45	69	43	52
MOL-C-2	2003	7,500	75	0	N.A.	N.A.	N.A.	N.A.

[a] DOC denotes date of construction.

[b] AADT denotes annual average daily traffic.

[c] PCA Ranking is the relative standing of a PCA rank within the PCA data set in percentage; that is, the project with a percent ranking of 100% means all projects have a higher PCA rank; hence this project has the worst performance. The project with a percent ranking of 0% means none of the projects has a higher PCA rank; hence this project has the best performance.

N.A. = project is younger than the indicated long-performance year.

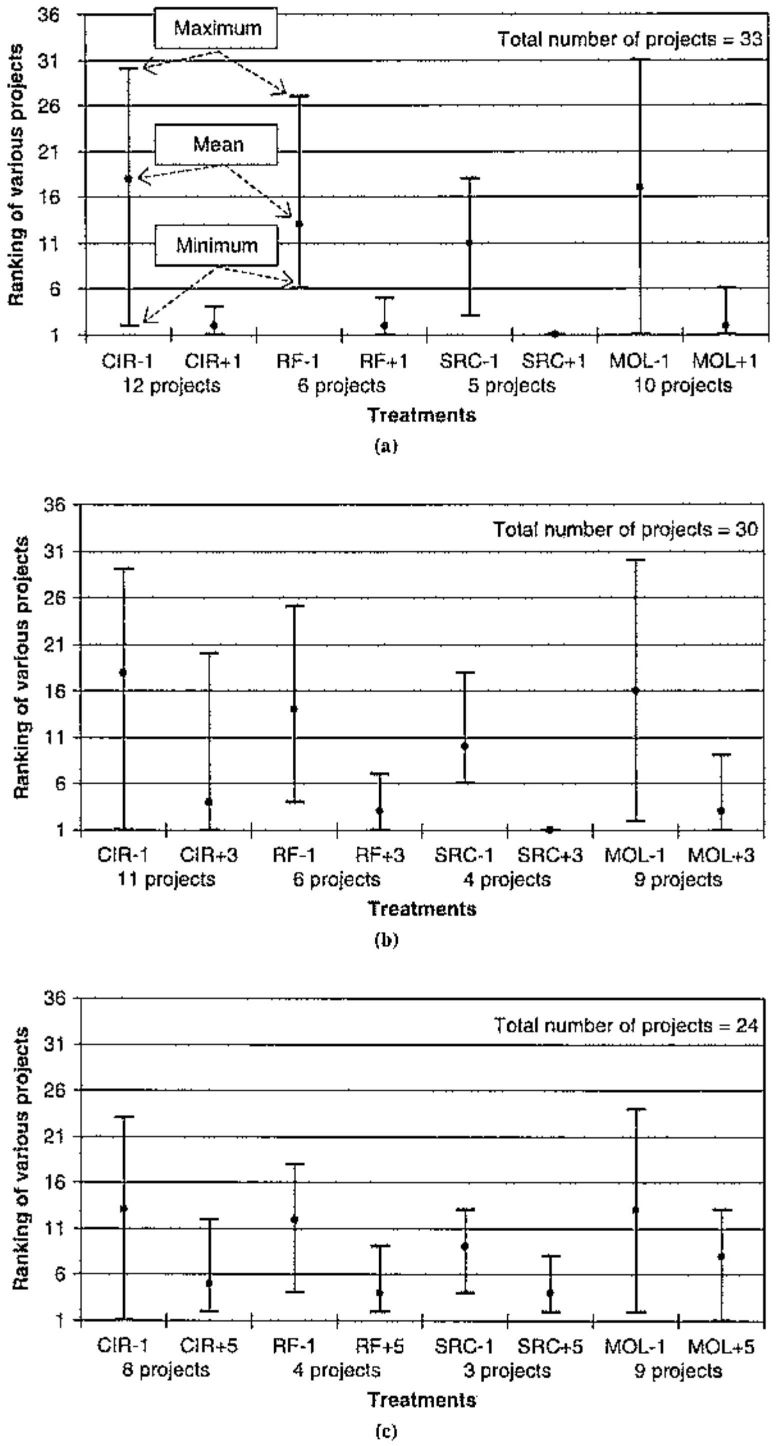

FIGURE 1 Comparison between rankings of various treatments at 1 year before treatment construction and (*a*) 1 year, (*b*) 3 years, and (*c*) 5 years after treatment construction.

these plots is to be able to assess the effectiveness of various treatments by comparing their historical performance as they relate to conditions of pavement before rehabilitation. In other words, a treatment applied on badly deteriorated pavements and that maintained good performance would be more effective than a treatment applied on less-deteriorated pavements and that maintained good performance. By examining data presented in Figure 1, one can observe the following:

- CIR and MOL treatments were applied on flexible pavements that experienced the widest range of pretreatment (−1) performance, and SRC treatment was applied on flexible pavements that experienced the narrowest range of pretreatment performance.
- After 1 year (+1) of treatment construction (Figure 1*a*), CIR, RF, and MOL treatments showed similar performance, while SRC treatment showed significantly better performance.
- After 3 years (+3) of treatment construction (Figure 1*b*), RF and MOL treatments showed similar performance, while SRC treatment still showed significantly better performance.
- After 5 years (+5) of treatment construction (Figure 1*c*), CIR and MOL treatments still performed similarly, while performance of RF and SRC treatments became similar and closer to the performance of CIR and MOL treatments. It should be noted that the four worst-performing CIR projects, based on (+3) analysis, were not included in the (+5) analysis due to the lack of 5 years of performance data from those projects.

The ranking according to the PCA data in Table 3 was also transformed into a percent ranking to evaluate the relative standing of a project PCA rank within the projects PCA data set at a certain year. In other words, the percent ranking shown in Table 4 is used to evaluate the standing of a project PCA rank in a certain year among all projects PCA rankings. For example, project CIR-B-2 had a PCA percent ranking of 78% at year −1 and a PCA percent ranking of 4% at year +5. This means that 78% of all projects (18 projects) were better in performance than CIR-B-2 at year −1, while only 4% of all projects (1 project) were better in performance than CIR-B-2 at year +5. The relative comparison of the PCA percent ranking by different years is a good indication of the relative effectiveness of various treatments, considering preconstruction pavement conditions. For example, project CIR-A-2 had a PCA percent ranking of 26% at year −1 and a PCA percent ranking of 87% at year +5. It means that only 6 projects of 24 had better performance at year −1, while 20 of the same 24 projects had better performance than CIR-A-2 at year +5. This indicates that the relative ranking of the CIR-A-2 project 5 years after construction (+5) was lower than its relative ranking 1 year before. That finding leads to the conclusion that, relative to other projects, the pavement condition of the CIR-A-2 project at +5 is worse than its condition at year −1.

The data in Tables 3 and 4 show that 1 year after construction, a total of 5 of 12 CIR projects performed among the worst. Four of those worst-performing five CIR projects (CIR-C-1, -2, -3, and -4) consisted of milling the top 2.0 in. of the existing layer and overlaying it with 2.0-in. dense grade HMA. Only one RF project (RF-1) of six ranked among the worst projects. The RF-1 project experienced severe alligator cracking (Type B) before construction of the treatment. All of the SRC projects ranked among the best-performing projects. Two MOL projects (MOL-A-1, B-4) ranked among the worst-performing projects.

Three years after construction, an additional two each of CIR, RF, and MOL projects performed among the worst projects, whereas SRC projects still outperformed the other treatments.

Five years after construction, five of eight CIR projects performed among the best projects; they included three of the four CIR-B projects. CIR-B treatment consists of milling the top 3.0 in. of the existing HMA layer and overlaying it with 3.0-in. dense graded HMA. Only two RF projects of four, one SRC project of three, and two MOL projects of nine ranked among the best-performing projects.

The PCA percent ranking data in Table 4 showed that there are two CIR projects (CIR-A-2 and CIR-B-1); one SRC project (SRC-A-2); and three MOL projects (MOL A-1, -2, and -3) in which their percent relative rankings 5 years after construction (+5) were significantly lower than their percent relative rankings 1 year before construction. A close examination of performance data summarized in Table 2 showed that four of those six projects had experienced severe alligator cracking (Type B) before construction of the CIR, SRC, and MOL treatments. This indicates that the existence of severe alligator cracking skewed the relative ranking of various projects.

CONCLUSIONS

The following general conclusions concerning the performance of reflective cracking treatments in Nevada are based on the combined analyses of distress data and PCA.

- PCA was conducted to identify any reflective cracking treatment that may be able to provide good long-term performance regardless of the conditions of pavement before its application. According to results of PCA as presented in Figure 1, this goal was not achieved. Generally, the performance of the reflective cracking treatment is highly dependent on conditions of pavement before construction of the treatment. This is supported by the data shown in Figure 1*c*, where the worse performance after 5 years in service was for CIR and MOL, which were applied to pavements having lower performance than the pavements where RF and SRC were applied.
- The PCA ranking data in Tables 3 and 4 showed that the CIR-A (CIR 2 in. and overlay 2.5 in.) and CIR-B (CIR 3.0 in. and overlay 3.0 in.) treatments, regardless of traffic level, are generally effective in stopping reflective cracking for 3 years and in retarding reflective cracking for 5 years, as long as the existing pavement does not show severe alligator cracking before application of those treatments. However, the CIR-C (CIR 2 in. and overlay 2 in.) treatment is ineffective in resisting reflective cracking.
- RF treatment showed marginal performance after 3 and 5 years of construction. RF treatment was ineffective when applied on a pavement with severe alligator cracking before application of the treatment, or on pavement with a traffic level above 3,000 AADT, or both.
- SRC treatment showed excellent performance up to 3 years after construction regardless of the traffic level and the existing pavement condition. However, 5 years after construction, reflective transverse cracking showed up considerably on the pavement surface.
- MOL treatment was effective in stopping reflective cracking up to 3 years after construction for projects with AADT lower than 5,000, or for projects with no severe alligator cracking before

TABLE 5 Statistical Analysis of Various Treatments Based on PCA Rankings at 1 Year Before Treatment Construction and 5 Years After Treatment Construction

Treatment	Number of Projects	1-Year Pre-construction (−1)		5-Year After Construction (+5)		Change in Relative Ranking
		Mean	SD	Mean	SD	
CIR	6	16	8	3	2	13
RF	4	12	6	4	3	8
SRC	3	9	4	4	3	5
MOL	7	16	7	7	7	9

application of the treatment, or both. After 5 years of construction, MOL treatment showed marginal performance by slowing down reflective cracking.

- Another way of looking at the effectiveness of various treatments is to examine the means and standard deviations of their relative rankings at pretreatment and the 5-year stages. This analysis was conducted on all projects having data from the 5 years of performance, and excluding the four projects in which severe alligator cracking skewed the ranking process. Table 5 summarizes the means and standard deviations data of the various projects, along with the change in the mean relative ranking. An effective treatment is one that has high mean and standard deviation for pretreatment performance and low mean and standard deviation for the 5 years of performance, coupled with the highest change in the mean ranking. According to this criterion, the evaluated treatments for mitigating reflective cracking under Nevada's conditions are ranked from best to worst after 5 years of construction as follows: CIR, MOL, RF, and SRC.

However, the long-term effectiveness of the CIR and MOL treatments is significantly hampered by the existence of severe alligator cracking on the projects before application of these treatments. Therefore, it is recommended that projects experiencing severe alligator cracking as classified by Nevada DOT's pavement distress manual (*13*) be subjected to either reconstruction or full-depth reclamation.

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Long-Term Performance of Reflective Cracking Mitigation Techniques in Nevada

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ABSTRACT

Hot mixed asphalt (HMA) overlay is one of the commonly used methods for rehabilitating deteriorated pavements. The Nevada Department of Transportation (NDOT) uses HMA overlays as a rehabilitation technique for the majority of the state's flexible pavements. One major type of distress influencing the life of an overlay is reflective cracking. In the past, NDOT has experimented with a number of techniques to reduce the impact of reflective cracking on HMA overlays like cold in-place recycling, reinforced fabrics, stress relief courses and mill and overlay. A number of projects were constructed under each category. This paper evaluates the long-term field performance of the various NDOT reflective cracking mitigation techniques used on 33 different field projects on flexible pavements. The performances of the various projects were analyzed in terms of the fatigue, transverse and block cracking measurements from the NDOT's Pavement Management System (PMS) data. Additionally, the statistical approach called Principal Component Analysis (PCA) was used to asses the effectiveness of each of the reflective cracking techniques. This study indicates that cold in-place recycling and mill and overlay were the most effective treatments for reflective cracking of HMA overlays over HMA pavements under Nevada's conditions except when the existing pavement is experiencing severe alligator cracking. In such situations it is recommended that the HMA pavement be subjected to reconstruction or full depth reclamation.

INTRODUCTION

Pavement rehabilitation is rapidly becoming one of the most important issues facing many highway departments. Hot mixed asphalt (HMA) overlay is one of the commonly used methods for rehabilitating deteriorated pavements. The Nevada Department of Transportation (NDOT) uses HMA overlays as a rehabilitation technique for the majority of the state's flexible pavements.

One major type of distress influencing the life of an overlay is reflective cracking (*1*). When asphalt overlays are placed over jointed or severely cracked existing rigid and flexible pavements, cracks will reflect to the surface in a relatively short period of time. Physical tearing of the overlay occurs because of movements under heavy wheel loads at joints and cracks in the underlying pavement layer. Therefore, the long-term performance of the HMA overlays will depend on their ability to resist reflective cracking. Reflective cracking in the overlay allows water to percolate into pavement structure and to weaken the HMA and the supporting layers, hence contributing to many forms of pavement deterioration.

Numerous previous efforts have been exerted to reduce or prevent reflective cracking of HMA overlays including the increase thickness of HMA overlay, the use of stress absorbing membranes inter-layers (SAMI), the use of fabrics and geotextiles membranes, and the fracturing of the existing concrete slabs. The basic principle of reflective cracking is that the tensile stresses at the interface of the crack and the new HMA overlay are significantly increased due to the discontinuity at the tip of the crack. The developed tensile stresses rapidly exceed the tensile strength of the HMA layer and the crack forms at the interface and quickly propagate to the surface. Combating reflective cracking can be achieved by either one of the two approaches: a) reduce the magnitude of the tensile stresses at the crack-overlay interface or b) increase the tensile strength of the HMA overlay.

The increase of the thickness of the HMA overlay as well as placing a stress absorbing membrane inter-layer follow the approach of reducing the magnitude of the tensile stresses at the crack-overlay interface. The stress absorbing membrane inter-layer usually consists of a single or a double chip seal. The chip seal is a highly flexible layer which reduces the magnitude of the tensile stresses before they intersect with the new HMA layer. The ability of the stress absorbing membrane inter-layer to reduce the tensile stresses increases as its thickness increase (i.e. single versus double chip seal), as its binder content increases, and as the flexibility of the binder increases. However, having a thick, rich and highly flexible stress absorbing membrane inter-layer may cause potential rutting and shoving problems under heavy traffic. An optimum design must be established in order to effectively mitigate reflective cracking without negatively impacting the long-term performance of the HMA overlay.

The fabrics and geotextiles technique follows the approach of increasing the tensile strength of the HMA overlay. These materials have high tensile strengths and if they are effectively bonded to the HMA layer, they will improve the tensile strength of the overlay. There are numerous brands of fabrics and geotextiles currently in the market covering a wide range of cost and strength properties. Selecting the best type of fabric or geotextile requires an in-depth assessment of their relative properties and their long-term performance.

The research effort documented in this paper was directed toward identifying an effective method to eliminate/retard the propagation of the cracks from the old surface layer through the new HMA overlay. In 2006, the Nevada Department of Transportation (NDOT) initiated a two-phase research project Phase I: to identify the most promising techniques to mitigate reflective cracking in HMA overlays, and Phase II: to identify an analytical model that can be used to predict the resistance of HMA overlays to reflective cracking and predict their long-term performance and to review the laboratory and field tests that are being used to evaluate the resistance of HMA overlays to reflective cracking. Based on this review and an in-depth investigation of the problem and upon completion of both phases, a system will be recommended for implementation in Nevada. This paper summarizes the findings and recommendations of the Phase I of this study.

BACKGROUND

Numerous studies were conducted throughout the years to assess the effectiveness of the various techniques that are currently available in the industry. In 1982, FHWA reported a study on the performance of fabrics in asphalt overlays from Colorado test sections *(2)*. The report revealed that the control section (1.5 inch AC overlay) developed 10% cracking in 1.25 years and 50% within 3.25 years, while the fabric section (1.5 inch AC overlay + fabric) developed less than 2% reflection cracking in 1.25 years and 30% within 3.25 years.

In 1984 and 1985, the evaluation of HMA overlays over deteriorated PCC pavements in Georgia indicated that 20% of the cracking area occurred in six years for a 6-inch HMA overlay compared to two years for a 4-inch HMA overlay *(3, 4)*. Reflective cracking appeared almost immediately after construction for a 2-inch overlay.

In 1989, Scofield *(5)* documented in a research report the history, development, and performance of asphalt rubber mixtures in Arizona. In that report the following conclusion was stated, "asphalt rubber has successfully been used as an encapsulating membrane to control pavement distortion due to expansive soils and to reduce reflection cracking in overlays on both rigid and flexible pavements." The research also indicated that during the twenty years of asphalt rubber use, ADOT evolved from using slurry applied asphalt rubber chip seals to utilizing reacted asphalt rubber as a binder in open and dense-graded HMA. In 1990, the Arizona Department of Transportation (ADOT) designed and constructed a large scale gap-graded Asphalt-Rubber (AR) test project in Flagstaff, Arizona on the very heavily trafficked Interstate 40 (*6, 7*). In 1999, the traffic exceeded 20,000 vehicles per day with 35% heavy trucks. The purpose of the test project was to determine whether a relatively thin overlay with AR and without a stress absorbing membrane interlayer could reduce reflective cracking. AR is a mixture of 80% hot paving grade asphalt and 20% ground tire rubber. It was reported that the AR overlay has performed beyond original expectations.

The California Department of Transportation (Caltrans) evaluated the increase of HMA thickness overlays to minimize reflective cracking. Research conducted by Predoehl (1989) in California showed that 4.8 inch of overlay is required to retard reflective cracking for 10 years *(8)*. In 1992, Caltrans evaluated the effectiveness of glassgrid in retarding reflective cracking caused by thermal fatigue *(9)*. As a result, the glassgrid retarded reflective cracking in the area of high tensile stresses. Therefore, Caltrans now considers glassgrid application for the overlay strategy.

In 1999, Buttlar et al. evaluated the cost-effectiveness of the Illinois Department of Transportation (IDOT) reflective cracking control system consisting of a nonwoven polypropylene paving fabric *(10)*. The performance monitoring indicated an increase in life spans by 1.1 and 3.6 years for paving fabric strip (over lane-widening) and area applications (over the entire pavement), respectively. Lane-widening and entire pavement applications were expected to have life spans of 12 and 14 years, respectively.

In 2002, the Texas Transportation Institute (TTI) performed a research project in cooperation with the Texas Department of Transportation (TxDOT) and FHWA to investigate and develop information that will aid in the evaluation of the relative effectiveness of commercially available geosynthetic materials in reducing the severity or delaying the appearance of thermally induced reflective cracking in HMA overlays *(11)*. The results showed that the performance of geosynthetics in addressing reflection cracking in HMA overlays has ranged from highly successful to disastrous failures.

In 2004, an experiment to assess the economy of various types of reflective cracking reduction techniques was conducted on I-25 near Colorado Springs, Colorado *(12)*. The performance of the various methods was widely variable, but in general geotextile, reinforced fabrics, fiberglass tape and crack sealer showed less reflective cracking than the control section.

REVIEW OF NEVADA DOT EXPERIENCE

In the past fifteen years, NDOT experimented with different techniques to reduce the impact of reflective cracking on HMA overlays. This research effort identified and reviewed the performance of the field projects where NDOT has implemented reflective cracking mitigation techniques. The design, construction, and traffic details of these projects were collected along with their corresponding long-term field performance. The information was analyzed to assess the effectiveness of the various techniques in mitigating reflective cracking under Nevada's conditions.

Performance Related Data

Pavement roughness, rutting, and cracking represent the major components of NDOT's pavement conditions survey program. The NDOT Pavement Management System uses the present serviceability index (PSI) to monitor the performance of the various pavement sections throughout the state. The PSI is very heavily dependent on the roughness of the pavement and it does not give enough weight to the cracking distresses which makes it un-useful in assessing the effectiveness of treatments for the mitigation of reflective cracking in HMA overlays. For the purpose of this research, the individual data collected on fatigue, transverse, and block cracking monitored over the service life of the selected pavements were used to asses the actual performance of the various reflective cracking mitigation techniques. The cracking types, extent and severity as defined by the NDOT Flexible Pavements Distress Identification Manual *(13)* are summarized as follows.

Fatigue Cracking

Fatigue cracking is caused by repeated traffic loading of the pavement. These cracks initiate at the bottom of the HMA layer and slowly work their way to the surface. Fatigue cracking usually starts as a longitudinal crack in the wheelpath which NDOT classifieds as Type A. Further weakening of the HMA and base layers coupled with repeated traffic loading leads to the progression of the longitudinal crack and the formation of interconnected cracks referred to as alligator cracking which NDOT classifies as Type B. The extent of type A fatigue cracking is measured as the total linear feet of this type of cracking in the wheelpath of the pavement area being surveyed. The extent of type B fatigue cracking is measured as the total square feet of this type of cracking in the wheelpath of the pavement being surveyed (i.e., 10 feet by 100 feet area at every milepost).

Transverse Cracking

Transverse cracking is primarily caused by: either the thermal stresses or reflection from cracks/joints in the layer underneath. The extent is measured as the total linear feet of cracking throughout the pavement area being surveyed (i.e., 10 feet by 100 feet area at every milepost).

Block Cracking

Block cracking starts as a combination of short transverse and non-wheelpath longitudinal cracking which NDOT classifies as type A. It is caused by age hardening and shrinkage of the HMA layer. Although traffic loading is not the primary cause of this type of distress, continued loading on the brittle surface will accelerate this distress and break the larger pieces into smaller pieces which NDOT classifies as Types B and C. The extent of type A is measured as the total linear feet of this type of cracking throughout the pavement area being surveyed. The extents of types B and C is measured as the total square feet of this type of cracking throughout the pavement area being surveyed

Long-term Field Performance of Selected NDOT Projects

The following list represents a summary of the various reflective cracking mitigation techniques that NDOT has evaluated within the past 15 years.

- Cold in-place recycling (CIR)
- Reinforced fabrics (RF)
- Stress relief courses (SRC)
- Mill and overlay (MOL)

A total of thirty-three projects were constructed under all categories. The projects locations varied between the Northern part and the Southern part of Nevada covering different environmental and traffic conditions. Table 1 summarizes the projects contract number, projects location, applied reflective cracking mitigation technique, date of construction (DOC), and the 2005 annual average daily traffic (AADT). The projects DOC varied between 1990 and 2003. Nineteen out of the thirty-three projects were located in northern Nevada. All of the long-term field performances were obtained from the NDOT pavement management system (PMS). The following represents brief description of the various treatments that were evaluated in this study.

Cold In-Place Recycling (CIR) Projects

Cold in-place recycling is carried out using specialized recycling machines, the heart of which is a milling drum equipped with a large number of hardened steel picks. In general, the CIR technology is used to build a strong flexible base course. The CIR is believed to strengthen the existing pavement by treating many types and degrees of distresses. Originally, the CIR projects were constructed on low traffic volume roads ranging from 30 to 300 AADT. However, some agencies, including NDOT, currently apply this treatment to roads with traffic varying from 1,000 to even 10,000 AADT. A total of twelve NDOT CIR projects constructed between 1992 and 2001 were analyzed in this study. The following is a description of the various CIR treatments applied.

- *CIR-A:* Contracts 2808a, 2808b, 2838 and 2935. CIR the top 2.0" of the existing HMA layer and overlaying it with 2.5" dense graded HMA and 0.75" open graded friction course (OGFC).
- *CIR-B:* Contracts 2819, 2873, 2961, and 3013. CIR the top 3.0" of the existing HMA layer and overlaying it with 3.0" dense graded HMA and 0.75" OGFC.
- *CIR-C:* Contracts 3025a, 3025b, 3025c and 2876. CIR the top 2.0" of the existing HMA layer and overlaying it with 2.0" dense graded HMA and 0.75" OGFC.

It is the NDOT standard practice to place a 0.75" OGFC within the first year of construction.

Reinforced Fabrics (RF) Projects

Paving fabrics are a special class of geosynthetic that provide the generally acknowledged functions of a stress-absorbing interlayer and a waterproofing membrane. A total of six NDOT projects with paving fabrics constructed between 1999 and 2001 were analyzed in this study. The construction consisted of cold milling 2.0" of the existing HMA layer, placing fiberglass yarns, and overlaying with 2.0" Type II dense graded HMA and 0.75" OGFC

Stress Relief Course (SRC) Projects

The stress relief course consists of a NDOT Type III (0.5 inch maximum size) dense graded HMA layer. The stress relieve course is placed between the existing pavement and the overlay layer and is supposed to act as a separator layer between the cracked surface and the overlay. A total of five NDOT projects with a stress relief course constructed between 1997 and 2003 were analyzed in this study. The following is a description of the various SRC treatments applied. This treatment consisted of cold milling 2.0" of the existing HMA layer, placing a 1" stress relieve course and overlaying with 2.0" Type II dense graded HMA and 0.75" OGFC.

Mill and Overlay (MOL) Projects

This technique consists of cold milling up to 2 inch of the existing HMA layer and replacing it with a HMA overlay. The intention is to reduce reflective cracking by eliminating surface cracks through cold milling and replacing with new HMA material. A total of ten NDOT projects constructed between 1990 and 2003 were analyzed in this study. A description of the various applied HMA overlays is as follows:

- *MOL-A:* Contracts 2384a, 2384b, 2432, and 2505. Cold milling 1.0" of the existing HMA layer and overlaying with 1.0" Type III dense graded HMA and 0.75" OGFC.

- *MOL-B:* Contracts 2651a, 2651b, 2651c and 2679. Cold milling 1.5" of the existing HMA layer and overlaying with 1.5" Type II dense graded HMA and 0.75" OGFC.
- *MOL-C:* Contracts 3028 and 2070. Cold milling 1.0" of the existing HMA layer and overlaying with 1.5" Type II dense graded HMA and 0.75" OGFC.

Overall Summary of the Performance of the Selected NDOT Projects

Table 2 summarizes the long-term field performance of the various NDOT projects analyzed in this study. The pavement distresses in terms of surface cracks before and after the application of the treatment are summarized in Table 2 for each project. Additionally, Table 2 shows, for each project, the severity of each type of distress considered along with the number of years after construction that the cracks appeared on pavement surface. In general, all projects experienced pre-rehabilitation surface cracks ranging from minor to severe.

The CIR treatment was mainly used on roadways with an AADT less than 6,000 except one project on US95 with 14,500 AADT. The performance data in Table 2 indicate the following trends for the CIR projects:

- The CIR project with the lowest AADT (CIR-A-4) did not experience any distresses after 6 years in service. On the other hand the CIR project with the highest AADT (CIR-B-4) was among the best performers after 6 years in service.
- Reflective transverse cracking was the most common type of distress on CIR projects. Seven CIR projects experienced reflective transverse cracking 1-2 years after construction. Three CIR projects experienced reflective transverse cracking 6-7 years after construction.
- Two CIR projects with medium AADT experienced fatigue cracking after 3 and 7 years in service.

The reinforced fabric treatment was used on roadways with AADT between 1,000 and 10,000. The performance data in Table 2 indicate the following trends for the RF projects:

- Three out of the six RF projects did not experience any distresses after 4-6 years in service.
- Reflective transverse cracking was the most common type of distress on the RF projects. Three out of six RF projects experienced reflective transverse cracking after 1-3 years in service.
- The two RF projects with the highest AADT (RF-1 and RF-6) were among the worst performers.

The 1-inch stress relief course after cold milling and before application of overlay was used on roadways with AADT between 1,900 and 40,000. The performance data in Table 2 indicate the following trends for the SRC projects:

- Three out of the five SRC projects did not experience any distresses. One of these projects is 8 years old and has the highest AADT (SRC-1) while the other two are 4 and 2 years old.
- Two out of the five SRC projects experienced reflective transverse cracking after 5 years in service.

The mill and overlay treatment was used on roadways with AADT between 1,700 and 40,000. The performance data in Table 2 indicate the following trends for the HMA projects:

- One mill and overlay project did not experience any distresses after 12 years in service (MOL-A-4).
- Reflective transverse cracking was the most common type of distress on the mill and overlay projects. The length of time after construction for the transverse cracking to reflect to the surface ranged from 1 to 5 years.
- The mill and overlay projects were the only ones that experienced block cracking after 5-6 years in service.
- The worst performing mill and overlay project was the one that had the highest AADT (MOL-A-1) which experienced reflective fatigue cracking after 1 year service.

Statistical Analysis of the Surface Cracking Data – Principal Component Analysis

The Principal Components Analysis (PCA) is a way of identifying patterns in data, and expressing them in such a way as to highlight their similarities and differences. A formal definition indicates that PCA is a method that reduces data dimensionality by performing a covariance analysis among factors. As such, it is suitable for data sets in multiple dimensions, such as a large data set of pavement distresses. The main applications of PCA are: (1) to *reduce* the number of variables and (2) to *detect structure* in the relationships among variables, that is to *rank variables*.

An example to understand the PCA analysis is provided here for combining two variables into a single factor. Typically, the correlation between two variables can be presented in a scatter-plot. A regression line can then be fitted that represents the "best" summary of the linear relationship between the variables. If we could define a factor that would approximate the regression line in such a plot, then that factor would capture most of the "essence" of the two variables. Therefore, single scores on that new factor, represented by the regression line, could then be used in future data analyses to represent the essence of the two items. In a sense, we have reduced the two variables to one factor. Note that the new factor is actually a linear combination of the two variables.

The example described above, combining two correlated variables into one factor, illustrates the basic idea of PCA. If we extend the two-variable example to multiple variables, then the computations become more involved, but the basic principle of expressing two or more variables by a single factor remains the same.

The most valuable product obtained from PCA is a linear parameter estimated from a linear combination of the original variables. The objective of the PCA is to reduce dimensionality by extracting the smallest number of variables (factors) that account for most of the variation in the original multivariate data and to summarize the data with little loss of information. In our case, the multivariate data corresponds to the NDOT cracking surveys for each year while the dimensionality represents the extent, severity, and years of occurrence of the various types of cracking. Therefore, in the case of cracking, the PCA tries to provide a combined indicator or a factor that interprets the simultaneous effects of fatigue, transverse, and block cracking in terms of their extent, severity, and years of occurrence.

Overall Ranking of the Performance of Selected NDOT Projects

The PCA analysis was conducted on all projects combined at one year before rehabilitation (-1) and at one (+1), three (+3), and five years (+5) after treatment application based on their measured surface cracks (fatigue, transverse, and block cracking). The SAS Macro called "factor" was used to perform the PCA analysis (*14*).

Table 3 shows the ranking of the various treatments based on the PCA analysis of the cracking data of the various projects. First, all thirty three projects were ranked based on their pre-treatment conditions (-1) and their condition at one year (+1) after treatment application. At (-1) the projects were ranked between 1 and 33 with a rank of "1" indicating the best conditions project and a rank of "33" indicating the worst conditions project. However, the data in Table 3 show that the maximum ranking is "31" instead of "33", this occurred because projects RF-2 and MOL-A-3 were both ranked as "6" and projects RF-4 and RF-5 were both ranked as "9" indicating that the conditions of the similarly ranked projects are statistically the same.

Then, the projects were ranked at +3 and +5 years after treatment application by re-conducting the PCA analysis at both the -1 and the analysis year (+3, or +5) excluding the projects that were younger than the indicated long-performance year. Subsequently, the ranking was based on the same total number of projects before (-1) and after (+3, +5) treatment application. A total of 30 and 24 projects were ranked at -1 and +3 years and at -1 and +5 years, respectively. It should be noted that the ranking at -1 year changes across Tables 3 and 4 because the number of projects that are ranked in -1 year is not constant since not all projects have performance data at years +3 and +5. As the number of projects used in the relative ranking process changes, the ranking of the individual projects also changes.

In the case of the ranking of projects at the +1, +3, and +5 years, there are several occasions where several projects are given the same rank. This occurred due to the statistically similar performance of these projects. For example in the case of ranking based on 1-year after construction (+1) in Table 3, a ranking of "1" is assigned to each project that did not experience any cracking in 1-year after construction. On the other hand if two projects showed cracking in 1-year after construction, the extent and severity of the cracking would then play a role in the ranking. For example, projects CIR-C-1 and CIR-C-2 both showed minor transverse cracking in year 1 but the PCA analysis assigned a ranking of "3" and "4", respectively. The reason for the worse ranking of project CIR-C-2 is that the extents of the minor transverse cracking of project CIR-C-2 is higher than the extent of the minor transverse cracking on project CIR-C-1. In summary, the projects are first ranked based on the year of cracking occurrence, followed by the severity of the cracking, and finally by the extent of the cracking. In the cases where all three factors are the same, then the projects are assigned similar ranks.

Figures 1.a, 1.b, and 1.c show a comparison between the ranking of the various treatments at one year before construction versus the ranking at one, three and five years after construction. The objective of these plots is to be able to assess the effectiveness of the various treatments by comparing their historical performance as they relate to the conditions of the pavement prior to rehabilitation. In other words, a treatment that was applied on badly deteriorated pavements and it maintained good performance would be more effective than a treatment that was applied on less deteriorated pavements and it maintained good performance. By examining the data presented in Figure 1, the following observations can be made:

- The CIR and MOL treatments were applied on flexible pavements that experienced the widest range of pre-treatment (-1) performance and the SRC treatment was applied on flexible pavements that experienced the narrowest range of pre-treatment performance.
- After one year (+1) of treatment construction (Figure 1.a), the CIR, RF, and MOL treatments showed similar performance while the SRC treatment showed significantly better performance.
- After three years (+3) of treatment construction (Figure 1.b), the RF and MOL treatments showed similar performance while the SRC treatment still showed significantly better performance.
- After five years (+5) of treatments construction (Figure 1.c), the CIR and MOL still performed similarly while the performance of the RF and SRC treatments became similar and closer to the performance of the CIR and MOL treatments. It should be noted that the four worst performing CIR projects (based on the (+3) analysis) were not included in the (+5) analysis due to the lack of the 5-years performance data from these projects.

The ranking according to the PCA data in Table 3 was also transformed into a percent ranking to evaluate the relative standing of a project PCA rank within the projects PCA data set at a certain year. In other words, the percent ranking shown in Table 4 is used to evaluate the standing of a project PCA rank in a certain year among all projects PCA rankings. For example, project CIR-B-2 had a PCA percent ranking of 78% at year -1 and a PCA percent ranking of 4% at year +5 meaning that 78% of all projects (18 projects) were better in performance than CIR-B-2 at year -1 while only 4% of all projects (1 project) were better in performance than CIR-B-2 at year +5. The relative comparison of the PCA percent ranking of different years is a good indication of the relative effectiveness of the various treatments taking into consideration pre-construction pavement conditions. For example, project CIR-A-2 had a PCA percent ranking of 26% at year -1 and a PCA percent ranking of 87% at year +5 meaning that only 6 projects out of 24 had better performance at year -1 while 20 projects out of the same 24 projects had better performance than CIR-A-2 at year +5. This indicates that the relative ranking of the CIR-A-2 project 5-years after construction (+5) was lower than its relative ranking 1-year prior to construction leading to the conclusion that, relative to other projects the pavement condition of the CIR-A-2 project at +5 is worse than its condition at year -1.

The data in Tables 3 and 4 show that 1-year after construction a total of five CIR projects out of twelve performed among the worst projects. Four out of these worst performing five CIR projects (CIR-C-1, -2, -3, and -4) consisted of milling the top 2.0" of the existing layer and overlaying it with 2.0" dense grade HMA. Only one RF project (RF-1) out of six ranked among the worst projects. The RF-1 project experienced severe alligator cracking (Type B) prior to the construction of the treatment. All of the SRC projects ranked among the best performing projects. Two MOL projects (MOL-A-1, B-4) ranked among the worst performing projects.

Three years after construction, additional two CIR, RF, and MOL projects performed among the worst projects whereas the SRC projects still outperformed the other treatments.

Five years after construction, five CIR projects out of eight performed among the best projects. The five CIR projects included three out of the four CIR-B projects. The CIR-B treatment consists of milling the top 3.0" of the existing HMA layer and overlaying it with 3.0" dense graded HMA. Only two RF projects out of four, one SRC project out of three, and two MOL projects out of nine ranked among the best performing projects.

The PCA percent ranking data in Table 4 showed that there are two CIR projects (CIR-A-2 and CIR-B-1), one SRC project (SRC-A-2), and three MOL projects (MOLA-1, -2, and -3) where their percent relative rankings 5-years after construction (+5) was significantly lower than their percent relative rankings 1-year prior to construction. A close examination of the performance data summarized in Table 2 showed that four out of these six projects had experienced severe alligator cracking (Type B) prior to the construction of the CIR, SRC, and MOL treatments. This indicates that the existence of severe alligator cracking skewed the relative ranking of the various projects.

CONCLUSIONS

The following general conclusions concerning the performance of reflective cracking treatments in Nevada are based on the combined analyses of distress data and PCA.

- The PCA analysis was conducted to identify any reflective cracking treatment that may be able to provide good long-term performance regardless of the conditions of the pavement prior to its application. Based on the results of the PCA presented in Figure 1, this goal was not achieved. In general, the performance of the reflective cracking treatment is highly dependent on the conditions of the pavement prior to the construction of the treatment. This is supported by the data shown in Figure 1.c where the CIR and MOL were applied to pavements having lower performance than the pavements where the RF and SRC were applied and showed worse performance after 5-years in service.

- The PCA ranking data in Tables 3 and 4 showed that the CIR-A (CIR 2" and overlay 2.5") and CIR-B (CIR 3.0" and overlay 3.0") treatments regardless of the traffic level are generally effective in stopping reflective cracking for 3 years and retarding reflective cracking for 5 years as long as the existing pavement does not show severe alligator cracking prior to the application of these treatments. On the other hand the CIR-C (CIR 2" and overlay 2") treatment is ineffective in resisting reflective cracking.

- The RF treatment showed marginal performance after 3 and 5-years of construction. The RF treatment was ineffective when applied on a pavement with severe alligator cracking prior to the application of the treatment and/or a traffic level above 3000 AADT.

- The SRC treatment showed excellent performance up to 3 years after construction regardless of the traffic level and the existing pavement condition. However 5 years after construction, reflective transverse cracking showed up considerably on the pavement surface.

- The MOL treatment was effective in stopping reflective cracking up to 3 years after construction for projects with AADT lower than 5000 and/or projects with no severe alligator cracking prior to the application of the treatment. After 5 years of construction the MOL treatment showed marginal performance by slowing down reflective cracking.

- Another way of looking at the effectiveness of the various treatments is to examine the means and standard deviations of their relative rankings at the pre-treatment and the 5-

years stages. This analysis was conducted on all projects having data on the 5-years performance and excluding the four projects where the severe alligator cracking skewed the ranking process. Table 5 summarized the means and standard deviations data of the various projects along with the change in the mean relative ranking. An effective treatment would be one that has high mean and standard deviation for pre-treatment performance and low mean and standard deviation for the 5-years performance coupled with the highest change in the mean ranking. Based on this criterion, the evaluated treatments for mitigating reflective cracking under Nevada's conditions are ranked from best to worst after 5-years of construction as follows:

- Cold in-place recycling (CIR)
- Mill and overlay (MOL)
- Reinforced fabrics (RF)
- Stress relief course (SRC)

However, the long-term effectiveness of the CIR and MOL treatments is significantly hampered by the existence of severe alligator cracking on the projects prior to the application of these treatments. Therefore, it is recommended that projects experiencing severe alligator cracking as classified by the NDOT pavement distress manual should be subjected to either re-construction or full depth reclamation.

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LIST OF TABLES

TABLE 1 Summary of NDOT Projects that Were Analyzed in this Study

Treatment	DOC*	Contract	Route	Location	Thickness of Surface Layer (in)[†]	Binder Grade	AADT*
CIR-A-1	1998	2808a	US50	North	2" CIR + 2.5" DGHMA	AC-20P	2,950
CIR-A-2	1997	2808b	US50	North	2" CIR + 2.5" DGHMA	AC-20P	2,950
CIR-A-3	1999	2838	SR396	North	2" CIR + 2.5" DGHMA	AC-20P	1,100
CIR-A-4	1999	2935	SR360	South	2" CIR + 3" DGHMA	AC-20P	800
CIR-B-1	1998	2819	US95	South	3" CIR + 3" DGHMA	AC-20P	5,550
CIR-B-2	1998	2873	US95	South	3" CIR + 3" DGHMA	AC-20P	5,550
CIR-B-3	1999	2961	US6	South	3" CIR + 3" DGHMA	AC-20P	2,000
CIR-B-4	1999	3013	US95A	North	3" CIR + 3" DGHMA	AC-20P	14,500
CIR-C-1	2003	3025a	US93	North	2" CIR + 2" DGHMA	AC-20P	5,000
CIR-C-2	2001	3025b	US93	North	2" CIR + 2" DGHMA	AC-20P	1,000
CIR-C-3	2001	3025c	SR208	North	2" CIR + 2" DGHMA	AC-20P	1,000
CIR-C-4	2001	2876	SR208	North	2" CIR + 2" DGHMA	AC-20P	1,500
RF-1	1999	2761	SR443	North	Fabric + 2" DGHMA	AC-20P	9,600
RF-2	1999	2932	US95	South	Fabric + 2" DGHMA	AC-20P	2,850
RF-3	2000	2980	US50	North	Fabric + 2" DGHMA	AC-20P	1,000
RF-4	2000	2980	US95	North	Fabric + 2" DGHMA	AC-20P	4,400
RF-5	2001	3006	IR80	North	Fabric + 2" DGHMA	AC-20P	7,200
RF-6	2001	3008	SR227	North	Fabric + 2" DGHMA	AC-20P	10,000
SRC-1	1997	2723	US95	South	1" SRC + 2" DGHMA	AC-20P	40,000
SRC-2	2000	3031	US395	North	1" SRC + 2" DGHMA	AC-20P	15,600
SRC-3	2000	3048	SR157	South	1" SRC + 2" DGHMA	AC-20P	2,700
SRC-4	2001	3045	US50	North	1" SRC + 2" DGHMA	AC-20P	1,900
SRC-5	2003	3162	US395	North	1" SRC + 2" DGHMA	PG 64 -28NV	29,100
MOL-A-1	1990	2384a	US95	North	1.0" DGHMA	AC-10	40,000
MOL-A-2	1993	2384b	US95	North	1.0" DGHMA	AC-20	5,500
MOL-A-3	1993	2432	SR157	South	1.0" DGHMA	AC-20	2,700
MOL-A-4	1993	2505	US95	South	1.0" DGHMA	AC-20P	3,350
MOL-B-1	1995	2651a	US95	South	1.5" DGHMA	AC-20P	2,050
MOL-B-2	1996	2651b	US95	South	1.5" DGHMA	AC-20P	1,700
MOL-B-3	1996	2651c	US95	South	1.5" DGHMA	AC-20P	1,700
MOL-B-4	1997	2679	US95	South	1.5" DGHMA	AC-20P	6,750
MOL-C-1	2000	3028	SR512	North	1.5" DGHMA	AC-20P	7,250
MOL-C-2	2003	2070	SR160	South	1.5" DGHMA	AC-20P	7,500

* DOC Denotes "Date of Construction" and AADT Denotes "Annual Average Daily Traffic."

[†] DGHMA Denotes "Dense Graded Hot Mix Asphalt"

TABLE 2 Pavement Distresses Summary of Selected NDOT Projects

Treatment		AADT	Age at 2005 (years)	Pavement Distresses Before Treatment Application (Severity)						Pavement Distresses After Treatment Application (Severity/Time in Years to Develop)		
				Fatigue cracking Type		Transverse Cracks	Block Cracking Type			Fatigue cracking Type A	Transverse Cracks	Block Cracking Type A
				A	B		A	B	C			
Cold In-Place Recycling	CIR-A-1	2,950	7	Sev	-	Mod	Min	-	-	-	Min/7	-
	CIR-A-2	2,950	8	Min	Sev	Mod	-	-	Min	-	Min/2	-
	CIR-A-3	1,100	6	-	-	Sev	Sev	Sev	Sev	-	Min/1	-
	CIR-A-4	800	6	Sev	Mod	Min	Min	Mod	Mod	-	-	-
	CIR-B-1	5,550	7	-	Sev	Mod	-	Min	Min	Min/3	Min/2	-
	CIR-B-2	5,550	7	Min	-	Min	Min	Sev	Min	Min/7	Min/7	-
	CIR-B-3	2,000	6	Min	-	Min	Sev	Sev	Sev	-	-	-
	CIR-B-4	14,500	6	Min	-	Min	Mod	-	-	-	Min/6	-
	CIR-C-1	5,000	2	Min	Min	Min	-	-	-	-	Min/1	-
	CIR-C-2	1,000	4	Min	Mod	Min	Mod	Mod	Min	-	Min/1	-
	CIR-C-3	1,000	4	Min	Min	Min	Mod	Mod	Min	-	Min/1	-
	CIR-C-4	1,500	4	Min	-	Sev	Mod	-	Min	-	Min/1	-
Reinforced Fabric	RF-1	9,600	6	Min	Sev	Mod	Sev	Mod	-	Min/5	Min/1	-
	RF-2	2,850	6	Min	Min	Sev	-	-	-	-	-	-
	RF-3	1,000	5	Min	Min	Sev	-	Min	Min	-	-	-
	RF-4	4,400	5	Min	Min	Min	-	-	-	-	Min/3	-
	RF-5	7,200	4	Min	Min	Min	-	-	-	-	-	-
	RF-6	10,000	4	Min	Min	Min	-	-	-	-	Min/2	-
Stress Relief Course	SRC-1	40,000	8	Mod	Sev	Mod	Mod	Min	-	-	-	-
	SRC-2	15,600	5	Min	Min	Mod	Sev	-	-	-	Min/5	-
	SRC-3	2,700	5	Mod	-	Mod	-	-	-	-	Min/5	-
	SRC-4	1,900	4	Min	Mod	Mod	-	-	-	-	-	-
	SRC-5	29,100	2	-	-	Min	-	-	-	-	-	-
Mill and Overlay	MOL-A-1	40,000	15	-	Sev	Min	Mod	-	-	Mod/1	Mod/1	-
	MOL-A-2	5,500	12	Mod	Sev	Mod	Min	-	-	Min/4	Min/2	-
	MOL-A-3	2,700	12	Mod	-	Mod	-	-	-	-	Min/5	-
	MOL-A-4	3,350	12	-	Sev	-	Mod	-	Sev	-	-	-
	MOL-B-1	2,000	10	-	Mod	-	Mod	-	Min	-	-	Min/5
	MOL-B-2	1,700	9	-	-	-	-	Sev	Sev	-	Min/5	-
	MOL-B-3	1,700	9	Mod	-	Mod	Mod	Sev	Sev	Min/5	Min/5	-
	MOL-B-4	6,750	8	Mod	-	Min	Mod	Min	-	-	Mod/1	Min/6
	MOL-C-1	7,250	5	-	-	Mod	-	-	-	-	Min/3	-
	MOL-C-2	7,500	2	Min	Min	Min	Mod	Mod	-	-	-	-

Note: Min Denotes "Minor", Mod Denotes "Moderate", Sev Denotes "Severe".

TABLE 3 NDOT Projects Information and Ranking of Treatments According to PCA

Treatment	DOC*	AADT*	Ranking[†]					
			-1[#]	+1[#]	-1[#]	+3[#]	-1[#]	+5[#]
CIR-A-1	1998	2,950	2	1	1	1	1	2
CIR-A-2	1997	2,950	7	1	8	10	7	12
CIR-A-3	1999	1,100	28	2	27	2	22	6
CIR-A-4	1999	800	21	1	20	1	16	2
CIR-B-1	1998	5,550	5	1	3	8	5	11
CIR-B-2	1998	5,550	26	1	26	1	19	2
CIR-B-3	1999	2,000	30	1	29	1	23	2
CIR-B-4	1999	14,500	16	1	15	1	12	2
CIR-C-1	2003	5,000	12	3	N.A.[§]	N.A.	N.A.	N.A.
CIR-C-2	2001	1,000	22	4	22	1	N.A.	N.A.
CIR-C-3	2001	1,000	24	4	23	7	N.A.	N.A.
CIR-C-4	2001	1,500	19	4	19	7	N.A.	N.A.
RF-1	1999	9,600	27	5	25	7	18	9
RF-2	1999	2,850	6	1	4	1	4	2
RF-3	2000	1,600	17	1	17	1	15	2
RF-4	2000	4,400	9	1	12	2	10	4
RF-5	2001	7,200	9	1	11	1	N.A.	N.A.
RF-6	2001	10,000	10	1	13	4	N.A.	N.A.
SRC-A-1	1997	40,000	11	1	9	1	6	2
SRC-A-2	2000	15,600	18	1	18	1	13	8
SRC-A-3	2000	2,700	8	1	10	1	9	3
SRC-A-4	2001	1,900	3	1	4	1	N.A.	N.A.
SRC-B-1	2003	29,100	14	1	N.A.	N.A.	N.A.	N.A.
MOL-A-1	1996	40,000	4	6	6	9	8	12
MOL-A-2	1993	5,500	1	1	2	5	2	10
MOL-A-3	1993	2,700	6	1	5	1	3	12
MOL-A-4	1993	3,350	25	1	24	1	20	2
MOL-B-1	1995	2,000	20	1	21	1	17	1
MOL-B-2	1996	1,700	31	1	30	1	24	7
MOL-B-3	1996	1,700	29	1	28	1	21	13
MOL-B-4	1997	6,750	15	4	16	6	14	7
MOL-C-1	2000	7,250	13	1	14	3	11	5
MOL-C-2	2003	7,500	23	1	N.A.	N.A.	N.A.	N.A.

* DOC Denotes "Date of Construction" and AADT Denotes "Annual Average Daily Traffic."

[†] Ranking from best to worst; i.e., the projects ranked as "1" had the best performance.

[#] -1: Previous year to construction, +1, +3, +5: one, three, and five years after construction.

[§] N.A.: Project is younger than the indicated long-performance year.

TABLE 4 NDOT Projects Information and Percent Ranking of Treatments According to PCA

Treatment	DOC*	AADT*	PCA Percent Ranking[†]					
			-1[#]	+1[#]	-1[#]	+3[#]	-1[#]	+5[#]
CIR-A-1	1998	2,950	3%	0%	0%	0%	9%	4%
CIR-A-2	1997	2.950	22%	0%	24%	100%	26%	87%
CIR-A-3	1999	1,100	91%	78%	90%	62%	91%	57%
CIR-A-4	1999	800	69%	0%	65%	0%	65%	4%
CIR-B-1	1998	5,550	13%	0%	7%	93%	17%	83%
CIR-B-2	1998	5.550	84%	0%	86%	0%	78%	4%
CIR-B-3	1999	2,000	97%	0%	97%	0%	96%	4%
CIR-B-4	1999	14.500	53%	0%	48%	0%	48%	4%
CIR-C-1	2003	5.000	41%	81%	N.A.[§]	N.A.	N.A.	N.A.
CIR-C-2	2001	1.000	72%	84%	72%	0%	N.A.	N.A.
CIR-C-3	2001	1,000	78%	84%	76%	83%	N.A.	N.A.
CIR-C-4	2001	1,500	63%	84%	62%	83%	N.A.	N.A.
RF-1	1999	9,600	88%	97%	83%	83%	74%	74%
RF-2	1999	2,850	16%	0%	10%	0%	13%	4%
RF-3	2000	1,000	56%	0%	55%	0%	61%	4%
RF-4	2000	4,400	28%	0%	38%	62%	39%	48%
RF-5	2001	7,200	28%	0%	34%	0%	N.A.	N.A.
RF-6	2001	10.000	34%	0%	41%	72%	N.A.	N.A.
SRC-A-1	1997	40.000	38%	0%	28%	0%	22%	4%
SRC-A-2	2000	15.600	59%	0%	59%	0%	52%	70%
SRC-A-3	2000	2,700	25%	0%	31%	0%	35%	43%
SRC-A-4	2001	1,900	6%	0%	10%	0%	N.A.	N.A.
SRC-B-1	2003	29.100	47%	0%	N.A.	N.A.	N.A.	N.A.
MOL-A-1	1990	40,000	9%	100%	21%	97%	30%	87%
MOL-A-2	1993	5.500	0%	0%	3%	76%	4%	78%
MOL-A-3	1993	2.700	16%	0%	17%	0%	9%	87%
MOL-A-4	1993	3,350	81%	0%	79%	0%	83%	4%
MOL-B-1	1995	2,000	66%	0%	69%	0%	70%	0%
MOL-B-2	1996	1,700	100%	0%	100%	0%	100%	61%
MOL-B-3	1996	1,700	94%	0%	93%	0%	87%	100%
MOL-B-4	1997	6,750	50%	84%	52%	79%	57%	61%
MOL-C-1	2000	7,250	44%	0%	45%	69%	43%	52%
MOL-C-2	2003	7,500	75%	0%	N.A.	N.A.	N.A.	N.A.

* DOC Denotes "Date of Construction" and AADT Denotes "Annual Average Daily Traffic."

[†] Percent Ranking is the relative standing of a PCA rank within the PCA data set in percentage; i.e., the project with a percent ranking of "100%" means all projects have a higher PCA rank, hence this project has the worst performance. On the other hand, the project with a percent ranking of "0%" means none of the projects has a higher PCA rank hence this project has the best performance.

[#] -1: Previous year to construction, +1, +3, +5: one, three, and five years after construction.

[§] N.A.: Project is younger than the indicated long-performance year.

TABLE 5 Statistical Analysis of the Various Treatments Based on the PCA Rankings at One-year Before Treatment Construction and Five-years After Treatment Construction

Treatment	Number of Projects	1-year Pre-construction (-1)		5-year After Construction (+5)		Change in Relative Ranking
		Mean	STD*	Mean	STD*	
CIR	6	16	8	3	2	13
RF	4	12	6	4	3	8
SRC	3	9	4	4	3	5
MOL	7	16	7	7	7	9

* Standard deviation

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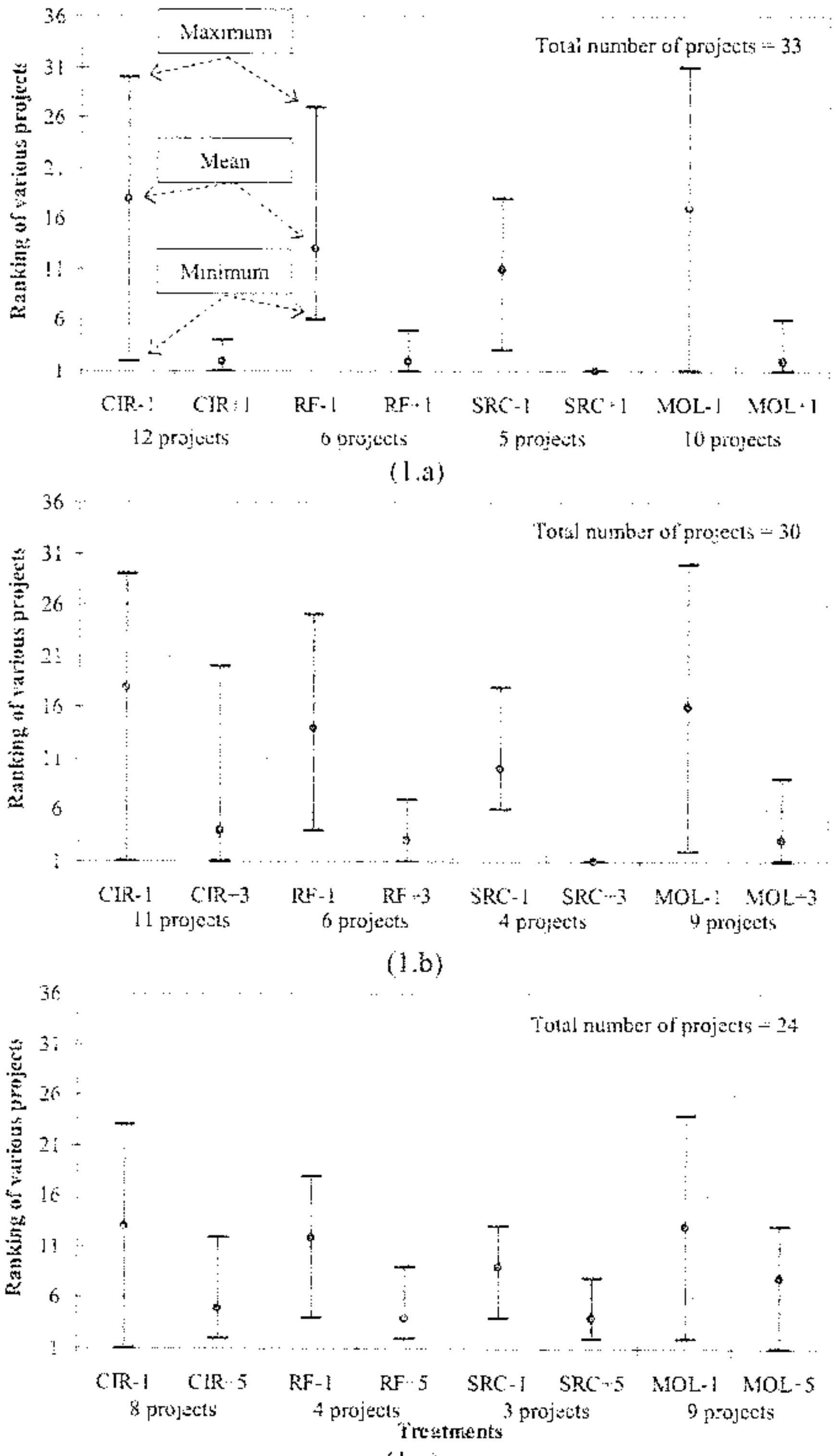

(1.a)

(1.b)

(1.c)

FIGURE 1 **Comparison between the ranking of the various treatments at 1-year before treatment construction and 1-year, 3-year, and 5-year after treatment construction**