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Performance Evaluation of Fog and Rejuvenating Seals on Gap and Open Graded Surfaces by Caltrans

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Abstract: California Department of Transportation (Caltrans) has been using fog or rejuvenating seals on shoulders and highways through maintenance activities. To safely and effectively utilize more fog or rejuvenating seals on the mainline of its highways, Caltrans placed a series of pilot projects during the past five years. This paper documents the laboratory and field findings from the fog or rejuvenating seal pilot studies on gap graded and open graded surfaces. Caltrans placed test sections in 2009 with six different fog or rejuvenating seal products on gap- and open-graded surfaces. Through field and laboratory studies on these products, Caltrans quantified the benefits and performance of the fog or rejuvenating seal products commonly used in California. After reviewing the positive results from these test sections, Caltrans placed another 12 pilot projects in 2012 and 9 pilot projects in 2013 under various surface types, locations, climates, and traffic levels. The California Pavement Preservation Center (CP2 Center) monitored the pilot projects and wrote project reports to document the surface texture, application rates, product performance, and skid resistance for these pilot projects. This paper presents the performance benefits and skid characteristics of the fog or rejuvenating seals.

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***Key words**: Fog seals; Hot mix asphalt; Rejuvenating seals; Skid resistance; Surface texture.*

Introduction

Based on Caltrans Maintenance Technical Advisory Guide [1], there are many advantages of using fog or rejuvenating seals. Fog seals improve sealing or waterproofing of existing pavement and slow the aging of binder or prevent further stone loss by holding aggregate in place, or by simply improving the surface appearance. Rejuvenating seals are a combination of various rejuvenating oils, and/or a mixture of asphalt emulsion and saturates (light fraction) applied to the asphalt pavement surface [2]. Rejuvenating emulsions restore the maltenes or light components that have oxidized and soften the existing binder, thus reducing the viscosity and improving the flexibility of the binder. These emulsions are also used to seal the pavement and reduce future oxidation [3].

Asphalt binders harden as they age because they gradually lose the lighter molecular weight part of oils and become oxidized. Asphalt hardening takes place at different rates depending on environmental conditions and the exposure to air. Permeable pavements or pavements with high void contents such as open graded mixes can age faster. Water ingress can also carry dissolved oxygen and trace elements that may promote aging. This means that pavements with open surfaces tend to age faster than those with closed surfaces. Pavements with aged binders can exhibit cracking under traffic and loss of binding ability, which leads to raveling [4].

Based on the Asphalt Emulsion Manufactures Association (AEMA), the 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 seal emulsions must penetrate 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 [5]. Fog and rejuvenating seals are presumed to have the potential to reduce cracking and raveling, and extend the pavement life. These pavement qualities may be difficult to measure in the laboratory [6].

Fog or rejuvenating seals are used to seal the existing surface, prevent raveling, and/or restoring properties of aged or oxidized binders, and as such, extending the pavement service life. In California, fog seals are also applied right after chip seals to improve rock retention and prevent windshield damage. Both field and laboratory studies, have shown the benefits of applying fog or rejuvenating seals [7, 8]. Different products showed different performances. The polymer modified emulsions generally had better performance in terms of curing time and aggregate retention [9].

Fog seals will protect the pavement surface from weathering and aging. On travelled ways, fog seals should only be used on surfaces with adequate surface texture [10]. Fog seals applied on tight surfaces without adding sand will create a slippery surface with low skid resistance, which raise safety concerns for traffic. On shoulders, gores, or dikes, surface texture with the application of fog seals is not as critical with regard to skid resistance.

Objectives

The objectives of this paper are to:

- Evaluate the performance of various fog or rejuvenating seal products commonly used in California, and
- Study the pavement surface texture requirements for fog seal applications on travelled ways of the Caltrans roadway network and relate it to skid resistance.

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Performance Studies on 2009 California Pilot Projects

After a test site was placed in 2007 on SR58 near Mojave, three additional sites were constructed in 2009 to evaluate different fog or rejuvenating seal products and their performances. At each site, Caltrans placed a total of six different products including CQS-1h, CRF, PASS-QB, Reclamite, TOPEIN C, and Styraflex [11, 12] for potential usage in California. The following are the brief introductions of the six products.

CQS-1h is a standard non-proprietary emulsified asphalt project which is commonly used by a number of agencies across the United States. CRF is a proprietary product produced by TRICOR Refining, LLC, formerly Golden Bear Refining. Product information is available on the company website located at www.tricorrefining.com. PASS-QB is a proprietary product produced by Western Emulsions; the QB indicates this is a quick breaking product. The emulsion is designed to penetrate small pores in the existing AC surface to soften the aged asphalt cement. The emulsion soap consists of asphalt, rejuvenator oil, and polychloroprene latex polymer. Styraflex ERA is a proprietary product produced by Valley Slurry Seal (VSS). It is a high polymer modified rejuvenating emulsion. Reclamite is a proprietary product supplied by TRICOR Refining, LLC. This product is a cationic emulsion which was developed to penetrate the AC surface and rejuvenate (soften) and co-mingle with the old asphalt binder.

The first project was placed on SR 128, in Boonville. The test sections were placed on June 7 and 8, 2009. This rural roadway is a located in slightly rolling terrain, and has two lanes with no shoulders with an AADT below 3,500. The existing pavement surface was open-graded hot mix asphalt. Boonville is located in a cool, coastal California climate in Caltrans, District 1. The second project was placed on US 395, in Alturas. The test sections were placed on June 16, 2009. Alturas is located in the upper northeast portion of California near both the Oregon and Nevada state lines in Caltrans, District 2. This area is located in the high desert plains and experiences severe winters. The existing surface was 1.5 inches of rubberized gap graded hot mix asphalt with high void content (greater than 10%) and a low binder content by weight of the mix. The highway is two lanes without shoulders.

The following are discussions of the performance of open-graded surface on SR 128 in Boonville, and gap-graded rubberized asphalt surface on US 395 in Alturas. The dense graded projects were not the focus of this study.

A number of tests were performed on these sections including; texture and skid tests, recovered binder, and Hamburg tests. Only a portion of the test results is included in this paper.

Fog or Rejuvenating Seals on Open Graded Mix on SR 128 in Boonville, California

Field Performance Study

Before construction, some pumping of base fines was observed through existing cracks. The open-graded HMA surface showed some raveling in the wheel paths. There were occasional small depressions or potholes. Fig. 1 shows typical distresses of the existing pavement prior to seal coat, showing fair condition. CP2 Center revisited the project site in 2011, two years after the seal coats. Table 1 summarizes the condition of the various test sections. The major distresses were raveling, transverse cracking, and some potholes. All seal coat test sections showed less pavement distress than the untreated control section, and especially, had less raveling distress.

Fig. 1. Existing Pavement Showing Cracking and Raveling.

Laboratory Performance Study

To evaluate the performance of the seal coat on the SR128 test site, a set of four 6-inch cores were taken at the control section, as well as per set from each of the six different products test sections. Several tests were performed by the CP2 Center using the cores. These tests included penetration and viscosity tests on recovered binders, stiffness test using Bending Beam Rheometer, and Hamburg Wheel Tests on control and treated cores. The Hamburg Wheel tests were performed under water at a temperature of 50oC. The cores with fog or rejuvenating seal products had better resistance to rutting and moisture damage than the untreated control section cores based on the graph shown in Fig. 2.

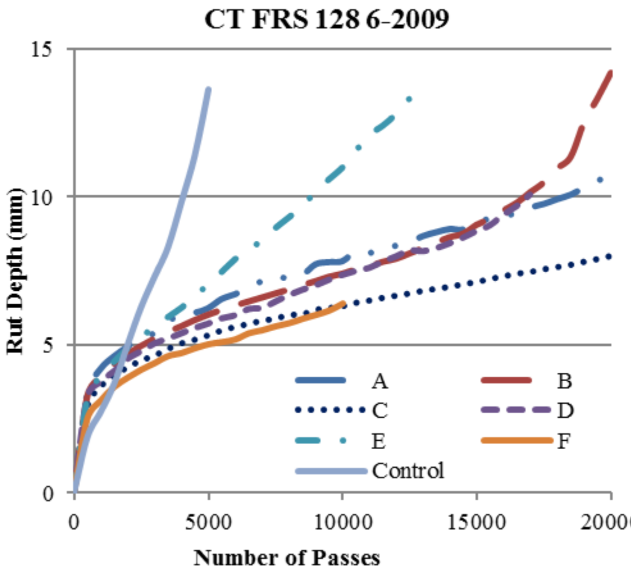

Fig. 2. Hamburg Test Results for Core Samples from SR 128 in Boonville.

Table 1. SR 128 Test Section Two Year Pavement Condition Survey Summary

Section	Transverse Cracking	Longitudinal Cracking	Potholes	Raveling	Overall Condition
Control	Throughout the Section	Isolated	None	Extensive	Poor
Product A	Similar to the Control, But Less	None	None	Some	Fair
Product B	Similar to the Control, But Less	None	Some	Some	Not as Good as the Product A
Product C	Similar to Control But Less	Isolated	Some	Some	Fair to Good
Product D	Similar to Control But Less	Isolated	Some	Some	Fair to Good
Product E	Similar to Control But Less	Isolated	Some	Some	Fair to Good
Product F	Similar to Control But Less	Isolated	Some	Some	Fair to Good

Table 2. Binder Tests For The Boonville Project State Route 128, June 2009

Core ID	Viscosity, 60℃, Poises	Penetration, 25℃, dmm*
A-1	18626	24
B-3	35217	18
C-1	44332	14
D-2	53095	15
E-1	44215	14
F-1	48771	13
G-1 (Control – no Seal)	216390	4

Table 2 shows the results of the viscosity and penetration tests on the recovered binder from the sample cores. Core G-1 represents the untreated sample. As one can see, the fog or rejuvenating seal treated samples had significantly low viscosity values than the untreated control sample. In terms of penetration, the fog or rejuvenating seal treated samples had higher penetration values, which indicate that the binder was softened by the fog or rejuvenating seals.

Fog or Rejuvenating Seals on Gap Graded Mix on US 395 in Alturas

Field Performance Study

The CP2 Center reviewed the performance of this project two years after construction in 2011. The results indicated that the seals were effective in controlling raveling compared to the control section. Fig. 3 illustrates that a fog seal seals the surface and lessens raveling when compared with the untreated control section.

Table 3 summarizes the condition of the pavement after 2 years. The predominant distress was thermal cracking with some minor longitudinal cracking.

Fig. 1. Visual Comparison of Fog Seal with Untreated Section at the US 395 Test Site.

Laboratory Performance Study

To evaluate the performance of the seal coat on the US 395 test site, a set of six inch cores were taken at the six different products test sections before and after fog or rejuvenating seal coat applications. Table 4, Parts a) and b) shows the results of the viscosity and penetration tests before and after seal coat treatment. The binder from treated cores had lower viscosity and higher penetration than untreated cores.

The Hamburg tests were performed under water with temperature of 50oC. Fig. 4 and 5 show the Hamburg Wheel Testing results for the six product sites before and after treatments. The fog or rejuvenating seal products had better resistance to rutting and moisture damage as the number of passes to reach 10 mm rut depth were much higher for treated than untreated surfaces.

Table 3. US 395 Testing Section Two Year Pavement Condition Survey Summary.

Section	Transverse Cracking	Longitudinal Cracking	Potholes	Raveling	Overall Condition
Control- in between Test Sections pavement	Throughout the Section	Isolated	None	Some	Fair
Product A	Similar to the control	None	None	Little to Some	Fair
Product B	Similar to the control	None	None	Little	Fair to Good
Product C	Similar to control	Isolated	None	Little	Fair to good
Product D	Similar to control	Isolated	None	Little	Fair to good
Product E	Similar to control	Isolated	None	Little	Fair to good
Product F	Similar to control	Isolated	None	Little	Fair to good

Table 4. Parts a) and b), Asphalt Test Results, Alturas Test Section.

a) State Route 395, Alturas (AS), 6-09, Untreated

	Viscosity, 60℃, Poises	Penetration, 25℃, dmm*
A-3	184410	5
B-3	244960	5
C-3	155640	6
D-3	133960	8
E-2	164670	5
F-1	208320	6

b) State Route 395, Alturas (AS), 6-09, Treated

	Viscosity, 60℃, Poises	Penetration, 25℃, dmm*
A-3	36420	19
B-3	44490	17
C-1	47015	16
D-1	45064	16
E-1	45151	14
F-2	50126	15

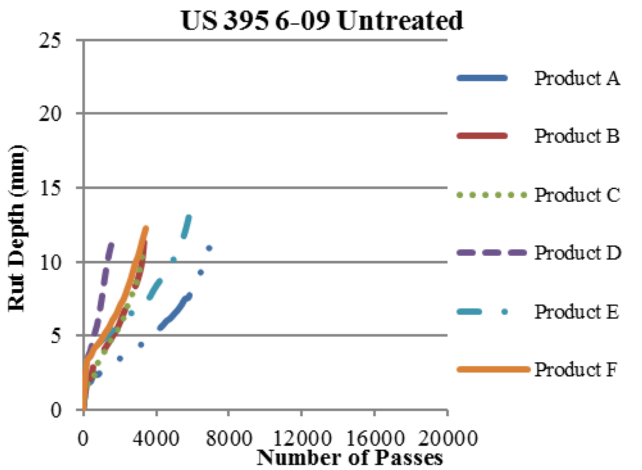

Fig. 4. Hamburg Tests on Samples before Fog Seal Treatment from US 395 Test Site

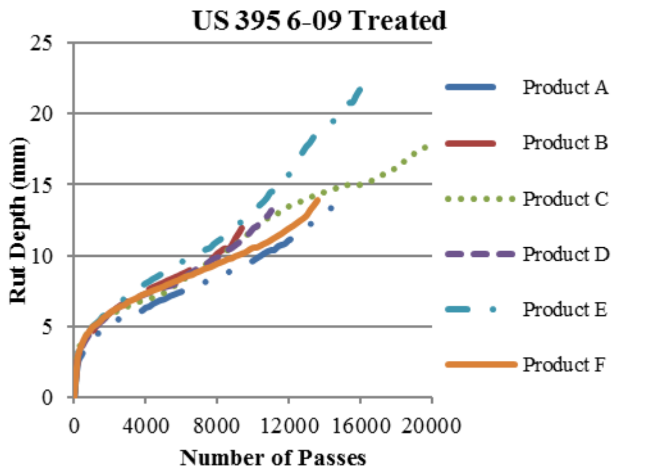

Fig. 5. Hamburg Tests on Samples after Fog Seal Treatment from US 395 Test Site

Summary of 2009 Performance Studies

Based on the field evaluation and laboratory study on the performance of the 2009 pilot projects, the following conclusions can be drawn:

- The field evaluation clearly showed that fog or rejuvenating seal treatment sections performed better than the untreated or control sections. The treatment reduced the rock loss and preserved the surface with slower rate of deterioration.
- Six different fog or rejuvenating seal products were evaluated in the fields. Although they all performed better than the control section, they performed differently.

Performance based laboratory testing was conducted using the cores extracted at various locations of the 2009 pilot projects. The Hamburg Wheel Track tests showed that fog or rejuvenating seal treated cores had better rutting resistance and less moisture damage than the control cores, but different products performed differently.

Texture and Skid Study on Gap and Open Graded Surfaces on 2012 and 2013, California Pilot Projects

After the positive results of the 2007 and 2009 test sections, Caltrans continued the pilot projects in 2012 to further study the surface texture, skid resistance, and proper application rates for fog and rejuvenating seals. The following tests were conducted at the 2012 pilot sites.

Field Performance Testing

Several tests were performed on the various projects to evaluate the effectiveness and safety of the fog seals. Tests included Circular Track Meter (CTM) ASTM E2157, Dynamic Friction Test (DFT) ASTM E1911, Ring Test, Sand Patch Test ASTM E965, British pendulum test (BPT) ASTM E303, and the ASTM skid trailer ASTM E274.

2012 Pilot Projects

In an effort to return to the use of fog seals as a strategy to extend the life of mainline pavements in California, Caltrans conducted a series of fog or rejuvenating seal pilot projects in 2012. The goals of these projects were to measure surface textures before and after fog seals; to determine optimum applications rates for fog seals, and the friction coefficient of the pavement. Application rates were studied using the ring test. The ring test is to evaluate the emulsion breaking times which is dependent on the temperature, climate, type of fog seal material, application rate, and pavement type. Based on the pilot projects, a 15-20 minutes emulsion breaking time can help to determine the proper fog or rejuvenating seal application rates. Longer breaking time indicates that application rate is too heavy and may cause skid loss. The surface texture information such as mean texture profile and Mean Texture Depth (MTD) were explored using a Circular Track Meter (CTM) and sand patch test, respectively. Pavement skid resistance was studied using a Dynamic Friction Tester (DFT), British Pendulum Tester (BPT), and the ASTM E274 skid trailer [13].

A total of 12 pilot projects were observed in Caltrans Districts 2,

Table 5. Caltrans 2012 Fog or Rejuvenating Seal Pilot Projects Information.

District	County	Highway	Construction Date (2012)	PM Starts	PM Ends	No. of Lanes	One/Two Way	Existing Pavement Type	Application Rates, gal/yd^2	Sanding Yes/No
2	Modoc	SR-395	7/31-8/1	45	61.5	2	Two	GG	0.12	Yes
2	Shasta	SR-299	8/18-8/19	24	30.3	4/2	Two	GG	0.12	Yes
2	Shasta	I-5	8/21-8/22	7.2	10.8	4	Two	OG	0.14	Yes
2	Siskiyou	SR-96	8/13-8/15	23.23	50	2	Two	Chip Seal	0.1	Yes
3	Placer	SR-193	9/10-9/11	1.8	3.3	2	Two	OG	0.11	Yes
3	Placer	SR-193	9/12	4	5.7	2	Two	DG	0.08	Yes
3	Sutter	SR-99	10/10-10/11	14.3	16.6	4	Two	OG	0.1	Yes
3	Sutter	SR-20	10/19	2.5	4.22	2	Two	OG	0.1	Yes
10	San Joaquin	SR-12	10/10-10/11	23.4	27.4	2	Two	Chip Seal/DG	0.10/0.07	No
10	Stanislaus	SR-132	8/26-8/27	41	51	2	Two	Chip Seal	0.12	No
10	Tuolumne	SR-120	10/1-10/2	7.4	11.3	2	Two	GG	0.11	Yes
10	Calaveras	SR-12	10/3-10/4	10.5	18.2	2	Two	GG	0.11	Yes

Table 6. Caltrans 2013 Fog or Rejuvenating Seal Pilot Projects Information.

District	County	Highway	Construction Date (2013)	PM Starts	PM Ends	No. of Lanes	One/Two Way	Existing Pavement Type	Application Rates, gal/yd^2	Sanding Yes/No
2	Tehama	I-5	7/8-7/9	0	5.6	4	Two	HMA-O	0.14	Yes
2	Tehama	I-5	6/19-6/20	5.6	11.34	4	Two	HMA-O	0.14	yes
2	Tehama	I-5	7/10-7/11	11.34	17.34	4	Two	HMA-O	0.14	Yes
2	Tehama	I-5	6/17-6/18	17.34	22.14	4	Two	HMA-O	0.14	Yes
3	Colusa	20	6/5-6/6	23.7	28.2	2	Two	RHMA-O	0.1	Yes
3	Glenn	45	6/4	17.2	20.7	2	Two	HMA-O	0.1	Yes
10	Tuolumne	120	8/7	32.8	35.8	2	Two	HMA-Dense	0.07	No
10	Tuolumne	120	8/6	46.8	51.65	2	Two	RHMA-G	0.09	No
10	Amador	104	8/16	0	5	2	Two	RHMA-G	0.11	Yes

3, and 10 with a variety of pavement types including open-graded, gap-graded, dense-graded, and chip sealed surfaces. Table 5 shows the locations, application rates, and surface type information of these pilot projects.

2013 Pilot Projects

To further study the performance and safety of fog or rejuvenating seals, Caltrans placed nine additional pilot projects in 2013. The goals of these later projects were the same as the earlier pilot projects. These pilot projects were placed in Caltrans Districts 2, 3, and 10 with a variety of pavement types including open-graded, gap-graded, and dense-graded. Because of the rough texture and high skid resistance of chip seals, no chip seal surfaces were selected for the 2013 study. Table 6 shows the locations, application rates, and surface type information of the 2013 pilot projects.

Summary of the 2012 and 2013 Pilot Projects

From the testing conducted in this study, the following conclusions were made:

- Generally, with all pavement types the MTD decreased when the fog seal application was applied. This was verified by both the sand patch test and the CTM. In addition, a direct correlation was demonstrated between the CTM and sand patch test results.
- Generally, skid resistance of the pavement surfaces decreased after the fog seal was applied but was immediately increased on the projects when sanding or texture sealing was applied as a precaution. The ASTM skid trailer and the DFT, which both provided data for high speed skid resistance, supported this trend. The BPT was used to determine the low speed skid resistance and how it changed with applications. The data gathered from the BPT tests also supported the same findings mentioned above.
- With increased application rates on both the open-graded and chip sealed surface, the MTD decreased. The effects of increased application rates on the gap-graded pavement were inconclusive and increased application rates on dense-graded pavements did not significantly change the MTD.
- Depending on materials, project sizes, and locations, the costs of fog seals are between \$0.40/yd^2 and \$0.60/yd^2 for these projects.

Texture and Skid Study on Gap and Open Graded Surfaces

One purpose of this study was to measure the surface friction and texture of an asphalt pavement after applying a fog or rejuvenating seal. When applied, the surface of asphalt pavement will experience a short term reduction of friction and loss of texture. Study by NCAT showed that the international friction index IFI F60 could reduce by 24% [14]. Friction is affected by a combination of microtexture and macrotexture of pavement surface, and fog seal

Table 7. Summary of Skid and Macrotexture Measurements for 2012 and 2013 Pilot Projects.

Location	Road Surface Type	Direction / Lane #	Construction Date	Texture (SP) (Before), mm	Texture (SP) (After), mm	Skid Number (Before)	Skid Number (After)
Sha-5-7.2/10.8	HMA-O	NB/#2	8/21/2012	2.23	1.9	54	41
Teh-5-0.0/5.6	HMA-O	NB/#1	7/8/2013	1.82	1.27	52	41
Teh-5-0.0/5.6	HMA-O	NB/#2	7/8/2013	1.15	1.1	47	32
Teh--5-17.3/22.1	HMA-O	NB/#1	6/17/2013	1.36	1.01		42
Teh-5-5.6/17.3	HMA-O	SB/#1	6/19/2013	1.47	1.01	52	39
Teh-5-5.6/17.3	HMA-O	SB/#2	6/19/2013	1.55	1.1	47	30
Teh-5-17.3/22.1	HMA-O	SB/#1	6/17/2013	2.03	1.13		39
Teh-5-17.3/22.1	HMA-O	SB/#2	6/17/2013		0.87	50	29
Col-20-23.7/28.2	HMA-O	WB/#1	6/5/2013	1.63	1.47	42	30
Gle-45-17.2/20.7	RHMA-O	SB/#1	6/4/2013	1.32	0.94	42	32
Cal-12-10.5/18.2	RHMA-G	WB/#1	10/4/2012	1.21	1.05	47	33
Ama-104-0.0/5.0	RHMA-G	EB/#1	8/16/2013	1.37	0.92	47	40
Ama-104-0.0/5.0	RHMA-G	WB/#1	8/16/2013	0.95	0.66	47	36
Tuo-120-46.8/56.5	RHMA-G	EB/#1	8/6/2013	1.06	0.94	51	35
Tuo-120-46.8/56.5	RHMA-G	WB/#1	8/6/2013	0.75	0.66	51	30
Tuo-120-7.4/11.3	RHMA-G	WB/#1	9/30/2012	1.38	1.25	50	42

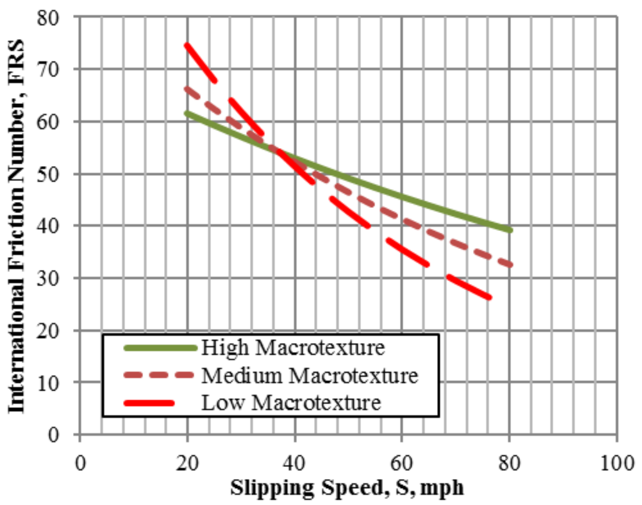

Fig. 7. IFI Friction Model for Different Macrotexture Depths.

application rates. Sand Patch, CTM are simply measures of the macrotexture. This study measured those characteristics to assess whether the reduced skid resistance levels were still acceptable for placing traffic on the highway. Table 7 is a summary of skid and macrotexture measurement results for the gap and open-graded flexible pavement surfaces of the 2012 and 2013 pilot projects. Friction was measured with an ASTM skid trailer (ASTM E274). Texture was measure using the Sand Patch (SP) (ASTM E965). Tests were performed at each project location before and after applying the fog or rejuvenation seals.

Macrotexture Summary

The pavement experienced a slight reduction in the macrotexture measurements after treatment based on Table 7. The reduction can be attributed to both the fog seal and application of sand filing up valleys of the surface texture. The purpose of the sanding was to enhance the friction of the surface immediately after fog seal application. The skid number usually increased after sanding applications.

The texture test results show that texture levels for open-graded asphalt were between 1.15 to over 2.00 mm before fog seal applications and were reduced between 0.87 and 1.90 mm after fog seal applications. For gap-graded asphalt surfaces, the macrotexture levels were between 0.75 and 1.38 mm before fog seal applications and between 0.66 and 1.05 mm after fog seal applications. These are typical values for the surfaces measured for RHMA-G and HMA-O, which are greater than typical macrotexture on dense graded HMA surfaces (0.50 and 0.75 mm).

Skid Testing Summary

In all cases, the average friction measurement exceeded the Caltrans recommended minimum skid resistance of 30 on all pavement surfaces, except at one location on Tehama County I-5 between post mile 17.3 and 22.1. The skid number on the first day after fog seal application at this location dropped to 29, and then the skid number came back to 34 a month later. Generally, the skid numbers dropped right after the fog seal application and returned to higher values within a few days. The application of sand increases the short term skid numbers.

Texture and Skid Correlations

Both microtexture and macrotexture contribute to the friction between tire and pavement. The microtexture dominates the friction at low speed while the macrotexture is an important high speed component for overall friction [15]. The macrotexture provides both the escape for the surface water and subsequently good contact between the tire and pavement when a vehicle travels at high speed. The friction component due to macrotexture increases with speed significantly, and at speeds above 65 mph (105 km/hr) accounts for over 95 percent of the friction (PIARC, 1987).

International Friction Index

The International Friction Index (IFI) was developed by Permanent International Association of Road Congress (PIARC) to standardize different friction and texture measurement methods. The IFI is composed of two numbers, *F*(60) and *Sp*, while *F*(60) is the international friction number and *Sp* is the speed constant (gradient). Both *F*(60) and *Sp* are closely related to the macrotexture of pavement surface.

Speed Constant

The friction changes with different sliding speed. The speed constant is related to the gradient of the friction - sliding speed curve. Based on ASTM E1960, *Sp* can be calculated using the following equation:

$$S_P = a + b \times TX \tag{1}$$

where
TX = Macrotexture, mm, and
a, *b* = Calibration constants dependent on the method used to measure macrotexture. For the CTM, measuring *MPD* (ASTM E1845) [16],

$$S_P = -3.75 + 107.6MPD_{CTM} \tag{2}$$

The *MPD* can be calculated using Sand Patch, *MTD* value as following:

$$MPD = 1.056\ MTD - 0.073 \tag{3}$$

International Friction Number

The international friction number can be calculated using the following equation:

$$F(60) = A + B \times FR(60) + C \times TX \tag{4}$$

where *A*, *B* = Calibration constants dependent on friction measuring device,
C = Calibration constant required for measurements using ribbed tire, and
FR(60) = Adjusted value of friction measurement *FR*(*S*) at a slip speed of S to a slip speed of 60 km/hr.

Based on a study by UCPRC (15), the constant *A*, *B*, and *C* for ASTM skid trailer are -0.023, 0.607, and 0.098, respectively. The *FR*(60) can be calculated using the following equation:

$$FR(60) = FR(S) \times e^{(\frac{S-60}{S_P})} \tag{5}$$

where *FR*(S) = Friction value at selected slip speed *S*.
S = Selected slip speed, km/hr.

Vice versa, one can calculate the friction at any speed *FR*(*S*) if the friction value are given for the standard speed, *FR*(60) by following equation:

$$FR(S) = FR(60) \times e^{-(\frac{S-60}{S_P})} \tag{6}$$

Recommended Minimum Macrotexture

Based on the previous section, both *Sp* and *F*(60) are directly related to the macrotexture of the pavement surface. From Eq. (1), it follows that the higher the macrotexture, the higher the speed constant, *Sp*. From Eq. (4), the higher the macrotexture, the higher the international friction number, *F*(60).

To further illustrate the importance of macrotexture, especially at high speed, the friction speed curve shown in Fig. 6 was developed using the constants developed by UCPRC in Eq. (4). Fig. 6 shows that the higher the macrotexture, the flatter the friction-speed curve and higher the friction at high speed. For low macrotexture surfaces, the friction drops significantly at high speed. Therefore, minimum macrotexture level should be provided to ensure the safety of vehicles under high speed and wet pavement conditions.

Based on the testing results of the 2012 and 2013 skid and texture measurement, the recommended minimum macrotexture for open and Gap-Graded RHMA are 1.15 and 0.75 mm, respectively. These two macrotexture values are corresponding to skid numbers that are greater or equal to 30 for the ASTM skid trailer test.

Calculated, using the UCPRC developed constants, the IFI corresponding to the minimum macrotexture for the HMA open-graded are *F*(60) = 19, and *Sp* = 74 mph (119 km/hr), while the IFI corresponding to the minimum macrotexture for the RHMA-Gap Graded are *F*(60) = 19, and *Sp* = 46 mph (74 km/hr).

Conclusions and Recommendations

Based on the fog or rejuvenating seal studies in 2007 and 2009, and the pilot projects placed by Caltrans in 2012 and 2013, the following conclusions and recommendations are made.

Conclusions

The following are the major conclusions from the fog or rejuvenating studies for the Caltrans pilot projects:

- The field evaluation showed that fog or rejuvenating seal treatment sections performed better than the untreated or control sections. The treatments reduced the raveling and had fewer pavement distresses. However, different products performed differently.
- Performance based laboratory testing were conducted on field cores. The Hamburg Wheel Track test results showed that fog or rejuvenating seal treated cores had better rutting resistance and less moisture damage than the untreated control cores. Again different products performed differently.
- Generally, the macrotexture decreased with the fog seal applications. This was verified by both the sand patch test and the CTM.
- Generally, skid resistance of the pavement surfaces decreased after the fog seal was applied but was increased on the projects that included sanding or texture sealing.
- High macrotexture surface generally has higher high speed friction than low macrotexture surface for the same type of pavement. Macrotexture is a very important parameter for the increasing speed constant and friction number of the international friction index.

- For the 2012 and 2013 pilot projects, the range of texture levels for open-graded asphalt were from 1.15 to over 2 mm. Generally, the skid numbers of these open-graded pavement pilot projects were higher than Caltrans recommended minimum skid number.
- For the 2012 and 2013 pilot projects, the range of texture levels for gap-graded asphalt were from 0.75 to 1.38. The skid numbers of these gap-graded pavement pilot projects were higher than Caltrans recommended minimum skid number.
- Data from these seal coat pilot projects show that they benefit the longevity of gap and open-graded pavements.

Recommendations

The following are the recommendations from this Caltrans fog seal study:

- The higher the macrotexture levels reduce the safety risk due to high speed skid loss. Based on the 2012 and 2013 Caltrans pilot studies, the recommended minimum macrotexture for open-graded mixes is 1.15 mm, and the recommended minimum macrotexture level for rubberized gap-graded mixes is 0.75 mm.
- Different fog or rejuvenating seal products perform differently. Some would have less friction than others. Sanding should be applied after fog seal applications to ensure that the initial skid friction meets the minimum standards for highways.

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