



**MAINTENANCE OPERATIONS DEGRADATION OF
AIRFIELD PAVEMENT MARKINGS**

John C. Jaskowiak, Capt

AFIT/GEM/ENV/12-M09

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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John C. Jaskowiak, BS

Captain, USAF

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John C. Jaskowiak, BS
Captain, USAF

Approved:

_____ //signed// _____ 9 Mar 12
Lieutenant Colonel William E. Sitzabee, PhD, P.E. (Chairman) Date

_____ //signed// _____ 24 Feb 12
Lieutenant Colonel Tay W. Johannes, PhD, P.E. Date

_____ //signed// _____ 24 Feb 12
Edward D. White III, PhD Date

Abstract

Pavement markings are an essential element in the navigational aids subsystem for any airfield. Most airfields still use waterborne paint as the primary marking material. However, several other materials are in use on roadways which asset managers could incorporate, providing more cost and time effective practices. An airfield experiences a host of maintenance operations which cause degradation of the pavement markings. Of particular concern are rubber removal operations, sweeping operations, and snowplowing operations. This research focuses on chemical rubber removal operations and sweeping operations. This study evaluates waterborne paint and thermoplastic markings to determine if marking materials perform differently from each other, and if maintenance operations cause different degradation rates among the same material. Evaluation criteria include retroreflectance, chromaticity, and coverage. The two materials experience different degradation characteristics under both treatments. Waterborne paint failed retroreflectance and chromaticity measurements after the first chemical rubber removal treatment. Thermoplastic failed chromaticity and coverage measurements after the third chemical rubber removal treatment. Neither material showed any appreciable amount of degradation in any of the three performance measurements when subjected to sweeping operations.

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This work is first and foremost dedicated to my beloved wife

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John C. Jaszkwiaak

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List of Acronyms

ACC	Asphalt Cement Concrete
AFI	Air Force Instruction
ASTM	American Society for Testing and Materials
CIE	International Commission on Illumination
ETL	Engineering Technical Letter
FAA	Federal Aviation Administration
FOD	Foreign Object Damage
ICAO	International Civil Aviation Organization
PCC	Portland Cement Concrete
USAF	United States Air Force
USN	United States Navy

MAINTENANCE OPERATIONS DEGRADATION OF
AIRFIELD PAVEMENT MARKINGS

Chapter 1: Problem Statement

1.1 Introduction

An airport is a relatively small area of land, but it receives an inordinately high amount of attention in both time and resources. A working airport has an almost limitless list of assets. Trying to manage all of these assets proves to be a monumental task. Each asset behaves in its own unique way, affecting how it interacts with itself, and how it interacts with other assets. One overarching asset is the pavement infrastructure. Within this asset, there are subsystems which when incorporated constitute the pavement infrastructure. This research effort focuses on the pavement markings subsystem.

In order to help focus this research on the pavement markings, a brief history of different materials used for pavement markings is discussed in terms of which is best for airfields when exposed to maintenance operations. One of the current problems of how to best manage this asset will be addressed as well as some research questions to help focus the effort. To answer these research questions, an outline of the experiment and proposed methodology will be discussed. This discussion will also include assumptions and limitations associated with the chosen research method. It will conclude with a discussion of the proposed significance of the research, some definitions of terms used, and what future research might focus on.

1.2 Background

Airfields use visual aids to include lights, signs, and pavement markings throughout the pavement infrastructure to direct pilots and all other operators on the airfield on where to park, where to taxi, where to drive, where to take off, and where to land. The visual aids constitute a necessary system for safe and efficient operations on an airfield; and the pavement markings are an integral subsystem of the overall visual aids system.

Pavement markings degrade over time and require maintenance to sustain effectiveness. Studies have shown that for roadway markings, depending on the marking material, the marking is replaced anywhere from every 6 months to 10 years (Migletz & Graham, 2002). Each time an airfield marking is replaced, that section of the airfield must be shut down for an extended period of time (USAF 1997). The shutdown of the airfield for a period of time is of great concern at airports which experience high volumes of traffic, such as Al Udied Air Base in Qatar or O'Hare International Airport in Chicago. For instance, one of the busier airfields in the military, Al Udied Air Base has an aircraft taking-off or landing every ten minutes (AFCESA, 2007). In contrast O'Hare has three aircraft landing or taking off every two minutes (Airports Council International, 2010). The potential operational and economic impacts of having to shut down a section of pavement for maintenance are quite high, especially if that section is on the runway. Airfield managers need to select pavement marking materials which will coordinate well with other planned maintenance on the airfield, to limit disruptions to the mission, pilots, and passengers.

Normal airfield operations and maintenance activities have a damaging effect on the airfield pavement system. Effective asset management of the pavement system will help to keep operations running in the most cost effective way possible. Federal airport marking standards describe what the markings placement, color, and style (Federal Aviation Administration (FAA), 2010). However, regulations and standards do not make good asset management plans on their own. Asset managers need to develop plans to meet the standards while effectively and efficiently using money.

Airfields are subjected to constant maintenance activities to include rubber removal, snow removal operations, and sweeping operations. Due to the build-up of rubber in the touchdown and braking areas of runways, rubber removal operations are necessary to maintain proper friction characteristics. The interval of rubber removal operations depends on how many aircraft and of what type land on the runway each day. Some airfields have such low traffic volume that they only need rubber removal once every two years, while others have such high traffic volume, they need rubber removal three times per year (Watkins, Boudreau, & Hansen, 2010). The current Air Force practice is to restripe the runway after every rubber removal operation.

Snow removal operations also assist in maintaining proper friction characteristics on the airfield surfaces. Each airfield has different standards on when to implement snow removal operations. According to the Air Force Instruction (AFI) 32-1002, bases which have an annual snowfall of six inches or more need to maintain a snow and ice removal plan (Force, Air Force Instruction 32-1002: Snow and Ice Control, 1999). Mull demonstrated that snow effects the life of a painted pavement marking(Mull & Sitzabee,

2011). Sweepers are employed on an as-needed basis from once per day, to several times per day to make sure foreign object damage (FOD) is kept to a minimum (Patterson, 2011). These recurring maintenance operations have been shown to have a detrimental effect on the life of a pavement marking.

According to the pavement marking synthesis accomplished by Migletz, et al. there are nine different pavement marking materials in common use on roadways (Migletz & Graham, 2002). Paint, by far is the most widely used material, followed by thermoplastics. Each material has its own advantages and disadvantages to include life cycle costs, expected life span, and ease of application.

1.3 Problem Statement

The question then becomes, which marking material is best suited for a particular purpose on an airfield? There are two different areas of an airfield which this research will focus on: the touchdown areas of the runway which experience rubber removal operations and taxiways which experience sweeping operations. Each area experiences different aircraft movements, maintenance operations, and marking needs.

Of the nine commonly used marking material types, this study focuses on only two due to funding limitations: waterborne paint, an FAA approved marking material, and thermoplastic, a material under development for use on runways (Federal Aviation Administration (FAA), 2009). Each of these materials has different life cycles, degradation characteristics, profiles, adherence properties, as well as many other distinguishing characteristics. Solvent-based paint and methacrylate are other FAA

approved materials. However, these two materials are being phased out of use by epoxies, thermoplastics, and polyurea.

1.4 Research Questions

To answer the problem presented, several questions need to be addressed. The first is whether or not rubber removal operations have a significant effect on material performance. Another related question is whether or not sweeping operations have a significant effect on material performance. This research does not include the effects of snow removal operations. If either, or both, of these factors do contribute significantly, can that effect be quantified? Based on the answers to those questions, what then, is the most efficient pavement marking material to use on each section of an airfield?

1.5 Research Approach

To answer the research questions, an extensive literature review was performed to understand material performance and the current asset management practices in use. In addition, data were obtained through empirical methods in a controlled experiment. The experiment subjected the two marking materials to chemical rubber removal operations and sweeping operations. During the course of the experiment retroreflectivity, chromaticity, and coverage were evaluated on a regular basis. The data were then analyzed using matched pair statistical methods.

1.6 Scope

This research effort will have some limitations, namely that not all the possible material types will be tested. Not testing all the material types limits the asset

management plan to just the two, when in fact a different material could prove to be a better fit for a particular application. Also, the controlled experiment will not be conducted on an active airfield, thus not subjecting the markings to the normal wear and tear they would have experienced. It is also not possible to determine ahead of time if the markings will be taken to failure. If the markings do not fail, then an accurate service life cannot be obtained.

1.7 Significance of Study

The resulting asset management plan from this study can be used by airfield managers as a new baseline for determining which pavement marking material types are best suited for different areas of their airfield. This will also help them to manage projects and other maintenance activities more efficiently by knowing which material to install based on service life, location, and planned construction. In the end, the asset management plan developed here will help airfield managers to operate more efficiently, resulting in fewer delays which means more time the airfield is open for operations and missions, as well as decreasing the overall cost of maintaining the airfield. The Civil Engineer Commodity Council (CECC) will be able to use the results to help strategically source markings for the Air Force, with a projected savings of \$21 million over the next five years (Council, 2011).

1.8 Definition of Terms

Several terms are used throughout this study which require specific attention to define. Retro-reflectivity, chromaticity, and coverage are three measures of a pavement marking's effectiveness as defined by the FAA (Cyrus H. M., 2003).

1.8.1 Retro-reflectivity

Retro-reflectivity is one of the key measures of an airfield pavement marker's performance. As defined by the American Society for Testing and Materials (ASTM), it is the amount of light, which after emitted from a headlight is reflected from the pavement marker back to the driver (ASTM, 2005). Pavement markings contain glass beads protruding from the surface, allowing light to pass through. The light refracts off the back of the bead, picking up the marking color, and then reflects back to the driver. The value of the reflection (R_L) is measured in millicandelas per meter squared of luminance ($\text{mcd}/\text{m}^2/\text{lux}$) and is known as the retro-reflectivity value.

The ASTM specifies a 30-meter geometry for measuring retro-reflectivity for roadway markings. The geometry is based on the driver sitting 1.3 meters above the ground seeing the pavement marking 30 meters in front of the headlight. Figure 1 shows the corresponding angles of refractance and reflectance at the bead location (Needham, 2011). The ASTM specified 30-meter geometry provides a consistent basis for obtaining measurements. Even though the position of a light on an aircraft is much lower than the pilot, and the pilot sits much higher than a car driver, the USAF and FAA use the 30-meter geometry as the standard for measuring pavement marking retroreflectivity (Cyrus H. M., 2003).

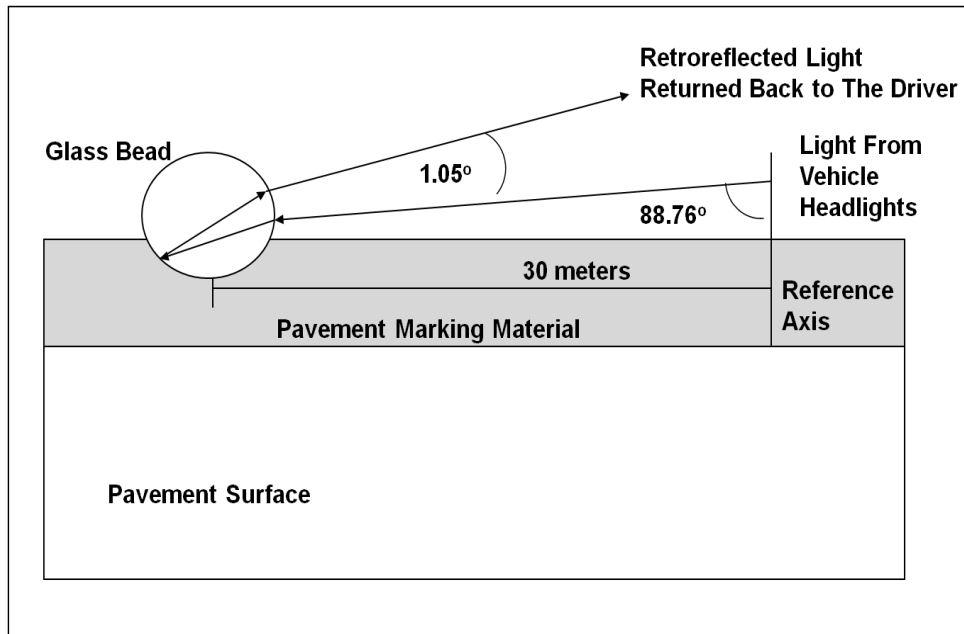


Figure 1 : Illustration of Retro-reflectivity

1.8.2 Chromaticity

Chromaticity is a measure of the quality of an object's actual color regardless of the luminance. The International Commission on Illumination (CIE) developed a color chart to plot true color in xyY space where x and y are coordinates on the color chart and Y denotes the color temperature; for this research we use a color temperature of 6500 Kelvin based on the standard set by the FAA. This color space provides a traditional xy coordinate system, within a given Y color temperature. Figure 2 shows the chart developed in 1931, which is still the standard today. This specific D_{65} color chart provides how a color is perceived to the human eye when the color is under direct sunlight at 6500 Kelvin. Direct sunlight is used because it provides the entire color spectrum, and is as close to white light as nature provides. The sunlight then renders the

colors as close to their true color as the eye can distinguish. The researchers used a spectrophotometer to measure the values of chromaticity. The device reads the color of the sample, adjusting for the ambient light to produce an xy coordinate on the D₆₅ color chart. This xy coordinate shows what the true color of the sample is when under white light.

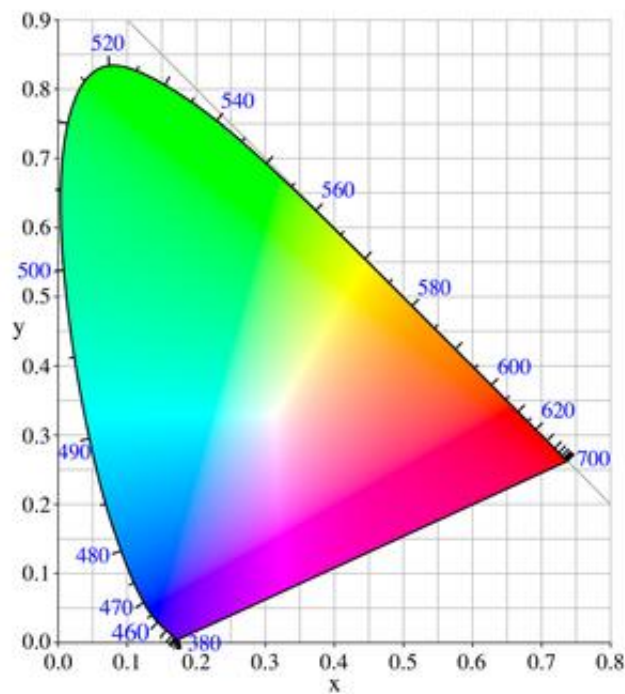


Figure 2: CIE 1931 D₆₅ Color Space Chromaticity Diagram

The FAA has established standards for the different colors of markings used on airfields. Each color has a box on the D₆₅ color chart. For a particular color to be within standards, the sample must fall within the specified corner points. Figure 3 shows the

FAA standard D65 color chart used for evaluating a pavement marking's failure. This research effort focuses on just the white color region.

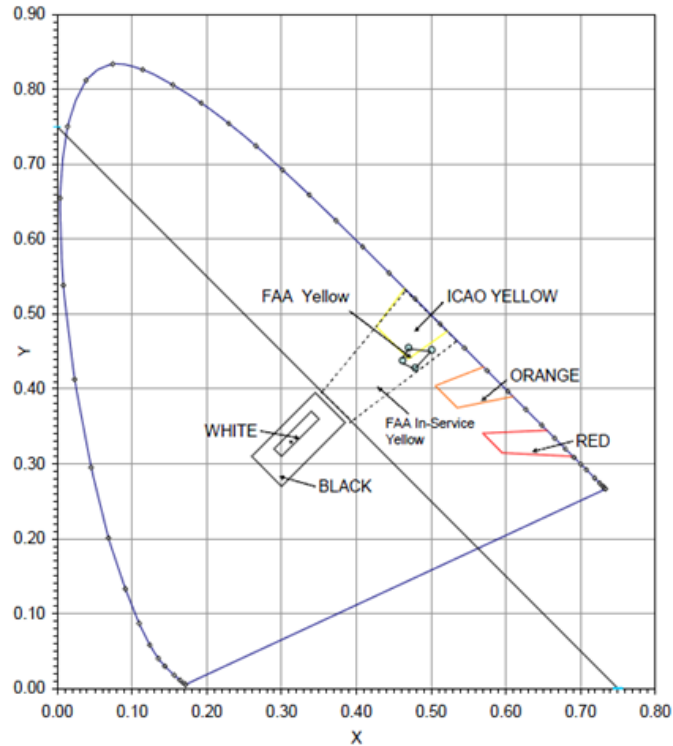


Figure 3: FAA Standard Illuminant D₆₅ Color Chart

1.8.3 Coverage

Coverage is a measure of the amount of marking material which still remains on the surface. The evaluation uses a 100 square inch transparent grid of 100 equal squares of either 10x10 or 5x20. The number of squares which have material removed are counted and subtracted from 100, thus giving a percent of material still left on the

pavement surface. Typically, several places along the pavement marking are chosen at random for evaluation(Cyrus H. M., 2003).

1.9 Organization/Purpose of Remaining Chapters

The next section of this document will consist of a review of literature associated with pavement markings and maintenance practices. Following that, a detailed explanation of the experiment and analysis practices will be discussed. Then the data results will be presented. After that, the results will be analyzed and recommendations made for asset management practices and future research efforts.

Chapter 2: Summary of Literature

2.1 Literature Review

This chapter discusses the current practices and body of knowledge on how different marking materials impact airfield operations. It also discusses specifications set forth by the United States Air Force (USAF) and the Federal Aviation Administration (FAA) for material selection, allowable maintenance operations, and dimensions of pavement markings.

2.2 Pavement Marking Materials

There are many pavement marking materials in use today on the roadways of America. A synthesis study conducted by Migletz et al. in 2002 showed there are four materials which constitute over 90% of the roadway pavement markings currently in use. However, only a small fraction of these are in use on America's runways.

Table 1 provides a quick synopsis of the studies conducted by the FAA of current and proposed pavement marking materials, the results obtained, and the resulting recommendations.

Table 1: FAA Studies of Possible Pavement Marking Materials

Author	Year	Material	Key Findings	Recommendations
Bagot	1995	Water-borne paint, epoxy, and methacrylic resin	<ul style="list-style-type: none"> All materials showed acceptable characteristics for use on airfields. Epoxy demonstrated high durability, especially in snowplow locations. Epoxy demonstrated yellowing after extensive ultraviolet exposure. 	<ul style="list-style-type: none"> Materials are suitable for use on airfields. Further research is required.
Cyrus and Frierson	2006	Polyurea	<ul style="list-style-type: none"> The material showed poor performance in high traffic areas. 	<ul style="list-style-type: none"> Further research is required.
Cyrus and Frierson	2006	Polyester	<ul style="list-style-type: none"> The material disintegrated after a very short time and should not be used on airfields. 	<ul style="list-style-type: none"> Do not use on any section of an airfield.
Cyrus and Previti	2008	Thermoplastic	<ul style="list-style-type: none"> Material can be applied to ACC as is but needs an additional binder before placing on PCC. Material flakes causing FOD and is recommended for only taxiway applications. 	<ul style="list-style-type: none"> Due to FOD potential, limit use to taxilanes. Further research is required.
Previti, Cyrus, and Gallagher	2010	Retro-Reflective Beads	<ul style="list-style-type: none"> Pilots could not detect a difference between Type I beads and Type III beads while on approach. Pilots involved in the study stated that they do not use runway markings while on approach at night. They use runway lights for guidance instead. 	<ul style="list-style-type: none"> Either Type I or Type III beads are acceptable for use on airfields.

2.2.1 Bagot (1995)

The scope of this study was to evaluate new marking materials for acceptable use on airfields, as well as to conduct a cost-benefit analysis. This study evaluated five different marking materials including: two water-borne paints, two epoxies, and one methacrylic. The study was conducted at three different airports to take advantage of differing climate conditions. The airports chosen were Atlantic City, Greater Pittsburgh, and Phoenix Sky Harbor International Airports.

Each of the materials was evaluated over a one year time period, with monthly evaluations for conspicuity, durability, rubber resistance, color retention, and friction. The researcher concluded that all the materials are acceptable for use on airfields based on the evaluation criteria, but recommended that additional research be conducted to determine if a different catalyst for the epoxy would reduce the yellowing effect. He also concluded that the epoxies and resin materials were more durable when subjected to snowplow operations.

2.2.2 Cyrus and Frierson (2006)

In 2006, Cyrus and Frierson conducted two separate studies, one evaluating polyurea and one evaluating polyester. Both studies were undertaken to evaluate the effectiveness of polyurea or polyester as a potential pavement markings to be used on airfields. The polyurea study showed that it was not effective in high traffic areas for either ACC or PCC surfaces when using Type III beads. However, when using Type I beads on PCC, the marking was still effective after six months. One of the significant findings was that if polyurea is to be used, the surface must first be cleared of seal coats.

The report lacks clarification or discussion on why polyurea was not effective in high traffic areas. Polyurea is a high durability marking material specifically designed for high traffic applications on roadways. We believe additional research must be accomplished to explain what specific conditions degrade polyurea to such a degree that it is not usable in high traffic areas on an airfield, while remaining well suited for high traffic areas on roadways.

The polyester study revealed that when used in simulated high traffic areas, the material disintegrated after a single day. The recommendation therefore is not to use this material for airfield markings.

2.2.3 Cyrus and Previti (2008)

This study evaluated the characteristics of thermoplastic marking materials at two different airports. The study was conducted at the FAA test center in New Jersey as well as Phoenix International Airport. The study had two significant findings. First, thermoplastic material can be applied and used on asphalt cement concrete (ACC) pavement as is, but must have an additional binder added when placed on Portland cement concrete (PCC) pavement. The other finding was that because of the thickness of the material, its tendency to flake off, and its low friction characteristics, it is suitable only for taxiways. The material showed acceptable retroreflectivity, chromaticity, and friction characteristics. “Currently, the FAA has no standard for retro-reflectivity limits. A previous paint marking study conducted by the FAA Airport Safety Technology Research and Development Section determined that the recommended minimum was 100 mcd/m²/lx for white and 70 mcd/m²/lx for yellow.” The FAA uses the same D₆₅ Color

Chart as developed by the International Civil Aviation Organization (ICAO) as shown in Figure 3 from section 1.8.2.

2.3 Pavement Marking Material Additives

Pavement markings on their own are not visible enough at night. Retroreflective beads are added to the material either during the application or during the manufacturing stage of the material. These beads come in either round beads of various sizes, or angular pieces as highly reflective elements. Two studies, one by the FAA and one by AFCESA evaluated the effect of different retroreflective additives to airfield pavement markings.

Table 2 summarizes the results from these studies.

Table 2: Retroreflective Bead Studies

Author	Year	Material	Key Findings	Recommendations
Ates	1995	Type I Beads vs Type III Beads	<ul style="list-style-type: none"> Despite large retroreflectance differences, pilots could not detect a difference between the two bead types. 	<ul style="list-style-type: none"> Recommend use Type I beads instead of the much more expensive Type III beads.
Previti, Cyrus, and Gallagher	2010	Retro-Reflective Beads	<ul style="list-style-type: none"> Pilots could not detect a difference between Type I beads and Type III beads while on approach. Pilots involved in the study stated that they do not use runway markings while on approach at night. They use runway lights for guidance instead. 	<ul style="list-style-type: none"> Either Type I or Type III beads are acceptable for use on airfields.

2.3.1 Ates (1995)

From 1991 until 1995, AFCESA conducted a series of two tests evaluating Type I beads versus Type III beads on active Air Force airfields. The first test consisted of two taxiway markings separated by six inches reflectorized using Type I beads on one marking and Type III beads on the other marking. Surveys of pilots demonstrated that Type I beads are suitable for taxiway marking purposes. After approximately seven months, both stripes had acceptable retroreflectance characteristics.

The second test compared the two bead types, but this time on opposite ends of a runway. Again, after months of wear and tear, both markings demonstrated acceptable retroreflectance characteristics. And, once again, the pilots surveyed were content with the Type I bead performance.

The study team concluded that even though the Type III beads had higher retroreflectance, a smaller amount of light was actually making it back to the pilot's eyes. This was due to the light entering the bead being returned in a very narrow band. Thus, unless the observer was in the narrow reflection band, the reflectance values would be very small. Opposed to this, Type I bead disperses the light in a wider range as shown in Figure 4 and Figure 5 and are thus easier to detect outside of a narrow band (Ates, 1995).

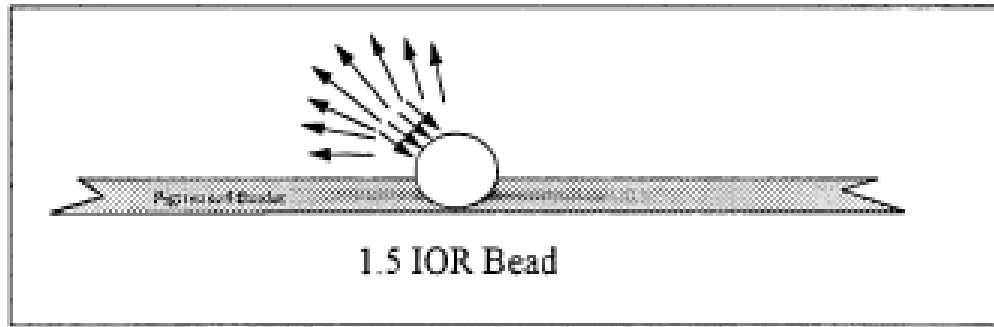


Figure 4: Type I Bead Retroreflectance Characteristics

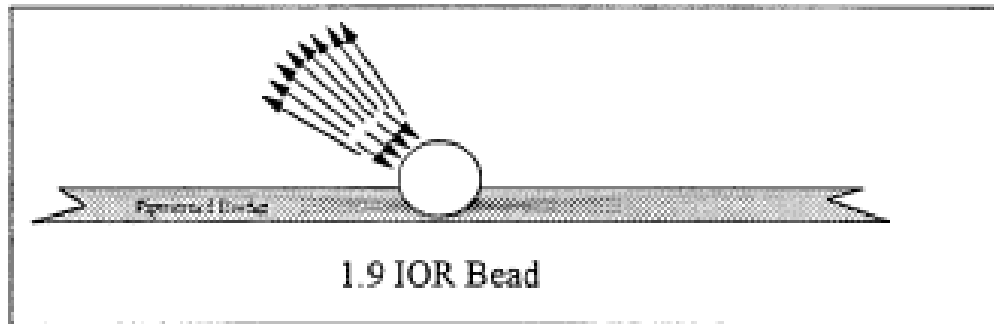


Figure 5: Type III Bead Retroreflectance Characteristics

2.3.2 Previti, Cyrus, Gallagher (2010)

The FAA conducted a study evaluating the performance of standard Type I beads and highly reflective Type III beads. The purpose of the study was to evaluate whether there is an appreciable difference detectable by people between the two different bead types. Despite Type III beads having a much higher initial retroreflectivity value, after eight months, both the Type I sample and the Type III sample were effectively the same in regards to retro-reflectivity readings. In addition to the measured readings, pilots were

asked to discern between the two different types. While on approach pilots reported at distances ranging from 0.9 to 6.0 miles from the runway threshold no visual differences between low-index Type I and high-index Type III installations. For nine out of ten pilots, there was no difference at any time.

2.4 Pavement Marking Layout

2.4.1 USAF ETL 04-2 (2004)

This Engineering Technical Letter (ETL) designates the size, position, and shape of all markings used on an airfield. All U.S. military services abide by this ETL for marking surfaces. Of particular note are the runway markings and the taxiway markings. Runway centerline markings vary in widths from 18 to 36 inches. Taxiway markings are a standard six inches wide. These measurements provide the basis for the stripe sizes used in the experiment for this thesis.

2.4.2 Split Plot Design

Factorial experiments where one or more factors are difficult to change and the others easier, utilize a split plot experiment design. The split plot design allows the researcher to conduct treatments on a set, leaving one variable constant for that block. For instance, if a researcher conducted an experiment with three temperature levels and four stirring rates the factorial design calls for 24 runs. If the temperature is difficult to change, the researcher is allowed to run all the tests at one temperature before moving onto the next temperature. If this were to be a completely randomized design, all the variables would have to be changed between runs, including temperature. The split plot

essentially saves time and money by grouping treatments together, realizing that there might be small effects within that block (Morris, 2011).

2.5 Treatments

Air Force Instructions (AFI) and Engineering Technical Letters (ETL) provide instructions and recommendations for how a specific function on an Air Force Base will operate. AFI 32-1002, Snow and Ice Control, provides instructions for the proper snow and ice control so that the airfield will continue to operate in any of the given conditions. The AFI states that the center of the runway must remain clear of snow throughout a snowfall event. This includes using snowplows, sweepers, and snow blowers as necessary to ensure a clear runway.

ETL 97-17 is a guide specification for rubber removal operations. The ETL allows for several different rubber removal methods to include: high pressure water, chemical detergent, high velocity abrasion, and grinding. High pressure water rubber removal consists of using jets of water up to 15,000 psi to cut through and lift rubber off of the runway. This process, if done well, will lift the rubber, but retain the pavement markings and the integrity of the pavement surface. If done poorly, the pavement surface and the pavement markings could suffer severe damage. Chemical rubber removal relies on very high pH chemicals to eat away the rubber, while a sweeper and water wash the solution off of the runway surface. High velocity abrasion uses the same principle as high pressure water, but uses sand or metal pellets as the abrasive medium instead of water. This process has the added complication of possibly leaving the medium on the runway, needing extra attention for complete clean-up to prevent FOD. Grinding as a

rubber removal method removes the rubber as well as a thin layer of the top of the pavement surface.

2.6 Evaluation Criteria

A study conducted by Cyrus was undertaken in order to establish a more uniform and repeatable inspection process for pavement marking evaluation for the FAA. The researcher, who is the head of the FAA's pavement marking branch, determined that retro-reflectivity, chromaticity, and coverage are the three evaluation criteria to be used in order to determine if a pavement marking is failed or not. The research concluded that "the retro-reflective threshold limit for yellow paint is 70 mcd/m²/lx and for white paint 100 mcd/m²/lx. The coverage threshold pass/fail limit is 50% (Cyrus H. M., 2003)." The limits for chromaticity are the same as identified on the D₆₅ Color Chart.

A retro-reflectometer set to the ASTM 30 meter geometry standard is used to evaluate retro-reflectivity. The retro-reflectometer can be either handheld or vehicle mounted. A spectrophotometer producing an xyY plot is used to evaluate chromaticity levels. And, a 100 square inch transparent grid is used to determine the percent coverage of the material.

2.7 Statistical Analysis

Experiments which are difficult to change one or more of the parameters rely on a split plot design. Split plot experiment design allows for the experiment combinations to be evaluated in batches instead of one at a time. A repeated measures experiment design is a subset of split plot experiment designs. Repeated measures allows several measurements to be taken on the same sample over time. The experiment used in this

research effort utilizes a repeated measures experiment design. In order to analyze the repeated measures, the researchers used Matched Pair analysis. Matched Pair analysis compares corresponding samples to each other and averages the differences in a set to determine if there is a significant difference from one set to another.

2.8 Review

As this section shows, there are a number of pavement marking materials currently on the market, but not being fully implemented on airfields due to a lack of research and understanding of their performance in that environment. Additional research needs to be conducted on epoxy, thermoplastic, and polyurea pavement markings, as well as glass beads in order to understand the degradation characteristics and potential safety concerns associated with each. The rest of this research effort focuses on these materials as a starting point for developing degradation models for each material. The research uses a split plot experiment layout to isolate and evaluate how different treatments affect the various materials.

Chapter 3: Methodology

3.1 Introduction

The previous discussion has shown that there are several pavement marking materials available for use, but few if any have actually made it to an active airfield. The current asset management practices rely on incomplete information, and thus need updating. A repeated measures split plot experiment was developed in order to help identify suitable materials for airfield use, and degradation rates for those materials. This chapter discusses two experiments. The first experiment, Experiment 1, is a small scale experiment of two materials, two treatments, and one pavement type which will validate the design of a much larger experiment. The second experiment, Experiment 2, is a large scale experiment incorporating four marking materials, two bead types, four treatments, and two pavement types. This research effort will not conduct Experiment 2, but will confirm the design by using Experiment 1. For the sake of completeness, each experiment is discussed in detail.

3.2 Experiment 1

The purpose of Experiment 1 is to evaluate the performance of different materials against treatments seen on an airfield. The evaluations will provide degradation rates for the materials in the given situations. Airfield managers may then use those degradation rates to further develop asset management plans for airfields. This experiment will also validate a larger scale experiment with more materials and treatments.

3.2.1 Marking Material

There are numerous pavement marking materials currently on the market. This experiment consists of two materials, waterborne paint and thermoplastic. In order to be consistent with airfield marking schemes, all the marking materials are white, corresponding with the color of runway centerline markings. Marking specialists applied both the paint and the thermoplastic. Before application, they cleaned the asphalt surface of any debris. They applied the materials in accordance with the manufacture's recommendations.

3.2.2 Layout

The experiment consists of two test decks of pavement markings. Each deck contains a stripe of waterborne paint and thermoplastic. The stripes of material are 30 ft long and 6 inches wide. The markings within each deck are spaced 12 inches apart. Figure 6 and Figure 7 show the test decks as placed on the asphalt runway for the National Museum of the United States Air Force on Wright-Patterson Air Force Base Area B. The runway is a semi-active runway with approximately ten take-offs and landings per year. The test decks have a sufficient buffer around them to allow for movement of machinery without having to traverse over the markings. Thus, the only factors affecting the markings are the applications of the prescribed treatments. Initial retroreflectivity and chromaticity readings were taken before any treatments were applied.



Figure 6: Chemical Treatment Test Deck

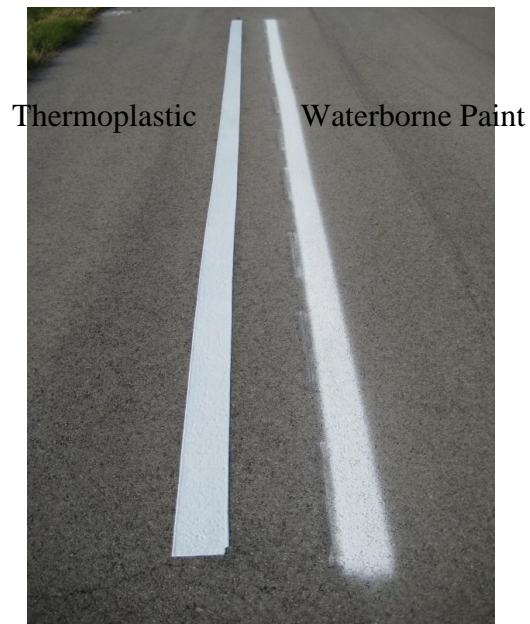


Figure 7: Sweeper Treatment Test Deck

3.2.3 Glass Beads

Overall, there are four sizes and shapes of beads on the market. These include Type I highway or standard, Type III airport, Type IV large, and highly reflective elements. Of the four bead types, this experiment calls for just one, the smaller Type I highway bead. As Needham noticed, bead type effects the degradation characteristics of a polyurea pavement marking; markings with Type I beads degrading differently than markings with highly reflective elements (Needham, 2011). The FAA has not authorized highly reflective elements to be used on airfields as of yet (Speidel, 2008). This study will use Type I beads because of availability and the use on Air Force runways (Force, 2010).

3.2.4 Pavement Type

There are typically two types of pavement currently in use on airfields, Portland Cement Concrete (PCC) and Asphalt Cement Concrete (ACC). The experiment uses only ACC pavement. The test location is at one end of a semi-active airfield. The airfield experiences approximately ten landings a year. Additionally, a recent construction project provided a new wearing course for the runway. Although the test is not on an active airfield, the surface is the same as would be found on an active airfield.

3.2.5 Treatments

This experiment consists of two treatments, sweeping and chemical rubber removal. Both operations are allowed under current Air Force practices (United States Air Force (USAF), 1997). The results for that analysis are discussed at length in the next chapter.

3.2.5.1 Sweeping

A Tymco model 500x sweeper was used to apply the sweeping treatments to the pavement markings. An operator trained on this particular sweeper, and familiar with airfield sweeping operated the equipment for all treatment applications. The overall sweeping width was wide enough to facilitate a single pass to cover the entire test deck and thus obtaining a uniform treatment application across all the markings in that test deck. The first treatment consisted of 25 passes of the sweeper over the test deck; the second and third treatments consisted of 30 and 150 passes respectively. The number of passes used for the first treatment roughly corresponds to the number of passes a sample location on an airfield would experience in a six month period.

3.2.5.2 Chemical Rubber Removal

The researchers were trained and used the Air Force approved chemical rubber removal process for application of the treatments. A copy of the training certificate is found in Appendix A and a detailed description of the process is found in Appendix B: Chemical Rubber Removal Process. The Air Force Research Lab's Airbase Technologies Directorate currently uses Avion50 as the preferred chemical in airfield rubber removal. With a pH of 14, Avion50 is a highly basic substance which deteriorates the rubber. To aid in the deterioration of the rubber, the chemical is agitated with a wire bristle sweeper attachment for a skid loader. The particular vehicle configuration is known as a Toolcat and is shown in Figure 8. The specific bristle configuration is found in Appendix C: Toolcat Set-up and Specifications. The combination of the chemical and mechanical agitation allows the rubber to be washed off of the runway without having to

resort to high pressure abrasion techniques. For this experiment, the chemical was applied at the recommended coverage amounts, agitated using a roadway sweeper for four hours, and then washed off using pressurized water, below 2,000 psi, from a firefighting vehicle.

One concern about the design of the experiment is the absence of rubber over the pavement marking. The lack of rubber could change how the treatment would affect the pavement marking on an active runway. However, this experiment depicts a worst-case scenario where the marking does not have rubber on it, but still receives the rubber removal treatment.



Figure 8: Toolcat Sweeper and Sprayer

3.2.6 Evaluation Criteria

A sample of material consists of one linear foot of marking. Thus, a single 30 foot marking accounts for 30 different samples of that material. The researchers evaluated each sample on the three failure criteria designated by the FAA: retroreflectivity, chromaticity, and coverage (Cyrus H. M., 2003). Measurements for each criterion were taken before the first treatment and after each subsequent application of the treatments.

3.2.6.1 Retroreflectivity

Retroreflectivity, one of the main indicators of a pavement marker's effectiveness, is the measure of how much light from a headlight reflects off of the marking and is directed back to the driver's eye (ASTM 2005). Roadway markings use the 30-meter geometry, as set forth by ASTM. The FAA uses the same geometry to measure markings on airfields (Cyrus & Previti, 2008). This study measures retroreflectivity with the same set-up. The FAA has established for white pavement markings, the minimum value for retroreflectivity is $100 \text{ mcd/m}^2/\text{lux}$.

A portable LTL-X retro-reflectometer was used to measure the retro-reflectance values for the pavement markings. The retro-reflectometer measures retro-reflectance using the ASTM 30-meter geometry. The researchers calibrated the device with the manufacturer supplied office calibration block before taking any measurements. Also, at the start of each day of taking measurements, we calibrated the device in the field using the manufacturer supplied field block, and again anytime there was a drastic shift in weather conditions.

3.2.6.2 Chromaticity

Chromaticity is the measure of the color of the marking. The FAA and the USAF have standard color values for each color. Within the standard, there is also a range that the color is allowed to deviate from. Chromaticity measures the color to determine if the marking is still within the specified range. The researchers used a Spectro-Duo spectrophotometer to measure the sample's chromaticity. The spectrophotometer measures the sample and displays the corresponding xy coordinate for the D₆₅ color chart. The sample coordinate is then compared to the coordinates given by the FAA for an acceptable white color marking.

The Spectro-Duo needed no calibration. Two methods were discussed for obtaining chromaticity measurements. The first, using a white calibration puck to measure ambient conditions. The second, using an enclosed white box with an independent light source. The measurements would be taken inside the box, providing consistent lighting conditions with no need for later translations. Since the markings need to appear white to operators on the airfield under a variety of environmental conditions this research effort chose to use the ambient light conditions. In an effort to measure ambient conditions, the researchers first measured a white puck before measuring a test stripe. The white puck is pure white, with no other colors present. Thus, the puck measurement gives the chart position for what pure white looks like for that specific environmental condition. If the puck measurements fall within the acceptable white range on the D₆₅ color chart, then the markings should also fall within the acceptable range if they are still white. If the puck measurements do not fall within

the acceptable white range, then the measurement for the puck and the measurements for the test stripe need to be translated to an acceptable range. As Chapter 4 shows, all the puck measurements fall within the specified range, and therefore the process for translating the measurements need not be discussed here.

3.2.6.3 Coverage

Coverage is evaluated using a 25 square inch transparent sheet. The sheet is divided into 100 blocks, each 0.25 inches square, with 20 rows and 5 columns. The researchers placed the sheet on the sample marking and counted the number of squares which showed pavement instead of just marking material as demonstrated in Figure 9. The number of squares showing more than 50 percent pavement was subtracted from 100 to give the percent coverage remaining. If the overall coverage is less than 50%, the marking fails.



Figure 9: Transparent Grid Used for Measuring Coverage

3.3 Experiment 2

Experiment 2 is designed as a more robust analysis of materials and treatments, based on the results of Experiment 1. The more robust experiment consists of both PCC and ACC pavement types; four marking material types to include waterborne paint, thermoplastic, polyurea, and epoxy. These materials are chosen because they represent approximately 90% of the material types used on roadways (Migletz & Graham, 2002).

Additionally, the design guides produced by the Federal Aviation Administration (FAA), the United States Air Force (USAF), and the United States Navy (USN) all agree on these materials as potential materials to be used on airfields. At least three treatments to include high pressure water rubber removal, ultra-high pressure water rubber removal, and chemical rubber removal. Appendix D demonstrates a notional layout of the materials and treatments.

3.3.1 High Pressure Water

The high pressure water treatment truck needs to meet Air Force specified standards. To be considered high pressure, the truck must be able to eject water between 4,000 psi and 15,000 psi. In order for the truck to be considered sufficient, it needs to demonstrate proper water pressure and rubber removal capabilities on a test strip. The Contracting Officer oversees the test strip and, in conjunction with the Civil Engineer, approves or disapproves the truck (Force, 2010). The effective width of the treatment is 20 inches, thus each pavement marking is treated separately. The jet head is powered up and runs until reaching a consistent state before beginning the application of the treatment for each marking. Or, the machine powers up to a constant velocity before beginning the application. Once application of the treatment starts, the operator does not turn the machine off until all the markings have received the treatment for that specific run.

3.3.2 Ultra-High Pressure Water

Although not currently approved, ultra-high pressure water rubber removal is being considered for inclusion in the Air Force's Rubber Removal ETL. Ultra-high

pressure water operates under the same basic principle as high pressure water rubber removal. The difference is that ultra-high pressure water rubber removal requires a nozzle pressure of over 40,000 psi. The same specifications hold for this treatment as for high pressure water rubber removal. The truck will reach a constant operating condition before application to the pavement markings. Once the truck has started application, it will not be shut down until all markings are complete.

3.4 Matched Pair Analysis

Repeated measures designs can be described in terms of the between-subjects design and the within-subjects design. The between-subjects design refers to the treatment design and the experiment design used for the experimental units. The within-subjects design refers to the repeated measures on each experimental unit. This experiment has two “treatments” (materials) for the between-subjects design. The within-subjects design consists of repeated measures on each sample section.

The researchers used Matched Pair analysis to determine if samples from the repeated measures experiment are statistically different from each other. The overall research $\alpha_e=0.05$. Using the Bonferroni approach for determining each t-test significance level, the $\alpha_c=0.004$ for each individual test. When conducting analysis within a test stripe, the matched pair consisted of the values obtained after a treatment compared against the immediate previous value. So, treatment one is compared against initial, treatment two is compared against treatment one, and treatment three is compared against treatment two. When conducting analysis between test stripes, the matched pair consists of the differences between the treatments. Thus, the difference from the initial value and

the first treatment of one stripe is compared against the corresponding difference from the other test stripe. The following chapters discuss the analysis and results from visual inspections of the materials as well as the matched pair results. Recommendations for asset managers and future research options follow the analysis and results.

Chapter 4: Results & Analysis

4.1 Introduction

The following chapter discusses the visual observations after each treatment as well as the statistical analysis from each treatment. Measurement results are shown in Appendix E: Experiment Data. Between subjects analysis includes paint versus thermoplastic within the chemical treatment test deck and paint versus thermoplastic within the sweeper treatment test deck. Analysis also includes the paint from the chemical treatment test deck compared to the paint from the sweeper treatment test deck as well as thermoplastic from the chemical treatment test deck versus the thermoplastic from the sweeper treatment test deck. Statistical analysis also evaluates whether each stripe had a significant difference from one treatment to the next. Table 3 and Table 4 show a synopsis of the results. An “✘” means that the marking failed that criteria for that treatment and a “✓” means the marking passed that respective criteria.

Table 3: Results for Chemical Treatment Test Deck

	Paint			Thermoplastic		
Treatment	1	2	3	1	2	3
R _L	✘	✘	✘	✓	✓	✓
Chromaticity	✘	✘	✘	✓	✓	✘
Coverage	✓	✓	✓	✓	✓	✘

Table 4: Results for Sweeper Treatment Test Deck

Treatment	Paint			Thermoplastic		
	1	2	3	1	2	3
R _L	✓	✓	✓	✓	✓	✓
Chromaticity	✓	✓	✓	✓	✓	✓
Coverage	✓	✓	✓	✓	✓	✓

4.2 Chemical Treatment Visual analysis

The paint which experienced the chemical treatment failed after the first treatment application. The retroreflectivity started with a mean above 200 mcd/m²/lux, but after the first treatment the mean had dropped below 90 mcd/m²/lux; a failing level according to both the USAF and the FAA. Additionally, the chromaticity levels which had started within the specified range had moved outside the range after every treatment application. Figure 10 shows the chromaticity values for the paint marking. The black box outlines the FAA approved area for a white pavement marking. Note the tendency of the marking to migrate to the upper right after each subsequent treatment. The only test which the paint did not fail was the coverage test. Visual inspection of the marking shows that even after the third treatment application, the marking was still above 80%, well above the specified 50% standard. On just a visual inspection the marking would have been considered passing on all accounts, but using retroreflectivity and chromaticity measurements, the marking failed after the first application.

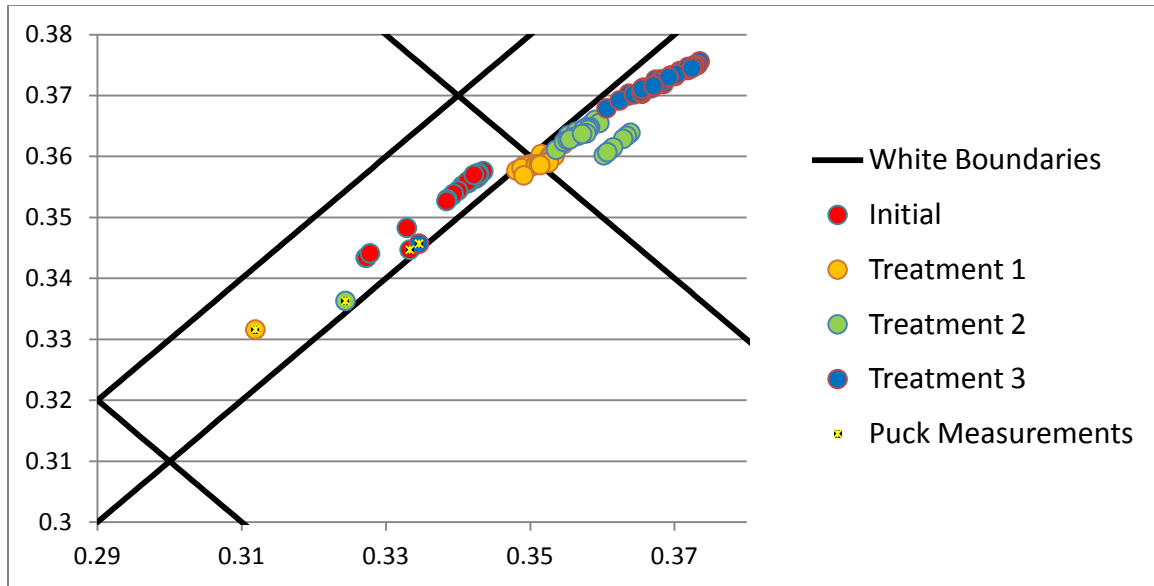


Figure 10: Chemical Treatment Test Deck Waterborne Paint Chromaticity Measurements (nominal units)

The thermoplastic marking which experienced the chemical treatments reacted vastly different than the paint marking. Throughout all the treatments, the thermoplastic maintained a passing level for retroreflectance. After the third treatment, the marking still maintained an average of $123 \text{ mcd/m}^2/\text{lux}$. However, this value was only obtained using three data points. During the washing process after the third treatment, most of the thermoplastic material experienced a catastrophic failure due to problems with surface bonding and peeled up from the asphalt surface as shown in Figure 11. The water pressure from the fire engine hand line, acting perpendicular to the pavement marking, dislodged the material and forced it off the asphalt. For future efforts, the water should be applied in parallel to the markings, not perpendicular. After the washing was complete, only the first three feet of the marking remained intact. Because of this, the

researchers could not obtain retroreflectance readings on anything but the first three feet. However, we were still able to collect chromaticity readings for the material which had peeled up. Figure 12 shows the material laid down in order to obtain the chromaticity readings. The researchers graphed the degradations for retroreflectance, and chromaticity in the x and y directions for both the waterborne paint and thermoplastic. The graphs and corresponding best fit regression lines with R^2 values are show in Figure 13, Figure 14, and Figure 15.



Figure 11: Catastrophic Failure of Thermoplastic



Figure 12: Thermoplastic Repositioned After Failure

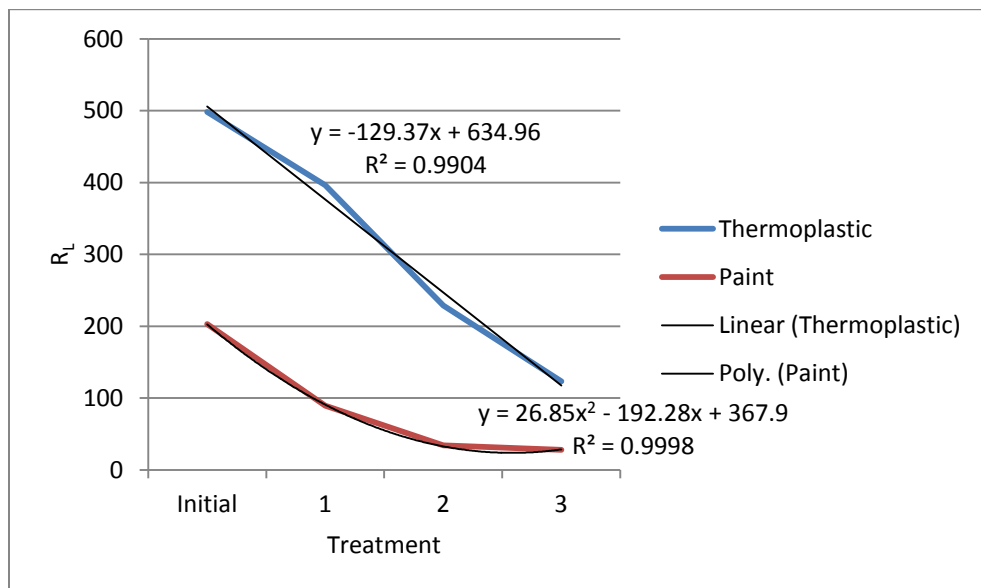


Figure 13: Chemical Treatment Retroreflectance (mcd/m²/lux)

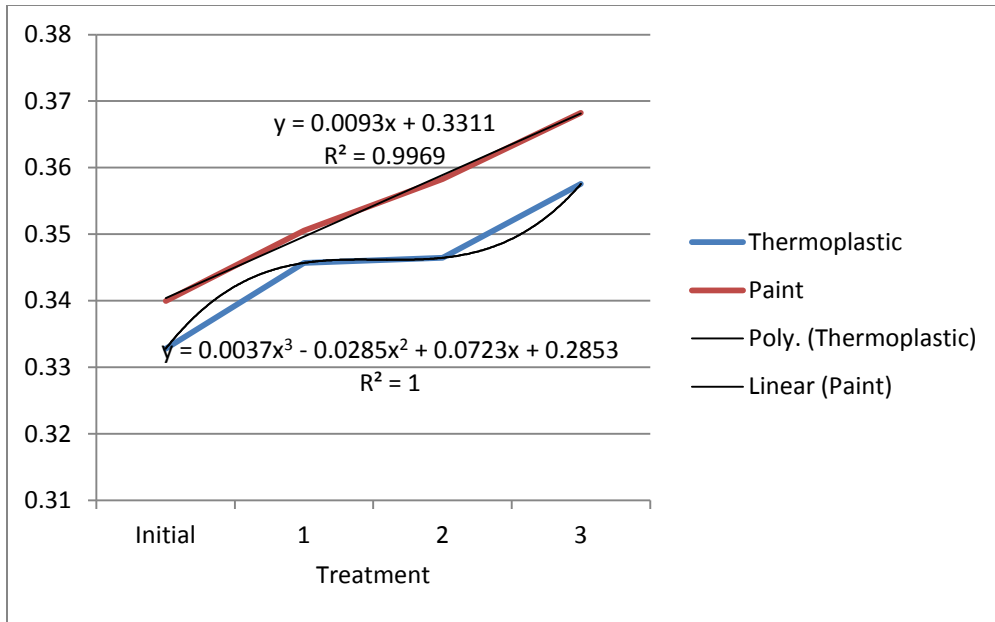


Figure 14: Chemical Treatment Chromaticity x

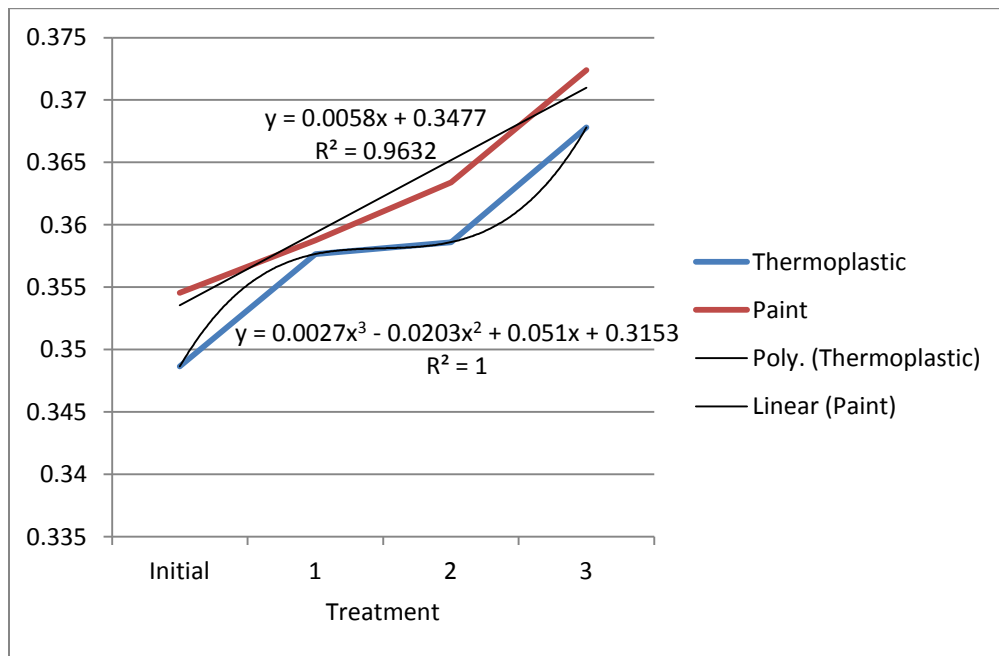


Figure 15: Chemical Treatment Chromaticity y

Charting the chromaticity readings reveals that after the third treatment, the marking was no longer inside the specified ranges. Figure 16 shows that the thermoplastic displays a similar trend to that of the waterborne paint in that the chromaticity readings tend to the upper right as chemical treatments are applied. A visual inspection of the thermoplastic material cross-section showed that the material retained a large majority of the reflective beads throughout its thickness. The main concern with this material is its adherence properties to the runway surface. This is consistent with what the FAA found in their evaluation of the material (Cyrus & Previti, 2008).

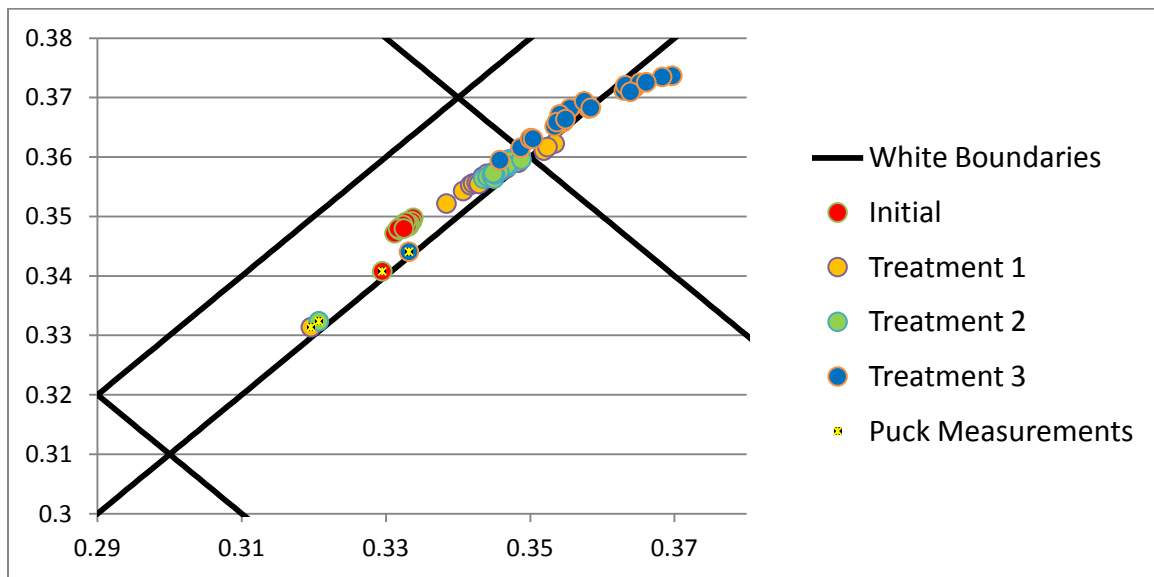


Figure 16: Chemical Treatment Test Deck Thermoplastic Chromaticity Measurements

The two materials subjected to the chemical rubber removal process reacted vastly different from one another. Paint failed in retroreflectance and chromaticity after

the first treatment application, where thermoplastic failed in coverage and chromaticity after the third treatment. Based on a runway rubber removal schedule of twice per year, the thermoplastic would last one year longer than the paint. Thermoplastic's advantage comes with requiring fewer applications and thus less time the runway is down for maintenance.

4.3 Sweeper Treatment Visual Analysis

Upon a visual analysis of the marking materials, both the waterborne paint and the thermoplastic performed well. After the last application of the treatment, both materials still retained most of their coverage. However, the thermoplastic did chip up a bit, losing approximately 16 inches from one end. Due to the lack of debris in the area, we assume the sweeper broke the material into small pieces and ingested those pieces. Both materials still appeared white after the third treatment, and both appeared to have acceptable amounts of retroreflectance. Figure 17 and Figure 18 show that the markings' color did not deviate much from the initial values, and all stayed within the acceptable white range.

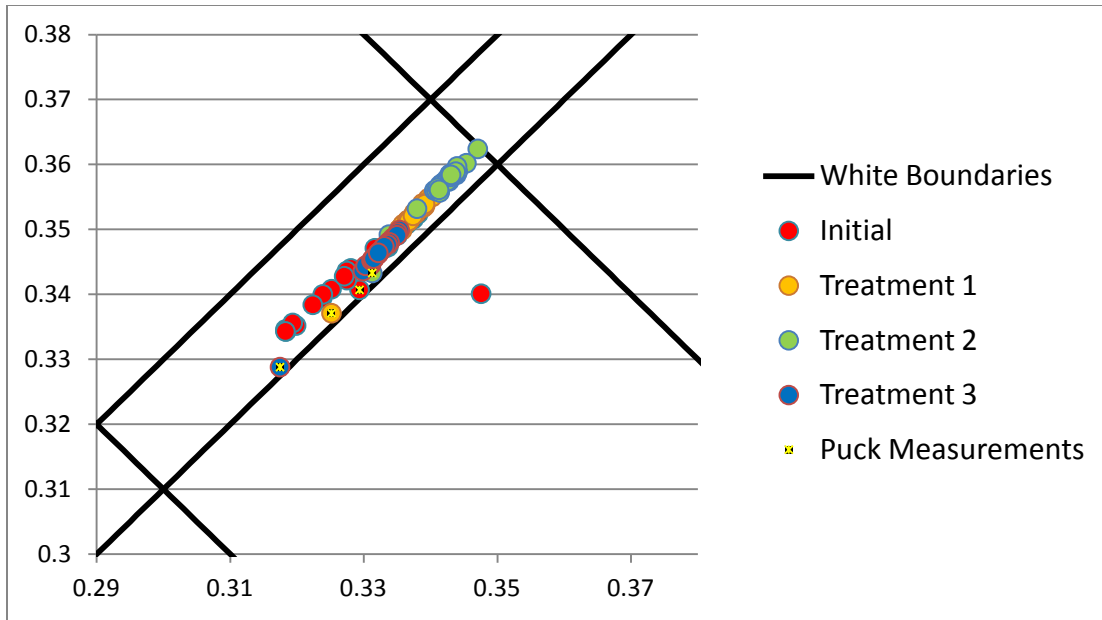


Figure 17: Sweeper Treatment Test Deck Waterborne Paint Chromaticity Measurements

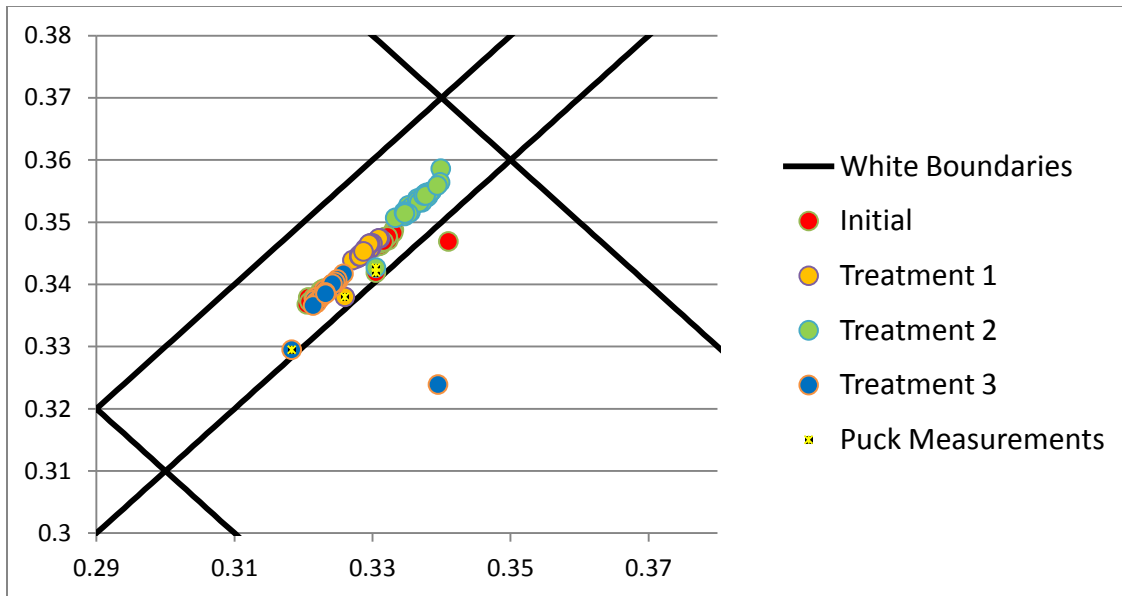


Figure 18: Sweeper Treatment Test Deck Thermoplastic Chromaticity Measurements

4.4 Matched Pair Analysis

The researchers ran several tests to determine statistical significance. This section deals mostly with those tests where the t-statistic determined a statistical difference. Using the Bonferroni method, in order for a test to be statistically significant at the 95% confidence level, each individual t-statistic p-value needs to be less than 0.0004. Any values above that cannot be considered significant without changing the overall confidence level. Appendix F: t-statistic Test Results shows all the test results. Observations other than what would be expected are highlighted in this section.

To determine the consistency of the materials used in the experiment, the researchers compared the initial values for each material against each other. Table 5 shows all the matched pair analysis results for the initial values. Within the chemical treatment test deck, the waterborne paint was statistically different from the thermoplastic in retroreflectance, chromaticity in both the x and y directions, but statistically no different in coverage. These results are not surprising as thermoplastic demonstrates higher initial retroreflectance reading over that of waterborne paint. Despite having different chromaticity readings, both materials fall within the FAA approved area for white pavement markings. Also, as was expected, both materials start with 100% coverage and therefore had no statistical difference.

Starting values for the sweeper treatment test deck had no statistical difference between the waterborne paint and thermoplastic materials, with the exception of the initial retroreflectance values. The thermoplastic material had a statistically higher initial value than the waterborne paint. When the waterborne paint stripes from the two test

decks were compared against each other, there was no statistical difference in the initial retroreflectivity values or the coverage. However, both the chromaticity measurements showed statistical differences. The thermoplastic test stripes between the two test decks showed no statistical difference in the chromaticity x measurement and coverage. However, the two stripes showed a difference in initial retroreflectivity values as well as in the chromaticity y measurement.

Table 5: Initial Values Matched Pair Analysis

Treatment Test Deck	Material	Measurement	Mean Difference	Prob > t	Significance
Chemical Treatment Test Deck	Paint vs. Thermoplastic	R _L	295.375	0.0001	different
		Chromaticity x	-0.0073	0.0001	different
		Chromaticity y	-0.006	0.0001	different
		Coverage	0	n/a	same
Sweeping Treatment Test Deck	Paint vs. Thermoplastic	R _L	411.233	0.0001	different
		Chromaticity x	-0.0019	0.2478	same
		Chromaticity y	-0.0006	0.5878	same
		Coverage	0	n/a	same
Chemical Treatment Test Deck vs. Sweeping Treatment Test Deck	Paint vs. Paint	R _L	3.56667	0.4434	same
		Chromaticity x	-0.0096	0.0001	different
		Chromaticity y	-0.0099	0.0001	different
		Coverage	0	n/a	same
Chemical Treatment Test Deck vs. Sweeping Treatment Test Deck	Thermoplastic vs. Thermoplastic	R _L	119.875	0.0001	different
		Chromaticity x	-0.0026	0.0079	same
		Chromaticity y	-0.0032	0.0002	different
		Coverage	0	n/a	same

4.4.1 Chemical Treatment Test Deck Analysis

Within the paint stripe for the chemical treatment, each iteration of the treatment caused a significant change in every measured parameter with the single exception of the coverage value difference from the initial values to after the first treatment as shown in Table 6. Within the thermoplastic stripe for the chemical treatment the values in Table 7 demonstrate that only some of the parameters experienced significant changes. Retroreflectivity did not have a significant change after the third treatment. Chromaticity values in the x direction and the y direction did not have significant changes after the second treatment; the first and third treatments both had significant changes. Coverage did not change until after the third treatment when the thermoplastic experienced a catastrophic failure as shown earlier.

Table 6: Within Paint Comparison for the Chemical Treatment

Measurement	Treatment Number	Mean Difference	Prob > t	Significance
R _L	1-Initial	-113.6	0.0001	different
	2-1	-55.233	0.0001	different
	3-2	-6.2	0.0001	different
Chromaticity x	1-Initial	0.01057	0.0001	different
	2-1	0.00776	0.0001	different
	3-2	0.00992	0.0001	different
Chromaticity y	1-Initial	0.00422	0.0001	different
	2-1	0.00464	0.0001	different
	3-2	0.00899	0.0001	different
Coverage	1-Initial	-0.3667	0.0697	same
	2-1	-4.7	0.0001	different
	3-2	-13.5	0.0001	different

Table 7: Within Thermoplastic Comparison for the Chemical Treatment

Measurement	Treatment Number	Mean Difference	Prob > t	Significance
R _L	1-Initial	-102.33	0.0001	different
	2-1	-167.42	0.0001	different
	3-2	-50	0.0287	same
Chromaticity x	1-Initial	0.01291	0.0001	different
	2-1	0.00076	0.4195	same
	3-2	0.01109	0.0001	different
Chromaticity y	1-Initial	0.00901	0.0001	different
	2-1	0.00095	0.1708	same
	3-2	0.0092	0.0001	different
Coverage	1-Initial	0	n/a	same
	2-1	0	n/a	same
	3-2	-87.5	0.0001	different

The researchers also analyzed the differences between the waterborne paint and the thermoplastic within the chemical treatment test deck. Results for this set of analysis are found in Table 8. The amount of degradation in retroreflectance between the two was statistically the same. This was unexpected as most assumptions are that the two materials have different degradation curves. However, after the second and third treatments, the change in retroreflectance of the waterborne paint was different from that of the thermoplastic. After the second application of the treatment, the waterborne paint material dropped below the FAA failure criteria of 100 mcd/m²/lux and left the linear degradation region and entered a nonlinear region.

Table 8: Between Paint and Thermoplastic for the Chemical Treatment

Measurement	Treatment Number	Mean Difference	Prob > t	Significance
R_L	1-Initial	12.2917	0.4452	same
	2-1	-113.83	0.0001	different
	3-2	-207.33	0.0001	different
Chromaticity x	1-Initial	0.0027	0.0721	same
	2-1	-0.0066	0.0001	different
	3-2	0.0021	0.9104	same
Chromaticity y	1-Initial	0.00489	0.0004	different
	2-1	-0.0042	0.0001	different
	3-2	0.00059	0.5578	same
Coverage	1-Initial	0.36667	0.0697	same
	2-1	4.7	0.0001	different
	3-2	-63.444	0.0001	different

After the first treatment and after the third treatment the waterborne paint and thermoplastic experienced statistically non-significant changes in the chromaticity x measurements. However, the changes after the second treatment were statistically significant. The material appears to follow a cubic trend, helping to explain why the changes would be the same between materials for the first and third treatments, but not the same for the second treatment. For chromaticity in the y direction, the waterborne paint and thermoplastic experienced statistically significant changes from each other after both the first and the second treatment, but statistically non-significant changes from each other after the third treatment.

4.4.2 Sweeper Treatment Test Deck Analysis

Matched Pair analysis, shown in Table 9, reveals that only one of the three sweeper treatments resulted in a significant change in retroreflectance values for the waterborne paint test stripe. Only the second treatment had a significant difference. This

occurred in the break-in region for the marking, as the retroreflectance was still increasing. It was not until the third treatment that the retroreflectance started to decrease.

Unlike retroreflectance, after each application of the treatment, the waterborne paint experienced statistically significant changes in chromaticity values for both the x and y directions. However, as shown in Section 4.3, all the readings were within the acceptable color range and did not show any particular trend. The test stripe did not lose any coverage throughout the treatments.

Table 9: Within Paint Comparison for the Sweeper Treatment

Measurement	Treatment Number	Mean Difference	Prob > t	Significance
R _L	1-Initial	1.56667	0.5926	same
	2-1	19.5	0.0001	different
	3-2	-5.3667	0.0397	same
Chromaticity x	1-Initial	0.00692	0.0001	different
	2-1	0.005	0.0001	different
	3-2	-0.0099	0.0001	different
Chromaticity y	1-Initial	0.00732	0.0001	different
	2-1	0.00541	0.0001	different
	3-2	-0.0109	0.0001	different
Coverage	1-Initial	0	n/a	same
	2-1	0	n/a	same
	3-2	0	n/a	same

The thermoplastic material exhibited a similar pattern to that of paint in regards to most of the measurements. Matched Pair analysis for retroreflectance in Table 10, shows that the first treatment had no effect; the second had a significant increase in

retroreflectance; while the third showed no difference. As opposed to the waterborne paint marking, the thermoplastic marking experienced a significant change in chromaticity for both the x and y directions after the first treatment. However, after that, no subsequent treatments showed a significant change. Like that of the waterborne paint, the thermoplastic does not show any visual trend for changes in chromaticity, and all measurements are well within the acceptable range. As for coverage, despite losing 16 inches off the end of the marking due to surface adhesion problems, that was not enough to constitute a statistically significant change.

Table 10: Within Thermoplastic Comparison for the Sweeper Treatment

Measurement	Treatment Number	Mean Difference	Prob > t	Significance
R _L	1-Initial	-18.1	0.022	same
	2-1	84.7333	0.0001	different
	3-2	-4.6552	0.4542	same
Chromaticity x	1-Initial	0.00044	0.6366	same
	2-1	0.00781	0.0001	different
	3-2	-0.0127	0.0001	different
Chromaticity y	1-Initial	0.00133	0.0943	same
	2-1	0.00814	0.0001	different
	3-2	-0.0149	0.0001	different
Coverage	1-Initial	0	n/a	same
	2-1	0	n/a	same
	3-2	-4.1667	0.2313	same

When comparing the waterborne paint stripe to the thermoplastic, the researchers found a couple interesting results. The results found in Table 11 show that for the first two treatments, the materials exhibited statistically significant changes in retroreflectance

values. However, after the third treatment, there was no statistical difference in changes to retroreflectance. With regard to chromaticity, the two materials had statistically different changes on all accounts except for the x direction after the third treatment. There was no statistical difference in any of the coverage measurements.

Table 11: Between Paint and Thermoplastic for the Sweeper Treatment

Measurement	Treatment Number	Mean Difference	Prob > t	Significance
R _L	1-Initial	-19.667	0.0004	different
	2-1	65.2333	0.0001	different
	3-2	0.48276	0.9445	same
Chromaticity x	1-Initial	-0.0065	0.0001	different
	2-1	0.00281	0.0001	different
	3-2	-0.0028	0.0016	same
Chromaticity y	1-Initial	-0.006	0.0001	different
	2-1	0.00274	0.0001	different
	3-2	-0.004	0.0001	different
Coverage	1-Initial	0	n/a	same
	2-1	0	n/a	same
	3-2	-4.1667	0.2313	same

4.4.3 Paint vs. Paint Analysis Between Treatment Test Decks

This section compares the waterborne paint stripe from the chemical treatment test deck against the waterborne paint stripe from the sweeper test deck. Table 12 shows the matched pair analysis results. Retroreflectance values between the two stripes were different for the first two treatments. However, after the third treatment, the retroreflectance differences were not statistically different. This might be caused by the stripe from the chemical treatment losing most of the beads at the end, causing a small

change in retroreflectance and the stripe from the sweeper treatment cresting the break-in period and thus not having much of a change. Although the differences are not statistically significant, simple observation shows that the two stripes are in very different parts of their life cycles.

Table 12: Paint Analysis Between Chemical and Sweeper Treatments

Measurement	Treatment Number	Mean Difference	Prob > t	Significance
R _L	1-Initial	115.167	0.0001	different
	2-1	74.7333	0.0001	different
	3-2	0.83333	0.7576	same
Chromaticity x	1-Initial	-0.0037	0.0283	same
	2-1	-0.0028	0.0004	different
	3-2	-0.0198	0.0001	different
Chromaticity y	1-Initial	0.0031	0.0367	same
	2-1	0.00077	0.1174	same
	3-2	-0.0199	0.0001	different
Coverage	1-Initial	0.36667	0.0697	same
	2-1	0.64887	0.0001	different
	3-2	13.5	0.0001	different

For the chromaticity measurements, the matched pair analysis showed some surprising results. After the first treatment, the change in chromaticity for each of the stripes was not statistically different. After the second treatment however, the changes in the x direction were statistically different where the changes in the y direction were not. After the third treatment, changes in both directions were statistically different between the stripes. A slow build up of chemical detergent left on the surface after washing might cause this increasing divergence for the test stripes.

For the coverage measurements, the two stripes showed significant differences in changes after the second and third treatments, but not after the first. The first chemical treatment only removed a very small amount of paint. However, the data shows that after each subsequent treatment, the chemical removed a greater amount of paint than the time before. This divergence caused the statistically different results for treatments two and three between test stripes.

4.4.4 Thermoplastic vs. Thermoplastic Analysis Between Treatment Test Decks

The matched pair analysis for the two thermoplastic test stripes as shown in Table 13 has very different results than those shown for the paint stripes. The changes between the two test stripes were all statistically significant with the two exceptions of the changes in coverage after the first and second treatments. The similarities in changes for coverage, in that they neither test stripe lost any coverage after the first or second treatment, is indicative of the nature of the material. Thermoplastic tends to fail catastrophically. Thus, the third chemical treatment almost entirely destroyed the test stripe and thus showed statistically different results from the test stripe in the sweeper treatment.

Table 13: Thermoplastic Analysis Between Chemical and Sweeper Treatments

Measurement	Treatment Number	Mean Difference	Prob > t	Significance
R _L	1-Initial	85.6667	0.0001	different
	2-1	253.625	0.0001	different
	3-2	207	0.0001	different
Chromaticity x	1-Initial	-0.0101	0.0001	different
	2-1	0.00455	0.0001	different
	3-2	-0.0236	0.0001	different
Chromaticity y	1-Initial	-0.009	0.0001	different
	2-1	0.00711	0.0001	different
	3-2	-0.0241	0.0001	different
Coverage	1-Initial	0	n/a	same
	2-1	0	n/a	same
	3-2	77.7778	0.0001	different

4.5 Conclusion

This section has presented the data obtained from the repeated measures split-plot experiment evaluating waterborne paint and thermoplastic pavement markings subjected to chemical rubber removal treatment and sweeper treatment. The researchers conducted several matched pair t-tests to determine if the mean from one sample was the same as the mean from another sample. The sample comparisons included treatment differences between waterborne paint and thermoplastic within a treatment test deck, waterborne paint differences between the two test decks, and thermoplastic differences between the two test decks. The next section evaluates the results and provides some recommendations for proper use of the materials and additional research opportunities.

Chapter 5: Conclusions

The marking materials used in this study performed as the literature suggested they would. The first two research questions presented in Chapter 1 deal with whether or not rubber removal operations or sweeping operations have a significant effect on material performance. Waterborne paint degraded quickly and no longer met the minimum requirements for retroreflectance and chromaticity after the first chemical treatment and the thermoplastic experienced catastrophic failure after the third chemical treatment. Conversely, the waterborne paint and thermoplastic strips which experienced the sweeper treatment never reached a failure point for any of the three criteria. Additionally, the two test stripes in the sweeper treatment test deck did not show any trends for any of the three measurement criteria.

The next research question presented was if either, or both, of these factors do contribute significantly, can that effect be quantified? In answer to this, the waterborne paint retroreflectance degrades at a rate of the following equation:

$$y = 26.85x^2 - 192.28x + 367.958 \text{ mcd/m}^2/\text{lux} \quad (1)$$

per chemical treatment where x is the treatment number. Thermoplastic degrades at approximately $130 \text{ mcd/m}^2/\text{lux}$ per chemical treatment. For changes in chromaticity, waterborne paint changes 0.0093 per treatment in the x direction and 0.0058 per treatment in the y direction. Thermoplastic changes follow a cubic function for both the x and y directions. The equations for chromaticity x and chromaticity y are respectively:

$$y = 0.0037x^3 - 0.0285x^2 + 0.0723x + 0.2853 \quad (2)$$

$$y = 0.0027x^3 - 0.0203x^2 + 0.051x + 0.3153 \quad (3)$$

where x is the treatment number.

The last question presented was, based on the answers to the previous questions, what then, is the most efficient pavement marking material to use on each section of an airfield? Since thermoplastic demonstrates adhesion problems and catastrophic failure resulting in FOD, the material should not be used for runways, therefore paint is the better of the two choices. However, if thermoplastic receives approval for runway use, it would be a good alternative to paint for runways.

Based on the analysis presented throughout Chapter 4, no material acted like the other material throughout even one treatment application. There were isolated occasions when materials would act similar to each other, but on the whole, no two materials reacted the same. These results validate the assumptions that a particular material will react differently under various airfield maintenance operations, and that differing materials will react differently under the same airfield operations.

Due to the limitations of this research effort, the best type of rubber removal operation for pavement marking service life needs to be addressed in future research. In addition, other airfield maintenance operations need to be considered. Other maintenance operations to research could include high pressure and ultra-high pressure water rubber removal and snow plowing.

Another key finding from the research is that a visual inspection of the pavement marking is not sufficient if we want to mandate a certain retroreflectance, color range, or

coverage. The first two measurements take specialized equipment, and the third is a painstaking slow approach and open to subjectivity. A visual inspection of retroreflectance and chromaticity does not provide an accurate assessment. Material might appear to be acceptable. But, when measured with specialized equipment, the material is well outside the acceptable range.

5.1 Key Findings

This research effort accomplished its main goal of conducting a pilot study evaluating the effects of different airfield maintenance operations on different pavement marking materials. The pilot study shows that materials behave differently from each other under the same and under different maintenance operations. Waterborne paint was shown to significantly degrade after just one chemical rubber removal treatment. This finding validates current Air Force practices of restriping after each chemical rubber removal operation. The key findings from this research are summarized as followed:

- Waterborne paint and thermoplastic demonstrate differing degradations in retroreflectivity, chromaticity, and coverage when subjected to the same treatment.
- Waterborne paint demonstrates differing degradations in retroreflectivity, chromaticity, and coverage when subjected to different treatments.
- Thermoplastic demonstrates differing degradations in retroreflectivity, chromaticity, and coverage when subjected to different treatments.
- Thermoplastic could experience catastrophic failure due to adhesion problems to the pavement surface.

- Retroreflectivity and chromaticity could be difficult to accurately measure without the use of specialized equipment.
- Additional research needs to look at additional materials and treatments in order to develop more robust asset management principles.

5.2 Future research

Future research needs to look at more pavement marking materials such as polyurea and epoxy, other bead types including Type IV large beads and highly reflective elements, other treatment types to include snowplowing and pressurized water rubber removal, as well as PCC pavement as was outlined for Experiment 2 in Chapter 3. Asset managers would then be able to use the results from these additional combinations to maximize pavement marking potential and thus save money and airfield downtime. Additional studies could look at a side by side comparison of two or more marking materials on the same runway. To gain the most benefit from these studies, the markings should be taken to failure.

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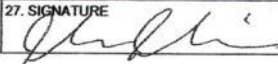
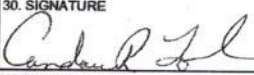
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Appendix A: Toolcat Training Certificate

REQUEST FOR DRIVER'S TRAINING AND ADDITION TO U.S. GOVERNMENT DRIVERS LICENSE					
PRIVACY ACT					
<p><i>This document contains information exempt from mandatory disclosure under the FOIA, Exemption 5 U.S.C. 522(b)(6) applies. This information is also protected by the Privacy Act of 1974 and must be safeguarded from unauthorized disclosure. Authority: E.O. 9397</i></p> <p><i>Principle Purpose: The principle purpose is to identify personnel applying for government drivers license or addition to an existing license.</i></p> <p><i>Routine Use(s): This form is used to certify vehicle operator proficiency training, familiarization training for contingency licensing, and document necessary changes to AF Form 2293 and AF Form 2296.</i></p> <p><i>DISCLOSURE IS VOLUNTARY: Disclosure of your personal information is voluntary; however, failure to disclose it may delay processing of your application.</i></p>					
SECTION I - TRAINEE INFORMATION					
1. NAME (Last, First, Middle Initial)		2. GRADE	3. EMPLOYEE # (OR&L will issue)		
Jaskowskiak, John C		O-3			
4. UNIT		5. DUTY PHONE (DSN)	6. DATE OF BIRTH		
AFIT/ENV		785-3636			
7. DAFSC	8. SEX	9. EYE COLOR	10. HAIR COLOR	11. HEIGHT	12. WEIGHT
	M			inches	lbs
13. CIVILIAN LICENSE NO.		14. STATE OF ISSUE	14a. STATE EXP. DT.	15. RESTRICTIONS	
16. TRAFFIC SAFETY COURSE DATE		17. MHE 3 YEAR CERTIFICATION DATE		18. CDL VERIFICATION/CLASS/EXP. DT.	
19. CAC EXPIRATION DATE		20. OF 345 REVIEW DATE			
21. VEHICLE(S) EQUIPMENT (Nomenclature and management code to be added.)					
D630 Bobcat Toolcat					
SECTION II - TRAINING CERTIFICATION (SELECT ONE STATEMENT ONLY)					
<input checked="" type="checkbox"/> I CERTIFY THE ABOVE TRAINEE HAS BEEN FULLY TRAINED ON THE VEHICLE(S)EQUIPMENT LISTED IN ITEM 21 USING AN APPROVED LESSON PLAN.					
<input type="checkbox"/> I CERTIFY THE ABOVE TRAINEE HAS BEEN PROVIDED FAMILIARIZATION TRAINING ON THE VEHICLE(S)EQUIPMENT LISTED IN ITEM 21 FOR "CONTINGENCY USE ONLY" OPERATION.					
22. TYPE/PRINT NAME OF TRAINER (Last, First, Middle Initial)		23. GRADE OF TRAINER	24. SIGNATURE		
Chapman, Michael L.		Contractor			
SECTION III - RECEIPT OF TRAINING STATEMENT					
I CERTIFY THAT I HAVE RECEIVED TRAINING AS INDICATED IN SECTION II AND NOW CONSIDER MYSELF TO BE QUALIFIED TO OPERATE THE VEHICLE(S)EQUIPMENT IN ITEM 21 TO THE IDENTIFIED LEVEL OF COMPETENCE.					
25. TYPE/PRINT NAME OF TRAINEE (Last, First, Middle Initial)		26. GRADE OF TRAINEE	27. SIGNATURE		
Jaskowskiak, John C		O-3			
SECTION IV - CERTIFICATION OF TRAINEE					
I CERTIFY THAT THE ABOVE TRAINEE HAS BEEN TRAINED BY A QUALIFIED TRAINER FOR VEHICLE(S)EQUIPMENT IN ITEM 21 FOR THE PURPOSE IDENTIFIED IN SECTION II.					
28. TYPE/PRINT NAME OF SQUADRON CC/CO/VCNCO (Last, First, Middle Initial)		29. GRADE OF SQUADRON CC/CO/VCNCO	30. SIGNATURE		
Fowler, Candace R.		Contractor	 DSN-523-2257		

AF FORM 171, 20110315

PREVIOUS EDITION MAY NO LONGER BE USED.

Appendix B: Chemical Rubber Removal Process

1. Pour 5 gallons of chemical from 5 gallon container into tank on back of Toolcat Bobcat. PPE includes nitrile gloves, safety glasses, and ABUs with sleeves rolled down.
2. Spray all chemical over test section which is approximately 6 feet wide by 40 feet long. This corresponds to the recommended application rate for the chemical.
3. Fill tank on Toolcat with approximately 50 gallons of water.
4. After chemical has set for 30 minutes start agitation.
5. Agitation consists of driving the Toolcat over the test section once every 10 minutes while operating the sweeping attachment, spraying water as necessary to ensure the chemical remains moist.
6. The Agitation phase lasts for 3 hours.
7. After the 3 hours, add additional water causing the chemical to foam, still sweeping in intervals of 10 minutes. Specific amount of water to be added in this stage is not set, but is done by site. Best guess is to add approximately 20 gallons of water.
8. The chemical is agitated 3 more times at intervals of 10 minutes.
9. Chemical treatment is now complete.
10. Fire department will wash the chemical foam off of the asphalt surface and into the grass in accord with approved procedures.
11. Only 1 treatment will be conducted in any given day.

Appendix C: Toolcat Set-up and Specifications

Re-pack broom with 75 convoluted steel and 19 flat polypropylene for a total of 94 wafers.

The following bristle wafer sequence will be used instead of the pattern provided from the Bobcat Manufacturer.

To maintain the intended usage and life span of the bristles, never “Bulldoze” or “Mop” with the broom. When operating properly, the broom should have a consistent “Flicking” action. When adjusted correctly, the broom should only be sweeping a continuous six inch width across the brooms length. Bristle wafers should be replaced when they no longer have a “Flicking” action (approximately three to five inches of remaining bristle length).

Start with...1 Poly (P), 7 Steel (S), 1(P), 1(S), 1(P), 7(S), 1(P), 1(S), 1(P), 7(S), 1(P),1(S), 1(P), 7(S), 1(P), 1(S), 1(P), 7(S), 1(P), 1(S), 1(P), 7(S), 1(P), 1(S), 1(P), 7(S),1(P), 1(S), 1(P), 7(S), 1(P), 1(S), 1(P), 7(S), 1(P), 4(S), 1(P)...Completed set.

Appendix D: Experiment 2 Design Layout

	PCC		ACC	
	Type I Beads	Type IV Beads	Type I Beads	Type IV Beads
Chemical Rubber Removal	Thermoplastic	<input type="text"/>	<input type="text"/>	<input type="text"/>
	Polyurea	<input type="text"/>	<input type="text"/>	<input type="text"/>
	Epoxy	<input type="text"/>	<input type="text"/>	<input type="text"/>
	Waterborne Paint	<input type="text"/>	<input type="text"/>	<input type="text"/>
Ultra High Pressure Water Rubber Removal	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
High Pressure Water Rubber Removal	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Sweeping Operations	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

Appendix E: Experiment Data

Chemical Treatment Test Deck				
Paint Retroreflectivity (mcd/m ² /lux)				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
1	128	156	56	48
2	241	130	49	41
3	228	146	61	49
4	166	133	42	39
5	163	103	38	32
6	175	98	33	35
7	215	76	33	32
8	188	82	30	27
9	212	82	34	23
10	223	73	34	24
11	210	87	36	24
12	215	75	30	21
13	183	100	30	23
14	195	83	33	29
15	208	69	30	24
16	201	49	28	24
17	198	25	24	20
18	209	32	25	20
19	223	66	28	22
20	232	83	32	31
21	201	87	35	27
22	189	98	33	27
23	209	103	32	27
24	261	86	30	24
25	233	78	23	24
26	204	79	30	22
27	189	88	33	26
28	185	82	29	25
29	196	101	31	21
30	208	130	41	26

Chemical Treatment Test Deck				
Paint Chromaticity x				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
Puck	0.3333	0.3119	0.3244	0.3346
1	0.3429	0.3495	0.3536	0.3636
2	0.3434	0.3483	0.3564	0.3606
3	0.3272	0.3491	0.3553	0.3637
4	0.3406	0.3491	0.3581	0.3624
5	0.3273	0.3499	0.3587	0.3657
6	0.342	0.3487	0.3564	0.3644
7	0.3424	0.35	0.359	0.3735
8	0.3435	0.3502	0.3577	0.3732
9	0.3428	0.3488	0.3575	0.368
10	0.3329	0.3487	0.3596	0.3674
11	0.3427	0.3485	0.3583	0.3719
12	0.3412	0.3481	0.3574	0.3728
13	0.3278	0.3495	0.3547	0.3707
14	0.3426	0.3495	0.3558	0.3681
15	0.3425	0.3511	0.3566	0.3706
16	0.3425	0.3488	0.3552	0.3695
17	0.3426	0.3515	0.3582	0.3727
18	0.3422	0.3546	0.358	0.3719
19	0.3415	0.3534	0.3555	0.3701
20	0.3418	0.3528	0.3575	0.3655
21	0.3429	0.3534	0.3578	0.3671
22	0.3428	0.3508	0.3572	0.3703
23	0.342	0.3508	0.3639	0.3724
24	0.3413	0.3512	0.3634	0.3668
25	0.3422	0.3526	0.3629	0.3685
26	0.34	0.3521	0.3613	0.3681
27	0.3392	0.3522	0.3615	0.3654
28	0.3394	0.3526	0.3606	0.3655
29	0.3385	0.3514	0.3602	0.3692
30	0.3384	0.3491	0.3607	0.3671

Chemical Treatment Test Deck				
Paint Chromaticity y				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
Puck	0.3447	0.3316	0.3363	0.3457
1	0.3568	0.3578	0.3611	0.37
2	0.3575	0.3576	0.3635	0.3679
3	0.3434	0.3584	0.3635	0.3703
4	0.3552	0.3584	0.365	0.3692
5	0.3434	0.3587	0.3656	0.3713
6	0.3565	0.358	0.3641	0.3702
7	0.3566	0.3583	0.366	0.3756
8	0.3576	0.3585	0.3647	0.375
9	0.3571	0.3578	0.3645	0.3726
10	0.3483	0.3579	0.3655	0.3726
11	0.3568	0.3577	0.3648	0.3742
12	0.3556	0.3577	0.3644	0.375
13	0.3441	0.3584	0.3624	0.374
14	0.3566	0.3584	0.3631	0.3726
15	0.3568	0.3593	0.3634	0.3738
16	0.3564	0.3581	0.3627	0.3733
17	0.3572	0.3604	0.3646	0.3748
18	0.3567	0.362	0.3644	0.3747
19	0.3557	0.3606	0.3628	0.3732
20	0.3563	0.3602	0.3638	0.3703
21	0.3573	0.3601	0.3638	0.3714
22	0.3571	0.3587	0.3637	0.3735
23	0.3566	0.3586	0.3639	0.3745
24	0.3559	0.3587	0.3634	0.3712
25	0.357	0.3597	0.3629	0.3719
26	0.3544	0.3591	0.3613	0.3722
27	0.3536	0.3591	0.3615	0.3706
28	0.3539	0.359	0.3606	0.3711
29	0.353	0.3586	0.3602	0.373
30	0.3527	0.3569	0.3607	0.3716

Chemical Treatment Test Deck				
Paint Coverage %				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
1	100	100	100	99
2	100	100	98	94
3	100	100	96	88
4	100	100	96	66
5	100	100	97	76
6	100	99	99	85
7	100	100	96	74
8	100	100	96	74
9	100	100	97	80
10	100	100	92	88
11	100	100	88	76
12	100	100	96	82
13	100	100	98	87
14	100	100	96	92
15	100	99	97	72
16	100	95	94	65
17	100	97	95	61
18	100	100	94	71
19	100	100	94	88
20	100	100	96	82
21	100	100	92	81
22	100	100	98	87
23	100	100	91	82
24	100	99	94	81
25	100	100	85	75
26	100	100	95	82
27	100	100	88	83
28	100	100	96	88
29	100	100	97	90
30	100	100	97	94

Chemical Treatment Test Deck				
Thermoplastic Retroreflectivity (mcd/m ² /lux)				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
1	454	255	167	117
2	424	334	171	106
3	485	358	181	146
4	408	333	162	
5	480	347	184	
6	456	400	216	
7	461	390	219	
8	453	399	227	
9	459	427	213	
10	440	408	206	
11	457	424	211	
12	543	461	244	
13	517	445	225	
14	538	425	238	
15	464	406	220	
16	483	419	246	
17	572	425	245	
18	616	437	288	
19	550	471	313	
20	519	421	279	
21	536	397	273	
22	555	405	241	
23	582	376	291	
24	510	343	228	

Chemical Treatment Test Deck				
Thermoplastic Chromaticity x				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
Puck	0.3295	0.3196	0.3207	0.3332
1	0.3331	0.346	0.3485	0.3697
2	0.3332	0.3407	0.3484	0.3645
3	0.3332	0.3384	0.3487	0.363
4	0.3322	0.3434	0.3471	0.3581
5	0.333	0.3433	0.347	0.3583
6	0.3326	0.344	0.347	0.3501
7	0.3337	0.3478	0.3473	0.3546
8	0.3338	0.3458	0.3472	0.3537
9	0.3329	0.3417	0.3463	0.3632
10	0.3336	0.3421	0.3465	0.3555
11	0.3333	0.3439	0.3477	0.3541
12	0.3331	0.3426	0.3471	0.3487
13	0.3328	0.3469	0.3464	0.35
14	0.3321	0.3448	0.347	0.3458
15	0.3329	0.3429	0.3467	0.3534
16	0.3312	0.3479	0.3443	0.3575
17	0.3318	0.3471	0.3435	0.3537
18	0.3329	0.3484	0.3441	0.3549
19	0.3331	0.3467	0.3447	0.3652
20	0.333	0.3519	0.3457	0.3584
21	0.3328	0.3482	0.345	0.3639
22	0.3324	0.3464	0.3451	0.3504
23	0.3317	0.3534	0.3449	0.3683
24	0.3325	0.3524	0.3488	0.3661

Chemical Treatment Test Deck				
Thermoplastic Chromaticity y				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
Puck	0.3408	0.3314	0.3324	0.3441
1	0.3489	0.3577	0.3608	0.3737
2	0.349	0.3543	0.3603	0.3717
3	0.3484	0.3522	0.3603	0.3712
4	0.3482	0.3567	0.3595	0.3682
5	0.3487	0.356	0.3593	0.3683
6	0.3489	0.3572	0.3596	0.3632
7	0.3495	0.3592	0.3594	0.3659
8	0.3498	0.358	0.3591	0.3654
9	0.3489	0.3553	0.3591	0.3721
10	0.3492	0.3556	0.3593	0.3682
11	0.3488	0.3564	0.3598	0.3672
12	0.3487	0.3557	0.3594	0.3616
13	0.3489	0.3585	0.3586	0.3631
14	0.3484	0.3574	0.3585	0.3595
15	0.3487	0.3555	0.3586	0.3652
16	0.3472	0.3592	0.3569	0.3694
17	0.3478	0.3589	0.3564	0.3659
18	0.3487	0.3591	0.3567	0.3664
19	0.3486	0.3581	0.3569	0.3725
20	0.3485	0.3611	0.3576	0.3683
21	0.3491	0.3591	0.3564	0.371
22	0.3486	0.3585	0.3571	0.3631
23	0.348	0.3623	0.3573	0.3735
24	0.348	0.3617	0.3596	0.3726

Chemical Treatment Test Deck				
Thermoplastic Coverage %				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
1	100	100	100	100
2	100	100	100	100
3	100	100	100	100
4	100	100	100	0
5	100	100	100	0
6	100	100	100	0
7	100	100	100	0
8	100	100	100	0
9	100	100	100	0
10	100	100	100	0
11	100	100	100	0
12	100	100	100	0
13	100	100	100	0
14	100	100	100	0
15	100	100	100	0
16	100	100	100	0
17	100	100	100	0
18	100	100	100	0
19	100	100	100	0
20	100	100	100	0
21	100	100	100	0
22	100	100	100	0
23	100	100	100	0
24	100	100	100	0

Sweeper Treatment Test Deck				
Paint Retroreflectivity (mcd/m2/lux)				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
1	101	179	192	202
2	190	195	214	216
3	180	170	191	180
4	182	194	213	200
5	200	200	229	221
6	215	211	232	223
7	215	207	210	230
8	202	207	223	219
9	203	194	210	209
10	198	199	217	215
11	218	216	238	232
12	217	202	232	221
13	211	206	227	224
14	212	202	226	230
15	207	212	228	217
16	230	235	253	214
17	207	202	218	220
18	220	223	240	245
19	211	220	231	226
20	228	234	297	242
21	219	216	238	241
22	217	212	236	228
23	230	229	243	248
24	206	201	213	217
25	214	223	233	224
26	203	198	216	209
27	210	203	221	218
28	204	211	227	229
29	220	217	232	231
30	225	224	247	235

Sweeper Treatment Test Deck				
Paint Chromaticity x				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
Puck	0.3294	0.3252	0.3313	0.3175
1	0.3337	0.3358	0.3471	0.3311
2	0.3275	0.3346	0.3414	0.331
3	0.3332	0.3349	0.3429	0.3299
4	0.3357	0.336	0.3415	0.3305
5	0.3281	0.3354	0.3454	0.3312
6	0.3346	0.3354	0.3411	0.3307
7	0.3252	0.3356	0.3427	0.3303
8	0.3238	0.3359	0.3429	0.3322
9	0.3339	0.3367	0.3439	0.3322
10	0.3375	0.3366	0.3428	0.3322
11	0.3358	0.3366	0.3438	0.3314
12	0.3321	0.3352	0.3406	0.3312
13	0.3199	0.3369	0.3428	0.3316
14	0.3183	0.3366	0.3409	0.3317
15	0.3343	0.3366	0.338	0.3313
16	0.3351	0.3368	0.3338	0.3315
17	0.3357	0.3385	0.3415	0.3324
18	0.3371	0.3384	0.3419	0.333
19	0.3376	0.3388	0.3441	0.3338
20	0.3275	0.3397	0.343	0.3354
21	0.3476	0.3388	0.344	0.3351
22	0.3317	0.3387	0.3425	0.3344
23	0.3239	0.339	0.3429	0.3339
24	0.3224	0.3403	0.3438	0.335
25	0.3184	0.3387	0.3425	0.3339
26	0.3194	0.3392	0.3414	0.333
27	0.3183	0.3378	0.3411	0.3324
28	0.3271	0.3392	0.343	0.3336
29	0.3382	0.3376	0.3431	0.3331
30	0.3365	0.3374	0.3413	0.3322

Sweeper Treatment Test Deck				
Paint Chromaticity y				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
Puck	0.3407	0.3371	0.3433	0.3288
1	0.3473	0.3499	0.3624	0.3445
2	0.3422	0.349	0.3561	0.3447
3	0.3471	0.3491	0.3577	0.3436
4	0.35	0.3507	0.3566	0.3445
5	0.344	0.3501	0.3602	0.3451
6	0.349	0.3501	0.3562	0.3446
7	0.3408	0.3501	0.3576	0.3444
8	0.3394	0.3508	0.358	0.3463
9	0.3484	0.3512	0.3584	0.3462
10	0.3516	0.3514	0.3574	0.3462
11	0.3505	0.3514	0.3586	0.3455
12	0.3468	0.3498	0.356	0.3452
13	0.3352	0.3514	0.3578	0.3455
14	0.3346	0.3513	0.356	0.3458
15	0.3489	0.3513	0.3532	0.3454
16	0.3491	0.3513	0.3492	0.3455
17	0.35	0.3532	0.3569	0.3466
18	0.3518	0.3534	0.3572	0.3473
19	0.3521	0.3535	0.3589	0.3481
20	0.3436	0.3548	0.3585	0.3499
21	0.3401	0.354	0.3597	0.3495
22	0.3471	0.3535	0.3578	0.3487
23	0.34	0.3534	0.3585	0.3481
24	0.3384	0.355	0.3589	0.3491
25	0.3343	0.3534	0.3574	0.348
26	0.3356	0.3536	0.3557	0.3472
27	0.3343	0.3524	0.3564	0.3465
28	0.3428	0.3539	0.3581	0.3477
29	0.3524	0.3526	0.3584	0.3474
30	0.3508	0.3521	0.3561	0.3464

Sweeper Treatment Test Deck				
Paint Coverage %				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
1	100	100	100	100
2	100	100	100	100
3	100	100	100	100
4	100	100	100	100
5	100	100	100	100
6	100	100	100	100
7	100	100	100	100
8	100	100	100	100
9	100	100	100	100
10	100	100	100	100
11	100	100	100	100
12	100	100	100	100
13	100	100	100	100
14	100	100	100	100
15	100	100	100	100
16	100	100	100	100
17	100	100	100	100
18	100	100	100	100
19	100	100	100	100
20	100	100	100	100
21	100	100	100	100
22	100	100	100	100
23	100	100	100	100
24	100	100	100	100
25	100	100	100	100
26	100	100	100	100
27	100	100	100	100
28	100	100	100	100
29	100	100	100	100
30	100	100	100	100

Sweeper Treatment Test Deck				
Thermoplastic Retroreflectivity (mcd/m ² /lux)				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
1	363	522	650	662
2	611	623	677	628
3	673	635	688	757
4	646	645	703	691
5	679	703	758	760
6	562	479	580	635
7	715	707	825	838
8	646	608	710	595
9	710	676	779	778
10	694	710	798	779
11	668	668	770	735
12	655	613	688	702
13	574	537	609	621
14	637	612	682	699
15	635	595	675	667
16	504	474	592	585
17	674	638	725	718
18	664	648	766	723
19	543	535	602	585
20	610	583	666	676
21	616	571	673	648
22	626	590	681	675
23	565	548	612	624
24	569	519	599	576
25	622	625	701	689
26	588	548	624	618
27	627	570	687	690
28	589	589	698	695
29	624	585	633	667
30	643	633	680	

Sweeper Treatment Test Deck				
Thermoplastic Chromaticity x				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
Puck	0.3305	0.326	0.3305	0.3183
1	0.3331	0.3311	0.3399	0.3251
2	0.333	0.3298	0.3347	0.324
3	0.3316	0.3286	0.336	0.3234
4	0.3323	0.3296	0.3351	0.3228
5	0.3318	0.3289	0.3381	0.3248
6	0.3316	0.3294	0.3347	0.324
7	0.3311	0.3281	0.3365	0.3236
8	0.332	0.3309	0.3384	0.3258
9	0.3306	0.3278	0.3352	0.323
10	0.329	0.3271	0.3333	0.3218
11	0.331	0.3286	0.3379	0.3243
12	0.3304	0.3287	0.3356	0.3233
13	0.341	0.3292	0.3386	0.3245
14	0.3312	0.3291	0.3355	0.3222
15	0.3312	0.3283	0.3378	0.323
16	0.3313	0.33	0.3377	0.3249
17	0.3322	0.329	0.3376	0.3216
18	0.3309	0.3297	0.3374	0.3246
19	0.3314	0.3282	0.3365	0.3395
20	0.3316	0.3296	0.3372	0.3234
21	0.3229	0.3282	0.3368	0.3219
22	0.3212	0.3289	0.3352	0.3219
23	0.3205	0.3282	0.3383	0.3225
24	0.3209	0.3296	0.3374	0.3241
25	0.3207	0.3295	0.3346	0.3242
26	0.3209	0.3281	0.3346	0.3228
27	0.3225	0.3286	0.3398	0.3232
28	0.3215	0.3281	0.3347	0.3214
29	0.3224	0.3282	0.3377	0.3232
30	0.3227	0.3287	0.3394	

Sweeper Treatment Test Deck				
Thermoplastic Chromaticity y				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
Puck	0.3419	0.338	0.3427	0.3295
1	0.3488	0.3474	0.3586	0.3407
2	0.3483	0.3459	0.3515	0.3395
3	0.3475	0.3452	0.3528	0.3392
4	0.3471	0.3457	0.3515	0.3384
5	0.3476	0.3448	0.3542	0.3406
6	0.3473	0.3458	0.351	0.3397
7	0.3464	0.3444	0.3538	0.3395
8	0.3474	0.3474	0.3548	0.3417
9	0.3467	0.3442	0.3527	0.3391
10	0.3453	0.3439	0.3507	0.3379
11	0.3462	0.3447	0.354	0.3396
12	0.346	0.3451	0.3524	0.3389
13	0.3469	0.3455	0.355	0.3402
14	0.3468	0.3451	0.3516	0.3375
15	0.3463	0.3446	0.3547	0.3385
16	0.3467	0.3466	0.3545	0.3408
17	0.3477	0.3458	0.3545	0.3375
18	0.3466	0.3466	0.3543	0.3404
19	0.3469	0.3445	0.3534	0.3239
20	0.3469	0.3457	0.3532	0.3387
21	0.3393	0.3446	0.3532	0.3372
22	0.3373	0.345	0.3514	0.337
23	0.3368	0.3445	0.3548	0.3379
24	0.3375	0.3464	0.3543	0.34
25	0.3379	0.3465	0.3517	0.3401
26	0.3372	0.3445	0.3515	0.3382
27	0.339	0.3449	0.3564	0.3387
28	0.3379	0.3447	0.3514	0.3366
29	0.3385	0.3445	0.3543	0.3385
30	0.3391	0.3453	0.3559	

Sweeper Treatment Test Deck				
Thermoplastic Coverage %				
Sample	Initial	Treatment 1	Treatment 2	Treatment 3
1	100	100	100	100
2	100	100	100	100
3	100	100	100	100
4	100	100	100	100
5	100	100	100	100
6	100	100	100	100
7	100	100	100	100
8	100	100	100	100
9	100	100	100	100
10	100	100	100	100
11	100	100	100	100
12	100	100	100	100
13	100	100	100	100
14	100	100	100	100
15	100	100	100	100
16	100	100	100	100
17	100	100	100	100
18	100	100	100	100
19	100	100	100	100
20	100	100	100	100
21	100	100	100	100
22	100	100	100	100
23	100	100	100	100
24	100	100	100	100
25	100	100	100	100
26	100	100	100	100
27	100	100	100	100
28	100	100	100	100
29	100	100	100	75
30	100	100	100	

Appendix F: t-statistic Test Results

Treatment Test Deck	Material	Measurement	Treatment Number	Mean Difference	Prob > t	Significance
Chemical Treatment Test Deck	Paint vs. Thermoplastic	R _L	Initial-Initial	295.375	0.0001	different
		Chromaticity x	Initial-Initial	-0.0073	0.0001	different
		Chromaticity y	Initial-Initial	-0.006	0.0001	different
		Coverage	Initial-Initial	0	n/a	same
Sweeping Treatment Test Deck	Paint vs. Thermoplastic	R _L	Initial-Initial	411.233	0.0001	different
		Chromaticity x	Initial-Initial	-0.0019	0.2478	same
		Chromaticity y	Initial-Initial	-0.0006	0.5878	same
		Coverage	Initial-Initial	0	n/a	same
Chemical Treatment Test Deck vs Sweeping Treatment Test Deck	Paint vs. Paint	R _L	Initial-Initial	3.56667	0.4434	same
		Chromaticity x	Initial-Initial	-0.0096	0.0001	different
		Chromaticity y	Initial-Initial	-0.0099	0.0001	different
		Coverage	Initial-Initial	0	n/a	same
Chemical Treatment Test Deck vs Sweeping Treatment Test Deck	Thermoplastic vs. Thermoplastic	R _L	Initial-Initial	119.875	0.0001	different
		Chromaticity x	Initial-Initial	-0.0026	0.0079	same
		Chromaticity y	Initial-Initial	-0.0032	0.0002	different
		Coverage	Initial-Initial	0	n/a	same

Treatment Test Deck	Material	Measurement	Treatment Number	Mean Difference	Prob > t	Significance
Chemical Treatment Test Deck	Paint	R _L	1-Initial	-113.6	0.0001	different
			2-1	-55.233	0.0001	different
			3-2	-6.2	0.0001	different
		Chromaticity x	1-Initial	0.01057	0.0001	different
			2-1	0.00776	0.0001	different
			3-2	0.00992	0.0001	different
		Chromaticity y	1-Initial	0.00422	0.0001	different
			2-1	0.00464	0.0001	different
			3-2	0.00899	0.0001	different
		Coverage	1-Initial	-0.3667	0.0697	same
			2-1	-4.7	0.0001	different
			3-2	-13.5	0.0001	different
Chemical Treatment Test Deck	Thermoplastic	R _L	1-Initial	-102.33	0.0001	different
			2-1	-167.42	0.0001	different
			3-2	-50	0.0287	same
		Chromaticity x	1-Initial	0.01291	0.0001	different
			2-1	0.00076	0.4195	same
			3-2	0.01109	0.0001	different
		Chromaticity y	1-Initial	0.00901	0.0001	different
			2-1	0.00095	0.1708	same
			3-2	0.0092	0.0001	different
		Coverage	1-Initial	0	n/a	same
			2-1	0	n/a	same
			3-2	-87.5	0.0001	different

Treatment Test Deck	Material	Measurement	Treatment Number	Mean Difference	Prob > t	Significance
Sweeping Treatment Test Deck	Paint	R _L	1-Initial	1.56667	0.5926	same
			2-1	19.5	0.0001	different
			3-2	-5.3667	0.0397	same
		Chromaticity x	1-Initial	0.00692	0.0001	different
			2-1	0.005	0.0001	different
			3-2	-0.0099	0.0001	different
		Chromaticity y	1-Initial	0.00732	0.0001	different
			2-1	0.00541	0.0001	different
			3-2	-0.0109	0.0001	different
		Coverage	1-Initial	0	n/a	same
			2-1	0	n/a	same
			3-2	0	n/a	same
Sweeping Treatment Test Deck	Thermoplastic	R _L	1-Initial	-18.1	0.022	same
			2-1	84.7333	0.0001	different
			3-2	-4.6552	0.4542	same
		Chromaticity x	1-Initial	0.00044	0.6366	same
			2-1	0.00781	0.0001	different
			3-2	-0.0127	0.0001	different
		Chromaticity y	1-Initial	0.00133	0.0943	same
			2-1	0.00814	0.0001	different
			3-2	-0.0149	0.0001	different
		Coverage	1-Initial	0	n/a	same
			2-1	0	n/a	same
			3-2	-4.1667	0.2313	same

Treatment Test Deck	Material	Measurement	Treatment Number	Mean Difference	Prob > t	Significance
Chemical Treatment Test Deck	Paint vs Thermoplastic Differences	R _L	1-Initial	12.2917	0.4452	same
			2-1	-113.83	0.0001	different
			3-2	-207.33	0.0001	different
		Chromaticity x	1-Initial	0.0027	0.0721	same
			2-1	-0.0066	0.0001	different
			3-2	0.0021	0.9104	same
		Chromaticity y	1-Initial	0.00489	0.0004	different
			2-1	-0.0042	0.0001	different
			3-2	0.00059	0.5578	same
		Coverage	1-Initial	0.36667	0.0697	same
			2-1	4.7	0.0001	different
			3-2	-63.444	0.0001	different
Sweeping Treatment Test Deck	Paint vs Thermoplastic Differences	R _L	1-Initial	-19.667	0.0004	different
			2-1	65.2333	0.0001	different
			3-2	0.48276	0.9445	same
		Chromaticity x	1-Initial	-0.0065	0.0001	different
			2-1	0.00281	0.0001	different
			3-2	-0.0028	0.0016	same
		Chromaticity y	1-Initial	-0.006	0.0001	different
			2-1	0.00274	0.0001	different
			3-2	-0.004	0.0001	different
		Coverage	1-Initial	0	n/a	same
			2-1	0	n/a	same
			3-2	-4.1667	0.2313	same

Treatment Test Deck	Material	Measurement	Treatment Number	Mean Difference	Prob > t	Significance
Chemical Treatment Test Deck vs Sweeping Treatment Test Deck	Paint vs Paint Differences	R _L	1-Initial	115.167	0.0001	different
			2-1	74.7333	0.0001	different
			3-2	0.83333	0.7576	same
		Chromaticity x	1-Initial	-0.0037	0.0283	same
			2-1	-0.0028	0.0004	different
			3-2	-0.0198	0.0001	different
		Chromaticity y	1-Initial	0.0031	0.0367	same
			2-1	0.00077	0.1174	same
			3-2	-0.0199	0.0001	different
		Coverage	1-Initial	0.36667	0.0697	same
			2-1	0.64887	0.0001	different
			3-2	13.5	0.0001	different
Chemical Treatment Test Deck vs Sweeping Treatment Test Deck	Thermoplastic vs Thermoplastic Differences	R _L	1-Initial	85.6667	0.0001	different
			2-1	253.625	0.0001	different
			3-2	207	0.0001	different
		Chromaticity x	1-Initial	-0.0101	0.0001	different
			2-1	0.00455	0.0001	different
			3-2	-0.0236	0.0001	different
		Chromaticity y	1-Initial	-0.009	0.0001	different
			2-1	0.00711	0.0001	different
			3-2	-0.0241	0.0001	different
		Coverage	1-Initial	0	n/a	same
			2-1	0	n/a	same
			3-2	77.7778	0.0001	different

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14. ABSTRACT Pavement markings are an essential element in the navigational aids subsystem for any airfield. Most airfields still use waterborne paint as the primary marking material. However, several other materials are in use on roadways which asset managers could incorporate, providing more cost and time effective practices. An airfield experiences a host of maintenance operations which cause degradation of the pavement markings. Of particular concern are rubber removal operations, sweeping operations, and snowplowing operations. This research focuses on chemical rubber removal operations and sweeping operations. This study evaluates waterborne paint and thermoplastic markings to determine if marking materials perform differently from each other, and if maintenance operations cause different degradation rates among the same material. Evaluation criteria include retroreflectance, chromaticity, and coverage. The two materials experience different degradation characteristics under both treatments. Waterborne paint failed retroreflectance and chromaticity measurements after the first chemical rubber removal treatment. Thermoplastic failed chromaticity and coverage measurements after the third chemical rubber removal treatment. Neither material showed any appreciable amount of degradation in any of the three performance measurements when subjected to sweeping operations.					
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