Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-06/0-5091-1		

4. Title and Subtitle	5. Report Date
ANALYZE EXISTING FOG SEAL ASPHALTS AND ADDITIVES: LITERATURE REVIEW	December 2005
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Nikornpon Prapaitrakul, Tom Freeman, and Charles J. Glover	Report 0-5091-1
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Project 0-5091
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080	Technical Report: September 2004 - December 2005
	14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Analyze Existing Fog Seal Asphalts and Additives

URL: http://tti.tamu.edu/document/0-5091-1.pdf

16. Abstract

Fog and rejuvenating seals have the potential to reduce and reverse the aging of asphalt pavements, reduce cracking and raveling, and provide a better, longer-lasting pavement.

The purpose of a fog seal is to coat, protect, and/or rejuvenate the existing asphalt pavement. Also, a fog seal can be used to decrease the permeability to water and air. To the extent such permeability reductions occur, a pavement's waterproofing will be improved and aging susceptibility due to binder oxidation will be reduced. Fog seal emulsions must penetrate into the voids in the pavement in order to seal off the surface. A slow setting emulsion diluted in water turns out to be a suitable fog seal material in this case. An emulsion that is too thick may not properly penetrate into the surface voids and will leave behind an excess amount of asphalt on the surface after the emulsion breaks, causing a slippery surface.

Rejuvenating emulsions contain oils that reduce the viscosity of an existing asphalt, thereby reducing the cohesive failure of the asphalt as the flexibility of binder is improved. In addition, rejuvenating oils can penetrate to fill voids in the pavement and minimize further binder oxidation since the rate of asphalt oxidation is highly dependent on the voids in the total mixture (VTM). An effective rejuvenator must penetrate into the pavement surface in order to be absorbed by the aged hardened asphalt, but also to avoid causing a binder-slick surface, especially in wet weather.

This report summarizes literature reports on fog seal and rejuvenator practices and research.

17. Key Words	18. Distribution Statement
Fog seal emulsion, rejuvenator, asphalt emulsion, enrichment treatment, flush coats, cationic emulsion, anionic emulsion, coal tar sealer, Gilsonite sealer, PASS sealer	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	22	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ANALYZE EXISTING FOG SEAL ASPHALTS AND ADDITIVES: LITERATURE REVIEW

by

Nikornpon Prapaitrakul
Graduate Research Assistant
Artie McFerrin Department of Chemical Engineering (TAMU)
and the Texas Transportation Institute

Tom Freeman
Engineering Research Assistant
Texas Transportation Institute

Charles J. Glover
Research Engineer
Artie McFerrin Department of Chemical Engineering (TAMU)
and the Texas Transportation Institute

Report **5091-1**
Project Number 0-5091
Research Project Title: Analyze Existing Fog Seal Asphalts and Additives

Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

December 2005

TEXAS TRANSPORTATION INSTITUTE
and the Artie McFerring Department of Chemical Engineering
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. Trade names are used solely for information and not for product endorsement. The engineer in charge of this project was Charles James Glover, Ph.D., P.E. (Texas, 48732).

ACKNOWLEDGMENTS

This report was prepared in cooperation with the Texas Department of Transportation. The authors thank Gerald Peterson, Project Director, Miles Garrison, Project Coordinator, and the members of TxDOT's Project Monitoring Committee.

TABLE OF CONTENTS

Page

ANALYZE EXISTING FOG SEAL ASPHALTS AND ADDITIVES: LITERATURE REVIEW

FOG SEALS AND REJUVENATORS

Fog seals have been used for pavement maintenance purposes for many years. According to the Asphalt Emulsion Manufacturers Association (AEMA), fog seal is defined as "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." (*1*) Fog seals are referred to as enrichment treatments since fresh asphalt is added to an aged surface to lengthen the pavement surface life (*2*). Fog seals, referred to as flush coats, are also useful in chip seal applications to hold chips in place in fresh seal coats. This method can help prevent vehicle damage due to flying chips. The Asphalt Institute also concludes that small cracks can be sealed by a fog seal (*3*, *4*).

Rejuvenators are agents used to restore properties of an asphalt. Most rejuvenators are proprietary materials and are difficult to specify except by brand name. Very little information is available that describes the expected performance when using rejuvenators to maintain pavements (*5*).

FUNCTION OF A FOG SEAL

The purpose of a fog seal is to coat, protect, and/or rejuvenate the existing asphalt pavement. Also, a fog seal can be used to decrease the permeability to water and air. To the extent such permeability reductions occur, a pavement's waterproofing will be improved and aging susceptibility due to binder oxidation will be reduced. Fog seal emulsions must penetrate into the voids in the pavement in order to seal off the surface. A slow setting emulsion diluted in water turns out to be a suitable fog seal material in this case. An emulsion that is too thick may not properly penetrate into the surface voids and will leave behind an excess amount of asphalt on the surface after the emulsion breaks, causing a slippery surface.

A fog seal emulsion wets the surface of pavement then breaks, forming a new asphalt film on the pavement surface. The rate at which the emulsion breaks primarily depends on weather conditions such as wind, rain, and temperature.

FUNCTION OF A REJUVENATOR

Rejuvenating emulsions contain oils that reduce the viscosity of an existing asphalt, thereby reducing the cohesive failure of the asphalt as the flexibility of binder is improved. In addition, rejuvenating oils can penetrate to fill voids in the pavement and minimize further binder oxidation since the rate of asphalt oxidation is highly dependent on the voids in the total mixture (VTM) (*6*). An effective rejuvenator must penetrate into the pavement surface in order to be absorbed by the aged hardened asphalt, but also to avoid causing a binder-slick surface, especially in wet weather (*6*).

MATERIALS

Fog seal emulsions can provide multiple improvements to the pavement. Some emulsions are single purpose (seal the pavement, penetrate into voids, or rejuvenate the binder), but most often more than one function is achieved by current commercial fog seal emulsions.

In some cases, fog seal emulsion can be positively charged (cationic), which can replace water from the surface of an aggregate or aged asphalt film (*7*). This type of emulsion breaks by loss of water and by chemical action. The cationic emulsified asphalt standard specification can be found in ASTM D-2397. On the other hand, a negatively charged (anionic) emulsion has no interaction with the aggregate surface and breaks due to water loss by evaporation and absorption through voids in the pavement (*7*).

The following is advertising information on several commercial fog seal emulsions currently in use.

- *Polymer-modified Asphalt Surface Sealer (PASS®)* (*8*)
  - Is a modified cationic emulsion containing a rejuvenating agent, specialized asphalt, and quality polymers.
  - Has been carefully formulated with cationic emulsifiers to break rapidly after application so that traffic can be resumed with minimal traffic delays.
  - Penetrates, seals, rejuvenates, and beautifies asphalt pavements.
  - Is applied at ambient temperatures ranging from 45 °F to 120 °F.
  - Prevents further weathering of the pavement surface by preserving the fine surface aggregate particles.
  - Normally diluted 1:1 and applied at a rate of between 0.08 and 0.12 gallons per square yard depending on surface conditions.
- *Coal-Tar Sealer* (*9*)
  - Follow Engineering Brief No. 44 of Federal Aviation Administration.
  - Bituminous material shall be composed of coal-tar oils and coal-tar prepared from a high temperature, coal-tar pitch conforming to the requirements of ASTM D 490, Grade 12.
  - Coal-tar sealer/rejuvenator has been applied at several airport pavements to date and appears to be performing satisfactorily.
  - Coal-tar sealer is applied through a pressure distributor at a temperature of 60 to 120 ^{o}F.
  - Typical application rate is around 0.05 to 0.08 gallons per square yard.
  - The cure time before traffic is allowed on the pavement is about 24 hours depending on the ambient temperature.

- After application the sealer becomes an integral part of the asphalt pavement, not merely a surface coating, and friction characteristics of the pavement are not affected appreciably.
- The purpose of this sealer is to provide a fuel resistant surface and to rejuvenate the asphalt binder.

- Gilsonite-Sealer-Binder *(GSB)* (*10*)

  - Gilsonite is a natural, unrefined asphalt ore that is mined in Utah that is rich in resins to help replenish the pavement's surface where oxidation first starts.
  - Gilsonite is 45 percent resin, and naturally very high in anti-oxidants, polar compounds, and anti-stripping chemicals. It has a high affinity, or attraction, to all kinds of aggregates.
  - GSB is a very strong binder and was studied and shown by the Army Corps of Engineers to be four times more effective in holding a pavement's surface together than the leading saturate oil rejuvenator.
  - GSB can double the service life of solid asphalt pavements. Under the correct conditions, GSB can be used effectively on any type of asphalt pavement.
  - GSB is applied by using a standard asphalt distributor at a rate between 0.10 and 0.15 gallons per square yard.
  - Emulsion is heated to about 160 ºF with approximately 0.5 to 1.5 lbs of Black Beauty sand spread over the GSB liquid per square yard.
  - GSB is applied to dry pavement in dry weather at least 50 ºF. .

Other commercial emulsions are Reclamite (oil emulsion) and Topien C (asphalt, oil, and additives) (*7*). In addition, 23 softening (rejuvenating) agent physical and chemical properties are reported by Anderson et al. (*11*).

TYPICAL FOG SEAL CONSTRUCTION

State of California Department of Transportation provides general guidelines for fog seal construction, which are discussed in this section (*7*).

Site Conditions

Warm and dry weather will make the low viscosity emulsion break quickly, which will lead to asphalt film formation on the pavement surface. Atmospheric temperature should be above 10 °C (50 °F), and pavement temperature should be above 15 °C (59 °F).

Surface Preparation

Prior to fog seal application, the pavement surface must be clean and dry. The pavement surface can be cleaned with a road sweeper, power broom, or flushed with a water pump-unit to remove dust, dirt, and debris. If flushing is required, it should be completed 24 hours prior to the application of the fog seal to allow adequate drying.

Material Preparation

Asphalt emulsions (original emulsions) contain up to 43 percent water, but must be diluted, generally, to 50 percent before further use. This additional dilution reduces viscosity and allows the application of small amounts of residual binder to be adequately controlled as shown in Figure 1. Dilution water must be potable and free from detectable solids or incompatible soluble salts (hard water).

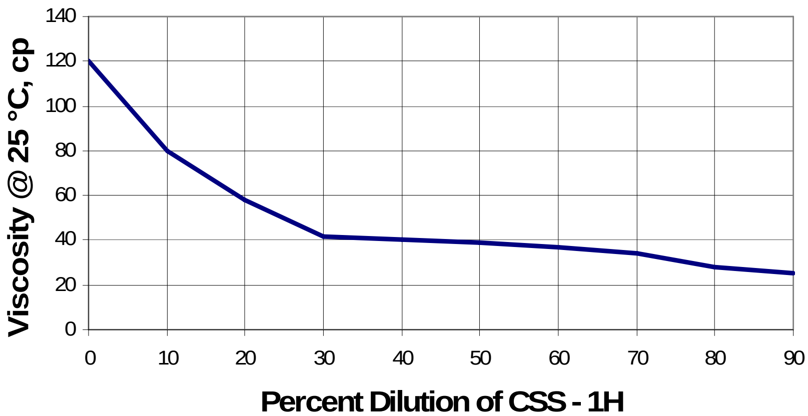

Figure 1. Viscosity Change with Dilution (*12*).

Check compatibility of water with the emulsion by mixing a small amount of the emulsion in a can (approximately 1 liter). After mixing the materials for 2 to 3 minutes with a stirrer, pour the resulting mixture through a pre-wetted 150 µm sieve. If more than 1 percent by weight of material is retained on the sieve, the water is not compatible and clogging in the spray jets may result.

About 0.5 to 1.0 percent of a compatible emulsifier solution can be used to treat incompatible water (the emulsion manufacturer can provide advice regarding compatible solutions). The emulsifier solution should be added to the water tanker and circulated for 10 to 15 minutes via the pump before adding it to the emulsion. Repeat compatibility test if a water treatment is used.

The emulsion should be diluted no more than 24 hours before its intended use (*13*). This is to avoid settlement of the diluted emulsion. Water is always added to the emulsion and not the other way around. The emulsion may be circulated using a centrifugal or other suitable pump to ensure uniformity (*13*).

Application Rates and Spraying

Properly calibrated distributor trucks are used to apply the emulsion. In some cases, if emulsions are modified, a special distributor may be required (*14*). Spray nozzles with 4 to 5 mm (1/8 to 3/16 inch) openings are recommended (*13*). The emulsion may be heated to 50 °C (122 °F) maximum, although, generally the emulsion is sprayed at ambient temperature (*13*). The emulsion is sprayed at a rate that is dependent on the surface conditions (see Table 1). Typical application rates for diluted emulsion (1:1) range from 0.15 to 1.0 liter per square meter (0.03 to 0.22 gallon per square yard) depending on the surface conditions (*12*, *15*). A 1:1 diluted emulsion is an original emulsion that has been subsequently diluted with an equal part water.

Table 1. AEMA Recommendations for Application Rates (*12*).

% Original Emulsion	Dilution Rate	Tight Surface *		Open Surface **	
		(l/m^2)	(gal/yd^2)	(l/m^2)	(gal/yd^2)
50	1:1	0.15 – 0.5	0.03 – 0.11	0.4 – 1.0	0.09 – 0.22

* *A tight surface is of low absorbance and relatively smooth (13).*
** *An open surface is relatively porous and absorbent with open voids (13).*

Ideally, one-half of the application should be sprayed in each direction to prevent buildup on one side of the stones only (this is particularly important in the case of chip seals and rough surfaces). Buildup on one side can result in a slippery surface and inadequate binder to fully enrich the surface or hold the stone (*7*).

The application temperature normally depends upon the type of emulsion. In most cases, emulsions should be applied under relatively warm and dry conditions (*8-10*).

Estimating Application Rates

To estimate the application rate, a 1 liter can of diluted emulsion (usually 1:1 dilution rate) is poured evenly over an area of 1 square meter. This represents a diluted application rate of 1 liter per square meter. The application rate is reduced if the emulsion is not absorbed into the surface after 2 to 3 minutes and repeated until the approximate application rate is found. If, after the first test, the surface looks like it can absorb more emulsion, the application rate of the emulsion is increased and tested over a new 1 square meter area. The process is repeated until the approximate application rate is found. This same procedure can be followed using gallons and square yards to determine application rate.

EVALUATION METHODS

Pavement Evaluation

After a fog seal application, surface condition and pavement performance should be evaluated in order to ensure the effectiveness of applied fog seal/rejuvenator. In this section, several methods for pavement evaluation are discussed.

Skid Resistance

Skid resistance is the force developed when a tire that is prevented from rotating slides along the pavement surface (*16*). Skid resistance is an important pavement evaluation parameter because:

- Inadequate skid resistance will lead to incidences of skid-related accidents.
- Most agencies need to provide a reasonably safe roadway to users.
- Skid resistance measurements can be used to evaluate various types of materials and construction practices.

Skid resistance changes over time. Typically it increases in the first two years following construction as the asphalt binder is worn away by traffic, then decreases over the remaining pavement life as aggregates become more polished. Skid resistance is also typically higher in the fall and winter and lower in the spring and summer. This seasonal variation is quite significant and can severely skew skid resistance data if not properly compensated (*17*).

Cracking

Pavement cracking is described as a type of distress that is generally caused by inadequate base support or brittle asphalt surface (*18*). Since cracks allow surface water to enter the subgrade and further destroy the stability of the subgrade, sealing should be accomplished as soon as practical. When cracking has progressed to the extent that failure of the roadway surface is imminent, repairs should be made as soon as possible. Cracking observations should be done periodically to ensure that corrective or preventive maintenance is implemented at the appropriate time.

Pavement Surface Condition

An excessive amount of asphalt on the pavement would cause a slippery surface, which could lead to vehicle control difficulty especially in wet weather (*7*). Also, fog seal material that is not properly cured will result in developing a soft asphalt binder film on the pavement surface, which can cause pavement deformation such as rutting. After the application of surface treatment, pavement examination is required periodically.

Aggregate Retention

Aggregate loss is one of the criteria used to evaluate the performance of a fog seal on chip seal applications. A convenient method to detect aggregate retention is to use visual examination, which can be subjective. Alternatively, for a more accurate representative method, photorecords were introduced. Rectangles, 12-inch by 9-inch, were painted on the pavement surface both in controlled and treated sections. Then close-up photographs were taken periodically to examine the individual stone lost with time (*5*). Also, surface texture may be determined using the sand-patch method (*19*)

Laboratory Evaluation

In addition to field evaluation, laboratory controlled tests also need to be performed in order to examine the capability of the treatment. Furthermore, any change in the property of core sample or asphalt binder due to fog seal/rejuvenating effect should be identified. The following are test methods used to measure mixture/binder properties.

Resilient Modulus

Indirect tension test for resilient modulus of asphalt mixture can be used for both laboratory-fabricated and field-recovered cores of asphalt mixtures. Mixture stiffness is measured in accordance with ASTM D 4123-82 to determine any improvement due to the rejuvenating process. For laboratory-aged sample, aging ratios can be calculated by dividing resilient moduli after aging by the corresponding values before aging.

Vialet Test

Vialet test has been shown to be an indicator of chip seal aggregate retention rate (*20*). Basically, loose hot mix is spread on a 7 by 7 inch steel plate with a 0.25-inch rim to prevent binder runoff. Then the sample is rolled with a hand-held rubber roller and left undisturbed at room temperature for 24 hours. After that, fog seal emulsion is applied and allowed to cure for 24 hours at 140 ^{o}F. The sample is then placed in a testing temperature for 2 hours prior to the testing. A steel ball with a diameter of 2 inches is dropped from a height of 18 inches above the sample. Percentage of material retained after impact is calculated.

Extraction/Recovery

In order to test the properties of asphalt binder from mixture cores, binder needs to be extracted and recovered from the whole mixture. Typical extraction method follows the standard procedure of ASTM D 2172. Asphalt binder is then recovered by using the Abson method, ASTM D 1856. For specific study, successive extraction/recovery was used to determine the extent to which asphalt binder would be softened by penetrated rejuvenator (*21*). The penetration phenomenon was proposed and referred to as “Black Rock Model” (*22*).

Asphalt Binder Viscosity

The convenient and appropriate method to determine the softening effect of rejuvenator on asphalt binder is to measure the viscosity of the sample at 140 ^{o}F (*23*). The two main types of viscometer are the tube and rotational instruments (*24*). Typically, the rotational type is more widely used because it is suitable for most applications and for non-Newtonian materials. The vast majority of rotational viscometers fall into two categories: those where two concentric cylinders rotate relative to one another around a common axis; and those consisting of a cone having a large vertex angle (approaching 180 degrees) and plate whose plane is through the apex of the cone. Many variations on this theme are possible, but in all types the test fluid is sheared between the rotating parts. Then the force exerted on the fluid can be used to calculate fluid viscosity.

Fourier transform infrared spectroscopy (FT-IR)

FT-IR can be applied for the study of bitumen characterization. The analysis is able to identify functional groups present in bitumen due to its ability to measure infrared light absorbed by covalent bonds in molecules. Each functional group will result in a unique intensity and frequency of light absorbed. FTIR has been applied to analyze functional groups in asphalt binder (*25*) and diffusion of oxygen into bitumen (*25, 26*).

FOG SEAL/REJUVENATOR PERFORMANCE

Fog seal/rejuvenators are used in many pavement applications, mostly for surface treatment and replenishing aged asphalt binder. Several literature references discuss the effectiveness of fog seal/rejuvenator on the pavement/core sample. The discussions follow.

Fog Seal on Chip Seal Application

Estakhri and Agarwal studied the effect of a fog seal on chip seal applications. Their conclusions are (*5*):

- Four test roads were treated with fog seal on chip seal application and observed for two years. For every test road, the aggregate retention rates of treated surfaces were improved over the corresponding control surfaces even at application rates as little as 0.03 gallon per square yard.
- Most of the stone loss in both treated and control sections occurred in the first year. Then they stabilized by the second year. Therefore, a fog seal application to a chip seal should be applied prior to its first winter.
- Based on the result of this study, fog seal applications are effective for reducing the rate of stone shelling if placed before the first winter after chip seal application.

Outcalt conducted an experiment on chip seal application (*4*). This field experiment consists of four test sections. Material usage for each section is described as follows:

- Section I: Lightweight chips (have a unit weight of 60 percent of the standard chips)
- Section II: Standard chips
- Section III: Standard chips with a fog seal of High Float Rapid Set (HFRS-2P) emulsion dilute 1:1 and applied at a rate of 0.05 gallon per square yard
- Section IV: Untreated control section

The sites were evaluated after a six-month period. Notable observations were:

- While the control section had the largest amount of cracks, the cracks in Section III (chip seal plus fog) were tighter than any other sections.
- According to falling-weight deflectometer (FWD) measurement, Section I (lightweight chips) and section III (chip seal plus fog) showed the lowest deflections.
- There was no measurable rutting in all sections.

Finally, after a four-year period of observation, these conclusions were made:

- Overall, the treated sections were in better condition than the untreated at the time of final evaluation.
- Skid resistance for all sections was high.
- Fog seal showed a significant improvement in short-term performance. However, there was no apparent long-term advantage to applying a fog seal over a standard chip seal.

Fog Seal on Asphalt Pavement/Core Sample

Estakhri and Agarwal also studied the effect of fog seal applications on regular asphalt pavement and laboratory compacted core samples (*5*). They made these conclusions after their study:

- Laboratory molded asphalt specimens were treated with fog seal and aged at 140 ^{o}F for six weeks to determine the effectiveness of fog seals at sealing the surface to reduce the hardening rate of the mixture. The resilient modulus test was used to determine mixture stiffness. After aging, stiffness of all specimens had increased. There was no significant improvement on specimens treated with a fog seal.
- Asphalt pavement treated with a fog seal was monitored for two years. There were no visual differences between treated and control sections.
- Limited data obtained from this study on fog seal performance suggested that fog seals applied at a rate of 0.05 gallon per square yard are not effective at reducing the aging rate. However, they can be used effectively to correct specific surface problem such as raveling.

Asphalt System Inc. reported the effect of GSB emulsion as a fog seal on Ohio Logan County Rd 154 (*10*). The skid resistance and visual observations were made every six months for five years. The following information was reported:

- After five years, asphalt core samples were taken from treated and untreated sections of the road and then evaluated using Marshall Stability as well as viscosity measurement on the extracted and recovered binder, using the Abson recovery method. The measurement shows that there is 30 percent higher oxidation in the untreated sample.

- Skid resistance over the five-year period of untreated and treated sections shows no significant difference.
- By visual observation, the untreated section had noticeable cracking while the treated section had little or no sign of cracking.

Rejuvenator on Asphalt Pavement/Core Sample

Anderson et al. conducted a study to determine the effect of rejuvenating agent on recycled asphalt mixtures and on laboratory-compacted mixture with aging (*11*). The conclusions of this study are discussed below:

- Four agents (flux oil, Reclamite, Dutrex, and dust oil) were selected as rejuvenating agents in this study. These agents were applied to recycled asphalt mixtures to restore the original asphalt binder properties. The results showed that Dutrex and dust oil were very effective at softening the aged binder. The Reclamite was not as effective as the first two. The flux oil was relatively ineffective due to its high quantity required to restore original binder properties.
- Marshall Stability of the recycled mixture was reduced due to the effects of the softening agent.
- Resilient modulus of the recycled mixture also decreased to within the range of the newly constructed pavement.
- Stiffness of mixtures due to laboratory aging was observed and was related to measured binder hardening. Heavily aged mixtures should consist of stiffer binder due to binder oxidation. However, the Reclamite mixture stiffened more than others while its binder stiffened less than others.

Estakhri and Agarwal studied the effect of a rejuvenating seal as a treatment for asphalt concrete (*5*) based on a study of the U.S. Army Corps of Engineers, which concluded that rejuvenating seals were effective at reducing the loss of surface fines; however, they were not effective at reducing the rate of cracking (*27*). From the study, Estakhri and Agarwal stated that:

- For asphalt mixtures that have high air void content (10 to 12 percent), mixture stiffness can be significantly reduced by the rejuvenators.
- Laboratory compacted mixtures were prepared using three different asphalt sources and three different rejuvenators and then evaluated. The results indicated that the combination of asphalt sources and rejuvenator types can influence the effectiveness of the rejuvenator.
- From field experiments, the method of controlling the skid resistance when using a rejuvenator was determined. Forty-five minutes to one hour after rejuvenator application, sand should be applied and lightly rolled. Surface sweeping is required after two hours. With this procedure, skid resistance of the pavement should be back to the original condition within 24 hours.
- According to this study, it is recommended that rejuvenators be applied on pavements with an air void content greater than 7 to 8 percent. Application of rejuvenators to high air void content pavement can reduce the stiffness of the mixture.

REFERENCES

1. The Asphalt Institute, "A Basic Asphalt Emulsion Manual," Manual Series No. 19, Lexington, Kentucky, 1999.

2. Booth, EHS, Gaughan, R., Holleran, G., "Some Uses of Bitumen Emulsions in SA and NSW," *Proceedings, Australian Road Research Board*, March 1988, pp. 387-401.

3. The Asphalt Institute, "A Basic Asphalt Emulsion Manual," Manual Series No. 16, Lexington, Kentucky, 1999.

4. Outcalt, W., "SHRP Chip Seal," Report No. CDOT-DTD-R-2001-20, Colorado Department of Transportation Research Branch, December, 2001.

5. Estakhri C. K. 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.

6. Brown E.R., "Preventive Maintenance of Asphalt Concrete Pavements," NCAT Report No. 88-1, 1988.

7. California Department of Transportation (CADOT), "Fog Seal Guidelines," Caltrans Division of Maintenance, October, 2003.

8. Western Emulsion, Inc., "PASS®," http://www.westernemulsions.com/pass/pass.html, 2002.

9. Federal Aviation Administration (FAA), "Engineering Brief No. 44: Coal-Tar Sealer/Rejuvenator," November, 1989.

10. Asphalt System, Inc., "True Story of Rejuvenation," The Solution, http://www.asi-roads.com/theSolution/theSolution.asp, Salt Lake City, Utah.

11. Anderson, D. I., Peterson, D. E., Wiley, M. L., Betenson, W. B., "Evaluation of Selected Softening Agents Used in Flexible Pavement Recycling," FHWA-TS-79-204, 1978.

12. Hicks, R. G., Holleran, G., "Purpose and Use of Fog Seal and Rejuvenators," Sealer Binder Workshop, Foundation for Pavement Preservation, Federal Highway Administration, March 2002.

13. Asphalt Emulsion Manufacturer's Association, "Recommended Performance Guidelines," AEMA, Washington, D.C., 1990.

14. Heydorn, A., "Applying Solvent-Based Sealers," *Pavement*, January, 1998, pp. 19-24.

15. Minnesota Department of Transportation (MNDOT), "Asphalt Pavement Maintenance: Field Handbook," Manual No. 2001-05, Minnesota Local Road Research Board, April, 2001.

16. Highway Research Board, *National Cooperative Highway Research Program Synthesis of Highway Practice 14: Skid Resistance*. Highway Research Board, National Academy of Sciences, Washington, D.C., 1972.

17. Jayawickrama, P.W., and Thomas, B., Correction of Field Skid Measurements for Seasonal Variations in Texas, *Transportation Research Record 1639*. Transportation Research Board, National Research Council, Washington, D.C., 1998, pp. 147-154.

18. Maintenance Operation Manual, Texas Department of Transportation (TXDOT), Revised September 2005.

19. Manual of Testing Procedures, Volume 2, Texas State Department of Highways and Public Transportation, TEX 436-A, January, 1983.

20. Stroup-Gardiner, M., Newcomb, D. E., Epps, J. A., and Paulsen, G. L., "Laboratory Test Methods and Field Correlations for Predicting the Performance of Chip Seals," *Asphalt Emulsions, ASTM STP 1079*, H. W. Muncy, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 2-19.

21. Noureldin, A. S. and Wood, L. E., "Rejuvenator Diffusion in Binder Film for Hot-Mix Recycled Asphalt Pavement," *Transportation Research Record*, Vol. 1115, 1987, pp. 51-61.

22. Carpenter, S. H., and Wolosick, J. R., "Modifier Influence in the Characterization of Hot-Mix Recycled Material," *Transportation Research Record 777*, Transportation Research Board, Washington, D.C., 1980, pp. 15-22.

23. *Asphalt Hot-Mix Recycling*. MS-20. The Asphalt Institute, College Park, Md., August, 1981.

24. Whorlow, R. W., *Rheological Techniques*, Third edition, Intl Specialized Book Service Inc, December, 2005.

25. Jemison, H. B., Burr, B. L., Davison, R. R., Bullin, J. A., and Glover, C. J., "Application and Use of the ATR, FTIR Method to Asphalt Aging Studies," *Fuel Sci. Technol. Int*. 10, 1992, pp. 795-808.

26. Davison, R. R., et al., "Verification of an Asphalt Aging Test and Development of Superior Recycling Agents and Asphalt." *Rep*., Texas Transportation Institute and Chemical Dept., Texas A&M University, College Station, Texas.

27. Brown, E. R., and Johnson, R. R., "Evaluation of Rejuvenators for Bituminous Pavements," AFCEC-TR-76-3, Air Force Civil Engineering Center, Tyndall Air Force Base, Florida, 1976.