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Laboratory Testing of Asphalt Surface Treatments for Airfield Pavements

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Abstract: The U.S. Army Engineer Research and Development Center conducted a study to provide recommendations for evaluating asphalt surface treatments for airfield pavements. The evaluation included an analysis of laboratory testing procedures to provide quantitative predictive performance capabilities. This paper contains testing results and provides guidance on selecting appropriate surface treatments based on laboratory testing procedures. Results indicate that ASTM D 2939 is appropriate for determining a product's fuel resistance. Calculations of the International Friction Index (ASTM E 1960) provided an effective quantitative procedure for predicting a product's impact on pavement friction. Tests performed to predict a product's ability to prevent oxidation and to predict delamination were inconclusive

***Key words**: Asphalt rejuvenators; Asphalt surface treatments; Fuel resistant sealers.*

Introduction

The United States Department of Defense maintains numerous airfields constructed of hot-mix asphalt (HMA) concrete pavement materials throughout the United States and worldwide. Over time, the asphalt cement that binds the aggregate matrix ages due to oxidation and volatilization of the binder. These processes lead to environmental distresses being formed in the pavement. Loss of aggregate adhesion and the formation of a variety of cracks can result from the aging of the pavement. These consequences can lessen the serviceability of the pavement or cause structural failure of the pavement. Another concern for deteriorating asphalt pavements is the possibility of foreign object damage (FOD). FOD is caused by the degradation of the pavement to the point where solid masses of materials become detached from the pavement surface. The separated FOD materials can cause severe damage to aircraft engines and bodies.

In addition to aging of asphalt, fuel spillages can cause deterioration of an asphalt pavement by weakening and loss of the asphalt cement. Since asphalt cement and common fuels are both of petroleum origin, they are miscible. Fuel that spills on a pavement is absorbed by the asphalt cement. The absorbed fuel decreases the viscosity of the binder and reduces its ability to hold aggregate in place. To mitigate this problem, a variety of materials have been developed to attempt to prevent damage to the asphalt from fuel spillage by providing a chemically resistant surface covering.

Maintenance of HMA pavements is often approached using one of two categories of materials developed for preventative maintenance: asphalt rejuvenators and asphalt surface coverings. Asphalt rejuvenators are considered to be materials that rehabilitate aged asphalt. Rejuvenators are often low viscosity fluids that are able to penetrate into a shallow depth, 0.6 to 1.3*cm* (¼ to ½*in.*), of the pavement. Moreover, rejuvenators have been shown to reduce the stiffness of asphalt binders, resulting in reduced brittleness and cracking in the penetrated pavement over time [1, 2]. Although application of an asphalt rejuvenator can increase the flexibility of a portion of the pavement, administration of rejuvenator substances in excess of prescribed amounts can lead to a reduction in the frictional characteristics of the pavement [3, 4].

The use of surface coverings is another technique used as preventative maintenance on asphalt pavements. Surface coverings are relatively thin (0.6 to 2.5*cm*) layers of sealant substances usually comprising emulsion-based fine aggregate mixtures. The surface coverings are placed on top of the existing pavement. Coverings may include slurry seals, micro-surfacing treatments, and thin surface overlays. The coverings are used to protect the pavement from environmental hazards as well as preserving the structural integrity of the pavement. Environmental hazards include the penetration of oxygen and ultraviolet light, both of which contribute at varying degrees to the oxidation and aging of the asphalt, and the penetration of water into the pavement. Furthermore, coverings prevent damaged portions of the underlying asphalt from degrading further and separating from the pavement, thus reducing FOD potential.

In addition to rejuvenators and surface coverings, other materials have been developed to help protect asphalt pavement against other forms of caustic attack. Bituminous asphalt, as a result of being of petroleum origin, is susceptible to corrosion from other petroleum products such as diesel and other fuels. Fuel spillages on airfield pavements, if unprotected, lead to penetration of fuel into the asphalt. These penetrating petroleum products dissolve the asphalt binder, leading to softening and loss of the binder from the asphalt matrix. The affected pavements can sustain excess rutting, cracking, and other related environmental distresses. To protect asphalt pavements from the possibility of fuel spillages, fuel resistant sealers (FRS) have been developed in an attempt to prevent the penetration of fuels into the interior of the pavement. In addition to preventing penetration of fuels and thusly removal of asphalt binder, application of these FRS also allows spilled fuels to be retained on the surface of the pavement until the substances can be removed or naturally evaporate.

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Traditionally, materials mainly consisting of coal tar have been used to protect asphalt pavements from the effects of fuel spillages. Coal tar is a by-product of the production of coke and natural gas fuels from coal. Many FRS are created from blends of emulsified coal tars and other additives, which may improve the general engineering properties of the sealers. After placement of the sealers, the coal tar prevents petroleum fuels from penetrating into the pavement until evaporation removes the fuel from the surface of the pavement. Coal tar, however, is not without adverse consequences when used as a sealer. Oftentimes, coal tar has a relatively short usable lifespan, around one year, before environmental stresses tend to appear. Additionally, coal tars have been shown to contain polycyclic aromatic hydrocarbons, a chemical that has negative health effects, including cancer [5, 6]. These cancer-causing agents have also been detected in runoff from parking lots sealed with coal tar products [7]. As a result of these undesirable traits inherent to coal tar sealers, other materials, such as acrylic or epoxy compounds, have been researched to fulfill the same function as FRS.

The objective of this study was to evaluate a number of testing methods to be used to examine the acceptability of preventative maintenance products for use on Department of Defense airfields. Evaluation procedures were researched and investigated in three separate categories for individual applications: (1) asphalt rejuvenators, (2) surface coverings, and (3) FRS. Three distinct investigation routes were pursued to account for these chief applications for which the treatments are used on airfields. Sample products were evaluated in laboratory testing and in small scale field testing with the purpose of assessing the feasibility of creating specifications for acceptance of products in a given surface treatment category. The study was not intended to determine the best product for use in these categories; rather, the study investigated and evaluated testing procedures that could potentially be used to rate the acceptance of a product for use on pavement maintenance and rehabilitation projects.

For each category of products in this study, a variety of independent tests was chosen to evaluate the products. Asphalt rejuvenators were to be investigated for their effects on the chemical and physical properties of the asphalt binder, the aging process of the binder, and the overall skid resistance of the pavement. Surface coverings were to be investigated for their adhesion to the underlying pavement, ability to protect the pavement from the environment, and skid resistance. FRS were to be investigated for their fuel resistance, ability to protect underlying asphalt from the environment, and effects on the skid resistance of the pavement.

Materials and Methods

A representative sample of various products from the asphalt industry marketed as possessing the stipulated properties for each category were attained and used in the testing for this study. An overview of the products used in the study can be seen in Table 1.

Several laboratory testing procedures were chosen to evaluate certain properties of asphalt pavement surface treatments and their effects on the pavement. Each of the tests was performed on a number of industry samples. The testing methods were then evaluated to determine their applicability to assess surface treatment products.

Table 1. Products Tested.

Product	Description
	Surface Coverings
Product 1	Polymer-modified asphalt emulsion. Contains premixed fibers, rubber, and aggregates.
Product 2	Coal-tar emulsion. Requires mixing with provided aggregate blend.
	Sealers
Product 3	Polymer-modified asphalt emulsion. Applied as sealant with no added aggregates.
Product 4	Polymer-modified, mineral-reinforced asphalt emulsion. Requires mixing with job-specific fine aggregate (not included).
	Fuel Resistant Sealers
Product 5	Acrylic-based polymer emulsion. Requires mixing with sand (not included).
	Rejuvenator/Sealers
Product 6	Polymer-modified asphalt emulsion. Does not require addition of aggregate.
Product 7	Coal-tar-based emulsion. Does not require addition of aggregate.
Product 8	Petroleum-based emulsion. Does not require addition of aggregate.

Fuel Resistance

Fuel resistance testing is used to assess the ability of a given material to prevent the penetration of petroleum fuels through the material. ASTM D 2939 [8] outlines a standard procedure for testing the fuel resistance of a material. The procedure uses kerosene as the testing fuel. The testing involves placement of the sealers onto ceramic tiles in two separate layers of given thicknesses. The layers are allowed to cure at 25^{o}C and 50 percent relative humidity for 96hrs before either the next layer is applied or the kerosene is placed on the sealer. Following completion of the sealer curing process, a metal ring of approximately $5cm$ ($2in$) in diameter and $2.5cm$ ($1in$) in height is applied to the surface of the sealer with solvent resistant cement, into which kerosene is added for the testing after the cement hardens. After the kerosene is allowed to stay on the sealer layers for 24hrs, the tiles are broken in half and inspected for leakage and failure of the sealer.

The testing undertaken in the laboratory involved a deviation from the ASTM standard for the testing procedure for fuel resistance. Coleman® Camp Fuel was used as the testing fuel instead of standard kerosene. The fuel is considered as a hydrotreated light petroleum distillate. The camping fuel consists of Cyclohexane, Nonane, Octane, Heptane, and Pentane. Coleman® Camp Fuel can be used to achieve comparable results in terms of fuel penetration to that of kerosene. During testing, the ring containing the fuel was covered to prevent evaporation.

Artificial Aging

Investigation of the chemical properties of asphalt binder before and after the use of an asphalt rejuvenator on the binder can be analyzed to determine the effectiveness of the rejuvenator. Additionally, the properties of the asphalt binder beneath protecting layers can be analyzed to investigate the ability of surface coverings to protect the underlying asphalt from environmental wear and aging. For this study, Fourier-Transform Infrared Spectroscopy (FTIR) was used to investigate the chemical properties of the asphalt binder in conjunction with the use of various surface treatments through artificial aging.

The aging of asphalt was simulated via heating in a forced draft oven. Control (no aging), 5-day, and 30-day samples were used in the experimental proceedings to assess the evaluation of the effects of rejuvenators and surface coverings on asphalt. In all aged samples, the samples were aged for the prescribed duration at 85℃ (185ºF). This temperature was selected from recommendations made to the Federal Highway Administration [9]. The asphalt core samples used in the testing were laboratory samples compacted to 96 percent of theoretical maximum density using a Superpave gyratory compactor and 6-*in* (15.24-*cm*) diameter molds. The asphalt mixture used was designed for use on Department of Defense airfields according to the Unified Facilities Guide Specification UFGS 32 12 15, Hot Mix Asphalt for Airfields [10]. The mixture contained a limestone aggregate with a maximum size of 12.5*mm* (½-*in*) and 5.5% PG 64-22 graded asphalt cement binder.

The testing of the effects of rejuvenators was conducted by aging unmodified samples for the given test periods, then applying rejuvenating products to the top surfaces of the samples. On the other hand, the surface coverings were investigated by applying the products prior to oven aging. Preemptive application of the coverings was designed to enable comparison of underlying asphalt to unprotected asphalt with similar aging conditions.

Upon completion of the aging procedure, the asphalt cement was recovered for testing. Only the asphalt cement near the surface of the sample was recovered because underlying material was not expected to have been significantly affected by the aging procedures. To eliminate effects from the edge of the samples, the 15.2-*cm* (6-*in*) cores were reduced in size by coring a 10.2-*cm* (4-*in*) sample from their center using an asphalt coring rig. For the rejuvenators, the top 1*cm* (3/8*in*) of the test sample was then removed using a saw. For surface coverings, the coating was first removed with the saw. Care was taken to only remove the coating by visibly inspecting the sample. After the coating was removed, the top 1*cm* (3/8*in*) layer of asphalt concrete was removed for testing.

The asphalt cement was extracted from the samples by breaking the sample into small pieces and placing in an Erlenmeyer flask with approximately 100*ml* of trichloroethylene. The sample remained in the flask overnight to allow most of the asphalt cement to dissolve. The solution was filtered over a #200 sieve and placed in a shallow pan under a laboratory hood to evaporate the solvent. The residue was collected and labeled for testing.

FTIR was used to monitor changes in asphalt cement chemical properties upon artificial aging. This technique creates a chemical "fingerprint" of materials. It uses infrared radiation to excite chemical bonds between atoms of each molecule. The absorption and transmission of different frequencies of radiation are used to identify the chemical composition of a substance.

In this study, the Attenuated Total Reflectance (ATR) method of FTIR was used to obtain spectra. ATR is a technique that reflects the source radiation off the surface of the sample. ATR-FTIR can be employed on solids or liquids and requires little effort to prepare samples for testing.

In addition to FTIR, the penetration of the recovered binder was measured according to ASTM D 946 [11]. This procedure has been used in previous studies and was selected as a reference procedure to evaluate the spectroscopy technique.

Skid Resistance

One of the major concerns for the use of any surface treatment on asphalt pavements is the effect of the treatments on the skid resistance of the pavement. Loss of surface friction on airfield pavements can lead to an increased risk of traffic incidents on the pavement, thus creating new problems for the pavement users. Therefore, materials to be used for any purpose on airfields should achieve a minimum allowable surface friction characteristic.

The Dynamic Friction Tester (DFT) is a method of testing the friction characteristics of a given surface area, as outlined in ASTM E 1911 [12]. The DFT measures the tangential friction force developed by the contact of rubber feet connected to a rotating disk with the test surface. The disk is rotated above the surface until a speed of 80*km/hr* (50*mph*) is achieved. Once the desired speed is reached, water is applied to the surface by the device and the disk is lowered into contact with the surface. The friction force developed is then calculated with respect to the rotational speed. The device needs only a small portion of pavement, 45 × 45*cm* (17.75 × 17.75*in*) to measure the friction characteristics of a material. Therefore, frictional effects of a surface treatment on asphalt can be tested at a small scale without having to apply the material to large areas of pavement.

In addition to the frictional characteristics, the macrotexture of a pavement surface also plays an important role in the pavement's trafficability characteristics. The surface texture of pavement at the macroscopic level can be used in conjunction with the friction characteristics of the pavement to evaluate the general surface quality of the pavement with respect to skid resistance and vehicle safety. Macrotexture for a given surface can be calculated in terms of the average Mean Profile Depth (MPD) of the surface. The MPD is a quantitative means of expressing the amount of irregularity present in the pavement surface. Moreover, larger surface profile depths generally equate to more advantageous frictional characteristics for the surface.

The macrotexture of a given surface can be analyzed using a Circular Texture Meter (CTM). This device, described in ASTM E 2157 [13], uses a laser to analyze the pavement surface and measure a profile of depths on the surface beneath the device. The system averages the depths of surface irregularities over the area of a circle approximately 28.5*cm* (11.2*in*) in diameter. The MPD is then calculated from these measurements. The MPD can be used along with the friction characteristics found using the DFT to determine the International Friction Index for the pavement, as outlined in ASTM E 1960 [14].

For this study, friction and texture characteristics were tested on 0.9 by 1.2*m* (3 by 4*ft*) surface patches. Various surface treatments were placed onto a pavement of approximately 25 years in age. No traffic was applied to the pavement during the test. In addition to

Fig. 1. Applying a Surface Treatment with a Garden Sprayer.

Fig. 2. Placing an Asphalt Sealer with a Squeegee.

sample patches of treatment products, control areas were analyzed for comparison. The products were placed and allowed to cure for approximately 24hrs before the friction testing took place. In addition to 1-day cure testing, the patches were tested for friction characteristics following a 50-day curing period. The second set of tests was conducted in locations slightly adjacent to the original tests. Three tests were taken at each location with the DFT during both testing dates. One measurement was taken on each section with the CTM during the first testing date; three measurements were taken with the CTM on the second testing date.

Test sections for this portion of the study were located on an unused pavement section at the U.S. Army Engineer Research and Development Center (ERDC) Vicksburg site. The pavement surface was cleaned by sweeping prior to any product application. Sections were marked for product placement by taping the treatment area and painting numeric identifiers by each section. Liquid products with an allowable viscosity were sprayed onto the pavement surface using a 3.8 liter garden sprayer (Fig. 1). Other products were applied using a squeegee (Fig. 2). Some products were measured to a specific quantity. Others were placed onto the surface until the pavement was thoroughly coated. Rejuvenators were spread onto the surface using the squeegee and then blotted with paper towels to remove excess material.

Pull-Off Strength

For seal coats and other pavement surface coverings, adhesion of the covering layer to the underlying pavement is imperative. Without sufficient adhesive strength, surface coverings cannot withstand high pressure traffic without being removed from the pavement or suffering cracking and failure. Adhesive qualities can be determined by the pull-off strength test outlined in ASTM D 4541 [15] using the Elcometer testing device. The test involves applying a circular dolly to the testing surface with epoxy or some other adhesive substance. A normal pulling force is then applied to the dolly at an increasing rate until failure occurs on the surface. Failure involves the removal of the dolly from the surface of the sample and can be achieved by either removal within the sealer layer (cohesive) or removal of the sealer layer from the substrate (adhesive). The device includes a gauge for measuring the approximate pressure applied to the dolly before failure; however, the system for measuring the applied force does not measure with the accuracy required for precise measurements. Therefore, the usefulness of this test lies in qualitative observations of the failure modes, as described above, of the products along with less practical estimates of the failure strength.

The testing procedure used in this study consisted of placement of sealers on samples, application of the testing dollies, and removal of the dollies from the surface. The seal coats were placed on the surface of laboratory-compacted asphalt samples following the manufacturers' guidelines for application rates and placement. The materials were allowed to cure for at least 5 days. That is, the sealers were placed and allowed to cure sufficiently to levels exceeding those at which the seal coats would normally be opened to traffic. Following the curing period, device dollies were attached using 2-hour, 27.6*MPa* (4000*psi*) strength generic epoxy. After overnight curing of the epoxy to the testing surfaces, the dollies were tested using the Elcometer device. Three samples were created for each product used in the testing. On each asphalt sample, three dollies were placed and tested; therefore, a total of 9 tests were conducted for each individual product application. Surfaces were inspected following the removal of the dollies from each sample to determine mode of failure for the each test.

Results and Discussion

Fuel Resistance

Five tests were run on four products (one test was run on untreated asphalt) for the fuel resistance testing. An overview of the results from the test can be seen in Table 2.

As shown in Table 2, after 24hrs of fuel application, the Product 1, Product 2, Product 4, and Product 5 samples all passed the fuel resistance tests. The failing test was the untreated asphalt covered sample. Materials that passed were able to prevent the penetration of the fuels for the allotted time period. Prevention for the allotted time allows the fuels to evaporate from the surface before damage can

Table 2. Results from Fuel Resistance Test.

Product	Fuel Resistance
Product 1	Passed
Product 2	Passed
Product 4	Passed
Product 5	Passed
PG 64-22 AC	Failed

occur to the pavement. In general, the materials that passed the fuel resistance test were those that can be applied to create a consistent sealed layer of protection.

The testing procedure outlined in ASTM D 2939 provides an acceptable representation of a product's ability to protect the underlying pavement from damage due to fuel spills. The test period (24hrs) allows sufficient time for fuels held on the surface of the pavement to be evaporated. This test is recommended for screening potential candidates where fuel resistance is required. Additionally, this test is supported by the Airport Asphalt Pavement Technology Program (Project 05-02) for a standard test for fuel resistance after reviewing alternative methods. However, the final report from this project was not complete at the time of this publication.

Artificial Aging

Only certain peaks within each FTIR spectra were used in the analysis. The two main absorption areas in each spectrum include the carbon-hydrogen bond peaks near 3000 and 1400cm^{-1}. Distinctive peaks from other chemical bonds such as carbonyls were generally not observed. These peaks have been associated with chemical formations found in oxidized asphalt [16]. Some spectra contained absorptive peaks from residual solvent or moisture in the sample. Due to the lack of conclusive findings, a detailed description of each spectra and its significance is not given. Fig. 3 shows representative FTIR spectra for the asphalt binder.

Table 3 shows the results from the penetration testing of the recovered asphalt cement for each set of samples. The average penetration of the unaged control samples was 27. The average penetration of the control samples aged for 5 days was 38. The increase in penetration was not expected and may have been caused by residual solvent in the sample. The average penetration of the control sample after aging for 30 days was 7. The decrease was expected due to stiffening of the binder through oxidation or loss of volatiles.

Most of the samples treated with sealers had penetration values similar to the control samples. This observation acknowledges that the 5-day penetration of the control sample was higher than expected. The rejuvenator/sealer and the two rejuvenators had average 5-day penetration values higher than the other samples. Product 7 had the highest average penetration after 5 days of aging. These results show that the rejuvenator/sealer and the rejuvenators did soften the binder. After 30 days of aging, the average penetration of Products 6 and 7 had decreased below the average penetration of the unaged control sample. The reduction in penetration may have been caused by volatilization of the rejuvenating product. Product 8 continued to soften the binder as evidenced by the very large increase in penetration. The 30-day sample for product 8 may have been treated with excessive quantities of rejuvenator

The artificial aging testing did not reveal differences in the chemical fingerprint of aged and unaged specimens. This method was not effective for predicting an asphalt sealer's ability to prevent oxidation of the binder on the pavement surface. Artificial aging has been attempted in several research projects, but the ability to differentiate

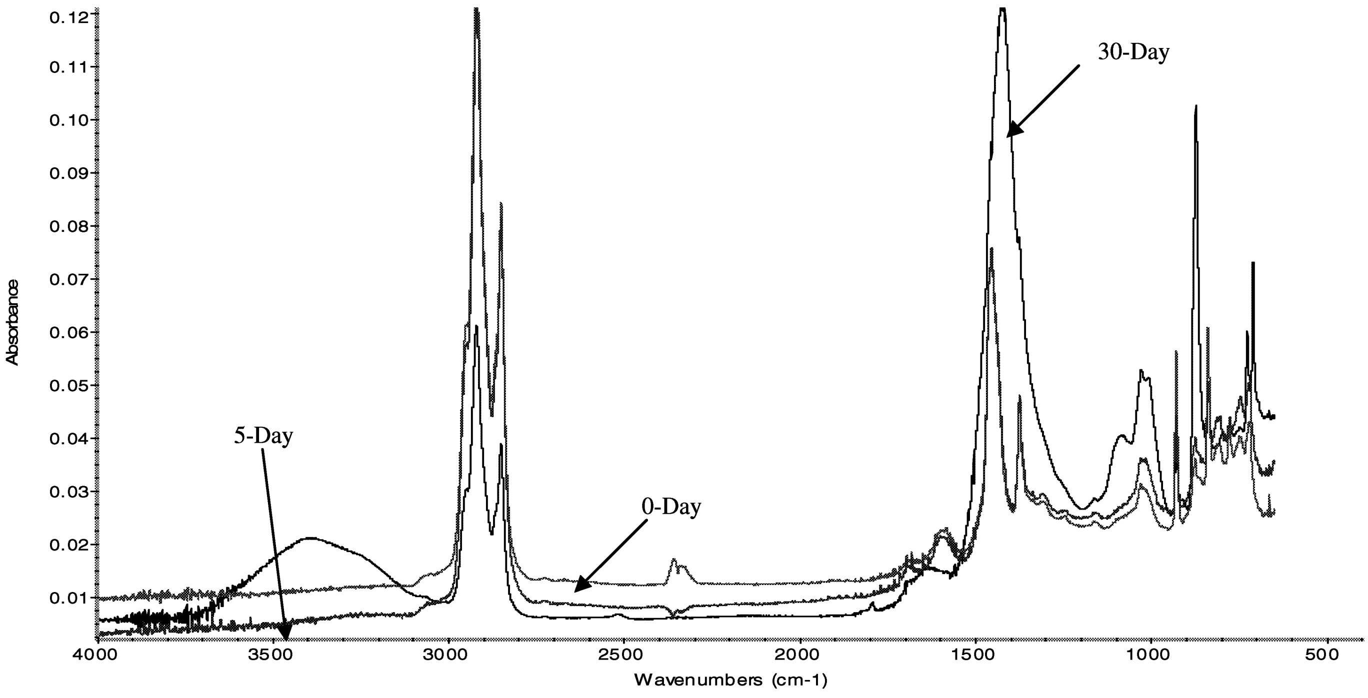

Fig. 3. FTIR Spectra Control.

Table 3. Penetration Test Results (0.1*mm*).

	0 Day				5 Day				30 Day			
	Pen1	Pen2	Pen3	Average	Pen1	Pen2	Pen3	Average	Pen1	Pen2	Pen3	Average
Control	27	26	28	27	42	37	35	38	7	7	8	7
Surface Coverings												
Product 1					18	17	17	17	6	10	10	9
Product 2					16	20	17	18	15	21	19	18
Sealers												
Product 3					16	16	15	16	9	8	9	9
Product 4					23	27	24	25	10	13	11	11
Fuel Resistant Sealers												
Product 5					18	22	21	20	21	15	16	17
Rejuvenator/Sealers												
Product 6					36	41	38	38	16	20	18	18
Product 7					80	65	68	71	20	23	19	21
Product 8					32	35	33	33	245	238	242	242

Table 4. Skid Resistance Test Patches.

Section	Product	Description
1	Product 2	Type A Aggregate
2	Product 2	Type B Aggregate
3	Product 2	Masonry Sand
4	Product 2	Spray seal – 2 Coats
5	Product 2	Spray seal – 1 Coat
6	Product 1	1 Coat
7	Product 1	2 Coats
8	Product 8	0.23*l/m*^{2}
9	Product 8	0.45*l/m*^{2}
10	Product 4	1 Coat
11	Product 4	2 Coats
12	Product 5	1 Coat
13	Product 5	2 Coats
14	Product 6	0.36*l/m*^{2}
15	Product 6	0.18*l/m*^{2}
16	Product 3	0.72*l/m*^{2}
17	Product 7	0.29*l/m*^{2}

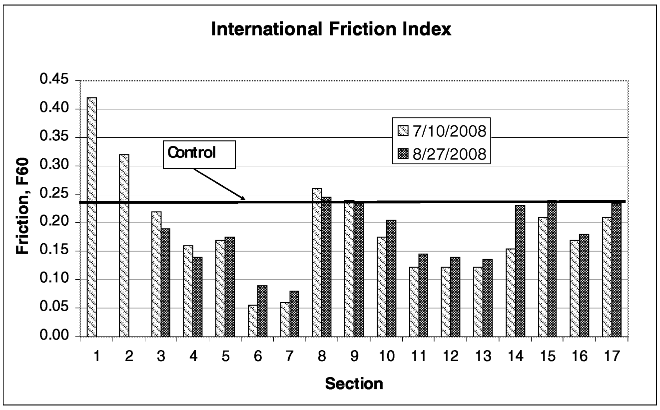

Fig. 4. International Friction Index.

performance of a sealer has not been successfully reported. Other test methods for artificially-aged specimens have included direct tensile testing or stability testing of the samples and viscosity testing of binder recovered from the aged specimens. At this time, a procedure for quantifying a product's ability to prevent oxidation is not available. Although longer aging times may have provided better results, they were not attempted due to the impracticality of the procedure for rapid performance assessment.

Penetration testing of the recovered asphalt binder provided some indication on the ability of rejuvenators to soften the binder and the ability of the surface coverings to protect the binder. However, these results are expected to be affected by sample preparation. Factors such as residual solvent in the binder or fines from the aggregate would be expected to alter the results. Penetration data are only used in this study to provide some qualitative comparison data.

Skid Resistance

The combined use of the DFT and the CTM resulted in the determination of the friction characteristics of a sample pavement. The coefficient of friction for the sample pavements is taken by the DFT at 0, 20, 40, 60, and 80*km/hr*. As per ASTM 1960, the International Friction Index (IFI) can be calculated by correlating the friction determined at 20*km/hr* with a speed constant of wet pavement friction (S_p) to a friction value at 60*km/hr* (F60). The speed constant is determined from the mean profile depth of the sample pavement. The results of the regressions for the pavements tested can be seen in Fig. 4 with a description of each section in Table 4. In Fig. 4, the control line represents the average baseline for IFI for the unmodified pavement used in the testing. Figs. 5 and 6 show the results for the DFT at 60*km/hr* and the CTM for each section. The DFT data for the 60*km/hr* tests were selected for presentation because this speed closely relates to the current criteria for measuring friction values on airfield pavements. The error bars in both figures represent one standard deviation for three data points from each test.

Fig. 4 shows the majority of the surface treatments caused at least a slight decrease in the frictional characteristics of the pavement. The treatments that increased the friction of the pavements were those that contained large aggregates and created a more textured

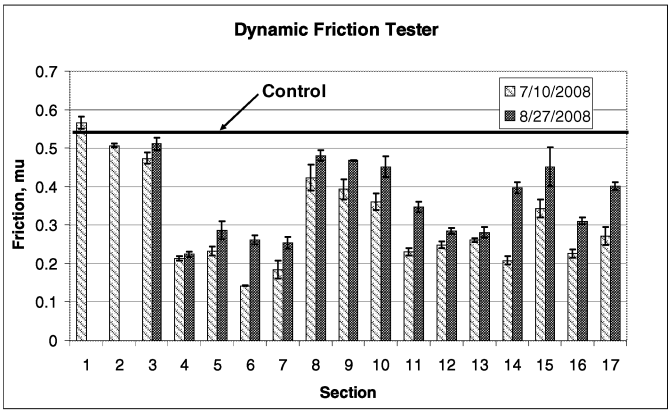

Fig. 5. Dynamic Friction Tester Results.

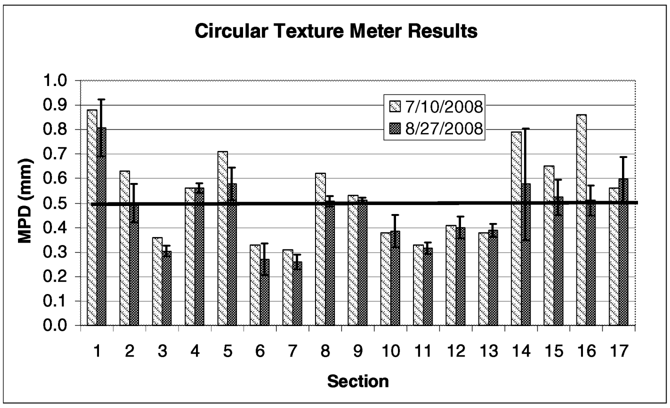

Fig. 6. Circular Texture Meter Results.

Table 5. Pull-off Failure Results.

Product	Strength, *MPa*	Failure Type
Product 1	2.83	cohesive
Product 2	2.07	both
Product 3	2.48	adhesive
Product 4	1.93	cohesive
Product 5	2.21	adhesive
Product 6	2.07	adhesive

surface. Contrary to previous results [4], sample patches treated with rejuvenators did not show as large of a decrease in skid resistance as expected. Although some of the patches treated with rejuvenator materials did show some decrease in friction (14, 15, and 17), others (8 and 9) did not show any marked decrease in frictional characteristics. The method of friction testing, however, could cause the unexpected readings for the rejuvenator patches. Moreover, the DFT tests friction by applying water to the surface of the test patches. The application of water during testing could remove material that did not penetrate the surface during the 24hrs curing time and lessen the effect of excess residue on the skid resistance of the treated surfaces. In spite of possible inaccuracies due to testing methods, the rejuvenated test patches that had some initial decrease in skid resistance did show an increase in friction in the later test date, as expected from Shoenberger's test results [4].

Test patches treated with surface coverings not containing large aggregate materials (3-7 and 10-13) were found to have a larger amount of friction loss compared to rejuvenator-treated and untreated pavements. These findings are in agreement with previous research that has shown seal coats with little to no large aggregates lower the skid resistance of pavements in comparison to untreated pavement [4]. Although the use of large aggregates in surface covering treatments may increase the surface friction of a pavement, these treatments also increase the danger of FOD damage to aircraft operating on airfield pavements with larger aggregates being removed by severe traffic loads.

The results from the DFT and CTM tests give the frictional characteristics of pavements in terms of the IFI. For this study, the IFI was used to address the effects of the surface treatments on the skid resistance of the pavement. The tests showed, in agreement with previous studies, surface coverings with large aggregates increase the skid resistance of the pavement; whereas, surface coverings without sufficient amounts of large aggregates substantially lower the skid resistance in comparison to untreated pavements. On the other hand, pavements treated with asphalt rejuvenators had only a marginally lower skid resistance than non-treated controls, possibly due to inherent features of the testing method.

Comparing the results for skid resistance testing to previous research shows the methods used in this study provide comparable results for the general effects of the application of surface covering products. However, the methods used do not show expected results for pavements treated with rejuvenators. Additional investigation is needed to study the effects of rejuvenator application amounts and cure times on the frictional characteristics of the pavement.

Overall, the combination of the DFT and CTM provided a portable, rapid measurement system for determining a pavement's frictional characteristics. Previous research with these devices has shown that accurate correlations can be drawn between it and other devices such as the Grip Tester. These devices could be used along with the existing ASTM guidance for measuring pavement friction for airfield pavements. Minimum friction values would need to be developed for airfields prior to implementation.

Pull-Off Strength

Six products were chosen to conduct the pull-off strength testing: Products 1 to 6. The testing was mainly concerned with the tensile strength of the interface between surface coatings and pavement surfaces; therefore, only the products that were considered surface coverings were tested. Moreover, liquid rejuvenators are generally designed to penetrate into the surface of the pavement, leaving negligible amounts of material to cover the material. The results of this portion of the study can be seen in Table 5.

Several notes should be made about the testing and results of the pull-off strength testing. Certain products, such as Product 6, are considered sealer/rejuvenators. In effect, these products are designed to penetrate into the surface of the asphalt. Therefore, although data were gathered for this product, the material layer tested on the specimens was more of a thin film than a substantive environmental barrier. Additionally, the Product 3 specimens created a slick surface, seemingly precluding the attachment epoxy from creating an adequate bond with the surface. The lack of bond formation for much of the testing on this product resulted in excessive failures in the test runs.

Some tests resulted in failures reported as having more than one failure mechanism. For instance, the Product 2 samples experienced both cohesive and adhesive failure. For the most part, however, the results indicate a specific failure mechanism for each product type. Mixed failure mode results along with occasional failure of the testing procedure highlights the necessity to perform repeated tests on untested areas of the samples in order to get more data and a more accurate view of the strength behavior of a given product application.

The strengths calculated and the accuracy of these measurements given the imprecise nature of the measurements taken with the Elcometer negates much of the usefulness of the strength values for the treatment materials. The results for the strengths calculated by tests on the same sample vary as much as 1.4*MPa* (200*psi*). Therefore, the more useful result of this test is the method of failure. The results show an increase in the occurrence of cohesive-type failures as the thickness of the treatment layer increases. Products that created only a thin layer upon application tended to result in adhesive failure as the thin layers were removed from the asphalt by the force.

The results for pull-off strength testing using the Elcometer device are expressed in terms of a descriptive failure mechanism of the pull-off testing along with an approximation of the strength required to initiate this failure. The standard testing procedure is accurate in giving a qualitative description of the failure mechanism of tested products, but is not accurate in determining strength values for the failure. The number of samples and test repetitions should be investigated in order to determine the amount of samples needed to get statistically adequate results for this method.

This test could provide an initial assessment of a product's ability to adhere to the existing pavement. The test may predict premature failure from loss of adhesion. However, the effect of aged pavement and sealers on the results is not known. Adhesive characteristics may change over time as the sealer deteriorates. Additionally, surface preparation and application technique is expected to have a large effect on the ability of a sealer to resist delamination. For these reasons, it is not expected that the Elcometer device will successfully predict loss of adhesion. It may be used as an initial screening device to examine failure mechanisms of unfamiliar products.

Conclusions

Test results indicate ASTM D 2939 provides an acceptable procedure for determining if an asphalt sealer is fuel resistant. All products that were marketed for fuel resistance passed this test. These materials have a good performance history in the field.

For this study, FTIR Spectroscopy was unable to quantify the ability of asphalt sealers to prevent oxidation when testing oven-aged specimens for five or 30 days at 85°C. This method of spectroscopy was not evaluated under alternate conditions. Penetration results revealed that the specimens aged for 30 days had a lower penetration than those aged for 5 days. The lower penetration is indicative of a stiffer binder. The stiffening of the binder is likely caused by a loss of volatiles or oxidation of the binder during the aging procedure.

The DFT and CTM provided an efficient procedure for evaluating multiple asphalt sealers in simulated field conditions. The devices were portable, required only one operator, and could collect the required data in a short time period (less than 15 minutes per site). The DFT and CTM results can be used to calculate an IFI for the pavement. Results from this calculation using the data obtained from these devices correlated well with observed characteristics and prior research. Sealers containing relatively large aggregate provided an increase in friction relative to the existing pavement. Many other sealers reduced the friction relative to the existing pavement.

The Elcometer device is capable of determining whether adhesive or cohesive failure is likely to occur in an asphalt sealer. The device also provides a value for pull-off strength. The failure mechanism provided by the Elcometer device was considered more reliable than the strength measured. Its ability to predict the failure mechanism for aged pavement is not known.

Asphalt sealers should be evaluated to determine their impact on frictional characteristics of the pavement prior to their use on an airfield. Small test areas are sufficient for observing the frictional characteristics of the sealer. The DFT and CTM are an example of one method to measure the friction. Other methods such as the Grip Tester are also appropriate but not discussed in this paper.

If the DFT and CTM are used to determine frictional characteristics of airfield pavements, further research should be conducted to provide a range of acceptable values that correlate with appropriate pavement friction.

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