Notes have been added here as background information for the PowerPoint slides. Further information on the study, including all the data, reports and photos can be found at www.pavementpreservation.org/fogseals/.

Study Participants – Acknowledgements

- **Federal Highway Administration (FHWA) - Sorenson**
- **Foundation for Pavement Preservation (FP2) - Eller**
- **Arizona Department of Transportation (ADOT) - Scofield**
- **State DOTs: MN, CA, AZ, MI**
- **GHK, Inc.**

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Research Participants Acknowledgements

- **Western Research Institute**
  - Binder extraction/ chemical & rheological tests
- **North Central Superpave Center**
  - Friction/permeability
- **Mathy Technology & Engineering**
  - Dynamic shear rheometer – torsion
- **University of Minnesota**
  - Bending beam rheometry on thin mix
- **University of Texas at El Paso**
  - Portable Seismic Pavement Analyzer
- **Akzo Nobel**
  - Emulsion surface tension & particle size tests

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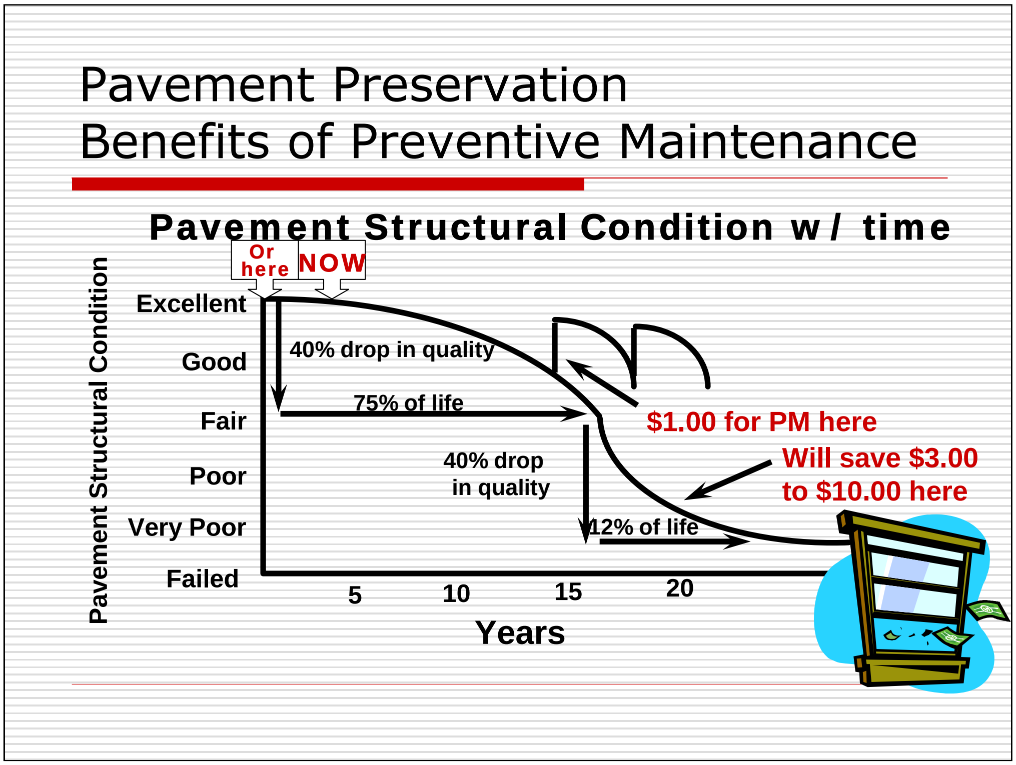
Industry Participants Acknowledgements

- **Tricor Refining**
  - Reclamite; ERA-1; ERA-25
- **Western Emulsions**
  - Pass QB
- **Blacklidge Emulsions**
  - LD-7
- **Asphalt Supply**
  - GSB-Modified
- **Koch Materials**
  - CSS-1
- **Flint Hills Refining**
  - CRS-2Pd
- **Paramount Refining**
  - CSS-1

Thanks to Tricor Refining, Western Emulsions, Blacklidge Emulsions, Asphalt Supply, Flint Hills Refining and Paramount Refining for donating their products, services and equipment.

An Effective Preservation Program

- **Cost effectively extends pavement life**
- **Minimizes extensive rehabilitation & resulting traffic congestion**
- **Improves ride quality & safety**
  - Provides smoother, high friction surfaces



A sound pavement preservation strategy not only reduces life cycle costs, but also results in better over-all road conditions.

Fog Seal

- **AEMA Definition:** a light spray application of dilute asphalt emulsion used primarily to seal an existing asphalt surface to reduce raveling and enrich dry and weathered surfaces
- **FHWA Definition:** the light application of diluted, slow setting asphalt emulsion without aggregate cover. The purpose of fog seals are to seal the pavement, inhibit raveling, and enrich hardened/oxidized asphalt.

Fog Seal

- **CALTRANS Maintenance Technical Advisory Guide:** a method of adding asphalt to an existing pavement surface to improve sealing or waterproofing, prevent further stone loss by holding aggregate in place, or simply improve the surface appearance. However, inappropriate use can result in slick pavements and tracking of excess material.

CALTRANS MTAG:

Rejuvenating Fog Seal

- Rejuvenating emulsions contain oils which soften an age-embrittled binder.

How Do We Do It?

- **Spray Applied Emulsified Surface Applications**
  - Seal & Bind
    - Dense
    - OGFC
    - AC-Rubber
    - Chip Seal
  - Restore AC

Fog and rejuvenator seals are diluted water-based emulsions that are sprayed onto pavement surfaces by a distributor. The emulsions are diluted to allow an even application of a very small amount of asphaltic material to the pavement surface. Traditionally, highway departments apply fog and rejuvenator seals to pavements to arrest pitting and raveling, to reduce shrinkage tendencies, to decrease permeability, to decrease damage from traffic and snow plows, and to rejuvenate the properties of the existing asphalt cement. They are also used to improve appearance and safety visibility by blackening the pavement.

REFERENCES

([i]) *Recommended Performance Guidelines.* Asphalt Emulsion Manufacturers Association, AEMA, Washington, D.C., 1990.

([ii]) Estakhri,CK and Agarwal,H. Effectiveness of Fog Seals and Rejuvenators for Bituminous Pavement Surfaces. *Research Report 1156-1F*, Project No. 1156, Texas Transportation Institute, College Station, 1991.

What do we know about Fog Seals?

- **Low cost preventive maintenance**
  - 13 cents to $1.60 per square yard
- **Emulsion must infiltrate HMA surfaces**
  - Fog seal
    - Light application of dilute asphalt emulsion
    - Hard residue meant to bind or seal
  - Rejuvenating fog seal
    - Light application of dilute oil or oil/asphalt emulsion
    - Alter rheology of oxidized asphalt near the surface

Fog and rejuvenator seals are the least expensive preventive maintenance surface treatments designed to protect and prolong the life of good pavements. Several different types of sealers and rejuvenators are readily available in the marketplace. Sealers such as SS-1 (Slow Setting emulsified asphalt) or CSS-1 (Cationic Slow Setting emulsified asphalt) are commonly used to “seal” the pavement surface or to “bind” or “lock” cover material or fines in-place reducing surface attrition. Rejuvenators are designed to penetrate into the existing asphalt cement and modify and improve existing chemical and rheological properties. The product selection is dependent upon the problem being solved and the existing pavement type. Rejuvenator products are most typically used on dense-graded asphalt surfaces, while fog seal products are more commonly used on chip seals and friction courses where binding or enrichment is the main purpose. However, both product types have been used on all three surface types.

In the embrittlement process of flexible pavements, the oxidation of asphalt occurs during both construction and the service life of the pavement. Asphalt hardening during construction can be predicted by laboratory aging procedures, allowing adjustment of the initial binder rheology for typical changes during hot mix asphalt (HMA) mixing and compaction. The long-term aging of the asphalt is much more difficult to predict. It depends upon the asphalt crude source, the environment and available oxygen as supplied through interconnected air voids. Sealers and rejuvenators are used in a preventive maintenance strategy to prevent surface asphalt from reaching the limiting stiffness where surface cracks begin to appear. If cracks develop, the aging accelerates due to infiltration of moisture and oxygen. Rejuvenators were developed in the late 1950s to prevent age-induced block cracking by softening hardened binders.

Some agencies, however, have discontinued or limited the use of fog and rejuvenator seals because of loss of skid resistance. This study was initiated to

Spray Applied Surface Seal :

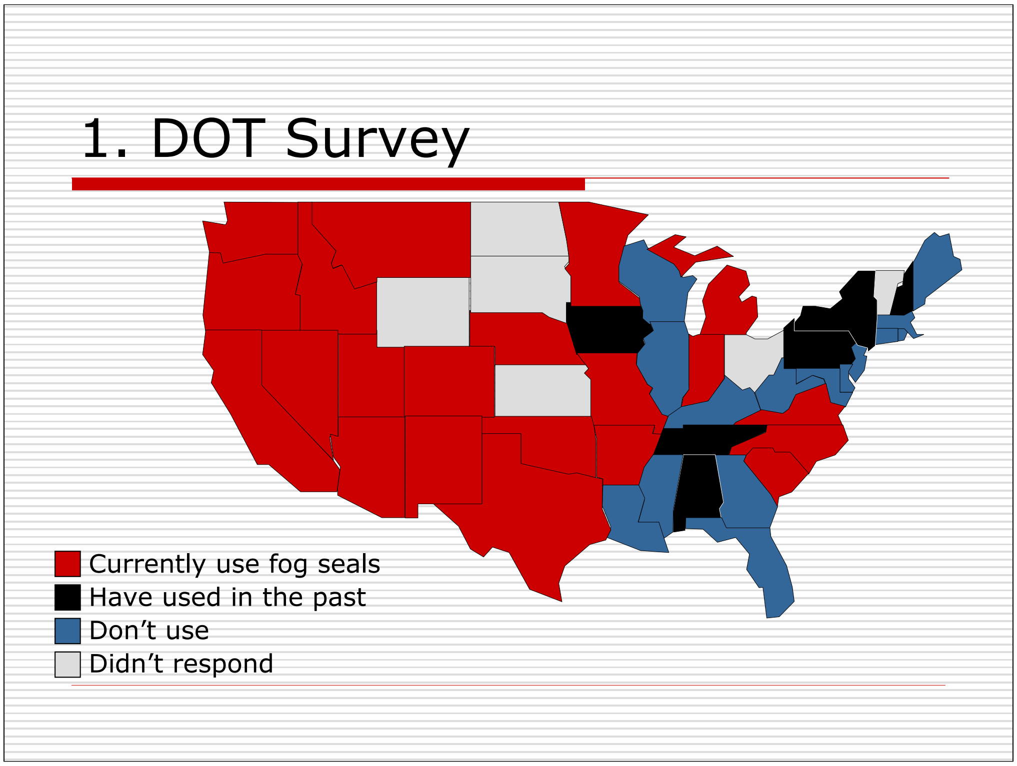
Study Objectives

- **Evaluate Effectiveness and Safety**
  - Sealers
  - Rejuvenators
- **Optimize Timing Of Applications**
  - *Right Place, Right Time, Right Application*
  - Evaluate lab methods as potential "triggers" for timing strategies
- **Technology Transfer**

This project has four main tasks: collecting existing information; placement of several experimental sections within different climates, traffic levels and surface characteristics; evaluation of field and laboratory test methods and data collected from the test sections; and disseminating the lessons learned.

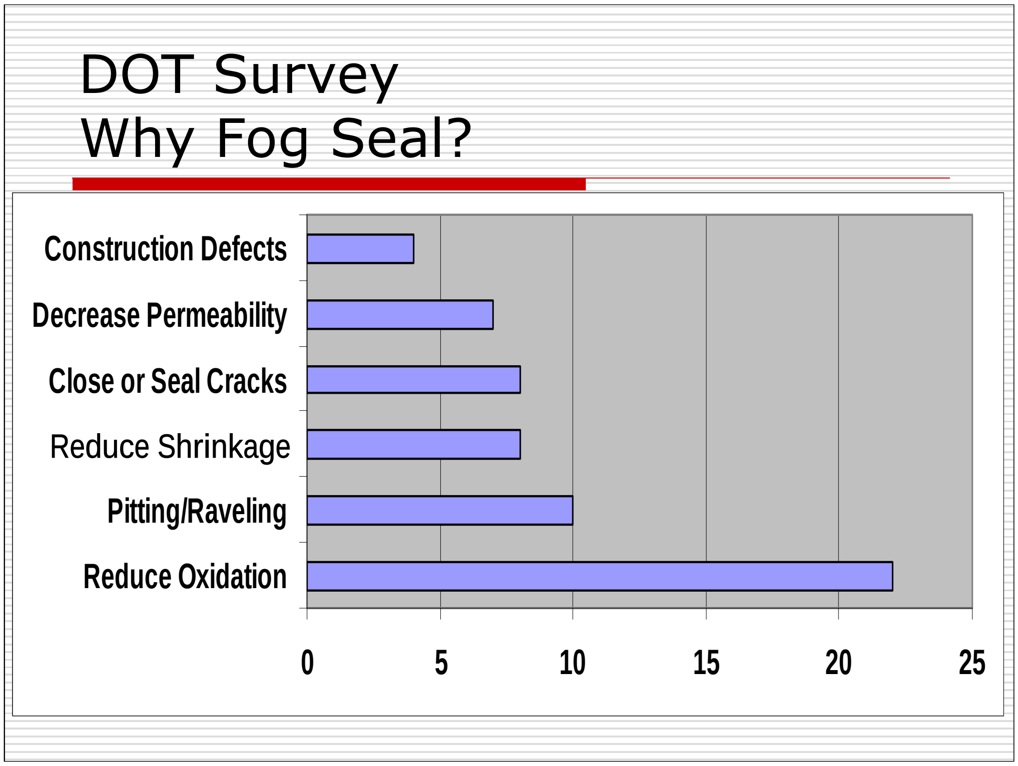
Spray Applied Surface Seal : The Project

- **Information gathering**
  - Government/industry/academia expert task group advisory meetings
  - State DOT survey
  - Literature search
  - Two national workshops
- **Field projects & lab testing**
  - Apply fog seals on different pavement types
  - Monitor performance vs. timing of applications
  - Evaluate safety concerns
  - Develop performance-related test methods
- **Information sharing of lessons learned**
  - Workshops, CD, website, www.pavementpreservation.org/fogseals/



CUSTOMER SURVEY

The project was initiated in 2001 with a comprehensive user survey of state highway departments. The survey found that 20 states have had success with fog and rejuvenator seals, 16 states reported they have never tried them, and six states reported they had discontinued their use. Twenty states reported they were cost-effective, and one state believed they were not. Four state-of-the-knowledge workshops were held in 2001 and 2002, with expert task groups of representatives from industry, user agencies and academics. Based on recommendations from these efforts, a study plan was developed.

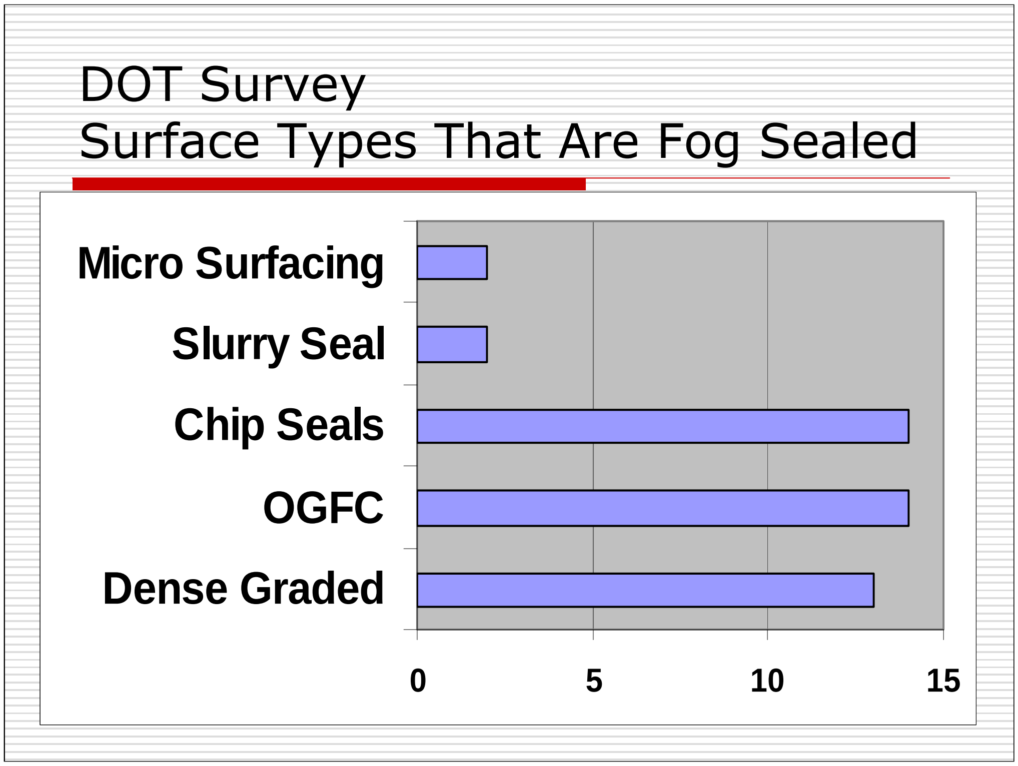


Traditionally, highway departments apply fog and rejuvenator seals to pavements to arrest pitting and raveling, to reduce shrinkage tendencies, to decrease permeability, to decrease damage from traffic and snow plows, and to rejuvenate the properties of the existing asphalt cement. They are also used to improve appearance and safety visibility by blackening the pavement. They have been found to be effective in tying down aggregates in chip seal surface treatments, preventing vehicle damage from loose chips as well as protecting the seal.([i])

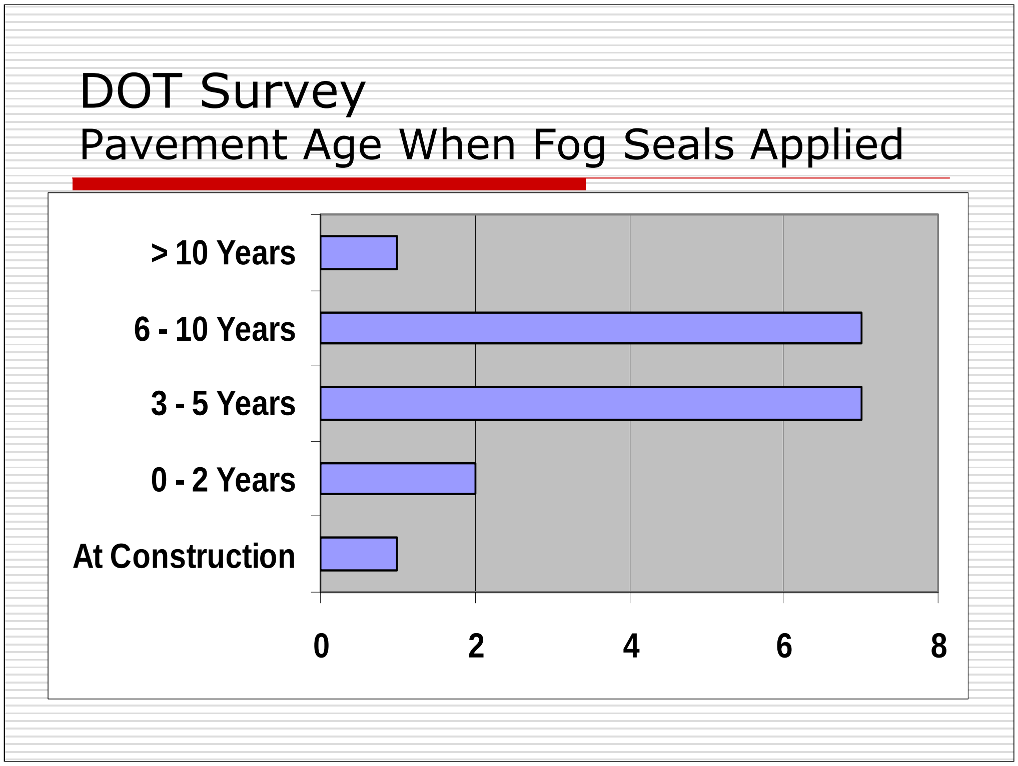
In the embrittlement process of flexible pavements, the oxidation of asphalt occurs during both construction and the service life of the pavement. Asphalt hardening during construction can be predicted by laboratory aging procedures, allowing adjustment of the initial binder rheology for typical changes during hot mix asphalt (HMA) mixing and compaction. The long-term aging of the asphalt is much more difficult to predict. It depends upon the asphalt crude source, the environment and available oxygen as supplied through interconnected air voids. Sealers and rejuvenators are used in a preventive maintenance strategy to prevent surface asphalt from reaching the limiting stiffness where surface cracks begin to appear. If cracks develop, the aging accelerates due to infiltration of moisture and oxygen. Rejuvenators were developed in the late 1950s to prevent age-induced block cracking by softening hardened binders.([ii])

([i]) Brown,ER, and Johnson,RR. Evaluation of Rejuvenators for Bituminous Pavements. *AFCEC-TR-76-3*, Air Force Civil Engineering Center, Tyndall Air Force Base, Florida, 1976.

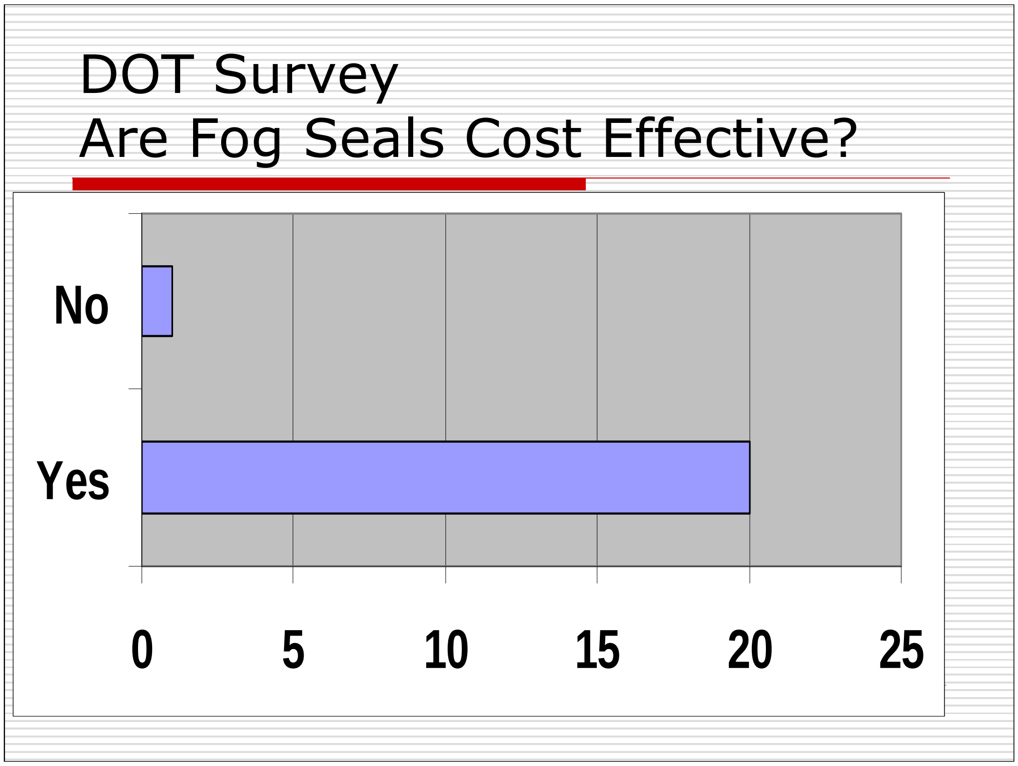
([ii]) Estakhri,CK and Agarwal,H. Effectiveness of Fog Seals and



Emulsified sealers and rejuvenators are best used as preventive maintenance treatments on pavements in good condition, but with surfaces that have begun the aging process. They can be used on any asphalt pavement that has sufficient permeability to allow emulsion infiltration, but traffic should be controlled until the seals have fully cured and friction numbers are restored to acceptable levels. The product selection is dependent upon the problem being solved and the existing pavement type. Rejuvenator products are most typically used on dense-graded asphalt surfaces, while fog seal products are more commonly used on chip seals and friction courses where binding or enrichment is the main purpose. However, both product types have been used on all three surface types.



One goal of the study is to determine the timing of sealing applications. The DOT survey showed that many agencies have a scheduled fog seal application program for preventive maintenance that begins between two and ten years after HMA construction, and some routinely use spray applied seals immediately after chip sealing.



Twenty states reported they were cost-effective, and one state believed they were not.

Upper Midwest Experiences

- **Nebraska - 600 miles planned for 2007**
  - Fog sealing lower volume roadways
- **South Dakota**
  - 280 miles: mainly fog seal on new chip seals
- **Iowa**
  - 222 miles of Interstate shoulder fog sealing
- **North Dakota**
  - 235 miles of fog seal on new chip seals
  - 35 miles of fog seal on new HBP pavements

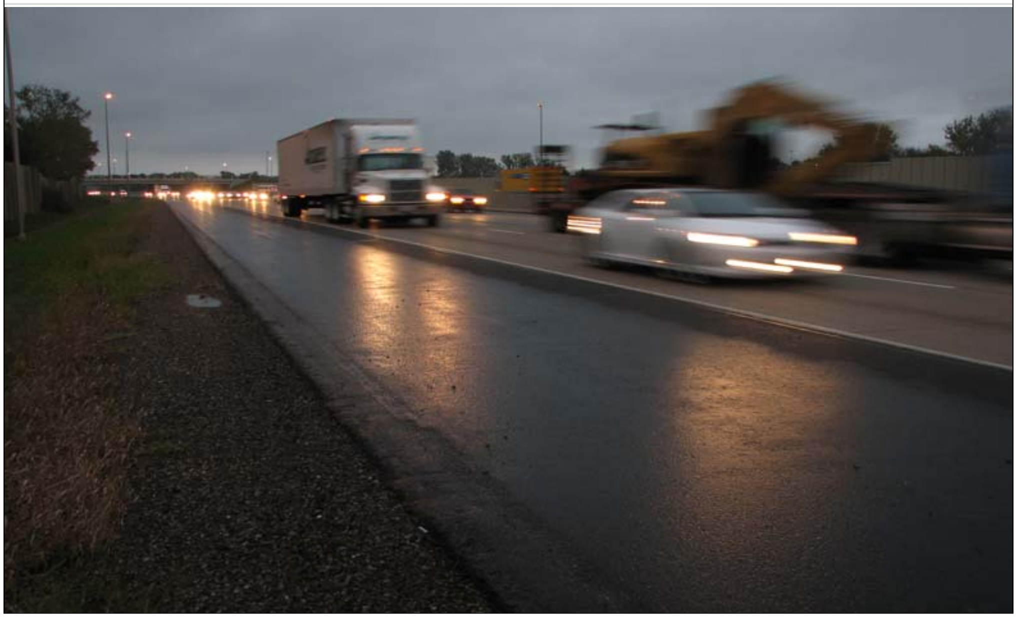
Minnesota's Experiences

- **Shoulder maintenance**
  - Road never traveled
  - 1st shoulder fogging contract let in 2006
    - Cost \$0.16 / yd^2
    - CRS-2pd
      - CRS-2p diluted
      - 3:1, emulsion : water
      - Minimum 50% residual AC
  - Maintenance forces applied 100,000 gals in 2007

Unsealed Shoulders

Sealed Shoulders

MN shoulders:
Shedding Light Rain



Sealed Rumble Strips

- **Research Project:**
  - Effects of rumble strips on HMA life
- **Fog**
  - During construction
    - Stopped
  - After construction
    - CRS-2pd

MNDOT – Fog Sealing Chip Seals

- Light, uniform application of asphalt emulsion
- Normally CSS-1h or SS-1h
- Cationic or anionic
- Strongly recommend dilution
  - Lower viscosity & better penetration
- 0.06 to 0.20 gal/yd^2 diluted

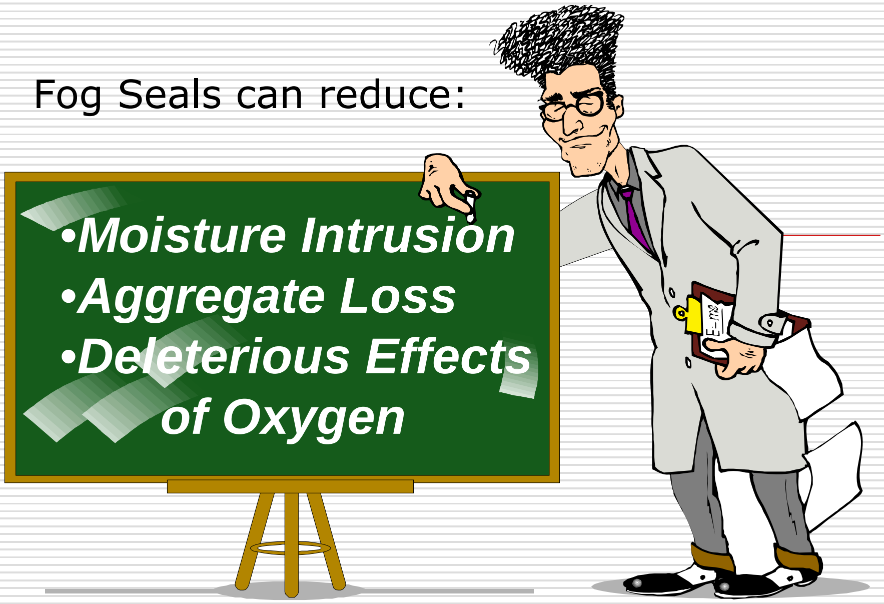

Why Fog Seal A Chip Seal?

Fog Seals Reduce Snowplow Damage

- Increased embedment
  - Additional residual asphalt
  - Lock down marginally embedded chips
- Pavement marking more visible – Use less paint
- Dark color accelerates melting of ice in winter
- Customer perceives new HMA overlay, not a chip seal

Pavement Preservation:
Early Intervention

Fog Seals can reduce:



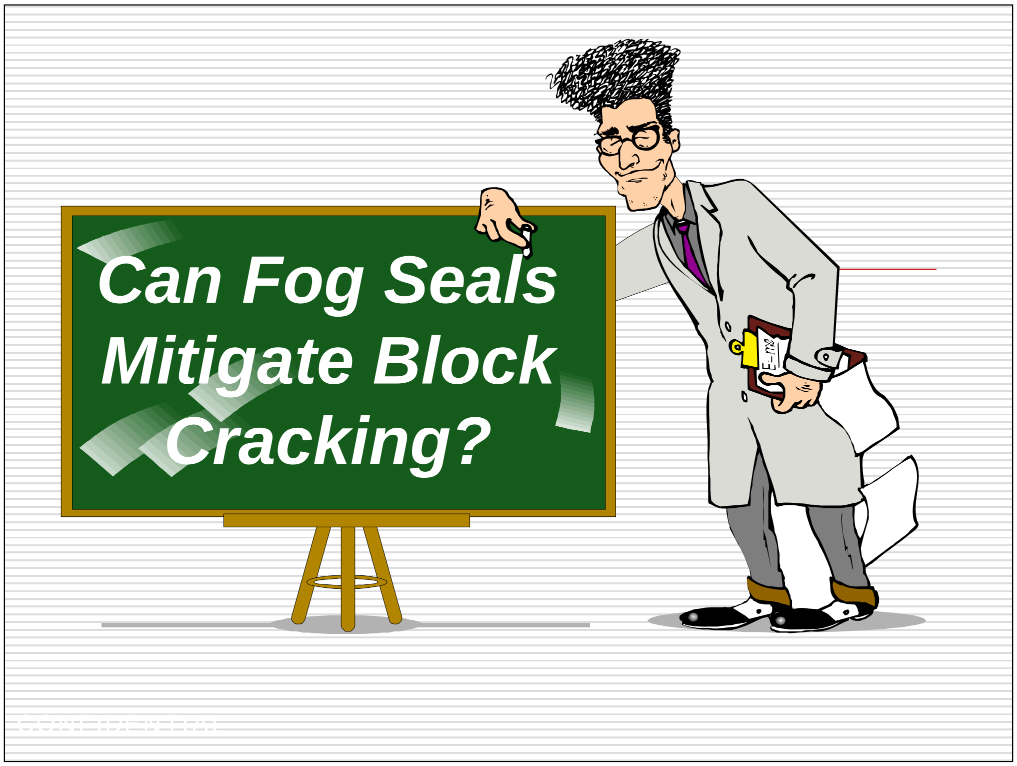
Much was learned from this study, including where and when to apply sealers, what test methods are useful, and how to avoid loss of friction problems. Some of the results are listed below. More in-depth information on this project, including project reports, field and laboratory data, photographs and results has been posted on the internet.([i])

Photo shows, as one example, the Minnesota 251 site during a light drizzle four years after fogging. The sealed section appears relatively impermeable to the water, whereas water is soaking into the adjacent unsealed area.

MN 251 Showing 4-Yr Old Fogged Section (back) Repelling Moisture during Light Rain Storm While Water is Penetrating into Unfogged Section (foreground)

([i]) Spray Applied Polymer Surface Seals. http://www.pavementpreservation.org/fogseals/index.htm. Accessed July 13, 2007.

On the Arizona project, the southbound control section which had been chip sealed with CRS-2P exhibited severe chip loss after four years, most likely due to snow plow damage. There was no visible chip loss on the test sections that had been fog sealed immediately, as shown in this photo.

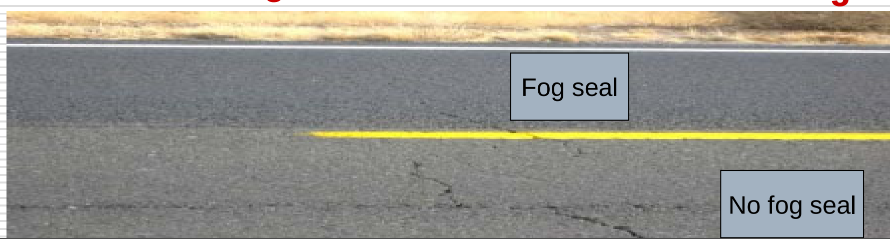

Can Fog Seals
Mitigate Block
Cracking?

Lessons Learned

Why Fog?
Prevent Damage from Asphalt Aging

Raveling

Block Cracking



The seals should be applied much earlier in a pavement's life if the conditions illustrated here are to be avoided.

Vallerga:

Age-Embrittlement

Conventional Wisdom:

Block cracking severity relates to falling ductility at 60ºF (15ºC)

- Loss of surface fines as ductility → 10cm
- Surface cracking starts as ductility → 5cm
- Serious block cracking as ductility → 3 cm

Ken Kandhal, "Low-Temperature Ductility in Relation to Pavement Performance", ASTM STP 628, 1977

Asphalt Oxidation Chemistry

The Products

Petersen, Mill, Greene

- **Oxidation Products**
  - Carbonyls form in three steps:
    - **Ketones**
    - **Carboxylic Acids, Aldehydes**
    - **Acid anhydrides**
  - Sulfoxides; Disulfoxides

For evolving rheology, carbonyls matter, sulfoxides don't!

What about further aromatization?

Asphalt Oxidation Chemistry

The Kinetics

Petersen, Van Gooswilligen, Mill, Glover

- **Oxidation Kinetics**
  - Temperature dependence
    - G* & Carbonyl follow Arrhenius (exp (1/T)
    - m-value – ??? (falls off a cliff)
  - Pressure dependence - exponential
  - Defined rate determining step
    - Bitumen, O_2, catalyst
  - Classic phenols inhibitors don't work
  - Identified reaction inhibitors (CN^-)

Auto-oxidation doesn't fit kinetics!

Asphalt Oxidation Chemistry

The Mechanisms

Petersen / Branthaver / Harnsberger, Beaver / King

- **Carbonyl Oxidation Mechanisms**
  - **Dual Mechanisms – 2 reaction rates**
    - one fast, but slows or stops with time
    - one slow, but continues indefinitely
  - **N-ETIO – Electron Transfer Mechanism**
    - Oxycyclics explain rate determining step, unusual carbonyl products (anhydrides), influence of catalysts
    - Initiated by triplet-to-singlet electron spin flip

Asphalt Oxidation

Predicting Performance

Global Aging Effects Model

- As developed for design guide (MEDG)
- Uses asphalt age-hardening approach by modeling high temp ή or G*

Mirza, M.W. and Witczak, M.W., "Development of a Global Aging System for Short- and Long-Term Aging of Asphalt Cements", AAPT, 1995

Asphalt Durability

Predicting Block Cracking

Challenge question:

Asphalt oxidation accelerates at high pavement temperatures, but does block cracking occur at lower temperatures?

If yes, why not use low temperature physical properties to predict block cracking?

Critique of Global Aging System:

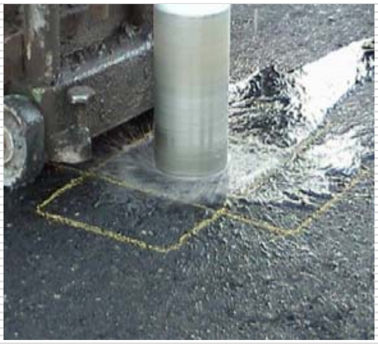
Christensen, D.W. and Bonaquist, R.F., "Volumetric Requirements for SuperPave Mix Design", NCHRP Report #567, TRB, 2006

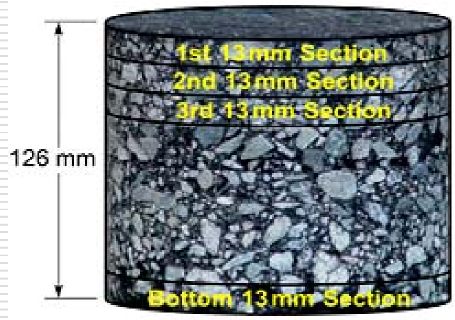
WRI Aging Study - Harnsberger
ARIZONA FIELD AGING

Hypothesis:

Asphalts from different crude oil sources will exhibit different field performance

ARIZONA VALIDATION SITE

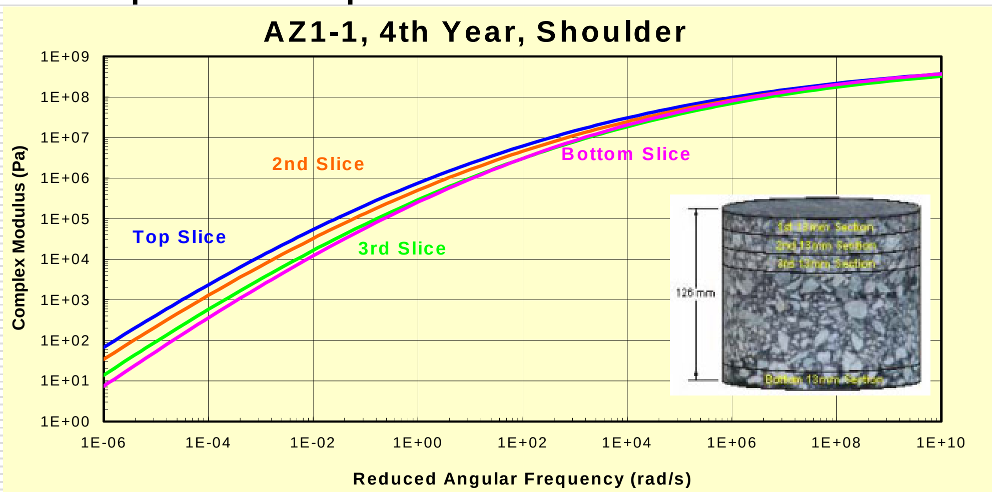




Constructed Nov. 2001
Shoulder cored Nov. 2005

2 – 63 mm lifts, 19-mm NMS dense graded aggregate, 4.7% AC)

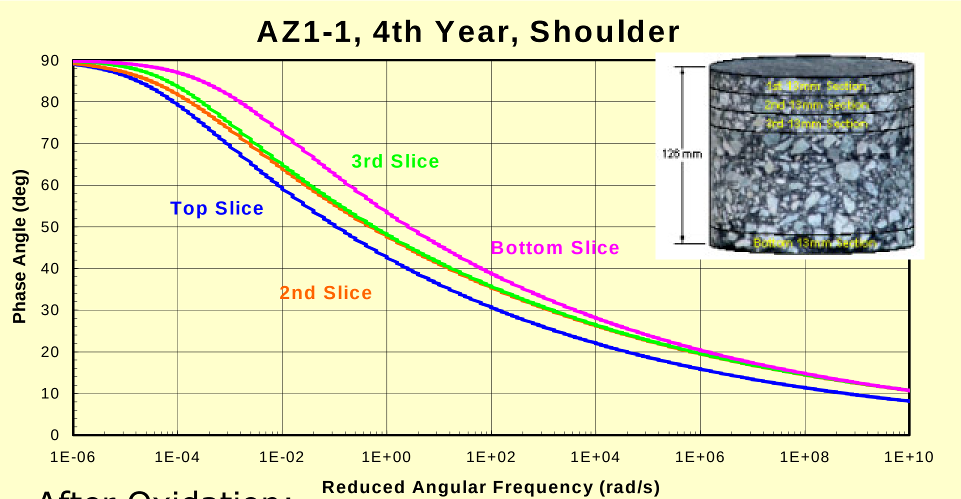
Effect Of Pavement Depth On Aged Asphalt Properties



After Oxidation:

Top slice > 2nd slice > 3rd slice > Bottom slice

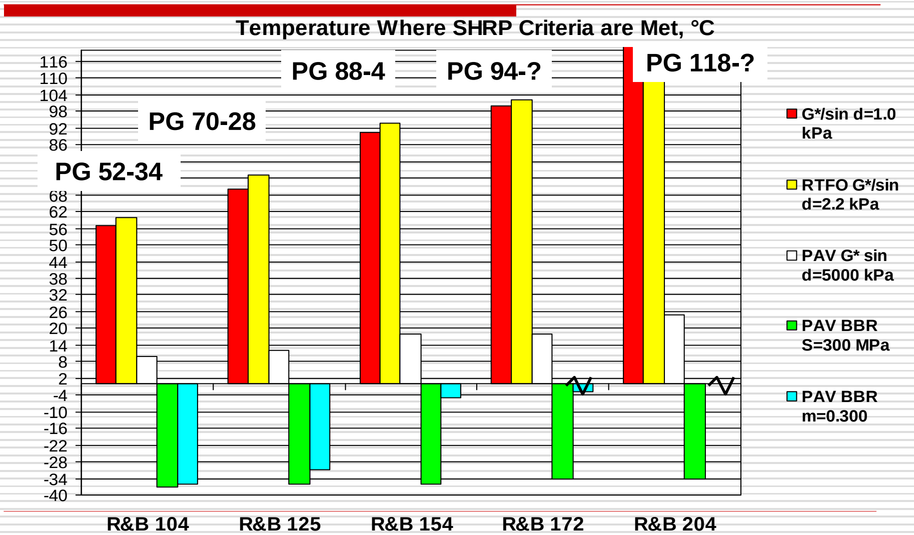
EFFECT OF PAVEMENT DEPTH ON AGED ASPHALT PROPERTIES



After Oxidation:

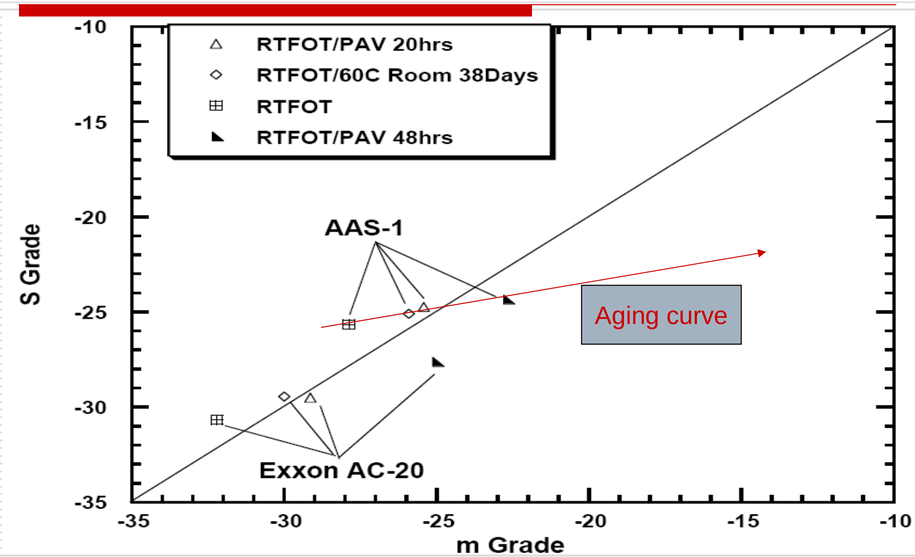
Top slice > 2nd slice > 3rd slice > Bottom slice

SuperPave Grading of Airblown AC



Increasing m-control with aging

for AAS-1 & Exxon AC-20 at Various Aging Times



Glover, et.al. FHWA/TX-05/1872-2

Lessons Learned

Fog Seal
Products

- **Sealer emulsions**
  - SS/CSS; CSS-1hP; Ralumac®
  - QS/CQS: LD-7®
  - RS/CRS; CRS-2Pd, HFE-100S
  - Gilsonite-based: GSB®-Modified

- **Rejuvenator emulsions**
  - Oils: ETR-1; ARA-1; Reclamite®
  - AC/Oil: Cyclogen®; ERA®
- **Hybrids**
  - PMAC/Oil: Pass QB®

Fog Seal and Rejuvenator Emulsion Products Used

Standard use water-based asphalt emulsions such as diluted SS-1 (Slow Setting emulsified asphalt) or CSS-1 (Cationic Slow Setting emulsified asphalt) are commonly used to "seal" and waterproof the pavement surface or to "bind" or "lock" cover material or fines in place reducing surface raveling. Suppliers have also developed emulsions specifically for fog seals. Rejuvenators are diluted water-based emulsions of oils designed to penetrate into the existing asphalt cement and modify and improve existing chemical and rheological properties.

The products used represented a cross-section of commercially available materials. The proprietary product descriptions below are given here to document and describe some of the types of products available as well as the specific materials used in this study. A list of all products on the market was developed at the beginning of the study ([i]), but old products are continually being discontinued and new products introduced.

Sealers

CSS-1h, CSS-1, CQS-1h and SS-1h The State Departments of Transportation were asked to use their standard fog seal emulsions. These emulsions met state or AASHTO M-140 (anionic) and M-208 (cationic) specifications.([ii])

CRS-2Pd Mn/DOT has actively expanded their fog sealing program since applying CSS-1h on the 2002 project. They believe that a manufacturer-diluted rapid-setting, polymer modified emulsion gives better results on chip seals. Therefore, CRS-2Pd emulsion (d for "diluted") was used in 2006. Other states also reported that they use polymer emulsions.

LD-7 was used on the 2006 Minnesota projects and developed as a fast-curing emulsion trackless tack coat, is also used to lock down aggregates on chip seals. Unique specifications call for a residue softening point greater than 152ºF.

GSB Sealer Binders Gilsonite-based emulsion GSB type B was reportedly used in 2002 on MN 251. GSB has been the subject of other research projects, including a Tennessee study. ([iii])

Rejuvenators

Pass®-QB quick-break emulsion system is designed specifically for fog seal applications, with an emulsion soap designed to penetrate small pores on the pavement surface. The residue contains asphalt, rejuvenator oil, and polychloroprene latex polymer.

Reclamite® Asphalt Preservative Seal is a cationic emulsion designed to penetrate and rejuvenate the top portion of the asphalt mix by fluxing with the binder. The specifications require a low residue asphaltene content (ASTM D-2006-70) of 0.4 to 0.75%.

ERA-1 and ERA-25 rejuvenator products represent different blends of asphalt with Reclamite base oil.

CRF® Restorative Seal is emulsion spray-applied by a distributor truck and sand spread over the surface. The surface is then drag-broomed to force sand into the voids and cracks.

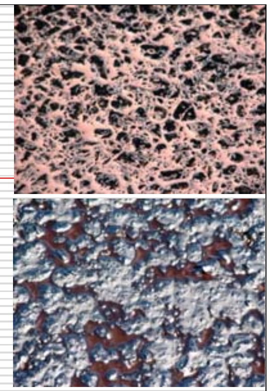
([i]) Product Listing of Sealers and Rejuvenators. http://www.pavementpreservation.org/fogseals/Project%20Library/Sealer_Rejuvenator_Products.pdf. Accessed July 16, 2007.

([ii]) AASHTO M-140 Emulsified Asphalt, AASHTO M-208 Cationic Emulsified Asphalt. AASHTO, 444 N Capitol St. NW, Washington, DC 20001.

([iii]) AASHTO Product Evaluation List. http://apel.transportation.org/programs/apel/products/evaluation.nsf/57556cf712a8c65b86256aa4002e4391/18130563b8550a7286256c2f006ace81?OpenDocument&Highlight=2,GSB. Accessed July 13, 2007.

Lessons Learned

Fog Seal
Product Selection



Curing rejuvenator (top) & fog (bottom) seals

- **Performance varies greatly**
  - Infiltration
  - Curing time to traffic
  - Effect on friction
  - Ability to soften existing binder
  - Tracking – Need for sanding
  - Dilution & Application rates
- **Product selection determined by:**
  - Surface type (dense, open, chip seal)
  - Project goal (sealing or rejuvenating)
- **Follow Supplier Recommendations!**

Spray Applied Binder Study

Testing Protocols

- **Pavement Field Testing**
  - Distress evaluation
  - Permeability/infiltration testing
  - Friction & texture measurement
  - Non-destructive testing for assessing when to apply treatments
- **Laboratory Testing**
  - Extracted binder chemical/rheological tests
  - Mixture tests on thin specimens (DSR, BBR)
  - Emulsion properties

The original plan called for tests of permeability, friction, surface texture, spectral wave analysis, chemical and physical properties of cores, roughness, texture, rut depth and noise characteristics. Based on early results and the constraints of the projects, the original test plan was modified. Some tests were discontinued, and others added as experimental findings dictated.

Cores were taken for laboratory testing at varying intervals from all the projects.

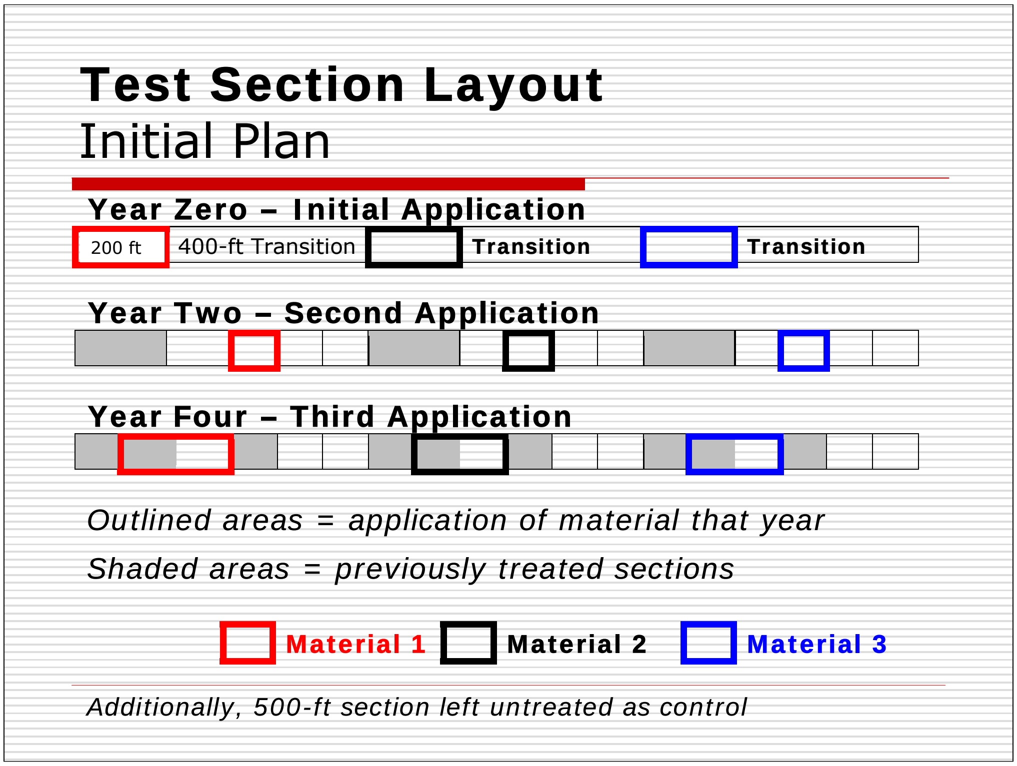
Friction and surface texture data were collected before construction and after one, 42 and 272 days on the early projects, and soon after construction on the 2006 projects. Photos and field observations were made on the Arizona, California SR78 and Minnesota SR251 projects in 2005.

THE FIELD TEST PLAN

Sealer/Rejuvenator Project Application Summaries

Arizona US 87 (Winslow, high desert, severe climate) Project Summary

Surface Application		9/12/2001 Application			10/19/2006
	gal/yd2Product	Mile Post	Product gal/yd2	Mile Post Sand	
AR-ACFC	372.562	Control	372.516		Control
Dense-Graded	Control	386.099		Control	386.146
Chip Seal	392.250	Control	392.203		Control
AR-ACFC	372.696	Pass QB 0.10	372.649	0.08	Pass QB
Dense-Graded	Pass QB 0.10	386.217	0.08	Pass QB	386.265
Chip Seal	392.031	Pass QB 0.06	392.000	0.08	Pass QB
AR-ACFC	372.829	Reclamite 0.10-0.12	372.781 2 lbs/ft2	0.08	Reclamite
Dense-Graded	Reclamite 0.07-0.09	386.348 2 lbs/ft2	0.08	Reclamite	386.367
Chip Seal	392.127	Reclamite 0.05	392.089	0.08 2 lbs/ft2	Reclamite
AR-ACFC	373.047	CSS-1h 0.08	373.047	0.08 2 lbs/ft2	CSS-1h
Dense-Graded	CSS-1h	386.712	0.08	CSS-1h	386.664



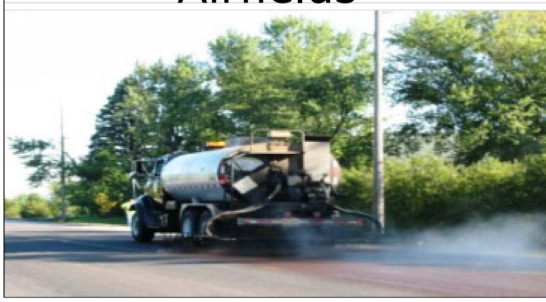
THE FIELD TEST PLAN

A test plan was laid out to apply test sections of several commercially available emulsions to a number of different pavement and climate types. The initial placement included 200-ft sections of the standard fog seal product used in that state as well as other products suppliers wished to include in the study. Several companies donated their materials, field support and application. 400-ft sections were left open between each section for future application, and there was at least one 500-ft control section left untreated in each project. The plan was to reapply sections of the same products on previously treated and untreated sections at two-year intervals with a variety of performance and material testing on the surface of and cores from test and control sections. Because of a change in leadership of the project, the unavailability of some products used for initial trials, and added testing of the effects on skid resistance of sanding on some of the sections, this plan was later altered.

Lessons Learned

Fog Seal
Where to Use?

- **Pavement Location**
  - Travel Lanes – Highways & Secondary
  - Shoulders
    - Color delineation for safety
  - Airfields



Several agencies reported they have reduced the need for shoulder reconstruction with a regular schedule of shoulder fog seals. If there is sufficient color contrast between the travel lane and shoulder, fog seals can also improve nighttime visibility. With no traffic, maintaining friction is much less critical. However, the surface does not densify as it would under traffic, so pavement permeability is typically higher. Therefore, emulsion application rates for shoulders are typically higher than those for adjacent travel lane.

Lessons Learned

Fog Seal

Where to Use?

- **Pavements in good condition**
  - Preferred:
    - Good friction & surface texture
    - No visible damage
    - AC/HMA rheology – before becoming too brittle; approaching critical “m” value
  - Acceptable:
    - Slight raveling or loss of surface fines
    - Minor surface cracking

Avoid “Worst First” --- Think Preservation!

Emulsified sealers and rejuvenators are best used as preventive maintenance treatments on pavements in good condition, but with surfaces that have begun the aging process. They can be used on any asphalt pavement that has sufficient permeability to allow emulsion infiltration, but traffic should be controlled until the seals have fully cured and friction numbers are restored to acceptable levels. Sanding generally improves early friction, as long as loose sand is removed before full speed traffic is restored.

Fog seals should not be used when a pavement has poor surface texture, large cracks, rutting, shoving, structural deficiencies or low friction numbers. The Minnesota SR251 project included crack sealing of thermal cracks a few months after the fog seal had been applied. When applied at the right time, the emulsified seals generally exhibited fewer new cracks than control sections.

Lessons Learned

Fog Seal

Where NOT to Use?

- **Pavements in poor condition**
  - Significant visible distress
    - Flushing
    - Large Cracks
    - Rutting, Shoving, Permanent Deformation
    - Structural Deficiencies
  - Low friction
- **Impermeable HMA**

Emulsified sealers and rejuvenators are best used as preventive maintenance treatments on pavements in good condition, but with surfaces that have begun the aging process. They can be used on any asphalt pavement that has sufficient permeability to allow emulsion infiltration, but traffic should be controlled until the seals have fully cured and friction numbers are restored to acceptable levels. Sanding generally improves early friction, as long as loose sand is removed before full speed traffic is restored.

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Lessons Learned

Fog Seal

When to Use?

- **Pavement Age**
  - Seal newer pavements
  - Rejuvenate age-embrittled pavements
- **Permeability Enables Infiltration**
  - Mix design (coarse, fine, open, SMA)
  - Construction density
  - Densification under traffic

When to Use Fog and Rejuvenator Seals

One goal of the study is to determine the timing of sealing applications. The DOT survey showed that many agencies have a scheduled fog seal application program for preventive maintenance that begins between two and ten years after HMA construction, and some routinely use spray applied seals immediately after chip sealing.

Observations of four-year old seals in this study showed that most materials exhibited minimal visible color difference between sealed and control sections because most asphalt residue had worn off of the surface aggregate. However, the water, raveling and cracking protection still appeared to be intact. While the most accurate approach would be a test parameter for determining when to reseal, the required testing is not practical for most agencies. Once aging models and product performance criteria are understood, it should not be difficult to establish timing models that require minimal testing for verification. A scheduled interval based on the climate, traffic and surface type of "every x years or observation of minor distress, whichever comes first" may be the best strategy. Possible triggers for sealing or resealing might include: very small surface cracks, permeability above a specified level, raveling, loss of fines or mastic from the surface, or rheological (DSR and/or BBR) tests indicating excessive age hardening. Older conventional wisdom suggests that surface pitting and raveling begins when binder ductility measured at 15ºC falls below 10 cm, and block cracking begins when the ductility reaches 5 cm.

Even if a simple timing approach is adopted, pavement permeability will remain a critical variable. If emulsions do not infiltrate into the surface, friction may be a problem and performance will not be satisfactory, resulting in accidents and potential disuse of spray applied seals. Field or lab permeability tests, infiltration tests such at the ring test (12), pour tests, or short trial sections on the pavement may be used. A more aggressive alternative might be a performance test for friction upon release to traffic or following a prescribed curing period, preferably based on a pre-project test strip. Caltrans recently funded research to be led by Dr. Gary Hicks at the regional Pavement Preservation Technical Center at Chico State which will deliver a performance specification for fog seals, including friction requirements.

Lessons Learned

Fog Seal

How to Use?

- **Emulsion grade and application rates vary with pavement surface type!**

Dense HMA

OGFC or Asphalt-Rubber

Chip Seal

Emulsified sealers and rejuvenators are best used as preventive maintenance treatments on pavements in good condition, but with surfaces that have begun the aging process. They can be used on any asphalt pavement that has sufficient permeability to allow emulsion infiltration, but traffic should be controlled until the seals have fully cured and friction numbers are restored to acceptable levels. Sanding generally improves early friction, as long as loose sand is removed before full speed traffic is restored.

Fog seals should not be used when a pavement has poor surface texture, large cracks, rutting, shoving, structural deficiencies or low friction numbers. The Minnesota SR251 project included crack sealing of thermal cracks a few months after the fog seal had been applied. When applied at the right time, the emulsified seals generally exhibited fewer new cracks than control sections.

Fog Seal

Dense HMAC

- **Objectives:**
  - **Reduce infiltration of moisture & oxygen**
  - **Rejuvenate oxidized asphalt**
  - **Prevent raveling**
  - **Seal small cracks and surface voids**

Don’t lose skid resistance!

Fog Seal
Emulsion Products for Dense HMA

- **Rejuvenator emulsions:**
  - Rejuvenator oils – Reclamite®, ETR-1, ARA
  - AC/rejuvenator blends - Cyclogen®
  - PMAC/rejuvenator oils – Pass QB®
- **Sealer emulsions:**
  - Dilute SS/CSS
  - Dilute QS/CQS
  - Specialty emulsions
    - LD-7®- GSB®

Lessons Learned

Fog Seal
OGFC

- **Objective:** Recoat aggregate or rejuvenate aged asphalt to reduce raveling
- **Emulsion grades:**
  - SS/CSS
  - CRS-2P/HFRS-2P
  - CQS/Micro-surfacing emulsion
  - PMA/rejuvenator oil blends

- **Caution: Maintain permeability!**

There is a renewed interest in open-graded friction courses (OGFC) and open asphalt rubber mixes to reduce back-spray in wet weather and reduce tire noise. Fog seals have prevented raveling problems traditionally associated with aging open-graded mixes. New Mexico successfully maintains many miles of OGFC with a scheduled fog seal program, usually using dilute polymer modified emulsions. The U.S. 87 project near Winslow, Arizona and the California 78 project included asphalt rubber sections. When developing a maintenance strategy for these open-graded mixes, it is important to maintain sufficient air voids for adequate drainage. Spraying too much binder or applying fog seals which trap large amounts of dust and blow sand in the aggregate matrix may eventually create problems.

Lessons Learned

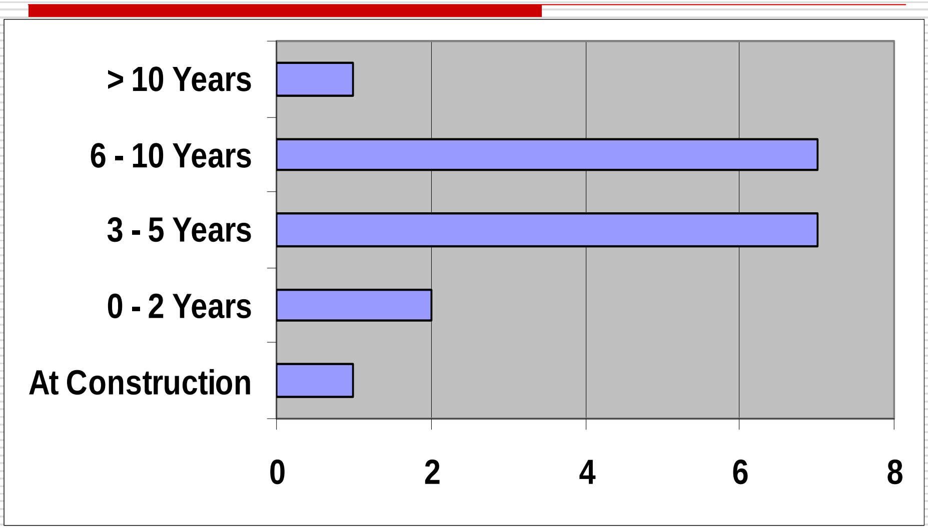
Fog Seal over Chip Seal

- **Objectives:**
  - Suppress dust
  - Tie down loose rock
    - Reduce windshield damage
    - Reduce chip loss / snow plow damage
  - Appearance: Black like hot mix!
- **Emulsion Grades:**
  - SS/CSS
  - CRS/RS/HFRS
  - Polymer-modified emulsions

Some agencies, especially Mn/DOT, have had success with fog sealing new chip seals. The projects in Arizona (Winslow) and Minnesota (Maple Island) included chip seal sections. The fog seal controls dust, ties down the chips, and gives a black surface. The fog seal reduces the likelihood of shelling and also protects the seal against snow plow damage, as reported by Mn/DOT experience. The black surface improves visibility and public acceptance. When fogging chip seals, proper embedment requires a given volume of asphalt, whether applied before or after the aggregate is spread. Chip seal designs should be respected by reducing the initial shot rate accordingly.

As a side observation, the value of chip seal as a protective coating to reduce the rate of asphalt aging was also verified. On the MN 251 project, the modulus of the HMA surface mix immediately below the chip seal was similar to the rejuvenated section after two and four years in service. The heavy binder application appears to seal the pavement to both oxygen and moisture

DOT Survey
Pavement Age When Fog Seals Applied



Lessons Learned

How to Apply Seals

- **Distributor: well calibrated**
  - Correct nozzles, angle, no clogs
  - Spray bar height, pattern, speed
  - Test strip recommended
- **Application rates – depend on surface & product**
  - Even, full coverage to protect
  - No excess material to track, cause skid problems
  - Experience, supplier recommendations

Application Procedures

As with any paving project, the treatment is most effective when placed using good construction practices. The Foundation for Pavement Preservation and FHWA have developed an excellent checklist. ([i]) From the field trial experiences, it is strongly recommended that a test strip be a pay item to help determine the correct application rate and expectations for curing time to traffic (friction), as well as ensuring proper equipment operation and calibration.

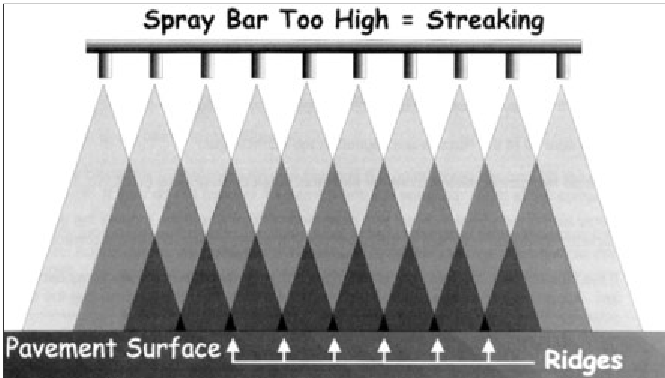
Equipment

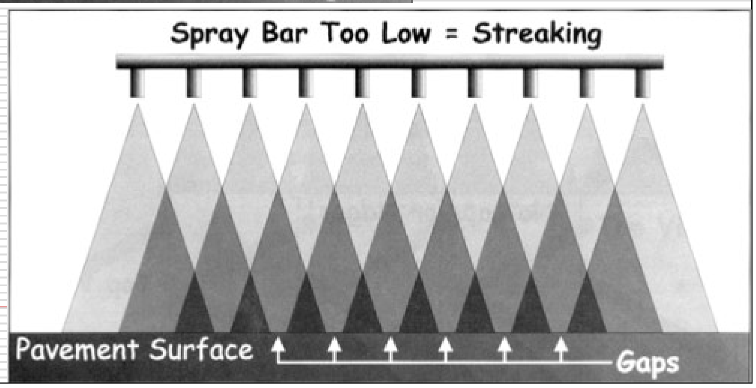
Asphalt distributors from a number of manufacturers were used on the field projects. When correctly calibrated for light emulsion application, all gave good results. However, a number of adjustments were made during the trials. Fog seals have much lower application rates than chip seals, but a complete, uniform coverage is necessary for proper sealing. The primary cause of poor fog seal construction is improper nozzles--the right type, angle, spray pattern and no clogged nozzles. The height of the spray bar and bar pressure determines the spray pattern, so that should be properly adjusted. Recommendations for equipment settings and calibration published by the Asphalt Emulsion Manufacturers Association (1) or equipment manufacturers describe industry best practices.

Application Rates

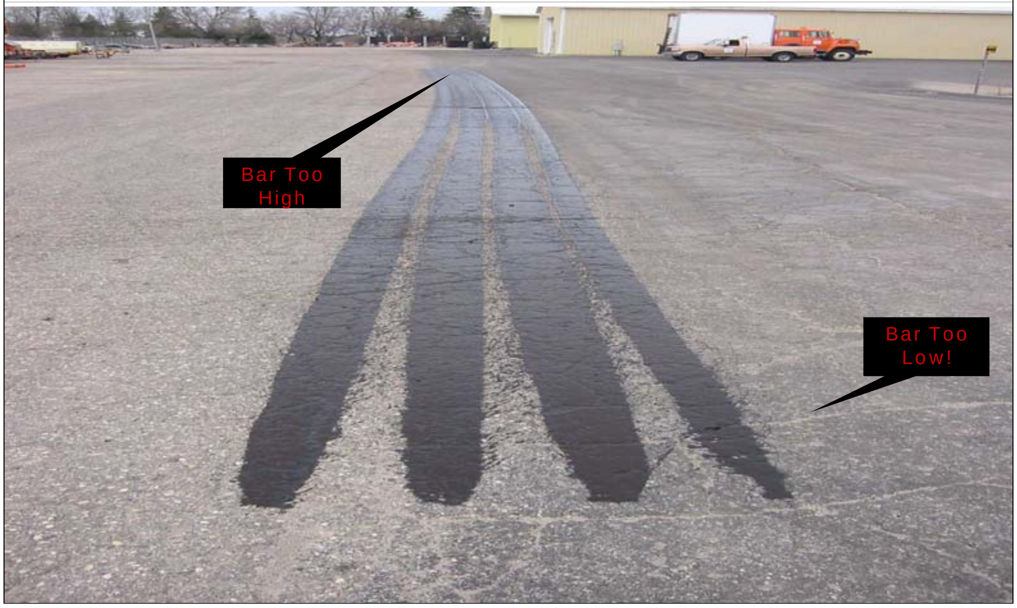
There were a number of different materials used in this study, with application rates varying from 0.06 to 0.15 gal/yd2. Emulsion residue contents and dilution ratios also varied markedly. Application rates, costs, and performance should be compared at comparable applied emulsion residue content. The suppliers generally had the best knowledge of their products, and should therefore be consulted for the correct range of shot rates for the surface to be treated.

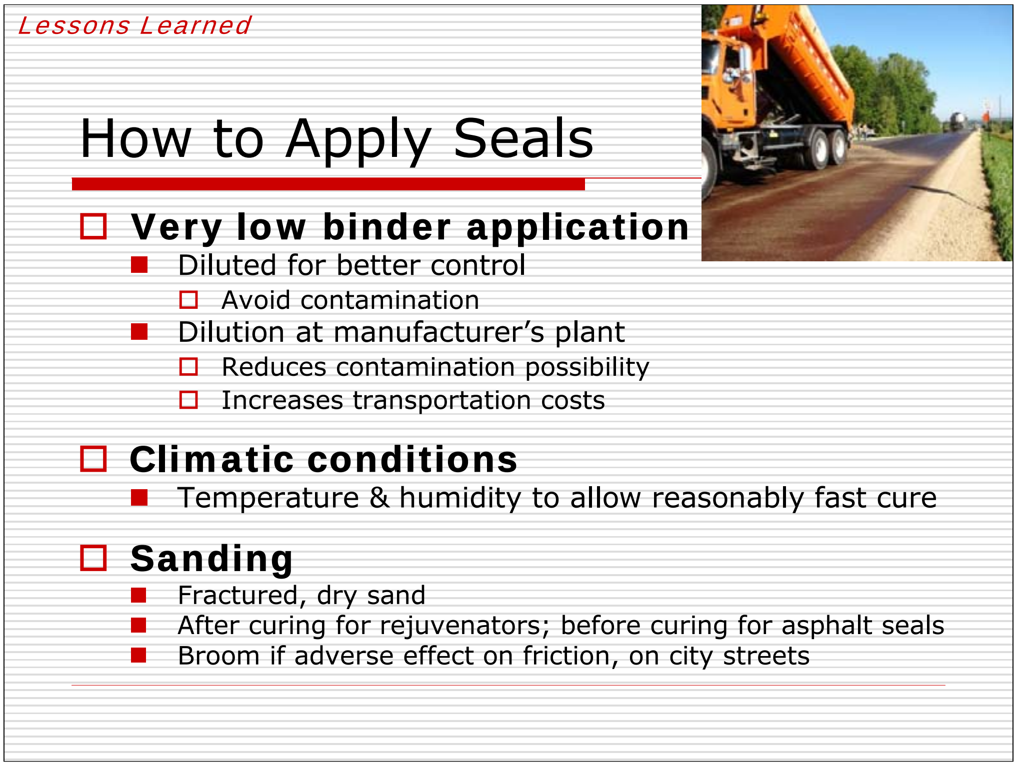
([i]) Pavement Preservation Checklist Series: Fog Seal Application. *Publication No. FHWA-IF-03-001*, Washington D.C., September 2002.


Spray Bar Too High = Streaking
Pavement Surface
Ridges


Spray Bar Too Low = Streaking
Pavement Surface
Gaps

Bar Height





Dilution

While at least one agency strongly recommends dilution of the emulsions at the manufacturer’s location to avoid over- or under-dilution and introduction of impurities than can break the emulsion or otherwise harm the performance, some manufacturers believe that transportation and mobilization costs can be saved by diluting on-site—with careful control of the dilution method, rate and water/solution.

Climatic Conditions

Because of knowledge of the success of local projects, agency and supplier recommendations for surface and air temperature should be strictly followed. At least one project was delayed to avoid run-off of uncured materials by an imminent rain.

Sanding

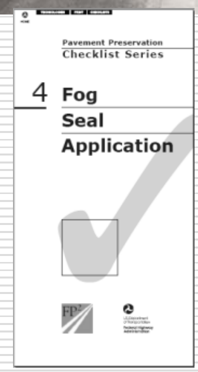
Sanding on the 2006 projects showed an immediate increase in friction. (The manufacturers of some of the rejuvenator products recommend sanding because of an oily coating on aggregate surfaces. In this study, the rejuvenators did best when sanded after they were allowed to infiltrate the surface. The stiffer asphalt emulsions did better when the sand was applied before the emulsion was fully broken. Some of the manufacturers say that sanding is not needed, and that was the case in this study, especially on the chip seals and more open surfaces. The application rate and type of sand are also factors to be considered. When sand is applied, it is recommended that a high quality, crushed sand with adequate fine aggregate angularity (FAA) be used to give the desired friction numbers. The sand should also be sufficiently small to prevent damage to windshields and relatively dry to avoid slowing cure. For specifications, a saturated surface dry condition is probably the maximum amount of moisture that should be allowed.

Loose sand can itself cause a loss in friction, so it should be broomed. Sand also creates clean-up problems for curb-and-gutter or other urban applications where surface water drains might be plugged. Hence, some agencies prefer sand be avoided. Sanding is not necessary for some products. The supplier's recommendations should be followed.

Lessons Learned

How to Apply Seals

- **Traffic control**
  - Pilot car, slow speed until friction returns to acceptable level
- **Test strip recommended**
  - For correct application rate
  - For equipment calibration
  - For traffic-return time
  - For no friction or tracking surprises
- **FHWA / FP² checklist**
  - http://www.pavementpreservation.org/fogseals/Bibliography/FHWA-FPP_Fog_Seal_Checklist.pdf



Traffic Control

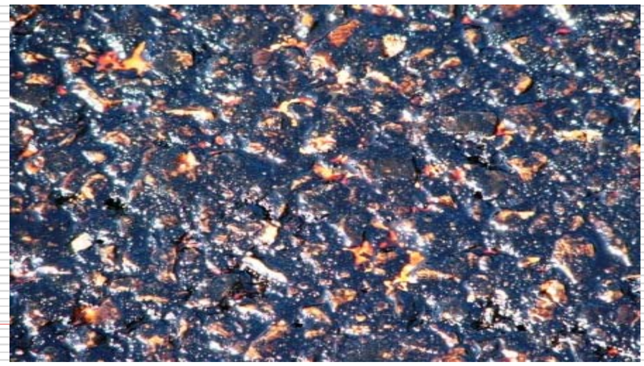
A test strip will be helpful in determining cure time and safe traffic return. Because of reduced friction and possible material tracking, strict traffic control with pilot cars is strongly recommended until the friction is at an acceptable level.

The checklist is also available from the National Center for Pavement Preservation and from FHWA Office of Asset Management.

Lessons Learned

Controlling Friction

- **If emulsion does not infiltrate a dense HMA, residue left on the surface significantly reduces friction.**

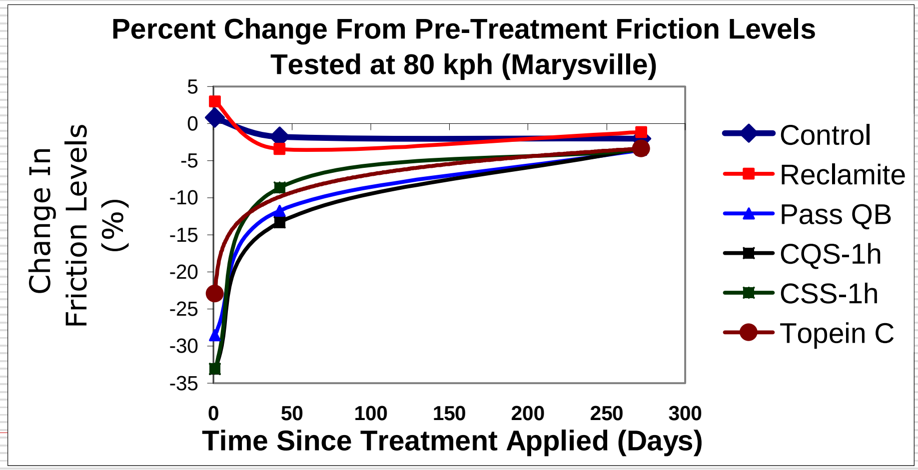


The surfaces of the rejuvenator sections were noticeably slippery, especially over very dense surfaces. Sanding mitigated the problem.

Lessons Learned

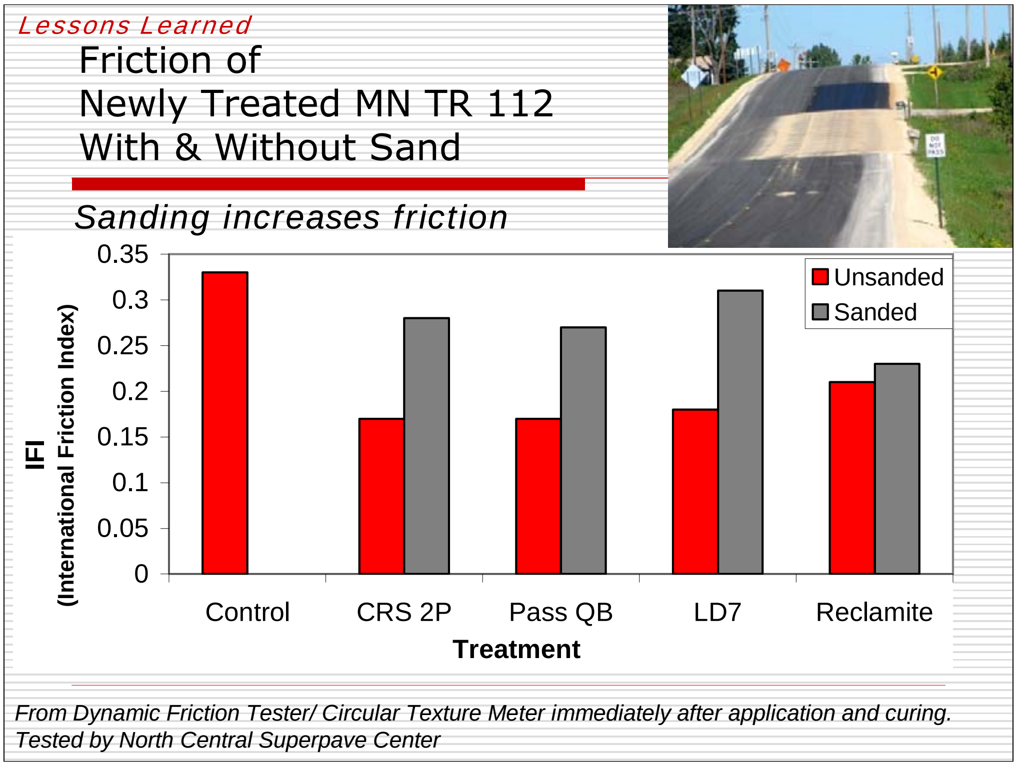
Fog Seal on Dense Surfaces
Effect on Skid Resistance

Friction initially reduced, but returns to original level with time



Change in Friction from Pre-Treatment Levels

The surface friction was generally lowered immediately after construction, but was regained with time. The graph shows the change in friction number over time on the I-5 Marysville, California project. The other projects had similar results. Because of the initial drop in friction, it is recommended that traffic be strictly controlled with pilot cars until the friction index reaches an acceptable level, especially on high speed highways. A fatal accident following improper application of an undiluted rejuvenator emulsion forced Caltrans to place a moratorium on the use of fog seals.



Friction of Newly Treated MN TR 112 With and Without Sanding

Sanding strategies should depend upon the emulsion residue rheology. The rejuvenator supplier recommended waiting twenty to forty minutes before sanding to avoid leaving oil-saturated sand on the surface. With harder residue emulsions, the sand was applied immediately after fogging, creating more surface texture. The graph shows that sanding greatly improved the early friction for all sealed sections, but did not quite achieve the pre-treatment level.

Fog Seal

Field Test Methods

- Pavement permeability
- Emulsion infiltration
- Surface modulus
- Surface texture
- Friction

FIELD AND LABORATORY TESTING

The original plan called for tests of permeability, friction, surface texture, spectral wave analysis, chemical and physical properties of cores, roughness, texture, rut depth and noise characteristics. Based on early results and the constraints of the projects, the original test plan was modified. Some tests were discontinued, and others added as experimental findings dictated. Numerous field and laboratory tests were evaluated in this study. The full results will be posted on the project website. ([i])

Because of the importance of surface friction to the usability of such seals, the researchers felt it was important to have an easy-to-run, on-site friction test. After preliminary testing, the portable Circular Texture Meter (CTM) ASTM E-2157 and Dynamic Friction Tester (DFT) ASTM E-1911 were selected for use on all the test sections. Some sites were also tested with a conventional skid trailer following ASTM E-274, Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire. Dr. Soheil Nazarian of the University of Texas at El Paso ran Portable Seismic Pavement Analyzer (PSPA) testing to monitor short term change in the modulus on three of the initial projects.

([i]) Spray Applied Polymer Surface Seals: Tests and Specs. http://www.pavementpreservation.org/fogseals/Pages/Tests_&_Specs.htm. Accessed July 16, 2007.

Lessons Learned

Pavement Permeability
Emulsion Infiltration

- **Pavement permeability**
  - Pre-seal – Will emulsion infiltrate surface?
    - Impacts emulsion application rate
    - Effectiveness of seal
  - Post-seal - Will seal protect the surface from moisture & air infiltration?
    - Performance over time
- **Emulsion infiltration**
  - Particle size, surface tension, viscosity
    - Impacts emulsion application rate
    - Effectiveness of sealer / rejuvenator
    - Ideal penetration depth: ½" for dense HMA

To be effective, fog seal emulsions must infiltrate into the pavement surface. It was hoped that permeability would be a key measure for both determining application rate of sealers and their effectiveness over time. While there is probably an ideal emulsion viscosity for adequate film thickness and infiltration into a pavement, the surface tension of the emulsion is a better indicator of the ability of the emulsion to infiltrate the surface. Because this testing was initiated very late in the study, there was insufficient data collected to reach definitive conclusions about optimal surface tension. Similarly, the particle size of the emulsion should equate with its ability to enter small pores in the pavement surface. Emulsified rejuvenator oil particles should be easier to deform and enter pores than higher viscosity asphalt droplets. However, only limited particle size data was collected for this study.

However, results from the field permeameter (NCAT) were difficult to obtain on highly permeable surfaces like CR 112, because of incomplete sealing. Laboratory permeability on field cores may be a better measure for predicting emulsion infiltration, and for evaluating the finished seal's ability to keep water out of the pavement.

Lessons Learned

Fog Seal

Emulsion Infiltration Test

- **Ring Test –** *a bit subjective, but useful*

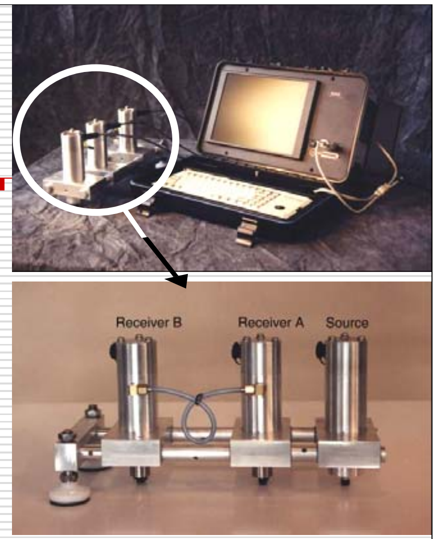
The Ring Test is subjective, but gives a quick and easy indication of the relative ability of emulsions to infiltrate into a pavement surface.

Method Of Test For Determining The Quantity Of Asphalt Rejuvenating Agent Required For An Asphaltic Pavement.
http://www.dot.ca.gov/hq/esc/ctms/CT_345.pdf. Accessed July 14, 2007.

Lessons Learned

Fog Seal Surface Modulus

- **Spectral Wave Analysis with Portable Seismic Pavement Analyzer (PSPA)**



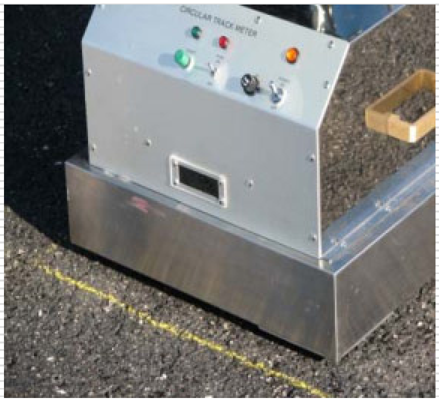
Results showed instrument not sensitive enough to detect differences in top 0.3” of pavement

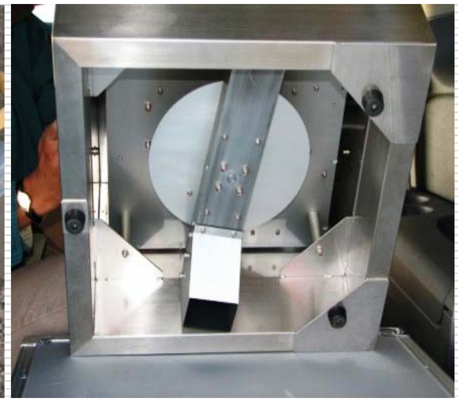
Testing by UTEP

The results from the Spectral Wave Analysis with Portable Seismic Pavement Analyzer (PSPA) indicated that the change in modulus between depths of 1 in. (which is the upper resolution of the device) to 4 in. was either small or insignificant. The rheological tests on the cores run at WRI and MTE indicate that 1 in. is too deep to capture the strongest aging effects. Furthermore, the fog seal emulsions rarely infiltrate into the pavement more than 0.5 in. Therefore, use of this device was abandoned early in the project.

Fog Seal
Pavement Friction

- **Circular Texture Meter ASTM E-2157**



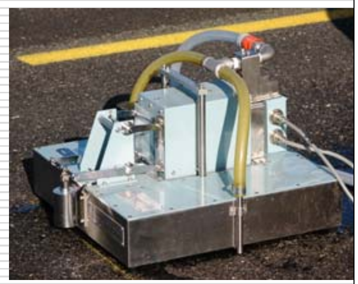


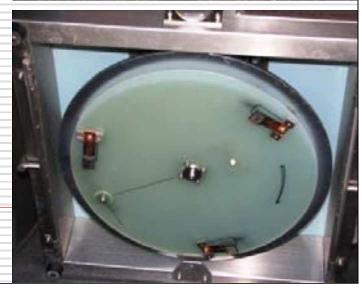
Portable, easy-to-use, repeatable

Lessons Learned

Fog Seal
Friction & Texture Testing

- **Dynamic Friction Test ASTM E-1911**
  - Good Repeatability
    - 3 replicates OK
  - Calculate IFI
    - Friction & Texture
    - Reasonable correlation with skid trailers

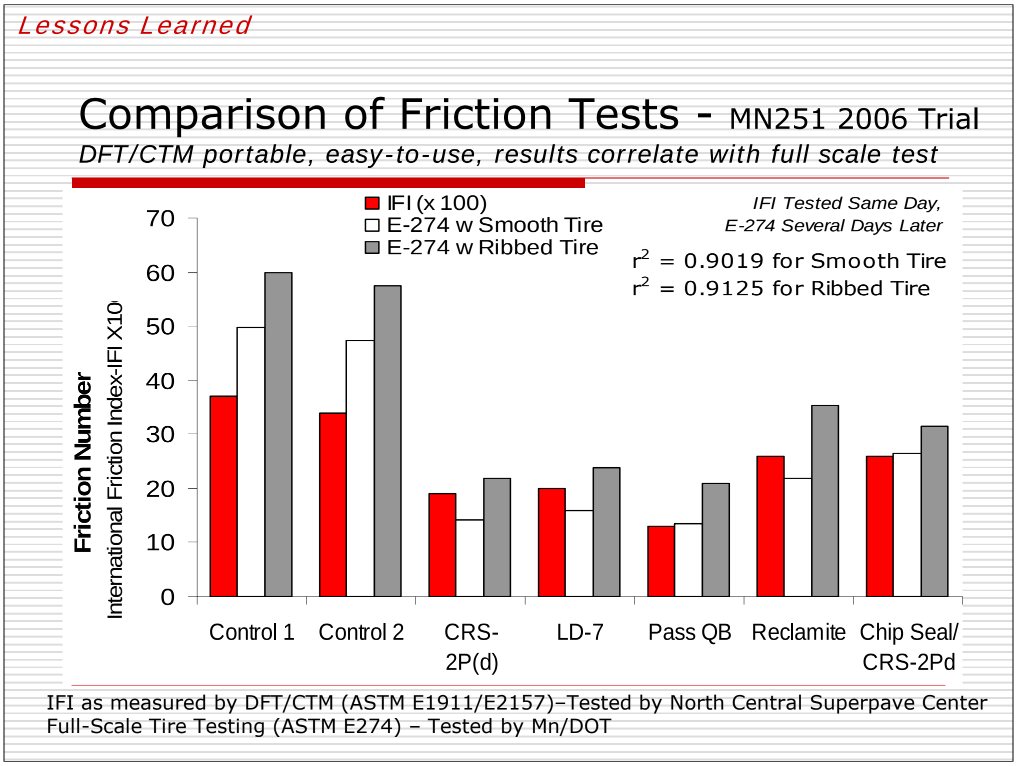




Portable, easy-to-use

Field friction testing (International Friction Index from the DFT and CTM) was repeatable, and the results consistent. Initial testing included six individual runs of each test per test section. Because of good repeatability, this was reduced to three repeatable runs. Loose sand must be swept before running DFT and CTM tests, or it will increase apparent surface texture, giving erroneously high calculated IFI measurements.

Circular Texture Meter (CT Meter) ASTM E-2157 and Dynamic Friction Tester (DFT) ASTM E-1911



The portable devices gave similar rankings but different absolute friction numbers than standard trailer testing (ASTM E-274), as shown in the graph. SR 251 is an aging dense-graded surface (except for the chip seal section).

Fog Seal
Lab Test Methods

- **Extracted binder rheology**
  - DSR
  - Low temperature characterization – BBR, DTT
- **Mixture tests on thin surface specimens**
  - DSR torsion (time to 5% strain) - MTE
  - BBR S & m-value – (500 g load) - UMinn
- **Lab permeability of pavement cores -** NCSC
- **Fog Seal emulsion properties**
  - Viscosity, surface tension, particle size – AKZO
- **Emulsion residue properties**

Cores were taken at various intervals from some of the projects and sent to Dr. Mike Harnsberger of the Western Research Institute (WRI) for extraction for chemical and rheological testing. Before testing, the cores were cut into horizontal slices to determine the properties at varying depths in the pavement. Core samples were also sent to Gerald Reinke at Mathy Technology & Engineering Services, Inc. (MTE) for rheological testing on the mix slices, to Dr. Becky McDaniel and Ayesha Shah of the North Central Superpave Center for permeability testing, and to Dr. Mihai Marasteanu of the University of Minnesota for a newly developed Static Bending Test on rectangular specimens cut from field cores using the Bending Beam Rheometer (BBR). 2006 project emulsion samples were sent by the suppliers to Dr. Alan James of Akzo-Nobel Surface Chemistry LLC for surface tension and particle size testing.

Lessons Learned

Fog Seal

Binder Properties

- **Binder Extraction**
  - Toluene/95% Ethanol
- **Binder Rheology**
  - DSR; G*, phase angle, MSCR
  - BBR: S, “m-value”, physical hardening
- **Binder Chemistry**
  - Infrared spectroscopy (IR) - carbonyl
  - Nuclear magnetic resonance (NMR) - branching
  - Differential scanning calorimetry (DSC)– wax
  - Elemental analysis – chemical fingerprint
  - HPLC - EH&S issues
  - Rostler, Corbett, asphaltenes

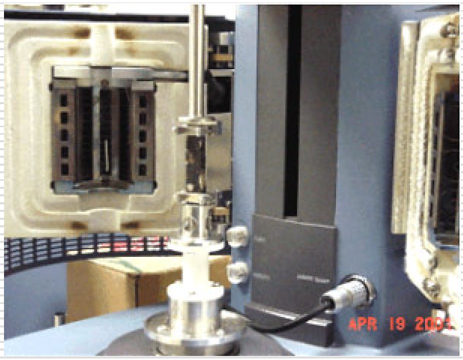
Test results: characterizations did not relate much to performance

The Western Research Institute ran several chemical analyses on products used for the initial trials. From the field trial results, physical performance testing of mix properties appears to give more reliable information regarding rejuvenator effectiveness than the chemical or physical testing of extracted binders.

Lessons Learned

Fog Seal
Surface Modulus

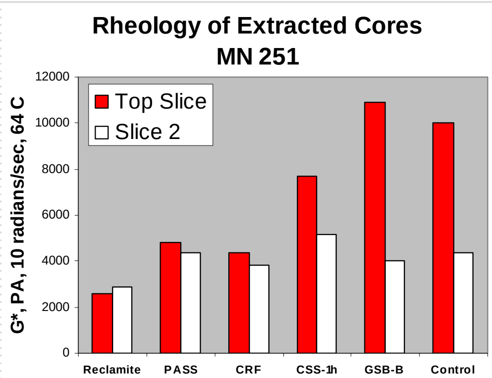
- **Dynamic Creep (DSR Torsion)**



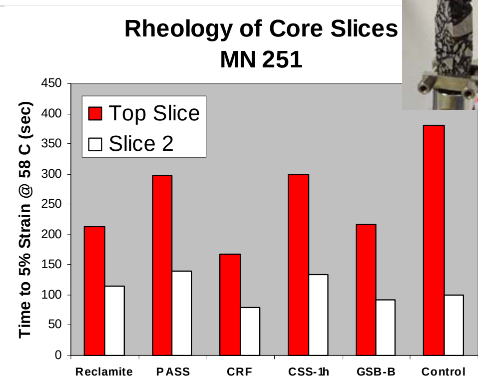
The MTE Dynamic Creep Test on Rectangular Specimens from Field Cores (DSR) following Reinke's protocol ([i]) has significant variability when testing single thin-sliced specimens cut from the pavement surface, but multiple replicates gave a clearer picture.

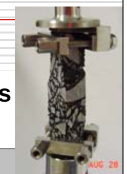
([i])Reinke,G, Glidden,S, Herlitzka,D, and Jorgenson,J. Laboratory Investigation of HMA Performance Using Hamburg Wheel Tracking and DSR Torsional Creep Tests. *ASTM Digital Library*, Volume 2, Issue 10, November 2005. http://journalsip.astm.org/JOURNALS/JAI/TOC/JAI2102005.htm. Accessed July 2007.

Rheology Testing of Field Samples



Tested by Western Research Institute
Dynamic Shear Rheometry on Liquid Samples Extracted from Field Cores (DSR)



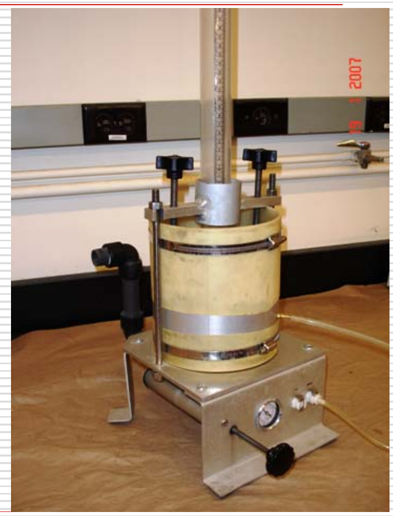


Tested by Mathy Technology & Engineering Services, Inc.
Dynamic Creep Test on Rectangular Specimens from Field Cores (DSR)

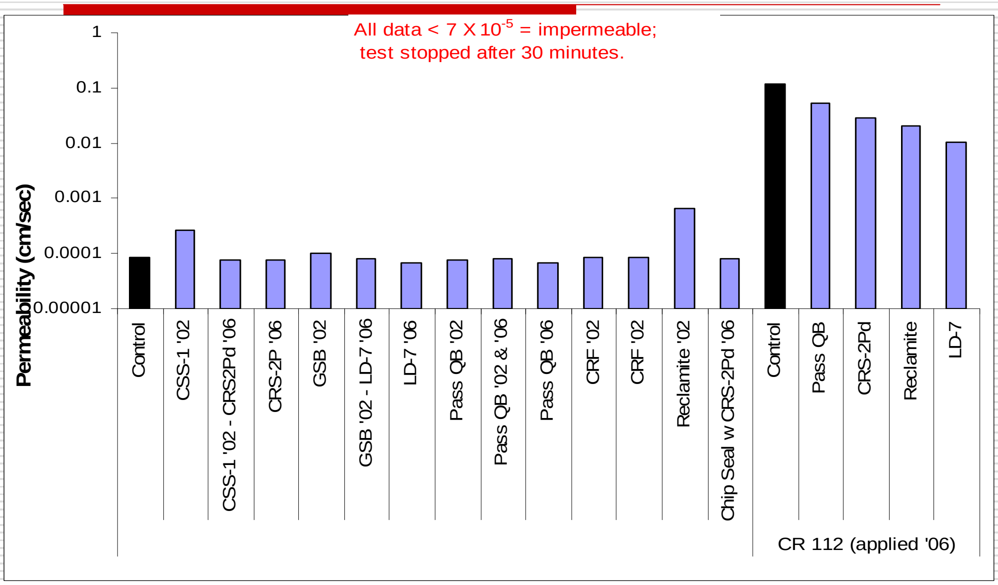
MN TH 251 Project - Dense-Graded, Impermeable Surface
Tests on binder from extracted cores by WRI, Tests on mix slices from cores by MTE

Fog Seal

Lab Permeability



Permeabilities – MN 251 & OCR 112



Lessons Learned

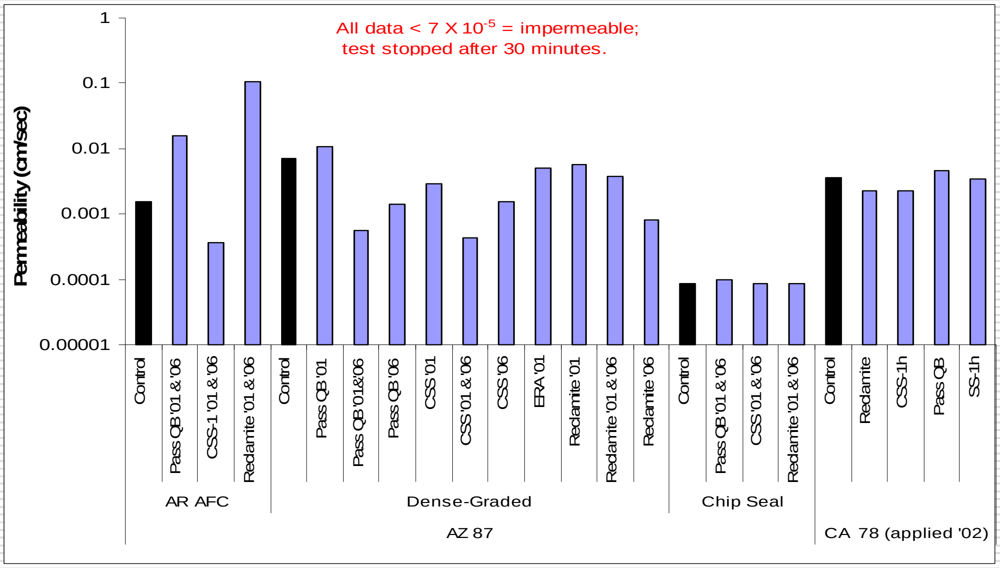
Fog Seal

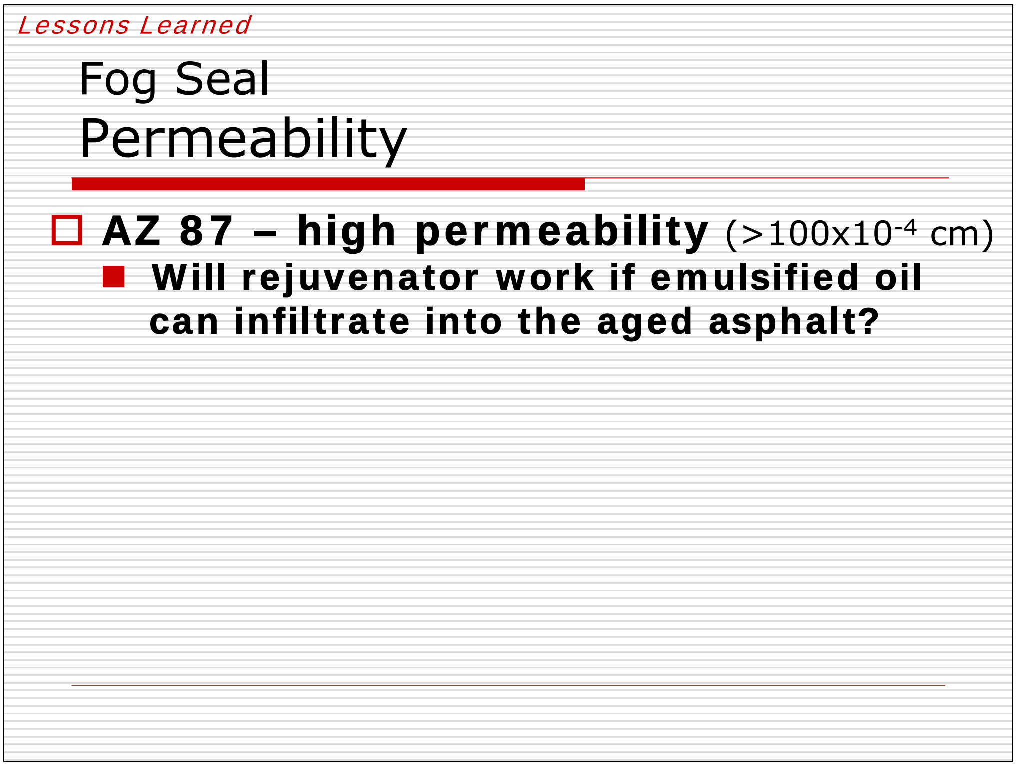
Permeability

- **MN 251 – low permeability** (<1x10^{-4} cm)
  - Emulsions did not infiltrate the surface
  - Binder extracted from top 1/2" indicates softening, but mixture tests do not confirm beneficial effect.
- **OCR 112 – high permeability** (1000x10^{-4} cm/sec)
  - **Fog seal emulsions reduced permeability up to 90%**
  - **But sealed pavement was still 100 times more permeable than MN 251 surface.**

These results seemed puzzling until lab permeability results for this pavement were found to be essentially zero. Clearly, rejuvenator oils could not infiltrate to soften oxidized asphalt near the surface. Only direct mixture testing could accurately characterize the mixture in the zone where block crack initiation is likely to occur. Fortunately, results for rejuvenator seals applied to the more permeable Arizona dense mix were much more in line with expectations that rejuvenator seals can soften aged asphalt. Here, the Reclamite rejuvenator emulsion did soften the pavement surface layer as would have been predicted by the binder extraction. In fact, the rejuvenated binder was even softer than the second thin pavement layer in both cases. As expected, the harder emulsion residues in the sealer products had much less impact on the rheology of the surface layer, although they do appear to help retard oxidation when applied to the right pavements at the right time.

Permeabilities for AZ & CA





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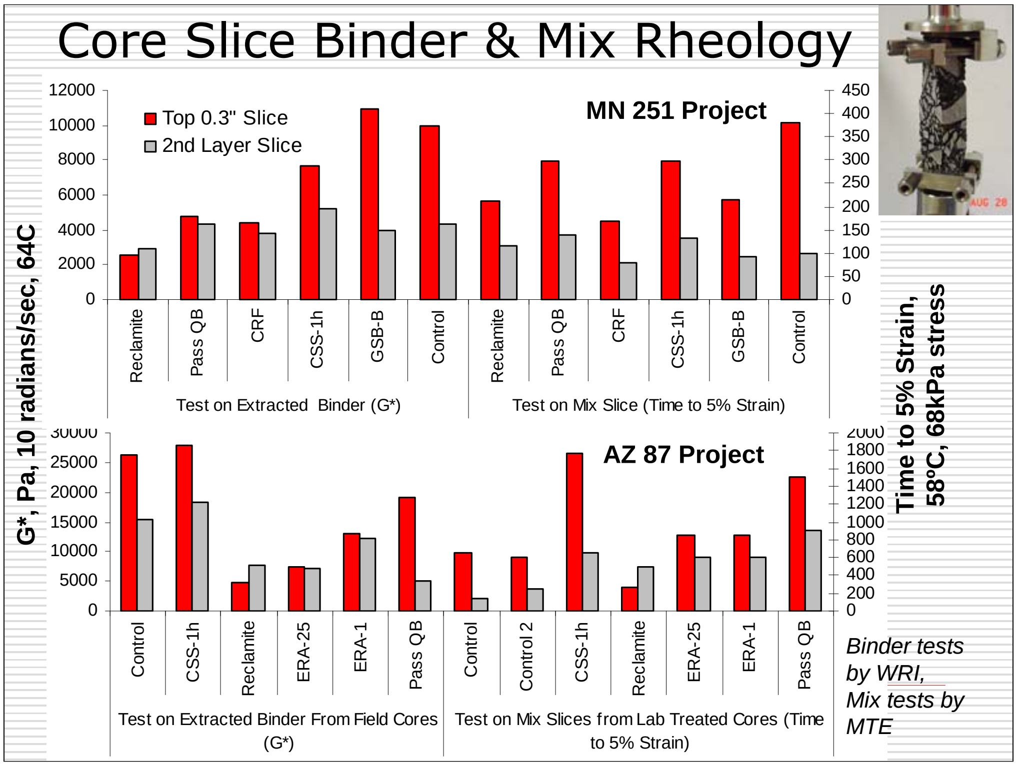

Core Slice Binder & Mix Rheology
MN 251 Project
Top 0.3" Slice
2nd Layer Slice
Reclamite
Pass QB
CRF
CSS-1h
GSB-B
Control
Test on Extracted Binder (G*)
Test on Mix Slice (Time to 5% Strain)
AZ 87 Project
Control
CSS-1h
Reclamite
ERA-25
ERA-1
Pass QB
Control 2
Test on Extracted Binder From Field Cores (G*)
Test on Mix Slices from Lab Treated Cores (Time to 5% Strain)
G*, Pa, 10 radians/sec, 64C
Time to 5% Strain, 58°C, 68kPa stress
Binder tests by WRI, Mix tests by MTE

Lessons Learned

Core Slice Binder & Mix Rheology

- **Conclusions:**
  - Rejuvenators soften AC near surface only if permeability is sufficient to allow infiltration.
  - Fog seal products with harder residues do not soften aged AC significantly, but can reduce pavement permeability enough to delay moisture intrusion.

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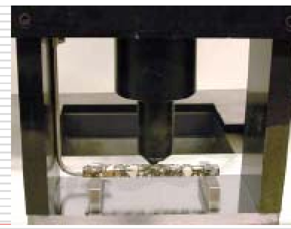
Fog Seal

Low Temperature Mix Stiffness & m-value

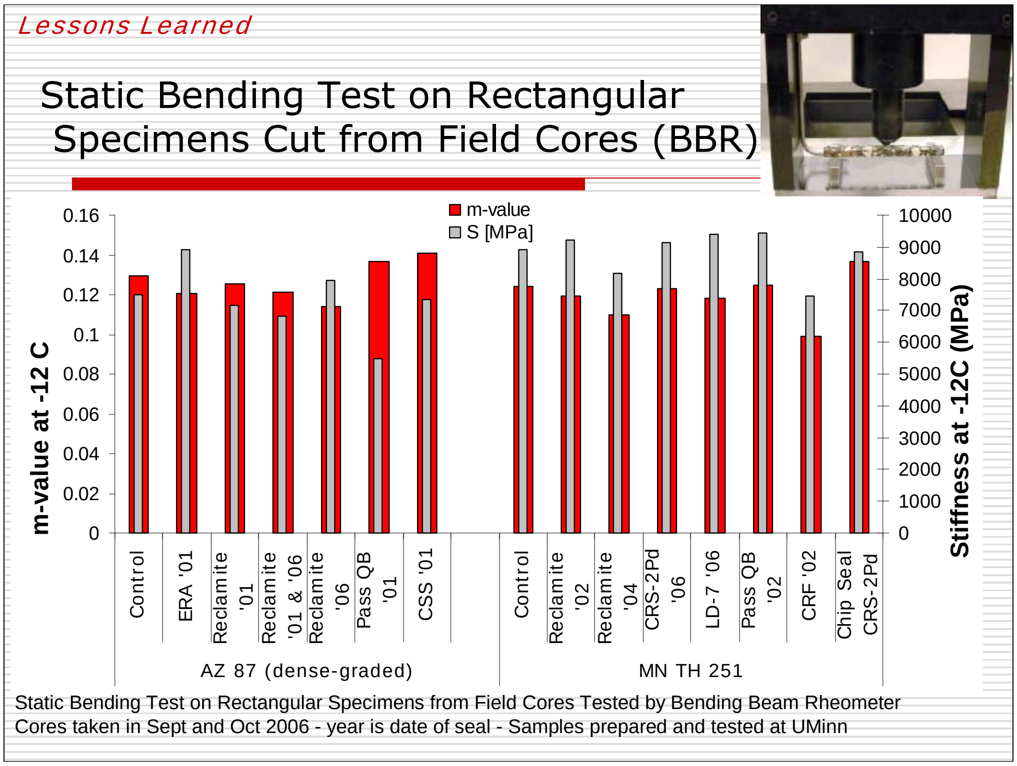
- **Bending Beam Rheometer (BBR)**
  - Standard BBR rectangular beams – 500 g load
    - $200 tile saw cuts surface mix specimens
  - Condition & test in BBR at -18 to -6ºC


Although age-hardening is typically characterized using high temperature rheological tests on mix specimens or extracted binders, it is much more likely that age-induced block cracking occurs at lower pavement temperatures where binders are stiff and brittle. Furthermore, research studies report that asphalt oxidation is particularly deleterious to low temperature relaxation properties as might be reported by Bending Beam Rheometer (BBR) m-value, Direct Tension Test (DTT) failure strain, low temperature ductility, or the R-value as derived from the rheological mastercurve.

Since results from DSR testing indicated that extracted binder rheology can be misleading when fog seals can not infiltrate the surface, the Static Bending Test ([i]) was selected to characterize low temperature mixture properties. The procedure only became available late in the project, so data is limited to only the later trials. Thin mixture specimens are cut from field cores to standard BBR specimen geometry and tested for low temperature stiffness and m-value at temperatures ranging from -18 C to -6 C. This test monitors the effectiveness of rejuvenating seals and might be used to set “trigger” parameters whereby appropriate preventive maintenance strategies can be implemented as aged pavements approach critical cracking conditions.

([i]) Zofka,A, Marasteanu,M, Clyne,T, Li,X, and Hoffmann,O. Development of Simple Asphalt Test for Determination of RAP Blending Charts. Mn/DOT report MN/RC – 2004-44, June, 2004.



BBR testing on cores taken from the Arizona and Minnesota projects are reported in the graph. Polymer in the CRS-2P(d) and Pass QB had a slightly positive effect on the m-value. The rejuvenator products did not improve the m-value, but in some cases did reduce the BBR stiffness below that of the control. It appears that the best protection from aging as measured by m-value was accomplished by chip sealing the pavement so that no further oxygen or moisture could enter the mix from the surface. Given the variability of testing such thin mixture specimens, each of these conclusions is only marginally significant and needs further verification.

Lessons Learned

Static Bending Test on Rectangular Specimens Cut from Field Cores (BBR)

Conclusions

- **Caution: Limited data; tests only in 2006/2007**
- **A promising new test**
  - Characterizes low temperature behavior where cracking from oxidation is most likely to occur
- **Dense-graded surface studies showed:**
  - Rejuvenators soften AC at low temperature, but may decrease m-value
  - Polymer modified sealers maintained slightly higher m-values than control
  - Chip seals appear to offer best protection from oxidation
- **Asphalt/rubber sections on CA 78 had large voids in mix; BBR results highly variable; no conclusions**

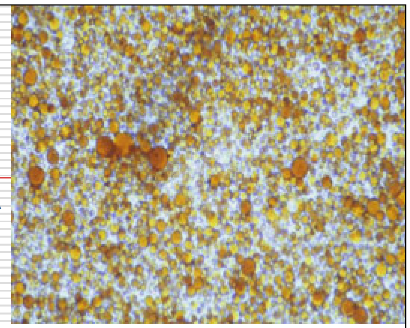
Although promising for conventional dense HMA mixes, BBR data from the open, asphalt rubber surface course on the California Salton Sea project had extremely high coefficients of variation and could not be used to draw any statistically valid conclusions.

On the Road Performance -
Raveling

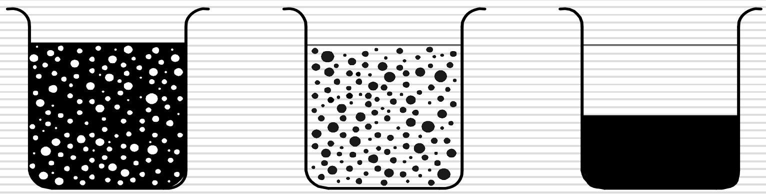
- **Raveling - measure mix cohesion**
  - **Raveling Test (Hobart Mixer)**
  - **Cantabro Abrasion (LA abrasion)**

Asphalt Emulsion

- *Emulsion = A non-continuous phase suspended in a continuous phase*
- ***Broken = complete separation of phases***



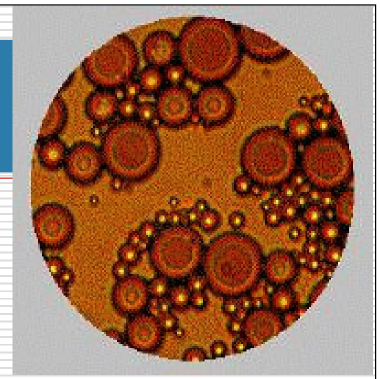
Photomicrograph of o/w asphalt emulsion
(round particles are asphalt)

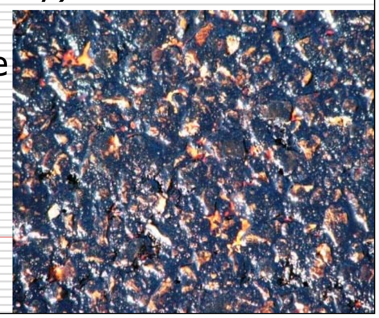


Broken is the “technical” term for a separation of phases. When an emulsion breaks, sometimes the asphalt rises to the top, sometimes it falls to the bottom, depending upon the specific gravity of the asphalt. Most asphalts have specific gravities very close to that of water (1.000), but are generally slightly higher.

Emulsion Infiltration

- **Pavement variables**
  - Permeability
  - Pore size
- **Emulsion variables**
  - Emulsion viscosity (Dilutability)
  - Emulsion surface tension
  - Asphalt droplet particle size





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Lessons Learned

Fog Seal Emulsion Properties

- Surface Tension

- Particle Size

- Disk Centrifuge
- Saybolt-Furol Viscosity

Not enough testing in this study for any conclusions

While there is probably an ideal emulsion viscosity for adequate film thickness and infiltration into a pavement, the surface tension of the emulsion is a better indicator of the ability of the emulsion to infiltrate the surface. Because this testing was initiated very late in the study, there was insufficient data collected to reach definitive conclusions about optimal surface tension. Similarly, the particle size of the emulsion should equate with its ability to enter small pores in the pavement surface. Emulsified rejuvenator oil particles should be easier to deform and enter pores than higher viscosity asphalt droplets. However, only limited particle size data was collected for this study.

Lessons Learned

Fog Seal
Emulsion Residue Properties

- **Need for Rheology-Based Specs.**
  - Modulus/Viscosity – DSR
  - Stiffness/m-value – BBR
  - Failure stress/strain – DTT
- **Need for chemical / physical controls for Rejuvenator Base Oils**
  - Current specs use Rostler
  - Need performance-based standards

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Field Observations

- **Notes & photos of MN, AZ & CA projects taken in 2005 & 2006**
  - Although some 2001 and 2002 seals not clearly visible, effects of treatment were

Four Year Old Seals

Minnesota

Arizona

California

The waterproofing of the seal is visible in the Minnesota (severe, wet climate) photo, the prevention of cracking is clearly evident in the Arizona (high desert, severe temperature fluctuations) photo, and the blackened surface of the fog seal is clear in the California (desert) photo.

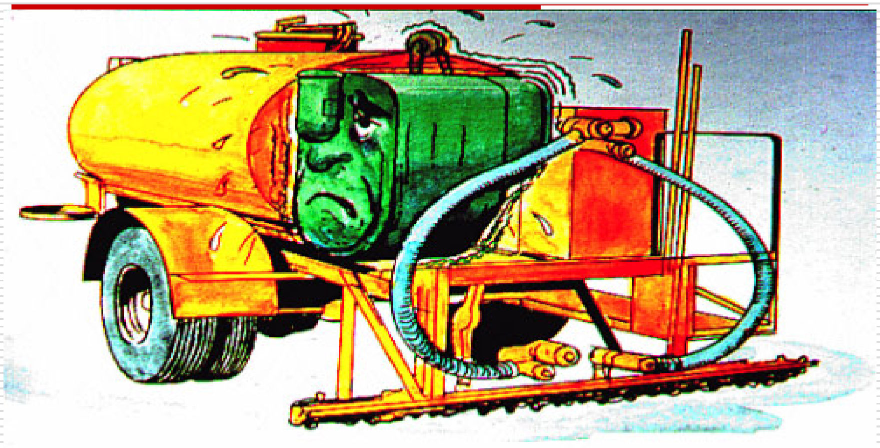
Summary Findings

- **Fog & rejuvenator seals are inexpensive & effective pavement preservation techniques**
  - Provide lasting protection
- **Primary constraint: friction loss**
  - Friction returns after time
  - Sanding helps significantly
  - Traffic control essential
- **DFT / CTM useful for quick friction testing**
- **Product selection must fit the use**

Summary Findings

- **Seals are particularly effective over chip seals, OGFC, shoulders**
  - Prevent short- and long-term aggregate loss
  - Prolong service life
- **Equipment calibration essential for success**
- **Performance-related specs need to be developed**
- **Full reports on project at: www.pavementpreservation.org/fogseals/**

Specifying Performance



Need for Improved Specifications for Fog and Rejuvenating Seals

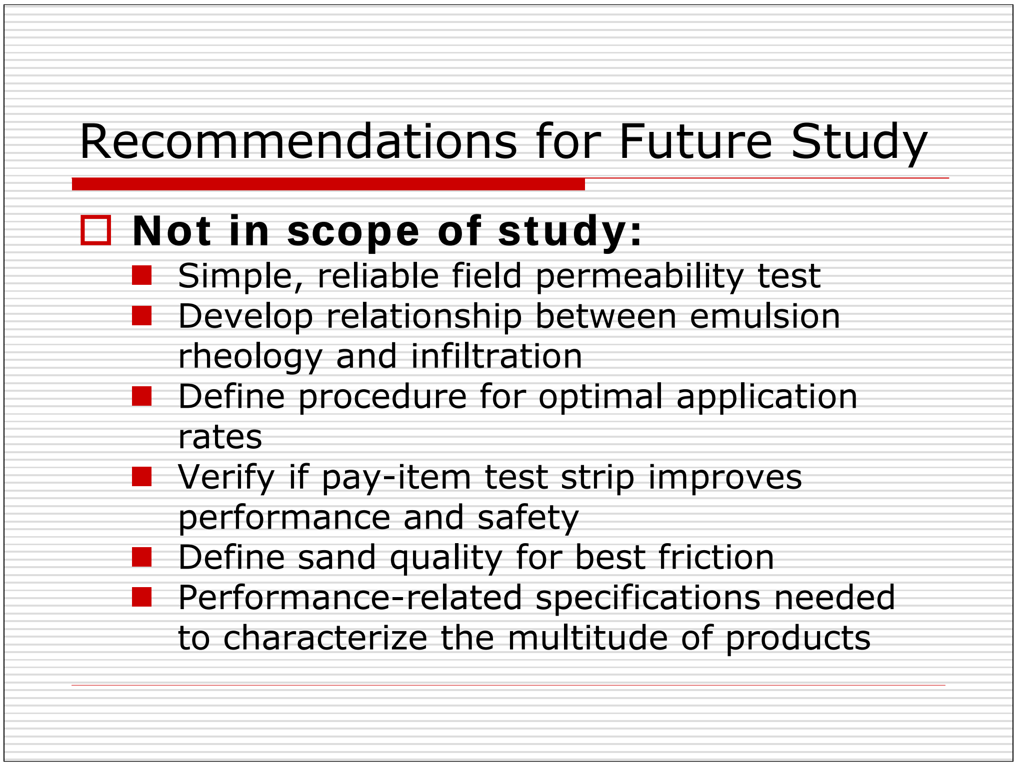
Shakir Shatnawi, P.E., Ph.D.

Office of Pavement Preservation
Caltrans

Prepared for the TRB Workshop
on
Fog and Rejuvenating Seals
January 21, 2007

Fog Seal
Lessons Learned Interactive CD

- Project final report
- Lessons Learned PPT presentation
- Workshop presentations
- Construction reports
- Photo Gallery
- Tests & Specifications
- Bibliography
- Caltrans MTAG for fog seals
- FHWA/FPP fog seal checklists
- DOT survey report
- Supplier product literature



CONCLUSIONS AND RECOMMENDATIONS

The state surveys, field trials and test results in this study demonstrate that fog and rejuvenator sealers are inexpensive and effective treatments for providing protection to pavements and prolonging pavement life. The primary constraint to the use of sealers on dense HMA mixes is a loss in friction following application. Sanding and strict traffic control until friction returns to a specified level can mitigate the problem. The easily portable Dynamic Friction Tester and Circular Texture Meters are useful devices for quick and repeatable field friction testing. Seals can also significantly prolong the life of seal coats, open-graded mixes and shoulders. Specific conclusions for timing, construction and testing may be found above in the Results and Discussion section, but it is recommended that a test strip be a pay item to correctly identify shot rates, equipment calibration and cure time for return to traffic before the project.

There were several topics beyond the scope of this project that warrant further study. They include:

Developing a simpler, more effective field permeability test applicable to fog seals;

Developing relationships between emulsion properties (surface tension, particle size, viscosity) and pavement permeability which can predict infiltration of the emulsions into the pavement surface;

Defining a procedure for determining optimum application rates;

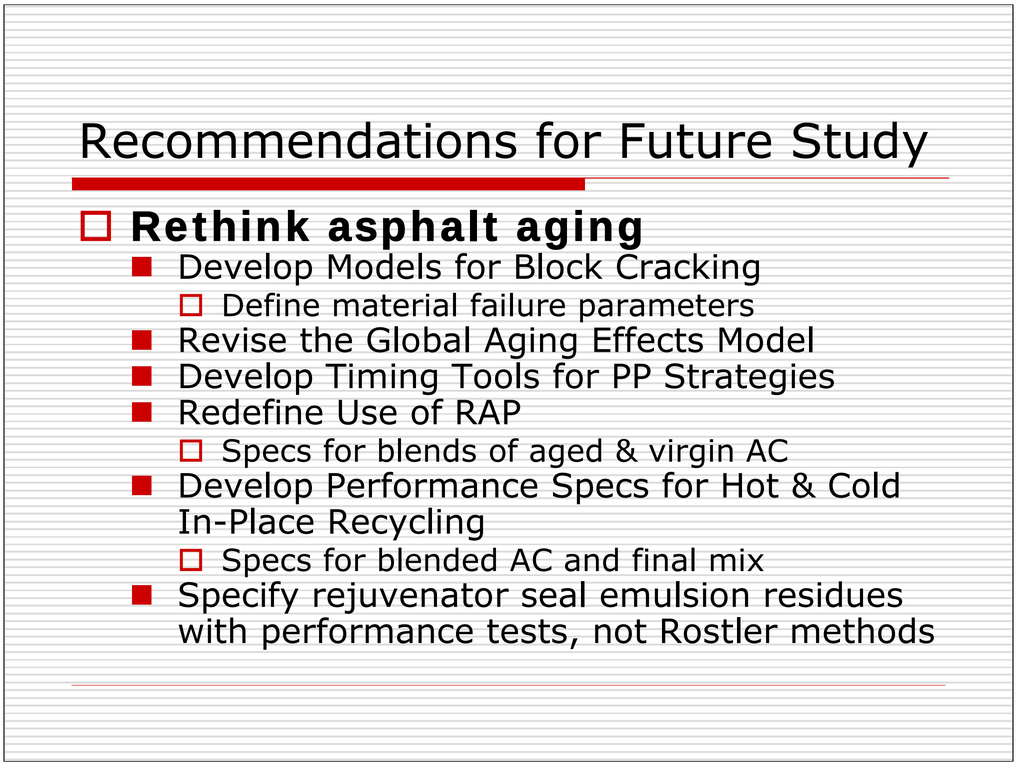
Verifying if a pay-item test strip can improve performance and safety;

Defining sand quality including angularity and maximum moisture content; and

Understanding whether vehicle control on newly sealed sections is adequately predicted by IFI. While the test results showed higher friction on some of the rejuvenator-treated sections, walking, driving and braking on those sections seemed to show that the surfaces were more slippery than the test results indicated.

Specification writing was also outside of the scope of this study. However, it is strongly recommended that performance-related specifications be developed, and it is hoped the results of this study will be useful in that endeavor. Some ideas generated here include defining desired physical properties of the surface following application, defining emulsion residue properties in mechanical or physical chemical terms for an emulsion purchase specification, and defining parameters that impact emulsion infiltration into the pavement, such as emulsion surface tension, particle size and viscosity. Also, there should be definition and specification of construction criteria such as application rates in terms of coverage and decrease in surface permeability, and release to traffic based on minimum friction index, break time and no tracking of material.

The final task of this study is dissemination of the information. The posting of the results on the internet (10) is being supplemented with workshops at several Pavement Preservation Partnership regional meetings in 2007 and 2008.



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