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Optimization of Pavement Marking Performance

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Optimization of Pavement Marking Performance

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Disclaimer

ABSTRACT

An experimental research study was conducted to evaluate the constructability, durability, and visibility of alternative pavement marking materials and application practices in South Dakota and to assess the cost-effectiveness of pavement marking alternatives for use on concrete and asphalt pavements.
The research was performed on seven pavement marking test sections on highways in different regions of South Dakota. The test sections were designed to represent different pavement marking material combinations and winter maintenance conditions. The parameters considered in this study were paint type (waterborne and epoxy), paint thickness (15, 17, 20, and 25 mils), paint color (white and yellow), reflective elements (glass beads and wet reflective elements), line type (edge line and skip line), pavement type (asphalt concrete and Portland cement concrete), pavement surface preparation (surface and inlaid applications), and winter maintenance region (wet freeze and dry freeze). The collected data included: 1) paint thickness measurements, 2) retroreflectivity of the pavement marking at different ages and under dry and wet conditions, and 3) visual rating of the pavement marking.

Data analysis included: 1) curve fitting of measured retroreflectivity with time, 2) investigation of the relationship between retroreflectivity and visual rating, 3) effect of the different parameters on retroreflectivity longevity, and 4) cost effectiveness of the different pavement marking alternatives. An interactive spreadsheet was developed to compare the unit costs of different pavement marking alternatives.

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State and Highway Transportation Officials
AC	Asphalt Concrete
ASTM	American Society for Testing Materials
DOT	Department of Transportation
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GSA	General Services Agency
LTTP	Long Term Technology Plan
MMA	Methyl Methacrylate
MRM	Mile Road Marker
MUTCD	Manual on Uniform Traffic Control Devices
NTPEP	National Transportation Product Evaluation Program
Ohio DOT	Ohio Department of Transportation
PCC	Portland Cement Concrete
QA	Quality Assurance
QC	Quality Control
RRPM	Reflective Raised Pavement Markers
SD	South Dakota
SDCL	South Dakota Codified Law
SDDOT	South Dakota Department of Transportation
TxDOT	Texas Department of Transportation
US	United States
VOC	Volatile Organic Compound
WEL	White Edge Line
WRE	Wet Reflective Elements
WSL	White Skip Line
YEL	Yellow Edge Line
YSL	Yellow Skip Line

EXECUTIVE SUMMARY

This report is part of SDDOT Research Project SD2008-05, "Optimization of Pavement Marking Performance." The objectives of this research were to: 1) evaluate the constructability, durability, and visibility of alternative pavement marking materials and application practices to standard waterborne paint on asphalt pavement surfaces, in consideration of SDDOT's pavement construction and maintenance practices, 2) compare the constructability, durability, and visibility of alternative pavement marking materials to epoxy materials in inlaid applications to concrete pavements, and 3) assess the cost-effectiveness of pavement marking alternatives for use on concrete and asphalt pavements.

The research covered in this report includes experimental studies of seven pavement marking test sections on highways in different regions of South Dakota. The test sections were designed to represent different pavement marking material combinations and winter maintenance conditions. The parameters considered in this study were the following: paint type (waterborne and epoxy), paint thickness (15, 17, 20, and 25 mils), paint color (white and yellow), reflective elements (glass beads and wet reflective elements), line type (edge line and skip line), pavement type (asphalt concrete and Portland cement concrete), pavement surface preparation (surface and inlaid applications), and winter maintenance region (wet freeze and dry freeze).

The collected data included: 1) paint thickness measurements, 2) retroreflectivity of the pavement marking at different ages and under dry and wet conditions, and 3) visual rating of the pavement marking. Data analysis included: 1) curve fitting of measured retroreflectivity with time, 2) investigation of the relationship between retroreflectivity and visual rating, 3) effect of the different parameters on retroreflectivity longevity, and 4) cost effectiveness of the different pavement marking alternatives. An interactive spreadsheet was developed to compare the unit costs of different pavement marking alternatives.

Based on the experimental and analytical work performed in this study, the following conclusions were made.

- Visual Rating may be used for casual qualitative inspection but is not adequate for assessing night time visibility.
- The back-calculated wet paint thickness was not in agreement with the specified paint thickness. The majority of the back-calculated values from the plate samples were less than the specified paint thickness.
- The decay rates of Type II and Type III paints were practically similar. Type II paints are used under adverse conditions, i.e., night striping, higher humidity (around 80%), low air movement, and lower surface temperatures, down to 10°C (50°F). Type III paints are used under normal weather conditions where higher durability and greater adhesion to glass beads is desired (General Services Administration, 2007).
- The initial retroreflectivity of yellow paint was consistently lower than that of white paint and, in most cases, was less than 200 mcd/m^2/lux.
- The retroreflectivity of yellow paint normally deteriorated in less than one year.
- Changing the specified paint thickness (15, 17, 20 mils) of waterborne paint resulted in marginal change in initial retroreflectivity and decay rate.
- The retroreflectivity of M247 in waterborne paint was, in most cases, higher than that of P40, but did not result in practically better life expectancy because the P40 has a lower decay rate than

M247 and eventually, after about a year, the retroreflectivity of M247 became lower than that of P40.

- The retroreflectivity of M247 in waterborne paint was equal to or marginally higher than that of Iowa Blend, but the decay rates of the two elements were practically identical.
- Changing the reflective elements in epoxy paint resulted in noticeable change in initial retroreflectivity (Megablend > Iowa Blend > Megablend + M247 > M247). However, the life expectancies were practically identical.
- The performance of surface-applied waterborne paint with M247 on AC was almost identical to that on PCC.
- The retroreflectivity deterioration rate of waterborne paint in wet freeze regions was, in general, higher than that in dry freeze regions.
- The retroreflectivity deterioration rate of inlaid epoxy paint was in general less than that of surface-applied epoxy paint.
- The addition of wet reflective elements (WRE) in both waterborne and epoxy paints may initially result in marginal benefit to wet retroreflectivity. However, the wet retroreflectivity deteriorates at a high rate (one year or less).

Based on the results of this study, the following recommendations are made:

- The SDDOT should develop a more robust quality control procedure for evaluating the actual pavement markings thickness and application rates of reflective elements.
- The SDDOT maintenance regions should implement full-term evaluation studies on pavement marking degradation in their respective regions. The collected data can be used to update the decay models in the cost comparison spreadsheet.
- The cost comparison spreadsheet developed in this study, combined with other factors such as the construction season time window and material availability, can be used to aid in selecting the optimum pavement marking.

1. INTRODUCTION

1.1 Problem Statement

Pavement markings encompass lane striping, raised lane markers, and painted symbols and messages. Pavement markings help channel and guide traffic flow in an orderly and safe stream, and provide an important role in traffic separation when it is necessary to identify distinct lanes or crossings. Markings must provide adequate visibility and reflectivity on all pavement surfaces, in all weather conditions, day and night, and in all seasons. As pavement markings deteriorate over time, roadway safety is compromised and costly replacement becomes necessary. The ideal pavement marking would provide retroreflectivity in all weather conditions and be durable enough to survive several years before replacement is warranted.

Pavement markings are applied using a variety of materials, including various types of paints, thermoplastics, reflective tapes, and raised markers. The performance of pavement markings is judged mainly by their (1) visibility in daytime and nighttime, under various weather conditions, and against the background color and texture of the pavement itself; (2) durability to withstand damage resulting from traffic, weather, and actions such as snow plowing and pavement maintenance; and (3) skid resistance and avoidance of impediments to any form of traffic, including cyclists and pedestrians.

In cold regions where highways are normally subjected to frequent snow plowing and winter maintenance procedures, the use of reflective raised pavement markers (RRPMs) is neither practical nor feasible. Therefore, dry and wet retroreflectivity is achieved through the use of reflective elements (beads) and wet reflective elements (WREs). The current pavement marking for asphalt concrete (AC) pavements, which constitute the majority of South Dakota's highway network, is waterborne paint applied directly to the roadway surface. Waterborne paint typically requires repainting of the centerline every year and the shoulder line every year or two, depending on snowplow damage. Winter road maintenance can have a major effect on markings on concrete pavements. To avoid plow blade damage to markings applied on the roadway surface, markings are inlaid into the pavement. Epoxy materials and preformed tape are typically used in inlaid applications, but other less expensive alternatives may be feasible if their period of performance warrants their substitution. Surface preparation, such as diamond grinding or carbide milling, may be a major consideration in determining the longevity of inlaid pavement markings.

The South Dakota Department of Transportation's (SDDOT) biennial customer satisfaction assessments consistently show that travelers consider pavement markings that are clearly visible both day and night and in adverse weather conditions as a highly important safety issue. At the same time, the cost of marking materials is rapidly increasing, making recognition and use of the most effective and cost-effective marking materials and application methods extremely important. Since there had been a lack of data on the performance of pavement markings in South Dakota, research on pavement marking material, retroreflectivity, and durability was needed in order to improve the procedure of marking material selection, placement, and evaluation. There was also a need for basic information on the performance of pavement markings under many different environments, degrees of snowplowing and winter maintenance, types of pavement, and types of pavement preparation.

The study covered in this report was designed to address research needs and to generate field data on the performance of different pavement markings types. The collected data were used to develop retroreflectivity decay models and to compare the cost effectiveness of the different pavement marking options.

1.2 Objectives

Three main objectives were addressed in this study. Following is a description of those objectives.

- Evaluate the constructability, durability, and visibility of alternative pavement marking materials and application practices to standard waterborne paint on asphalt pavement surfaces in consideration of SDDOT's pavement construction and maintenance practices. The work was initiated with a thorough search of the available literature in the area of pavement marking materials and the material and methods used in the State of South Dakota. With the consent of SDDOT and the technical panel, different marking materials and application techniques were selected for inclusion in the study. Test sections representing the selected different pavement marking combinations were constructed in different geographic locations in South Dakota. The research team collected data on the durability and visibility of the pavement marking applied in the test sections.
- Compare the constructability, durability, and visibility of alternative pavement marking materials to epoxy materials in inlaid applications to concrete pavements. The collected data were analyzed in order to determine the performance of different combinations of waterborne and epoxy pavement marking materials, paint thicknesses, retroreflective elements, wet reflective elements, winter maintenance conditions, and other parameters. Based on the collected data, decay models were developed to represent the different pavement marking combinations. The performance of the different pavement marking combinations was assessed and compared.
- Assess the cost effectiveness of pavement marking alternatives for use on concrete and asphalt pavements. Unit costs for the material and installation of the pavement marking types included in this study were obtained from SDDOT. Based on the unit costs and the decay models, a spreadsheet was developed to determine and compare the cost effectiveness of the different pavement marking types.

1.3 Scope

As part of this research project, SDDOT constructed seven pavement marking test sections on highways in different regions of South Dakota. The test sections were designed to represent different pavement marking material combinations and winter maintenance conditions. The parameters considered in this study were paint type (waterborne and epoxy), paint thickness (15, 17, 20, and 25 mils), paint color (white and yellow), reflective elements (glass beads and wet reflective elements), line type (edge line and skip line), pavement type (asphalt concrete and Portland cement concrete), pavement surface preparation (surface and inlaid applications), and winter maintenance region (wet freeze and dry freeze).

The collected data included: 1) paint thickness measurements, 2) retroreflectivity of the pavement marking at different ages and under dry and wet conditions, and 3) visual rating of the pavement marking. Data analysis included: 1) curve fitting of measured retroreflectivity with time, 2) investigation of the relationship between retroreflectivity and visual rating, 3) effect of the different parameters on retroreflectivity longevity, and 4) cost effectiveness of the different pavement marking alternatives.

2. LITERATURE REVIEW

2.1 Introduction

This section presents a review of the literature relevant to the pavement markings used on the highway system in South Dakota. The review covers topics related to pavement marking materials, typical methods of evaluation of pavement markings, correlations between performance of pavement markings and safety, and typical degradation trends of the materials used in South Dakota.

2.2 Pavement Marking Materials

A pavement marking material typically consists of two basic components: binder (glue) and reflective elements. The binder, which normally contains the color pigment that provides the desired marking color, is the matrix that holds the reflective elements on the pavement marking. Reflective elements are normally glass beads, which when embedded in the binder provide reflectivity during nighttime driving conditions. Wet reflective elements (WREs) are sometimes added to provide reflectivity during wet pavement surface conditions.

2.2.1 Pavement Marking Paint

There are many types of binding materials available from a number of vendors. The pavement marking materials can be classified as either conventional traffic paint or durable pavement marking.

Conventional paints include solvent and water-based paints. Durable pavement markings encompass a wide array of, material including epoxy, thermoplastic, preformed tapes, polyurea, modified urethane, and methyl methacrylate (MMA). A pavement marking is often referred to by the type of its binding material. Due to cost considerations and winter weather and maintenance conditions that inflict significant adverse effects on certain pavement marking types, SDDOT in the past has limited the binding material used on South Dakota highways to waterborne paint, epoxy paint, and preformed tape. Preformed tape is sometimes used in heavy traffic metropolitan areas and at interstate exits where marking damage due to winter maintenance may be minimal.

Prior to 1995, the majority of traffic paints were solvent-borne. In 1995, the U.S. Environmental Protection Agency (EPA) introduced new regulations for volatile organic compounds (VOC), which set the maximum allowable VOC concentration for marking materials. Because solvent-borne paints have VOC concentrations higher than the maximum VOC concentration allowed by the EPA, waterborne paints now dominate the pavement marking paint market (Durant, 2000). According to Migletz and Graham (2002), 89% of state transportation agencies use waterborne paint in their highway systems. Of those reporting agencies, 60% of the total mileage of centerlines on their state highways is waterborne paint. Waterborne traffic paint comprises the majority of SDDOT's pavement marking inventory. The waterborne pavement marking paint used in South Dakota is typically one of two types: standard waterborne paint and durable (or high build) waterborne paint. Standard waterborne paint meets the Federal Specification TT-P-1952E types I and II, while high-build waterborne paint meets type III. (US GSA, 1994). Typical waterborne paint thickness varies between 15 and 25 mils. High-build waterborne paint is formulated to be applied at higher rates, resulting in increased wet thickness of up to 30 mils. Markow (2008) reported data on the service life of pavement marking from several transportation agencies and determined that the service life for waterborne paint ranges between one-half to two years with a mean of 1.1 years. Table 2.1 shows the use of waterborne paint pavement marking in Texas (TxDOT, 2004).

Table 2.1 Use of Waterborne Paint Pavement Marking

-	Concrete			Asphalt			Surface Treatments		
-	AADT <1,000	AADT 1,000 – 10,000	AADT >10,000	AADT <10,000	AADT 10,000 – 50,000	AADT >50,000	AADT <1,000	AADT 1,000 – 10,000	AADT >10,000
Use[1]	Y	Y	L	Y	L	N	Y	L	N
Thickness	15–25 mils			15–25 mils			15–25 mils		
Surface prep.	Clean & dry.			Clean & dry.			Clean, dry, & remove loose stones.		
Expected service life	Up to 1 year			Up to 1 year			Up to 1 year[2]		
Approx. bid price (per lf)	$0.08			$0.08			$0.08		
Estimated cost per year of service life (per lf)	$0.08			$0.08			$0.08		

Footnotes:
1. Y = suitable for use; N = not recommended; L = limited use.
2. On new surface treatments, paint should only be used as a temporary marking for up to 6 months.

Epoxy paint is a two-component system consisting of an epoxy resin and a catalyst. The epoxy resin, which carries the color pigments for the pavement marking, is mixed with the catalyst, which acts as the hardener. Epoxy paint can be applied to a wet thickness that is comparable to that of waterborne paint. Epoxy paints provide exceptional adhesion to pavement surfaces and resistance to abrasion if proper application methods are used. Proper application of epoxy paint includes removal of existing pavement markings prior to the application of new paint and following the manufacturer's application recommendations. The pavement surface must also be free of dirt, dust, moisture, and other contaminants. Markow (2008) reported that the service life of epoxy paints ranges between one and four years with a mean of 3.3 years. Although the durability of epoxy paints is approximately three times that of waterborne paints, the longer drying or curing time for epoxy, which sometimes is in excess of 40 minutes, is considered a common drawback (Gates et al., 2003). Table 2.2 shows the use of epoxy pavement marking in Texas (TxDOT, 2004).

Table 1.2 Use of Epoxy Paint Pavement Marking

-	Asphalt			Concrete			Surface Treatments		
-	**AADT** <1,000	**AADT** 1,000 – 10,000	**AADT** >10,000	**AADT** <10,000	**AADT** 10,000 – 50,000	**AADT** >50,000	**AADT** <1,000	**AADT** 1,000 – 10,000	**AADT** >10,000
Use[2]	Y	Y	Y	Y	Y	Y	Y	Y	Y
Thickness	15–25 mils			15–25 mils			15–25 mils		
Surface prep.	Remove old mkgs, clean, & dry			Remove old mkgs, clean, & dry			Remove old mkgs, clean, & dry		
Expected service life	Up to 4 years	Up to 4 years	Up to 3 years	Up to 4 years	Up to 4 years	Up to 3 years	Up to 4 years	Up to 4 years	Up to 3 years
Approx. bid price (per lf)	$0.40			$0.40			$0.40		
Estimated cost per year of service life (per lf)	$0.10	$0.10	$0.13	$0.10	$0.10	$0.13	$0.10	$0.10	$0.13

Footnotes:

1. A wide variety of epoxy materials are currently available, possessing varying degrees of quality. The information in this table is based on the cost and performance of special formulations of epoxy that are designed for high-quality and high-durability pavement markings commonly used by state DOTs nationwide.
2. Y = suitable for use.

Thermoplastics have been used as a pavement marking material in the United States since the late 1950s. Thermoplastics have been the most common pavement marking material used on roadways in Texas for years (TxDOT, 2004). The popularity of thermoplastic markings can be attributed to several factors, including readiness for immediate use, high durability, good retroreflectivity, and relatively low cost. Thermoplastic materials are very sensitive to the variables governing application, warranting strict quality control during application. The variables that influence the durability and retroreflectivity performance of thermoplastic markings include material composition, application procedure, roadway surface, traffic, and environment. The ability for thermoplastic materials to bond to the roadway surface is based on the thermal properties of the thermoplastic binder and the roadway surface along with the porosity of the surface. Thermoplastic is well-suited for use on asphalt surfaces because the thermoplastic develops a thermal bond with the asphalt via heat fusion. When applied to hydraulic cement concrete surfaces, bond formation occurs by the liquid thermoplastic seeping into the pores of the concrete and forming a mechanical lock to the concrete surface. Primers are recommended prior to thermoplastic application on all hydraulic cement concrete surfaces and asphalt surfaces that are more than two years old, heavily oxidized, or have exposed aggregates. Suitable application temperatures for thermoplastics range from 400–450°F, with 420°F as the recommended temperature for most applications. For proper bonding, the pavement surface must be free of dirt, dust, moisture, and other contaminants. Pavement and air temperatures must be at least 50°F and 55°F, respectively, to ensure proper rate of cooling. Table 2.3 shows the use of thermoplastic pavement marking in Texas (TxDOT, 2004).

Table 1.3 Use of Thermoplastic Pavement Marking

	Asphalt			Concrete			Surface treatments		
	AADT < 1,000	**AADT 1,000 - 10,000**	**AADT > 10,000**	**AADT < 10,000**	**AADT 10,000 - 50,000**	**AADT > 50,000**	**AADT < 1,000**	**AADT 1,000 - 10,000**	**AADT > 10,000**
Use	Y	Y	Y	L	L	N	Y	Y	Y
Material suggestions	TxDOT standard			specific concrete formulation		-	TxDOT standard		
Typical minimum thickness (new)	90 mils			90 mils	90 mils	-	100 mils		
Typical minimum thickness (restripe)	60 mils			60 mils	60 mils	-	60 mils		
Surface prep.	Clean & dry			Clean, dry, & primer-sealer (refer to Item 678 or manufacturer recommendations).		-	Clean, dry, & remove loose stones.		
Expected Service Life	up to 4 years	up to 4 years	up to 3 years	up to 4 years	up to 4 years	-	up to 4 years	up to 4 years	up to 3 years
Approx. bid price for new surface in 2002 (per lb)	$0.20			$0.35		-	$0.20		
Estimated cost per year of service life (per lf)	$0.05	$0.05	$0.07	$0.07	$0.09	-	$0.05	$0.05	$0.07

Footnotes:
1. TxDOT Specification Thermoplastic unless noted otherwise.
2. Y = suitable for use; N = not recommended; L = limited use.

Polyurea markings are a two-component durable pavement marking material. Polyurea materials are marketed as durable pavement markings that provide exceptional color stability, resistance to abrasion, and adhesion to all pavement surfaces. Polyurea markings appear to be less sensitive to pavement surface moisture than thermoplastics and can be applied at temperatures as low as freezing. Most of these materials are marketed as fast-curing materials, achieving proper bonding and no-track conditions in two minutes or less. One of the drawbacks associated with polyurea materials is that some types must be applied by special striping equipment, which limits the number of contractors available to apply the material. Other polyurea materials, however, can be applied by a standard epoxy truck. The type of truck required is based on the resin-catalyst mix ratio. Polyurea mixes with a 2:1 mix ratio can be applied with a standard epoxy truck. Table 2.4 shows the use of polyurea pavement marking in Texas (TxDOT, 2004).

Table 2.4 Use of Polyurea Pavement Markings

-	Asphalt			Concrete			Surface Treatments		
-	AADT <1,000	AADT 1,000 – 10,000	AADT >10,000	AADT <10,000	AADT 10,000 – 50,000	AADT >50,000	AADT <1,000	AADT 1,000 – 10,000	AADT >10,000
Use[2]	Y	Y	Y	Y	Y	Y	Y	Y	Y
Thickness	15–25 mils			15–25 mils			15–25 mils		
Surface prep.	Remove existing markings, clean, & dry			Remove existing markings, clean, & dry			Remove existing markings, clean, & dry		
Expected service life	Up to 4 years	Up to 4 years	Up to 3 years	Up to 4 years	Up to 4 years	Up to 3 years	Up to 4 years	Up to 4 years	Up to 3 years
Approx. bid price (per lf)	$1.00			$1.00			$1.00		
Estimated cost per year of service life (per lf)[3]	$0.25	$0.25	$0.33	$0.25	$0.25	$0.33	$0.25	$0.25	$0.33

Footnotes:
1. The cost and performance of polyurea is based on limited experimentation both in Texas and nationwide.
2. Y = suitable for use.
3. Prices include a proprietary retroreflectivity-enhancing ceramic element embedded into the marking surface. Polyurea materials applied without the proprietary ceramic element may be less expensive.

Modified urethanes are a two-component, durable marking material with similar performance characteristics to those of polyurea and epoxy. Material costs are reported to be slightly more expensive than epoxy but less than polyurea. This product is marketed as being slightly more durable than epoxy but with much quicker cure times (two minutes) and better ultraviolet color stability. This material can be sprayed from any standard epoxy truck. Because so little experience exists with modified urethane pavement marking materials, they can be used only on an experimental basis within Texas, although this material seems to have promise on concrete roadways. More data are needed before conclusive recommendations can be made. Table 2.5 shows the use of modified urethane pavement marking in Texas (TxDOT, 2004)

Table 2.5 Use of Modified Urethane Pavement Marking

-	Asphalt			Concrete			Surface Treatments		
-	**AADT <1,000**	**AADT 1,000 – 10,000**	**AADT >10,000**	**AADT <10,000**	**AADT 10,000 – 50,000**	**AADT >50,000**	**AADT <1,000**	**AADT 1,000 – 10,000**	**AADT >10,000**
Use[2]	L	L	L	L	L	L	L	L	L
Thickness	Manuf. Recommendations			Manuf. Recommendations			Manuf. Recommendations		
Surface prep.	Remove Existing Markings, Clean & Dry			Remove Existing Markings, Clean & Dry			Remove Existing Markings, Clean & Dry		
Expected service life	Up to 4 years	Up to 4 years	Up to 3 years	Up to 4 years	Up to 4 years	Up to 3 years	Up to 4 years	Up to 4 years	Up to 3 years
Approx. bid price (per lf)	$0.63			$0.63			$0.63		
Estimated cost per year of service life (per lf)	$0.16	$0.16	$0.21	$0.13	$0.16	$0.21	$0.16	$0.16	$0.21

Footnotes:
1. Based on use in other states.
2. L = limited use.

Methyl Methacrylate (MMA) is a nonhazardous, two-component, durable pavement marking material. The material exists as a solid that is mixed in a static mixer immediately prior to application. MMA can be sprayed or extruded onto the pavement. The material forms a strong bond to the pavement surface by exothermic reaction (release of heat) that occurs during the mixing process. Methyl methacrylate was originally marketed as an environmentally friendly alternative to solvent-borne paints. However, MMA has been shown to provide much longer service life than standard traffic paint. A service life of greater than three years is common. In addition, the material is designed to be resistant to oils, antifreeze, and other common chemicals found on the roadway surface. MMA reportedly bonds well to concrete pavements. MMA materials are usually applied at thicknesses of 40 mils. Because MMA does not rely on the addition of heat to cure, it is an attractive material in cold-weather climates. Research in cold-weather climates has shown very good performance for MMA. Costs for methyl methacrylate have been reported to be comparable to those of epoxy materials. As with all other two-component marking materials, a drawback to the use of MMA is that it requires special equipment for application. Table 2.6 shows the use of methyl methacrylate pavement marking in Texas (TxDOT, 2004).

Table 2.6 Use of Methyl Methacrylate Pavement Marking

-	Asphalt			Concrete			Surface Treatments		
-	**AADT** <1,000	**AADT** 1,000 – 10,000	**AADT** >10,000	**AADT** <10,000	**AADT** 10,000 – 50,000	**AADT** >50,000	**AADT** <1,000	**AADT** 1,000 – 10,000	**AADT** >10,000
Use	Limited use			Limited use			Limited use		
Thickness	40 mils			40 mils			40 mils		
Surface prep.	Remove existing markings, clean, & dry			Remove existing markings, clean, & dry			Remove existing markings, clean, & dry		
Expected service life	Up to 5 years			Up to 5 years			Up to 5 years		
Approx. bid price (per lf)	$2.50			$2.50			$2.50		
Estimated cost per year of service life (per lf)	$0.50			$0.50			$0.50		

The estimated cost per year of service life (per linear foot of road) was lowest for thermoplastic pavement marking followed by waterborne paint and epoxy paint. As previously stated, thermoplastic materials are very sensitive to the variables governing application, warranting strict quality control during application. The strict quality control during application prevents the thermoplastic pavement marking from being the most attractive alternative.

Some of the pavement marking materials previously described require contractors with special equipment that is not readily available in South Dakota. As such, the cost of some pavement markings would be prohibitive, and therefore not suitable for South Dakota. Therefore, the pavement marking paints considered for this study were waterborne paint and epoxy.

2.2.2 Reflective Elements

Reflective elements allow the pavement marking to be seen at night and in certain adverse weather conditions by reflecting light from the vehicle's headlights back to the driver of the vehicle. The process of seeing the reflected light is called "retroreflectivity." In general, retroreflectivity is the intensity of light that is emitted from a source, called luminance, divided by the intensity of the light that illuminates the surface of an object from the luminance light. Retroreflectivity can be quantitatively measured by the coefficient of retroreflected luminance, RL. The coefficient of retroreflected luminance is defined by the American Society for Testing Materials (ASTM, 2009) as "the ratio of the luminance of a projected surface to the normal illuminance at the surface on a plane normal to incident light, expressed in candelas per square meter per lux ($cd/m^2/lux$)." Due to the low values of luminance exhibited by pavement marking, the coefficient of retroreflective luminance in pavement marking is normally expressed in units of *milli* candelas per square meter per lux ($mcd/m^2/lux$).

The pavement marking retroreflectivity depends upon the type of the reflective elements embedded in the binder. This report will cover the two types that are normally used by SDDOT and were part of the study. The two types are glass spheres and wet reflective elements.

2.2.2.1 Glass Spheres

Glass spheres, also called glass beads, have a sand-like texture and vary in size between approximately 5 and 50 mils. The picture in Figure 2.1 shows glass beads next to the tip of a ball-point pen, which is shown as a reference scale.

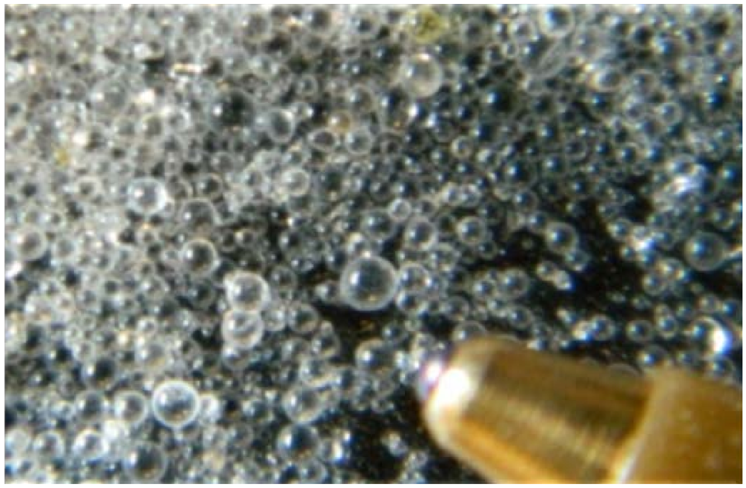


Figure 2.1 Glass Spheres

Glass spheres need to be partially embedded in a reflective substance (paint) in order to be retroreflective. The depth of embedment of the glass sphere is critical for proper retroreflectivity. Figure 2.2 illustrates how the direction of the retroreflected light is affected by the depth of the bead's embedment. When the bead is too shallow, the light emitted from the vehicle's headlight passes through the glass sphere and does not reflect back; whereas, when the bead is too deep, the light gets reflected away from the driver. Rasdorf et al. (2008) stated that an optimum embedment depth occurs when approximately 60% of the glass sphere is embedded in the paint.

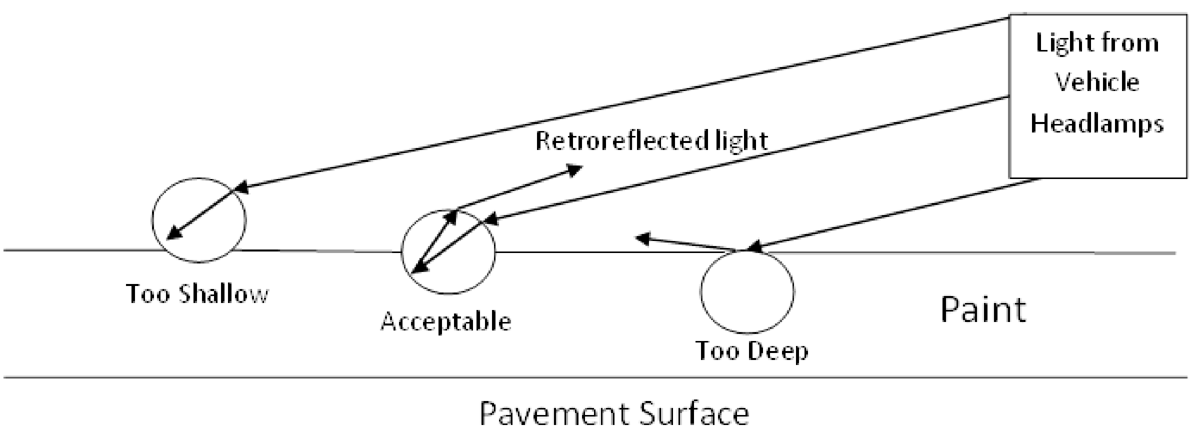


Figure 2.2 Effect of Glass Spheres Embedment Depth on Headlight Retroreflectivity

2.2.2.2 Wet Reflective Elements

Wet reflective elements (WREs) are proprietary products that were developed to improve retroreflectivity under wet pavement surface conditions. A wet reflective element consists of a ceramic bead core with thousands of micro-spheres attached to the ceramic core. WREs are color coordinated to match the color of the pavement marking. Thus, white WRE beads are applied to white pavement markings and yellow WRE beads are applied to yellow pavement markings. Figure 2.3 shows WRE beads next to the tip of a ball-point pen, while Figurer 2.4 shows the microspheres when viewed with a microscope.

Figure 2.3 White Wet Reflective Elements

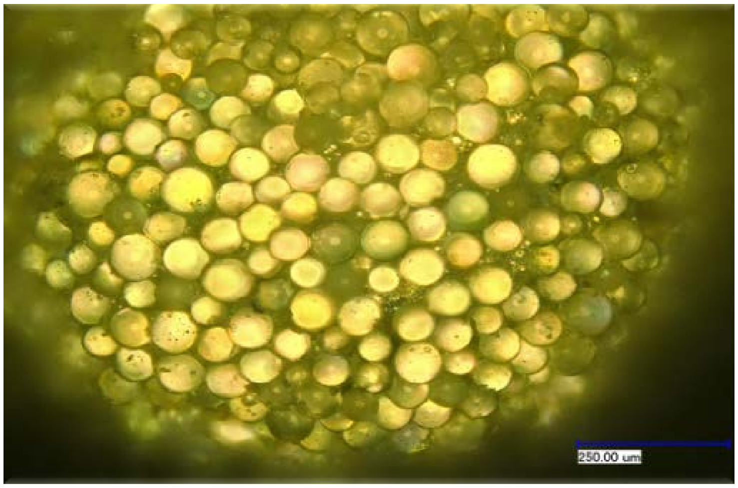


Figure 2.4 Microscopic View of a Single WRE Bead

2.3 Pavement Marking Performance Evaluation

Subjective and objective methods have been used by transportation agencies for field evaluation of pavement marking durability and visibility. Durability is dependent on the resistance of the pavement marking material to wear or loss of adhesion to the pavement surface, while visibility is the ability to see the pavement marking during nighttime. Objective evaluation is performed with an instrument that measures retroreflection quantitatively. Subjective evaluation requires an individual to make a condition assessment based on criteria such as percent of the pavement marking remaining and sight distance to visible pavement markings at night.

2.3.1 Measurement of Retroreflection

Pavement marking retroreflection is measured using an instrument called a retroreflectometer, or reflectometer for short. Figure 2.5 shows a reflectometer being used in the field. Reflectometer measurements provide numeric values for retroreflectivity in units of mcd/m^2/lux. Typical reflectometers are based on either a 12-meter geometry or a 30-meter geometry. The 12-meter geometry has an observation angle of 1.5 degrees and an entrance angle of 86.5 degrees, whereas the 30-meter geometry has an observation angle of 1.05 degrees and an entrance angle of 88.76 degrees. Figure 2.6 illustrates the 30-meter geometry. The 30-meter geometry reflectometer can be either a mobile unit mounted on a vehicle or a handheld unit. When this study was conducted, the reflectivity measurements collected by SDDOT were done with 30-meter geometry handheld reflectometers model Delta LTL-X-30-meter.

Figure 2.5 Retroreflectivity 30-Meter Geometry (Rasdorf et al., 2008)

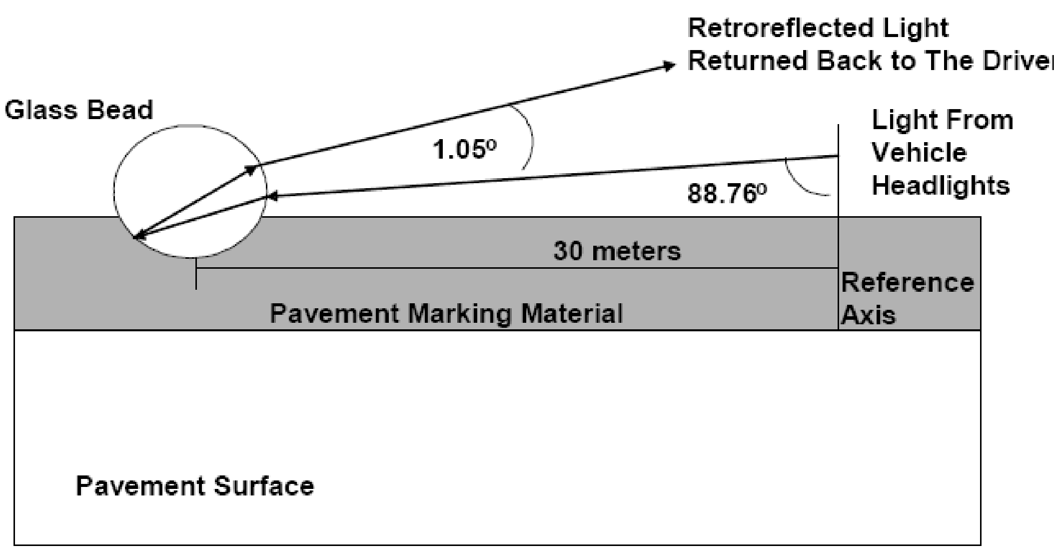


Figure 2.6 Retroreflectivity 30-Meter Geometry (Rasdorf et al., 2008)

2.3.2 Visual Rating – Ohio DOT Method

In a questionnaire to state departments of transportation, Migletz and Graham (2002) reported that almost 65% of the responding agencies perform subjective dry performance evaluations at night for pavement markings in addition to collecting retroreflectivity readings from reflectometers. Of the responding agencies, 39% subjectively evaluate pavement marking adhesion to the pavement surface and 31% subjectively evaluate glass sphere retention. According to Migletz and Graham (2002), the Ohio Department of Transportation (Ohio DOT) uses a subjective durability numeric rating that ranges from 1 to 10 in increments of 1. The rating reflects the percentage of marking remaining on the pavement. A rating of 1 represents 10% of the marking remaining and a rating of 10 represents 100% of the marking remaining. The rating is recorded by comparing the pavement marking condition to a graphic scale. Figure 2.7 shows a diagram of the visual rating scale used by the Ohio DOT.

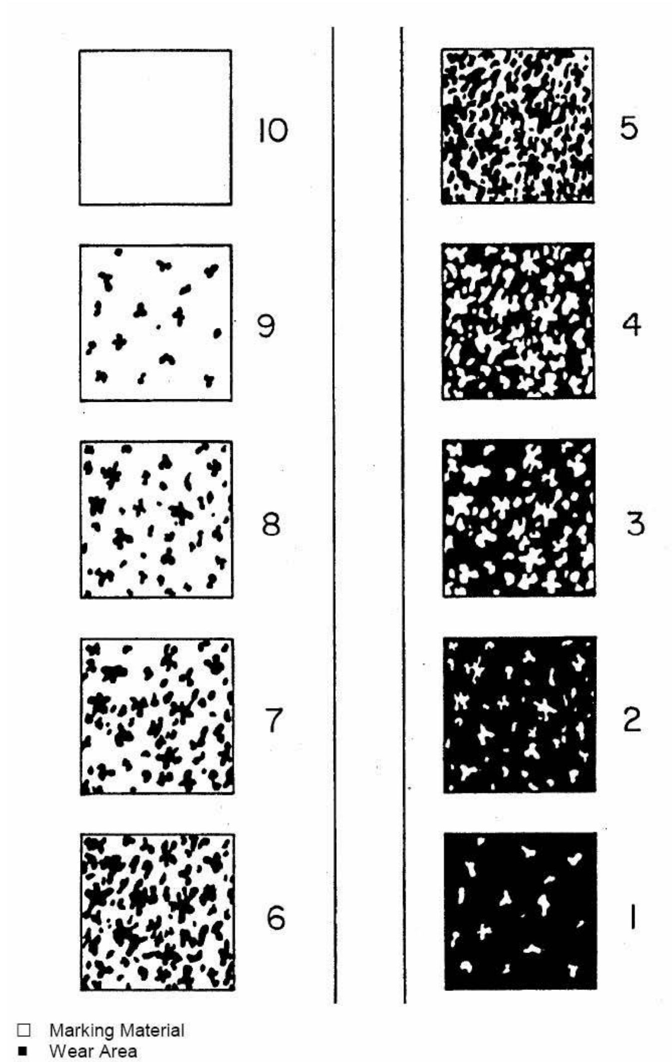


Figure 2.7 Ohio DOT Durability Scale (Migletz and Graham, 2002)

Retroreflectivity under wet conditions is particularly critical as adequate values measured on a dry pavement do not necessarily imply adequate performance under wet conditions (Andrady, 1994). Typically, performance will decrease in wet conditions and the degradation is a result of flooding of the marking optics and a change in the optical media, thereby reducing retroreflectivity and the visibility distance. It is also important to note that daytime visibility is not as critical as nighttime visibility, and that is why many performance evaluations are done at night.

2.4 Pavement Marking and Retroreflectivity Degradation

Many factors influence the degradation rate of pavement markings, including the type of paint material, the paint application method and rate, the type of pavement, the type of marking line, traffic volume, and winter maintenance activities. While retroreflectivity will degrade with the degradation of the pavement marking, the loss of glass spheres or other reflective elements with time has a major influence on retroreflectivity (Rasdorf et al., 2008).

Sarasua et al. (2003) reported that newly placed pavement marking exhibits initial increase in retroreflectivity for a short period of time after which the retroreflectivity starts to decreases. Fu and Wilmot (2008) have shown that exponential decay models for retroreflectivity achieve better accuracy at or near the end of the marking service life. Figure 2.8 shows a qualitative representation of retroreflectivity decay with time.

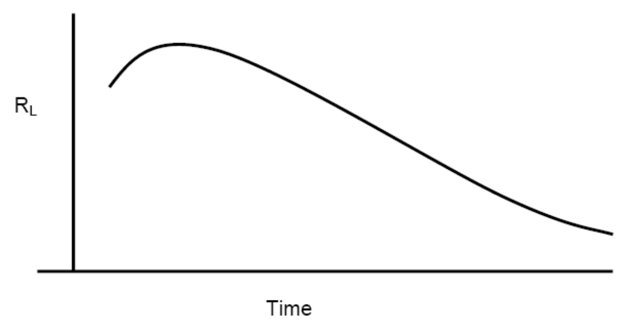


Figure 2.8 Retroreflectivity Decay Trend (Sarasua et al., 2003)

Snowplowing in cold regions accelerates the degradation of retroreflectivity. Following a snowplowing event, retroreflectivity is reduced due to significant loss of glass spheres (Sarasua et al., 2003). Figure 2.9 shows a qualitative representation of the effect of snowplowing on retroreflectivity.

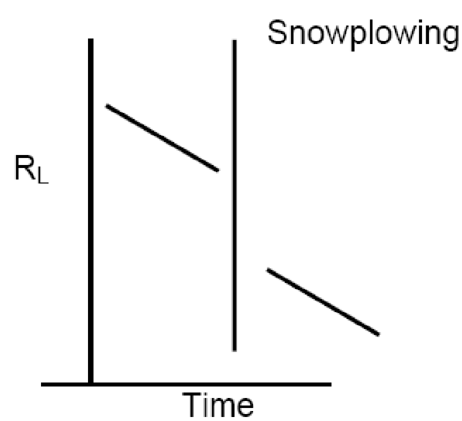


Figure 2.9 Effect of Snowplowing on Retroreflectivity (Sarasua et al., 2003)

Due to the detrimental effect that snowplowing has on retroreflectivity, pavement markings are sometimes placed in recessed grooves in the pavement to protect them from the blade of a snowplow. A study done in Vermont (Crum and Fitch, 2007) highlighted the difference in retroreflectivity degradation of a recessed pavement marking and a surface applied pavement marking in an area where snowplowing is common. Results from the Crum and Fitch (2007) study are shown in Figure 2.10 and Figure 2.11 for a white edge line and a yellow edge line, respectively.

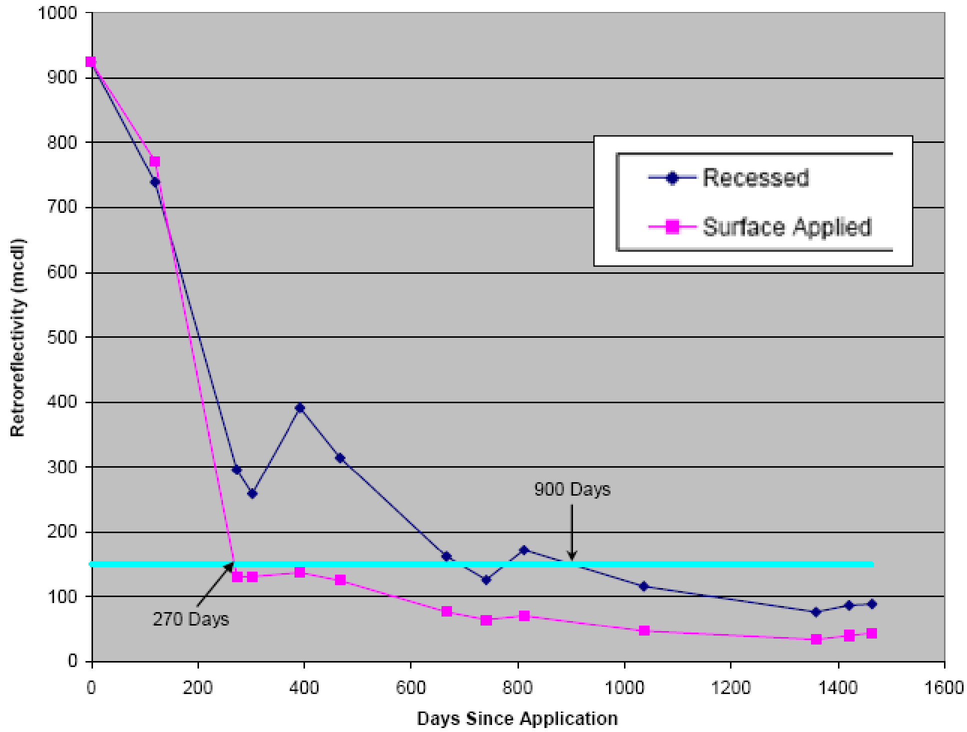


Figure 2.10 Effect of Inlay on White Edge Line Retroreflectivity (Crum and Fitch, 2007)

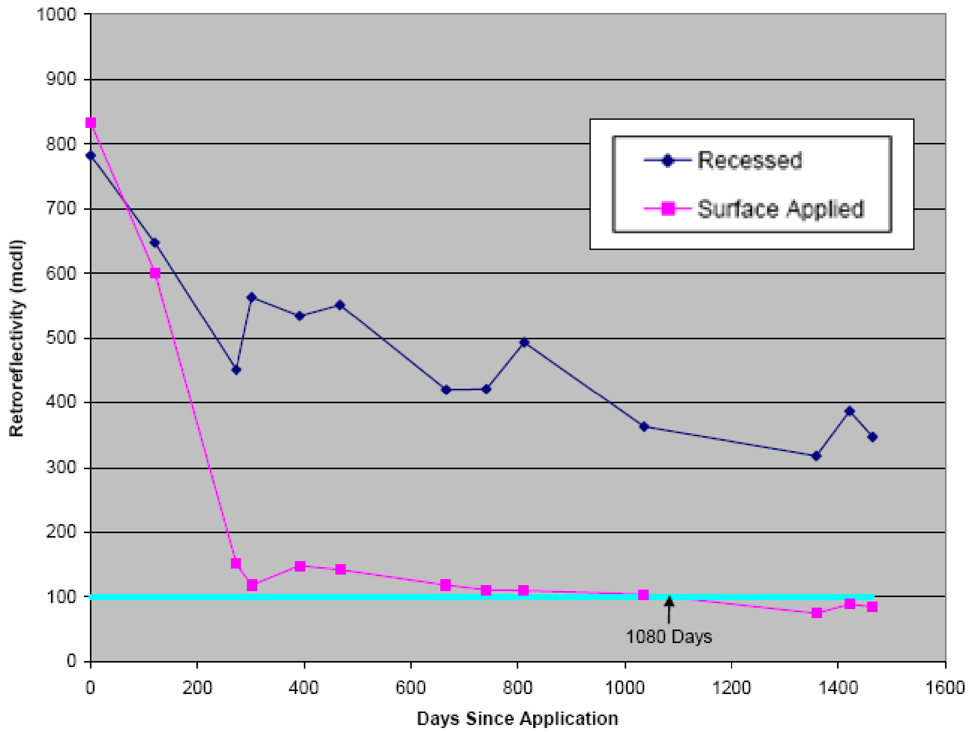


Figure 2.11 Effect of Inlay on Yellow Edge Line Retroreflectivity (Crum and Fitch, 2007)

2.5 Retroreflectivity Threshold

Many studies have been conducted to examine the effect of pavement marking performance criteria, such as retroreflectivity or sight distance, on the frequency of highway crashes. The overarching objective was to establish minimum performance criteria for mitigating crashes that could result from inadequate pavement marking visibility. The minimum retroreflectivity for an acceptable level of visibility can be referred to as the retroreflectivity threshold. It should be noted that the retroreflectivity threshold used by SDDOT is 100 (mcd/m^2/lux).

According to Carlson et al. (2009), many recent studies have identified a statistical correlation between reduced retroreflectivity and increased number of crashes. However, Donnell et al. (2009) concluded that while higher retroreflectivity may be related to lower crash frequencies on two-lane highways, such a correlation is marginally significant for yellow centerlines.

Smadi et al. (2008) analyzed records of crash data that could be attributed to pavement marking retroreflectivity such as crashes at dawn, dusk, or night. Crashes that occurred in wet conditions or caused by wild animals or other objects were eliminated from the analyzed data. The study found a statistically significant correlation between the frequency of crashes and retroreflectivity only when the retroreflectivity was less than 200 mcd/m^2/lux, and that there was no statistical correlation between the frequency of crashes and retroreflectivity when the retroreflectivity was above 200 mcd/m^2/lux. This may suggest that if the pavement marking's retroreflectivity is above 200 (mcd/m2/lux), the safety of drivers on the highway system is not affected by the retroreflectivity level.

Parker and Meja (2003) examined the effect of drivers' ages on the acceptable level of retroreflectivity for adequate visibility. They concluded that acceptable ranges of retroreflectivity were 80 to 130 mcd/m^2/lux for drivers under age 55, and 120 to 165 mcd/m^2/lux for drivers older than 55.

Debaillon et al. (2008) reviewed the results from several pavement marking visibility research studies and developed a model to evaluate minimum retroreflectivity standards. The study concluded that the minimum retroreflectivity should vary according to speed and presence of retroreflective raised pavement markers (RRPMs). Table 2.7 presents the minimum recommended values from the study. Retroreflective raised pavement markers (RRPMs) are not used on South Dakota highways and, therefore, are not part of this study.

Table 2.7 Recommended Minimum Retroreflectivity Values (Debaillon et al., 2008)

Recommended Minimum Retroreflectivity Values (mcd/m^2/lx)

Roadway Marking Configuration	Without RRPMs ≤50 mph	55-65 mph	≥70 mph	With RRPMs
Fully marked roadways (with centerline, lane lines, and edge line, as needed)*	40	60	90	40
Roadways with centerlines only	90	250	575	50

*Applies to both yellow and white pavement markings

Migletz and Graham (2002) reported the FHWA retroreflectivity threshold values that were applicable at the time of their study. These values are summarized in Table 2.8.

Table 2.8 FHWA Retroreflectivity Threshold Values Applicable in 2002 (Migletz and Graham, 2002)

Threshold Retroreflectivity Values Used in FHWA Research (mcd/m^2/lx)

Material	Roadway Type/Speed Classification: Non-Freeway (≤ 40 mph)	Non-Freeway (≥ 45 mph)	Freeway (≥ 55 mph)
White	85	100	150
White with RRPMs or Lighting	30	35	70
Yellow	55	65	100
Yellow with RRPMs or Lighting	30	35	70

Notes: Retroreflectivity values are measured at 30-meter geometry

The 2009 Edition of the Manual on Uniform Traffic Control Devices (MUTCD) with Revisions 1 and 2 in May 2012 (FHWA, 2012) included a place holder under Section 3A.03 for future text based on FHWA rulemaking for "Maintaining Minimum Pavement Marking Retroreflectivity." However, a recent publication entitled "Know Your Retro" by the FHWA (2010) presented minimum values of retroreflectivity levels based on posted speed and type of road. The FHWA publication referred to Section 3A.03 of the MUTCD as follows: "The new MUTCD Section 3A.03 requires agencies to use a method designed to maintain longitudinal pavement markings to a minimum level of retroreflectivity outlined in Table 3A-1." Table 2.9 presents a a tabulation of the minimum retroreflectivity levels as presented in Table 3A-03 in the FHWA 2010 publication.

Table 2.9 Minimum Maintained Retroreflectivity Levels[1] for Longitudinal Pavement Markings (FHWA, 2010)

	Posted Speed (mph)		
	≤30	**35–50**	**≥55**
Two-lane roads with center line markings only[2]	n/a	100	250
All other roads[2]	n/a	50	100

- Measured at standard 30-m geometry in units of mcd/m2/lux
- Exceptions:
  - When RRPMs supplement or substitute for a longitudinal line (see Section 3B.13 and 3B.14), minimum pavement marking retroreflectivity levels are not applicable as long as the RRPMs are maintained so that at least three are visible from any position along that line during nighttime conditions.
  - When continuous roadway lighting assures that the markings are visible, minimum pavement marking retroreflectivity levels are not applicable.

3. EXPERIMENTAL WORK AND RESULTS

This section covers the experimental work done in this study and the data collected to evaluate the performance of different combinations of pavement markings. Seven pavement marking test sections were constructed by SDDOT on highways in different regions of South Dakota. The test sections were designed to represent different pavement marking material combinations and winter maintenance conditions. The parameters considered in this study were paint type (waterborne and epoxy), paint thickness (15, 17, 20, and 25 mils), paint color (white and yellow), reflective elements (glass beads and wet reflective elements), line type (edge line and skip line), pavement type (asphalt concrete and Portland cement concrete), pavement surface preparation (surface and inlaid applications), and winter maintenance region (wet freeze and dry freeze). The collected data included: 1) paint thickness measurements, 2) retroreflectivity of the pavement marking at different ages and under dry and wet conditions, and 3) visual rating of the pavement marking.

3.1 Pavement Marking Material

3.1.1 Paint Material

Two waterborne paint types and one epoxy paint type were investigated in this study. The waterborne paints meet the federal specification TT-P-1952E types II and III (US GSA, 1994). The waterborne paint TT-P-1952E type II and TT-P-1952E type III will be referred to as Type II and Type III, respectively. Type III can be applied at greater wet thicknesses and has greater adhesive qualities than Type II. The waterborne paints have typical track free time of approximately five minutes, but can vary depending on the paint manufacturer and application temperatures. The third type of paint used in this research is a two-component external mixed epoxy that has approximately a 40-minute track free time. The SDDOT certification and accreditation approved product list of pavement markings identifies this product as a Slow Dry (Type II) Epoxy, which in this study is referred to as epoxy. Epoxy paint is considered a durable pavement marking.

3.1.2 Reflective Elements

The reflective elements used in this research were glass spheres and WRE. Glass sphere types are differentiated by grain size distribution specification. The WRE beads were a proprietary product. Four different glass sphere specifications were included in this study. The four types were AASHTO M247 Type I (AASHTO, 2004), Iowa DOT Specification, SDDOT Megablend, and P40 Gradation, and are referred to as M247, Iowa Blend, Megablend, and P40, respectively. Table 3.1 shows the gradation of the four glass sphere types. Other minimum specifications for all the glass spheres include the following: 80% of the beads are true spheres, the beads have an index of refraction of 1.51, and 10% by weight of the beads are direct melt glass beads.

Table 3.1 Gradation Specifications

M247	
U.S. Mesh	**Percent Passing**
#16	100
#20	95-100
#30	75-95
#50	15-35
#100	0-5

Iowa Blend	
U.S. Mesh	**Percent Passing**
#16	99-100
#20	75-95
#30	55-85
#50	10-35
#100	0-5

Megablend	
U.S. Mesh	**Percent Passing**
#16	95-100
#20	90-100
#30	70-95
#50	10-35
#150	0-5

P40	
U.S. Mesh	**Percent Passing**
#20	90-97
#30	50-75
#40	15-45
#50	0-15
#80	0-5

The glass spheres were dropped on the freshly placed paint at a specified application rate. Figure 3.1 shows the process of paint application and dropping of the glass beads. In this study, the minimum reflective element application rates when a single glass sphere gradation was used were 8 lb./gal. for waterborne paint and 25 lb./gal. for epoxy paint. The application rates when M247 and Megablend were used simultaneously with epoxy paint were 15 lb./gal. and 10 lb./gal. for M247 and Megablend, respectively.

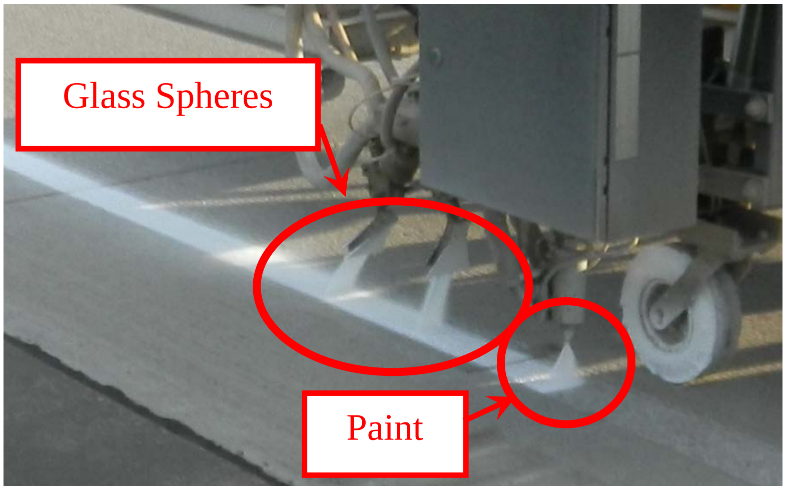


Figure 3.1 Glass Sphere Application

Unlike glass spheres, WREs are self-retroreflective and do not need to be partially embedded in a reflective matrix to be retroreflective. The WRE color is coordinated with the color of the marking paint. WREs are applied simultaneously with glass spheres in a dual drop system as seen in Figure 3.2. In this research, the minimum reflective element application rate when a dual drop of M247 glass spheres and a WRE was used with Type III paint was 6 lb./gal. and 5 lb./gal. for M247 and WRE, respectively. When the dual drop of P40 glass spheres and a WRE was used with epoxy paint, the rate was 14.5 lb./gal. and 5.5 lb./gal. for P40 and WRE, respectively.

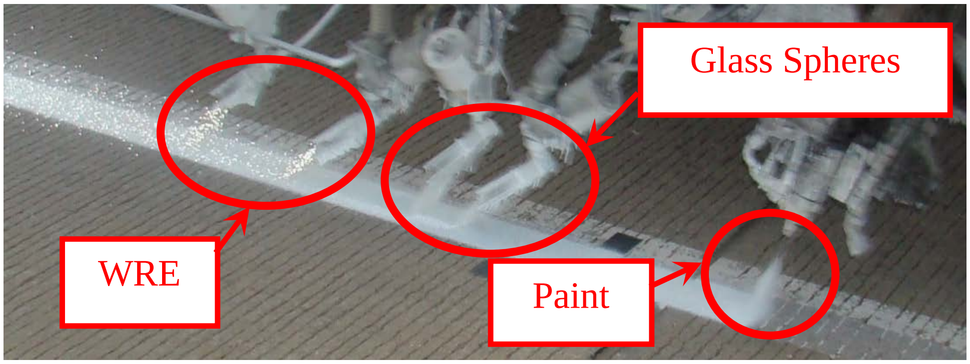


Figure 3.2 Glass Sphere/WRE Dual Drop Application

3.2 Test Sections

Previous studies (Zhang et al., 2011; Carlson et al., 2010) have shown that test setups consisting of either test decks or test sections can be used effectively to evaluate the performance of pavement marking materials. Each type setup has its own advantages and disadvantages. The advantages and disadvantages of each type are summarized in Table 3.2.

Table 3.2 Primary Advantages and Disadvantages of Test Sections and Test Decks

	Advantage	Disadvantage
Test Section	Easier to use existing projects for section Good geographic representation with varying conditions Focus on evaluating external impact factors of interest Develop state or regional calibration factors for other products being tested in other states or NTPEP Evaluate inlaid technology for PMM Represents actual field conditions	Need to identify many appropriate striping projects Potential limit of the number of products / combinations Intensive coordination and travel QA/QC issues – lack of control of experimental environment
Test Deck	Extensive testing of different products/combinations Well-controlled experimental environment	Limited to single location No geographic diversity No environmental diversity Difficult application for in-lay products Difficult to transfer evaluation of results Expensive to install Coordination of traffic control (esp. on interstate highways) Extra signage required

The test section setup was adopted and implemented in this study because it provided better representation of actual field conditions to which the pavement marking is subjected. Seven test sections were selected in diverse geographic locations in the state to represent "dry freeze" and "wet freeze" winter maintenance methods employed by SDDOT. Dry freeze areas are parts of the country that undergo a number of freeze-thaw cycles (15+) annually but have little precipitation during the winter. The winter maintenance method in dry freeze regions is more chemical than mechanical. Western South Dakota uses a more chemical approach as its winter maintenance method because it is in the dry freeze zone. Wet freeze areas are parts of the country that undergo a number of freeze-thaw cycles annually (15+) and there is a lot of precipitation during the winter. The winter maintenance method in wet freeze regions is more mechanical than chemical. Eastern South Dakota uses a more mechanical approach as its winter maintenance method because it is in the wet freeze zone. Figure 3.3 shows the locations of wet and dry freeze in the United States.

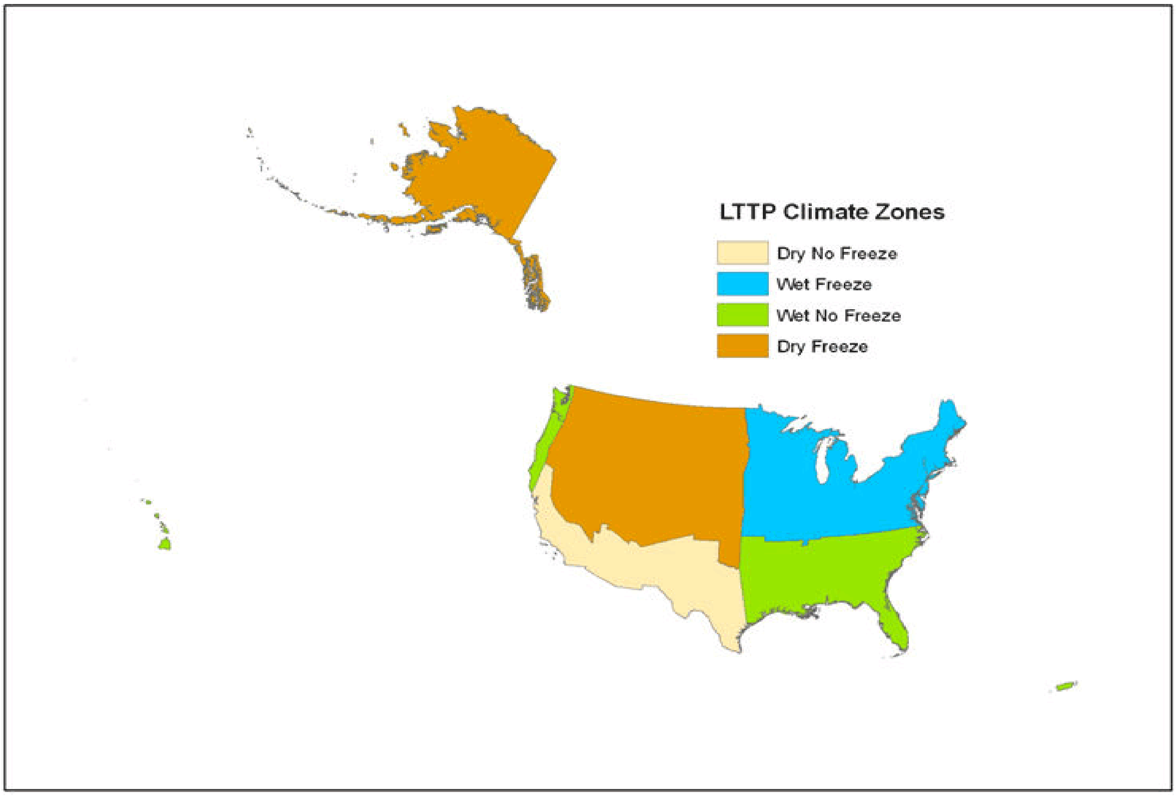


Figure 3.3 Location of Wet Freeze and Dry Freeze in the United States

Although it would be ideal to preselect pavement marking materials prior to the start of research, it was recognized that when using test sections, material selection could be influenced by many factors, including available equipment, available marking products, contract sequencing, and construction season. Several parameters were considered in selecting the pavement marking materials for this study. Those parameters included geographic location (winter maintenance), pavement type, pavement preparation, paint type, paint thickness, paint color, line type, and reflective element type. The values of the parameters used in the test sections of this study are summarized in Table 3.3.

Table 3.3 Summary of Pavement Material Parameters

Parameter	Parameter Value
Winter Maintenance	Wet Freeze Dry Freeze
Pavement Type	Asphalt Concrete - (AC) Portland Cement Concrete - (PCC)
Pavement Preparation	Surface Applied Inlay Applied
Paint Type	Federal Specification (TT-P-1952E) Type II - (Type II) Federal Specification (TT-P-1952E) Type III - (Type III) Traffic Epoxy Paint Slow Dry (Type II) - (epoxy)
Paint Thickness (varies by paint type)	15 mils 17 mils 20 mils 25 mils
Paint Color	White Yellow
Line Type	Edge Line Skip Line
Reflective Element Type	AASHTO M247 Type I - (M247) IowaDOT Specification - (Iowa Blend) SDDOT Megablend - (Megablend) P40 Gradation - (P40) Wet Reflective Elements - (WRE) Proprietary Product

The pavement marking materials and application methods used in this study were selected by taking into consideration material availability and the ability of SDDOT crews and local contractors to apply the selected pavement markings. Once the parameters were selected, the test section locations were identified. The locations of the seven test sections are shown in Figure 3.4.

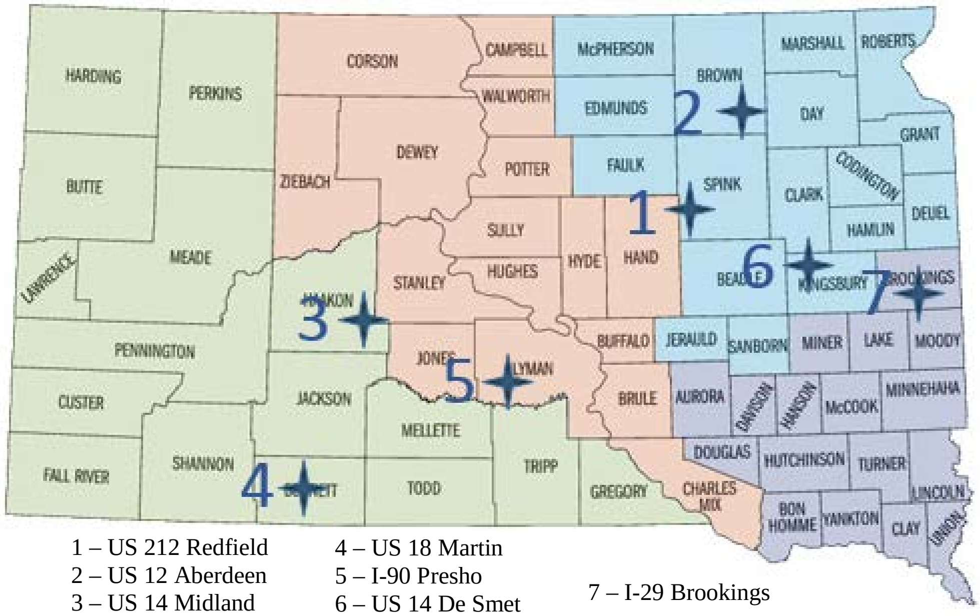


Figure 3.4 Location of the Pavement Marking Test Sections

A test matrix consisting of different parametric combinations was developed to satisfy the goals of the research. The test sections included in this study can be classified into three main categories: waterborne paint in wet freeze regions, waterborne paint in dry freeze regions, and epoxy paint in wet freeze regions. Within each category, several pavement marking cases that cover different parametric combinations were selected and applied. The pavement marking cases are summarized in Table 3.4, Table 3.5, and Table 3.6 for the waterborne/wet freeze, waterborne/dry freeze, and epoxy/wet freeze categories, respectively. In all, there were 69 pavement marking cases reflecting different parametric combinations. The combinations shown in these tables are numbered from 1 through 69. This numbering system has been adopted throughout this report whenever a reference is made to a specific pavement marking case.

Table 3.4 Waterborne Paint – Wet Freeze Test Sections

Test Section/ Winter Maintenance	Case No.	Paint Type/ Line Type	Color	Thickness	Reflective Element	Pavement Type/Surface Preparation
US 212 Redfield, SD/ Wet Freeze	1	Type II/Edge Line	White	15 mils	M247	AC/Surface
	2	Type II/Edge Line	White	17 mils	M247	AC/Surface
	3	Type II/Edge Line	White	15 mils	P40	AC/Surface
	4	Type II/Edge Line	White	17 mils	P40	AC/Surface
	5	Type III/Edge Line	White	17 mils	M247	AC/Surface
	6	Type III/Edge Line	White	20 mils	M247	AC/Surface
	7	Type III/Edge Line	White	17 mils	P40	AC/Surface
	8	Type III/Edge Line	White	20 mils	P40	AC/Surface
	9	Type II/Skip Line	Yellow	15 mils	M247	AC/Surface
	10	Type II/Skip Line	Yellow	17 mils	M247	AC/Surface
	11	Type II/Skip Line	Yellow	15 mils	P40	AC/Surface
	12	Type II/Skip Line	Yellow	17 mils	P40	AC/Surface
US 12 Aberdeen, SD/ Wet Freeze	13	Type III/Edge Line	Yellow	15 mils	M247	PCC/Surface
	14	Type III/Skip Line	White	15 mils	M247	PCC/Surface
	15	Type III/Edge Line	White	15 mils	M247	PCC/Surface
	16	Type III/Edge Line	Yellow	20 mils	M247	PCC/Surface
	17	Type III/Skip Line	White	20 mils	M247	PCC/Surface
	18	Type III/Edge Line	White	20 mils	M247	PCC/Surface
	19	Type III/Edge Line	Yellow	15 mils	Iowa Blend	PCC/Surface
	20	Type III/Skip Line	White	15 mils	Iowa Blend	PCC/Surface
	21	Type III/Edge Line	White	15 mils	Iowa Blend	PCC/Surface
	22	Type III/Edge Line	Yellow	20 mils	Iowa Blend	PCC/Surface
	23	Type III/Skip Line	White	20 mils	Iowa Blend	PCC/Surface
	24	Type III/Edge Line	White	20 mils	Iowa Blend	PCC/Surface

Table 3.5 Waterborne Paint – Dry Freeze Test Sections

Test Section/ Winter Maintenance	Case No.	Paint Type/ Line Type	Color	Thickness	Reflective Element	Pavement Type/Surface Preparation
US 14 Midland, SD/ Dry Freeze	25	Type III/Edge Line	White	15 mils	M247	AC/Surface
	26	Type III/Skip Line	Yellow	15 mils	M247	AC/Surface
	27	Type III/Edge Line	White	20 mils	M247	AC/Surface
	28	Type III/Skip Line	Yellow	20 mils	M247	AC/Surface
	29	Type III/Edge Line	White	15 mils	P40	AC/Surface
	30	Type III/Skip Line	Yellow	15 mils	P40	AC/Surface
	31	Type III/Edge Line	White	20 mils	P40	AC/Surface
	32	Type III/Skip Line	Yellow	20 mils	P40	AC/Surface
US 18 Martin, SD/ Dry Freeze	33	Type III/Edge Line	White	15 mils	M247	PCC/Surface
	34	Type III/Skip Line	Yellow	15 mils	M247	PCC/Surface
	35	Type III/Edge Line	White	20 mils	M247	PCC/Surface
	36	Type III/Skip Line	Yellow	20 mils	M247	PCC/Surface
	37	Type III/Edge Line	White	15 mils	Iowa Blend	PCC/Surface
	38	Type III/Skip Line	Yellow	15 mils	Iowa Blend	PCC/Surface
	39	Type III/Edge Line	White	20 mils	Iowa Blend	PCC/Surface
	40	Type III/Skip Line	Yellow	20 mils	Iowa Blend	PCC/Surface
Interstate 90 Presho, SD/ Dry Freeze	41	Type II/Edge Line	Yellow	17 mils	M247	PCC/Inlay
	42	Type II/Edge Line	White	17 mils	M247	AC/Inlay
	43	Type II/Edge Line	Yellow	17 mils	M247	AC/Inlay
	44	Type II/Skip Line	White	17 mils	M247	AC/Inlay
	45	Type II/Edge Line	White	17 mils	P40	AC/Inlay
	46	Type II/Edge Line	Yellow	17 mils	P40	AC/Inlay
	47	Type II/Skip Line	White	17 mils	P40	AC/Inlay
	48	Type III/Edge Line	White	25 mils	M247 + WRE	AC/Inlay
	49	Type III/Edge Line	Yellow	25 mils	M247 + WRE	AC/Inlay
	50	Type III/Skip Line	White	25 mils	M247 + WRE	AC/Inlay

Table 3.6 Epoxy Paint Test Sections

Test Section/ Winter Maintenance	Case No.	Paint Type/ Line Type	Color	Thickness	Reflective Element	Pavement Type/Surface Preparation
US 14 DeSmet, SD/ Wet Freeze	51	Epoxy/Edge Line	White	20 mils	P40	PCC/Inlay
	52	Epoxy/Skip Line	Yellow	20 mils	P40	PCC/Inlay
	53	Epoxy/Edge Line	White	20 mils	P40 + WRE	PCC/Inlay
	54	Epoxy/Skip Line	Yellow	20 mils	P40 + WRE	PCC/Inlay
Interstate 29 Brookings, SD/ Wet Freeze	55	Epoxy/Edge Line	White	20 mils	M247	PCC/Surface
	56	Epoxy/Edge Line	Yellow	20 mils	M247	PCC/Surface
	57	Epoxy/Skip Line	White	20 mils	M247	PCC/Surface
	58	Epoxy/Edge Line	White	20 mils	M247	PCC/Inlay
	59	Epoxy/Edge Line	Yellow	20 mils	M247	PCC/Inlay
	60	Epoxy/Skip Line	White	20 mils	M247	PCC/Inlay
	61	Epoxy/Edge Line	White	20 mils	M247+Megablend	PCC/Inlay
	62	Epoxy/Edge Line	Yellow	20 mils	M247+Megablend	PCC/Inlay
	63	Epoxy/Skip Line	White	20 mils	M247+Megablend	PCC/Inlay
	64	Epoxy/Edge Line	White	20 mils	Iowa Blend	PCC/Inlay
	65	Epoxy/Edge Line	Yellow	20 mils	Iowa Blend	PCC/Inlay
	66	Epoxy/Skip Line	White	20 mils	Iowa Blend	PCC/Inlay
	67	Epoxy/Edge Line	White	20 mils	Megablend	PCC/Inlay
	68	Epoxy/Edge Line	Yellow	20 mils	Megablend	PCC/Inlay
	69	Epoxy/Skip Line	White	20 mils	Megablend	PCC/Inlay

The test section construction started in the summer of 2009 and concluded in the summer of 2011. Depending on the date of construction, the field measurements and data collection spanned at least one winter maintenance cycle. Some of the test sections underwent several winter maintenance cycles. Test sections ranged in length from four to 25 miles. The shortest length per test case was one mile. Following is a description of the seven test sections implemented in this study.

3.2.1 US 212 Redfield Test Section

The US 212 Redfield test section is a two-lane highway located on US Highway 212 west of Redfield, SD, between mile road marker (MRM) 290 and 305. The pavement markings were placed during the fall of 2010 and data collection lasted until the summer of 2012. The collected data covered two cycles of wet freeze winter maintenance during the data collection time period. The pavement marking was waterborne paint, surface applied to AC pavement, and included white edge lines and yellow skip lines. Both waterborne paint Type II and Type III were applied in this test section. Type II was applied at 15 and 17 mils wet thickness while Type III, with the exception of yellow skip lines, was applied at 17 and 20 mils wet thickness. Both M247 and P40 glass spheres were applied separately to all of the waterborne paint types and thicknesses on this test section.

3.2.2 US 12 Aberdeen Test Section

The US 12 Aberdeen test section is located on the eastbound lanes of the four-lane highway east of Aberdeen, SD, between MRM 299 and 303. The pavement markings were placed during the summer of 2011 and data collection lasted until the summer of 2012, including data from one cycle of wet freeze winter maintenance. The pavement marking was waterborne Type III paint, surface applied to PCC pavement, and included white edge lines, white skip lines, and yellow edge lines. M247 and Iowa Blend glass spheres were applied separately to both wet thicknesses of 15 and 20 mils on this test section.

3.2.3 US 14 Midland Test Section

The US 14 Midland test section is a two-lane highway located on US Highway 14 west of Midland, SD, between MRM 160 and 168. The pavement markings were placed during the summer of 2011 and data collection lasted until the summer of 2012, including data from one cycle of dry freeze winter maintenance. The pavement marking was waterborne Type III paint, surface applied to AC pavement, and included white edge lines and yellow skip lines. M247 and P40 glass spheres were applied separately to both wet thicknesses of 15 and 20 mils on this test section.

3.2.4 US 18 Martin Test Section

The US 18 Martin test section is on a two-lane highway located on US Highway 18 west of Martin, SD, between MRM 142 and 148. The pavement markings were placed during the summer of 2011 and data collection lasted until the summer of 2012, including data from one cycle of dry freeze winter maintenance. The pavement marking was waterborne Type III paint, surface applied to PCC pavement, and included white edge lines and yellow skip lines. M247 and Iowa Blend glass spheres were applied separately to both wet thicknesses of 15 and 20 mils on this test section.

3.2.5 I-90 Presho Test Section

The I-90 Presho test section is a four-lane highway located on Interstate 90 (I-90) east of Presho, SD, between MRM 228 and 250. The pavement markings were placed during the summer of 2009 and data collection lasted until the spring of 2011, including two cycles of dry freeze winter maintenance. Both waterborne paint Type II and Type III were inlaid in this test section and included white edge lines, white skip lines, and yellow edge lines. M247 and P40 glass spheres were applied separately with Type II waterborne paint at a wet thickness of 17 mils on AC pavement. An M247 + WRE combination was applied with Type III waterborne paint at a wet thickness of 25 mils on an AC pavement. M247 glass spheres were applied with Type II waterborne paint at a wet thickness of 17 mils for a yellow edge line on a PCC pavement.

3.2.6 US 14 De Smet Test Section

The US 14 De Smet test section is a two-lane highway located on US Highway 14 east and west of De Smet, SD, between MRM 364 and 389. The pavement markings were placed during the summer of 2011 and data collection lasted until the summer of 2012, including one cycle of wet freeze winter maintenance. The pavement marking was epoxy paint inlaid on PCC pavement, and included white edge lines and yellow skip lines. P40 glass spheres and P40 + WRE were applied separately to a wet epoxy paint thickness of 20 mils on this test section.

3.2.7 I-29 Brookings Test Section

The I-29 test section is located on the northbound lanes of the four-lane Interstate 29 (I-29) south of Brookings, SD, between MRM 118 and 127. The pavement markings were placed during the summer of 2011 and data collection lasted until the summer of 2012, including one cycle of wet freeze winter maintenance during the data collection time period. The pavement marking was epoxy paint, surface applied and inlaid on PCC pavement, and included white edge lines, white skip lines, and yellow edge.

M247, Iowa Blend, Megablend, and M247 + Megablend glass spheres were applied separately to a wet epoxy paint thickness of 20 mils on this test section.

3.3 Methods of Evaluation

The application of pavement markings was observed by research personnel in the field during installation. Field notes, photography, and plate samples were obtained during field observations.

The plate samples consisted of inserting a 1/16-inch thick by 2-inch long by 10-inch wide metal plate under the pavement marking machine nozzles and obtaining an in-place sample of the pavement marking paint film as seen in Figure 3.5. The samples were returned to the laboratory for future reference. Plate samples should be evaluated with caution since the volume of paint displaced by reflective elements and the volume of paint lost to the edges of the plate are unknown. Plate samples were obtained at the US 212 Redfield, US 12 Aberdeen, I-90 Presho, US 14 De Smet, and I-29 Brookings test sections.

Figure 3.5 Metal Plate for Paint Thickness Measurement

Between one week and one month after applying the markings, research personnel returned to the site to obtain initial retroreflectivity measurements and digital photography. Retroreflectivity measurements were obtained on dry pavement using the portable retroreflective measurement device. Three measurements were obtained randomly on a 10- to 12-foot-long pavement marking at three to nine locations along each pavement marking combination in the test sections. Similar measurements were made periodically at the same locations to capture retroreflectivity decay with time. For pavement marking combinations with WREs, both dry and wet retroreflective readings were taken and recorded. Wet conditions were simulated by spraying water on the pavement marking until the marking was fully saturated, then a retroreflective reading was taken with the reflectometer in the same manner as on dry pavement. The location of the retroreflectivity measurement was marked so that future measurements can be made at the same location. Retroreflectivity measurements were obtained when temperatures were above 45°F on a monthly basis during the first year after marking application and then every four months thereafter until the test section was abandoned.

Visual rating was also obtained over a 15-foot-long pavement marking for six of the seven test sections. Evaluation of the I-90 Presho test section did not include a visual rating assessment. Visual rating and retroreflectivity measurements of a pavement marking case were performed simultaneously and at the same pavement marking stretch in order to determine if a correlation exists between the two evaluation methods.

3.4 Field Measurement Results

This section presents a summary of the field data that were collected in this study. The measured field data included retroreflectivity, visual rating, and pavement marking paint thickness.

3.4.1 Retroreflectivity

A plot of the measured retroreflectivity values versus the age of the pavement marking for each test section was made. There were approximately three-month-long gaps in the plots that represent winter maintenance periods during which data were not collected. The data grouping is based solely on paint type and color, and makes no distinction among the other pavement marking parameters. However, the effect of the different parameters is discussed in detail in Chapter 0 of this report. In general, the retroreflectivity readings varied between values in excess of 600 mcd/m^2/lux to less than 100 mcd/m^2/lux, and the white paint retroreflectivity was consistently higher than the yellow paint retroreflectivity. The graphs that compare the retroreflectivity of white and yellow paint are shown in Appendix B.

3.4.2 Visual Rating

Visual rating was assessed for all test sections except the Presho test section on I-90. The visual ratings of the epoxy paint test sections (De Smet and Brookings) remained at 10 for the duration of the data collection phase. The graphs that illustrate the summary of the measured visual rating versus the age of the pavement marking are shown in Appendix B. The measurements from the De Smet and Brookings test sites are not presented in these graphs. For the duration of data collection, the visual rating varied between a high of 10 and a low of 5.

3.4.3 Paint Thickness

Plate samples of paint thickness were taken at five of the seven test sections. SDDOT field verification of the specified wet paint thickness is done indirectly by verifying the volume of the paint used for a given length of pavement marking lines.

Using the dry to wet film ratio provided by paint manufacturers, the wet film paint thickness was back calculated from the dry thickness of paint on the plate samples. A Mitutoyo 342-361 Digital Point Micrometer, seen in Figure 3.6, was used to measure the paint thicknesses. The micrometer's design made it possible to measure the paint thickness between glass spheres. Only waterborne paint sample plates could be measured since the higher rate of reflective elements used with epoxy paint made it impossible to measure paint thickness between reflective elements on the epoxy paint samples.

Figure 3.6 Mitutoyo 342-361 Digital Point Micrometer

The dry paint thickness was determined by subtracting the measured plate thickness from the measured sample plate (plate + dry paint) thickness. The sample plate thickness was measured at spots on the plate that did not include reflective elements. The sample plate thickness was found by taking an average of 10 random measurements between reflective elements. The plate thickness was found as the average of five random measurements. The wet paint film thickness was calculated from the measured dry paint thickness and the dry-to-wet film ratio provided by the paint manufacturer. For Type II waterborne paint, the dry-to-wet ratio used was 9.8/16. For Type III waterborne paint, the dry-to-wet ratio used was 10/16 when the specified wet thickness was 15 to 20 mils, and 16/25 when the specified wet thickness was 25 mils. Figure 3.7 shows the calculated wet film paint thickness versus the specified wet film paint thickness for the waterborne test sections where plate samples were obtained. In **Figure**, the diagonal line represents data points where the measured and calculated wet paint thicknesses are equal. Data points above the diagonal line represent the cases when the measured thickness exceeds the specified wet paint thickness, while data points below the diagonal line represent the cases when the measured thickness is less than the specified wet paint thickness. The data indicate that for the majority of the 15 mil and 20 mil cases, the measured paint thickness was less than the specified paint thickness. It is important to note that the quantity of plate samples obtained in this study is relatively small when compared with the number of miles of pavement markings applied. Thus, the plate samples represent a small percentage of the total pavement markings and may not necessarily reflect a trend.

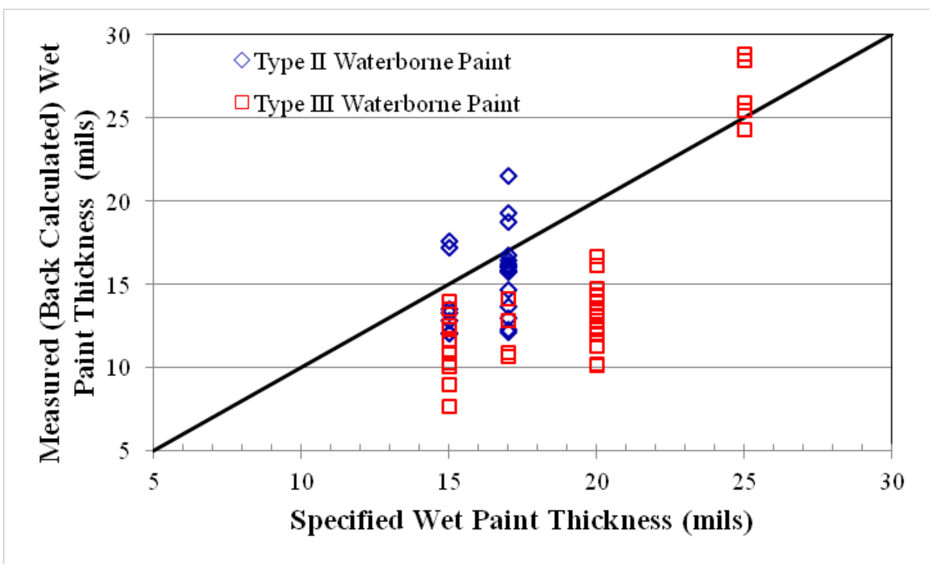


Figure 3.7 3/8″ Measured versus Specified Wet Paint Thickness

4. DATA ANALYSIS

This section covers the analysis of the data presented in Section 3. The analytical work included: 1) an investigation of possible correlation between retroreflectivity and visual rating, 2) development of retroreflectivity decay equations for the different pavement marking combinations, 3) parametric analysis of retroreflectivity decay, and 4) cost comparisons of the different pavement marking options.

4.1 Retroreflectivity versus Visual Rating

Visual rating is essentially a daytime qualitative assessment that determines how much of the pavement marking is remaining on the pavement. Retroreflectivity is a quantitative measurement that determines if the pavement marking is functioning properly at night. The data collected in this study were used to determine if a correlation exists between retroreflectivity and visual rating.

In this study, a retroreflectivity measurement of a pavement marking location was accompanied with a visual rating assessment of the same location. Results of the retroreflectivity and visual rating analysis are shown in Appendix B. For the 40 cases considered, R^2 varied between a minimum of 0.02 and a maximum of 0.84. Of the 40 cases, 25 cases had an R^2 value below 0.50, 10 cases had an R^2 value between 0.5 and 0.7, and only five cases had an R^2 value above 0.70. The R^2 values for retroreflectivity versus visual rating indicate weak to moderately strong correlations for all pavement marking cases. The number of data points presented in each plot was dependent upon the data collection duration which varied from one test section to another, and even from one pavement marking combination to another within the same test section. The inconsistency in the data collection was imposed by the construction schedule of the test sections. Due to the inconsistency in the data populations and the limited amount of data in some of the pavement marking cases, the data obtained were insufficient to perform parametric analysis on the factors that influence the relationship between retroreflectivity and visual rating.

4.2 Retroreflectivity Exponential Decay Model

Many studies have implemented exponential decay equations to model retroreflectivity degradation with time (Thamizharasan et al., 2003; Sarasua, et al., 2003; Kopf, 2004). Based on the work done in previous studies, Equation 4.1 was used in this study to model retroreflectivity deterioration.

$$r = A e^{-Bt} \qquad \text{Equation 4.1}$$

Where

t	=	time in months from installation
r	=	retroreflectivity at time t from installation
A	=	initial retroreflectivity at installation (at t = 0)
B	=	rate of decay coefficient

Retroreflectivity measurements were plotted versus the age of the pavement marking and the best fit exponential decay model was developed for each pavement marking case. As an example, the retroreflectivity data from the US 212 Redfield test section for a yellow skip line, Type II waterborne paint, 15 mil thickness, and M247 reflective elements surface applied on asphalt concrete pavement are plotted in Figure 4.1. Also plotted in

Figure are the data points for the corresponding visual rating. Each data point in Figure 4.1represents the average of the measurements made at a specific pavement marking age. The vertical line passing through each data point represents the range of the measurements at that data point. Figure 4.1 also shows the best fit exponential decay equation and the corresponding coefficient of determination for the retroreflectivity data.

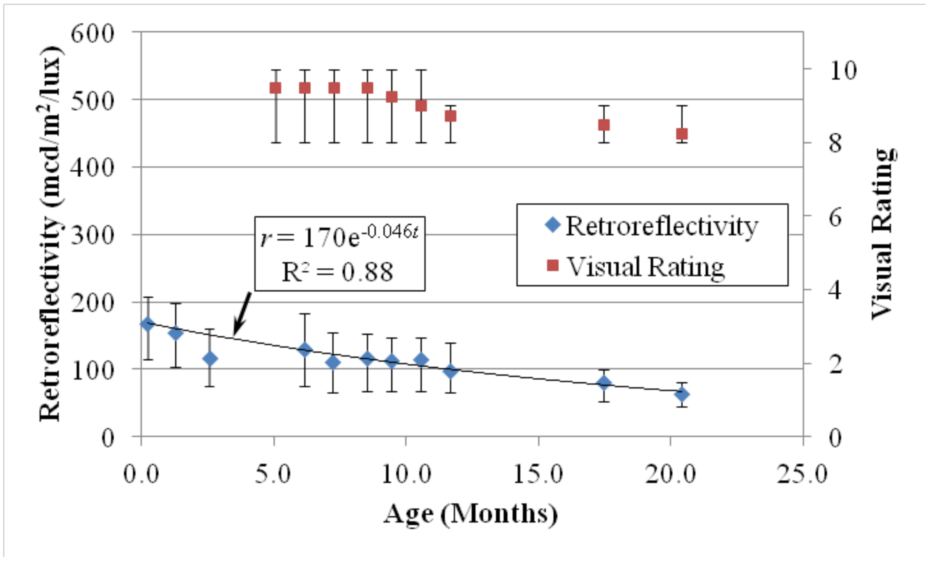


Figure 4.1 Retroreflectivity Decay Model for a Data Set from the US 212 Redfield Test Section

Retroreflectivity decay models were developed for every pavement marking case considered in this study. Table 4.1, Table 4.2, and Table 4.3 present the *dry* retroreflectivity decay models for the wet freeze waterborne paint cases, dry freeze waterborne paint cases, and epoxy paint cases, respectively. Table 4.4 presents the *wet* retroreflectivity decay models for the pavement marking cases where WREs were used.

- Based on the information presented in Table 4.1 through Table 4.4, the following observations are made.

<u>Dry retroreflectivity decay models for the wet freeze waterborne paint cases (Table 4.1)</u>

- Except for case #12, the coefficient of determination (R^2) varied between 0.54 and 0.98 with 83% of the R^2 values at or above 0.70. The R^2 value for case #12 was 0.36.
- All of the yellow paint cases exhibited initial retroreflectivity below 200 (mcd/m2/lux). The initial retroreflectivity of the white paint cases varied between 255 and 430 (mcd/m2/lux). It should be noted that the retroreflectivity threshold used by SDDOT is 100 (mcd/m^2/lux).
- The decay rate coefficient for the yellow paint cases varied between 0.026 and 0.050, while those for the white paint cases varied between 0.033 and 0.100.

<u>Dry retroreflectivity decay models for the dry freeze waterborne paint cases(Table 4.2)</u>

- The negative coefficient of determination (R^2) for cases #37, #41, and #48 indicates that the exponential decay model is a poor representative for the data in those three cases.
- Except for the cases with a negative R^2, the R^2 varied between 0.04 and 0.90 with 44% of the R^2 values above 0.70 and 44% of the R^2 values below 0.50.
- All of the yellow paint cases with only glass spheres as reflective elements exhibited initial retroreflectivity below 200 mcd/m^2/lux. The initial retroreflectivity of the white paint cases with only glass spheres as reflective elements varied between 225 and 400 mcd/m^2/lux.
- When WREs were used, the initial retroreflectivity was 310 mcd/m^2/lux for the yellow paint case, and 550 and 590 mcd/m^2/lux for the two white paint cases.

- The decay rate coefficient for the yellow paint cases varied between 0.001 and 0.044, while those for the white paint cases varied between 0.018 and 0.036.

Decay models for the epoxy paint cases (Table 4.3)

- The negative coefficient of determination (R^2) for case #60 indicates that the exponential decay model is a poor model for the data in that case.
- Except for the case with a negative R^2, the R^2 varied between 0.26 and 0.98 with 74% of the R^2 values above 0.70 and 21% of the R^2 values below 0.50.
- The initial retroreflectivity of the yellow paint cases with only glass spheres as reflective elements varied between 150 and 275 mcd/m^2/lux. The initial retroreflectivity of the white paint cases with only glass spheres as reflective elements varied between 360 and 555 mcd/m^2/lux.
- When WREs were used, the initial retroreflectivity for the yellow paint case was 315 mcd/m^2/lux; and for the white paint case, the retroreflectivity was 370 mcd/m^2/lux.
- The decay rate coefficients for yellow paint cases varied between 0.005 and 0.029, while those for the white paint cases varied between 0.005 and 0.035.

Wet retroreflectivity decay models for the pavement marking with WRE cases (Table 4.4)

- The R^2 values for the waterborne paint cases varied between 0.24 and 0.67. The R^2 values for the epoxy paint cases were 0.89 and 0.93.
- The initial retroreflectivity of the yellow epoxy paint case was the highest at 280 mcd/m^2/lux. The initial retroreflectivity of the white paint cases varied between 140 and 210 mcd/m^2/lux.
- The decay rate coefficients for the two yellow paint cases were 0.095 and 0.103, while those for the white paint cases varied between 0.121 and 0.161.

Table 4.1 Exponential Decay Models for Wet Freeze Waterborne Paint

Test Section/ Winter Maintenance	Case No.	Decay Model Equation	R^2	Initial Retroreflectivity (*A*)	Decay Coefficient (*B*)
US 212 Redfield, SD/ Wet Freeze	1	$r = 360\ e^{-0.098*t}$	0.62	360	-0.098
	2	$r = 330\ e^{-0.1*t}$	0.71	330	-0.100
	3	$r = 260\ e^{-0.052*t}$	0.84	260	-0.052
	4	$r = 285\ e^{-0.059*t}$	0.79	285	-0.059
	5	$r = 440\ e^{-0.074*t}$	0.72	440	-0.074
	6	$r = 430\ e^{-0.06*t}$	0.92	430	-0.060
	7	$r = 320\ e^{-0.08*t}$	0.54	320	-0.080
	8	$r = 330\ e^{-0.056*t}$	0.73	330	-0.056
	9	$r = 170\ e^{-0.046*t}$	0.88	170	-0.046
	10	$r = 155\ e^{-0.046*t}$	0.89	155	-0.046
	11	$r = 150\ e^{-0.03*t}$	0.57	150	-0.030
	12	$r = 160\ e^{-0.038*t}$	0.36	160	-0.038
US 12 Aberdeen, SD/ Wet Freeze	13	$r = 155\ e^{-0.05*t}$	0.87	155	-0.050
	14	$r = 300\ e^{-0.053*t}$	0.88	300	-0.053
	15	$r = 320\ e^{-0.034*t}$	0.91	320	-0.034
	16	$r = 165\ e^{-0.034*t}$	0.98	165	-0.034
	17	$r = 325\ e^{-0.046*t}$	0.80	325	-0.046
	18	$r = 350\ e^{-0.037*t}$	0.89	350	-0.037
	19	$r = 140\ e^{-0.026*t}$	0.85	140	-0.026
	20	$r = 260\ e^{-0.035*t}$	0.90	260	-0.035
	21	$r = 255\ e^{-0.033*t}$	0.90	255	-0.033
	22	$r = 155\ e^{-0.04*t}$	0.89	155	-0.040
	23	$r = 305\ e^{-0.068*t}$	0.87	305	-0.068
	24	$r = 295\ e^{-0.035*t}$	0.87	295	-0.035

Table 4.2 Exponential Decay Models for Dry Freeze Waterborne Paint

Test Section/ Winter Maintenance	Case No.	Decay Model Equation	R^2	Initial Retroreflectivity (A)	Decay Coefficient (B)
US 14 Midland, SD/ Dry Freeze	25	$r = 305e^{-0.018*t}$	0.48	305	-0.018
	26	$r = 135e^{-0.004*t}$	0.20	135	-0.004
	27	$r = 385e^{-0.031*t}$	0.77	385	-0.031
	28	$r = 165e^{-0.019*t}$	0.60	165	-0.019
	29	$r = 245e^{-0.029*t}$	0.87	245	-0.029
	30	$r = 115e^{-0.014*t}$	0.76	115	-0.014
	31	$r = 295e^{-0.018*t}$	0.61	295	-0.018
	32	$r = 140e^{-0.001*t}$	0.04	140	-0.001
US 18 Martin, SD/ Dry Freeze	33	$r = 300e^{-0.022*t}$	0.43	300	-0.022
	34	$r = 110e^{-0.025*t}$	0.78	110	-0.025
	35	$r = 375e^{-0.024*t}$	0.72	375	-0.024
	36	$r = 140e^{-0.022*t}$	0.90	140	-0.022
	37	$r = 290e^{-0.018*t}$	-0.33	290	-0.018
	38	$r = 125e^{-0.044*t}$	0.87	125	-0.044
	39	$r = 380e^{-0.025*t}$	0.79	380	-0.025
	40	$r = 155e^{-0.008*t}$	0.41	155	-0.008
Interstate 90 Presho, SD/ Dry Freeze	41	$r = 140e^{-0.004*t}$	-1.11	140	-0.004
	42	$r = 350e^{-0.024*t}$	0.49	350	-0.024
	43	$r = 140e^{-0.014*t}$	0.55	140	-0.024
	44	$r = 400e^{-0.022*t}$	0.42	400	-0.022
	45	$r = 225e^{-0.026*t}$	0.62	225	-0.026
	46	$r = 155e^{-0.008*t}$	0.83	155	-0.008
	47	$r = 320e^{-0.02*t}$	0.86	320	-0.020
	48	$r = 550e^{-0.032*t}$	-0.07	550	-0.032
	49	$r = 310e^{-0.023*t}$	0.88	310	-0.023
	50	$r = 590e^{-0.036*t}$	0.46	590	-0.036

Table 4.3 Exponential Decay Models for Epoxy Paint

Test Section/ Winter Maintenance	Case No.	Decay Model Equation	R^2	Initial Retroreflectivity (A)	Decay Coefficient (B)
US 14 DeSmet, SD/ Wet Freeze	51	$r = 450e^{-0.027*t}$	0.96	450	-0.027
	52	$r = 150e^{-0.009*t}$	0.26	150	-0.009
	53	$r = 370e^{-0.035*t}$	0.90	370	-0.035
	54	$r = 315e^{-0.012*t}$	0.36	315	-0.012
Interstate 29 Brookings, SD/ Wet Freeze	55	$r = 360e^{-0.022*t}$	0.36	360	-0.022
	56	$r = 220e^{-0.029*t}$	0.85	220	-0.029
	57	$r = 375e^{-0.022*t}$	0.86	375	-0.022
	58	$r = 400e^{-0.02*t}$	0.90	400	-0.020
	59	$r = 220e^{-0.014*t}$	0.52	220	-0.014
	60	$r = 360e^{-0.007*t}$	-0.034	360	-0.007
	61	$r = 445e^{-0.025*t}$	0.79	445	-0.025
	62	$r = 235e^{-0.007*t}$	0.72	235	-0.007
	63	$r = 465e^{-0.005*t}$	0.77	465	-0.005
	64	$r = 510e^{-0.03*t}$	0.90	510	-0.030
	65	$r = 250e^{0.005*t}$	0.86	250	0.005
	66	$r = 475e^{0.01*t}$	0.75	475	0.010
	67	$r = 555e^{-0.03*t}$	0.96	555	-0.030
	68	$r = 275e^{-0.025*t}$	0.98	275	-0.025
	69	$r = 505e^{-0.008*t}$	0.72	505	-0.008

Table 4.4 Exponential Decay Models for Wet Paint Containing WRE

Test Section/ Winter Maintenance	Case No.	Decay Model Equation	R^2	Initial Retroreflectivity (A)	Decay Coefficient (B)
Interstate 90 Presho, SD/ Dry Freeze	48 (wet)	$r = 140e^{-0.121*t}$	0.24	140	-0.121
	49 (wet)	$r = 190e^{-0.095*t}$	0.67	190	-0.095
	50 (wet)	$r = 210e^{-0.124*t}$	0.28	210	-0.124
US 14 DeSmet, SD/ Wet Freeze	53 (wet)	$r = 190e^{-0.161*t}$	0.89	190	-0.161
	54 (wet)	$r = 280e^{-0.103*t}$	0.93	280	-0.103

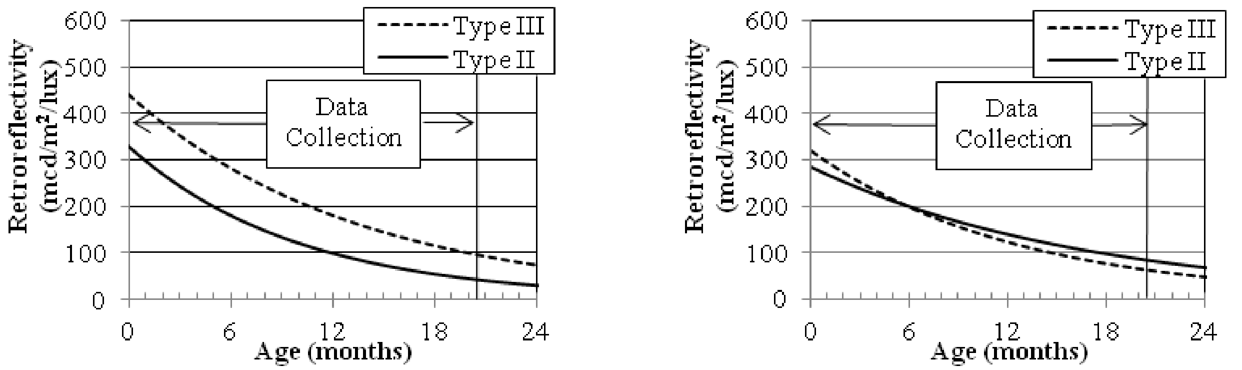
4.3 Parametric Analysis of Retroreflectivity

A parametric analysis was conducted to determine the influence of the different parameters on retroreflectivity. The values of the parameters were presented in Table 4.3. The analysis was performed by changing the value of one parameter while maintaining all other parameters unchanged. The influence of a particular parameter on retroreflectivity was assessed by examining the change in initial retroreflectivity and in retroreflectivity decay. Retroreflectivity decay was considered as the ratio of the retroreflectivity at 12 months to the initial retroreflectivity, expressed as a percentage. Following are the results of the parametric study.

4.3.1 Effect of Waterborne Paint Type

This study investigated two types of waterborne paint: Type II and Type III. Type III can be applied at a greater wet thicknesses and is presumably more durable than Type II (General Services Administration, 2007). Retroreflectivity and durability may not necessarily be related, but the adhesion quality of the paint may have an influence on the retention of the reflective elements in the paint matrix.

Figure 4.2 shows retroreflectivity decay based on paint type for white edge line marking placed on AC in wet freeze regions (Redfield test section). In Figure 4.2(a) the reflective element is M247 while in Figure 4.2(b) the reflective element is P40. In both cases, the paint thickness is 17 mils. The data collection timeline is also indicated in the plots. Table 4.5 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay equation.



(a) M247, 17 mils, WEL; Redfield Test Section **(b)** P40, 17 mils, WEL; Redfield Test Section

Figure 4.2 Effect of Paint Type; Waterborne Paint in on AC Wet Freeze

Table 4.5 Data Comparison for the Effect of Paint Type; Waterborne Paint on AC in Wet Freeze

Reflective Element	Paint Type	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
M247	Type II	2	0.71	330	0.100	30
	Type III	5	0.72	440	0.074	41
P40	Type II	4	0.79	285	0.059	49
	Type III	7	0.54	320	0.080	38

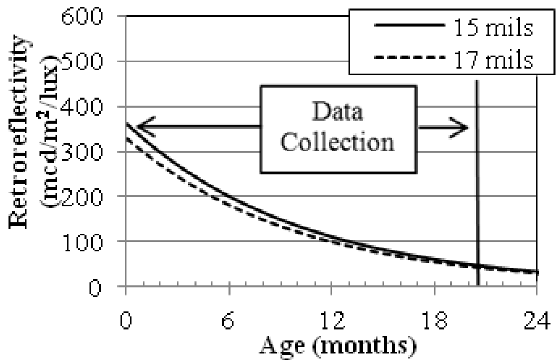
Type III paint resulted in higher initial retroreflectivity than Type II paint. When M247 elements were used, the initial retroreflectivity of Type III paint was 1.33 times that of Type II paint. On the other hand, when P40 was used the initial retroreflectivity of Type III paint was 1.12 times that of Type II.
The difference between Type II paint and Type III paint retroreflectivity decay was marginal. With M247, the retroreflectivity at 12 months of Type II and Type III paint was 30% and 41%, respectively, of the initial retroreflectivity. With P40, retroreflectivity at 12 months of Type II and Type III paint was 49% and 38%, respectively, of the initial retroreflectivity.

4.3.2 Effect of Paint Thickness

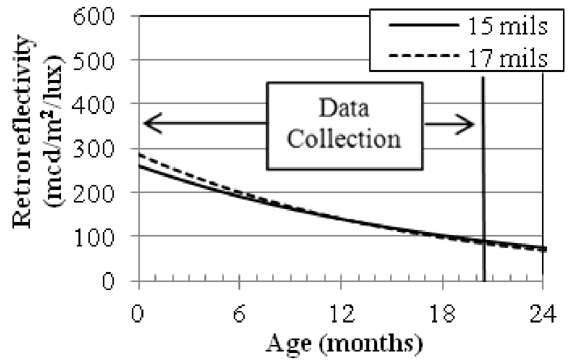
Several waterborne paint thicknesses were implemented in this study. The paint thicknesses were: 1) 15 mils and 17 mils for Type II waterborne paint in *wet freeze* regions on *AC pavement*, 2) 17 mils and 20 mils for Type III waterborne paint in *wet freeze* regions on *AC pavement*, 3) 15 mils and 20 mils for Type III waterborne paint in *wet freeze* regions on *PCC pavement*, 4) 15 mils and 20 mils for Type III waterborne paint in *dry freeze* regions on *AC pavement*, and 5) 15 mils and 20 mils for Type III waterborne paint in *dry freeze* regions on *PCC pavement*. Following are the results from the effects of paint thickness.

4.3.2.1 Type II Waterborne Paint, Wet Freeze Region, AC Pavement

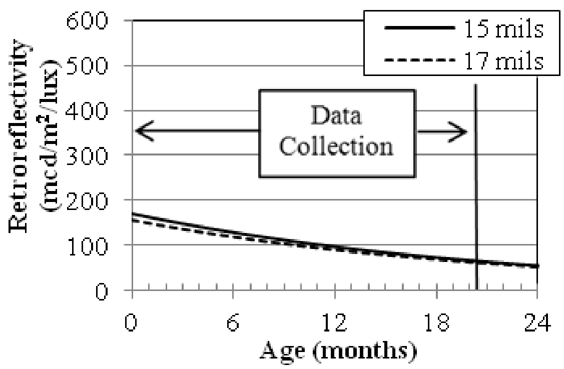
Figure 4.3 shows retroreflectivity decay based on specified paint thicknesses of 15 and 17 mils of Type II waterborne paint placed on AC in wet freeze regions (Redfield test section). In Figure 4.3(a) and (c) the reflective element is M247 while in Figure 4.3(b) and (d) the reflective element is P40. In Figure 4.3(a) and (b) the pavement marking line type is white edge line while in Figure 4.3(c) and (d) the pavement marking line type is yellow skip line. Table 4.6 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay equation.



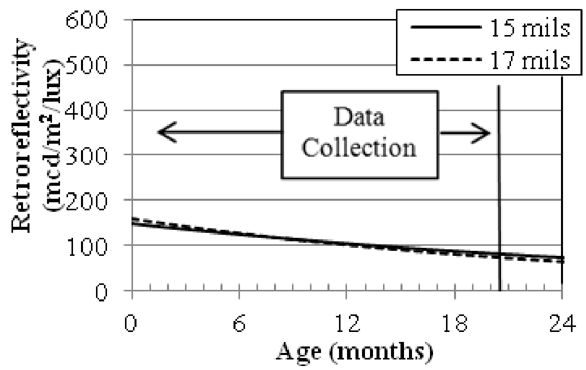
(a) WEL and M247; Redfield Test Section



(b) WEL and P40; Redfield Test Section



(c) YSL and M247; Redfield Test Section



(d) YSL and P40; Redfield Test Section

Figure 4.3 Effect of Paint Thickness; Type II Waterborne Paint on AC in Wet Freeze

Table 4.6 Data Comparison for the Effect of Paint Thickness; Type II Waterborne Paint on AC in Wet Freeze

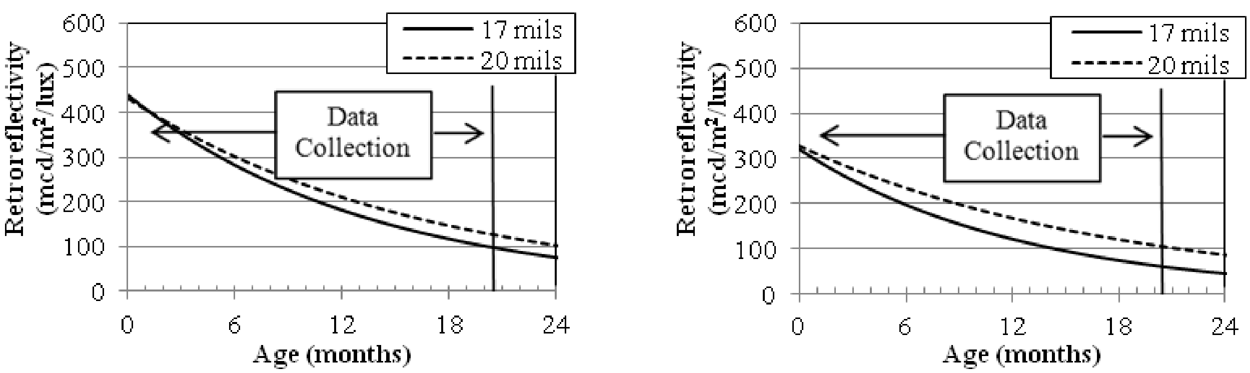
Paint and Line Type	Reflective Element	Paint Thickness	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type II White Edge Line (WEL)	M247	15 mils	1	0.62	360	0.098	31
		17 mils	2	0.71	330	0.100	30
	P40	15 mils	3	0.84	260	0.052	54
		17 mils	4	0.79	285	0.059	49
Type II Yellow Skip Line (YSL)	M247	15 mils	9	0.88	170	0.046	58
		17 mils	10	0.89	155	0.046	58
	P40	15 mils	11	0.56	150	0.030	70
		17 mils	12	0.36	160	0.038	63

The yellow paint combinations exhibited low initial retroreflectivity that ranged between 150 and 170 mcd/m^2/lux. The retroreflectivity of the yellow paint combinations reached the threshold of 100 mcd/m^2/lux at approximately 12 months. Due to its poor performance, the yellow paint in Figure 4.3(c) and (d) will not be discussed further.

The results indicate that for the same combination of paint type, line type, and reflective element on AC in a wet freeze region, a change in the specified white paint thickness from 15 mils to 17 mils resulted in marginal change in initial retroreflectivity and decay rate.

4.3.2.2 Type III Waterborne Paint, Wet Freeze Region, AC Pavement

Figure 4.4 shows retroreflectivity decay based on specified paint thicknesses of 17 and 20 mils of Type III waterborne paint placed on AC in wet freeze regions (Redfield test section). In Figure 4.4(a) the reflective element is M247 while in Figure 4.4(b) the reflective element is P40. In both cases, the pavement marking line type is white edge line. Table 4.7 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay equation.



(a) WEL and M247; Redfield Test Section **(b)** WEL and P40; Redfield Test Section

Figure 4.4 Effect of Paint Thickness; Type III Waterborne Paint on AC in Wet Freeze

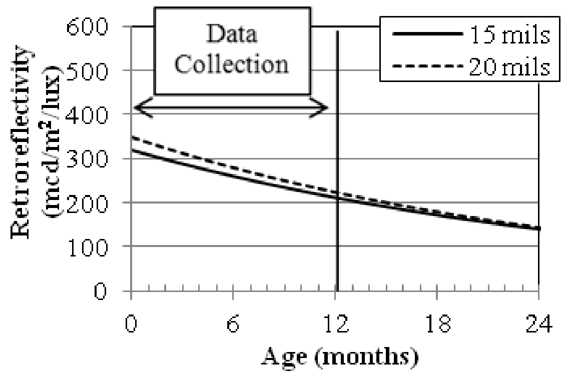
Table 4.7 Data Comparison for the Effect of Paint Thickness; Type III Waterborne Paint on AC in Wet Freeze

Paint and Line Type	Reflective Element	Paint Thickness	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type III White Edge Line (WEL)	M247	17 mils	5	0.72	440	0.074	41
		20 mils	6	0.92	430	0.060	49
	P40	17 mils	7	0.54	320	0.080	39
		20 mils	8	0.73	330	0.056	51

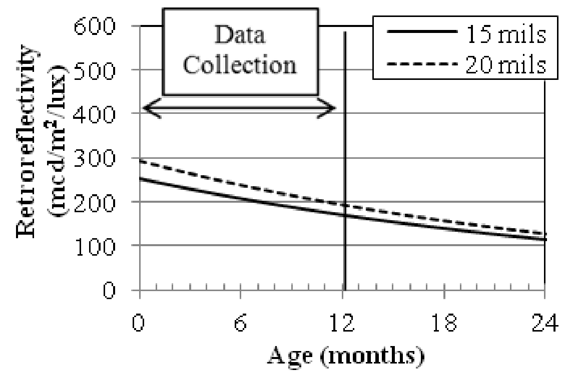
The results indicate that for the same combination of paint type, line type, and reflective element on AC in a wet freeze region, the initial retroreflectivity was practically unchanged when the specified paint thickness was changed from 17 mils to 20 mils. However, the decay rate for the specified paint thickness of 20 mils was marginally lower than that for the specified 17 mils.

4.3.2.3 Type III Waterborne Paint, Wet Freeze Region, PCC Pavement

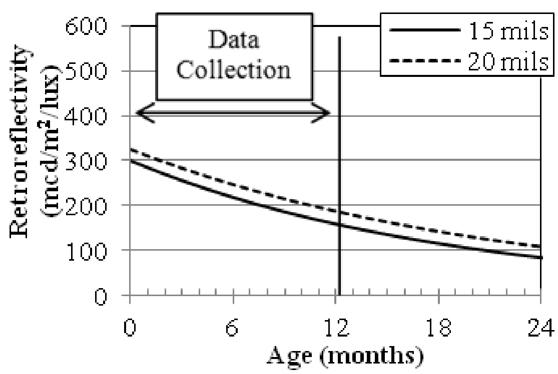
Figure 4.5 shows retroreflectivity decay based on specified paint thicknesses of 15 and 20 mils of Type III waterborne paint placed on PCC in wet freeze regions (Aberdeen test section). In Figure 4.5(a), (c), and (e) the reflective element is M247 while in Figure 4.5(b), (d), and (f) the reflective element is P40. In both cases, the pavement marking line type is white edge line. In Figure 4.5(a) and (b) the pavement marking line type is white edge line. In Figure 4.5(c) and (d) the pavement marking line type is white skip line. In Figure 4.5(e) and (f) the pavement marking line type is yellow edge line. Table 4.8 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



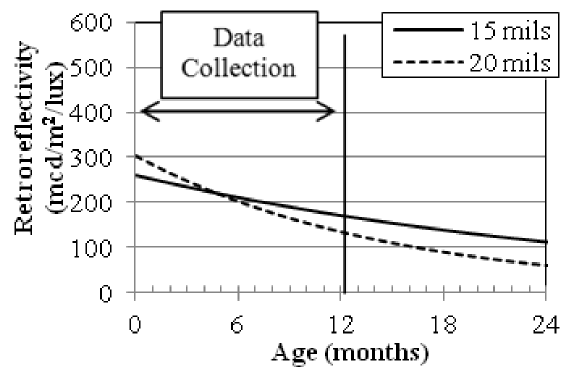
(a) WEL and M247; Aberdeen Test Section



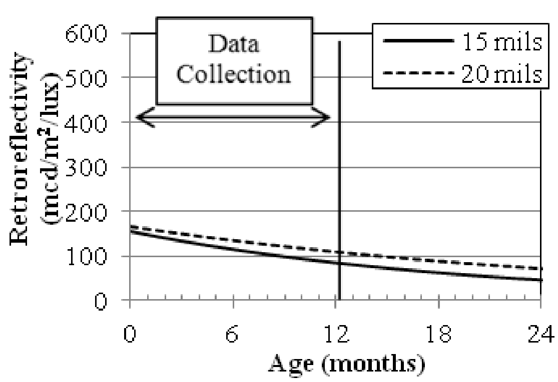
(b) WEL and Iowa Blend; Aberdeen Test Section



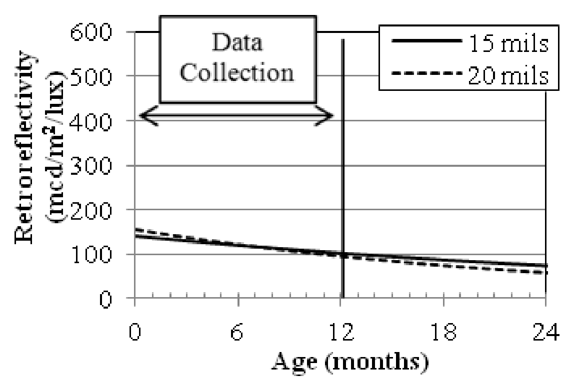
(c) WSL and M247; Aberdeen Test Section



(d) WSL and Iowa Blend; Aberdeen Test Section



(e) YEL and M247; Aberdeen Test Section



(f) YEL and Iowa Blend; Aberdeen Test Section

Figure 4.5 Effect of Paint Thickness; Type III Waterborne Paint on PCC in Wet Freeze

Table 4.8 Data Comparison for the Effect of Paint Thickness; Type III Waterborne Paint on PCC in Wet Freeze

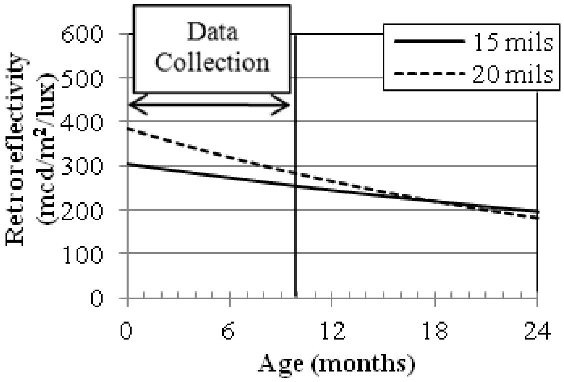
Paint and Line Type	Reflective Element	Paint Thickness	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type III White Edge Line (WEL)	M247	15 mils	15	0.91	320	0.034	66
		20 mils	18	0.89	350	0.037	64
	Iowa Blend	15 mils	21	0.90	255	0.033	67
		20 mils	24	0.87	295	0.035	66
Type III White Skip Line (WSL)	M247	15 mils	14	0.88	300	0.053	53
		20 mils	17	0.85	325	0.046	56
	Iowa Blend	15 mils	20	0.90	260	0.035	66
		20 mils	23	0.87	305	0.068	44
Type III Yellow Edge Line (YEL)	M247	15 mils	13	0.87	155	0.050	55
		20 mils	16	0.98	165	0.034	66
	Iowa Blend	15 mils	19	0.85	140	0.026	73
		20 mils	22	0.89	155	0.040	62

The yellow paint combinations exhibited low initial retroreflectivity that ranged between 140 and 165 mcd/m^2/lux. The retroreflectivity of the yellow paint combinations reached the threshold of 100 mcd/m^2/lux at approximately 12 months. Due to its poor performance, the yellow paint in 2 (e) and (f) will not be discussed further.

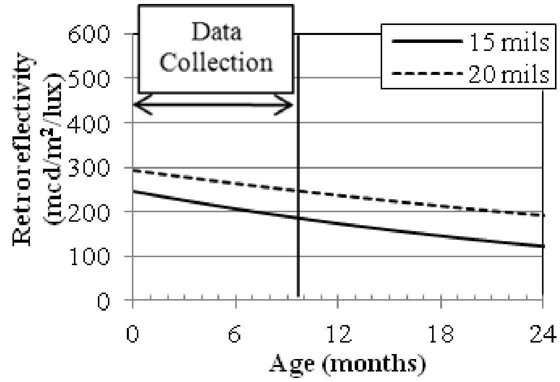
Except for the case of white skip line with Iowa blend shown in **Error! Reference source not found.**(d), the results indicate that for the same combination of paint type, line type, and reflective element on PCC in a wet freeze region, a change in the specified white paint thickness from 15 mils to 20 mils resulted in marginal changes in initial retroreflectivity and decay rate. For the white skip line with Iowa blend, increasing the specified paint thickness from 15 mils to 20 mils resulted in a 17% increase in initial retroreflectivity and a 33% decrease in the percentage of initial retroreflectivity remaining at 12 months.

4.3.2.4 Type III Waterborne Paint, Dry Freeze Region, AC Pavement

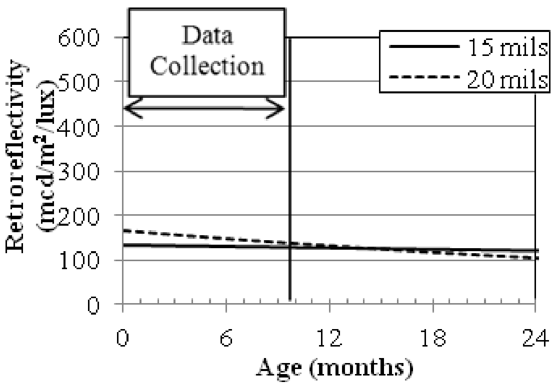
Figure 4.6 shows retroreflectivity decay based on specified paint thicknesses of 15 and 20 mils of Type III waterborne paint placed on AC in dry freeze regions (Midland test section). In Figure 4.6(a) and (c) the reflective element is M247 while in Figure 4.6(b) and (d) the reflective element is P40. In Figure 4.6**Figure** (a) and (b) the pavement marking line type is white edge line while in Figure4.6(c) and (d) the pavement marking line type is yellow skip line. Table 4.9 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



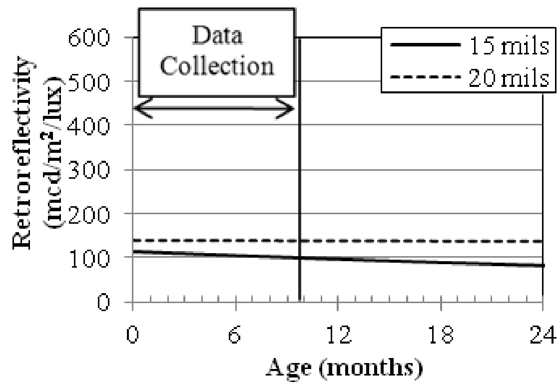
(a) WEL and M247; Midland Test Section



(b) WEL and P40; Midland Test Section



(c) YSL and M247; Midland Test Section



(d) YSL and P40; Midland Test Section

Figure 4.6 Effect of Paint Thickness; Type III Waterborne Paint on AC in Dry Freeze

Table 4.9 Data Comparison for the Effect of Paint Thickness; Type III Waterborne Paint on AC in Dry Freeze

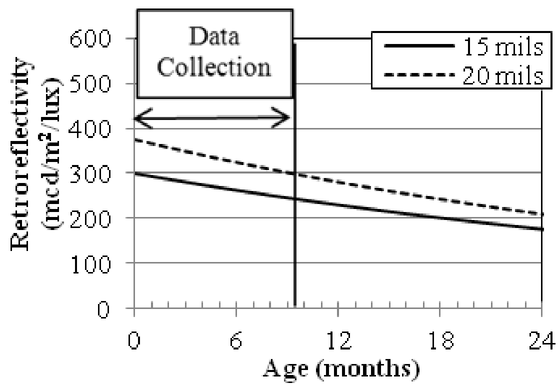
Paint and Line Type	Reflective Element	Paint Thickness	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type III White Edge Line (WEL)	M247	15 mils	25	0.48	305	0.018	81
		20 mils	27	0.77	385	0.031	69
	P40	15 mils	29	0.87	245	0.029	71
		20 mils	31	0.61	295	0.018	81
Type III Yellow Skip Line (WEL)	M247	15 mils	26	0.20	135	0.004	95
		20 mils	28	0.60	165	0.019	80
	P40	15 mils	30	0.76	115	0.014	85
		20 mils	32	0.04	140	0.001	99

The decay models for the cases shown in Figure 4.6 were based on a limited amount of data (10 months) and should be interpreted with caution.

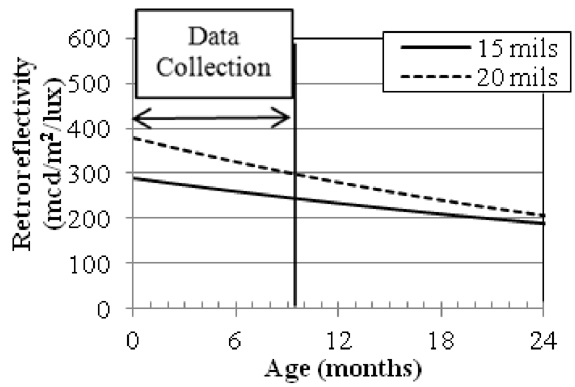
The yellow paint combinations exhibited low initial retroreflectivity that ranged between 115 and 165 mcd/m^2/lux. Except for the case of 20 mils and P40, the retroreflectivity of the yellow paint combinations reached the threshold of 100 mcd/m^2/lux at approximately 12 months. The case of 20 mils and P40 did not exhibit retroreflectivity decay and maintained its low initial retroreflectivity of approximately 140 mils. Due to its poor performance, the yellow paint in **Figure** (c) and (d) will not be discussed further. The results indicate that for Type III white paint on AC in a dry freeze region, a change in the specified white paint thickness from 15 mils to 20 mils resulted in an increase in initial retroreflectivity. When M247 was used, the initial retroreflectivity of the 20-mil thick paint was 1.26 times that of the 15 mils thickness. When P40 was used, the initial retroreflectivity of the 20 mils thick paint was 1.20 times that of the 15 mils thickness. The decay rate of the 20 mils with the M247 was higher than that of the 15 mils. However, the decay rate of the 20 mils with the P40 was lower than that of the 15 mils. In all cases, the retroreflectivity decay model remained above 100 mcd/m^2/lux for more than 24 months. The reader is reminded that Figure 4.6 was based on a limited amount of data (10 months) and should be interpreted with caution.

4.3.2.5 Type III Waterborne Paint, Dry Freeze Region, PCC Pavement

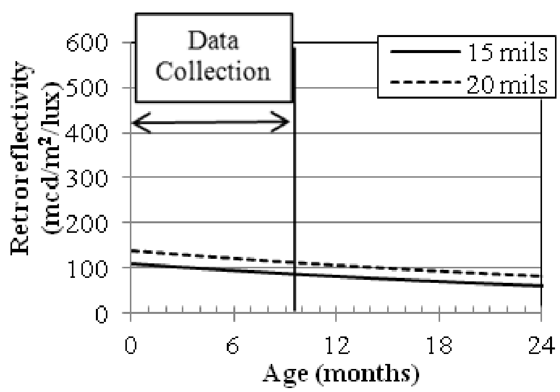
Figure 4.7 shows retroreflectivity decay based on specified paint thicknesses of 15 and 20 mils of Type III waterborne paint placed on PCC in dry freeze regions (Martin test section). In Figure 4.7(a) and (c) the reflective element is M247 while in Figure 4.7(b) and (d) the reflective element is Iowa Blend. In Figure 4.7(a) and (b) the pavement marking line type is white edge line while in Figure 4.7(c) and (d) the pavement marking line type is yellow skip line. Table 4.10 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



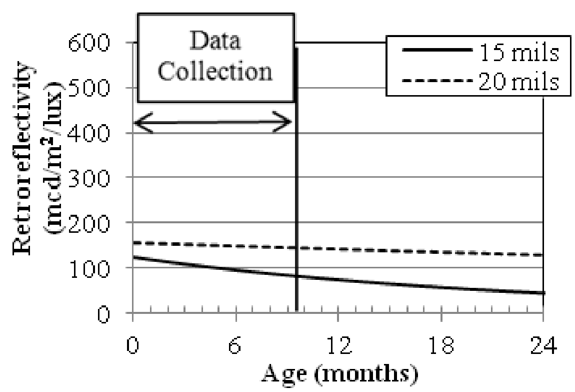
(a) WEL and M247; Martin Test Section



(b) WEL and Iowa Blend; Martin Test Section



(c) YSL and M247; Martin Test Section



(d) YSL and Iowa Blend; Martin Test Section

Figure 4.7 Effect of Paint Thickness; Type III Waterborne Paint on PCC in Dry Freeze

Table 4.10 Data Comparison for the Effect of Paint Thickness; Type III Waterborne Paint on PCC in Dry Freeze

Paint and Line Type	Reflective Element	Paint Thickness	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type III White Edge Line (WEL)	M247	15 mils	33	0.43	300	0.022	77
		20 mils	35	0.72	375	0.024	75
	Iowa Blend	15 mils	37	-0.33	290	0.018	81
		20 mils	39	0.79	380	0.025	74
Type III Yellow Skip Line (YSL)	M247	15 mils	34	0.78	110	0.025	74
		20 mils	36	0.90	140	0.022	77
	Iowa Blend	15 mils	38	0.87	125	0.044	59
		20 mils	40	0.41	155	0.008	91

The decay models for the cases shown in Figure 4.7 were based on a limited amount of data (10 months) and should be interpreted with caution.

The yellow paint combinations exhibited low initial retroreflectivity that ranged between 110 and 155 mcd/m^2/lux. Due to its poor performance, the yellow paint in Figure 4.7(c) and (d) will not be discussed further.

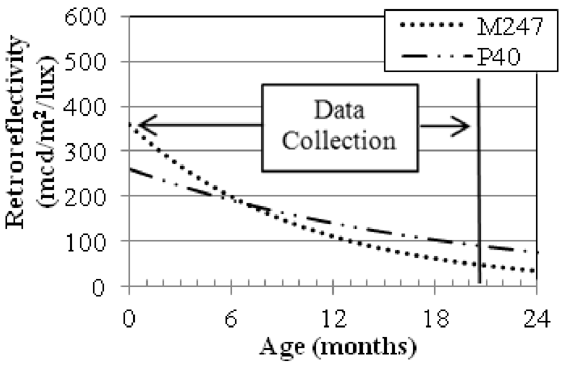
The results indicate that for Type III white paint on PCC in a dry freeze region, a change in the specified white paint thickness from 15 mils to 20 mils resulted in an increase in initial retroreflectivity. When M247 was used, the initial retroreflectivity of the 20-mil thick paint was 1.25 times that of the 15-mil thickness. When Iowa Blend was used, the initial retroreflectivity of the 20-mil thick paint was 1.31 times that of the 15-mil thickness. The decay rate of the 20 mils was marginally higher than that of the 15 mils. In all cases, the retroreflectivity decay model remained above 100 mcd/m^2/lux for more than 24 months. The reader is reminded that Figure 4.7 was based on a limited amount of data (10 months) and should be interpreted with caution. The limited data may have caused the negative R^2 value for the decay curve for the case of Iowa Blend with 15 mils.

4.3.4 Effect of Reflective Element

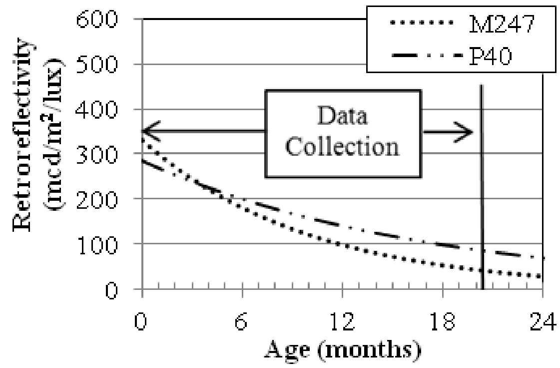
Following are the results of the analysis of the effect of reflective element on retroreflectivity performance.

4.3.4.1 M247 versus P40, Waterborne Paint, Wet Freeze Region, AC Pavement

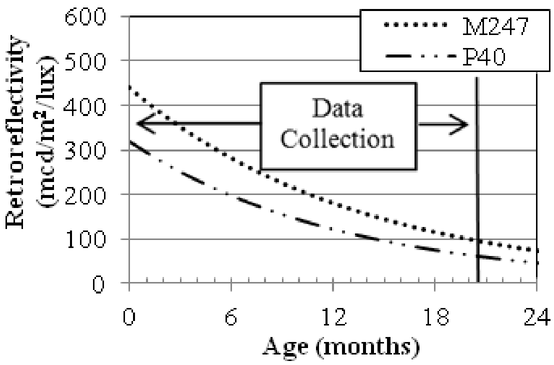
Figure 4.8 shows retroreflectivity decay based on reflective elements M247 and P40 of Type II and Type III waterborne paint placed on AC in wet freeze regions (Redfield test section). In Figure 4.8(a) and (b) the paint is Type II WEL in 15 mils and 20 mils, respectively. In Figure 4.8(c) and (d) the paint is Type III WEL in 17 mils and 20 mils, respectively. In Figure 4.8(e) and (f) the paint is Type II YSL in 15 mils and 17 mils, respectively. Table 4.11 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



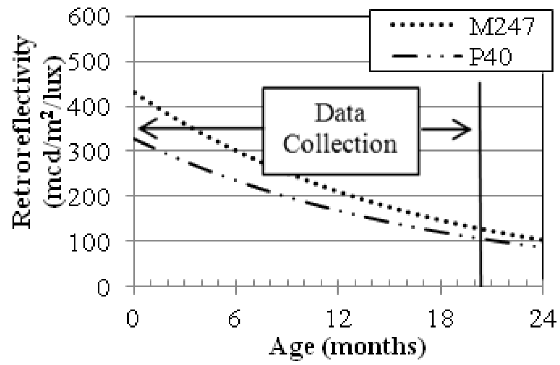
(a) Type II WEL and 15mils; Redfield Test Section



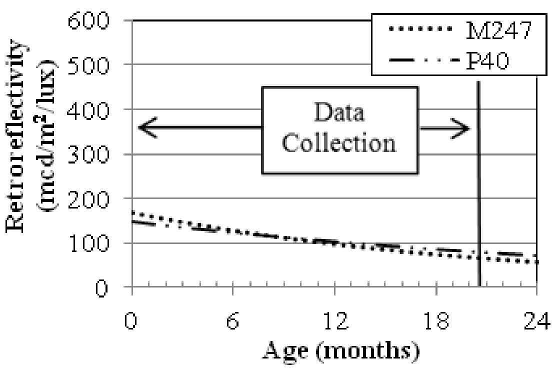
(b) Type II WEL and 17mils; Redfield Test Section



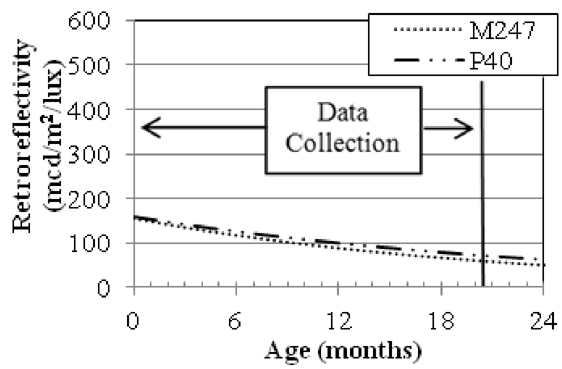
(c) Type III WEL and 17mils; Redfield Test Section



(d) Type III WEL and 20mils; Redfield Test Section



(e) Type II YSL and 15mils; Redfield Test Section



(f) Type II YSL and 17mils; Redfield Test Section

Figure 4.8 M247 versus P40; Waterborne Paint on AC in Wet Freeze

Table 4.11 Data Comparison for the Effect of Reflective Element; M247 versus P40; Waterborne Paint on AC in Wet Freeze

Paint and Line Type	Paint Thickness	Reflective Element	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type II White Edge Line (WEL)	15 mils	M247	1	0.62	360	0.098	31
		P40	3	0.84	260	0.052	54
	17 mils	M247	2	0.71	330	0.100	30
		P40	4	0.79	285	0.059	49
Type III White Edge Line (WEL)	17 mils	M247	5	0.72	440	0.074	41
		P40	7	0.54	320	0.080	38
	20 mils	M247	6	0.92	430	0.060	47
		P40	8	0.73	330	0.056	51
Type II Yellow Skip Line (YSL)	15 mils	M247	9	0.88	170	0.046	58
		P40	11	0.57	150	0.030	70
	17 mils	M247	10	0.89	155	0.046	58
		P40	12	0.36	160	0.038	63

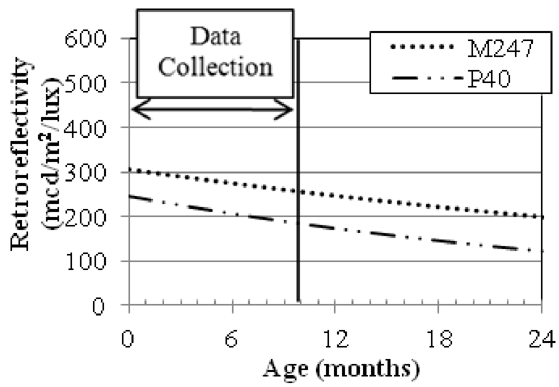
The yellow paint combinations exhibited low initial retroreflectivity that ranged between 150 and 170 mcd/m^2/lux. Due to its poor performance, the yellow paint in Figure 4.8(e) and (f) will not be discussed any further.

The results indicate that white paint with M247 exhibited consistently higher initial retroreflectivity than the respective P40 paint combination. When M247 was used, the initial retroreflectivity ranged between 1.16 to 1.38 times that of P40.

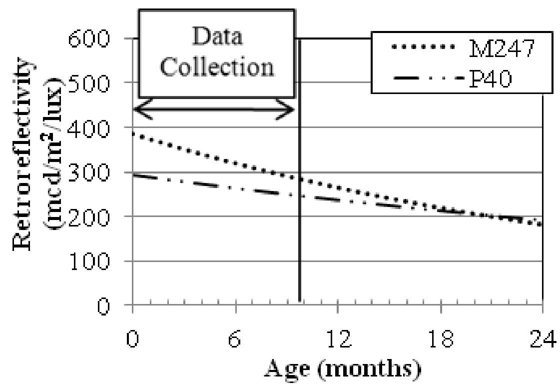
With Type II white paint, M247 exhibited a higher decay rate than the respective P40 paint combination; at 12 months, the percent of initial retroreflectivity remaining for the P40 ranged between 1.63 and 1.74 times that of the M247 cases. With type III white paint, however, the differences in the decay rate between the respective M247 and P40 were marginal.

4.3.3.2 M247 versus P40, Waterborne Paint, Dry Freeze Region, AC Pavement

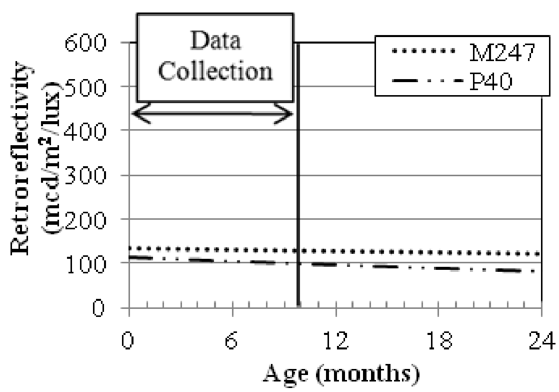
Figure 4.9 shows retroreflectivity decay based on reflective elements M247 and P40 of Type III waterborne paint placed on AC in dry freeze regions (Midland test section). In Figure 4.9(a) and (b) the paint is Type III WEL in 15 mils and 20 mils, respectively. In Figure 4.9(c) and (d) the paint is Type III YSL in 15 mils and 20 mils, respectively. Table 4.12 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



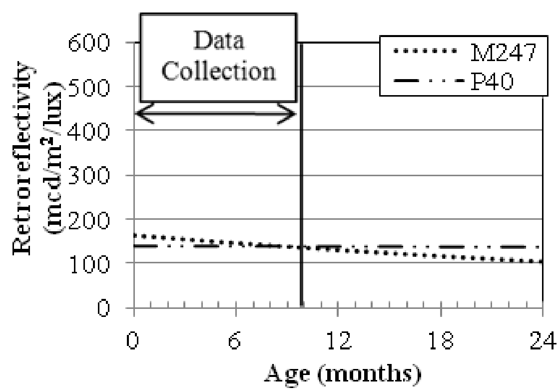
(a) WEL and 15 mils; Midland Test Section



(b) WEL and 20 mils; Midland Test Section



(c) YSL and 15 mils; Midland Test Section



(d) YSL and 20 mils; Midland Test Section

Figure 4.9 M247 versus P40; Waterborne Paint on AC in Dry Freeze

Table 4.12 Data Comparison for the Effect of Reflective Element; M247 versus P40; Waterborne Paint on AC in Dry Freeze

Paint and Line Type	Paint Thickness	Reflective Element	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type III White Edge Line(WEL)	15 mils	M247	25	0.48	305	0.018	81
		P40	29	0.87	245	0.029	71
	20 mils	M247	27	0.77	385	0.031	69
		P40	31	0.61	295	0.018	81
Type III Yellow Skip Line (YSL)	15 mils	M247	26	0.20	135	0.004	95
		P40	30	0.76	115	0.014	85
	20 mils	M247	28	0.60	165	0.019	80
		P40	32	0.04	140	0.001	99

The decay models for the cases shown in Figure 4.9 were based on a limited amount of data (10 months) and should be interpreted with caution.

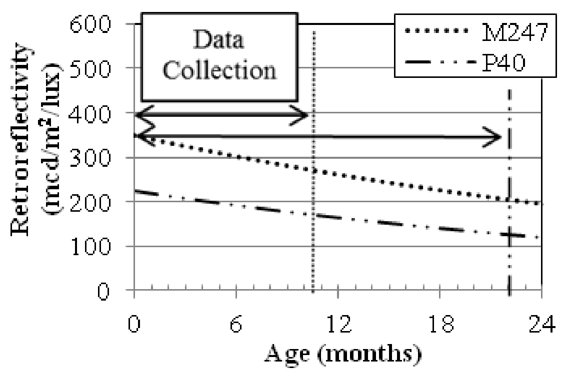
The yellow paint combinations exhibited low initial retroreflectivity that ranged between 115 and 165 mcd/m^2/lux. Due to its poor performance, the yellow paint in Figure 4.9(c) and (d) will not be discussed further.

The results indicate that white paint with M247 consistently exhibited higher initial retroreflectivity than the respective P40 paint combination. When M247 was used, the initial retroreflectivity ranged between 1.24 to 1.31 times that of P40.

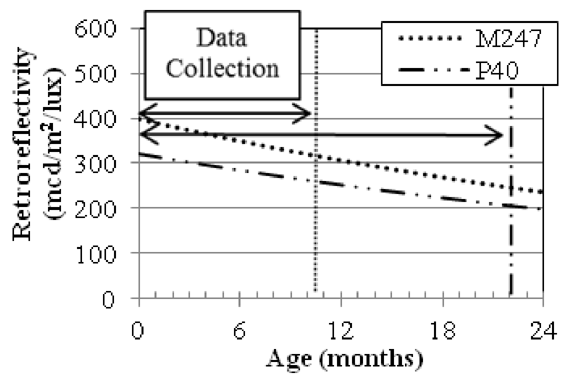
The influence of the reflective element on the decay rate did seem to follow a clear trend. For a specified paint thickness of 15 mils, M247 exhibited a marginally lower decay rate than the respective P40 paint combination. For a specified paint thickness of 20 mils, however, M247 exhibited a marginally higher decay rate than the respective P40 paint combination. At 12 months, the percent of initial retroreflectivity remaining for the P40 was 0.88 and 1.17 times that of the M247 for the 15 mils and 20 mils cases, respectively.

4.3.3.3 M247 versus P40, Inlaid Waterborne Paint, Dry Freeze Region, AC Pavement

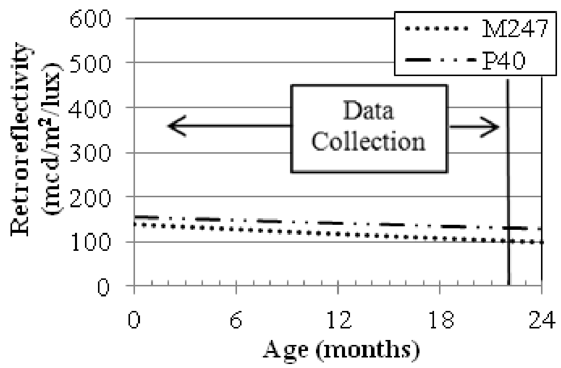
Figure 4.10 shows retroreflectivity decay based on reflective elements M247 and P40 of Type II waterborne paint inlaid on AC in dry freeze regions (Presho test section). In Figure 4.10(a) and (b) the paint is 17 mils WEL and WSL, respectively. In **Figure** (c) the paint is 17 mils YEL. Table 4.13 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



(a) WEL; Presho Test Section



(b) WSL; Presho Test Section



(c) YEL; Presho Test Section

Figure 4.10 M247 versus P40; Inlaid Type II Waterborne Paint on AC in Dry Freeze

Table 4.13 Data Comparison for the Effect of Reflective Element; M247 versus P40; Inlaid Type II Waterborne Paint on AC in Dry Freeze

Paint and Line Type	Paint Thickness	Reflective Element	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type II White Edge Line (WEL)	17 mils	M247	42	0.49	350	0.024	75
		P40	45	0.62	225	0.026	73
Type II White Skip Line (WSL)	17 mils	M247	44	0.42	400	0.022	77
		P40	47	0.86	320	0.020	79
Type II Yellow Edge Line (YEL)	17 mils	M247	43	0.55	140	0.004	95
		P40	46	0.83	155	0.008	91

The decay models for the M247 cases shown in Figure 4.10(a) and (b) were based on a limited amount of data (10 months) and should be interpreted with caution.

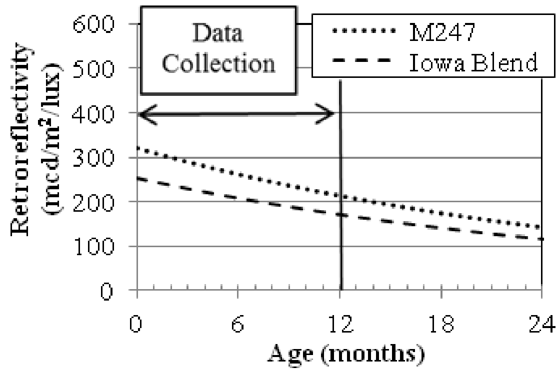
The yellow paint combinations exhibited low initial retroreflectivities of 140 and 155 mcd/m^2/lux. Due to its poor performance, the yellow paint in Figure 4.10(c) will not be discussed any further.

The results indicate that white paint with M247 exhibited consistently higher initial retroreflectivity than the respective P40 paint combination. When M247 was used, the initial retroreflectivity was 1.56 to 1.25 times that of P40 for the WEL and WSL, respectively.

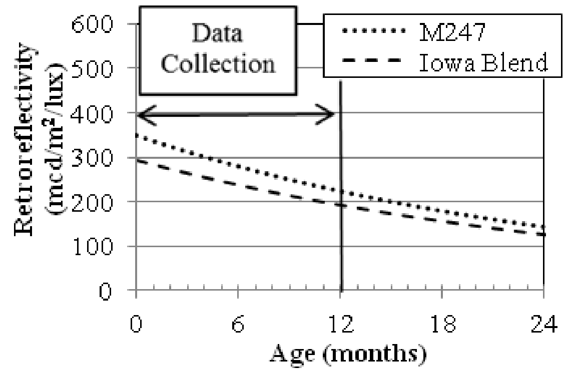
The decay rates of the M247 and P40 were virtually identical. For Type II WEL paint, the percent of initial retroreflectivity remaining was 75% and 73% for the M247 and P40, respectively. For Type II WSL, the percent of initial retroreflectivity remaining was 77% and 79% for the M247 and P40, respectively.

4.3.3.4 M247 versus Iowa Blend, Waterborne Paint, Wet Freeze Region, PCC Pavement

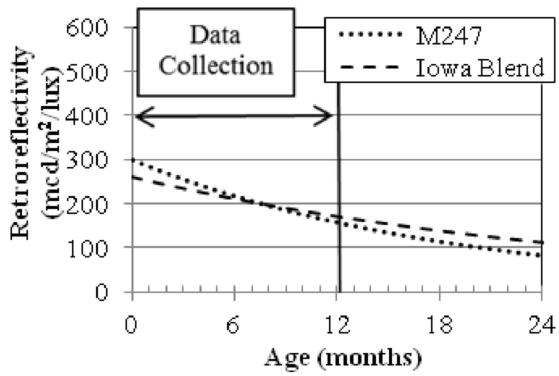
Figure 4.11 shows retroreflectivity decay based on reflective elements M247 and Iowa Blend of Type III waterborne paint placed on PCC in wet freeze regions (Aberdeen test section). In Figure 4.11(a) and (b) the paint is Type III WEL in 15 mils and 20 mils, respectively. In Figure 4.11(c) and (d) the paint is Type III WSL in 15 mils and 20 mils, respectively. In Figure 4.11(e) and (f) the paint is Type III YEL in 15 mils and 20 mils, respectively. Table 4.14 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



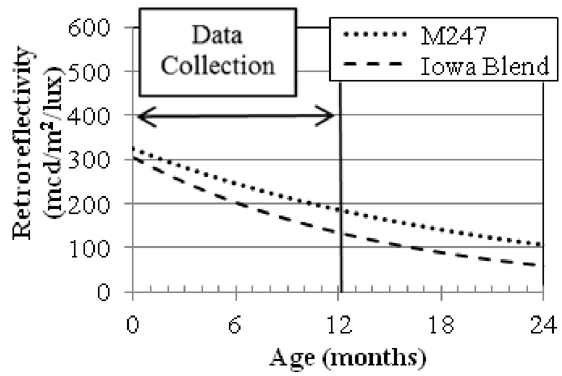
(a) WEL and 15 mils; Aberdeen Test Section



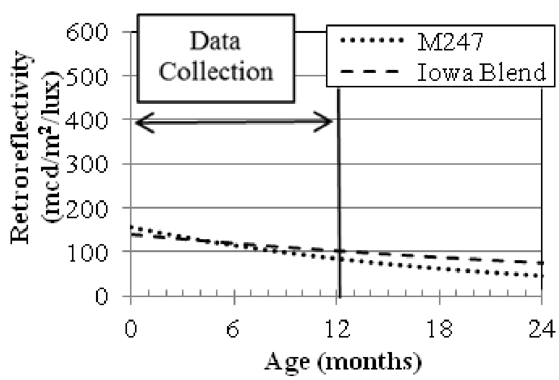
(b) WEL and 20 mils; Aberdeen Test Section



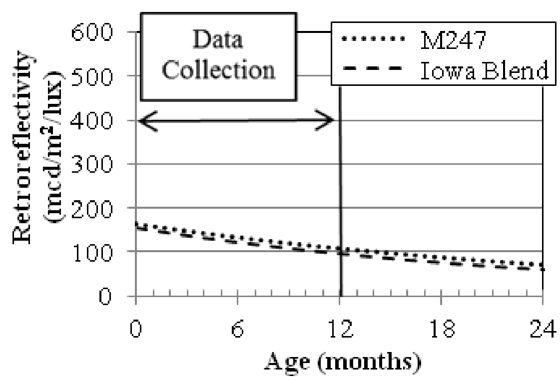
(c) WSL and 15 mils; Aberdeen Test Section



(d) WSL and 20 mils; Aberdeen Test Section



(e) YEL and 15 mils; Aberdeen Test Section



(f) YEL and 20 mils; Aberdeen Test Section

Figure 4.11 M247 versus Iowa Blend; Waterborne Paint on PCC in Wet Freeze

Table 4.14 Data Comparison for the Effect of Reflective Element; M247 versus P40; Waterborne Paint on PCC in Wet Freeze

Paint and Line Type	Paint Thickness	Reflective Element	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type III White Edge Line (WEL)	15 mils	M247	15	0.91	320	0.034	66
		Iowa Blend	21	0.90	255	0.033	67
	20 mils	M247	18	0.89	350	0.037	64
		Iowa Blend	24	0.87	295	0.035	66
Type III White Skip Line (WSL)	15 mils	M247	14	0.88	300	0.053	53
		Iowa Blend	20	0.90	260	0.035	66
	20 mils	M247	17	0.80	325	0.046	58
		Iowa Blend	23	0.87	305	0.068	44
Type III Yellow Edge Line (YEL)	15 mils	M247	13	0.87	155	0.050	55
		Iowa Blend	19	0.85	140	0.026	73
	20 mils	M247	16	0.98	165	0.034	66
		Iowa Blend	22	0.89	155	0.040	62

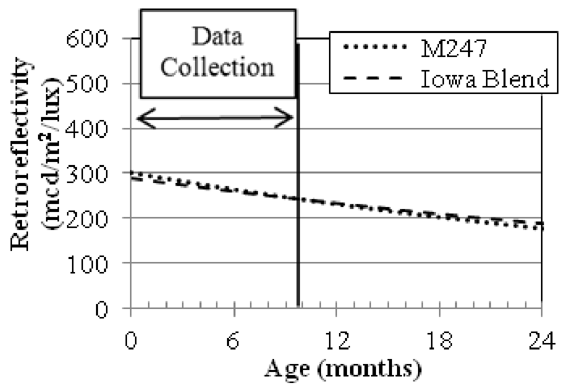
The yellow paint combinations exhibited low initial retroreflectivity that ranged between 140 and 165 mcd/m^2/lux. Due to its poor performance, the yellow paint in Figure 4.11(e) and (f) will not be discussed further.

The results indicate that white paint with M247 exhibited consistently higher initial retroreflectivity than the respective Iowa Blend paint combination. When M247 was used, the initial retroreflectivity ranged between 1.07 to 1.25 times that of Iowa Blend.

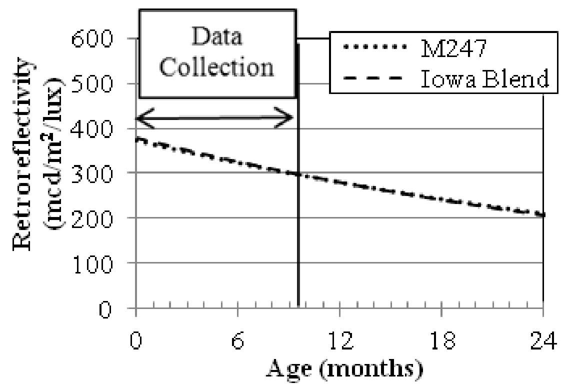
The influence of the reflective element on the decay rate did seem to follow a clear trend. For WEL in 15 and 20 mils thicknesses, the decay rates of the M247 and Iowa Blend were virtually identical. For WSL in 15 mils thickness, M247 exhibited a higher decay rate than that of Iowa Blend, while for WSL in 20 mils thickness, M247 exhibited a lower decay rate than that of Iowa Blend. At 12 months, the percent of initial retroreflectivity remaining for the M247 was 0.80 and 1.32 times that for the Iowa Blend, respectively.

4.3.3.5 M247 versus Iowa Blend, Waterborne Paint, Dry Freeze Region, PCC Pavement

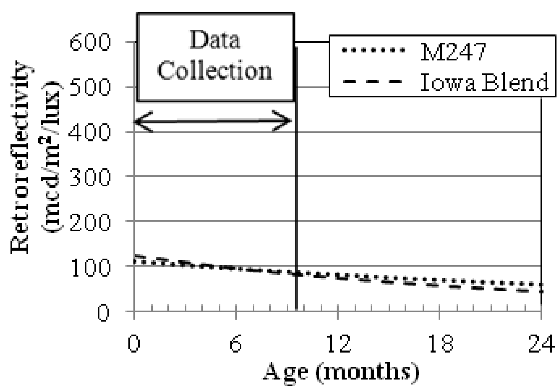
Figure 4.12 shows retroreflectivity decay based on reflective elements M247 and Iowa Blend of Type III waterborne paint placed on PCC in dry freeze regions (Martin test section). In Figure 4.12(a) and (b) the paint is Type III WEL in 15 mils and 20 mils, respectively. In Figure 4.12(c) and (d) the paint is Type III YSL in 15 mils and 20 mils, respectively. Table 4.15 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



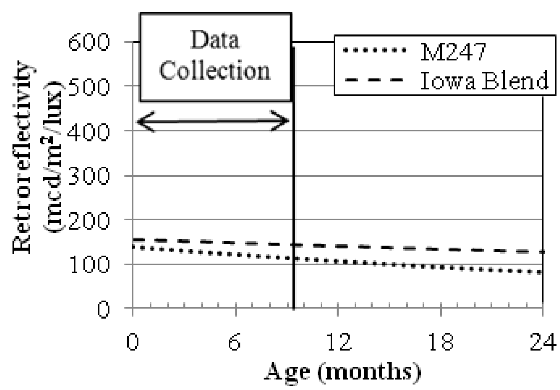
(a) WEL and 15 mils; Martin Test Section



(b) WEL and 20 mils; Martin Test Section



(c) YSL and 15 mils; Martin Test Section



(d) YSL and 20 mils; Martin Test Section

Figure 4.12 M247 versus Iowa Blend; Waterborne Paint on PCC in Dry Freeze

Table 4.15 Data Comparison for the Effect of Reflective Element; M247 versus P40; Waterborne Paint on PCC in Dry Freeze

Paint and Line Type	Paint Thickness	Reflective Element	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type III White Edge Line (WEL)	15 mils	M247	33	0.43	300	0.022	77
		Iowa Blend	37	-0.33	290	0.018	81
	20 mils	M247	35	0.72	375	0.024	75
		Iowa Blend	39	0.79	380	0.025	74
Type III Yellow Skip Line (YSL)	15 mils	M247	34	0.78	110	0.025	74
		Iowa Blend	38	0.87	125	0.044	59
	20 mils	M247	36	0.90	140	0.022	77
		Iowa Blend	40	0.41	155	0.008	91

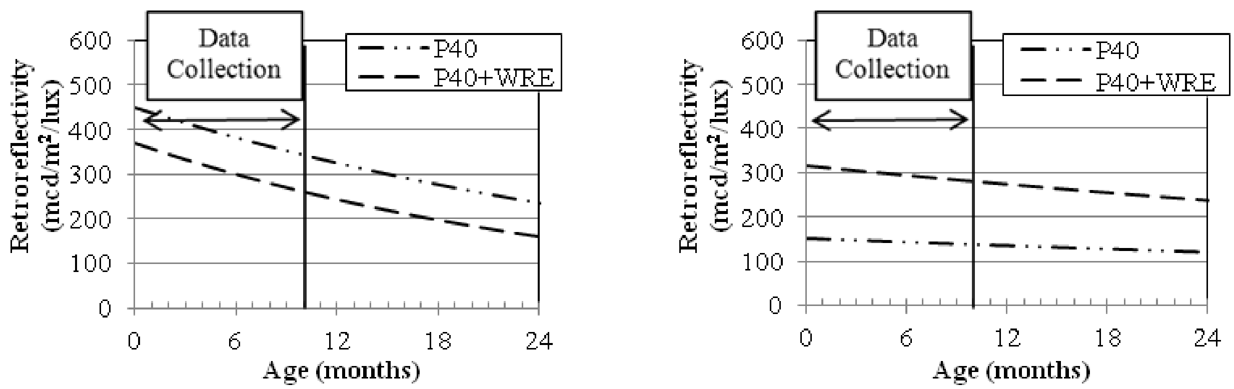
The decay models shown in Figure 4.12 were based on a limited amount of data (10 months) and should be interpreted with caution.

The yellow paint combinations exhibited low initial retroreflectivity that ranged between 140 and 165 further.

The results indicate that M247 and Iowa Blend exhibited almost identical initial retroreflectivity and decay for the same specified paint thickness.

4.3.3.6 P40 versus P40+WRE; Inlaid Epoxy Paint, Wet Freeze Region, PCC Pavement

Figure 4.13 shows retroreflectivity decay based on reflective elements P40 and a combination of P40 + WRE epoxy paint inlaid on PCC in wet freeze regions (De Smet test section). In Figure 4.13(a) and (b) the paint is WEL and YSL, respectively. Table 4.16 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



(a) WEL; De Smet Test Section **(b)** YSL; De Smet Test Section

Figure 4.13 P40 versus P40+WRE; Inlaid Epoxy on PCC in Wet Freeze

Table 4.16 Data Comparison for the Effect of Reflective Element; P40 versus P40+WRE; Inlaid Epoxy on PCC in Wet Freeze

Paint and Line Type	Paint Thickness	Reflective Element	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Epoxy White Edge Line (WEL)	20 mils	P40	51	0.96	450	0.027	
		P40 + WRE	53	0.90	370	0.035	
Epoxy Yellow Skip Line (YSL)	20 mils	P40	52	0.26	150	0.009	
		P40 + WRE	54	0.36	315	0.012	

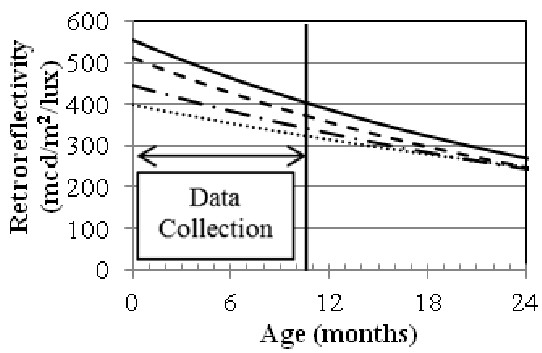
The decay models shown in Figure 4.13 were based on a limited amount of data (10 months) and should be interpreted with caution.

The yellow paint with P40 elements only exhibited low initial retroreflectivity of 150 mcd/m²/lux. However, when P40 was used in combination with WRE, the initial dry retroreflectivity increased to 315 mcd/m²/lux.

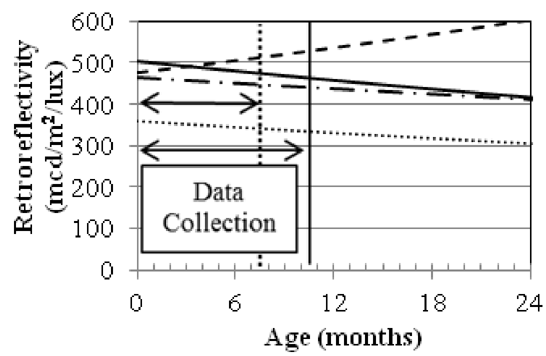
The results indicate that white epoxy paint with P40 elements only exhibited higher initial retroreflectivity than white epoxy paint with a combination of P40 + WRE. However, the decay rates were almost identical for the two cases and the addition of WRE did not seem to have an influence on the decay rate of white epoxy paint.

4.3.3.7 Comparison of M247, Megablend, M247+Megablend, and Iowa Blend; Inlaid Epoxy Paint, Wet Freeze Region, PCC Pavement

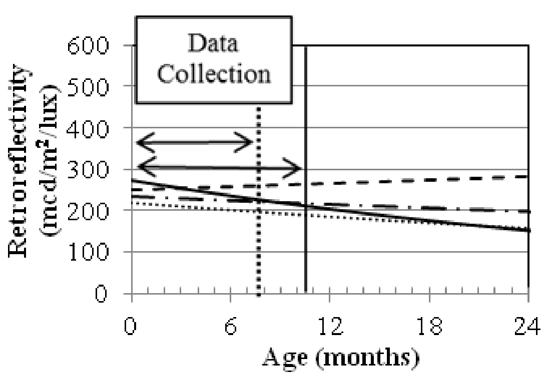
Figure 4.14 shows retroreflectivity decay based on reflective elements M247, Megablend, M247 + Megablend, and Iowa Blend epoxy paint inlaid on PCC in wet freeze regions (Brookings test section). In Figure 4.14(a), (b), and (c) the paint is WEL, WSL, and YEL, respectively. Table 4.17 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



(a) WEL; Brookings Test Section



(b) WSL; Brookings Test Section



(c) YEL; Brookings Test Section

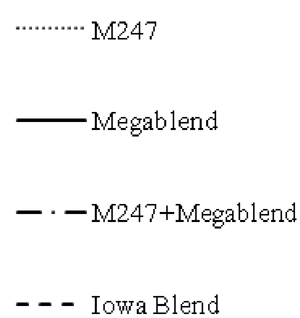


Figure 4.14 M247, Megablend, M247+Megablend, and Iowa Blend; Inlaid Epoxy Paint on PCC in Wet Freeze

Table 4.17 Data Comparison for the Effect of Reflective Element; M247, Megablend, M247+Megablend, and Iowa Blend; Inlaid Epoxy Paint on PCC in Wet Freeze

Paint and Line Type	Paint Thickness	Reflective Element	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Epoxy White Edge Line (WEL)	20 mils	M247	58	0.90	400	0.020	79
		Megablend	67	0.96	555	0.030	70
		M247+Megablend	61	0.79	445	0.025	74
		Iowa Blend	64	0.90	510	0.030	70
Epoxy White Skip Line (WSL)	20 mils	M247	60	-0.03	360	0.007	92
		Megablend	69	0.72	505	0.008	91
		M247+Megablend	63	0.77	465	0.005	94
		Iowa Blend	66	0.75	475	-0.010	N.A.**
Epoxy Yellow Edge Line (YEL)	20 mils	M247	59	0.52	220	0.014	85
		Megablend	68	0.98	275	0.025	74
		M247+Megablend	62	0.72	235	0.007	92
		Iowa Blend	65	0.86	250	-0.005	N.A.**

The decay models shown in Figure 4.14 were based on a limited amount of data (7 to 10 months) and should be interpreted with caution.

The data presented in Figure 4.14(b) and (c) shows an increasing retroreflectivity with time for the Iowa Blend case. Moreover, the aforementioned data were based on approximately seven months duration for the M247 case and 10 months for the other cases. Therefore, the decay trends in Figure 4.14(b) and (c) will not be analyzed due to lack of confidence in the time-dependent decay behavior and inadequate data size.

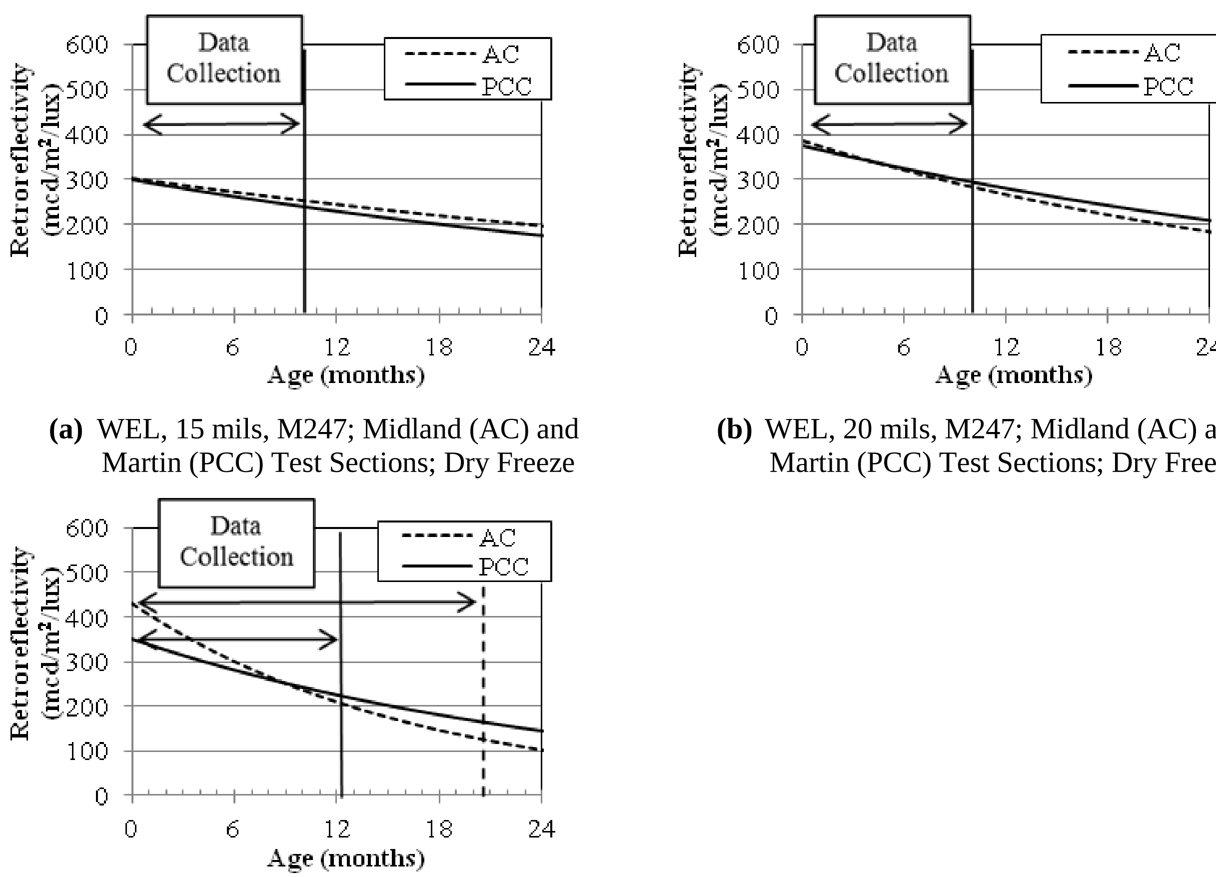
The initial dry retroreflectivity seems to be substantially higher in epoxy paint than in waterborne paint. In Figure 4.14(a), the initial retroreflectivity of the white epoxy paint was 400, 555, 445, and 510 mcd/m^2/lux for M247, Megablend, M247 + Megablend, and Iowa Blend, respectively. In Figure 4.14(c), the initial retroreflectivity of the yellow epoxy paint was 220, 275, 235, and 250 mcd/m^2/lux for M247, Megablend, M247 + Megablend, and Iowa Blend, respectively.

The dry retroreflectivity decay rates in white epoxy paint with different reflective elements appear to be fairly similar. At 12 months, the percent of initial retroreflectivity remaining was 79%, 70%, 74%, and 70% for M247, Megablend, M247 + Megablend, and Iowa Blend, respectively. Therefore, the reflective element type does not appear to have a substantial influence on the performance of white epoxy paint.

4.3.4 Effect of Pavement Type

Both AC and PCC pavements were incorporated in this study in order to determine the effect of pavement type on retroreflectivity. Only surface-applied waterborne paint was used for the comparative analysis. Although both white and yellow paint colors were incorporated in the test matrix, only results from the white color paint are presented and compared in the following analysis since the retroreflectivity of the yellow color paint was extremely low and did not allow for meaningful interpretation of the effect of pavement type.

Figure 4.15 shows retroreflectivity decay based on pavement type. The paint was Type III waterborne with M247 reflective elements, surface applied in different thicknesses and in different winter maintenance regions. Figure 4.15(a) and (b) show results from dry freeze regions (Midland and Martin test sections) of paint having a specified paint thicknesses of 15 and 20 mils, respectively. Figure 4.15(c) shows results from wet freeze regions (Redfield and Aberdeen test sections) of paint having a specified paint thickness of 20 mils. Table 4.18 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



(a) WEL, 15 mils, M247; Midland (AC) and Martin (PCC) Test Sections; Dry Freeze

(b) WEL, 20 mils, M247; Midland (AC) and Martin (PCC) Test Sections; Dry Freeze

(c) WEL, 20 mils, M247; Redfield (AC) and Aberdeen (PCC) Test Sections; Wet Freeze

Figure 4.15 AC versus PCC; Waterborne Type III Paint in Dry Freeze and Wet Freeze

Table 4.18 Data Comparison for the Effect of Pavement Type; AC versus PCC; Waterborne Type III Paint in Dry Freeze and Wet Freeze

Paint, Element, and Line Type	Paint Thickness	Pavement Type	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
Type III M247 White Edge Line (WEL)	15 mils	AC	25	0.48	305	0.018	81
		PCC	33	0.43	300	0.022	77
	20 mils	AC	27	0.77	385	0.031	69
		PCC	35	0.72	375	0.025	74
	20 mils	AC	6	0.92	430	0.060	49
		PCC	18	0.89	350	0.037	64

The decay models shown in Figure 4.15(a) and (b) were based on a limited amount of data (nine months) and should be interpreted with caution. The data presented in Figure 4.15(c) were based on 12-month and 20-month data collection periods for the PCC and the AC pavements, respectively and, therefore, should also be interpreted with caution.

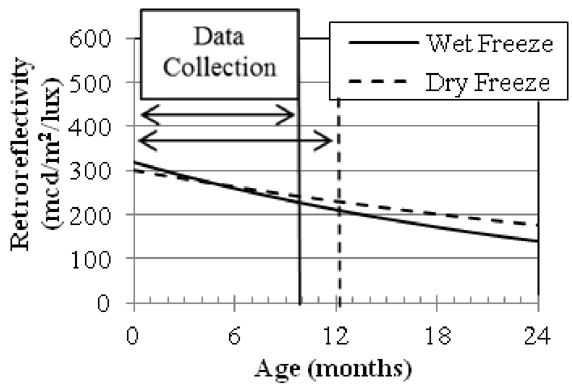
The data presented in Figure 4.15(a) and (b) indicate that for the same paint parameters, the initial retroreflectivity and the decay rates were practically identical for the PCC and AC pavements in dry freeze regions.

The data presented in Figure 4.15(c) indicate that the retroreflectivity decay rate of waterborne paint on AC pavement was higher than that on PCC pavement. At 12 months, the percent of initial retroreflectivity remaining was 49% and 64% for the AC and PCC pavements, respectively. The AC and PCC pavements were at different geographic locations (Redfield and Aberdeen). Therefore, the difference in the decay rates could be reflective of the severity of the winter maintenance effects in different geographic locations within a wet freeze region rather than the type of pavement.

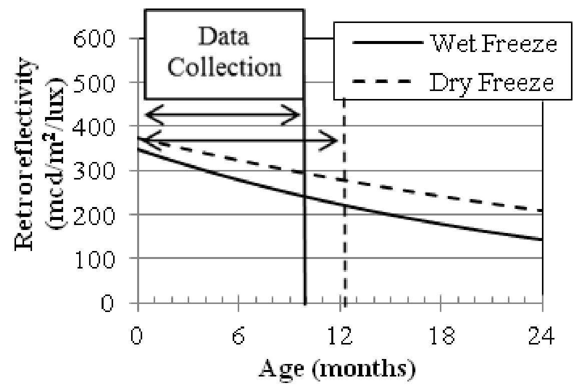
4.3.5 Effect of Winter Maintenance Region

Wet freeze and dry freeze winter maintenance regions were incorporated in this study in order to determine the effect of winter maintenance on retroreflectivity. Only surface-applied waterborne paint was used for the comparative analysis.

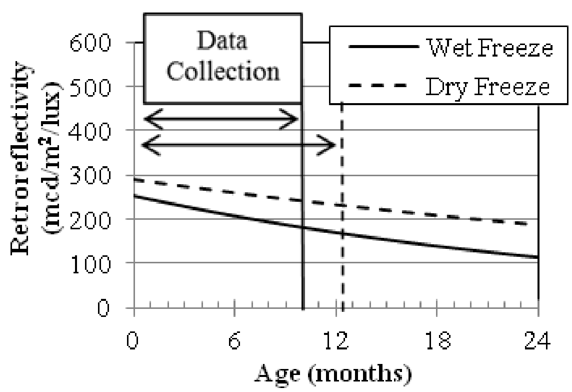
Figure 4.16 shows retroreflectivity decay based on the winter maintenance region (wet freeze versus dry freeze). The paint was Type III waterborne that was surface-applied in different thicknesses and using different reflective elements. Figure 4.16(a) and (b) show results of the cases of paint on PCC pavement incorporating M247 elements and having specified paint thicknesses of 15 and 20 mils, respectively. Figure 4.16(c) and (d) show results of the cases of paint on PCC pavement incorporating Iowa Blend elements and having specified paint thicknesses of 15 and 20 mils, respectively. Figure 4.16(e) and (f) show results of the cases of 20-mil thick paint on AC pavement incorporating M247 and P40 elements, respectively. Table 4.19 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



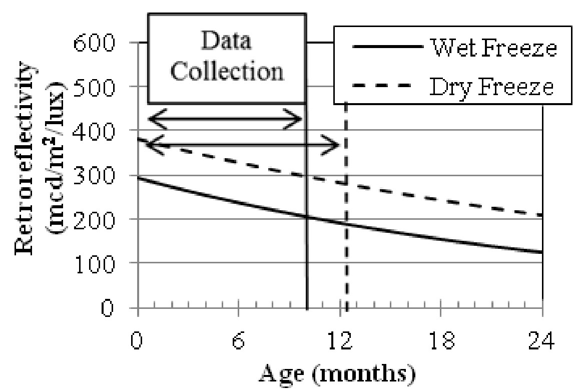
(a) M247 and 15 mils; PCC



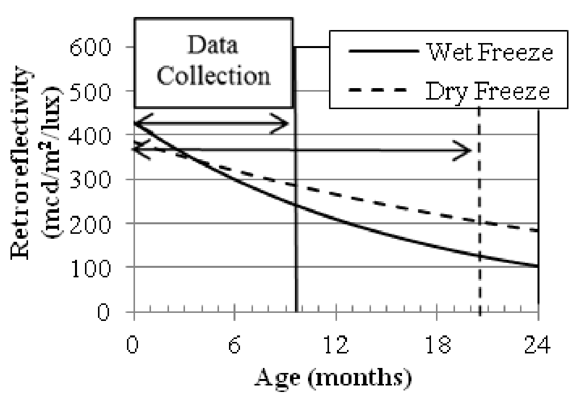
(b) M247 and 20 mils; PCC



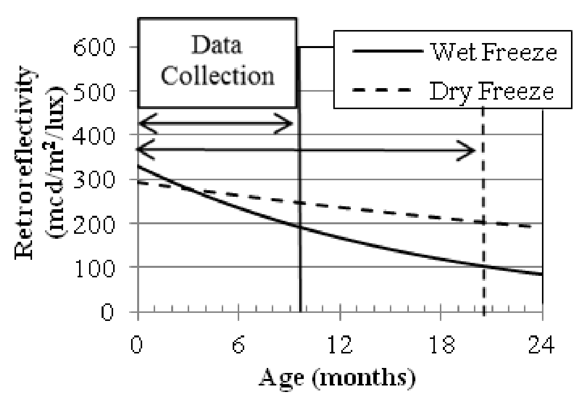
(c) Iowa Blend and 15 mils; PCC



(d) Iowa Blend and 20 mils; PCC



(e) M247 and 20 mils; AC



(f) P40 and 20 mils; AC

Figure 4.16 Dry Freeze versus Wet Freeze; Type III Waterborne Paint

Table 4.19 Data Comparison for the Effect of Winter Maintenance Regions

Reflective Element	Paint Thickness	Region	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
M247	15 mils	Wet Freeze (Aberdeen)	15	0.91	320	0.034	66
		Dry Freeze (Martin)	33	0.43	300	0.022	77
	20 mils	Wet Freeze (Aberdeen)	18	0.89	350	0.037	64
		Dry Freeze (Martin)	35	0.72	375	0.024	75
Iowa Blend	15 mils	Wet Freeze (Aberdeen)	21	0.90	255	0.033	67
		Dry Freeze (Martin)	37	-0.33	290	0.018	81
	20 mils	Wet Freeze (Aberdeen)	24	0.87	295	0.035	66
		Dry Freeze (Martin)	39	0.79	380	0.025	74
M247	20 mils	Wet Freeze (Redfield)	6	0.92	430	0.060	49
		Dry Freeze (Midland)	27	0.77	385	0.031	69
P40	20 mils	Wet Freeze (Redfield)	8	0.73	330	0.056	51
		Dry Freeze (Midland)	31	0.61	295	0.018	81

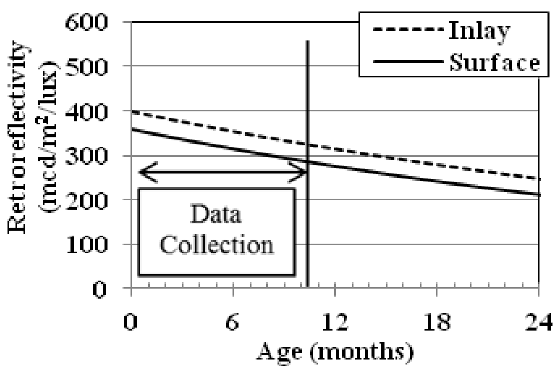
The decay models shown in Figure 4.16(a), (b), (c), and (d) were based on a limited amount of data (10 to 12 months) and should be interpreted with caution. The data presented in **Figure** (e) and (f) for the wet freeze region were based on 10 months of data collection and, therefore, should also be interpreted with caution.

The data presented in Figure 4.16 indicate that for all cases the retroreflectivity decay of the pavement marking in wet freeze regions was consistently higher than that in dry freeze regions. The difference in the retroreflectivity decay of dry freeze and wet freeze regions was marginal in the cases of paint on PCC, but substantial in the cases of paint on AC.

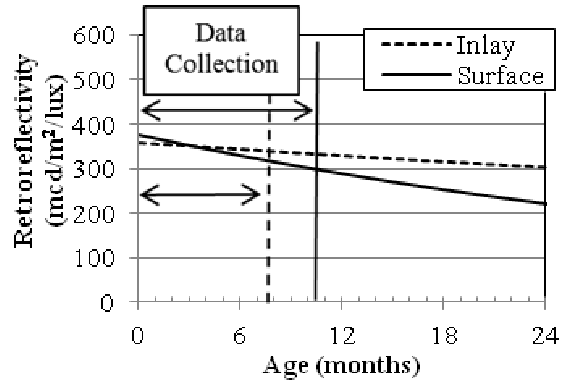
4.3.6 Effect of Pavement Surface Preparation

The effect of placing pavement markings into a recessed groove (inlay), as opposed to surface application, on retroreflectivity decay was investigated in this study. The investigation of the effect of pavement surface preparation (inlay versus surface applied) was limited to epoxy paint only since SDDOT does not normally specify recessed grooves for waterborne paint.

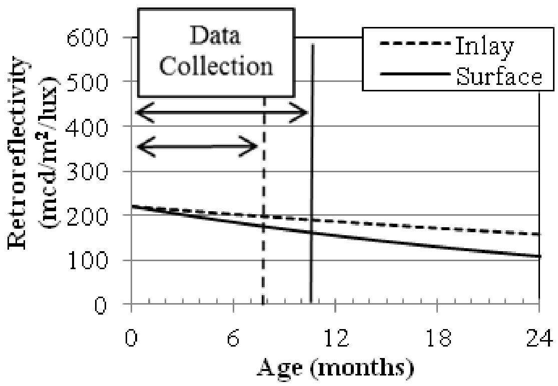
Figure 4.17 shows retroreflectivity decay based on pavement surface preparation. The paint was 20 mils thick epoxy with M247 reflective elements on PCC pavement in a wet freeze region (Brookings test sections). Figure 4.17(a), (b), and (c) show results for white edge line, white skip line, and yellow edge line, respectively. Table 4.20 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



(a) WEL; Brookings Test Section



(b) WSL; Brookings Test Section



(c) YEL; Brookings Test Section

Figure 4.17 Inlay versus Surface-Applied; Epoxy Paint, Wet freeze Region

Table 4.20 Data Comparison for the Effect of Inlay versus Surface-Applied; Epoxy Paint, Wet freeze Region

Line Type	Surface Preparation	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
White Edge Line (WEL)	Inlay	58	0.90	400	0.020	79
	Surface	55	0.36	360	0.022	77
White Skip Line (WSL)	Inlay	60	-0.03	360	0.007	92
	Surface	57	0.86	375	0.022	79
Yellow Edge Line (YEL)	Inlay	59	0.52	220	0.014	85
	Surface	56	0.85	220	0.029	71

The decay models shown in Figure 4.17(a), (b), and (c) were based on a limited amount of data (seven to 10 months) and should be interpreted with caution.

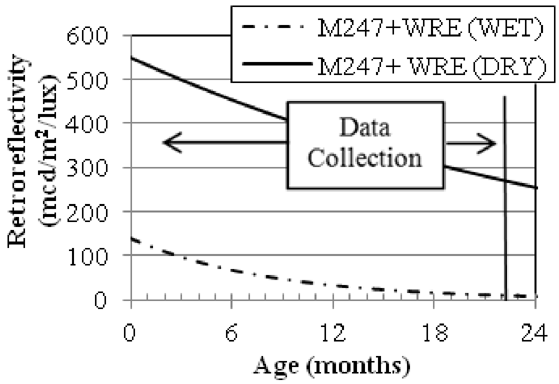
The data presented in Figure 4.17(a), (b), and (c) indicate that for the same paint parameters, the decay rate of inlaid epoxy paint was marginally lower than that of surface applied. The percent of initial retroreflectivity remaining after 12 months increased from 77, 79, and 71 for the surface applied paint to 79, 92, and 85 for the inlaid WEL, WSL, and YEL, respectively.

4.3.7 Effect of WRE on Retroreflectivity in Wet Conditions

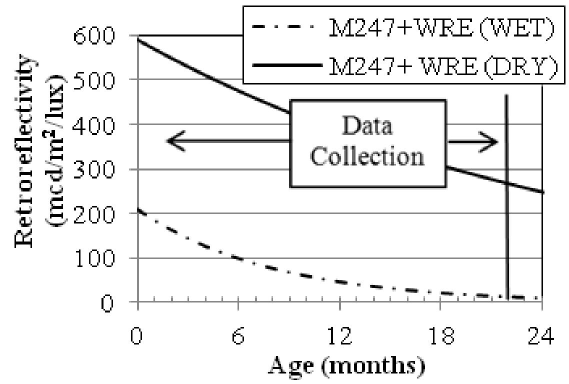
In wet driving conditions the excess water on pavement markings drain off relatively fast when the marking is surface applied. Projects that used inlaid markings specified the groove depth to be the sum of the marking thickness (specified) plus 15 mils with a tolerance of 5 mils. When the marking is inlaid, a layer of water is retained in the pavement grooves, thus creating a refractive layer above the marking. This refractive layer reduces retroreflectivity. Wet reflective elements were developed to mitigate this problem. It should be noted that the retroreflectivity of inlaid-applied pavement markings without WRE and only glass spheres is essentially zero when covered by water.

4.3.7.1 Type III Waterborne Paint, Inlaid, Dry freeze Region

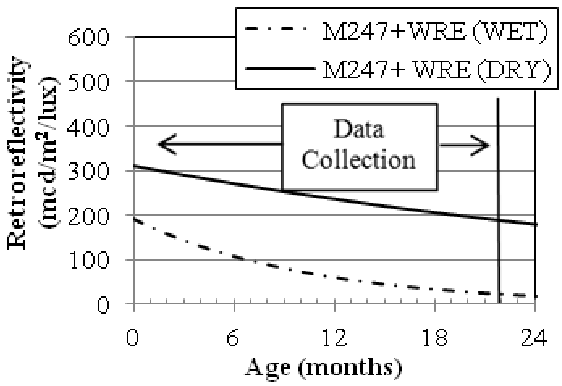
Figure 4.18 shows wet and dry retroreflectivity decay when WRE and M247 are combined and used with Type III waterborne paint in dry freeze regions (Presho test section). Figure 4.18(a), (b), and (c) show results of the cases of WEL, WSL, and YEL, respectively. Table 4.21 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



(a) WEL; Presho Test Section



(b) WSL; Presho Test Section



(c) YEL; Presho Test Section

Figure 4.18 Dry and Wet Retroreflectivity of Type III Waterborne Paint with WRE and M247 Elements

Table 4.21 Data Comparison for the Effect of WRE on Dry and Wet Retroreflectivity of Type III Waterborne Paint

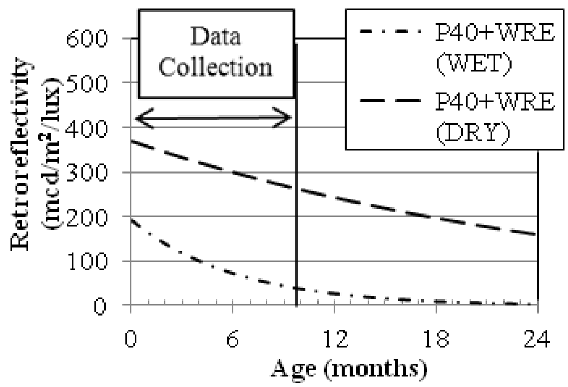
Line Type	Surface Moisture Condition	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
White Edge Line (WEL)	Wet	48 (wet)	0.24	140	0.121	23
	Dry	48	-0.07	550	0.032	68
White Skip Line (WSL)	Wet	50 (wet)	0.28	210	0.124	23
	Dry	50	0.46	590	0.036	65
Yellow Edge Line (YEL)	Wet	49 (wet)	0.67	190	0.095	32
	Dry	49	0.88	310	0.023	76

The data presented in Figure 4.18 indicate that when WREs were used, the initial dry retroreflectivity of Type III waterborne paint was enhanced significantly. With white paint, the initial dry retroreflectivity was 550 and 590 mcd/m^2/lux for the WEL and WSL, respectively, and 310 mcd/m^2/lux for the YEL. The use of WRE also showed substantial improvement in the long-term dry retroreflectivity of Type III waterborne paint. For the white paint cases, the dry retroreflectivity was still above 200 mcd/m^2/lux after 24 months.

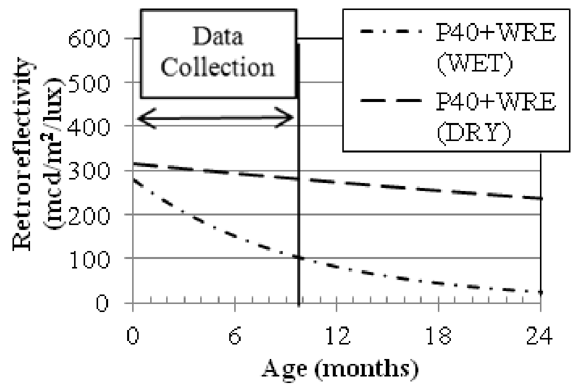
The data also indicate that the use of WREs was ineffective in providing adequate wet retroreflectivity for Type III waterborne paint. Under wet conditions, the initial retroreflectivity dropped significantly from the dry retroreflectivity. The drop was from 550 to 140 mcd/m^2/lux for the WEL case, from 590 to 210 mcd/m^2/lux for the WSL, and from 310 to 190 mcd/m^2/lux for the YEL. The wet retroreflectivity also dropped below 100 mcd/m^2/lux in six months or less.

4.3.7.2 Epoxy Paint, Inlaid, Wet Freeze Region

Figure 4.19 shows wet and dry retroreflectivity decay when WRE and P40 are combined and used with epoxy paint in wet freeze regions (De Smet test section). Figure 4.19(a) and (b) show results of the cases of WEL and YSL, respectively. Table 4.22 shows a comparison of the initial retroreflectivity and decay rates along with the coefficient of determination (R^2) of the respective best fit decay.



(a) WEL; De Smet Test Section



(b) YSL; De Smet Test Section

Figure 4.19 Dry and Wet Retroreflectivity of Epoxy Paint with WRE and P40 Elements

Table 4.22 Data Comparison for the Effect of WRE on Dry and Wet Retroreflectivity of Epoxy Paint

Line Type	Surface Moisture Condition	Case No.	R^2	Initial Retroreflectivity	Decay Rate Coefficient	% of Initial Retroreflectivity after 12 months
White Edge Line (WEL)	Wet	53 (wet)	0.89	190	0.161	14
	Dry	53	0.90	370	0.035	66
Yellow Skip Line (YSL)	Wet	54 (wet)	0.93	280	0.103	29
	Dry	54	0.36	315	0.012	87

The decay models shown in Figure 4.19 were based on a limited amount of data (10 months) and should be interpreted with caution.

The data presented in Figure 4.19 indicate that when WREs were used, the initial dry retroreflectivity of epoxy paint was comparable to initial dry retroreflectivity seen in other paint cases. The initial dry retroreflectivity was 370 and 280 mcd/m^2/lux for the WEL and YSL, respectively. The long-term dry retroreflectivity of epoxy paint with WREs and P40 remained above 100 mcd/m^2/lux after 24 months. The data also indicate that the use of WREs was ineffective in providing adequate wet retroreflectivity for epoxy paint. Under wet conditions, the initial retroreflectivity dropped significantly from the dry retroreflectivity for the WEL case, but the drop was marginal for the YSL case. The drop was from 370 to 190 mcd/m^2/lux for the WEL case and from 315 to 280 mcd/m^2/lux for the YSL. The wet retroreflectivity also dropped below 100 mcd/m^2/lux in six months for the WEL case and in approximately 10 months for the YSL.

4.4 Cost Analysis

Selection of the optimum pavement marking combination would require a decision-making process that considers desired level of retroreflectivity and marking life expectancy before replacement is needed, and cost analysis to compare the unit cost of the different pavement marking options. The desired retroreflectivity level is normally set by transportation officials based on road and traffic conditions, while the frequency of marking replacement would be influenced by the construction season window and availability of resources. In order to assist SDDOT with the decision-making process, a cost analysis tool consisting of an interactive spreadsheet was developed in this study. A screen shot of the spreadsheet is shown in Figure 4.20.

SOUTH DAKOTA DOT, DEPARTMENT OF TRANSPORTATION			
Library:	Dry Freeze - AC - Type II -WEL- 15 mils - Surface - w/M247		WEL=White Edge Line
	Dry Freeze - AC - Type III -WEL- 20 mils - Surface - w/M247		WSL=White Skip Line
	Dry Freeze - AC - Type III -WEL- 20 mils - Surface - w/P40		YEL=Yellow Edge Line
Defined Retroreflectivity (R_L) Minimum Standard:	100 (mcd/m²/lux)	Minimum R^2: 0.5	YSL=Yellow Skip Line
Winter Maintenance Region:	Dry Freeze (East River)		
Pavement Type:	Asphalt		
Paint Color:	White		

Option A	Option B	Option C
Paint Type:	Paint Type:	Paint Type:
Waterborne Paint Type II (State Spec.)	Waterborne Paint Type III (High Build)	Waterborne Paint Type III (High Build)
Line Type:	Line Type:	Line Type:
Edge	Edge	Edge
Wet Paint Thickness:	Wet Paint Thickness:	Wet Paint Thickness:
15 mils	20 mils	20 mils
Reflective Elements:	Reflective Elements:	Reflective Elements:
AASHTO M 247, Type I Gradation	AASHTO M 247, Type I Gradation	P40 Gradation
Pavement Preparation:	Pavement Preparation:	Pavement Preparation:
None (Typical Air)	None (Typical Air)	None (Typical Air)

Pavement Marking Combination A:		Pavement Marking Combination B:		Pavement Marking Combination C:	
Degradation Equation:	R=360e^(-0.098*months)	Degradation Equation:	R=430e^(-0.06*months)	Degradation Equation:	R=330e^(-0.056*months)
Equation R^2:	0.62	Equation R^2:	0.92	Equation R^2:	0.73
Equation Data Set Age (Months):	20.4	Equation Data Set Age (Months):	20.4	Equation Data Set Age (Months):	20.4
Initial R_L (mcd/m²/lux):[A]=	360	Initial R_L (mcd/m²/lux):	430	Initial R_L (mcd/m²/lux):	330
Decay Factor:[B]=	-0.098	Decay Factor:	-0.06	Decay Factor:	-0.056
Life Expectancy (Months):	13	Life Expectancy (Months):	24	Life Expectancy (Months):	21
Cost ($/Mile/Year):	298	Cost ($/Mile/Year):	214	Cost ($/Mile/year):	244

Figure 4.20 Pavement Marking Cost Analysis Spreadsheet

The interactive spreadsheet allows the user to compare the unit costs of three pavement marking alternatives at any one time. The user can select from fields embedded in the spreadsheet cells the pavement marking combination that reflects winter maintenance conditions, the pavement type, the paint type, the line type, the paint thickness, the pavement preparation type, and the reflective element. The library of the available options is based on the pavement marking cases considered in this study. The spreadsheet returns a normalized cost in terms of Dollars/Mile/Year, plus other relevant information on the decay model used. The life expectancy of a pavement marking option was considered as the time needed for the retroreflectivity decay model to reach a threshold retroreflectivity of 100 mcd/m²/lux. The material and installation costs were based on information provided by SDDOT officials at the time.

Since some of the decay models had negative R^2 value or were based on a limited duration of data collection, warning statements were embedded in the spreadsheet to alert the user when such anomalies are encountered. The unit costs for the different cases are summarized in Table 4.23 through Table 4.25. The results presented in those tables were based on the decay models developed in this study and the material and installation costs prevailing at the time. However, the spreadsheet library can be easily modified to take into consideration changes in material and installation costs, or updates of the decay models should new data become available.

Table 4.23 Cost Analysis of Waterborne Wet Freeze Test Sections

Test Section/ Winter Maintenance	Case No.	Duration of Data Collection (months)	Theoretical Life Expectancy (months)	Cost ($/Mile/Year)
US 212 Redfield, SD/ Wet Freeze	1	20.4	13	298
	2	20.4	12	362
	3	20.4	18	212
	4	20.4	18	244
	5	20.4	20	216
	6	20.4	24	214
	7	20.4	15	298
	8	20.4	21	244
	9	20.4	12	87
	10	20.4	10	116
	11	20.4	14	74
	12	20.4	12	Error/Low R^2
US 12 Aberdeen, SD/ Wet Freeze	13	12.1	9	456
	14	12.1	21	47
	15	12.1	34	114
	16	12.1	15	362
	17	12.1	26	51
	18	12.1	34	153
	19	12.1	13	309
	20	12.1	11	486
	21	12.1	27	36
	22	12.1	16	79
	23	12.1	25	159
	24	12.1	31	168

Table 4.24 Cost Analysis of Dry Freeze Waterborne Test Sections

Test Section/ Winter Maintenance	Case No.	Duration of Data Collection (months)	Theoretical Life Expectancy (months)	Cost ($/Mile/Year)
US 14 Midland, SD/ Dry Freeze	25	9.7	62	Error/Low R^2
	26	9.7	75	Error/Low R^2
	27	9.7	43	119
	28	9.7	26	51
	29	9.7	31	126
	30	9.7	10	100
	31	9.7	60	Error/Service Life
	32	9.7	336	Error/Low R^2
US 18 Martin, SD/ Dry Freeze	33	9.6	50	Error/Low R^2
	34	9.6	4	262
	35	9.6	55	Error/Service Life
	36	9.6	15	87
	37	9.6	59	Error/Low R^2
	38	9.6	5	197
	39	9.6	53	Error/Service Life
	40	9.6	55	Error/Low R^2
Interstate 90 Presho, SD/ Dry Freeze	41	10.4	50	Error/Low R^2
	42	22.3	24	1368
	43	10.4	63	Error/Low R^2
	44	22.3	31	1051
	45	22.3	55	600
	46	22.3	58	509
	47	9.7	62	Error/Low R^2
	48	9.7	75	Error/Low R^2
	49	9.7	43	119
	50	9.7	26	51

Table 4.25 Cost Analysis of Epoxy Test Sections

Test Section/ Winter Maintenance	Case No.	Duration of Data Collection (months)	Theoretical Life Expectancy (months)	Cost ($/Mile/Year)
Interstate 29 Brookings, SD/ Wet Freeze	55	10.4	58	Error/Low R^2
	56	10.4	27	1538
	57	10.4	60	696
	58	10.4	69	731
	59	7.6	56	900
	60	7.6	183	Error/Low R^2
	61	10.4	60	849
	62	10.4	122	Error/Service Life
	63	10.4	307	Error/Service Life
	64	10.4	54	933
	65	10.4	-176	Error/No Decay
	66	10.4	-156	Error/No Decay
	67	10.4	57	887
	68	10.4	40	1253
	69	10.4	202	Error/Service Life

5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

In cold regions where highways are normally subjected to frequent snow plowing and winter maintenance procedures, the use of reflective raised pavement markers (RRPMs) is neither practical nor feasible. Therefore, dry and wet retroreflectivity is achieved through the use of reflective elements (beads) and wet reflective elements (WREs). The current pavement marking for asphalt concrete (AC) pavements, which constitute the majority of South Dakota's highway network, is waterborne paint applied directly to the roadway surface. Waterborne paint typically requires repainting of the centerline every year and the shoulder line every year or two, depending on snowplow damage. Winter road maintenance can have a major effect on markings on concrete pavements. To avoid plow blade damage to markings applied on the roadway surface, markings are inlaid into the pavement. Epoxy materials and preformed tape are typically used in inlaid applications, but other less expensive alternatives may be feasible if their period of performance warrants their substitution. Surface preparation, such as diamond grinding or carbide milling, may be a major consideration in determining the longevity of inlaid pavement markings.

The South Dakota Department of Transportation's (SDDOT) biennial customer satisfaction assessments consistently show that travelers consider pavement markings that are clearly visible both day and night and in adverse weather conditions as a highly important safety issue. At the same time, the cost of marking materials is rapidly increasing, making recognition and use of the most effective and cost-effective marking materials and application methods extremely important. Since there had been a lack of data on the performance of pavement markings in South Dakota, research on pavement marking material, retroreflectivity, and durability was needed in order to improve the procedure of marking material selection, placement, and evaluation. There was also a need for basic information on the performance of pavement markings under many different environments, degrees of snowplowing and winter maintenance, types of pavement, and pavement preparation.

The study covered in this report was designed to address the research needs and to generate field data on the performance of different pavement markings types. The collected data were used to develop retroreflectivity decay models and to compare the cost effectiveness of the different pavement marking options. The objectives of the study were to:

- Evaluate the constructability, durability, and visibility of alternative pavement marking materials and application practices to standard waterborne paint on asphalt pavement surfaces, in consideration of SDDOT's pavement construction and maintenance practices.
- Compare the constructability, durability, and visibility of alternative pavement marking materials with epoxy materials in inlaid applications to concrete pavements.
- Assess the cost-effectiveness of pavement marking alternatives for use on concrete and asphalt pavements.

As part of this research project, SDDOT constructed seven pavement marking test sections on highways in different regions of South Dakota. The test sections were designed to represent different pavement marking material combinations and winter maintenance conditions. The parameters considered in this study were: paint type (waterborne and epoxy), paint thickness (15, 17, 20, and 25 mils), paint color (white and yellow), reflective elements (glass beads and wet reflective elements), line type (edge line and skip line), pavement type (asphalt concrete and Portland cement concrete), pavement surface preparation (surface and inlaid applications), and winter maintenance region (wet freeze and dry freeze).

The collected data included: 1) paint thickness measurements, 2) retroreflectivity of the pavement marking at different ages and under dry and wet conditions, and 3) visual rating of the pavement marking. Data analysis included: 1) curve fitting of measured retroreflectivity with time, 2) investigation of the relationship between retroreflectivity and visual rating, 3) effect of the different parameters on retroreflectivity longevity, and 4) cost effectiveness of the different pavement marking alternatives.

5.2 Conclusions

Based on the experimental and analytical work performed in this study, the following conclusions were made.

- Visual rating may be used for casual qualitative inspection but is not adequate for assessing night time visibility.
- The back-calculated wet paint thickness was not in agreement with the specified paint thickness. The majority of the back-calculated values from the plate samples were less than the specified paint thickness.
- The decay rates of Type II and Type III paints were practically similar.
- The initial retroreflectivity of yellow paint was consistently lower than that of white paint and, in most cases, was less than 200 mcd/m^2/lux.
- The retroreflectivity of yellow paint normally deteriorated in less than one year.
- Changing the specified paint thickness (15, 17, 20 mils) of waterborne paint resulted in marginal change in initial retroreflectivity and decay rate.
- The retroreflectivity of M247 in waterborne paint was in most cases higher than that of P40, but did not result in practically better life expectancy.
- The retroreflectivity of M247 in waterborne paint was equal to or marginally higher than that of Iowa Blend, but the decay rates of the two elements were practically identical.
- Changing the reflective elements in epoxy paint resulted in noticeable change in initial retroreflectivity (Megablend > Iowa Blend > Megablend + M247 > M247). However, the life expectancies were practically identical.
- The performance of surface-applied waterborne paint with M247 on AC was almost identical to that on PCC.
- The retroreflectivity deterioration rate of waterborne paint in wet freeze regions was in general higher than that in dry freeze regions.
- The retroreflectivity deterioration rate of inlaid epoxy paint was in general less than that of surface-applied epoxy paint.
- The addition of WREs in both waterborne and epoxy paints may initially result in marginal benefit to wet retroreflectivity. However, the wet retroreflectivity deteriorates at a high rate (one year or less).

5.3 Recommendations

The following actions are recommended for future implementation.

- A cost/benefit analysis should be based on the pavement marking life-cycle cost (cost per mile per year of acceptable retroreflectivity performance) rather than the initial construction cost per foot as is normally set in a bid or contract price. The cost comparison spreadsheet developed in this study, combined with other factors such as the construction season time window and material availability, should be used to aid in selecting the optimum pavement marking option.
- Since material, labor, and equipment costs and material availability vary from one year to another, the life-cycle cost for the different pavement marking options presented in this study should not be used as a basis for future selection of the optimum pavement marking option. Therefore, the unit costs presented in the cost comparison spreadsheet should be updated annually to reflect the most current material and installation prices.
- Wet reflective elements improve initial retroreflectivity. However, the retroreflectivity of yellow pavement marking was shown to deteriorate rapidly. Therefore, yellow paint should be re-applied annually to maintain acceptable retroreflectivity levels.
- The SDDOT should develop a more robust quality control procedure for evaluating the actual pavement markings thickness and application rates of reflective elements.
- The SDDOT maintenance regions should implement full-term evaluation studies on pavement marking degradation in their respective regions. The collected data can be used to update the decay models in the cost comparison spreadsheet. For future studies on pavement marking, it is recommended that the results of this study be used to select a limited number of pavement marking options that have exhibited good performance with a reasonable life-cycle cost.

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APPENDIX A. QUESTIONNAIRE

This appendix presents the results of a questionnaire that was used to survey the regional traffic engineers from the South Dakota DOT as well as surrounding state DOTs.

A.1 Research Questionnaire

State DOTs were contacted via email and were asked to complete the attached questionnaire. The questionnaire is presented in Table A.1. Specifically, the following SDDOT transportation engineers and neighboring State Department of Transportation personnel were interviewed using the survey questionnaire:

- South Dakota, Alan Petrich,
- South Dakota, Darren Griese,
- South Dakota, Doug Kinniburgh,
- South Dakota, Scott Jansen,
- Iowa, William Zitterich,
- Nebraska, Kevin Wray,
- North Dakota, Matthew Luger,
- Montana, Jim Wingerter,
- Minnesota, Mitch Bartelt,
- Wyoming, Jeff Brown

Table A.2 provides a detailed summary of pertinent responses.

Table A.1 Questionnaire

1. How do you select materials (marking material, glass beads, RPMs, etc.) for long-term pavement markings for your system of roads? (Mark all that may apply)
   - ☐ Retroreflective Performance
   - ☐ Economics
   - ☐ Specifications
   - ☐ Durability
   - ☐ Pavement Surface Type
   - ☐ ADT
   - ☐ Surface Condition
   - ☐ Pavement life remaining
2. Do you use something other than low bid in purchasing pavement marking paint and/or glass beads? If yes, please briefly describe.
3. How do you decide when to remove and replace long-term pavement markings? (e.g., removing one type of marking in preparation for applying another type of marking.) (Mark all that may apply)
   - ☐ Economic Feasibility
   - ☐ Visual Inspection
   - ☐ Predetermined time schedule
   - ☐ Retroreflective Performance
4. What types of specifications are used to provide quality pavement markings? (prescriptive, performance-based, warranty provisions, other)
   - ☐ Prescriptive
   - ☐ Performance Based
   - ☐ Warranty Provisions
   - ☐ Other (specify): _______________
   - ☐ We use more than one
5. What is the cost per linear foot for obtaining and placing each of the marking materials used on your system of roads?

   Waterborne Paint: _____ Epoxy: _____ Solvent Based Paint: _____
   Preformed Tape: _____ Polyurea: _____ Thermoplastics: _____
   Methyl Methacrylate: _____ RRPMs: _____ Polyester: _____
   Other (specify): ____________ _____
6. What is the specified applied thickness (mils) for each marking material you use?

   Waterborne Paint: _____ Epoxy: _____ Solvent Based Paint: _____
   Preformed Tape: _____ Polyurea: _____ Thermoplastics: _____
   Methyl Methacrylate: _____ RRPMs: _____ Polyester: _____
   Other (specify): ____________ _____
7. What are the specified bead type, size, and application rate (lbs/gallon) for each material?

   Waterborne Paint: _________________ _____ Epoxy: _________________ _____
   Solvent Based Paint: _________________ _____ Polyester: _________________ _____
   Thermoplastics: _________________ _____ Polyurea: _________________ _____
   Methyl Methacrylate: _________________ _____ RRPMs: _________________ _____
   Preformed Tape: _________________ _____ Other (specify) __________: ____________ _____
8. Have you had any performance/durability problems on concrete surfaces with pavement marking materials? If yes, please specify materials and problem.
9. How is the pavement surface prepared for application of long-term pavement markings?
10. How do you control the quality of long-term pavement markings at the time of application?
    - ☐ Specify Initial Retroreflectance
    - ☐ Specify Environmental Conditions
    - ☐ Enforce No-Track Time (drying time)
    - ☐ Other (specify): _______________

11. What evaluations do you do to substantiate performance of long-term pavement markings other than retroreflectivity?
12. Do you specify a minimum retroreflectivity level for the initial application?

☐ YES ☐ NO

13. If you answered yes to the previous question list the minimum retroreflectivity levels (in millicandelas/m^2/lux) that you use: (List system and level)

    Minimum Retroreflectivity at Application: ________

    Minimum Retroreflectivity to indicate end-of-service-life: ________

14. How often do you evaluate the retroreflectivity and performance of long-term pavement markings?

☐ Every Year ☐ Every Other Year

☐ Seasonally ☐ Other (specify): ___________

15. Have you conducted any research on pavement markings? If so please give a brief description as to when the research was done, the purpose of the study, and the title of the final report.
16. Have you documented a reduction in traffic crashes/accidents or other benefits as a result of pavement markings?

☐ YES ☐ NO

17. What are the two most significant problems/challenges facing your agency in regards to pavement marking performance?

18. Other comments or suggestions?

Table A.2 Detailed Summary of Responses from the Survey

Question	Summary of Responses
How do you select materials (marking material, glass beads, RPMs, etc.) for long-term pavement markings for your system of roads?	The most prominent responses were that retroreflectivity, economics, and durability of the pavement markings were used in selecting pavement marking materials. All five of the regional traffic engineers in South Dakota selected these options as well as 5 out of the 6 responses from the surrounding states. Other options that were a consensus among the South Dakota regional traffic engineers were the type of pavement to which the markings were to be applied and the surface condition of the pavement. The option that was used the least to help select pavement marking materials was the use of specifications, as only 3 out of 5 South Dakota regional traffic engineers use this and 2 out of 6 from the surrounding states.

Question	Summary of Responses
Do you use something other than low bid in purchasing pavement marking paint and/or glass beads? If yes, please briefly describe.	Of the 5 regional traffic engineers in South Dakota, 3 of them responded that they only use 'low bid' on selecting pavement marking materials while 2 of the regional traffic engineers indicated that they use other means to select pavement marking materials as well. Doug Kinniburgh, the regional traffic engineer for the Rapid City region, stated that they primarily use 'low bid' to select pavement marking materials, but "have purchased small quantities of materials to place as experimental markings over the years." Cliff Reuer, regional traffic engineer for the Pierre region, noted that material that the state maintenance crews use is selected based on a 'low bid' process. However, on resurfacing and chip seal projects, the prime contractor of the project selects a subcontractor to apply/supply the material based on the material specifications in the contract for that particular project. Of the 6 responses from the states surrounding South Dakota, 3 indicated that they only use 'low bid' to select pavement marking materials while the states of Wyoming and Minnesota slightly vary on their selection and Iowa has an entirely different process they follow. Jeff Brown, a principal engineer for the WYDOT, said that he primarily uses the 'low bid' system; however, direct purchasing is done on unique products like a "long pot life epoxy" that they use. William Zitterich, an assistant maintenance engineer with the IADOT, stated that they use retroreflectivity of the beads and paint line to select pavement marking materials. He goes on to say that the beads and paint must meet a minimum reflectivity performance level. Mitch Bartelt, from the MNDOT, indicated that they use 'low bid' for latex pavement markings, but, for epoxy, they use HPS4 for restriping as it has a fast dry time along with most other characteristics of a standard epoxy. The state of Iowa was the only state that was surveyed that does not use some variation of the 'low bid' process to select pavement marking materials.

Question	Summary of Responses
How do you decide when to remove and replace long-term pavement markings? (e.g., removing one type of marking in preparation for applying another type of marking.)	All 5 regional traffic engineers from South Dakota along with the responses from all 6 surrounding states selected the use of visual inspection as a means of deciding when to remove/replace long-term pavement markings. The use of retroreflective performance was also nearly unanimous as all 5 SDDOT regional traffic engineers selected this option as well as 5 of the 6 surrounding states, with the state of North Dakota not selecting this option as they only use visual inspection. Economic feasibility was also selected in many of the surveys as 4 of the 5 regional traffic engineers in South Dakota selected this along with 3 of the 6 surrounding states. By far, the least popular option to help select when to remove/replace long-term pavement markings was a predetermined time schedule as only the SDDOT regional traffic engineer for the Mitchell region, Scott Jansen, and the MNDOT, represented by Mitch Bartelt, selected this option. Scott stated that they sometimes use a predetermined time schedule because of their experience with respect to long-term pavement markings based on past history and available data. Mitch Bartelt stated that restriping is primarily determine by retroreflective performance in Minnesota, while some districts are on predetermined restriping schedules as almost all districts restripe latex pavement markings yearly.
What types of specifications are used to provide quality pavement markings? (prescriptive, performance-based, warranty provisions, other)	The most popular response for this question was that the use of more than one specification is used to provide quality pavement markings. Of the 5 regional traffic engineers within the SDDOT, 3 selected this option as well as 4 of the 6 states that surround South Dakota. The remaining 2 regional traffic engineers from the SDDOT along with the state of Minnesota selected the use of prescriptive specifications in order to provide quality pavement markings on their roadways. The only remaining response from this question was that the state of Iowa uses performance-based specifications to provide quality pavement markings. ‘Warranty provisions’ was not individually selected as a response for this question, but it was indicated by one regional traffic engineer from the SDDOT and 2 of the surrounding states that ‘warranty provisions’ was one of the types of specifications that they use as they selected the option that of, ‘we use more than one’ for this question.

Question	Summary of Responses
What is the cost per linear foot for obtaining and placing each of the marking materials used on your system of roads?	Only 3 of the 5 SDDOT regional traffic engineers responded to this question, and each of the three responses only provided the cost per linear foot for waterborne paint, epoxy paint, and preformed tape. The range of the responses is quite large, especially for the placement of waterborne paints. Scott Jansen and Alan Petrich gave the cost of one linear foot of waterborne paint pavement marking to be \$0.02-0.03 and \$0.04, respectively. Cliff Reuer listed a price of \$0.40 per linear foot of waterborne paint pavement markings. This is ten times higher than the other two responses from the SDDOT. Alan, Cliff, and Scott gave estimated costs of \$0.24, \$2.25, and \$0.32-0.35 for epoxy paint pavement markings. As with the waterborne paints, Cliff indicated a cost that was about ten times higher for epoxy paint pavement markings. The cost of one linear foot of preformed tape pavement markings was given as \$2.19, \$2.50, and \$2.85 by Alan, Cliff, and Scott, respectively. The range of costs for preformed tape is much more agreeable than the range given for the waterborne paint and epoxy paint pavement markings. Estimated costs were received from each of the 6 states that surround South Dakota, with the types of pavement marking materials that prices were given for varying. First off, 5 of the 6 states gave estimated costs for the placement of one foot of waterborne paint pavement markings. William Zitterich from Iowa gave an estimate of \$0.07-0.08, Mitch Bartelt from Minnesota gave an estimate of \$0.19, Jeff Brown from Wyoming gave an estimate of \$0.045, Matt Luger from North Dakota gave an estimate of \$0.06, and Jim Wingerter from Montana gave a cost of \$19 per gallon of paint applied. The general theme of all responses that gave an estimate for waterborne paint pavement markings shows that one could expect this to cost, on average, about \$0.06 per linear foot. There are two outliers from the general consensus with Minnesota estimating a price of \$0.19 and Cliff Reuer from the SDDOT Pierre region estimating a price of \$0.40 per foot.

Question	Summary of Responses
What is the cost per linear foot for obtaining and placing each of the marking materials used on your system of roads? (CONTINUED)	Also for the responses from South Dakota's surrounding states, 4 of the 6 responses provided an estimate for the price of placing epoxy paint pavement markings. Mitch, Jeff, Matt, and Jim provided epoxy prices of $0.29 per linear foot, $0.24 per linear foot, $0.23 per linear foot, and $19/gallon, respectively. These costs agree with the estimates from the SDDOT regional traffic engineers. Jeff, Matt, Mitch, and Kevin also provided the estimated cost to apply one linear foot of preformed tape pavement markings. The estimates were $4-5, $2.86, $2.58, and $2.40, respectively. The estimates from Matt, Mitch, and Kevin are very close to the estimates from the SDDOT regional traffic engineers' estimates and Jeff's estimate is about 50% higher. There were also two estimates received on the cost to apply one linear foot of polyurea pavement markings from Mitch and Kevin. Mitch's estimate was $1.10 per linear foot and Kevin's estimate was $1.00 per linear foot. This is a very small sample size, but the two prices given are very close to each other and are probably a good representative of the expected cost to apply polyurea pavement markings. Kevin and Jeff each provided a cost estimate to place one linear foot of thermoplastic pavement markings, with the estimates being $0.90 and $10.00-15.00, respectively. These two estimates not close to agreeable, thus these numbers may not provide a good representative of what one should expect the cost to be to apply thermoplastic pavement markings. The last cost estimate that was received from the survey responses was an estimate of $3.00-4.00 per linear foot to apply methyl methacrylate (MMA) pavement markings from Jeff. This price closely compares to the cost to apply preformed tape pavement markings.

Question	Summary of Responses
What is the specified applied thickness (mils) for each marking material you use?	All five regional traffic engineers from the SDDOT agreed that the applied thickness of waterborne paint pavement markings should be 15 mils, with the response from Darren giving a range of 15-20 mils. The specified waterborne paint pavement marking thicknesses from the states that surround South Dakota are 16 mils for Wyoming, 15-20 mils for Minnesota, 16 mils for Montana, 16 mils for North Dakota, and 15-16 mils for Iowa. All of the specified thicknesses from the SDDOT and the surrounding states strongly agree. Scott and Alan provided the thickness that they specify for epoxy pavement markings as 20 mils, with Alan noting that this was based on manufacturer's recommendations. Doug did not specify a thickness, but noted that he uses the thickness that the manufacturer recommends. For epoxy paint pavement markings, Wyoming specifies 20 mils, Minnesota specifies 20-25 mils, Montana specifies 20 mils, and North Dakota specifies 20 mils. Once again, the specified thicknesses from the SDDOT and the surrounding states strongly agree for epoxy paint pavement markings. Scott, Alan, Doug, and Darren provided the specified thickness of preformed tape to be 80-120 mils, 75-90 mils, 0.06", and 80 mils, respectively. North Dakota, Nebraska, Wyoming, and Minnesota each provided a specified thickness for preformed tape pavement markings. The thicknesses specified were 65 mils, 100 mils, 65 mils, and 65 mils. Excluding Nebraska, South Dakota specifies a larger thickness for preformed tape pavement markings than the surrounding states. Alan also provided a specified thickness for MMA pavement markings of 20 mils. Alan also noted that he follow the manufacturer's recommended thickness for polyurea and thermoplastic pavement markings. Doug also noted that he followed the manufacturer's recommended thickness for polyurea, thermoplastic, and MMA pavement markings.
What is the specified applied thickness (mils) for each marking material you use? (CONTINUED)	Nebraska also provided the specified thicknesses for polyurea and thermoplastic pavement markings to be 20-22 mils and 125 mils, respectively. Wyoming specifies up to 125 mils for thermoplastic pavement markings and 60 mils for MMA pavement markings. Montana also provided a specified thickness for thermoplastic pavement markings of 275-400 mils.

Question	Summary of Responses
What are the specified bead type, size, and application rate (lbs/gallon) for each material?	For waterborne paint pavement markings, Alan and Darren gave responses of 7 lbs/gal (type I) and 6 lbs/gal (M247), respectively. Scott and Doug each noted that these rates were state specified. For waterborne paint pavement markings for the states that surround South Dakota, Montana, Wyoming, Iowa, and Minnesota specify 8 lbs/gal, with Iowa specifying M247 glass beads Wyoming specifying Type I. North Dakota specifies 6 lbs/gal of M247 glass beads for waterborne paint. For epoxy paint pavement markings, Alan specifies 25 lbs/gal (type I) of glass beads. Scott did not provide a rate, but noted that he uses "Megablend" glass beads for epoxy. Montana, Wyoming, and North Dakota each specify 25 lbs/gal for epoxy pavement markings. Wyoming specifies 12.5 lbs/gal each of Type I and Type II glass beads and North Dakota specifies M247 glass beads. Minnesota specifies 8 lbs/gal of M247 glass beads for epoxy paint pavement markings. Other than Minnesota, there is a common theme of using 25 lbs/gal of glass beads for epoxy paint pavement markings. The only other response for this question from the SDDOT traffic engineers was from Alan as he gave a bead rate of 25 lbs/gal (type I) for MMA pavement markings. Wyoming also provided a bead rate for MMA pavement markings, and this was 10 lbs/gal of Type I glass beads. The last bead rate that was given for this question was a 6lb/100 square feet for thermoplastics from the state of Montana.
Have you had any performance/durability problems on concrete surfaces with pavement marking materials? If yes, please specify materials and problem.	Scott Jansen stated that if pavement markings are not applied in recessed grooves, snow plows remove reflective elements. Alan Petrich noted that the main problem that he has encountered is that there is less adhesion of pavement markings on polished concrete surfaces, and this causes accelerated wear of the pavement markings in high ADT locations. Cliff Reuer mentioned that when the SDDOT first started using epoxy paint, the markings would turn gray and blend in with the color of the concrete. According to Jim Wingerter, epoxy and waterborne paints do not last very long due to severe weather and snow plowing. William Zitterich stated that the curing compound residue on new concrete pavement will cause paint to not stick as well and will result in a loss of paint. Mitch Bartelt said that concrete surfaces are usually not problematic as Minnesota typically grooves-in tape skips and sandblast before epoxy edgelines are installed.

Question	Summary of Responses
How is the pavement surface prepared for application of long-term pavement markings	The general consensus among the regional traffic engineers for the SDDOT is that they apply pavement markings in shallow grooves for long-term pavement markings, with Scott noting that the top of the marking should be approximately 15 mils below the pavement surface Minnesota typically grooves-in tape skips and sandblasts before epoxy edgelines are installed on concrete. For asphalt pavements, Minnesota usually inlays tape during paving operations and/or installs epoxy a minimum of 3 days after paving. William Zitterich from the Iowa DOT stated that long-term pavement markings are applied in dry, dust-free grooves. However, Iowa applies very little long-term pavement markings as they usually just place waterborne paint on a clean pavement surface. Wyoming typically removes the old pavement markings before applying new epoxy markings and they place MMA and preformed tape markings in grooves. When placing preformed tape pavement markings, North Dakota typically places them in recessed grooves, tests for moisture in the pavement, and follows manufacturer's recommendations. For epoxy pavement markings, North Dakota removes the existing pavement marking before placing the new markings. Seal coats must be completely cured and then brushed before placing epoxy pavement markings. Nebraska noted that they place the pavement markings in recessed grooves.
How do you control the quality of long-term pavement markings at the time of application?	All 5 of the regional traffic engineers for the SDDOT specify initial retroreflectivity levels, 4 of the 5 enforce a no-track time at the time of application and 3 of the 5 specify environmental conditions at the time of application. Alan, Doug, and Scott noted that field sampling and testing of the materials is done to ensure that the products conform to the specifications and that field inspection is done to be sure that the manufacturer's recommendations are followed when the pavement markings are placed. All 6 states that surround South Dakota specify initial retroreflectivity levels for pavement markings, with North Dakota noting that the NDDOT only uses this for epoxy paint pavement markings. Nebraska and Wyoming enforce a no-track time after the application of pavement markings and North Dakota, Wyoming, Montana, and Minnesota all specify environmental conditions for the application of pavement markings. Other notes from this question are that Nebraska has a 180-day acceptance period and Wyoming specifies the resin used in the paint.

Question	Summary of Responses
What evaluations do you do to substantiate performance of long-term pavement markings other than retroreflectivity?	For the SDDOT, all 5 regional traffic engineers noted that night and day visual inspections are done for pavement markings. North Dakota, Montana, Wyoming, Iowa, and Minnesota all stated that they also use visual inspections for pavement markings. Nebraska checks the durability of the materials by checking the percent of the pavement marking remaining.
Do you specify a minimum retroreflectivity level for the initial application?	All 5 regional traffic engineers for the SDDOT and all DOTs of the 6 states that surround South Dakota specify a minimum retroreflectivity level. However, the SDDOT regional traffic engineers and North Dakota noted that they only specify minimum retroreflectivity levels for sprayable durable pavement markings (epoxy).
If you answered yes to the previous question list the minimum retroreflectivity levels (in millicandelas/m^2/lux) that you use	Alan, Cliff, Scott, and Doug listed the minimum retroreflectivity levels for epoxy pavement markings as 260 for white and 160 for yellow. Alan also notes that South Dakota does not have an established state-wide standard to replace pavement markings based on retroreflectivity levels, but, as a guideline, he uses minimum retroreflectivity levels of 100 for white markings and 70 for yellow markings. Darren lists the minimum retroreflectivity levels as 350 for white markings and 275 for yellow markings. He also lists the end-of-service-life retroreflectivity levels as 100 for white and 80 for yellow. North Dakota specifies minimum retroreflectivity levels of 275 for white and 180 for yellow. Wyoming specifies 200 for their pavement markings. Iowa gave minimum retroreflectivity levels as 300 for white and 200 for yellow with end-of-service-life levels being 150 for white and 100 for yellow. Minnesota listed different minimum retroreflectivity levels for tape, epoxy, and latex pavement markings. For tape they use 600 for white and 500 for yellow. For epoxy the minimum levels are 300 for white and 200 for yellow, and for latex they use 275 for white and 180 for yellow. For the end-of-service-life levels, Minnesota does not have anything specified, but they typically use 100 for white and 80 for yellow to indicate the need of a restriping project. Nebraska gave minimum retroreflectivity levels for polyurea pavement markings as 500 for white and 350 for yellow. Montana provided minimum retroreflectivity levels as 0.20 candelas/foot-candle/ft^2 for white and 0.15 candelas/foot-candle/ft^2 for yellow.

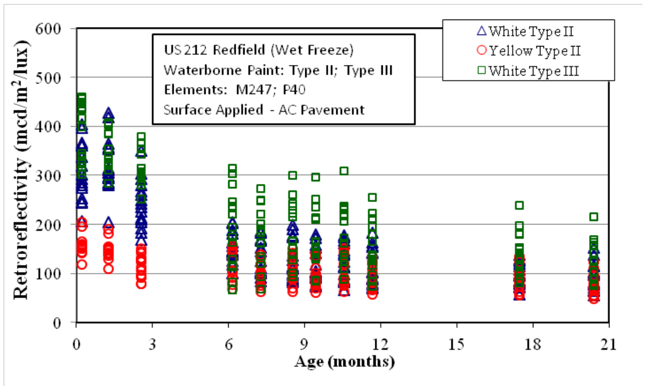
Question	Summary of Responses
How often do you evaluate the retroreflectivity and performance of long-term pavement markings?	All 5 of the SDDOT regional traffic engineers indicated that they evaluate the retroreflectivity and performance of long-term pavement markings every year. Of the surrounding states, only Montana and Nebraska indicated that they evaluate long-term pavement markings every year. North Dakota stated that they only evaluate the performance of long-term pavement markings at the time of application. Iowa evaluates the performance of long-term pavement markings twice each year, once in the spring and once in the fall. Minnesota noted that readings are taken as requested. Some districts ask for and use more retroreflectivity readings and others less.
Have you conducted any research on pavement markings? If so please give a brief description as to when the research was done, the purpose of the study, and the title of the final report.	Scott Jansen noted that several different informal projects have been done over the past 22 years. He goes on to say that they install the markings on a project and track their performance over time. Future applications are based on this experience. Records of these projects were kept by other offices within the DOT. Mitch Bartelt of the MNDOT said that there is currently a research project by the MNDOT Safety section evaluating the use of enhanced edgelines. Three countermeasures are being experimented with in this project, and they are sections with 6” wide edgelines, edgeline rumble stripes, and grooved-in wet-reflective edgelines. These test lines were constructed in 2008 and they expect the project to come to a conclusion in 2011. William Zitterich of the IADOT stated that they have conducted research on pavement markings and that most of it is an internal test without a formal written report. The IADOT has conducted a project to see if it was cost effective to put the centerline paint stripe in a groove. The IADOT is currently working with Iowa State University and the Iowa Highway Research Board on a wet-reflective paint research project comparing many different wet-reflective paint products. ISU is in the middle of a research project on a zero-velocity bead applicator to go on their paint trucks that will increase paint truck speed and also reduce the bead use. William finished by saying that there will be a formal report for this when the project is completed. Matt Luger of the NDDOT provided a web address where one can review pavement markings studies by the NDDOT. The web address is: www.dot.nd.gov/disions/materials/reserachtype.asp ?type=1&ctgry=pavement%20markings

Question	Summary of Responses
Have you documented a reduction in traffic crashes/accidents or other benefits as a result of pavement markings?	All 5 regional traffic engineers for the SDDOT along with all surrounding states except Iowa answered 'NO' to this question. Iowa stated that the IADOT is currently working with Iowa State University to find the relationship between paint line retroreflectivity and accident rate. The project is currently under way. Minnesota also noted that the project he discussed in question 15 may show a documented reduction in the accident rate upon the project's completion in 2011.
What are the two most significant problems/challenges facing your agency in regards to pavement marking performance?	Alan Petrich said that the two most significant problems/challenges he faces are providing pavement markings on the highway system 365 days a year and also selecting the most cost-efficient markings for the segment of highway being marked. Cliff Reuer listed his most significant problems/challenges as snow plow damage, truck turning movements at intersections, and sand/salt abrasion. Dough Kinniburgh answered that funding to be able to maintain and expand durable markings is his biggest challenge. Scott Jansen stated his two biggest problems/challenges as the damage to markings not recessed by snow plows and winter maintenance abrasives, and the quality of the work done by contractors. Darren Griese answered that available funding is the biggest challenge he faces when trying to provide adequate pavement markings. Mitch Bartelt of the MNDOT listed pavement markings on sealcoat, chip seal, and micro seal surfaces as the biggest problem he faces. William Zitterich from the IADOT stated that damage of the paint lines due to snow plows along with the damage of the paint lines due to maintenance operations repairing edge ruts as his two biggest problems/challenges that he faces. Jeff Brown from the WYDOT answered that one challenge is finding the perfect balance between the low cost waterborne markings that the WYDOT forces them to apply and the higher cost (better performing) contract epoxy work. He went on to say that another challenge he has is in the rural part of the state as it can be tough finding locations to put together a large enough project to ensure good bid prices when contracting out more expensive durable markings. Kevin Wray of the NEDOR listed his two biggest challenges as snow plow/winter driving damage and vehicle damage in high traffic areas.

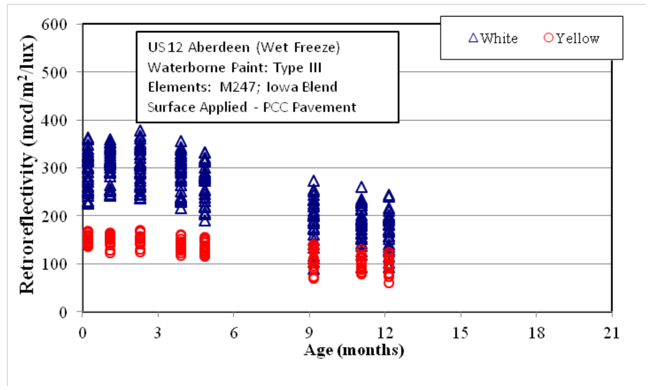
Question	Summary of Responses
What are the two most significant problems/challenges facing your agency in regards to pavement marking performance? (CONTINUED)	Jim Wingerter of the MTDOT listed durability and application as the two biggest challenges that he faces. Matt Luger from the NDDOT listed his two biggest challenges as maintaining retroreflectivity levels and durability.
Other comments or suggestions?	Scott Jansen commented on the typical service life that he expects for the different types of pavement markings that he applies: He stated that non-recessed waterborne paint markings on rural roads typically last 9 months to 2 years depending on ADT and size of the community. He went on to say that non-recessed waterborne paint on urban roads typically lasts 2 weeks to 9 months depending on ADT and size of the community. Next, Scott noted that recessed epoxy pavement markings usually last 5 years on rural concrete interstate highways and rural 2-lane concrete roadways, and 2-3 years on urban concrete interstate highways. Lastly he listed the expected service life of recessed cold applied plastic pavement markings as 7 years in urban locations.

APPENDIX B. DETAILED FIGURES

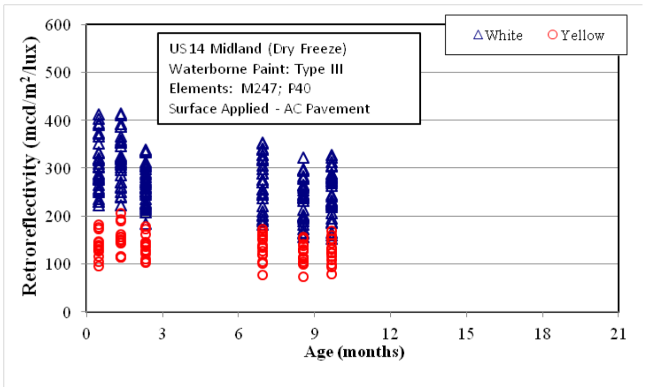
Figure B.1 Measured Retroreflectivity versus Pavement Marking Age



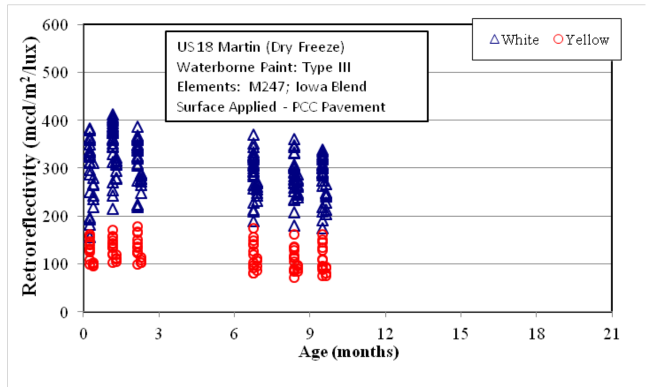
(a) US 212 Redfield



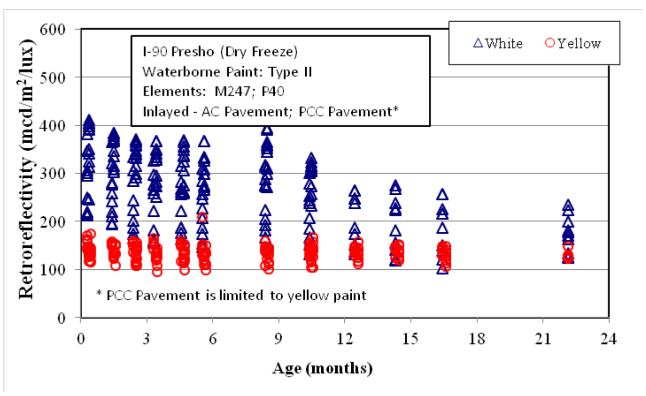
(b) US 12 Aberdeen



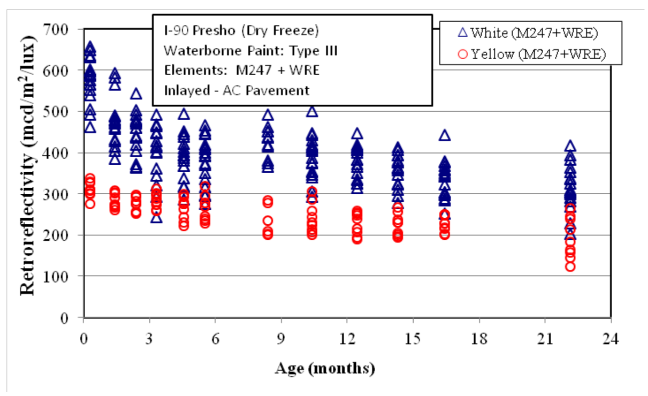
(c) US 14 Midland



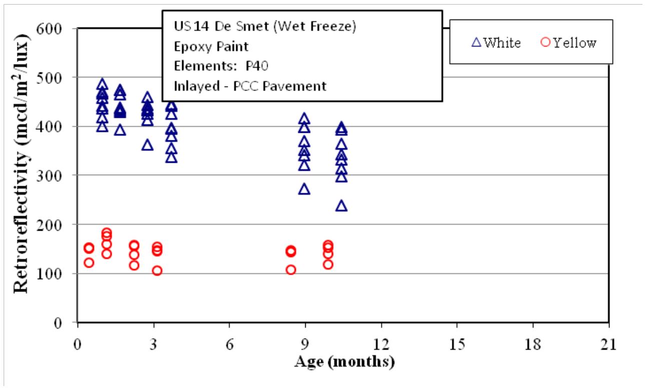
(d) US 18 Martin



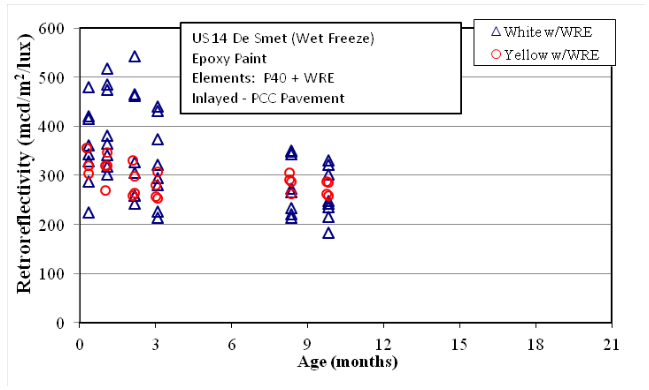
(e) I-90 Presho (Glass beads Only)



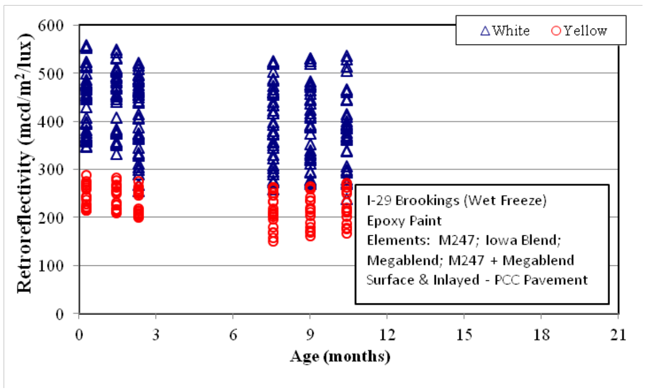
(f) I-90 Presho (Glass Beads + WRE)



(g) US 14 De Smet (Glass Beads Only)

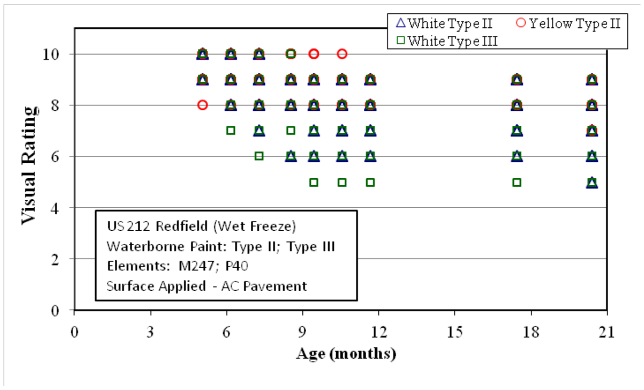


(h) US 14 De Smet (Glass Beads + WRE)

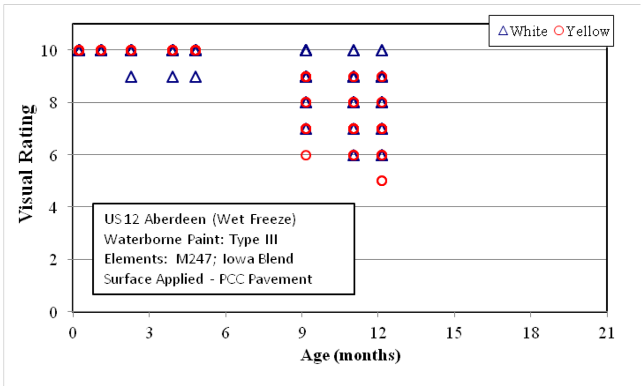


(i) I-29 Brookings

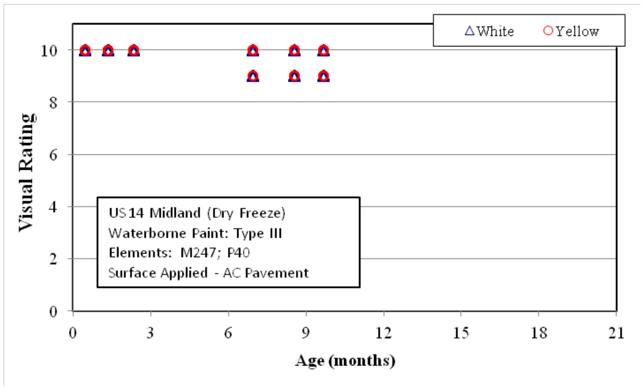
Figure B.2 Measured Visual Rating versus Pavement Marking Age



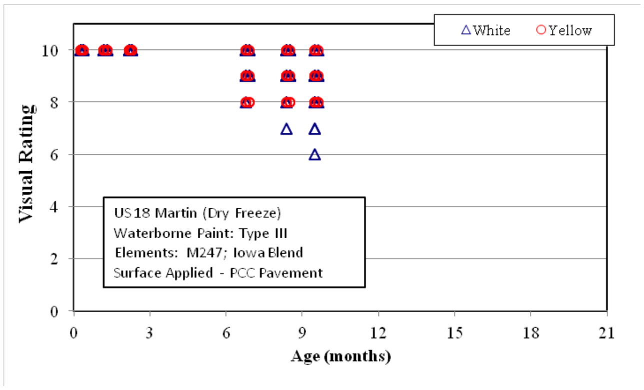
(a) US 212 Redfield



(b) US 12 Aberdeen

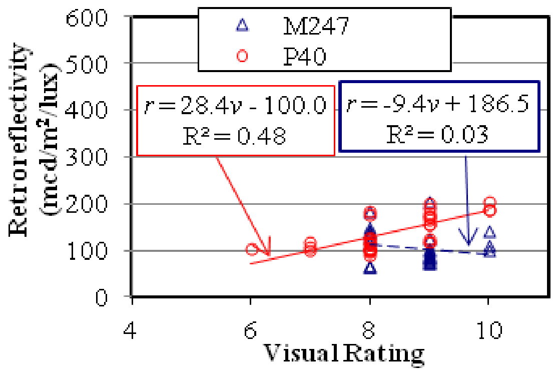


(c) US 14 Midland

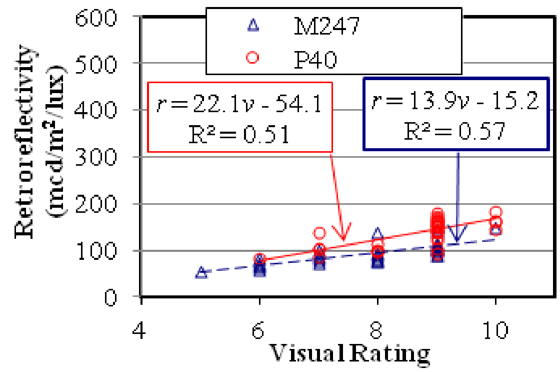


(d) US 18 Martin

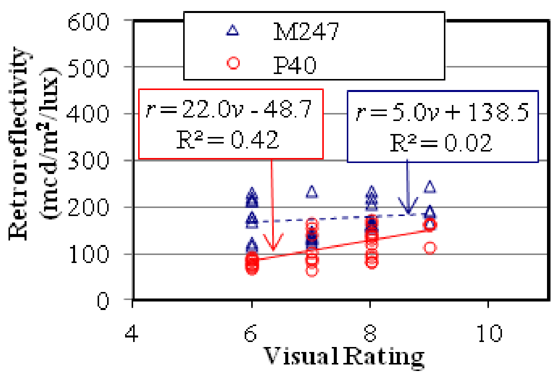
Figure B.3 Retroreflectivity versus Visual Rating for the US 212 Redfield Test Section



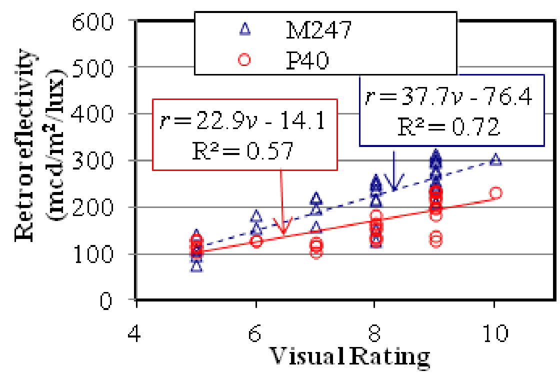
(a) Type II, 15 mils, WEL on AC



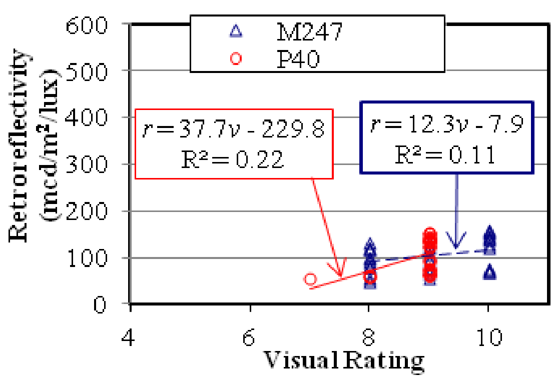
(b) Type II, 17 mils, WEL on AC



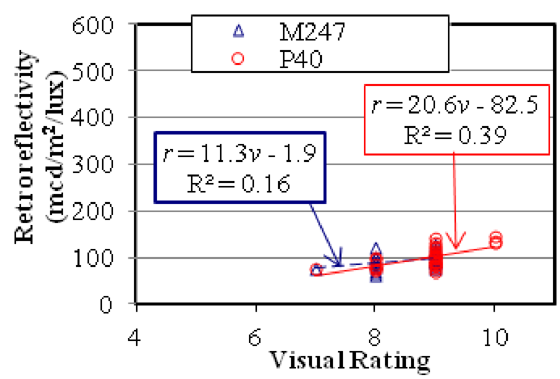
(c) Type III, 17 mils, WEL on AC



(d) Type III, 20 mils, WEL on AC

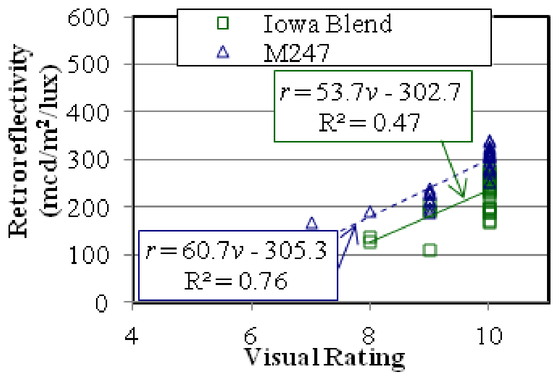


(e) Type III, 17 mils, WEL on AC

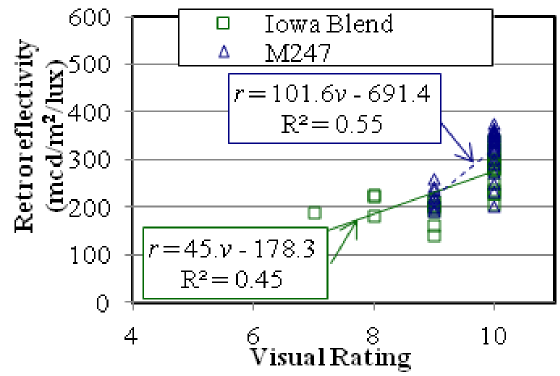


(f) Type III, 20 mils, WEL on AC

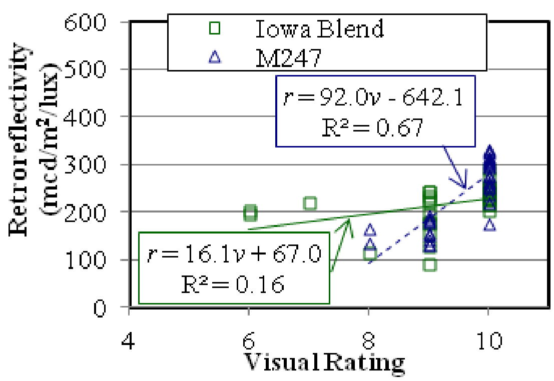
Figure B.4 Retroreflectivity versus Visual Rating for the US 12 Aberdeen Test Section



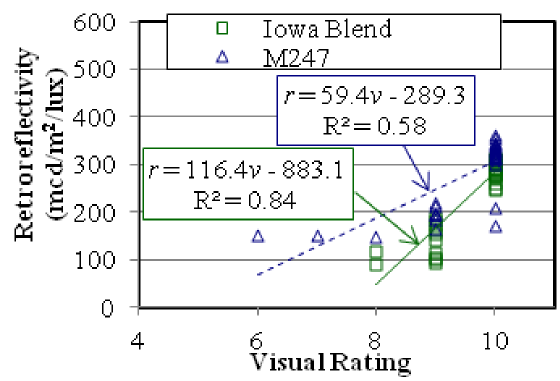
(a) Type III, 15 mils, WEL on PCC



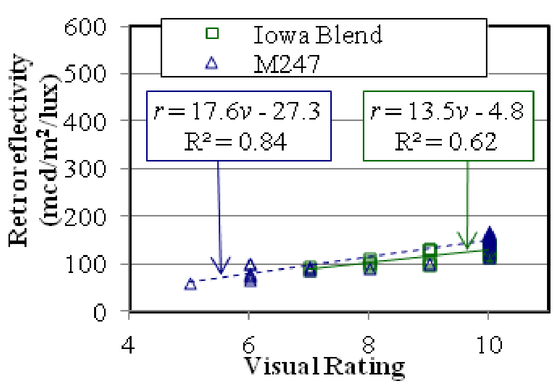
(b) Type III, 20 mils, WEL on PCC



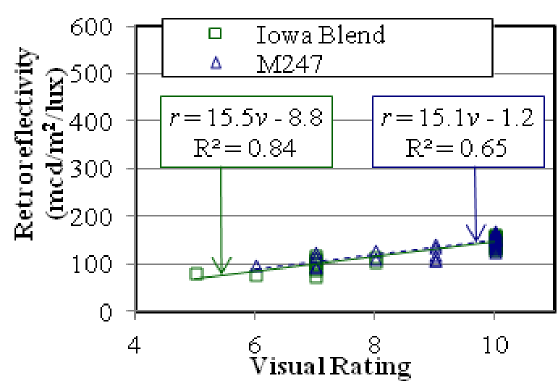
(c) Type III, 15 mils, WSL on PCC



(d) Type III, 20 mils, WSL on PCC

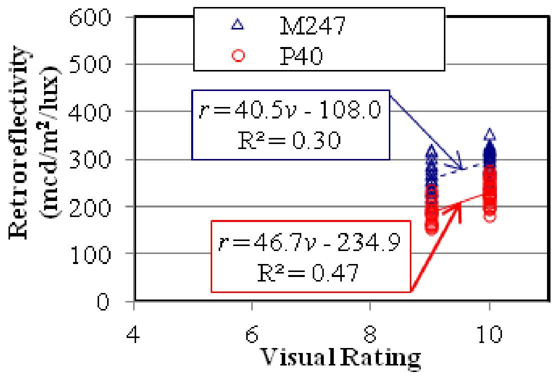


(e) Type III, 15 mils, YEL on PCC

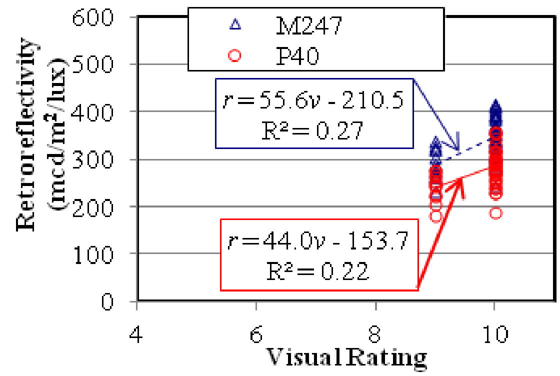


(f) Type III, 20 mils, YEL on PCC

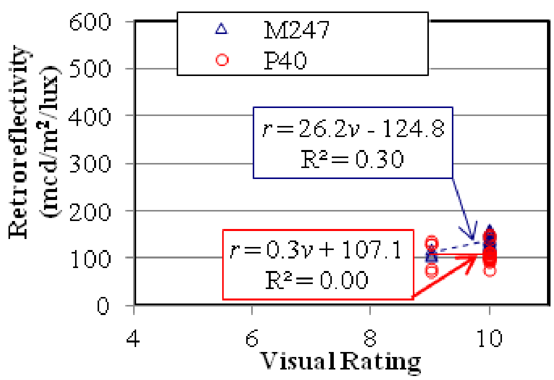
Figure B.5 Retroreflectivity versus Visual Rating for the US 14 Midland Test Section



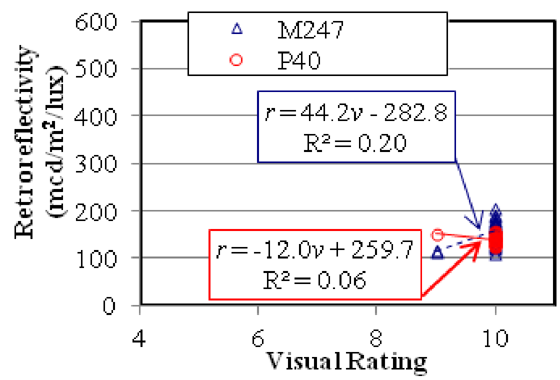
(a) Type III, 15 mils, WEL on AC



(b) Type III, 20 mils, WEL on AC

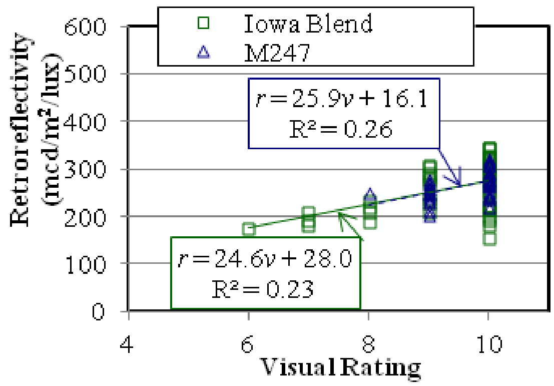


(c) Type III, 15 mils, YSL on AC

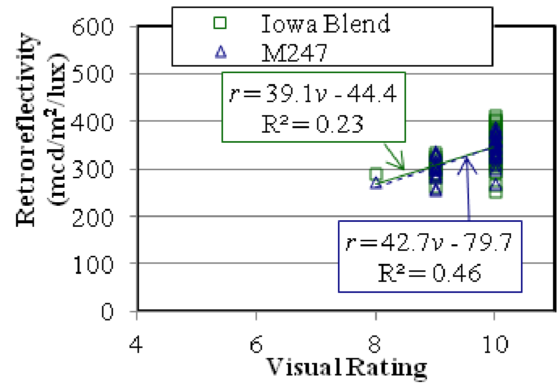


(d) Type III, 20 mils, YSL on AC

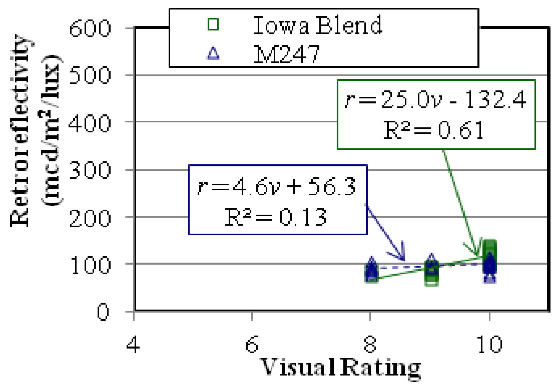
Figure B.6 Retroreflectivity versus Visual Rating for the US 18 Martin Test Section



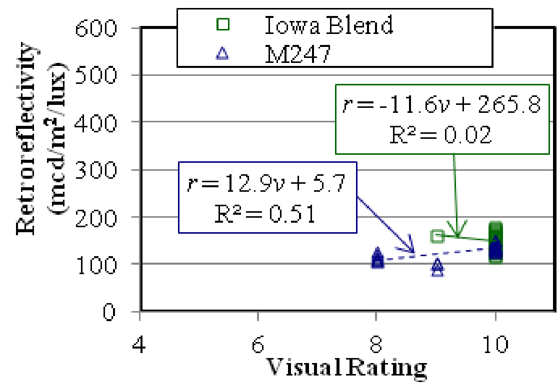
(a) Type III, 15 mils, WEL on PCC



(b) Type III, 20 mils, WEL on PCC



(c) Type III, 15 mils, YSL on PCC



(d) Type III, 20 mils, YSL on PCC

APPENDIX C. COSTS

Table C.1 Basic Costs

Product	Cost	Units			
Paints					
White Waterbourne Paint Type II (STATE SPEC.)	17	$/Gallon			
Yellow Waterbourne Paint Type II (STATE SPEC.)	17.5	$/Gallon			
White Waterbourne Paint Type III (High Build)	17	$/Gallon			
Yellow Waterbourne Paint Type III (High Build)	17.5	$/Gallon			
Epoxy	M247	Iowa Blend	Mega Blend	M247+ Mega Blend	Units
White Epoxy Type II (Slow Cure) w/Reflective Elements	0.35	0.35	0.35	0.35	$/Feet
Yellow Epoxy Type II (Slow Cure) w/Reflective Elements	0.35	0.35	0.35	0.35	$/Feet
Reflective Elements					
P40 Gradation	0.334	$/Pound			
AASHTO M 247, Type I Gradation	0.334	$/Pound			
Dual Reg. SD-IA Blend Gradation	0.334	$/Pound			
SD Reg. Mega Blend Gradation	0.334	$/Pound			
Wet Reflective Elements	2	$/Pound			
Pavement Preperation					
Surface Preperation	0.31	$/Feet			
Grooving for 4" Pavement Marking PCC	0.45	$/Feet			
Grooving for 4" Pavement Marking AC	0.45	$/Feet			