ERDC/GSL TR-14-11

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Field Evaluation of Ultra-High Pressure Water Systems for Runway Rubber Removal

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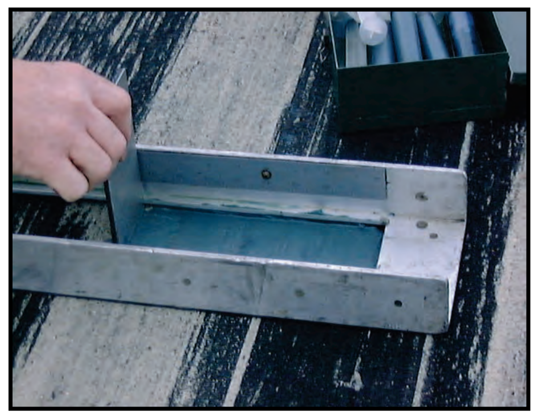
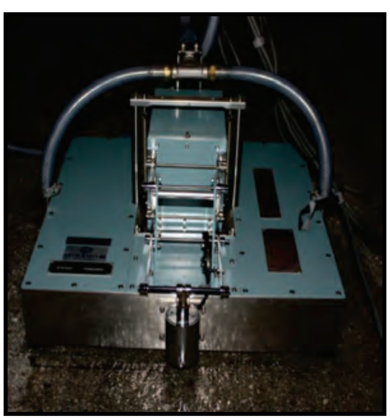
April 2014





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Aaron B. Pullen

Applied Research Associates, Inc.
421 Oak Avenue
Panama City, FL 32401

Lulu Edwards and Jeb S. Tingle

Geotechnical and Structures Laboratory
US Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180

Craig A. Rutland

Civil Engineering Branch, Engineering Division
Air Force Civil Engineering Center
Tyndall Air Force Base, FL 32403-5319

Final report

Prepared for Headquarters, Air Force Civil Engineer Center
Tyndall Air Force Base, FL 32403-5319

Abstract

Runway rubber removal is a maintenance function employed to ensure safe landing areas for aviation operations. Rubber deposits accumulate on runway areas where aircraft tires touch down and braking occurs. This tire rubber buildup occludes pavement microtexture and macrotexture, causing a significant loss in available skid resistance during wet conditions. Reduction of available pavement microtexture in a wet environment prevents the development of adhesional friction, which can lead to viscous hydroplaning. Reduction of pavement macrotexture prevents removal of bulk water from the tire-pavement contact area and prevents development of the hysteresis frictional component. The US Army Engineer Research and Development Center (ERDC) in Vicksburg, MS, was tasked by the Air Force Civil Engineer Center (AFCEC) to evaluate the performance of ultra-high pressure water (UHPW) rubber removal technologies; this work was conducted in collaboration with Applied Research Associates, Inc. (ARA). Several types of commercial UHPW water blasting systems were tested on an ungrooved portland cement concrete (PCC) runway and data were compared using statistical methods. Runway pavement skid resistance characteristics, such as friction and surface texture, were evaluated before and after rubber removal operations. Equipment run times, consumable resources, and climatic conditions were monitored.

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Preface

This study was conducted for and funded by the US Air Force Civil Engineer Center (AFCEC), located in Tyndall Air Force Base, FL. Dr. Craig A. Rutland from AFCEC provided guidance during the project. The field evaluation was completed during September 2011.

The work was performed by the Airfields and Pavements Branch (APB) of the Engineering Systems and Materials Division (ESMD), US Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL) and Applied Research Associates, Inc. (ARA).

The Federal Highway Administration (FHWA) Pavement Surface Characteristics (PSC) loan program provided pavement friction and texture measuring equipment for this study. Dr. Zoltan Rado of Pennsylvania State University provided technical expertise. Tom Yager, National Aeronautics and Space Administration (NASA) Langley Research Center Senior Research Engineer, helped direct the project. Thane Lundberg, AFFTC Flight Test Engineer (FTE), provided input and testing coordination. Kenneth Crawford, 95th Air Base Wing (ABW) Civil Engineering Project Manager (CEPM) provided coordination and support of field testing.

At the time of publication, Dr. Gary L. Anderton was Chief, APB; Dr. Larry N. Lynch was Chief, ESMD; and Dr. David A. Horner was the Technical Director for Force Projection and Maneuver Support. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Dr. David W. Pittman.

COL Jeffrey R. Eckstein was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square feet	0.09290304	square meters
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

1.1 Background

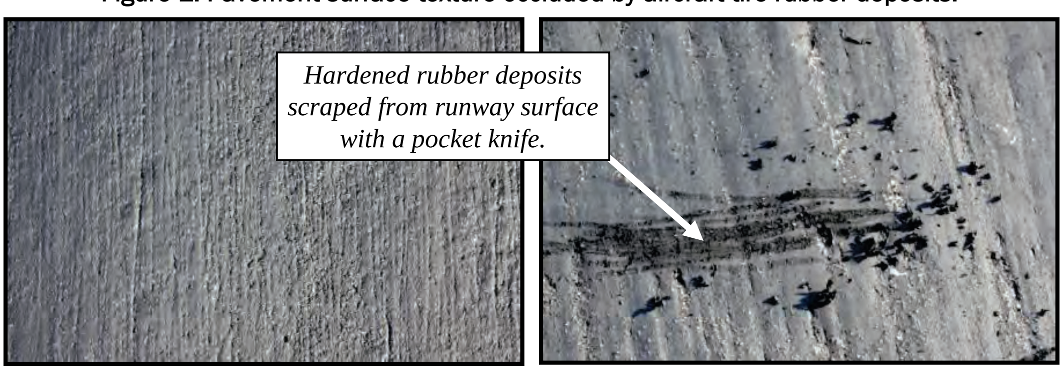
Pilots rely on runway pavements to have adequate skid resistance to safely land aircraft. Runway pavement skid resistance tends to degrade over time due to several factors. Two primary factors are mechanical wear from aircraft tires rolling and braking on the runway surface and the accumulation of contaminants on the runway surface.

Contaminants can be rubber deposits, dust particles, jet fuel, oil spillage, water, snow, ice, and slush. Each of these may cause a loss of tire-pavement friction on a runway. The most persistent contaminant problem is the rubber deposited from the tires of landing aircraft.

Aircraft tires, stationary at time of landing, skid for some time until the tangential speed of the tires equalizes to the aircraft travel speed. During this 'spin-up' period, intense heat caused by friction at the tire-pavement interface changes the composition of some of the tire rubber, melting it into a hard carbonized layer on the runway (Speidel 2006). According to one author, the Space Shuttle, touching down at 220 knots, can wear through 11 tire plies if a crosswind is present at Kennedy Space Center (Currey 1988).

Thin layers of rubber are deposited throughout the course of landings, eventually overtaking a pavement's surface texture as shown in Figure 1. This tire rubber buildup obscures pavement markings and eventually occludes pavement texture, causing a significant loss in available skid resistance during wet conditions.

Figure 1. Pavement surface texture occluded by aircraft tire rubber deposits.



1.2 Objectives

The purpose of this research project was to compare the performance characteristics of ultra-high pressure water (UHPW) rubber removal systems. Specific objectives of this research included:

- Compare commercially available UHPW runway rubber removal technologies with equipment identified during the Foreign Comparative Test (FCT).
- Identify measures which may assist in the development of specifications for future procurements.
- Identify technologies that may offer additional military and operational utility which may warrant further development or testing.
- Observe and measure field operation and maintenance of each system.
- Measure improvements in pavement surface characteristics imparted by each technology.

1.3 Scope

This research effort consisted of evaluating performance characteristics of three commercially available UHPW runway rubber removal systems. Each system was evaluated for possible selection as an easily operable technology for restoring runway pavement texture and pavement-tire friction to safe aircraft operating levels with no unintended pavement damage. The efficacy of each system was evaluated based upon improvements imparted to pavement surface characteristics as well as simplicity of system operation and maintenance.

1.4 Report organization

This report is presented in eight chapters. Chapter 1 provides background information on runway skid resistance and rubber removal. Chapter 2 is a literature review discussing measuring pavement surface characteristics and runway rubber removal techniques. Water blasting test articles are presented in Chapter 3. Chapter 4 describes the experimental design and pavement surface characteristics measuring equipment. Chapter 5 presents results and discussion. Chapter 6 summarizes key findings in this study. The final chapter lists all documents referenced in this research.

2 Literature Review

2.1 Pavement texture

In 1699, French physicist Guillaume Amontons proposed that friction between two bodies is influenced by surface roughness (Simpson 1988). Wet pavement-tire friction largely depends on pavement texture. Pavement textures may appear smooth, but are actually characterized by undulations and asperities. Common methods to achieve surface texture in portland cement concrete (PCC) pavements include wire tining, burlap dragging, and brush finishing. Aggregate gradation, size, and shape primarily influence the surface texture of bituminous pavements.

Pavement textures are classified based on the magnitude of amplitudes and wavelengths deviating from a true planar surface. Table 1 presents the three categories of pavement texture defined by the Permanent International Association of Road Congresses (PIARC 1987).

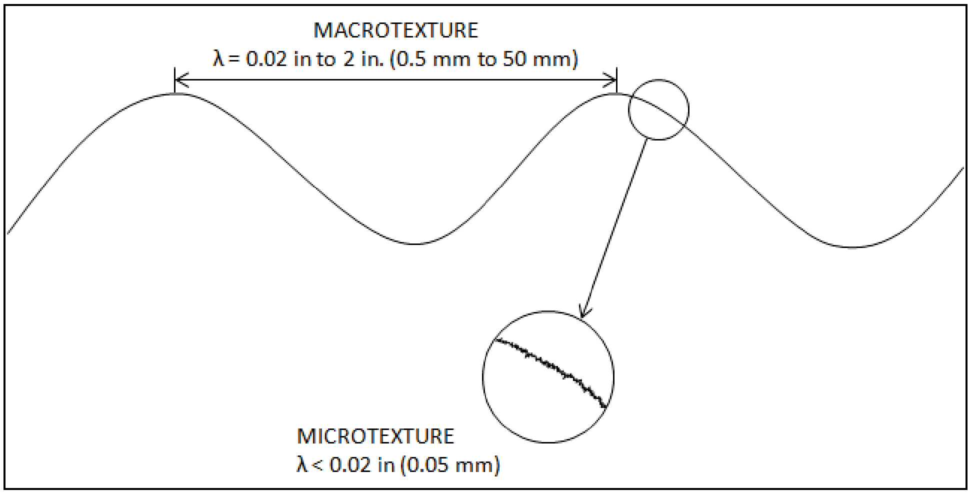
Table 1. Pavement texture classifications (adapted from PIARC 1987).

	Wavelength (λ)	Amplitude (A)
Microtexture	< 0.02 in. [0.5 mm]	0.04 to 20 mils [1 to 500 μm]
Macrotexture	0.02 to 2 in. [0.5 to 50 mm]	0.005 to 0.8 in [0.1 to 20 mm]
Megatexture	2 to 20 in. [50 to 500 mm]	0.005 to 2 in [0.1 to 50 mm]

The principal function of macrotexture is to provide escape channels for rainwater, which would otherwise be trapped in the tire pavement contact patch. Once the bulk of the water is displaced, pavement microtexture controls the intimacy of contact between the tire rubber and the pavement surface by breaking through the thin water film that remains (Raymond 2006). Figure 2 illustrates both microtexture and macrotexture.

The risk of hydroplaning increases as rubber deposits reduce available pavement texture. Hydroplaning is a condition that can develop whenever a tire is moving on a wet surface. Poor macrotexture contributes to dynamic hydroplaning. Dynamic hydroplaning occurs when tires lose contact with a flooded pavement and ride on a layer of water. Viscous hydroplaning occurs when a thin film of water remains between the tire and the pavement with insufficient microtexture to break through the film.

Figure 2. Pavement microtexture and macrotexture.



When an aircraft tire makes contact with pavement, available pavement-tire friction is primarily the result of two principal frictional force components: adhesional shear forces and hysteresis loss forces. As a tire rolls, contact points between the rubber and asperities on the pavement exact strong intermolecular forces on each other. The adhesion component results from the small-scale bonding of tire rubber and the pavement surface (NCHRP 2006). Adhesional forces are known to be strong between smooth dry surfaces, so adhesional friction may actually increase on a rubber contaminated runway in dry conditions. However, adhesional friction is drastically reduced during wet weather operations (Simpson 1989). Tire rubber is a viscoelastic material. Hysteresis losses are attributed to the energy loss due to deformation of two materials when in contact with each other. Figure 3 illustrates the adhesional and hysteresis friction components.

2.2 Tire-pavement friction testing

Runway rubber contamination is easy to identify. Visual evaluations are important for identifying drainage problems such as ponding and groove deterioration; however, they are not sufficient to determine poor skid resistance. Airfield managers with heavy aircraft traffic should schedule routine friction surveys in accordance with Engineering Technical Letter (ETL) 04-10: Determining the Need for Runway Rubber Removal (HQ AFCESA 2011). This guidance is based on procedures currently in use by the Federal Aviation Administration (FAA) and suggests scheduling friction evaluations on runway touchdowns with 20 percent or more wide body aircraft landings as outlined in Table 2.

Figure 3. Components of tire-pavement friction (Mohamed et al. 2004).

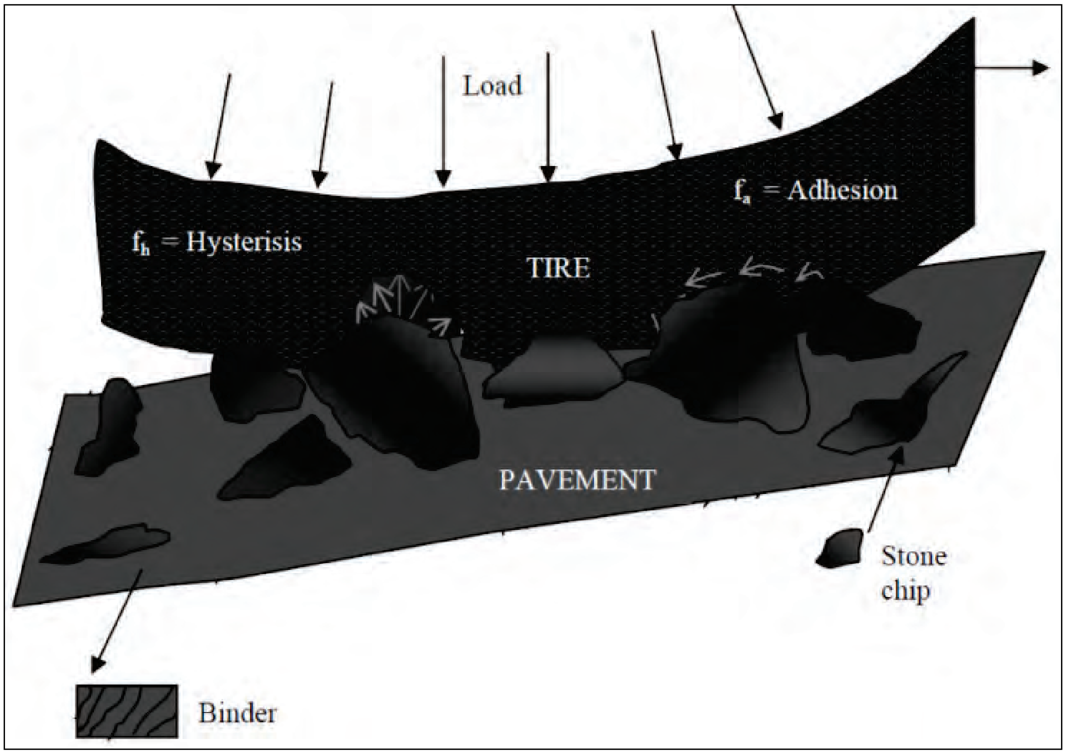
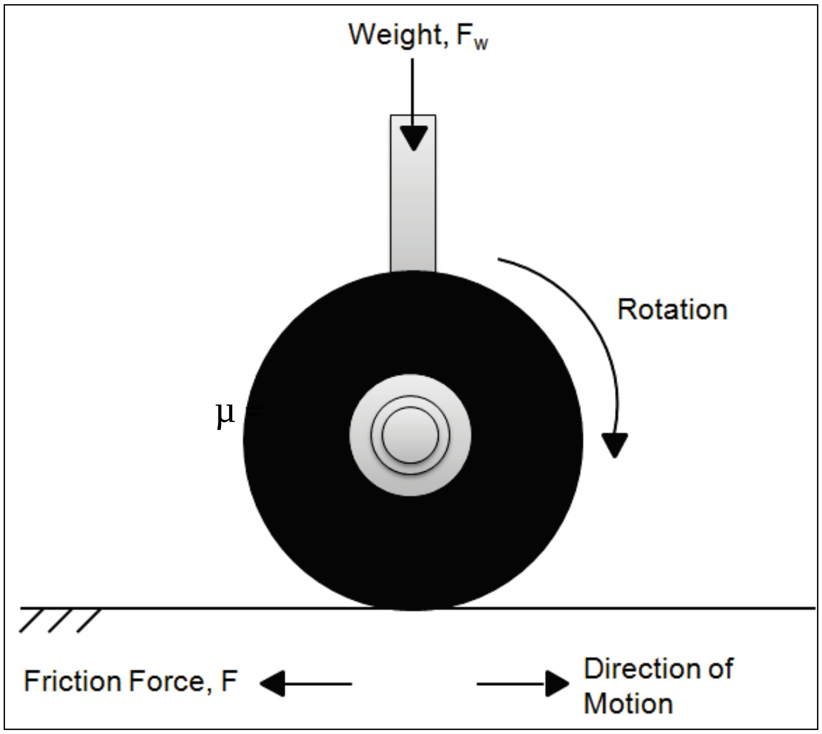


Table 2. Friction testing frequency (adapted from Federal 1997).

Number of Daily Minimum Aircraft Landings Per Runway End	Minimum Friction Testing Frequency
Less than 15	1 year
16 to 30	6 months
31 to 90	3 months
91 to 150	1 month
151 to 210	2 weeks
Greater than 210	1 week

Friction evaluations are conducted with continuous friction measuring equipment (CFME). This equipment measures and reports nondimensional tire-pavement friction coefficients, μ, or Mu numbers along the runway. Mu is the ratio of tangential friction between tire-tread rubber (F) and the horizontal traveled surface perpendicular force or vertical load (F_w) as illustrated in Figure 4.

Figure 4. Pavement-tire coefficient of friction (adapted from NCHRP 2006).



Mu numbers are nondimensional friction coefficients and can be used as guidelines for identifying when to schedule rubber removal. CFME operating principals are further discussed in Chapter 3. A Hartsfield-Jackson Atlanta International Airport aviation manager provided perceptive comments on the merits of using friction and texture measurements for scheduling rubber removal:

> *One of the challenges of effective maintenance of runway pavement surfaces for the airport operator is to determine the full extent of any rubber contaminated or reduced-texture areas and establish the amount/type of treatment required. Friction survey measurements combined with surface texture assessments can provide quantitative and objective data in support of this requirement* (Watkins et al. 2010).

2.3 Rubber removal methodologies

Several techniques for rubber removal are available. Widely accepted methods used by industry are water blasting, chemical removal, shot-blasting, and mechanical removal. The US Air Force (USAF) does not allow shotblasting on airfields.

A rubber removal synthesis study by the Airport Cooperative Research Program (ACRP) provides the following definitions for each methodology (ACRP 2008):

- Water blasting: This a process that removes rubber by using water pumped through a rotary device at some specified pressure. The unit moves slowly along the surface to be cleaned. Specifications differentiate between "high-pressure" (2,000 psi to 15,000 psi) and "ultra-high-pressure" (pressures >15,000 psi to 40,000+ psi). This type of process is also termed "ultra-high pressure water" rubber removal.
- Chemical removal: This is a process that depends on the use of some chemical-based compound to soften the rubber deposits and put them in a form that can be separated from the pavement using brushes, brooms, scrapers, or other tools. The resultant debris and residue are then flushed from the runway using pressurized water. Depending on the environmental regulations in a given area, this process may also include vacuuming the residue for disposal offsite. This process is also referred to as "detergent" or a "foam-based" removal method.
- Shotblasting: This is a process that relies on a machine that propels some form of abrasive particle onto the runway surface and blasts away the contaminants. There are a number of different proprietary machines that range in pattern width from roughly 6 in. to 6 ft. The process involves a system that vacuums the debris, separates the abrasive particles for recycling, and stores the resultant debris for disposal. This process is also referred to as "high-velocity impact removal" and "shot-peening."
- Mechanical removal: This process is defined as any mechanical form of rubber removal that is not covered in the previous three methods. It includes grinding, milling, wire-bristle brushing, scraping with blades, and other mechanical means to remove rubber. "Sandblasting" is also included in this category to differentiate it from shotblasting.

3 Equipment Description

Three UHPW rubber removal systems were evaluated in this study during September 2011: Cyclone 4006, Stripe Hog SH8000R, and a miniaturized Trackjet. The following sections provide descriptions of these systems.

3.1 Cyclone 4006

Nilfisk-Advance in Tempe, AZ, manufactures the Cyclone 4006 rubber removal system shown in Figure 5. This unit has a cantilevered cab design, providing the operator direct line-of-sight view of the cleaning path.

Figure 5. Cyclone 4006 rubber removal system.

The system as tested had a 36-in.-diam cleaning head, powered by a Tier III turbocharged liquid cooled engine, residing in a cast aluminum housing. This system has a debris recovery system which uses cyclonic action in conjunction with a macerator pump to pump runway contaminants to a galvanized reclamation tank with powered dump and powered door for easy maintenance. The Cyclone 4006 can be operated by a single operator using a joystick controlled hydrostatic drive. Water is pumped at 6 gallons per minute (gpm) at operating water pressures of up to 43,000 psi for rubber removal. The 30-ft-long by 10-ft-tall by 8-ft-wide vehicle had a maximum travel speed of 12 miles per hour (mph). The Cyclone 4006 houses a 1,600-gal fiberglass water tank. The entire system has a dry weight of

28,000 lb. The system can remove rubber or airfield markings. The system, as tested, was not C-130 transportable.

3.2 Stripe Hog SH8000R

Waterblasting Technologies in Stuart, FL, manufactures the SH8000R rubber removal system shown in Figure 6. The tested model features a closed-loop 1,000-gal capacity water recycling plant to filter and re-use water vacuumed from the pavements surface.

Figure 6. SH8000R rubber removal system.

The SH8000R has two blasting heads, which can be fitted with spray bars ranging from 6 in. up to 22 in. This system has the capability of removing rubber contaminates from runway pavements as well as markings from vertical surfaces such as barrier walls. The SH8000R has a stainless steel water tank with 2,000-gal water storage capacity and 1,600-gal waste storage capacity. Water is pumped to the cleaning heads at 12 gpm at an operating pressure of 40,000 psi. The SH8000R is 37 ft long with a gross vehicle weight (GVW) of 66,000 lb. The system can remove rubber or airfield markings. The system, as tested, was not C-130 transportable.

3.3 Trackjet

Weigel Hochdrucktechnik GmbH & Co. of Mellrichstadt, Germany manufacturers the Trackjet rubber removal system shown in Figure 7. The system, as tested, consisted of a 2010 Daimler AG Mercedes-Benz Unimog U400 vehicle integrated with power take-off (PTO) driven water blasting and debris recovery systems for runway rubber removal.

Figure 7. Trackjet UHPW rubber removal system.

The U400 is powered by a 200 hp Euro III liquid cooled diesel engine with a top speed governed at 15 mph. It has a wheel base span of 121 in. and dry weight of 13,327 lb. Its dimensions are 95 in. wide by 219 in. long. The loading height of the vehicle is 91 in. A 660-gal Musthane water bladder is fitted to the rear of the vehicle.

The Trackjet cleaning module is shown in Figure 8. The 7.87-in. blasting head is housed in this unit and has an 86-in.-wide cleaning path. Potable water is filtered to 1 μm and pumped at 6.34 gpm to the blasting head. The blasting head is attached to a hydraulic driven swivel joint, which rotates and translates about a track. The maximum operating pressure of the blasting head is 36,000 psi.

This is a miniaturized version of the full-size machine and is C-130 transportable. This unit has a reduced production capacity and efficiencies due a smaller platform vehicle, scaled down debris recovery system, and smaller water storage capacity. The system can remove rubber or airfield markings.

Figure 8. Trackjet cleaning module.

4 Field Evaluation

4.1 Overview

This effort provides a performance-based comparison between three commercially available UHPW water blasting systems. The evaluation was conducted on the touchdown zone of an ungrooved portland cement concrete (PCC) runway with rubber tire buildup contamination at Edwards Air Force Base. Several friction and texture measurement devices were used to characterize the surface of the runway before and after rubber removal. A comparison of improvements measured in surface texture properties following rubber removal are presented for each technology.

Pavement macrotexture was measured with both the circular track meter (CT meter) and National Aeronautics and Space Administration (NASA) volumetric grease smear method. Pavement surface drainage capability was measured with an outflow meter. A GripTester MK1 C-type continuous friction measuring device performed full-scale friction tests. The dynamic friction (DF) tester measured a continuous spectrum of dynamic friction coefficients and international friction index (IFI) calculations at a given spot. These methods are shown in Figure 9.

Figure 9. Pavement surface characteristics measurements.

DF Tester CT Meter NASA grease smear test

Outflow Meter GripTester®

4.2 Friction and texture measurement devices

Equipment used to measure pavement texture and skid resistance is further described in the following sections.

4.2.1 Circular track meter

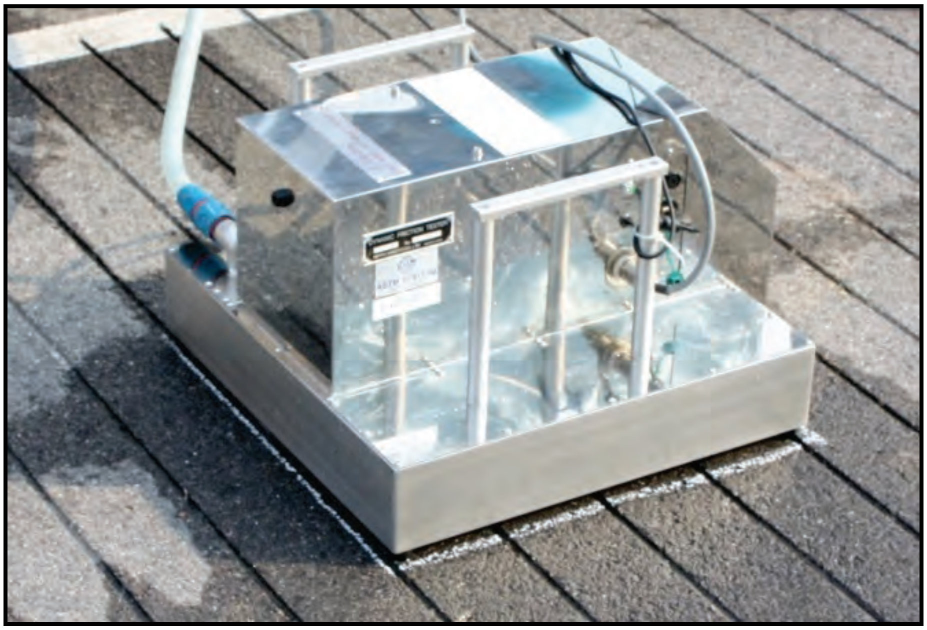
Figure 10 shows the CT meter, also known as the circular track meter. The CT meter uses a laser displacement system to measure the vertical profile of a pavement surface, giving an indication of pavement macrotexture (ASTM E 2157(American Society for Testing and Materials International 2009c)). The CT meter has integrated software which calculates and reports mean profile depth (MPD) and root mean square (RMS) values. This unit collects measurements over an 11.18-in.-diam area, covering the same footprint as the DF Tester.

Figure 10. Circular track meter.

4.2.2 Dynamic friction tester

The dynamic friction (DF) tester shown in Figure 11 is a portable device used to measure pavement dynamic friction coefficients. During operation, a rotating disk fitted with three spring-loaded rubber sliders is lowered onto a wetted pavement surface (ASTM E 1911 (ASTM 2009b)). Torques generated by the rotating disk are converted to friction coefficients. Dynamic friction coefficients are reported graphically as a function of speed from 0 to 50 mph. Raw data from each measurement is tabulated in a 10-column by 100-row matrix. Each data row represents data collected for 1 kilometer per hour (km/hr), and each column represents a 0.1 km/hr data point; therefore, this table can be used to determine friction coefficients measured at tenths of a kilometer/hour.

Figure 11. Dynamic friction tester.



4.2.3 GripTester MK1 C-type

The GripTester MK1 C-type is a continuous friction measuring device which measures pavement-tire friction by the braked wheel, fixed-slip principle. The GripTester has three wheels: two drive wheels and one measuring wheel. The measuring wheel is fixed to the rear axle of the GripTester. This axle is instrumented with strain gauges which measure horizontal drag force and vertical load force at the tire. This unit delivers a 0.014 in. film of water in front of the measuring tire via a 150-gal self-watering system. The self-watering system was calibrated frequently to ensure the amount of water produced for the required water depth was consistent and applied evenly at the front of the measuring tire. A 10 in. by 4.53 in. (ASTM E 1844 (ASTM 2008)) specification smooth tread tire was used at a 14.5 percent slip ratio. The measuring tire was periodically checked for wear and scrubbed before use to prevent contaminants from influencing readings. Tire pressure was held at 20 psi. Readings are taken as the GripTester is towed behind a support vehicle as shown in Figure 12 (ASTM 2008).

Figure 12. GripTester MK1 C-type.

As the GripTester is in tow, the measuring tire is slipped by a chain drive transmission from the primary two-wheeled axle. Dynamic friction readings are calculated from strain gauge data and are stored in a computer tethered to the GripTester by serial cable. Movement of a drive sprocket on the front axle is measured by an inductive proximity sensor. These data determine speed and distance during operation. The on-board computer calculates and stores the survey speed for each 32.8 ft of friction readings.

4.2.4 Hydrotimer outflow meter (ASTM E2380(ASTM 2009d))

The Hydrotimer is a patented and self-contained outflow meter. Its operation is simply a drain-down test with the primary purpose of checking water drainage through texture voids in pavement surfaces. A rubber sealing ring mounted on its base for contacting the surface insures zero outflow when a test is conducted on a glass smooth surface. Therefore, a test conducted on a surface with inter-connected texture voids will result in an incomplete seal and an outflow of water. The measured volume of water is timed by on-board electronics with a liquid crystal display (LCD). A measured volume of water is released in the center of the sealing ring while an electronic timer measures elapsed time for the water to pass through texture voids in the pavement under the seal. The Hydrotimer outflow meter is shown in Figure 13. Higher time readings indicate smooth surfaces with poor macrotexture, such as a piece of glass or a heavily rubber contaminated runway. Shorter time readings indicate surfaces with good macrotexture, such as areas where rubber is removed.

Figure 13. Hydrotimer outflow meter.

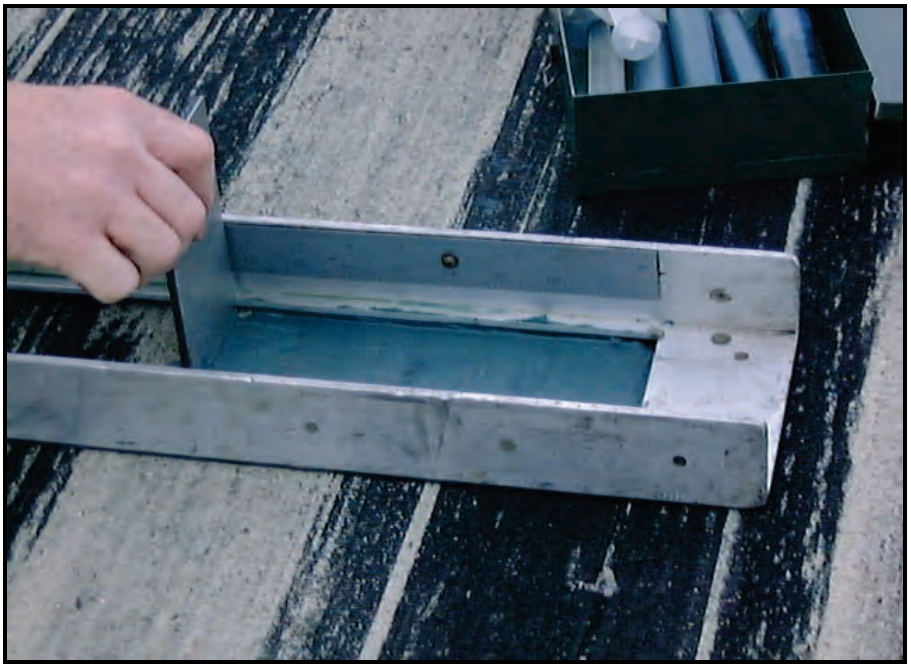
4.2.5 NASA grease smear test (FAA AC/5320-12C)

The NASA grease smear test is used to characterize the macrotexture of a pavement surface by measuring the average distance between the peaks and valleys in the pavement texture. A 1-in.^{3} volume of grease is expelled from a syringe inside a 4-in.-wide aluminum template shown in Figure 14. Grease is spread across the pavement surface and into pavement surface voids with a rubber squeegee. The distance the smear covers is measured, and the area that is covered by the grease is computed. Lastly, an average texture depth is calculated by dividing the volume of grease by the area of the smear.

4.3 Experiment location

Edwards AFB is located at the western edge of Southern California's Mojave Desert about 100 miles northeast of Los Angeles, 90 miles northwest of San Bernardino, and 80 miles southeast of Bakersfield. The base lies on the border of three counties: Kern, San Bernardino, and Los Angeles. The area surrounding the base is Antelope Valley, which consists of two dry lakes: Rogers Lake and Rosamond Lake. The base is located 2,302 ft above sea level.

Figure 14. NASA grease smear test.



4.4 Edwards AFB runway layout

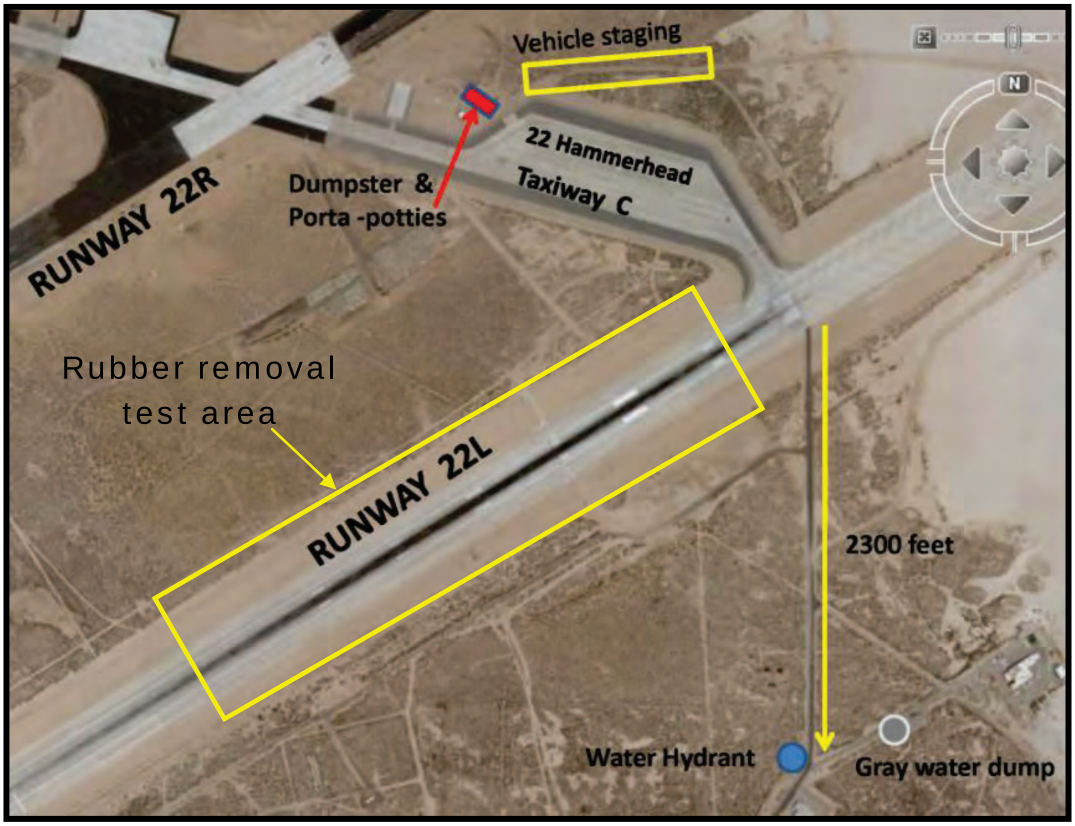
Edwards AFB has two parallel runways: Runways 04R/22L and 04L/22R. Aircraft tire rubber deposits were removed from Runways 22L, 04R, and 22R during this effort.

Runway 04R/22L is 15,000 ft long and 300 ft wide, consisting of ungrooved PCC. Runway 14L/22R is 12,000 ft long and 200 ft wide, consisting of ungrooved PCC touchdowns with an ungrooved hot mix asphalt (HMA) interior.

Figure 15 presents an overview of Runway 22L, gray water and solids discharge area, designated fire hydrant, and vehicle staging area. Figure 16 shows all work areas in an airfield layout plot. The performance evaluation of each rubber removal system was held on Runway 22L over a 50-ft-wide by 3,000-ft-long test area, spanning the runway center line. This area is further subdivided into test sections illustrated in Figure 17, and test locations are labeled in Figure 18. Rubber removal was provided on Runways 04R and 22R for Edwards AFB; however, these areas were not included in the comparative evaluation due to light rubber buildup.

Figure 19 shows the surface condition of Runway 22L contaminated with rubber deposits prior to testing.

Figure 15. Test site overview.



4.5 Test procedure

Each equipment package in the test matrix was tested in accordance with the manufacturers' recommendations and operated by manufacturers' personnel to remove operator bias. Test procedures were as follows:

4.5.1 Initial pavement surface effects measurements

- Located test areas, marked test section boundaries with paint markings and safety cones, and prepared each test point by sweeping away any loose material with a broom.
- Performed mean profile depth pavement measurements with CT meter.
- Performed pavement friction measurements with DF tester.
- Performed outflow time measurements with Hydrotimer outflow meter.
- Performed continuous friction measurements using the GripTester. The GripTester was operated in "drive mode," which means that it collected friction measurements by passing over the test area at 40 mph.

Figure 16. Airfield diagram.

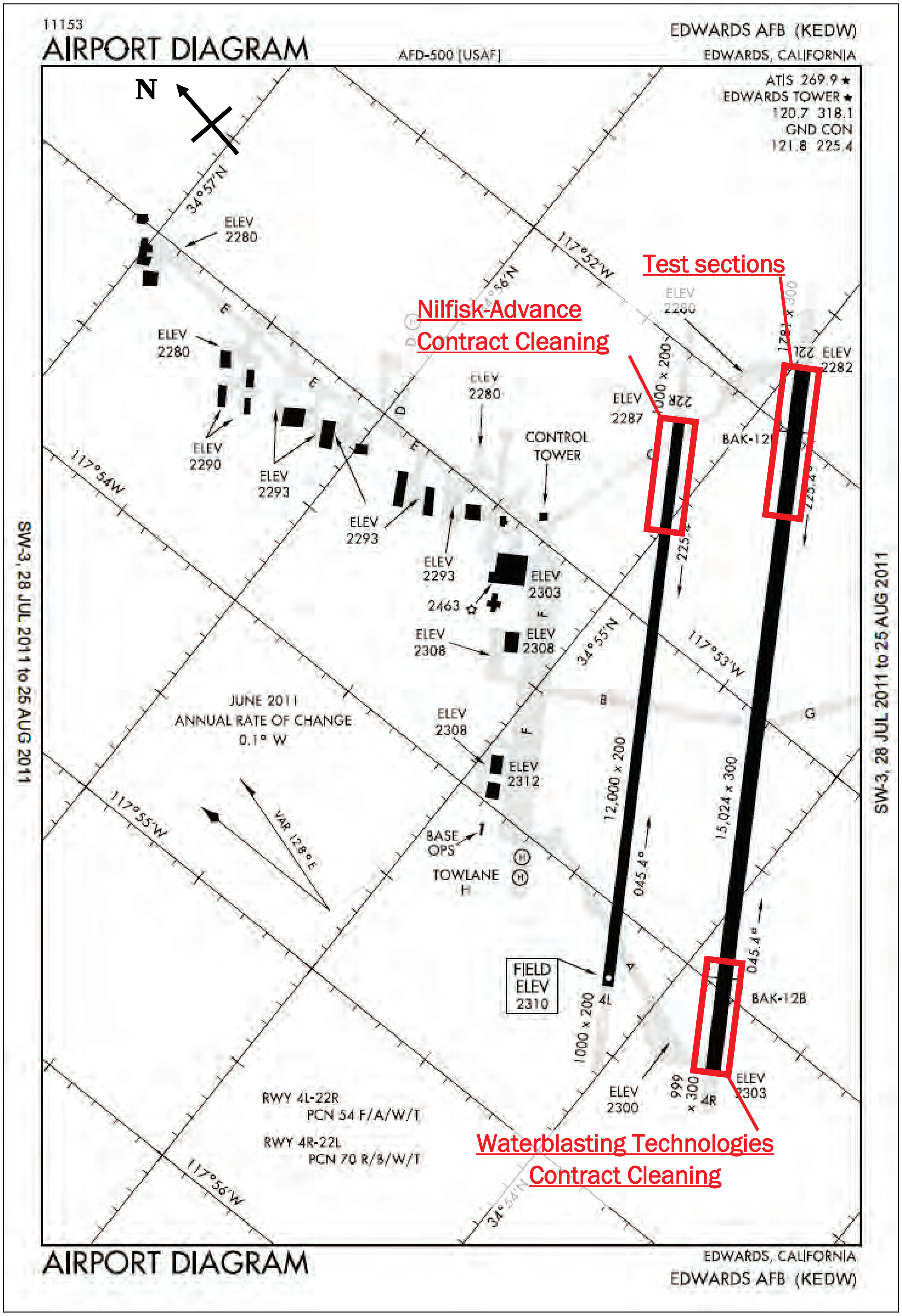


Figure 17. Runway 22L test sections.

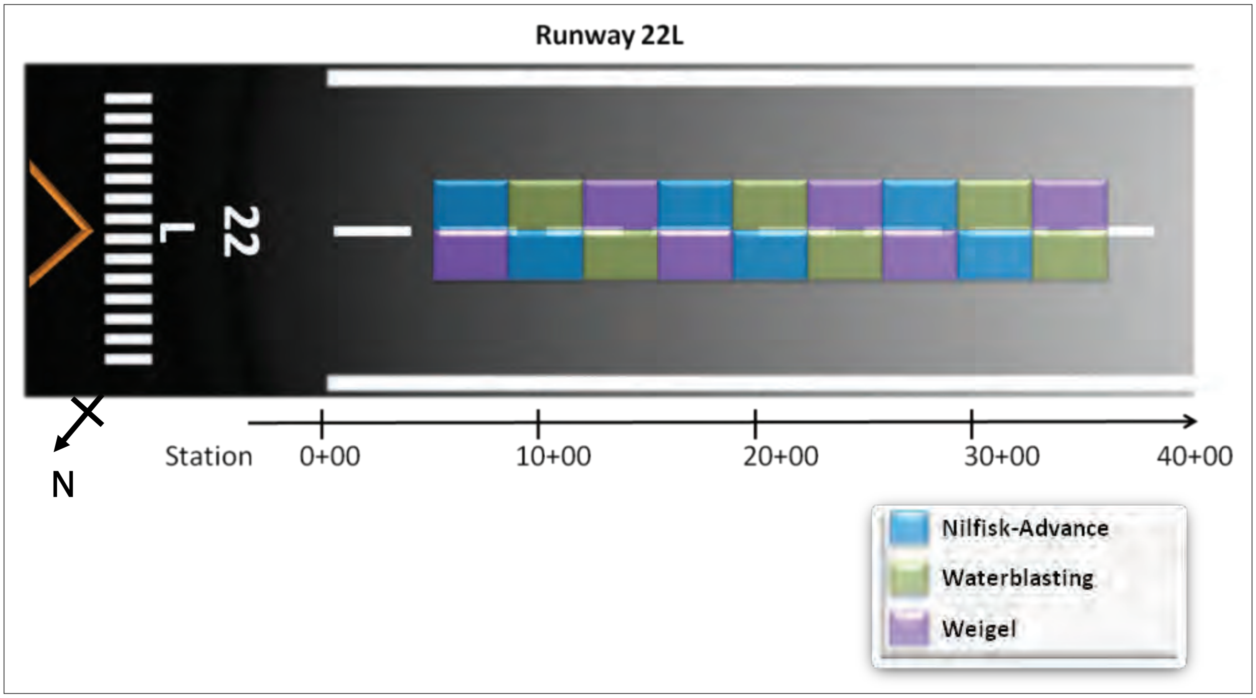


Figure 18. Runway 22L test locations.

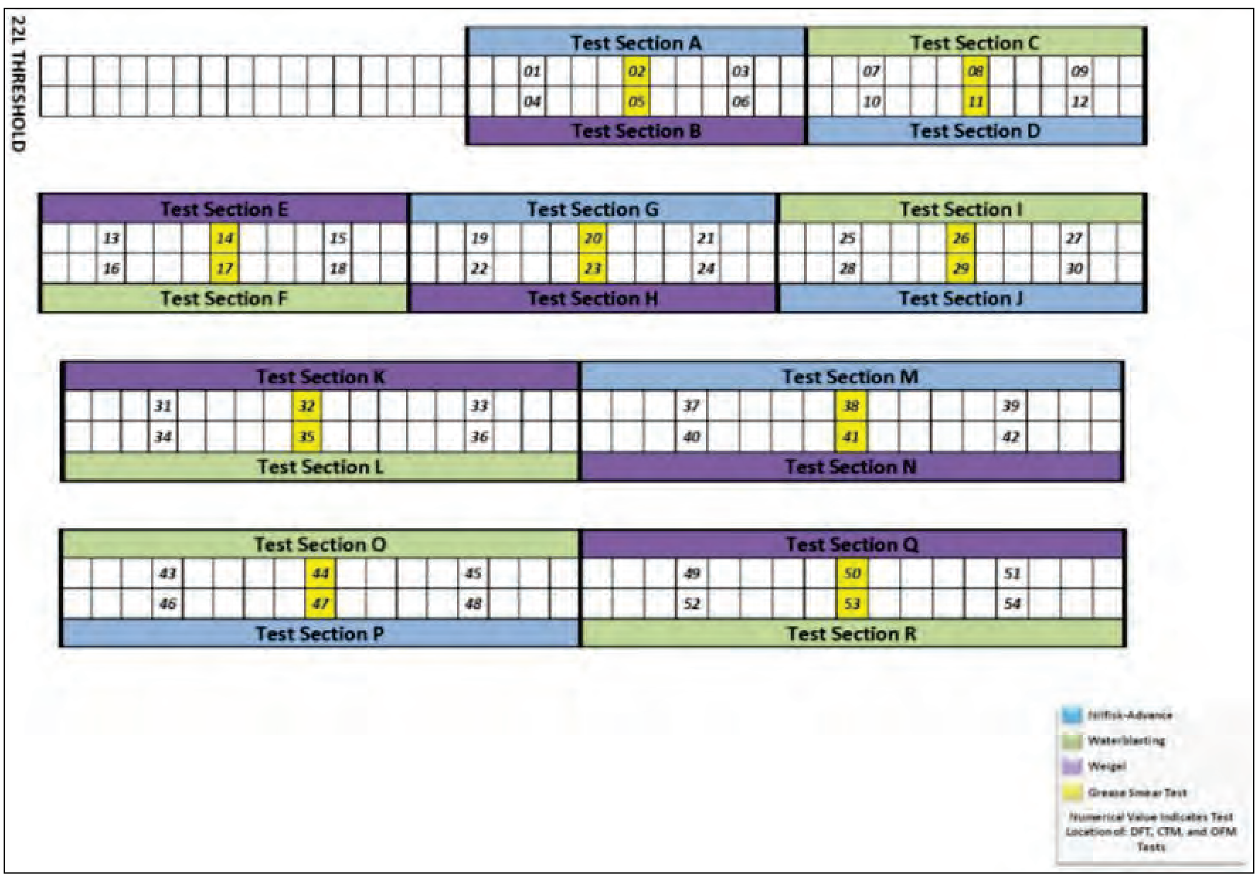
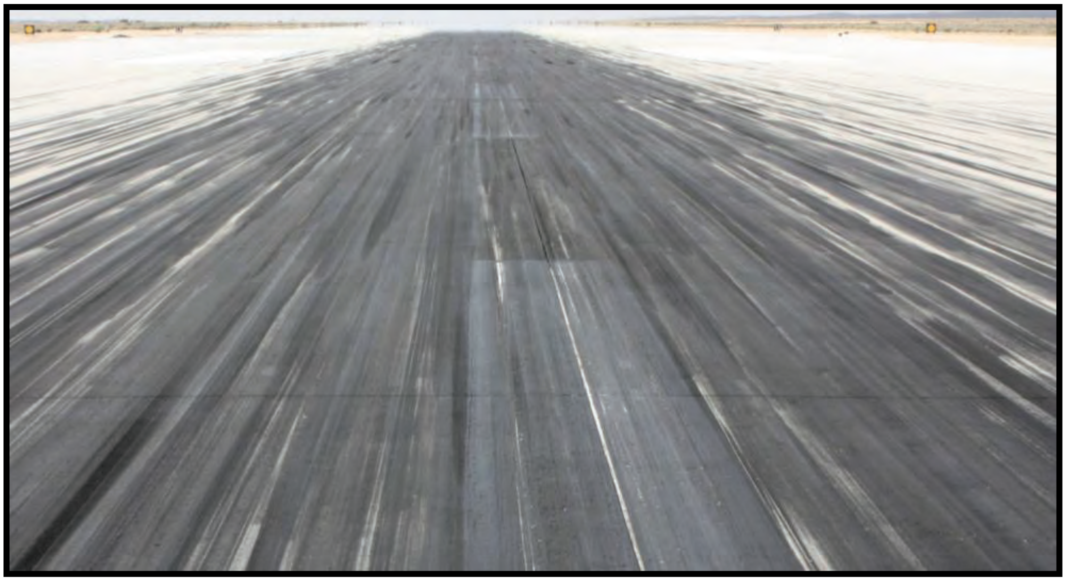


Figure 19. Runway 22L contaminated with rubber deposits prior to testing.



- Performed NASA volumetric grease texture measurements at designated test locations, as well as in areas with no rubber contamination in the same paving lane.
- Performed transverse and longitudinal runway slope measurements every 500 ft along the runway. Made sure the arrow on the level was always pointing toward the primary end.

4.5.2 Perform rubber removal

- Each engineer accompanying an UHPW system was assigned a tower radio and was responsible for escorting his or her group into and out of controlled movement areas (CMAs).
- Noted the climatic conditions during operations.
- Filled each system at designated fire hydrant near test area.
- Recorded resources used by each system during rubber removal operations: time, water, and fuel onto data sheets provided.
- Photographed all rubber removal operations, especially pavement areas before and after rubber is removed.
- Escorted equipment to and from gray water discharge area and fire hydrant when required.
- Noted any equipment issues or failures, including but not limited to any on-site maintenance.

4.5.3 Post-rubber removal pavement surface effects measurements

Repeated texture and friction measurements.

4.5.4 Data analysis procedure

The initial or pre-test measurements serve as a base line for data interpretation and analysis. Comparisons of pre-test and post-test measurements determine if there is a statistically significant difference in surface friction and texture following rubber removal. Such tests permit data to be represented in a manner providing conclusive evidence of the changes each technology imparts to the pavement surface.

An analysis of variance (ANOVA) was performed to test if statistically significant differences exist between treatment effects. If differences in means were found to be statistically significant, post-hoc pair-wise t-tests were performed to compare populations.

Measurement populations were assumed to have similar variances, so a pooled standard deviation (s_p) was calculated:

$$S_p = \sqrt{\frac{\sum_{i=1}^{n_1}\left(x_{1i} - \overline{x}_1\right)^2 + \sum_{i=1}^{n_2}\left(x_{2i} - \overline{x}_2\right)^2}{n_1 + n_2 - 2}} \quad (1)$$

The test statistic used for judging the significance of the difference in two population means was the ratio of the difference in the means to the standard error of the difference in the means, a calculated value of t:

$$t_{calc} = \frac{\left|\overline{x}_1 - \overline{x}_2\right|}{s_p\sqrt{\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \quad (2)$$

The reference distribution for judging the significance of the difference between the population means of two groups was the Student's t-distribution. The null and alternative hypotheses for the two-sided two-sample t-test were:

$$\text{null hypothesis, } H_0 = H_1 - H_2 \quad (3)$$

$$\text{alternative hypothesis, } H_a \neq H_1 - H_2 \quad (4)$$

The decision to reject the null hypothesis and to accept the alternative hypothesis was made by comparing t_{calc} to the critical or tabular value of Student's t at a level of risk of α for the number of degrees of freedom associated with the standard error of the difference in means. Degrees of freedom associated with the critical value of the test statistic are given approximately by:

$$df = \frac{\left(\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{(n_1-1)}+\frac{\left(\frac{s_2^2}{n_2}\right)^2}{(n_2-1)}} \quad (5)$$

Populations were judged at the 95 percent level of confidence.

4.5.5 Data collection

The GripTester, DF tester, and CT meter, have integrated data acquisition systems where measurements are stored electronically to a computer. Figure 20 presents field data collection sheets used for recording outflow time measurements and monitoring each system's production and use of consumable resources.

Figure 20. Field data collection sheets.

OUTFLOW TIME DATA SHEET

Edwards AFB Runway 22 L Hydrotimer Outflow Meter Measurements

Date: ______________

Operator initials: ______________

Test Section	Location	Outflow Time (Sec.)	Test Section	Location	Outflow Time (Sec.)	Test Section	Location	Outflow Time (Sec.)	Test Section	Location	Outflow Time (Sec.)
A	01		F	16		K	31		P	46	
	02			17			32			47	
	03			18			33			48	
B	04		G	19		L	34		Q	49	
	05			20			35			50	
	06			21			36			51	
C	07		H	22		M	37		R	52	
	08			23			38			53	
	09			24			39			54	
D	10		I	25		N	40				
	11			26			41				
	12			27			42				
E	13		J	28		O	43				
	14			29			44				
	15			30			45				

VENDOR COLOR KEY

- Nilfisk-Advance
- Waterblasting
- Weigel

NOTES: ______________

Vendor Name		
Date		
Test Location/Number		
Weather: *(Clear, Over Cast, Light Rain, Moderate Rain, Heavy Rain)*		
Temperature of Pavement	Before RR	After RR
Cleaning Start Time		
Cleaning End Time		

	Reasons For Stopping	Time Stopped	Time Started
Work Stoppage			
Work Stoppage			
Work Stoppage			
Work Stoppage			
Work Stoppage			
Work Stoppage			

Clean Out Time	
Water Consumption	
Gas Consumption	
Pavement Condition Remarks	
Joint Sealant Remarks	

Signature: ______________

5 Results and Discussion

5.1 Visual assessment

Figure 21 presents an overview of Runway 22L before and after rubber removal. The stray rubber marks in the lower photograph occurred during flight operations after completion of rubber removal and before photographs could be taken. Test sections were defined by the runway center line; cones were spaced 333 ft apart as shown in Figure 22.

Figure 23 shows test sections C, D, E, F, and G during testing. The Trackjet had completed cleaning of sections E and H. The Cyclone 4006 is shown removing rubber from section D.

Figure 24 presents a typical pavement surface on Runway 22L after Cyclone 4006 rubber removal. Cyclone 4006 rubber removal produced a uniformly clean pavement with some light staining, but the pavement surface is visibly free of rubber deposits.

Figure 21. Overview of Runway 22L before and after rubber removal.

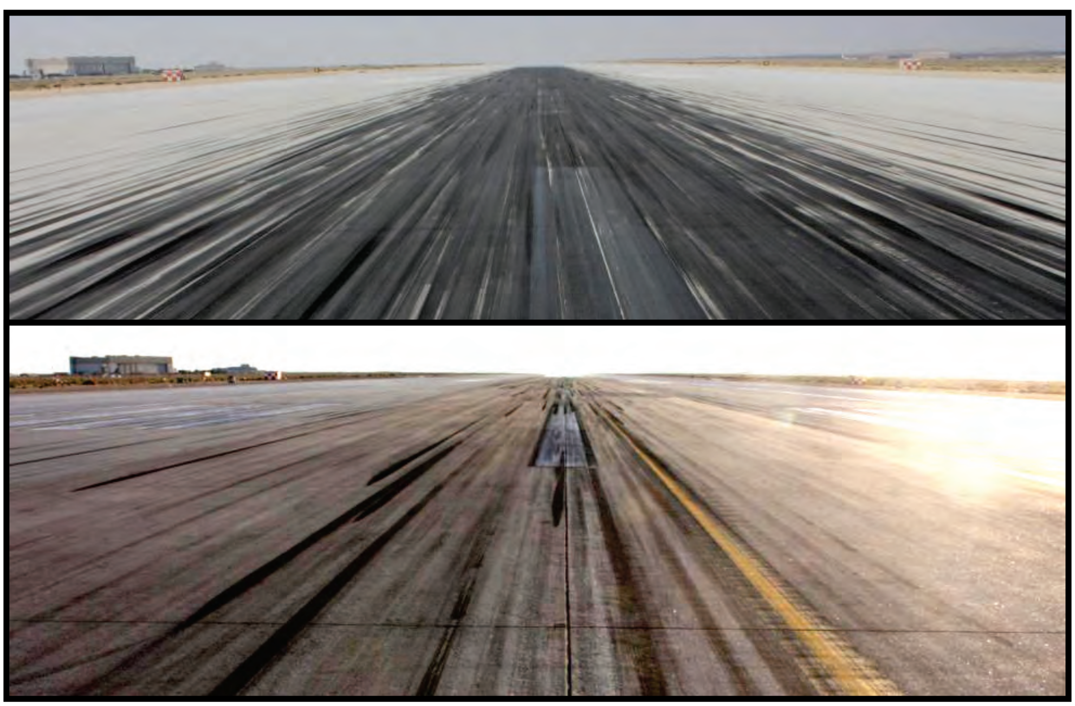


Figure 22. Test sections delineated by cones.

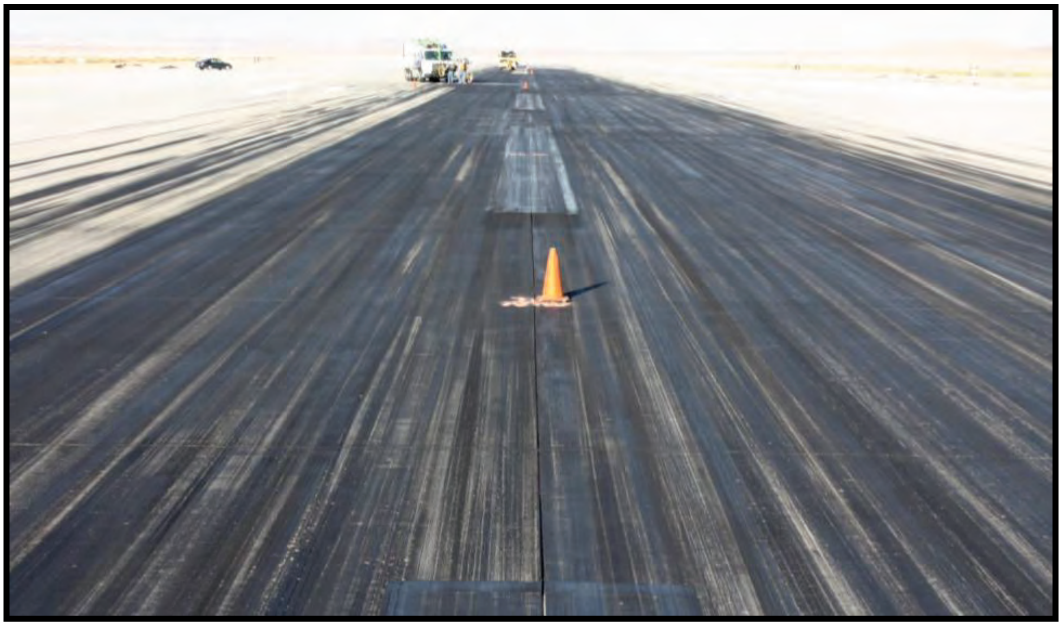


Figure 23. Test sections C, D, E, F, and G during testing.

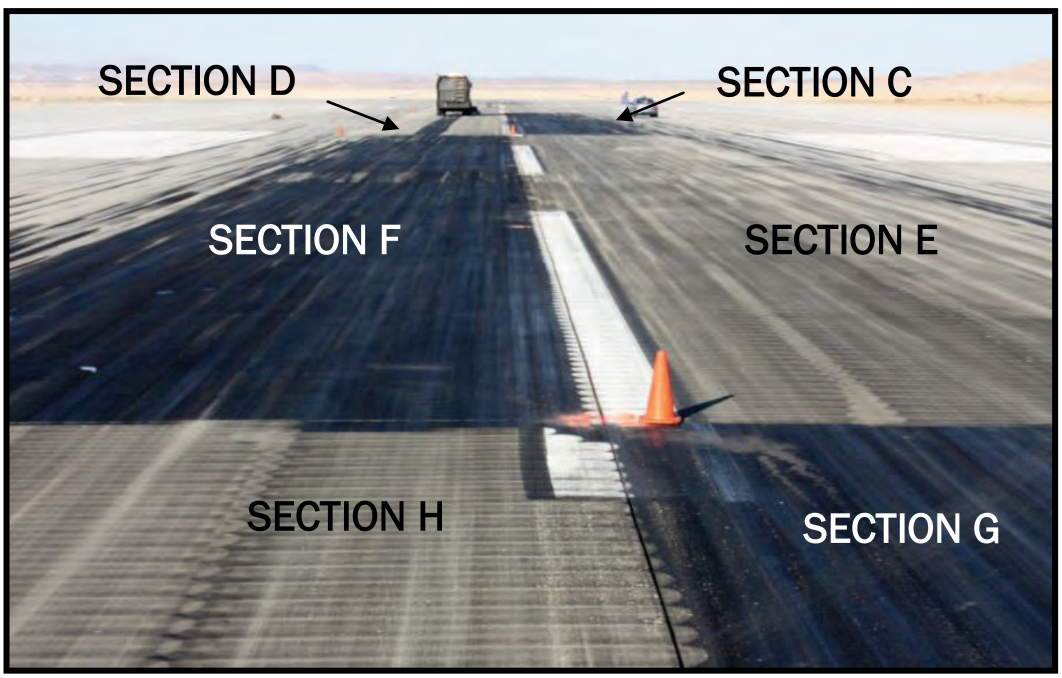


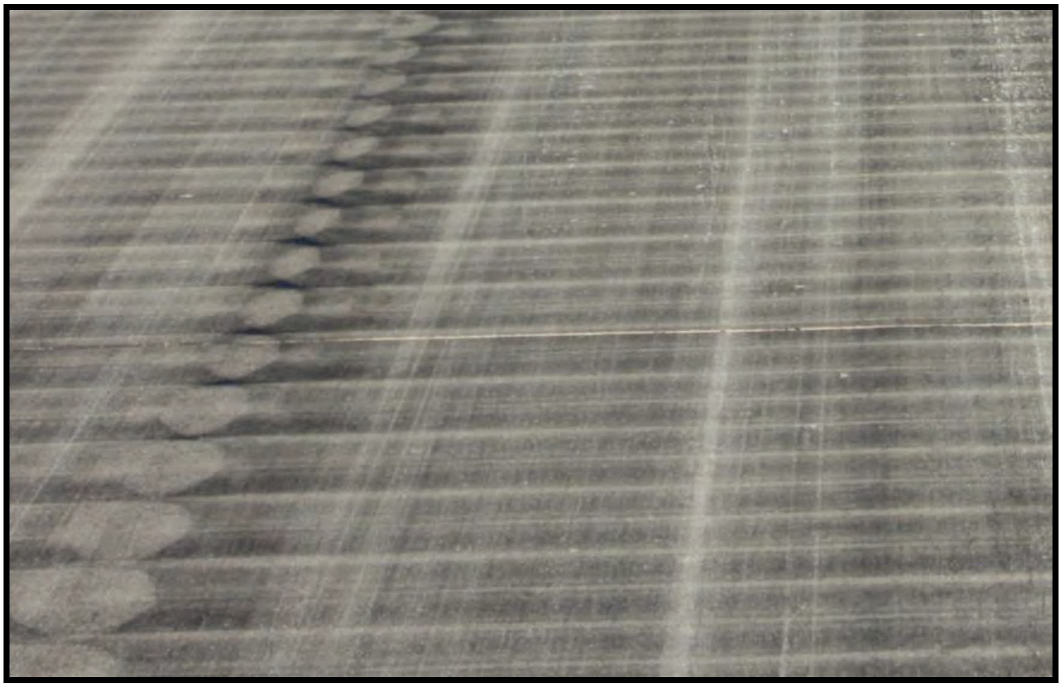
Figure 24. Typical pavement surface on Runway 22L after Cyclone 4006 rubber removal.

The SH8000R removed most visible rubber deposits; however, this system left behind some considerable dark streaks on the pavement surface as shown in Figure 25.

Figure 25. Typical pavement surface on Runway 22L after SH8000R rubber removal.

Pavements cleaned by the Trackjet retained the most staining (Figure 26). Areas where the translating robotic cleaning head overlap are essentially ‘double-covered’ and lighter, leaving a tiger striped pattern.

Figure 26. Typical pavement surface on Runway 22L after Trackjet rubber removal.



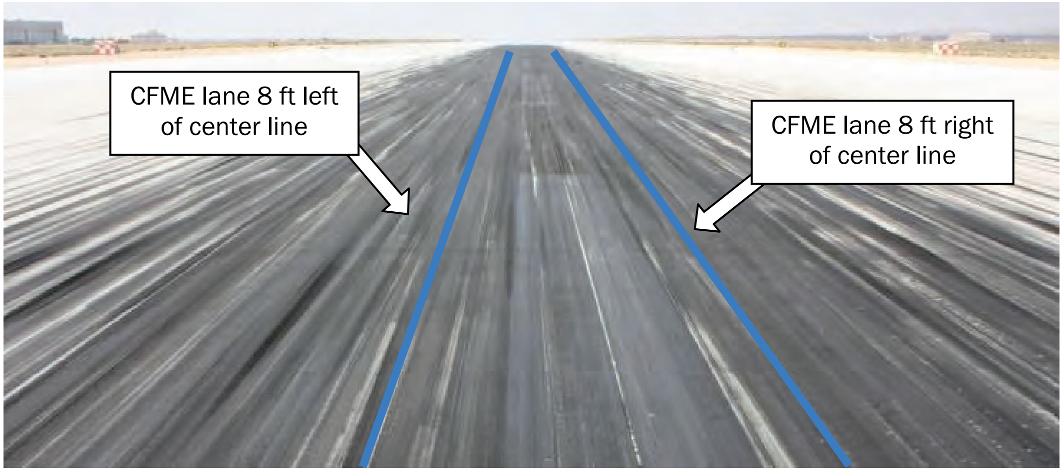
5.2 Friction measurements

5.2.1 Continuous friction measurements

Figure 27 shows the GripTester used to collect friction measurements on Runway 22L. Friction surveys were conducted on areas identified as having the heaviest rubber buildup, 8 ft on both sides of the runway center line as indicated in Figure 28. Surveys were conducted at speeds of both 40 mph and 60 mph.

Figure 27. Findlay Irvine GripTester MK1 C-type.

Figure 28. Runway 22L CFME measurement lanes prior to rubber removal.



5.2.1.1 40-mph GripTester survey

Figure 29 presents the pre- and post-rubber removal GripTester results in the left offset lane when operated at 40 mph. Figure 30 presents results from the right offset lane at 40 mph. These charts represent friction measurements from all 16 test sections. There are three condition thresholds on each chart: green, yellow, and red. These criteria are defined in Table 3 and originate from the FAA standards adopted from FAA AC 150/5320-12C (FAA 1997).

Friction coefficients measured to the right of the runway center line were relatively higher than measurements left of the center line. Small differences in how each PCC lane is textured may largely influence available skid resistance. Most areas experienced improvements in available friction after rubber removal. Rubber is not homogenously deposited over the runway surface. Some measured areas may have more rubber contamination than other measured areas; therefore, areas with less rubber buildup may show little to no improvement in available friction after rubber removal. It is likely that some runway areas were constructed with greater macrotexture and may continue to provide adequate frictional properties when contaminated with rubber deposits. The largest improvements in available friction were measured over the first 2,000 ft of Runway 22L. Approximately 54 percent of measurements falling beneath the minimum action level were restored to safe operating levels.

Figure 29. Runway 22L GripTester results 8 ft left of center line (40 mph).

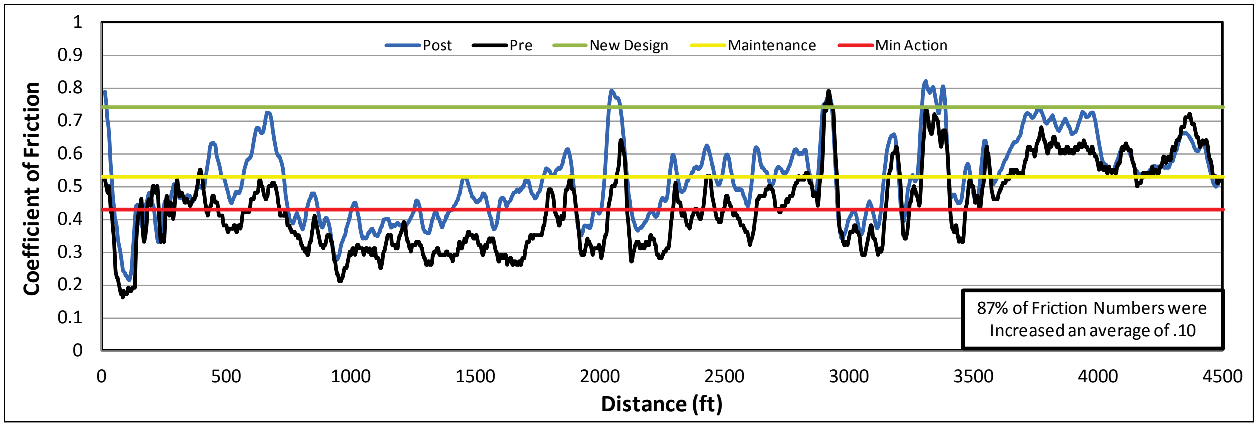


Figure 30. Runway 22L GripTester results 8 ft right of center line (40 mph).

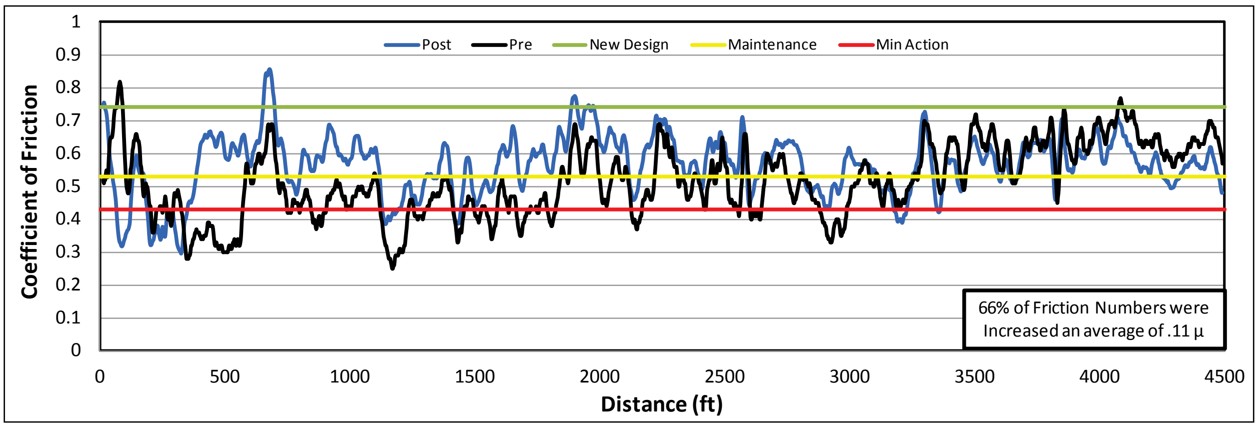


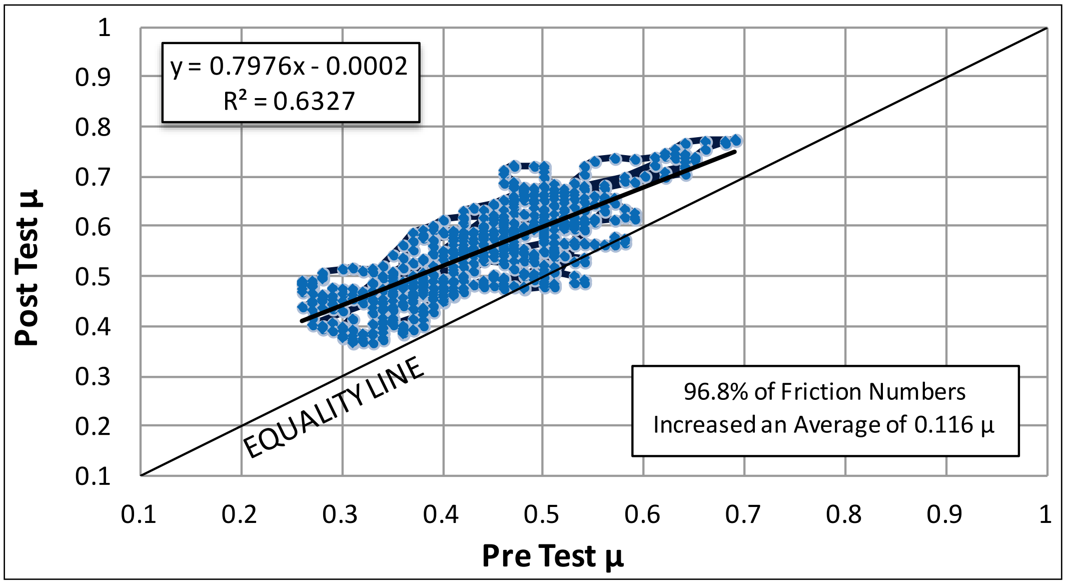
Table 3. FAA friction classification levels (40 mph).

Friction Level	40 MPH	Deterioration Below Maintenance Planning Level for ≥ 500 ft	Deterioration Below Maintenance Planning Level for ≥ 1000 ft
New Design	0.74	No corrective action is required	No corrective action is required
Maintenance Planning	0.53	No corrective action is required	Conduct an extensive evaluation into the cause(s) and extent of the friction deterioration and take appropriate corrective action.
Minimum Friction Level	0.43	Corrective action should be taken immediately	Corrective action should be taken immediately

Paired t-tests were performed to determine if improvements in available pavement skid resistance following rubber removal with each system were statistically significant at the 95 percent confidence level.

Friction measurements increased in 97 percent of the pavement area cleaned by the Cyclone 4006. The mean friction gain for these areas was 0.116 µ. Figure 31 presents pre- and post-rubber removal friction values for the pavement sections cleaned by the Cyclone 4006. These data are assumed to be approximately normally distributed for this pair-wise analysis.

Figure 31. Cyclone 4006 pre- and post-friction coefficients (40 mph).

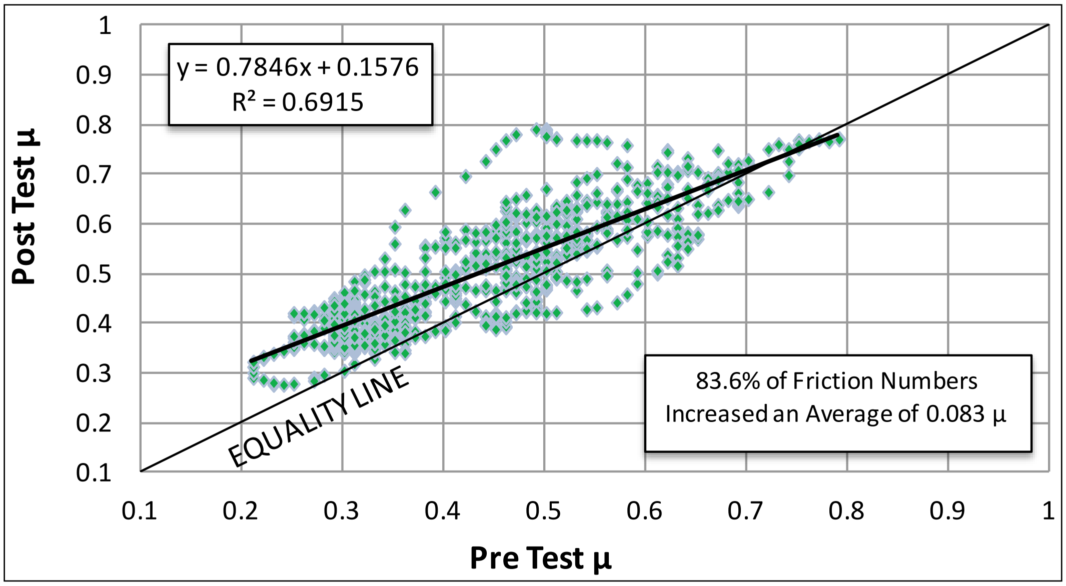


Comparison of initial friction measurements (*M* = 0.439, *SD* = 0.0894) and post-rubber removal friction measurements (*M* = 0.550, *SD* = 0.0892) indicate a statistical gain in available friction after rubber removal using the Cyclone 4006, with a $t(1,498) = 24.21$ and $p = 1.58E\text{-}109$.

Friction values increased in 84 percent of the pavement area cleaned by the SH8000R. The mean friction gain for these areas was 0.083 µ. Figure 32 presents pre- and post-rubber removal values for the pavement sections cleaned by the SH8000R. These data are assumed to be approximately normally distributed for this pair-wise analysis.

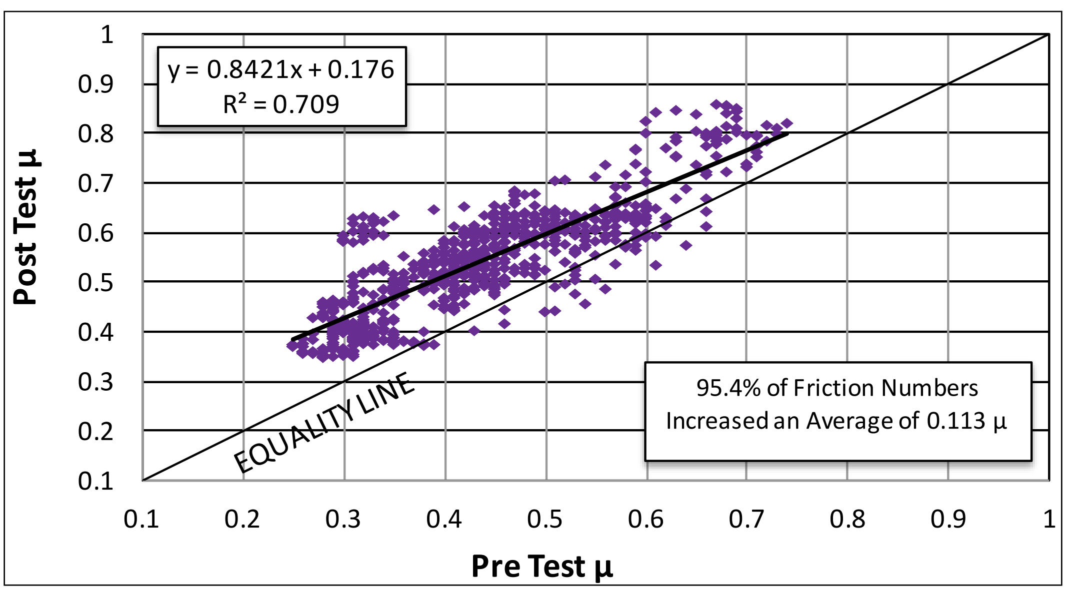
Comparison of initial friction measurements (*M* = 0.444, *SD* = 0.125) and post-rubber removal friction measurements (*M* = 0.506, *SD* = 0.118) indicate a statistical gain in available friction after rubber removal with the SH8000R, with a $t(1,500) = 9.881$ and $p = 2.39E\text{-}22$.

Figure 32. SH8000R pre- and post-friction coefficients (40 mph).



Friction measurements increased in 95 percent of the pavement area cleaned by the Trackjet. The mean friction gain for these areas was 0.113 µ. Figure 33 presents pre- and post-rubber removal friction values for the pavement sections cleaned by the Trackjet. These data are assumed to be approximately normally distributed for this pair-wise analysis.

Figure 33. Trackjet pre- and post-friction coefficients (40 mph).



Comparison of initial friction measurements (*M* = 0.435, *SD* = 0.111) and post-rubber removal friction measurements (*M* = 0.541, *SD* = 0.111) indicated a statistical gain in available friction after rubber removal using the Trackjet, with a t(1,574) = 19.02 and p = 8.74E-73.

Pavement-tire friction coefficients measured sections cleaned by the Cyclone 4006 showed the most improvement, followed by the Trackjet. The SH8000R had the most inconsistent results, which is evident by the most number of data points below the line of equality. At the 95 percent confidence level, pavement areas cleaned by all three technologies exhibited statistically significant gains in available skid resistance. A one-way ANOVA comparing friction gains from each treatment revealed statistically significant differences between the groups, with an *F* (2, 2,286) = 137.88 and a *p* = 2.92E-57.

Since the ANOVA indicates statistically significant differences in treatment effects, a pair-wise t-test procedure was used to compare the means to determine if the calculated differences in means were statistically significant given the scatter of data. Tests of the three a priori hypotheses were conducted using Bonferroni adjusted alpha levels of 0.0167 per test (0.05/3). The results of these tests are presented in Figure 34. The value tabulated in each cell is the *P* value that resulted from the pair-wise t-test for the combination of treatments represented by the cell. A lower *P* value indicates a greater statistical significance. In Figure 34, all cells with a *P* value less than 0.05 are highlighted in orange. This indicates that there was a greater than 95 percent probability that differences calculated between the two methods were statistically significant.

Using these analyses, it was calculated that friction gains in test sections cleaned by the Cyclone 4006 (*M* = 0.112, *SD* = 0.0571) were statistically greater than friction gains in test sections cleaned by the SH8000R (*M* = 0.0619, SD = 0.0708), *t*(1,499) = 14.96, p = 2.79E-47. No statistically significant distinction was found between friction gains in test sections cleaned by the Cyclone 4006 and Trackjet (*M* = 0.106, *SD* = 0.0628), *t*(1,536) = 1.75, *p* = 0.08. However, friction gains measured in Trackjet test sections were statistically greater than friction gains measured in SH8000R test sections, with a *t*(1,537) = 13.00 and *p* = 9.35E-37. A comparison of mean friction gains following rubber removal is provided in Figure 35.

Figure 34. P value matrix for post-rubber removal friction gains (40 mph).

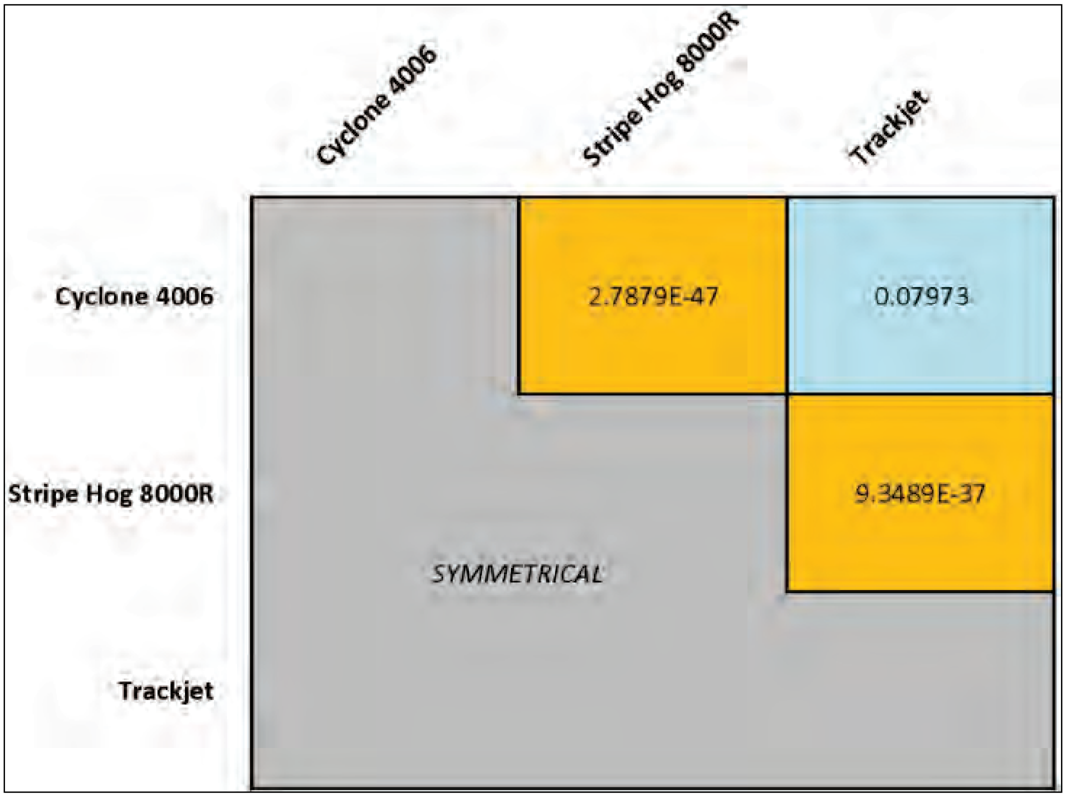
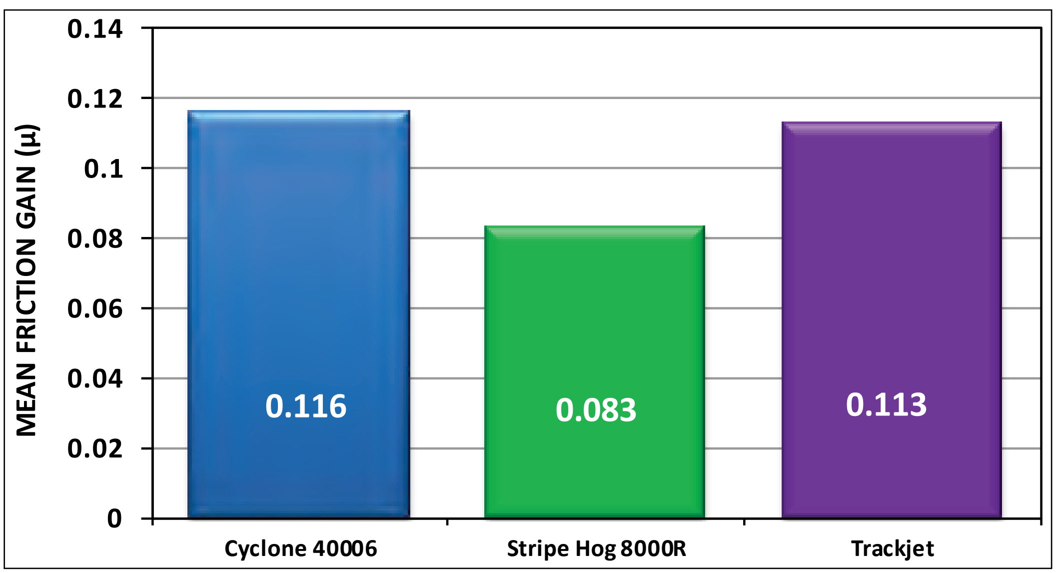


Figure 35. Comparison of mean friction gains following rubber removal (40 mph).



5.2.1.2 60-mph GripTester survey

Figure 36 presents the pre- and post-rubber removal GripTester results in the left offset lane when operated at 60 mph. Figure 37 presents results from the right offset lane when operated at 60 mph. These charts represent friction measurements from all 16 test sections. There are three condition thresholds on each chart: green, yellow, and red. These criteria are defined in Table 4 and originate from the FAA standards adopted from FAA AC 150/5320-12C (FAA 1997).

Figure 36. Runway 22L GripTester results 8 ft left of center line (60 mph).

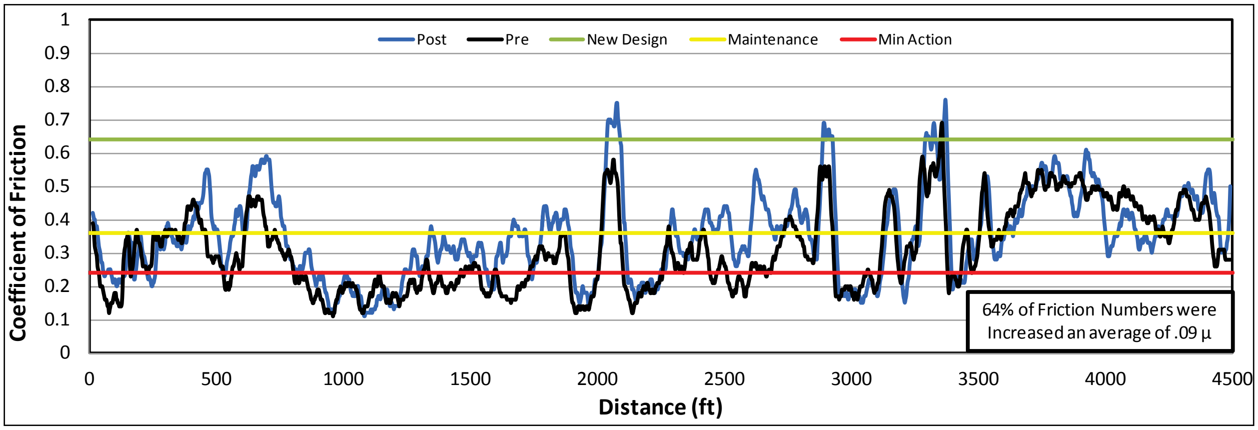


Figure 37. Runway 22L GripTester results 8 ft right of center line (60 mph).

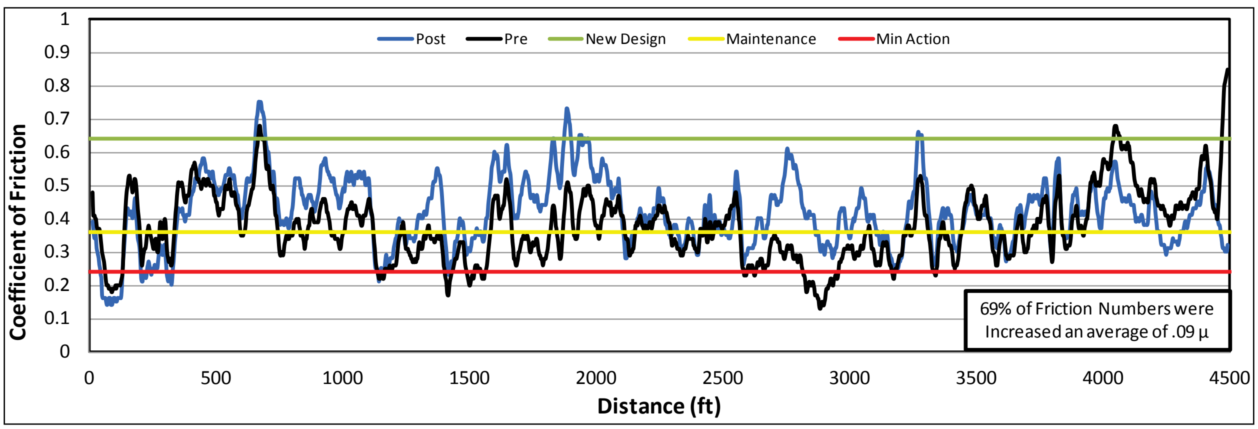


Table 4. FAA friction classification levels (60 mph).

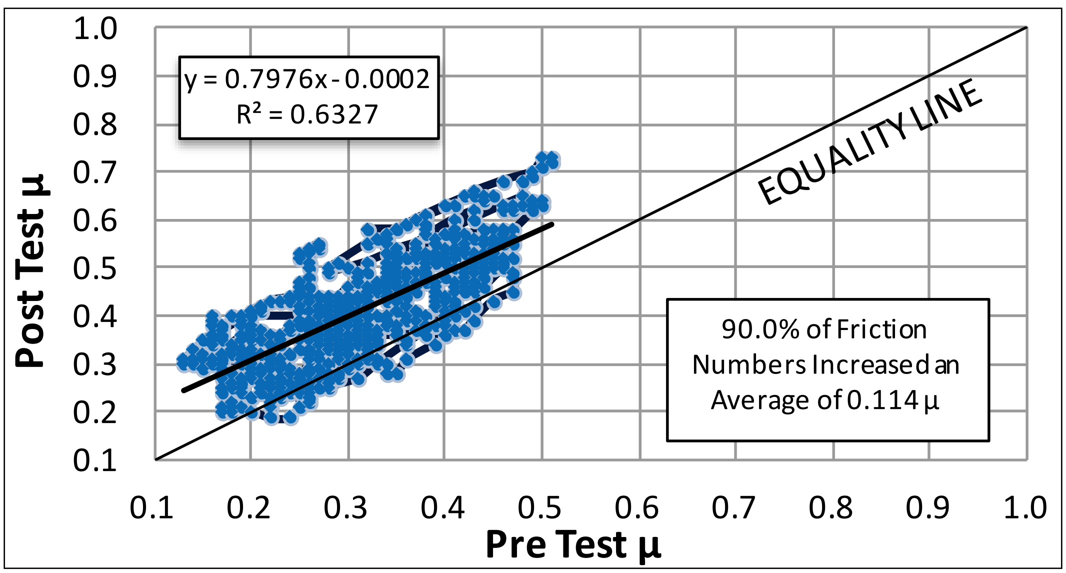
Friction Level	60 MPH	Deterioration Below Maintenance Planning Level for ≥ 500 ft	Deterioration Below Maintenance Planning Level for ≥ 1,000 ft
New Design	0.64	No corrective action is required	No corrective action is required
Maintenance Planning	0.53	No corrective action is required	Conduct an extensive evaluation into the cause(s) and extent of the friction deterioration and take appropriate corrective action.
Minimum Friction Level	0.24	Corrective action should be taken immediately	Corrective action should be taken immediately

Friction coefficients measured to the right of the runway center line were relatively higher from Runway 22L stations 0+00 to 20+00. Small differences in how each PCC lane was textured may largely influence available skid resistance. Most areas experienced improvements in available friction after rubber removal. The largest improvements in available friction were measured between Runway 22L stations 10+00 and 30+00.

Paired t-tests were performed to determine if improvements in available pavement skid resistance following rubber removal with each system were statistically significant at the 95 percent confidence level.

Friction measurements increased in 90 percent of the pavement area cleaned by the Cyclone 4006. The mean friction gain for these areas was 0.114 µ. Figure 38 presents pre- and post-rubber removal friction values for the pavement sections cleaned by the Cyclone 4006. These data are assumed to be approximately normally distributed for this pair-wise analysis.

Figure 38. Cyclone 4006 pre- and post-friction coefficients (60 mph).

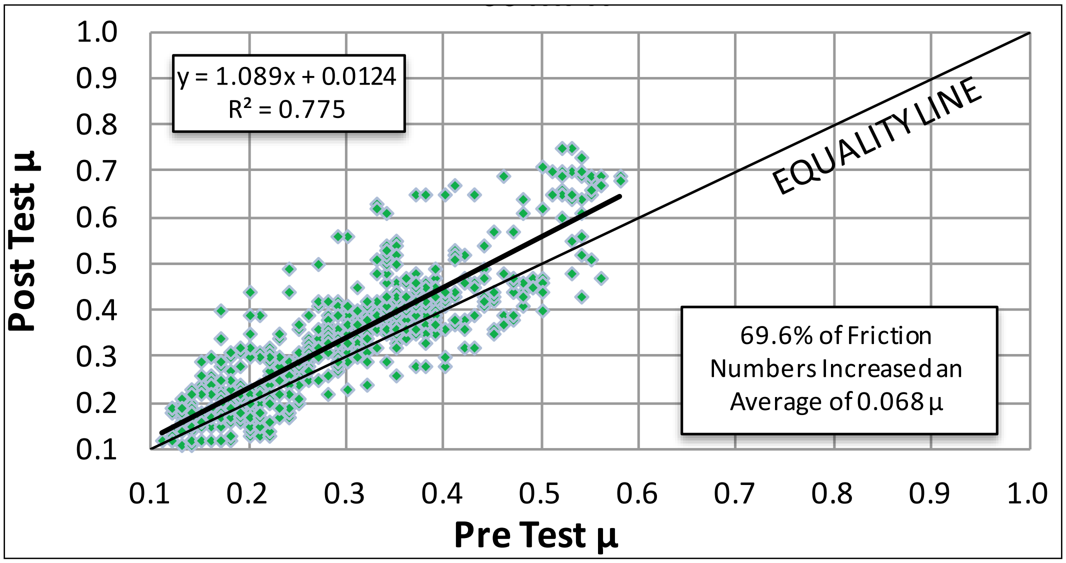


Comparison of initial friction measurements (*M* = 0.311, *SD* = 0.0912) and post-rubber removal friction measurements (*M* = 0.412, *SD* = 0.1090) indicated a statistical gain in available friction after rubber removal using the Cyclone 4006, with a $t(1{,}498) = 19.35$ and $p = 1.30E\text{-}74$.

Friction values increased in 70 percent of the pavement area cleaned by the SH8000R. The mean friction gain for these areas was 0.068 µ.

Figure 39 presents pre- and post-rubber removal values for the pavement sections cleaned by the SH8000R. These data are assumed to be approximately normally distributed for this pair-wise analysis.

Figure 39. SH8000R pre- and post-friction coefficients (60 mph).



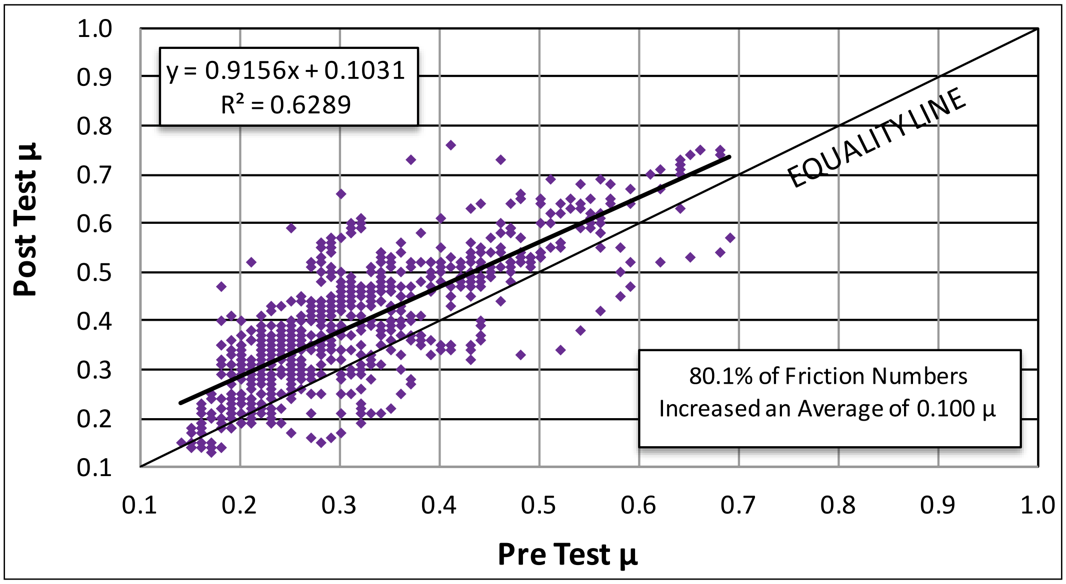
Comparison of initial friction measurements (*M* = 0.296., *SD* = 0.112) and post-rubber removal friction measurements (*M* = 0.334, *SD* = 0.139) indicated a statistical gain in available friction after rubber removal using the Cyclone 4006, with a $t(1{,}500) = 5.949$ and $p = 3.34E\text{-}09$.

Friction measurements increased in 80 percent of the pavement area cleaned by the Trackjet. The mean friction gain for these areas was 0.100 µ. Figure 40 presents pre- and post-rubber removal friction values for the pavement sections cleaned by the Trackjet. These data are assumed to be approximately normally distributed for this pair-wise analysis.

Comparison of initial friction measurements (*M* = 0.321, *SD* = 0.115) and post-rubber removal friction measurements (*M* = 0.397, *SD* = 0.133) indicated a statistical gain in available friction after rubber removal using the Trackjet, with a $t(1{,}500) = 11.83$ and $p = 3.14E\text{-}31$.

Pavement-tire friction coefficients measured sections cleaned by the Cyclone 4006 showed the most improvement, followed by the Trackjet. The SH8000R showed the most inconsistent results, which was evident by the most number of data points below the line of equality. At the 95 percent confidence level, pavement areas cleaned by all three technologies

Figure 40. Trackjet pre- and post-friction coefficients (60 mph).



exhibited statistically significant gains in available skid resistance. A one-way ANOVA comparing friction gains from each treatment revealed statistically significant differences between the groups, with an *F* (2, 2,249) = 134.72 and a *p* = 5.51E-56.

Since the ANOVA indicates statistically significant differences in treatment effects, a pair-wise t-test procedure was used to compare the means to determine if the calculated differences in means were statistically significant given the scatter of data. Tests of the three a priori hypotheses were conducted using Bonferroni adjusted alpha levels of 0.0167 per test (0.05/3). The results of these tests are presented in Figure 41. The value tabulated in each cell is the *P* value that resulted from the pair-wise t-test for the combination of treatments represented by the cell. A lower P value indicates a greater significance. In Figure 41, all cells with a *P* value less than 0.05 are highlighted in orange. This indicates that there is a greater than 95 percent probability that differences calculated between the two methods are statistically significant.

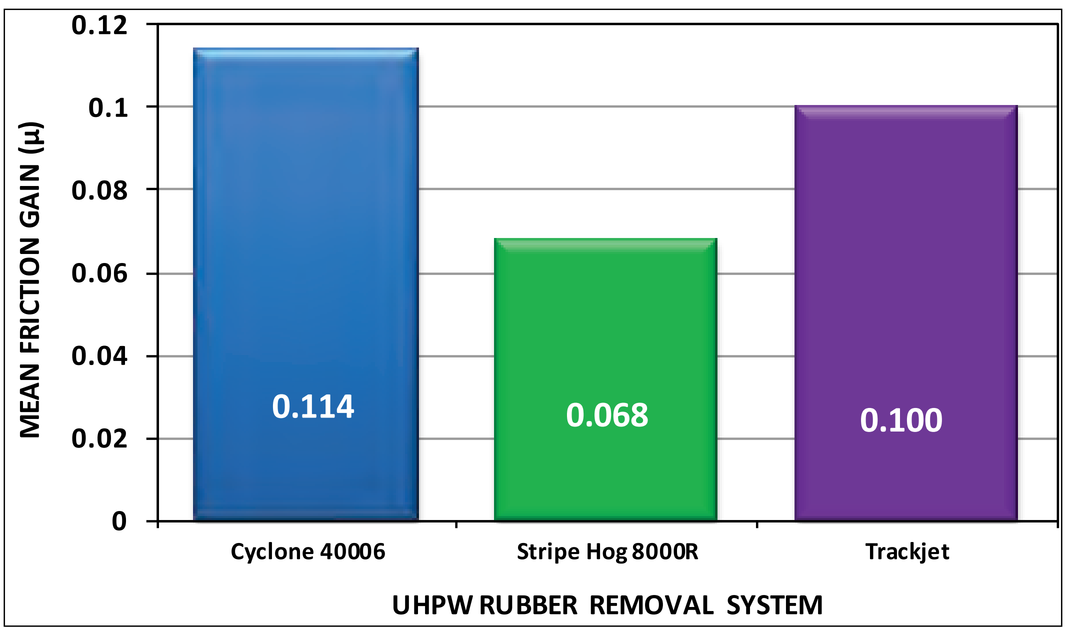
Using these analyses, the friction gains calculated in test sections cleaned by the Cyclone 4006 (*M* = 0.1004, *SD* = 0.0710) were statistically greater than friction gains in test sections cleaned by the SH8000R (*M* = 0.0387, *SD* = 0.0665), with a t(1,498) = 17.35 and a *p* = 1.39E-61. Friction gains in test sections cleaned by the Cyclone 4006 were statistically greater than friction gains in test sections cleaned by the Trackjet (0.0760, *SD* = 0.0817), with a *t*(1,499) = 6.18 and a *p* = 8.27E-10. Lastly, friction gains measured in

Trackjet test sections were statistically greater than friction gains measured in SH8000R test sections, with a $t(1{,}500) = 9.70$ and a $p = 1.27E\text{-}21$. A comparison of mean friction gains following rubber removal is provided in Figure 42.

Figure 41. P value matrix for post-rubber removal friction gains (60 mph).

	Cyclone 4006	Stripe Hog 8000R	Trackjet
Cyclone 4006		1.3864E-61	8.2711E-10
Stripe Hog 8000R			1.2725E-21
Trackjet	SYMMETRICAL		

Figure 42. Comparison of mean friction gains following rubber removal (60 mph).



5.2.2 International friction index

The complete frictional properties of runways can be characterized when both microtexture and macrotexture of the runway are properly determined. Microtexture is typically associated with low to medium speed skid resistance while macrotexture controls the high speed frictional properties. Macrotexture is also the prominent factor for runway surface drainage and hydroplaning. In addition to mitigating the hydroplaning phenomena, high macrotexture greatly influences the gradient of skid resistance. It is imperative to consider both friction values and the gradient of the skid resistance to properly characterize the rate of the decay of friction as a function of aircraft speed.

The Permanent International Association of Road Congresses (PIARC), now known as the World Road Association (PIARC), recognized that friction and surface texture measurements significantly rely on the type of the equipment used (Wambold 1995). PIARC conducted a landmark study in 1992 on 47 different friction and texture measuring devices at 54 sites in Europe. The outcome of the research was an International Friction Index (IFI) to harmonize and compare texture and skid resistance measurements independent of the measuring equipment. IFI allows harmonization of friction measurements with different measurement devices to a universal calibrated index. IFI consists of two components: calibrated wet friction at 60 km/hr (F60) and a speed constant (S_p). F60 and S_p have been proven to sufficiently characterize the speed dependence of wet pavement-related measurements of various types of friction measuring equipment. The subsequent procedure was followed to calculate the parameters of the IFI. These parameters were determined for both initial and post-rubber removal measured data to evaluate the impact of each rubber removal system on runway pavement skid resistance. The speed constant (S_p) of wet pavement friction can be calculated as:

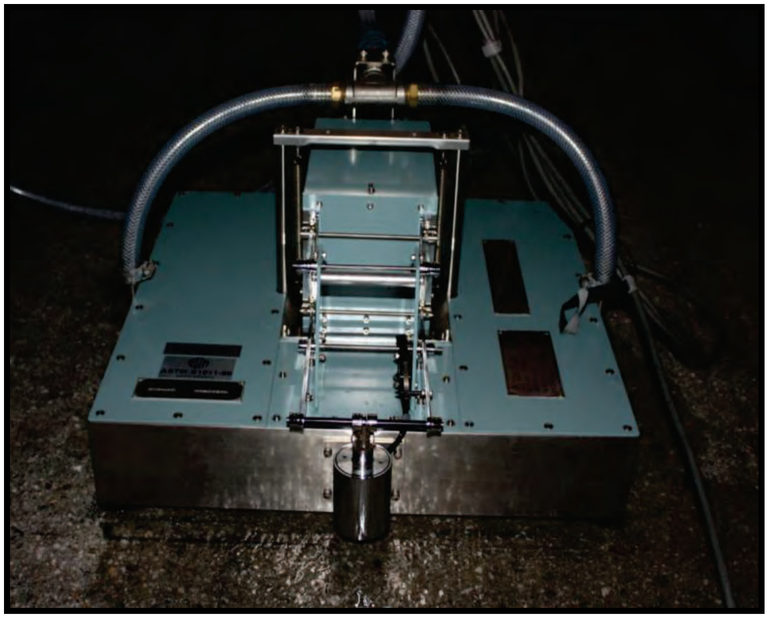
$$S_p = a + b \times TX \tag{6}$$

where:

S_p = speed constant (km/hr)
TX = macrotexture measurement (mm)
a and b = calibration constants depending on the type of macrotexture measuring equipment (a = 14.2 and b = 89.7 according to ASTM E-1845 (ASTM 2009a))

Friction values at different slip speeds were determined using the dynamic friction tester (DFT) shown in Figure 43.

Figure 43. Dynamic friction tester.



These results were used to develop skid number-slip speed curves for comparative studies. Equation 7 presents the mapping relationship used to adjust a measured friction at any given speed (*S*) to a reference speed of 60 km/hr.

$$FR60 = FRS \times e^{\left[\frac{S-60}{S_p}\right]} \tag{7}$$

where:

$FR60$ = adjusted value of friction for a slip speed of S
S = slip speed (km/hr)
S_p = speed constant (km/hr)

The adjusted friction values were calculated using Equation 6, and texture data were used to calculate $F60$ using Equation 8:

$$F60 = A + B \times FR60 + C \times TX \tag{8}$$

where:

$F60$ = harmonized friction value
A, B and C = calibration constants dependent on measuring device as suggested by ASTM E-1960 (ASTM 2011) (for dynamic friction tester (DFT) calibration constants are $A = -0.034$, $B = 0.771$ and $C = 0$).
TX = macrotexture measurement (mm)

The gradient of skid resistance is further used in this research to characterize runway skid resistance at high speed.

Table 5 presents IFI(60) results using the approach presented. Comparisons were made on both sides of the Runway 22L center line cleaned with each technology. These comparisons were made at three different sections along the 3,000-ft test area: beginning, middle and towards the end of the touchdown and braking zones to account for different magnitudes of surface contamination. Rubber deposits were observed to be heaviest over the first 2,000 ft of the test area and then to taper down over the final 1,000 ft.

IFI calculations revealed that section E had the lowest average initial IFI(60), a value of 0.21 before rubber removal. After rubber removal, the IFI(60) statistically improved by 53 percent to 0.44. The lowest average initial IFI(60) was calculated for section Q, which was one of the last test sections toward the center of the runway, where less rubber is normally observed as it experiences less braking action. Results for this section indicate that rubber removal was able to improve the IFI(60) values by 19 percent.

This improvement in skid resistance could be attributed to the UHPW systems removing the few stray rubber deposits present and imposing some degree of retexturing, or roughening the pavement surface.

The average initial IFI(60) values for Cyclone 4006, Trackjet and SH8000R test sections were calculated as 0.28, 0.31, and 0.28. The post-rubber removal average IFI(60) values were 0.49, 0.49, and 0.46, respectively. The average improvement in the IFI(60) values were 44 percent for Cyclone 4006, 39.6 percent for Trackjet and 39.7 percent for SH8000R. All rubber removal systems were able to significantly improve the skid resistance on the runway.

Table 5. International friction index (IFI) calculations.

IFI(60)											
Location ID	PRE	POST	Average PRE	Average POST	Average Improvement (%)	Location ID	PRE	POST	Average PRE	Average POST	Average Improvement (%)
Cyclone 4006						Trackjet					
Section A						Section B					
1	0.32	0.44				4	0.44	0.52			
2	0.28	0.47	0.31	0.47	34	5	0.44	0.53	0.43	0.52	18
3	0.34	0.50				6	0.41	0.52			
Section G						Section H					
19	0.24	0.49				22	0.21	0.47			
20	0.26	0.48	0.24	0.48	50	23	0.23	0.47	0.23	0.48	51
21	0.21	0.46				24	0.26	0.52			
Section M						Section N					
37	0.28	0.28				40	0.27	0.49			
38	0.29	0.51	0.28	0.49	43	41	N/A	N/A	0.25	0.47	48
39	0.26	0.48				42	0.22	0.46			
SH8000R						Cyclone 4006					
Section C						Section D					
1	0.24	0.42				4	0.30	0.53			
2	0.24	0.28	0.25	0.38	36	5	0.28	0.52	0.30	0.53	44
3	0.25	0.46				6	0.31	0.55			
Section I						Section J					
19	0.26	0.45				22	0.25	0.50			
20	0.24	0.44	0.25	0.45	45	23	0.23	0.49	0.24	0.51	53
21	0.24	0.46				24	0.25	0.54			
Section O						Section P					
37	0.32	0.52				40	0.23	0.50			
38	0.35	0.55	0.32	0.52	39	41	0.24	0.43	0.29	0.48	40
39	0.28	0.49				42	0.39	0.51			
Trackjet						SH8000R					
Section E						Section F					
13	0.21	0.46				16	0.23	0.44			
14	0.19	0.45	0.21	0.44	53	17	0.29	0.42	0.25	0.43	43
15	0.21	0.42				18	0.23	0.43			
Section K						Section L					
31	0.23	0.44				34	0.22	0.51			
32	0.24	0.51	0.25	0.48	48	35	0.25	0.49	0.24	0.50	52
33	0.28	0.42				36	N/A	N/A			
Section Q						Section R					
49	N/A	N/A				52	0.36	0.45			
50	0.43	0.52	0.46	0.56	19	53	0.32	0.44	0.35	0.46	23
51	0.49	0.60				54	0.38	0.48			

Table 6 shows the calculations for the speed constant (S_p). The speed constant is basically a measure of the rate of decay in skid resistance with tire slip speed. For two runway surfaces with equal IFI(60) values, the surface with a higher speed constant (S_p) performs better in terms of higher skid resistance at higher speeds. Therefore it is imperative to consider both IFI(60) values and speed constant (S_p) for determination of improvement in runway frictional properties after rubber removal operations.

The speed constant results revealed that section *O* has the highest initial average (S_p), a value of 62.77. As stated earlier, sections located toward the end of the touchdown and braking zones had a relatively smaller amount of rubber contamination as reflected in the results. Analysis of post-rubber removal showed that the maximum (S_p) value was 67.42 in section *O*. The highest improvement in speed constant was 15 percent at sections *L* and *M*. Sections *Q*, *B*, and *I* showed a speed constant loss of about 2 percent after rubber removal.

Average speed constant (S_p) values were also calculated to characterize the efficiency of maintaining desired frictional properties at high travel speeds. The speed constant values were averaged over each class of data categorized by the type of equipment used in the rubber removal process. The average initial (S_p) values for Cyclone 4006, Trackjet and SH8000R test sections were calculated as 43.5, 45.8 and 48.7. The post-rubber removal average (S_p) values were 48.9, 47.6 and 51.5, respectively. The average improvement in speed constant (S_p) for Cyclone 4006, Trackjet and SH8000R systems were calculated as 11.1 percent, 4.4 percent and 5.1 percent, respectively. The (S_p) results were in line with trends measured for IFI(60) and mean profile depth (MPD) analysis results.

5.3 Texture measurements

Analysis of circular track meter and NASA grease smear test results are provided in the following sections.

5.3.1 Mean profile depth

The circular track meter (CT meter), shown in Figure 44, was operated in accordance with the manufacturer's recommendations. In the few cases that a pavement experienced small losses in MPD following rubber removal, changes in surface texture may have been negligible or beyond the CT meter's level of precision. A PIARC reproducibility study using two different systems and test crews found measurements to be replicated within 10 percent or 0.15 mm (Wambold 1995).

Table 6. Speed constant calculations.

IFI(60)											
Location ID	PRE	POST	Average PRE	Average POST	Average Improvement (%)	Location ID	PRE	POST	Average PRE	Average POST	Average Improvement (%)
Cyclone 4006						Trackjet					
Section A						Section B					
1	45.30	49.18				4	56.36	56.06			
2	42.70	44.30	46.53	51.97	10	5	52.57	49.98	58.58	57.22	-2
3	51.58	62.44				6	66.82	65.63			
Section G						Section H					
19	44.80	49.28				22	36.53	41.61			
20	52.07	52.57	45.30	51.41	12	23	41.91	43.40	43.73	46.72	6
21	39.02	52.37				24	52.77	55.16			
Section M						Section N					
37	36.33	45.79				40	39.22	43.10			
38	39.22	43.90	38.32	45.30	15	41	N/A	N/A	38.27	42.01	9
39	39.42	46.19				42	37.32	40.91			
SH8000R						Cyclone 4006					
Section C						Section D					
7	40.41	40.31				10	39.02	44.40			
8	34.43	36.63	39.52	41.61	5	11	40.81	45.79	44.90	49.75	10
9	43.70	47.89				12	54.86	59.05			
Section I						Section J					
25	63.44	62.64				28	41.81	45.89			
26	60.55	56.96	56.46	55.16	-2	29	36.53	44.00	44.93	50.05	10
27	45.40	45.89				30	56.46	60.25			
Section O						Section P					
43	45.30	49.38				46	42.80	47.69			
44	97.52	99.22	62.77	67.42	7	47	40.41	43.50	41.01	45.00	9
45	45.50	53.67				48	39.81	43.80			
Trackjet						SH8000R					
Section E						Section F					
13	37.82	42.70				16	57.95	57.36			
14	36.53	38.62	37.52	40.84	8	17	42.70	44.40	46.82	48.62	4
15	38.22	41.21				18	39.81	44.10			
Section K						Section L					
31	32.64	35.13				34	45.50	45.60			
32	39.81	43.20	38.05	41.04	7	35	44.30	60.55	44.90	53.07	15
33	41.71	44.80				36	N/A	N/A			
Section Q						Section R					
49	50.68	50.78				52	35.73	36.43			
50	46.49	44.50	58.55	57.62	-2	53	44.60	44.30	42.17	43.07	2
51	78.49	77.59				54	46.19	48.49			

Figure 44. Circular track meter.

Figure 45 through Figure 47 present CT meter test results at locations along Runway 22L. Most areas experienced an increase in MPD after rubber removal. Paired t-tests were performed to determine if improvements in available pavement macrotexture following rubber removal with each system were statistically significant at the 95 percent confidence level.

Figure 45. Cyclone 4006 Runway 22L pre- and post-MPD.

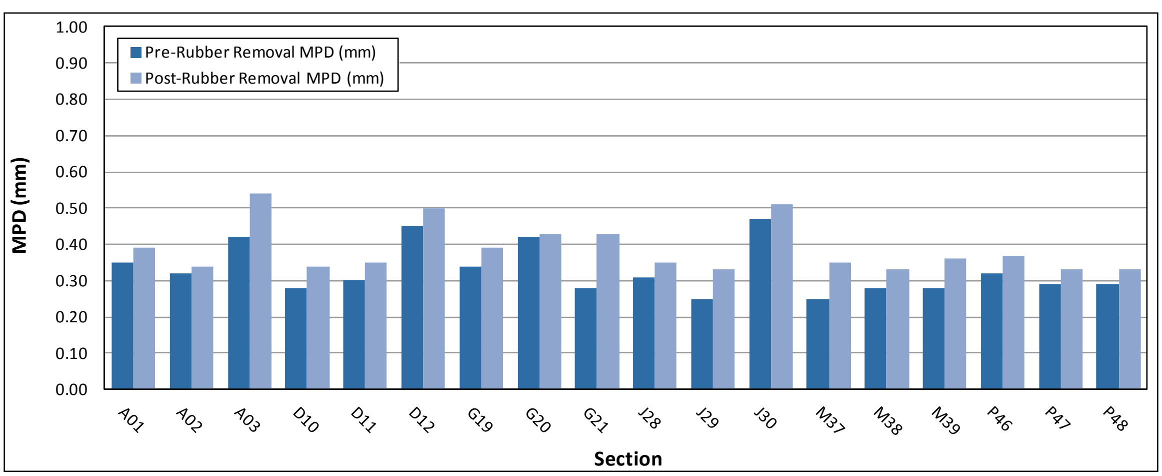


Figure 46. SH8000R Runway 22L pre- and post-MPD.

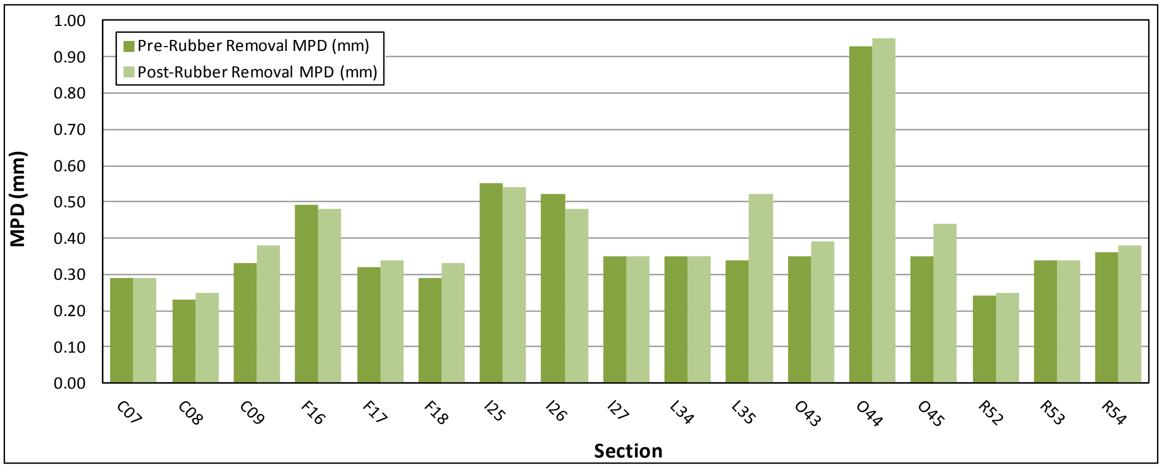
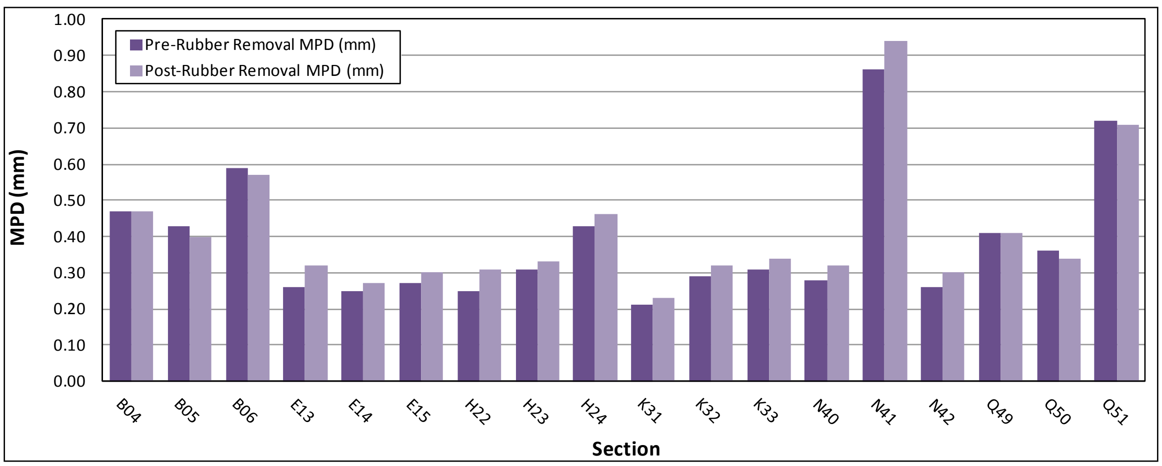


Figure 47. Trackjet Runway 22L pre- and post-MPD.



A gain in MPD was measured over 100 percent of the pavement sections cleaned by the Cyclone 4006. The average MPD gain for these areas was 0.059 mm.

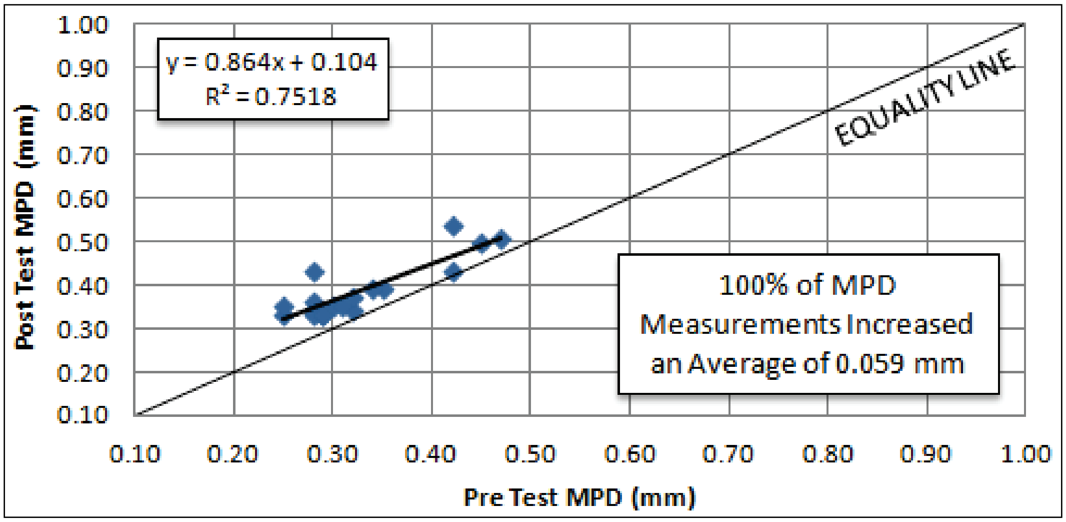
A comparison of the initial MPD measurements (M = 0.328, SD = 0.0678) and post MPD measurements (M = 0.387, SD = 0.0675) indicated that there was a statistical increase in MPD after rubber removal using the Cyclone 4006, with a $t(34)$ = 2.64 and p = 6.28E-3.

Data in Table 7 were used to develop the chart shown in Figure 48, which compares pre- and post- rubber removal MPD measurements. A gain in MPD was measured over 100 percent of the pavement sections cleaned by the Cyclone 4006. The average MPD gain for these areas was 0.059 mm.

Table 7. Cyclone 4006 pre- and post-MPD.

Section	Pre-Cleaning MPD (mm)	Post-Cleaning MPD (mm)	MPD Gain (mm)
A01	0.35	0.39	0.04
A02	0.32	0.34	0.02
A03	0.42	0.54	0.12
D10	0.28	0.34	0.06
D11	0.30	0.35	0.05
D12	0.45	0.50	0.05
G19	0.34	0.39	0.05
G20	0.42	0.43	0.01
G21	0.28	0.43	0.15
J28	0.31	0.35	0.04
J29	0.25	0.33	0.08
J30	0.47	0.51	0.04
M37	0.25	0.35	0.10
M38	0.28	0.33	0.05
M39	0.28	0.36	0.08
P46	0.32	0.37	0.05
P47	0.29	0.33	0.04
P48	0.29	0.33	0.04

Figure 48. Cyclone 4006 Pre- and Post-MPD.

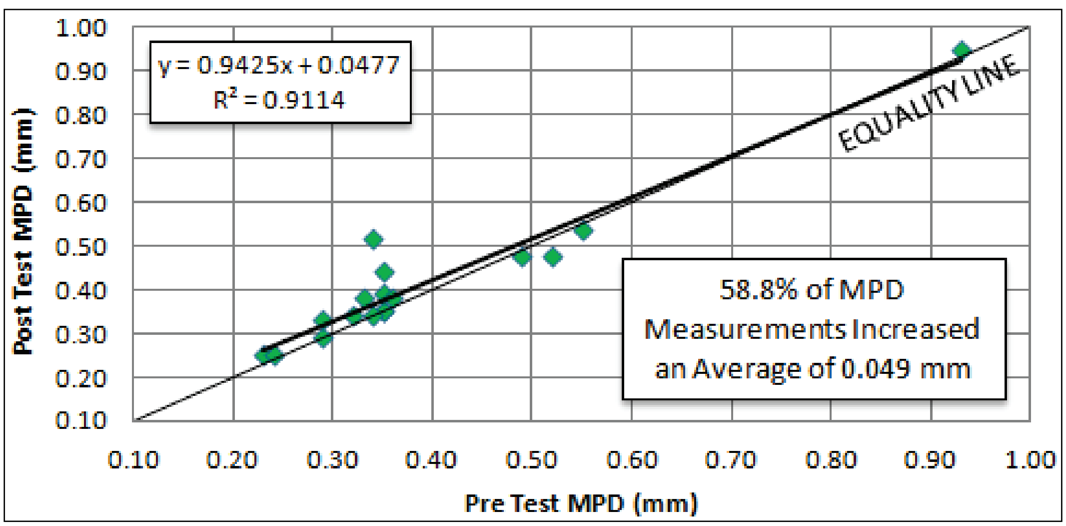


A gain in MPD was measured over 59 percent of the pavement sections cleaned by the SH8000R. The average MPD gain for these areas was 0.049 mm. Data in Table 8 were used to develop the chart shown in Figure 49, which compares pre- and post-rubber removal MPD measurements.

Table 8. SH8000R pre- and post-MPD.

Section	Pre-cleaning MPD (mm)	Post-cleaning MPD (mm)	MPD Gain (mm)
C07	0.29	0.29	0.00
C08	0.23	0.25	0.02
C09	0.33	0.38	0.05
F16	0.49	0.48	-0.01
F17	0.32	0.34	0.02
F18	0.29	0.33	0.04
I25	0.55	0.54	-0.01
I26	0.52	0.48	-0.04
I27	0.35	0.35	0.00
L34	0.35	0.35	0.00
L35	0.34	0.52	0.18
O43	0.35	0.39	0.04
O44	0.93	0.95	0.02
O45	0.35	0.44	0.09
R52	0.24	0.25	0.01
R53	0.34	0.34	0.00
R54	0.36	0.38	0.02

Figure 49. SH8000R pre- and post-MPD.



Comparison of initial MPD measurements (M = 0.390, SD = 0.165) and post MPD measurements (M = 0.415, SD = 0.162) yielded no statistical gain at the 95 percent confidence level in MPD after rubber removal using the SH8000R with a $t(32) = 0.45$ and $p = 2.03$.

A gain in MPD was measured over 67 percent of the pavement sections cleaned by the Trackjet. The average MPD gain for these areas was 0.038 mm. Data in Table 9 were used to develop the chart shown in Figure 50, which compares pre- and post-rubber removal MPD measurements.

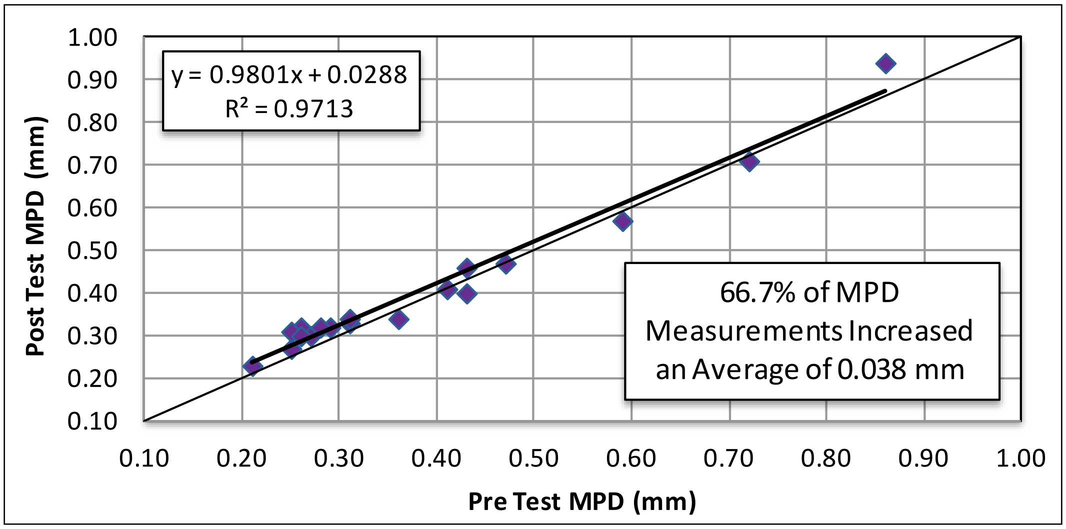
Comparison of initial MPD measurements (M = 0.387, SD = 0.177) and post MPD measurements (M = 0.408, SD = 0.176) yielded no statistical gain at the 95 percent confidence level in MPD after rubber removal using the Trackjet, with a $t(34) = 0.36$ and a $p = 0.72$.

At the 95 percent confidence level, only sections cleaned by the Cyclone 4006 exhibited statistically significant gains in MPD. A one-way ANOVA comparing MPD gains from each treatment revealed statistically significant differences between the groups, with an $F\,(2, 50) = 5.28$ and a p = 8.31E-3.

Table 9. Trackjet pre- and post-MPD.

Section	Pre-cleaning MPD (mm)	Post-cleaning MPD (mm)	MPD Gain (mm)
B04	0.47	0.47	0.00
B05	0.43	0.40	-0.03
B06	0.59	0.57	-0.02
E13	0.26	0.32	0.06
E14	0.25	0.27	0.02
E15	0.27	0.30	0.03
H22	0.25	0.31	0.06
H23	0.31	0.33	0.02
H24	0.43	0.46	0.03
K31	0.21	0.23	0.02
K32	0.29	0.32	0.03
K33	0.31	0.34	0.03
N40	0.28	0.32	0.04
N41	0.86	0.94	0.08
N42	0.26	0.30	0.04
Q49	0.41	0.41	0.00
Q50	0.36	0.34	-0.02
Q51	0.72	0.71	-0.01

Figure 50. Trackjet pre- and post-MPD.



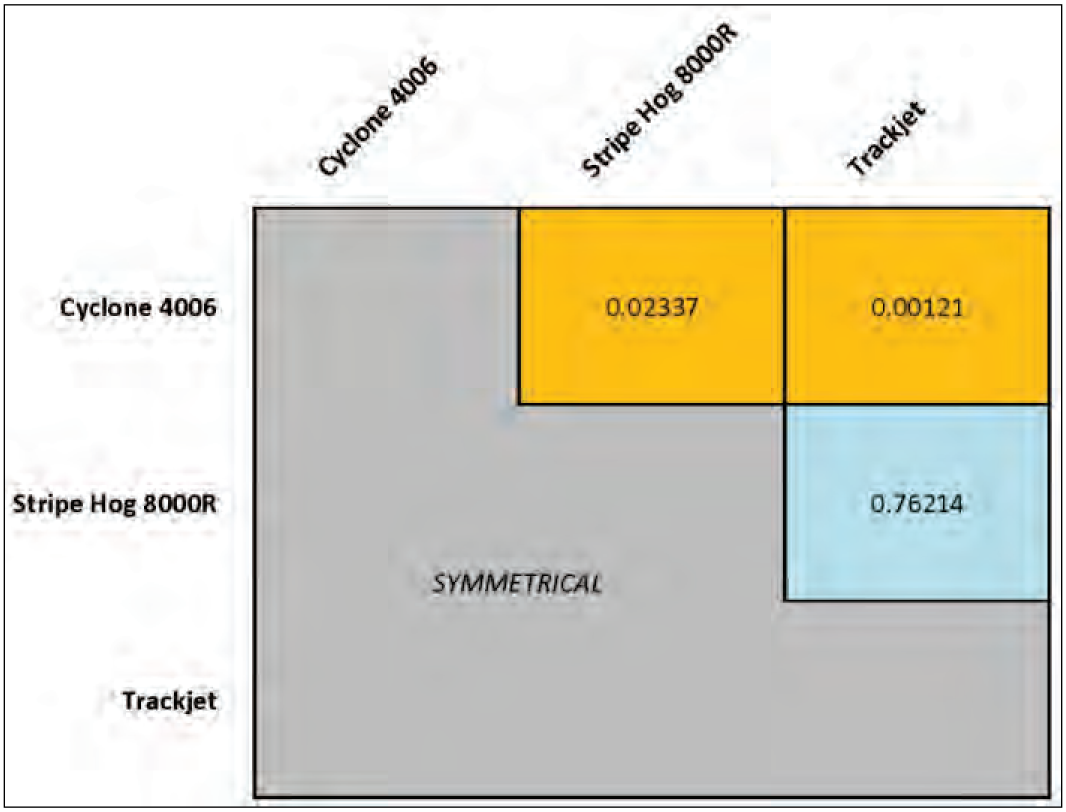
Since the ANOVA indicates statistically significant differences in treatment effects, a pair wise t-test procedure was used to compare the means to determine if the calculated differences in means were statistically significant given the scatter of data. Tests of the three a priori hypotheses were conducted using Bonferroni adjusted alpha levels of 0.0167 per test (0.05/3). The results of these tests are presented in Figure 51. The value tabulated in each cell is the *P* value that resulted from the pair-wise t-test for the combination of treatments represented by the cell. A lower *P* value indicates a greater significance. In Figure 51, all cells with a *P* value less than 0.05 are highlighted in orange. This indicates that there is a greater than 95 percent probability that differences calculated between the two methods are statistically significant.

Using these analyses, the mean MPD gains measured over Cyclone 4006 test sections (M = 0.0594, SD = 0.0349) were statistically higher than test sections cleaned by the SH8000R (M = 0.0253, SD = 0.0493), with a $t(33) = 2.38$ and a $p = 0.012$ and the Trackjet (M = 0.0211, SD = 0.0301), with a $t(34) = 3.53$ and a $p = 0.0012$. MPD gains over test sections cleaned by the SH8000R and Trackjet were not statistically different, with a $t(33) = 0.305$ and a $p = 0.762$.

5.3.2 Average texture depth

Paired t-tests were performed to determine if improvements in available pavement macrotexture as measured with the NASA grease smear test and quantified with average texture depth following rubber removal with each system were statistically significant at the 95 percent confidence level.

Figure 51. P value matrix for post-rubber removal MPD gain.

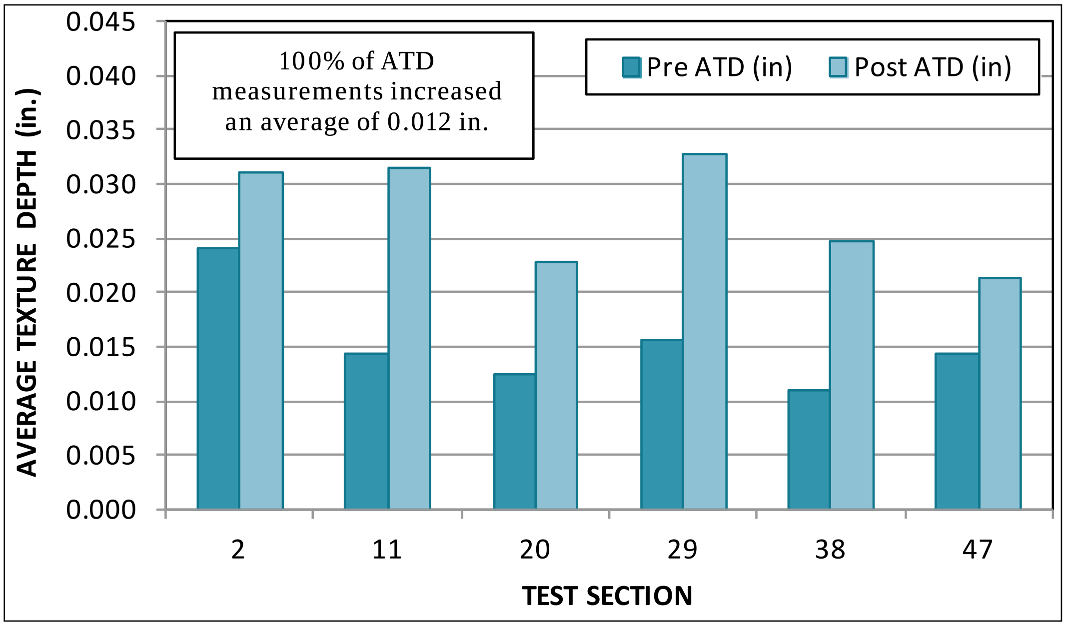


All sections cleaned by the Cyclone 4006 experienced an increase in the average texture depth (ATD). The mean ATD gain for these areas was 0.012 in. Data in Table 10 were used to develop the chart shown in Figure 52, which compares pre- and post-rubber removal ATD measurements.

Table 10. Cyclone 4006 pre- and post-ATD.

Section	Pre-cleaning ATD (in.)	Post-cleaning ATD (in.)	ATD Gain (in.)
A02	0.024	0.031	0.007
D11	0.014	0.032	0.017
G20	0.013	0.023	0.010
J29	0.016	0.033	0.017
M38	0.011	0.025	0.014
P47	0.014	0.021	0.007

Figure 52. Cyclone 4006 pre- and post-ATD.



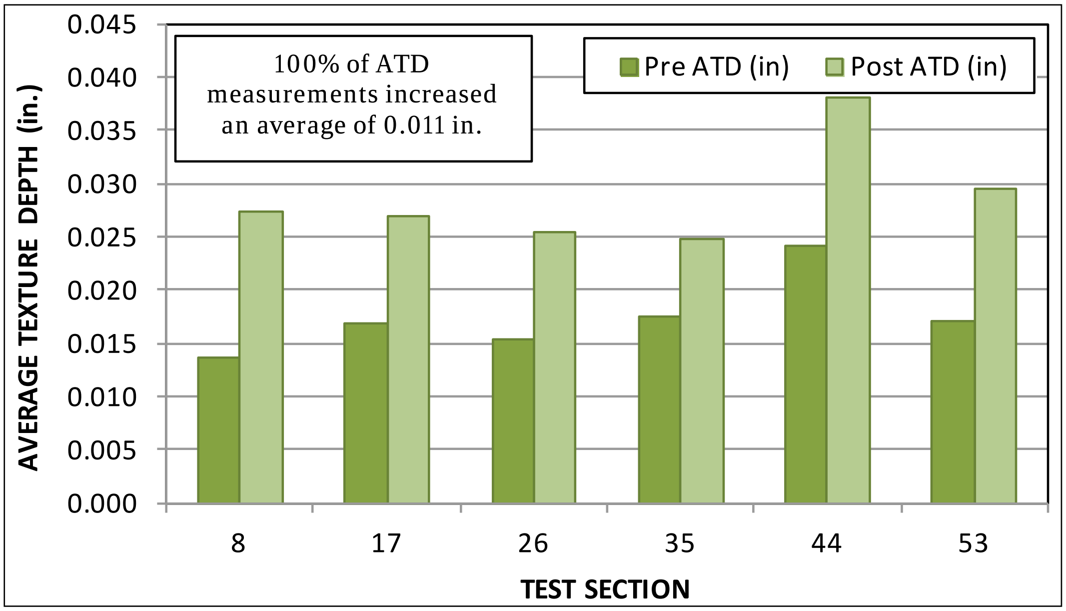
Comparison of initial ATD measurements (M = 0.015, SD = 0.00461) and post ATD measurements (M = 0.027, SD = 0.00497) indicated that there was a statistical increase in ATD after rubber removal using the Cyclone 4006, with a $t(10)$ = 4.37 and a p = 1.41E-3.

All sections cleaned by the SH8000R experienced an increase in ATD. The mean ATD gain for these areas was 0.011 in. Data in Table 11 were used to develop the chart shown in Figure 53, which compares pre- and post-rubber removal ATD measurements.

Table 11. SH8000R pre- and post-ATD.

Section	Pre-cleaning ATD (in.)	Post-cleaning ATD (in.)	ATD Gain (in.)
C08	0.014	0.027	0.014
F17	0.017	0.027	0.010
I26	0.015	0.025	0.010
L35	0.018	0.025	0.007
O44	0.024	0.038	0.014
R53	0.017	0.030	0.012

Figure 53. SH8000R pre- and post-ATD.



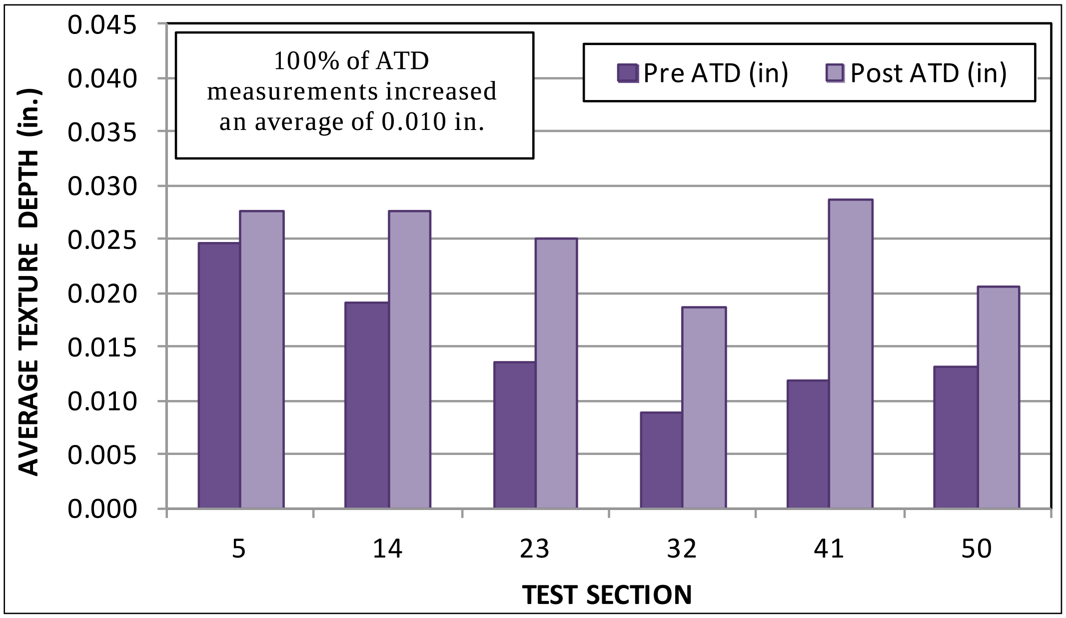
Comparison of initial ATD measurements (M = 0.017, SD = 0.00355) and post ATD measurements (M = 0.029, SD = 0.00492) indicated that there was a significant increase in ATD after rubber removal using the SH8000R, with a $t(10) = 4.52$ and a p = 1.11E-3.

All sections cleaned by the Trackjet experienced an increase in ATD. The mean ATD gain for these areas was 0.010 in. Data in Table 12 were used to develop the chart shown in Figure 54, which compares pre- and post-rubber removal ATD measurements.

Table 12. Trackjet pre- and post-ATD.

Section	Pre-cleaning ATD (in.)	Post-cleaning ATD (in.)	ATD Gain (in.)
B05	0.025	0.028	0.003
E14	0.019	0.028	0.009
H23	0.014	0.025	0.012
K32	0.009	0.019	0.010
N41	0.012	0.029	0.017
Q50	0.013	0.021	0.007

Figure 54. Trackjet pre- and post-ATD.



Comparison of initial ATD measurements (*M* = 0.015, *SD* = 0.00571) and post ATD measurements (*M* = 0.025, *SD* = 0.00417) indicated that there was a statistical increase in ATD after rubber removal using the Trackjet, with a $t(10) = 3.29$ and a $p = 8.14E\text{-}3$.

Evidence was provided at the 95 percent confidence level that rubber removal with each system generated improvements in pavement macrotexture. ATD gains were relatively uniform with each system; furthermore, a one-way ANOVA comparing ATD gains from each treatment revealed no statistically significant differences between the groups, with an $F\,(2, 15) = 3.68$ and a $p = 0.551$.

5.3.3 Outflow time

Outflow meter tests were performed prior to and after rubber removal at the same location in each test section. Outflow time (OFT) is the measured parameter for this test. OFT is the length of time required for a volume of water to pass between a rubber seal and the surface of the pavement. Surfaces with smooth macrotexture, such as a pane of glass, would result in high OFTs. Shorter OFTs are anticipated after rubber removal, as shorter test times indicate a rough macrotexture and better surface drainage. Outflow meter testing is shown in Figure 55.

Figure 55. Outflow time measurements.

Figures 56 through 58 present the outflow meter test results at locations along Runway 22L. A reduction in OFT indicates improvement of macro-texture on the runway.

Figure 56. Cyclone 4006 Runway 22L pre- and post-OFT.

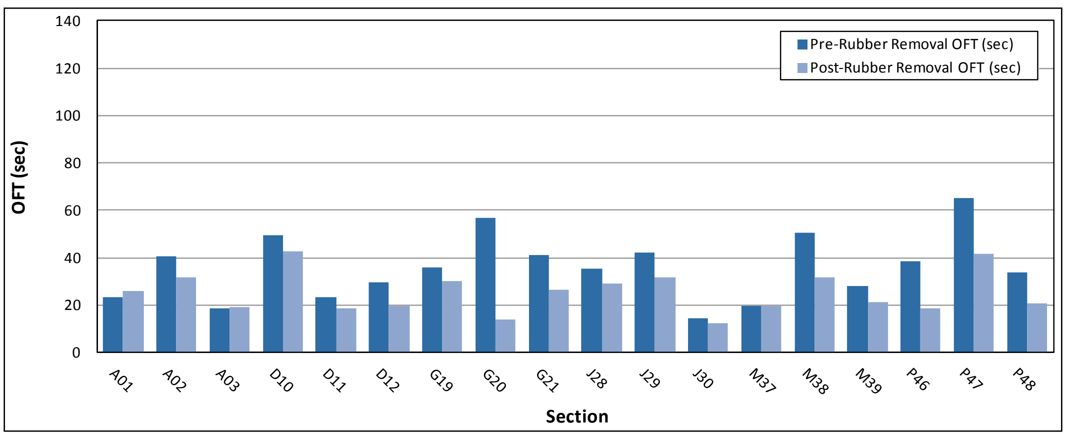


Figure 57. SH8000R Runway 22L pre- and post-OFT.

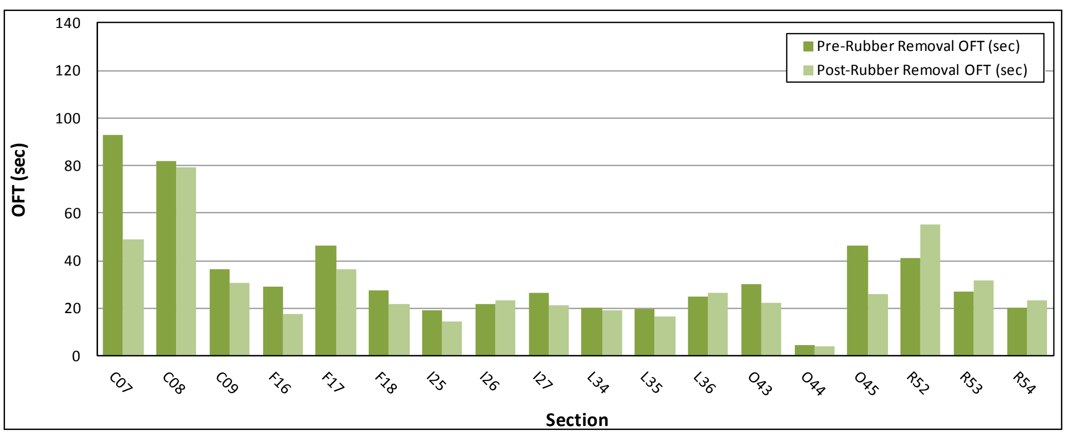
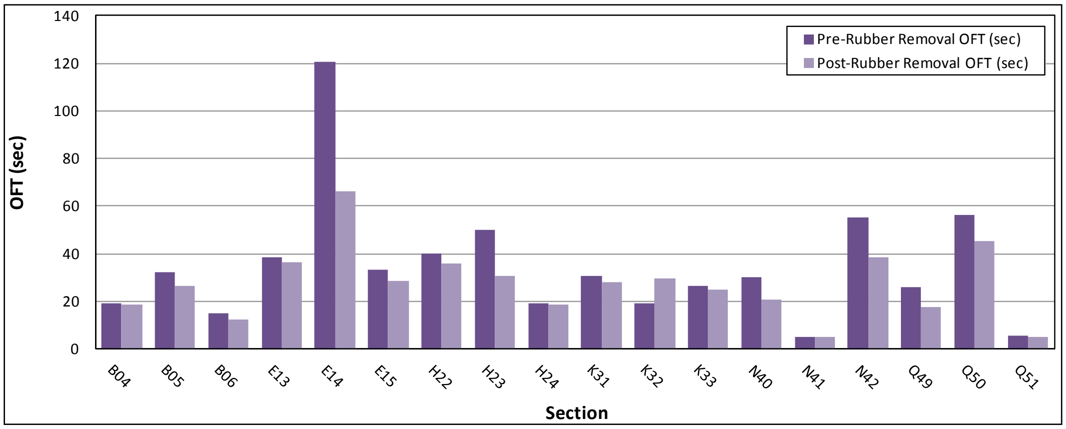


Figure 58. Trackjet Runway 22L pre- and post-OFT.



The precision of the outflow meter used for this experiment is 0.143 sec with a coefficient variation (CV) of 0.63 percent. Most test areas experienced a decrease in outflow time subsequent to rubber removal; however, a few sections did have increased outflow times. These increases could be due to tests not being conducted in the same location. Every effort was made to test over the same footprint. Unfortunately, pavement texture is non-homogenous and largely variable, so a slight deviation in measurement location could contribute to data outliers in OFT measurements.

Paired t-tests were performed to determine if reductions in pavement OFT following rubber removal with each system were statistically significant at the 95 percent confidence level. A reduction in OFT was measured over 83 percent of the pavement sections cleaned by the Cyclone 4006. The mean OFT loss for these areas was 13.01 sec. Data in Table 13 were used to develop the chart shown in Figure 59, which compares pre- and post-rubber removal OFT measurements. Comparison of initial OFT measurements (M = 35.92, SD = 13.80) and post-OFT measurements (M = 25.25, SD = 8.61) indicated that there was a statistical reduction in OFT after rubber removal using the Cyclone 4006, with a $t(34) = 2.78$ and a p = 8.75E-3.

A reduction in OFT was measured over 72 percent of the pavement sections cleaned by the SH8000R. The mean OFT loss for these areas was 9.42 sec. Data in Table 14 were used to develop the chart shown in Figure 60, which compares pre- and post-rubber removal OFT measurements. Comparison of initial OFT measurements (M = 34.19, SD = 21.97) and post-OFT measurements (M = 28.80, SD = 17.31) yielded no statistically significant reduction in OFT after rubber removal using the SH8000R, with a $t(34) = 0.82$ and a $p = 0.42$.

Table 13. Cyclone 4006 pre- and post-OFT.

Section	Pre-cleaning OFT (sec)	Post-cleaning OFT (sec)	OFT Reduction (sec)
A01	23.16	25.74	-2.58
A02	40.75	31.5	9.25
A03	18.75	19.21	-0.46
D10	49.34	42.86	6.48
D11	23.53	18.83	4.7
D12	29.75	19.59	10.16
G19	36.08	30.14	5.94
G20	56.62	13.94	42.68
G21	40.89	26.69	14.2
J28	35.19	29.02	6.17
J29	42.18	31.53	10.65
J30	14.32	12.17	2.15
M37	19.49	19.67	-0.18
M38	50.66	31.87	18.79
M39	28.19	21.19	7
P46	38.57	18.5	20.07
P47	65.36	41.51	23.85
P48	33.69	20.56	13.13

Figure 59. Cyclone 4006 pre- and post-OFT.

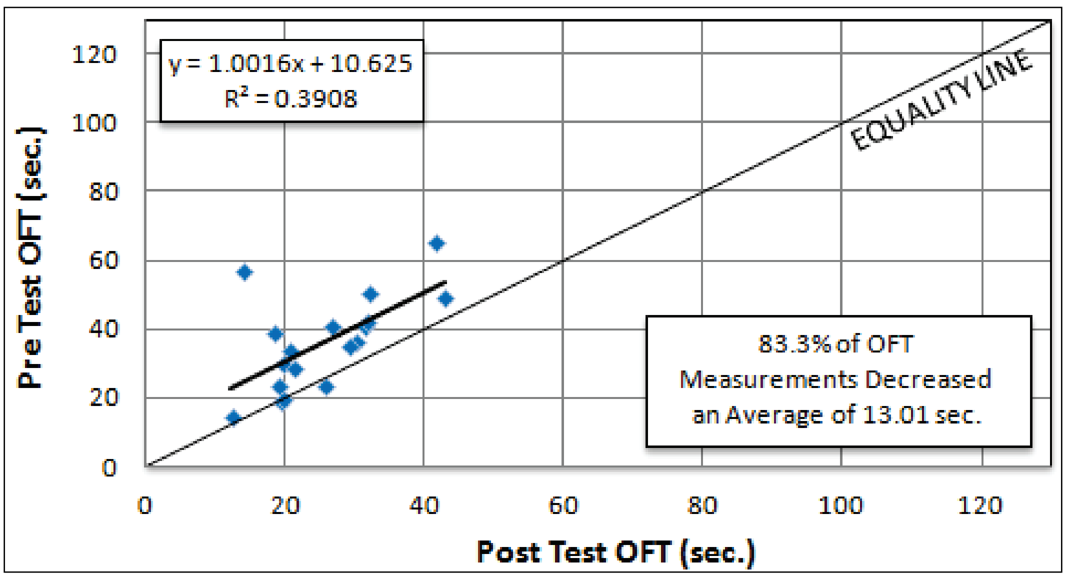
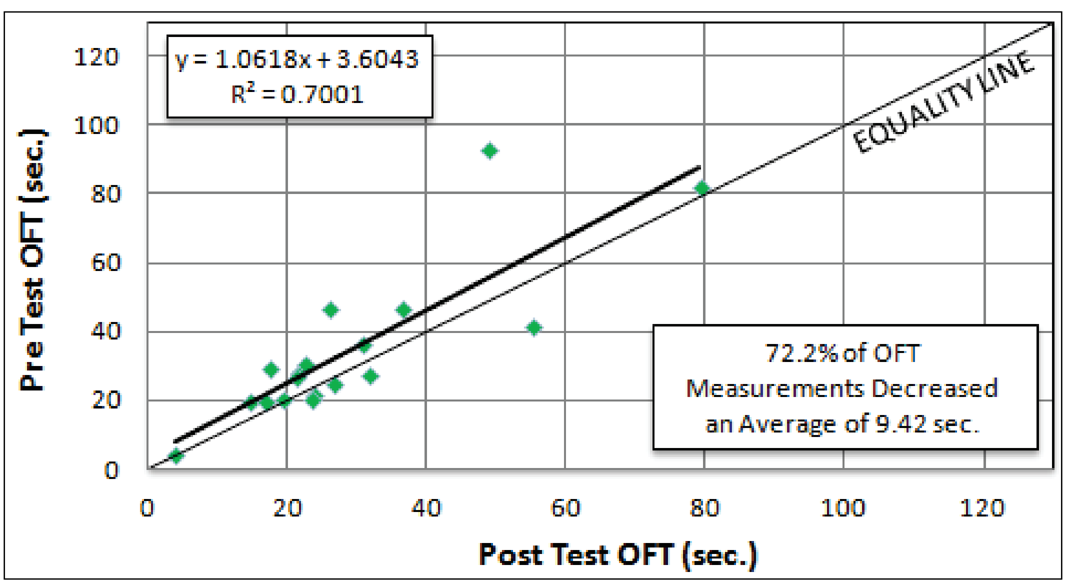


Table 14. SH8000R Pre- and Post-OFT

Section	Pre-cleaning OFT (sec)	Post-cleaning OFT (sec)	OFT Reduction (sec)
C07	92.77	48.83	43.94
C08	81.81	79.12	2.69
C09	36.35	30.57	5.78
F16	29.16	17.52	11.64
F17	46.46	36.28	10.18
F18	27.74	21.55	6.19
I25	19.37	14.54	4.83
I26	21.58	23.59	-2.01
I27	26.26	21.26	5.00
L34	20.23	19.35	0.88
L35	19.45	16.66	2.79
L36	24.97	26.71	-1.74
O43	30.13	22.36	7.77
O44	4.40	3.89	0.51
O45	46.19	25.98	20.21
R52	41.32	55.09	-13.77
R53	27.09	31.56	-4.47
R54	20.07	23.56	-3.49

Figure 60. SH8000R pre- and post-OFT.



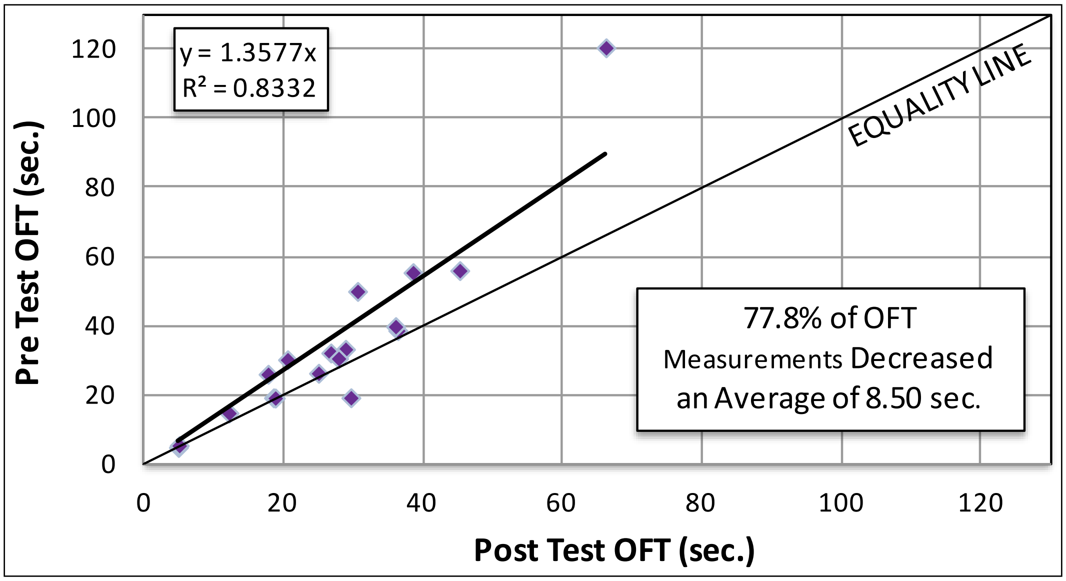
A reduction in OFT was measured over 78 percent of the pavement sections cleaned by the Trackjet. The mean OFT loss for these areas was 8.50 sec. Data in Table 15 were used to develop the chart shown in Figure 61, which compares pre- and post-rubber removal OFT measurements. Comparison of initial OFT measurements (M = 34.56, SD = 26.07) and post-OFT measurements (M = 27.11, SD = 14.67) revealed no statistically significant reduction in OFT after rubber removal using the Trackjet, with a $t(34)$ = 1.06 and a p = 0.30.

At the 95 percent confidence level, only sections cleaned by the Cyclone 4006 exhibited statistically significant reductions in OFT. A one-way ANOVA comparing OFT reductions from each treatment revealed no statically significant difference between the groups, with an F (2, 51) = 0.86 and a p = 0.551.

Table 15. Trackjet pre- and post-OFT.

Section	Pre-cleaning OFT (sec)	Post-cleaning OFT (sec)	OFT Reduction (sec)
B04	19.25	18.49	0.76
B05	32.21	26.7	5.51
B06	14.84	12.11	2.73
E13	38.68	36.31	2.37
E14	120.41	66.16	54.25
E15	33.28	28.81	4.47
H22	39.83	35.99	3.84
H23	50.00	30.54	19.46
H24	19.19	18.74	0.45
K31	30.61	27.82	2.79
K32	19.27	29.58	-10.31
K33	26.35	24.94	1.41
N40	30.26	20.5	9.76
N41	4.91	4.85	0.06
N42	55.43	38.49	16.94
Q49	26.06	17.71	8.35
Q50	56.02	45.19	10.83
Q51	5.46	4.97	0.49

Figure 61. Trackjet pre- and post-OFT.



The outflow meter did not materialize as a good device for judging quality of rubber removal due to poor reproducibility and large data scatter in this experiment.

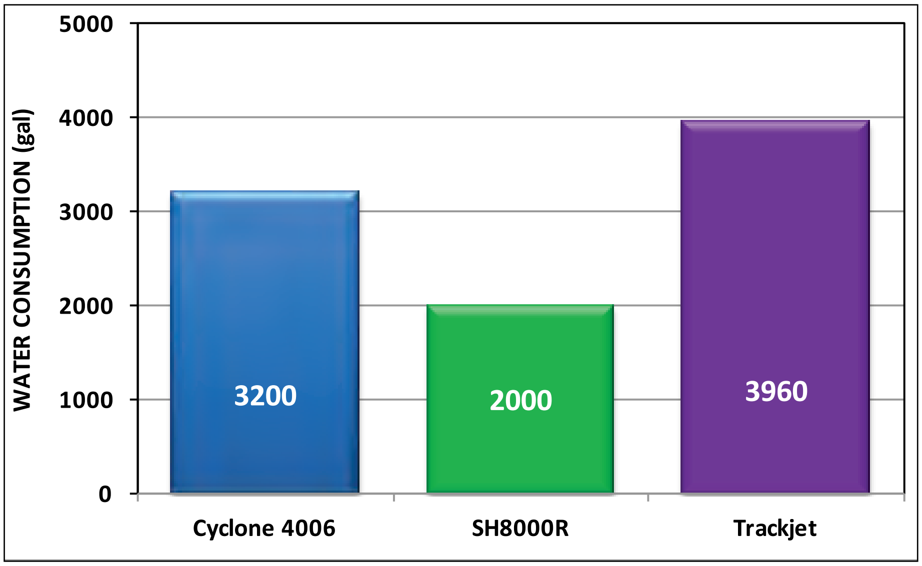
5.4 General operating characteristics

The performance criteria for this evaluation focuses on comparing measured improvements to pavement surface characteristics, such as pavement-tire friction coefficients and texture, following rubber removal with each technology. Though water consumption, fuel consumption, and production are not criteria for this comparison, these characteristics were measured for each process and will be presented in this section.

It should be noted that the machines were not operated at maximum or minimum production rates. If the equipment had been operated at different rates the resulting staining and friction characteristic previously noted may have differed.

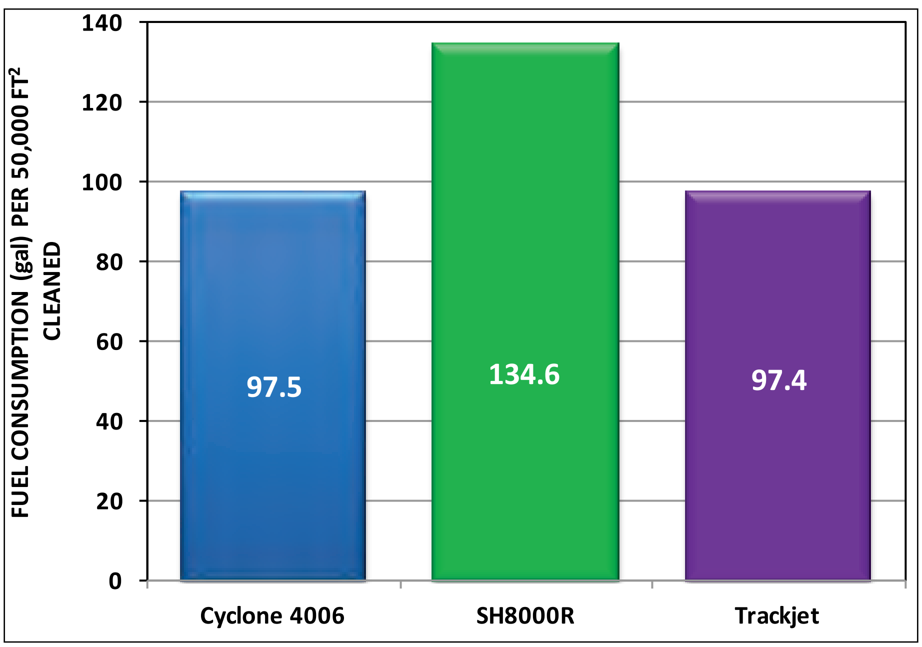
Figures 62 and 63 present the quantities of water and fuel each UHPW system used to clean six test sections. Figure 64 provides the time to clean each test section; corresponding times and production rates are presented in Table 16. Figure 65 presents average time per area cleaned.

Figure 62. Water consumption.



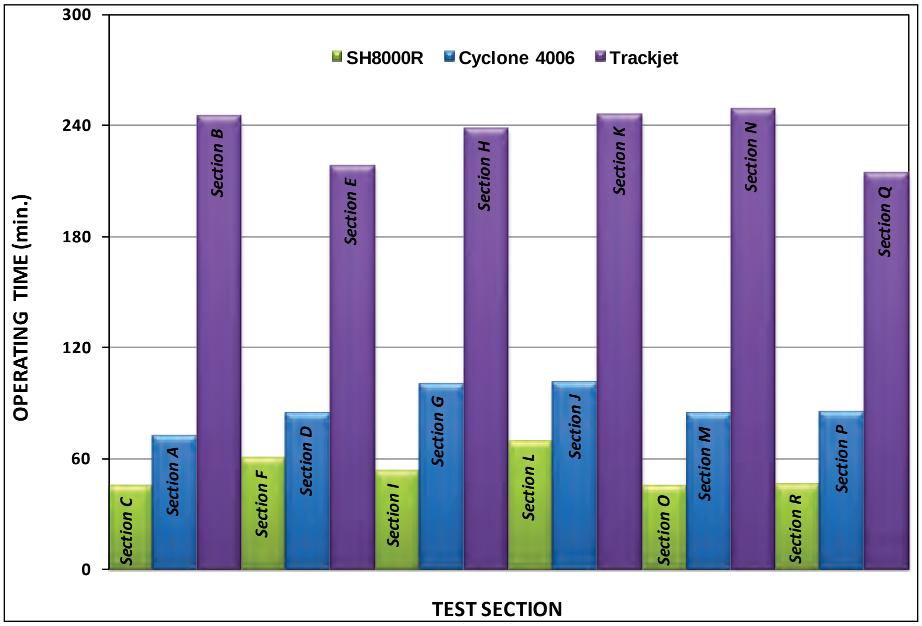
For reference only. Trackjet system not manufactured for production. Water consumption is not part of evaluation criteria.

Figure 63. Fuel consumption.



For reference only. Trackjet system not manufactured for production. Fuel consumption is not part of evaluation criteria.

Figure 64. Elapsed test section cleaning times.



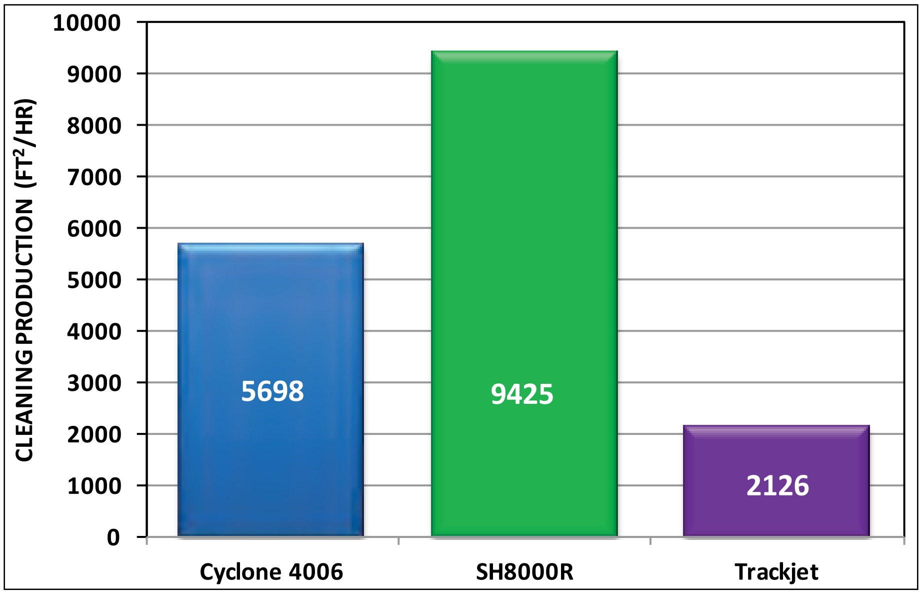
**For reference only. Trackjet system not manufactured for production. Cleaning production rate is not part of evaluation criteria.*

Table 16. Production rates.

System	Section	Operating Time (min)	Fill/Cleanout/ Work Stoppage Time (min)	Average Time (min)	Average Production Rate (ft^2/hr)
Cyclone 4006	A	72	0	88	5,698
	D	84	0		
	G	100	5		
	J	101	0		
	M	84	0		
	P	85	28		
SH8000R	C	45	0	53	9,425
	F	60	24		
	I	53	5		
	L	69	18		
	O	45	0		
	R	46	0		
Trackjet	B	245	117	235	2,126[a]
	E	218	92		
	H	238	113		
	K	246	108		
	N	249	68		
	Q	214	80		

[a] For reference only. Trackjet system not manufactured for production. Cleaning production rate is not part of evaluation criteria.

Figure 65. Overall cleaning production rate.



For reference only. Trackjet system not manufactured for production. Cleaning production rate is not part of evaluation criteria.

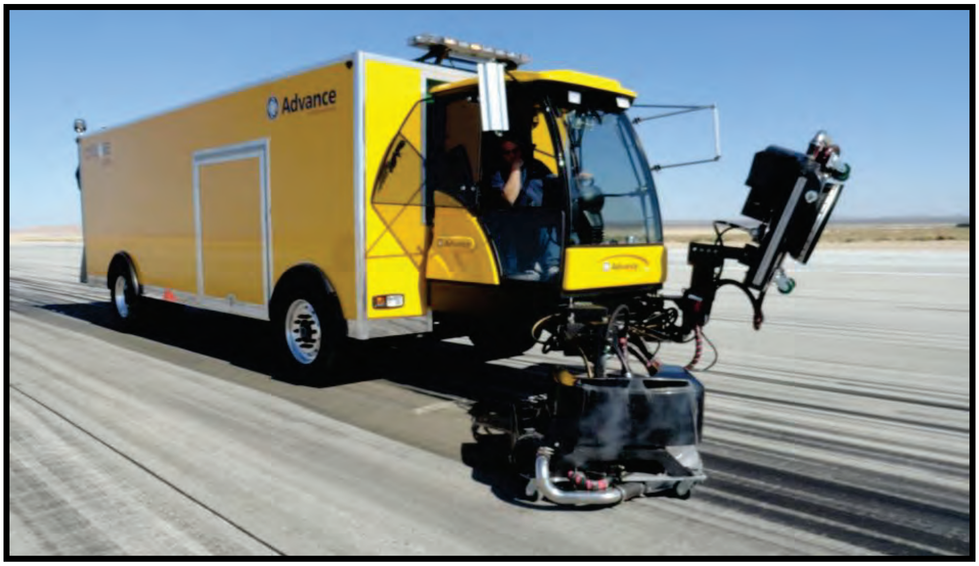
These metrics were measured while having each system maneuver within six separate 25-ft by 333-ft test sections. Ideally, UHPW systems make long passes along the length of a runway touchdown zone with fewer overlaps and maneuvers during cleaning. It is reasonable to assume that each system is capable of higher production and improved efficiencies under normal operational conditions.

This information is provided for reference only. The Trackjet was specially manufactured for C-130 transportability, so this unit requires a larger amount of operational maintenance when compared to a larger production oriented UHPW systems. The SH8000R system features on-board water recycling; therefore, this system uses less water.

5.4.1 Cyclone 4006

The Cyclone 4006, shown in Figure 66, operated each shift without work stoppage or maintenance after filling with water from an infield fire hydrant and performing a nozzle check. The Cyclone 4006 operates noticeably quieter than the SH8000R and Trackjet, as it does not employ the use of vacuum for debris recovery. The slurry of rubber and water collected during rubber removal is slung to the outside of the cleaning head and then pumped via a macerator pump to a chamber where solids and liquids are separated.

Figure 66. Cyclone 4006.



The macerator pump and the resulting quieter operation of the unit is a technology that offers additional military and operational utility which should be further tested and developed. The unit could be operated without hearing protection; personnel in the cab were able to converse on a radio while the machine was operating which may allow teams operating this unit to meet mission requirements with fewer personnel. Units using suction to remove water and debris are loud enough that a driver concentrating on the operation needs one person to follow along the outside to ensure the unit is not damaging pavement, and one person to be far enough away that they can safely operate and monitor a radio and be close enough to the operation to ensure the unit can respond within seconds to either in-flight emergencies or attacks on the airfield by combatants. The quieter operation of the unit may also make it more difficult for combatants to target the airfield.

During the testing, one of the USAF project engineers was provided with 10 min of instruction on the equipment operation then allowed to operate the unit for approximately 1 hr in lieu of the manufacturer's representative. It was noted that the USAF engineer operated the unit at the same production rates resulting in typical rubber removal and friction improvement without any additional adjustments and without damaging the equipment, pavement, or joint seals. This quick instruction was facilitated by the ability to easily communicate in the cab. This ability to rapidly train in the field is a technology/capability that offers additional military and operational utility which should be further tested and developed. The ability to rapidly and consistently train military operators in the field is critical to fielding this capability.

Once initial operation began, the unit was able to effectively clean the airfield with no adjustments to nozzles, heads, pressure, or other components while both the SH8000R and Trackjet required several adjustments to sustain production and eliminate damage.

Figure 67 shows the Cyclone 4006 filling with water at the hydrant. The Cyclone 4006 had to refill its 1,600-gal fiberglass water tank once while cleaning six test sections, using a total of 3,200 gal of water. Figure 68 presents the Cyclone 4006 removing rubber on Runway 22L. The Cyclone 4006 gray water discharge process is shown in Figure 69, and the dump process is presented in Figure 70. The dump process is relatively quick and simple. Solids are unloaded through a door that hinges at the top of the vehicle. The door placement alleviates clearance issues with taller waste containers. The Cyclone 4006 used 97.5 gal of fuel, and water consumption is estimated at 3,200 gal. Its 1,600-gal fiberglass water tank was filled twice while cleaning six test sections. Average time spent cleaning each test section was 88 min, equating to a mean production rate of 5,689 ft^2/hr.

Figure 67. Cyclone 4006 filling with water at hydrant.

Figure 68. Cyclone 4006 removing rubber on Runway 22L.

Figure 69. Cyclone 4006 gray water discharge.

Figure 70. Cyclone 4006 dumps solids.

5.4.2 Trackjet

The Trackjet system used for testing was purpose-built for C-130 aircraft transport. Some components on the Trackjet are scaled down for the unit to meet air transport weight and dimensional requirements. With a smaller platform vehicle, water reservoir, and vacuum recovery chambers, this system has limited production compared to full-scale production oriented Trackjet models. The Trackjet is shown removing rubber on Runway 22L in Figure 71.

The U400 Unimog platform vehicle did not provide adequate power to the Trackjet for this test. To aid preventing the engine from overheating, the heater inside the cab of the Unimog had to constantly run. The Unimog doors are open in Figure 71 for operator comfort. The average ambient temperature during testing was 80.7°F.

Figure 71. Trackjet removing rubber on Runway 22L.

Solid wastes have to be removed frequently from two vacuum chambers at the rear of the Unimog due to the scaled-down design of its debris recovery system. Cleaning the vacuum chambers requires a designated cleanout area set up to handle the process. Figure 72 shows the Trackjet cleanout process. A generator, halogen lights, a pressure washer, shovels, a sump pump, and container to transfer solids were used to support the cleanout process. A berm lined with heavy plastic and sandbags was constructed to capture gray water during this cleaning. Mesh filters in each chamber had to be thoroughly cleaned by high pressure water in order for the chambers to maintain adequate vacuum pressure for debris recovery. Figure 73 shows solids collected in a Trackjet vacuum chamber.

The Trackjet used 97.4 gal of fuel. Its 660-gal flexible water bladder was filled six times while cleaning six test sections, so water consumption is estimated at 3,960 gal. Average time spent cleaning each test section was 235 min, equating to a mean production rate of 2,126 ft^2/hr.

5.4.3 SH8000R

The SH8000R features a closed-loop 1,000-gal water recycling plant, allowing the reuse of water. Neither the Trackjet nor the Cyclone 4006 recycled water. The SH8000R is shown removing rubber on Runway 22L in Figure 74.

Figure 72. Trackjet cleanout.

Figure 73. Solids collected in a Trackjet vacuum chamber.

Figure 74. SH8000R removing rubber on Runway 22L.

The SH8000R is outfitted with two cleaning heads supplied with a 12-gpm flow rate, approximately twice the flow rate used by the Cyclone 4006 and Trackjet technologies. The SH8000R used the least water and had the highest production rate.

In select areas, the SH8000R operator had difficulty establishing an effective combination of water pressure and speed settings to achieve a uniformly clean pavement surface. Inadequate settings contributed to a less than uniform distribution of water at the pavement surface, resulting in some rubber deposits left on the runway. In this case, it was often difficult to determine if rubber was simply being left on the pavement or if water jets were lightly etching the pavement surface. An example of this condition is shown in Figure 75. Evidence of light scoring was found behind the SH8000R in one isolated area. This pavement damage area is shown in Figure 76. Once noted by the researchers, this issue was corrected by the contractor. It was noted that one of the shrouds was damaged while the unit was cleaning near the aircraft arresting system.

Figure 75. Comparison of water pressure distribution between SH8000R and Trackjet.

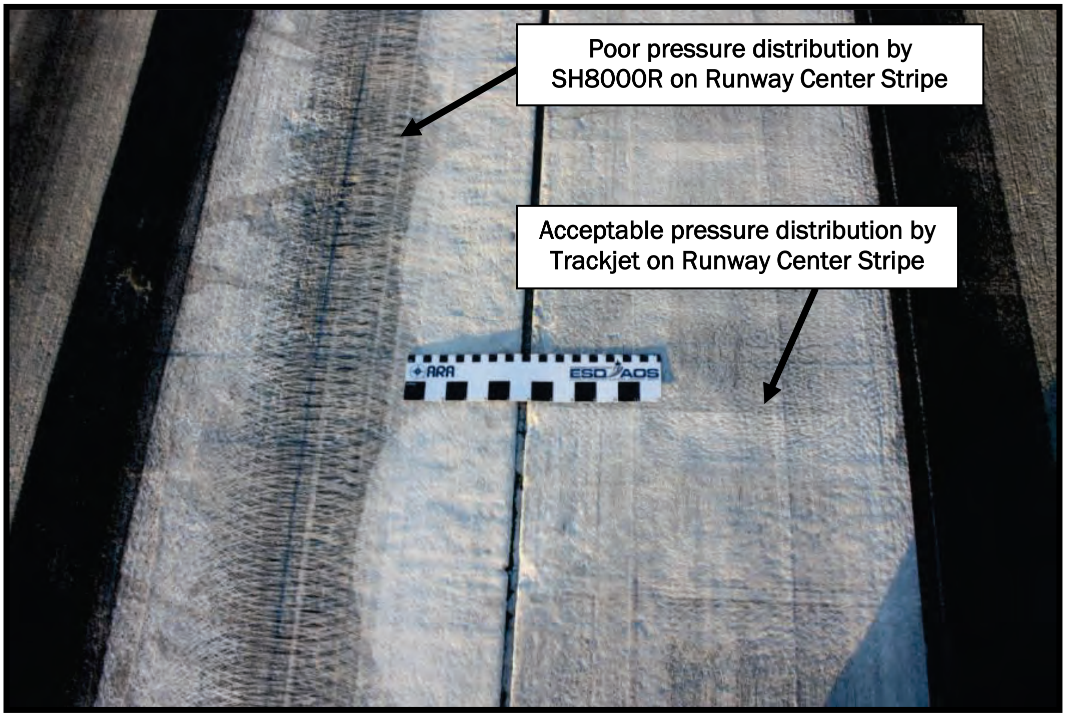


Figure 76. SH8000R PCC etching.

The SH8000R gray water discharge process is shown in Figure 77, and the dump process is presented in Figure 78. The dump process required two individuals at the rear of the bed to dislodge solids resting on a fabric material.

Figure 77. SH8000R gray water discharge.

Figure 78. SH8000R dumps solids.

The SH8000R used 134.6 gal of fuel. Its 2,000-gal stainless steel water tank was filled one time while cleaning six test sections, so water consumption is estimated at 2,000 gal. Average time spent cleaning each test section was 53 min, equating to a mean production rate of 9,425 ft^2/hr.

6 Conclusions

- Each UHPW rubber removal system restored skid resistance to PCC runway pavement that had fallen below the minimum FAA friction threshold (FAA 1997). CFME measurement analysis indicates that the friction gains imparted by the Cyclone 4006 and Trackjet were statistically higher than those of the SH8000R at the 95 percent confidence level.
- IFI calculations prove all rubber removal systems were able to statistically improve the skid resistance of the runway. Average speed constant values were most improved by the Cyclone 4006.
- Statistical gains in MPD were only measured over pavement sections cleaned by the Cyclone 4006. MPD gains over test sections cleaned by the SH8000R and the Trackjet were not statistically significant to the 95 percent confidence level.
- NASA grease smear tests show all rubber removal systems were able to statistically improve pavement ATD. ATD gains from each treatment revealed no statistical differences between groups.
- Statistically significant reductions in OFT were only measured over pavement sections cleaned by the Cyclone 4006. OFT reductions over test sections cleaned by the SH8000R and the Trackjet were not statistically significant to the 95 percent confidence level.
- The macerator pump in combination with cyclonic head and Cyclone 4006 controls and system integration technology offer additional military and operational utility. This technology can potentially reduce manpower, hamper the enemy's ability to target operations, decrease training requirements and improve reliability.
- All rubber removal systems evaluated were effective in improving runway friction characteristics for the PCC runway used in this demonstration. The performance of each system is a function of many variables. Each vendor was allowed to operate his system at his own settings. Since the dwell time over a particular location is proportional to the effectiveness in removing rubber deposits in that location, slowing production rates may increase the effectiveness of rubber removal operations.

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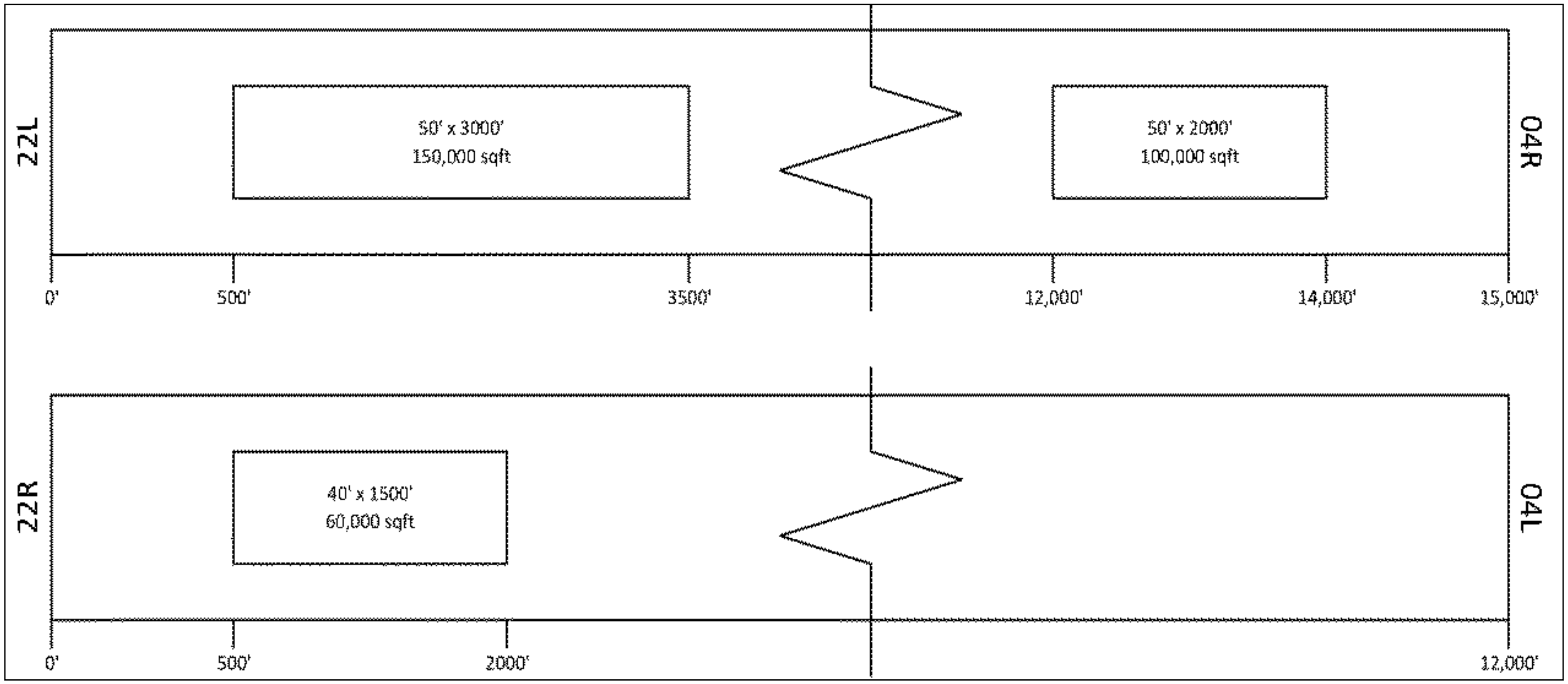
Appendix A: Work Plan

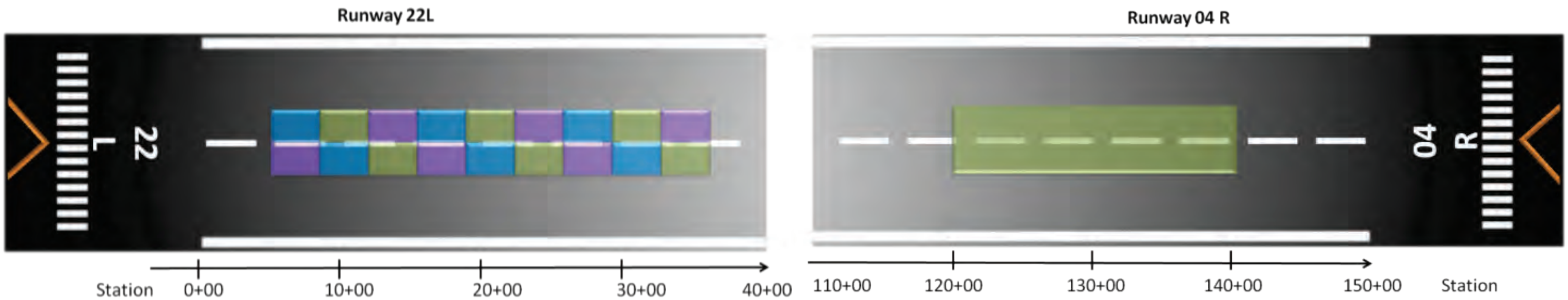
SCHEDULE OVERVIEW



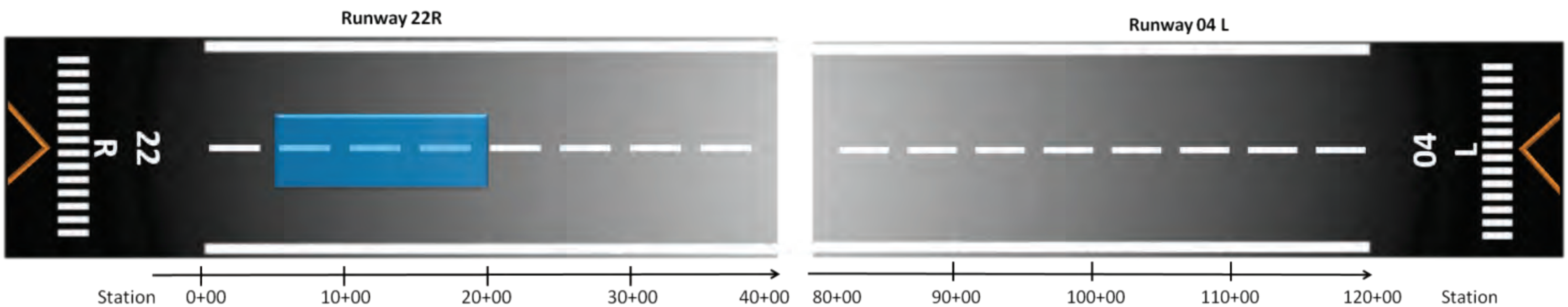
SUN	MON	TUES	WED	THURS	FRI	SAT
		13 ☼ ARRIVE	14 ☼ INBRIEF UNLOAD EQUIPMENT	15 ● RUNWAY 22 L	16 ● RUNWAY 22 L	17 ☼ RUNWAY 22 L
18 ☼ RUNWAY 22L RUNWAY 22R RUNWAY 04R	19 ● RUNWAY 22L	20 ● RUNWAY 22L	21 ● RUNWAY 22L	22 ☼ OUTBRIEF LOAD EQUIPMENT	23 ☼ DEPART	□

<u>TEST MATRIX OVERVIEW</u>

Edwards AFB Runway 22L/04R



Edwards AFB Runway 22R/04L



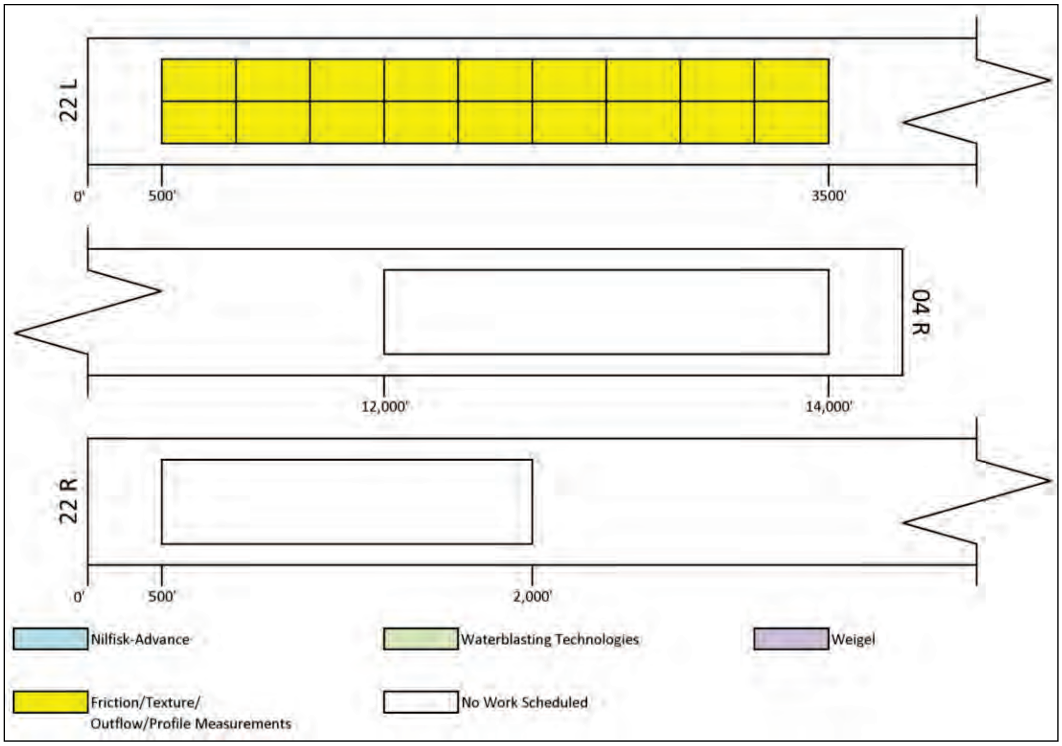
WORK SCHEDULE

DATE	SHIFT	PARTY	ACTIVITY	RUNWAY	LOT SIZE		LOT QUANTITY	TOTAL AREA (ft^2)
					Width (ft)	Length (ft)		
9/14	9 AM – Until	ARA/ERDC	BASE INBRIEF / SETUP	–	–	–	–	–
9/15	8 PM – 7 AM	ARA/ERDC	SURFACE MEASUREMENTS	22L	25	333	18	150,000
9/16	8 PM – 3 AM	WEIGEL	RUBBER REMOVAL	22L	25	333	3	25,000
9/17	1 PM – 11 PM	NILFISK-ADVANCE	RUBBER REMOVAL	22L	25	333	6	50,000
		WATERBLASTING TECH.	RUBBER REMOVAL	22L	25	333	6	50,000
		WEIGEL	RUBBER REMOVAL	22L	25	333	3	25,000
9/18	11 AM – 9 PM	ARA/ERDC	SURFACE MEASUREMENTS	22L	25	333	18	150,000
		NILFISK-ADVANCE	RUBBER REMOVAL	22	40	1500	1	60,000
		WATERBLASTING TECH.	RUBBER REMOVAL	04R	50	2000	1	100,000
9/19	8 PM – 7 AM	NILFISK-ADVANCE	RUBBER REMOVAL	22L	25	333	6	50,000
		WATERBLASTING TECH.	RUBBER REMOVAL	22L	25	333	6	50,000
		WEIGEL	RUBBER REMOVAL	22L	25	333	3	25,000
9/20	8 PM – 7 AM	WEIGEL	RUBBER REMOVAL	22L	25	333	3	25,000
9/21	8 PM – 7 AM	ARA/ERDC	SURFACE MEASUREMENTS	22L	25	333	18	150,000
9/22	9 AM	ARA/ERDC	BASE OUTBRIEF	–	–	–	–	–

REQUIREMENTS FOR VENDORS

VENDOR	Friday 9/16	Saturday 9/17	Sunday 9/18	Monday 9/19	TOTAL RUBBER REMOVAL AREA CONTRACTED
Nilfisk-Advance	Stage Equipment (Optional)	50,000 ft^2 Rubber Removal	60,000 ft^2 Rubber Removal	50,000 ft^2 Rubber Removal	160,000 ft^2
Waterblasting Technologies	Stage Equipment (Optional)	50,000 ft^2 Rubber Removal	100,000 ft^2 Rubber Removal	50,000 ft^2 Rubber Removal	200,000 ft^2

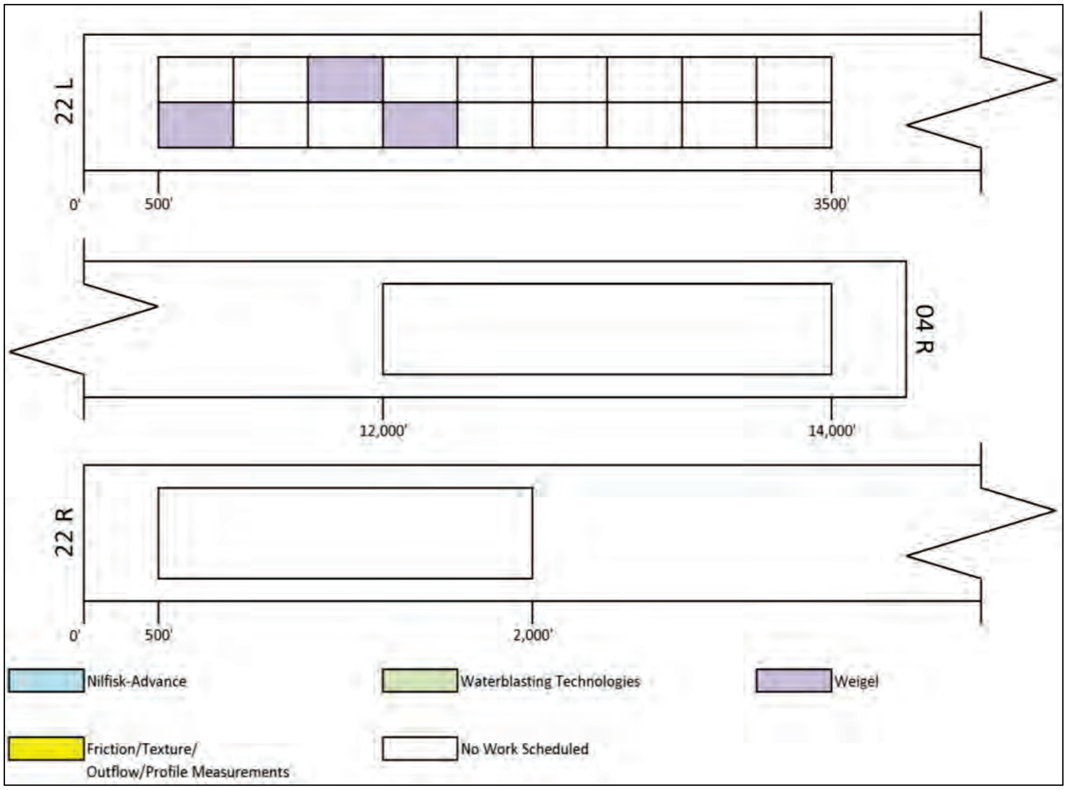
THURSDAY 9/15



SHIFT ACTIVITIES

Perform initial friction/texture/outflow/profile measurements over entire 150,000 ft^2 test area on Runway 22L Touchdown.

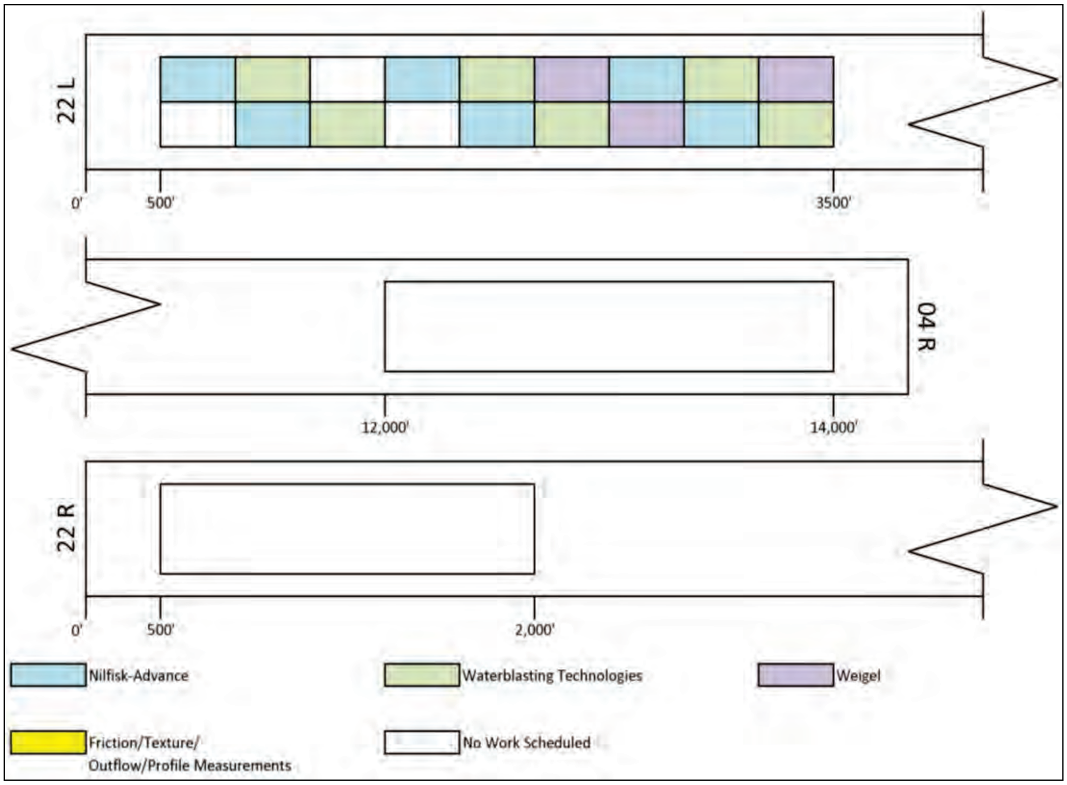
FRIDAY 9/16



SHIFT ACTIVITIES

Weigel system to remove rubber from three 25-ft × 333-ft test lots ($25,000\ ft^2$) in Runway 22L Touchdown Test Area.

SATURDAY 9/17



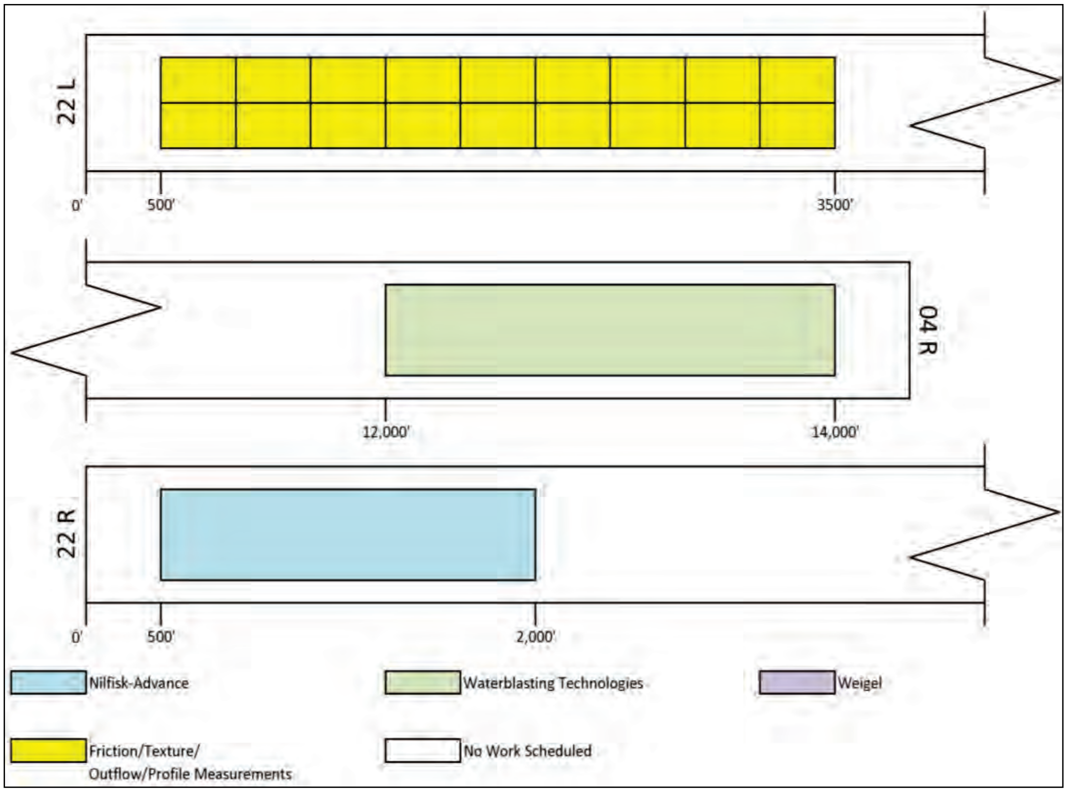
SHIFT ACTIVITIES

Nilfish-Advance system to remove rubber from six 25-ft × 333-ft test lots (50,000 ft^2) on Runway 22L Touchdown Test Area.

Waterblasting Technologies system to remove rubber from six 25-ft × 333-ft test lots (50,000 ft^2) on Runway 22L Touchdown Test Area.

Weigel system to remove rubber from three 25-ft × 333-ft test lots (25,000 ft^2) in Runway 22L Touchdown Test Area.

SUNDAY 9/18



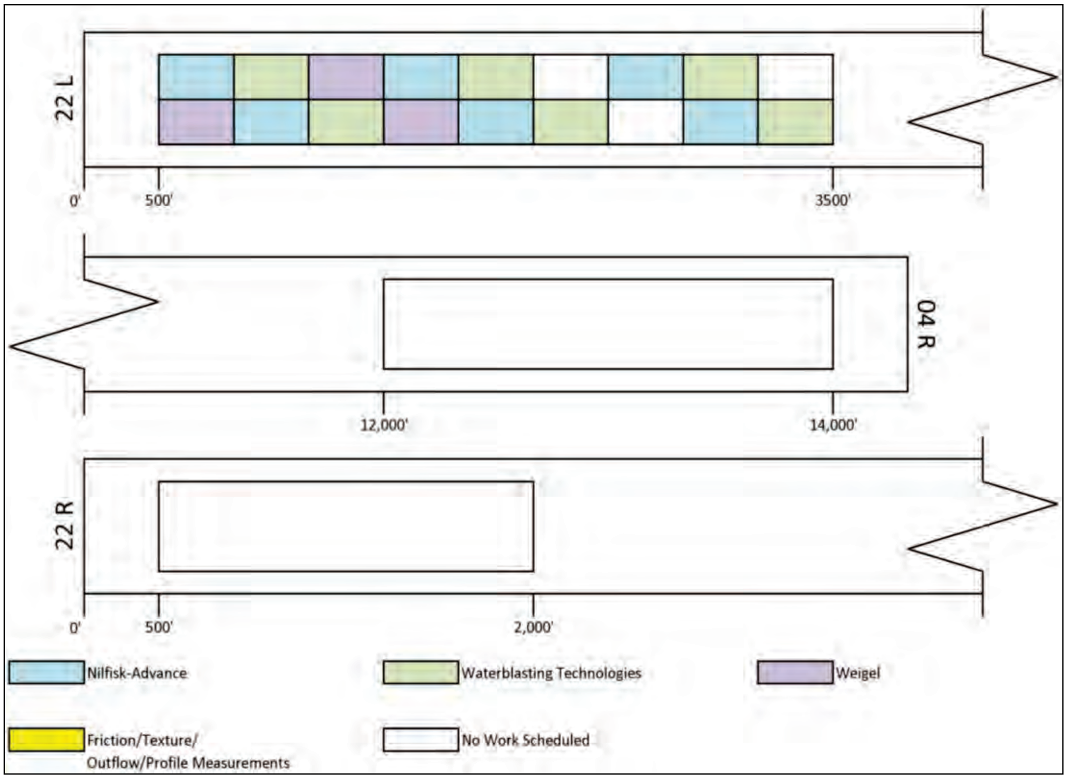
SHIFT ACTIVITIES

Perform intermediate friction/texture/outflow/profile measurements over entire 150,000 ft^2 test area on Runway 22L Touchdown.

Nilfish-Advance system to remove rubber from 40-ft × 1,500-ft Runway 22R Touchdown Area (60,000 ft^2).

Waterblasting Technologies system to remove rubber from 50-ft × 2,000-ft Runway 04R Touchdown Area (100,000 ft^2).

MONDAY 9/19



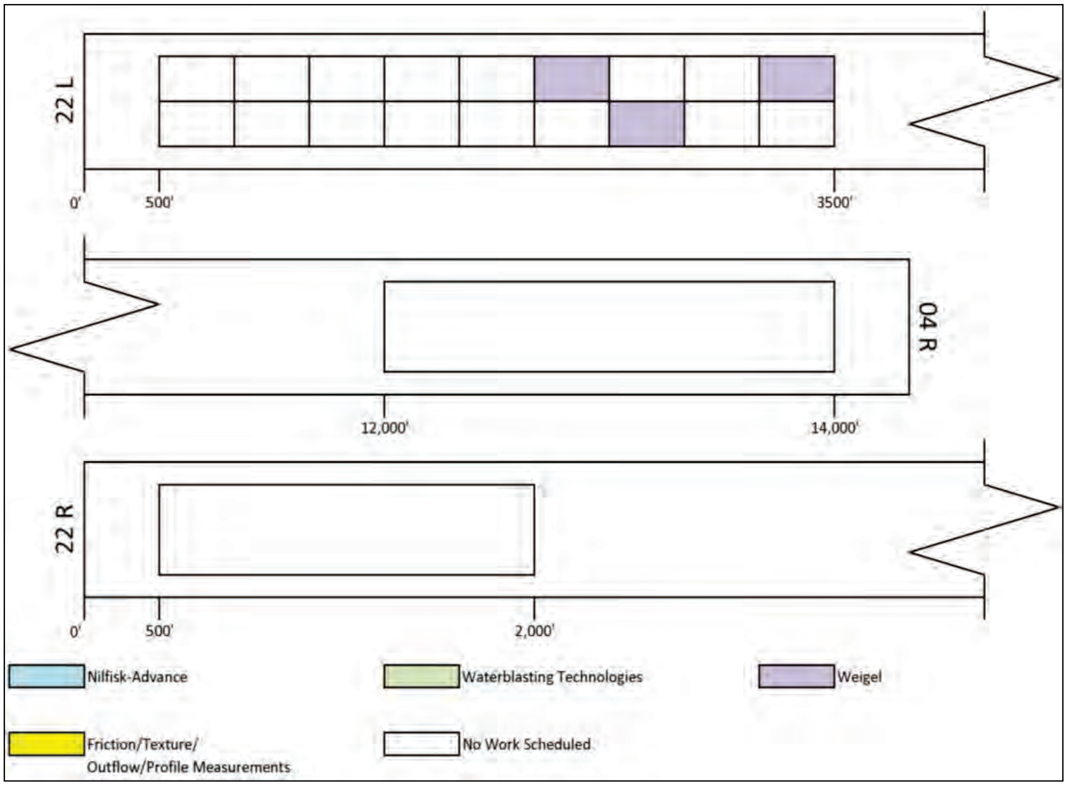
SHIFT ACTIVITIES

Nilfish-Advance system to remove rubber from six 25-ft × 333-ft test lots (50,000 ft^2) on Runway 22L Touchdown Test Area.

Waterblasting Technologies system to remove rubber from six 25-ft × 333-ft test lots (50,000 ft^2) on Runway 22L Touchdown Test Area.

Weigel system to remove rubber from three 25-ft × 333-ft test lots (25,000 ft^2) in Runway 22L Touchdown Test Area.

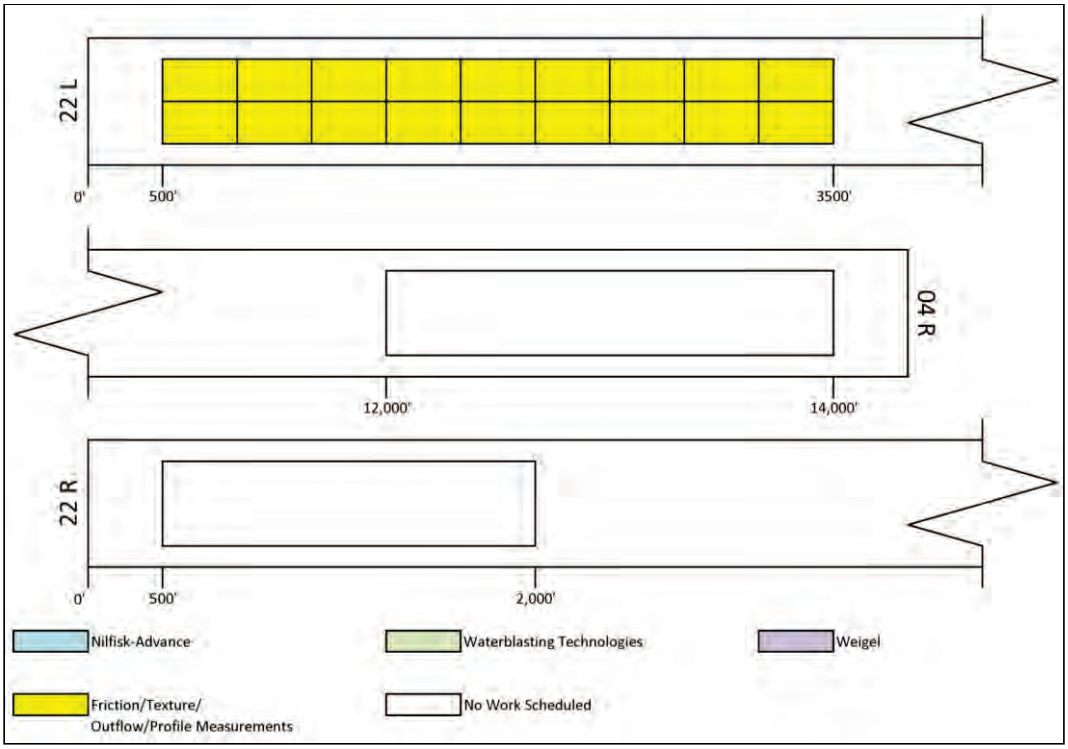
TUESDAY 9/20



SHIFT ACTIVITIES

Weigel system to remove rubber from three 25-ft × 333-ft test lots ($25,000 \text{ ft}^2$) in Runway 22L Touchdown Test Area.

WEDNESDAY 9/21



SHIFT ACTIVITIES

Perform friction/texture/outflow/profile measurements over entire 150,000 ft^2 test area on Runway 22L Touchdown.

REPORT DOCUMENTATION PAGE

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		5b. GRANT NUMBER
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6. AUTHOR(S) Aaron B. Pullen, Lulu Edwards, Craig A. Rutland, and Jeb S. Tingle		**5d. PROJECT NUMBER**
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		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Runway rubber removal is a maintenance function employed to ensure safe landing areas for aviation operations. Rubber deposits accumulate on runway areas where aircraft tires touch down and braking occurs. This tire rubber buildup occludes pavement microtexture and macrotexture, causing a significant loss in available skid resistance during wet conditions. Reduction of available pavement microtexture in a wet environment prevents the development of adhesional friction, which can lead to viscous hydroplaning. Reduction of pavement macrotexture prevents removal of bulk water from the tire-pavement contact area and prevents development of the hysteresis frictional component. The US Army Engineer Research and Development Center (ERDC) in Vicksburg, MS, was tasked by the Air Force Civil Engineer Center (AFCEC) to evaluate the performance of ultra-high pressure water (UHPW) rubber removal technologies; this work was conducted in collaboration with Applied Research Associates, Inc. (ARA). Several types of commercial UHPW water blasting systems were tested on an ungrooved portland cement concrete (PCC) runway and data were compared using statistical methods. Runway pavement skid resistance characteristics, such as friction and surface texture, were evaluated before and after rubber removal operations. Equipment run times, consumable resources, and climatic conditions were monitored.

15. SUBJECT TERMS

Rubber removal
Friction measurement
Ultra-high pressure water rubber removal

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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